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Bogda Mountains: image taken September 1st, 1999 by LANDSAT 7. The Turpan Depression, nestled at the foot of China’s Bogda Mountains, is a strange mix of salt lakes and sand dunes, and is one of the few places in the world that lies below sea level. Image courtesy of USGS National Center for EROS and NASA Landsat Project Science Of

Small figures from top to down: detail of Fig. 2 from Alba et al., detail of Fig. 2 from Tarantino et al.; detail of Fig. 2 from Fabris et al.; detail of Fig. 5 from Mei et al.
Editorial of AIT President

Dear Readers,

It was in the year 1986 that the Italian Remote Sensing Society (AIT) was founded; in October 1987, the Board of Directors approved the following: “After deliberating, a decision is made to print a four-monthly news bulletin to be handed over free of charge to the Members ... and to evaluate the possibility of an annual brilliant-looking edition. A decision is made to start working right away on the first issue, planned to be printed before the end of year 1987. Mr. Mogorovich, as Scientific Secretary, is appointed editor of this first issue, assisted by Mr. Dainelli, as Secretary General. Mr. Tonelli is requested to check the possibility to renew his membership to the Journalist Association”.

Due to some justifiable delays, the first issue of the journal “AIT Informa” is published only in May 1988. After 23 years of honorable history and 43 published issues, I believe it is of capital importance to verify whether the principles upon which the journal was founded are still valid and if, in the meantime, it has fulfilled the needs considered essential in the Parma meeting.

Doubtless our journal has rediscovered its fundamental aim of informing the Members, as thought by the founders, and of providing high quality technical and scientific content. In June 1993 the journal is renamed “Rivista Italiana di Telerilevamento” and is given a new look edition which will be maintained up to today in its main contents.

Its look, “brilliant” as it was stated, has always been a prior feature, whose style, graphics, colour images and layout have provided a solid added value making it reader-friendly and elegant at the same time.

Furthermore, in the latest years, the considerable publication of scientific papers in English language, that led to the inevitable and desired name “Italian Journal of Remote Sensing”, coincided with the auspice that Francesco Greco expressed in the first issue’s editorial: “It is the desire of all AIT members and mine too, to be an active part of the European Remote Sensing community and to contribute to the spreading and development of Remote Sensing for enhanced conditions of life. Through our “AIT informa” we wish to invite all the other Remote Sensing Associations in Europe and in the world to establish a real communication channel with us and provide us with timely information about their activities and initiatives for inclusion in future issues of the “AIT informa”, on permanent basis.”.

It is for these reasons, and because of what was expressed by Director Marco Marchetti in the following editorial, that our Society Board of Directors, together with our journal’s Editors, has decided to change the current typographical layout and to take up an electronic format, in order to better pursue the Society aims and to face the international scientific community challenges and keep up with the consistent technological progresses. This way a greater timeliness in the publication of the scientific contents is guaranteed and the increasing request for publication by Italian and foreign authors can be fulfilled, ensuring at the same time its distinguishing high editorial and content quality.

Hoping you will favorably approve the changes proposed, I guarantee, on behalf of the AIT’s Board of Directors, that major efforts will be taken to make sure that the value of our journal will be nourished and strengthened in the future.

Greatest regards,

Piero Boccardo
AIT President
Ehil tö ihe d'l Presid nte AIT

Cari Lettori,

Nella realtà, a causa di alcuni e giustificabili ritardi, nel maggio viene edito il primo numero della rivista che assume la denominazione di AIT Informa.

Dopo anni di onorata carriera e di 43 numeri editi, credo che sia fondamentale verificare se i presupposti su di cui la rivista venne fondata siano tuttora validi e se, nel contempo, essa abbia ottemperato alle esigenze che nella riunione di Parma vennero considerate imprescindibili.

Senza ogni dubbio, la rivista della nostra Associazione, che nel giugno 1993 assume una nuova veste grafica, che, nei suoi contenuti principali, ha mantenuto sino ad oggi, prendendo il nome di “Rivista Italiana di Telerilevamento” e che nel 2007 riporta come sottotitolo “Italian Journal of Remote Sensing”, ha ricoperto il suo ruolo fondamentale, come sostenuto dai suoi fondatori, di informazione per i soci e di un elevato contenuto tecnico/scientifico. La sua veste tipografica (“brillante”, come viene esplicitamente enunciato), è da sempre stata una caratteristica fondante, in cui, stile, grafica, immagini a colori e impaginazione, hanno fornito un consistente valore aggiunto garantendo nel contempo, una notevole facilità di lettura e l’eleganza editoriale che l’ha sempre contraddistinta.

Inoltre, negli ultimi anni, la consistente pubblicazione di contributi scientifici in lingua inglese, che ha portato all’inevitabile e auspicata denominazione di “Italian Journal of Remote Sensing”, è concisa con l’auspicio riportato da Francesco Greco nell’editoriale del primo numero: “It is the desire of all AIT members and mine too, to be an active part of the European Remote Sensing community and to contribute to the spreading and development of Remote Sensing for enhanced conditions of life. Through our “AIT informa” we wish to invite all the other Remote Sensing Associations in Europe and in the world to establish a real communication channel with us and provide us with timely information about their activities and initiatives for inclusion in future issues of the “AIT informa”, on permanent basis.”.

Proprio per queste ragioni, e per quanto riportato dal Direttore Marco Marchetti nell’editoriale seguente, che il Consiglio Direttivo della nostra Associazione, di concerto con il Comitato Redazionale della nostra rivista, ha ritenuto, con lo scopo di meglio perseguire i fini dell’Associazione stessa, le sfide che ci impone la comunità scientifica internazionale e i consistenti avanzamenti tecnologici, di abbandonare l’attuale assetto tipografico per passare ad un formato elettronico. Ciò per consentire una maggiore tempestività nella pubblicazione dei contributi scientifici e per soddisfare la sempre maggiore richiesta di pubblicazione da parte di autori italiani e stranieri, garantendo, nel contempo, l’alta qualità editoriale e di contenuti che ha sempre contraddistinto la nostra pubblicazione.

Confidando in un vostro positivo accoglimento di questa sostanziali modifiche, garantisco, a nome di tutto il Consiglio Direttivo dell’AIT, di impegnarmi e di profondere tutti gli sforzi necessari affinché il patrimonio che la nostra rivista costituisce, si accresca e si consolidi nel prossimo futuro.

Un caro saluto,

Piero Boccardo
Presidente AIT
Editorial of Editor-in-Chief

Dear readers, dear members,
this is the last issue published on paper of the Italian Journal of Remote Sensing. In the Editorial of AIT President you will find a synthesis of the history of our journal which represents an efficient and a very beautiful tool we have inherited from our predecessors. It’s my job to remember that the transition to the on line journal, which has been proposed by the Editorial board and approved by the Council, should not be considered solely a way to save money but rather an opportunity for our community to strengthen the comparison at international level (which is a typical characteristic of technologies we are using). In fact, on line publication of papers will allow for a simplified and rapid spreading of new technologies and methodologies. Certainly the transition to the on line journal can have some unwanted effects, like the risk of superficiality or the risk of losing some stakeholders. However, we are hopeful that our choice will bring advantages for researchers and we are confident that the strictness we are persecuting will reward the quality of the journal. I wish to thanks all of you for the trust you ever gave me. In addition, thanks to the Associated Editors and the Editorial staff members for their great engagement and skill, without their work nothing should be possible.

Best regards,

Marco Marchetti
Editor-in-Chief
Editoriale del Direttore

Cari lettori e cari soci,
è con gioia ma anche con una certa apprensione che ci accingiamo a fare un ulteriore passo in avanti nella breve storia della nostra rivista. Nell’editoriale del Presidente AIT troverete il racconto del percorso che abbiamo fatto finora e del quale dobbiamo ringraziare i nostri predecessori per averci lasciato in eredità uno strumento efficiente e molto bello.
È mio compito e mia premura sottolineare che la migrazione online della rivista, ipotizzata da tempo e approvata dal Consiglio su proposta della redazione, non deve essere considerata solo una via di puro risparmio, peraltro utile e capace di liberare risorse necessarie per altre iniziative, ma piuttosto una opportunità di crescita dell’intera comunità, capace di potenziare il confronto internazionale (caratteristica di base delle tecnologie di cui facciamo uso) e transdisciplinare. Infatti, la pubblicazione on line degli articoli permette sia una diffusione più semplice e rapida delle innovazioni tecnologiche e metodologiche, sia una maggiore diffusione di proposte che potranno trovare riscontro anche in ambiti e settori che attualmente ci sono poco familiari. Certamente la scelta di accedere in modo specialistico alla rete nasconde anche delle insidie, non ultimo il rischio della superficialità e della incapacità di gestione e approfondimento della complessità, fino alla possibilità di escludere alcuni dei portatori di interesse. Tuttavia sappiamo che le scelte procedurali intraprese porteranno dei vantaggi che potranno trovare riscontro in ambiti e settori che attualmente ci sono poco familiari. Inoltre, sappiamo che il rigore che cerchiamo di perseguire premierà la qualità dei lavori e nel tempo sarà riconosciuta.
Concludo questo messaggio ringraziando tutti della fiducia sempre dimostratami e sottolineo il grande impegno e la competenza degli associate editors e della redazione senza il cui lavoro niente sarebbe possibile.

Un caro saluto,

Marco Marchetti
Direttore
Introduction to the special issue

Dear Readers,
the present and next forthcoming special issues of the Italian Journal of Remote Sensing are dedicated to contributions to the 14th National Conference of Federation of Scientific Associations for Territorial and Environmental Information (ASITA) held in Brescia on November 9 12 2010.
These selected papers deal with remote sensing applied to different disciplines, from environmental resources and man-made objects detection to disaster management. In addition, techniques for data pre-processing are addressed as well.
Alba et al. and Brovelli and Lucca focus on LiDAR’s data filtering while Nex and Rinaudo present an integrated approach for automated extraction of man-made outlines from terrestrial and aerial laser scanner systems.
Tarantino et al. present land cover maps derived by the integration of high spatial resolution satellite images and contextual information. Mei et al. present a method for paved areas extraction with field data and hyperspectral images. The work of Salvatori et al. deals on snow cover monitoring with images from digital camera systems.
Multi-temporal analysis based on historical aerial photographs are used by Fabris et al. to estimate landslide displacement while the potential of object-oriented techniques to extract forest cover from historical panchromatic frames is investigated by Savio.
Bresciani et al. present the use of remote sensing data to assess vegetation health in lake environment. Masetti et al. evaluate mosaicking and analysis of backscatter angular responses as adequate techniques to quickly characterize the seafloor adjacent to shipwrecks.
Remote sensing applications for rapid mapping supporting post disaster management are presented instead by Ajmar et al. and Casella et al.
Finally, field tests on GNSS and inertial systems for transport fleet monitoring in urban environment are carried out by Fastellini et al.
We thank all the reviewers for their contribution, they ensured the quality of this special issue in publishing high content quality. Special thanks to our colleagues from the Editorial office, Francesca Bottalico and Chiara Lisa for their continuous and efficient work.

With our best regards,

Gherardo Chirici and Davide Travaglini
Editors
Cari Lettori,

questo numero speciale della Rivista Italiana di Telerilevamento e il prossimo sono dedicati ai lavori presentati alla 14a Conferenza Nazionale della Federazione delle Associazioni Scientifiche per le Informazioni Territoriali e Ambientali (ASITA) che si è tenuta a Brescia dal 9 al 12 novembre 2010.

Gli articoli selezionati trattano dell’utilizzo del telerilevamento in differenti discipline, dal rilevamento delle risorse ambientali e dei manufatti alla gestione delle catastrofi naturali. Inoltre, sono inclusi in questo numero speciale alcuni lavori dedicati alla pre-elaborazione dei dati telerilevati.

I lavori di Alba et al. e Brovelli e Lucca riguardano il filtraggio dei dati LiDAR mentre Nex e Rinaudo presentano un approccio integrato per l’estrazione automatica di manufatti con sistemi laser scanner terrestri e aerei.

Tarantino et al. hanno utilizzato immagini satellitari ad alta risoluzione spaziale integrate con informazioni contestuali ai fini della produzione di carte di uso del suolo. Mei et al. presentano una metodologia per l’estrazione e la classificazione di superfici asfaltate con dati a terra e immagini iperspettrali. Il lavoro di Salvatori et al. descrive i risultati ottenuti con un sistema di monitoraggio della copertura nevosa basato su sistemi di ripresa fotografici.

Fabris et al. hanno effettuato un’analisi multitemporale di rilievi aerofotogrammetrici per stimare le deformazioni di un’area in frana; Savio ha valutato la potenzialità delle tecniche object-oriented per la delimitazione delle coperture forestali da fotografìi storici pancromatici.

Bresciani et al. hanno stimato lo stato di salute della vegetazione in ambiente lacustre con immagini GeoEye-1. Masetti et al. hanno valutato le potenzialità delle tecniche di mosaicatura e di analisi della risposta angolare di backscatter per la caratterizzazione dell’area di fondale adiacente a relitti.

Applicazioni del telerilevamento a supporto della gestione degli eventi catastrofici sono presentate da Ajmar et al. e Casella et al. Infine, Fastellini et al. presentano i risultati di una serie di test eseguiti con differenti piattaforme di sensori GNSS in ambiente urbano.

Desideriamo ringraziare tutti i reviewers per avere contribuito alla pubblicazione di questo numero speciale di alto contenuto qualitativo. Un ringraziamento particolare va alle colleghi dell’Ufficio Editoriale della rivista, Francesca Bottalico e Chiara Lisa per il loro continuo ed efficiente lavoro.

Cordiali saluti,

Gherardo Chirici e Davide Travaglini
Editors
Assessing common reed bed health and management strategies in Lake Garda (Italy) by means of Leaf Area Index measurements

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Abstract
During a 6-year monitoring program (2005-2010), LAI measurements were collected in the field and obtained from Remote Sensing data (GeoEye-1 image, 2010) to assess the health of common reed beds in the southern part of Lake Garda (Italy). In particular, data were gathered to assess the effects of management strategies on the physiological status of reed beds and to collect information for defining further conservation programs. Results point to the central role played by water levels both on reed plot re-growth efficiency and on reed health; cutting back the reeds, however, (which is done exclusively in winter) seems to have a negligible impact on common reed beds while removing detritus from their midst appears to have a positive effects on reed health and in general on the quality of the littoral zone in question.

Keywords: common reed beds, GeoEye-1, management strategies, Remote Sensing Techniques, water level.

Introduction
Common reed beds constitute one of the most important habitats for conserving environmental equilibrium at water-terrestrial interfaces; for example, along the southern shores of Lake Garda (Northern Italy) their presence ensures an effective ecosystem in certain riparian and littoral zones [Bresciani et al., 2007]. The common reed (Phragmites australis (Cav.) Trin. Ex Steud.) is a cosmopolitan plant that belongs to the helophytes (order: Glumiflorae); it is one of the most productive herbaceous species [Brix, 1999] and its aerenchyma enhances oxygen availability in saturated soils (i.e. in wetland or littoral sediments) [Brix and Schierup, 1989]. Globally, P. australis plays an important role in the nitrogen, phosphorus and silicon balance [Struyf et al., 2007] and it also strongly influences the detritus food chain [Wetzel, 2001] and benthic processes [Longhi et al., 2006]. Finally, common reeds provide shelter for certain organisms such as epiphyte ciliates (Protozoa), thereby helping to keep bacterial loads in waters under control [Osborne and Kovacic, 1993]. Common reed beds are a key stage of ecological successions in lentic water [Englomer and
Podani, 2001] and show very high biodiversity values: they are an ideal habitat for fish, amphibians and birds (i.e. for animal growth, nutrition, reproduction, etc.); furthermore, riparian reed beds act as cleaning filters for water. A recent study demonstrated that nitrogen removal efficiency ranges from 10-15% of the total nitrogen sediment content; similarly they remove significant amounts of heavy metals [Saltonstall & Stevenson, 2007]. Like most graminaceous taxa, *P. australis* is a hardy species, which is well-adapted to a wide range of environmental conditions [Ostendorp, 1991], the main ecological stressors that could affect its growth capacity are: water levels [e.g. Engloner, 2009], salinity [e.g. Mauchamp and Mésleard, 2001], and climatic conditions (specially winter weather) [e.g. Zemlin et al., 2000]; also soil fertility and nutrient availability are extensively investigated factors affecting reed growth and morphology.

*P. australis* tends to be an invasive species [Meyerson et al., 2000], and despite its great ecological usefulness, it needs suitable management, in particular eradication where *P. australis* is an exotic species, as in the case of North-America [Lelong et al., 2007], or when its excessive expansion leads to a decrease in floristic biodiversity [e.g. Farnsworth & Meyerson, 1999; Williams and Grosholz, 2008]. On the other hand, in the European lakes affected by major influxes of tourists, the species has been strictly contained in order to keep reed bed size and conditions stable [e.g. Güsewell, 2003]. Despite this, over the last few decades, a considerable decrease in the number of common reed beds has been observed in several European wetland systems [den Hartog et al., 1989; Van der Putten, 1997; Gigante et al., 2010]. In these cases, management programs have aimed to increase the surface area and improve the health of the common reed [e.g. Sinnassamy and Mauchamp, 2001].

Studying changes in the surface area, structure and function of common reed beds is very important for determining the causes and consequences of their degradation [Papastergiadou et al., 2008] and for developing practical approaches to sustainable wetland management [Adam et al., 2010]. Accurate mapping is an important tool for understanding the wetland functions and for monitoring their response to natural and anthropogenic disturbances [Baker et al., 2006]. According to existing literature, the major causes of wetland degradation are hydrological regime changes in terms of water level fluctuations and changes to water quality and quantity [Lazaridou et al., 2001] and the structural alteration of hydro-hygrophilous environments [Ehrenfeld, 2000].

The decline in reed beds along lake shores is known as the die-back syndrome *(a visible abnormal and non-reversible spontaneous retreat, disintegration or disappearance of a mature bed of common reed within a period not longer than a decade)* [Van der Putten et al., 1989]. This occurs with macroscopic changes such as reed retreat from deep water [Ostendorp, 1989] or reed clumping as well as with morphological changes (e.g. structural changes in rhizome, culms thinning).

Detailed research into reed health for management purposes requires integrated information to improve our understanding of the spatial and temporal dynamics of common reeds [Marks et al., 1997].

Remote Sensing has been identified as a complementary tool to conventional mapping techniques [Girard and Girard, 1999; Özesmi and Bauer, 2002]. Aerial and satellite photography can be used to detect evident changes in wetland plant communities in response.
Common reed management
During the 1960s and ‘70s, urban planning allowed building close to the shoreline which led to a consequent decrease in the surface area available for common reeds to grow. At the end of the 1970s, the Lombardy Region passed law no. 33/1977, designed to stop the loss of aquatic vegetation. Despite this, the overall area of common reed beds continues to decrease slowly to this day principally as a result of burning, uprooting and illegal cutting, resulting in a new settlement of coastal areas. The lack of maintenance practices, due to an overly restrictive interpretation of the regional law, has led to an accumulation of organic detritus and waste that has badly affected the health of the common reed, and in turn that of the local wildlife and water quality [Bresciani et al., 2009].

As a result, since 2003 a pilot project to manage Lake Garda’s common reeds has been in place. The conservative techniques defined (clearing and cutting back vegetated areas) were based both on an extensive review of relevant literature [e.g. Sinnassamy and Mauchamp, 2001; ANPA, 2002] and on experience gained in the field.

The main principle that has guided the experimental management of southern Garda’s reed beds has been the search for the time, means and least invasive methods for the habitat. Management operations have been based on the following basic rules: 1) winter mowing; 2) cuts at different heights to ensure the necessary oxygen to the rhizomes; 3) lack of cuts for each managed site to ensure dry material and protection for the next breeding season; 4) removal of cut material and waste from the treatment site; 5) interventions in reeds placed distant from each other in alternate years; 6) use of equipment (e.g. boats) in order to minimize damage to the rhizomes. The importance of the reed bed monitoring program started in 2003 was confirmed by the issue of a regional regulation on the protection and conservation strategies for the minor fauna, flora and vegetation. (Regional law no. 10/2008).

Study area
Lake Garda belongs to a distinct typology of Italian Subalpine lakes located in the southern edge of the Alps, characterized by great depths and large volumes. Located in the most densely populated and industrialized region of Italy (Lombardy, Veneto and Trentino-Alto Adige), Lake Garda represents an essential renewable resource for the environment of the surrounding regions due to the multiple uses to which its waters are put (human consumption, irrigation, energy, transportation, recreational purposes) [Giardino et al., 2007].

The largest Italian lake (368 km²), thanks to smooth shores in the southern area, is characterized by the widespread presence of aquatic vegetation. Common reeds, with approximately 35 ha occupied over about 57 linear kilometers of coast [Sotgia, 2010], have ensured that biodiversity has been maintained, that the shores have been consolidated and that an oligotrophic water system has been preserved.

Besides reeds, the ecotonal areas of Lake Garda are characterized by the presence of well-developed riparian vegetation (Salix alba L., Populus nigra L.) and dense aquatic plant mats prevalently dominated by Lagarosiphon major (Ridley) M oss, Vallisneria spiralis L., Potamogeton ssp., Najas marina L. subsp. marina and Chara globularis J.L. Thuiller. In southern Garda the presence of reed beds provides habitats for wildlife, mostly birds and fish.
Materials and methods
In the southern region of Lake Garda highlighted in Figure 1 we selected certain sensitive areas, which showed reduced colonization by reed vegetation. In these areas we have measured LAI over several reed habitats and for different periods of the year since 2005 with the objective of monitoring vegetation re-growth.

The structural complexity of the reed beds imposed measure replicates in order to gather the spatial variability of sampling plots and consequently to analyze both the border- and the inside-zones, with greater attention paid to investigating the common reeds grown in both wet and dry conditions. In total, we carried out 17 field campaigns between 2005 and 2010 (May-September) covering over 50 reed areas in southern Garda. All field sampling campaigns are summarized in Table 1.

LAI measurements were carried out with two instruments: the AcuPAR L80 ceptometer (2006-2010) and a hemispherical camera (2005-2006). The AcuPAR is a portable photosynthetically active radiation (PAR, 400-700 nm) sensor that measures canopy PAR interception to estimate LAI non-destructively and in real time. Hemispherical photographs were acquired with a fish eye lens (Field Of View: 180°) mounted on a Nikon CoolPix E 990 camera placed below the canopy in a nadir position. Hemispherical photos were processed with the software can-eye 3.2 [Baret and Weiss, 2004], which separates the area covered by the vegetation from the area covered by the sky to derive LAI.

In addition to field measurements, LAI values were derived from a GeoEye-1 image acquired on 26 August 2010. GeoEye-1 has four spectral bands, with spectral ranges of 450–510 nm (blue), 510–580 nm (green), 655–690 nm (red), and 780–920 nm (near infrared). These four bands...
have an approximate spatial resolution of 1.65 m (GeoEye, 2010). GeoEye-1 also has a higher resolution panchromatic band that covers a spectral range from 450 to 800 nm. From the GeoEye-1 reflectance bands, corrected for the illumination angle, we obtained NDVI [Rouse et al., 1973].

\[ NDVI = \frac{\rho_{\lambda_2} - \rho_{\lambda_1}}{\rho_{\lambda_2} + \rho_{\lambda_1}} \] [1]

where \( \rho_{\lambda_1,2} \) is the reflectance of the red and near infrared multispectral bands of the GeoEye-1 sensor.

A linear regression model was used to investigate the relation between NDVI values and LAI measures in 14 different sampling plots; the equation obtained was then inverted and used to estimate LAI values over the entire GeoEye-1 image. The results were validated considering the field measurements collected on 10 September 2010 (n = 14). Along with the LAI measurements, the accumulation of organic material, biometric (stem density on m², leaf weight, stem length), physio-chemical and biological measurements of water (pH, oxygen, total coliform, phytoplankton and ciliates Protozoa) were also examined in the reed beds.

<table>
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Inter-annual lake levels, water temperature and conductivity fluctuations were obtained by the Sirmione Environmental Monitoring Centre (CRA), while the meteorological parameters (air temperature, etc.) were acquired by the “Osservatorio Bianchi” M eteo Stations in Sirmione. These data are analyzed in order to evaluate which of these parameters influence the growth and re-growth efficiency of the reed beds in the area in question.

Results

The first stage of our research was to assess whether LAI is a useful parameter for monitoring reed beds in southern Lake Garda. The number of stems is a key parameter for describing a reed bed: a large number of stems per surface unit indicates good health status for \textit{P. australis} [ Eid et al., 2010]. LAI, which is a biomass indicator, is strongly correlated with density; in addition, the same types of clones of \textit{P. australis} produce a limited and constant number of leaves [Rolletschek et al., 1999] that tend to be curved and for this reason they are not the only factor for determining LAI values. The correlation between LAI and stem density values measured was quite sufficient ($r^2=0.76$) to accept LAI as a useful index for studying reed bed areas.

Having ascertained that LAI is a useful parameter for studying reed beds, the range of field LAI highlighted the extreme specificity of each individual reed bed and the great variability between one reed bed and another, even within the same lake ecosystem. The same variability can be found in the chemical/physical properties and fauna of reed beds [Bresciani, 2002]. For example, in the measurements made on approximately 30 reed beds in the months of June 2009 and 2010, LAI values of between 1.5 m$^2$m$^{-2}$ and 4.5 m$^2$m$^{-2}$ were recorded. Considerable variability was also found within the same reed bed depending on contact with the water; on average, the dry zones showed LAI values 15% greater than submerged areas, as also recorded by Coops et al. [1994]. LAI measurements also enabled us to assess the differences within each individual reed bed between winter mown and non-mown areas. A comparison in the 2005-2010 period showed that, in most cases, managed areas showed higher LAI values than non-managed areas (Fig. 2), confirming how winter mowing reinvigorates the vegetation. Observing patterns over time, the difference between managed and non-managed reed beds was evident for the years 2005-2007 (22-35%). These values concur with other studies carried out to assess the effects of cutting and clearing reed beds in Europe [Güsewell et al., 2000] and in South Africa [McKeean, 2001]. Starting from 2008, the difference decreased with an extreme case in August of that same year, when the LAI in non-managed reed beds was significantly greater (+10%) than in managed reed beds.

The same data-set shows LAI patterns in the six-year monitoring campaign and identifies how, in the last two years, the average values (of the reed beds measured in each measuring campaign) are on average lower than the earlier years’ monitoring; in fact, between mid June and mid July, the values decreased from approximately 4 m$^2$m$^{-2}$ in the first three years to less than 3 m$^2$m$^{-2}$ in 2008 and 2010. We also point out how the range of values between the minimum and the maximum (i.e. variability between reed beds) increased decisively in the last two years of monitoring.

This datum is also backed by the areal decrease in the reed beds recorded between 2007 and 2010 which led to a 12% loss in the total surface area occupied in the southern part of Lake Garda [Sotgia, 2010]. To investigate the causes we used the most commonly controlled parameters to understand the dynamics of reed bed growth and health. The most important of these are: water
levels, air and water temperature, solar irradiance, precipitation and salinity [Engloneer, 2009]. Since the most delicate period for reed bed formation is early spring, when the phenological cycle of germination starts [Clevering et al., 2001], we correlated both the environmental and meteorological parameter values close to the spring equinox and also the average annual LAI values acquired in the reed beds at the end of the growth phase.

Table 2 shows the environmental and meteorological parameter values from 2005 to 2010 and indicates the R² values obtained; none of the regressions turned out to be statistically significant except for the one with water levels, which was highly significant (*** p<0.001). In fact, both spring and average year water levels are highly correlated to LAI values with R² greater than 0.80. Figure 3a shows the rising water level trend over the last few years while Figure 3b shows how LAI values are inversely correlated to the levels of the lake.

Table 2 – Meteo conditions (air and water temperatures, solar radiation, rainfall and water levels) and all the physio-chemical characteristics of the water measured in the reed beds studied.
In Lake Garda, our data show that water levels strongly affect the growth of *P. australis* (Tab. 2, Fig. 3). In fact, prolonged submerged periods may affect the survival of shoots and consequently the decrease of LAI. This fact is supported by various studies that have highlighted water levels as one of the driving factors forcing *P. australis* development: the abundance of stems is much greater when the reed beds are not submerged in water for too long and/or when water levels are too high [e.g. Russell and Kraaij, 2008; Mauzamp et al. 2001b]. In fact, average water levels in southern Garda were at their highest in 2009-2010. The fall in average LAI values recorded in the 2-year period from 2009 to 2010 is also associated with a series of adverse meteorological conditions (heavy storms and rough waves) which, as pointed out by Coops et al. [1996], may have aggravated the decline in the number of reed beds on the shores of the lake.

Another important factor in assessing reed bed health and in understanding which reed beds require effective management is the amount of organic material that accumulates within the reed beds. During the monitoring campaign we observed reed beds in which a large amount of organic material had accumulated. This consisted both of reed stems and dry leaves and also human waste. Although this factor has been considered less influential for reed bed growth than water levels [Clevering, 1998], our data showed that, within the same reed bed, where organic material had accumulated, LAI values were in fact on average lower (2.4 ± 0.6) than in areas without such accumulated waste (3.3 ± 0.7).

Figure 4 shows the linear regression correlation between the LAI values measured on 25 August 2010 and the NDVI values derived from the GeoEye-1 image acquired one day after. The good correlation enabled us to use this relation to estimate the LAI from NDVI.

\[
LAI = 0.1 \times NDVI + 0.25 \quad [2]
\]

The results obtained were validated with independent field data collected in the September 2010 measuring campaign: the estimated LAI corresponded to the LAI measured in the field with \( R^2 = 0.7 \) and RMSE=15%.

The advantage of Remote Sensing is that the LAI map can be extended across the study area to have data available on all 158 reed beds in southern Lake Garda.

These results confirmed the great variability in LAI values between the Garda reed beds (Fig. 2) and showed how cutting operations do not damage the reed beds with high water levels.
(over 60 cm above the zero hydrometric level, Fig. 3). In fact, as Figure 5 and the statistical analyses show, the LAI values of managed reed beds are not statistically different from the non-managed reed bed values; on the contrary, they showed how the higher differences are observed between the dry reed bed areas and the ones with high water levels.

![Graph showing regression between field LAI and NDVI.](image)

**Figure 4 - Regression between field LAI and NDVI.**

![Bar chart showing average LAI values.](image)

**Figure 5 – Average LAI values obtained from the GeoEye-1 image in different areas of managed and non-managed reed beds in 2010 plotted with one standard deviation bars.**

The empirical relationship of equation 2 allowed us to produce LAI maps over all Lake Garda’s reed bed areas shown in Figure 6; these maps were used to identify which reed beds were in the most precarious conditions and which were the thinnest areas (low LAI s), i.e. the ones that will require management strategies over the next few years if the reed beds are to be protected.
These maps in fact clearly show that the managed areas are characterized by higher LAI values (yellow to red colour keys) compared to unmanaged reed beds. This product can guide the choice of sites where field surveys should confirm the need of management to restore healthy conditions of reed beds. Our results confirm the usefulness of satellite images and empirical methods for deriving spatially distributed information. Indeed empirical relationships between LAI and VIs such as the NDVI are widely used in the Remote Sensing community [Turner et al., 1999], despite it appearing to be strictly site- and species-dependent [Colombo et al., 2003]. Finally, the GeoEye-1 image showed to have both geometric and radiometric characteristics suitable for monitoring reed bed habitats of the southern shores of Lake Garda.

**Conclusions**

Monitoring reed beds in the southern part of Lake Garda by means of LAI measurements, associated with macromorphological measurements (e.g. stem density, stem height, number of nodes, stem diameter), gave useful information for strategic management purposes. LAI measurements are made with two aims in mind: (i) to check reed bed health after winter mowing and the clearance of accumulated organic material and (ii) to identify which reed beds need management strategies. The measurements showed how management interventions do not damage the plants; on the contrary, they tend to improve the density and vigor of *P. australis*. Overall, in the cases monitored during 2010 the LAI of the non-managed reed beds do not differ significantly from the LAI of the managed reed beds. We did, however, notice a decrease in this difference in 2009-2010. In that 2-year period, the average LAI values probably decreased due to a rise in lake water levels and because of adverse weather conditions. As a consequence of the low LAI values of these two years management foreseen for year 2011 will not include winter mowing but only the removal of accumulated organic material.
The use of GeoEye-1 satellite images along with field measurements proved to be extremely useful. This sensor has suitable radiometric and geometric characteristics for monitoring the reed habitats of southern Lake Garda. It gave synoptic and detailed information about all the Garda reed beds. The results achieved have encouraged the local town councils to periodically purchase these images in order to build up a useful picture of the lake so that they can decide on their management strategies, with a good cost/benefit ratio.

Acknowledgements
Our monitoring campaign was run in partnership with the local southern Garda town councils and with the Provinces of Brescia and Verona. Our heartfelt thanks go to all the volunteers of the local environmental associations who took part in our monitoring operations over the last few years. We acknowledge the anonymous reviewers for their valuable comments on the manuscript. We are grateful to Mrs R. Mackay for the English revision of the manuscript.

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Bresciani et al. Assessing common reed bed health and management strategies


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Landslide displacement estimation by archival digital photogrammetry

Massimo Fabris, Andrea Menin and Vladimiro Achilli

Abstract

Archival multi-temporal aerial photogrammetry allows to measure displacements of a landslide area when images are co-registered in the same reference system. In this paper we investigated three photogrammetric surveys performed in 1998, 2004 and 2007 in an area of the northern Apennine (Bologna). The study of morphological changes was carried out measuring in stereoscopic vision twelve natural points as roof corner of buildings. Changes were estimated comparing the respective coordinates of the points. Our DEM shows the morphological features and the kinematic of this sliding area with an average grid resolution of 5 m and a maximum elevation error of about 10 cm. Results can improve the geomorphological studies of sliding areas and assist in reducing future hazards.

Keywords: Archival photogrammetry, landslide area, DEM, vectors displacement.

Introduction

Digital Elevation Models (DEM s) reconstruct the three-dimensional ground surface and can be used to analyse the morphological features of the Earth’s surface [Walstra et al., 2004; Baldi et al., 2005; Brückl et al., 2006; Chandler et al., 2007]. Digital photogrammetry is one of the most powerful tools to measure coordinates of large amount of points which are used to extract high resolution DEM s. Digital models are traditionally generated using automatic or semi-automatic procedures based on well defined shape comparison methodologies or on the grey/colour level distribution in the corresponding areas of the images [Heipke, 1995; Kraus, 1998].

Models at high resolution and precision acquired repeatedly over an area undergoing to significant morphological changes, can be used to evaluate the morphological changes of its surface and therefore can estimate the mass movements [Kääb et al., 1997; Baldi et al., 2005; Baldi et al., 2008; Fabris et al., 2010]. Measuring the position of natural and artificial points distributed in the study area recognised on multi-temporal stereoscopic images, allow to define displacement vectors of ground points.

Although this photogrammetric approach is less accurate than other measurement methodologies such as classical topographic techniques or GPS, high accuracies can be achieved using a large number of ground points that can provide a general view of the ongoing processes [Brückl et al., 2006; Baldi et al., 2008]. Photographic archives, available for the last 60-70 years in Italy as well as in other countries, represent an extensive source of historical data that, in some cases, can allow to model the ground deformation of instable areas at local scale, during some decades. In the case of historical image processing, a photogrammetric method known as
archival photogrammetry is used to extract metric information from historical photos [Chandler and Cooper, 1988a, 1988b; Chandler and Brunsden, 1995; Walstra et al., 2004; Chandler et al., 2007; Baldi et al., 2008].

In this paper we present the results of a surface displacement survey for a sector of a landslide area located in Pianoro (Bologna, Italy), based on analyses of aerial photogrammetric surveys performed in 1998, 2004 and 2007. In this case the movements were measured by comparing coordinates of some natural points located on the landslide as the value of the observed deformation was not revealed through the multi-temporal DEMs comparison method.

The aerial photogrammetric surveys
Deformation analysis was performed using three set of stereoscopic aerial photographs taken with a metric camera in August, 9, 1998 (scale 1:8500), July, 13, 2004 (1:7500) and August, 28, 2007 (1:7400). For all the dataset, the study area was included in a single stereo pair. The black and white photo frames were scanned using Wehrli Raster Master RM2 photogrammetric scanner at 12 µm resolution to obtain digital images with ground resolutions ranging from 9 to 10 cm. Multi-temporal analysis of the photogrammetric surveys requires defining a common reference system, which can be obtained by identifying a large number of common tie points that can be recognised on multi-temporal stereoscopic models and located in stable parts of the study area [Chandler and Cooper, 1988a, 1988b; Walstra et al., 2004; Chandler et al., 2007; Baldi et al., 2008]. The orientation and spatial positioning of the aerial photos, necessary for the restitution procedures, are estimated by means of the presence in the photos of special ground points characterised by known coordinates (Ground Control Points - GCP). Generally, the coordinates of GCPs are surveyed simultaneously together with the photogrammetric survey, using classical topographic techniques.

In this case we identified in the three surveys fifteen natural points located outside the deformation area, in presumably stable zones. These points correspond mainly to corners of buildings and objects that can be unambiguously identified in the images. The reference coordinates of these GCPs were measured in 2009 by the GPS methodology. The images orientation procedures were carried out with the Socet Set (SoftCopy Exploitation Tool Set) v. 5.4 software, obtaining orientation residuals in agreement with the scale of the three photogrammetric surveys and the ground pixel size (Tab. 1).

| Table 1M | Main features of the three aerial photogrammetric surveys used in this study. |
|----------|-------------------------------|-----------------|-----------------|
| Date of survey | 9th August 1998 | 13th July 2004 | 28th August 2007 |
| Number of images | 2 | 2 | 2 |
| Metric camera | Wild 15/4 UAG-S | Wild 15/4 UAG-S | Wild 15/4 UAG-S |
| Calibrated focal length (mm) | 152.9 | 153.28 | 153.28 |
| Average scale | 1:800 | 1:7500 | 1:700 |
| Scans resolution (dpi) | 2100 | 2100 | 2100 |
| Ground pixel size (cm) | 10 | 9 | 9 |
| Number of GCPs | 10 | 13 | 15 |
| RMS values of GCP and tie point coordinates | E (m) | 0.04 | 0.03 | 0.02 |
| | N (m) | 0.04 | 0.02 | 0.02 |
| | H (m) | 0.03 | 0.02 | 0.03 |
From the 2007 survey, we extracted automatically two DEMs over the deformation area by the ATE (Automatic Terrain Extraction) method. The first with grid size of 5 m that covers all the stereoscopic area generating the correspondent orthophoto (Fig. 1a), while the last at high resolution (1 m grid size), corresponding to the zone studied in detail (panel of Fig. 1a).

**Figure 1**

- **a)** Orthophoto of the deformation area (Pianoro, Bologna) and detail of the high resolution zone analyzed; **b)** 3D model of the automatic DEM.

### Expected accuracy

The evaluation of the expected accuracy was performed using the known relations of Kraus [1998]. Depending on the scale of the images used in this study, varying from 1:8500 to 1:7400, and on the adopted scanning resolution (2100 dpi, corresponding to
12 micron on the image), the dimension of the pixel on the ground ranges from 0.09 to 0.10 m. To evaluate the mean vertical accuracy $\sigma_z$, it is possible to use the equation [Kraus, 1998]:

$$\sigma_z = m_b \frac{Z}{b} \sigma_{p} \quad [1]$$

where,

$m_b$ is the mean image scale, $Z$ is the flight height, $b$ is the distance between image centres (base of the stereo pairs), $\sigma_{p}$ is the horizontal accuracy.

By adopting a horizontal accuracy of the stereoscopic measurement in the order of pixel size, we obtain a mean vertical error varying between 0.13 and 0.18 m, for the larger and smaller image scale, respectively. These theoretical values were correct by means of empirical relationships [Kraus, 1998; D’Aghata and Zanutta, 2007] due to the differences between the normal photogrammetric case and the real case. Finally the values ranging from 18 to 24 cm. These values were assumed as vertical errors for manual measurements.

Taking into account the capability of the correlation algorithms, adopted in the digital analysis, to work at sub-pixel level, we could assume an $\sigma_{p}$ max of the order of the pixel size for the 2007 DEM (about 10 cm).

**Automatic correlation parameter**

The efficiency of the automatic approach of the Socet Set software is provided by a correlation parameter that represents for each extracted point, the quality of the automatic determination of the point elevation. It indicates the success of the correlation or the questionability of the measurement and this value is defined as Figures Of Merit (FOM). The integer numerical value range from 0 to 99. A FOM lower than 33 indicates that the correlation algorithms failed or the results are questionable, and an interactive review by an operator is required. Values greater than 32 indicate a successful automatic correlation and in this case, the values are proportional to the correlation coefficients of the images matching. When the FOM of a specific post is not acceptable (i.e. lower than 33), thus its elevation is obtained by interpolation or extrapolation procedure (depending on FOM value) from the surrounding data. In this case-study, the points that provided FOM values lower than 33 are 34.8% and belong to 9 different categories. The distribution of events corresponding to a positive FOM shows a max value for FOM 88. In Figure 2 the distribution of points with FOM lower than 33 overlaps the correspondent orthophoto. The points characterized by unsatisfactory FOM are located on urban and densely vegetated areas where the automatic correlation get worse.

**Stereoscopic measurement of natural points**

To analyse the geomorphological changes occurring on the study area with the best precision of the method, we adopted another approach based on identifying homologous points in multi-temporal sets of photographs, comparing coordinates and computing the three-dimensional motion vectors. The analysis was performed in the deformation
area (panel of Fig.1) measuring the movements between two subsequent aerial photogrammetric surveys.

Twelve natural ground points (roof corners of three buildings) were identified and measured from 1998, 2004 and 2007 photogrammetric models using stereo viewing methods. Then, we provided the coordinates of the homologous points in the three different epochs. Comparing the coordinates of the homologous points located inside the deformation area, 3D vectors representing displacement during the analysis period, were obtained [Baldi et al., 2008]. In the first time interval (1998-2004, Fig. 3a) the movements are in the order of 1±8 cm in East, 1±11 cm in North and 1±7 cm in altitude and within the limits of precision of this method.

In the period 2004-2007 (Fig. 3b), ground deformations are in the order of 0±17 cm in East, 3±18 cm in North and 5±13 cm in altitude and the vectors are directed along the max slope of the sliding area.

Moreover, in the same period some evident cracks opened in the buildings. The maximum measured displacements are in the order of 25 cm, and are close to the limit of the accuracy of the photogrammetric method.
Figure 3 – Vectors displacement in the first (1998-2004, a) and second (2004-2007, b) period.
Conclusions

Multi-temporal archival aerial photographs were used to measure the active deformation taking place in the time span 1998-2007 at Pianoro (Bologna, northern Italy). The analyzed aerial images acquired in 1998, 2004 and 2007 are characterized by a similar mean scale and ground sample distances. From the 2007 survey, was automatically extracted a first DEM of the deformation area with grid size of 5 m, and a second model at higher resolution at 1 m of the studied zone, using Socet Set software. The analysis of the correlation parameter FOM show (Fig. 2) an automatic correlation difficulty over urban and densely vegetated areas. Due to the small size of the ground movements, was not possible to estimate the displacements of the landslide by the comparison of multi-temporal DEMs as the precision and threshold of detection of the method was below the size of the effective ground deformations. For this reason we preferred to use a method based on identifying homologous points on multi-temporal sets of photographs. The comparison of respective coordinates allowed to extract 3D vectors.

Results provided displacements in the order of 14 cm in the first period (1998-2004), and more significant values in the last time interval (2004-2007). Displacements show directions along the maximum slope and normal to the contour lines. The size of the detected movements are of the order of 25 cm, and are close to the limit of the precision of this method that can be successfully used at low costs to improve the geomorphological studies of sliding areas and assist in reducing future hazards.

References


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Contextual information for the classification of high resolution remotely sensed images

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Abstract
The use of remote sensed images in many applications of environmental monitoring, change detection, risks analysis, damage prevention, etc. is continuously growing. Classification of remote sensed images, exploited for the production of land cover maps, involves continuous efforts in the refinement of the employed methodologies. The pixel-wise approach, which considers the spectral information associated to each pixel in the image, is the standard classification methodology. The continuous improving of spatial resolution in remote sensors requires the focus on what is around a single pixel with the integration of “contextual” information. In order to produce more reliable land cover maps from the classification of high resolution images, this paper analyzes the effectiveness of the integration of contextual information comparing two different pixel-wise techniques for its extraction: 1) the post-classification filtering with a Majority filter applied to the map produced by the standard Maximum Likelihood algorithm; 2) the segmentation algorithm SMAP. The results were compared. A GeoEye-1 image, exploited in the framework of the Asi-Morfeo project, was considered.

Keywords: contextual information, Maximum Likelihood, Majority filter, SMAP.

Introduction
Remote sensing is effectively adopted in many application fields such as environmental monitoring, risks analysis, damage prevention, monitoring of anthropic actions, change detection, etc. The availability of new sensors, able to provide very high spatial resolution images (below 5 meters), even with the loss of spectral resolution, has encouraged the scientific community to develop more accurate methodologies to obtain reliable land cover maps. The traditional algorithms for classifying remotely sensed data are based on a “pixel-wise” approach, which considers spectral information associated to each pixel independently. At high spatial resolution the information of the spatial dependency, i.e. “spatial context” of what surrounds every pixel, becomes meaningful and should be considered.

This observation is also supported by the inherent need of integrating additional information due to the reduced spectral resolution of those sensors. According to Stuckens et al. [2000] and Mohn et al. [1987], a couple of approaches can be adopted to extract the context from an image: 1) using a “moving window”, with an odd number of pixels (generally a 3x3 sized window suffices, while larger windows are appropriate for small pixel sizes and/or large land cover entities); 2) an “image segmentation”
approach. The former technique consists in extracting the contextual information from the pixels in the neighborhood of every pixel within a moving search window. The integration of the contextual data can be done: 1.a) at classification time, so that each pixel is assigned to the class with the highest probability in the considered window [Di Zenzo et al., 1987; Kartikeyan et al., 1994; Nishii and Eguchi, 2005]; 1.b) after classification, with the use of a majority filter that assigns each pixel to the most frequent class in the moving window. Other more refined models were also proposed in [Kim, 1996].

Approach 2) groups pixels in the scene according to some spectral similarity measures, by creating contiguous clusters. Segmentation algorithms can be based on: 2.a) “region growing and merging” such as the ECHO (Extraction and Classification of Homogeneous Objects) algorithm [Kettig and Landgrebe, 1976]: it is based on the assumption that neighboring pixels with similar spectral properties belong to the same region and they should be merged. In [Haralick and Shapiro, 1985] authors declare that those algorithms do not perform well on complex scenes; 2.b) “boundary detection”, based on the idea that two neighboring pixels with different spectral responses, belong to different regions and an edge can be found between them by thresholding the gradient image or using other more refined edge detection techniques [Marr and Hildreth, 1980]; 2.c) “hybrid models”, based on both previous approaches, such as the mixed segmentation schemes [Stuckens et al., 2000] which are specifically useful for complex scenes with abrupt changes and spatial discontinuities; 2.d) “statistical models” such as non linear regression [Acton, 1996] or kriging interpolation (geostatistics) [Fiorentino et al., 2006]; 2.e) ”Markov Random Fields models” (MRF) [Kedham and Belhadj-Aissa, 2001; Tsai and Tseng, 1997; Provost et al., 2004], with the simultaneous classification of all pixels, or their variations such as the “multiscale MRF” approach in Bouman and Shapiro [1994] and Congalton and Green [1999]. In McCauley and Engel [1995] the performances of two algorithms based both on a refined “image segmentation” approach, i.e. SMAP (multiscale MRF) and ECHO (“region growing/merging”) were considered and compared with a purely spectral Maximum Likelihood algorithm, by applying them on an image acquired from an airborne scanner, for a scene characterized mainly by agricultural fields.

The aim of this paper was to integrate contextual information into the classification of high resolution remotely sensed images, and to investigate the resulting contributions to the overall classification accuracy, by comparing the two main approaches for the extraction of contextual information, as previously introduced. In fact, filtering with a post-classification Majority filter applied on the land cover map produced by a Maximum Likelihood algorithm (ML) – as representative of the “moving window” technique – and the multiscale MRF algorithm (SMAP, Sequential Maximum A Posteriori) [Bouman and Shapiro, 1994] – as representative of the “image segmentation” technique – were considered. The glaring result of the application of those techniques was the reduction of the “salt-and-pepper” effect typical of a traditional pixel-wise classification.

ITT ENVI© and the GRASS software [Grass Manuals; Grass Web Site] were used for data processing, and a GeoEye-1 image available in the framework of ASI-MORFEO project [Morfeo-Project Web Site] was analyzed.

This paper is organized as follows: section 2 explains the two methodologies used for contextual classification; section 3 contains a short description of the data set; section 4 gives some details about the different experiments and discusses the results. Finally section 5 summarizes the conclusions of the experimental work.
Methodologies for the extraction of contextual information

**Maximum Likelihood classifier and Majority post-classification filtering**

ML is a statistical, pixel-based purely spectral algorithm based on the maximization of the a posteriori probability \( P(\omega | X) \) that an assigned pixel \( X \) (a \( N \)-components vector equal to the number of spectral bands) belongs to an assigned class \( \omega_i \) (\( i \) equal to the number of classes) [Duda et al., 2006].

According to the Bayes’ formula:

\[
\arg \max_{\omega_i} P(\omega_i | X) = \arg \max_{\omega_i} \frac{p(X | \omega_i) p(\omega_i)}{p(X)} \quad [1]
\]

where:

- \( p(X | \omega_i) \) is the conditional probability density function to find a pixel given an assigned class and it is assessed from ground truth data considering a multivariate Gaussian distribution probability and computing mean and covariance matrix for each class;
- \( p(\omega_i) \) is the prior probability for each class.

A well-known limitation of the ML algorithm is its Gaussian hypothesis in the data distribution, because in real cases data trends could be quite different and typically multimodal. The majority filter, applied to post-classification, is a classical filter that works on a fixed size window, and assigns the central pixel of the window to the most frequent class in its neighborhood. When a dominant class cannot be found, the pixel is assigned to the class which is encountered as first. In most practical cases, a small 3x3 pixels window size can be adopted, while larger windows are appropriate for small size pixels and/or large land cover entities [Stuckens et al., 2000]. In this way the contextual information coming from neighbors of each pixel is considered.

**SMAP segmentation algorithm**

SMAP (Sequential Maximum A Posteriori) is a segmentation algorithm, based on the multiscale Bayesian framework proposed by Bouman and Shapiro [Bouman and Shapiro, 1994]. It combines an approach of Gaussian mixture model for classes distribution, to maximize separability among the classes and specialize each spectral signature, with a hierarchical multiscale segmentation method for contextual classification. The main idea behind that approach is that each class, as provided by the user, can be expressed as a linear combination of a certain number of “hidden” subclasses, each one governed by an independent Gaussian distribution. The subclasses are computed according to a principle of maximum synthesis (Minimum Description Lenght) as proposed by Rissanen [1983] in the codes theory context [Grunwald, 2005]. The model uses a Markov chain in scale to model the class labels that form the segmentation, but refines the Markov chain framework by embedding a hierarchical tree based classifier to model the transition probabilities between adjacent scales. The tree based classifier models complex transition rules with only a moderate number of parameters [Cheng, 1999; Cheng and Bouman, 2001]. The SMAP classifier builds a multiscale pyramidal representation for the classified map. Using
the mixed-model subclasses and a multibands image it produces a segmented classification by considering the attributions of the pixels to the classes in the neighbor of each pixel, on the basis of a different scale-dependent weight [Bouman and Shapiro, 1992]. The correspondence among neighboring pixels results less relevant moving from a coarser to a finer scale. The SMAP minimizes the misclassification probability by considering the best matching among the scales introduced before. Its great advantage compared to other Markovian approaches is the absence of a global optimization approach for the stochastic relaxation, with a gain in convergence speed.

**Data set description**

The image taken in consideration was a GeoEye-1 scene acquired on the 18th of August 2009 for an area between the towns of Varenna and Esino Lario in Lombardia region (Italy) (Fig. 1) with 4 multispectral bands in the visible and near infrared at the spatial resolution of 2 meters. It has been orthorectified using RPC method and a DTM at 20 meters in the WGS84/UTM32 system. It belongs to the dataset of the Asi-Morfeo Project [Morfeo-Project Web Site].

![Figure 1 – RGB composition of the Geeye-1 image.](image)

Ground truth has been acquired by photo interpretation of a set of ortophotos on Lombardia region, freely available on the web portal of the region. Six main classes are identified in the scene: Broad leaved – Shrub – Pasture – Bare soil – Water – Urban. A large set of polygons for a total of almost 20000 pixels as training set (TR), and almost 130000 pixels as test set (TE) were acquired for every class.

**Experimentation and results**

*Experimentation*

Some experiments have been conducted in order to asses improvements in the classification
accuracy of high resolution remotely sensed images by integration of contextual information. The two approaches for the extraction of contextual information described in section 2 were considered: the “moving window” technique with the use of a ML classifier and the application of a posteriori Majority Vote filtering, and the “image segmentation” technique represented by the SMAP multiscale MRF algorithm. Further experiments were considered too: in order to discriminate the contribute of the contextual approach, the SMAP algorithm was modified by skipping the Gaussian mixture model subclasses computation, and, at the same time, the Gaussian mixture model resulting subclasses were used within the ML classic algorithm, as well. The parameters computed to assess the performances of the different classifications have been the Overall Accuracy percentage value (OA%) and the Kappa coefficient (K), introduced by Cohen [1960] and adapted to the classification of remotely sensed images by Congalton and Green [1999].

**Results**

The experiments analyzed and compared are detailed in Table 1 and summarized as follows:

Table 1 – Classification results (OA% e K) in training and test for the different experimentations.

<table>
<thead>
<tr>
<th>CASE</th>
<th>CLASSIFICATION EXPERIMENT</th>
<th>TRAINING (19504 pixels)</th>
<th>TEST (130511 pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>OA% ±δ%</td>
<td>K</td>
</tr>
<tr>
<td>a</td>
<td>ML standard (without Gaussian mixture model)</td>
<td>79.43 ±0.57</td>
<td>0.69</td>
</tr>
<tr>
<td>b</td>
<td>ML standard + Majority Vote post classification filtering</td>
<td>86.07 ±0.48</td>
<td>0.78</td>
</tr>
<tr>
<td>c</td>
<td>SMAP modified (without Gaussian mixture model)</td>
<td>91.69 ±0.39</td>
<td>0.87</td>
</tr>
<tr>
<td>d</td>
<td>ML modified (with a Gaussian mixture model)</td>
<td>85.58 ±0.49</td>
<td>0.77</td>
</tr>
<tr>
<td>e</td>
<td>ML modified (with a Gaussian mixture model) + Majority Vote post classification filtering</td>
<td>92.43 ±0.37</td>
<td>0.87</td>
</tr>
<tr>
<td>f</td>
<td>SMAP standard (with a Gaussian mixture model)</td>
<td>90.50 ±0.41</td>
<td>0.85</td>
</tr>
</tbody>
</table>

a) Classification with standard ML (i.e. without a Gaussian mixture model);

b) Classification with standard ML (again without a Gaussian mixture model) and application of a posteriori Majority Vote filtering on a 3x3 pixel sized moving window. The application of a post-classification attribution criterion leads to the introduction of contextual information and the use of locally dominant probability reduces the number of isolated pixels: this produces a clear improvement in test of about the 7% in OA and 0.1 in K coefficient (see Tab. 1, case: a and b);

c) Classification with SMAP without the Gaussian mixture model. This algorithm obtains the best results in training and in test with an improvement of about the 5% in OA and 0.07 in K coefficient in comparison with the best result obtained with ML + Majority Vote filtering (see Tab. 1, case: a, b, c);

d) Classification with a ML coupled to a Gaussian mixture model. For each class,
according to the dispersion of their statistics (ground truth), a set of subclasses \( \{ \omega_i \} \) associated to a class \( \omega \) as identified and the statistic parameters (mean and covariance matrix) of each \( \omega_i \) were computed. A total number of 41 subclasses were found and the corresponding classified map was produced, then the subclasses corresponding to each parent class \( \omega \) were merged together to get a final six classes map. The training set specialization involves an OA increasing of almost the 6% in training respect to case a). However the excessive specialization produces often a reduced capacity of generalization because noise variations are apparently captured and embedded in the classifier (the increasing in test is almost negligible: about 1% of OA and it remains the same for the K coefficient) (see Tab. 1, case: a and d);

e) Classification with ML modified with a Gaussian mixture model and a successive application of a posteriori Majority Vote filtering on a 3x3 sized moving window. In comparison with case d) there is an increasing of about 5% in OA and 0.06 in K coefficient (see Tab. 1, case: d and e) but the approach without the Gaussian mixture model (case b) resulted in an almost negligible difference. The improvement obtained in the approaches which make use of Majority Vote showed that using a contextual algorithm improves results regardless the number of considered classes;

f) Classification with SMAP standard (with a Gaussian mixture model). As in the case c this algorithm showed the best results both in training and in test, with an improvement of about the 5% in OA and 0.07 in K coefficient compared to the best result obtained by ML with mixture model (see Tab. 1, case: e and f).

Results are the same of the case c; compared to case b.
As expected, there is a slightly decreasing in test – almost 0.5% of OA% and 0.01 of K respect to case c – due to an excessive specialization of classes that results in noise increasing for final classification.
In Tables 2-5 local results of different classes for all experiments are analyzed by computing their confusion matrices that leads to the following considerations:

<table>
<thead>
<tr>
<th>TEST</th>
<th>BROAD LEAVED</th>
<th>SHRUB</th>
<th>PASTURES</th>
<th>BARE SOIL</th>
<th>WATER</th>
<th>URBAN</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNCLASSIF</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BROAD LEAVED</td>
<td>95.55</td>
<td>32.97</td>
<td>2.01</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
<td>62.68</td>
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<tr>
<td>SHRUB</td>
<td>2.70</td>
<td>41.91</td>
<td>0.07</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11.37</td>
</tr>
<tr>
<td>PASTURES</td>
<td>1.50</td>
<td>22.92</td>
<td>97.78</td>
<td>0.05</td>
<td>0</td>
<td>0.02</td>
<td>16.06</td>
</tr>
<tr>
<td>BARE SOIL</td>
<td>0.26</td>
<td>2.18</td>
<td>0.12</td>
<td>59.08</td>
<td>0.57</td>
<td>16.69</td>
<td>2.39</td>
</tr>
<tr>
<td>WATER</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>95.55</td>
<td>0.02</td>
<td>2.98</td>
<td></td>
</tr>
<tr>
<td>URBAN</td>
<td>0</td>
<td>0.02</td>
<td>0.02</td>
<td>40.77</td>
<td>3.88</td>
<td>83.28</td>
<td>4.52</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 3 – Confusion matrix in test for ML standard algorithm + Majority Vote filtering (Table 1, case: b).

<table>
<thead>
<tr>
<th>TEST Class</th>
<th>BROAD LEAVED</th>
<th>LEA VED</th>
<th>SHRUB</th>
<th>PASTURES</th>
<th>BARE SOIL</th>
<th>WATER</th>
<th>URBAN</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNCLASSIF</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BROAD LEAVED</td>
<td>89.35</td>
<td>35.65</td>
<td>2.08</td>
<td>0.14</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>59.76</td>
</tr>
<tr>
<td>SHRUB</td>
<td>8.11</td>
<td>37.21</td>
<td>0.08</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>13.37</td>
</tr>
<tr>
<td>PASTURES</td>
<td>2.22</td>
<td>25.28</td>
<td>97.82</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>17.03</td>
</tr>
<tr>
<td>BARE SOIL</td>
<td>0.32</td>
<td>1.86</td>
<td>0.02</td>
<td>59.08</td>
<td>0.57</td>
<td>17.98</td>
<td>2.40</td>
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<tr>
<td>WATER</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>95.82</td>
<td>0</td>
<td>2.99</td>
<td></td>
</tr>
<tr>
<td>URBAN</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>40.68</td>
<td>3.61</td>
<td>82.02</td>
<td>4.45</td>
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<td>Total</td>
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<td>100</td>
<td>100</td>
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</tbody>
</table>

Table 4 – Confusion matrix in test for SMAP standard algorithm (Table 1, case: f).

<table>
<thead>
<tr>
<th>TEST Class</th>
<th>BROAD LEAVED</th>
<th>LEA VED</th>
<th>SHRUB</th>
<th>PASTURES</th>
<th>BARE SOIL</th>
<th>WATER</th>
<th>URBAN</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNCLASSIF</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BROAD LEAVED</td>
<td>97.09</td>
<td>40.76</td>
<td>7.40</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>65.93</td>
</tr>
<tr>
<td>SHRUB</td>
<td>1.88</td>
<td>38.04</td>
<td>0.12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10.00</td>
</tr>
<tr>
<td>PASTURES</td>
<td>0.72</td>
<td>17.60</td>
<td>92.27</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>13.81</td>
</tr>
<tr>
<td>BARE SOIL</td>
<td>0.31</td>
<td>3.45</td>
<td>0.14</td>
<td>34.51</td>
<td>0.20</td>
<td>8.66</td>
<td>1.95</td>
<td></td>
</tr>
<tr>
<td>WATER</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>99.14</td>
<td>0.12</td>
<td>3.10</td>
<td></td>
</tr>
<tr>
<td>URBAN</td>
<td>0</td>
<td>0.15</td>
<td>0.06</td>
<td>65.39</td>
<td>0.66</td>
<td>91.22</td>
<td>5.21</td>
<td></td>
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<tr>
<td>Total</td>
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<td>100</td>
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<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5 – Confusion matrix in test for ML modified algorithm with the Gaussian mixture model + Majority Vote filtering (Table 1, case: e).

<table>
<thead>
<tr>
<th>TEST Class</th>
<th>BROAD LEAVED</th>
<th>LEA VED</th>
<th>SHRUB</th>
<th>PASTURES</th>
<th>BARE SOIL</th>
<th>WATER</th>
<th>URBAN</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNCLASSIF</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BROAD LEAVED</td>
<td>96.02</td>
<td>56.62</td>
<td>5.24</td>
<td>0.14</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>68.82</td>
</tr>
<tr>
<td>SHRUB</td>
<td>2.24</td>
<td>17.24</td>
<td>0.15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5.34</td>
</tr>
<tr>
<td>PASTURES</td>
<td>1.22</td>
<td>23.14</td>
<td>94.55</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15.62</td>
</tr>
<tr>
<td>BARE SOIL</td>
<td>0.52</td>
<td>2.97</td>
<td>0.05</td>
<td>35.04</td>
<td>0.02</td>
<td>5.95</td>
<td>1.83</td>
<td></td>
</tr>
<tr>
<td>WATER</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>99.04</td>
<td>0.03</td>
<td>3.09</td>
<td></td>
</tr>
<tr>
<td>URBAN</td>
<td>0</td>
<td>0.02</td>
<td>0.01</td>
<td>64.82</td>
<td>0.93</td>
<td>94.02</td>
<td>5.30</td>
<td></td>
</tr>
<tr>
<td>Total</td>
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<td>100</td>
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<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
The SMAP algorithm results effective for discriminating the Broad Leaved classes probably because of a higher spectral homogeneity which characterizes these classes compared to others. In Figure 2(c) it is possible to see the best recognition for the river (class: Water) and Broad Leaved by means of the SMAP algorithm;

The use of a Gaussian mixture model results effective for the class Urban, characterized by a remarkable spectral heterogeneity at high resolution.

Figure 2 - (a) RGB detail of the Geoeye-1 scene; (b) Standard ML classified map + Maj.Vote; (c) SMAP classified map with Gaussian mixture model.

Conclusions
The aim of this short paper was to assess the effectiveness of integrating contextual information in classification of high resolution remote sensed images, by comparing two approaches for the extraction of context. The impact of using Gaussian mixture modeling for the classes to discriminate different land covers has been considered too. Globally, the use of the pure contextual approach obtains the best results as OA percentage and K coefficient, with a remarkable reduction of isolated (i.e. misclassified) spots in the classified map which results smoother. The glaring result is the reduction of the “salt-and-pepper” effect, visible in other typical pixel-wise classification.

The performance of the multiscale MRF “image segmentation” approach seems to overcome the “moving window” post classification approach with an increasing of the 5% in the OA%: such value could encourage the addition of contextual information in series to a standard pixel-wise classification as in the “moving window” post classification approach. The use of a Gaussian mixture model results in a reduced capacity of generalization because an excessive specialization seems to cause catching variations due to image noise. However, when considering the local contribution to each class, there are some limits in recognition of classes with remarkable spectral heterogeneous density, such as a urban class for high-resolution images, which is better managed by using a Gaussian mixture model.

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References


Grass Web Site, http://grass.itc.it/.


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Field tests on GNSS and inertial systems for transport fleet monitoring in urban environment

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Abstract
The paper describes the results of a series of tests carried out with different sensor platforms (geodetic GNSS with or without RTCM corrections, low cost GNSS, integrated GNSS/INS) in a real urban environment with a relevant presence of satellite obstructions (tall buildings, trees, ...) causing frequent and prolonged GNSS outages. The different systems have been tested simultaneously on the same test paths, in order to analyse their behaviour in typical situations and make possible a series of comparisons. The results of the tests have been useful for the design of a vehicle monitoring system installed on a public and scholastic transport fleet.

Keywords: GNSS, INS, Integrated sensors, MEMS, Automotive Vehicle Location.

Foreword
Overview and research objective
The kinematic positioning of terrestrial vehicles through single or integrated sensor systems (GNSS, GNSS/INS, odometers, ...) has assumed in the last years a growing importance, for the monitoring of transport fleets and in other relevant sectors such as Mobile Mapping, Machine Control, Precision Farming and any application involving the tracking and (in some cases) the attitude determination of a moving vehicle.

The availability of low cost GNSS receivers and inertial sensors (MEMS) has made possible to design and build integrated sensor systems with a limited budget, suitable for widespread applications interesting the mass market.

When tracking systems are used in difficult environments like urban areas or narrow roads bordered by trees, the recurrent outages found with a GNSS standalone receiver (caused by losses of lock and/or multiple reflections) can be compensated through the integration of the satellite data with an inertial sensor.

The low cost inertial sensors, based on miniaturised gyroscopes and accelerometers (MEMS - Micro Electro Mechanical Systems) permit to obtain, through integration in time, position and body frame attitude parameters. The accuracy of most MEMS-based inertial platforms is still limited, determining relevant drift errors in the integrated solutions if these are protracted, with no satellite data, for more than a few seconds. Therefore, the GNSS/MEMS integration in a low cost system does not give a fully affordable and continuous kinematic solution, but permits to bridge small GNSS outages and/or to improve the results of a stand alone GNSS receiver.
General information about the concepts and the theory of GPS/INS integration can be found e.g. in Grewal et al. [2006], Hide et al. [2009] and Salychev [2006]. The objective of the present research has been to study and test different tracking systems, evaluating in particular the performances of low cost GNSS-only or GNSS/INS systems suitable for applications of vehicle fleet monitoring on a broad scale.

Previous experiences at the DICA
The performance of a real time positioning system is noticeably improved in the areas where differential corrections (code or code/phase RTCM) are offered by a GNSS permanent network.

The Laboratory of Geomatics at the DICA, together with the Umbrian Regional Council, has set up and operates the GNSS permanent network GPSUMBRIA, composed of 12 permanent stations and distributing post-processing data (RINEX and Virtual RINEX) and code and phase RTCM corrections. By means of such network, researches have been carried out at the DICA during the last years, analysing sequences of positions obtained through navigation grade (high performance, high budget) GNSS/inertial systems mounted on experimental vehicles and comparing them with post-processing solutions.

The navigation grade systems offer very good performances in terms of accuracy and dependability. In return, their cost represents an important drawback that reduces their application field, making them unsuitable when the number of vehicles to control is high and the budget to invest is small. In such cases (like the application described in the last paragraph) it is necessary to base the project on low cost hardware, carefully selecting the components to meet the requirements, and verifying their correct operation trough comparisons with higher performance systems.

Experimental vehicle and instruments under test
For the experimental campaign, a vehicle has been equipped with a number of different devices, in order to test the instruments simultaneously on the same trajectories and experimental conditions.

All instruments have been mounted on the vehicle roof, on a support placed along the longitudinal axis of the van (Fig. 1). The instrumentation under test include (in order of cost from highest to lowest):

a) Two Topcon Hiper Pro (geodetic GPS/GLONASS receivers); from such receivers can be obtained solutions (position + velocity) at a subdecimeter accuracy, both in post processed kinematic through the recorded raw data, and in real time by means of the RTCM code/phase corrections coming from GPSUMBRIA; with two receivers mounted along the vehicle axis, the pitch and yaw attitude parameters can be obtained;

b) XSENS MTi-G: a low cost GPS/INS integrated system including a L1 C/A code GPS receiver and a MEMS based IMU; from the GPS/INS data fusion are derived navigation data (3D position and velocity), the 3D accelerations and the space attitude (Euler angles or body frame quaternions) of the vehicle, at high frequencies (up to 350 Hz);

c) Falcom Fox-LT: an AVL (Automotive Vehicle Location) system comprising a new generation, high sensitivity GPS chipset U-Blox 5 (50 channels, L1 C/A code) and
a customizable quad band GPRS modem; suitable for many applications, including real time vehicle tracking, fleet management, emergency and safety services, route verification, etc.;

d) *Microdata MisMatch*: an AVL system with an user interface specially designed for the public transport fleet monitoring; includes a TELIT GPS/modem module (GM862-GPS) based on a Sirf Star III chipset (20 channels, L1 C/A code), a quad band GPRS modem, an interface with the vehicle and motor control instruments and a terminal for communications with the fleet control centre by means of a graphical touch-screen display and a hands-free voice system;

e) *Magnex*: a very low cost GPS receiver based on a SkyTraq Venus 5 chipset (44 channels L1 C/A code), high tracking sensitivity (< 158 dBm), EGNOS support, internal memory; for navigation purposes the receiver can be connected (bluetooth) to a smartphone, a PDA or a notebook.

Figure 1 - Experimental vehicle with the installed instrumentation (particular above).

With the above described vehicle, many test runs have been effected, collecting a relevant amount of data. An analysis of the results and a comparison among some of the different solutions and trajectories computed is given in the following paragraphs. The tests had
been scheduled on the purpose of designing a monitoring system for a public transport buses fleet, so the performances of the different systems under test have been evaluated with particular reference to such application.

**GNSS Post-processing solutions**

Post-processing solutions, to be utilised as reference for comparison with the other techniques, have been computed for all test runs. The post-processed trajectories have been computed from the double frequency GPS/GLONASS raw data acquired and recorded by the couple of Topcon geodetic receivers (a in par. 2). The sampling interval has been set at 1 second. As fixed base has been assumed a GPS/GLONASS permanent station belonging to the GNSS network GPSUMBRIA. The software utilised for this computation is Trimble Total Control (build 311). Scientific references on post-processing kinematic can be found on Kaplan [2006] and Misra and Enge [2006]. Figure 2 shows the trajectory obtained for one of the test runs. The blue dots indicate phase (fixed ambiguity) solutions; the red dots are differenced code solutions; the yellow dots represent trajectory stretches reconstructed by means of the XSENS GPS/INS device (see further, par. 6). Such a relevant discontinuity in the post-processed solution has been caused by the many obstructions placed along the path.

**GNSS Network Real Time Kinematic solutions**

From the two Topcon geodetic receivers have also been obtained code-phase real time solutions. On such purpose, during the tests, phase-code RTCM corrections transmitted by the Ntrip caster of the GPSUMBRIA permanent network have been acquired and elaborated by each of the two receivers in NRTK (Network Real Time Kinematic) mode, utilising a VRS (Virtual Reference Station) data stream. Fixed solutions have been obtained for only part of the trajectories; the float solutions percentage is relevant (about 30%), mostly caused by the presence of obstructions along the path. The NRTK-VRS solutions have been put in comparison with the post processing trajectories, matching the time scales and considering only the fixed phase ambiguity epochs. The results of the comparison for an example test track are shown in Figure 3. The float solutions evidence the highest discrepancies, as could be expected. The fixed VRS solutions show generally a good correspondence with the fixed post processed ones. Although, there are some epochs where relevant differences (up to 3 meters) are evidenced. Such bad solutions are probably caused by false ambiguity fixing (however not evidenced by the RTK software neither by the post-processing elaboration). Analyzing this problem in a deeper way, it can be noticed that most discrepancies show where fixed solutions were obtained between series of float solutions due to obstructions. Such effect is visible in Figure 4, referring to the same road stretch of the central part of Figure 3. The comparison between post processed and NRTK solutions on the data set of Figure 3 gives the results summarized in Tables 1 and 2. The relatively high RMS for the discrepancies of the fixed VRS solutions derives from the presence of the outliers mentioned above.
The experience has confirmed that with NRTK positioning a relevant percentage of gaps and float solutions occur in difficult environments. The ambiguity fixing times are reducing with the evolution of the RTK software and algorithms, but it is still difficult to obtain a very good continuity of fixed solutions. The recording of the raw data and a subsequent post processing can bridge some of the gaps found in real time, but this is not a solution for applications such as fleet monitoring. To reconstruct in real time a trajectory as complete as possible, the best option is the integration of GNSS with inertial sensors (par. 6).
Figure 3 - Differences NRTK – postprocessing.

Figure 4 - NRTK fixed solutions between series of float solutions.
GPS Code standalone solutions
The instruments under testing include three different systems utilising undifferenced pseudorange observations (standalone GPS), already described: *Falcom Fox-LT*, *Microdata MisMatch* and *Magnex*, listed respectively as c), d) and e) in the description of the test vehicle (see above) and Figure 1. The *Magnex* is a very low budget system, whose data have shown some scattering and discrepancies in the time scale. Thus, in this paper are mainly analysed the results of the first two systems (*Falcom Fox-LT* - with U-Blox chipset and *MisMatch* - with Sirf Star chipset). The sampling interval has been set in all cases at 1 Hz.

Figure 5 shows a comparison on the satellite tracking sensitivity of two different receivers (*Falcom* and *MisMatch*). The upper dots represent the GPS satellite availability on the test site (from the almanac). The *Falcom* device (grey dots) has evidenced a better sensitivity with respect to the *MisMatch* (black dots).

After a careful calibration of the time scales of the three systems, the positions obtained by means of the different receivers have been compared with the reference trajectories (fixed solutions in post processing). The comparison has only been made for the horizontal components N and E, because these are the most relevant for a of fleet monitoring purpose.

![Figure 5 - GPS satellites tracking sensitivity.](image)

Figures 6 and 7 show the N and E differences between the post processed fixed solutions and the positions obtained respectively by the *Falcom* and the *MisMatch*. The behaviour is what could be expected from code-only receivers with no RTCM correction: differences in the range of about ±10 meters for both instruments, with a comparable accuracy. The most important differences occur in the proximity of high buildings. The statistic parameters of the comparisons are resumed in Tables 3 and 4.
Table 3 - Comparison between Falcom Fox-LT and post-processing fixed solutions.

<table>
<thead>
<tr>
<th>East</th>
<th>North</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.904</td>
<td>-2.762</td>
<td>Average (m)</td>
</tr>
<tr>
<td>2.481</td>
<td>3.485</td>
<td>RMS (m)</td>
</tr>
</tbody>
</table>

Table 4 - Comparison between MisMatch and post-processing fixed solutions.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.277</td>
<td>-0.397</td>
<td>Average (m)</td>
</tr>
<tr>
<td>2.239</td>
<td>4.478</td>
<td>RMS (m)</td>
</tr>
</tbody>
</table>

Figure 6 - Differences Falcom Fox LT – Postprocessing.

The test has evidenced a substantially satisfying behaviour of the Falcom and MisMatch receivers, with average accuracies of a few meters, suitable for navigation applications such as the fleet management. The tracking sensitivity is quite good, such as the capacity of computing solutions even in bad satellite coverage conditions. The third GPS standalone receiver (Magnex) has shown a less affordable behaviour, as shown in Figure 8, which evidences sometimes differences of tenth of meters with respect to the true position.
Figure 7 - Differences MisMatch – Postprocessing.

Figure 8 - Magnex trajectory (white dots) vs true path (white lines).
**GPS/INS solutions**

In difficult environments with many obstructions the standalone code receivers show their limits and drawbacks, showing position errors exceeding the expected values (> 10 meters) and relevant gaps between subsequent positions.

![Figure 9 - Typical behaviour of a GPS/MEMS integrated system.](image)

With a GPS/INS integrated system the inertial device is able to fill the gaps in the GPS positioning. For low cost MEMS-based GPS/INS system the drift effect is sensible and degrades considerably the position accuracy after just a few epochs. The behaviour of a low cost GPS/MEMS integrated system is schematised in Figure 9.

The equipment under test included an integrated positioning/attitude determination system, the XSENS MTi-G (b in Figure 1). Figure 10 shows a screen shot of the XSENS control interface: in different windows are shown the acceleration, velocity and attitude components, the GPS time and the real time computed trajectory.

![Figure 10 - XSENS user interface (MT SDK).](image)
The tests on the XSENS platform, carried out simultaneously to the other instruments referred above, have produced very good results.

In Figure 11 a standalone code solution (Mismatch) is compared with the XSENS solution, and both are superimposed to an ortophoto map of the test area. The XSENS trajectory is much more continuous and presents a better agreement with the map than the standalone trajectory: the integration with the MEMS sensor has proven able to fill the gaps and reduce the effect of GPS standalone outliers. As already shown in Figure 2, from the XSENS platform has been obtained in most cases a complete trajectory description.

Like in the previous cases, also for the XSENS solution a comparison has been made with the post processed results. Figure 12 shows the plot of the N, E differences for one of the trajectories, evidencing a better accuracy with respect to the standalone code receivers seen in the previous paragraph; most differences, with only a few exceptions, are contained in the interval ±5 m. The gaps in the plot refers to epochs with no post processing solutions available, where no comparison has been possible. The statistic summary of the comparison is shown in Table 5.

![Figure 11 - Standalone receiver MisMatch (black dots) vs. GPS/INS receiver XSENS (grey dots).](image)

<table>
<thead>
<tr>
<th></th>
<th>East</th>
<th>North</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark grey</td>
<td>0.461</td>
<td>-1.183</td>
</tr>
<tr>
<td>Dark grey</td>
<td>2.162</td>
<td>3.029</td>
</tr>
</tbody>
</table>

**Table 5 - Statistic summary of the comparison XSENS vs. post-processing.**
Figure 12 - Comparison between XSENS and post processed solutions.

Figure 13 - Drift effect shown by the Xsens platform.
The strong drift effect typical of the MEMS sensors has been noticed during the tests, as shown for example in Figure 13, where a straight road passes under a big building and the reconstructed trajectory (white dots) shows an evident distortion.

**Application to a public transport fleet monitoring**

For a company of Perugia (central Italy) operating public and scholastic transport service, has been designed and realised a system for the real time monitoring and management of a fleet composed of about 100 minibuses. In the vehicles has been installed the MisMatch device, described and tested as in the former paragraphs. The articulation of the system is schematically represented in Figure 14. The WGS84 position of each vehicle is sent by GPRS modem to a control centre, which records the service data in a SQL database and shows in real time the position of all vehicles on a video map representing roads and bus lines. The display of the onboard device presents to the driver the service data (travel times, stops, variations from the time table, ...) and permits him to communicate and interact with the control centre.

The database of the lines and the bus stops at the control centre has been realised by means of the MisMatch itself, driving along the lines with the first prototypal vehicle. Besides the real time management, the control centre also archives all information relative to each service turn, creating graphs and statistics.

**Final remarks**

The systems tested on a difficult urban environment characterised by many obstructions have shown a behaviour substantially on line with the expectations. The systems based on GPS standalone receivers have evidenced a relevant percentage of bad solutions (gaps and outlier) caused by obstructions and multipaths. A low cost MEMS device has been able to
bridge gaps due to GPS outages, but only for limited time spans, showing a relevant drift which degrades the accuracy on longer periods. Other solutions are under study, based on filtering techniques and the implementation of a software receiver.

Acknowledgements
We would thank the ACAP Soc. Coop. of Perugia, for their helpfulness and the interest shown in the experimentation of integrated systems for vehicle fleet monitoring.

References

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Filtering vegetation from terrestrial point clouds with low-cost near infrared cameras

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Abstract
In applications relating to the reconstruction of a rock face's surface by Terrestrial Laser Scanning (TLS), the overgrown vegetation does not allow one to correctly accomplish this task. In standard Airborne Laser Scanning surveys, the vegetation is filtered out by using spatial filters that exploit the availability of multiple echoes. The same approach does not work efficiently in the case of a rock face. This is due to the morphological complexity, that is typical of such surfaces. For this reason a new system for the automatic recognition of vegetation using a NIR camera was designed and implemented. It is based on a set of images acquired with a low-cost SLR digital camera modified to capture also the NIR component. Such camera is integrated and calibrated with respect to the TLS sensor. A vegetation filter based on the analysis of the NIR component allows one to locate vegetated areas, that can be automatically removed from the data set. In the paper we would like to give an introduction to the procedure used for camera setup, calibration, and the filtering algorithms implemented.

Keywords: terrestrial laser scanning, filtering vegetation, NIR camera, point clouds, NDVI filter.

The investigated problem
The investigation about rock face stability is a relevant issue in several disciplines like Geology, Geotechnics and Structural Engineering. The concern of rock face instability has a high impact on the social life because of the large number of rock faces with instability problems which are spread in mountain areas. This represents a source of risk for the community due to the presence of roads, human settlements, touristic activities and the like.

The field of Geomatics has given an important contribute to this topic in the latest years [Rabatel et al., 2008]. In many cases a close cooperation between people involved in other disciplines was the best strategy to tackle with this complex task [Arosio et al., 2009]. Laser Scanning and Photogrammetry, especially, have been largely adopted for the acquisition and modeling of the 3D surface [Alba et al., 2005; Abellán et al., 2006]. A recurrent problem in the analysis of rock faces is the presence of areas covered by bushes and vegetation, which do not allow the proper acquisition of the bare surface of the object. This is an important drawback in applications aimed at modeling the surface for geomorphological analysis [Azzoni et al., 1995; Federici et al., 2009; Ferrero et al., 2011], that have become very
popular in the latest years after the diffusion of Terrestrial Laser Scanning (TLS) sensors. Indeed, such kind of instruments allows the straight-forward acquisition of a 3D dense point cloud describing the surface of an object. More information about TLS technology, data processing methods and applications can be found in [Heritage et al., 2009], [Shan and Toth, 2009], and [Vosselman and Maas, 2010]. Moreover, [Lemmens, 2010] gives a review of the up-to-date instruments.

On the other hand, photogrammetry can be applied in many cases with similar results, as demonstrated in [Roncella and Forlani, 2005], [Barazzetti et al., 2011b]. This technique features some advantages, like the lower cost and the easier transportability that enable also applications from UAV platforms [Eisenbeiss, 2008]. However, in the case of slope modeling the orientation and 3D reconstruction process is still more complex than with TLS, even though this gap will be quickly bridged due the recent great improvements in the automation of both tasks [see e.g. Barazzetti et al., 2010].

The presence of vegetation is even more critical in monitoring applications [Monserrat and Crosetto, 2008]; [Abellán et al., 2009, 2011], because the growth of flora can drastically change the shape of the surfaces. Consequently, the problem of vegetation filtering has to be afforded in order to accomplish the above-mentioned tasks. In the literature a wide range of solutions have been proposed in the case of DTM generation from Airborne Laser Scanning (ALS) data. The reported methods are probably too many to be listed here. For a more exhaustive analysis the reader is referred to [Vosselman and Maas, 2001] and [Forlani and Nardinocchi, 2007]. The actual scientific research objectives point toward a complete automation of the filtering process, although this is not a simple task and usually requires a final editing.

Vegetation filtering in ALS is mainly based on the ability to detect and analyze each single pulse generated from different responses of the reflected laser signal (multiple echoes). If an item has a single response, its return is normally classified as ground or building, but if the pulse has multiple responses it could be classified as vegetation. Indeed, the laser beam diverges up to a diameter of a few tens of centimeters when it reaches the topographic surface. Such large beam can partially go through the vegetation and partially be reflected by leaves and wood, giving rise to a multiple echo. This principle is schematically depicted in Figure 1. Obviously, this analysis is here described in a very simplified way, but today there exist advanced algorithms and some of them are implemented in commercial packages. They take into account the behavior of neighboring points, noise, intensity, the local shape of the object, etc. In addition, the latest generation of LiDAR sensors, implementing the Full Waveform (FWF) recording capability, makes possible more accurate analyses [Mallet and Bretar, 2009]. In this case, the analysis is not only limited to trees and tall vegetation, but also low bushes might be potentially filtered out.

The registration of multiple echoes or FWF responses is a common characteristic of all sensors used in ALS practice. On the other hand, the same approach cannot be pursued in TLS because of several reasons. First of all current commercial instruments cannot measure multiple pulses (although this option will be added soon). At the present time, only the last series V-Line® of Riegl [Riegl, 2011] permits the acquisition of this data. In next section the potential of the Riegl VZ1000 sensor will be presented by using data coming from a real case study. In addition, some experimental sensors are also capable to apply FWF to terrestrial scene capture [see e.g. Stilla, 2011]. However, when the vegetation is very
dense the laser beam cannot penetrate the vegetation, so that also the use of an instrument with a multiple-echoing function is not efficient. From this consideration it is clear that other filtering methods should be investigated. In ALS practice, the most common filtering methods take advantage of two important aspects: (i) the redundancy of the information contained in the point cloud; (ii) the prevalent growing direction of trees and vegetation, which is substantially perpendicular to the ground surface. This property makes quite simple their identification in aerial LiDAR surveys. Unfortunately, the problem of vegetation reduction on rock faces is more complex because vegetation grows in a direction that is not orthogonal to the rock surface, and furthermore in some cases the growth might be very irregular. This makes its automatic recognition really difficult.

In the paper we would like to present different techniques for vegetation reduction on rock faces. First of all, a new generation of TLS that is able to acquire multi-echoes is illustrated in the next section. Secondly, some spatial filters used in ALS have been adapted and tested with rock faces in order to analyze their advantages and weaknesses. Unfortunately, none of these techniques has allowed us to solve the problem in a general way. For these reasons, a new automatic method for vegetation recognition has been planned by using a high resolution camera able to acquire images in the near infrared (NIR) spectra. After a preliminary camera calibration for computing both inner orientation parameters and lens distortion coefficients, the co-registration parameters between camera and terrestrial laser scanner are evaluated. This task allows one to assign each 3D scanned point with the NIR value captured on the same area. The previous procedure can be carried out in an automatic way because both sensors are co-registered.

As it is well known, the response of NIR bandwidth is highly sensitive to vegetation. A suitable classification technique is then applied to discriminate green areas from the others. The correspondence with the point cloud allows one to find all 3D points that have to be filtered out. On the other hand, the eliminated areas cannot be used for further processing. The only possibility of filling these gaps is to interpolate a surface with the neighboring points. Finally, the last part of the paper includes both conclusions and future developments.

The new terrestrial laser scanner generation

Five years after the construction of the first Full Waveform ALS sensor, in 2009 Riegl Laser Measurement Systems company launched its V-Line® terrestrial laser scanner series providing echo digitization and online FWF analysis. Therefore, today such TLS instruments can discriminate between several return pulses. The user has the option to select the operational mode: sampling the multiple pulses which feature the largest amplitudes, or recording the first or the last pulses only. Due to the fact that this kind of instruments was released quite recently, the literature is still poor of examples and experiences. An interesting case involving the analysis of multiple echoes for vegetation reduction is shown in [Doneus et al., 2009], where the authors highlight the ability of TLS with FWF analysis to detect various objects along the path of the laser beam.

In this paragraph we want to present a test with the new Riegl VZ-1000 in order to analyze the potential of this instrument for the recognition and elimination of vegetation during the survey of a rock face. The Riegl VZ-1000 provides high speed data acquisition, reaching ranges up to 1400 m using a narrow infrared laser beam and a fast scanning mechanism. Its main features are reported in Table 1.
Figure 1 - On the left the Full Waveform (FW) scanning principle is represented (the footprint of the laser footprint is exaggerated to better illustrate how it works), while on the right the corresponding recorded signal is shown.

Table 1 - Technical specifications of RIEGL VZ-1000 laser scanner capable of multi-echo recording.

<table>
<thead>
<tr>
<th>Instrument type</th>
<th>RIEGL VZ-1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>terrestrial</td>
</tr>
<tr>
<td>Measurement range</td>
<td>up to 1,400 m (with 90% reflectivity surfaces)</td>
</tr>
<tr>
<td>Repeatability</td>
<td>±5 mm</td>
</tr>
<tr>
<td>Effective measurement rate</td>
<td>up to 122,000 meas./sec</td>
</tr>
<tr>
<td>Field of view</td>
<td>100°×360°</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>NIR</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>0.3 mrad</td>
</tr>
<tr>
<td>Angular stepwidth</td>
<td>0.0024°</td>
</tr>
</tbody>
</table>

Two different tests were carried out on rock faces near the city of Lecco (Italy). The first experiment (outside an open pit with terraces) was performed to analyze the multi echo function and to distinguish between vegetation and rock face. In Figure 2A the scan of the rock face acquired from a distance of 100 m is shown, where different colors indicate diverse echoes: green is the last target, blue the first one and other colors are intermediate targets. The processing software from Riegl company allows the automatic selection of the last target only, in order to obtain the surface of the rock face. In this particular case the method gave very good results because the vegetation was not very close to the rock face. In some cases, e.g. for natural rock faces, where the vegetation grows close to the surface, the instrument cannot discriminate two consecutive echoes. The minimum distance is determined by the laser pulse width and the receiver bandwidth; for the Riegl VZ-1000 (Fig. 3) laser scanner such multiple-echo range resolution is about 0.80 m. The instrument cannot distinguish the echo pulses for shorter distances between scatters within the same laser shot, resulting in a measured point with an range ambiguity.
The second test was carried out on another rock face with vegetation. In this case we tested the TLS with longer distances, between 600 and 1200 m. A single scan was acquired at the narrowest angular resolution, obtaining approximately 11 million points. The results are shown in Figure 2B. Unlike the previous case, it is not possible to separate the vegetation layers from the rock surface. Probably the response of the signal is too weak for very long distances.

All tests have shown the possibility to recognize and eliminate the vegetation layer by using the multi-target capability. The technology of online waveform processing still has some limitations, e.g. the incapability to discriminate two consecutive echoes for distances under the multiple-echo range resolution (in this case 0.80 m, that however is a large value for applications to rock faces), and the difficult registration of multiple echoes for long distances.

The current release of Riegl VZ-1000 does not record the full returned laser signal, but its discretization. This limit does not enable more in-depth analyses at post-processing stage, so that vegetation layers located at shorter distances than range resolution could be recognized.

Figure 2 - On the left (A) a 3D Image of a laser scan acquired on open pit with terraces by using a terrestrial laser scanner Riegl V=1000 with multi-echo capability; on the right (B) scan of Mount San Martino, Lecco, Italy; colors correspond to different echoes: first target (blue), last target (green), intermediate targets (other colors).

Filtering methods based on spatial filters

In the technical literature the problem of vegetation filtering has been widely investigated by using different kinds of spatial filters. These have been mainly applied to ALS data with the purpose of automatic DTM generation or as a preliminary task in building extraction. Basically, all these filtering techniques are used on the point cloud obtained from last echo points, which should exclude those points classifiable as tree canopy. That solution, that is usually not adopted in TLS, is focused to get rid of the gross vegetation mass. The remaining 3D points can be mainly grouped into bare ground, roads, buildings, moving objects, infrastructures, and residual vegetation. Although all the other classes are characterized by a continuous and quite regular surface, after a preliminary filtering the last one should be made up of small groups of points. Consequently, these points are considered as outliers which are not compatible with the DTM, and then they are identified by applying a spatial filter.
In the following sub-sections two different spatial filters (octree and iterative filter, respectively) adopted in ALS practice have been applied to a few case studies where the object is a rock face. Under this assumption, filters are applied to the raw point cloud, without any preliminary analysis based on the availability of multiple echoes. Among all existing filters, the selected ones seemed the only ones that could be successfully tailored for terrestrial applications, and more precisely for rock faces.

**Octree filtering**

This filter works on the point cloud data, which is re-organized as an octree data structure [Vosselman and Maas, 2010]. This kind of tree data structure is commonly used for handling large sets of 3D points. The point cloud is split into many small cuboidal volumes (cells), whose size is selected by the operator (Fig. 4). The concept of the filter is quite simple, when it is applied to topographic data like in the case of ALS surveys. After assuming vegetation points as outliers that are above the terrain, the point closer to the ground is unlikely to belong to vegetation. Then, the orientation of the cells is selected so that the axes x-y are parallel to the mean ground surface, and then z is roughly parallel to the local plumb line. The point with the minimum z coordinate inside each cell is then selected as representative of the terrain. An exception is due to the situation where a cell contains vegetation points only. This can be solved by selecting a bigger cell size. Unfortunately, this option increases the probability of obtaining a point on the ground but also results in a low-pass filtering
with a consequent detriment of the DTM resolution. In the case of rock faces, the x-y axes of cuboids have to be selected so that they are aligned to the average spatial orientation of the rock face. Consequently, the z axis would result orthogonal to this. This operation is not easy in many locations. When possible, the whole face can be divided into several reference planes, as proposed for the following method in the next paragraph. On the other hand, this solution may be quite complex as an octree filter is largely sensible to the orientation of cuboids. Another problem found with the octree method is due to the fact that vegetation does not feature a prevalent growing direction. Indeed, the effectiveness of this method in topographic applications is based on the hypothesis that the z direction of cuboids is roughly orthogonal to the ground, which is also the direction of growth for the tall vegetation.

![Octree structure](image)

*Figure 4 - Octree structure: image (a) shows the subdivision in cubes, image (b) the tree arrangement.*

**Iterative method**

This filter fits an interpolating surface to the data and accepts individual points by measuring their distances to the surface [Axelsson, 2000]. Only the points at a distance lower than a predefined threshold are accepted. The filter requires the preliminary generation of a raster digital elevation model (DEM) from the original unorganized point cloud $S^{(0)}$. Like in the previous method, the axes $x$-$y$ of the reference plane of DEM are chosen parallel to the mean slope surface along a reference plane $\pi$. The whole point cloud $S^{(0)}$ is then projected onto $\pi$ and rasterized according to a given cell size ($\Delta$). The $z$ values computed for each cell by interpolating the original point cloud are then used to evaluate the DEM elevation. The influence of the adopted interpolation technique on the final result has not been thoroughly investigated in this research. On the other hand, the high point density, typical of laser scanning surveys, should made quite independent the raster generation from the interpolation method.
If the case the rock face has a complex shape, the whole point cloud $S$ will be split into several regions $S_i$, each of them with its own reference plane $\pi_i$. This task could be also performed in automatic way as addressed in [Alba and Scaioni 2010b]. The subdivision in many regions is crucial for complex situations, but the sensitivity of the final result is slightly less than that with a octree filtering.

Once the raster DEM has been created, only the points with $z_{min}$ inside each cell are selected. The remaining points form a sub-set $S^{(1)}$ of the full dataset $S^{(0)}$. This is used to create a new raster DEM. Lastly, the original point cloud $S^{(0)}$ is compared to the latest DEM surface. All the points of $S^{(0)}$ closer than a threshold ($d_{max}$) are kept. Then process is repeated iteratively by reducing at each step the size of both parameters $\Delta$ and $d_{max}$ until the vegetation is completely removed.

In the event that more than one reference surface has been setup, the same procedure is repeated for each surface.

### Application of spatial filters to rock faces

The problem of vegetation filtering has been investigated in several test-sites, but we present here only the most important because of its significant growing of vegetation. The rock face is located in the province of Lecco (Lombardy, Italy) on mount Sasso di San Defendente, in the mountain range of Prealps. As can be seen in Figure 5, the rock face is located just at the border of the county road SP65. In Figure 6, a panoramic image of this rock face is reported. The presence of continuous small rock detachments threaten the car traffic, which (fortunately) is quite reduced. The rock face is constituted by a kind of limestone ("Calcare di Esino") that is typical of the Prealps [Francani, 1971]. In particular, this rock face has many cracks and discontinuities and the effect of water, ice and thermal shock caused several small detachments.

This rock face has been selected as a test site for experimenting several techniques for the assessment and the evaluation of rock fall risk as well as for monitoring purpose. As described in [Arosio et al. 2009], the use of integrated techniques is very often the only way to forecast possible failures in rock faces. We focus here on the laser scanning survey, which was adopted to model the surface of the slope. This model, which was captured at different epochs, was used to compare the surfaces in order to locate deformations and rock detachments. More details can be found in [Alba and Scaioni, 2010a].

The laser scanning survey was carried out by a time-of-flight (ToF) long-range laser scanner Riegl LMS-Z420i. Technical documentation about this instrument can be directly found on the vendor website (www.riegl.com). In order to acquire the point cloud of the entire rock face two different scans were necessary. The parameters of the scans are reported in Table 2. These were aligned by using some retro-reflective targets applied to the rock face and to some places in the nearby areas.

In order to reduce, localize, and filter out the vegetation mass in the acquired point clouds, the raw data captured in “multi-scan” modality have been resampled. This option is used to improve the precision of range measurements and it is based on the repetition of the same scan $n$ times. This operation averages the range values measured $n$ times per each angular position of the laser beam. If $\sigma_r$ is the intrinsic precision of range, the use of the “multi-scan” technique will result in an improvement as $\sigma_r' = \pm \sqrt{\frac{\sigma_r}{n}}$. During this phase a threshold on the standard deviation $\sigma_r'$ can be established to eliminate all points with poor precisions.
In Figure 6 a point cloud before and after resampling the “multi-scan” points by adopting a threshold of ±15 mm is shown. It is noteworthy that this operation can eliminate a large part of the vegetation on the cliff. Such option is not normally used in the standard processing pipeline, but has to be activated by the user. In this case this procedure was really useful on and, to a certain extent, it can be compared to the use of last echo point clouds in ALS. Then the resampled dataset has been filtered by applying both methods described in the previous paragraphs. The octree filter has allowed us to remove the vegetation when large size cells were adopted, with a consequent loss of resolution. The iterative method is more laborious but it is able to remove more vegetation without loosing the original resolution. The main drawback of the iterative method is its incapability of separating the vegetation from overhangs and nooks on the rock surface. Consequently they are normally removed. For this reason it is essential a manual check of the points eliminated and, if necessary, an interactive editing of these errors (see Fig. 7).

Table 2 - Properties of laser scans acquired.

<table>
<thead>
<tr>
<th>Scan</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanning time (min)</td>
<td>42</td>
<td>43</td>
</tr>
<tr>
<td># total measured points</td>
<td>13.26M</td>
<td>13.74M</td>
</tr>
<tr>
<td>Angular resolutions (deg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horiz.</td>
<td>0.038</td>
<td>0.039</td>
</tr>
<tr>
<td>Vert.</td>
<td>0.038</td>
<td>0.039</td>
</tr>
<tr>
<td>Resolution (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Max.</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Acquisition range (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min.</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Max.</td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>Field-of-View (deg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horiz.</td>
<td>94.86</td>
<td>99.639</td>
</tr>
<tr>
<td>Vert.</td>
<td>52.326</td>
<td>54.211</td>
</tr>
<tr>
<td>Laser beam spot-size (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min.</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Max.</td>
<td>0.006</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Filtering of vegetation by a low-cost NIR camera
Near infrared (NIR) is a section of the electromagnetic spectrum with a frequency lower than visible light but greater than thermal radiation. NIR radiation has a wavelength ranging between 750-1400 nm. The associated phenomena are essentially similar to those regarding light, although the response of materials to visible light is different than that of infrared light. NIR images are used for the automatic recognition of the vegetation layer with techniques that are now well-established in Remote Sensing from space sensors [Turker, 1979]. The study of the spectral behavior of the vegetation offers a set of quantitative relationships between remotely sensed data and parameters of vegetation: they are identified as indices that depend on the relationship between the typical bands of absorption and reflection. These arithmetical relationships, called vegetation indices, are mainly composed of red and NIR wavelengths. They are closely related to the amount of plant biomass and the concentration of chlorophyll. Several vegetation indices have been proposed in literature, but in this paper we do not want to analyze this issue. The reader is referred to [Carlson and Ripley, 1997] for a comprehensive review.
The idea that was developed along the research described in this paper is based on the use of NIR images to support the localization of the vegetation in TLS point clouds of rock faces. To achieve this task three main issues have been considered:

1. the selection of a NIR sensor featuring characteristics suitable for this application, with a particular attention toward a low-cost solution;
2. definition of an algorithm to detect “green” areas in NIR images;
3. mapping each laser scans with classified NIR images, and then detecting which 3D points correspond to “green” areas.

In the next paragraphs the solutions found for each item are reported. Eventually, some results obtained along an experimental application are illustrated in the last section.

Figure 7 - Data filtering by the iterative method applied to test-field in Figure 6. The light gray areas represent the point filtered out after the first filtering step, the white the ones filtered out after the second step, while the white ellipses represent the final manual corrections.

Creation of a low-cost NIR camera

A wide range of sensors that allow the acquisition of NIR images are available on the market. However, the choice of the camera for TLS applications focused on the analysis of rock faces has been influenced by the factors listed in the previous section. In addition, the sensor resolution should be comparable to that of the adopted TLS. Indeed, the distance from the sensor to the rock face can be very different according to the location and the geometry of each site. The only way to guarantee a sufficient resolution is given by a camera equipped with different lenses. Our choice fell on a commercial reflex (SLR) digital camera Nikon D100 (3008×2000 pixels), which was modified in order to acquire also images in the NIR region of the light spectrum. Most digital cameras available on the market have CCD (or CMOS) sensors able to register the electromagnetic radiation in both visible and NIR spectral bandwidths. As a SLR digital camera is sold for normal photographic purposes, the visual quality of the final image is enhanced with a filter applied in front of the CCD sensor. The main goal of this filter (usually called Bayer filter) is the decomposition of the electromagnetic information that each pixel acquires. Light is therefore decomposed into 3 components, where each pixel can measure only a single channel (red, green, blue).
Most lenses cannot correctly focus each wavelength on the sensor plane. This problem generates a loss of definition. To overcome this drawback it is possible to apply a filter that removes the infrared component, but this filter can be manually removed from the camera, while the Bayer filter is often fixed.

In the Nikon D100 camera adopted in experiments, the infrared filter can be manually removed, as shown in Figure 8. To modify the spectral sensitivity of the camera, we first open the case of the camera and remove the visible pass-band filter located in front of the sensor matrix. The filter was then replaced by an optical window transparent to visible and NIR wavelengths and preserving the same optical path for the light rays. After this operation the cameras are sensitive above 700 nm and additional filters are added in front of the lenses to obtain the desired spectrum range for the data acquisition. More details about the solution adopted can be found on the Internet (www.lifepixel.com). The operation is not difficult and a user without professional experience in photographic camera repair can do it.

**Figure 8 - Some steps of the manual removal of the NIR filter on a Nikon D100 camera.**

**Filtering algorithm on the NIR images**

Different tests were carried out in order to determine the best index capable of discriminating the vegetation from the background rock. In our experiments we have verified that good results can be obtained with the Normalized Difference Vegetation Index (NDVI). This is a well-known parameter based on a combination of the red channel \( \rho_R \) with the NIR channel \( \rho_{NIR} \). As proposed by [Kriegler et al., 1969], this index can be computed as follows:

\[
NDVI = \frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + \rho_R} \quad [1]
\]
NIR information can be recorded by the modified SLR camera with a black filter on the lens, while the red channel can be always acquired by the modified SLR but using a NIR filter.

Once the NDVI index has been evaluated for the whole image, a threshold is used to identify all vegetated areas. In this way, a binary classification mask can be created. It contains information on the parts of the rock face that have to be filtered out because they correspond to vegetation. The mask has the same size the NIR image has ($n_x \times n_y$).

On the other hand, the mask could feature isolated and sparse points, or areas classified as vegetation with only a small separation. In order to regularize this result, two further processing steps are applied. The first consists in filling the holes in the region classified as vegetation, i.e. to remove single or small groups of pixels which have not been recognized. Secondly, a median filter is employed to remove any sparse point and to obtain a more regular classification mask. Examples of these processing steps can be seen in Figure 9.

Once the processing of all the NIR images has completed, the computed classification masks will be used to discriminate those 3D points in the point cloud which have been classified as vegetation. Indeed, more than one NIR image might be needed for classifying a laser scan.

**Figure 9** - Results of the application to test-field rock face of the filtering procedure based on NIR images. White areas always show the areas classified as vegetation. Sub-figure (A) shows the binary map obtained with NDVI classification; (B) the binary map after NDVI+hole filling filters; (C) the binary map after NDVI+hole filling+median filters.

**Mapping NIR images onto the laser scans**

As mentioned in the last item at the beginning of this section, the images captured by the low-cost NIR camera have to be mapped onto a laser scan. Obviously, in the case of a large rock face requiring more TLS stand-points and several scans, the filtering procedure must be repeated per each of them.

Each laser scan is internally referred to a Cartesian reference system that is called *intrinsic*...
reference system (IRS). A generic point of a scan is then located in the IRS by using a triplet of coordinates \( x, y, z \). A NIR image, like a generic image in another part of the light spectrum (e.g. an RGB image), can be mapped without ambiguity onto the laser scan. To carry out this task, the image has to be oriented in the IRS, requiring the knowledge of the interior (IO) and exterior orientation (EO) parameters [Kraus, 2008]. The former include the principal distance \((c)\), the coordinates of the principal point \((\xi_0, \eta_0)\) in the photo reference system defined by the 2D Cartesian axes \(\xi\) and \(\eta\), and the additional parameters (APs) of a model to compensate for the effect of lens distortion [Luhmann et al., 2006]. The APs have been incorporated into the terms \(\Delta\xi\) and \(\Delta\eta\) and they are the same for all the images captured by the same camera. Their computation is performed by the user through a procedure that is called camera calibration [Fraser, 1997]. This will be described in the following. The former parameters consist in the attitude angles \((\omega, \varphi, \kappa)\) of the image and the coordinates of the perspective centre \((x_0, y_0, z_0)\) with respect to the IRS.

Disregarding at the moment how all the parameters can be computed, the relation between a point of the scan and its corresponding image point is given by the collinearity equations:

\[
\begin{align*}
\xi &= \xi_0 + \Delta\xi - c \left( \frac{r_{11}(x - x_0) + r_{12}(y - y_0) + r_{13}(z - z_0)}{r_{21}(x - x_0) + r_{22}(y - y_0) + r_{23}(z - z_0)} \right) \\
\eta &= \eta_0 + \Delta\eta - c \left( \frac{r_{21}(x - x_0) + r_{22}(y - y_0) + r_{23}(z - z_0)}{r_{31}(x - x_0) + r_{32}(y - y_0) + r_{33}(z - z_0)} \right)
\end{align*}
\]

where the terms \(r_{ij}\) are the elements of the rotation matrix that depends on the rotation angles [Kraus, 2008]. The classification of all points of the scan can be carried out by re-projecting each of them on the NIR images. Indeed, a portion of the slope that has been scanned might not be visible in an image due to occlusions, while it could be present in another scan taken from a different point of view. To ensure more clarity, we can assume one image only where at each point \(x, y, z\) of the scan corresponds an image point with photo coordinates \(\xi\) and \(\eta\). This has to be compared to the classification mask, which however is expressed in pixel coordinates \((i, j)\) as shown in Figure 10.

The relation between both systems is given by:

\[
\begin{align*}
\xi &= \left| j - 0.5(n_i + 1) \right| \delta\xi, \\
\eta &= \left| 0.5(n_i + 1) - 1 \right| \delta\eta
\end{align*}
\]

assuming that \(\delta\xi = \delta\eta = p\) is the pixel size of the NIR image (no significant differences along the \(\xi\) and \(\eta\) axes have to be usually considered in SLR cameras). By using the computed pixel coordinates, the value on the classification matrix can be found with the nearest neighbour criterion. The original point on the laser scan is then classified according to the value read on the classification matrix. After the definition of the model mapping NIR (and RGB) images onto a point cloud, the procedures adopted for computing IO and EO parameters are here reported.
The first is the computation of the IO parameters for the camera employed. After removing the filter, the camera can be calibrated with the traditional photogrammetric procedure based on a free- network bundle adjustment and a set of image points (coded targets) automatically matched [Cronk et al., 2006]. This operation could also be carried out with natural points, if an object with good texture is selected [Barazzetti et al., 2011a]. This operation allows the estimation of $c$, $\xi_0$, $\eta_0$ and all APs according to the model proposed by Brown [1972]. Neglecting APs would result in a low quality final result, especially when dealing with consumer SLR cameras. Calibration was carried out by matching some coded targets obtaining a set of image points that were employed as input elements for the bundle adjustment. After the estimation of the final LS solution, it is possible to check the covariance matrix of all IO parameters, that is indispensable to verify the quality of the estimated values. Indeed, some distortion coefficients are correlated among them and a statistical evaluation is always recommended [Remondino and Fraser, 2006]. It is also important to remember that, according to a standard photogrammetric calibration, some images must be taken by rolling the camera (±90°). The use of a free net bundle adjustment does not require any 3D information about the calibration polygon (e.g. ground control points), because the rank deficiency, i.e. a 7-parameter similarity transformation, is removed with some conditions on the covariance matrix [Fraser, 1982; Papo and Perelmuter, 1982].

The second problem is the computation of the EO parameters for each camera pose, i.e. per each NIR image. Theoretically, if the IO is already known from calibration, every image could be oriented by measuring some control points that can be viewed in both laser scan and image. In photogrammetry, the orientation of a single image is referred to as space resection problem and could be accomplished by at least 3 control points per image. On the other hand, as addressed in [Forlani and Scaloni, 2002], the Least Squares solution computed by using the linearized collinearity equations (2) needs good approximations for instantiate the solving system [Mikhail, 1983]. Other methods are required to provide such initial values:
usually these work without initial information, but they need a higher number of control points (5-6 according to the adopted algorithm). In this application another solution has been selected. The laser scanner Riegl LMS-Z420i allows one to mount a camera on its head. This is maintained in a fixed and stable position with a special support (see Fig. 11), so that the EO parameters of the camera will be always the same and can be computed only once. This task is called mounting calibration of the laser-camera system. In this case, it was carried out following the procedure implemented by the commercial package RiscanPro® which is coupled to the Riegl scanner. Some retro-reflective targets must be surveyed with the laser scanner and are also contemporaneously imaged with the camera. They provide a set of corresponding points needed for the estimation of the transformation between the camera and laser reference systems. This operation could be completed with a single image. However, the results with this weak configuration were not sufficient for metric purposes. The procedure was then carried out with a 360° calibration polygon, that provided satisfactory results with a residual misalignment similar to the precision of the sensor.

**Experimental application**

The new camera was tested in the same test field described in previous section (Fig. 6). A set of images was acquired by using two different filters in order to acquire (i) RGB and (ii) NIR images. Both are placed in front of the camera lens without removing the mounting device. In this way we have, for each pose, NIR and RGB components and the OE parameters. In Figure 12 RGB (A) and NIR (B) images projected on the point cloud are shown.

During the acquisition the NIR wavelength is recorded on the three different RGB channels of the SLR sensor. This should be converted in a single channel before applying the NDVI algorithm while the RED channel is extracted directly from the RGB image. For each pose the algorithm produces a vegetation mask that can be reprojected on the point cloud by using known EO parameters. In this case a binary information is associated to each point and then the points recognized as vegetation are deleted.

Figure 12 shows some phases of the automated processing, in particular in sub-figure (E) the filtered rock face is illustrated.

In the case the project involves more than a single scan, these can be transformed from their respective IRS to a common ground reference system (GRS). This means that both 3D points with associated information (e.g. RGB or NIR mapped images) can be registered to the new unique reference system. A 3D rigid-body transformation allows one to pass from a point $x_i, y_i, z_i$ in the $i$-th IRS to the GRS $(X, Y, Z)$:

$$
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = R \begin{bmatrix} x_i \\
y_i \\
z_i
\end{bmatrix} + T_{o} + T_{z} + T_{y} + T_{x} \quad \text{(4)}
$$

where $R_i$ is a rotation matrix depending on 3 angles, similar to that used in collinearity equations (2), and $T_{x}, T_{y}, T_{z}$ are 3 shifts in space. The estimation of the 6 unknown parameters per each scan can be performed on the basis of a set of ground control points (GCPs) which have been measured in the GRS, or by using techniques which extract common points or features between different scans [see Vosselman and Maas, 2010].
Conclusions

The proposed procedure for vegetation filtering is based on a modified SLR digital camera which is transformed in a low-cost NIR sensor. This task is quite simple and can be operated by a non-expert user as well. The use of this camera coupled with a laser scanner instrument allows the assignment of a NIR value to each scanned 3D point. The NIR response of vegetation is a well assessed knowledge, which has been exploited for years in satellite and airborne Remote Sensing applications for classification purposes. Consequently, all the areas which are classified as vegetated in the NIR images will give rise to a binary mask to be used for discarding the corresponding 3D points. The process exploits the standard NDVI filter, but also include same further processing steps to cluster the “green” areas which are close to one another.

Some tests carried out on real datasets provided satisfactory results and proved that this strategy could be a viable solution. On the other hand, these experiments concerned a small case study with confortable operational conditions. The solution based on the low-cost NIR camera seems to be a valid approach for cliffs with a limited extension and a reduced average distance from the data acquisition stand-point.
In future the development of specifically tailored sensors could extend the use of this solution. Also the integration to terrestrial laser scanners with FWF capability is supposed to give a support in removing vegetation points which could not been classified at hardware level. Either the effectiveness of the proposed algorithms and the operational aspects need to be validated through a wider testing activity. A more extensive experimentation to rock faces covered by diverse species of vegetation, featuring different density, depth and width of “green” areas, and variate spectral response has to be carried out in the future. In addition, more test-fields with different geometric characteristics have to be accomplished, considering various extensions of the rock surface to be analysed and average distances from the sensors.

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Remote characterization of seafloor adjacent to shipwrecks using mosaicking and analysis of backscatter response

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Abstract
The paper’s aim is to evaluate mosaicking and analysis of backscatter angular responses as adequate techniques to quickly characterize the seafloor adjacent to shipwrecks, extending the results of a limited number of grabs. Both techniques have been applied to the case-study of the VLCC Haven shipwreck site, applying the approach known as Geocoder among the available methods. From these results, the development of the research activities will attempt to improve techniques and to generalize a methodological approach for the analysis of backscatter coming from an area of seafloor with the presence of one or more anthropic objects.

Keywords: backscatter, mosaic, multibeam, seafloor classification, shipwreck.

Introduction
An acoustic wave propagating in water meets a series of obstacles either in the water column itself (e.g., plankton, air bubbles, fish shoals) or at the boundary interfaces of the medium (seabed and surface of the sea). After these collisions, a part of the transmitted energy comes back to the sonar system. In the case of a monostatic configuration (transmitter and receiver located at the same point), this energy is called backscatter.

As a function of the available system typology and the related purpose of utilization, the energetic components of an echo are then either desirable (if the obstacle is the target wanted) or not (reverberation jamming the useful signal). In both cases, understanding their properties is essential to the functioning of the acoustic system because the echoes need to be received in the best conditions, or because they need to be reduced or filtered out as much as possible [Lurton, 2002].

Depending on the purpose of the user, there are many different types of information that is possible to extract from the seafloor acoustic data including physical (i.e. porosity), acoustic (i.e. attenuation), geotechnical (i.e. elastic and shear strength moduli) properties, and also the general morphology (i.e. relief) at different scales. In the absence of a specific task, a seafloor characterization system aimed at extracting information about sediment texture probably is most generally useful. In fact, the grain size is important for a number of engineering, environmental, and military applications [Mayer, 2011]. For the particular case of the environmental risk assessment of shipwrecks, this information is useful for many scopes (i.e. what intervention
adopts to minimize the environmental impact, monitoring of oil patches).

The use of the multibeam echosounders (MBES) started in the seventies for bathymetric purposes. But only in the last two decades their potentialities for seafloor characterization from the reflected energy measurements have emerged [De Moustier, 1991]. In the recent years, a certain number of different approaches have been developed to process the MBES reflectivity data in order to map discrete geographical areas of the seafloor with the same acoustic signature. This process is generally called acoustic segmentation [Preston et al., 2004].

In the work presented in this paper, we analyze the backscatter coming from the seabed – acquired by a MBES – to mainly remotely identify the sediment type of an area adjacent to an anthropic object (i.e. the shipwreck of the VLCC Haven). Among the various available ones, the approach called Geocoder is applied [Fonseca and Calder, 2007; Fonseca et al., 2009]. The deducted results are ground-truthed by grabbing.

The expected results of this work are to evaluate the advantages of the Geocoder approach to quickly and entirely identify – with the help of a limited number of seafloor samples – the sediment type of seafloor areas characterized by the presence of shipwrecks.

**Backscatter, roughness and angle of incidence**

An acoustic wave meeting an interface between two mediums produces – in function of the angle of incidence, the different acoustic impedances (products of sediment density and sound speed), and other parameters that are characteristics of each medium – a set of waves refracted in the second medium and another set reflected and diffused (scattered) in the first one.

The ratio between the acoustic intensity coming back from the target in direction of the source and the intensity incident on the same obstacle is called \( \text{target strength} \) \( (TS) \). This ratio is related to the physical nature of the obstacle, to the structure (internal and external) and to the characteristics of the incident signal (angle and frequency).

During the propagation, the intensity of the transmitted acoustic wave \( (\text{source level}, SL) \) is subject to \( \text{transmission loss} \) \( (TL) \) mainly due to geometrical spreading and medium absorption.

In the specific case of the seabed, the \( \text{target strength} \) mentioned before can be determined using the \( \text{backscattering cross-section} \) which can be decomposed into two parts: the dimension of the seabed actually insonified by the acoustic system \( (A_s) \) and the corresponding \( \text{backscattering strength} \) for unit of surface \( (BS_s) \).

So the level in decibel of the backscattering signal \( (\text{echo level}, EL) \) can be estimated using the monostatic active sonar equation [Kinsler et al., 2000]:

\[
EL = SL - 2TL + TS = SL - 2TL + 10 \log_{10} A_s + B_s \quad [1]
\]

The interactive process is influenced by the local characteristics of the seabed, which – as a function of the frequency and of the angle of the incident acoustic wave – can be more or less represented as an ideal plan surface. The irregularities of the surface shed the acoustic energy in all the directions (Fig. 1): one part, called coherent, is reflected without
deformations – except the transmission loss – in a direction specular to the incidence; whereas, the remaining part is scattered all around the space, including the direction of the source (backscatter). The relation between the two over mentioned parts – specular and scattered – is mainly a function of the surface roughness.

![Figure 1 – Reflection (coherent part) and scattering of an acoustic wave incident a rough surface.](image)

The roughness of the seabed – depending by the geological (i.e. rock, mud, ...) or biological (living organism, shell, ...) origin – covers a wide scale of sizes (from a few millimeters to meters). Furthermore, there are some scales – i.e., ripples of some centimeters present on the topography of a sandy seabed – which produce different physical processes at the same time. Applying the Fourier transform to the seabed relief, it is possible to quantify the energetic distribution in different spatial harmonic components, each one defined by a spatial wavelength ($\lambda$) and a wave number ($K = \frac{2\pi}{\lambda}$). In the case of a surface of random roughness, the power spectrum ($S_K$) tends to decrease with wave number, as larger amplitudes are associated with longer wavelengths (Fig. 2). For a given seafloor area, the variance $h^2$ of relief amplitude can be estimated by the integral of its spatial spectrum over all components [Lurton, 2002]:

$$h^2 = \int S_K dK \quad [2]$$

Beyond the surface roughness, the scattered part of the acoustic signal is tightly influenced by the angle of incidence. For angles of incidence close to the normal, the incident wave is reflected by the facets oriented to work as a mirror. This way corresponds to the maximum level of measured backscatter intensity and it is called
facet reflection. At oblique angles of incidence, the backscatter comes back as a product of a series of little contributors (scatterers), variously distributed in function of the local roughness. This process occurs in the so-called Bragg scattering domain. A composition of the two over mentioned regimes (facets reflection and Bragg scattering) – in function of the local roughness – can be used to realize a simple theoretical model for the scattering of an acoustic wave on a rough surface (Fig. 3).

Figure 2 – Spatial spectrum of a random rough surface through Fourier transform of the relief.

Figure 3 – Simple model of backscattering strength response of the seafloor in function of the angle of incidence and the microscale roughness.
Acoustic response of the seabed

The seabed mainly acts as a rough surface which spreads the incident acoustic wave. Among the energy scattered, the backscatter represents the source of information used by the acoustic seafloor mapping systems. Part of the incident intensity can penetrate into the seabed due to the little contrast of impedance between water and sediments. At the high frequency usually used by shallow-water MBES, the bottom penetration is small and the interaction is bounded to the surface (reflection from a non-plane interface), with possible complications related to the stratified or heterogeneous nature of the sediment. Heterogeneities can have various natures, but they are mainly represented by air bubbles entrapped in the sediment. Their response is usually modeled by a random distribution of scatterers whose contributes interferes with each other.

In literature there are different parameters to describe the variety of sediment types. The most common parameters representative of the sediment hardness are: the main grain size in Phi units \( M \); the porosity \( n \); the density \( \rho \); the relative compressional velocity \( c_r \) referenced to the speed of sound in water; the absolute compressional velocity \( c \) for a seawater value of 1,500 m/s; the reflection coefficient at normal incidence \( V_0^\circ \); the compressional wave absorption coefficient \( \alpha \); the absolute shear wave velocity \( c_s \); etc. Whilst, parameters representative of the sediment roughness may be: the roughness spectral strength \( \Omega_0 \), the standard deviation of the roughness along a unit distance \( h \), and the roughness slope standard deviation \( \delta \).

There is an obvious correlation between the sediment hardness and its roughness. For example, the roughness parameters globally increase with the acoustic impedance and, then, with the mean grain size of the sediment.

At frequencies used by acoustic seafloor mapping systems – from tens to hundreds of kHz – the backscatter coming from the seabed can be separated into a part scattered by the interface relief (either as facets reflection close to the nadir or by the scatterers due to local roughness at grazing angle) and another part which penetrates the sediment and is reflected back by volume heterogeneities (Fig. 4). This last process can also become predominant at oblique angles of incidence.

MBES imaging and remote characterization

The principle of sonar imaging for a MBES is mostly the same of a sidescan sonar system (SSS): the signal backscattered is recorded as a function of time and its instantaneous intensity varies with the roughness and so with the nature of the insonified seabed strip swept by the signal. But there are differences which make the process more complicated: with MBES data, time signal is available only after the beamforming and the sonar image is performed on the basis of a digital terrain model (DTM) created by bathymetric measurements; the central point of a beam is positioned on the swath and the image pixels are distributed around it until the boundary with the neighbor beam is reached. The sonar image so obtained has a geometrical distortion more reduced than a SSS imaging, which uses only the oblique-distance measurement and supposes a plane surface. At the same time, the presence of co-located bathymetry and reflectivity information in the MBES data permits to apply at the backscatter values more accurate corrections due to the effects of footprint size and local slope.
However, using systems at comparable frequencies, the quality of MBES imagery is generally less satisfying than SSS products. This is due to different issues: the along-track resolution is usually less fine; the directivity diagrams, although they improve the SNR, are prone to modulate the amplitude of the data collected (i.e., the resulting image without appropriate corrections is striated at constant angles parallel to the ship’s track); the angle of incidence of a MBES – usually hull mounted – is less grazing than for a SSS towed close to the seafloor. In particular, this last issue makes the detection of intensity contrast for micro-relief facets difficult.

For all the above mentioned arguments, it is easy to understand why the quality of a MBES image is usually lower than one obtained by SSS data. So MBES imaging should be more properly assimilated to measurement of average reflectivity and used to map variations in seabed types.

As for many common applications (navigation, dredging, fishery, ...) only a restricted identification of the seabed type – i.e. using an around ten classes – is required, this objective can simply be obtained by the analysis of the measured backscatter. However, none of the geological (granulometry, mineral constituents, ...) and geotechnical (density, compression modulus, ...) characteristics of the sediment can be directly identified by MBES reflectivity.

It is also possible trying to extract some geological and geotechnical sediment parameters by comparison with a model. This approach – only proven under simplifying assumptions – has a limited validity for the number of parameters to obtain in comparison of the small number of information that can be extracted from the backscattered acoustic signal.

Two main approaches coexist to characterize the seabed with MBES. The first – surely
more ambitious – aims at solving the “inverse problem”: to extract the characteristics of the sediment from the acoustic data available. This implies large modeling efforts to correlate acoustics data observed experimentally and the geological characteristics, in particular for the presence of porous media, living organisms, variously layered sediments, etc.

This approach, theoretical reachable, is too highly conditional – a large number of input parameters and very few observations – and sometimes hard to ground-truth, i.e. in deepwater [Lurton, 2002]. However, an increasing number of mathematical models has been developed to obtain a better physical understanding of backscatter coming back from the seabed [Mulhearn, 2000]. There are models that consider backscatter versus grazing angle, i.e. Stockhausen [1963], Crowther [1983], Stanton [1984], Jackson et al. [1986], Boyle and Chotiros [1995], and other which consider its behavior versus time from a pulse transmission, i.e. Bergem et al. [1999], Clarke et al. [1988].

The second approach – definable pragmatic – categorizes useful classifying parameters among the data acquired by the MBES. Also if usually deprived of any direct physical significance, these parameters are provided of sufficient discriminatory power. The MBES data are calibrated in function of these parameters, over a certain number of validated configurations. If there is a new case, it can be identified by comparing them with the existing database. Despite this approach can appear restrictive, the largest part of the practical applications available nowadays are based on it. For instance, RoxAnn [Murphy et al., 1995] and QTC-View [Collins et al., 1996], ones of the first commercial systems in this field, work on the output of a standard ship’s echosounder to analyze in various way the acoustic returns from the seafloor. These systems are not seafloor classifiers, but rather segmentation systems that divide the seafloor into regions of consistent acoustic return type [Mayer, 2011]. The results obtained – empirical and site specific – require a certain number of sediment samples to correlate acoustic answers and seabed parameters [Hamilton et al., 1999].

Recent approaches to the problem of the acoustic segmentation are mainly based on: the texture analysis applied to backscatter mosaic [Preston et al., 2004; Preston, 2009], the extraction of features based on the relationship between the reflectivity and the angle of incidence [Hughes Clarke, 1994; Fonseca and Calder, 2007; Fonseca and Mayer, 2007; Parnum et al., 2007], the analysis of entire backscatter curves [Canepa and Pace, 2000; Hamilton and Parnum, 2011].

**Issues linked to the backscatter mosaicking**

A backscatter mosaic image is a grid of square pixels, each one representing an area of \( m \times m \) square meters on the seabed [Augustin et al., 1994]. It is built by grouping and averaging individual backscatter intensity – at different angles of incidence and from different acoustic swaths – into pixels values representing a normalized amplitude and the original angular information removed. At the same time, as a consequence of the mosaic resolution chosen, some pixels may contain interpolated value from the surrounding measured reflectivity values.

In the mosaicking process, there are two main obstacles: MBES does not log directly the absolute value of backscatter, but relative magnitude whose calculation is not clearly defined in the technical documentation of the system manufacturer; the need to remove the backscatter angular response, which represents how the backscatter strength changes with the angle of incidence.

The removal of the angular variations of the backscatter, due to different angular response, is
an essential operation to create a consistent mosaic – without angular variation along the swath – for an area of homogeneous seafloor. This result is difficult to obtain because the angular response is an intrinsic characteristic of the seafloor. Thus, we need to know some information about the seabed type before to create the relative backscatter mosaic. This prerequisite is not properly practical as the primary aim of an acoustic mosaic is proper to obtain some indications around the seafloor nature [Fonseca and Calder, 2007].

**Analysis of the backscatter angular response**

The variation along-swath of the backscatter intensity linked to the angle of incidence – one of the two problems for a correct mosaicking – represents, at the same time, the main source of information in various methods of remote seafloor characterization. In practice, by the analysis of the backscatter angular response, it is possible to estimate important acoustic and physical properties as grain size, impedance, attenuation and roughness of the superficial sediments.

In this technique, the signal level for a given beam, sometimes averaged on a series of consecutive pulses, is corrected for some terms of the sonar equation [1] to obtain the target strength. This is then corrected for the swath footprint in function of the geometry, of the beam amplitude and of the signal time duration. So the unit backscattering strength obtained – corrected by the refraction for the sound velocity profile and by the bathymetry extracted by the digital seabed model – is assumed to be only function of the angle of effective incidence on the seafloor and the sedimentary facies.

However, the information obtained is enough coarse as it is possible to fall into ambiguities due to different seabed types with similar acoustic responses at the same angles. Moreover, there are two additional sources of difficulties in the application of the above method: inaccurate measurements of backscatter strength and not uniform sediment types of seafloor across the swath [Fonseca et al., 2009].

**The case-study of the VLCC Haven**

The unfortunately famous VLCC Haven shipwreck – one of the biggest of the Mediterranean with its 344 meters of length overall – has been chosen as a case-study to apply the mosaicking and the analysis of the backscatter angular response. The main body lies on a muddy seafloor off the coast of Arenzano (Genoa) at a depth of about 75 meters (Fig. 5 and Fig. 6), whilst a part of the bow with the bulb is at more than 500 meters of depth.

The sinking – dating back to April 14th, 1991 – was due to a fire caused by a violent explosion abreast of the forward tank. After the sinking, the combusted and semi-combusted residues were removed from the seashore and the seabed as far as the 10-meters isobath, and were pumped from the shipwreck tanks and premises. The residues present on the seabed at a depth beyond 10 meters have been left to environmental auto-decomposition processes.

In 1998, at the end of a dispute lasting about eight years, the Italian Prime Minister solved the dispute concerning compensation for the sinking related damages, with an out-of-court settlement. Part of the damage compensation was employed to perform both decontamination operations on the shipwreck and interventions of environmental restoration of the sea and coast area, which were most damaged by the accident’s harmful effects. The shipwreck decontamination operations formally ended on June 12th, 2008.
From the environmental point of view, the decontamination operation of the *Haven* represents an important pilot experience at the international level because of both the location of the hydrocarbon tanks and the shipwreck position, lying on shallow seabed a few nautical miles from a tourist coastal zone [Masetti and Orsini, 2009].

The acoustic data of this case-study were recorded using the MBES Kongsberg Simrad EM300, hull mounted at the Aretusa ship, hydrographic vessel of the Italian Navy [Masetti et al., 2010]. The tool Mosaic Editor – based on the Geocoder engine – of the hydrographic data processing software Caris HIPS&SIPS 7 was used to create mosaics and analyze the sediment properties of the acoustic image obtained. This choice was mainly due to the array of detailed backscatter corrections and accurately modeled seafloor characterization algorithms of the Geocoder approach.

The workflow, started with the import of the acquisition lines, was developed with the application of tide corrections and the editing to remove any spikes or bad data through the editors for navigation, attitude and bathymetry. After this cleaning, a step common to the bathymetric processing, the Geocoder engine algorithms of backscatter correction were applied to the data [Fonseca and Calder, 2005; Mayer et al., 2007].

The backscatter information are collected by this Kongsberg MBES as reflectivity (backscattering strength) for each beam and seabed image reflectivity (amplitude) for each of the contributor samples at the bottom detection of a beam. The data can be

---

**Figure 5** – Bathymetric map (in meters) of the case-study area.
used for the seafloor characterization, but require some post-processing corrections to increase their accuracy and remove the distortion of the real-time Time Variable Gain (TVG) model applied during the acquisition [Hammerstad, 2000].

Figure 6 – 3D view of the shipwreck based on the bathymetric data acquired.

Figure 7 – Beam pattern window showing the real answer of the transducer, the predicted one on the basis of the MBES frequency and sediment type, the resulting correction to apply to remove the transducer artifacts.
The Kongsberg seabed image data are not corrected for beam pattern variations in the receiver beams. Thus, the *beam pattern correction* has been applied to remove angular artifacts due to the transducer. This correction is based on a beam pattern file generated by the user to identify and remove this effect (Fig. 7). To obtain a good result, the file has been created on a flat, homogeneous and target-free area characterized by a well known sediment type. This file has been applied to all the survey data to correct them uniformly, obtaining a better acoustic image.

The processed imaging data were stored as Georeferenced Backscatter Raster (GeoBaR). GeoBaRs use BASE Surface technology and share in all of the benefits of that technology such as data caching, which helps provide scalability [MacDonald and Collins, 2008]. Using these GeoBaRs, a preliminary mosaic was created and, after the application of proper supervised adjustments (i.e. contrast, brightness) the final product was realized (Fig. 8).

![Figure 8 – Backscatter mosaic of the area adjacent to the VLCC Haven shipwreck.](image)

It is now possible to spatially identify mosaic regions with similar acoustic properties – called “acoustic themes” – defined using conventional, subjective and by-eye interpretation. The same method has been proven to be effective for SSS backscatter data, particularly in regions with sharp demarcations between neighboring seabed types [Brown, 2004].

From the analysis of the obtained mosaic, the uniformity of the reflectivity emerges and,
on the basis of the mentioned acoustic themes assumption, it could be possible to deduct the uniformity of the seabed sediment around the shipwreck object of the investigation. However, this assumption is recognized to be less effective for seafloor with a high level of seabed heterogeneity or a gradual change in the seabed characteristics because the backscatter behavior doesn’t present clear demarcations [Brown, 2008].

At the same time, a certain number of artifacts – i.e., corresponding at the normal incidence of some acquisition lines in the northern part of the survey area – are present in the final product (Fig. 9 left); whilst the area closer to the shipwreck is of difficult visual interpretation (Fig. 9 right).

![Figure 9 – Artifacts present at normal incidence in some acquisition lines in the northern part of the backscatter mosaic (left); zoom on the shipwreck site (right).](image)

An objective automated classification of the acoustic data based on the backscatter signal were conducted to avoid uncertainty or low confidence in the acoustic themes. This classification is based on a series of parameters calculated from the stacking of consecutive time series over a spatial scale that approximates half of the swath width (a stack of 20 – 30 consecutive sonar pings). Thus, each stacked angular response defines two distinct seafloor patches (one for the port side and another for the starboard side). These sediment analysis capabilities are one of the most innovative aspects of the Geocoder approach. It is made possible by the accurate removal of acquisition artifacts found in the source data and derived from years of published research in this field. The Geocoder sediment analysis engine – based on the ARA model [Fonseca and Mayer, 2007] and realized in SIPS with the name of Sediment Analysis Tool (SAT) – has been applied to the corrected imaging data. The results returned (i.e., sandy mud and muddy sand) are largely common for the entire area, showing the same homogeneity obtained by the visual interpretation (Fig. 10). This analysis, as in the case of the visual interpretation of the mosaic (Fig. 9 right), has also given results of difficult interpretation and high variability for the area closer to the shipwreck.

Summarizing, the described mosaicking technique, requiring the removal of information linked to the angular response, reduces the ability to make a quantitative seabed characterization on the obtained mosaic and it presents a series of artifacts. Whilst, the analysis of angular responses only permits to characterize the seafloor, but
with a spatial resolution limited to the swath width of the sonar. A combined approach could improve the spatial resolution of the angular response analysis and could produce mosaics more homogeneous, with fewer along-track and across-track artifacts [Fonseca and Calder, 2007]. The quality of the backscatter analysis and mosaicking results has been directly verified through the execution of a limited number of seabed samples through grabs (Fig. 11). Due to the target of this work, limited to the sediment type classification, these samples have been only visual inspected to define the mean grain size.

Figure 10 – Sediment Analysis Window: the real backscatter answer is modeled as the product of interface, volume and Kirchoff backscatter components.

Figure 11 – Seabed sampling through grabs.
Conclusions
The backscatter mosaicking and analysis processes applied to the seafloor adjacent to the VLCC Haven shipwreck have allowed for quickly characterization of the area – 2 hours for the MBES acquisition and the sampling operation, less than 1 hour for the data processing, both bathymetry and seafloor classification – extending the results of a limited number of grab samples to the remaining part of the survey with a good level of confidence.

The content of this paper represents a preliminary report, coming from the first part of a University of Genoa Ph.D. research project entitled “Georeferencing and Environmental Risks Monitoring of Shipwrecks using MBES data”. From these results, the development of the research activities will attempt to improve techniques and to generalize a methodological approach for the analysis of backscatter coming from an area of seafloor characterized by the presence of one or more anthropic objects.

At the same time, it will attempt to define uniform criteria to collect the information coming from MBES data into a modern shipwrecks’ GeoDB. In fact, only the standardization of databases allows the accessibility and comparability for various States [ICRAM CEDRE, 2007]. This characteristic should be a fundamental element for a wreck identification program – in particular for a closed basin as the Mediterranean – to ensure permanent monitoring and continuous updating of the shipwreck sites to prevent pollution effects (i.e., spillage of oil from the tanks).

The main research outcome could be the possibility to use MBES data as a low-cost method to monitor conditions of the large number of shipwreck presents in oceans. Furthermore, this research could give an important contribution to the creation of a Decision Support System (DSS) – based on a large geo-database with vessel, cargo and sink event information – used to define the criteria and the priorities for decontamination operations related to potential polluting shipwrecks.

Acknowledgments
The authors wish to thank the Cpt. Carlo Marchi and all the crew of the Italian Navy’s Hydrographic Ship “Aretusa” for the support during the acquisition of the acoustic data and the ground truthing operations. The methods and guidelines presented in this paper do not necessarily represent the policy of the Istituto Idrografico della Marina.

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Filtering LiDAR with GRASS: overview of the method and comparisons with Terrascan

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Abstract
The paper presents a procedure developed to calibrate the value of parameters used in GRASS algorithms that perform LiDAR’s data filtering. These cascade commands, developed by the Geomatic Laboratory of the Politecnico di Milano, were empirically calibrated for low spatial resolution LiDAR data. UCODE_2005 from USGS was the software employed in the calibration, mainly chosen because of its flexibility and adaptability to every kind of model; it carries out an inverse model calibration in an iterative way and performs the sensitivity analysis on the parameters. In the end the filtering results obtained after the calibration were compared to the one obtained with the software TerraScan in a completely automatic procedure.

Keywords: LiDAR, GRASS, TerraScan, filtering, comparison, method.

Introduction
The airborne LiDAR system (Light Detection and Ranging) is a recent technology that permits the creation of 3D models (DTM, DSM). The system is characterized by high point density (up to several points per square meter) and high accuracies (10-15 cm). Because of its recent development, this system still presents some uncertainties in data filtering process, that is the automatic distinction, by the use of specific algorithms, between points that belong to bare earth, vegetation and buildings.
In this work a comparison between two LiDAR point cloud filtering results, in particular on terrain and vegetation extraction, is carried on.
On one hand the GRASS LiDAR filtering algorithms, developed by the Laboratory of Geomatic at the Politecnico di Milano – Polo di Como [Brovelli et al., 2004] were used, on the other hand the filtering results obtained with the proprietary software TerraScan both in manual and automatic procedure were available.
The paper will also present the detailed description of the calibration procedure developed for the GRASS algorithms.

Filtering Algorithms
The two filtering software considered in this work are based on two different filtering algorithms; the LiDAR modules in GRASS are based on the algorithm developed at the Geomatic Laboratory of Politecnico di Milano, while TerraScan is based on the Axelsson
algorithm. Different kinds of filtering algorithms are available, and it is possible to classify them taking into account their characteristics; for example filters can use different input type (the raw cloud data or the result of a rasterization procedure) and can perform the analysis in one step or in an iterative way.

Other features of different algorithms consist in the number of points classified each time, in the return pulse used, in usage of solely the last pulse of LiDAR or, on the opposite, the usage also of the first one [Brovelli and Cannata, 2002; Tarsha-Kurdi et al., 2006].

Some filters use other kinds of information like aerial images, existing DEMs [Bretar and Chehata, 2007; Matikainen et al., 2007; Secord and Zakhor, 2007], land use maps, cadastral maps and a wide variety of multispectral data [Steinle and Vogtle, 2001].

**GRASS filtering algorithms**

The cascade commands are three (v.lidar.edgedetection, v.lidar.growing, v.lidar.correction) and they are present in the last release of GRASS (GRASS GIS 7.0). These algorithms can be classified as morphological and for each of them many parameters, ensuring algorithms flexibility, have to be set.

- **v.lidar.edgedetection** allows the detection of the edges of objects, where an edge can be thought as a consistent change in the height value corresponding to a small shift of the horizontal position.
  
  The output contains the classification of the nature of the measurement points (edge, non-edge).
  
  The parameters to be set are the approximation step in East and North direction (See, Sen), the Tikhonov regularising parameter with bilinear splines ($\lambda_g$), the two thresholds $t_g$ and $T_g$ for the gradient magnitude, the threshold $\theta_g$ for the edge direction, the Tikhonov regularising parameter with bicubic splines ($\lambda_r$).

- **v.lidar.growing**: this command fills-in the edge previously obtained using the idea that the inner part of an object has generally a greater height than its edges.
  
  The output contains the classification in four classes (terrain, terrain with double pulse, object with double pulse, object).
  
  The parameters to be set are the rasterizing grid resolution to be used in the region growing algorithm (td) and the minimum difference to assume a double pulse for each cell (tj).

- **v.lidar.correction**: this command corrects imprecision that the v.lidar.growing procedure can generate, especially in morphologically complex landscape.
  
  The parameters to be set in the last command are the spline steps in East and North direction (Sce, Scn), the Tikhonov regularising parameter with bilinear splines ($\lambda_c$), the two thresholds $t_c$ and $T_c$ for residuals analysis.

During last year the LiDAR algorithms were updated, in particular all the performance have been increased; all the modules are now optimized for larger datasets (GRASS 7.0).

**UCODE_2005**

UCODE 2005 is a software developed by United States Geological Survey (USGS) that performs model calibration with nonlinear regression methods and sensitivity analysis in a iterative procedure.

It can be applied with any application model or set of models; the only requirement is
that they have numerical (ASCII or text only) input and output files [Poeter et. al., 2008].
UCODE_2005 is built using the JUPITER API capabilities and conventions, which facilitates inter program communications.
The estimated parameters can be defined with user-specified functions: for example prior, or direct, information on estimated parameters also can be included in the regression.
UCODE_2005 needs different files to work, and the most important one is the configuration file (.in) [Poeter and Hills, 1998]. The .in file specifies the command to run the model, the parameters to be evaluated and their information (starting value, lower reasonable value, largest reasonable value, scale parameter values, adjustability, fractional amount of perturbation for sensitivity, applied log-transformation, maximum fractional change between iterations, etc...), and the other files needed for the calibration procedure: the model input file (.if), the model input file template (.tpl), the model output file (.est), the model output file structure (.ins).
The program requires for running the definition of the parameters to be estimated and the definition of the observations that it uses to verify every iteration results.
In the present work all the parameters had been defined inside the configuration file while for the observations an ad hoc file (.flo) was created; it contained all the observations used by the software to verify the accuracy of the simulated equivalent values.
Observations to be matched in the regression can be any quantity for which a simulated equivalent value can be produced, thus simulated equivalent values are calculated using values that appear in the application model output files and that can be manipulated with additive and multiplicative functions, if necessary.
The files .if (model input file) and .tpl (input file template) are used by UCODE_2005 to update the parameter values at every iteration.
In the configuration file the last pair of files to be defined are the model output file (.est) and the model instruction file (.ins). The former is the file in which the results of the model at every iteration are saved, the latter specifies the format of the output file.

**GRASS – UCODE_2005 integration**
In order to perform the calibration procedure on the algorithm parameters it was necessary to integrate the two software packages (UCODE_2005 and GRASS GIS).
The integration is due to the need of commands to work within GRASS environment (Fig. 1).
The UCODE_2005 files can be presented in the configuration file divided in different section (command line, parameters, observations, model input file and model output file).
The integration between the two packages is performed thanks to an intermediate script that reads the current value of the parameters and passes it to the “GRASS script” in order to perform the filtering step.
At every iteration UCODE_2005 executes the intermediate script that reads the actual parameter values in the UCODE_2005 model input file and executes the “GRASS script” which in turn executes some commands and creates the numerical output file.
UCODE_2005 finally reads the output file accordingly to the Model output file component and compares the simulated observations with the observations value. Depending on their difference UCODE_2005 updates the parameters values in the model input file and iterates the process.
As calibration area a small region with some buildings is usually chose; the calibration procedure is carried on independently for each LiDAR module [Brovelli and Lucca, 2009]; at first the v.lidar.edgedetection parameters are calibrated, then the edge detection is performed with the resulting parameters value and on the following algorithm the calibration is performed; the algorithm results are rasterized and each cell has a simulated equivalent value.

The observations to be compared with the output are created rasterizing the result of a building map of the area (digitized with the support of an ortophoto or directly provided in a vector format).

After the calibration procedure a validation in an independent zone is performed to evaluate the accuracy of the results; in this second area the algorithms with the calibrated parameter values are executed and the result, after rasterization, is compared with the raster building map.

**GRASS TerraScan comparison**

The calibration procedure was applied to a data set covering costal areas of Sardinia region (Italy). For the same area the filtering results obtained with TerraScan were available, so some comparisons between the two packages were possible.

**TerraScan Axellson’s algorithm**

Axelsson developed in 1999 a filtering algorithm based on TIN densification that is used in the commercial software TerraScan. The algorithm derives a TIN network from the neighbouring minima as a first approximation of the bare earth. In iterative steps the TIN is modified by adding other laser points that meet certain distance and orientation criteria in relation to the triangles that contains them [Sithole, 2005].

The vegetation and the buildings are classified using a cost function based on the second derivatives on the elevation differences [Axelsson, 1999].
The model assumes that the buildings consist of connected planar surfaces and because of this any change of direction of the roof will cause a non-zero value of the second derivatives; vegetation instead is modelled as points with randomly distributed second derivatives. The TerraScan classification procedure based on Axelsson algorithm was carried on in three different steps: at first a division between ground and over-ground points is carried on, then, on the over-ground points is performed the building classification and as last step the vegetation is extracted. In case of manual classification, after each step a manual check and reclassification of uncertain points is done by the user.

**Data description**

The LiDAR dataset was obtained with the Optech ALTM Gemini LiDAR system and an inertial Applanix system at a fly height around 1400 m. On the same area both an orthophoto and a false color infrared image with spatial resolution equal to 20 cm were available; they were made by a digital ADS40 camera contemporary to the LiDAR survey. The area selected for the filtering comparison is mostly flat but very complex from the morphological point of view (Fig. 2): a residential sub-area, an industrial one, different vegetated sub-areas and the sea are present.

Two TerraScan filtering results were kindly provided by Blom-CGR (the Italian company of Blom ASA group) for the comparison: a completely automatic and a semi-automatic one. The command sequence in TerraScan to obtain the two filtering results is the same: at first the points are divided in two main classes (ground and over-ground) and the terrain points
are extracted. On the over-ground points a building extraction algorithm is performed. At last, on the remaining points the vegetation ones are extracted; at the end four classes are present: ground, building, vegetation and unclassified points.

The difference of the semi-automatic procedures consists on the manual intervention of the user who reclassifies uncertain points after each classification step. This is a huge work, in fact the average manual editing efficiency, depending both on the morphological complexity of the area and on the final accuracy in classification, is about 4-5 km\(^2\) in 8 hours.

**Data processing**

The first step consisted in the parameter calibration using the procedure described in the previous paragraphs.

Then the calibrated parameters (Tab. 1) were used to filter the LiDAR data points of the area.

After the filtering step only the classes obtained from the correction step were taken into consideration for further processing.

<table>
<thead>
<tr>
<th>Table 1 - Calibrated parameters for the GRASS filtering algorithms.</th>
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<tbody>
<tr>
<td><strong>v.lidar.edgedetection</strong></td>
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<tr>
<td>Parameter</td>
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<td>-----------</td>
</tr>
<tr>
<td>See</td>
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<tr>
<td>Seña</td>
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<td>Tg</td>
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<tr>
<td>tg</td>
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<tr>
<td>λg</td>
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<td>θg</td>
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<td>λr</td>
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<table>
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<tr>
<th><strong>v.lidar.growing</strong></th>
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<td>tj</td>
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<td>td</td>
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<tr>
<th><strong>v.lidar.correction</strong></th>
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<tbody>
<tr>
<td>Sce</td>
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<tr>
<td>Sceña</td>
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<tr>
<td>λc</td>
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<td>Tc</td>
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</table>

In order to improve the information of the area using all the data available and to improve the detection of vegetated area, a classification on the false color infrared and on the orthophoto was carried on with GRASS.

The imagery set of commands in GRASS allows the classification of an area by taking
into consideration different images or image channels; in this way the use of both the two images has been possible. The classification was performed with a maximum likelihood function after the training sample selection; the four classes obtained correspond mainly to ground, vegetation, buildings and sea (or dark shadows) (Fig. 3).

![Figure 3 - Training sample and classification.](image)

**Classification comparison**
The analysis is done only between the two automatic procedures (GRASS result is shown in Fig. 4 and TerraScan automatic and semi automatic results in Fig. 5).
As the Figures legend shows, with TerraScan four classes are obtained: ground, building, vegetation and unclassified points; with GRASS we obtain four classes different from the previous one: terrain (category 1), which corresponds to the bare Earth, terrain with double pulse (category 2), which corresponds mainly to low vegetation, object with double pulse (category 3), which corresponds to medium-high vegetation and edges of objects, and object (category 4), which corresponds in the most of cases to the inner part of objects. Therefore the only common category is the ground one (called terrain in GRASS).

![Figure 4 - GRASS filtering result.](image)

The two packages classify as ground around 70% (GRASS – Tab. 2) and 67% (TerraScan – Tab. 3) of points; further analysis performed only on this class showed that the terrain and ground classes coincide for the 80% of points.
This result pointed out that there may be problems in the extraction of ground points; therefore it was decided to perform further comparisons focusing on this problem. The comparison with the semi-automatic procedure by means of TerraScan was not considered at this stage since the purpose of the work is the evaluation of the automatic software performances and in the case of semi-automatic TerraScan the filtering result was significantly improved by the user manual reclassification.

<table>
<thead>
<tr>
<th>Table 2 - Results of filtering for GRASS.</th>
</tr>
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<tbody>
<tr>
<td>Class</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Terrain</td>
</tr>
<tr>
<td>Terrain with double pulse</td>
</tr>
<tr>
<td>Object with double pulse</td>
</tr>
<tr>
<td>Object</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Figure 5 - TerraScan automatic and semi automatic results.

<table>
<thead>
<tr>
<th>Table 3 - Results of filtering for automatic TerraScan.</th>
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<tbody>
<tr>
<td>Class</td>
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<tr>
<td>----------</td>
</tr>
<tr>
<td>Ground</td>
</tr>
<tr>
<td>Vegetation</td>
</tr>
<tr>
<td>Building</td>
</tr>
<tr>
<td>Unclassified</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Ground – vegetation analysis
To perform advanced analysis on the points classified as ground or vegetation it was decided to work on a sub region of the whole dataset (Fig. 6). The first analysis is performed on all points classified as vegetation from the two filtering packages with respect to the result of the classification (Tab. 4). The Table show that the most of the points (for both the software) fall into the imagery vegetation class (TerraScan: 87.84%, GRASS: 86.10%).
The Table also shows that some points fall on building and shadow classes, thus it is not possible to identify them as error; they are probably due to the classification process because an orthophoto instead of a true orthophoto was available for the analysis.

In fact, orthophotos are generally (and also in this case) orthorectified using the DTM; on the opposite, to take care of the buildings height effects, a better solution is to orthorectify them by means of a dense DSM [Barazzetti et al., 2010].

A further analysis was done on the points belonging to the intersection between the vegetation class of one software and the other software ground class. Points classified as ground by TerraScan and as category 2 by GRASS (Fig. 7) and points falling in the vegetation class for TerraScan and in the terrain for GRASS (Fig. 8) were extracted; on these points the same computation was done after rasterization in order to compare the results with the classified imagery (Tab. 5).

As Table 5 shows both the software have problems in the correct vegetation identification; in fact some points that fall into the imagery vegetation class are classified as ground by TerraScan and as vegetation by GRASS (86.25%) and vice-versa (77.42%).

Considering the amount of those points, Table 5 shows that the error by TerraScan are greater than the one by GRASS (31575 points versus 15845 points).

The last step focused on height analysis of points belonging on the previously described intersections (Tab. 6).
The percentages in the Table were calculated considering the total number of cells of the map. The null cells correspond to pixels in which points were not classified as low vegetation (category 2) for GRASS and ground for TerraScan (Fig. 9) or vice versa (Fig. 10); in the Figures only the first two height classes are represented since they contain the most of the classified points.

The results presented in Table 6 confirm that TerraScan has more problems in detection of points belonging to low vegetation.
Figure 9 - Height analysis, ground (TerraScan) and category 2 (GRASS) points.

Figure 10 – Height analysis, terrain (GRASS) and vegetation (TerraScan) points.

Table 6 – Height analysis.

<table>
<thead>
<tr>
<th>GRASS (terrain with double pulse – category 2) – TerraScan (ground)</th>
<th>GRASS (terrain) – TerraScan (vegetation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ≤ h ≤ 1</td>
<td>2912</td>
</tr>
<tr>
<td>1 &lt; h ≤ 3</td>
<td>2548</td>
</tr>
<tr>
<td>3 &lt; h ≤ 5</td>
<td>15</td>
</tr>
<tr>
<td>h &gt; 5</td>
<td>0</td>
</tr>
<tr>
<td>Null</td>
<td>211017</td>
</tr>
<tr>
<td>Total</td>
<td>211017</td>
</tr>
</tbody>
</table>

Conclusions

The paper proposes two main topics concerning LiDAR data filtering; the former is related to the development of an automatic calibration procedure for the GRASS filtering algorithms, the latter is related to the comparison between the results obtained applying the calibrated parameters and the one from the software TerraScan.

The calibration procedure was implemented with the integration of UCODE_2005 and GRASS with very good results; moreover it can be repeated with different LiDAR
resolution dataset and the parameters value can be applied to other data belonging to the same survey.

Concerning the comparison between the filtering results, the paper shows that both the two packages have problems in the procedure: GRASS mainly in the correct extraction of hand made structures and TerraScan in vegetation detection.

The results obtained (enforced also by other tests accomplished by the authors) prove that the GRASS procedure, once parameters have been calibrated considering the characteristics of data and the landscape morphology, is comparable with the TerraScan one. To be more precise, GRASS is able to better identify the low vegetation points; on the contrary Terrascan is more reliable in the hand-made structure detection. In any case neither GRASS nor Terrascan obtain automatically a filtering accuracy higher than 95%, value that in most of cases is considered as reference for tolerance; therefore a manual step, time consuming and costly, must follow the automatic filtering. This means that further refinements in the procedure and algorithms are required for both tools.

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LiDAR or Photogrammetry: Integration is the answer

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Abstract

In the last few years, LiDAR and image-matching techniques have been employed in many application fields because of their quickness in point cloud generation. Nevertheless, the use of only one of these techniques is not sufficient to extract automatically reliable information.

In this paper, an integration approach of these techniques is proposed in order to overcome their individual weakness. The goal of this work is the automated extraction of man-made object outlines in order to reduce the human intervention during the data processing simplifying the work of the users. This approach has been implemented on both terrestrial and aerial applications, showing the reliability and the potentiality of this kind of integration.

Keywords: image matching, LiDAR, terrestrial, aerial, integration.

Introduction

The automated extraction of object geometries from laser scans and photogrammetric images has been a topic of research for decades. Both techniques offer the opportunity to collect reliable and dense 3D point data over objects or surfaces under consideration. In particular, soon after the laser scanner devices had been developed to a commercial level, many people speculated that photogrammetry would be totally replaced by laser scanners. On the other hand, other researches asserted that image matching techniques would be able to produce the same point clouds of LiDAR instruments without using expensive instruments. However, it has afterwards become more obvious that neither technique would assure complete and consistent results, in every operative condition.

LiDAR allows a direct and simple acquisition of positional information, collecting thousands of points per second and giving the possibility to acquire full waveform data. Nevertheless, this technique has non-negligible drawbacks due to the impossibility of directly obtaining radiometric and semantic information. Then, laser scanners are not able to give the exact position of the object breaklines [Cheng et al., 2004]. Still, LiDAR data has no redundancy, while the advantage of images is the similarity to human vision, well-known internal geometry, good interpretability and ability to capture texture and multichannel reflectance information [Rönholm et al., 2007]. Anyway, image-matching techniques cannot assure to generate point clouds without blunders in every operative condition (especially in terrestrial ones). A mayor sting obstacle in the way of automation in photogrammetry is the complicated and sometimes unreliable matching procedure, especially when dealing with converging imagery with significant depth variations [Habib et al., 2004] or with...
the presence of bad-textured areas. The Semi-Global Matching [Hirshmuller, 2008] has partially solved this kind of problems.

Both techniques request several automated and manual interventions, once the point cloud has been acquired, in order to extract the information of interest for the 3D model or drawing production: this work cannot be performed in a complete automatic way and, nowadays, this step represents the true bottleneck of the whole process. The segmentation and classification algorithms are not able to give affordable results in every operative condition: the need of an experienced user to complete processes, hours of work using complicated (and expensive) software and PC able to manage millions of points are usually requested. The same happens when drawings are requested: in these conditions, the plotting is manually performed, taking long time to achieve a complete product.

Many authors have suggested to face the weakness of these techniques and to improve the automation of their processing exploiting their complementary nature. Some papers consider this integration as a possibility of improving the produced point cloud [Alshawabkeh et al., 2004; Remondino et al., 2008] in terms of completeness and reliability. Other papers have described this integration considering it as a sharing of radiometric and ranging information in order to simplify the information extraction from laser scanner data. These works, however, only consider single images [Ardissone et al., 2007] and the extraction of information from data is performed manually, using only point cloud data. Other examples show tightly integration in terrestrial applications [Becker and Haala, 2007]. In these works, photogrammetry is employed to determine the position of littler details of the façade while the position of these details on the model is defined by LiDAR data. A similar approach, but applied to aerial cases, is described in [Cheng et al., 2008]. The first step of this approach is the LiDAR data segmentation by means of a region growing algorithm. Then, using this information, the extraction (guided by LiDAR data) of the buildings from images is performed. In McIntosh and Krupnik [2002], edges are detected and matched in aerial image stereo-pairs, refining the DSM produced by airborne laser scanner data and improving the representation of surface discontinuities, especially building walls or straight lines. The result of this approach is the generation of a TIN comprising the breakline information.

Starting from these works, a new integration approach is proposed in this paper: this approach is focused on the extraction of man-made manufacture outlines (building breaklines, roof outlines, etc.) both in terrestrial and aerial applications. LIDAR and photogrammetric techniques continuously share information during the whole processing in order to complete the image and the point cloud information. These techniques work independently and share information to perform these tasks in a more complete and reliable way, overcoming their individual limits and achieving better results than each technique separately. The final goal is to try satisfying the exigencies of the final users (photogrammetrists, surveyors, planners, designers, etc.) reducing the time of production of a drawing and limiting the manual intervention in post processing phases.

In the following, the potentiality and the reliability of this kind of integration will be shown in different applications.

**The algorithm**

The proposed algorithm tries to merge image matching and LiDAR data processing. The main idea of this process is quite simple: the reliable information of laser scanners are
used as approximate DSM in order to help the matching algorithms and, then, the obtained information are employed to speed up the drawing production or the point cloud segmentation and the modelling. Combining this information the individual weakness of each singular technique can be overcome, reaching a reliable result in almost all the operative conditions.

The matching algorithm has been implemented considering a multi-image approach as these techniques allow an improvement to be made in geometric precision and reliability with respect to image pairs [Zhang, 2005]. The implemented algorithm, then, considers the epipolar geometry between images in order to reduce the search area in adjacent images, and thus decreasing the number of blunders to a great extent. The run on the epipolar line is further reduced by the approximate z-value that is provided by the LiDAR data. The extracted edges can be checked and improved using the LiDAR information in order to define the 3D geometric outlines of the surveyed objects. This kind of information can be used as rough drawing of the object or it can be used as additional information in the segmentation and modelling processes. This approach has been initially implemented in terrestrial applications but it is then adapted to aerial cases, achieving good results in both these applications. The proposed algorithm can be divided into the following steps. A general workflow for both terrestrial and aerial applications is shown, in Figure 1.

**Data acquisition**
The data acquisition conditions the goodness of the achievable results: good image quality and a noiseless LiDAR acquisition can improve the results of the automated algorithms.
In the terrestrial acquisitions, several tests have shown that the images should be acquired according to two different configurations in order to achieve better results in the matching process: the ad hoc multi-image configuration [Nex and Rinaudo, 2009] and the sequence of converging images [Nex, 2010]. The central image of both configurations will be considered as reference image in the following matching process. In aerial acquisitions, high overlaps between images and adjacent strips are mandatory. The LiDAR data, in terrestrial cases, is acquired close to the reference image position in order to have approximately the same occluded areas as the reference image. Median filtering reduces the noise of the LiDAR point cloud that usually affects the data.

**Image pre-processing**

In order to enhance the images, two different approaches are used considering two different topics: the edge extraction from the reference image and the matching process. In order to improve the edge extraction, the reference image is previously processed using a non-linear Edge Preserving Smoothing (EPS) filter. In particular, the Sigma Filter [Lee, 1983] has been used: this algorithm is able to smooth the little radiometric variations preserving and enhancing the main edges on the image. The boundaries of the man-made objects on the image are sharpened and smoothed deleting the little radiometric changes that affect the surfaces of these elements. Therefore, the edge extraction allows the object boundaries to be extracted, neglecting the useless information. In general, the pre-processing allows number of detected edges to be increased respect to the original image [Nex, 2010]. On the opposite, the radiometric variations (texture) are of primary relevance in the matching process and they must be stressed to improve the results. For this reason, an Adaptive Gaussian Smoothing is performed in order to filter the image according to the noise level evaluated on the uniform areas of the image. Then, the image enhancement is achieved using a Wallis filter.

**Image orientation (3 or more images)**

In the aerial case, images and LiDAR data are already oriented in the same reference system. In terrestrial cases, the A²SIFT (Auto-Adaptive Scale Invariant Feature Transform) operator [Lingua et al., 2009] has been adopted in the tie-point extraction: for a detailed description of the algorithm, refer to [Lingua et al., 2009]. Then, a robust relative orientation (Least Median Square, LMS) is performed in order to eliminate any mismatch [Lingua and Rinaudo, 2000]. The extracted tie points are merged together with the Ground Control Points (GCP) and a bundle block adjustment is performed. Images are oriented in a Photogrammetric Reference System (PRS) in order to have the z-coordinate normal to the main plane of the façade. Sub-pixel accuracy is requested in order to perform the following matching algorithms.

**Edge extraction from reference image**

The central image is chosen as reference image, as it has been already said. After that, the edge extraction is performed by the well-known Canny operator. The final goal is to define only some “dominant” points able to provide a quite good approximation of the edge trend for its reconstruction in the matching process. The dominant points are recorded and linked by straight edges [Nex, 2010].
The edges are only extracted in the regions of interest: i.e. façade glass, in terrestrial acquisitions, is always excluded as it could create mismatches and blunders due to reflection.

**LIDAR data registration**

In the aerial case, images and point clouds are usually registered in the same coordinate reference system. In contrast, the point cloud of terrestrial acquisitions is registered in the PRS by means of a spatial roto-translation. This step is made possible using the coordinates of the reflective markers that are both visible on the point cloud and the images. In this way, the information between the images and the point cloud are shared.

**Edge matching between images**

A multi-image matching algorithm has been set up. This process can be divided in three steps. The first algorithm is a modification of the Multi-Image Geometrically Constrained Cross Correlation MIGC$^3$ [Zhang, 2005]. Through this algorithm, the dominant points of each edge are matched in all the images in order to reconstruct the breakline positions in 3D. The images are preliminarily undistorted (using the camera calibration data) in order to ease them into a central perspective [Nex, 2010].

The MIGC$^3$ is able to match a high percentage of the extracted dominant point. Nevertheless, more than one reliable solution can be possible considering only the cross correlation values. A relational matching technique has been developed in order to solve these ambiguous matches and to improve the rate of the successfully matched points. This algorithm integrates the figural continuity constraint through a probability relaxation approach [Kittler and Hanhock, 1989; Christmas et al., 1995] and it is able to solve several ambiguities of the matching process. The method uses the already matched dominant points as “anchors” and defines, in an iterative way, the more suitable match between candidates imposing a smoothing constraint.

Finally, a Multi-Image Least Square Matching (MILSM) [Baltsavias, 1991] with the epipolar constraint has been performed for each extracted point to improve the accuracy up to a sub-pixel dimension. Considering an affine transformation between patches, the estimation of all these parameters is often ill-posed on the image patch of an edge. For this reason, the parameters are initially orthogonalised and the Student t-test is performed to determine their significance is evaluated excluding any undeterminable parameters [Gruen, 1984].

**Edge filtering & blunder detection**

Blunders are initially deleted from extracted edges using a filter that considers the reciprocal point positions on the same edge: the position of a point is “predicted” considering the neighbouring dominant points of the edge and then the difference between the predicted and real position of the point is evaluated. If the difference value is higher than a threshold, the point is deleted [Nex and Rinaudo, 2009]. This filter works well if the blunders are isolated from each other.

A second, more robust, filter can be used to correct the edges when several blunders are close together: this algorithm uses LiDAR data to verify the correctness of each dominant point: when it is farther than a threshold from the point cloud, the point is deleted (see Fig. 2).
Figure 2 - Edge Filtering using the LiDAR information.

**Geometric edge extraction**

Image matching allows radiometric edges to be extracted. Most of these edges are due to shadows or radiometric changes but they have no geometric correspondence. Only geometric boundaries are of interest in surveying graphic drawings and modelling. For this reason, each dominant point on the extracted edges is considered with respect to the LiDAR point cloud and it is verified whether a geometric discontinuity occurs in the data close to the edge point. An edge breakline is detected considering the shape of the point cloud close to each dominant point. Few (4-6) neighbouring points (black points in Fig. 3) around the dominant point are considered, and the local curvature is evaluated. In general, curvatures will be high in at least one direction when a geometric discontinuity occurs. LiDAR point clouds usually smooth the geometric boundaries so a double check is performed evaluating the curvature between the neighbouring points and the dominant points (dark grey point in Fig. 3) and only LiDAR data using a correspondent point (the grey point in Fig. 3 instead of the dominant point) on the LiDAR data. In this way, two maximum curvature angles ($\alpha_1$, $\alpha_2$) are evaluated. Two different thresholds ($T_1$ and $T_2$, where $T_1 > T_2$) are set for each of them. When $\alpha_1 > T_1$ and $\alpha_2 > T_2$, a dominant point on a geometric edge has been detected. For a more detailed description refer to [Nex, 2010].

**Edge smoothing**

The edges extracted by the matching algorithm are random noise affected and they cannot be directly used in the drawing production or in the segmentation process. For this reason, a smoothing is needed in order to define a regular shape of the object, easing the edges in lines and curves. The great majority of edges in both close range and aerial applications can be classified in sets of lines and second order curves. Therefore, each edge must be split in different basic entities that describe its linear or curved parts separately: to do that, the changes in direction of the edge are considered [Nex, 2010]. Then, each separate basic entity is simplified in lines and curves. The line and the curve equations are fitted with a robust least square approach using the dominant point information. At first the linear
model is fitted: if the linear model gives high residuals, the second order curve model will be fitted. When the curve model does not correctly fit the data, the edge is re-processed splitting them in *sub-basic entities*. After the fitting of the entities, the whole edge is finally reconstructed by linking them together in a unique smoothed edge. The improvement given by the smoothing can be easily noticed in Figure 4, where several lines on a façade before (a) and after (b) the smoothing are considered.

![Figure 3 - Radiometric and Geometric edges and search area in the geometric filtering.](image)

![Figure 4 - Difference in the noise level between the unsmoothed (a) and the smoothed data (b).](image)

**Export edges in CAD**

Geometric edges are exported to CAD in order to give a good preliminary data for the graphic drawing realization of the survey or to be used as additional information in the segmentation and modelling process [Chiabrando et al., 2010].

The algorithm has been completely implemented in a *Matlab* code: the computation time has not been assessed during the performed tests.
Experimental tests
Several tests have been performed on both terrestrial and aerial applications: the main topic of these tests has been to show, on one hand, the geometric accuracy and, on the other hand, the effectiveness of the approach. The geometric accuracy assessment has been already discussed in [Nex and Rinaudo, 2009] and in [Lingua et al., 2010], where results comparable to manual restitution have been achieved.
In the following a brief summary of the results achieved is given: in particular, the examples of the achieved results on historical façades and on urban areas will be presented.

Valentino Royal Castle façade - Torino
The following test was performed on several parts of the Royal castle of Valentino (the Politecnico di Torino Architecture Faculty headquarter) in Torino. A point cloud of the court palace was acquired and several parts of the palace were considered in order to evaluate the performances of the algorithm in different conditions. The tests were performed using a Riegl LMS-420 in the LiDAR acquisitions and a calibrated Canon EOS-5D in the image acquisitions.

In particular, the “loggia” (Fig. 5) of the palace was analyzed acquiring seven images with a converging geometry. The taking distance was about 15 m. The 83% of the dominant points were successfully matched and only the 5% of these points were filtered during the blunder detection process.
The results achieved after this step are reported in Figure 6. The quality of the matched edges usually decreases in the parts of the façade tilted respect to the image planes. Then, the geometric filtering did not succeed in the complete deletion of the edges due to radiometric variations.
The smoothing was performed considering the complete set of edges (radiometric and geometric). The results were satisfying, especially if the complexity of the façade is considered (Fig. 7).

A second portion of the façade was a building corner. In this test, 5 images according to an ad hoc geometric configuration were acquired. As in the previous tests, glasses were deleted in order to avoid blunder generation during the matching process (Fig. 8). The quality of the extracted edges was high in terms of completeness all over the image (see Fig. 8): 132412 dominant points were extracted in the analysed area. The 84% of these points were successfully matched, achieving a very good result. Then, only the blunder detection process (Fig. 9) deleted the 7% of the matched points.
The edges were filtered according to the geometric edge filtering. The results are very similar to the data before this step: only few shadows were removed, while some decorations were preserved because curvatures in correspondence of these details are very high. Finally, the edge smoothing was performed. The results in Figure 10 show the effectiveness of this step in all the parts of the façade: the algorithm was able to automatically recognize the arcs from the lines and ease them in regular lines and second order curves.
A set of six images acquired from an Intergraph DMC camera (13824 x 7680 pixels) were available. These images were acquired with an overlap of about 60% in the flight direction. A Ground Sample Distance (GSD) of about 9 cm in the first strip and 11 cm in the second one was available because of the different flight height (about 100 m of difference). Luckily, this problem did not compromise the results of the proposed approach.

The DSM was created starting from a point cloud (2 pts/m²) acquired by ALTM Gemini 167 kHz Optech instrument: only the first pulse was considered in the point cloud generation. Only patches of 3500 x 4000 pixels were extracted from the reference image and from the corresponding area on the other images. The extracted area considered a very dense urban area of the city.

The edge extraction succeeds in an almost complete description of the main outlines of the buildings, as shown in Figure 11: 185692 dominant points were extracted all over the analyzed area. Nevertheless, several edges were incomplete and the outline description was sometimes influenced by the radiometric variations of the roofs. In particular, several useless edges were detected in correspondence of shadows around radiometric variations on the roofs or in correspondence of vegetated areas.

The extracted edges were matched all over the image: the percentage of successfully matched points, on the whole area, was approximately 81%. This percentage is pretty high, especially if it is considered that the great part of unmatched points is concentrated in correspondence of wooded areas, roads and shadows. These points are rarely matched as their position changes during the image acquisition, in particular when the first strip images respect to the second strip (that was acquired several minutes later) are considered. On the contrary, more than the 95% of points in correspondence of the roofs outlines, also in presence of repetitive patterns, were correctly matched.

The extracted edges were filtered, according to the above-described approach. Thanks to this process, most of the blunders were correctly deleted. As it can be easily understood, most of these points are concentrated on the wooded areas, on the shadows and on the cars.
Then, the geometric filtering was performed on the edges in order to extract only the edges with a geometric correspondence. Nevertheless, this process does not succeed in the deletion of all the radiometric edges; the edges (due to shadow), close to the breaklines, were not cancelled by the filter (Fig. 12). The use of a denser point cloud did not appreciably improve the results, as the local curvature of the point cloud was still high in correspondence of these points and the algorithm was not able to filter the information in the correct way. In these conditions, a manual intervention was still required to complete the work.

Figure 11 - Extracted edges on the reference image in the test area.

Figure 12 - Edge before (a) and after (b) the geometric edge filtering in correspondence of a building.
Finally, the edge smoothing was realized in order to ease the noisy edges in lines and curves. Most of the edges were smoothed in a reliable way, as shown in Figure 13. Nevertheless, only a part of the buildings was completely described because of the incomplete edge extraction results.

![Figure 13 - Smoothed edges in 3D (edges before the geometric filtering).](image)

**Conclusion**

A new integration approach between the LiDAR data processing and the multi-image techniques has been presented. The paper described the improvement this integration can give in comparison to each technique separately: the automation of the process has been increased while the manual intervention has been reduced to few operations in all the considered applications.

The data requested in the drawing production is automatically chosen as a “clever” selection of only useful data (lines in 3D). On planar surfaces, this method usually provides the necessary data to designers to complete the final drawing without any additional information (point clouds or topographic surveys). On curved surfaces, the extracted lines allow the decimation of the point cloud to be performed, defining the boundaries of each element of the façade.

The photogrammetric algorithms have been fully developed, as the matched edges are almost complete in every operative condition. The rate of points correctly matched is usually over 80% in both terrestrial and aerial applications. Then, the number of mismatches is reduced and they can be easily deleted by using the LiDAR information. In general, the results depend on the image-taking configuration: high overlaps and high number of images are recommended. The algorithm can achieve good results for repetitive patterns, particularly if more than three images are used. The number of mismatches is usually low and decreases
as the number of images increases.

On the contrary, several improvements are still requested to exploit the full potentiality of the method in the geometric filtering of the edges. Dense point clouds in the laser scanner acquisition are not strictly necessary during the matching process while they are instead requested in the filtering of geometric edges. The more the laser scanner data is dense the more the filtering is accurate; anyway, useless data are not successfully filtered and a manual intervention is still required.

Due to the complexity of the object to be described, the edge extraction is still the most critical step of the proposed approach. The edge extraction performed by an edge extractor sometimes does not succeed in the correct outlines determination as it is usually influenced by the presence of shadows or radiometric variations, especially in the aerial applications. This problem influences the goodness of the following steps of the workflow limiting the completeness of the result. The edge preserving smoothing algorithm can only reduce this problem, but it is not able to completely solve it. For this reason, several improvements in the edge extraction will be performed. In particular, the reliability of the image segmentation will be used to improve the building outlines determination: the goal of this study will be the automatic extraction of outlines only in correspondence of useful data.

In conclusion, this work showed the potentiality of this kind of integration, even if several improvements have to be performed. The possibility to use multi-echo point clouds and multi-spectral images will increase the automation in the extraction of useful information for the modelling and map production, ending this process to other elements, such as vegetation, and making possible new solutions and new applications.

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Earthquake damage assessment based on remote sensing data. The Haiti case study

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Abstract
Haiti was hit by a devastating earthquake on 12 January 2010. Timely triggering of the Earth Observation satellites, and absence of cloud cover, allowed to acquire very high-resolution satellite imagery over the main affected areas within a few hours of the disaster. ITHACA performed a first damage assessment based on remotely sensed data, to support the emergency response activities carried out by the humanitarian agencies. This paper aims to highlight not only the adopted methodology and the main cartographic outputs, but also the operational procedures required to make well known analysis techniques effective in an application context.

Keywords: earthquake, remote sensing, damage assessment, Haiti, rapid mapping.

Introduction
“Rapid impact assessment after a catastrophic event is crucial for initiating effective emergency response actions” [Brunner et al., 2010]. The acquisition of field data, supporting the aforementioned impact assessment, in areas hit by severe earthquakes is indeed a hard task, mainly due to the restricted physical accessibility of the affected areas (i.e. unpredictable road conditions, landslides and soil fractures, lack of means of communications with the affected population, panic, growing of diseases, lack of food and water, hazards due to instable buildings). To cope with the accessibility and time constraints issues, “the use of EO (Earth Observation) data in earthquake contexts, especially for damage assessment purposes, has been widely proposed and a number of results have been presented after every event, mostly based on optical data and manual interpretation” [Polli et al., 2010]. The goal of this paper is to show how well established optical remote sensing techniques allow to carry out earthquake damage assessment in a very short time, exploiting the synergetic capabilities of geospatial tools and instruments such as EO satellites, Web mapping, GIS software and volunteer mapping. The main issues faced will be discussed and possible solution to improve the adopted approach will be proposed.

Case study
The 12th of January 2010 Haiti was hit by a catastrophic earthquake of magnitude 7.0 Mw, with an epicentre near the town of Léogâne, approximately 25 km (16 miles) West of Port-au-Prince, the Haiti’s capital. The earthquake caused major damage in Port-au-Prince, Jacmel and other settlements in the region. Amongst the widespread
devastation and damage throughout Port-au-Prince and elsewhere, vital infrastructures necessary to respond to the disaster were destroyed or severely damaged. Thankfully, timely triggering of the Earth Observation satellites, and absence of cloud cover, allowed to acquire very high-resolution satellite imagery over the main affected areas within a few hours of the disaster. GeoEye satellite acquired the first satellite imagery the day after the quake (13 January 2010), with a Ground Sample Distance (GSD) of 50 cm. The Google Crisis Response Team made the imagery immediately and universally accessible as base layers in Google Earth and Google Maps (also as KML and GeoTiff files). The DigitalGlobe company triggered its own high resolution satellite constellation (World-View 1 and 2, Quickbird) and completely covered Haiti in 5 days (from the 13th to the 17th of January). The imagery was distributed by means of OGC Web Services and as KML and GeoTiff files by the Digital Globe Crisis Event Services.

The decision to provide free access to the data allowed to overcome licensing issues that may interfere with rapid response activities. It was possible to use the imagery to extract the features of interest required to produce early impact maps supporting the emergency response activities, without any licensing constraints even for the derived information.

15 cm imagery were then acquired starting from the 17th of January and again distributed by Google. High resolution SAR radar imagery as well as thermal and LiDAR data were widely acquired over the main affected areas.

It is therefore evident why "This event will also be known as one of the first events where technology (especially high-resolution imagery) was embraced at such a large scale in a real operational sense. Almost from the very onset of the disaster, high-resolution satellite imagery was available to provide the first glimpse of the devastation caused by this earthquake" [Eguchi et al., 2010].

**Damage assessment**

ITHACA, thanks to the cooperation with the United Nations World Food Programme (UN WFP) HQ and WFP staff deployed in the field, was involved in the satellite based damage assessment. Although several automatic or semi-automatic remote sensing based techniques exist to identify collapsed building after an earthquake, the calibration stage of such methods is a time consuming procedure and the accuracy is not completely predictable. It was therefore decided to adopt a manual interpretation approach in order to have results as reliable as possible. Due to the huge amount of data available, the resolution of the imagery and the tight time constraint, it was obvious that a coordinated volunteer approach was the only possible solution.

**Adopted methodology**

ITHACA identified a methodological framework aimed at responding to the following needs:

1) to involve a large number of volunteers with experience in the field of photogrammetry and remote sensing and proved skills in interpreting vertical images;

2) to work with free software with limited requirements and capable to manage open data formats;

3) to have a minimal set of technical specification on the features of interest to be pinpointed on the images;

4) to allow an easy, quick and effective coordination of the volunteers, including management and merging of each single output.
The identified methodology addresses the aforementioned issues, specifically:

1) the Italian Association of Professors and Researchers in the field of Geomatics (AUTEC) was directly involved in the call for volunteers;
2) the Google Earth virtual world platform was adopted;
3) a short document highlighting the main instruction to be followed by each volunteer was edited and shared;
4) a GIS procedure was set up in order to:
   − divide the area of interest in grid cells and take note of the ones already assigned or completed, allowing to have a near-real time view of the status of the work and supporting the coordination activities;
   − merge all the outcomes produced by the different volunteers, including possible import/export activities;
   − synchronize the damage assessment dataset with the WFP Spatial Data Infrastructure (refer to section SDI of the present paper).

Specifically, each volunteer was requested to focus on the following features of interest: collapsed/damaged buildings, road network accessibility, spontaneous camps, landslides. The analysis was based on a multi-temporal change detection activity between the satellite data acquired before and after the event (the analysis was updated in the following days exploiting the availability of 15 cm aerial images). The identified point features were then submitted to the coordinator in KML/KMZ data format.

**Main outputs**
The typical output of the damage assessment activity is a cartographic product, that helps the decision makers to answer questions such as how much food aid is needed, and support the WFP staff in the field in finding the best way to deliver it to the hungry population. The damage assessment results have therefore to be combined with updated, reliable and easily accessible reference base datasets, that are indeed key factors for the success of emergency operations. Short-term emergency response capacities, long-term risk reduction, development and environmental protection activities are sectors where a Spatial Data Infrastructure (SDI) may strongly improve efficiency.

**SDI**
The term Spatial Data Infrastructure is often used to denote the relevant base collection of technologies, policies and institutional arrangements that facilitate the availability of and access to spatial data. An SDI provides a basis for spatial data discovery, evaluation, download and application for users and providers within all levels of government, the commercial sector, the non-profit sector, academia and the general public. SDIs facilitate access to geographically-related information using a minimum set of standard practices, protocols and specifications. SDIs are commonly delivered electronically via internet.

In the framework of a collaboration established with UN WFP, ITHACA has developed an SDI platform conceived for responding to humanitarian emergencies, especially in the early stages, in every portion of the globe. Due to ITHACA/WFP competences and technical and accessibility constraint to data sources, datasets included and made available through WFP SDI are generally at low or medium scale (up to an equivalent of 1/250.000). If this constraint is generally acceptable when dealing, in the first stages of the emergency response, with large
scale disasters (e.g. floods and windstorms), in case of earthquake events the consequences have an high spatial variability that requires detailed reference data, especially for infrastructures and buildings. Data with such characteristics are generally not easy to retrieve, mainly due to licensing constraints in developed countries. In developing countries lack in data availability and/or inadequate levels of update are the critical factor [Bishop et al., 2000].

**Volunteer mapping**

In the context of Volunteer Geographic Information (VGI) [Goodchild, 2008], initiative such as OpenStreetMap and Google Map Maker are having a tremendous impact, providing detailed and updated data available for emergency response, even if adopting completely different licensing policies. In fact, OpenStreetMap provides data under the Creative Commons licensing terms, while Google Map Maker is the only owner of the produced data, that are made available during emergencies but with specific constraints. The disrupting effect of both initiatives is to embark in the emergency response effort a wide community of volunteers that, thanks to the simplicity of the provided tools and to the high levels of services interoperability, contribute to the cause by acquiring huge amount of new data by means of manual interpretation of recent satellite or aerial images or by means of instruments such as GPS/GNSS receivers. The effectiveness of that approach is demonstrated by burst of data acquired over Port-au-Prince, and more generally over Haiti, in the very first days after the earthquake (Fig. 1).

**Data distribution**

Volunteer based datasets and field data were included into the WFP SDI platform and allowed to perform detailed spatial analysis and to produce maps based on personalized templates (Fig. 2). Those maps, as well as the vector data, were distributed by consolidated communication networks such as: pre-defined mailing lists, downloading services made available on several web sites coupled with search engines, dissemination in several emergency response dedicated web sites by means of GeoRSS technology. Due to the size of the event and for the interest of an enlarged community for accessing to geographic data, a specific WebGIS application was designed and implemented, including editing capabilities on specific datasets.

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**Figure 1** – OpenStreetMap coverage on Port-au-Prince before (left), as of 15 February (middle) and as of 26 February (right) . Data source: OSM.
Conclusions
The response to the Haiti earthquake clearly demonstrated that remote sensing played a crucial role during the damage assessment phase. From the data acquisition point of view, it was indeed evident the capability of the satellite data providers and space agencies to timely trigger the satellite constellation and to effectively and quickly distribute the imagery. From the data processing point of view, the use of automatic or semi-automatic classification techniques was limited in the first days after the earthquake and provided indications of the level of damages only at block/grid level and not at building level. Furthermore, the analysis was mainly based on optical remotely sensed data, since thankfully there was a very low cloud coverage during several days after the earthquake. It should be important to strengthen the research lines focused on the use of SAR radar data (both amplitude and phase information) for damage assessment purposes and not only to estimate the ground displacements. Concerning the accuracy of the identified damages, recent studies [Saito et al., 2010] highlighted that vertical imagery (and in certain conditions also oblique ones) may be limiting in discriminating the level of damage of some buildings. In the summary of the 2nd International Workshop on Validation of geo-information products for crisis management, it is explicitly reported that a validation of a “joint damage assessment (using airborne images) performed with around 6000 geo-tagged photos collected in the field gave an overall accuracy of 60% only”. It is therefore crucial to rely also on information acquired in the field, especially by means of GPS/GNNS devices allowing to geo-tag the acquired information [Ajmar et al., 2010]. Volunteer contribution was crucial for mapping both large scale reference datasets, to be
use as backdrop in the map products, and in identifying the damages on the remotely sensed
data. Concerning the volunteer damage assessment, during the Haiti experience it was
clear the need for automatic tools/applications supporting the coordination activities, that
otherwise are indeed time consuming and may slow down the release of the analysis results.
Coordination should be also taken into account in order to avoid any duplication of efforts
among different bodies working on the damage assessment. Finally, it is important to
highlight that the identification of the features of interest is an activity that should be carried
out before the event, taking into account the different needs of different type of users. E.g.
during the response to the Haiti earthquake all the involved actors immediately focused on
the collapsed buildings (crucial information for the SAR teams and detailed assessed during
the recovery stage), but after a few days WFP specifically requested updated information on
the road network accessibility and on the location of the main spontaneous gathering areas,
to better organize the food distribution activities in the field.

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Leica ADS40 imagery for disaster management

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Abstract
Every year environmental disasters such as storms, floods and earthquakes cause thousands of deaths and a great deal of damage around the world. The scientific community is involved in the endeavour of monitoring environmental problems, preventing disasters and supporting rescue efforts. Geomatics is heavily concerned with all the aspects of disaster management. The paper focuses on the Leica ADS digital camera as a tool for performing post-disaster rapid mapping.  

Keywords: photogrammetry, three-line pushbroom camera, disaster management.

Introduction
Many different surveying systems are used to support disaster and crisis management: according to the sensor type, optical, radar and laser devices; concerning the platform carrying the sensor, terrestrial, airborne and space-borne. Within aerial optical sensors, many solutions are available, depending on the format of the camera used and on the aerial vehicle adopted. Large-format digital aerial cameras can be effectively used for crisis management and present some advantages: very high acquisition rates, image quality, very accurate exterior orientation parameters (EOPs) measured by GNSS/IMU systems. The ADS40 camera (produced and delivered by Leica Geosystems, Switzerland) and its successors, ADS40-SH52 and ADS80 can be useful for crisis management. They can operate at several thousand metres and the corresponding image footprint can be as large as 10 km, across-track; they acquire at the same time the panchromatic (PAN), RGB and near-infrared (NIR) channels, so that the panchromatic, colour and colour-infrared (CIR) images can be formed; finally they are equipped with very accurate and reliable GNSS/IMU (Leica IPAS20) devices which measure EOPs directly. Image acquisition by aerial large-format digital cameras can be very quick when direct georeferencing (DG) is performed: thanks to the direct measurement of the EOPs, the image orientation phase only takes a few hours after landing. Direct georeferencing sometimes shows accuracy and reliability problems, but the second and third generations of the Leica ADS camera perform very well and present accuracy figures not exceeding the pixel size.  

Several examples of the use of ADS40 imagery for disaster management can be found in world literature. Concerning Italy, an ADS40 camera, owned by Blom CGR (Parma), was used to acquire several images of L’Aquila area immediately after the earthquake that hit the city in April 2009: this is one on the case studies considered in the paper.  

A more recent example refers to an oil spill problem which hit the Lambro river in Northern Italy: in the early morning of 23rd February 2010, 10 million litres of gas oil, situated in
Villasanta, leaked from their tanks into the Lambro river. On that occasion a Casa airplane, owned by Blom CGR, flew above the area, equipped with ADS40-SH52 camera and a multispectral sensor MIVIS. The camera acquired four strips of 80 km in length; the GSD (Ground Sampling Distance) was 15 cm.

The paper focuses on fast orientation methodologies for the Leica ADS40-SH52 camera, therefore the direct georeferencing methodology is uniquely considered. Mainly, geometric accuracy and camera productivity are investigated.

The three considered case studies
Three case studies are considered to evaluate the ADS40 camera in disaster management, all acquired by Blom CGR, located in Parma, Italy. The Company is equipped with several aerial cameras, analogue and digital, including two second-generation ADS40 cameras and two Vexcel UltraCam XP ones; it has a fleet of 9 aircrafts including a pressurized Lear Jet 25C (Fig. 1), which can operate very quickly, at long range and at high flying altitudes.

![Figure 1 - The Lear Jet 25C operated by Blom CGR.](image)

The case studies are named L’Aquila, Emilia and Pavia. The first one was inserted into the paper because it refers to a real disaster management situation. The Emilia block covers a large area and illustrates which kind of surveying can be performed in region-sized disasters: accuracy assessment is performed, even though with a limited number of check points, and productivity considerations are carried out. Finally, the Pavia dataset was acquired above a photogrammetric test site and allowed for a rigorous geometric accuracy assessment. Table 1 below summarizes the main geometric parameters of the acquired blocks.

<table>
<thead>
<tr>
<th>Site</th>
<th>Average flying height [m]</th>
<th>GSD [cm]</th>
<th># trips</th>
<th>Block size [Km²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L’Aquila</td>
<td>2500</td>
<td>25</td>
<td>-</td>
<td>572</td>
</tr>
<tr>
<td>Emilia</td>
<td>6800</td>
<td>68</td>
<td>8</td>
<td>5000</td>
</tr>
<tr>
<td>Pavia</td>
<td>2000</td>
<td>20</td>
<td>3</td>
<td>67</td>
</tr>
</tbody>
</table>

The L’Aquila dataset
On 6th April 2009, in the Abruzzo Region, at 3:32 local time, an earthquake of 5.8 on the Richter scale was registered. The epicentre was near L’Aquila, which, together with surrounding villages, suffered most damage. Three hundred and seven people died, making this the deadliest earthquake that has hit Italy in the last 30 years.
A few hours after the earthquake, Blom CGR, operating in the frame of the Telaer Consortium, started the operations in order to acquire a photogrammetric coverage above L’Aquila and the surrounding area. More precisely, the entire area was acquired with three sensors: the Leica ADS40-SH52 camera (some images are shown in this paper), the Optech ALTM Gemini lidar sensor and a Pictometry® device for oblique image capture. As examples of the damages caused by the earthquake, some images of the city centre and of the surrounding areas are shown (Fig. 2).

![Figure 2 - From left to right: details of the damages suffered by a church and by two suburban areas](image)

**The Emilia dataset**
Since 1988, the Blom CGR has regularly acquired images of the whole Italian territory, inside TerraItaly™ project. The first flights were performed with analogue cameras, while more recently the ADS40 has been used. The average relative flying height of the project is 6800 m, corresponding to a GSD of 68 cm; the image footprint is 8000 m, across-track. The TerraItaly™ flying configuration appears well suited for disaster management. The *Emilia* block was acquired in July 2008 above the western part of Emilia. The flight is constituted by eight East-West strips, embracing an area larger than 5000 km²: each strip is approximately 120 km long. The territory imaged in the dataset is varied and contains flat areas, mountains and the sea, so it is very challenging for data processing.

**The Pavia dataset**
In mid March 2008 a test flight was performed by the Blom CGR with a Casa 212 plane equipped with a second-generation Leica ADS40 camera with an SH52 sensor head. Three sub-blocks were acquired at the 800 m, 2000 m and 6000 m flying heights. The 2000 m block was depicted for proper assessment of geometric issues and is constituted by four East-West strips and a cross one; two of the former have the same flight path, but are flown in opposite directions. GSD value is approximately 20 cm. Forty check points are available, constituted by white squares painted on the ground, 60 cm in size. They were very accurately measured with redundant static GPS.

**Geometric accuracy assessment of direct georeferencing**
Geometric accuracy of direct georeferencing is analyzed first, in order to preliminarily check whether the paper’s assumption is correct: with second and third generations of
the Leica ADS camera, direct georeferencing is sufficient for rapid response mapping. Two datasets are only considered, the *Emilia* and *Pavia* blocks, for which ground control information is available.

**The Emilia dataset**

The block was acquired for industrial purposes and not for science. There are 14 CKPs, 6 known in x, y and z, while the remaining 8 only in z; their coordinates are known with a sufficient accuracy.

Image coordinate measurements of CKPs were manually performed in stereo mode at Blom CGR. Table 2 shows results for both CKP sets: for the 6 full control points, the RMSEs are, in GSD units, respectively 0.7, 1.3 and 1.1 for the x, y and z components; for the 8 altimetric ones, the RMSE is 0.6 for z.

The worst result is 1.3, in GSD units; we recall again that the available CKPs only have a sufficient quality: they don’t contain blunders, but are rather noisy, as we stated with further analysis, not documented here. Therefore, random noise contained in the control coordinates presumably gives a significant contribution to the noise figures reported.

<table>
<thead>
<tr>
<th>Set</th>
<th># CKP</th>
<th>Comp</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D CKP</td>
<td>6</td>
<td>Mean [m / GSD units]</td>
<td>-0.033 / 0.1</td>
<td>-0.845 / 1.2</td>
<td>0.612 / 0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STD [m / GSD units]</td>
<td>0.69 / 0.7</td>
<td>0.29 / 0.4</td>
<td>0.508 / 0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RMSE [m / GSD units]</td>
<td>0.40 / 0.7</td>
<td>0.881 / 1.3</td>
<td>0.79 / 1.1</td>
</tr>
<tr>
<td>Z CKP</td>
<td>8</td>
<td>Mean [m / GSD units]</td>
<td>-</td>
<td>-</td>
<td>0.302 / 0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STD [m / GSD units]</td>
<td>-</td>
<td>-</td>
<td>0.276 / 0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RMSE [m / GSD units]</td>
<td>-</td>
<td>-</td>
<td><strong>0.09</strong> / 0.6</td>
</tr>
</tbody>
</table>

**The Pavia dataset**

The block considered here is constituted by only 3 parallel strips, East-West oriented. Forty signalized check points were used for accuracy assessment. The image coordinate measurements of these points were manually performed in mono mode at the Geomatics Laboratory of the University of Pavia. Table 3 shows geometric accuracy results: the RMSEs are, in GSD units, 0.7 in planimetry (x, y) and 1.1 in altitude (z). Geometric accuracy proves to be almost within pixel size, for all the components and this is a very good result for direct georeferencing.

<table>
<thead>
<tr>
<th>Set</th>
<th># CKP</th>
<th>Comp</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG</td>
<td>0</td>
<td>Mean [m / GSD units]</td>
<td>0.078 / 0.4</td>
<td>-0.022 / 0.1</td>
<td>0.107 / 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STD [m / GSD units]</td>
<td>0.110 / 0.6</td>
<td>0.130 / 0.7</td>
<td><strong>0.19</strong> / 1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RMSE [m / GSD units]</td>
<td>0.135 / 0.7</td>
<td>0.131 / 0.7</td>
<td>0.220 / 1.1</td>
</tr>
</tbody>
</table>
Productivity and promptness issues
In the present section, productivity and response time issues are treated, according to the direct experiences of the Blom CGR people. The quick orthophoto expression is used in the following, which was introduced by the authors in order to give a name to a particular product which was specifically developed for rapid mapping purposes. The orthophoto production chain can be very quickly summarized as follows: image acquisition, image orientation, DTM production (only if there isn’t one, already), orthoprojection of the single images, image mosaicing and colour balancing. The last two tasks require the definition of seam lines, which is usually performed in a semi-automatic way, needing user supervision and editing. Image mosaicing and colour balancing are particularly demanding when frame imagery is acquired and a great number of parts are involved; line cameras have a great advantage because no stitching nor balancing is needed along-track, but only across-track. Quick orthos represent a further step: the single orthoprojected strips are kept separated and delivered to the final user. He has the very minor inconvenience of jumping from one image to the next one, which is over-exceeded by the advantage of much faster delivery time. Furthermore, the quick orthos mentioned here were produced by means of direct georeferencing: the exterior orientation parameters coming from the GNSS/IMU system were used without any refinement; no ground control points (GCPs) nor tie points (TPs) were used. Finally, the orthoprojection was performed using an existing, nation-wide DTM, owned by the Company itself.

The L’Aquila dataset
L’Aquila block was subdivided into three parts which were acquired on April 6th, 7th and 8th. Image processing was performed in two steps, respectively producing quick orthophotos having ground resolutions of 1 m and 0.25 m. The examples shown here are cropped from the 0.25 m images. By the evening of April 9th, all the quick orthophotos were delivered: the total area surveyed is 572 square kilometres wide.

The Emilia dataset
The whole block was acquired in roughly two hours. By examining the files containing the exterior orientation parameters, which are also associated with a time tag, the productivity has been quantified. Considering the whole time spent for the core part of the block (excluding the approaching and return flights and the initialization manoeuvres, if needed), the time dedicated to image acquisition is 65% and flight turns take 35%.
Assuming the Emilia block configuration, productivity is 3100 square kilometres per hour. As the Lear Jet plane carrying the camera has four hours of autonomous flight, it is possible to survey at least 6000 square kilometres per flight, if the airport is not too far.
According to the Blom CGR people’s experiences, emergency data processing for a similar amount of data is organized as follows: one unit performs trajectory calculation, requiring 2-4 hours; another unit performs in parallel the data download, requiring one hour for each hour of acquisition. The production of quick orthophotos, which are the most typical output of emergency mapping, requires approximately ½ hour for a strip
of 10 km, corresponding to an area of 82 square kilometres, provided that a DTM of the area is available. The time reported refers to the production of four independent orthoprojected components, corresponding to red, green, blue and NIR channels, so that all the useful images can be quickly generated in a second time: PAN, RGB and CIR. Since the Emilia block is formed by strips 120 km long, it takes about 6 hours to obtain the orthoprojection of an entire strip. The production of several strips does not necessarily imply a linear increase in processing time, since the Leica software is able to perform parallel processing, if there is a dedicated hardware platform; this means that as many strips as the number of the nodes (nodes are the CPUs belonging to the special hardware used for parallel computing) in the system can be computed simultaneously. Blom CGR has a 32-node system, so they are capable of processing in parallel a very large block. In conclusion, it can be stated that, in emergency conditions, the quick orthophotos for the Emilia block configuration may be carried out the same day, provided that a sufficient DTM is available.

Conclusions
The paper deals with the use of the Leica ADS40-SH52 camera for rapid mapping in disaster management. Only the direct georeferencing mode is considered. Three blocks are taken into consideration; some examples and reflections are presented, concerning the productivity of the camera and its geometric accuracy. The L’Aquila block is presented because it was acquired in a real emergency situation and the delivery time of the fast orthophotos produced could be documented. The Emilia block is an example of a large survey. The acquisition rate is 3000 square kilometres per hour with 68 cm GSD; geometric accuracy is below 1.3 GSD, for all the components, which is sufficient for rapid mapping purposes. The block was acquired for industrial purposes and there is a limited number of check points. Therefore our results can’t be as reliable as we would like, but they are confirmed by the Pavia block. Finally, the Pavia block allows for rigorous and reliable assessment and presents accuracy values which are not greater than 1 GSD.

The Leica ADS40 camera has several strengths for disaster management: it is highly productive, with respect to the GSD; has a good geometric accuracy even in the direct georeferencing mode.

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Snow cover monitoring with images from digital camera systems

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Abstract
Snow cover extension is one of the most important parameters for the study of climate variations, of hydrological balance and also for the management of touristic activities in mountain areas. Recently, webcam images collected at daily or even hourly intervals are used as tools to observe the snow covered areas; those images, properly processed, can be considered a very important environmental data source. This paper presents the Snow-noSnow software specifically designed to automatically detect the extension of snow cover from webcam images. The software was tested on images collected on Alps (ARPV webcam network) and on Apennine in a pilot station properly equipped for this project by CNR-IIA.

Keywords: snow cover monitoring, digital images, software, Alps, Apennines.

Introduction
The seasonal snow cover represents one of the most important land cover class in relation to environmental studies in mountain areas, especially considering its variation during time. The snow cover and its extension play a relevant role for the studies on the atmospheric dynamics and the evolution of climate and also on the analysis and management of water resources. Moreover, in mountainous areas snow represents a relevant economic resource for the winter tourism. Considering all these elements, it is clear that monitoring the snow cover state improves the scientific knowledge on the meteo-climatic phenomena and plays an important role for the sustainable management on the mountain territory and its resources.

Typically, the snow monitoring is performed through traditional systems like the weather stations scattered on the territory [Cagnati, 2003], automatic snow height sampling stations using probes [Cagnati, 1984] or digital cameras [Gook-Hwan et al., 2007], products derived from satellite images [Casacchia and Salvatori, 2006; Salvatori, 2007; Salzano et al., 2008]. Satellite images like those from NASA-NSIDC (http://nsidc.org/) and NOAA-IMS (http://www.natrice.noaa.gov/ims/) are also used for snow cover daily monitoring at regional scale [Cianfarra and Valt, 2009; Spisni et al., 2011]. Detailed investigations would require higher spatial resolution sensors but the revisit time of those sensors is often incompatible with the
snow persistence at soil. Thus images captured by digital cameras become a useful tool at local scale providing images even when the cloud coverage makes impossible the observation by satellite sensors. Recently, images taken using digital cameras have been used since they collect data with a high temporal and spatial resolution at low cost [Hinkler et al. 2002]. Hinkler et al. [2003] have used multispectral images (green, red and near infrared-NIR) taken using a fixed camera shooting a coastal area in Arctic region (Ny Ålesund, Svalbard), in order to monitor albedo variations of the snow cover during the melting period. In mountain regions, Corripio [2004] have used long shot of the Mer de Glace (Mont Blanc), taken with different field of views (6 megapixel camera) to evaluate the extension of the seasonal snow cover. The images that have been analysed in the abovementioned papers, have been taken manually and within a limited period of time. These observing techniques performed using photo cameras in relation to specific research projects have a limited importance when applied to environmental monitoring, especially when dealing with the study of climatic variations where extended data and images- series represent the real added value as shown by Buus-Hinkler et al. [2006] who have used images captured by a fixed camera and Landsat TM images to monitor the relationship between snow and vegetation covers in the Arctic environment.

In this perspective the networks of cameras, especially those with a fixed long shot, started to play a relevant role in an environmental perspective. During the past 10 years, in the Alpine region many webcams have been installed and their images have been mainly used for touristic purposes and to a very limited extent for environmental monitoring or in order to provide support to snow field observations. When suitably processed these images can be used for scientific purposes, having a good resolution (at least 800x600x16 million colours) and a very good sampling frequency (hourly images taken through the whole year). When stored in databases, these images represent therefore an important source of information for the study of recent climatic changes, to evaluate the available water resources and to analyse the daily surface evolution of the snow cover. One of the most important webcam network within the Italian Alps is the one managed by ARPA Veneto, implemented in 1999 with the financial contribution of the InterReg II Italia-Austria Programme “AVEN 33000 - Produzione e diffusione congiunta dei servizi meteorologici a supporto delle attività turistiche delle Alpi orientali”. The images from the network are being exploited by the personnel charged of weather and avalanche forecasting in order to perform a visual monitoring of the territory in the Arabba Avalanche Center (cfr. http://www.arpa.veneto.it/csvdi/svm/ebarcav/index.html).

Recently, many webcam have been installed along the Apennines (http://www.meteoappennino.it/index.php?option=com_wbcam&Itemid=86). They are mainly devoted to have an overlook on the snow cover condition for touristic and recreational use. Cameras located in the monitoring stations are programmed to take hourly pictures every day. Due to the high number of collected images there was the need to make available an autonomous tool to handle such a large image database performing a detailed analysis of them. In order to obtain quantitative information on the snow cover directly from images, the Italian National Research Council - Institute for Atmospheric Pollution Research (Monterotondo-Rome) and ARPA Veneto-Arabba Avalanche Center (CVA) have agreed to collaborate in order to develop a common project, called Snow-noSnow.

This project has the goal of monitoring areas at different scales, particularly analysing areas close to the camera and with homogeneous land features in order to obtain information on the
snow presence/absence, its persistence and distribution within the examined area. One of the first results of this project is the development of a dedicated software for the snow cover analysis through the processing of images taken from webcams and fixed or mobile digital cameras.

**The monitoring network**
The monitoring equipment installed in two different places in Alps and Apennines is provided by Sistemi Video Monitoraggio S.r.l. (Romito Magra-SP) and is equipped with a high resolution digital camera (Canon Powershot SX110 IS, 1/2.3” CCD, 3456x2592 pixel, 6mm objective - 35 mm equivalent focal length of 36mm), a specific hardware for data logging and transmission, placed into a waterproof case, a power supply unit using AC or photovoltaic panels with a buffer battery. Data transfer is performed using an intranet connection with the receiving station located in Arabba through a fax modem GSM connection. In the Apennine station, due to the lack of GSM connection, data are stored locally and automatically copied on a backup hard disk. The system is controlled by the VM9 software, developed by SVM S.r.l. and Erdmann Video System [Valt, 2002].

**The ARP AV station**
For the present work the images taken from the camera of the Cima Pradazzo station (Falca), (46°21’24”N, 11°49’20”E) have been used. This station is located at 2200 m asl in the Dolomites. The field view of the camera ranges from a medium shot looking at the TreValli ski runs to a long shot on the northern part of the Pale di San Martino, the Cime del Focobon (3054 m) and Monte Mulaz (2906 m). The choice of this field of view is related to the different kind of snow represented into the image that ranges from untrampled to groomed snow; the areas in the long shot remain covered by snow for a long time. The camera is installed close to the snow monitoring station of Cima Pradazzo, equipped with snow and weather sampling and monitoring instruments, between the others snow height, internal and surface temperature sensors.

**The CNR-IIA Apennine station**
In order to make available a series of images of an area in the Apennines, a brand new experimental station has been conceived and implemented by CNR-IIA in the territory of the Monti della Laga - Gran Sasso-Monti della Laga National Park. The station is located along the S.S. 260 “Picente” just after the km 11,500; the camera is mounted on the east side of a building belonging to the Municipality of Amatrice (Province of Rieti) that make it available to CNR (42°35.396N, 13°19.787E, 1300 m a.s.l.). Close to the CNR-IIA station, a manual seasonal weather monitoring station is located in an area called Peschiere (42°60’N, 13°33’E, 1270m asl); it is handled by the Meteomont Service (State Forestry Corps); data collected only during winter are available on the web. CNR-IIA is going to install an automatic meteo station close to the camera. The station is equipped with the same digital camera, hardware and software of the ARP AV stations. The study area is located on the right bank of the Fosso Cerruglia; it is a slight slope, characterized by a xeric grassland. The area is easily reachable and scarcely frequented, it represents a very good point for the observation of the snow cover and the natural vegetation. In the images the mountain chain of the Monti della Laga comprised between Monte Gorzano (2458 m) and Cima della Laghetto (2369 m) is distinguishable.
The Snow-noSnow Software

The software Snow-noSnow has been appropriately developed in order to support this activity; it identifies the extension of the snow cover as shown in the images automatically taken with a very limited human intervention. The software architecture is based on different functions representing the preparatory steps of the main processing routine. Snow-noSnow is handled through an interface where the images to be processed and the ‘mask’ to be applied for the analysis have to be selected. The mask can be easily prepared using any drawing software. The areas covered by the mask must be homogeneous; the possibility to handle a single or multiple masks solves the problem of studying areas with different land features. The software is able to handle a single or multiple masks. A single mask typically covers a large part of the image where only the sky and areas at a distance are excluded. The multiple masks are useful when it is important to analyse different parts of the image with different surface characteristics. The software has an additional feature, it could select a set of images to be processed, as specified by date and hour of the capture (Fig. 1).

Each time an image is processed, a specific function is activated; it performs a series of validations, identifying the images to be rejected due to malfunctions or to bad weather conditions (heavy snowfall, rainfall or fog). Bad images are identified through a statistical analysis of RGB values throughout the whole image and are excluded from the processing steps. The core function of the software is based on a binary snow-no snow classification algorithm that allows the real identification of snow covered surfaces. The procedure foresees a statistical analysis of RGB values of all pixels in the mask and allows, using mathematical criteria, to identify a threshold value to be linked to the snow cover thus allowing its detection. The classification procedure is based on statistical criteria and does not require human intervention other than the initial selection of the dataset. The flexibility of the selection of different parts of the image, through the use of different masks, makes possible to evaluate different parts of territory having different land features. Images are processed according to the following steps. The jpg image is separated into its RGB components; for each part of the image inside the predefined mask the Digital Number (DN) frequency histograms are calculated. A smoothing function is applied to the frequency histogram of blue component calculated as an average of the 5 nearest points. It is clear that the DN frequency distribution within the area inside the mask will be different according to the amount of snow-covered pixels. A preliminary statistical analysis, prior to the definition of the algorithm was performed analysing around 300 images captured in both areas. It showed that the blue component corresponding to snow covered areas is always ≥ 127. The histogram of the values inside the masks shows a bimodal distribution in 90% of cases; when snow is totally missing the histogram is shifted to low DN values, in case of high snow coverage it is shifted to highest values (this occurs in all the three components).

To consider the DN frequency distribution, the value of x-axis corresponding to the first local minimum beyond x≥127 is selected as the threshold value for image classification. When there are no local minima the DN=127 is selected as the threshold value. When the blue component obtained from a jpg image is processed, snow always shows higher values also and mainly in the shaded areas. In fact, in the blue wavelength range, snow cover presents reflectance values always >0.8 [Salvatori, 2007], which are significantly higher than those measured on other types of natural surfaces. Therefore during the classification procedure only the blue component was chosen, thus reducing by one third the processing time.
Anyway, applying the same procedure to the three components the same results are obtained: the unclassified pixels percentage variation is always lower than 1%. Once the software was compiled, the resulting classifications were compared with those obtained by photointerpretation and by a segmentation image routine implemented in ENVI. This last procedure allow us to segment the image into areas of connected pixels based on a defined range of DN values. For each image the DN values were manually selected from DN frequency distribution as well as automatically calculated by Snow-noSnow. The average discrepancy between results automatically obtained from Snow-noSnow and those obtained running the ENVI segmentation routine for each image, is lower than 0.5%. The difference is mainly due to how the algorithm identifies the pixels to be connected. Being the difference negligible, a comparison with the original image was performed based on visual interpretation; for example considering a 100% snow-covered image, 2-3% of snow-
covered pixels is not detected by the software due to the presence of shaded snow-covered associated to the surface roughness.

There are two different modes to use the software in order to calculate the snow cover surface extension. In the first mode the image is analysed in order to obtain a percentage value of the snow cover referred to the pixel number. In this case it is sufficient to make available an image and the mask corresponding to the investigated area. The second mode requires a more sophisticated elaboration that, taking into account the land features and the camera field of view, could provide as a result a percentage value correlated to the actual area expressed in square meters. In this case it is mandatory to use images that can be corrected according to specific coefficients calculated for the topographic features and acquisition geometry of the observed area. The following are the preliminary procedures to adopt for the creation of a weighted mask:

- correction of the image optical deformation. Typically this correction is performed taking into account the CCD size and the focal length of the camera objective [Corripio, 2004];
- creation of a digital elevation model (DEM);
- image rectification;
- superimposition of DEM on top of the rectified image;
- definition of the number of pixels for each element of the DEM grid;
- calculation of the ratio between surface unit of each element of the DEM grid and the number of pixels occurring in the same element;
- provide to each pixel a surface value derived from the size of each element of the DEM grid. Creation of a ‘weighted mask’ where each pixel into the mask has its own surface value.

At this point the software is capable to process the image, using the abovementioned routine, providing a value corresponding to the amount of the snow cover into the study area. The output of Snow-noSnow is represented by:

- the frequency histograms for each of the three components, where the threshold used to identify the considered pixels is highlighted;
- the resulting image showing the pixels classified as ‘snow’;
- the value corresponding to the percentage of ‘snow’ pixels compared to the total amount of pixels into the mask (mode 1) and/or the surface snow covered area value (mode 2).

When more images are being processed the output file contains threshold value and pixel percentage values for each of the analysed images. These output features allow to follow the trend of the snow cover relying on quick processing times being thus useful for people collecting field measurements.

**Results**

The analysis of images captured by monitoring stations during the past 3 years in the Alps and last year in the Apennines shows the capabilities of the Snow-noSnow software to follow in detail the seasonal and daily evolution of the snow cover. The processing procedure has been applied to images taken at the CNR-IIA Apennines station where a DEM of the medium shot area was made available after a topographic survey having the position of the camera as the reference point. In the Apennines area where snow cover variation could be
sudden, the software was particularly effective. The analysis of the hourly images taken at the CNR-IIA station shows how in less than 24 hours the snow cover could vary from 0 up to 85% and then back to 0. This shows how meaningful is the variation of snow persistence at soil in the Apennines. Data that will be collected at the CNR-IIA station in the coming years would represent a meaningful element for the climate studies at local level. The added value resulting from this analysis and estimation of the snow cover is particularly relevant during the deposition and melting phases. During these periods, only punctual data are collected by traditional instruments and used for different analysis (avalanche forecasts, estimation of snow water equivalent, dynamics of snow as related to river runoff). As shown by the analysis of images of Alpine areas, information provided by Snow-noSnow will compensate the potential estimate errors associated to the snow cover thickness values measured by a snow gauge. During a melting period, in fact, snow can be discontinuously distributed on the surface and a snow gauge is only able to detect snow thickness at one point as occurred in Cima Pradazzo on May 16th 2008 (Fig. 2a).

The spatial analysis performed with Snow-noSnow expressed as a percentage of snow covered pixels, shows an ablation trend going beyond May 15th. The same occurred during the ablation phase both in 2009 and 2010 (Fig. 2b, 2c).

Since the software allows to analyse different parts of an image, it is possible to take advantage of this feature applying it to a mask corresponding to areas that could be considered an infinite distance away. Knowing the extension value of these areas in square meters it is possible to estimate the surface of snow covered areas also without a DEM simply converting the percentage of pixels expressed by the software into a percentage of square meters into the mask. The images taken in Cima Pradazzo could be analysed to monitor the snow cover using different masks corresponding to different altitude belts. The information about the snow coverage in the studied areas were successfully used by snow technicians to schedule theirs surveys.

Conclusions and further developments

Images taken from fixed digital cameras could be very useful to monitor snow covers while they provide data collected continuously, under controlled conditions and also in cloudy conditions. Taking as true data coming out from photointerpretation, results show that using Snow-noSnow only 1% of pixels is misinterpreted. The results obtained through the use of Snow-noSnow are thus comparable to the one achieved by photo-interpretation and could be considered as better than the ones obtained using the image segmentation routine implemented into ENVI. Additionally, Snow-noSnow operates in a semi-automatic way and has a reduced processing time.

The analysis of this kind of images could represent an useful element to support the interpretation of remote sensing images, especially those provided by high spatial resolution sensors. The foreseen improvements would provide unbiased information about some parameters relates to snow cover expressed until now by subjective evaluations, in order to study the effects of the wind at high altitudes [Sung-Hyun et al., 2007].

It is foreseen to implement a routine for the estimation of the snow volumes to be used into the models for the calculation of snow water equivalent.

From the instrumental point of view, it is currently undergoing a testing for the analysis of snow surface features variation through NIR images.
Figure 2 - Snow cover percentage calculated with Snow-noSnow on the image of Cima Pradizzo and snow height measured by the snow gauge during three different yearly ablation period (a-2008; b-2009; c-2010). The spatial analysis performed using Snow-noSnow shows the presence of snow covered areas also when the values of the snow gauges indicate the absence of snow.

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Analisi delle superfici asfaltate tramite dati di campo e immagini iperspettrali MIVIS

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Riassunto
Le superfici asfaltate rappresentano una porzione consistente delle aree urbane e grazie alla loro bassa risposta spettrale e alle loro peculiarità geometriche sono facilmente riconoscibili sulle immagini. Il presente lavoro propone una metodologia per l’estrazione e classificazione di superfici asfaltate da immagini MIVIS utilizzando firme spettrali acquisite in campo organizzate in un database. L’analisi dei valori di riflessenza delle bande 2 e 16 ($\lambda=0,46$-0,74 $\mu$m) ha permesso di estrarre dalle immagini le aree asfaltate e di calcolare il valore da utilizzare nella classificazione. Le prime 28 bande del MIVIS sono state sottoposte ad una analisi MNF e le prime 9 componenti così ottenute sono state classificate con il metodo Spectral Angle Mapper.

Parole chiave: asfalto, reticolo stradale, firme spettrali, immagini iperspettrali.

Analysis of paved areas with field data and MIVIS hyperspectral images

Abstract
Paved surfaces represent a significant portion of urban areas and because of their low spectral response and their particular geometric characteristics are easily recognizable on the images. This paper proposes a methodology for the extraction and classification of paved areas by a MIVIS image using spectral signatures of asphalt measured in field and organized in a database. The analysis of the reflectance values of band 2 and 16 ($\lambda =0,46$-0,74 $\mu$m) allowed the extraction of the paved areas and the calculation of the threshold value for the subsequent classification. The first 28 MIVIS bands were processed with MNF analysis and the first 9 components thus obtained were classified by the Spectral Angle Mapper method.

Keywords: asphalt, paved surfaces, spectral signature, hyperspectral images.

Introduzione
Uno dei principali obiettivi delle amministrazioni locali in materia di gestione del patrimonio stradale è quello di istituire e tenere aggiornata una cartografia stradale al fine di migliorarne gli standard di sicurezza. Il monitoraggio dell’intera rete stradale è quindi un’azione indispensabile per valutare il livello di degrado, attualmente desumibile da parametri fisici.
puntuali, e per definire un coefficiente di priorità di intervento. Numerosi lavori presenti in letteratura [Noronha et al., 2002; Roberts et al., 2004; Herold et al., 2004, 2005, 2008; Prearo et al., 2005] attestano un crescente interesse circa le numerose applicazioni che possono derivare dall’uso di immagini telerilevate in materia di monitoraggio e gestione della rete stradale. Per le loro caratteristiche geometriche e spettrali le superfici asfaltate sono infatti un elemento territoriale ben individuabile su immagini riprese a diverse risoluzioni (spaziali e spettrali) e spesso rappresentano anche un elemento indispensabile per la loro interpretazione ed analisi multi temporale [Salvatori et al., 2009]. Le informazioni derivate dall’analisi di immagini e da rilievi a terra possono essere inoltre utilizzate per la realizzazione di cartografie aggiornabili e interrogabili, se inserite all’interno di un sistema informativo territoriale e/o di un database.

Sebbene sensori come il Thematic Mapper del Landsat e l’HRV dello SPOT apportino un valido contributo circa la gestione territoriale a grande scala di aree naturali e urbane, il telerilevamento ad alta risoluzione spettrale può largamente ottimizzare le procedure per la realizzazione di cartografie ad hoc [Manière et al., 1990]. In effetti l’utilizzo di sensori aviotrasportati, dotati di una elevata risoluzione sia spaziale che spettrale, ha permesso un considerevole miglioramento in molteplici linee tematiche consentendo di derivare informazioni sulle caratteristiche chimico-fisiche dei materiali indagati soprattutto a piccole scale [Clark, 1999].

Per analizzare il reticolo stradale, in letteratura vengono utilizzate immagini iperspettrali AVIRIS [Herold et al., 2008] e MIVIS [Pascucci et al., 2008] abbinando alle procedure per l’elaborazione delle immagini campagne di misura spettro radiometriche e/o indagini PMS (Pavement Management System).

Gli algoritmi classificativi utilizzati per l’analisi della rete stradale variano a seconda del tipo di immagini e sono utilizzati in maniera da enfatizzare sia la componente geometrica che quella spettrale. L’Object Oriented [Noronha et al., 2002; Pascucci, 2008], il Pixel and Segment Classification [Guindon et al., 2004], l’Analysis of Variance – ANOVA [Herold et al., 2004], il Spectral Fitting [Clark et al., 2003], il Matched Filters [Ben Dor et al., 2001] e lo Spectral Angle Mapper [Kruse et al., 1993] sono tra i classificatori maggiormente utilizzati per questo tipo di lavoro. In particolare lo Spectral Angle Mapper è un classificatore impiegato solitamente con immagini iperspettrali che valuta la similitudine spettrale tra i pixel dell’immagine e gli endmember, ossia spettri estratti da punti noti dell’immagine, rappresentativi delle superfici da classificare. Le immagini iperspettrali offrono elevate potenzialità per l’estrazione e la classificazione delle pavimentazioni stradali sebbene per la loro interpretazione è comunque necessario un accurato studio delle caratteristiche spettrali degli asfalti, dei diversi componenti utilizzati per la loro messa in posto nonché delle numerose tipologie di alterazioni e deterioramenti che possono essere riconosciute su tali materiali.

Gli asfalti utilizzati per le pavimentazioni stradali sono costituiti principalmente da una miscela di bitume e materiale inerte. Il termine bitume indica, in questo contesto, una miscela di idrocarburi naturali o residuati derivanti dal petrolio, che fa da legante per il materiale roccioso che costituisce lo scheletro [European Asphalt Pavement Association EAPA; http://www.eapa.org/]. I clasti rocciosi (inerti) che compongono lo scheletro hanno litologia e dimensioni diverse in funzione delle disponibilità locali di inerti e della destinazione di uso [Bassi, 1993].

Le superfici di asfalto, generalmente rappresentate da assi viari e da aree di parcheggio, presentano generalmente valori di riflessanza spettrale complessivamente molto bassa. Nell’intervallo di
lunghezze d’onda compreso tra 350 e 2500 nm, la risposta radiometrica degli asfalti, misurata in campo, è dominata dalla presenza del bitume, il quale assorbe quasi totalmente la radiazione solare incidente, mentre la natura degli inerti e le loro dimensioni incidono solo marginalmente sull’andamento spettrale [Herold et al., 2004; Salvatori et al., 2009].

Una superficie asfaltata può essere modificata dall’azione meccanica dovuta al traffico veicolare e dal deterioramento naturale del bitume causato principalmente dalla reazione con l’ossigeno presente in atmosfera, dall’azione fotochimica dovuta alla radiazione solare e dal riscalдamento superficiale. A seguito di questi processi si manifesta la perdita dei composti oleosi (sia per volatilizzazione che per assorbimento) con conseguente variazione nella composizione dello strato superficiale e ridistribuzione degli inerti [Bell, 1989].

Il deterioramento e l’invecchiamento degli asfalti si riflettono sull’andamento spettrale, infatti, alle lunghezze d’onda del visibile, gli asfalti appena deposti presentano una risposta spettrale più bassa di quelli vecchi a causa della maggiore percentuale di bitume presente sulla superficie. Il processo di ossidazione e l’esposizione della componente rocciosa caratterizza la comparsa dei picchi di assorbimento degli ossidi di ferro a 520, 670 e 870 nm mentre la perdita dei composti oleosi determina la scomparsa dei picchi caratteristici degli idrocarburi. Inoltre, per gli asfalti vecchi, c’è un significativo cambio di pendenza nella firma spettrale tra 2100-2200 nm e tra 2250-2300 nm dovuto rispettivamente all’influenza dei minerali silicatici e degli idrocarburi [Herold et al. 2005, 2008; Levinson et al., 2007]. L’assorbimento degli idrocarburi è particolarmente evidente a 1750 nm e dopo i 2100 nm con un significativo doppietto a 2310 e a 2350 nm [Cloutis, 1989].

Sulla base di queste considerazioni, il presente lavoro propone una metodologia che, partendo da dati radiometrici campo, permette di classificare le superfici asfaltate a partire da immagini iperspettrali MIVIS al fine di valutare il loro stato di usura superficiale.

**Area di studio**

Per lo svolgimento di questo lavoro sono state scelte immagini iperspettrali MIVIS, disponibili presso l’Istituto sull’Inquinamento Atmosferico – CNR, nelle quali ricadessero sia aree fortemente urbanizzate, quali aree residenziali, industriali e assi viari di vario tipo, che aree marcatamente rurali nelle quali la componente “asfalto” fosse limitata. Tali immagini sono state acquisite ad una quota di volo pari a 1500 metri s.l.m. corrispondente ad una dimensione del pixel a terra di 3 m x 3 m.

Le immagini analizzate, riprese in momenti diversi nella stagione primavera-estate, sono relative a diversi settori del centro e sud Italia. Nello specifico sono state prese in considerazione 13 strisciate MIVIS (di lunghezza variabile dai 5 ai 30 km circa) che ricadono nella Regione Campania: Provincia di Caserta (zona Sud-Est) e di Napoli (zona Nord ed Est), nella Regione Lazio: Provincia di Roma (Guidonia) e Rieti (Montopoli di Sabina), e nella Regione Sicilia: Provincia di Siracusa ed Augusta.

A seconda della disponibilità tali immagini sono state analizzate sia in valori di radianza che di riflettanza.

**Dati di campo**

*Acquisizione dei dati al terreno*

Per questo lavoro sono stati utilizzati i dati provenienti da campagne di misura spettroradiometriche al terreno, effettuate da questo laboratorio nell’arco di due anni,
contemporaneamente all’acquisizione delle immagini MIVIS. Le firme spettrali sono state acquisite nell’intervallo di lunghezze d’onda compreso tra 350-2500 nm mediante spettroradiometro portatile (Fieldspec 3-ASD) utilizzando una superficie in Spectralon come riferimento lambertiano. Le misure sono state effettuate in un arco di tempo di circa 2 ore a cavallo del momento di massima insolazione e con la fibra ottica posta a 50 cm sulla verticale del target in modo da considerare, dato un angolo di vista di 25°, un’area di circa 20 x 20 cm (Fig. 1). Per una migliore caratterizzazione spettrale delle superfici sono state rilevate 10 firme spettrali per ogni tipologia di target indagato.

![Figura 1 - Acquisizione firme spettrali di campo di asfalti (a) e sistema di riferimento (b).](image)

Tenendo conto del contributo dell’effetto di adiacenza dei pixel [Leone et al., 1995], è stata posta particolare cura nell’effettuare le misurazioni su target collocati all’interno di siti geometricamente rilevanti (es. aree di sosta) al fine di ottenere firme spettrali statisticamente significative di aree riconoscibili sulle immagini. Inoltre i siti di misura sono stati selezionati ad adeguata distanza da alberi o palazzi per evitare gli effetti d’ombra che possono ridurre le dimensioni effettive della superficie “omogenea” riconoscibile sulle immagini.

Nel complesso sono state acquisite e analizzate circa 5000 firme spettrali di asfalti e 1500 firme di target antropici come pavimentazioni in cemento e coperture artificiali (Tab. 1). Alcune di queste firme sono state utilizzate per la calibrazione delle immagini tramite il metodo dell’empirical line, altre come punti di controllo a terra della bontà delle elaborazioni effettuate. Tutte le firme inerenti gli asfalti sono state inoltre oggetto di ulteriori elaborazioni, all’interno del database appositamente realizzato, al fine di analizzarne le caratteristiche spettrali.

Sono stati selezionati siti con rivestimenti in asfalto il più possibile omogenei, con la minor presenza di alterazione e dissesto superficiale nonché di segnaletica orizzontale poiché tali elementi influenzano la risposta radiometrica delle superfici [Herold et al., 2004]. Per minimizzare gli errori legati alla geometria del sistema di ripresa delle immagini, le misure a terra sono state eseguite principalmente lungo l’asse centrale delle immagini MIVIS.

Nel corso delle campagne di misura sono stati registrati dati meteorologici al fine di poter
poi prendere in considerazione, per questo lavoro, unicamente le misure radiometriche che possono essere considerate eseguite in condizioni meteo simili. Per ogni misura è stato inoltre calcolato l’angolo di elevazione solare il quale ha consentito di utilizzare proficuamente dati acquisiti in tempi e luoghi diversi.

Tabella 1 - Dettaglio del numero di strisciate acquisite con sensore MIVIS e del numero di spettri di campo elaborati.

<table>
<thead>
<tr>
<th>Area</th>
<th>Strisciate</th>
<th>Spettri asfalti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provincia di Caserta</td>
<td>3</td>
<td>1300</td>
</tr>
<tr>
<td>Provincia di Napoli</td>
<td>4</td>
<td>3400</td>
</tr>
<tr>
<td>Provincia di Roma</td>
<td>2</td>
<td>400</td>
</tr>
<tr>
<td>Provincia di Rieti</td>
<td>1</td>
<td>80</td>
</tr>
<tr>
<td>Provincia di Siracusa ed Augusta</td>
<td>3</td>
<td>200</td>
</tr>
</tbody>
</table>

Oltre alle misure radiometriche sono stati acquisiti i dati descrittivi delle superfici analizzate, codificandoli in maniera opportuna per essere inseriti all’interno del database. Per la definizione del colore degli asfalti sono state utilizzate delle tessere di confronto ottenute adoperando le tonalità di grigio corrispondenti all’asse centrale della scala di Munsell (M) (10 classi) e per ogni target misurato è stata acquisita una foto digitale (Nikon Coolpix S560). Al fine di ottenere fotografie confrontabili tra loro, anche se acquisite in condizioni di illuminazione diverse, è stato costruito un “regolo di calibrazione” (dimensioni di 40 cm x 40 cm) costituito da un’alternanza di tasselli da 5 cm bianchi e neri che fungono sia da scala dimensionale che da riferimento cromatico. Prima di ogni foto è stata eseguita la calibrazione manuale del bianco, ad una distanza di circa 10 cm dal lato bianco del regolo, per uniformare i diversi fotogrammi e renderli quindi confrontabili tra loro (Fig. 1). È stato cosi possibile, mediante l’estrazione da queste foto dei valori R.G.B., validare le classi di colore assegnate ai target durante il lavoro di campo.

Per ciò che riguarda i dati inerenti le caratteristiche fisiche degli asfalti, quali granulometria, morfologia dei grani e percentuale di bitume sui clasti, si è fatto uso delle tabelle appositamente elaborate [Salvatori et al., 2009]. La scelta di acquisire questi dati accessori si è resa necessaria poiché le pavimentazioni sono generalmente costituite da miscele di leganti bituminosi ed inerti costituiti da materiale grossolano, sabbia naturale o di frantoio e filler (aggregato fine di natura generalmente calcarea). Le percentuali e dimensioni di questi costituenti variano a seconda dello strato stradale da realizzare, ne risulta che il loro intervallo granulometrico può essere estremamente variabile e da ciò può derivare una variazione nelle caratteristiche radiometriche delle superfici. Pertanto, per l’analisi dimensionale degli inerti presenti sulla superficie, si è fatto uso della scala granulometrica di Udden-Wentworth del 1922 prendendo in considerazione unicamente i 10 termini compresi tra le classi Ciottoli grossolani (128-64 mm) e Sabbia fine (0,25-0,125mm). Infatti è tra queste due classi che ricadono le granulometrie più spesso utilizzate per la realizzazione di conglomerati bituminosi [FHWA 1996 - Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-96)].

Per la morfologia dei grani è stata adottata la classificazione di Powers del 1953,
comunemente utilizzata in ambito sedimentologico, mentre per quanto riguarda la litologia degli aggregati sono state prese in considerazione solo le 4 tipologie di inerti più ricorrenti: carbonatici, silicatici, riciclati (materiali derivato dalla frantumazione e vagliatura di materiali provenienti dalle demolizioni di strutture antropiche di varia natura) e misti.

Poiché la quantità di legante presente sullo stato superficiale dell’asfalto influenza in maniera consistente la risposta radiometrica, sono state definite 5 classi “bitume” (da 0-20% a 80-100%) che descrivono la percentuale presente sui singoli clasti.

Inoltre, considerando che i valori di riflettanza delle superfici asfaltate possono essere modificati anche dalla presenza di piccole percentuali di superfici coperte da segnaletica stradale orizzontale [Herold et al., 2004], è stata annotata la sua eventuale presenza e colore.


**Analisi dei dati di campo e definizione delle classi di asfalto**
Tutte le informazioni raccolte in campo sono state inserite all’interno di un database relazionale, appositamente predisposto, che ha consentito, in analogia con quanto affermato da Manière et al. 1990, di manipolare in modo efficiente una grande quantità di dati mediante l’esecuzione di query mirate; l’acquisizione di queste caratteristiche tessiturali e composizionali ha permesso di uniformare la tipologia di spettri da elaborare e quindi di definire le classi da utilizzare nelle successive elaborazioni.

Come prima analisi sono state selezionate quelle misure spettrali riferite a superfici che non presentavano nessun tipo di dissesto e/o alterazione suddividendole in base alla percentuale di bitume sui clasti e al colore.

La scelta di utilizzare il dato cromatico, come elemento distintivo per la scelta delle classi da riconoscere sulle immagini, è motivata dall’osservazione che il colore complessivo di una superficie asfaltata, percepito dall’occhio umano, è strettamente correlato con la percentuale di bitume che ricopre i singoli granuli.

La risposta radiometrica di una superficie asfaltata infatti è dominata dalla presenza del bitume e si modifica quando questo viene rimosso, a causa dell’usura, poiché diviene dominante il contributo radiometrico del tipo di materiale che costituisce gli inerti. Alle lunghezze d’onda del visibile e infrarosso vicino, infatti la forma dello spettro non presenta picchi caratteristici; è debolmente concava per asfalti appena deposti, ma diviene convessa per superfici “vecchie” (deposte da circa un mese) con la comparsa di picchi di assorbimento degli ossidi di ferro in corrispondenza di 520, 670 e 870 nm [Herold et al., 2004; Preparo et al., 2005; Salvatori et al., 2009]. La risposta spettrale varia sostanzialmente nel primo mese per poi stabilizzarsi nell’arco di circa un anno (Fig. 2).

Pertanto, per definire le tipologie di asfalti, si è scelto di esaminare nel dettaglio i valori di riflessione compresi nell’ intervallo spettrale da 400 a 870 nm. L’analisi della risposta radiometrica ha evidenziato che i valori di riflessione alle lunghezze d’onda di $\lambda=0,46$ μm e $\lambda=0,74$ μm (bande 2 e 16 del MIVIS) possono essere considerati rappresentativi delle caratteristiche degli spettri nell’intervallo di studio.

Dai dati spettrali disponibili per questo lavoro, sono stati estratti i valori corrispondenti a $\lambda=0,46$ μm e $\lambda=0,74$ μm considerando solo le superfici corrispondenti ad asfalti non alterati.
e privi di segnaletica. Proiettando in un grafico questi valori, utilizzando per le ascisse i valori corrispondenti a 0,74 μm e per le ordinate quelli corrispondenti 0,46 μm, è possibile osservare una correlazione lineare esprimibile con l’equazione del tipo \( y = ax + b \). In funzione dell’area geografica presa in esame, il coefficiente angolare può assumere valori compresi tra circa 0,5 e 0,8 mentre b assume generalmente valori prossimi a zero (Tab. 2).

![Figura 2 - Firme spettrali di asfalti acquisite in due siti (A e B - Rieti). Il sito A rappresenta un asfalto “vecchio” messo in posto da circa un anno; la misura A2 è stata acquista un mese dopo la misura A1. Nel sito B le acquisizioni sono state effettuate nel momento della posa (B1), dopo un’ora (B2) e dopo un mese (B3).](image)

**Tabella 2 - Coefficienti ottenuti dall’analisi delle lunghezze d’onda \( \lambda = 0,46 \) μm e \( \lambda = 0,74 \) μm a partire dagli spettri di campo.**

<table>
<thead>
<tr>
<th>Area</th>
<th>a</th>
<th>R²</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Augusta e Siracusa</td>
<td>0,595</td>
<td>0,900</td>
<td>0,011</td>
</tr>
<tr>
<td>Caserta</td>
<td>0,706</td>
<td>0,969</td>
<td>-0,003</td>
</tr>
<tr>
<td>Napoli Nord</td>
<td>0,693</td>
<td>0,959</td>
<td>0,004</td>
</tr>
<tr>
<td>Napoli Est</td>
<td>0,712</td>
<td>0,938</td>
<td>-0,002</td>
</tr>
<tr>
<td>Montopoli di Sabina (RI)</td>
<td>0,814</td>
<td>0,979</td>
<td>-0,001</td>
</tr>
<tr>
<td>Guidonia (RM)</td>
<td>0,817</td>
<td>0,924</td>
<td>-0,026</td>
</tr>
</tbody>
</table>

L’omogeneità dei valori ottenuti sembra suggerire l’esistenza di una retta che può essere definita come “retta degli asfalti”. Lungo tale retta sono stati riconosciuti 4 cluster corrispondenti a 4 raggruppamenti cromatici che, espressi come classi Munsell possono essere suddivisi in: \( |1<M<2|, |3<M<4|, |5<M<6| \) e \( |7<M<8| \) (Fig. 3).
Tali raggruppamenti sono stati considerati come “classi asfalto” nelle successive fasi di classificazione immagine.

**Elaborazione delle immagini**

Le superfici di asfalto sono generalmente di facile individuazione sulle immagini da remoto ma se si cerca di discriminarele in base alle loro caratteristiche strutturali si incontrano notevoli difficoltà. Ciò è dovuto a molteplici fattori tra cui lo stato di conservazione delle superfici, le patine di alterazione e le condizioni di illuminazione al momento della ripresa delle immagini [Heiden et al., 2005; Lacherade et al., 2005]. Pertanto, nel caso si vogliano effettuare delle classificazioni supervised, il processo di individuazione dei training set o degli endmember da usare nelle procedure di classificazione diviene particolarmente impegnativo e si deve quindi far ricorso a complesse procedure di image processing integrate dalla analisi spettrale di dati raccolti in campo o in laboratorio [Heiden et al., 2007].

Pertanto, nel tentativo di approcciare la classificazione delle immagini in maniera completa, e per valutare la corrispondenza tra i dati telerilevati e i dati di campo, prima di procedere con la classificazione delle immagini MIVIS, è stata effettuata un’analisi preliminare delle singole bande corrispondenti all’intervallo spettrale 400-870 nm. Per confermare l’esistenza della “retta degli asfalti” anche su immagini iperspettrali MIVIS è stato analizzato lo scatterogramma ottenuto con le bande 2 e 16 (rispettivamente $\lambda=0,46 \mu m$ e $\lambda=0,74 \mu m$) di tutte le 13 aree disponibili per il presente lavoro sia quelle espresse in valori di radianza che di riflessione (Fig. 4).

Gli scatterogrammi 2D ottenuti con il software ENVI (IIT), mostrano che i pixel corrispondenti alle superfici asfaltate si raggruppano essenzialmente in un unico insieme di forma ellittica definibile come una “macro classe asfalti”, analoga a quella delineata utilizzando i dati di campo. Evidenziando tale classe sullo scatterogramma, già in questa fase preliminare dell’elaborazione, è possibile ottenere una rapida definizione delle superfici asfaltate dall’immagine MIVIS. Nello scatterogramma, i pixel corrispondenti alle aree vegetate e ai suoli, infatti, sono ben raggruppati in altri insiemi chiaramente distinti da
quello corrispondente alle superfici asfaltate.
Dagli scatterogrammi sono stati quindi estratti i valori corrispondenti ai pixel ricadenti nella classe “macro classe asfalti”. Per questi dati, esportati come file ASCII ed elaborati all’interno di MICROSOFT EXCEL, analogamente a quanto effettuato con i dati di campo, è stata calcolata la retta interpolante del tipo \( y = ax + b \). I coefficienti angolari della rette, calcolate sulle diverse immagini, variano da 0,681 e 0,858 ed i termini b assumono generalmente valori prossimi a zero anche in immagini espresse in radianza (Tab. 3).
L’esistenza della “macro classe asfalti” è identificabile nello scatterogramma di tutte le immagini esaminate ed è riconoscibile già a video; applicando un *density slice* ai valori dello scatterogramma è possibile evidenziare i massimi di addensamento dei pixel. Ciò consente l’immediata identificazione delle superfici asfaltate direttamente sull’immagine. Ovviamente tale metodo si è rivelato particolarmente efficiente nelle aree con una elevata percentuale di antropizzazione, in cui i pixel asfaltati occupano buona parte della scena. Al contrario, in aree di rurali, essendo presenti molte meno strade e piazzali asfaltati, il metodo risulta più difficile da applicare in quanto si corre il rischio di non notare particolari addensamenti sullo scatterogramma e quindi di sottostimare le tipologie di superfici asfaltate.
Per aumentare il dettaglio delle informazioni ricavabili dalle immagini, la “macro classe asfalti” è stata a sua volta suddivisa in base alle 4 classi cromatiche definite con le osservazioni di campo. La segmentazione della macro classe, eseguita direttamente sullo scatterogramma, ha permesso pertanto di ottenere una prima rapida classificazione degli asfalti presenti nell’immagine (Fig. 5). Il confronto con i rilievi di campo relativi alle aree analizzate ha confermato la validità dei risultati ottenuti con tale segmentazione.
Infine, per verificare ulteriormente la applicabilità delle classi colorimetriche individuate e la possibilità di impiegare le immagini MIVIS per lo studio degli asfalti in maniera sistematica, è stata effettuata una classificazione SAM adoperando le 4 classi ricavate dall’analisi dei dati di campo su un’area test.
Sulle prime 28 bande è stata applicata l’analisi in componenti principali (*routine MNF-Minimum Noise Factor*) che ha permesso di ridurre la dimensionalità spettrale dell’immagine da classificare.

Figura 4 - Scatter plot ottenuto selezionando le bande 2 e 16 dell’immagine MIVIS(sx) di un’area ricadente all’interno della Provincia di Napoli: individuazione di un’unica classe lungo la retta relativa agli asfalti(dx).
Tabella 3 - Coefficienti ottenuti dall’analisi delle lunghezze d’onda \( \lambda = 0,46 \, \mu m \) e \( \lambda = 0,74 \, \mu m \) a partire dagli scatter plot delle 13 immagini analizzate. Per le aree di Caserta e Napoli Nord i coefficienti derivano dalle immagini espresse in valori di riflessenza, mentre per le altre aree da immagini espresse in valori di radianza.

<table>
<thead>
<tr>
<th>Area</th>
<th>Spettri asfalti</th>
<th>( a )</th>
<th>( R^2 )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caserta</td>
<td>56000</td>
<td>0,639</td>
<td>0,975</td>
<td>0,002</td>
</tr>
<tr>
<td>Napoli Nord</td>
<td>100000</td>
<td>0,650</td>
<td>0,941</td>
<td>0,015</td>
</tr>
<tr>
<td>Paesi Vesuviani</td>
<td>66000</td>
<td>0,828</td>
<td>0,937</td>
<td>6474</td>
</tr>
<tr>
<td>Montopoli di Sabina</td>
<td>3000</td>
<td>0,713</td>
<td>0,905</td>
<td>3822</td>
</tr>
<tr>
<td>Guidonia</td>
<td>50000</td>
<td>0,858</td>
<td>0,970</td>
<td>4331</td>
</tr>
<tr>
<td>Augusta e Siracusa</td>
<td>30000</td>
<td>0,681</td>
<td>0,810</td>
<td>12744</td>
</tr>
</tbody>
</table>

Tabella 4 - Matrice di confusione.
(Classi: A1=1\(<\)M<2; A2=3\(<\)M<4; A3=5\(<\)M<6; A4=7\(<\)M<8)

<table>
<thead>
<tr>
<th>Dati di riferimento</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classi</td>
<td>25</td>
<td>21</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>Non classificati</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>A1</td>
<td>24</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>A2</td>
<td>0</td>
<td>21</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>A3</td>
<td>0</td>
<td>0</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>A4</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>26</td>
</tr>
<tr>
<td>Totale</td>
<td>25</td>
<td>21</td>
<td>33</td>
<td>26</td>
</tr>
</tbody>
</table>

Le prime 9 componenti ottenute sono state quindi classificate utilizzando l’algoritmo *Spectral Angle Mapper* (implementato in ENVI) individuando sull’immagine le *Region Of Interest* (ROI), ottenute intersecando i dati emersi dall’analisi scatterogrammetrica e i dati relativi ai rilievi di campo, e impiegando i corrispondenti coefficienti angolari derivati della “retta degli asfalti” come valori soglia.

La classificazione ottenuta ha una accuratezza del 90,47% e un coefficiente \( K = 0,87 \) ed è direttamente confrontabile con quella derivata dall’analisi dei valori dello scatterogramma (Fig. 5). Sebbene la classificazione ottenuta applicando la SAM abbia prodotto dei valori elevati di accuratezza per le quattro classi di asfalto individuate (Tab. 4), si ritiene che esista un errore residuo da imputare al fatto che alcune coperture di capannoni industriali sono realizzate in materiali catramosi o comunque costituiti da materiale litologicamente simile agli inerti utilizzati negli asfalti; tali coperture sono state inserite nella classe asfalti A3 (es. riquadro bianco in Fig. 5) e sebbene sia stato impossibile constatare la natura di tali coperture, i rilievi al terreno, abbinati alla foto interpretazione di immagini ad alta risoluzione spaziale, hanno di fatto avvalorato tale ipotesi.
Conclusioni
L’interesse crescente per il monitoraggio delle aree urbane tramite l’utilizzo di immagini riprese da sensori remoti ha sollecitato lo studio delle caratteristiche radiometriche delle superfici asfaltate in quanto queste rappresentano uno degli elementi di maggior interesse per la gestione e il monitoraggio della rete stradale. A causa della loro bassissima riflettività gli asfalti sono infatti facilmente individuabili sulle immagini ma, al tempo stesso, è difficile discriminare la tipologia e di conseguenza lo stato di conservazione. Nello svolgimento di questo lavoro, la possibilità di disporre di un numero statisticamente rilevante di misure radiometriche di campo, correlate con le osservazioni sulla composizione e sullo stato di conservazione delle superfici asfaltate, ha permesso di definire 4 classi di asfalto da riconoscere sulle immagini iperspettrali MIVIS. Elaborando le bande 2 e 16, con l’approccio metodologico descritto in questo lavoro, è possibile definire una “macro classe asfalti” che, a sua volta, può essere segmentata nelle 4 classi di asfalto definite analizzando i dati radiometrici di campo. Inoltre, la definizione dell’equazione della “retta degli asfalti” che interpola la suddetta macro classe, permette di ricavare per ogni immagine analizzata il valore di soglia da utilizzare con l’algoritmo Spectral Angle Mapper per l’estrazione e classificazione delle superfici asfaltate. Entrambi i metodi di classificazione si sono rivelati particolarmente adatti a estrarre informazioni relativamente alle superfici coperte da asfalto. Infatti poiché le classi cromatiche, definite in questo lavoro, possono essere correlate con lo stato di usura delle superfici è possibile ottenere una prima stima dello stato di conservazione delle superfici con tempi di elaborazioni particolarmente ridotti. Come ulteriore sviluppo del presente lavoro, verrà investigata la potenzialità della banca dati spettrale nello studio di superfici asfaltate con diversi gradi di dissesto e stato di conservazione.
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Tecniche object-oriented per l’estrazione delle coperture forestali da fotogrammi storici pancromatici

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Riassunto
Le fotografie aeree storiche rappresentano un’insostituibile risorsa informativa da cui si possono desumere con elevato dettaglio informazioni sulle dinamiche spaziali delle coperture forestali nel medio-lungo periodo, con importanti ricadute nella comprensione dei meccanismi alla base dei processi di cambiamento e nell’impostazione delle future linee gestionali. In questa ricerca sono state testate le potenzialità delle tecniche object-oriented per delineare una procedura oggettiva e scalabile su area vasta di estrazione dei limiti del bosco dai fotogrammi del volo GAI. L’implementazione nel classificatore di algoritmi di calcolo dei parametri statistici di tessitura basati sulle matrici di co-occorrenza spaziale, rispetto all’impiego delle sole statistiche spettrali, ha determinato un aumento del valore del $KIA$ da 0,84 a 0,91.

Parole chiave: telerilevamento pancromatico, classificazione ad oggetti, tessitura, land cover.

Object-oriented techniques for the extraction of forest cover from historical panchromatic frames

Abstract
The historical aerial photos are an irreplaceable source of information for details pertaining to the spatial dynamics of the forestry cover in the mid and long-term, with key implications for interpreting the mechanisms underlying the processes of change and in planning future management guidelines. In this study the object-oriented techniques potentialities have been tested to outline a wide-reaching objective and scalable procedure of extracting wood limits from the GAI flight frames. The implementation of algorithms of the statistic parameters of the texture calculus based on the grey level co-occurrence matrix, compared to the use of spectral statistics alone, caused an increase in the value of the $KIA$ from 0.84 to 0.91.

Keywords: panchromatic remote sensing, object-oriented classification, texture, land cover.

Introduzione
La domanda informativa sulle foreste si presenta con connotazioni diverse a seconda della scala a cui la si analizza. Se a livello transnazionale prevalgono istanze legate ad una stima complessiva dell’entità delle risorse forestali, ad una scala nazionale o regionale emergono, oltre a queste, esigenze conoscitive orientate ad una valutazione che consenta di calibrare politiche di tutela delle risorse coerenti con una loro valorizzazione economica in una visione sinottica.
che sappia cogliere le possibili ricadute nel breve e nel lungo periodo. In questo contesto gli obiettivi di conservazione, valorizzazione e gestione di determinati siti coinvolgono nuovi orizzonti scientifici e tecnici, che si aprono verso la comprensione dei meccanismi con cui l’ambiente ed, in particolare, gli ecosistemi forestali spontaneamente si assestano verso nuovi equilibri imposti dai cambiamenti conseguenti alle attività umane. Un’importante chiave di lettura di questo complesso quadro viene dallo studio diacronico di quello che può definirsi “paesaggio culturale”, prodotto della coazione tra meccanismi ecologici e trasformazioni economico-sociali. Dall’analisi retrospettiva delle dinamiche dell’uso agro-forestale delle terre e delle diverse tipologie di trasformazioni e persistenze è possibile generare dei modelli predittivi ed impostare, in particolare, le possibili linee gestionali per i boschi di neoformazione, cioè insediatisi in tempi relativamente recenti su suoli privi di copertura arborea, con attenzione alle problematiche che le tendenze evolutive in atto possono determinare per quanto riguarda le relazioni tra la risorsa boschiva e gli altri elementi costitutivi del paesaggio. Questi boschi di origine secondaria, risultato del declino dell’economia agricola montana e del progressivo abbandono di pratiche di utilizzo del territorio silvo-pastorale dimensionate su scala familiare, da un lato conducono ad una semplificazione paesaggistica che si traduce in una riduzione degli ecotoni e quindi della biodiversità, dall’altro assumono un importante ruolo come serbatoi di carbonio o come preziose fonti di energia rinnovabile. Ai processi di espansione naturale del bosco, si aggiungono quelli di evidente matrice antropica, che generalmente sono facilmente riconoscibili dall’analisi di foto aeree di diverse epoche, perché vanno a definire consistenti spostamenti dei margini del bosco e limiti netti con conformazioni ben differenti dalle geometrie irregolari generate dai processi di successione secondaria. Queste situazioni attualmente pongono difficoltà gestionali correlate alla sbilanciata distribuzione planimetrica delle fasi cronologiche ed alla fragilità strutturale dei popolamenti, caratterizzati da alte perticaie o fustaie adulte monoplane e monospecifiche, particolarmente vulnerabili agli eventi meteorici ed a problematiche fitosanitarie. In tali contesti risulta complesso, a livello pianificatorio aziendale, modulare gli interventi selvicolturali nell’ottica di garantire una ripresa costante e duratura nel tempo [Corona et al., 2010]. Lo studio dell’evoluzione del paesaggio silvo-pastorale si attua, pertanto, attraverso un confronto tra le coperture boschive di differenti periodi storici (Fig. 1) in un orizzonte temporale sufficientemente ampio a rendere analizzabili sia i fenomeni di matrice antropica, sia i processi naturali di successione secondaria. Questi vincoli temporali e la necessità di rappresentare il fenomeno con adeguato dettaglio geometrico limitano le basi informative utilizzabili alla fotogrammetria aerea. Infatti, la risoluzione dei primi satelliti è maggiore a 30 metri e, comunque, per periodi precedenti al 1972 (lancio del primo Landsat) non vi è disponibilità di immagini. Un elemento critico nella derivazione di cartografie di uso del suolo a partire da foto aeree storiche, oltre alle problematiche legate al recupero della metricità dell’immagine, è, tuttavia, rappresentato dalla loro scarsa informazione spettrale. Fino agli inizi degli anni ’90 le foto aeree in bianco e nero sono state in assoluto le più usate per il loro costo più contenuto in relazione alle tecnologie allora disponibili (fino a 10 volte inferiore alle emulsioni a colori). Le pellicole pancromatiche hanno, tuttavia, la caratteristica e la limitazione di avere una scarsa sensibilità spettrale nei confronti dei verdi [Amadesi, 1977], di conseguenza queste emulsioni pongono evidenti limitazioni a derisioni tematiche che riguardino la vegetazione. Soluzioni innovative a queste problematiche vengono dalle applicazioni dei sistemi di analisi delle immagini basati sul paradigma object-oriented in grado di implementare classificatori operanti con logica fuzzy.
In questo contesto il presente contributo si propone di definire procedure semi-automatiche di estrazione delle coperture forestali da fotogrammi pancromatici storici alternative alle usuali tecniche di fotointerpretazione e digitalizzazione manuale, che consentano di ridurre al minimo il concorso manuale del fotointerprete, determinando, soprattutto nell’applicazione su vasti comprensori, una drastica riduzione dei tempi di produzione dell’output vettoriale. Inoltre, le procedure di segmentazione dinamica dell’immagine si contraddistinguono, rispetto alla fotointerpretazione manuale, per una maggiore oggettività del metodo di rappresentazione della complessità strutturale del paesaggio.

Area di studio e materiali utilizzati
L’area di analisi interessa la porzione settentrionale della Comunità Montana della Spettabile Reggenza dei Sette Comuni (Vicenza), compiendo parte dei Comuni di Rotzo, Roana, Asiago, Gallio, Foza, Enego. Questo contesto territoriale è ampiamente documentato sotto il profilo storico, socio-economico e gestionale, pertanto è stato abbastanza agevole relazionare i processi di trasformazione ai fattori principali che li hanno generati.
E’ stata analizzata una scena che ricopre una superficie molto estesa (circa 30.000 ha) con l’obiettivo di mettere a punto una procedura di classificazione speditiva, riproducibile su scala regionale.
Le immagini oggetto di classificazione sono le foto aeree del volo GAI (Gruppo Aeronautico Italiano) del 1954 scansionate in formato TIFF ad una risoluzione di 600 dpi. I fotogrammi utilizzati provengono da un preliminare lavoro di ortorettifica eseguito dall’Università IUAV di Venezia su committenza della Regione del Veneto e, in tale contesto, sono stati ricampionati forzando i pixel ad una GSD (Ground Sample Distance) di 2 m con un errore residuo minore di 2 pixel. La superficie sulla quale sono stati eseguiti i test ed estratto lo strato tematico è ricoperta da 9 fotogrammi appartenenti alle strisce 21 e 22A (Fig. 2). Il dato vettoriale relativo alle coperture forestali nel 2007 è, invece, stato ricavato dalla “Carta della copertura del suolo del Veneto” alla scala 1:10.000, database geografico realizzato dalla Regione del Veneto nel contesto dell’attuazione del progetto europeo GSE Land. Le formazioni boschive in questo caso sono state individuate a partire dalle

Figura 2 - Area di studio e fotogrammi selezionati.

Nel confronto multitemporale è stato adottato quest’ultimo standard, che consente di comparare i risultati con gli esiti di gran parte delle attività di monitoraggio forestale prodotte dalla comunità scientifica nell’ultimo decennio. Il processo di produzione del dato vettoriale relativo alle coperture forestali del 1954 e del 1991, pertanto, si è conformato alle specifiche di estensione minima (0,5 ha) e di copertura arborea minima (10%) previste dalla definizione di bosco FRA2000.

Approccio object-oriented e descrittori statistici di tessitura
La definizione di una procedura supervisionata per la classificazione delle coperture boschive a partire dalle immagini pancromatiche del volo GAI pone problematiche differenti e maggiori difficoltà rispetto all’analisi di immagini più recenti. L’interpretazione di questi fotogrammi a
256 livelli di grigio deve affrontare elevatissimi livelli di incertezza, in quanto ad un determinato valore di DN (Digital Number) possono corrispondere differenti classi di copertura del suolo. Questa incertezza aumenta ancor più in territori ad orografia accidentata, nei quali i diversi gradi di ombreggiatura, determinati da differenti condizioni di pendenza ed esposizione, rendono ancor meno univoca e, pertanto, attendibile una classificazione su base spettrale. In questo contesto l’approccio object-oriented è l’unico possibile, dal momento che la risposta radiometrica del singolo pixel non è direttamente correlabile al land cover. Il numero di descrittori (features) spettrali associabili ad un oggetto generato dalla segmentazione, tuttavia, rispetto ad immagini RGB, si riduce drasticamente dal momento che, nelle immagini mono-banda, i valori della media (mean) dei DN di ciascun oggetto corrispondono ai valori della luminosità (brightness) e che, in virtù di tale eguaglianza, la differenza massima (maximum difference) per ogni oggetto è pari a 0. Le uniche informazioni spettrali utilizzabili sono, pertanto, la media e la deviazione standard (standard deviation), ma da sole, come si vedrà negli esempi che seguono, queste statistiche sono insufficienti a realizzare una separazione delle classi tale da produrre una classificazione stabile.

Nelle aree montane, alle quote più elevate, un contributo al miglioramento dell’accuratezza tematica può venire dall’integrazione di modelli di distribuzione della vegetazione forestale su base altitudinale. L’utilizzo di funzioni di appartenenza costruite a partire da informazioni ancillari, quale un accurato DTM, pur consigliato, esula, tuttavia, dagli obiettivi di questo studio, che mira a determinare le modalità più efficaci di estrazione dall’immagine del suo contenuto semantico.

Un metodo che consente di ottenere risultati ben più accurati rispetto alla classificazione su base esclusivamente spettrale si basa sull’integrazione delle proprietà tessiturali delle diverse classi di copertura del suolo. La tessitura di un’immagine si può definire come la variazione spaziale dei valori dei toni di grigio secondo una disposizione ricorsiva e geometricamente identificabile. Le caratteristiche di tessitura consentono di analizzare l’omogeneità, la dipendenza lineare dei toni di grigio, il contrasto, il numero e la natura dei confini presenti e la complessità dell’immagine [Haralik et al., 1973]. Per un osservatore umano l’associazione ad una superficie di un particolare tipo di tessitura è intuitiva ed immediata e le definizioni che se ne danno sono tipicamente qualitative (pertanto soggettive) e legate al suo carattere percettivo. Le tecniche per descrivere le caratteristiche tessiturali in modo oggettivo possono essere di tipo strutturale o statistico. L’approccio strutturale descrive il posizionamento delle primitive di tessitura (textel) deterministiche attraverso concetti di adiacenza, vicinanza o periodicità, pertanto è più adatto all’analisi di immagini di strutture artificiali che alla descrizione di scene naturali. Le coperture forestali, come appaiono dalle immagini aeree, sono caratterizzate da tessiture costituite da primitive elementari molto piccole con caratteristiche irregolari e, per descriverne la variabilità, sono più appropriati i metodi basati sull’analisi di parametri statistici [Keller et al., 1989].

Nello specifico, sono stati sperimentati algoritmi per l’estrazione di parametri statistici di tessitura calcolati sulle matrici di co-occorrenza. Le matrici di co-occorrenza spaziale (GLCM, grey level co-occurrence matrix) proposte da Haralick [1973] si basano su statistiche del secondo ordine, ovvero sulla costruzione di un istogramma bidimensionale dei livelli di grigio misurati ai capi di un segmento posizionato in modo casuale nell’immagine con una determinata orientazione. Il software Definiens Professional, utilizzato per la segmentazione e la classificazione dei fotogrammi pancromatici del volo GAI, offre la possibilità di calcolare le statistiche relative alla
tessitura in una delle quattro direzioni possibili (0°, ovvero in direzione verticale, 45°, 90°, ossia in direzione orizzontale, 135°). Per ciascun pixel di un oggetto dell’immagine viene considerata la co-occorrenza tra il pixel più vicino in una delle quattro direzioni ed il pixel più vicino nel verso opposto [Navulur, 2007], comprendendo anche i pixel circostanti all’oggetto con distanza di uno, per eliminare gli effetti di bordo. Il calcolo delle statistiche di tessitura può anche essere eseguito contemporaneamente in tutte e quattro le direzioni; in questo caso il software opera su quattro matrici di calcolo ed i tempi di elaborazione si allungano sensibilmente.

Le prestazioni delle statistiche di tessitura risentono sensibilmente della modalità di ricampionamento delle immagini adottata nelle fasi di pre-elaborazione (ortorettifica e mosaicatura). In questo lavoro è stato adottato il metodo nearest neighbor, perché è l’unico a mantenere inalterato il valore di luminosità dei pixel [Gomarasca, 2004; Chirici e Corona, 2006], pur presentando l’inconveniente di produrre un più marcato effetto scalinatura, che, tuttavia, può essere facilmente corretto applicando opportuni algoritmi di regolarizzazione dei contorni (smoothing) contestualmente all’esportazione in formato vettoriale dell’output tematico della classificazione. Le altre modalità di ricampionamento introducono una redistribuzione dei valori dei DN nell’immagine di output attraverso tecniche di interpolazione che hanno in comune la caratteristica di “smussare” le differenze tra i valori dei DN e di eliminare i valori estremi, compromettendo l’analisi delle statistiche tessiturali, che il software Definiens Professional calcola su matrici di co-occorrenza costruite utilizzando finestre mobili di dimensione 3x3.

Criteri di selezione dei descrittori

L’analisi delle co-occorrenze spaziali, ha lo svantaggio di generare una grande mole di dati e ciò comporta, in relazione al tipo e al numero di descrittori statistici di tessitura utilizzati, alla dimensione dell’immagine da analizzare ed alle capacità computazionali del processore impiegato, tempi di elaborazione anche estremamente lunghi.

Per questo motivo è importante limitare l’impiego delle statistiche tessiturali a quelle che meglio descrivono la natura delle classi rappresentate. Alcuni di questi descrittori riguardano caratteristiche specifiche dell’immagine o la presenza di strutture organizzate, altre caratterizzano la complessità e la natura delle transizioni dei toni di grigio.

Le 8 statistiche di tessitura che il software Definiens Professional può calcolare per ciascun oggetto prodotto dalla segmentazione sono:

- secondo momento angolare (GLCM Ang. 2nd moment): è un indicatore dell’omogeneità dell’oggetto e, quindi, della numerosità delle transizioni dei toni di grigio (è uguale alla somma dei quadrati delle frequenze delle co-occorrenze);

- omogeneità (GLCM Homogeneity): se l’oggetto è localmente omogeneo, i valori più elevati della matrice di co-occorrenza spaziale si concentrano lungo le diagonali; l’omogeneità diminuisce in misura esponenziale in funzione della distanza dei valori elevati della matrice dalla sua diagonale;

- contrasto (GLCM Contrast): all’opposto dell’omogeneità, il contrasto esprime la misura delle variazioni locali dei DN, pertanto presenta valori elevati per oggetti con tessitura molto pronunciata;

- dissomiglianza (GLCM Dissimilarity): simile alla precedente statistica, aumenta in modo lineare in relazione alla presenza all’interno dell’oggetto di primitive di tessitura con alto contrasto;
- entropia (GLCM Entropy): ha valori bassi quando l’oggetto presenta coppie di livelli di grigio dominanti per una certa direzione;
- deviazione standard (GLCM Standard deviation): misura la dispersione dei valori della matrice di co-occorrenza attorno alla media;
- correlazione (GLCM Correlation): esprime il grado di dipendenza lineare dei livelli di grigio di pixel adiacenti;
- media (GLCM Mean): misura il valore di un pixel ponderato con la frequenza della sua comparsa in combinazione con un determinato valore del pixel vicino [Haralik et al., 1973; Baatz et al., 2001].

Pur essendo noto il significato di ciascuno di questi indicatori dell’organizzazione spaziale delle primitive di tessitura, a poco aiuta una valutazione visiva dei fotogrammi per individuare quelli più efficaci a discriminare le classi da rappresentare, poiché nelle immagini che rappresentano scene naturali le caratteristiche di tessitura possono variare da zona a zona con modalità stocastiche.

La scelta delle statistiche di tessitura da implementare nell’algoritmo di classificazione, in una prima analisi, è stata fatta sulla base di esempi applicativi documentati in letteratura [Halounová, 2003; Laliberte e Rango, 2009]. In uno studio pilota eseguito da Halounová [2003] per conto del Ministero per l’Agricoltura della Repubblica Ceca, finalizzato alla definizione di una procedura di classificazione semi-automatica per distinguere boschi di latifoglie e di conifere ed aree deforestate a partire da foto aeree panchromatiche con risoluzione geometrica di 50 cm, i descrittori statistici di tessitura più efficaci nel migliorare l’accuratezza della classificazione sono risultati la media e la dissomiglianza. Diversa è l’indicazione di Laliberte e Rango [2009], i quali indicano l’entropia come la migliore statistica di tessitura in grado di discriminare gli arbusteti dai pascoli su immagini aeree a risoluzione sub-decimetrica.

In seconda analisi, sono stati evitati gli abbinamenti di descrittori statistici in grado di produrre risultati fortemente correlati. Di conseguenza sono stati esclusi l’omogeneità (correlata con la dissomiglianza: r ≈ -0.95), la deviazione standard (correlata con la dissomiglianza: r ≈ 0.91) e il secondo momento angolare (correlato con l’entropia: r ≈ -0.87) [Hall-Beyer, 2007].

Con questo approccio, delle 8 statistiche di tessitura calcolate dal software, è stato selezionato un sottoinsieme di 5 statistiche, il cui potenziale risolutivo è stato ulteriormente analizzato adottando il processo automatico di ottimizzazione Feature Space Optimization (FSO). Tale processo è d’ausilio alla determinazione della combinazione di descrittori che meglio contribuisce a discriminare le classi di interesse, mediante il calcolo automatico della distanza tra le classi determinata dall’algoritmo standard nearest neighbor nello spazio multidimensionale definito dai descrittori selezionati [Baatz et al., 2001; Grignetti et al., 2009].

I test applicativi di FSO sono stati eseguiti contestualmente alla definizione dei parametri di segmentazione, al fine di verificare l’esistenza di relazioni tra le potenzialità risolutive degli algoritmi di classificazione e le dimensioni medie degli oggetti generati dalla segmentazione e, pertanto, di valutare se anche questo aspetto possa rientrare tra i criteri di individuazione dei parametri ottimali.

Le prove di segmentazione sono state eseguite attraverso un approccio reiterativo per prova ed errore, variando di volta in volta la combinazione dei parametri guida [Chirici e Corona, 2006; Chirici et al., 2006]. Sono stati ritenuti adeguati ad un’idonea classificazione dell’immagine quei parametri che hanno consentito di evitare un’eccessiva frammentazione e nel contempo
di produrre un dettaglio sufficiente a differenziare il bosco dalle altre tipologie di copertura del suolo, anche con riferimento alle dimensioni minime degli oggetti, che devono consentire l’identificazione di aree forestali e di patch non boscate con estensione di almeno 0,2 ha. Benché nel confronto diacronico si faccia riferimento alla definizione di bosco FRA2000 (che adotta un’unità minima di 0,5 ha), il riferimento dimensionale di 0,2 ha è stato scelto allo scopo di produrre una base di dati intermedia che potesse successivamente adeguarsi anche alla definizione di bosco prevista dalla legislazione regionale (che prevede appunto una superficie minima di 0,2 ha).

**Figura 3 - Esempi di segmentazione e numero di oggetti generati sull’intera scena analizzata.**

Inizialmente sono stati adottati i parametri suggeriti da Gennaretti et al. [2009] (scale=40; shape=0,7; color=0,3; compactness=0,5) (Fig. 3). Gli oggetti così generati, in conseguenza allo scarso peso assegnato all’eterogeneità spettrale, hanno forma per lo più compatta, ma rappresentano con accuratezza le discontinuità di copertura del suolo in virtù delle ridotte dimensioni. Le successive prove di segmentazione, invece, sono state eseguite aumentando progressivamente di 20 unità il fattore di scala ed innalzando l’overall fusion value attraverso una graduale riduzione del fattore di forma (shape) fino a 0,3. Gli oggetti prodotti sono di dimensioni mediamente maggiori, ma risultano, fino ad un valore massimo del parametro scale=120, ugualmente coerenti con l’estensione minima e con le classi da rappresentare, poiché delineano in modo più accurato le eterogeneità spettrali dell’immagine (in Figura 3 si riportano a titolo esemplificativo solo tre dei cinque risultati delle segmentazioni eseguite con progressione del fattore di scala pari a 20).

Per ciascun output di segmentazione è stato avviato il processo di FSO, dapprima utilizzando le sole caratteristiche spettrali, successivamente introducendo, oltre a queste, i 5 descrittori tissuturali selezionati, ovvero la media, la dissomiglianza, la correlazione, l’entropia e il contrasto, calcolati come valor medio delle statistiche estratte nelle quattro direzioni. Anche la classificazione è stata eseguita sia utilizzando le sole statistiche spettrali, sia implementando nel classificatore standard nearest neighbor anche le tre statistiche di tessitura che hanno maggiormente contribuito a determinare, nel processo di FSO, la massima distanza di separazione tra le classi (maximum separation distance) (Fig. 4).
Figura 4 - Valori di separation distance ottenuti sull’area di analisi segmentata con scale=120, shape=0,3, compactness=0,5. L’implementazione nel processo di FSO dei descrittori statistici di tessitura determina un marcato aumento della distanza di separazione tra le classi (grafico in basso) rispetto all’impiego delle sole statistiche spettrali (grafico in alto).

Studi precedenti hanno, infatti, dimostrato che l’impiego di più di tre statistiche tessiturali, a fronte di tempi di calcolo più lunghi, non produce miglioramenti significativi nell’accuratezza della classificazione [Trianni, 2005].

Ad ogni scala di segmentazione la selezione delle aree di training è stata effettuata, tramite fotointerpretazione, in modo da rappresentare l’eterogeneità delle classi bosco/non bosco, in relazione anche ai diversi gradi di ombreggiatura indotti dalla morfologia del terreno, e la variabilità dimensionale degli oggetti. Il numero di oggetti utilizzato come samples corrisponde a circa il 2% del numero degli oggetti dell’intera scena da classificare. Questo valore percentuale è inferiore a quello adottato in altre sperimentazioni (Lamonaca [2006] e Giuliarelli et al. [2007] suggeriscono di utilizzare almeno il 3–4% dell’intera immagine), ma consente di ridurre i tempi necessari all’esecuzione del processo di classificazione, dipendenti, oltre che dalle caratteristiche dell’hardware utilizzato e dal numero e dalla tipologia dei descrittori implementati nell’algoritmo di classificazione, anche dalla numerosità delle aree di training.

Infine sono state valutate le differenti prestazioni tramite matrice di contingenza tra classificazioni ed aree di controllo e calcolo dell’indice KIA (Kappa Index of Agreement) (Fig. 5).
Figura 5 - Diagramma di flusso del processo di classificazione con riferimento all’approccio adottato.

**Risultati**

La distanza di separazione, misurata attraverso il processo $FSO$, è servita per stimare il contributo potenziale dell’informazione tessitutale al miglioramento della discriminazione tra le due classi di interesse (bosco/non bosco). A tutte le scale di segmentazione, l’integrazione delle statistiche di tessitura ha determinato una distanza di separazione tra le classi pressoché doppia rispetto al classificatore basato esclusivamente sulle statistiche spettrali (Fig. 4).

Nell’algoritmo di classificazione, pertanto, sono state implementate, oltre alla media ed alla deviazione standard dei $DN$ di ciascun oggetto, le tre statistiche di tessitura che in tutti i test eseguiti hanno evidenziato il maggiore potenziale risolutivo, ossia la media, la dissomiglianza e l’entropia, determinate, in una prima definizione dell’algoritmo, dal valore medio delle statistiche calcolate sulle matrici costruite nelle quattro direzioni.

Proprio con riferimento all’angolo $\theta$ di calcolo della matrice di co-occorrenza spaziale, le strategie suggerite in letteratura non sono univoche. Haralik et al. [1973], oltre ad Halounová [2004], suggeriscono di estrarre le statistiche di tessitura in tutte le quattro possibili direzioni e poi calcolarne il valore medio. Peddle e Franklin [1989] sostengono invece che in molti casi le statistiche della $GCLM$ calcolate considerando una appropriata direzione possono essere più idonee nella discriminazione di alcune classi di copertura del suolo. Ulteriori test, eseguiti attraverso il processo di $FSO$, di fatto hanno confermato la seconda
di queste tesi, pur evidenziando un aumento modesto della distanza di separazione tra le classi (Tab. 1), che non ha determinato miglioramenti nell’accuratezza della classificazione. Il calcolo delle statistiche tessiturali sulle matrici costruite in una sola direzione, tuttavia, ha mostrato il vantaggio di ridurre drasticamente (del 40-50%) i tempi di elaborazione, ma richiede un’analisi preliminare (che utilizza come guida il tool FSO) necessaria all’individuazione, per ciascuna delle tre statistiche tessiturali utilizzate, dell’angolo $\theta$ più efficace nella separazione delle classi. Questa analisi deve essere ripetuta per ogni scena da classificare, perché la migliore direzione di calcolo della matrice di co-occorrenza spaziale può variare localmente in relazione alle caratteristiche della copertura del suolo ed ai fattori che influiscono sulle condizioni di illuminazione (posizione del sole, orografia).

**Tabella 1 - Potenziale discriminante delle features di tessitura in relazione alla direzione di calcolo (risultati relativi all’intera scena segmentata con scale=120, shape=0,3, compactness=0,5 calcolati con il tool FSO).**

<table>
<thead>
<tr>
<th>Descrittori</th>
<th>Distanza progressiva di separazione</th>
<th>Descrittori</th>
<th>Distanza progressiva di separazione</th>
</tr>
</thead>
<tbody>
<tr>
<td>Media (tessiturale)</td>
<td>0,263</td>
<td>Media (tessiturale)</td>
<td>0,263</td>
</tr>
<tr>
<td>(tutte le direzioni)</td>
<td>(45°)</td>
<td>(0°)</td>
<td>1,479</td>
</tr>
<tr>
<td>Dissomiglianza</td>
<td>1,316</td>
<td>Entropia (135°)</td>
<td>1,666</td>
</tr>
<tr>
<td>(tutte le direzioni)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entropia (tutte le direzioni)</td>
<td>1,521</td>
<td>Media (spettrale)</td>
<td>1,9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviazione standard</td>
<td>1,912</td>
<td>Deviazione standard</td>
<td>2,037</td>
</tr>
</tbody>
</table>

La scena analizzata presenta alcune situazioni non classificabili, rappresentate prevalentemente dalle coperture nuvolose e dalle ombre generate dai rilievi. Queste superfici, che interessano circa il 4% dell’area di studio, sono state mascherate ed escluse sia dalla selezione delle aree di training (samples), sia dall’individuazione delle aree di controllo impiegate per calcolare la matrice di errore, e sono state sottratte anche dal computo delle variazioni di superficie forestale nell’analisi multitemporale.

Nella fase di verifica dell’accuratezza della classificazione le geometrie delle aree di controllo sono state determinate utilizzando parametri di segmentazione differenti da quelli impiegati per classificare l’immagine (scale=90; shape=0,7; compactness=0,5), allo scopo di utilizzare siti di controllo in nessun caso corrispondenti con gli oggetti classificati alle diverse scale di segmentazione. Queste aree, inoltre, sono state determinate evitando sovrapposizioni con gli oggetti utilizzati per l’apprendimento del classificatore, che produrrebbero una sovrastima dell’indice $KIA$. Le aree di controllo, determinate tramite fotointerpretazione, sono state distribuite secondo uno schema casuale stratificato, cercando, pertanto, di rappresentare, come nella selezione dei poligoni di training, la variabilità all’interno delle classi di interesse. Per ciascuna classe sono stati selezionati 80 test sites (Congalton [1991] suggerisce di selezionarne almeno 75 per classe), che includono 1.099.194 pixel afferenti alla classe bosco e 892.404 pixel alla classe non bosco (in totale il 2,23% dell’intera scena).
I risultati della classificazione sono stati valutati sia attraverso la rappresentazione grafica e statistica della *classification stability*, sia tramite il calcolo dei valori di accuratezza e dell’indice *KIA*.

La *classification stability* evidenzia la differenza tra i valori di appartenenza fuzzy di ciascun oggetto alle classi bosco/non-bosco sulla base dei descrittori impiegati. Quando l’algoritmo di classificazione assegna ad un oggetto valori di appartenenza fuzzy simili, la differenza tra gli indicatori di appartenenza assume valori prossimi a 0 e la classificazione di quell’oggetto si considera “instabile”. Al contrario, quanto maggiore è la differenza tra il valore di appartenenza tra la prima classe (quella con il grado di appartenenza fuzzy più elevato) ed il secondo miglior risultato di assegnazione ad una classe, tanto più la classificazione può considerarsi “stabile”. Questo indicatore non opera attraverso la selezione di aree di controllo e, pertanto, costituisce uno strumento di valutazione speditiva delle prestazioni dell’algoritmo di classificazione. Nella sua rappresentazione tabellare riporta per ciascuna classe le principali statistiche (media, deviazione standard, minimo, massimo) relative alla *classification stability* degli oggetti classificati (Tab. 2). L’*output* grafico rappresenta gli oggetti classificati con tonalità che vanno dal rosso (classificazione instabile) al verde (classificazione stabile).

**Tabella 2 - Statistiche di classification stability relative alla classificazione della scena segmentata con scale=120, shape=0,3, compactness=0,5 ottenute sia utilizzando le sole caratteristiche spettrali, sia integrando anche i tre descrittori statistici di tessitura selezionati.**

<table>
<thead>
<tr>
<th>Descrittori: Media (spettrale) + Deviazione standard</th>
<th>Classe</th>
<th>N. oggetti</th>
<th>Media</th>
<th>Dev. standard</th>
<th>Minimo</th>
<th>Massimo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>non bosco</td>
<td>10.547</td>
<td>0,370</td>
<td>0,280</td>
<td>2,253055573e-005</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>bosco</td>
<td>14.765</td>
<td>0,3313</td>
<td>0,209</td>
<td>2,241134644e-005</td>
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</table>

<table>
<thead>
<tr>
<th>Descrittori: Media (spettrale) + Deviazione standard + Media (tessiturale) + Dissomiglianza + Entropia</th>
<th>Classe</th>
<th>N. oggetti</th>
<th>Media</th>
<th>Dev. standard</th>
<th>Minimo</th>
<th>Massimo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>non bosco</td>
<td>11.665</td>
<td>0,5204</td>
<td>0,306</td>
<td>0,00061070994</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>bosco</td>
<td>13.647</td>
<td>0,4011</td>
<td>0,247</td>
<td>0,000262370463</td>
<td>1</td>
</tr>
</tbody>
</table>

Il calcolo dell’indice *KIA*, effettuato per ciascun *output* di segmentazione, ha evidenziato una correlazione, nell’impiego delle statistiche di tessitura, tra accuratezza tematica e dimensione media degli oggetti. Questo probabilmente accade perché oggetti di piccole dimensioni sono meno rappresentativi dell’organizzazione spaziale dei toni di grigio, in relazione alle classi d’interesse da discriminare, rispetto a regioni più ampie dell’immagine. I valori dell’indice *KIA* più elevati, pertanto, sono stati ottenuti adottando i parametri di segmentazione *scale*=120, *shape*=0,3, *compactness*=0,5, con un significativo contributo delle statistiche di tessitura nell’aumento dell’accuratezza:

- media (spettrale) + deviazione standard: *KIA*=0,84;
- media (spettrale) + deviazione standard + media (tessiturale) (45°) + dissomiglianza (0°) + entropia (135°): *KIA*=0,91.
Criticità
La maggior parte degli errori di classificazione ha riguardato superfici analizzabili con difficoltà anche tramite fotointerpretazione. Queste situazioni sono rappresentate dalle formazioni a pino mugo localizzate nella parte settentrionale dell’Altopiano dei Sette Comuni, che non staccano un’ombra netta e, pertanto, sono difficilmente distinguibili dalle praterie in quota, e dagli orno-ostrieti distribuiti sui pendii meridionali del Corno Rosso e del Monte Spitz, che al momento della ripresa aerea (2 ottobre 1954) risultavano parzialmente privi della copertura fogliare. La corretta attribuzione tematica, in questi casi, ha richiesto un’attenta revisione fotointerpretativa. La comparazione con fonti aerofotogrammetriche più recenti ha rappresentato un supporto solo orientativo alla verifica a video, in quanto la dinamicità dei fenomeni di trasformazione e l’evoluzione temporale degli stessi obbliga ad un processo interpretativo più complesso, che deve essere risultato dell’interpolazione tra fonti bibliografiche ed archivi storici di dati [Mancini et al., 2008]. Il presente lavoro, finalizzato alla definizione di una procedura speditiva di estrazione tematica, non ha affrontato questo approfondimento analitico. Di conseguenza i casi non risolvibili con sicurezza tramite fotointerpretazione sono stati fatti rientrare nell’insieme delle aree non classificabili.

Altro elemento di criticità rappresentato dalla verifica della correttezza della classificazione in relazione al grado minimo di copertura delle chiome previsto dalla definizione di bosco FRA2000. L’esecuzione di questo controllo è affidata all’esperienza del fotointerprete e, pertanto, si basa su valutazioni soggettive che possono rappresentare fonte di errore.

Confronto multitemporale
Pur non volendo entrare nel dettaglio dei risultati ottenuti dal confronto multitemporale nell’area di studio, appare interessante, più in generale, evidenziare la rilevanza che assume la scala temporale di osservazione delle dinamiche spaziali dei popolamenti forestali nel determinare l’approccio interpretativo e la scelta degli strumenti di analisi.

In generale quanto maggiore è il lasso di tempo che intercorre tra due rilevamenti, tanto maggiore sarà l’entità dei mutamenti e tanto più elevata la probabilità che le cause generatrici siano legate a particolari eventi storici o alle trasformazioni socioeconomiche che hanno caratterizzato quel territorio, piuttosto che alle naturali dinamiche di successione forestale [Preto, 1994].

Comparando i fotogrammi del volo GAI del 1954 con le foto aeree del volo “Montagna Veneta 1991”, è stato preso in considerazione un primo intervallo temporale di 37 anni che ha segnato sostanziali modifiche all’assetto territoriale dell’area di studio (la superficie forestale è aumentata del 24%). A modellare i boschi ed il paesaggio dell’intero comprensorio, oltre al progressivo declino del pascolo ovino, furono, soprattutto, le estese opere di ricostituzione boschiva (Fig. 6) eseguite tra gli anni ‘50 e ‘60, che compensarono le ingenti distruzioni e i danneggiamenti cui andò incontro l’Altopiano dei Sette Comuni durante le due guerre.

Il secondo intervallo temporale considerato analizza le dinamiche avvenute tra il 1991 e il 2007, periodo durante il quale le esigue opere di coniferamento di incolti e pascoli abbandonati sono di entità tale da non interferire sulla valutazione complessiva dei fattori di potenziale rilevanza funzionale nelle dinamiche di espansione del bosco.
L’opportunità di approfondire il livello di analisi, fino a relazionare i processi di trasformazione ai principali fattori naturali e gestionali che li hanno generati, si è scontrata, tuttavia, con la necessità di adottare tecniche di monitoraggio più accurate, in grado di evidenziare i processi di ricolonizzazione avvenuti in un intervallo temporale di soli 16 anni. Anche in questo caso, attraverso procedure diverse da quelle esposte in questo contributo, applicate ad immagini con risoluzione metrica e sub-metrica, le potenzialità del paradigma object oriented hanno consentito di spazializzare i processi e di produrre precise stime quantitative sulla loro consistenza, validate, con esito positivo, attraverso i classici metodi di natura inventariale [Savio, 2011].

Figura 6 - Rimboschimenti monospecifici di abete rosso eseguiti tra Piana della Futa e Malga Xomo, Comune di Foza (VI).

**Conclusioni**

L’esperienza condotta dimostra che alcuni descrittori statistici della tessitura basati sulla costruzione delle matrici di co-occorrenza spaziale, implementati nel classificatore standard nearest neighbor disponibile nel software Definiens Professional, si rivelano efficaci strumenti di analisi del contenuto semantico di fotografì storicì pancromaticì ed, in particolare, contribuiscono in misura significativa a discriminare le coperture forestali dalle altre classi di uso del suolo.
I test eseguiti utilizzando il tool FSO, oltre ad indirizzare la scelta dei tre indicatori statistici di tessitura più adeguati a differenziare le classi di interesse, hanno evidenziato che il contributo delle singole statistiche tessiturali nel determinare la massima distanza di separazione tra le classi cambia al variare dei parametri di segmentazione. In particolare si è osservato che il peso dell’entropia decresce all’aumentare della dimensione media degli oggetti, mentre tende ad assumere maggiore importanza il contributo della media e della dissomiglianza.

Le prestazioni dell’algoritmo di classificazione che integra questi tre descrittori statistici di tessitura sono significativamente correlate con la scala di segmentazione. Si assiste, infatti, ad un tendenziale incremento della separazione tra le classi e dell’accuratezza tematica della classificazione in rapporto all’aumento delle dimensioni medie degli oggetti, relazione che vale finantoché l’elevazione del fattore di scala non determina un deterioramento dell’accuratezza geometrica.

Questa relazione suggerisce di orientare la calibrazione dei parametri di segmentazione verso una minor frammentazione dell’immagine, pur sempre entro limiti che garantiscono il requisito della coerenza degli oggetti generati con la rappresentatività delle classi di interesse. La riduzione del numero degli oggetti, assieme al miglioramento dell’accuratezza tematica della classificazione semi-automatica, consente di contenere sensibilmente i tempi della successiva revisione manuale e di rendere l’intera procedura scalabile su ampi comprensori.

Ringraziamenti
Ritengo doveroso menzionare l’importante contributo dei revisori, i cui commenti hanno consentito un sostanziale miglioramento dei contenuti del manoscritto.

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Abstracts

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Comparing the performance of fuzzy and crisp classifiers on remotely sensed images: a case of snow classification

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This study deals with the evaluation of accuracy benefits offered by a fuzzy classifier as compared to hard classifiers using satellite imagery for thematic mapping applications. When a crisp classifier approach is adopted to classify moderate resolution data, the presence of mixed coverage pixels implies that the final product will have errors, either of omission or commission, which are not avoidable and are solely due to the spatial resolution of the data. Theoretically, a soft classifier is not affected by such errors, and in principle can produce a classification that is more accurate than any hard classifier. In this study we use the Pareto boundary of optimal solutions as a quantitative method to compare the performance of a fuzzy statistical classifier to the one of two hard classifiers, and to determine the highest accuracy which could be achieved by hard classifiers. As an application, the method is applied to a case of snow mapping from Moderate-Resolution Imaging Spectroradiometer (MODIS) data on two alpine sites, validated with contemporaneous fine-resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data. The results for this case study showed that the soft classifier not only outperformed the two crisp classifiers, but also yielded higher accuracy than the maximum theoretical accuracy of any crisp classifier on the study areas. While providing a general assessment framework for the performance of soft classifiers, the results obtained by this inter-comparison exercise showed that soft classifiers can be an effective solution to overcome errors which are intrinsic in the classification of coarse and moderate resolution data.
Atmospheric correction of ENVISAT/MERIS data over inland waters: Validation for European lakes

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Traditional methods for aerosol retrieval and atmospheric correction of remote sensing data over water surfaces are based on the assumption of zero water reflectance in the near-infrared. A nother type of approach which is becoming very popular in atmospheric correction over water is based on the simultaneous retrieval of atmospheric and water parameters through the inversion of coupled atmospheric and bio-optical water models. Both types of approaches may lead to substantial errors over optically-complex water bodies, such as case II waters, in which a wide range of temporal and spatial variations in the concentration of water constituents is expected. This causes the water reflectance in the near-infrared to be non-negligible, and that the water reflectance response under extreme values of the water constituents cannot be described by the assumed bio-optical models.

As an alternative to these methods, the SCAPE-M atmospheric processor is proposed in this paper for the automatic atmospheric correction of ENVISAT/MERIS data over inland waters. A-priori assumptions on the water composition and its spectral response are avoided by SCAPE-M by calculating reflectance of close-to-land water pixels through spatial extension of atmospheric parameters derived over neighboring land pixels. This approach is supported by the results obtained from the validation of SCAPE-M over a number of European inland water validation sites which is presented in this work. MERIS derived aerosol optical thickness, water reflectance and water pigments are compared to in-situ data acquired concurrently to MERIS images in 20 validation match-ups. SCAPE-M has also been compared to specific processors designed for the retrieval of lake water constituents from MERIS data. The performance of SCAPE-M to reproduce ground-based measurements under a range of water types and the ability of MERIS data to monitor chlorophyll-a and phycocyanin pigments using semiempirical algorithms after SCAPE-M processing are discussed. It has been found that SCAPE-M is able to provide high accurate water reflectance over turbid waters, outperforming models based on site-specific bio-optical models, although problems of SCAPE-M to cope with clear waters in some cases have also been identified.
Chlorophyll retrieval with MERIS Case-2-Regional in perialpine lakes

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Semi-analytical remote sensing applications for eutrophic waters are not applicable to oligo- and mesotrophic lakes in the perialpine area, since they are insensitive to chlorophyll concentration variations between 1 and 10 mg/m³. The neural network based Case-2-Regional algorithm for MERIS was developed to fill this gap, along with the ICOL adjacency effect correction algorithm. The algorithms are applied to a collection of 239 satellite images from 2003–2008, and the results are compared to experimental and official water quality data collected in six perialpine lakes in the same period. It is shown that remote sensing estimates can provide an adequate supplementary data source to in situ data series of the top 5 m water layer, provided that a sufficient number of matchups for a site specific maximum temporal offset are available.

A two-step optimization procedure for assessing water constituent concentrations by hyperspectral remote sensing techniques: An application to the highly turbid Venice lagoon waters

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Over the past few years, the increased spectral and spatial resolution of remote sensing equipment has promoted the investigation of new techniques for inland and coastal water monitoring. The availability of new high resolution data has allowed improvements in models based on the radiative transfer theory for assessing optical water quality parameters. In this study, we fine-tuned a physical model for the highly turbid Venice lagoon waters and developed an inversion technique based on a two-step optimization procedure appropriate for hyperspectral data processing to retrieve water constituent concentrations from remote data. In the first step, the solution of a linearized analytical formulation of the radiative transfer equations was found. In the second step, this solution was used to provide the initial values in a non-linear least squares-based method. This effort represents a first step in the construction of a feasible and timely methodology for Venice lagoon water quality monitoring by remote sensing, especially in view of the existing experimental hyperspectral satellite (Hyperion) and the future missions such as PRISMA, EnMap and HyspIRI. The optical properties of the water constituents were assessed on the basis of sea/lagoon campaigns and data from the literature. The water light field was shaped by an
analytical formulation of radiative transfer equations and the application of numerical simulations (Hydrolight software). Once the optical properties of the Venice lagoon bio-optical model were validated, the inverse procedure was applied to local radiometric spectra to retrieve concentrations of chlorophyll, colored dissolved organic matter and tripton. The inverse procedure was validated by comparing these concentrations with those measured in the laboratory from in situ water samples, then it was applied to airborne (CASI and MIVIS) and satellite (Hyperion) sensors to derive water constituent concentration maps. The consistent results encourage the use of this procedure using future missions satellite (PRISMA, EnMAP and HyspIRI).

Validating an integrated strategy to model net land carbon exchange against aircraft flux measurements

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Aircraft eddy covariance technique is a modern and powerful means to directly measure net ecosystem exchange (NEE) over relatively large land areas. The NEE measurements taken by a specifically developed aircraft platform (Sky Arrow ERA) over a transect in Central Italy during an 18-month period are used to validate a recently proposed modeling strategy. The strategy is based on the integration of the outputs from a NDVI-driven parametric model, C-Fix, and a model of ecosystem processes, BIOME-BGC, and can simulate both gross and net land carbon fluxes over different spatial and temporal scales. The application of this strategy to 1-km resolution ground and remotely sensed data descriptive of the study area enables the production of NEE estimates comparable to the aircraft measurements. The agreement between the two data series is high, especially when averaging the modeling outputs over areas consistent with the Sky Arrow footprint (i.e. 1–2 pixels apart from the flight line). Fractional forest cover and NDVI are the two model driving variables which explain most spatial variability of the aircraft NEE measurements. The modeling strategy yields the best performances for spring–summer seasons, when vegetation photosynthetic and respiratory processes are higher and easier to simulate. These performances are finally commented with specific emphasis on the contribution brought by remote sensing information.

Grape quality assessment in vineyards affected by iron deficiency chlorosis using narrow-band physiological remote sensing indices

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The present study investigated the use of physiological indices calculated from hyperspectral remote sensing imagery as potential indicators of wine grape quality assessment in vineyards affected by iron deficiency chlorosis. Different cv. Tempranillo/110 Richter vineyards located in northern Spain, affected and nonaffected by iron chlorosis, were identified for field and airborne data collection. Airborne campaigns imaged a total of 14 study areas in both 2004 and 2005 using the AHS hyperspectral sensor, which acquired 20 spectral bands in the VIS-NIR region. Field measurements were conducted in each study site to obtain leaf and grape physiological parameters potentially linked to wine quality. Simulations carried out with the rowMCRM radiative transfer model demonstrated the feasibility of estimating leaf chlorophyll a+b ($C_{ab}$) content using TCARI/OSA VI from AHS spectral bands. In addition to traditional structural vegetation indices (NDVI) and successful canopy-level chlorophyll indices (TCARI/OSA VI), other innovative physiological indices sensitive to changes in carotenoid ($Car$) and anthocyanin ($Anth$) content in leaves were assessed from the imagery. The row MCRM model simulations were used to evaluate canopy structural effects on these physiological indices as a function of the typical row-structured canopy variables in vineyards (LAI, crown width, row distances, $C_{ab}$ content and soil background effects). Modeling results concluded that $Car$ (Gitelson-Car2) and $Anth$ (Gitelson-Anth) indices were highly affected by canopy structure ($C_w$, $V_s$) and soil background ($\rho_s$). Field measurements of grape composition and quality were used to assess potential relationships with physiological indices sensitive to foliar pigment content ($C_{ab}$, $Car$ and $Anth$). NDVI and TCARI/OSA VI indices yielded lower relationships for CIRG and IMAD must quality parameters than $Car$ and $Anth$ physiological indices. These results suggest that the increase in carotenes and anthocyanins due to drought, thermal damage or micronutrient deficiencies is a better indicator to detect phenolic ripening difficulties for vines affected by iron chlorosis than chlorosis detection. Therefore, the potential use of physiological remote sensing indices related to carotene and anthocyanin pigments demonstrates their importance as grape quality indicators in vineyards affected by iron chlorosis.

Soil moisture variations monitoring by AMSU-based soil wetness indices: A long-term inter-comparison with ground measurements

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Soil moisture controls the partitioning of rainfall into runoff and infiltration and, consequently, the runoff generation. On the catchment scale its routine monitoring can be performed through remote sensing technologies. Within this framework, the purpose of this study is to investigate the potential of the Advanced Microwave Sounding Unit (AMSU), radiometer on board the NOAA (National Oceanic and Atmospheric Administration) satellites and operating since 1998, for the assessment of soil wetness conditions by comparing soil moisture data with both those measured in situ and provided by a continuous rainfall-runoff model applied to four catchments located in the Upper Tiber River (Central Italy). In particular, in order to perform a robust analysis an
extensive and long-term period (nine years) of data was investigated. In detail, the Soil Wetness Variation Index, derived from the AMSU data modified in order to take account of the difference between the soil layer investigated by the satellite sensor and that used as a benchmark, was found to be correlated both with the in-situ and modeled soil moisture variations showing correlation coefficients in the range of 0.42–0.49 and 0.33–0.48, respectively. As far as the soil moisture temporal pattern is concerned, higher correlations were obtained (0.59–0.84 for the in-situ data and 0.82–0.87 for the modeled data set) partly due to the soil moisture seasonal pattern that enhances the correlation. Overall, the root mean square error was found to be less than 0.05m³/m³ for both the comparisons, thus assessing the potential of the AMSU sensor to quantitatively retrieve soil moisture temporal patterns. Moreover, the AMSU sensor can be considered as a useful tool to provide a reliable and frequently updated global soil moisture data set, considering its higher temporal resolution now available (about 4 passes per day) thanks to the presence of the sensor aboard different satellites.

PM$_{10}$ remote sensing from geostationary SEVIRI and polar-orbiting MODIS sensors over the complex terrain of the European Alpine region

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The subject of this study is to investigate the capability of spaceborne remote sensing data to predict ground concentrations of PM$_{10}$ over the European Alpine region using satellite derived Aerosol Optical Depth (AOD) from the geostationary Spinning Enhanced Visible and InfraRed Imager (SEVIRI) and the polar-orbiting MODerate resolution Imaging Spectroradiometer (MODIS). The spatial and temporal resolutions of these aerosol products (10 km and 2 measurements per day for MODIS, $\sim$25 km and observation intervals of 15 min for SEVIRI) permit an evaluation of PM estimation from space at different spatial and temporal scales. Different empirical linear relationships between coincident AOD and PM$_{10}$ observations are evaluated at 13 ground-based PM measurement sites, with the assumption that aerosols are vertically homogeneously distributed below the planetary Boundary Layer Height (BLH). The BLH and Relative Humidity (RH) variability are assessed, as well as their impact on the parameterization. The BLH has a strong influence on the correlation of daily and hourly time series, whilst RH effects are less clear and smaller in magnitude. Despite its lower spatial resolution and AOD accuracy, SEVIRI shows higher correlations than MODIS ($r_{SEV} \sim 0.7$, $r_{MOD} \sim 0.6$) with regard to daily averaged PM$_{10}$. Advantages from MODIS arise only at hourly time scales in mountainous locations but lower correlations were found for both sensors at this time scale ($r \sim 0.45$). Moreover, the fraction of days in 2008 with at least one satellite observation was 27% for SEVIRI and 17% for MODIS. These results suggest that the frequency of observations plays an important role in PM monitoring, while higher spatial resolution does not generally improve the PM estimation.
Ground-based Sun Photometer (SP) measurements are used to validate the satellite-based AOD in the study region and to discuss the impact of aerosols' micro-physical properties in the empirical models. A lower error limit of 30 to 60% in the PM$_{10}$ assessment from space is estimated in the study area as a result of AOD uncertainties, variability of aerosols properties and the heterogeneity of ground measurement sites. It is concluded that SEVIRI has a similar capacity to map PM as sensors on board polar-orbiting platforms, with the advantage of a higher number of observations. However, the accuracy represents a serious limitation to the applicability of satellites for ground PM mapping, especially in mountainous areas.

**ASCAT soil wetness index validation through in situ and modeled soil moisture data in central Italy**

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Reliable measurements of soil moisture at global scale might greatly improve many practical issues in hydrology, meteorology, climatology or agriculture such as water management, quantitative precipitation forecasting, irrigation scheduling, etc. Remote sensing offers the unique capability to monitor soil moisture over large areas but, nowadays, the spatio-temporal resolution and accuracy required for some hydrological applications (e.g., flood forecasting in medium to large basins) have still to be met. The Advanced SCATterometer (ASCAT) onboard the Metop satellite (VV polarization, C-band at 5.255 GHz), based on a large extent on the heritage of the ERS scatterometer, provides a soil moisture product available at a coarse spatial resolution (25 km and 50 km) and at a nearly daily time step. This study evaluates the accuracy of the new 25 km ASCAT derived saturation degree product by using in situ observations and the outcomes of a soil water balance model for three sites located in an inland region of central Italy. The comparison is carried out for a 2-year period (2007–2008) and three products derived from ASCAT: the surface saturation degree, $m_s$, the exponentially filtered soil wetness index, SWI, and its linear transformation, SWI*, matching the range of variability of ground data. Overall, the performance of the three products is found to be quite good with correlation coefficients higher than 0.92 and 0.80 when the SWI is compared with in situ and simulated saturation degree, respectively. Considering SWI*, the root mean square error is less than 0.035 m$^3$/m$^3$ and 0.042 m$^3$/m$^3$ for in situ and simulated saturation degree, respectively. More notably, when the $m_s$ product is compared with modeled data at 3 cm depth, this index is found able to accurately reproduce the temporal pattern of the simulated saturation degree in terms of both timing and entity of its variations also at fine temporal scale. The daily temporal resolution and the reliability obtained with the ASCAT derived saturation degree products represent the preliminary step for its effective use in operational rainfall-runoff modeling.
Iso-Kinematic Maps from statistical analysis of PS-InSAR data of Piemonte, NW Italy: Comparison with geological kinematic trends

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SAR interferometry based on Permanent Scatterers (PS-InSAR™) is used here to study the present crustal mobility of a large area of NWItaly, in the Piemonte region. Thirty-eight satellite scenes (ERS SAR), taken from May 1992 to January 2001, were analysed for detecting more than 2 million PS on the study area. Continuous velocity surface maps (Iso-Kinematic Maps: IKM) were obtained from geostatistical and spatial cluster techniques (Hot Spot analysis) of PS “short-period” data, to identify relative ground motions and to compare them with “long-period” tectonic mobility trends, i.e. those inferred at regional scale over geological times (some million years). The comparison was made by individuation of homogeneous kinematic areas, represented in the IKM, and characterization of the boundaries between them (Iso-Kinematic Boundaries: IKB). The IKB were used as tools to assess if the PS-InSAR data on present-day crustal mobility could fit with the distribution of real tectonic structures or field geological elements. IKM were drawn for uplifting geological sectors of Piemonte (Maritime Alps, Gran Paradiso, Langhe) where moderate to very low seismicity is recorded, and gravitational instabilities of rock mass on mountain slopes are widespread. The land sectors have been chosen in order to test the suitability of IKM in very different geomorphological conditions. Different types of correspondence between the IKM and the geological kinematic trend were found: - a first type in which the kinematic trend of short-period (a decade of years, i.e. the PS-InSAR detection time span) is in agreement with a long-period tectonic trend (some million years) and seem to be driven by well known faults subparallel to the IKB. These kinematic trends can be hidden by the slope movement due to gravitational instabilities; - a second type in which the kinematic trend of short-period does not strictly correspond to the longperiod trend, but can be considered as minor-order, uplifting-subsidence cycles, even if in contrast with the long-period kinematic trend. Alternatively, the short-period kinematic trends could reflect the action of deep-seated geological forces or structures, not yet known or inferable (at least with the recorded PSInSAR velocities) on the basis of the available geological data and models.

Clear and cloudy sky investigations using Raman lidar and airborne interferometric measures from the European AQUA Thermodynamic Experiment

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A dataset of ground, airborne and satellite data was measured during the comprehensive 2004
EAQUATE (European AQUA Thermodynamic Experiment) Italian campaign. We have used ground based and airborne data to evaluate the consistency of Raman lidar temperature and humidity profiles with NAST-I (The National Polar-orbiting Operational Environmental Satellite System Airborne Sounder Testbed-Interferometer) spectral radiance measurements in clear conditions, and the consistency of total cloud optical depth measured by the Raman lidar with the same quantity retrieved from NAST-I measurements. Lidar measurement of temperature and humidity profiles can resolve short time changes in mixing ratio due to its high time resolution. Brightness temperature simulations of clear sky, performed using lidar-derived profiles, are within 1 K difference with respect to data when averages over 25 cm\(^{-1}\) and emission from layers below 7 km are considered. High spectral resolution simulations agree with NAST-I measurements with a mean percentage difference less than 0.5% in the whole \(\nu_2\) water vapour band. The simulations in cloudy conditions are based on crystal properties obtained assuming either an appropriate mixture of crystal habits (that for the first time is tested against high spectral resolution measurements) or pristine solid columns. Lidar-derived cloud base and top altitudes and lidar temperature and humidity profiles are exploited, for the first time, as inputs in a recently developed infrared cloud properties retrieval procedure. Total cloud optical depths, retrieved from 800 to 980 cm\(^{-1}\) NAST-I radiances, have values that, when converted to short-wave wavelengths, are in the range 0.05–2.2 and agree with lidar measurements to within experimental errors. A closer agreement is obtained with the mixture of habits. Simulated high resolution brightness temperatures based on retrieved cloud parameters (optical depths and effective dimensions) are compared with measured values in all the atmospheric windows covered by the NAST-I sensor. The agreement obtained in the 800–980 cm\(^{-1}\) interval is generally better for the mixture of habits, but solid columns produce smaller residuals in the 2000–2150 and 2400–2600 cm\(^{-1}\) spectral intervals. Uncertainties related to the surface properties (i.e. skin temperature) are recognized to be the main sources of error in the infrared retrieval of cloud properties and affect the comparison between forward simulations and NAST-I data in all the infrared window bands not used for the inverse problem.

**Mapping Burned Areas in a Mediterranean Environment Using Soft Integration of Spectral Indices from High-Resolution Satellite Images**

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This article presents a new method for burned area mapping using high-resolution satellite images in the Mediterranean ecosystem. In such a complex environment, high-resolution satellite images represent an appropriate data source for identifying fire-affected areas, and single postfire data are often the only available source of information. The method proposed here integrates several spectral indices into a fuzzy synthetic indicator of likelihood of burn. The indices are interpreted through fuzzy membership functions that have been derived with a partially data-driven approach exploiting training data and expert knowledge. The final map of fire-affected areas is produced by applying a region growing algorithm on the basis of seed pixels selected on a conservative threshold of the synthetic fuzzy score. The algorithm has been developed and tested on a set of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes acquired...
over Southern Italy. Validation showed that the accuracy of the burned area maps is comparable or even better [overall accuracy (OA) > 90%, K > 0.76] than that obtained with approaches based on single index thresholds adapted to each image. The method described here provides an automatic approach for mapping fire-affected areas with very few false alarms (low commission error), whereas omission errors are mainly related to undetected small burned areas and are located in heterogeneous sparse vegetation cover.

**Comparison of global inventories of CO emissions from biomass burning derived from remotely sensed data**

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We compare five global inventories of monthly CO emissions named VGT, ATSR, MODIS, GFED3 and MOPITT based on remotely sensed active fires and/or burned area products for the year 2003. The objective is to highlight similarities and differences by focusing on the geographical and temporal distribution and on the emissions for three broad land cover classes (forest, savanna/grassland and agriculture). Globally, CO emissions for the year 2003 range between 365 Tg CO (GFED3) and 1422 Tg CO (VGT). Despite the large uncertainty in the total amounts, some common spatial patterns typical of biomass burning can be identified in the boreal forests of Siberia, in agricultural areas of Eastern Europe and Russia and in savanna ecosystems of South America, Africa and Australia. Regionally, the largest difference in terms of total annual amounts (CV>100%) and seasonality is observed at the northernmost latitudes, especially in North America and Siberia where VGT appears to overestimate the area affected by fires. On the contrary, Africa shows the best agreement both in terms of total annual amounts (CV =31%) and of seasonality despite some overestimation of emissions from forest and agriculture observed in the MODIS inventory. In Africa VGT provides the most reliable seasonality. Looking at the broad land cover types, the range of contribution to the global emissions of CO is 64–74%, 23–32% and 3–4% for forest, savanna/grassland and agriculture, respectively. These results suggest that there is still large uncertainty in global estimates of emissions and it increases if the comparison is carried by out taking into account the temporal (month) and spatial (0.5° ×0.5°cell) dimensions. Besides the area affected by fires, also vegetation characteristics and conditions at the time of burning should also be accurately parameterized since they can greatly influence the global estimates of CO emissions.
Operational Monitoring of Daily Crop Water Requirements at the Regional Scale with Time Series of Satellite Data

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This work presents a simple, cost-effective, and operational approach to monitor crop water requirements at the regional scale for water management and monitoring purposes. The recommended Food and Agricultural Organization of the United Nations methodology (FAO-56) calculates crop evapotranspiration using crop-specific coefficients (Kc), which vary according to the crop type, health, and phenological stage. This approach, though widely applied for irrigation planning, cannot always match the appropriate crop coefficient with the actual crop phenological stage and health condition, especially in anomalous situations. Previous research demonstrated that crop coefficients and spectral vegetation indexes are correlated. Recent studies have used this relationship with high-resolution satellite data from different sensors to provide information to irrigation advisory services. However, high-resolution data are not feasible for an operational and routine monitoring of water consumption and needs. This paper tests the usefulness of time series of coarse resolution satellite data such as those collected by the moderate-resolution imaging spectroradiometer (MODIS) sensor, to monitor crop coefficients temporal and spatial variability and therefore crop water needs at the regional scale taking advantage of the peculiar characteristics offered by MODIS in terms of high temporal resolution and preprocessed products availability. The outlined methodology takes into account the actual growing stage of the crops and nearly real-time vegetation variations, overcoming some limitations of the traditional FAO approach while preserving the maximum operability. The analysis was carried out in the South Milan agricultural area on data referring to 2003 and 2004. The results agreed with those of other studies and proved to be able to account for the anomalous conditions of the summer in 2003. These results were then compared with those obtained using the traditional FAO crop coefficient curves built with data collected during field campaigns in the same years in rice fields. Constraints, limitations, and possible uses are discussed.

In situ measurements and satellite remote sensing of case 2 waters: first results from the Curonian Lagoon

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In this study we present calibration/validation activities associated with satellite MERIS image
processing and aimed at estimating chl a and CDOM in the Curonian Lagoon. Field data were used to validate the performances of two atmospheric correction algorithms, to build a band-ratio algorithm for chl a and to validate MERIS-derived maps. The neural network-based Case 2 Regional processor was found suitable for mapping CDOM; for chl a the band-ratio algorithm applied to image data corrected with the 6S code was found more appropriate. Maps were in agreement with in situ measurements. This study confirmed the importance of atmospheric correction to estimate water quality and demonstrated the usefulness of MERIS in investigating eutrophic aquatic ecosystems.

**Application of remote sensing in water resource management: the case study of Lake Trasimeno, Italy**

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Satellite multi-sensor data were used to investigate the evolution in time and space of Lake Trasimeno, a shallow and turbid lake in central Italy. Large-swath MERIS and MODIS sensors were proposed for regular broad scale monitoring of water quality, having compared the retrieved chlorophyll-a (Chl-a) concentration, Secchi disk (SD) depth and surface water temperature with the 2005–2008 time-series of the in situ data. Although, in a shorter time span, also the MERIS-derived total suspended matter (TSM) matched the in situ data. MERIS-derived water quality products confirmed the meso-eutrophic conditions of Lake Trasimeno (average Chl-a = 8.5 mg/m³) and the low levels of transparency (average SD = 1 m). A negative correlation found between water levels and Chl-a suggest the importance of maintaining water levels as close as possible to the hydrometric zero. A spatial analysis of TSM also reveals how small tributaries may affect the load of suspended solids in the southern part of the lake. Higher spatial resolution satellite images were exploited both to describe land use/cover transformation from 1978 to 2008 and to assess the recent changes in macrophyte colonisation patterns. Land cover change detection analysis results showed a decrease in cultivated areas starting from the early Nineties and the subsequent increase in unproductive terrain (bare land and pastures) and natural woods as well as the changing fragmentation of agricultural areas through time. A reduction in macrophyte beds from 2003 to 2008 was also observed. We expect the results of this study to support local water authorities in redrawing the management plan of Lake Trasimeno.

**Remote sensing of suspended particulate matter in Himalayan lakes: a case-study of alpine lakes in the Mount Everest region**

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This study presents satellite data and in situ measurements to estimate the concentration of suspended solids in high-altitude and remote lakes of the Himalayas. Suspended particulate matter (SPM) concentrations measured in 13 lakes to the south of Mount Everest (Nepal) in October 2008 and reflectance values of the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) onboard ALOS, acquired a few days after the fieldwork activities concluded, were combined to build a relationship ($R^2 = 0.921$) for mapping SPM concentrations in lakes of the Mount Everest region. The satellite-derived SPM concentrations were compared with in situ data ($R^2 = 0.924$) collected in the same period in 4 additional lakes, located to the north of Mount Everest (Tibet, China). The 13 water samples collected in lakes in Nepal were also used to investigate the absorption coefficients of particles $a_p(\lambda)$ and colored, dissolved organic matter $a_{CDOM}(\lambda)$, with the aim of parameterizing a bio-optical model. An accurate model ($R^2 = 0.965$) to estimate SPM concentrations from $a_p(\lambda)$ was found and could be adopted in the future for retrieving suspended solids from satellite imagery independently of ground measurements. In such a remote area, remote sensing was demonstrated to be a suitable tool to characterize the state of lakes, whose loads of suspended solids might be assumed to be direct and quick-responding indicators of deglaciation processes and glacier-lake interactions. As a macrodescriptor of water quality, the assessment of SPM in glacial lakes of the Himalayas might also be of interest for resource use in the downstream region.

A regional snow-line method for estimating snow cover from MODIS during cloud cover

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The objective of this study is to propose and evaluate a method for snow cover mapping during clouds using the daily MODIS/Terra snow cover product. The proposed SNOWL approach is based on reclassifying pixels assigned as clouds to snow or land according to their relative position to the regional snow-line elevation. The accuracy of the SNOWL approach is evaluated over Austria, using daily snow depth measurements at 754 climate stations and daily MODIS/Terra images in the period July 2002–December 2005. The results indicate that the SNOWL method provides a robust snow cover mapping over the entire region even if the MODIS/Terra cloud cover is as large as 90%. Cloudiness is decreased from 60% (MODIS/Terra) to 10% (SNOWL) without hardly any change in mapping accuracy. Sensitivity analyses indicate that the estimation of the regional snow-line elevation is particularly sensitive to the misclassification of cirrus clouds as snow in the period between May and October.
Dis-aggregation of airborne flux measurements using footprint analysis

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Aircraft measurements of turbulent fluxes are generally being made with the objective to obtain an estimate of regional exchanges between land surface and atmosphere, to investigate the spatial variability of these fluxes, but also to learn something about the fluxes from some or all of the land cover types that make up the landscape. In this study we develop a method addressing this last objective, an approach to disentangle blended fluxes from a landscape into the component fluxes emanating from the various land cover classes making up that landscape. The method relies on using a footprint model to determine which part of the landscape the airborne flux observation refers to, using a high resolution land cover map to determine the fractional covers of the various land cover classes within that footprint, and finally using multiple linear regression on many such flux/fractional cover data records to estimate the component fluxes. The method is developed in the context of three case studies of increasing complexity and the analysis covers three scalar fluxes: sensible and latent heat fluxes and carbon dioxide flux, as well as the momentum flux. A basic assumption under the dis-aggregation method is that the composite flux, i.e. the landscape flux, is a linear average of the component fluxes, i.e. the fluxes from the various land elements. We test and justify this assumption by comparing linear averages of component fluxes in simple ‘binary landscapes’, weighted by their relative area, with directly aircraft observed fluxes. In all case studies dis-aggregation of mixed values for fluxes from heterogeneous areas into component land cover class specific fluxes is feasible using robust least squares regression, both in simple binary ‘landscapes’ and in more complex cases. Both the differences between land cover classes and the differences between synoptic conditions can be resolved, for those land cover classes that make up sufficiently large fractions of the landscape. The regression F-statistic and the closely associated p-values are good indicators for this latter prerequisite and for other sources of uncertainty in the dis-aggregated flux estimates that render it meaningful or not. An analysis of the effect of various sources of errors in input data, footprint estimates and of skewed land cover class distributions is presented. A validation of flux estimates obtained through the dis-aggregation method against independent ground data proved satisfactorily. Recommendations for the use of the method are given as are suggestions for further development.
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