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Application of terrestrial laser scanner to cyclostratigraphy

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Application of Terrestrial Laser Scanner to cyclostratigraphy

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*...questo grandissimo libro [...] /
io dico l'universo [...] è scritto
in lingua matematica...*

Galileo Galilei
Il Saggiatore, 1623

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Extended abstract

Introduction

IN order to be reliable, cyclostratigraphic studies need to be founded on the analysis of large, high resolution datasets, that describe long and continuous sections [Hinnov, 2000]. The longer is the studied section and the higher is the resolution in the measurement of a certain attribute (e.g. facies distribution, bed thickness, stable isotope ratios) along the section, the higher is the chance to recognize cyclicities in that attribute and potentially find in it the clue of the influence of Milankovian periodicities.

These requirements are not easy to match, since it is difficult to find long and continuous sections, and the difficulty increases going back into the geological past because geological record becomes progressively more fragmentary. If a long and almost continuous section is available, a difficulty that often arises is the long time that traditional methods (e.g. facies analysis, chemical analyses) take to collect the needed high resolution dataset.

In an attempt to find a solution for these problems, in this thesis the potential of application of Terrestrial Laser Scanner to cyclostratigraphic studies is discussed and a new method of collection of high resolution geological data is proposed.

Terrestrial laser scanner (TLS)

TLSs are instruments that provide the spatial position of a large number of physical points distributed on the surface of an observed object. These points make up the so-called point cloud in which each point is characterized by spatial coordinates and measured intensities, where the intensity associated is the power carried by the backscattered component of the laser pulse and is proportional to the reflectance of the target. TLS offers high resolution and high accuracy of measurement and the possibility to scan and analyze targets in remote without perspective deformations. Moreover, scans are not influenced by the illumination conditions of the target because TLS are instruments that operate with an active sensor (i.e. a laser source).

In the study presented here a Optech ILRIS 3D6 TLS was used (standard deviation (STD) = ~ 7 mm at 50 m distance, actual resolution = 17.7 mm [Lichti and Jamtsho, 2006]). Acquisition time varies in function of the area to scan and of the desired resolution, but in general can be considered very fast. As an example, less than 15 minutes were necessary to acquire a 12 m $\times$ 7 m surface with 8 mm sampling step generating 1.3 million points.

TLS intensity study

Differences in intensity values are often visible in point clouds; they are related to several factors like roughness and geometry of acquisition (e.g. distance and angle of incidence, [Reschetyuk, 2006]) but also depend on the interaction between laser light (of a certain wavelength) and the material that make up the target [Lu et al., 2005]. In particular, if an outcrop constituted of limestones and marls is scanned with an Optech ILRIS 3D scanner ($\lambda = 1535$ nm), marls systematically show lower intensity values. This empiric observation is in accordance with the fact that in the SWIR (Short Wave InfraRed) band reflectance is highly influenced by absorption induced by the presence of H₂O-bearing clay minerals [Hunt and Salisbury, 1970, Clark, 1999].

The link between intensity and geological parameters was studied in order to verify if it is possible to obtain semi-quantitative lithological information from TLS data. Results point out that a linear inverse relationship exists between intensity and clay content in limestones and marls. A series of experiments has been carried out dealing with the influence of geometrical (in particular, distance of acquisition) and environmental (e.g. moisture) conditions. Original Matlab scripts were developed for the correction of intensities in function of the distance of acquisition, fundamental pre-processing phase before the interpretation of data. In-depth study on the influence of lithology has been then carried out.

The study of the intensity recorded scanning artificial targets of limestone and clay allowed to confirm that values stored by ILRIS 3D are influenced by the mineralogy of the target, since clay showed intensities $\sim 30\%$ lower than the limestone due to the reflectance minimum of clay minerals in the infrared band [Clark, 1999]. Moreover, it was demonstrated that the moistening of the targets does not cancel the mineralogical signal since clays show intensities lower than limestones both in wet and dry conditions. This suggested that the intensity data can be studied also in scans obtained in field conditions, where a natural moisture is often present.

The section of Nomi (neighbourhood of Trento, Southern Alps, Italy) which encompasses part of the Lower Jurassic Rotzo Formation [Avanzini et al., 2007, Barbieri and Grandesso, 2007] was chosen to test in the field TLS's intensity sensitivity to variations of the clay content in marls and limestones. The outcrop is characterized by limestone-marl alternations and appears as a nearly vertical wall with planar, well recognizable bedding of nearly constant thickness. Rock samples were collected at progressive stratigraphic heights within the area of TLS acquisitions. On the basis of TLS data related to the Nomi section, the distributions of the intensities were computed for each sampled layer and the modes of the probability distribution functions were considered as characteristic intensities for each layer. A series of CHNS (carbon, hydrogen, nitrogen and sulphur gas-chromatographic ana-

lyzer) analyses were carried out on the samples in order to obtain an estimate of the clay content in different layers. With this elemental analysis is possible to estimate the amount of H contained in a rock from dried and crushed samples (5-10 mg). The obtained percentage in weight of the element was considered proportional to the clay content in the studied lithotypes.

Comparison between reflectance values derived from TLS acquisition of an outcrop and the clay abundance curves obtained from CHNS analysis of rock samples taken from the same stratigraphic section shows that there is a linear inverse relationship between reflectance and the abundance of clay minerals in the considered rocks. Humidity greatly influence intensity particularly in the case of ILRIS instrument, whose wavelength ($\lambda = 1535$ nm) corresponds to a strong water-related absorption peak. For this reason, the effects of surface and interstitial humidity on the intensity of the considered lithotypes (limestones, marls and marly limestones) were studied. Results pointed out that even if it is not possible to associate an absolute value of clay abundance to a certain value of intensity, it is always possible to distinguish between marls and limestones and appreciate relative differences calibrating the intensity on a case by case base.

Reflectance series

Reflectance series obtained from TLS data are proposed as a tool to evaluate the variation of clay content along a stratigraphic section constituted by limestones and marls. The possibility to evaluate the fluctuations of clay abundance is particularly important in a cyclostratigraphic perspective since these changes represent variations in sediment supply that can be linked to Milankovitch periodicities. Reflectance series can be considered a stratigraphic log in which reflectance values are associated with the correspondent stratigraphic heights. A reflectance series is obtained projecting the TLS generated points describing a stratigraphic section on a line perpendicular to the average dip of the layers and averaging intensity values within a selected range of stratigraphic heights.

Cyclostratigraphic study of reflectance series

In order to verify the possibility to use reflectance series generated from TLS data in cyclostratigraphic analyses the methodology was tested on previously studied stratigraphic sections.

A section in the Paleocene "Scaglia Rossa" of the South Ardo river section [Agnini et al., 2005] in the Belluno Basin (Southern Alps, Italy) was considered. This section was chosen because of its prominent lithological alternations, already interpreted as Milankovitch-driven in a nearby section [Poletti et al., 2004], moreover, good biochronostratigraphic constraints are available [Giusberti et al., 2007]. The study of South Ardo river section reflectance series points out the presence of strong composite periodicity in the reflectance values associated with the limestone-marl couplets. The power spectrum shows a prominent peak, recognizable between 4 and 5 cycles/m, which represents the thickness encompassed by the limestone-marl couplets. If this peak is interpreted as the obliquity signal, other peaks are present at frequencies which ratios match those of eccentricity, short and long precession with obliquity. These evidences further support the interpretation of a Milankovian (obliquity) origin of the lithological alternations as identified by TLS acquisitions.

The second considered case study is the Contessa quarry section (Gubbio, central Apennines, Italy) where the Aptian-Albian Marne a Fucoidi Formation outcrops. Also in this case the section is constituted by a clear alternation of marls and limestones. The stratigraphic interval represented by the Marne a Fucoidi have been studied in the past from a sedimentological point of view [Calesini, 1981, Tateo et al., 2000] and has very good bio-chronostratigraphic [Silva and Silter, 1995] constrains, moreover, the Formation was studied from a cyclostratigraphic point of view [Grippo et al., 2004]. The time series analysis of the reflectance series, which encompasses ~ 40 m of the section was carried out. Evolutionary spectrum highlights high spectral power at ~ 2 cycles/m. This is in accordance with previous work in which this frequency was linked to the short eccentricity (~ 100 kyr).

Moreover, some new features were highlighted. In the evolutionary spectrum, at ~ 2 cycles/m two spectral lines with roughly parallel trend are evident and can be followed throughout the entire section. Shifts in the frequency of the spectral lines are visible, suggesting variable sedimentation rates. In the lower part the look of the spectral lines is chain-like in analogy with what can be observed in the evolutionary spectrum obtained from the time series analysis of the standard ETP curve [Laskar, 1990, Paillard et al., 1996].

Conclusions

Experimental results suggest that TLS surveying can supply information on relative clay abundance in marls and limestones, providing a remote sensing technique to retrieve quickly high resolution lithological data even from inaccessible outcrops. The obtained information is placed in the 3D space allowing a precise characterization of complex surfaces, without the problem of perspective deformations.

Reflectance series are proposed as a way to represent variations of intensity, and then relative variations of clay abundances, along a scanned stratigraphic section constituted mainly of marls and limestones.

The results obtained in the study of cyclicities in the reflectance series of the Ardo and Contessa sections, encompassing stratigraphic intervals previously characterized from a cyclostratigraphical point of view, constitute an encouraging confirmation of the potential of TLS in providing data suitable for cyclostratigraphic analysis.

The presence of the couplet spectral line in the Contessa evolutionary spectrum as well as its analogy with the spectrum of the standard ETP curve further support the orbital origin of the signal that apparently include two close components of eccentricity. The possibility of following the spectral lines throughout the entire section also constitutes a confirmation of this interpretation.

These evidences confirm that TLS can give geological informations suitable of cyclostratigraphic study, opening new perspectives of research in cy-

clostratigraphy, allowing to take advantage of long range, high resolution and rapidity in data acquisition offered by these instruments.

Riassunto

Introduzione

Lo studio di sezioni stratigrafiche lunghe e continue da cui sia possibile ricavare dati ad alta risoluzione permette di effettuare analisi ciclostratigrafiche valide e aumenta l'affidabilità dei risultati eventualmente ottenuti [Hinnov, 2000]. Infatti, più lunga è la sezione considerata e maggiore è la risoluzione con cui un determinato carattere geologico (p. es. distribuzione delle facies, serie di spessori, analisi isotopiche), maggiore è la possibilità di individuare eventuali ciclicità che potrebbero poi essere interpretate come dovute ad oscillazioni dei parametri orbitali terrestri (ciclicità milankoviane). In particolar modo, lo studio di sezioni lunghe permette, in parte, di ovviare al problema di eventuali disturbi che possono a luoghi mascherare il segnale ciclico. Gli effetti di disturbi locali, che possono essere particolarmente deleteri se la sezione è corta, risultano invece attenuati in serie lunghe.

Le sezioni lunghe e continue non sono tuttavia molto abbondanti e non sono facili da trovare. Inoltre, anche avendo la fortuna di avere a disposizione una sezione con le caratteristiche desiderate, si possono incontrare seri problemi operativi, logistici e di sicurezza dal momento che, sovente, le migliori esposizioni si trovano in corrispondenza di pareti poco o punto accessibili. I metodi di studio tradizionale, quali analisi di facies, raccolta di campioni per analisi isotopiche o misura manuale degli spessori degli strati, possono essere applicati quando è possibile toccare con mano l'affioramento e dunque

sono di difficile utilizzo in parete. I costi in termini di tempo e denaro, poi, aumentano all'aumentare dello spessore stratigrafico che si vuole considerare e alla risoluzione che si desidera raggiungere. Infine, altro problema connesso alla reperibilità di sezioni lunghe e continue è che, è mano a mano che si considerano tempi geologici più antichi, il record stratigrafico diviene via via più frammentario.

In questa tesi viene discussa la possibile applicabilità del laser scanner terrestre (TLS) a studi ciclostratigrafici, mirata a cercare di trovare delle risposte ad alcuni dei problemi citati. In particolare vengono presentati i risultati dello studio, dell'implementazione e della validazione di un nuovo metodo per l'acquisizione di dati geologici ad alta risoluzione, atti ad essere studiati da un punto di vista ciclostratigrafico.

Il laser scanner terrestre (TLS)

I TLS sono strumenti che operano secondo i principi del radar. Un impulso laser è diretto sull'oggetto che si intende analizzare e poi si registra il segnale di ritorno. In questo modo viene determinata la posizione spaziale del punto in cui il raggio ha colpito l'oggetto. Il processo avviene in maniera iterativa e il risultato è una nuvola di punti che descrive in tre dimensioni la morfologia superficiale del bersaglio. Ciascun punto di una nuvola di punti è caratterizzato dalle sue coordinate tridimensionali rispetto al sistema di riferimento del laser, espresse sotto forma cartesiana o polari, e da un valore di intensità relativo alla potenza del raggio di ritorno. Le riprese laser scanner sono caratterizzate da elevata accuratezza ed alta risoluzione, inoltre possono essere ripresi oggetti lontani (anche diverse decine di metri) dallo strumento ottenendo una rappresentazione tridimensionale e quindi non soggetta a deformazioni prospettiche. Infine, dal momento che i laser sono sensori attivi le condizioni di illuminazione non influenzano il risultato di una ripresa TLS.

Nel lavoro qui presentato è stato utilizzato il laser scanner Optech Ilris 3D (a 50 m deviazione standard (STD) = ~ 7 , risoluzione effettiva 17.7 mm). Si tratta di un laser scanner appartenente alla tipologia "in tempo di volo".

In questa categoria di laser scanner la distanza dal bersaglio, adifferenze di quanto accade nei triangolatori in cui è determinata con metodi trigonometrici, viene calcolata misurando il tempo trascorso tra l'invio di un'impulso e l'arrivo dell'impulso di ritorno (che deve avere una potenza maggiore di una certa soglia per essere registrato) e moltiplicandola per la velocità della luce. I laser scanner a tempo di volo sono quelli che vengono utilizzati per riprese a grandi distanze, dal momento che hanno portate che possono essere anche di diverse centinaia di metri. Per questa ragione sono anche quelli maggiormente impiegati nelle Scienze della Terra. I tempi di acquisizione variano in funzione delle caratteristiche tecniche dello strumento, dall'area che deve essere ripresa e dalla risoluzione desiderata, ma possono essere generalmente considerati molto rapidi. Nel caso dell'Iris 3D, per la ripresa di una superficie di $12\text{ m} \times 7\text{ m}$ con un passo di campionamento di 8 mm, sono necessari 15 minuti e ne risulta una nuvola di 1.3 milioni di punti.

Studio dell'intensità registrata dal TLS

Come già detto, oltre al dato geometrico, a ciascun punto di una nuvola di punti è associato un valore di intensità. Le differenze in questi valori sono dovute a numerosi fattori, quali la scabrezza della superficie, la distanza del punto di ripresa dall'oggetto in esame e l'angolo di incidenza del raggio laser con la superficie dell'oggetto [Reschetyuk, 2006], ma sono anche legate al fatto che materiali diversi interagiscono in maniera diversa con la radiazione elettromagnetica, a seconda della lunghezza d'onda di quest'ultima [Lu et al., 2005]. Ciò è evidente osservando la scansione, effettuata con il laser Iris 3D, di un affioramento roccioso costituito da calcari e marne. I punti che descrivono le parti marnose presentano sistematicamente una intensità minore di quella dei punti posizionati sulle parti calcaree. Tenendo conto che il laser dell'Iris 3D opera nell'infrarosso vicino (SWIR = Short Wave InfraRed), questa osservazione trova fondamento nello studio degli spettri di riflettanza. Le lunghezze d'onda in questa banda ed in particolare quelle attorno ai 1400-1500 nm (L'Iris opera a 1535 nm) presentano elevati livelli

di assorbimento da parte dei minerali argillosi per la presenza di H_2O nel reticolo cristallino di questi [Hunt and Salisbury, 1970, Clark, 1999].

L'intensità registrata dal TLS è stata studiata per comprendere meglio il legame tra intensità e litologia al fine di verificare la possibilità di ottenere dai dati laser scanner informazioni semi quantitative sulle caratteristiche litologiche delle rocce sedimentarie. I risultati ottenuti mettono in luce un rapporto di proporzionalità inversa tra l'intensità e il contenuto in argilla in marne e calcari.

L'influenza di parametri quali le caratteristiche geometriche dell'acquisizione (con particolare riferimento alla distanza), la temperatura ambientale e l'umidità è stata studiata in una serie di esperimenti. E' stato messa appunto una metodologia operativa volta a consentire l'interpretazione dei dati in chiave geologica. In particolare sono stati messi a punto script in ambiente Matlab al fine di effettuare la correzione dei dati di intensità in funzione della distanza tra strumento e bersaglio.

Conferma che la mineralogia è in grado di influenzare l'intensità registrata dall'Iris 3D è stata data dal fatto che nella scansione di bersagli artificiali costituiti da calcare ed argilla i secondi mostrano intensità inferiori di circa il 30% rispetto a quelle ottenute sui calcari, in linea con quanto ottenuto in analisi spettroscopiche [Clark, 1999].

La possibilità di ottenere informazioni sul carattere litologico dalle intensità laser scanner è stata studiata sul terreno nella sezione stratigrafica di Nomi (Valle dell'Adige, Trento, Italia) in cui affiora una porzione della Formazione di Rotzo, di età Giurassica inferiore [Avanzini et al., 2007, Barbieri and Grandesso, 2007]. La sezione è costituita da alternanze di marne, calcari, calcari argillosi e argille in strati da centimetrici a decimetrici, con spessore e giacitura costante. Da campioni raccolti a progressive altezze stratigrafiche sono state ottenute, tramite analisi cromatografica CHNS, le stime sul contenuto in argilla nei livelli campionati (per fare ciò il contenuto in idrogeno è stato considerato proporzionale al contenuto in argilla). La sezione è stata poi ripresa con il laser scanner e sono state calcolate le distribuzioni dei valori

di intensità su ciascuno strato preso in esame. La moda delle distribuzioni è stata considerata intensità caratteristica dello strato corrispondente. Il confronto tra i valori di intensità caratteristiche e i rispettivi contenuti in argilla mette in evidenza una relazione di proporzionalità lineare inversa tra i due valori. È stata studiata anche l'influenza dell'umidità superficiale sull'intensità registrata dall'Iris 3D, dal momento che l'acqua provoca un forte assorbimento nella banda del laser ($\lambda = 1535 \text{ nm}$). I risultati hanno dimostrato che la presenza di umidità non provoca un azzeramento delle differenze di riflettanza tra litologie diverse, in altre parole, il segnale mineralogico è preservato. D'altra parte la forte influenza dell'umidità e di molti altri fattori sul dato di intensità che si riferisce pur sempre alla sola superficie del bersaglio rendono impossibile associare un valore assoluto di abbondanza dell'argilla a un'intensità. Se una calibrazione vuole essere effettuata deve essere realizzata di volta in volta. Le variazioni relative di intensità rimangono comunque apprezzabili.

Questi risultati rendono sensato il tentativo di studiare le intensità con le metodologie proprie della ciclostratigrafia.

Serie di riflettanza

Il fatto che le intensità siano correlabili in maniera semi-quantitativa al contenuto in argilla di marne e calcari presenta risvolti particolarmente importanti nell'ottica di un utilizzo del TLS in ciclostratigrafia. Il contenuto in argilla, infatti, è un parametro sedimentario che dipende da variazioni nel regime di sedimentazione che possono essere influenzate dai cicli milankoviani. Lo studio delle variazioni del contenuto in argilla in una sezione stratigrafica può dunque mettere in luce tali ciclicità. Al fine di analizzare da un punto di vista ciclostratigrafico le intensità fornite dal laser scanner serviva un modo per poter valutare l'andamento delle intensità lungo una sezione stratigrafica scelta. Le serie di riflettanza sono qui proposte come uno strumento atto a rappresentare le variazioni dell'intensità (cioè di contenuto argilloso) lungo sezioni stratigrafiche costituite da marne e calcari. Una serie di riflet-

tanza è ottenuta a partire da una nuvola di punti proiettando i punti su una retta perpendicolare alla giacitura media degli strati e mediando le intensità ad altezze stratigrafiche progressive in intervalli costatanti scelti. In questo modo una serie di riflettanza può essere considerata un log stratigrafico che associa ad una certa altezza stratigrafica un valore di intensità. Trattandosi di una serie storica una serie di riflettanza può essere studiata con i metodi dell'analisi tempo-frequenza.

Studio ciclostratigrafico delle serie di riflettanza

La metodologia messa a punto è stata testata su due sezioni in cui affiorano intervalli stratigrafici precedentemente caratterizzati da un punto di vista ciclostratigrafico. In tal modo si è inteso verificare l'effettiva possibilità di utilizzare in ciclostratigrafia i dati ottenuti tramite riprese laser scanner.

La prima sezione considerata si trova nella gola del torrente Ardo (Belluno, Italia) [Agnini et al., 2005]. Nella sezione sono rappresentate rocce appartenenti al dominio paleogeografico del Bacino di Belluno, in particolare affiora la Scglia Rossa (s.l) di età paleocenica. L'intervallo affiorante comprende il limite tra le biozone NP4 e NP5 [Giusberti et al., 2007] ed è caratterizzato da una spiccata alternanza di calcari e marne in strati tabulari di spessore decimetrico. Il medesimo intervallo stratigrafico è già stato studiato da un punto di vista ciclostratigrafico nella vicina sezione di Ponte nelle Alpi [Poletti et al., 2004] ed è inoltre dotato di ottimo inquadramento biostratigrafico. Lo studio della serie di riflettanza della sezione del torrente Ardo mette in risalto una forte ciclicità composita nei valori di intensità registrati dal TLS ed associati alle coppiette marna-calcare. L'analisi di Fourier della serie evidenzia un picco ad elevata potenza a frequenze tra i 4 e i 5 cicli/metro. Se si attribuisce il picco alla precessione lunga altri picchi sono presenti alle frequenze a cui dovrebbero apparire i segnali precessione breve e obliquità. Ulteriore conferma dell'origine delle alternanze emerge contando le coppie presenti nei tre metri superiori della zona NP4 tra la prima comparsa di *Sphenolithus spp.* e la prima comparsa di *Fasciculithus spp.* [Agnini

et al., 2005]. L'intervallo di tempo rappresentato attribuendo le coppie alla precessione lunga risulta di 370 kyr in accordo con la durata ottenuta dai dati biostratigrafici [Agnini et al., 2007].

La seconda sezione scelta è quella della cava Contessa (Gubbio, Appennino centrale, Italia). Nella sezione affiora nella sua interezza la Formazione delle Marne a Fucoidi (Aptian-Albiano), essenzialmente costituita da alternanze di calcari e marne. La Formazione è stata studiata in passato sia da un punto di vista sedimentologico [Calesini, 1981, Tateo et al., 2000] che biostratigrafico [Silva and Silter, 1995], inoltre, è stata sottoposta ad analisi ciclostratigrafica [Grippo et al., 2004]. L'analisi dello spettro evolutivo della serie di riflettanze (~ 40 m) ottenuta dalla scansione laser della sezione mette in risalto elevata potenza spettrale a ~ 2 cicli/m, in accordo con quanto riscontrato negli studi precedenti che interpretano questa frequenza come il segnale dell'eccentricità [Grippo et al., 2004]. Emergono anche elementi di novità. Nello dello spettro evolutivo a ~ 2 cicli/m sono visibili due linee spettrali che possono essere seguite in tutta la sezione con andamento grosso modo parallelo, sia pur con spostamenti in frequenza che suggeriscono la presenza di tasi di sedimentazione variabili. Nella parte iniziale le linee spettrali sono molto ravvicinate e assumono un aspetto "a catena". Lo stesso andamento nell'eccentricità è stato riscontrato da [Cozzi et al., 2005] nello spettro evolutivo della curva ETP standard [Laskar, 1990, Paillard et al., 1996] ed è attribuito alla presenza dei segnali di eccentricità lunga e breve.

Conclusioni

I risultati sperimentali suggeriscono che il TLS fornisce un dato di intensità che è legato a caratteri geologici. In particolare in marne e calcari è possibile legare le variazioni in intensità a variazioni dell'abbondanza in argilla. Il laser scanner, dotato di elevata portata, è quindi in grado di dare informazioni litologiche su affioramenti inaccessibili o di difficile accesso con il vantaggio, dato dal carattere tridimensionale delle misure, di poter caratterizzare in remoto, senza deformazioni prospettiche, superfici complesse.

Le serie di riflettanza sono proposte come una rappresentazione delle variazioni di intensità e quindi di abbondanza in argilla lungo una sezione stratigrafica costituita da calcari e marne.

I risultati dello studio, tramite analisi di Fourier, delle serie di riflettanza ottenute dalla scansione delle sezioni del torrente Ardo e della Contessa, dove affiorano intervalli stratigrafici precedentemente caratterizzati da un punto di vista ciclostratigrafico, sono in linea con quanto riscontrato in bibliografia e costituiscono una incoraggiante conferma della potenzialità del TLS di fornire dati utili per la ciclostratigrafia. Elementi di novità emergono dallo studio dello spettro evolutivo della serie della Contessa. Nella parte iniziale della sezione si riconosce una coppia di linee spettrali ad andamento analogo a quello del segnale dell'eccentricità nello studio della curva ETP standard. La coppia, ad andamento subparallelo, è visibile in tutta la sezione, pur con variazioni di frequenza imputabili a variazioni nel tasso di sedimentazione. Questi elementi confermano l'interpretazione che associa all'eccentricità il segnale rilevato e sembrano evidenziare le due componenti, lunga e breve, di questo parametro orbitale.

Le conferme ottenute aprono nuove ed interessanti prospettive nell'applicazione del TLS a studi ciclostratigrafici.

Introduction

1.1 Elements of cyclostratigraphy

CYCLOSTRATIGRAPHY studies the cyclicities in sedimentary successions due to the influence of oscillations of Earth's orbital parameters on sedimentation. These oscillations can induce global climatic or eustatic changes that can be recorded by sediments.

The hypothesis of an influence of orbital parameters on sedimentary processes had his origin at the end of the XIX century. Gilbert (1895) studied the Cretaceous successions of Colorado (USA) and interpreted the rhythmic character of the layering as orbitally-driven. On the basis of his observations, Gilbert estimated the duration of the lower Cretaceous obtaining results that are in agreement with those of the present geochronological time scales. Milankovitch [Milankovitch, 1941] gave a mathematical basis to the theory of the influence of orbital parameters on the glaciations. The validity of this approach has been later confirmed by several studies [Hays et al., 1976, Imbrie et al., 1984]. Now it is universally accepted that variations in the amount of incoming solar radiation, caused by the variation of the position of the Earth with respect to the Sun, result in climatic changes that can be recorded in sediments.

The way in which the variations of insolation (i.e. incoming solar radia-

tion) caused by Earth's orbital parameters are recorded as stratigraphic signals is very complex and will not be treated here (a summary can be found in [Crowley and North, 1991, Allen and Anderson, 1993, Bradley, 1999]). However, the main orbital parameters which influence sedimentation (i.e. are able to force the way the sediments deposit) are the following:

- *Eccentricity*. Measure of the departure of the Earth's orbit from circular shape. Its variations have major components on periods of approximately 400 kyr (long eccentricity), 130 kyr and 95 kyr (short eccentricity).
- *Obliquity*. The angle between Earth's axis and the plane of the Earth's orbit varies from 22.1° and 24.5°, and back, in approximately 40 kyr.
- *Precession*. It is a gyroscopic motion that causes a change in the direction of Earth's axis rotation relative to the fixed stars. It has a period of approximately 26 kyr. By interacting with Eccentricity, the precession of the Earth's orbit gives rise to the climatic precession parameter. It is this latter parameter, oscillating with two principal modes of periods 24 kyr and 19 kyr, to influence Earth's climate.

The term *cylce* refers to a complete oscillation of a forcing parameter, while the term *cyclothem* indicates the physical clue of a cycle in the sedimentary record [Sadler, 1994]. This means that a cyclothem can be the product of the cyclic oscillation of a factor able to influence sedimentation. Cyclothem in sedimentary successions are quite common. They can be recognized in outcrops, being represented by regular repetitions of observable rock characteristics, such as lithofacies or bed thicknesses (Figure 1.1), or can be highlighted by specific analyses, like, for example, fluctuations in CaCO_3 content or isotopic ratios.

It must be remembered that cyclothem can be generated also by free oscillations of sedimentary systems that are not necessarily linked to Milankovian cyclicities. A free oscillation is generally due to mechanisms that are internal to a system and rule the way it develops. In this case cyclothem

are referred to as *autocycles*. It was demonstrated that various sedimentary environments can be suitable for the formation of autocycles. As an example, peritidal carbonates, turbidates and switching delta lobes are subjected to autocyclic depositional mechanisms [Einsele et al., 1991].

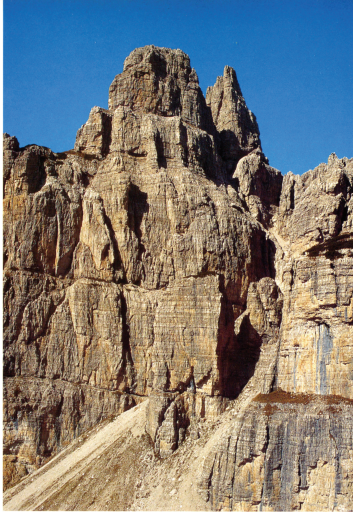


Figure 1.1: *Cyclothems in the Dolomia Principale Formation (Cima del Toro, Dolomites, northern Italy).*

On the contrary, in the case in which cyclicities reflect oscillations of a sedimentary system that are forced by control factors external to the system, they are defined *allogenes* [Schwarzacher, 1993]. This is the case of the oscillations of orbital parameters that are able to influence the behaviour of sedimentary environments and are not intrinsic to them.

Since the periods of Milankovian oscillations vary very slightly through geological time, it comes straightforward that having the possibility to attribute a cyclothem to one of the Earth's orbital parameters means to give a precise duration to that cyclothem. This implies a transformation from space to time domain that has strong consequences for stratigraphy. One of the most important applications of cyclostratigraphy is, indeed, the refinement of the geologic time scale.

However, things are not as plain as it seems because the constance of the orbital parameters becomes less certain in remote geological times. The insolation curve can be calculated with high confidence until 50 Myr before present [Laskar et al., 2004]. For more ancient epochs the periods of oscillations in orbital parameters are uncertain because, at present, it is not possible to know the characteristics of Earth's orbit so back in the past.

Needless to say that the only cyclothems that have importance for chronos-

stratigraphic applications are the allocyclic ones, since autocycles can have extremely variable frequencies in the time domain and often it is not possible to estimate a frequency at all. The problem is that, in principle, sedimentary deposits can record both allocyclicities and autocyclicities and in a stratigraphic section is possible to find both of them together [Strasser, 1991, Yang et al., 1998].

There are several criteria by which the recognition of allocyclicities is possible. They are just listed in the following:

- cyclothems are diagenetic.
- they have high lateral continuity.
- they are continuous in time.
- they are composed by subtidal facies only.
- they are constituted by carbonate symmetric cycloems.
- their duration can be constrained by radiometric datations or varve counting.
- periods highlighted by time series analysis of a series of cyclothems have ratios similar to those of the Milankovitch periods.

Cyclotratigraphic studies had a strong development during late 1970s, 1980s and 1990s when many sedimentary formations, in which cyclic repetitions of some properties were found, were interpreted as influenced by orbital forcing. At the beginning attention was focused on Quaternary deposits [Hays et al., 1976, Imbrie et al., 1984] and then on older geological times [Beaufort, 1994, Kent and Olsen, 1999].

Orbitally forced stratigraphy has very good reliability and is near-continuous for the Cenozoic, thanks to the large amount of data collected for this Era and for the good knowledge of the dynamics of the Earth's orbit. For times older than Late Cretaceous, the linkage to the present of orbital

parameters becomes more difficult the more in the past we go. Moreover, the geological record becomes increasingly fragmentary and the lack of continuous sections becomes more evident.

In order to obtain reliable cyclostratigraphic interpretations it is crucial to recover affordable, long, continuous and high-resolution stratigraphic signals [Hinnov, 2000]. This can be difficult if a long and continuous series is not available, but, even if it is, problems can arise. Cyclostratigraphic data can be collected in the field with classical facies analysis (facies ranking) or can derive from laboratory analyses aimed at measuring a certain parameter of interest (e.g. CaCO_3 content, isotope series, etc.). Field work is very time consuming and often it is not worthwhile to afford the study of tens of meters of stratigraphic section. Chemical analyses, on their hand, have high costs and sometimes can produce data with limited value. This is true in particular if stratigraphic successions have been interested by diagenesis that altered the original chemical parameters.

In an attempt to solve these problems, studies have been undertaken to develop tools able to collect quickly and with high resolution data suitable of cyclostratigraphic analysis. Several authors [Herbert and Fischer, 1986, Bond et al., 1992, D'Argenio et al., 1998, Grippo et al., 1998, Grippo et al., 1999] applied, with good results, optical densitometry in core logging to recover high resolution stratigraphic information. A weakness of this approach is that the technique can be used on short ranges and necessitates of having a long and continuous core to log. It is obvious that a core with the required characteristics is seldom available and is very expensive in terms of costs and time if it has to be drilled *ex novo*. Long and very well exposed sections can be found in outcrop, but often, being constituted by high walls, they are hard to reach or it is impossible to approach them without incurring in safety issues. A long-range logging approach was then proposed by [Schwarzacher, 2005] with the successful application of photographic techniques to study the cyclicities in the Dachstein Limestones of the Northern Calcareous Alps (Austria). If on one hand this technique allows to consider sections that

would be otherwise inaccessible, on the other hand there are also limitations connected with it. A first condition that cannot be always satisfied is to find a suitable point of view in front of the chosen section to avoid perspective deformations in the photographic acquisition. Another problem is that a camera works as a passive sensor. In this case a strong influence is given by illumination conditions that can change during the day, and also depend on the morphology of the object that determines the distribution of shadows on the surface.

An instrument that may bypass the principal limitations of the described methods, while preserving some of their advantages, is Terrestrial Laser Scanner. Terrestrial Laser Scanners have some characteristics that make it a possibly useful instrument in providing quickly and with high resolution geological data suitable of cyclostratigraphic analyses. This potential is discussed in this thesis.

1.2 Terrestrial Laser Scanner

General information

Terrestrial Laser Scanners (TLS) are instruments that work following the principles of radar and produce a three-dimensional reconstruction of the surface of an object in the form of a point-cloud, that is, a set of points distributed on the surface of the object, each with 3D coordinates in the TLS reference frame. TLS differs from the airborne laser scanners because the laser source is coupled with a system of rotating mirrors that directs the beam towards the target. Depending on the way the 3D coordinates are calculated TLS can be subdivided in two groups:

- *time-of-flight TLS*. A laser pulse is directed to the target and the time between the emission and the detection of the returning beam is measured and converted into a distance which is in turn transformed in the spatial three-dimensional coordinates of the hit point.
- *triangulation TLS*. In this case the position of a point in the space is calculated only from geometrical information. The distance between the laser source and the camera is known and the angle of the laser beam emitted from the laser is determined by calibration.

The acquisition process in both laser scanner types is performed iteratively and the resulting point-cloud (Figure 1.4(b)) is made up of contiguous points distributed on the surface of the target, with 3D coordinates with respect to the position of the instrument and with a density of distribution given by the sampling step set by the operator.

Triangulation TLS have ranges within few meters, but can reach very high accuracy (fractions of a millimeter), time-of-flight TLS have longer range (several hundreds meters) but lower accuracy (centimetric at about 100 m).

Time-of-flight TLS are the ones that better match the requirements needed for stratigraphic applications, since acquisition of sections in outcrop conditions is generally performed at a distance of several meters, sometimes tens

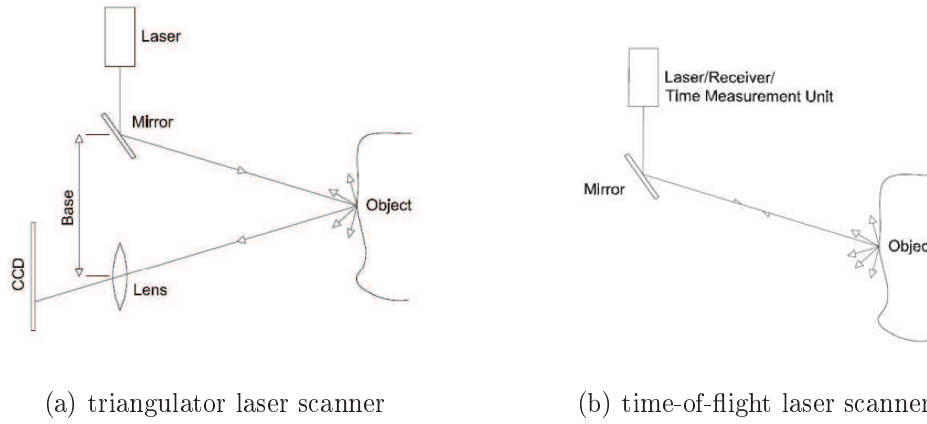


Figure 1.2: from [Bohler et al., 2001]. (a) Scheme of a triangulation laser scanner. (b) Scheme of a time of flight laser scanner.

of meters or more. There are various types of time-of-flight TLS. Differences between them regard in particular the maximum range (from tens to hundreds meters) and the wavelength of the laser beam (infrared or in the visible band). The resolution is generally in the order of the centimeter at 20 m. Acquisition time can be different and is a function of the area to scan, of the desired resolution and also depends on the TLS type, but is generally very fast. As an example, with the ILRIS 3D (Figure 2.5), the instrument used in this work, less than 15 minutes were necessary to acquire a 12 m x 7 m surface with 8 mm sampling step generating 1.3 million points. It must be underlined, anyway, that technical development in this field is at present very fast and new, faster and more accurate machines are continuously produced.

Figure 1.3 reports the technical specifications of the Optech ILRIS 3D (Figure 2.5) [Optech, 2008].

TLS in Earth Sciences

The capability of TLS of describing quickly and with high resolution the morphology of the surface of an object of interest even if it is placed afar from the observer, made this instrument useful in various fields. Applications can be found in Architecture, Archaeology [Doneus and Neubauer, 2005,

Parameter	Unit	
Wavelength	nm	1535 (infrared)
Laser class		1 (eyesafe)
Range (20% target reflectivity)	m	800
Minimum acquisition distance	m	3
Validity range of square inverse intensity-distance law	m	15-1150 ^a
Laser beam divergence	mrاد	0.17
Laser beam divergence at 50 m	mm	21
Resolution at 50 m distance	mm	17.7 ^b
Single point acquisition accuracy at 50 m	mm	7
Modeling accuracy at 50 m	mm	3
Minimum spot spacing at 50 m distance	mm	1.3
Scan velocity	pts/s	2000

a: Personal Communication from Optech Inc.

b: from Lichti and Jamtsho (2006).

Figure 1.3: from [Franceschi et al., 2008]. Optech ILRIS 3D technical specifications.

Neubauer et al., 2005], Engineering, just to make some examples.

Earth Sciences also proved to be rich ground for TLS's employment [McCaffrey et al., 2005, Jones et al., 2009].

The typical application of TLS involves the acquisition of the three-dimensional geometry of an object of interest, which is also the aim of laser scanning in geology. TLS is used, for example, to estimate the volume of a rock mass, to monitor landslide bodies [Bitelli et al., 2004, Teza et al., 2007, Teza et al., 2008] also integrated with other remote sensing systems [Teza, 2006], or can be used for the recognition of fractures on inaccessible rock walls [Slob and Hack, 2004, Slob et al., 2005].

TLS are used in the realization of photorealistic 3D virtual models. From the point-cloud a triangulated irregular network (TIN) is created and photographs of the outcrop are draped on the TIN model. In recent years there has been a powerful drive in developing techniques for the realization of digital outcrop models (DOMs) [Bellian et al., 2005] with applications especially in petroleum geology. A DOM constitutes a 3D framework representing the surface of an outcrop on which it is possible to transfer datasets obtained by

various surveying techniques (e.g. facies analysis, gamma ray logging, coring, seismic and many others). The final result of placing all these attributes in the three dimensional space is a virtual outcrop model (VOM) that allows a better understanding of the distribution of the measured characteristics in the volume of a sedimentary body. Oil companies apply TLS with other 3D rendering methods to produce petroleum reservoir analogues, useful to better plan the exploitation of hydrocarbon reservoirs. A review of the state of the art in the application of VOMs in petroleum geology can be found in [Pringle et al., 2006].

TLS has applications also in structural geology and in the study of mechanics of rock masses [Lato et al., 2008], where the production of 3D models of outcrops is coupled with the tracing in the three dimensions of faults or other structural features.

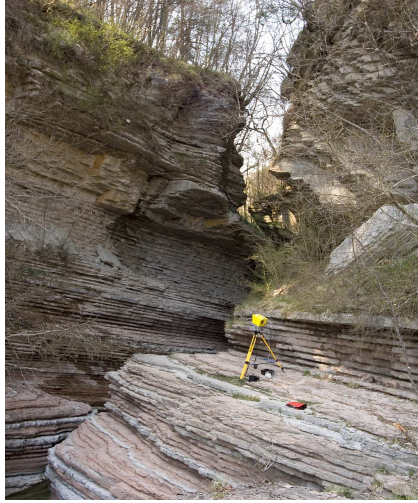
Other applications of TLS in Geology can be found in [Clerici et al., 2005].

TLS intensity and cyclostratigraphy

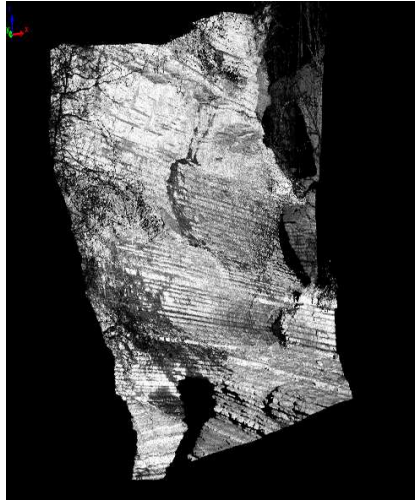
Besides the geometrical coordinates, an intensity value is associated to each point of a TLS generated point-cloud. The intensity represents the power of radiation that comes back to the receiver and it is proportional to the reflectance of the scanned object. In optics, reflectance is defined as the fraction of electromagnetic power that is reflected at an interface and depends on several factors, distance, angle of incidence between the laser beam and the surface, incident wavelength etc. What is important for the aims of this study is that the intensity recorded by TLS depends also on the physical nature of the material that constitutes the target, which in this study is represented by a stratigraphic section (see Appendix B).

An empirical observation ignited this study of TLS intensity data: if a stratigraphic section made up of marl and limestone alternations is scanned with an ILRIS 3D laser scanner, clear differences in intensities of the points are visible (Figure 1.4). In particular, what is evident is that the points placed on marly or clayey beds systematically show intensities lower than

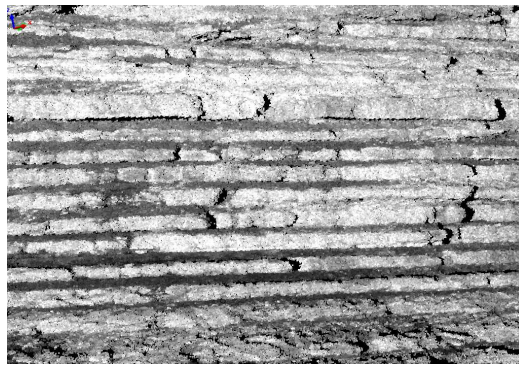
those placed on calcareous beds.



(a) stratigraphic section



(b) TLS-generated point cloud



(c) particular of (b)

Figure 1.4: *The TLS acquisition of the section in (a) generates the point-cloud in (b). In (c) a particular of the point-cloud (b) is shown. Bedding is very clearly visible; limestone beds appear brighter, while marly beds appear darker.*

The geological meaning of TLS intensity, in particular its dependence on the lithological characteristics of rock, will be at the heart of discussion in the next chapters. In Chapter 2 it will be discussed how intensity recorded by Optech ILRIS 3D TLS is linked to lithological characteristic of limestones and marls, in particular to their content in clay minerals and, consequently

to the carbonate content.

It is appropriate to underline that the discrimination of different rock properties, including rock composition (lithology), would prove useful also in other geological disciplines. Lithological differences can, for example, influence the mechanical behavior of rock masses or drive the flow of fluids (water, oil) possibly contained in them by means of their spatial distribution.

The content in clay minerals is, most importantly, a sedimentological parameter and its variations are linked to changes in sediment supply that can be induced by several factors. From this statement the potential importance of TLS in cyclostratigraphy comes straightforward. Limestone-marl alternation often constitute the main component of sedimentary deposits, especially those of marine origin, and in particular those that formed in basinal hemipelagic environments. In many cases, such deposits show rhythms in carbonate and clay contents and have been the subject of countless studies aimed at their cyclostratigraphic interpretation. Famous examples are constituted by the Cretaceous basinal formations of Italy, such as the Scisti a Fucoidi of the Marche-Umbria basin in the Central Apennines or the Scaglia Rossa (s.l) of the Belluno basin in the Southern Alps. The possibility to extract quantitative or semi-quantitative informations about the abundance of clay in these rocks with TLS could result particularly valuable in overcoming some of the cited problems that can be encountered in cyclostratigraphic studies with traditional methods.

This topic and the validation of this new application of TLS will be treated in Chapters 3 and 4.

One could object that information on the lithology can be collected in-remote also with other techniques, like those cited in Section 1.1 or also [Rein and Sirocko, 2002], but several of the TLS's characteristics make it a more valuable instrument in some situations. TLS is capable to render geometries accurately and three dimensionally. The 3D nature of the dataset provides that the intensity data is distributed three-dimensionally on the section, with obvious advantages if the spatial distribution of the intensity on the section

is studied. This is an advantage with respect to 2D data acquired with optical cameras or optical scanners for which perspective deformations can be important, especially at great distances or if an appropriate view point is not available. The long range permits to analyze targets at larger distances than those affordable with other scanner types. TLS works, unlike other scanning techniques (e.g. optical scanners), with an active sensor that makes intensity data independent from the illumination conditions of the target. This is a significant advantage with respect to optical scanners which work with passive sensors whose intensity data can vary if the lighting of the target changes. As it can be noticed in studies that apply passive sensors for the discrimination of different materials on an object [Brusco et al., 2006], the necessity of having a uniform illumination of the surface can imply the settlement of complex lighting apparatuses. Finally, the high speed of acquisition allows to study long stratigraphic sections and collect huge datasets in short times.

Summarizing, the characteristics that make TLS a potentially valuable tool in cyclostratigraphic studies can be synthesized in five points:

1. **Intensity value recorded.** An intensity value proportional to the reflectance of the outcropping rocks is stored by the TLS. It is recorded as an intensity value associated to each point of a point-cloud and then is distributed three-dimensionally in space.
2. **Active sensor.** TLS works with an active sensor. For this reason the illumination conditions of the target do not influence the recorded data. Obstacles surrounding an outcrop (e.g. vegetation) or its morphology in itself can produce shadows on the surface. Intensity data recorded by passive sensor would be influenced by the shadows. This does not happen in the case of TLS.
3. **High accuracy and high resolution.** The acquisition process generates a high resolution dataset which describes three-dimensionally the surface morphology of the considered stratigraphic section.

4. **Long range.** Long range allows the scanning of hardly reachable sections whose study would be difficult or even impossible with traditional methods.
5. **Short acquisition times** Since the acquisition process is very fast, the study of long stratigraphic sections is possible, a condition that, as already shown, is of crucial importance in cyclostratigraphic studies.

Chapter 2

Interpretation of TLS intensity data

FROM the theory of reflectance spectroscopy is known that different materials interact in different ways with electromagnetic radiation (see Appendix B). This happens also in the case of laser radiation emitted by a TLS. This interaction influences the intensity of the backscattered beam of the material that constitute a target [Kurazume et al., 2002]. Obviously this phenomenon occurs for rocks, since atoms in the rock forming minerals absorb a specific amount of the energy of the incident radiation. When reflectance values are plotted as a function of the wavelength a reflectance spectrum is obtained. In this spectrum features as maxima and minima are characteristic of the considered material. Spectroscopy studies reflectance spectra and allows the recognition of different types of rocks even if they cannot be directly touched.

Phenomena here briefly exposed are the base for the development of remote sensing techniques that are widely used in the study of satellite images, both for the study of Earth and for space exploration. Data acquisition usually is performed by optical spectrometers that record electromagnetic radiation reflected by objects in a certain wavelength range with a passive sensor.

Even though TLS records an intensity datum proportional to the reflectance of the surface they are not spectrometers. There are two great

differences between spectrometers and TLSs. First of all, TLS is an active instrument which has a source that shoots a laser beam on the object of interest; secondly, since TLS emission takes place at a precise wavelength from collected data is not possible to obtain a complete reflectance spectrum. Albeit this limitations, TLS record a "wavelength specific" reflectance which can give informations on some characteristics of the scanned rocks.

It cannot be forgotten, however, that TLS are instruments which have not been conceived and projected for collecting lithological information. Moreover, since the intensity datum refers to the surface of an object, several factors can mask the lithological signal and make the intensity data useless for geological purposes. This has been a general assumption that so far prevented attempts of use of intensity in geological application of TLS.

The geological interpretation of TLS intensity must then be supported by evidences that the recorded data can be effectively linked to lithological characteristic of the rocks.

The sections of this chapter are taken from [Franceschi et al., 2008] where the Authors discuss the results of a series of experiments aimed at constraining the geological meaning of TLS intensity. The presented data acquisition and processing protocol has to be followed to make TLS dataset acquired with Optech ILRIS 3D suitable of cyclostratigraphic analysis (Figure 2.1).

2.1 Intensity data processing

Once a laser scanner acquisition is performed, a suitable parsing software transforms the raw data provided by the instrument into a format that can be easily managed by the TLS data inspection and processing software, i.e. Innovmetric PolyWorksTM, Maptek I-Site StudioTM, Leica CycloneTM, and others; see [POB, 2008] for a survey. After the data parsing, the point cloud is the set $\{(x_i, y_i, z_i, l_N(x_i, y_i, z_i)), i = 1, \dots, N\}$, where $l_N(x_i, y_i, z_i)$ is an 8-bit digital number (DN) representing the distance-corrected intensity normalized to the range 0-255 and N is the number of points backscattering a useful

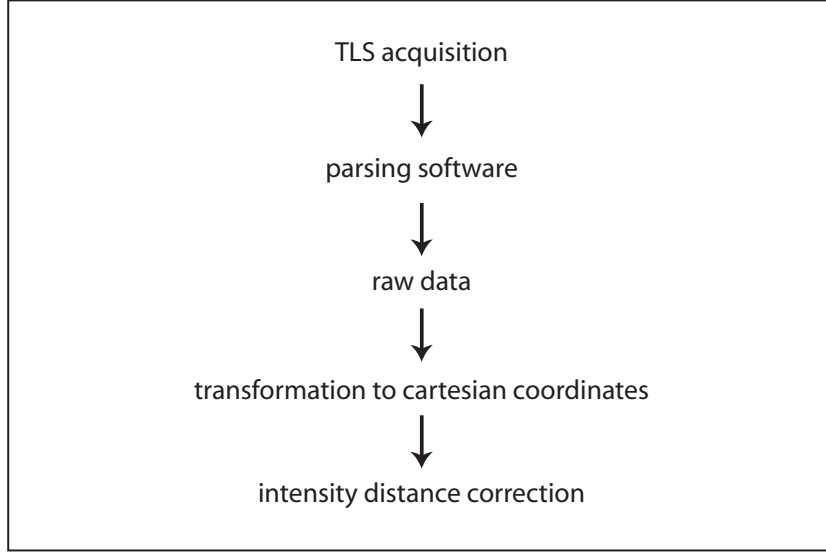


Figure 2.1: *Work-flow for TLS data processing.*

component of the signal returned (in particular, the points where saturation of the receiver occurred are excluded by the parsing software). In this way, two targets acquired at different distances but having the same reflectance at the laser wavelength return similar l_N . Generally, the parsing algorithms provided by TLS manufacturers are not open source software. Therefore despite the fact that data inspection is very simple and the 3D view pleasant, the intensity information could be altered and uncontrolled artifacts could arise in reflectance reconstruction or in intensity-based computations. The raw intensity, as directly provided by the instrument and expressed by a 16-bit DN, is here used instead of the 8-bit DN provided by the parsing software.

Figure 2.2 shows an example of acquisition geometry for a time-of-flight TLS. In a spherical coordinate frame, if (d, φ, α) is the position of an acquired target, the corresponding raw intensity is given by:

$$l(d, \varphi, \alpha) = RD(d)G(\varphi, \alpha) \quad (2.1)$$

where R is the material reflectance at the specific wavelength and humidity level, $D(d)$ is the distance factor for a perfectly reflective Lambertian material

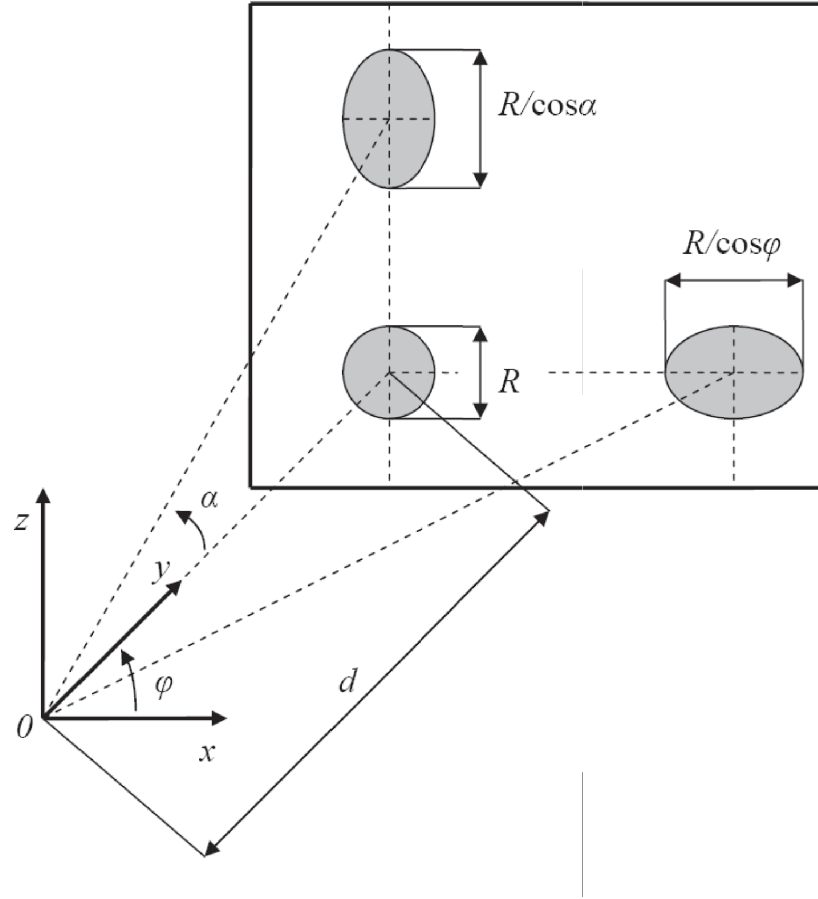


Figure 2.2: from [Franceschi et al., 2008]. Principle of time-of-flight terrestrial laser scanner. The angular coordinates φ and α of the laser beam are defined by the scanning sub-system (mechanism based on rotating/tilting mirrors), and the distance d is computed by the travel time of the nanosecond laser pulse. The surface is scanned changing the angles by discrete steps $\Delta\varphi$ and $\Delta\alpha$, i.e. $\varphi_m = \varphi_0 + m\Delta\varphi$ and $\alpha_m = \alpha_0 + m\Delta\alpha$, where φ_0 and α_0 are the longitude and latitude of the starting point. The particular case of a vertical wall is shown, in order to explain the effect of angle between the line-of-sight and the normal direction to the surface. A good instrumental practice requires that this angle must be kept as small as possible.

(i.e. a diffuse reflector) illuminated and seen on normal incidence and takes into account both the observation geometry and the macro-roughness (that

is surface irregularities). The influence of the air mass is not considered here, since scans were realized from very short distances, with good visibility and in good atmospheric conditions. The aim is to evaluate R from: the intensity $I(d, \phi, \alpha)$ provided by the instrument, the function $D(d)$ which can be easily obtained from the detector response at distance $S(d)$ provided by the manufacturer, and the function $G(\varphi, \alpha)$ defined on the basis of acquisition geometry and the nature of the surface.

In the case of Optech ILRIS 3D TLS, the receiver output signal vs. distance map is:

$$\log_{10} S(d) = \log_{10} S_0 + m \log_{10}(d/d_0) \quad (2.2)$$

where S is the signal, $m = -2$, $d_0 = 15\text{m}$ and $\log_{10} S_0 = 1.74$. This relationship, from the results of carried on experiments, holds only if $d > 15\text{ m}$ and implies that, $S(d) = 1/d^2$, as expected because the area illuminated by a laser beam increases with the squared distance. If $d < 15\text{ m}$, the relationship between S and d is strongly non-linear and the data provided by an ILRIS instrument cannot be considered reliable in the intensity-based stratigraphic analysis here described.

Another aspect that was considered in the analysis of TLS intensity is the effect of the angle of incidence between laser beam and the target, factors that can play an important role in determining the intensity of the backscattered component of the beam [Feng et al., 2001, Kemeny and Post, 2003]. Obviously, for a TLS the incidence coincides with the laser line-of-sight (LOS) and, in the case of nearly vertical and planar surfaces (as in the case of a vertical outcrop), the angle of incidence is the one between the LOS and the outcrop's surface.

The behaviour of the laser beam as it reaches the surface influences the entity of the reflected power (Figure 2.3). The two extreme cases are constituted by reflective and lambertian surfaces. In the case of a perfectly reflective surface all the incident energy is reflected and no energy returns in the direction it was emitted, in the case of a lambertian surface, on the contrary, the energy is also backscattered and its amount is constant with

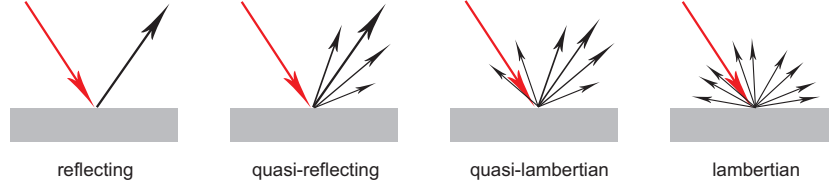


Figure 2.3: *Scheme of the possible interactions between light and matter without absorption. Natural surfaces usually have behaviour between quasi-reflecting and quasi lambertian. In these two cases a significant amount of radiation is reflected also in the direction of the laser beam.*

the angle between the normal to the surface and the LOS. From this follows that if the observed material is Lambertian, it is simply $G(\varphi, \alpha)$. Different behaviours need to be treated with different $G(\varphi, \alpha)$ functions, which can be very complex. If a rough surface is illuminated by a source, since many randomizing events can occur before the light leaves the surface, the scattered light is diffused and the behavior of the surface is lambertian [Carrascosa et al., 1985]. [Pesci and Teza, 2008] showed that a surface characterized by a macro-roughness of the order of magnitude of the spot size (i.e. the size of irregularities is in the range between some mm and ~ 10 mm if the spot diameter is 20-30 mm) has a lambertian-like behavior, that is the intensity does not depend on the incidence angle of the laser beam. On the contrary, if the observed surface is smooth compared to the spot size, the incidence angle strongly influences the measured intensity and a correction is necessary for reflectance computation. Since natural extended surfaces (e.g., rocks in outcrops) are usually characterized by macro-roughness, the intensity is almost independent from the incidence angle of the laser beam (Figure 2.4). This is true if no large exposed discontinuity planes are acquired, since they could appear to be smooth at the centimetric scale of a laser spot. Possible large discontinuity surfaces must therefore be recognized by point cloud inspection or, if a large outcrop is studied, by automated procedures [Slob et al., 2005].

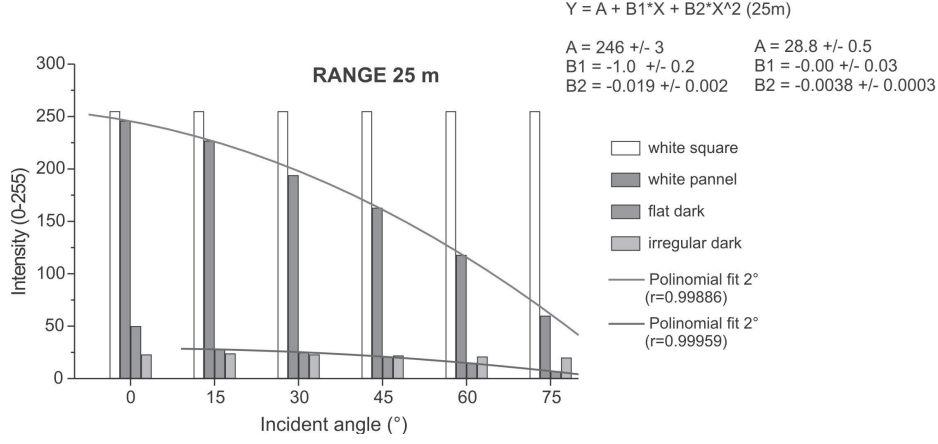


Figure 2.4: from [Pesci and Teza, 2008]. The plot shows how intensity response of irregular surfaces is less sensitive to the increasing of the angle between the LOS and the surface.

The results here presented are based on the assumption that the acquired surfaces have lambertian-like behavior. In other words, if the raw intensities (16-bit DN) of two targets observed at distances d_1 and d_2 are I_1 and I_2 respectively, the ratio between the corresponding reflectances is

$$\frac{R_1}{R_2} = \frac{I_1}{I_2} \left(\frac{d_2}{d_1} \right)^2 \quad (2.3)$$

with both d_1 and d_2 exceeding 15 m, regardless of the surface orientation. If the observed surface asperities were smaller than the size of the footprint, another intensity correction would be necessary.

2.2 Influence of environmental and lithological parameters

2.2.1 Indoor and in field experiments

An efficient protocol for data acquisition is an unavoidable requirement for any TLS survey, especially if the main objective of the analysis is the study of the intensity response of the beds of a stratigraphic succession having thickness in the order of centimeters. If the accuracy at a reference distance d_{ref} is σ_{ref} , and the needed accuracy is $\sigma = f_d d_{ref}$, $d \leq f_d d_{ref}$ represents the constrain on the distance between instrument and target is $\sigma \leq f_d d_{ref}$. The viewpoint should allow a quasi-normal incidence on largest part of the investigated surface. This is necessary because accuracy worsens, as the angle of incidence increases. If a vertical wall, parallel to x -axis, is observed from the origin of the reference frame (Figure 2.2), the footprint of a point along the normal direction ($\varphi = \alpha = 0$) consists of a circle. If another point on this plane with angular coordinates $(\varphi, 0)$ is considered, the footprint is an ellipse which major axis is parallel to x -axis and which ratio between the half-axes is $1/\cos \varphi$, diverging with $\varphi \rightarrow 90^\circ$ [Pesci et al., 2007]. To maintain the accuracy within reasonable limits, angles between the instrument line-of-sight and the observed surface larger than 75° - 80° should be avoided. If necessary, more than one viewpoint must be considered, providing a series of partial point clouds that can be easily registered into a common reference frame by means of an alignment algorithm.

In this work the Optech ILRIS 3D (Figure 2.5) TLS was used. Although the ILRIS 3D allows geometric modeling at distances larger than 3 m (lower limit range), the acquired intensity data show a behavior diverging from the expected $I(d) \propto 1/d^2$ if the distance is lower than 15 m. In order to perform a correct intensity analysis, the requirement $d > 15$ m on the acquisition distance is therefore necessary (see Section 2.1). These technical specifications are not given by the instrument's manufacturer. For example, Optech does

not declare the fact that the relationship $I(d) \propto 1/d^2$ holds only if $d > 15$ m, and the minimum acquisition distance of 3 m declared in the technical specifications is deceiving when intensity is considered. The motivation of the anomalous behavior is considered confidential by Optech.



Figure 2.5: *Optech ILRIS 3D TLS.* The knowledge of the minimum acceptable distance of acquisition is necessary both for planning scan acquisition and for a valid intensity evaluation and interpretation. This information must either be asked to the manufacturer or obtained via preliminary tests on calibrated targets.

- Influence of humidity.
- Influence of the distance between the TLS and the target.
- Influence of the environmental temperature in which an acquisition is performed.
- Influence of the geological characteristics of the target.

The experiments were carried out both on artificial targets and in the field, on a real section. Experimental results are presented and discussed in Chapters 2.2.2 and 2.2.3.

In order to verify the effects of humidity on the TLS-based intensity values, two rectangular targets (50 cm $\times$ 40 cm) composed respectively of limestone and clay were acquired from a distance of 20 m. The targets were acquired in dry and wet conditions. The targets were dried in an oven at 50°C for 3

hours before scanning, while the acquisition in wet conditions was executed immediately after target moistening.

The infield case study was the Nomi section (Southern Alps, Trento, Italy) which encompasses part of the Lower Jurassic Rotzo Formation [Avanzini et al., 2007, Barbieri and Grandesso, 2007]. The outcrop appears as a nearly vertical wall with planar layers of nearly constant thickness (Figure 2.6).

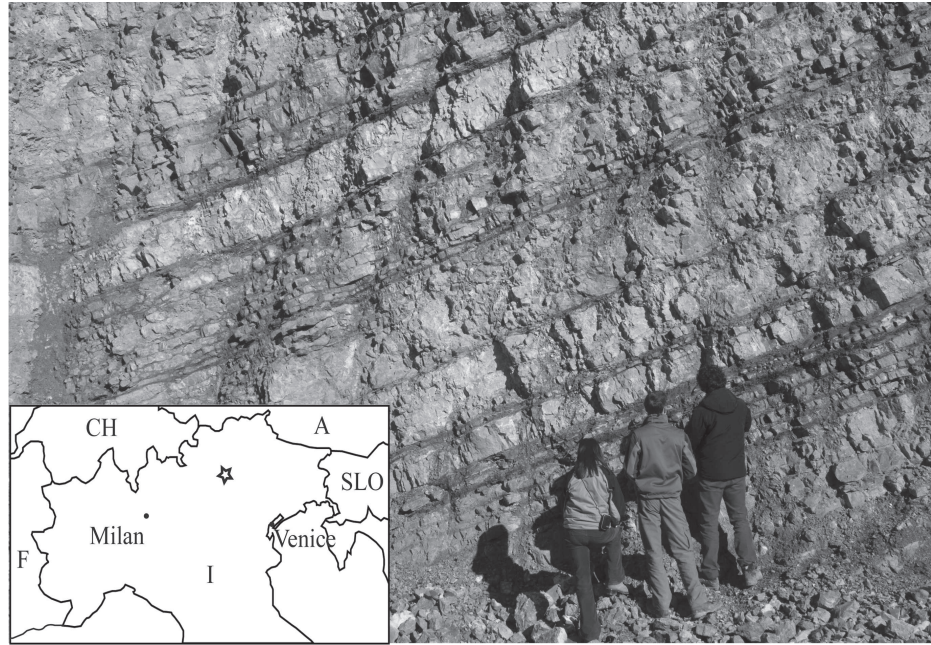


Figure 2.6: *from [Franceschi et al., 2008]. Rotzo Formation at Nomi and location of the studied section. Note the planar dip and the constant thickness of the bedding.*

A series of point clouds was obtained from different distances, in order to evaluate the influence of various parameters on the intensity. Scans have been acquired at 20 m and 30 m with a mean sampling step at the surface of 8 mm; therefore, the angular step was consequently defined. The chosen sampling step is close to the spatial resolution of the instrument, which is 17.7 mm at 50 m and linearly increases with the distance. As an example the result of one of the scans of the Nomi section is shown in Figure 2.7(b).

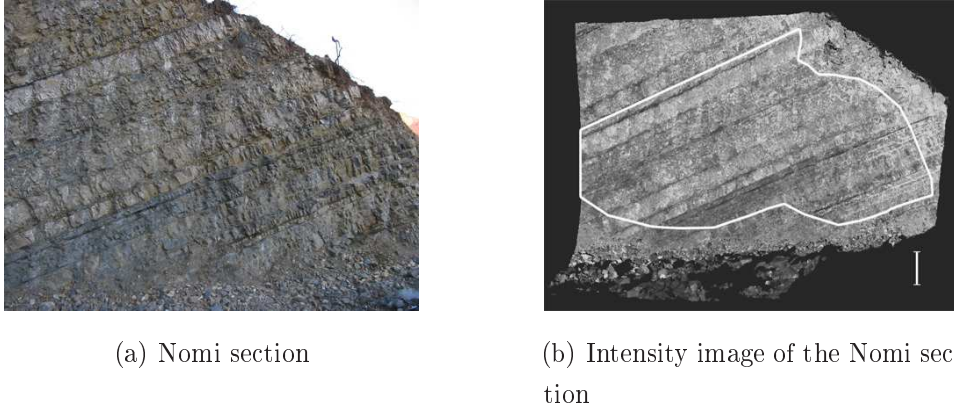


Figure 2.7: *Nomi section (a) and its intensity image obtained by Ilris 3D TLS (b). White line comprises the area of the point cloud in which rock samples for CHNS analysis were collected. Intensity values of the points within the same area were used in the generation of the reflectance series. Scale bar 1m.*

Temperature variations were monitored during acquisition by means of a FLIR ThermaCAMTM SC640 thermo-camera, which is a high-performance instrument characterized by 0.65 mrad spatial resolution (about 1 cm at 30 m distance), 0.1°C thermal resolution and equipped by a 640×480 pixel array [FLIR, 2008]. The thermograms were taken at regular time intervals during the day in order to evaluate temperature changes due to the varying amount of incident solar radiation on the surface when the TLS observations were carried out. Figure 2.8 shows three examples of thermic images of the section. The first (top) one was taken with the outcrop in complete shadow, in the second (middle) the outcrop was in complete sunlight, the third (bottom) was taken with the outcrop again in complete shadow. Note the variations in thermic response given by the rocks in the three moments. Particularly interesting is that in the second image, the one in which highest temperatures are recorded marly and clayey layers appear brighter than the limestones. In the third image, the temperatures are decreased, but the limestones appear considerably brighter than marly beds. This fact is probably due to the low thermic conductivity of the limestones.

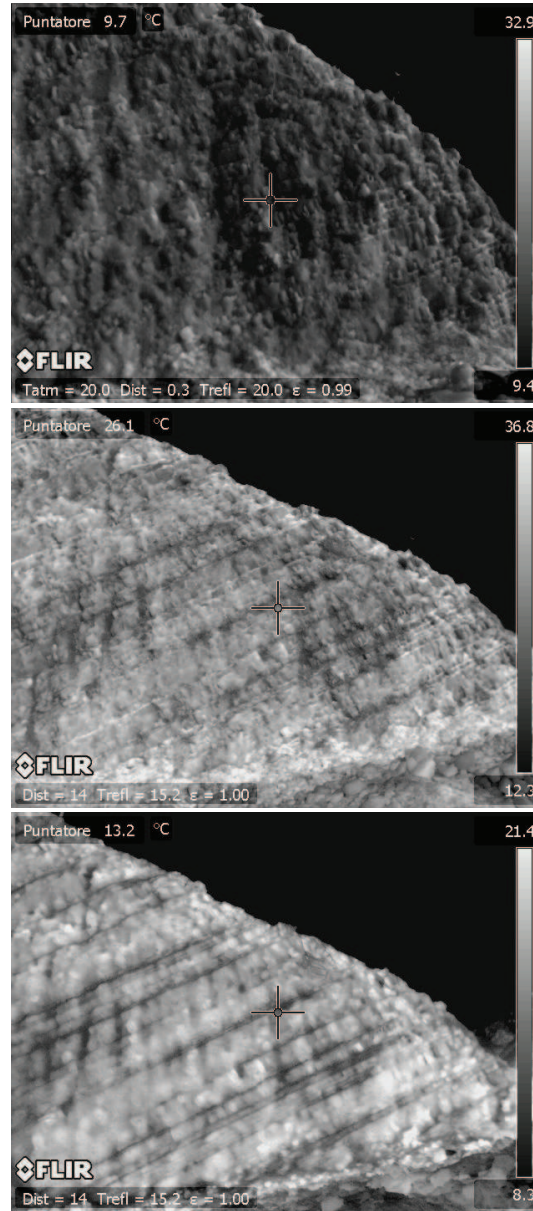


Figure 2.8: *Thermic images of the Nomi section taken at different times during the same day. Top ~ 12.30 p.m., middle ~ 3.30 p.m., bottom ~ 5.00 p.m.*

Finally, rock samples were collected at progressive stratigraphic heights within the area of TLS acquisition (Figure 2.7). A series of CHNS (carbon, hydrogen, nitrogen and sulfur analyzer) analyses were carried on the samples in order to obtain an estimate of the clay content in different layers (see Appendix D). In this technique gas chromatography is used for an elemental analysis in order to estimate the amount of hydrogen contained in a rock from dried and crushed samples (5-10 mg).

2.2.2 Data analysis

As expected, the comparison of TLS intensity values measured in different temperature conditions, shows that, despite significant differences in thermic behaviour of the different lithotypes Figure 2.8, intensity is not sensitive to temperature variations in the range between $\sim 10^{\circ}\text{C}$ and $\sim 40^{\circ}\text{C}$. This fact is also confirmed by the acquisition of the same target from the same station at different times during a day, that is under varying incident solar radiation.

Figure 2.9 shows the statistical distribution of intensity values obtained scanning two artificial targets (50 cm $\times$ 40 cm rectangles) composed of clay and limestone material respectively, on both dry and wet conditions. The different intensity is clearly related to the different nature of the materials. Moreover, dry clay shows intensity approximately 30% lower than that of dry limestone.

Moistening, besides causing a shift towards lower values of the intensity on the targets, increases the difference in intensity between clay and limestone. The intensity response of the two materials remains clearly distinguishable in all cases, with clay always darker than limestone.

An attempt was made to estimate the influence of clay minerals on TLS intensity of sedimentary rocks in the in-field case study. In Figure 2.10 the results of the CHNS analyses performed on the rock samples are displayed. The percentage in weight of H (expressed as H_2O) is plotted versus the percentage in weight of C (expressed as CaCO_3). The linear relationship between the two variables is clear and the correlation coefficient, of -0.87, rises to nearly 1 (0.098) when two easily recognizable outliers are rejected. Anomalous response of the outliers may be explained by significant organic matter and hydrocarbon content because, being rich in carbon and hydrogen, these two components can make the ratio change significantly. This result implies that, in the case of the Nomi section, the rock can be considered as constituted by two phases: one containing the carbon (i.e., the calcium carbonate) and another one containing the hydrogen (i.e., the clay minerals). For this reason, the H content can be considered directly proportional to the clay abundance

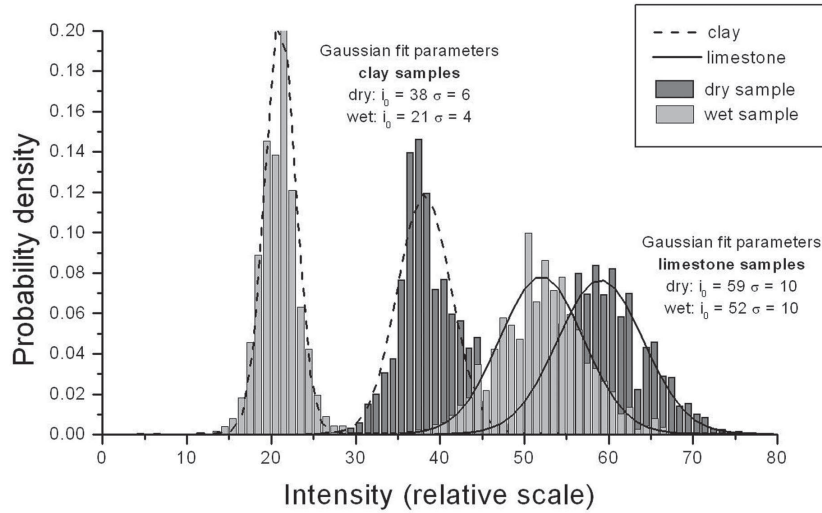


Figure 2.9: from [Franceschi et al., 2008]. Distributions of intensities on square targets (50 cm $\times$ 40 cm rectangles) made up of clay and limestone. The fact that clay shows lower intensity than limestone is in accordance with the reflectance spectra of clay minerals and carbonates [Clark, 1999].

in the rocks, since it is assumed here that clays contained in the rocks have constant composition. This assumption is reasonable, as the depositional environment do not vary significantly throughout the section.

On the basis of TLS data related to the Nomi section, the distributions of the intensities were computed for each sampled layer and the modes of the probability distribution functions were considered as characteristic intensities for each layer.

The comparison between H content (i.e. clay abundance) obtained from samples via CHNS and the characteristic intensity of the correspondent layers is shown in Figure 2.11, while in Figure 2.12 shows the relationship between I and the CaCO_3 content. The relationship between H content (expressed as H_2O and interpreted to be proportional to clay content) and intensity is clear and the correlation coefficient $r = -0.85$ is obtained if a linear fitting is

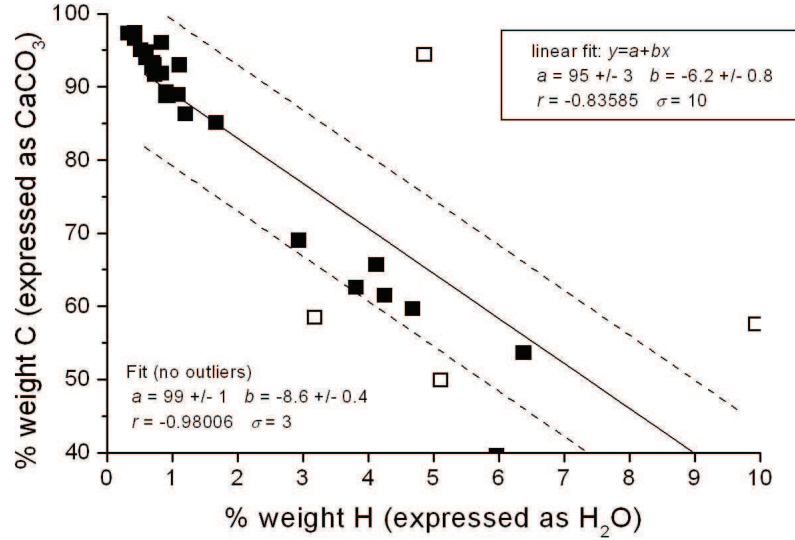


Figure 2.10: from [Franceschi et al., 2008]. Relationship between percentage in weight of H (expressed as H_2O) and C (expressed as $CaCO_3$) obtained from CHNS analyses on samples collected at the Nomi section. The inverse linear relationship is clear. The recognized outliers can be caused by the presence of organic matter in the samples, with a consequent shift to higher values of the amount C and H detected in the analysis.

applied.

2.3 Discussion

The results presented in this Chapter prove that intensity values of ILRIS 3D TLS can be used to recognize rock types in a stratigraphic section constituted by limestones and marls. Clay abundance is the most important geological factor which modifies the recorded intensity values is clay abundance in the rocks because clay minerals have strong influence on the emission wavelength of the laser beam.

The experiments just described were a necessary preliminary step since

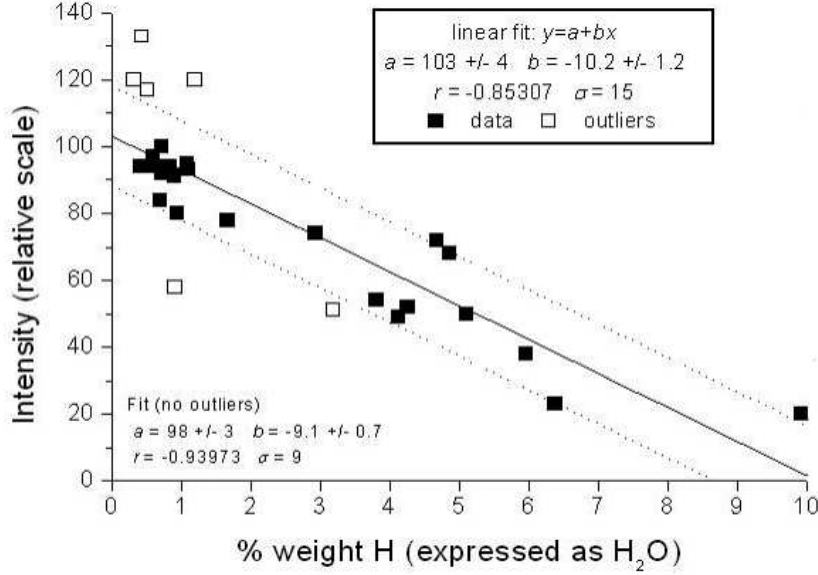


Figure 2.11: from [Franceschi et al., 2008], modified. Relationship between characteristic intensities of the sampled layers calculated from intensity values of the TLS point cloud of the Nomi section and percentage in weight of H (expressed as H_2O). The correlation coefficient is $r = -0.85$ if a least square linear fitting is applied. 95% prediction bounds are shown.

no test has been performed so far to evaluate the effective capability of TLS in recording lithological variations in sedimentary rocks. Moreover it was possible to establish a data acquisition protocol and highlight some limitations of the instrument not specified by the manufacturer.

Even if results are encouraging and confirm empiric observations on the different response in intensity of different lithologies, attention should be paid in the interpretation of the TSL data. The recognition of clay can be hampered by other factors.

Above all, humidity greatly influences intensity, particularly in the case of ILRIS 3D instrument. The laser source of ILRIS 3D has a 1535 nm wave-

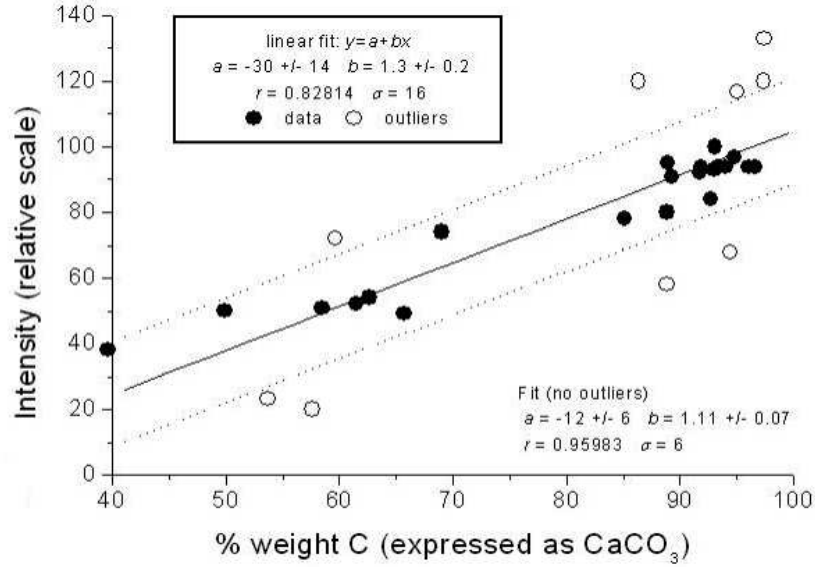


Figure 2.12: from [Franceschi et al., 2008], modified. Relationship between characteristic intensities of the sampled layers calculated from intensity values of the TLS point cloud of the Nomi section and percentage in weight of C (expressed as CaCO_3). The correlation coefficient is $r = -0.82$ if a least square linear fitting is applied. 95% prediction bounds are shown.

length, in the SWIR band. That wavelength corresponds to a strong water-related absorption peak. Thus, the measured intensity is strongly sensitive to water content and therefore depends on weather conditions [Lu et al., 2005]. If some wet areas are present on the target, the strong water absorption of the near IR wavelengths causes a severe fall in the reflectance values. For this reason, the effects of surface and interstitial humidity on the intensity of the considered lithotypes (limestones, marls and marly limestones) were studied in both indoor and outdoor experiments. Results indicate that it is not possible to associate an absolute value of clay abundance to a certain value of intensity. Thus, a general calibration of the reflectance values with the clay abundance is not proposed here. However, experiments show also that the

presence of humidity does decrease the intensity, but does not eliminate the differences of reflectance between limestones and marls. The fact that the effect of humidity is stronger in a clay than in a limestone target is due to the different physical properties of clays and limestones. Clays are able to absorb and retain on the surface a huge amount of water because they are characterized by high porosity and because of their mineralogical properties which allow them to retain a great number of water molecules. Limestones have lower porosity than clays and cannot retain moisture in their crystal lattice. Although it is not possible to generally associate a reflectance value to an absolute clay abundance value, it is always possible to distinguish between those lithotypes and appreciate relative differences calibrating, if needed, the intensity on a case by case base.

The fact that no significant effects related to Sun heating occurred in the considered range of temperature should be noted. This means that a series of acquisitions performed in a same day, with constant general humidity conditions but different temperature of the observed surface, can provide similar intensity data on similar materials. If an outcrop is observed from several viewpoints, the partial point clouds can be therefore registered together on a common reference frame without risk of mixing of inhomogeneous data.

Alteration coatings, if extensively developed, can severely affect the intensities. The effect of alteration should be also evaluated, but in the considered cases rocks did not present strong alteration. Its effect was then considered negligible and not studied in this thesis. Future developments should certainly consider this aspect.

Chapter 3

Reflectance series

IT has been shown (Chapter 2) that TLS intensity values are linked to the abundance of clay minerals in rocks that can be considered essentially constituted by calcium carbonate and clay minerals. To make TLS data useful in stratigraphic analysis and in particular in cyclostratigraphy is necessary to find a way to study the variations of intensity along a stratigraphic section. Since intensity is linked to variations in clay abundance that reflect variations in sediment supply it could be interesting, from a cyclostratigraphic point of view, to study how intensity varies in a section because the abundance of clay is a sedimentological parameter which in principle can be influenced by Milankovian periodicities.

Reflectance series are here proposed to represent variations of intensity along a stratigraphic section.

A reflectance series can be considered a stratigraphic log in which the distance-corrected intensity values I are associated with the corresponding stratigraphic heights z , i.e. a map where $I = I(z)$. In this form, reflectance series can be considered time series and can be studied with time series analysis. This statement is valid even if reflectance series are not ordered, because, being it extracted from a stratigraphic series, the superposition principle applies (see Appendix A).

3.1 Point cloud pre-processing

To obtain a reflectance series, a point cloud has to undergo some pre-processing steps [Remondino, 2003]. The pre-processing is performed via Innovmetric PolyWorksTM Iminspect module [Innovmetric, 2008, POB, 2008]. Some steps needed to be accomplished by original MatlabTM scripts reported in Appendix C.

In order to process ILRIS 3D raw data in PolyworksTM they must have their coordinates changed to cartesian reference system since in the original form coordinates are expressed as spherical. This process can be performed by `ls_raw2carty` MatlabTM script (see Appendix C). After that the point cloud can be inspected to identify all the points that do not describe the section of interest. In particular, all points representing vegetation or debris coverage must be deleted as well to areas of the point cloud characterized by recognizable streaming water or high moisture (Figure 3.4(a) and Figure 3.4(b)). After the cleaning, the remaining points should be the ones which better describe the rocks properties of the section and whose intensities will be used in the reflectance series generation. Once the point cloud has been cleaned, intensities should be corrected in function of the distance of acquisition. This operation can be performed using `ls_sea_fit` MatlabTM script (see Appendix C). The average dip of the layering is then calculated and a roto-translation is applied to the point cloud in order to orient layers horizontally with respect to the TLS reference frame. In the new configuration, the z -axis coincides with the stratigraphic height (Figure 3.3(b)).

3.2 Reflectance series generation

After the pre-processing steps the reflectance series has to be generated. The attribution of a reflectance value to each stratigraphic height of the considered section is necessary. The approach proposed in this thesis is to project all the points on a line perpendicular to the calculated average dip and then calculate a characteristic intensity from the distributions of the intensity val-

ues in a selected interval. This operation aims to consider as many points as possible in determining the intensity value for a certain stratigraphic height. This should allow to average out variations in intensity due to local factors (e.g., undetected humid, vegetated or altered portions of the outcrop in the cleaned point cloud) and give higher reliability to the obtained intensities.

Let z_R be the desired resolution of the reflectance series. In order to optimize the available information, this resolution should be similar to the sampling step applied in the TLS acquisition. Let z_L and z_H be the minimum and maximum elevation of the rotated point cloud, with respect to the point cloud reference frame. For each positive integer k such that $z_L + kz_R \leq z_H$, the points whose elevation z satisfies the condition $z \in [z_L + (k-1)z_R, z_L + kz_R]$ are searched and the corresponding distance-corrected intensities are considered. As an example, if an outcrop having 12 m width is acquired with 8 mm sampling step and $z_R = 10$ mm is considered, each interval corresponds to ~ 1800 points.

The reflectance distribution is then analyzed and the corresponding mode is considered as the characteristic value for the elevation interval. In this way the couple (z_k, I_k) is obtained, where $z_k = kz_R/2$ and I_k is the mode. The tails in such a distribution may appear, but they cannot be considered significant because they are related to boundary effects between different layers as well as to local peculiarities in moisture and other surface conditions. For this reason the use of mode of distribution instead of the mean is required. If a distribution is unimodal, the mode (as well as the median) is generally not characterized by large tails; this is the case of the distributions considered here. The mode can be easily computed by means of non-parametric estimation of the corresponding probability distribution function [Bowman and Azzalini, 1997]. The reflectance series of a 12 m $\times$ 7 m size outcrop acquired with an 8 mm sampling step is considered (the point cloud has therefore 1.3 million points) and is computed in 78 minutes using an IntelTM PremiumTM 4 521 Dual Core CPU with 2.8 GHz clock (supported by 2 Gb RAM). In the reflectance series generation `ls_mediancoll` MatlabTM script (see Appendix

C) can be used.

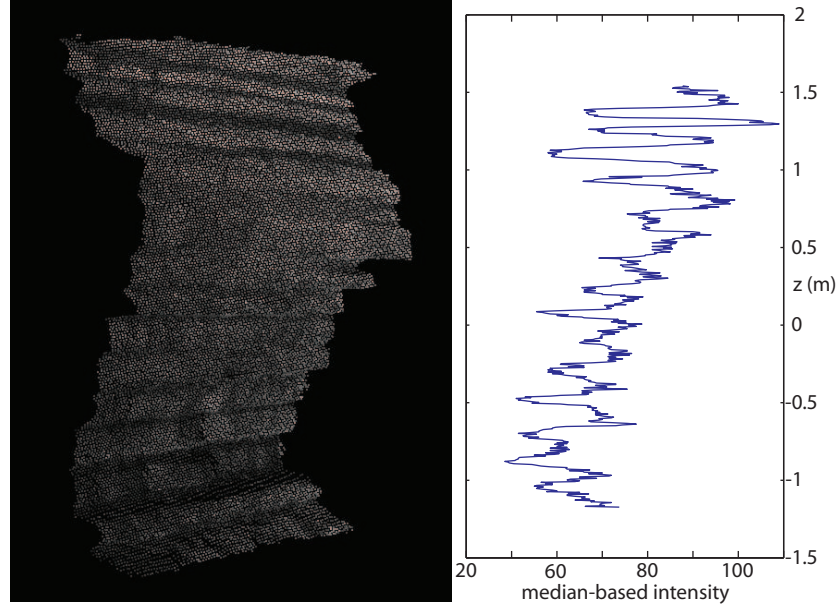


Figure 3.1: *Example of point-cloud and correspondent reflectance series.*

Figure 3.1 shows an example of point-cloud and the correspondent reflectance series. The complete procedure of data processing is given in the following:

1. Pre-processing of the point clouds [Remondino, 2003], including the registration on a common reference frame of the partial point clouds if two or more viewpoints are considered, and data cleaning (for example, disturbing elements like grass and trees must be deleted). Moreover, extended discontinuity surfaces must be recognized.
2. Computation of the distance-corrected intensity as a 16-bit DN for each point.
3. Re-orientation of the stratigraphic succession, to put layers horizontal, so that in the new configuration bedding dip plane is parallel to the xy plane of the point cloud's reference system (Figure 3.3(a) and Figure 3.3(b)).

4. Generation of the reflectance series.

The intensity data obtained at Nomi were analyzed, applying to the point-cloud the procedure described in this Chapter and in Chapter 2, in order to provide the reflectance series. Figure 2.7 shows the intensity image obtained by the TLS acquisition, the area enclosed by the white line is the one considered in the generation of the reflectance series.

In the reflectance series local maxima and minima are evident. The high spatial resolution highlights the correlation between high amplitude variations of intensity and lithological changes; in fact rock layers are clearly recognizable in the curve. Typically, maxima and minima correspond to limestones and to marls or clays, respectively. In Figure 3.2 the reflectance series of the Nomi section is plotted on a photographic image of the studied stratigraphic interval of the outcrop. The correspondence between limestone and clayey layers with local maxima and minima respectively is evident. Comparing intensities at local maxima and minima of the curve with the clay abundance of the correspondent layers, obtained from the collected samples, the correlation coefficient is $r = -0.72$.

3.3 Discussion

The slight decrease of the correlation coefficient with respect to the value of -0.85 obtained by comparing hydrogen contents with the characteristic intensities of the sampled layers (Figure 2.11) may be explained by boundary effects at bed joints that can be enhanced if beds are not perfectly planar. As an example, irregularities of the boundary can cause points belonging to different layers to be averaged together into the same point of a reflectance series. Furthermore, intensity values of the reflectance series account for a vertical interval which is a function of the series resolution z_R . This vertical interval might be significantly different from the total layer thickness. The correlation coefficient however remains significantly high, and this fact

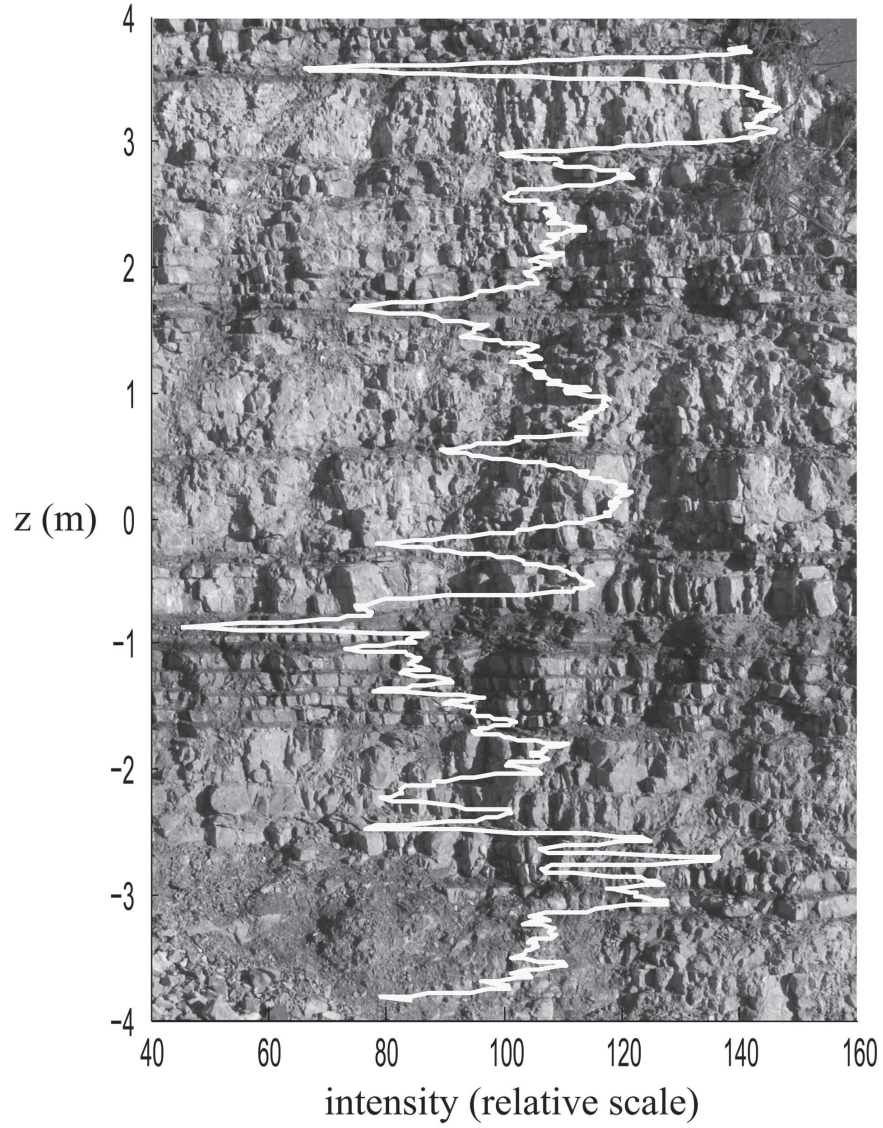


Figure 3.2: from [Franceschi et al., 2008]. Reflectance series obtained by TLS of Rotzo Formation at Nomi plotted on a photographic image of the correspondent stratigraphic interval of the section. Relative maxima correspond to limestones, while relative minima correspond to marls and clayey layers. The slight discrepancy between the curve and the represented layers is due to perspective deformation of the picture.

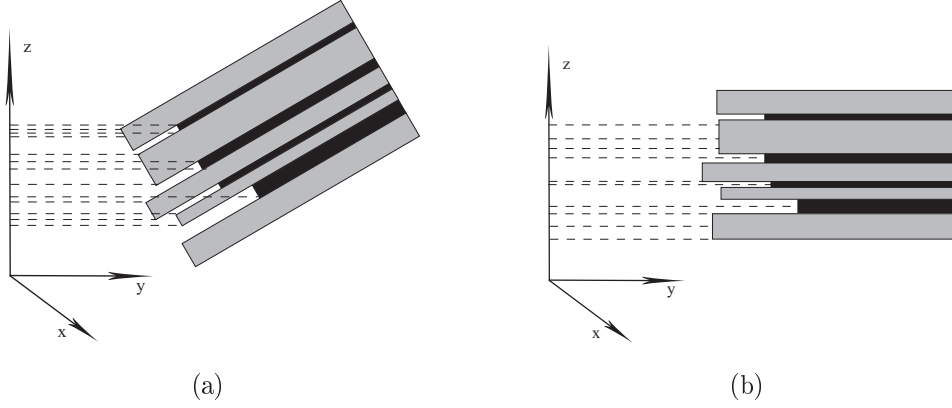


Figure 3.3: *2D scheme of the re-orientation phase of the point cloud. In (a) beds dip with respect to the reference frame and the projection of the points on the z axis results in overlap of points belonging to different layers. In (b) the re-orientation avoids the overlap problem.*

demonstrates that reflectance series are able to record variations in clay content along a stratigraphic section.

For the same reason the re-orientation phase is crucial. If it is poor, points belonging to different layers would be computed in the averaging process as shown in Figure 3.3(a), decreasing the reliability of the lithological interpretation of the reflectance series. Obviously, it is important to choose outcrops with plane parallel layering. The presence of folds or faults in the area of point-cloud selected for the reflectance series calculation must be likewise avoided. These structures are often present in outcrops, especially in the large ones. If folds or faults are recognized in the point-cloud, during the processing phases they should be taken into account and the areas in which they are developed should not be considered.

The presence of debris or vegetation (e.g. moss, grass) on the outcrops can influence the intensity recorded by TLS and then produce undesirable effects also on reflectance series because the intensity datum refers to the surface of the scanned object. The cleaning should be conducted as better as possible, but it is clear that a non-detectable, unwanted local variability will always influence some of the points. If this is true and can in principle



Figure 3.4: *Example of the cleaning of a point-cloud. The parts of point cloud that must be deleted are highlighted in red.*

rise doubts on the reliability of the geologic interpretation of intensity, local variations in intensity due to factors different from the lithology are averaged because the number of points involved in generation of a reflectance series is generally very high (several thousands or tens of thousands points). This is confirmed by the results of the previously described experiments. Anyway good practice should be a careful chose of outcrops as much clean as possible. Areas characterized by debris coverage, streaming water or vegetation should be avoided or removed in the pre-processing phase (Figure 3.4(a) and Figure 3.4(b)). Despite these limitations, reflectance series showed to be representative of the clay content and demonstrated to be a valid tool to represent variations in clay abundance in the considered rocks. In the next Chapter, reflectance series will be subjected to time series analysis and their usefulness in cyclostratigraphic studies will be tested.

Chapter 4

Validation of the methodology

IN this Chapter the TLS-based cyclostratigraphic study of two stratigraphic sections is presented. The sections are the Ardo creek section (Southern Alps) in which the Paleocene Scaglia Rossa (s.l.) outcrops and the Contessa section (Central Apennines) modeled in Cretaceous rocks and encompassing the entire Marne a Fuocidi Formation. The sections were chosen because they match the characteristics needed for a good TLS acquisition and because the considered stratigraphic intervals were in the past subject of several cyclostratigraphic interpretations. They constitute good case-studies to test the developed methodology and the potential of application of TLS to cyclostratigraphy.

The reflectance series obtained from the TLS acquisitions of the sections have been studied via time series analysis. The interpretation of the power spectra is discussed in the following chapters. Time series analysis was carried out with the MatlabTM `ptm` function which uses the line spectral estimator after [Thomson, 1982].

4.1 Ardo creek section

4.1.1 Geological setting

The Ardo creek valley is situated towards south the city of Belluno (north east Italy), nearby the village of S. Antonio Tortal and runs, approximately from SE to NW, on the southern limb of the Belluno syncline. The Belluno syncline is a large major structure of the Southern Alps structural domain and is occupied by the Val Belluna valley. Its axis is SW-NE oriented and the shape is asymmetrical. The north western limb is strongly deformed for the presence of the major shear zone testified by the cropping out of the Belluno line, one of the most important south-verging thrust of the Southern Alps. The south eastern limb is modeled in a gently NW dipping monoclyne that passes towards SW to a wide antitline.

The stratigraphic succession of the Belluno syncline contains rocks whose age ranges from the Late Triassic (Dolomia Principale Fm.) to the Middle Eocene (Flysh di Belluno). These deposits testify the regional rifting phase that the southern passive continental margin of the Tethys (Adria promontory) underwent and that, according to [Winterer and Bosellini, 1981], caused the progressive breaking up and drowning of the former shallow water carbonate platforms. A set of NS oriented normal faults developed, that structured from east to west a series of highs and lows, known as platforms and basin, or troughs. The stratigraphic successions of the Val Belluna testify the progressive filling of one of these structural lows, the Belluno basin.

The Ardo creek section (Figure 4.1) is cut in the Early Paleogene deep water deposits commonly known as Scaglia Rossa (s.l.), and shows evident tabular layering constituted essentially by alternation of marls and limestones. This stratigraphic interval was studied since the 1970s [Grandesso, 1975], the biostratigraphical setting being then refined in the early 2000s. The part of section that was considered in this work is Danian-Selandian in age and, from a biostratigraphical point of view, encompasses the top of the NP4 and base of the NP5 biochronozones [Agnini et al., 2007, Giusberti et al.,

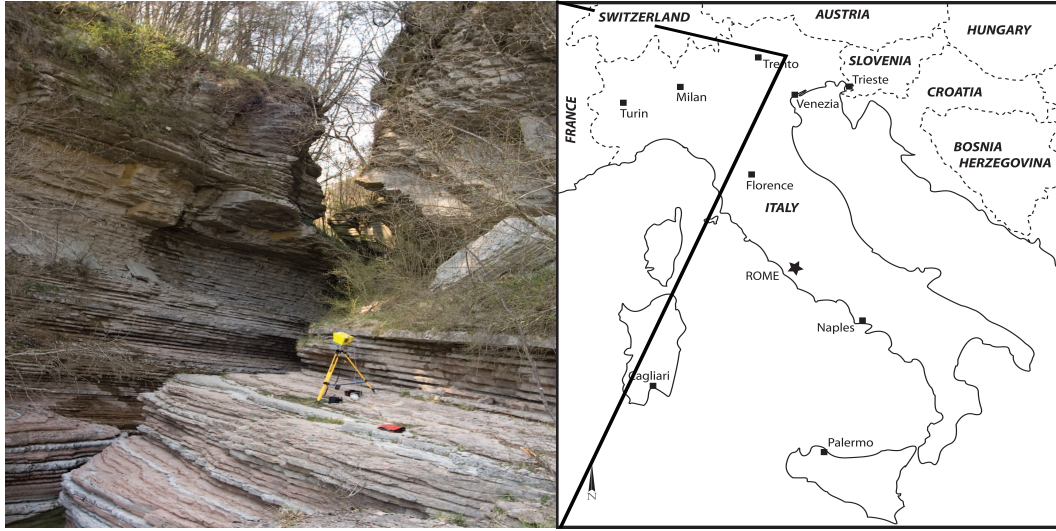


Figure 4.1: *The well developed limestone-marl alternations of the Scaglia Rossa (s.l) in the Ardo creek gorge (Belluno, northern Italy) and location of the studied section.*

2007].

In this section the availability of accurate biostratigraphy couples with the presence of former cyclostratigraphic studies that interested roughly the same stratigraphic intervals. [Poletti et al., 2004] studied the limestone-marl couplets of the Ponte nelle Alpi section (nearby the city of Belluno) with a multidisciplinary approach aimed at determining the origin of these alternations. The Ponte nelle Alpi section encompasses a stratigraphic interval from the top of the P2 to the base of the P2 biochronozones [Berggren et al., 1995], thus including also the NP4 and NP5 zones represented in the Ardo section. Spectral analysis carried on the carbonate content time series highlighted cyclicities which ratios agree with those of the Milankovich periodicities.

Summarizing, the Ardo creek section was chosen for a first validation of the proposed methodology TLS data-based cyclostratigraphic studies for the following reasons:

1. The exposition conditions are good. The outcrop is a vertical wall with planar layers gently dipping towards NNW. With the chosen acquisition

position, beds dip towards left and towards the TLS.

2. The outcrop is not interested by faults or folds.
3. The rocks are essentially constituted by limestone-marl alternations.
4. Cyclostratigraphic interpretation of the same stratigraphic interval has been already carried out in previous works.

4.1.2 Time series analysis of the Ardo reflectance series

The Ardo section was scanned with ILRIS 3D TLS from a mean distance of ~ 20 m and applying mean sampling step of 8 mm.

The resolution of the reflectance series allows to well recognize the beds. Calcareous beds correspond to maxima, marly ones correspond to minima. Pre-processing was aimed at eliminating points representing vegetated and debris-covered areas. Moreover, some areas characterized by moisture were noticed and canceled.

These areas are evident because their intensity is very low with respect to adjacent points along strike that obviously describe the rock properties correctly. The remaining points were exported in ASCII format and treated to have distance-corrected intensities following the previously described procedure. After the re-orientation the points were processed and the reflectance series generated (Figure 4.2). Note that in Figure 4.2 the y axis, which corresponds to the stratigraphic thickness, has negative values because the reference system is the one of the TLS, that was positioned, topographically above the base of section.

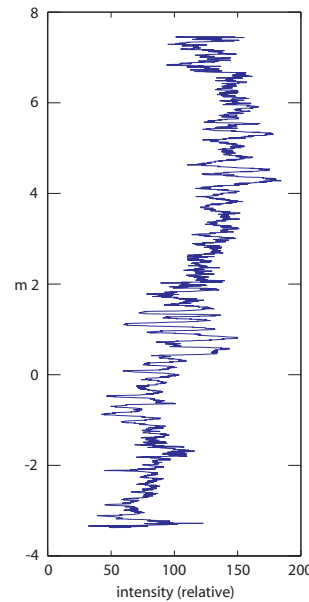


Figure 4.2: *Reflectance series of the Ardo section.*

Once the reflectance series was obtained, it was studied by time series analysis to highlight possible cyclicities. The obtained power spectrum is shown in Figure 4.3. Several peaks are visible in the spectrum and much of the spectral power is concentrated between 4 and 5 cycles/m, corresponding to the 20-25 cm thickness of the limestone-marl couplets. This demonstrates that TLS recognizes a cyclicity connected to the limestone-marl alternations.

Keeping in mind that intensity showed to be linked to the relative variations of clay abundance in these rocks, this suggests that the cyclicity detected in reflectance series represents oscillations in clay content. This result is in agreement with the analyses in [Poletti et al., 2004] that pointed out cyclicities connected with the fluctuations in carbonate content, when it is assumed that the Ardo succession includes only a carbonate and a clay component.

In order to better clarify the interpretation of the spectrum where spectral power results spread between 4 and 6 cycles/m, an evolutionary spectrum (see Appendix A for explanation) was calculated from the reflectance series. The evolutionary spectrum is shown in Figure 4.4 and in the same figure are also plotted the spectrum of Figure 4.3 and the reflectance series of Figure 4.2. In the evolutionary spectrum a quite continuous and well defined spectral line is visible. In the lower part of the section the frequency is around 6 cycles/m, while in the middle and upper part it is shifted to lower frequencies (around 4 cycles/m).

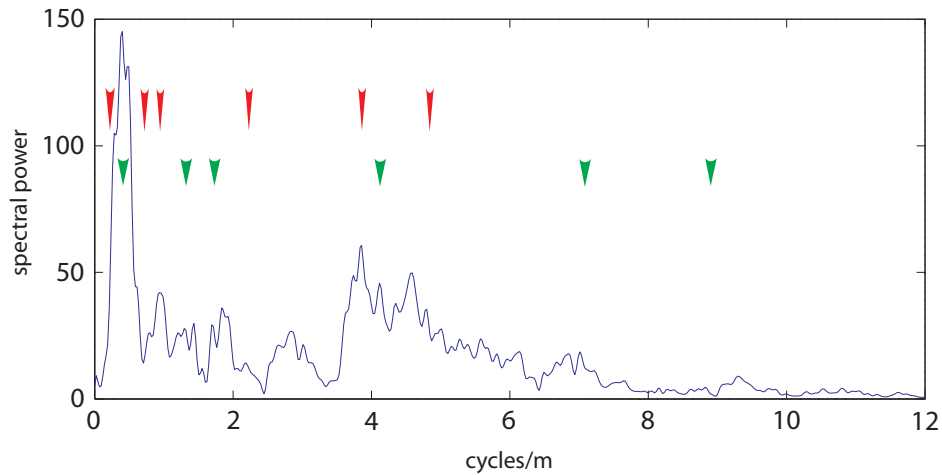


Figure 4.3: *Power spectrum (2π Thomson multitaper spectrum) of the Ardo reflectance series. Red arrows mark the position of orbital frequencies if the high spectral power is attributed to long precession, where green arrows are placed interpreting the peak as obliquity. Further comments in the text.*

4.2 Discussion

The spectral line recognizable in the evolutionary spectrum and his trend towards higher frequency suggest possible variations in sedimentation rates, with an increase in the middle-upper part of the section underlined by the lowering of the frequency of the spectral line.

Since the Ardo section encompasses the upper part of the NP4 biozone comprising its boundary with the NP5 and good biochronostratigraphic constraints are available it is possible to have an estimate of the time span represented by the last 3 m of the NP4 between the first occurrence of *Sphe-nolithus* spp. and the first occurrence of *Fsciculithus* spp. [Agnini et al., 2005]. After [Agnini et al., 2007] is possible to estimate in ~ 370 kyr the time span represented in the interval. The couplet count in the interval points out that ~ 12 limestone-marl couplets are present. If for each couplet is considered the representation of an orbital cycle (i.e. it is of the same duration) this leads a duration of ~ 30 kyr. This duration is closer to the precession band (~ 26 kyr) than to the obliquity (~ 40 kyr). In this perspective the couplets should be more likely interpreted as precession cycles. This conclusion would be in agreement with the one that seems suggested in [Giusberti et al., 2007] for the limestone-marl couplets of the Forada section (some km to the west with respect to the Ardo creek) which however encompasses more high stratigraphic interval (NP10 zone). If this is correct the interpretation of the couplets is different from that proposed by [Poletti et al., 2004] where the ~ 40 cm-thick limestone-marl couplets of the Ponte nelle Alpi section are interpreted as obliquity cycles.

The time series analysis was then carried out on the corresponding 3 m in the reflectance series. Several peaks are recognizable in the spectrum. Figure 4.5 shows the spectrum and the correspondent reflectance series interval. The evident peak at 4 cycles/m is given by the limestone-marl couplets.

A technique that can be used to support the Milankovian interpretation of a peak in a power spectrum is to suppose that a certain peak is the signal of a certain orbital parameter. It is then possible to check if other significant

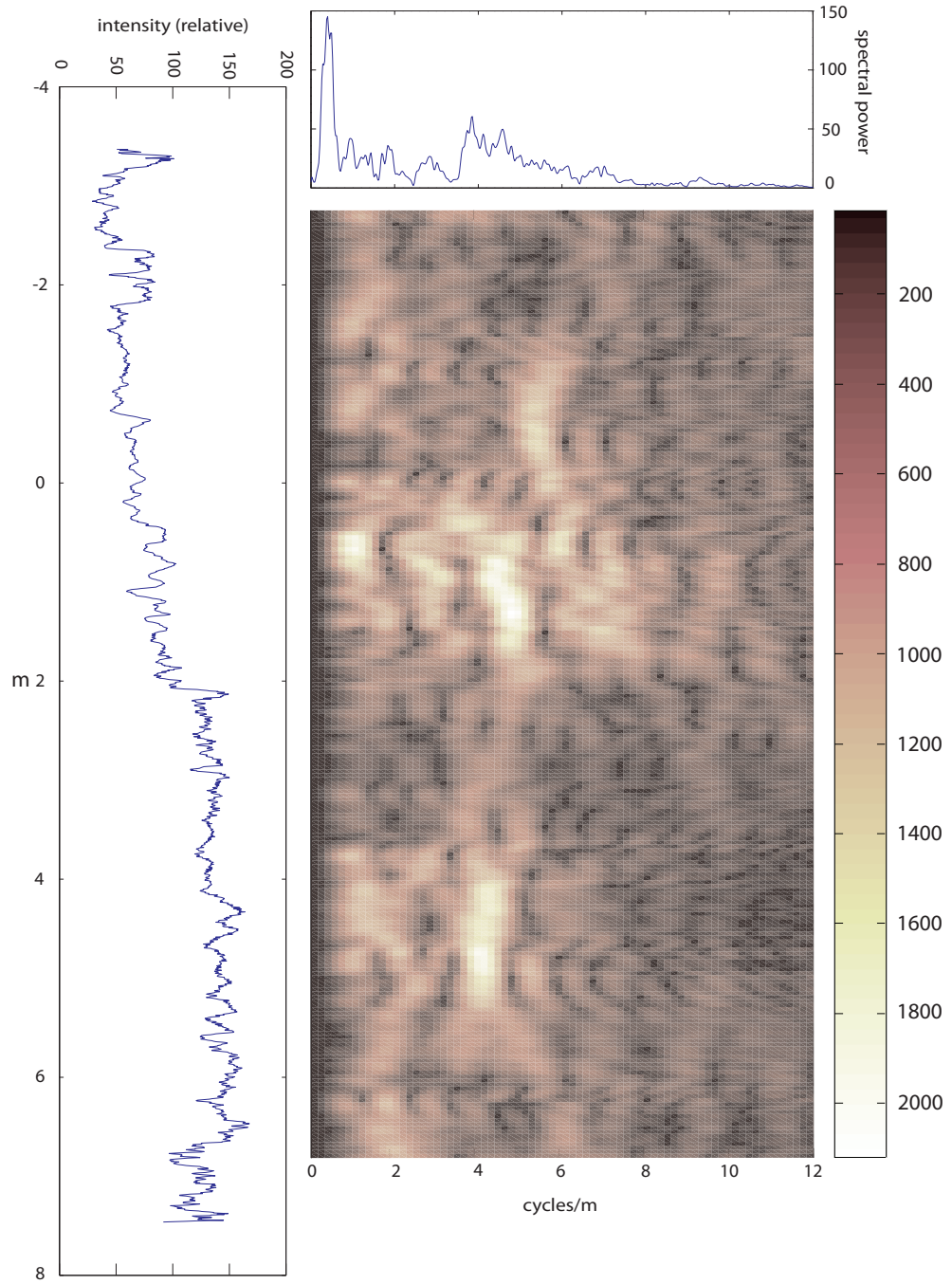


Figure 4.4: *Evolutionary spectrum of the Ardo reflectance series. On the figure are plotted also the reflectance series (left) and its simple power spectrum (top). More explanations in the text.*

peaks are found at the frequencies that should correspond to the other orbital parameters. These frequencies can be calculated from the ratios between the durations of the orbital parameters. In Figure 4.3 red arrows are placed at the frequencies at which the signals of eccentricity (~ 400 , ~ 100 , ~ 90 kyr), obliquity (~ 40 kyr) and precession (long and short) should appear if the limestone-marl couplet (peak at approximately 4 cycles/m) is interpreted as precession. The green arrows, on the contrary, are placed attributing the couplets to the obliquity.

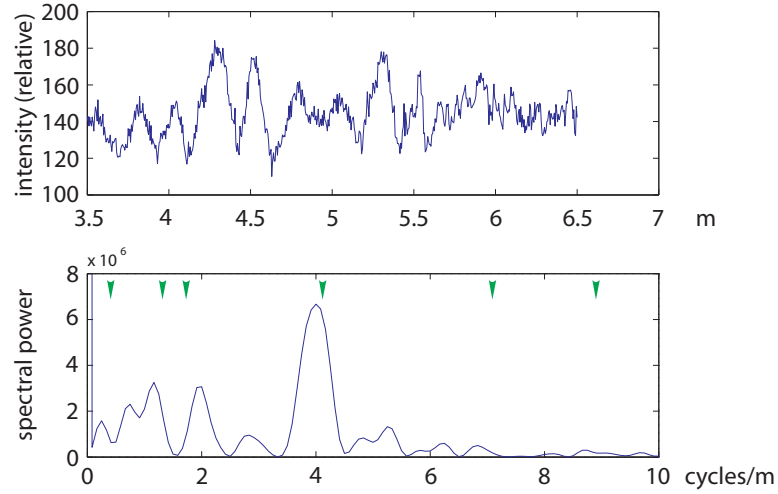


Figure 4.5: *Power spectrum (2π Thomson multitaper spectrum) of the upper part of the Ardo reflectance series. Green arrows are placed as in Figure 4.3. Further comments in the text.*

Apparently there is a better matching between the green arrows and the peaks of the spectrum and this seem to support the obliquity option. The green arrows are reported also in Figure 4.5 that refers to the upper part of the section. In this case also a good matching is found and the arrows fall very close to peaks in the spectrum, further supporting this interpretation. In particular the two peaks that should correspond to two components of eccentricity cycle (130 kyr and 95 kyr) are close to the theoretical position marked by the arrows. Rises in power are also visible at higher frequencies, close to the frequencies at which precession should appear, but they are very

low.

The last element that seems to agree with the attribution of the limestone-marl couplets to obliquity is that in the evolutionary spectrum the most evident spectral feature seem to be a single, well defined line. Obliquity does not have multiple components like precession should have.

The in-depth analysis of this aspect is however beyond the aims of this thesis and further studies should be carried out. The evaluation of the statistical significance of the peaks would be desirable in order to assess the noise level and model in the power spectrum. What is important to underline for the scope of this work is that the study of TLS reflectance series highlighted cyclicities that in other sections have been attributed to variations in carbonate content, which is in turn inversely related to the clay content, thus confirming the capability of TLS in detecting variations in these lithological parameters.

4.3 Contessa quarry section

4.3.1 Geological setting

The Contessa quarry is located near the city of Gubbio (Umbria, Apennines, central Italy). The quarry is cut in the valley of the San Donato creek, at the base of the north western slope of the Monte Foce. The outcropping rocks are comprised between the Aptian (lower Cretaceous) and the Cenomanian (upper Cretaceous) and from a paleogeographical point of view were deposited in the Umbria Marche Basin [Passeri, 1994]. In the quarry the Marne a Fucoidi Formation (formerly Scisti a Fucoidi), Aptian - Albian in age, is exposed in all its thickness ($\sim 70-80$ m) [Cita et al., 2007]. Figure 4.6 shows a panoramic view of the Contessa section.

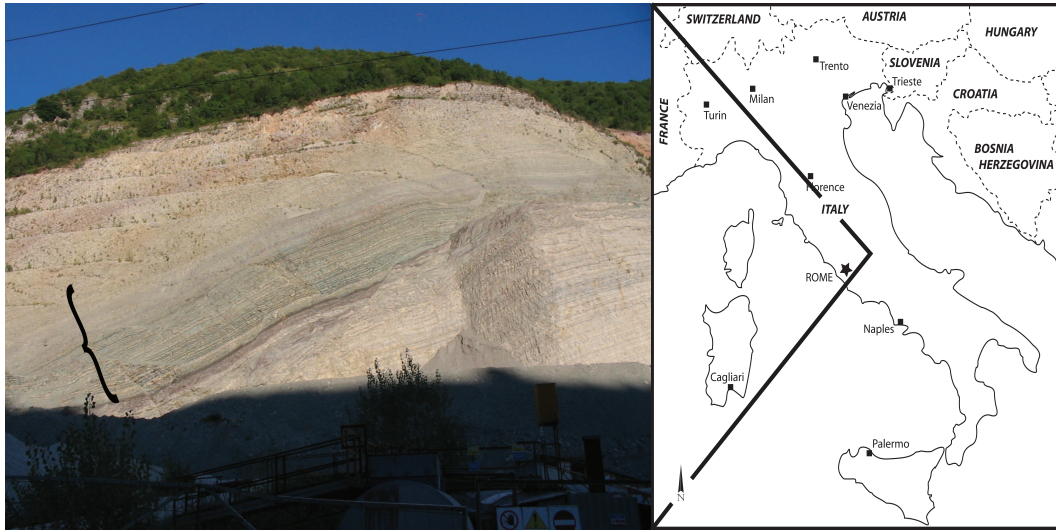


Figure 4.6: *Panoramic view and location of the Contessa section (Gubbio, central Italy). Curly bracket marks the outcropping Marne a Fucoidi Fm. (thickness ~ 80 m).*

As in the case of the Ardo creek section several factors make the Contessa section a suitable case study for the validation of the developed methodology.

1. The exposition conditions are ideal. The quarry walls are nearly vertical and the layering dips transversally towards left, thus permitting

the scan of a longer stratigraphic interval avoiding problems related to a high incidence angle of scan (see Chapter 2, Section 2.2).

2. There are few faults that cut the outcrop and produce little displacement. Those faults are easily identified in the field and avoided during scan.
3. The rocks are essentially constituted by limestone-marl alternations.
4. There are several studies that deal with the cyclostratigraphic analysis of the Marne a Fucoidi [Galeotti et al., 2003, Grippo et al., 2004, Fischer et al., 2009].
5. Logistic conditions are good and the outcrop can be easily reached with all the equipment.

The Marne a Fucoidi are constituted by polychrome coccolith-foraminiferal marls deriving from the lithification of marly globigerinid ooze deposited at high depth (~ 2 km) [Silva and Silter, 1995]. The Formation is characterized by a rhythmic interbedding of claystones, marls, marly limestones and limestones organized in plane parallel beds with thicknesses ranging from 5 cm to 25 cm [Calesini, 1981]. The sedimentological and mineralogical study on the clays of a portion of the Marne a Fucoidi (Amadeus Segment) carried out by [Tateo et al., 2000] demonstrates that the rocks of the Formation are essentially constituted by Calcite, Quartz and Sheets silicates. The latter have percentage in weight ranging from 10% to 30%.

The cyclical trend of the Marne a Fucoidi is evident and it is highlighted by chromatic variations and fluctuations in the CaCO_3 content (Figure 4.7(a)).

A great opportunity for the study of the cyclicity in the Scisti a Fucoidi was given by the drilling of the Piobbico core (Urbino, Italy) in 1982. The approximate duration of the Albian stage (12 Myrs) and the estimated accumulation rates (4-5 mm/kyr) allowed to interpret the bedding couplets of ~ 10 cm as precessional cycles [deBoer, 1982]. The limestone-marl couplets

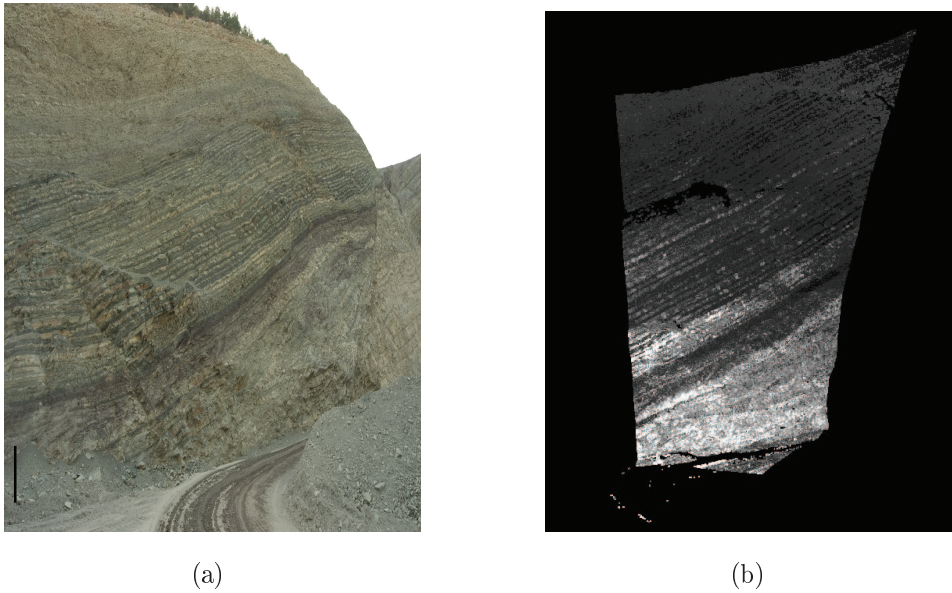


Figure 4.7: *Particular of the Marne a Fucoidi of the Contessa section (scale bar in (a) = 2m and TLS-generated intensity image (b)).*

were interpreted respectively as peaks and lows in pelagic carbonate productivity and were linked to variations in the temperature and fertility of the waters [Fischer et al., 1991, Erba, 1992].

[Galeotti et al., 2003] studied the black shale deposition in an interval (Amadeus Segment) of the Marne a Fucoidi, highlighting orbital modulation. More recently, [Grippo et al., 2004] the Piobbico core was studied performing time series analysis on a digitized and image-processed photographic log of the core. The color recorded by the camera allows to distinguish drab and red facies and is linked to the passage from anaerobic to aerobic conditions and vice versa and with the CaCO_3 content. The photo-log analysis yielded to the confirmation of the cyclicities highlighted in previous studies. In particular the cycle (of ~ 40 cm thickness) attributed to the short eccentricity, is evident from time-series analysis. The signal of the obliquity is instead not detected through all the core, but only in some intervals.

4.3.2 Time series analysis of the Contessa reflectance series

The Contessa section was scanned with TLS at distances ranging from 20 to 40 m. The chosen sampling step was approximately 8 mm. As in the case of the Ardo section, clear differences in intensity values were recognizable in the TLS point-cloud (Figure 4.7(b)). The outcrop conditions of the Contessa section, with beds dipping towards left with respect to the scanning direction allowed the acquisition of a stratigraphic thickness larger than the one that could be obtained with horizontal bedding.

This was done scanning the outcrop from three different viewpoints. The obtained point-clouds were pre-processed following the protocol described in Chapter 2 and 3. The point-clouds were cleaned and only the points that describe the section of interest were left, the intensity were corrected and referred to the same reference distance. Finally the re-orientation was performed separately on all the point clouds. This was necessary because the rotations needed to complete the re-orientation depend on where the origin of the TLS reference system is placed in the 3D space with respect to the outcrop. This position changes if the viewpoint changes. Moreover, it is important to remember that, when working with an ILRIS 3D, a rotation or a tilting of the scanner produce changes in the position of the reference system, even if minimal. For these reason it is advisable to re-orient different point-clouds to obtain a better alignment.

The reflectance series were generated with the MatlabTM script `ls_mediancoll` (see Appendix C) and had to be merged to obtain a single reflectance series on which time series analysis was performed. This was done because the linking of reflectance series obtained in adjacent intervals of the same section allows to generate long reflectance series with a higher resolution than that possible with a single TLS acquisition. However the linking must be done carefully because it could result in an offset that could alter significantly the phase of cyclicities in the section, making them less easy to detect.

There are two possible ways to perform the linking.

The first consists in individuating a reference bed common to the couple of scans which have to be linked. The area selected on the point-cloud of the lower stratigraphic interval must have his stratigraphic top adjacent to, but not overlapping with, the point-cloud of the upper stratigraphic interval. In this way the lower reflectance series begins

where the upper one ends. Limitations of this approach are that it can be difficult to recognize the reference layers, and cutting of the point clouds must be extremely accurate. If these operations are not performed properly this can result in a phase displacement of some parts of the whole reflectance series. When the time series analysis is carried out, this displacement can induce the disappearing of spectral features or the generation of false peaks. These drawbacks can be avoided by including overlapping areas in the merged point cloud. Subsequently, it is possible to link the curves automatically with a cross correlation algorithm. With this second approach problems can arise when the reflectance response of the intervals of section differs due to the non uniform conditions of the surface. In this case the correlation algorithm may fail to detect the correct overlapping. Another difficulty in using cross correlation algorithms arises with curves that have a certain degree of cyclicity. Since the same patterns are returning in different points of the curve the algorithm might find several points with high correlation coefficient possibly producing a wrong alignment.

The better approach should be chosen case by case.

The reflectance series obtained from the Contessa scans were merged using both methods, but the manual alignment gave the best results due to cyclicity of the series. After merging, jumps in reflectance values were found in correspondence of the merging points. Moreover, a trend toward higher intensity values was visible (Figure A.3). These characteristics of the curve are attributed to the presence of dust on the surface of the outcrop. The section is located in an active quarry and nearby one of the access roads to the quarry front. Trucks move along the road every day. As a result, dust is risen and deposits on the outcrop. The dust coverage is higher in the upper

part of the of section that is not interested by active quarrying. The effect of the dust (mostly made up of limestone dust) is to increase the overall intensity response of the rocks. This is most likely the cause of the increase of the intensity in the higher part of each reflectance series. In order to reduce

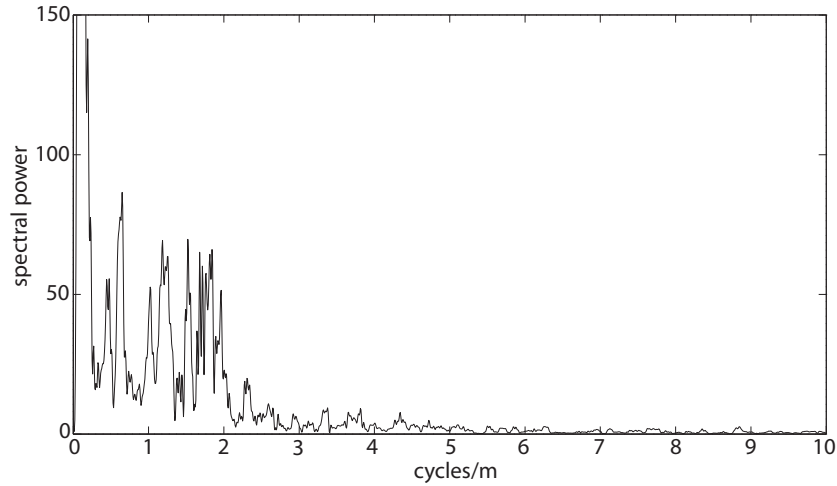


Figure 4.9: *Power spectrum (2π Thomson multitaper spectrum) of the Contessa reflectance series. Comments in the text.*

the trend, that is not desirable during time series analysis, the reflectance series was subjected to a smoothing spline detrend procedure. Detrend is a routine procedure which is carried on during time series analysis. The essential meaning of the process is further explained in Appendix A. After the detrending the reflectance series shown in Figure 4.8 was obtained, representing a thickness of about 40 m. It is interesting to notice that the reflectance series reflects well the variation of the bedding style along the section with the beds thicker in the lower part and thinning progressively towards the higher part. As in the case of the Ardo reflectance series (Figure 4.2) the stratigraphic thickness (y axis) starts from negative values because it refers to the TLS's reference system.

The reflectance series was processed with time series analysis methods in order to single out possible cyclicities. Figure 4.9 shows the result of the time series analysis on the Contessa reflectance series. A series of high peaks can

be recognized between 0.5 and 2 cycles/m. This makes the spectrum unclear and the interpretation difficult.

From a reflectance series it is possible to extract evolutionary spectra (see Appendix A). The evolutionary spectrum of the Contessa series is shown in Figure 4.10. The spectrum shows that high spectral power is recognized in the lower part of the section around 2 cycles/m. In particular two spectral lines are evident and show chain-like intersection. Moving upwards they seem to divide and move to higher frequencies in the middle part of the section. Finally, in the upper part the spectral power is again found around 2 cycles/meter. At higher frequencies the power is lower, except for two intervals at approximately 4 cycles/m.

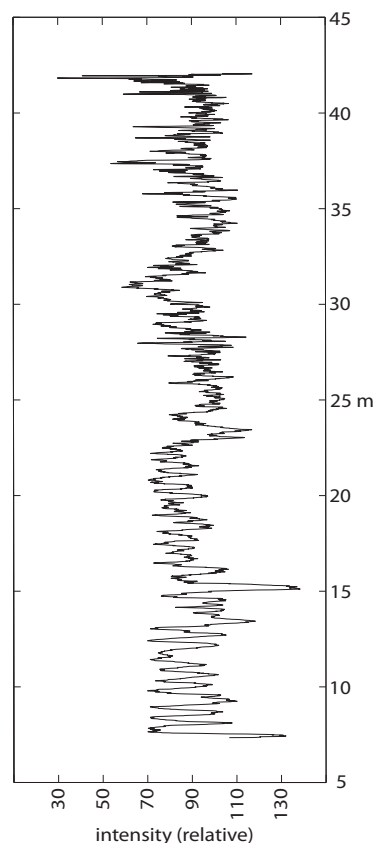


Figure 4.8: *Reflectance series of the Contessa section after detrending procedure.*

4.4 Discussion

The recognition of high spectral power at frequencies of approximately 2 cycles/m is in accordance with the results obtained by Grippo ([Grippo et al., 2004]) in the study of the Piobbico core, where a cycle of ~ 50 cm was pointed out. The cycle was interpreted by the Authors as the signal of the eccentricity orbital oscillations.

An interesting consideration can be done observing the doublet visible in the evolutionary spectrum of the Contessa section. Figure 4.11 (from [Cozzi et al., 2005], modified) shows the eccentricity-tilt-precession (ETP) curve de-

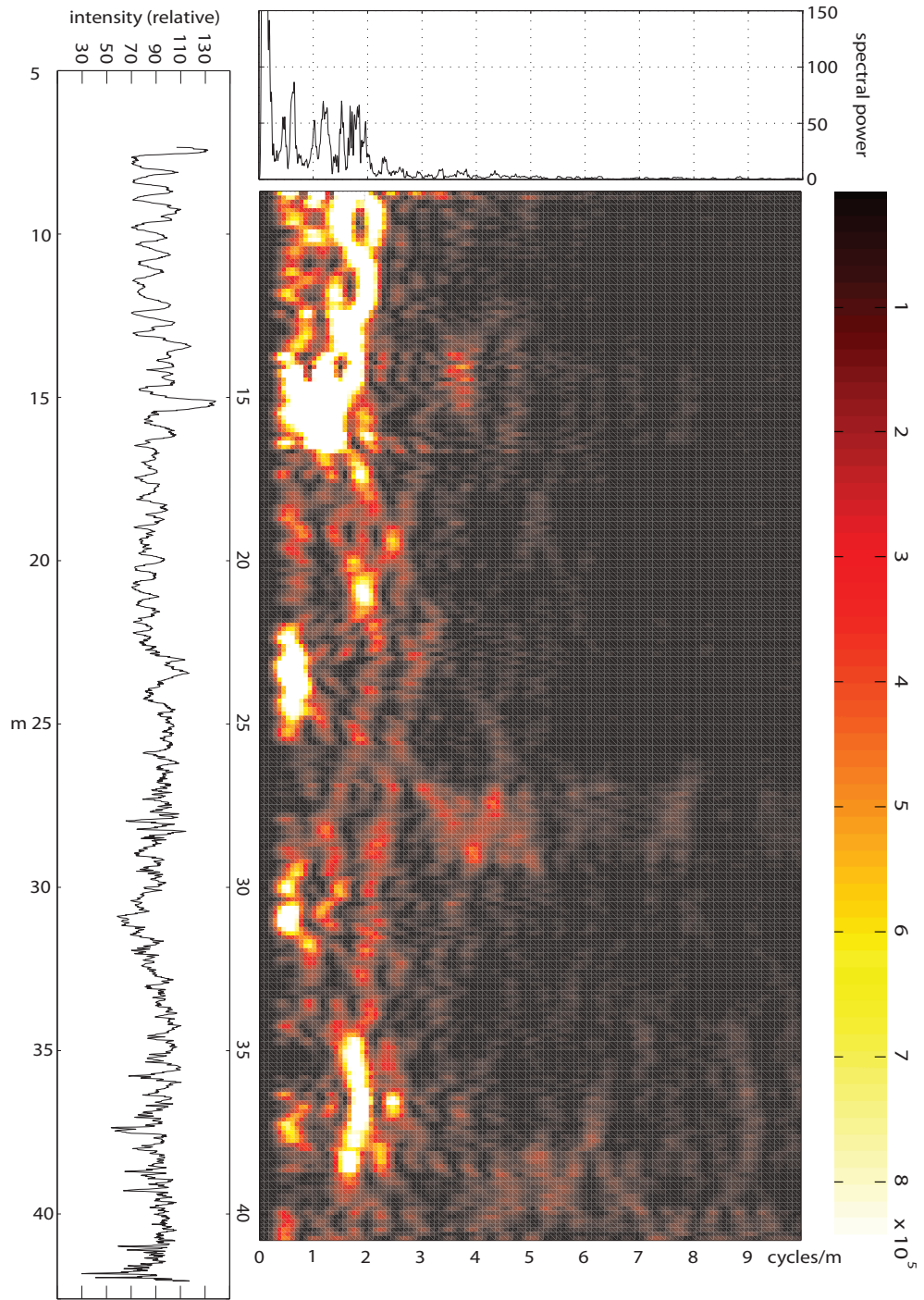


Figure 4.10: *Evolutionary spectrum of the Contessa reflectance series. On the figure are plotted also the reflectance series (left) and its simple power spectrum (top). More explanations in the text.*

rived from the LA90(0,1) orbital solution [Laskar, 1990]. Two doublet trends are visible and they refers to eccentricity and precession respectively. The occurring of the doublet is due to the fact that eccentricity and precession have a doublet structure, meaning they have two principal frequencies. As a consequence, in a spectrogram they appear like double peaks. The analogy between the trend of the eccentricity in the evolutionary spectrum of of the ETP curve in Figure 4.11 and the trend of the spectral lines at ~ 2 cycles/m in the evolutionary spectrum of Figure 4.10 is clear. This evidence further support the interpretation of the spectral signal in the Contessa reflectance series as the result of the eccentricity cycle, highlighting a feature that was not identified in previous cyclostratigraphic studies.

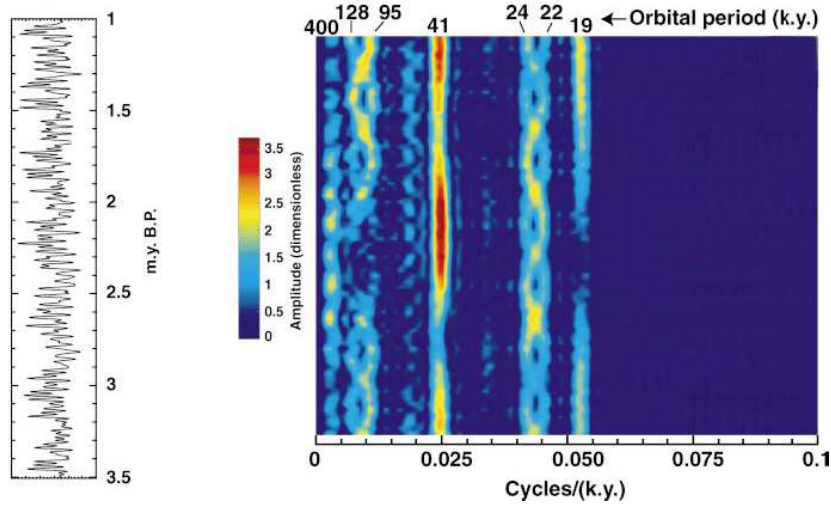


Figure 4.11: from [Cozzi et al., 2005], modified. Evolutionary spectrum of the ETP curve [Laskar, 1990] shown on the left, computed over 325 k.y. 2p prolate-tapered windows at 20 k.y. steps [Paillard et al., 1996].

The trend disappears in the middle and upper part of the spectrogram, but two spectral lines running roughly parallel are always visible. This phenomenon could be linked to variations in the sedimentation rates. The shifting towards higher frequencies would be connected to an increase of the sedimentation rate in the middle part of the section, followed by a later decrease

in the upper part, testified by the shift of the doublet again to lower frequencies, similar to the ones detected in the lower part of the section. Moreover, as shown in Figure 4.10, the variations in the sedimentation rates and the consequent shifting in the frequencies of the spectral peaks are likely the responsible for the look of the spectrum of the reflectance series (plotted in the upper part of Figure 4.10). The several peaks between 1 and 3 cycles/m are actually the track of the moving of the same peak along the reflectance series.

Chapter 5

Conclusions

IN this thesis a new application of TLS to Earth Sciences was presented and discussed.

The possibility to use ILRIS 3D TLS as a tool to collect large, high resolution datasets suitable for cyclostratigraphic analysis was studied. A series of experiments were performed with the objective of understanding the influence of geometrical, environmental and lithological factors on TLS acquisition and constraining the geological meaning of intensity values.

A new method was developed in order to evaluate and correct the intensities in function of the geometry of the acquisition and obtain an estimate of the reflectance of the materials at the laser wavelength at a given reference distance. Original MatlabTM scripts were developed to perform the correction and compare the intensity values associated to each point of a TLS point-cloud.

Experimental results show that the intensity recorded by ILRIS 3D is linked by an inverse linear relationship to the relative variations of clay content in limestone and marls due to the interaction between the mineralogical characteristics of these rocks and the laser light which is in the infrared band. This represents an important achievement because it constrains the geological meaning of TLS-recorded intensity and makes its application meaningful for stratigraphic scopes, and in particular for cyclostratigraphy. Clay con-

tent, indeed, is a sedimentological parameter linked to changes in sediment supply that can be influenced by Milankovitch periodicities.

Reflectance series are the tool developed to study the variability of intensity, and than of clay content, along a stratigraphic section made up of limestones and marls. Original MatlabTM scripts were implemented to extract reflectance series from TLS-generated point-clouds.

Since a reflectance series can be considered a stratigraphic series, time series analysis can be applied for the study of sedimentary cyclicity highlighted by variations in intensity values.

Time series analysis was performed on reflectance series obtained from the limestone-marl alternation of sections encompassing stratigraphic intervals already known to bear Milankovitch periodicities.

In the Paleocene pelagic deposits of the Ardo creek section (Scaglia Rossa s.l.), time series analysis of the reflectance series was able to highlight the presence of a strong cyclicity corresponding to the ~ 20 cm limestone-marl couplets, in accordance with the work of [Poletti et al., 2004].

The same analysis was carried on the Contessa section, encompassing the Cretaceous Marne a Fucoidi Formation. The study of reflectance series from this section highlights cyclicities that are in agreement with those pointed out in previous works with different methods. In particular, high power is found at ~ 2 cycles/m, probably representing short eccentricity in agreement with several works [Park and Herbert, 1987, Premoli-Silva et al., 1989a, Premoli-Silva et al., 1989b, Grippo et al., 2004].

These results constitute a validation of the reliability of the cyclostratigraphic study of reflectance series. Thus laser scanning confirms to be a reliable technique to capture cyclical lithological variations in stratigraphic sections.

The here proposed approach is substantially different from classical spectroscopic logging of cores aimed at lithologic characterization [Mix et al., 1992] or photolog techniques applied to cyclostratigraphic studies [Grippo et al., 2004]. TLS acquisition and data processing can be performed in a

quite short time span even if large outcrops are considered. As an example the acquisition, processing and cyclostratigraphic analysis of the Contessa section took two days to be realized. Moreover, thanks to the long range of the instrument, areas characterized by hard or difficult access can also be considered. Study can be performed directly on outcrop in the field, provided that some requirements are matched, without the need to drill expensive cores or carry on time consuming field work, especially needed if sections are long and monotonous. In addition, TLS is an active instrument. This proved to be an advantage with respect to passive sensors (e.g. optical spectrometers or simply digital cameras) because the recorded data do not depend on the illumination conditions of the target. The acquisition and interpretation of the intensity data is not biased by the perspective of the acquisition as in 2D scans, because each intensity value is associated to a point placed in a three dimensional reference system.

The fact that TLS can detect relative variations in clay abundances in the considered lithotypes does not hamper the value of reflectance series in cyclostratigraphic studies. If a calibration has to be done in situ validation is necessary, but could be limited to easy-access zones, with appreciable gain in operation time and reducing safety issues.

It could be argued that a limitation of the method is that it can be applied only when dealing with limestones and marls. If it is true on one hand, on the other limestone-marl alternations are a widespread facies association in the geological record, often studied for their sedimentary cyclicity. Clay content analysis by TLS may reveal as a new powerful instrument in such paleoclimate and cyclostratigraphic studies.

Of course, the TLS approach has some limitations and for this reason TLS cannot substitute classical methods, but should be considered a valuable tool in collecting data for refining and widening the understanding of cyclicities in sedimentary rocks. The use of an active instrument showed some advantages with respect to previously applied techniques. The obtained results pointed out the possibility to achieve lithological discrimination using one

single wavelength laser source. Interesting developments could arise for the lithological characterization of rocks if laser sources at selected wavelengths could be integrated in a TLS instrument.

*The Road goes ever on and on
Down from the door where it
began.
Now far ahead the Road has
gone,
And I must follow, if I can,
Pursuing it with eager feet,
Until it joins some larger way
Where many paths and errands
meet.
And whither then? I cannot say.*

J. R. R. Tolkien
The Lord of the Rings

Appendix A

Time series analysis

Aim of this Appendix is to give some information about time series analysis. The topic is complex and it is beyond the scopes and nature of this work to offer a complete and exhaustive treatment of it. Specific treatment of time series analysis can be found in [Brigham, 1988]. Only general concepts will be expounded here in order to explain qualitatively why this technique is applied to cyclostratigraphy. The tools and expedients used in the time series analysis of Ardo and Contessa sections (Chapter 4) are also briefly explained here without the claim of completeness.

Time series

A *time series* is defined as a sequence of data points, that is a series of observations performed at certain intervals. These intervals may be represented by any variable. This is an important statement because it means that to have a time series it is not strictly necessary to have observations acquired in time. Moreover, in a time series the observations do not necessarily need to be evenly distributed [Scargle, 1981].

As pointed out by various Authors (e.g. Preto & Hinnov, 2000 and references therein), observations made on stratigraphic sections meet the requirements needed to form a time series: they are ordered in time, because of the

superposition principle, though they are usually unevenly spaced.

Time series are *realizations* of a *process*. In probability theory a process can be defined intuitively as the rule able to produce a realization. Stratigraphic series are realizations of sedimentary processes which result from complex physical events often very difficult to model.

It is possible to distinguish between *deterministic processes* and *stochastic processes*. In a deterministic process no randomness exists in the development of the realizations of the process, that is, on the basis of the knowledge of starting conditions, it is always possible to predict the realization. In a stochastic process, on the contrary, realizations can be calculated only as probability distributions.

Time series analysis comprises the methods developed to understand the nature of the phenomenon (i.e. the process), that generated the time series from a sequence of observations. In particular, *spectral analysis* is a type of time series analysis appropriate to examine cyclic behaviour. Spectral analysis is a procedure that decomposes a time series into a spectrum of cycles of different lengths. This type of analysis is a frequency analysis, because it studies a time series with respect to the frequency domain, rather than with respect to the time domain. As highlighted in Chapter 1, cyclostratigraphy aims at studying sedimentary deposits in order to understand if the processes (i.e. the sedimentary processes) that generated a certain stratigraphic sequence (i.e. a realization of the sedimentary process) have been influenced by the cyclic variations of orbital parameters. As a consequence, Cyclostratigraphic studies can take advantage of spectral analysis to highlight cyclicities in stratigraphic series and help the interpretation of what forced their generating processes.

Fourier transform

The assumption behind the application of time series analysis to cyclostratigraphy is that the natural process which generates a stratigraphic series can

be considered, at list partially, forced by a deterministic (astronomical) process. A time series could thus be decomposed into a deterministic component, carrying the astronomical forcing signal, and a random component, usually referred at as noise. Thus, the deterministic component is "masked" by random elements that make the story increasingly complex. Random elements can have various origins. They can be introduced by the climatic system or by sedimentary processes, and/or when the realization of the process (i.e. the a stratigraphic section) is measured and represented as a time series.

The problem is then to find a tool able to analyze these complex functions and to extract the original astronomical signal. For cyclostratigraphic scopes, this tool needs to be able to recognize elements of periodicity because orbital cycles are very complex, but always quasi-periodical.

The fundamental mathematical tool appropriate to recognize a periodical component in a signal is the *Fourier transform*. A more complete treatment of Fourier transform can be found in Brigham ([Brigham, 1988]).

A simple example of its meaning is showed in Figure A.1.

Fourier theorem.

A periodic function $f(x)$, which is reasonably continuous, may be expressed as the sum of a series of sine and cosine terms (called the Fourier series), each of which has specific amplitude and phase coefficients known as Fourier coefficients.

Fourier analysis derives from the study of Fourier series and describes complex functions breaking them into simpler basic functions that are easier to understand. This break-up process is the Fourier transform. It is called "transform" because it operates a transformation of coordinates from time domain to the frequency domain. In effect, the Fourier transform decomposes a function into its oscillatory (and periodic) components.

Fourier transform is reversible, and if the Fourier transform of a function exists it is possible to go back up to the original function from the Fourier transform. Because of reversibility, the Fourier transform is called a repre-

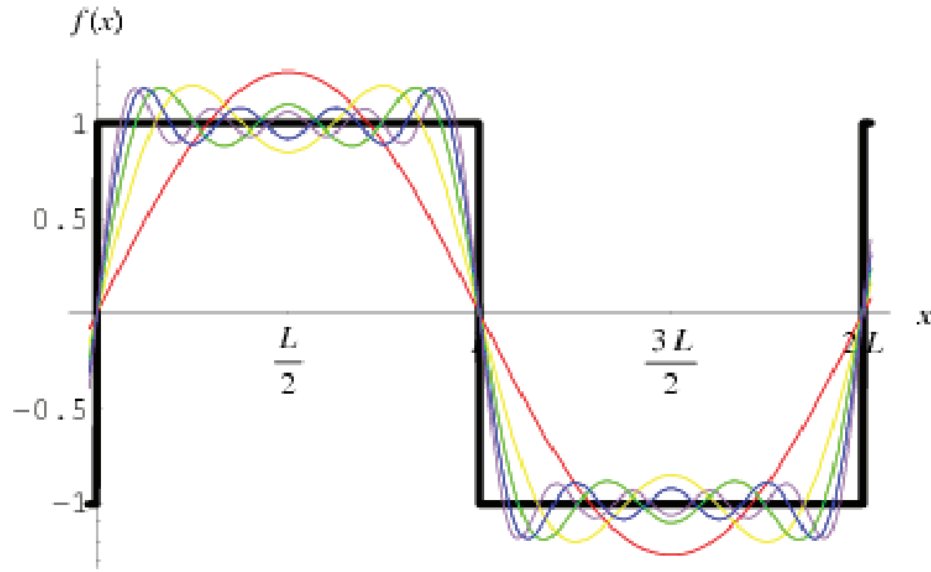


Figure A.1: Example that shows how a square wave can be expressed as a sum of sine and cosine.

sensation of the function, in terms of frequency instead of time, thus, it is a frequency domain representation.

Fourier transform is a complex function and each oscillatory component is characterized by both amplitude and phase.

The Fourier transform of a given function can be graphically represented as a Fourier *power spectrum* where the squared amplitude of every Fourier Coefficient is plotted against the frequency.

The interpretation of the power spectrum can be derived by the Parseval's theorem, which shows that the Fourier transform is unitary; that is, in a broad sense, the sum (or integral) of the square of a function is equal to the sum (or integral) of the square of its transform. The power spectrum of a function represents how the power is distributed in the frequency domain. This means that, if some frequency values play a major role in determining a function of interest, they will appear as higher peaks in the power spectrum of the function.

Discrete Fourier transform

It is important to underline that the general form of the Fourier theorem applies to continuous functions. In the case of time series the continuity condition is not matched. This happens because a time series comes out from a series of discrete measurements that, in the luckiest case, were taken at regular time intervals. This, in other words, means that a time series is a sampled version of the function that has to be analyzed with the Fourier transform. Stratigraphic time series comes from discrete sampling of certain properties of a stratigraphic section and generally are not taken at regular time intervals. Moreover, stratigraphic time series are limited in space and consequently in time. The problem thus becomes, how to obtain power spectra of discrete and limited time series.

The discrete Fourier transform (DFT) is one of the specific forms of Fourier analysis. As the Continuous Fourier Transform it changes one function into another, which is called the frequency domain representation (DFT), of the original function. The difference with the Fourier transform is that the DFT requires an input function that is discrete and whose non-zero values have a finite value.

From what has been said it is clear that the DFT is a suitable tool for the analysis of time series obtained from stratigraphical sections.

The time necessary for the calculation of a DFT is quite long. To reduce computational time, during the 1960s an algorithm called Fast Fourier Transform (FFT) was developed and is now available in many softwares for time series analysis like MatlabTM calculus package.

Given a time series of a certain variable obtained from a stratigraphic section it would be always possible to analyze it with a FFT in order to obtain a power spectrum of the series. From the spectrum it will be possible to see if frequencies with particularly high spectral power appear in the time series. High peaks in the power spectrum will represent spatial cyclicities that have particular importance (i.e. recur often) in determining the function that links the considered variable with the space (i.e. the variation of the

measured parameter along the stratigraphic section). The longer is the time series and the higher the sampling frequency, the higher will be the resolution of the power spectrum that can be calculated.

Detrend

One of the problems that are often encountered in the study of stratigraphic series is their *non-stationarity*. This means that they usually do not have constant mean and variance. An example of non-stationary is given in Figure A.2 from [Preto, 2001], where the thickness series of the Latemar platform (southern Alps, Italy) is shown. Figure A.3 shows the non-stationarity of the intensity values in the middle part of the reflectance series obtained from the TLS acquisition of the Contessa section.

Non-stationarity in stratigraphic series can be represented by trends of variable complexity recognizable in the series. Causes can be of various nature. As an example a linear trend in a thickness series can be due to a progressive rise in sedimentation rates and the consequent increase in bed thickness, but more complex trends are often found [Goldhammer et al., 1987].

The main problem that rises in presence of a non-stationary time series is that most of the power is contained in the trend, and may mask oscillatory components in a power spectrum. If possible, the trend should be deleted or at least reduced to have a more reliable spectral estimation. This is done performing a detrend on the curve. Detrending procedures are routine procedures that are applied in order to reduce trends in time series. Substantially, a smoothing function is fitted to the time series, and then subtracted to get closer to stationary conditions and have a more reliable spectral estimation.

Detrend can be performed with functions of various order, but must be done carefully, and should be based on the understanding on the generating causes. Generally, the fitting with polynomial functions of the fourth order or higher might result in the subtraction of otherwise detectable oscillatory

components and is thus to be avoided.

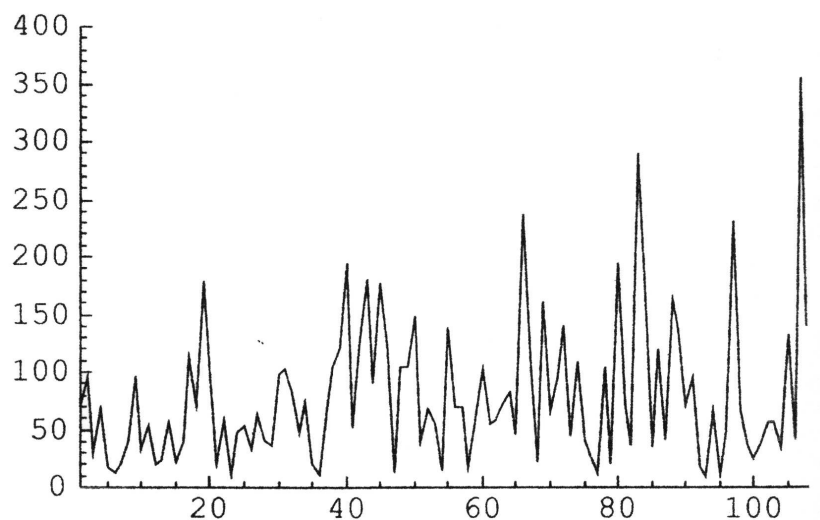


Figure A.2: *Example of non-stationarity in a thickness series. From [Preto, 2001].*

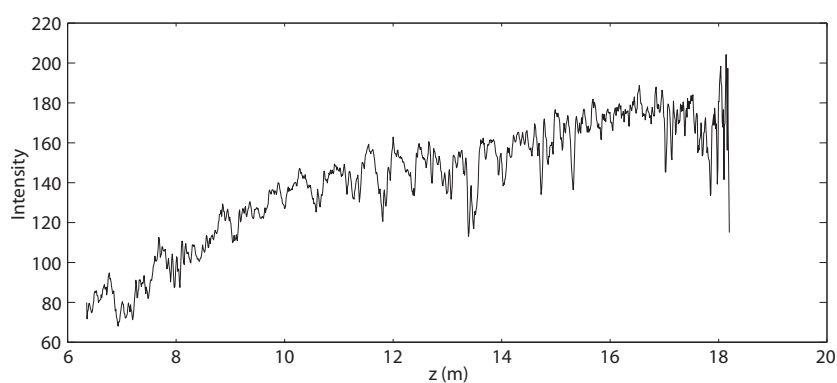


Figure A.3: *Example of non-stationarity in the reflectance series of the middle part of the Contessa section.*

Evolutionary spectra

As already pointed out stratigraphical time series can be often characterized by trends due to variations in sedimentation rates during geologic time. A

consequence of these variations is that the dominant frequencies that compose the power spectrum are not constant. This means that cyclothem can have variable thickness along a stratigraphic section. Supposing that a cyclothem is linked to orbital cyclicities, this implies that in the same time span different amounts of sediment were deposited. If a power spectrum of a series with those characteristics is generated it would probably show several peaks or wide, less sharp, peaks, encompassing a larger frequency range. The interpretation of such spectra is then difficult because the identification of important cyclicities could be biased. A way to overcome the problem of mobile peaks is the study of *evolutionary spectra*.

An evolutionary spectrum is realized generating many power spectra of fixed length at progressive intervals on a time series, computing spectra from successive short segments. The considered intervals should be chosen carefully because if they are too short some peaks can be missed, whereas an excessive widening results in loss of resolution. An evolutionary spectrum usually consists in a 2D plot (see Figure 4.10 as an example) in which on the x axis are plotted the frequencies and on the y axis the stratigraphic heights. For the representation of the peaks a colour scale is chosen and peaks are coloured in tones of different intensity in function of their height. In other words the plot is composed by many power spectra, placed side by side and seen from top. In an evolutionary spectrum a peak that does not change frequency along the section will appear as a recognizable straight coloured line, while peaks that change spatial frequency along the sections will result in curved spectral lines. Obviously evolutionary spectra are particularly useful in long series, or at least in series that are long with respect to the length of the cyclicities that has to be detected, because in a long series is possible to select longer intervals for the power spectra generation. Evolutionary spectra are particularly useful in testing the stability of periodic components of a time series. If stable peaks (i.e. peaks that are recognizable in long intervals of the series) are absent this represents a clue of the lacking of a deterministic component, that is the series may be the product of a random process.

Appendix **B**

Remote sensing

In this appendix, some of the physical principles that rule the interaction of matter and electromagnetic radiation are presented. These principles are the basis of remote sensing (RS) techniques. A detailed treatment of these phenomena is beyond the scope of this thesis and details can be found, for example, in [Hunt, 1982, Salisbury, 1993, Clark, 1999]. Specific notions about the interaction of infrared radiation with carbonates and clay minerals will be given hereafter.

According to the classic electromagnetic theory, radiation has an oscillatory nature. An electromagnetic wave consists of coupled magnetic and electric fields which oscillates in space and time. The distance in space between two adjacent crests is the wavelength (λ) which is commonly measured in nm or μm . If time is considered, the interval between two crests is defined as the period (T) of the wave. The period is the inverse of the frequency (f), so $f = 1/T$. The inverse relationship $v = f\lambda$ (where v is the speed of the wave) links frequency and wavelength.

Electromagnetic radiation can be classified into types according to the frequency (f) of the wave. The two extreme classes are the radio waves and the gamma rays which have, respectively, the lower and highest frequency. The range of all possible electromagnetic radiation frequencies is called electromagnetic spectrum. Commonly the electromagnetic spectrum

is divided in function of the wavelength into classes called spectral ranges: a) ultraviolet (UV), from 0.001 to 0.4 μm , b) visible, from 0.4 to 0.7 μm , near-infrared (NIR), from 0.7 to 3.0 μm , middle-infrared, from 3.0 to 30 μm and far-infrared, from 30 μm to 1 mm.

All bodies at temperature higher than 0 °K emit electromagnetic radiation at a wavelength characteristic of the materials of which they are constituted. At Earth's environmental temperature the emission has very low intensity and very sensible instruments are necessary to detect it.

Besides emitting energy, bodies also interact with electromagnetic radiation when it hits them. Incident radiation is partly transmitted, partly absorbed and partly scattered. The radiation that is scattered away from the surface can be measured. Essentially, it is possible to say that the amount of scattering versus absorption controls the amount of photons that are reflected from a surface. The ways in which photons interact with matter depend on physical properties of the latter and on the wavelength of the incident radiation. The discipline that studies the interaction of electromagnetic radiation and matter as a function of the wavelength is the *spectroscopy*.

To characterize quantitatively the interaction between matter and electromagnetic radiation is useful to define the following physical quantities:

- *Transmittance*. Fraction of incident light at a specified wavelength that passes through a sample. The transmittance of a sample is sometimes given as a percentage.
- *Absorbance*. Represents the amount of incident light that is absorbed during the passage through a sample. It is defined as the negative logarithm of the ratio between transmitted and incident light intensity. It is appropriate to remember that absorbance is different from *absorption*, being the first a mathematical quantity while the second refers to a physical process.
- *Reflectance*. Fraction of incident electromagnetic power that is reflected at an interface.

Remote sensing (RS) is the scientific discipline that tries to gather information about an object with a device that is not physically in contact with it. RS can be performed with various sensors and it concerns a wide range of disciplines, nevertheless it had strong development in Earth Sciences and Space exploration because it allows to investigate the Earth's surface or that of planets from great distances (such as those at which satellites operate). The study of aerial and satellite images aimed at characterizing the Earth surface is a classical application of RS. In this applications, RS, in order to achieve its goals, studies the reflected electromagnetic radiation and links its characteristics to the nature of the investigated objects.

RS can be passive or active. In passive RS the natural energy (radiation) emitted or reflected by an object is detected by a sensor. As an example of passive RS is represented by the study of satellite and aerial images where the the most common source of the reflected radiation is that constituted by sunlight. In active RS, on the other hand, an active source of electromagnetic radiation (e.g. a laser source) is used to scan an object and is coupled with a passive sensor that measures the radiation reflected or backscattered from the target. RADAR is an example of active remote sensing as well as TLS. Both in passive and active remote sensing the attention is concentrated on the radiation that reaches the receiver sensor after having hit the considered target. This radiation, being proportional to the reflectance of the object, can give information on its characteristics.

By measuring the interaction of various materials with the electromagnetic radiation it is possible to obtain their reflectance spectra. A reflectance spectrum, or spectral reflectance, of a material is a plot in which the reflectivity is displayed in function of the wavelength of the incident radiation. Maxima and minima recognizable in the spectra are often characteristic of a material, thus giving a spectral signature (fingerprint) of a material. Figure B.1 [Clark, 1999] shows reflectance spectra of some minerals. Maxima in the spectra correspond to wavelengths at which a material is particularly reflective, and a large amount of the incident radiation is backscattered and

can be detected. Minima, on the other hand, are found at wavelength that are strongly absorbed and poorly reflected.

In a simplified picture, absorption can be ascribed essentially to two processes [Hunt, 1982].

- Electronic processes. The absorption of incident photons causes a change in the energy state of some atoms from a lower to a higher energy level. A particular kind of this process is the crystal field effect that regards the transition elements (Ni, Cr, Co, Fe, etc.) contained in the crystalline lattice. Absorption can also happen for charge transfer between ions in a mineral, or for the passage of electrons from the so called "*valence band*" in which they occupy fixed positions to the "*conduction band*" in which they can move freely. Last kind of electronic absorption is the one due to the presence of "color centers" in the crystalline lattice, caused by the presence of defects in the mineral structure.
- Vibrational processes. They are due to the fact that bonds between atoms, and between or within molecules of a crystal lattice can vibrate. Depending on the number N of atoms, molecules can vibrate in $3N-6$ fundamental modes. Besides the fundamental modes of vibration there are others frequencies, at which the vibration occur, that are approximately multiples of the fundamental ones or of combinations of these. These frequencies are called overtones.

As already pointed out, reflectance spectra have clear differences that are the basis on which the possibility to distinguish between materials with a remote sensing approach is founded. Materials that absorb a lot of radiation in certain wavelengths will appear dark in correspondence of those wavelength because the amount of reflected radiation is small, whereas they will appear bright in the parts of the electromagnetic spectrum where they have high reflectance. It is straightforward that if an object constituted by two materials is observed in a spectral range where the two materials have

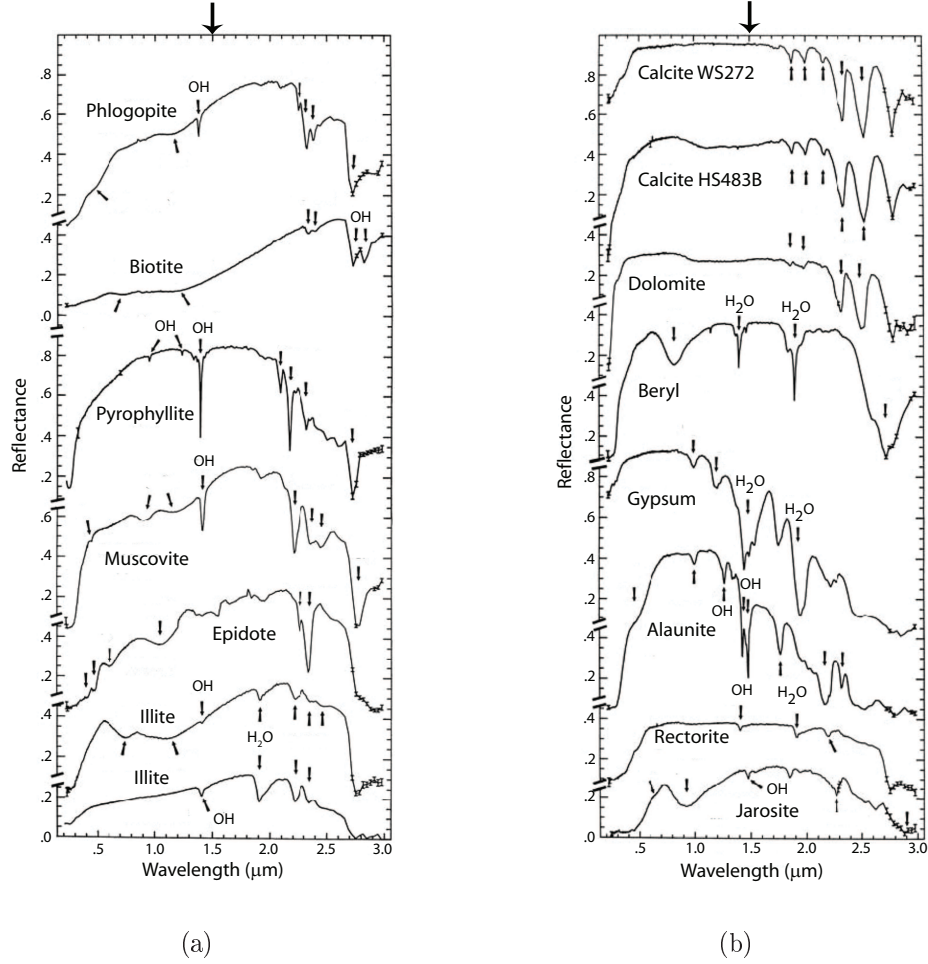


Figure B.1: Reflectance spectra of several minerals are shown. In (a), from [Clark, 1999], it is possible to notice that phlogopite, biotite, pyrophyllite, muscovite and illite, all clay minerals, show vibrational absorption bands due to O-H bonds around ~ 1.5 nm wavelength (marked with the arrow). In (b), from [Clark et al., 1990], the same feature is not visible in the reflectance spectra of Calcite and Dolomite.

different reflectance, it will be possible to distinguish them since one will appear dark and the other bright. In this way, it will be also possible to map the distribution of the two materials on the surface of the object.

The spectral characteristics of minerals are particularly important when dealing with rocks, since rocks are constituted by an assemblage of minerals. A widely diffused application of RS is, indeed, the mapping of rocks from satellite images, that results particularly useful in the study of large extensions or of areas difficult to reach directly.

Reflectance spectra of Figure B.1(a) show that clay minerals are characterized by several absorption bands. Many of them are caused by vibrational processes connected to fundamental modes and overtones of the vibrations in bonds of water and OH (hydroxyl) ions in the minerals. Clay minerals have the capacity of hosting a large amount of water and hydroxyl ions due to the structure of their crystal lattice. A high absorption band is visible around $\lambda = 1.4 - 1.5 \mu\text{m}$, that is the wavelength of emission of the ILRIS 3D laser scanner. Also reflectance spectra of carbonate minerals show absorption features, due to vibrational processes, but at 1.4-1.5 μm no absorption is visible Figure B.1(b). The reflectance of carbonate minerals at that wavelengths results 40%-50% higher than that of the clay minerals.

This observation suggests that TLS equipped with infrared laser light should be sensible to this difference in reflectance. Since sedimentary successions can be made up by carbonate rocks with variable amounts of clay (marls or clayey limestones) differences in intensity in the acquisition of these rocks are expected. The topic is widely discussed in Chapter 2.

Appendix C

MatlabTM scripts

In this appendix the original MatlabTM scripts used in data processing of ILRIS 3D TLS data are presented. These softwares were tested and developed in collaboration with Dr. Giordano Teza and Dr. Nereo Preto of the Dipartimento di Geoscienze of the Università degli Studi di Padova. Giordano Teza and Nereo Preto materially wrote the scripts.

The scripts are reported in the following. The steps of the work-flow for intensity data processing and reflectance series generation are described in Chapter 3.

Scripts for intensity data processing

ls_raw2carty

This script permits to transform the raw data provided by ILRIS 3D TLS from polar to cartesian coordinates. This passage is necessary to pre-process raw data in PolyworksTM since the InnovMetric software accepts only data in cartesian coordinates.

```
function [x,y,z,I] = ls_raw2carty(p,t,r,I);  
%  
% ===== FROM RAW DATA TO CARTESIAN =====  
% Coordinate transformation for laser scanner measurements  
5 % =====
```

```

%
%[x,y,z,I] = ls_raw2carty(phi,theta,rho,Ir),
%
% where the input data dare phi, theta, rho represent the
10 % point cloud with intensity Ir, expressed in spherical coordinates.
%   phi : azimuth;
%   theta: elevation;
%   rho : range.
% The angles are expressed in degrees.
15 % Please note that the azimuth is measured from the y-axis (usual
% convention: from the x-axis), according to Optech parser.
% Please note that the angles are an half of the usually considered angles.
%
% If Ir is not normalized in the range [0,255], the normalization can be
20 % optionally performed. If the normalization is performed, the corresponding
% parameters are stored in a file.
% Before the normalization, statistical data about the intensity are
% presented, and the user can delete the extreme values (note that the
% stored parameters are related to the cleaned data if some point is
%   excluded).
25 %
% The output data x,y,z,I are the Cartesian coordinates and the
% corresponding intensity.
%
%[x,y,z,I] = ls_raw2carty(A)
30 %
% where A is a matrix arranged as
%
%   [phi theta rho I]
%
%
35 % Computations are as above, both the A-matrix is considered.
%
%[x,y,z,I] = ls_raw2carty
%
% As above, but the name of the file contaning the A matrix is interactively
40 % asked.
%
% This function calls SAVECOND.

% G. Teza, 2007, 2008.
45
format long e

if nargin < 1
    nowell = 0;
50    defans = { ' ' };
    while nowell == 0

```

```

    try
        prompty = {'Raw data filename (extension is necessary):'};
        fields = {'filein'};
55         acquis = inputdlg(prompty, 'RAW DATA FILE', 1, defans);
        if ~isempty(acquis)
            acq = cell2struct(acquis, fields);
            filei = acq.filein;
        else
60             filei = [];
        end
        A = load(filei, '-ascii');
        sza = size(A);
        if sza(2) < 4, nindno = 0; else nindno = 1; nowell = 1; end
65     catch
        nindno = 0;
    end
    if nindno == 0
        menoval = menu(sprintf('%s IS INVALID FILENAME', char(filei)), ...
70         'ANOTHER FILENAME', 'EXIT');
        if menoval == 2, nowell = 1; fatto = 0; else defans = {char(
            filei)}; end
        else
            nowell = 1; fatto = 1; % Good data
        end
75     end
    elseif nargin == 1
        A = p;
        sza = size(A);
        if sza(2) < 4, fatto = 0; else fatto = 1; end
80     elseif nargin == 4
        lp = length(p); lt = length(t); lr = length(r); li = length(I);
        if (lp == lt) & (lt == lr) & (lr == li)
            fatto = 1;
        else
85             fatto = 0;
        end
    else
        fatto = 0;
    end
90     if fatto == 0
        x = []; y = []; z = []; I = [];
        help ls_raw2carty; disp('No computation have been performed'); return
    end
95     if nargin <= 1
        p = A(:, 1); t = A(:, 2); r = A(:, 3); I = A(:, 4);

```

```

end

100 maxi = max(I); mini = min(I);
    if (maxi > 255)|(maxi <= 1)|(mini < 0)
        [mx,sx] = histnorm(I,20,1);    % Histogram with the main statistical
            parameters
        menno = menu(sprintf('INTENSITIES:\n Max: %3.5f, Min: %3.5f',maxi,mini)
            ,...
            'NORMALIZE THE INTENSITIES AFTER DATA CLEANING',...
105     'NORMALIZE THE INTENSITIES WITHOUT DATA CLEANING',...
            'NO NORMALIZATION, BUT DATA CLEANING',...
            'NO NORMALIZATION, NO DATA CLEANING');

    if (menno == 1)|(menno == 3)
110     nowell = 0;
        while nowell == 0
            prompty = {'Minimum accepted intensity','Maximum accepted
                intensity'};
            defans = {num2str(mini),num2str(maxi)};
            fields = {'minp','maxp'};
115     acquis = inputdlg(prompty,'INTENSITY RANGE',1,defans);
            if ~isempty(acquis)
                acq = cell2struct(acquis,fields);
                maxin = str2num(acq.maxp);
                minin = str2num(acq.minp);
120     if (minin >= mini)&(minin < maxin)&(maxin <= maxi)
                    menacc = menu(sprintf('Entered values: %5.3f, %5.3f',
                        minin,maxin),...
                        'OK','ANOTHER CHOICE','STOP');
                    else
                        menacc = menu('Invalid choice','Another choice','Exit');
125     menacc = menacc+1;
                    end
                    if menacc == 1, nowell = 1; end
                else
                    menacc = menu('Invalid choice','Another choice','Exit');
130     menacc = menacc+1;
                end
                if menacc == 3, nowell = 1; end
            end
        if menacc == 1
135     if (minin > mini)|(maxin < maxi)
                maxi = maxin; mini = minin;
                J = find((I >= minin)&(I <= maxin));
                p = p(J); t = t(J); r = r(J); I = I(J);
                end
140     end

```

```

end

if menno == 1
    I = round(255*(I-mini)/(maxi-mini));
145    prompt = {'Transformation parameters filename (extension not
               necessary):'};
    fields = {'filepar'}; defans = {'param.txt'};
    acquis = inputdlg(prompt, 'PARAMETERS FILE', 1, defans);
    if ~isempty(acquis)
        acq = cell2struct(acquis, fields);
150        filep = acq.filepar;
    else
        filep = [];
    end
    filenan = savecond(filep, 'txt', 'PARAMETERS FILE');
155    if ~isempty(filenan)
        P = [maxi; mini]; save(filenan, 'P', '-ascii');
    else
        disp('WARNING, NO PARAMETERS ARE SAVED');
    end
end
160 end
end

p = 2*p*pi/180; t = 2*t*pi/180; r = r/100;

165 x = r.*sin(p).*cos(t); y = r.*cos(p).*cos(t); z = r.*sin(t);

lx = length(x);
B = zeros(lx, 4);
B(:, 1) = x; B(:, 2) = y; B(:, 3) = z; B(:, 4) = I;
170
prompt = {'Filename (extension is necessary):'};
fields = {'filenanew'}; defans = {'filepoly.xyz'};
acquis = inputdlg(prompt, 'OUTPUT DATA FILE', 1, defans);
if ~isempty(acquis)
175    acq = cell2struct(acquis, fields);
        filena = acq.filenanew;
    else
        filena = [];
    end
end
180 filenan = savecond(filena, 'xyz', 'OUTPUT DATA FILE');
    if ~isempty(filenan), dlmwrite(filenan, B, '\t'); end

```

ls_seafit

This script has been implemented to correct intensities of raw data in function of the distance of acquisition. This is a fundamental passage, necessary for a reliable interpretation of TLS data.

```
function [xs,ys,zs,Is,IRs,nx,ny,nz] = ls_seafit(x,y,z,I,x0,y0,z0,sd,ser,
        typefit,typevel,typecor);

%
% =====
%                      LOCAL FIT AND INTENSITY CORRECTION
% =====
5 % =====
%
%[xs,ys,zs,Is,IRs,nx,ny,nz] = ls_seafit(x,y,z,I,x0,y0,z0,sd,ser,typefit,
        typevel,typecor);
%
% Input data:
10 %
%   x,y,z      : point cloud (p.c.);
%
%   I          : original intensity;
%
%   x0,y0,z0   : viewpoint, i.e. laser scanner position;
15 %
%   sd         : side of the p.c. subdivision (this subdivision is performed
%               in order to optimize the computation effort. If sd is
%               unassigned, or is not a positive number, the default choice
20 %               sd = 2 is assumed;
%
%   ser        : search radius for the surface fitting. If ser is unassigned,
%               or is not a positive number smaller than sd, it is
%               interactively asked;
25 %
%   typefit    : type of local surface fitting. If typefit = 1, planar fit is
%               performed. If typefit = 2, quadric fit is considered. If
%               typefit = 3, cubic fit is performed. If typefit is not a
%               member of the set [1 2 3], it is interactively asked.
30 %
%   typevel    : type of computation speed. If typevel is 0, a slow algorithm
%               is considered. In such a case, the computation is performed
%               in each point of the p.c., considering a neighborhood
%               centered
%               in this point and having radius ser. For each point where the
35 %               local fit is successfully achieved, specific intensity
%               corrections are applied.
%               If typevel is 1, a fast algorithm is considered. In such a
%               case, the p.c. is subdivided in subsets having radius 2*ser,
```

```

%           and the local fit is performed in each of these subsets. The
40 %           same intensity correction is applied to all the points
%           belonging to a same subset.
%           If typevel is unassigned or is not in [0 1], the algorithm
%           choice is interactively performed.
%
45 %   typecor : type of correction. If typecor is 1, distance correction only
%           is applied. If typecor is 2, both distance and angular
%           correction are applied. If typecor is unassigned or is
%           outside the set [1 2], the type of correction is
%           interactively
%           asked.
50 %
% Output data:
%
%   xs,ys,zs : point cloud (note that the order of points can be changed
%           because the local fit requires a general indexing);
55 %
%   Is       : corresponding intensity;
%
%   IRs      : corrected intensity on the basis of geometric conditions,
%           i.e. orientation of the illuminated surface and distance.
60 %   Regarding to orientation, the thete-angle between the
%           line-of-sight and the normal to surface is computed and
%           the correction is 1/cos(theta). The correction factor
%           is 1 if and only if the incidence is normal (theta = 0).
%           Regarding to the distance, the correction is operated
65 %   considering the value at 15-m as reference, i.e. the
%           distance correction factor is 1 if d = 15 m;
%
%   nx,ny,nz : x-,y-, and z-component of the normal unit vector at the
%           point whose coordinates are (x,y,z). If the combination
70 %   "slow computation" with "distance correction only" si
%           chosen, these unit vectors are not computed (empty vectors
%           are therefore rendered).
%
% The returned outputs are the points where IRs has a numeric value;
75 % if the computations provide a NaN IRs value, the correponding point
%   is suppressed.
%
% NOTE THAT THE COORDINATES ARE CONSIDERED IN METERS.
%
80 % Valid cases of input data are as follows:
%
% [xs,ys,zs,Is,IRs,nx,ny,nz] = ls_seafit(x,y,z,I,x0,y0,z0,sd,ser,typefit,
%           typevel);
% [xs,ys,zs,Is,IRs,nx,ny,nz] = ls_seafit(x,y,z,I,x0,y0,z0,sd,ser,typefit);

```

```

%[xs,ys,zs,Is,IRs,nx,ny,nz] = ls_seafit(x,y,z,I,x0,y0,z0,sd,ser);
85 %[xs,ys,zs,Is,IRs,nx,ny,nz] = ls_seafit(x,y,z,I,x0,y0,z0,sd);
%[xs,ys,zs,Is,IRs,nx,ny,nz] = ls_seafit(x,y,z,I,x0,y0,z0);
%[xs,ys,zs,Is,IRs,nx,ny,nz] = ls_seafit;
%
% In the last case, the name of the file containing the point cloud is
90 % interactively asked, and the data related to viewpoint are interactively
% inserted.
% Other combinations of input data are not foreseen.
%
% This function calls LS_NORMGEN and SAVECOND.
95
% G. Teza, 2008.

dref = 15; % Reference distance (the correction factor is 1 is the
           % distance between laser scanner and target is dref, and
100 % the correction is not computed if the distance is
           % lower than this limit, i.e. the corresponding IRs is NaN).

langle = 85; % Limit-angle. If the angle between line-of-sight and
            % normal to the surface exceeds this limit, the correction
105 % is not computed (the corresponding IRs is NaN).

% === INPUT DATA MANAGEMENT ===

if nargin < 12, typecor = 0; end
110 if nargin < 11, typevel = []; end
    if nargin < 10, typefit = []; end
    if nargin < 9, ser = []; end
    if nargin < 8, sd = []; end
    if nargin < 7, x = []; end
115 if ~ismember(typecor,[1 2]), typecor = []; end
    if ~ismember(typevel,[0 1]), typevel = []; end
    if ~ismember(typefit,[1 2 3]), typefit = []; end
    if isempty(sd)|(sd < 0)|(~isnumeric(sd)), sd = 2; end
    if (ser < 0)|(~isnumeric(ser)), ser = []; end
120
    if isempty(x)
        %— importing of data from file
        nowell = 0;
        defans = {' '};
125 while nowell == 0
            try
                prompty = {'ASCII data filename (extension necessary):'};
                fields = {'filein'};
                acquis = inputdlg(prompty,'INPUT DATA FILE',1,defans);
130 if ~isempty(acquis)

```

```

        acq = cell2struct(acquis, fields);
        filei = acq.filein;
    else
        filei = [];
135    end
    A = load(filei, '-ascii');
    sza = size(A);
    if sza(2) >= 4
        x = A(:,1); y = A(:,2); z = A(:,3); I = A(:,4);
140        nindno = 1; nowell = 1;
    else
        nindno = 0;
    end
catch
145    nindno = 0;
end
if nindno == 0
    menoval = menu(sprintf('%s IS INVALID FILENAME', char(filei)), ...
        'ANOTHER FILENAME', 'EXIT');
150    if menoval == 2, nowell = 1; fatto = 0; else defans = {char(
        filei)}; end
    else
        nowell = 1; fatto = 1; % Good data
    end
end
155 %—— choice of viewpoint
if fatto == 1
    nowell = 0;
    prompty = {'viewpoint x-coordinate', 'viewpoint y-coordinate', '
        viewpoint z-coordinate'};
    defans = {'0', '0', '0'};
160    fields = {'x0', 'y0', 'z0'};
    while nowell == 0
        acquis = inputdlg(prompty, 'VIEWPOINT COORDINATES', 1, defans);
        if ~isempty(acquis)
            acq = cell2struct(acquis, fields);
165            x0 = str2num(acq.x0); y0 = str2num(acq.y0); z0 = str2num(
                acq.z0);
        else
            x0 = []; y0 = []; z0 = [];
        end
        if isempty(x0) | isempty(y0) | isempty(z0)
170            menno = menu('INVALID INPUTS:', 'ANOTHER CHOICE', 'EXIT');
            menno = menno+1; % in order to unify the possible cases
        else
            menno = menu(sprintf('CHOSEN DATA ARE %5.5f, %5.5f, %5.5f',
                x0, y0, z0), ...

```

```

                                'CONFIRM THE CHOICE','ANOTHER CHOICE','EXIT');
175         end
            if menno == 1, fatto = 1; nowell = 1; end
            if menno == 3, fatto = 0; nowell = 1; end
        end
    end
180 else
        fatto = 1;
    end

    if fatto == 0
185         xs = []; ys = []; zs = []; Is = []; IRs = []; nx = []; ny = []; nz = [];
            return;
        end

        lx = length(x); ly = length(y); lz = length(z); lI = length(I);
190 if (lx ~= ly) |(lx ~= lz) |(ly ~= lz) |(lx ~= lI)
            help ls_seafit;
            error('Sets x, y, z, and I must have the same length');
        end

195 if isempty(typevel)
        menve = menu('COMPUTATION SPEED:',...
                    'SLOW COMPUTATION (ADVISED IF ONLY DISTANCE CORRECTION IS PERFORMED)'
                    ,...
                    'RAPID COMPUTATION (ADVISED IF BOTH DISTANCE AND ANGULAR CORRECTIONS ARE PERFORMED)');
    else
200         menve = typevel+1;
    end

    if isempty(typecor)
        typecor = menu('TYPE OF CORRECTION:',...
205         'PERFORM THE DISTANCE CORRECTION ONLY',...
        'PERFORM BOTH DISTANCE AND ANGULAR CORRECTIONS');
    end

    if typecor == 1
210         nx = []; ny = []; nz = []; % The normal unit vector is not defined
            if menve == 1
                if isempty(ser), ser = sd; end
            else
                if isempty(ser)
215                 ser = ciapaser('Radius of the ''same correction'' set','
                                CORRECTION SET');
                                % ancillary function, see below
                end
            end
        end
    end
end

```

```

        gr = 1;
    end
220 end

    if typecor == 2
        if isempty(typefit)
            gr = menu('TYPE OF LOCAL FITTING:',...
225         'PLANAR','QUADRIC SURFACE','CUBIC SURFACE');
            if gr == 1
                strfit = 'plane';
            elseif gr == 2
                strfit = 'quadric surface';
230         else
                strfit = 'cubic surface';
            end
        else
            gr = typefit;
235         end
        if isempty(ser)
            ser = ciapaser(...
                sprintf('Search radius for %s fit (in m):',strfit),...
                'RADIUS OF THE SEARCH NEIGHBORHOOD');
240         end
    end
    end
    ser2 = 2*ser; % diameter of the search set

    %—— Bounding box and general information
245 xb1 = min(x); xb2 = max(x);
    yb1 = min(y); yb2 = max(y);
    zb1 = min(z); zb2 = max(z);
    geninf = sprintf('\n%s:\n %d points\n x-range = [%6.3f, %6.3f]\n y-range =
        [%6.3f, %6.3f]\n z-range = [%6.3f, %6.3f]\n',...
        'GENERAL INFORMATION ON POINT CLOUD',lx,xb1,xb2,yb1,yb2,zb1,zb2);
250 disp(geninf);
    %meninf = menu(geninf,'OK');

    %===== COMPUTATIONS =====

255 nelx = ceil((xb2-xb1)/sd); nelz = ceil((zb2-zb1)/sd); nt = nelx*nelz;
    xs = NaN*ones(lx,1); ys = NaN*ones(lx,1); zs = NaN*ones(lx,1);
    Is = NaN*ones(lx,1); IRs = NaN*ones(lx,1);

    if (typecor == 1)&(menve == 1)
260     nx = []; ny = []; nz = []; ser = sd;
    else
        nx = NaN*ones(lx,1); ny = NaN*ones(lx,1); nz = NaN*ones(lx,1);
    end

```

```

n = 0;      % Index of point cloud element
265 nn = 0;   % Index of "computation square"
nf = 0;     % Case "rapid computation"

naux = 0;
for k = 1:nelz % z-iterations (subdivision of p.c. in horizontal stripes)
270
    if menve == 1 % In such a case, both extended and effective bands must
        be defined
        zmi1 = zb1+(k-1)*sd-ser; zma1 = zb1+k*sd+ser;
        %—— extended band:
        [xc1,yc1,zc1,Ic1] = sq_or_ba(x,y,z,I,3,zmi1,zma1); % Ancillary
            function — see below
275
        zmi2 = zb1+(k-1)*sd; zma2 = zb1+k*sd;
        %—— effective band:
        [xc2,yc2,zc2,Ic2] = sq_or_ba(xc1,yc1,zc1,Ic1,3,zmi2,zma2,k,nelz);
    else % In such a case, only the effective band must be defined
        zmi2 = zb1+(k-1)*sd; zma2 = zb1+k*sd;
280
        [xc2,yc2,zc2,Ic2] = sq_or_ba(x,y,z,I,3,zmi2,zma2,k,nelz);
    end

    for kk = 1:nelx % x-iterations (subdivision of each stripe in squares)

285
        nn = nn+1;
        if menve == 1 % In such a case, both extended and effective square
            must be defined
            xmi3 = xb1+(kk-1)*sd-ser; xma3 = xb1+kk*sd+ser;
            [xc3,yc3,zc3,Ic3] = sq_or_ba(xc1,yc1,zc1,Ic1,1,xmi3,xma3);
            xmi4 = xb1+(kk-1)*sd; xma4 = xb1+kk*sd;
290
            % [xc4,yc4,zc4,Ic4] = sq_or_ba(xc3,yc3,zc3,Ic3,1,xmi4,xma4,kk,
                nelz);
            [xc4,yc4,zc4,Ic4] = sq_or_ba(xc2,yc2,zc2,Ic2,1,xmi4,xma4,kk,nelz
                );
        else
            xmi4 = xb1+(kk-1)*sd; xma4 = xb1+kk*sd;
            [xc4,yc4,zc4,Ic4] = sq_or_ba(xc2,yc2,zc2,Ic2,1,xmi4,xma4,kk,nelz
                );
295
        end

        disp(sprintf('Processing of square %d (on a total of %d) in progress
            ...',nn,nt));

        if menve == 1
300
            le4 = length(xc4); % Number of elements of squared part of p.c.
            if le4 >= 1
                if typecor == 1
                    fd = d_factor(xc4,yc4,zc4,x0,y0,z0,dref);

```



```

else
335     nz5 = ceil((zma2-zmi2)/ser2);
        nx6 = ceil((xma4-xmi4)/ser2);
        for m = 1:nz5
            zmi5 = zmi2+(m-1)*ser2; zma5 = zmi2+m*ser2;
            [xc5,yc5,zc5,Ic5] = sq_or_ba(xc4,yc4,zc4,Ic4,3,zmi5,zma5,m,
                nz5);
340     for mm = 1:nx6 % x-iterations (subdivision of each stripe
                in squares)
            xmi6 = xmi4+(mm-1)*ser2; xma6 = xmi4+mm*ser2;
            [xc6,yc6,zc6,Ic6] = sq_or_ba(xc5,yc5,zc5,Ic5,1,xmi6,xma6
                ,mm,nx6);
            [xr,yr,zr,lr] = cen_set(xc6,yc6,zc6,Ic6,xmi6,xma6,
                zmi5,zma5); % Ancillary function, see below

345     xrr = xr; yrr = zr; zrr = -yr;
        xc6r = xc6; yc6r = zc6; zc6r = -yc6;
        %

        [nxrr,nyrr,nzrr,xfnr,yfnr,zfnr,Ifn] = ls_normgen(xc6r,
            yc6r,zc6r,Ic6,xrr,yrr,zrr,ser,gr);
        %

350     nxr = nxrr; nyr = -nzrr; nzz = nyrr; % Inverse
            transformation
        %xfn = xfnr; yfn = -zfnr; zfn = yfnr;
        %

        fd = d_factor(xr,yr,zr,x0,y0,z0,dref);
            % Ancillary function, see below
        if typecor == 2
355         fa = a_factor(xr,yr,zr,nxr,nyr,nzz,x0,y0,z0,langl)
            ; % Ancillary function, see below
        else
            fa = 1;
        end
        %

360     nef = length(xc6);
        ni = nf+1; nf = nf+nef;
        if ~isnan(nxr)
            xs(ni:nf) = xc6; ys(ni:nf) = yc6; zs(ni:nf) = zc6
                ;

```

```

Is(ni:nf) = Ic6;   IRs(ni:nf) = Ic6*fd*fa;
365   nx(ni:nf) = nxr*ones(nef,1);
      ny(ni:nf) = nyr*ones(nef,1);
      nz(ni:nf) = nzs*ones(nef,1);
      end
    end
370   end
      end
      %figure; plot(xc1,zc1,'.',xc4,zc4,'.r'); xlabel('x'); axis image;
      pause
      disp('done');

375   end
end

Iex = find(isnan(IRs));
xs(Iex) = []; ys(Iex) = []; zs(Iex) = []; Is(Iex) = []; IRs(Iex) = [];
380 if typecor == 2
      nx(Iex) = []; ny(Iex) = []; nz(Iex) = [];
      end

      if isempty(xs), disp('WARNING: NO VALID CORRECTIONS'); return; end
385

%==== DATA SAVING ====

mensa = menu('SAVE THE RESULTS AS AN ASCII FILE?',...
390   'YES, FILE FOR POLYWORKS',...
      'YES, FILE FOR DATA ANALYSIS',...
      'YES, FILES FOR POLYWORKS AND DATA ANALYSIS',...
      'NO');
if (mensa == 1)|(mensa == 3)
395   [xs,ys,zs,IRs,J] = ls_num2poly(xs,ys,zs,IRs);
      Is = Is(J);
      if (typecor ~= 1)|(menve ~= 1)
          nx = nx(J); ny = ny(J); nz = nz(J);
      end
400 end
      if (mensa == 2)|(mensa == 3)
          filenan2 = condy('FILE FOR DATA ANALYSIS');
          if ~isempty(filenan2)
              ls = length(xs);
405              if (typecor ~= 1)|(menve ~= 1)
                  A = zeros(ls,8);
                  A(:,6) = nx; A(:,7) = ny; A(:,8) = nz;
              else
                  A = zeros(ls,5);

```

```

410         end
            A(:,1) = xs; A(:,2) = ys; A(:,3) = zs;
            A(:,4) = Is; A(:,5) = IRs;
            save(filename2, 'A', '-ascii');
        end
415 end

%==== ANCILLARY FUNCTIONS ====

420 function ser = ciapaser(str_prompt, str_boxname);
% Interactive acquisition of the search radius 'ser'. The input dialog box
% has prompt 'str_prompt' and box name 'str_boxname'.
% The default value ser = 0.05 is considered.
prompty = {str_prompt};
425 fields = {'ser'}; defans = {'0.05'};
acquis = inputdlg(prompty, 'RADIUS OF THE SEARCH NEIGHBORHOOD', 1, defans);
iok = 0;
if ~isempty(acquis)
    acq = cell2struct(acquis, fields);
430    ser = str2num(acq.ser);
    if ser > 0, iok = 1; end
end
if iok == 0, ser = 0.05; end
%— end function

435 function [xe, ye, ze, le] = sq_or_ba(x, y, z, I, n, limin, limax, k, kmax);
% Computation of square or band on the basis of n-th variable
% (1: x, 2: y, 3: z) with the minimum and maximum limits limin
% and limax respectively, i.e. the set [xe ye ze le] contains
440 % the elements of [x y z I] whose n-th variable satisfies the
% requirement.
% If k is assigned and it is k < kmax, the condition on limax
% is 'strictly less than limax'; elsewhere, the condition is
% 'less than or equal to limax'.
445 if nargin == 7, k = 1; kmax = 1; end
    if n == 1
        if k < kmax
            J = find((x >= limin) & (x < limax));
        else
450            J = find((x >= limin) & (x <= limax));
        end
    elseif n == 2
        if k < kmax
            J = find((y >= limin) & (y < limax));
455        else
            J = find((y >= limin) & (y <= limax));
        end
    end
end

```

```

        end
    else
        if k < kmax
460         J = find((z >= limin) & (z < limax));
        else
            J = find((z >= limin) & (z <= limax));
        end
    end
end
465 xe = x(J); ye = y(J); ze = z(J); Ie = I(J);
%----- end function -----

function [xce,yce,zce,Ice] = cen_set(x,y,z,I,xmi,xma,zmi,zma);
% Assigned the set [x y z], whose x and z ranges are [xmi, xma]
470 % and [zmi, zma] respectively, this function finds the element
% (xce,yce,zce) of the set whose distance from the set center is
% minimum.
xme = (xmi+xma)/2; zme = (zmi+zma)/2;
vdi = (x-xme).^2+(z-zme).^2;
475 [midi,Imidi] = min(vdi);
if length(Imidi) > 1, Imidi = Imidi(1); end
xce = x(Imidi); yce = y(Imidi); zce = z(Imidi); Ice = I(Imidi);
%----- end function -----

480 function fd = d_factor(xt,yt,zt,x0,y0,z0,dref);
% Computation of the distance factor, respect to the reference
% distance dref. The viewpoint position is (x0,y0,z0), whereas
% the target position is (xt,yt,zt). If fd is lower than dref,
% fd = NaN is returned.
485 dref2 = dref^2;
if isempty(xt)|isempty(yt)|isempty(zt), fd = NaN; return; end
dt = (xt-x0).^2+(yt-y0).^2+(zt-z0).^2;
lt = length(xt);
if lt > 1
490     fd = NaN*ones(lt,1);
        J = find(dt >= dref2);
        fd(J) = dt(J)/dref2;
    elseif dt >= dref2
        fd = dt/dref2;
495 else
        fd = NaN;
    end
%----- end function -----

500 function fa = a_factor(xt,yt,zt,nxt,nyt,nzt,x0,y0,z0,langl);
% Computation of the angle factor related to the observation
% of a target whose position and normal unit vector are (xt,yi,zt)
% and [nxt nyt nzt] respectively, from a viewpoint whose position

```

```

    % is (x0,y0,z0). Such a factor is 1/cos(theta), where theta is
505 % the angle between the line-of-sight and the normal to the
    % observed target.
    % The input variable langle is the limit theta angle; if theta
    % exceeds langle (expressed in deg), then fa is NaN.
    if isempty(xt)|isempty(yt)|isempty(zt), fa = NaN; return; end
510 nv = [nxt nyt nzt]'; % normal vector
    sx = xt-x0; sy = yt-y0; sz = zt-z0;
    sv = [sx sy sz]';
    nsv = norm(sv);
    if nsv < 10^3*eps, fa = NaN; return; end % Case "no observability"
515 sv = sv/nsv;
    dps = dot(-nv,sv); % dot product is cos(theta)
    ldps = cos(langle*pi/180);
    if dps >= ldps
        fa = 1/dps;
520 else
        fa = NaN;
    end
    %—— end function —————

525 function filenan = condy(str_natype);
    % Interactive choice of an ASCII filename. The string 'str_natype'
    % indicates the name of data-type.
    prompty = {'Filename (extension not strictly necessary):'};
    fields = {'filenanew'}; defans = {'prova.txt'};
530 acquis = inputdlg(prompty, str_natype, 1, defans);
    if ~isempty(acquis)
        acq = cell2struct(acquis, fields);
        filena = acq.filenanew;
    else
535         filena = [];
    end
    format long e;
    %——
    filenan = savecond(filena, 'txt', str_natype);
540 %——
    %—— end function —————

```

Scripts for reflectance series generation

ls_mediancoll

This script was developed to generate reflectance series from a given point-cloud. Input data are constituted by 4-by- n matrices in which the first three columns contain respectively the x, y, z coordinates and the fourth column contains the intensity data I . The matrix is formed by the points of the TLS point-cloud selected as suitable to generate a reflectance series. Points' intensity has to be already corrected in function of the distance from the acquisition station and the points have to be already re-oriented.

The matrix is first ordered by the z values and then a moving average is applied to calculate an intensity value with a step selected by the operator. After this passage a dialog box will appear with a series of possible options. It is possible to visualize the distribution of the intensities and cut it between values selected by the operator.

In `ls_mediancoll` the median of the intensities in the chosen interval are calculated. This can be useful when relevant tails are recognizable in the distributions of the intensity values.

```
function [zs, Is, ns] = ls_mediancoll(A, step, opsub, opwid);
%
%[zs, Is, ns] = ls_mediancoll(A, step, opsub, opwid)
%
5 % Assigned a N-by-4 point cloud whose data are stored inside the matrix
%
%   A = [x y z I],
%
% this function extracts the 'z' coordinates and the intensity data 'I', to
10 % provide the intensities 'Is' which are computed from 'I' considering the
% z-step 'step'. The integer 'ns' is the length of the zs and Is vectors.
%
% The fact that the reference frame is such that the x-axis is parallel to
% the point cloud basis, y-axis is along the line-of-sight and z-axis is
15 % vertical is assumed.
%
% If 'step' is unassigned, is negative or is greater than 1/10 of the
% whole z-interval, this input data is interactively asked.
% if 'opsub' has every non-zero value, subsampling options are presented.
20 % If 'opsub' is zero, empty or unassigned, no subsampling is performed.
```

```

% If 'opwid' has each non-zero value, point cloud width options are
% presented. In such a case, the user can reduce the x-extension of the
% point cloud.
% If 'opwid' is zero, empty or unassigned, no width-managing options are
25 % presented.

% G. Teza, 2008, from a preliminary idea of N. Preto.

if nargin < 4, opwid = 0; end
30 if nargin < 3, opsub = 0; end
if nargin < 2, step = 0; end
if isempty(opsub), opsub = 0; end
if isempty(opwid), opwid = 0; end

35 if opwid ~= 0
    xmi = min(A(:,1)); xma = max(A(:,1));
    prompty = {'Minimum x:', 'Maximum x:'};
    fields = {'xmi', 'xma'}; defans = {num2str(xmi), num2str(xma)};
    nowell = 0;
40 while nowell == 0
        acquis = inputdlg(prompty, 'x-RANGE', 1, defans);
        if ~isempty(acquis)
            acq = cell2struct(acquis, fields);
            xmin = str2num(acq.xmi);
45 xman = str2num(acq.xma);
            if isempty(xmin) | isempty(xman) | (xmin >= xman)
                iok = 0;
            else
                xmi = xmin; xma = xman; iok = 1; nowell = 1;
50 end
        else
            iok = 0;
        end
        if iok == 0
55 menstep = menu(sprintf('DEFAULT x-RANGE IS CHOSEN (%3.3f -> %3.3f)', xmi, xma), ...
                    'OK', 'ANOTEHR CHOICE');
            if menstep == 1, step = zint_10; nowell = 1; end
        end
    end
60 if iok == 1
        [Iexx, Jexx] = find((A(:,1) < xmi) | (A(:,1) > xma)); % possible
            exclusion
            if ~isempty(Iexx)
                A(Iexx, :) = [];
            end
65 end
end

```

```

end

[nr,nc] = size(A);

70 % Preliminary sorting and extraction
A = sortrows(A,3);
z = A(:,3);
I = A(:,4);
75
if opsub ~= 0
    mensub = menu(sprintf('THE POINT CLOUD HAS %d ELEMENTS. SUBSAMPLING:',nr
        ),...
        '1/2','1/4','1/8','1/16','1/32','NO SUBSAMPLING');
    if mensub < 6
80         fact = 2^(mensub);
        z = z(1:fact:end);
        I = I(1:fact:end);
    end
end
85
miz = z(1); maz = z(end); % z-extremes
zint = maz-miz;
zint_10 = zint/10;
disp(' ');
90 if (step <= 0)|(step > zint_10)
    prompt = {'Please enter the step'};
    fields = {'step'}; defans = {num2str(zint_10)};
    nowell = 0;
    while nowell == 0
95         acquis = inputdlg(prompt,'STEP',1,defans);
        if ~isempty(acquis)
            acq = cell2struct(acquis,fields);
            step = str2num(acq.step);
            if (step <= 0)|(step > zint_10), iok = 0; else iok = 1; nowell =
                1; end
100         else
            iok = 0;
        end
        if iok == 0
            menstep = menu(sprintf('DEFAULT STEP (%3.5f) IS CHOSEN',zint_10)
                ,...
                'OK','ANOTEHR CHOICE');
105         if menstep == 1, step = zint_10; nowell = 1; end
        end
    end
end
end

```

```

110   menist = menu('PLOT OF 10 INTENSITY DISTRIBUTIONS','YES','NO');

   ns = ceil(zint/step);
   maze = miz+ns*step; % Effective maximum
115   zs = (miz+step/2 : step : maze-step/2)'; % Column-vector of z-interval
       centers
   Is = NaN*ones(ns,1);
   Ims = NaN*ones(ns,1);
   for k = 1:ns
       zmax = miz+(k+1)*step;
120       if k == 1
           iz = find((z >= miz) & (z <= zmax));
       else
           iz = find(z <= zmax);
       end
125       if ~isempty(iz)
           Iiz = I(iz);
           Is(k) = median(Iiz);
           %Ims(k) = mean(I(iz));
           % The vectors z and I are now partially redefined taking into
               account that
130           % z is already sorted
           if menist == 1
               stevis = round(ns/10);
               if stevis < 1, stevis = 1; end
               if ismember(k,[1:stevis:ns])
135                   figure; hist(Iiz,20);
                       title(sprintf('Intensity distribution - %d-th step on %d',k,
                                   ns));
               end
               end
               z(iz) = []; I(iz) = [];
140       end
       disp(sprintf('Step %d/%d performed',k,ns));
   end

   figure;
145   plot(Is,zs,'*-'); %hold on; plot(Ims,zs,'r'); hold off;
       xlabel('Median-based intensity'); ylabel('z');

```

Appendix D

CHNS analysis

CHNS (carbon, hydrogen, nitrogen, sulfur analyzer) is an analytic method widely used in the study of soils, minerals and rocks. Applications can be found in various branches of Earth Sciences, from Sedimentology [Tucker, 1988] to petroleum Geology and Paleoceanography [Emerson and Hedges, 1988], especially because they give the possibility to provide carbonate and organic carbon content and to get some idea of the composition of the organic matter.

The instrument consists in a chromatographer coupled with a furnace able to reach considerably high temperatures (1800°C) Figure D.1. Chromatographic techniques are used to separate mixtures. Analytical chromatography normally operates with small amounts of material and seeks to measure the relative proportions of analytes in a mixture. In the case of CHNS N_2 , CO_2 , H_2O and SO_2 are the detected components.

The rock samples collected at the Nomi section were crushed in an onyx pestle and reduced to dust. 10-20 mg of dry material were weighted, placed in tin capsules and inserted in the autosampler. At regular time steps the samples pass in a quartz tube (at 1030°C) in which a mixture of helium and oxygen is used to produce a flash combustion (1800 °C). The obtained gases pass then through a gas chromatographic column in which the relative proportions of carbon, hydrogen, nitrogen and sulfur are determined and

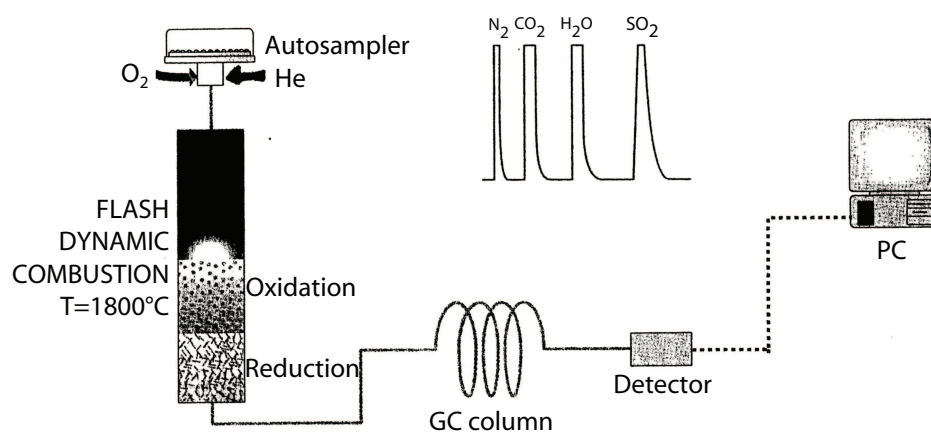


Figure D.1: Scheme of a CHNS analyzer.

transmitted in digitized form to a PC station.

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