

Fakultät Umweltwissenschaften

Photogrammetric techniques for

across-scale soil erosion assessment

Developing methods to integrate multi-temporal high resolution topography data at field plots

DISSERTATION

Zur Erlangung des akademischen Grades **Doktoringenieur** (Dr.-Ing.)

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Abstract

Soil erosion is a complex geomorphological process with varying influences of different impacts at different spatio-temporal scales. To date, measurement of soil erosion is predominantly realisable at specific scales, thereby detecting separate processes, e.g. interrill erosion contrary to rill erosion. It is difficult to survey soil surface changes at larger areal coverage such as field scale with high spatial resolution. Either net changes at the system outlet or remaining traces after the erosional event are usually measured. Thus, either quasi-point measurements are extrapolated to the corresponding area without knowing the actual sediment source as well as sediment storage behaviour on the plot or erosion rates are estimated disrupting the area of investigation during the data acquisition impeding multi-temporal assessment. Furthermore, established methods of soil erosion detection and quantification are typically only reliable for large event magnitudes, very labour and time intense, or inflexible.

To better observe soil erosion processes at field scale and under natural conditions, the development of a method is necessary, which identifies and quantifies sediment sources and sinks at the hillslope with high spatial resolution and captures single precipitation events as well as allows for longer observation periods. Therefore, an approach is introduced, which measures soil surface changes for multi-spatio-temporal scales without disturbing the area of interest. Recent advances regarding techniques to capture high resolution topography (HiRT) data led to several promising tools for soil erosion measurement with corresponding advantages but also disadvantages. The necessity exists to evaluate those methods because they have been rarely utilised in soil surface studies.

On the one hand, there is terrestrial laser scanning (TLS), which comprises high error reliability and retrieves 3D information directly. And on the other hand, there is unmanned aerial vehicle (UAV) technology in combination with structure from motion (SfM) algorithms resulting in UAV photogrammetry, which is very flexible in the field and depicts a beneficial perspective. Evaluation of the TLS feasibility reveals that this method implies a systematic error that is distance-related and temporal constant for the investigated device and can be corrected transferring calibration values retrieved from an estimated lookup table. However, TLS still reaches its application limits quickly due to an unfavourable (almost horizontal) scanning view at the soil surface resulting in a fast decrease of point density and increase of noise with increasing distance from the device. UAV photogrammetry allows for a better perspective (birds-eye view) onto the area of interest,

but possesses more complex error behaviour, especially in regard to the systematic error of a DEM dome, which depends on the method for 3D reconstruction from 2D images (i.e. options for additional implementation of observations) and on the image network configuration (i.e. parallel-axes and control point configuration). Therefore, a procedure is developed that enables flexible usage of different cameras and software tools without the need of additional information or specific camera orientations and yet avoiding this dome error. Furthermore, the accuracy potential of UAV photogrammetry describing rough soil surfaces is assessed because so far corresponding data is missing.

Both HiRT methods are used for multi-temporal measurement of soil erosion processes resulting in surface changes of low magnitudes, i.e. rill and especially interrill erosion. Thus, a reference with high accuracy and stability is a requirement. A local reference system with sub-cm and at its best 1 mm accuracy is setup and confirmed by control surveys. TLS and UAV photogrammetry data registration with these targets ensures that errors due to referencing are of minimal impact. Analysis of the multi-temporal performance of both HiRT methods affirms TLS to be suitable for the detection of erosion forms of larger magnitudes because of a level of detection (LoD) of 1.5 cm. UAV photogrammetry enables the quantification of even lower magnitude changes (LoD of 1 cm) and a reliable observation of the change of surface roughness, which is important for runoff processes, at field plots due to high spatial resolution (1 cm²). Synergetic data fusion as a subsequent post-processing step is necessary to exploit the advantages of both HiRT methods and potentially further increase the LoD.

The unprecedented high level of information entails the need for automatic geomorphic feature extraction due to the large amount of novel content. Therefore, a method is developed, which allows for accurate rill extraction and rill parameter calculation with high resolution enabling new perspectives onto rill erosion that has not been possible before due to labour and area access limits. Erosion volume and cross sections are calculated for each rill revealing a dominant rill deepening. Furthermore, rill shifting in dependence of the rill orientation towards the dominant wind direction is revealed.

Two field plots are installed at erosion prone positions in the Mediterranean $(1,000 \text{ m}^2)$ and in the European loess belt (600 m^2) to ensure the detection of surface changes, permitting the evaluation of the feasibility, potential and limits of TLS and UAV photogrammetry in soil erosion studies. Observations are made regarding sediment connectivity at the hillslope scale. Both HiRT methods enable the identification of local

sediment sources and sinks, but still exhibiting some degree of uncertainty due to the comparable high LoD in regard to laminar accumulation and interrill erosion processes. At both field sites wheel tracks and erosion rills increase hydrological and sedimentological connectivity. However, at the Mediterranean field plot especially dis-connectivity is obvious. At the European loess belt case study a triggering event could be captured, which led to high erosion rates due to high soil moisture contents and yet further erosion increase due to rill amplification after rill incision. Estimated soil erosion rates range between 2.6 tha⁻¹ and 121.5 tha⁻¹ for single precipitation events and illustrate a large variability due to very different site specifications, although both case studies are located in fragile landscapes. However, the susceptibility to soil erosion has different primary causes, i.e. torrential precipitation at the Mediterranean site and high soil erodibility at the European loess belt site.

The future capability of the HiRT methods is their potential to be applicable at yet larger scales. Hence, investigations of the importance of gullys for sediment connectivity between hillslopes and channels are possible as well as the possible explanation of different erosion rates observed at hillslope and at catchment scales because local sediment sink and sources can be quantified. In addition, HiRT data can be a great tool for calibrating, validating and enhancing soil erosion models due to the unprecedented level of detail and the flexible multi-spatio-temporal application.

Kurzfassung

Bodenerosion ist ein komplexer geomorphologischer Prozess, welcher durch verschiedene Faktoren mit variierender Intensität in unterschiedlichen räumlichen und zeitlichen Skalen beeinflusst wird. Bisherige Methoden zur Messung der Bodenerosion arbeiten meist innerhalb bestimmter Skalen und erfassen dadurch lediglich innerhalb der jeweiligen Skale wirksame Prozesse, die zwischen den Skalen sehr verschieden sein können (z.B. Flächenspülung versus Rillenerosion). Veränderungen der Bodenoberfläche mit hoher räumlicher Auflösung bei gleichzeitig großer Gebietsabdeckung (z.B. Einzelhänge) zu erfassen, ist besonders schwierig. Üblicherweise werden entweder Nettoänderungen am Systemauslass gemessen oder verbleibende Erosionsspuren nach dem Abtragsereignis dokumentiert. Dadurch werden entweder quasi-punkthafte Messungen auf das Einzugsgebiet durch Extrapolation übertragen, ohne den Ursprung des ausgetragenen Substrats bzw. das Sedimentretentionsvermögen auf dem Feld zu kennen, oder es werden Erosionsraten mit Methoden gemessen, die den Untersuchungsplot während der Datenakquise stören und somit multitemporale Betrachtungen verhindern. Weitere Verfahren zur Detektion von Bodenerosion sind nur zuverlässig für Erosionsereignisse mit großer Magnitude, sehr arbeits- und zeitintensiv oder unflexibel.

Ein Verfahren ist erforderlich, dass die Untersuchung von Bodenerosionsprozessen unter natürlichen Bedingungen auf Einzelhängen erlaubt und dabei lokale Sedimentquellen und -senken auf dem Hang mit hoher räumlicher Auflösung identifiziert und quantifiziert sowie einzelne Niederschlagsereignisse erfasst, aber gelichzeitig längere Beobachtungszeiträume zulässt. Es wird ein Ansatz vorgestellt, der Änderungen der Bodenoberfläche in mehreren räumlichen und zeitlichen Skalen misst, ohne das Untersuchungsgebiet zu stören. Bisherige Fortschritte bei den Techniken zur hochaufgelösten Beschreibung der Geländeoberfläche resultieren in mehreren vielversprechenden, unterschiedlich geeigneten Werkzeugen zur Bodenerosionsmessung. Eine Bewertung der neuen Methoden ist nötig, da sie bisher kaum im Bereich der Bodenerosionsforschung eingesetzt wurden.

Einerseits kommt das terrestrische Laserscanning (TLS) zum Einsatz, welches eine hohe Fehlerzuverlässigkeit besitzt und 3D-Informationen direkt berechnet. Andererseits wird ein unbemanntes Luftfahrzeug (UAV) in Kombination mit dem Structure-from-Motion (SfM) Algorithmus angewandt. Diese Variante der UAV Photogrammetrie ist sehr flexibel im Gelände einsetzbar und besitzt einen günstigen Blickwinkel zur Bodenoberfläche. Die Untersuchung der Eignung des TLS zeigt, dass der verwendete Scanner einen systematischen distanzabhängigen und zeitlich stabilen Fehler aufweist, der mittels einer lookup-Tabelle korrigiert werden kann. Aufgrund der schrägen Aufnahmegeometrie des TLS stößt diese Methode jedoch schnell an seine Grenzen, da mit zunehmender Distanz zum Scanner rasch die Punktdichte ab- und das Rauschen zunehmen. Im Gegensatz dazu ermöglicht die UAV Photogrammetrie einen besseren Blick (Vogelperspektive) auf das Untersuchungsgebiet. Jedoch ist das Fehlerverhalten komplexer. Insbesondere der Geländemodellwölbungsfehler, der durch die Methode der 3D-Rekonstruktion aus 2D-Bilddaten (v.a. die Berücksichtigung zusätzlicher Parameter) und die Aufnahmekonfiguration (v.a. achsen-parallele Konfigurationen) beeinflusst wird, ist hierbei relevant. Es wird ein Vorgehen entwickelt, dass den flexiblen Einsatz verschiedener Kameras sowie unterschiedlicher Software ermöglicht, ohne zusätzliche Parameter oder spezielle Aufnahmegeometrien zu berücksichtigen und dennoch den Wölbungsfehler minimiert. Des Weiteren wird das Genauigkeitspotential der UAV Photogrammetrie zur Beschreibung rauer Bodenoberflächen untersucht, denn bisherige Angaben diesbezüglich sind nahezu vakant.

Beide Methoden der hochauflösenden Geländeerfassung werden zur multi-temporalen Messung von Bodenerosionsprozessen (insbesondere die Rillen- und Interrillenerosion) verwendet, die zu geringen Geländeveränderungen führen. Daher ist ein Referenzsystem mit hoher Stabilität und Genauigkeit wichtig. Es wird ein lokales Referenznetz definiert, dass eine sub-cm Genauigkeit aufweist und minimal 1 mm beträgt. Die Stabilität wird durch Kontrollmessungen bestätigt. Die exakte Referenzierung mit installierten Marken ermöglicht einen minimalen Registrierungsfehler der UAV- und TLS-Daten. Ein Vergleich beider hochauflösender Geländeerfassungsmethoden zeigt, dass TLS v.a. zur Detektion von größeren Erosionsformen geeignet ist (LoD von 1.5 cm), während UAV Photogrammetrie ebenfalls kleinere Veränderungen messen kann (LoD von 1 cm). Außerdem kann die Methode der UAV Photogrammetrie Rauigkeitsveränderungen der Bodenoberfläche, welche relevant für die Abflussbildung sind, zuverlässig auf dem Einzelhang hochaufgelöst (1 cm²) erfassen. Anschließende Datenverarbeitung in Form einer synergetischen Datenfusion ist notwendig, um die positiven Eigenschaften des TLS und der UAV Photogrammetrie zu nutzen und möglicherweise das Genauigkeitspotential weiter zu steigern.

Der beispiellose Detailgrad bedingt die Notwendigkeit zur automatischen Extraktion geomorphologischer Merkmale aufgrund der hohen Quantität an neuer Information. Deshalb wird eine Methode entwickelt, die eine akkurate und hochaufgelöste Rillenextraktion und Rillenparameterberechnung realisiert. Die erreichte hohe Auflösung und Genauigkeit war bisher nicht möglich aufgrund von Einschränkungen infolge des Arbeitsaufwandes oder der Gebietszugänglichkeit. Erosionsvolumen und Querschnitte werden für jede Rille berechnet und lassen eine Dominanz der Rillenvertiefung erkennen. Außerdem wird ein lateraler Rillenversatz in Abhängigkeit der Orientierung zur hauptsächlichen Windrichtung detektiert.

An zwei erosionsanfälligen Standorten im Mediterranraum (1,000 m²) und im Europäischen Lößgürtel (600 m²) werden Feldplots installiert, um die Wahrscheinlichkeit zur Detektion von Bodenoberflächenänderungen zu erhöhen, damit die Machbarkeit, das Potential und die Grenzen der Methoden betrachtet werden können. Verschiedene Aspekte der Sedimentkonnektivität werden auf dem Hang beobachtet. Beide Methoden der hochauflösenden Geländeerfassung erlauben die Detektion lokaler Bodenmaterialverlagerungen. Jedoch sind die Unsicherheiten bezüglich lateraler Akkumulations- sowie Interrillenerosionsprozesse, aufgrund eines vergleichsweise hohen LoD, weiterhin groß. In beiden Fallstudien erhöhen Traktorspuren und Erosionsrillen die Konnektivität. Auf dem Einzelhang im Mediterranraum ist aber besonders die Dis-konnektivität des Sediments sichtbar. Im Europäischen Lößgürtel konnte ein Initiationsereignis erfasst werden, dass zu hohen Bodenerosionsraten aufgrund sehr hoher Bodenfeuchte führte und anschließend in Folge von Rilleneinschneidung die Erosion durch Rillenverstärkung noch weiter steigerte. Die berechneten Bodenabtragsraten betragen zwischen 2.6 tha-1 und 121.5 tha-1 für Einzelereignisse und weisen eine hohe Variabilität, aufgrund sehr unterschiedlicher Gebietscharakteristiken, auf. Beide Regionen befinden sich in fragilen Landschaften. Jedoch hat die Erosionsanfälligkeit verschiedene Ursachen; Im Mediterranraum sind es Starkniederschläge und im Europäischen Lößgürtel ist es die hohe Erodibilität des Bodens.

Zukünftig kann die Methode der hochauflösenden Geländeerfassung auf größere Skalen ausgeweitet werden (z.B. kleine Einzugsgebiete). Somit kann die Bedeutung von Gullys für die Sedimentkonnektivität zwischen Hang und Vorfluter neu betrachtet werden. Des Weiteren können die meist unterschiedlichen gemessenen Erosionsraten am Hang und im Einzugsgebiet, aufgrund der Detektion lokaler Veränderungen, anders beleuchtet werden. Die Methode ist außerdem, infolge des beispiellosen Detailgrades und der flexiblen Anwendung in verschiedenen räumlichen und zeitlichen Skalen, sehr gut zur Kalibrierung, Validierung und Weiterentwicklung von Bodenerosionsmodellen geeignet.

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List of abbreviations

BA	bundle adjustment
BBA	bundle block adjustment
CC	compact camera
CMVS	cluster-based multi-view stereo
CSC	compact system camera
DEM	digital elevation model
DoD	DEM of difference
DSM	digital surface model
DTM	digital terrain model
GCP	ground control point
GPS	global positioning system
HiRT	high resolution topography
IMU	inertial measurement unit
LEM	landscape evolution model
LiDAR	light detection and ranging
locRMSH	local root mean square height
LoD	level of detection
PMVS	patch-based multi-view stereo
RMSH	root mean square height
RMSE	root mean squared error
SfM	structure from motion
SLR	single lens reflex camera
SP	scan position
TLS	terrestrial laser scanning
UAV	unmanned aerial vehicle
VSfM	Visual SfM

1. Introduction

To date, soil erosion quantifications under field conditions, and thus under the impact of the natural earth surface process forces, are either limited to point measurements, refer to entire plots or even catchments, or register solely erosion forms of large magnitudes. In particular, less obvious erosion forms, such as sheet erosion, have indeed been observed but so far not quantified within large field plots or at hillslopes. However, this is necessary to address the issues regarding sediment connectivity and scale aspects. The soil surface has to be surveyed across scales, i.e. not solely limited to splash erosion at small plots and rill erosion at larger plots, to allow for an integrated assessment of soil erosion. Such an approach can enable new insights into sediment connectivity at hillslope scale, i.e. sink – source interaction from small patches. Furthermore, a future prospect would be the transferability to larger scales, i.e. sediment connectivity between hillslope and channel.

Methods to measure high resolution topography (HiRT) data, implying very detailed information about the morphology of the earth surface, offer new opportunities in this regard. Especially, the usage of terrestrial laser scanning (TLS) and unmanned aerial vehicle (UAV) photogrammetry are suitable for soil erosion assessment. Both methods are contactless and measure with high accuracy and resolution covering large areas. Thus, there is a need to evaluate the performance of these recent methods and evaluate its excess value to measure soil surface changes potentially identifying new process interactions and significance.

1.1. Thesis structure

This thesis is arranged in a cumulative manner. The integrated individual scientific articles are published in international peer-reviewed journals. Each publication is preceded by a cover page depicting additional information regarding citation information and publication history. The merged articles exhibit the formal constraints of the corresponding journal they are published in and thus possess some formal inconsistencies due to each journals formatting standard, which also includes reference style. Therefore, the according chapters (2, 3, 4) should be treated as isolated articles. The articles are antedated by the introduction and enclosed by the synthesis.

Specific adaptations were made to the manuscript to enable a nearly consistent layout. Figure numbering, table numbering as well as equation numbering are slightly adapted to the chapter numbering to fit into the overall thesis structure. Furthermore, in chapter 2 and chapter 4 slight irregularities regarding figure numbering are adjusted (i.e. Fig. 2-5 and Fig. 4-10 – 4-13) for better readability. Figure and table style (position and size) have been minimally changed to allow for uninterrupted text flow. The reference list at the end of the thesis refers solely to literature citations made in the introduction and synthesis (chapter 1 and chapter 5). Moreover, chapter headings corresponding to the individual articles have been customised for a comprehensible context.

Consecutively, the thesis is structured the following: An introduction to the severe issue and relevant processes of soil erosion is made and photogrammetric techniques and algorithms, allowing for high resolution topography data, are presented. Subsequently, three main chapters comprise the individual publications. Firstly, the performance of TLS for multi-temporal soil erosion measurement at field scale in a Mediterranean landscape is investigated, secondly the performance of UAV photogrammetry regarding systematic errors and applicability to measure soil surfaces in the field is assessed, and thirdly soil surface changes at field scale with very high resolution using UAV photogrammetry is examined. Afterwards, an approach is introduced to fuse TLS and UAV data and finally new insights revealed from the new HiRT methods are presented.

1.2. Soil erosion

1.2.1. Process and impact

Soil erosion is a very complex natural geomorphologic process causing the relocation of earth surface material due to forces of water or wind, which is additionally influenced by agricultural management. The process is a major driving factor of land degradation, with severe ecological (e.g. decrease of biodiversity) and economical (e.g. food security) consequences (Morgan, 2005). Soil erosion is especially intense on arable land (García-Ruiz et al., 2015) if further conditions, e.g. such as substrate susceptibility or inclined surfaces, are complied. At agricultural sites tolerable soil erosion rates are exceeded by far (Montgomery, 2007, Verheijen et al., 2009). Thereby, tolerable erosion is reached if soil erosion equals soil formation due to weathering and dust deposition, which globally averages 0.1 mm a⁻¹ for the case of physical conversion of consolidated bedrock to soil (Stockmann et al., 2014) but can deviate strongly (Montgomery, 2007). In the following, soil

erosion due to water is discussed in more detail because of its predominant relevance at the investigated study sites of this thesis (Fig. 1-1).



Figure 1-1: Flow chart illustrating the complexity of soil erosion due to the force of water.

Particle detachment and transport: Soil particles are detached by raindrop impact (i.e. splash) and/or hydrologically connected overland flow (Bryan, 2000), which can happen in concentrated (i.e. in rills) and dissipative (i.e. in interrill areas) form. Overland flow is distinguished between saturation runoff and Hortonian runoff (Hendriks, 2010). The former happens due to saturation excess, e.g. during low intensity precipitation events on wet soils with good infiltration capacity leading to soil saturated, for instance occurring during precipitation events with high intensities, which exceed soil infiltration rates. This effect could be accelerated on dry or crusted soils with low infiltration capacities.

Initially the combination of raindrop impact and the beginning of shallow surface flow are the most effective processes regarding soil detachment (Parsons et al., 1993). An increase of flow depth during prolonged precipitation causes a decrease of raindrop energy at the surface due to increasing energy dispersion (Torri et al., 1987). The significance of flow detachment becomes predominant (Parsons et al., 2004). Snowmelt is another influence that needs to be considered for soil erosion in temperate climates because of facile runoff generation over still frozen subsoil (e.g. Hayhoe et al., 1995, Singh et al., 2008). Soil erosion in interrill areas is due to raindrop impact and shallow overland flow (e.g. Sharma, 1995), while rill erosion occurs due to runoff only (e.g. Parsons et al., 2004). To initiate rills supercritical flow is assumed to be a prerequisite (e.g. Boon & Savat, 1981, Govers, 1985, Merrit, 1984). However, erosion rills are also documented during (turbulent) subcritical flow (e.g. Abrahams & Parsons, 1996). For rill incision the presence of standing waves is important (e.g. Abrahams et al., 1986).

Soil particle detachment and transport and thus sediment yield is either limited due to transport capacity or sediment availability, i.e. transport-limited versus detachment-limited respectively (Morgan, 2005). For instance, during smaller precipitation events soil erosion can be transport-limited because restricted runoff volume inherits the transport of larger grain sizes (e.g. size-selectivity of splash and sheet erosion after Malam Issa et al., 2006). In contrast, rainfall events with high intensity are more likely detachment-limited because sediment supply might be the only constraint during high discharges.

Erosive and erodible factors (more detail in Morgan, 2005): Soil particle detachment, due to overcoming of shear stress and/or due to the effect of rainfall energy, and soil particle transport depends on a large variety of factors, which are in addition spatio-temporally variable (Bryan, 2000).

Precipitation characteristics: Rainfall intensity influences the magnitude of soil erosion due to the impact of raindrop energy on the soil surface (e.g. Poesen & Savat, 1981; large drops during thunderstorms versus small drops during drizzling rain) as well as the ability of the soil surface to include the water (e.g. Morin & Benyamini, 1977; infiltration versus runoff). Furthermore, duration of the precipitation event is relevant because it will determine the accumulated water volume (e.g. Willgoose & Perera, 2001; saturation versus runoff). Another interesting criterion to consider is the impact of raindrops accelerated by wind (e.g. Ries et al., 2014).

Soil characteristics: Besides the erosive-effective forces, erodible site circumstances need to be evaluated, as well. Soil texture (e.g. influencing particle weight and cohesion), soil structure and aggregate stability (e.g. influencing sealing and crust formation; e.g. Agassi et al., 1981, Bresson et al., 2006), pore distribution and continuity (e.g. influencing soil permeability; e.g. Arya & Paris, 1980), and soil depth (e.g. influencing water storage capacity) are strongly influencing the variability of soil detachment and runoff generation. Also, chemical characteristics affect soil erosion, e.g. due to their significance for dispersion

or coagulation (e.g. Faulkner, 2013). Soil moisture is another important condition because during low to intermediate storm intensities erosion is promoted on wet soils (saturation excess) in contrast to dry soils (no saturation excess but solely Hortonian runoff possible; e.g. Calvo-Cases et al., 2003).

Topography: The shape of the surface is important regarding gradient, hillslope length and catchment area. An increasing slope accelerates flow velocity, which further rises non-linearly with increasing discharge (Govers, 1992) leading to increased erosion (e.g. Zhang et al., 2003). An increasing slope length increases flow accumulation and thus again resulting in higher erosion (e.g. Cochrane & Flanagan, 1996). Exposition is also influencing the rate of soil erosion with higher values for the windward facing slopes due to higher hydrological rainfall there (Beullens et al., 2014). Furthermore, surface roughness is relevant due to its significance for flow dissipation, flow deceleration as well as for local water retention and sediment storages, but also for the definition of possible preferential flow paths (e.g. Takken et al., 1998, Darboux et al., 2001).

Land use: The utilisation of the surface is relevant regarding vegetation because plant cover limits raindrop impact and runoff due to an increased infiltration capacity (e.g. along roots) and flow dissipation. In contrast, on recently abandoned land (e.g. Cerdà, 1997) and bare surface between crop sequences (e.g. olive trees or vineyards; e.g. Faulkner et al., 2003, Martínez-Casanovas & Sánchez-Bosch, 2000) the surface is completely delivered to the natural forces due to precipitation. Furthermore, land management itself is relevant for soil erosion because of soil relocation at inclined fields due to tillage erosion (e.g. Lindstrom et al., 1992) and because of the influence of the tillage practice, for instance comparing conventional and conservation tillage with much lower rates for the latter (e.g. Cogo et al., 1983, Seta et al., 1992).

On-site and off-site impacts (more detail in Morgan, 2005): Soil erosion has direct consequences at the site itself, but also indirectly at remote locations. For instance, loss of fertile soil due to depletion of organic matter as well as nutrients and decrease of soil profile depth and subsequent decrease of water storage capabilities are on-site impacts. Whereas off-site impacts are, amongst others: increase of flood likelihood due to decreased water storage in shallow soils, crop loss due to plant burial by sediments, water reservoir and river pollution due to concentration of nutrients, release of carbon due to soil aggregate breakdown, and aggradations or silting of dams and retention basins. Costs for

compensating on-site and off-site effects of soil erosion in the European Union amounts to 45.5 billion dollar per year (Montanarella et al., 2007) and are amongst the highest estimates world-wide (Telles et al., 2011).

Fragile landscapes: Soil erosion occurs especially in landscapes with low resilience, which are thus prone to the impact of natural forces. Agricultural utilised fields at inclined terrain are amongst those.

In temperate Europe the European loess belt is such a region. Thereby, the soil characteristic, comprising low aggregate stability, is the essential factor for the landscapes fragility (Pecsi & Richter, 1996). The soils fertility promotes intensive farming with conventional tillage practices and energy plant crops, which amplifies the fragile circumstance.

In the Mediterranean a long history of cultivated land use (especially during Roman times) and climatic characteristics make the landscape fragile (e.g. Poesen & Hooke, 1997, García-Ruiz et al., 2013). Generally, the summers are dry because of the influence of sub-tropic high pressure centres while the winters are moist due to the extension of the polar front with associated low pressure cyclones. Precipitation variability as well as the rainfall intensity is high. The Mediterranean is dominated by shallow soils because water shortage prevents fast solution and leaching of the soils (Sala & Coelho, 1998).

Thus, in both study areas similar processes shape the surface, but with different weights of influencing factors and thus different appearance. Cammeraat (2002) compared similar contradicting landscapes and revealed the importance of thresholds and scale-specific non-linear processes impeding simple up-scaling of erosion measurements within both varying environments.

1.2.2. Scale issues

The complexity of soil erosion becomes especially apparent considering soil detachment and transport processes at different spatial and temporal scales. Thereby, the concepts of hydrological and sedimentological connectivity have to be recognised describing the movement of matter between landscape units, i.e. of water for the former and of sediment for the latter (Bracken & Croke, 2007). Thus, sediment connectivity is strongly interrelated (but not necessarily equal) to hydrologically connectivity because soil detachment and transport is controlled by hydrology (Bracken et al., 2015).

Boardman (2006) highlights the differences when soil erosion is measured at plot, hillslope (field) or catchment scale. No linear up-scaling of the measurements from smaller to larger scales is possible due to the spatio-temporal variability of soil erosion. To understand soil erosion, Bracken et al. (2015) emphasise the importance to describe sediment connectivity as function of event frequency magnitude distribution, synchronisation between erosion processes, and process feedback. This is also communicated by Lexartza-Artza & Wainwright (2009), who state that sediment connectivity should not only be noticed in the form of structural connectivity, i.e. description of elements defining the erosion system and its change through time, but also as functional connectivity, i.e. considering the dynamic system behaviour and process feedbacks.

To illustrate the relevance of event frequency and magnitude distribution Bracken et al. (2015) describe the case that connectivity (considering the pathway of runoff and sediment through a catchment) at large scale can significantly be influenced by lower magnitude events (with possible higher frequency) at small scales. For instance, sediment is constantly built-up in a local source due to low intensity rainfall and subsequently might be suddenly eroded and transported through scales during an extreme event. System boundaries, e.g. the slope foot, can function as accumulation spots and decrease sediment connectivity, e.g. between hillslope and channel (Cammeraat, 2004, Fryirs, 2013).

For hillslopes, the relevance of sediment connectivity and event frequency magnitude distribution can be exemplary presented as follows: During small rainfall intensity events, which typically occur with high frequencies, sediment is solely locally transported and remains at the hillslope. During higher intensity precipitation events, with mostly lower frequency, hydrological connectivity between hillslope and channel establishes resulting in sedimentological connectivity if the event duration is sufficient. Thus, high magnitude events allow for longer sediment yields out of the hillslope system. This highlights the significance of extreme events in the Mediterranean due to common dry soil conditions (i.e. relevance of Hortonian runoff). Whereas, within the temperate loess belt sediment yield from hillslopes can occur as well during moderate events on more frequent wet soils (i.e. relevance of saturation excess runoff).

Scale related soil erosion quantification: There are different options to measure soil erosion, which are differently suitable for varying scales. Soil erosion measurement can be

distinguished between indirect and direct methods, with the former referring to surveying of accumulation of sediment or reduction of soil profiles predominantly for historical erosion assessment (Cerdan et al., 2006).

methods	assessment type	condition naturalness	measurable erosion processes	minimal sampling frequency	spatial scale	spatial resolution [m]
discharge measurement (turbidity)	sediment catching	field	interrill, rill, gully, channel	continuous	catchment	area- averaged
reservoir survey	sediment catching	field	interrill, rill, gully, channel	event based	catchment	area- averaged
gutter (at bounded plot)	sediment catching	field	interrill, rill	event based	plot, (hillslope)	area- averaged
Gerlach trap	sediment catching	field	interrill, rill	event based	plot, hillslope	area- averaged
erosion pin	surface change	field, laboratory	interrill	event based	plot, hillslope	point
splash cup, splash funnel	sediment catching	field, laboratory	splash	event based	plot	spot- averaged
profiler/pin metre	form mapping	field, laboratory	rill, gully	event based	plot, hillslope	2D: 10 ⁻³ 3D: 10 ⁰ - 10 ¹
(satellite-) remote sensing	surface change, form mapping	field	gully	return interval of device	hillslope, catchment	10 ⁰ - 10 ²
(small format) aerial photography	surface change, form mapping	field	rill, gully	event based	hillslope, catchment	10 ⁻² - 10 ⁰
close-range photogrammetr.	surface change	laboratory	interrill, rill	continuous	(micro-) plot	10 ⁻³
transects (e.g. roller chain)	form mapping	field, laboratory	rill	event based	plot, hillslope	2D: 10 ⁻² 3D: 10 ⁰ - 10 ²
TLS	surface change	field, laboratory	interrill, rill	event based	(micro-) plot	10 ⁻³ - 10 ⁻²
tracers (e.g. ¹³⁷ Cs, ⁷ Be, ²¹⁰ Pb)	isotope concentrati on	field	interrill	retrospecti. till event based	hillslope, catchment	spot- averaged

Table 1-1: Comparison of different soil erosion measurement techniques (more detail in Morgan, 2005, Jester & Klik, 2005, Casalí et al., 2006, Vrieling, 2006, Walling, 2009, Porto et al., 2014, Thomsen et al., 2015).

Table 1-1 illustrates direct methods in regard to spatial and temporal scales as well as process registration. Not mentioned are rainfall simulators, which can be very suitable to control course of the experiment either on small plots in the field or in the laboratory (e.g. Iserloh et al., 2013, Ries et al., 2013). Measured erosion values are either solely associable

to the point where it is measured or has to be averaged for a certain area. The introduced methods inherit the difficulty to assess the reliability of the measured soil erosion rate (Stroosnijder, 2005, Boardman, 2006). García-Ruiz et al. (2015) reveal from a large global data set that erosion rates are negatively correlated to the size of the study site and that the monitoring duration as well as the applied measurement method has as an impact on the measured rate.

The differing sizes of the areas under investigation results in the registration of different processes. Micro-plots (< few m²) emphasise the assessment of interrill erosion due to splash and shallow overland flow. Larger plots additionally consider further erosion forms. Thereby, plot shape is relevant. Longer plots put higher weights at the measurement of erosion due to runoff (i.e. sheet and rill erosion) compared to wider plots with smaller potential upslope drainage area. Plots are too small for gully erosion, which can be quantified with methods designed for hillslopes and catchments.

The erosion rates measured at small scales often do not agree with measurements at larger scales because for instance local sediment stores are not considered (e.g. de Vente et al., 2013), highlighting the significance to understand sediment connectivity within the catchment (Bracken et al., 2015). Methods that enable temporal and spatial highly resolved (4D) surface surveys beyond the plot scale can contribute to better understand the spatio-temporal variability of soil erosion. Furthermore, scale should not only be considered in regard to space and time but also in regard to the investigated process, e.g. to develop erosion models (Brazier et al., 2011). These models need to be calibrated and evaluated regarding their performance, accentuating the need for "scale-independent" assessment techniques.

1.3. High resolution topography

Methods to generate High Resolution Topography data have been recognised as an essential element for digital assessment of earth surface processes and landforms (Tarolli, 2014, Passalacqua et al., 2015). During the last two decades terrestrial and airborne LiDAR (Light Detection and Ranging) has emerged as an established high resolution surveying tool in geosciences (Vosselman & Maas, 2010). More recent advances in computer vision and digital photogrammetry now permit 3D reconstruction of a scene using overlapping images (Structure from Motion (SfM) after Ullman, 1979, Snavely et al., 2008) to create precise

digital surface models requiring only basic photogrammetric knowledge and minimal investment in survey equipment (Smith et al., 2015, Eltner et al., 2015a). Simultaneous development of easy-to-handle Unmanned Aerial Vehicles (UAV, e.g. Grenzdörfer et al., 2008, Eisenbeiß, 2009, Colomina & Molina, 2014) further boosted the establishment of SfM photogrammetry.

LiDAR (more detail in chapter 1.2.1) allows for the survey of the earth surface at a vast variety of spatial scales (from sub-mm to many km). Concerning flexibility this can yet be outperformed by SfM photogrammetry (more detail in chapter 1.2.2) because a single consumer grade camera, can be utilised to achieve this spatial diversity. In addition to the versatile extent of spatial scales, the straightforward HiRT data retrieval and fast processing enables a significant increase in the temporal resolution, which becomes prominent in regard to the morphometric monitoring of earth surface processes. The variation of temporal scales (from single events to lasting time series or from sub-seconds to decades) allows for a new perspective on the significance and interaction of events of different magnitudes and frequencies (low frequency and large magnitude versus high frequency and small magnitude) in controlling landscape evolution. Thus, HiRT will eventually allow for new insights into processes and morphologies of fast changing environments – e.g. assessing the influence of single precipitation events on small catchments under agricultural use.

However, precise and stable geo-referencing remains an essential crux for successful monitoring (more detail in chapter 2.3.2.), especially in dynamic and fragile landscapes. Furthermore, development of automatic geomorphic feature extraction is also required for effective data handling (more detail in chapter 4.2.5.) of large data sets, typical for HiRT data, and subsequent exploitable information treatment for data interpretation. But if these challenges are accounted for, HiRT provides a new perspective onto geomorphologic processes due to a novel consideration of spatial and temporal scales. The recent technological and algorithmic advances lead to the possibility of a flexible measurement of large areas of interest of the earth surface with high spatial and temporal resolution and accuracy.

As a result, progress in processing of reconstructed point clouds and subsequent raster data products derived from SfM photogrammetry becomes relevant to exploit the potential of this data, which has been recognised recently in different geomorphic applications (Eltner et al., 2015a evaluate 61 studies). However, so far most approaches have been static and just recently the number of studies of multi-temporal applications increases (13 out of 61 studies in the review of Eltner et al., 2015a).

1.3.1. Terrestrial Laser Scanning

TLS is a ground-based survey system that actively images the area of interest, which is widely used in geosciences for high resolution surface recording (e.g. Schneider, 2009, Heritage & Large, 2009a, Vosselman & Maas, 2010, Jaboyedoff et al., 2012). TLS realises the direct retrieval of scaled 3D information. The basic principle implies the registration of distance measurement and corresponding registration of vertical and horizontal angles (Fig. 1-2). Thereby, within the scanning device an origin is defined from which a polar axis emerges to which both angles are measured. In combination with the registered distance these polar coordinates are usually transformed into Cartesian coordinates for further data processing.

Different methods exist to retrieve the distance information – i.e. usage of triangulation principle for close-range applications, phase measurement techniques for intermediate distances and utilisation of the time-of-flight principle for intermediate to large distances (more detail in Petrie & Toth, 2009a, Beraldin et al., 2010). The latter option is implemented in the device used in this dissertation (Riegl LMS Z420i). Time-flight-measurement implies that a laser impulse is emitted and the time measured, which is needed by the signal to travel to the surface and back (Joeckel & Stober, 1999).



Figure 1-2: Illustration of the functional principle of terrestrial laser scanning.

To record the entire surface the emitted laser pulses of the Riegl LMS Z420i are deflected in vertical and horizontal direction using rotating/oscillating mirrors and the rotation of the device itself. The resulting distances are calculated under consideration of the speed of light (Fig. 1-2). The registration of the returned signal happens when a specific threshold of signal intensity is exceeded (Thiel & Wehr, 2004). Thus, received signal intensity influences the accuracy of the distance measurement.

Scanning solely at one scan position can impede the holistic capturing of the area of interest due to occlusion effects, potentially leading to data gaps. To allow for comprehensive data the scanning device has to be utilised from further positions. The resulting point clouds are then aligned into one coordinate system using for instance registration targets or iterative closest point (ICP) algorithms over temporal stable surfaces. Thereby, the ICP approach rotates and shifts the point cloud to a reference until distances between the two are minimised (Lichti & Skaloud, 2010).

Resolution and accuracy: Several factors influence the performance of TLS to record the earth surface with corresponding point clouds. Regarding resolution, achievable minimal point distance (angular resolution) and beam divergence, and thus resulting footprint at the surface, are system related effects (Heritage & Large, 2009b). Both increase with distance (Fig. 1-3). But also increasing incidence angles cause their growth, highlighting the importance of the surface orientation towards the TLS device for possible resolutions besides the impact of distance.



Figure 1-3: Resolution influenced by angular resolution and beam divergence that increase with distance and incidence angle.

Footprint and incidence angle also affect the accuracy of TLS, which is thus distance related. Furthermore, system related influences such as erroneous axis alignment affect the accuracy performance. Atmospheric conditions need to be considered, as well, because the distance is calculated using the speed of light, which changes in air if atmospheric conditions alter (Joeckel & Stober, 1999). However, this is not as relevant for short distances. In regard to the TLS device Riegl LMS Z420i an accuracy of \pm 5 mm in 100 m is achievable (Riegl LMS, 2005).

The accuracy of TLS is also influenced by surface characteristics. Surface colour, surface type and the form of reflection affect the returned signal intensity (Boehler, et al., 2003, Heritage & Large, 2009b). Regarding surface type and wetness, some materials cause partial signal absorption and in addition material composition influences the form of reflection, i.e. specular and/or diffuse (e.g. Petrie & Toth, 2009b, Heritage & Large, 2009b). As for resolution, surface orientation towards the scanning device is relevant again, because with increasing incidence angles footprints at the surface increase and thus the amplitude of the signal intensities decrease and furthermore reliable assignment of the location of actual signal reflection within the increasing footprint becomes difficult (e.g. Gordon, 2008). Moreover, surface roughness is an essential parameter that needs consideration for reliable accuracy assessment (Smith, 2014). The rougher the surface the more difficult will be its precise description by TLS point clouds (Brasington et al., 2012, Lague et al., 2013). With increasing footprint, e.g. due to increasing distance and incidence angle, roughness related errors increase (Fig. 1-4). Within the footprint it becomes difficult to correctly assign the distance measurement and multiple reflections may lead to signal blending, resulting in the edge effect with consequent edge smoothing or comet tails.



Figure 1-4: Accuracy of distance assignment influenced by incidence angle, footprint and surface roughness.

Most errors are well describable, apart from the distance miscalculations due to surface roughness, and thus can be calibrated. TLS inherits the advantage of reliable and mostly constant error characterisation (Lichti, 2010a, Lichti, 2010b). Furthermore, a high automation of digital elevation model (DEM) calculation due to recent advances in point cloud processing tools eventually leads TLS to being a very suitable method for fast generation of HiRT. Therefore, its potential for soil erosion studies should be accounted for in more detail. However, if investigations in Mediterranean badlands with high magnitude of surface changes (Vericat et al, 2014, Nadal-Romero et al. 2015) are set aside, no studies exist where multi-temporal evaluation of soil erosion at field scale are performed (more detail in chapter 2.1).

1.3.2. Unmanned Aerial Vehicle photogrammetry

UAV photogrammetry defined after Eisenbeiß (2009) comprises photogrammetric surveying from an UAV platform, which carries the photogrammetric measurement device – for instance a consumer grade camera, thermal camera, infrared camera, hyperspectral camera or a LiDAR system. Furthermore, UAV is defined after Colomina & Molina (2014) as an unmanned aircraft with a corresponding ground control station and communication data link between the station and the flying device. A vast variety of UAVs exist (Watts et al., 2012, Colomina & Molina, 2014) and can be distinguished for instance corresponding to their performance. In regard to licensing, flexibility and handling of the device, microdrones are especially relevant in geo-scientific studies, thereby meaning UAVs with maximal flying heights of 250 m, maximal ranges of 10 km and flight endurances below 1 hour (van Blyenburgh, 1999). Micro-drones further are characterised by low weights (less than 5 kg after Colomina & Molina, 2014).

1.3.2.1. UAV perspective

In contrast to TLS the application of UAVs allows for a favourable bird's eye view bypassing the disadvantages of occlusion effects at rough surfaces. Small aerial platforms have already been used in geosciences 30 years ago for small format aerial photography (see more detail in Aber et al., 2010). UAVs can be used for area coverage between square metres and several hectares and thus can help to close the gap between terrestrial imaging utilisation covering small areas (sub-m²) and manned aircraft image capturing covering large areas (many km²) (Eisenbeiß, 2009). Furthermore, the temporal scale can be approached from a new perspective, as well, because flexible data acquisition enables observations of high temporal frequency. Technological advances, especially in recent years (e.g. Watts et al., 2012), allow to easy handle low-cost (compared to manned aircraft) flying devices, which has increased the recognition of the potential of UAVs for earth surface observations (Carrivick et al., 2013). The new spatio-temporal conditions are especially relevant regarding soil erosion assessment because the aerial perspective from low flying heights allows measuring the impact of single precipitation events at entire hillslopes with high resolution and under field conditions, which is in contrast to previous methods.

Some developments leading to increased UAV applications: The first aerial platforms used were balloons, kites, airships and other flight devices such as model

helicopters or even para-gliders (Aber et al., 2010). These devices were either limited in their range and steering options or heavy due to utilised combustion engines possibly resulting in stricter official flight regulations. In contrast, recent developments of fixed wing and copter micro-drones enable new scopes of UAV applications.

Especially, copters (Fig. 1-5) are very flexible due to vertical take-off and the option for position hold at the image capturing point allowing for better image quality. Facilitation of UAV deployment is realised due to integrated flight stabilisers as well as GPS (global positioning system) and IMU (inertial measurement unit) devices, which allow for an UAV flight in auto-pilot mode and thus the realisation of pre-defined programmed flight patterns. The IMU measures the roll, nick and pitch movement of the aerial platform. Active stabilising camera mounts installed at the UAV platform that allow for constant camera viewing direction are another development facilitating data acquisition. In addition, these mounts permit the capturing of off-nadir images that can be useful if vertical structures (e.g. coastal cliffs or rockfall movements) are to be monitored. Last but not least, the integration of redundant as well as 'fail-safe' systems minimises the risk of the total loss of an UAV and its payload and increases the confidence to use such devices (Carrivick et al., 2013).

Remaining limits: Although micro-drones usually use rechargeable batteries with low weights, thus minimising the load to carry, flight times are still an important constraint regarding UAV (especially copters) performance in the field, yet they are increasing steadily (e.g. by developing copter fixed wing hybrid – Hochstenbach et al., 2015, Thamm et al., 2015). Furthermore, UAVs are weather prone because their operation during rain or strong winds is limited. Another important possibly restricting condition that has to be considered are legal regulations (Watts et al., 2012), which differ between countries. For the study areas investigated in this dissertation different governmental terms had to be respected. In Germany a general flight permission, lasting up to two years, is needed to use an UAV. For that, the micro-drone has to weigh below 5 kg, the flying height is constrained to maximal 100 m and the UAV must be operated in visual range (BMVI, 2012). In Spain a micro-drone with a weight below 25 kg, a flight altitude below 120 m and an application within the visual range can be used if a certificate, stating the ability to fly an UAV, is given (MPR, 2014).

Nevertheless, rapid advancement in regard to UAV hardware and sensors is still ongoing, e.g. substantiated by the special issue "UAV Sensors for Environmental Monitoring" by Gonzalez Toro & Tsourdos (2015). However, studies dealing with the application of UAV for multi-temporal soil erosion assessment, especially at hillslope scale, are still missing despite its obvious suitability – i.e. large area coverage with high resolution, flexible utilisation after every precipitation event, surface change detection as gross and net sediment export, and data acquisition without disturbing the area of interest (Fig. 1-5).



Figure 1-5: Illustration of an UAV (octocopter) used for soil surface change detection (image P. Baumgart).

1.3.2.2. SfM photogrammetry

Concurrent to the progress in the development of aerial platforms, algorithmic advances led to the vast recognition of image based 3D reconstruction that evolved from digital photogrammetry and computer vision. SfM photogrammetry refers to fully automatic reconstruction of 3D scenes from 2D images (without the need to assign initial values) including dense matching and the option to integrate ground control points (GCPs). This recent method (but also many other photogrammetric solutions) in combination with new realisations of aerial perspectives convenes in the increasing utilisation of UAV photogrammetry in geomorphic surveys and soil erosion studies (more detail in chapter 4.1.). Although SfM photogrammetry can be performed without extended knowledge about the geometric implementations to retrieve 3D information from 2D images, a basic understanding should be provided to account for possible errors and avoid inappropriate data handling (further reading e.g. Luhmann et al., 2014, Pears et al., 2012, Kraus, 2007, Mikhail et al., 2001).

Geometric principles: Algorithms evolving from computer vision and digital photogrammetry are used to retrieve the 3D digital elevation model (DEM) from multiple 2D image information. Thereby, the standard pinhole camera model establishes the functional context between the spatial object points and planar image points. This can be described mathematically by the collinearity constrain, which is also displayed by the perspective projection (Fig. 1-6).



Figure 1-6: Schematic illustration of the collinearity constraint, after Kraus (2007).

In the perspective projection image point, object point and projection centre are represented by a straight line. The orientation (rotation of the axis by the three angles $\omega \phi \kappa$) and position (three coordinates $X_0 Y_0 Z_0$ of the projection centre) of the camera coordinate system within the object coordinate system is defined as the exterior (extrinsic) orientation. In contrast, the interior (intrinsic) orientation illustrates the inner camera geometry, which is defined by the principle point, meaning the orthogonal projection of the projection centre into the image plane (described by the image coordinate system), and the principle distance between the projection centre and the principle point, meaning the focal length of the lens focused at infinity. Additional parameters can be added, which usually comprise radial distortion, tangential distortion and decentering due to lens misalignments,

and affinity as well as shear due to analogue-digital conversion effects on non-quadratic pixels (e.g. Kraus, 2007).

If the orientation and camera model parameters of two images are known, the coordinates of the 3D object points can be determined by spatial intersection. Conversely to the retrieval of 3D information from orientated images, a minimum of three ground control points (GCPs) can be used to determine the orientation of a camera. Usually camera orientations and positions are unknown during image capture. Therefore, bundle adjustment (BA) techniques, developed in photogrammetry, allow to simultaneously determine the parameters of the camera configuration network and 3D coordinates of the object points for a large number of images. The term bundle refers to rays evolving from the object point. Tie points, i.e. homologous points between images that represent the object point, are used as input for the BA procedure and possibly some (at least 3) GCPs to geo-reference the image block. Camera coordinate systems are rotated and shifted during the BA to achieve best intersection of the rays evolving from the corresponding image points (Fig. 1-7). BA can be extended by a simultaneous camera self-calibration to estimate the interior camera orientation (e.g. Kraus, 2007).



Figure 1-7: Schematic illustration of 3D reconstruction from 2D information with the BA (Kraus, 2007).

During BA the residual reprojection error is minimised, mostly after the least squares method. This reprojection error is defined as the difference between the observed image point and the predicted image point calculated from a model, which is defined as a function of 3D points visible in the image and the interior and exterior camera orientation parameters (Triggs et al., 2000).

The orientation of a reconstructed image block can be separated into a relative and an absolute orientation, the former describing the orientation and position between the images within an arbitrary system and the latter describing the orientation and position of the image block within a superior coordinate system (i.e. geo-referenced image block). Generally, BA can be performed one- or two-staged, the latter firstly estimating the relative image block orientation and afterwards calculating the absolute orientation whereas the former performs the reconstruction of the image network configuration and the geo-referencing simultaneously (e.g. Kraus, 2007).

Image matching: Image point identification and assignment of corresponding homologous points in overlapping images (image matching) is automated in the data processing workflow of SfM. Thereby, area and feature based algorithms are distinguished. In many implementations, interest operators are used to select suitable image matching points. A popular feature based technique is applying the SIFT operator (Lowe, 1999, 2004), which extracts scale invariant keypoints that are characterised by significant changes of intensity. At the keypoints' position a feature descriptor, determined by image gradients comprising several scales, is calculated to describe the surrounding. These n-dimensional vectors are subsequently matched between images.

SfM: The orientation parameters of all images as well as object point coordinates and interior camera geometry are reconstructed utilising the information on the positions of the homologous image points. A large number of image points is usually retrieved by the interest operators with a high likelihood of false matches. BA assumes a Gaussian distribution of the reprojection error and thus large outliers disturb this assumption and might hinder converging of the least square fit. To avoid this influence of the blunders mostly the RANSAC (random sampling consensus) algorithm after Fischler & Bolles (1981) is implemented, using the F-Matrix (fundamental matrix) as model to be estimated (Hartley & Zissermann, 2004). The F-Matrix, comprising the epipolar geometry and thus considering the co-planarity constraint, is used to define the relative orientation between two images (Fig. 1-8). Estimates for the principle distance are usually retrieved from the EXIF tag, which stores some metadata of the captured image. The initial estimates of the camera

orientations are subsequently refined by an iterative BA, adding one image at a time (Snavely et al., 2008).



Figure 1-8: Schematic illustration of the epipolar geometry (after Pears et al., 2012).

Dense matching: After the image block has been oriented dense matching can be performed, which reconstructs a lot more surface points to generate a DEM with very high resolution (more detail in chapter 3.2.4). Thereby, the knowledge about the reconstructed epipolar geometry is utilised to decrease processing time because corresponding image points are searched along the epipolar line (1D) instead of searching in the entire image (2D). Dense matching can be performed in the manner of stereo matching or multi-view stereo matching, which considers more than two images. Stereo matching uses either local or global constraints to account for matching difficulties due to occlusion and ambiguities (more detail in Brown et al., 2003, Szeliski, 2011). Local methods are window-based, whereas global methods consider energy minimisation functions for a global optimisation over the entire image or image scan lines. The local or global constraints are usually applied to image pairs and multi-view approaches are merely performed afterwards due to geometric considerations during point cloud fusion. However, also real multi-view stereo matching algorithms exist that usually perform matching in the object space, which is contrary to the stereo matching implemented in the image space (Remondino et al., 2014).

SfM versus classical photogrammetry: SfM enables the fast reconstruction of a scenery from a large number of images acquired in rather irregular network schemes (Snavely et al., 2008), which depicts a slight difference to the classical photogrammetry (Fig. 1-9). Furthermore, SfM especially focuses on automation, which diverges from classical photogrammetry that also emphasises accuracy (Pierrot-Deseilligny & Clery, 2011). Another deviation between SfM and the classical photogrammetry is the different consideration of GCPs during the image based surface reconstruction (James & Robson,

2014a). SfM solely performs the image based reconstruction in an arbitrary system and thus performs BA in a two-staged manner focusing on the relative orientation. Thus, a seven parameter 3D-Helmert-transformation (eq. 2-1) has to be performed to retrieve the absolute orientation.

Photogrammetric approaches use optimised GCP schemes in order to control error propagation and maintain a rather homogeneous 3D point coordinate precision over the entire image block. The missing integration of GCPs in SfM applications can lead to the systematic so-called 'dome error' (James & Robson, 2014, Wu, 2014). This error is already well-known in classical photogrammetry. Thereby, error increases with increasing number of stereo models between subsequent control points considered in BA due to systematic and random errors (Kraus, 2007). Unfavourable parameter correlation because of insufficient geometric information, e.g. inheriting to distinguish between the effects of camera parameters and orientation parameters, can lead to inadequate parameter estimation (Mikhail et al., 2001).



Figure 1-9: Illustration to summarise SfM photogrammetry (in Eltner et al., 2015a): a) Example of a captured micro-plot (1 m²), b) matched pair of images with homologous points, c) resolved image network geometry and reconstructed corresponding sparse point cloud, d) point cloud after dense matching, e) meshed DEM of the micro-plot.

To put SfM photogrammetry in a nutshell four main steps can be summarised (Fig. 1-9): Firstly, homologous image points are detected and matched. Secondly, the camera network geometry and spatial object points are reconstructed with an iterative BA. Thirdly, the oriented images are used for dense matching exploiting epipolar constraints. And finally, the reconstructed model has to be scaled and geo-referenced.

1.4. Thesis objectives

High resolution topography methods have yet not been implemented in soil erosion studies. Therefore, a workflow needs to be established that permits their application as a standard technique for event-based long-term observation across a large variety of geomorphological systems. Data integration from different sensors and processing approaches promise unprecedented accuracy levels for soil surface change detection over large areas due to synergetic exploitation of each methods' benefit. Six main objectives of this thesis can be expressed, which are as follows:

- (1) Two powerful HiRT methods (TLS and UAV photogrammetry) have to be evaluated regarding their suitability for soil erosion investigations under field conditions at the hillslope scale. More precisely, TLS reveals disadvantageous scan geometry when applied to gently rolling hills due to the configuration scheme of an almost horizontal surface survey. UAV photogrammetry principally lacks implementations in soil sciences. Thus, the development of data acquisition concepts and processing chains is important for further applications.
- (2) Systematic and random errors regarding the 3D description of the soil surface are assumed for both HiRT methods. Therefore, approaches are developed for error detection and correction. As a rather flexible alternative to conventional calibration techniques utilising a source of superior accuracy for error assessment, photogrammetric techniques can achieve comparable accuracy levels by exploiting self-calibration techniques. Nevertheless, to validate this performance as well as to estimate TLS errors the source of superior accuracy is also utilised. Subsequently results are applied to the field data, mutually identifying errors from TLS and UAV photogrammetry DEMs.
 - On the one hand, TLS is expected to be reliable regarding error consistency and thus detected errors are corrected with a calibration function.
 - On the other hand, UAV photogrammetry is assumed to be more complex concerning 3D data retrieval than TLS. Hence, more inconstant error behaviour, e.g. due to unfavourable parameter correlation from parallel-axes image configurations, is possible. A method is suggested to avoid this error propagation.
- Furthermore, because UAV photogrammetry is a new method in the field of environmental sciences, evaluation of accuracy performance under field conditions is still rare and needs to be addressed.
- (3) Soil erosion studies have to be performed event based to assess soil surface changes due to precipitation and subsequent runoff. Thus, different aspects regarding multitemporal data processing are approached.
 - A large variety of magnitudes of changes have to be captured due to the intended measurement of soil erosion in its different shapes, i.e. from interrill to rill erosion. Thereby, a suitable stable and precise reference is essential, especially concerning small magnitude events.
 - A need for the automation of data processing is obvious due to the high data amount resulting from frequent data acquisition over large areas. The development of a tool for automatic geomorphologic feature extraction and corresponding parameter calculation is performed, e.g. to measure erosion rills at large field plots, which is manually not possible with high accuracy and resolution.
- (4) Performance estimation highlights advantages and disadvantages of both HiRT methods to measure soil surfaces. Accordingly, integrated fusion of the TLS and UAV photogrammetry data is implemented using the synergetic effects of both measurement approaches.
- (5) The novel HiRT methods enable the quantification of local erosion and accumulation schemes at the hillslope. Thus, investigations concerning the sediment dynamics are performed to estimate the storage potential at the field plot and to measure gross and net surface changes. Furthermore, execution of multi-temporal observations allows for the assessment of single precipitation events as well as intra-annual to interannual soil erosion tendencies at different frequencies and magnitudes.
- (6) Overall, TLS and UAV photogrammetry are promising techniques to allow for a fresh look at soil erosion. Thus, sediment connectivity at the hillslope scale in the Mediterranean is investigated, soil surface changes at a large field plot in the European loess belt observed, and concluding a holistic view sought regarding the possibilities of HiRT methods for soil erosion studies.

2. TLS implemented: quantification of soil erosion at hillslope scale

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Accuracy constraints of terrestrial Lidar data for soil erosion measurement: application to a Mediterranean field plot

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Abstract: Applications of terrestrial laser scanning (TLS) to measure soil erosion are yet limited, although this topographic mapping method allows for large area coverage with high resolution and reliable precision. However, restricting factors are accurate and stable references for multi-temporal change detection and adverse scanning geometries. At agricultural fields the plot is usually situated on gentle slopes provoking low viewing angles of the scanning device onto the surface, which inherits the risk of high data noise. In this study, TLS is exploited from a high tripod to measure soil erosion at an Andalusian hillslope ($2 \times 1000 \text{ m}^2$). In the Mediterranean sediment yield reveals discontinuous pattern and TLS is a promising method to quantify these surface changes. A stable reference system is defined, resulting in multi-temporal registration accuracy better than 7 mm. Further, an mm-accurate calibration plot (60 m^2) is designed to evaluate scan geometry and radiometry (i.e. incidence angle, footprint, and intensity) in dependence of distance related errors. A lookup table is determined to correct systematic errors of the field data. The Andalusian field plot is captured during a winter season and during single precipitation events. Estimated erosion rates amount 10 and 2.4 t ha⁻¹, respectively. Surface changes with magnitudes larger 1.5 cm are reliably measured. TLS can be implemented to estimate soil erosion with cm-resolution if errors are carefully accounted for.

Keywords: terrestrial laser scanning (TLS), multi-temporal referencing, scan geometry, soil erosion, hillslope scale, Mediterranean

2.1. Introduction

Terrestrial Laser Scanning (TLS) is a method for high resolution topographic survey mapping, which is widely recognised in geosciences (Shan and Toth, 2008; Heritage and Large, 2009; Vosselman and Maas, 2010). A great advantage is the measurement of large areas up to several hectares without disturbance of the investigated object, for instance due to instrument installations, which is beneficial for area based soil surface change detection. However, applications in soil erosion studies are yet limited and surveys are mostly conducted under restricted conditions. Erosion measurements with TLS are either performed on steep slopes with almost vertical viewing direction, on very small plots, or at locations where erosion magnitudes are very high.

Schmid and Hildebrand (2004) are one of the firsts to test TLS for soil erosion. They conduct field surveys on a small plot at a logged forest site and reveal the difficulty to clearly distinguish soil erosion from consolidation. However, they state, if a very precise reference could be setup, mm-accuracy is possible. On small plots of a few square metres different investigations are conducted to measure soil surface roughness to estimate its influence on soil erosion (Haubrock et al., 2009; Smith et al., 2011; Eitel et al., 2011; Vericat et al. 2014). In contrast, Hancock et al. (2008) are the first to measure rill erosion on a larger plot (60 m long) from further distance at a steep slope. Rills are detected broadly and thus high underestimation of rill erosion is assumed. At larger study areas erosion forms of larger magnitudes - i.e. gullies - are usually measured (Perroy et al., 2010; Lucía et al., 2011; Höfle et al., 2013). Recent studies on actively agriculturally utilised areas are performed by Ouédraogo et al. (2014), who generate digital surface models (DEMs) with m²-resolution at watershed scale, and by Barneveld et al. (2013), who calculate high resolution models of soil surfaces for different plots at field scale. However, the mentioned studies on larger plots have not yet conducted multi-temporal measurements, which entail the need for a precise reference system.

Soil erosion – especially interrill erosion – usually occurs with low magnitudes. If eventbased soil surface changes are to be measured at larger field plots, stable references need to be defined and data acquisition has to be performed with very high accuracy as well as resolution. These requirements have already been demonstrated for different geomorphic surveys using TLS – e.g. change detection of rock slopes (Abellán et al., 2009), coastal cliffs (Rosser et al., 2005), river bluffs (Day et al., 2013), or sand dunes (Feagin et al., 2014). Lague et al. (2013) further highlight the importance of accuracy consideration for multitemporal geomorphic change measurement with TLS.

However, it is difficult to achieve high data resolution and accuracy for soil erosion studies at cultivated fields because agriculturally utilisation is common at gentle rather than steep slopes, which results in unfavourable scanning geometry due to low viewing angles. The resulting data noise increases with increasing distance to the scanning device. Soudarissanane et al. (2011) show the importance of scan geometry, i.e. incidence angle and range, on point precision. Also, Schürch et al. (2011) highlight difficulties emerging from sub-horizontal surface measurement of complex topographies. Possibilities to correct errors, which evolve from TLS, are self-calibration algorithms (e.g. Lichti, 2007; Schneider and Maas, 2007). Thereby, adjustment is performed to estimate different parameters (e.g. scanner orientation and position as well as internal scanner geometry) of a geometric model that describes the TLS system. Approximate values for the adjustment are derived either from distinct points or from flat target observations. Object related errors can be included into the adjustment as additional parameters to account for effects due to TLS beam geometry. Dorninger et al. (2008) use planar features at the area of interest to calibrate the scanner. However, this is not possible for soil surfaces due to their rough morphology. But the detection of errors, e.g. along a plane calibration plot, can be performed offsite and correction values subsequently assigned to the field data. Hodge et al. (2009) tested TLS data for errors under laboratory conditions and subsequently applied the results to the field data of fluvial sediments.

Soil erosion is a severe issue in the vulnerable Mediterranean landscape. Beside lithogenic backgrounds, high potentials in relief energy, and intense agriculture cultivations, water is the main factor influencing soil erosion (e.g. Poesen and Hooke, 1997; Faust and Schmidt, 2009). Torrential precipitations (high intensity and short duration) are typical (Poesen and Hooke, 1997) and very effective at eroding soil (Bracken and Kirkby, 2005). Low organic matter content as well as slow soil formation rate and thus shallow soil profiles are typical for the Mediterranean (Poesen and Hooke, 1997, Cantón et al., 2011). Hence, runoff and consequently sediment yield respond fast to precipitation due to high rainfall intensity and low soil infiltration capacity (Poesen and Hooke, 1997). The long history of human activity in the Mediterranean is another factor promoting soil vulnerability (García-Ruiz et al., 2013).

The Mediterranean is one of the worldwide erosion hotspots (Boardman, 2006), which depicts unique runoff and sediment yield pattern. Hydrological connectivity is discontinuous at the hillslope scale, particularly when vegetation is present (Calvo-Cases et al., 2003; Puigdefábregas, 2005), due to the short duration of erosive-effective precipitation events (Yair and Raz-Yassif, 2004) and soil physical thresholds (Cammeraat, 2002). Open or closed plots are current methods for measuring soil erosion in the Mediterranean, which declare erosion volumes or weights per area, although local relocation information is needed (Boardman, 2006) to asses these source – sink – patterns. TLS can help to qualify and quantify non-linear interaction of erosion factors at different spatial scales (Boix-Fayos et al., 2006; Lesschen et al., 2009). In the Mediterranean highest portion of total sediment yield per year occurs due to one or two precipitation events (López-Bermúdez et al., 1998; De Santiesteban et al., 2006; González-Hidalgo et al., 2007). At inter-annual scale this erosion variability amplifies when long-term erosion rates are dominated by large scale events of low frequency (Martinez-Mena et al., 2001; Ollesch and Vacca, 2002). However, low magnitude events are also relevant for long-term rates due to their high frequency (Romero-Díaz et al., 1988). The temporal and spatial complex soil erosion characteristics in the Mediterranean, i.e. sediment yield connectivity and variability, highlight the necessity to assess area-based surface changes with high resolution.

In this study, scan geometry is investigated for low incidence angles, which is inevitable for soil erosion measurements with TLS on agricultural utilised fields that are commonly situated at gentle slopes. The influence on point accuracy is studied for a calibration plot and field data. A method is introduced, which detects systematic errors and subsequently assigns corresponding correction values. At a large field plot in Andalusia (Spain) the corrected data are tested for its suitability to detect soil surface changes of different magnitudes. In this regard, the definition of a stable reference system for multi-temporal change detection with TLS is illustrated. Soil erosion is measured with cm-accuracy after a semi-annual and a monthly period, which allows for analysing complex erosion pattern typical for the Mediterranean landscape.

2.2. Study area

The study area is located in a Mediterranean landscape in the south of Alcalá de Guadaíra in Andalusia, Spain (Fig. 2-1). The location of the investigated field plot is chosen because detailed studies on soil erosion are missing in the region. Although, the landscape

exhibits a high morphodynamic, which is investigated for the marl landscape in the south of the study area (Faust, 1995; Faust and Schmidt, 2009), where soil conditions are different but climatic circumstances are similar. Moreover, communication with the local farmer indicates that the selected hillslope is erosion-prone because frequent observations of distinct erosion rills are made, which was confirmed during field work. The field plot is situated in an area dominated by Tertiary calcareous sandstone. Hence, the soil is very rich in calcium carbonate. However, only remnants of originally in-situ formed soils are abundant at a few preserved locations due to long cultivation and erosion history of that area. Recent tillage is mostly performed on colluvial deposits or lithogenic background material. For an estimation of the composition of the tillage horizon, 40–50 % of substrate is lost via decalcification and prior to the granulometry measurement. The remaining grain sizes contain 10–15 % clay, 5–10 % silt and 20–30 % sand. Surfaces are expected to have a high runoff threshold because of the abundance of sand and a corresponding elevated infiltration capacity. Soil type is addressed as colluvium, which is indicated by present brick fragments. The hydrological conditions of the selected field plot are common for the Mediterranean. Thus, precipitation occurs from October until May with two small peaks in spring and autumn and exhibits high inter-annual variability (Renschler et al., 1999; García-Ruiz et al., 2013). In western Andalusia the highest erosive precipitation events occur in October (Renschler et al., 1999), which are significant for soil erosion after a dry summer leading to dry soils (Faust, 1995; Romero-Díaz et al., 1999).



Figure 2-1: Graphical representation of the investigation area: a) Location of the study area, outline of the field plot, and position of the reference points (vicinity points) of the local reference system for multi-temporal change detection. b) Positions of the terrestrial laser scanner (SP) during the first and second field campaigns (field plot east) as well as the third and fourth field campaigns (field plot west). c) Photo of prepared field plot east before data acquisition. d) Photo of prepared field plot west before data acquisition.

The field plot has a size of $40 \times 50 \text{ m}^2$ but is divided into eastern and western parts, which are observed separately (Fig. 2-1). Two different temporal scales are considered. The eastern part has been studied from Sep. 06, 2012 until Mar. 03, 2013 to capture the rainy winter season. Cumulative precipitation totalled 468 mm, with a maximum daily value of 61 mm. The western part of the field plot has been investigated from Sep. 11, 2013 until Oct. 30, 2013. This time three precipitation intervals in total amounting 112 mm are observed. The highest daily value conducts 31 mm. The field plot is a straight slope with an average inclination of 8°. Conservation tillage, which leaves significant amount of crop residue at the soil surface to reduce erosion susceptibility, is the common agricultural preparation practice. However, during this study the surface has been freshly harrowed and rolled before the investigation of each plot site.

2.3. Methods

2.3.1. Data acquisition

The field plot is captured with a terrestrial laser scanner (Riegl LMS Z420i) utilising time-of-flight principle for distance estimation. The TLS is installed on a 4-m high tripod to compensate for unfavourable scan geometry due to a low viewing angle onto the field plot (Fig. 2-2). The TLS is situated around the plot with at least one scan position at each plot side to guarantee a sufficient coverage of the area of interest. Scan positions can be compared to each other for accuracy assessment if the same area is covered with high scan overlaps (Barneveld et al. 2013) and viewing angles are not too conflictive.



Figure 2-2: Photo illustrates applied terrestrial laser scanner Riegl LMS Z420i on 4 m high tripod.

Angular step width between adjacent laser spots is set to 0.024° resulting in one point every 4 mm at a distance of 10 m. The beam divergence of the scanner system is 0.014° leading to a laser spot size of 12.5 mm at the same distance if object direction is perpendicular and if beam emergence size amounts 1 cm. Same surface areas are measured several times with only small laser spot shifts because spot size is higher than step width. This high point information redundancy, which is further increased by overlap from different scan positions, is important in the subsequent processing chain because random errors can be corrected by adjustment methods (e.g. smoothing due to averaging) if a Gaussian distribution is assumed.

During the first two field campaigns (field plot east) the scanning device is set at four positions around the entire plot (Fig. 2-1). The western scan position is located further away from the eastern field plot compared to the other scan positions because the western field plot, consisting of conserving field stubbles, is also captured. However, vegetation cover is too high for TLS to penetrate to the ground and hence the stubble covered western field plot has to be excluded from further analysis. Scan position density is higher during the last two field campaigns (field plot west) because the scanning device is solely located around the western part of the entire field plot. Furthermore, the scanning device is setup at six scan positions. However, the differing data acquisition configurations are consistent for each field plot side and thus do not influence multi-temporal surface change detection.

2.3.2. Data registration

In this study, high stability and accuracy of reference are necessary because multitemporal surface changes with low magnitudes are observed. A total station is used for reference measurement. Four geodetic defined points of reference (vicinity points) are installed at man-made structures (e.g. the basis of utility poles) surrounding the field plot in distances not further than 500 m (Fig. 2-1). Additionally, reference points (field points) on 60 to 100 cm long marking pipes, which are embedded into the surface (Eltner et al., 2013), are setup in immediate neighbourhood of the field plot (Fig. 2-3).

The vicinity points as well as the field points (assuming their stability) are used to define a local reference system for multi-temporal change detection. On the one hand, the vicinity points allow for a stable bearing of the multi-temporal reference net because large angles are spanned. On the other hand, the field points enable increased measurement accuracy because of small distances to the total station, which is located close to the field

plot. Furthermore, combined usage of vicinity points and field points induces high redundancy of stable points defining the reference system, which additionally increases net accuracy. Also, vicinity points function as backup of the temporal stability of the reference net because field points are installed at farming land inheriting some risk of point movement due to soil reworking.



Figure 2-3: Map illustrates position of un-surveyed and surveyed registration targets, which are used during every field campaign for transforming point clouds from single scan positions into a single project coordinate system. Different grey-scale represents different field campaigns. Un-surveyed targets are designed to guarantee a stable bedded registration net, while survey targets are further used to register the point cloud from the project coordinate system to the local coordinate system for the multi-temporal data comparison. Furthermore, positions of field points designed for net adjustment of total station measurements are displayed.

Stability of the field points is verified for every field campaign via an unconstrained adjustment, which calculates the parameters of a 3D-Helmert-transformation between the measured point coordinates of two consecutive field campaigns (eq. 2-1):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + \lambda R \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$
(2-1)

This similarity transformation is a coordinate transformation between an initial (x, y, z) and a target (X, Y, Z) system that implies seven parameters - three translations (X_0, Y_0, Z_0) , three rotations (implemented in the rotation matrix (*R*) representing the rotations to the coordinate axes) and a scale (λ) , which usually equals 1 in the case of laser scanning. Residual gaps between the coordinates of the target system and the transformed coordinates of the initial system are examined for every point to identify shifted marking pipes.

Each scan position needs to be transformed into the local reference system for multitemporal change detection. First, individual scan positions are registered into a project coordinate system by transforming each scan position and orientation into one single system. Thereby, each field campaign corresponds to a unique project coordinate system. Afterwards, TLS point clouds are transformed from the project coordinate system into the local reference system.

Two different kinds of registration targets are located around the field plot and captured from every scan position (Fig. 2-3). On the one hand, retro-reflective cylinders are setup with diameters of 7.5 cm during the first campaign and with diameters of 5 cm during the remaining campaigns. The cylinder's centre is determined automatically after scanning with very high resolution. They are located behind the scanner positions to guarantee a stable bearing of the registration geometry. The targets remain unsurveyed and solely serve to register single scan positions to the project coordinate system. On the other hand, retro-reflective cylinders with a diameter of 6 cm are exploited. These targets are surveyed by total station to enable the registration to the local reference system. Thereby, constrained net adjustment is performed using assumed error-free vicinity points and confirmed stable field points. Surveyed and unsurveyed cylinders are used for coordinate transformation into the project coordinate system. Net adjustment and coordinate transformation are calculated with the open source software "Java Graticule 3D – JAG3D".

2.3.3. Data processing

After the field campaigns the acquired TLS point clouds need to be processed to reduce data noise. In the first step, vegetation is filtered with the open-source solution CANUPO (Brodu and Lague, 2012), which eliminates vegetation points by applying a classifier that is defined for several scales.

Afterwards, random errors are minimised by point cloud smoothing. Redundant information, which results from high overlap due to angular step width setting and scan position configuration, is used to adjust the data points to actual surface representation. Abellán et al. (2009) already demonstrate the advantage of TLS point cloud smoothing to reveal further surface details due to noise reduction with nearest neighbour averaging. In this study, different algorithms of the C++ point cloud library PCL (Rusu and Cousins, 2011) are executed for data processing. First, the point cloud is treated with a moving least square filter, which fits every point into a surface of a specified polynomial order by considering points within a specified search radius. Afterwards, outliers are detected by accounting for spatial and statistical criteria. On the one hand, a maximal number of points within a defined search radius need to be present to be considered as outlier. On the other hand, mean and standard deviation of distances to a fixed number of neighbours are compared. An outlier is identified, if the difference between both statistical values is above a certain threshold. Finally, a voxel filter reduces the point density by keeping only the centroid of the points within a voxel of a defined size. Comparison between the solely vegetation filtered, raw point cloud and the PCL processed point cloud serves as quality control of data processing. A point reduction between 15 % and 45 % and an average point movement of 5 mm, which is within the instruments specific accuracy range (of 1 cm), is revealed. Hence, data processing reduces only random noise that results from instrument performance.

The filtered point cloud is converted into a raster for multi-temporal change detection. Only the point with minimum height is kept if more than one point falls into a raster cell to increase the probability of capturing an actual ground point. However, isolated erroneous points might still be missed during the filtering process. They are removed by a local peak detector algorithm that searches for local minima and maxima within a raster.

Concluding, an inverse distance weighted (IDW) algorithm is applied to interpolate remaining gaps in the digital terrain model (DTM). This simple algorithm is adequate because only small holes are filled, whereas larger vacancies due to vegetation are left open to avoid uncertain multi-temporal volume estimations at strongly interpolated areas. The resulting raster resolution amounts 2 cm at the eastern field plot and 1 cm at the western field plot. Resolutions are different because of dissimilar point densities due to different data acquisition configurations.

2.3.4. Scan geometry

Viewing angles onto the field plot are exceedingly low even though a high tripod is used to compensate unfavourable scan geometry. Different geometry parameters are calculated to evaluate the general point quality and to detect possible error sources as well as dependencies resulting from poor scan configuration. Distance to the scanner, incidence angle, and laser footprint are considered.

The scanner distance *d* is estimated by determining the absolute value of the vector *D* from the scanners origin $(X_{TLS}, Y_{TLS}, Z_{TLS})$ to the target point (X_{pt}, Y_{pt}, Z_{pt}) , which corresponds to the slope distance (eq. 2-2):

$$d = \left| \vec{D} \right| = \begin{pmatrix} X_{TLS} - X_{pt} \\ Y_{TLS} - Y_{pt} \\ Z_{TLS} - Z_{pt} \end{pmatrix}$$
(2-2)

The incidence angle α is determined between vector *D* and *N* (e.g. Soudarissanane et al. 2011), which is the surface normal at the target points' position (eq. 2-3).

$$\alpha = 90^{\circ} - \arccos\left(\frac{\vec{D}\vec{N}}{|\vec{D}||\vec{N}|}\right)$$
(2-3)

Finally, the footprint *F* (in m) is calculated after Schürch et al. (2011). The parameter is influenced by the distance, incidence angle, and beam divergence β . In this study footprint calculation is extended by the laser emergence size of *b* to achieve the actual laser spot size at the target (eq. 2-4).

$$F = dsin\left(\frac{\beta}{2}\right)\left(\frac{1}{sin(\alpha - \beta/2)} + \frac{1}{sin(\alpha + \beta/2)}\right) + \frac{b}{\cos(\alpha + 90^{\circ})}$$
(2-4)

2.3.5. Accuracy assessment

Possible error sources need to be considered to evaluate accuracy and reliability of the TLS data. A mm-accurate calibration plot is designed for estimation and subsequent mitigation of systematic errors. Therefore, an unpolished, lithic building floor, made of granite, is measured, which inherits favourable reflection characteristics and is neither too reflective nor too dark to avoid interference with the distance measurement. A local grid with a resolution of 1 m^2 is defined and corresponding grid points are measured with a total station. Calibration plot size is about $4 \times 15 \text{ m}^2$. The plot is used to calculate scan geometries and estimate errors of different magnitudes, even below system specifications. Another method is the simulation of TLS data, which is performed by Hodge (2010), who estimates error magnitudes and their sources for complex surfaces because consulting field data for error estimation is difficult due to the irregular topography. Soudarissanane et al. (2011) model the contribution of the scan geometry to noise by applying planar features, which is also performed in this study.

The scanning device is setup on the 4-m high tripod at both transverse plot sides. Initial registration of the generated point cloud is performed with retro-reflective flat markers (Ø 5 cm), which are determined in the same coordinate system as the calibration plot. However, referencing geometry is unstable and error prone because registration targets can only be placed in front of the scan positions due to restricting building architecture. Furthermore, the retro-reflective targets reveal systematic height shifts (Fig. 2-4), which is probably due to high reflection characteristic, leading to oversaturation of the returned laser signal (Pesci and Teza, 2008a). Pfeifer et al. (2007) use the same scanner type as in this study and detect a retro-reflective target offset of 2 cm. Fine registration is conducted after initial registration by an iterative closest point (ICP) algorithm, minimising repetitively the point distances between the calibration plot and the point cloud (Besl and McKay, 1992), to account for the registration uncertainties.



Figure 2-4: Point cloud demonstrates heightening effect of flat retro-reflective target due to underestimation of distance measurement because of oversaturation at the receiver of the TLS. For accurate registration bump should be levelled. Photo in the upper left displays an example of the applied retro-reflective targets.

Deviation between the co-registered point clouds and the plot is calculated for each scan position to estimate the TLS error. The resulting point difference is related to distance d (eq. 2-2) to the scanning device and a distance dependent lookup table for error correction is calculated (eq. 2-5). Thereby, a moving average a is estimated at each point difference considering a fixed number n of point differences x, which are enumerated in relation to distance d.

$$a_m = \frac{1}{n} \sum_{i=0}^{n-1} x_{m+i}$$
(2-5)

2.4. Results and discussion

2.4.1. Multi-temporal reference

The reliability of the local reference net is a prerequisite of multi-temporal change detection. The field points are controlled regarding their temporal stability (Table 2-1). During the first study period solely point movement of the second field campaign in March 2013 can be analysed because during the first campaign in September 2012 marking pipes are initially installed. Movement of almost all field points is detected resulting in an average horizontal and vertical point deviation of 12.2 and 5.1 mm, respectively, which is probably due to too close passing of agricultural engines. Hence, only vicinity points at the man-made structures are used to estimate the parameters of the transformation into the local reference system. During the second study period solely isolated points moved at the western field plot, which are excluded from further data processing resulting in a minimal average horizontal and vertical point stability of 3.0 and 1.3 mm¹, respectively. Thus, at the

Table 2-1: Position stability of the registration targets at the field plot (field points)	between two	subsequent
field campaigns represented by the standard deviation of point differences (std-dev).	1	

	Field plot eas	st	Field plot west		
	06.09.2012 -	03.03.2013	10.09.2013 30.10.2013		
	Horizontal	Vertical	Horizontal	Vertical	
Std-dev [mm]	12.2	5.1	3.0	1.3	

Multi-temporal referencing of the registration targets is performed after stability of field points has been tested. At the eastern plot the error of net adjustment is exceptionally

¹ Table 2-1 and corresponding values in the manuscript are corrected due inconsistent declaration in the original paper.

high during the first field campaign (12.1 mm in horizontal direction) due to flickering because of high temperatures during data acquisition (Fig. 2-5). However, this source of error is negligible during the remaining campaigns because of cooler atmospheric conditions. Referencing accuracies at the western field plot are presented for two options, either using vicinity points solely or vicinity as well as field points for referencing, to highlight the advantage of redundant point information and stable net bearing. Accuracies in horizontal direction are increased from 2.7 to 1.6 mm and from 4.5 to 2.0 mm. In contrast, vertical errors are changed marginally from 0.9 to 0.8 mm and 1.6 to 1.0 mm.



Figure 2-5: Performance of the multi-temporal reference net represented by the accuracy of the net adjustment of the total station measurement illustrated for both cases, either using vicinity points only (vic pts only) or using vicinity and field points (vic and field pts).

Finally, individual scan positions are registered to the project coordinate system and subsequently transformed into the local reference system. Accuracies are better than 7 mm for both transformations (Table 2-2).

Table 2-2: Performance of the TLS point cloud referencing to the project coordinate system and the local coordinate system. Accuracy (standard deviation std-dev) and number (nbr) of used targets are displayed.

	Field plo	t east			Field plot west			
	06.09.2012		03.03.2013		11.09.2013		30.10.2013	
	Std-dev	Target nbr	Std-dev	Target nbr	Std-dev	Target nbr	Std-dev	Target nbr
Project coordinate system	5.1 mm	15	5.0 mm	22	6.7 mm	13	5.9 mm	20
Local reference system	6.0 mm	7	6.1 mm	10	6.6 mm	9	5.0 mm	10

2.4.2. Error correction

2.4.2.1. Calibration plot

A quasi-plane is used as calibration plot to estimate the impact of scan geometry onto data noise. Fig. 2-6 and 2-7 illustrate the changing scan geometries and point deviations with increasing distance to the scanning device, respectively. Analysis is done for both scan positions, but solely one scan position is displayed because changes of scan geometry and noise behaviour are similar in magnitude and localisation at both scan positions.



Figure 2-6: Calculated scan geometries at the calibration plot (dots: signal intensity with corresponding moving average (black line); squares: incidence angle; triangles: laser spot size).

Footprint increases almost linear to 5 cm at a distance of 15 m (Fig. 2-6). The consideration of footprint size is important because large laser spot sizes can result in edge effects and multiple reflections at irregular surfaces, which cause blending of range measurements. However, Schürch et al. (2011) could reveal that the influence of footprint size is marginal at complex surfaces. Incidence angle increases logarithmically to 60° within a distance of 8 m. The increasing incidence angle causes an increase of footprint size, which results in a decrease of intensity of the returned laser signal because the same emitted energy is scattered over an increasing area. In this study, intensity decreases with increasing distance with a small variation of intensity decline at a distance of 7 m, which is also detected by Blaskow and Schneider (2014). A possible explanation is a system internal signal processing of the intensity values (Kaasalainen et al., 2008 and 2011). Overall, estimated scan geometries highlight high incidence angles, large footprints and low intensity values with increasing distance at sub-horizontal measured surfaces.



Figure 2-7: Systematic TLS error detected with mm-accurate calibration field. Diagrams illustrate point deviations and moving average (red line) between calibration plot and TLS of uncorrected (a) and corrected (b) data. Maps illustrate height difference of uncorrected (c) and corrected (d) point clouds of the entire calibration area.

Point deviation between the TLS point cloud and the calibration plane displays a systematic error pattern (Fig. 2-7c), even though the error remains within the system specific declaration of accuracy of 1 cm. The source of error is directly or indirectly related to the distance, which is indicated by a horizontal circular deviation pattern, although the scanner is setup with a non-vertical tiltmount. The profile of the point distances to the calibration plane reveals a sinusoidal shape with a local maximum at 7 m (Fig. 2-7a) corresponding to the distance at which intensity values vary. Pfeifer et al. (2008) mention a possible influence of intensity on distance measurements due to manufacturer's integration of intensity values for raw travel-time corrections, which might be the case here. This effect is not as obvious for objects scanned from vertical directions than for sub-horizontal surfaces that are usually measured in soil erosion studies.

Point deviations increase significantly at a distance greater than 12 m, which might be due to the incidence angle exceeding 70°. Soudarissanane et al. (2011) already measure an increase of noise at high incidence angles and assume that this is due to non-perfect Lambertian scatter behaviour of the surface. Also, Lichti (2007) identifies large outliers of range measurements for incidence angles greater than 65°.

Point deviations are smoothed and the resulting curve is applied as distance dependent lookup table to correct the original point cloud (Fig. 2-7b). The standard deviation of point

difference of the TLS point cloud to the calibration plane decreases from 5.9 to 1.5 mm. Remaining differences (Fig. 2-7d) are due to the resolution of the calibration plane, which was measured with a point distance of 1 m. Hence, small bulges in the floor are not captured.

The introduced method of scanner calibration is applicable to other geomorphic studies, especially if sub-horizontal surfaces are of interest. Only requirement is a quasiplane, which exhibits superior accuracy. Particularly temporary stable and distant dependent uncertainties, which reveal systematic error patterns, can be corrected with a lookup table. Thus, the approach allows for the investigation of system-specific errors, which are usually difficult to detect when complex structures – common for geomorphic applications – are scanned.

2.4.2.2. Field data

Intensity changes of the reflected signals of the soil surface are evaluated to determine relations to the calibration plot, especially in regard of the local variation at 7 m (Fig. 2-8). The field data reveal an intensity increase until 7 m and a subsequent decrease until 15 m, which is similar to the calibration plot. Afterwards, intensity increases again. The intensity change pattern of the field data is also detected by Blaskow and Schneider (2014) and Pfeifer et al. (2007, 2008) using the same scanner type. The changes of intensity are assumed to be mainly due to the increasing distance and not incidence angle because Pesci and Teza (2008b) show that incidence angle has almost no influence on signal intensity at irregular surfaces.



Figure 2-8: Intensity changes with increasing distance to the scanning device at every scan position during the field campaign 30.10.2013.

Scan positions are compared to each other for accuracy assessment because of missing references (Fig. 2-9). A systematic error, similar to the one discovered with the calibration plot, is indicated during each field campaign. Therefore, the obtained lookup table from the calibration is applied to the field data. However, point deviations within the field data are not as obvious as within the calibration data, which is probably due to higher noise levels of rough surfaces masking the systematic error. The systematic error is more distinguishable after noise reduction due to point cloud smoothing (Abellán et al., 2009). It should be kept in mind that temporary stability of the error is necessary (Lichti, 2007; Dorninger et al., 2008) if field data are corrected with the lookup table from the calibration plot.

In Fig. 2-9 an offset of each compared point cloud to the reference scan positions is indicated, although values are in most cases smaller than 5 mm. In addition, point clouds are tilted because offset increases with increasing distance to the scanning device. Possible error sources are an oversaturation of registration targets or difficulties to model the cylinder's centre with increasing distance to the scanning device due to a decreasing number of laser spots that hit the target (Pesci and Teza, 2008a). Slight miss-alignments of the resulting registration can cause significant discrepancies augmenting with increasing distance to the targets. Another error source might be system-intern intensity adjustment, which is already assumed for close-range (7 m) and is possible for further distances as well. Finally, increasing incidence angles can also cause the offset and shift because either differing reflected parts of the increasingly stretched laser pulse (Kern, 2003) or increasing deviations between ellipse centre and the centre of the laser cone (Gordon, 2008) affect the measured distance.

Statistical measures of the TLS point cloud accuracy (Table 2-3) show a standard deviation ranging from 9 to 16 mm. The first two field campaigns (eastern field plot) are less accurate than the last two campaigns (western field plot). Generally, accuracy values should be regarded as too pessimistic because it is not possible to measure identical surface points from different scan positions. Hence, an interpolation error has to be assumed. The point cloud from the scan position, which is to be compared, exhibits the highest point density and reliability closest to the scanner, which corresponds to the area of the lowest point density and reliability of the reference point cloud because the scan positions are furthest to the compared one. Significance of this circumstance increases with increasing distances between the individual scan positions resulting in lower point densities, higher portion of high incidence angles, and stronger intensity changes. Thus, at the eastern field

plot greater error overestimation is assumed due to larger distances between the scan positions, producing sparser point clouds and hence increased impact of data interpolation uncertainties. At the western field plot scan positions are considerably closer and hence accuracy values are higher, highlighting the importance of TLS setup for estimating the degree of error with overlapping TLS point clouds.



Figure 2-9: Uncorrected (a) and corrected (b) averaged point deviations between every single compared scan position (SP) and the merged reference SPs during field campaign 30.10.2013. Solid lines are single SPs while hollow line illustrates averaged deviation of all SPs. SP 4 is excluded due to large noise due to intense vegetation cover at the bottom of the field plot.

An error estimate needs to be assigned to each DTM for multi-temporal change detection. Thereby, registration errors are neglected because magnitudes are significantly lower (Table 2-2) than errors due to scan geometry and data interpolation (Table 2-3). Particularly, the accuracy of the transformation of each scan position to one project coordinate system can be disregarded because that error is already incorporated when scan positions are compared to each other. At the western field plot the measured accuracies of 9 and 11 mm, according to Table 2-3, are used as accuracy estimates of the final DTMs. However, at the eastern field plot accuracy estimation is not as obvious because data analysis showed unfavourable scanner positioning for sub-cm accuracy assessment. Therefore, same error as for the western field plot is assumed due to missing reliable accuracy values and a presumably strong error overestimation. Hence, an uncertainty of 1 cm, which corresponds to the average error of both field campaigns at the western field plot, is assigned to both DTMs of the eastern field plot. This value coincides with the manufacturer error report. Suitability of comparing point clouds, which result from different scan positions that sample the same area of interest, to assess data accuracy decreases with increasing complexity of the respective surface models.

Table 2-3: Point deviations between each scan position and merged reference scan positions. Statistical values are averaged from all scan positions.

	06.09.2012	03.03.2013	11.09.2013	30.10.2013
Mean [m]	-0.005	-0.007	-0.004	-0.002
Std-dev [m]	0.016	0.013	0.011	0.009

The accuracy of the DTM of difference of the compared DTMs is estimated considering error propagation theory, which calculates the influence of uncertainties of single variables at the error of a function - i.e. the resulting accuracy of the DTM of difference after subtraction of the DTMs with their corresponding uncertainty. A level of detection (*LoD*) is calculated according to the propagated error, which represents surface changes for a defined confidence interval. In this study, an *LoD* of 1.5 cm is calculated for a confidence interval. In this study, an *LoD* of 1.5 cm is calculated for a confidence interval of 85%. Brasington et al. (2003) and Lane et al. (2003) give more detail on estimating *LoD* using error propagation.

2.4.3. Multi-temporal surface changes

Fig. 2-10 illustrates the surface changes during the investigation of the eastern (06.09.2012 - 03.03.2013) and western (11.09.2013 - 30.10.2013) field plot. At the eastern field erosion occurs mainly on the western part of the plot. The eastern part is less affected

due to denser vegetation cover. Further, wheel tracks are clearly distinctive. They are forming due to consolidation because of soil reworking with heavy machinery, which further results in reduced infiltration capacity. Hence, runoff is promoted and forced within the lowered paths. Cerdan et al. (2002) already indicate the importance of agriculturally induced paths of concentrated flow for soil erosion. Furthermore, down-slope tillage lines foster runoff and hence sediment yield. However, these linear features of erosion are frequently disrupted due to across-slope ridges. These ridges form local retention areas, which cause disconnected down-slope sediment yield and hence frequent non-continuous erosion fields. Calvo-Cases et al. (2003) already describe discontinuous runoff pattern at hillslope scale, which is accompanied with non-uniform sediment yield in this study. Also, Cammeraat (2004) argues that small earth dams increase roughness and thus infiltration capacity, which delays overland flow. The across-slope ridges themselves are also reworked. Local redistribution of surface material is visible, revealing smoothing due to erosion of the upper crest of the ridge and subsequent accumulation behind the obstacle. Across the upper field plot a large rill, which arises outside the plot, develops during the winter season. The rill is shallow, partly masked by wheel tracks, and proceeds across tillage lanes. It has a depth about 1 cm and ends in an alluvial fan within the plot.

Negative volumetric changes at the entire eastern plot amount 1.44 m³ during the winter season, which corresponds to an average height change of 1.6 mm. If wheel tracks are excluded from the analysis, changes amount 0.56 m³ corresponding to height changes of 0.7 mm (Table 2-4). Positive height changes amount 0.09 m³ (0.1 mm). While positive changes are predominantly assigned to accumulation in the alluvial fan and behind ridges, negative changes are not exclusively assignable to erosion processes. The field plot was freshly tilled immediately prior to the first field campaign. Therefore, consolidation can also cause a decrease of the surface. Eltner et al. (2014) already highlight the difficulty to distinguish between consolidation and erosion from high resolution topographic data if the soil surface has been recently reworked.

Table 2-4: Measured soil surface changes on both field plots. Estimated volumetric changes in m³ and height changes in mm for *LoD* of 85 % confidence interval.

		Negative soil surface change		Positive soil s	surface change
		Entire plot	Without wheel track	Entire plot	Without wheel track
06.09.2012	m ³	1.44	0.56	0.09	0.09
- 03.03.2013	mm	1.62	0.70	0.10	0.11
11.09.2013	m ³	0.28	0.15	0.07	0.06
- 30.10.2013	mm	0.30	0.17	0.08	0.07



Figure 2-10: Soil surface changes during the winter season (Oct. 2012 - Mar. 2013) and during the single precipitation events in September and October 2013. Highlighted area at the western plot shows surface changes due to horse tracks and highlighted area at eastern plot shows surface changes due to an erosion rill with an adjacent alluvial fan. LoD is 1.5 cm for a confidence interval of 85 %.

At the western field plot three single precipitation events of different magnitudes have been captured during the investigation period. Surface changes are not as significant as for the longer investigation interval of the eastern plot. Negative volumetric changes at the entire plot amount 0.28 m³ corresponding to an average height change of 0.3 mm. Changes without the wheel tracks amount 0.15 m³ corresponding to 0.2 mm. Positive changes constitute 0.07 m³ (0.1 mm).

Height changes are mainly due to filling and widening of horse tracks across the western field plot. Apart from that, only minor surface decrease at the upper part of the plot is distinguishable. However, wheel tracks are obvious again, which are less developed than at the eastern plot. The tracks reveal an interesting discontinuous pattern, possibly indicating the influence of patchy vegetation in the middle of the field plot. These natural obstacles can cause local runoff disruption and hence decreased soil detachment capability or even sediment accumulation (Cammeraat, 2002), although surface heightening is not visible. However, TLS data uncertainty more likely masks accumulation than erosion

because the spatial distribution of accumulation exhibits a lateral dominance. Hence, sediment dispersion takes place over large areas with low magnitudes of height changes. In contrast, erosion mainly occurs in concentrated flow and is therefore effective in smaller areas but with higher magnitudes of vertical variations. The disrupted pattern of negative surface height change at the location of the wheel tracks indicates that consolidation is not the only possible cause of change. Sediment relocation has to take place as well because otherwise the wheel tracks would be identifiable throughout the entire field plot.

At the eastern and western field plots different temporal scales are considered. Hence, different processes for sediment yield are assumed due to changing soil and hydrological characteristics. During the short observation period at the western field plot Hortonian runoff is assumed as only feasible overland flow because after a long and dry summer soil moisture is very low and the high sand content of the soil results in high permeability only allowing for precipitation events with high intensity to cause runoff (Castillo et al., 2003). In contrast, during the wet winter season at the eastern plot it is assumed that, besides infiltration excess overland flow, saturation excess overland flow during rainfall with lower intensity can also occur due to high soil moisture content (Calvo-Cases et al., 2003; Castillo et al., 2003) because of several sequences of low and intermediate precipitation events. Also, Casalí et al. (1999) observe soil erosion for events with lower precipitation intensity if soil moisture is high.

The measured and calculated theoretical erosion rates (excluding the wheel tracks) range from 10.0 t ha⁻¹ during the winter season at the eastern plot to 2.6 t ha⁻¹ during the short study period at the western field plot, thereby an average bulk density for sandy substrate of 1.6 g cm⁻³ is assumed. The erosion rates are compared to a variety of other studies conducted in the Mediterranean and displayed in Table 2-5. However, certainly no completeness is claimed. Similarities to this study are chosen in regard of lithology and soil texture (i.e. higher sand contents) as well as land use (i.e. bare soils or winter cereals). Bracken and Kirkby (2005) demonstrate the importance of lithology for soil erosion in semi-arid environment and reveal that soils with higher sand contents exhibit lower erosion rates. Further, the significance of land use for sediment yield in the Mediterranean is highlighted by several authors - e.g. Kosmas et al. (1997), López-Bermúdez et al. (1998), De Santiesteban et al. (2006) and Nunes et al. (2011). Especially, cultivated soils (i.e. winter cereals) with frequent missing plant cover in autumn and winter after ploughing and

sowing depict high erosion vulnerability because of overlapping conditions of bare soil and torrential precipitation season.

Boix-Fayos et al. (2005) review erosion rates in SE Spain and state that measured mean sediment yield under field conditions is always lower than 6 t ha⁻¹ a⁻¹ but exhibits high variability due to the applied method and natural conditions, which is also obvious in Table 2-5. Therefore, the possibility of comparing the results of this study to other studies is limited. Nevertheless, if rain amounts and investigation period are considered, it can be exposed that values of this study are usually higher than other studies where bounded plots are used. This might be due to material depletion within the plots (Ollesch and Vacca, 2002; Dunjó et al., 2004; Boix-Fayos et al., 2007), different stone contents, or due to the fact that TLS also measures consolidation and local relocation within the field, which is particularly important in the Mediterranean where discontinuous sediment yield is typical (e.g. Cammeraat, 2002; Calvo-Cases et al., 2003). However, these erosion patterns as well as consolidation are not assessed when sediment yield is solely captured at the plot outlet.

If soil erosion is measured from rills and small gullies (Table 2-5: De Santiesteban et al, 2006), higher values of sediment yield, compared to this study, are obvious, which might be due to higher significance of linear erosion features for soil loss volumes compared to interrill erosion (Govers and Poesen, 1988; Vandael and Poesen, 1995; Di Stefano et al., 2013; Eltner et al., 2014). The influence of rills and ephemeral gullies on sediment yield is also possible for tracer measurements in small catchments (Table 2-5: Porto et al, 2014). In this study, solely one rill occurs at the eastern field plot. However, higher erosion amounts are usually expected during this winter season because erosion rills are present at the sown field outside the investigated plot. It is assumed that they are missing within the studied area due to a biological soil crust, which formed sometime during the winter season. Already Knapen et al. (2007) and Meastre et al. (2011) demonstrated the importance of these crusts for decreasing soil erosion rates.

Concluding, it has to be noted that in this study both observation periods are too short to allow for statements concerning long-term erosion rates due to the high inter-annual precipitation and sediment yield variability in the Mediterranean (Poesen and Hooke, 1997; Cammeraat, 2002).

Table 2-5: Representative examples for soil erosion rates in the Mediterranean. Selection is based on similarities in lithology (focusing on higher sand contents) and/or land use (focusing on (almost) bare surfaces). Precipitation, method, temporal scale and slope can vary significantly. Sediment yield of some authors is converted to ease comparability.

Reference	Location	Method	Slope	Lithology/soil texture	Land use/vegetation	Time span/event	Precipitation	Sediment yield
This study	SW Spain	TLS at open hillslope	8°	Calcareous	Bare (anterior wheat)	6 months	468 mm	10 t ha-1
		plots (20×50 m ²)		sandstone		2 months	112 mm	2.6 t ha ⁻¹
Francis, 1986	SE Spain	Bounded plots (1×3 m²)	6°	Marl with sandstone layers	Recently abandoned	10 months	324 mm	1.8-3.2 t ha ⁻¹
Romero-Díaz et al.,	SE Spain	Open plots in small	15°	Marl with	Plant cover 35%	1 year	142 mm	0.1 t ha ⁻¹
1988		catchment		sandstone	(shrubs)		288 mm	2.6 t ha ⁻¹
		(50×60 m ²)		particles cover			445 mm	2.4 t ha ⁻¹
Albaladejo and Stocking, 1989	SE Spain	Micro-catchment (786 m²)	12°	Loamy clay	De-vegetated	2 years	126 mm	14.6 t ha ⁻¹
Kosmas et al., 1997	Different Medit. sites	Bounded plots (8×20-2×10 m ²)	4°-21°	Marls to sandstones	Winter wheat	4 to 5 years	276–583 mm a ^{.1*}	0.2–0.9 t ha ⁻¹ a ⁻¹
Martinez-Mena et	SE Spain	Micro-catchment	19°	Sandy clay loam	Plant cover 10 - 30%	Highest storm	77 mm	0.9 t ha ⁻¹
al., 2001	-	(328 m^2)			(shrubs)	event per year	49 mm	0.8 t ha ⁻¹
							18 mm	0.7 t ha ⁻¹
							72 mm	5 t ha ⁻¹
Ollesch and Vacca, 2002	Sardinia	Bounded plots (2×10 m ²)	7°-25°	High sand contents	Different land uses (shrubs to plantations)	Max. erosion per month	540 mm a ^{-1*}	0.2–9.9 t ha ⁻¹
Chirino et al., 2006	SE Spain	Bounded plots	22°	Loam and loamy	Bare (degraded) soil	1 year	483 mm	2.1 t ha ⁻¹
		$(2 \times 8 \text{ m}^2)$		limestone			288 mm	0.9 t ha ⁻¹
							241 mm	2.8 t ha ⁻¹
De Santiesteban et al., 2006	NE Spain	Rills/gully measurement in small catchments	-	Loam to silty loam	Winter cereals	one annual field measurement	508–546 mm a ^{-1*}	2–115 t ha ⁻¹ a ⁻¹
Nunes et al., 2011	Portugal	Bounded plots (2×8 m²)	-	Sandy loam	Cereal crop	1 year	500 mm 1200 mm	4.1 t ha ⁻¹ 6.3 t ha ⁻¹
Porto et al., 2014	Sicily	Tracer (²¹⁰ Pb, ¹³⁷ Cs) in catchment (0.86 ha)	16°	Silt loam	Durum wheat	50–100 years	500 mm a ^{-1*}	34–39 t ha ⁻¹ a ⁻¹

* average annual precipitation

2.5. Conclusion

TLS allows for area-based soil erosion measurement at the field scale with high resolution if surface changes reach magnitudes larger than 1.5 cm. However, several difficulties need to be considered for accurate erosion rate estimation. A very stable and exactly measured reference system is necessary for multi-temporal change detection. In this study, reference points on man-made structures in further distances as well as registration targets on marking pipes immediately surrounding the area of interest are suitable to achieve referencing accuracies below 7 mm. The accuracy of the DTM generated from TLS enables surface change detection of larger magnitudes (cm-scale), but distinguishing height changes due to consolidation and marginal but steady processes – i.e. interrill erosion – is less reliable. Measured erosion rates are minimum values and higher sediment yields are probable, which result from sub-cm scale.

In this study, challenging unfavourable scan geometries due to low viewing angles of the laser scanner are investigated. They are unavoidable when agriculturally utilised fields, commonly situated at gentle slopes, are captured to measure soil erosion. Hence, a calibration plot is designed to evaluate changing scan geometry (footprint size, incidence angle, and intensity) with increasing distance to the scanner. Further the calibration plot can be used to define the magnitude and possible source of errors. In close range to the scanner position systematic high shifts of the measured laser scanner point cloud are detected, which are assumed to be due to system-intern processing of intensity values. A corresponding calculated lookup table is used to correct the replicated error in the field data, where the systematic shift is obvious. Hence, results of scanner calibration with a simple quasi-plane are transferred to a soil surface survey, which can also be applied to other geomorphic studies implementing TLS. Accuracy assessment suggests a dense net of scan positions for reliable determination of erosion rates at shallow slopes.

At a Mediterranean field plot the measurement of two different periods (winter season and three single precipitation events) reveals surface changes of differing magnitudes. The importance of wheel tracks for soil surface decrease is obvious and discontinuous sediment yield pattern is observable. If longer investigation periods are possible, TLS might be able to solve issues concerning up-scaling of erosion rates from plot scale to hillslope scale, which is especially important in regard of sediment yield connectivity in the Mediterranean.

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3. UAV photogrammetry analysed: error assessment of a new high resolution method for soil sciences

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Abstract: Recent advances in structure from motion (SfM) and dense matching algorithms enable surface reconstruction from unmanned aerial vehicle (UAV) images with high spatial resolution, allowing for new insights into earth surface processes. However, accuracy issues are inherent in parallel-axes UAV image configurations. In this study, the quality of digital elevation models (DEMs) is assessed using images from a simulated UAV flight. Five different SfM tools and three different cameras are compared. If ground control points (GCPs) are not integrated into the adjustment process with parallel-axes image configurations, significant dome-effect systematic errors are observed, which can be reduced based on calibration parameters retrieved from a test field captured with convergent images immediately before or after the UAV flight. A comparison between DEMs of a soil surface generated from UAV images and terrestrial Laserscanning data show that natural surfaces can be very accurately reconstructed from UAV images, even when GCPs are missing and simple geometric camera models are considered.

Keywords: accuracy, dome error, geomorphology, SfM, soil surface, UAV

3.1. Introduction

During the last decade algorithmic advances in digital photogrammetry, as well as computer vision have led to the technique of structure from motion (SfM) for image based surface reconstruction. Photogrammetry has traditionally emphasised accuracy and precision, whereas computer vision stresses automation. Open-source and commercial solutions exist for automatic estimation of extrinsic and intrinsic image parameters, which implement different image matching algorithms, adjustment techniques, camera models and ground control considerations, depending on the intended applications. Besides advances in image matching (Gruen, 2012) and orientation, vast progress in dense matching results in digital elevation models (DEM) with very high resolution, allowing for surface reconstruction of almost every image pixel (Haala, 2013). Simultaneously to advances in image based surface reconstruction, the technology of unmanned aerial vehicles (UAV) open new perspectives for surface measurement (e.g. Eisenbeiss, 2006; Rau et al., 2011; Neitzel and Klonowski, 2011). The new aerial sensor platforms operate at low cost and enable flexible and frequent data acquisition missions using a variety of sensors (Colomina and Molina, 2014).

These software- and hardware-based developments enhance the recognition of SfM within different fields of earth sciences, especially geomorphology. Multi-temporal observations are possible due to the rapid and automatic calculation of high resolution and accurate DEMs, allowing for new insights into processes shaping the earth surface. Areas of operation include aeolian landscapes (Hugenholtz et al., 2013), braided rivers (Javernick et al., 2014), coastal environments (Harwin and Lucieer, 2012) or soil erosion studies (Ouédraogo et al., 2014; Eltner et al., 2015; Stöcker et al., 2015).

However, evaluation of systematic or random errors in DEMs generated from overlapping UAV images for environmental applications can be limited due to missing reference data of higher accuracy. Usually, chosen reference are either differently distributed RTK-GPS points (e.g. Javernick et al., 2014; Lucieer et al., 2014), which may be suitable for accuracy assessment but lack the point density to quantify the quality of overall surface representation, or LiDAR data (e.g. Fonstad et al., 2013).

A specific problem of applying UAV images and SfM methods is the dome effect, which is caused by the axes-parallel configuration of data acquisition common for these platforms, as well as an insufficient camera model and/or missing consideration of ground control (Wackrow and Chandler, 2008; Rosnell and Honkavaara, 2012; James and Robson, 2014). A more detailed explanation for the dome effect is given by Wackrow and Chandler (2011), who investigate this error for an image pair. James and Robson (2014) state that DEM shape and estimation of radial distortion are not separable unless additional information (e.g. GCPs) is available. They introduce three suitable approaches to mitigate dome error: consideration of a reliable camera model, usage of oblique images or exploiting the relationship between radial distortion parameters and dome magnitude.

If a UAV and SfM are used for geomorphologic applications, the actual surface representation has to be considered besides systematic errors, especially relevant for natural surfaces that usually comprise a high degree of roughness, e.g. such as soils. The potential of overlapping images to reconstruct natural soil surfaces with high accuracy has already been illustrated (Rieke-Zapp and Nearing, 2005; Jester and Klik, 2005; Heng et al., 2010; Nouwakpo et al., 2014). However, these studies calculate precise surface models under laboratory conditions. In contrast, data acquisition has to be conducted under field conditions to evaluate surface changes caused by complex earth surface processes under natural conditions. Eltner et al. (2015) already illustrate the suitability of UAV and SfM to measure soil surfaces with high accuracy. Thereby in general, dense matching is a key element that controls how closely reconstructed DEMs describe reality, especially of rough surfaces.

In this study, the following four objectives are defined:

- (1) The performance of five software solutions, implementing different parameters and algorithms for image based 3D reconstruction, are compared in terms of accuracy and precision using DEMs generated from simulated UAV flights relative to an independent reference measurement.
- (2) Three different cameras are utilised to investigate the effect of camera specifications and stability on data quality. This is because UAVs often carry lightweight consumer-grade cameras with expected poorer performance for DEM calculation.
- (3) A solution is suggested to solve for unfavourable dome errors observed for less rigorous SfM approaches. The introduced method corresponds to an implementation of the suggestion by James and Robson (2014) to use an appropriate geometric camera model.
- (4) Part of a natural soil surface originally evaluated for soil erosion studies is reconstructed from UAV images and compared to TLS data to evaluate

applicability of the developed approach to mitigate dome error and to assess surface representation by dense matching under field conditions, which is important for geomorphic studies.

3.2. Methods

3.2.1. Camera calibration

In this study, a compact camera (CC), a mirrorless interchangeable lens camera (also referred to as compact system camera, CSC) and a single lens reflex camera (SLR) are used for image acquisition (Table 3-1).

Table 3-1: Parameters of the different cameras used: pixel size, focal length, sensor size and radial distortion parameters A1 and A2 according to the geometric model described by Brown (1971).

Camera	Pixel size (μm)	Focal length (mm)	Sensor size (mm)	A1 (mm ⁻³)	A2 (mm ⁻⁵)
СС	2.0	5.2	7·4 x 5·5	-1·9E-4 ± 2·1E-5	-1·5E-4 ± 2·8E-6
CSC	4.8	16.0	23•5 x 15•6	-3•9E-5 ± 9•2E-7	4·8E-7 ± 1·1E-8
SLR	8.5	28.5	36·0 x 24·0	-9·4E-5 ± 1·5E-7	1·6E-7 ± 6·9E-10

The CC is the consumer-grade Panasonic Lumix DMC-LX3, which has a small sensor and integrates a zoom lens. This camera is assumed to exhibit the most unstable camera geometry. The CSC is the Sony NEX-5N and utilised with a more stable lens with a fixed focal length. The SLR is the Nikon D700, equipped with a full format sensor and also applied with a lens with a fixed focal length (Nikkor 28 mm 1:2.8D). Pixel size, focal length and sensor size of all three cameras are increasing in order of the previous introduction.

All cameras were calibrated immediately prior to capturing the surface of interest to obtain stable camera parameters that do not change over time, e.g. due to camera movement. Principal point, focal length and distortion parameters were estimated. An inhouse calibration field with a size of 3.0×3.5 m was used before the simulated UAV flights, while a temporary calibration field with a size of 1.2×1.5 m was used during the field campaign, allowing for almost simultaneous camera calibration (Fig. 3-1). In both cases coded markers were used and distributed in three dimensions to minimise correlations between calculated internal and external camera parameters (Luhmann et al., 2006). At least ten images were captured, including camera rolls and convergent viewing angles for optimal parameter estimation. The in-house field was measured at an approximate distance of 4 m, while images of the temporary field were acquired at a distance of c. 2 m. The focus was fixed and did not change between calibration and UAV flight. After the test fields were
imaged, determination of 2D image coordinates and subsequent calculation of camera parameters and precise 3D object coordinates of the markers were performed in Aicon 3D Studio (v10.06), based on a free network bundle adjustment. This bundle adjustment software requires initial 3D coordinates for some of the markers (at least 5), which were determined using a measuring tape. Although this had relatively low precision (cm-level), it was sufficient, as the aim of these initial values is to indicate the mutual position of the markers.



Figure 3-1: Camera calibration performed with an in-house test field (left image) and a temporary test field for application during field surveys (right image).

Results of the camera calibration with the in-house test field reveal significant differences between cameras, especially concerning the radial distortion (Fig. 3-2). Radial distortion is illustrated for the same object area captured with the corresponding angle of aperture instead of sensor size, to allow comparison of the distortion of the different cameras. The magnitude of the distortion is strongest for the SLR. The importance of tangential distortion parameters are in most cases marginal for the camera model compared to the radial distortion (Luhmann et al., 2006). In this study, they were only of significance for the CC, where tangential distortion parameters were distinctively higher than the associated standard deviations.



Figure 3-2: Radial distortion calculated for the same object area captured with corresponding angle of aperture of each camera.

3.2.2. Reference data

Two different surfaces are utilised in this study. First, a planar building floor is captured to investigate systematic errors. Second, a natural soil surface is measured to evaluate the performance of SfM tools during ordinary field applications.

3.2.2.1. Building floor

All reference measurements for the building floor were performed with a total station. The floor is an almost planar surface made of granite, with size of 4 m x 15 m (Fig. 3). The surface was measured by the total station with a grid resolution of 1 m. Point precisions are better than 1 mm, based on manufacturer specifications. The area between the measured points is interpolated, resulting in a triangulated mesh as reference DEM. 12 ground control points (GCPs) were established, ten along the edges of the reference object and two in the centre. Artificial objects, made of boxes and corrugated plates (1 m² brown corrugated cardboard), were setup on the building floor (Fig. 3-3). The corrugations are considered to assess dense matching performance, while planar areas of the floor were used to assess height accuracy.

The corner points of the corrugations were surveyed using the total station, and the following approach was conducted to model the shape of the corrugations: The positions of the maximal and minimal wave heights of some waves were measured. Corresponding wavelengths and amplitudes were identified. These parameters were assigned to the remaining waves assuming a constant and stable corrugation form. An accuracy of 3 mm was estimated for both corrugated plates confirmed by measured corrugations that are not used for modelling (Zenker, 2014).



Figure 3-3: Oblique view onto the building floor measured with a total station. Included are two corrugated plates (brown) and two boxes. Green clip illustrates surface texture of the granite floor and blue clip displays the corrugations in more detail. Red stripe displays profile position, which illustrates dome error in Fig. 3-5.

3.2.2.2. Soil surface

The surface used for field testing is located in Andalusia (Spain) and measured frequently for soil erosion assessment (Fig. 3-4). The investigated area in this study has a size of about 9 m x 15 m. The soil surface was captured by terrestrial laser scanning (TLS) to generate a suitable reference for the DEM reconstructed from the UAV images. The Riegl LMS-Z420i is used, which works with the time of flight principle. The device used in this study exhibits an accuracy of 7.5 mm (Mulsow et al., 2004; Schneider, 2009). The laser scanner was placed at three positions around the field plot to avoid data gaps, and the ensuing point cloud was processed to minimise noise and remove outliers (Eltner and Baumgart, 2015), resulting in a point density of about 1 point per 0.5 cm². Afterwards, the point cloud is meshed with Delaunay triangulation.



Figure 3-4: TLS model (ground plot) of the investigated soil surface, which is used for comparison with UAV image-based reconstructed point clouds. Location of ground control points (GCP) and scan positions (SP) are illustrated.

Five GCPs were located around the field plot to register UAV and TLS data. Further temporary tie points are situated evenly distributed, also behind the scanner to guarantee stable registration geometry of the individual scan positions. Retro-reflective cylinders were applied for TLS alignment, which exhibit known uncertainties due to the signal intensity processing (Blaskow and Schneider, 2014; Eltner and Baumgart, 2015). Hence, an iterative closest point (ICP) algorithm (Besl and McKay, 1992) was performed for final fine registration between the UAV and TLS data, which results in an average registration accuracy of 0.2 mm.

3.2.3. Data acquisition

Different approaches of image acquisition are conducted to obtain the surface data. The building floor was captured with simulated UAV flights at a height of 4.5 m, with the three described cameras mounted on a handheld pole. The cameras are triggered manually resulting in an approximate length- and crosswise image overlap of 80 %.

The soil surface was measured during an actual UAV mission at a height of 12 m with the AscTec Falcon 8 equipped with the CSC. This platform is an octocopter and includes IMU and GPS units, which enable programmed flight patterns for image capturing in auto-pilot mode. Furthermore, an actively stabilising camera mount is integrated, especially important for low flying altitudes because nick and roll movements of the UAV are compensated and hence allow for consistent image overlap. During the field campaign, overlap is crosswise 85 % and lengthwise 75 %. Also, the Falcon 8 can be programmed to maintain its position at the assigned waypoints for a given time, to stabilise the copter during image capture, thus ensuring blur-free image acquisition.

The different configurations of data acquisition of the building floor and soil surface result in different resolutions and potential accuracies (Table 3-2). Hence, ground resolution as well as accuracy is lower for the soil surface due to a higher flying altitude.

Table 3-2: Flight planning parameters depending on the camera type and on the surveyed surface, i.e. either
building floor or soil surface. Theoretical lateral and vertical accuracy values are estimated for the axes-
parallel normal stereo-case in regard of error propagation theory (assuming error-free base as well as focal
length and assuming a measuring accuracy of 0.29 pixels due to quantisation noise).

	Building floor			Soil surface
Camera type	SLR	CSC	СС	CSC
Flying altitude (m)	4.5	4.5	4.5	12.0
Ground resolution (mm)	1.4	1.3	1.8	2.4
Lateral accuracy (mm)	0.4	0.4	0.5	1.0
Vertical accuracy (mm)	1.8	1.8	2.4	5.3

3.2.4. Data processing

In this study, five different software solutions were used for data processing (Table 3-3). Visual SfM (VSfM; Wu, 2011) and Bundler (Snavely et al., 2006) are basic SfM tools, whereas AgiSoft PhotoScan (v1.0.4), Pix4D (v1.1) and APERO (Pierrot-Deseilligny and Clery, 2011) are more complex programs. All solutions perform photo-based 3D reconstruction and dense matching based on differing algorithms and parameter considerations. However, several workflow steps are similar. For instance, homologous image points are detected and allocated automatically due to image matching by the scaleinvariant feature transform (SIFT) operator (Lowe, 1999) or an adaption of that feature detector. The interest operator extracts keypoints characterised by significant intensity changes. A corresponding feature descriptor is calculated that is determined by image gradients to describe the area surrounding a keypoints' position.

	-	-			
Software	Visual SfM	Bundler	PhotoScan	Pix4D	APERO
Camera	principal	principal	principal distance,	principal distance,	principal distance,
model	distance,	distance,	principal point,	principal point,	principal point,
	two radial	one radial	three radial	three radial	three radial
	distortion	distortion	distortion	distortion	distortion
	parameters,	parameter,	parameters,	parameters,	parameters,
			tangential	tangential	
			distortion,	distortion,	
	model for	model for	one model for all	one model for all	one model for all
	each image	each image	images	images	images
Refinement	fast multi-	BBA	BBA	BBA with	BBA with
of camera	core bundle			integration of initial	integration of
parameters	adjustment			camera values	initial camera
					values
Dense	PMVS/	PMVS/	proprietary	proprietary	MicMac
matching	CMVS	CMVS*			
Geo-	external	external	GCPs integrated in	GCPs integrated in	GCPs integrated in
referencing	sfm-georef	sfm-georef	BBA	BBA	BBA
License	freeware	open-	commercial	commercial	open-source
		source			
Further	Wu, 2007;	Snavely et	Verhoeven, 2011	Küng et al., 2011	Pierrot-Deseilligny
reading	Wu et al.,	al., 2006		-	and Clery, 2011
	2011				

Table 3-3: Comparison of used image-based 3D reconstruction tools and their settings in this study.

* Bundler downscales images for SIFT. Hence, in this study, downscaled focal length from Bundler output is adjusted to corresponding full image size and down-scaled images are replaced with full size images before performing PMVS/CMVS to exploit entire image information for dense matching.

Matched keypoints are used to estimate initial values of camera orientation and position, mostly by implementing RANSAC (Fischler and Bolles, 1981), which enables handling of large numbers of matches with many potential outliers in a robust and fast manner. After calculating initial estimates, bundle block adjustment (BBA) is performed to

refine external and internal camera parameters. In contrast to the more complex programs for image-based reconstruction, the basic SfM tools integrate very simple camera models and do not support consideration of GCPs within the adjustment. In addition, the more complex tools enable the input of camera position and orientation as estimates for the BBA.

With the calculated interior and exterior image geometry it is possible to perform dense matching resulting in a DEM with very high resolution. Local and global algorithms (Brown et al., 2003) are implemented by the 3D reconstruction tools. Local matching considers constraints assigned to small kernels surrounding the pixel of interest, such as when performing matching with normalized cross correlation (e.g. patch-based multi-view stereo (PMVS) by Furukawa and Ponce (2010) or its enhancement (cluster-based multiview stereo, CMVS) presented in Furukawa et al., 2010). However, local variations are prone to ambiguity. In contrast, global matching uses constraints applied to entire scan lines or images, such as by minimising cost functions (e.g. MicMac by the Institut Géographique National (IGN); Pierrot-Deseilligny and Paparoditis, 2006). Global algorithms are, however, computationally intensive. Hence, algorithms that combine local and global characteristics have been developed, such as semi-global matching (SGM), which performs pixel-wise matching and subsequently minimises the aggregation of matching costs from multiple one-dimensional path directions through the image (Hirschmüller, 2005).

The basic SfM tools solely calculate relative image position and orientation due to missing GCP integration and thus need to be geo-referenced afterwards. In this study, sfm-georef from James and Robson (2012) is used, which first performs spatial intersections of the image points corresponding to the GCPs to estimate their object point coordinates within the relative coordinate system. Subsequently, this point information together with the global coordinates of the GCPs are utilised to execute an adjustment procedure to find the necessary parameters for a Helmert-transformation.

3.2.5. Dome effect and its handling

UAV image based surface reconstruction reveals clear differences between the basic SfM tools (VSfM and Bundler), which implement simple camera models and do not consider GCPs, and the more complex tools (PhotoScan, Pix4D, APERO) because DEMs calculated with the former display a distinctive dome (Fig. 3-5). This error is too large to consider these DEMs for further applications. Hence, a different approach is performed that still utilises the basic SfM tools for surface reconstruction. The dome is minimised by using

distortion-corrected images and disabling radial distortion estimation during processing. Image undistortion is performed with an in-house implementation, which considers the calibrated camera parameters from the test fields. However, it is also possible to calibrate the camera and subsequently undistort images with freeware solutions, i.e. AgiSoft Lens, which for instance is used by Kaiser et al. (2014) in a study to measure soil erosion.

James and Robson (2014) also introduce an effective routine for mitigating dome errors resulting from axes-parallel image acquisition. Similar to this study, they utilise convergent images for more reliable camera calibration. However, in this study images for calibration are captured prior to the analysis, while in their study oblique images are acquired during the UAV mission. If oblique imagery is not possible, they suggest a mitigation approach utilising the relationship between radial distortion and dome magnitude, though this implies the necessity of reliable reference. In contrast, the approach of this study inherits the advantages that different camera models can be estimated, no GCPs or other reference is needed, and finally image configurations can be used where oblique images are not possible. An adequate geometric camera model, reflected in the undistorted images, is implemented to reconstruct the surface of interest.

3.3. Results

3.3.1. Dome effect

Fig. 3-5 displays the systematic error of a dome within the DEMs calculated with the basic SfM tools. Different factors that might influence the dome effect can be distinguished. On the one hand, it is obvious that DEMs calculated from images of cameras with stronger radial distortion depict larger dome magnitudes. The SLR, which shows largest radial distortion, reveals the largest deviation from the reference data, followed by the CC. The CSC, which possesses only low radial distortion, exhibits the lowest error. Also, the SLR and compact cameras reveal more complex distortion characteristics (Fig. 3-2) than the CSC, which might influence dome magnitude. On the other hand, parameterisation of radial distortion is relevant: Bundler considers an additional term to attenuate large values of distortion (Snavely et al., 2008), which can be the cause of a less significant dome compared to VSfM. In addition, almost similar dome magnitudes occur for the SLR and compact cameras, even though radial distortion of the SLR is distinctively higher than the CC (Table 3-1 and Fig. 3-2). Furthermore, the more complex camera model (two radial distortion parameters) in Bundler can be another cause for lower dome errors than in

DEMs calculated with VSfM, which solely considers one parameter for radial distortion. Generally, both basic SfM tools are not able to accurately estimate radial distortion, which results in the dome error, the magnitude of which reflects the accuracy with which the parameters have been calculated.



Figure 3-5: Illustration of systematic error (dome) resulting from processing of distorted images (original: circle markers) in SfM software (VSfM: upper diagram; Bundler: lower diagram) that does not consider GCPs or sufficient camera calibration if undistorted images (undistorted: cross markers) are used. Different cameras are considered (SLR: green; CSC: red; CC: blue). Point deviations are demonstrated for extracted points along a profile across the reference plot, whose position is displayed in Fig. 3-3.

Implementing undistorted images and disabling radial distortion estimation (i.e. fixed with zero) in the SfM workflow results in an elimination of the dome effect. However,

camera stability and reliability of the estimated parameters are important for the final accuracy. Fig. 3-5 shows that for the CC camera, dome magnitude could be reduced significantly for VSfM, but for Bundler no distinctive changes between distorted and undistorted images are visible. Nevertheless, within VSfM a small dome effect remains for the undistorted CC images as well. Movements of the zoom lens camera can result in changes of the camera geometry because of flexible lens alignment (Shortis et al., 2006; Sanz-Ablanedo et al., 2010). Furthermore, uncertain camera calibration is another possible cause for insufficient correction of image distortion. The calibration of the compact camera produces the highest standard deviations of the estimated distortion parameters, indicating their lower reliability compared to the other two cameras (Table 3-1). Therefore camera parameters of the CC that are calibrated with the test field may not be applicable for producing undistorted images, as the resulting images still have significant remaining distortion.

3.3.2. Performance of photo-based reconstruction and dense matching

A first evaluation of the performance of the photo-based reconstruction tools is conducted by assessing the GCP residuals (Table 3-4). Basic SfM tools and the more complex tools need to be considered differently. Image refinement is performed in two stages in Bundler and VSfM. Hence, relative alignment is followed by absolute alignment with sfm-georef because GCPs are not implemented in the BBA, resulting in higher errors. In contrast, PhotoScan, Pix4D and APERO enable to consider GCP information. Thus, GCP residuals depend on the weighting of the observations in the adjustment and might not be representative for the actual accuracy of the surface points. Accuracy depends on the applied camera for the basic SfM tools, whereas influence of the camera type on BBA performance is not distinguishable for the more complex tools.

		Bı	uilding flo	Soil surface	
		SLR	CSC	СС	CSC
Visual SfM	Original	207.6	16.1	64.9	36.3
	Undistorted	2.4	6.4	20.0	17.4
Bundler	Original	23.4	16.7	20.8	27.0
	Undistorted	1.4	6.7	17.1	17.2
PhotoScan	Original	0.2	0.8	0.3	9.1
Pix4D	Original	1.5	1.6	4•4	7.3
APERO	Original	< 0.1	< 0.1	< 0.1	0.2

Table 3-4: RMSE of the absolute values of the 3D coordinate discrepancy vectors at each GCP (mm).

Point deviations between the meshed building floor based on the total station measurements and the point cloud reconstructed from the images acquired during the simulated UAV flight are measured to assess the accuracy of photo-based reconstruction. Local height offsets in Fig. 3-6 are due to limited resolution of the total station points (1 point per metre) of the building floor, which can cause underestimation or missing detection of local bulges, because the floor surface reveals higher elevation differences than originally assumed by qualitative assessment. Deviations are analysed for the nearly planar area of the building floor (excluding corrugated plates and boxes) to measure height accuracy and for the corrugated plates to evaluate the achievable surface representation by the dense matching algorithms. Average differences to the floor plane are ≤ 1 mm for all reconstruction tools and the SLR and compact system camera (Table 3-5). These differences are even lower than the estimated theoretical accuracy for the normal stereo-case (Table 3-2). The results from the CC are around 14 and 9 mm for VSfM and Bundler calculations respectively, due to the remaining dome effect in the DEM.



Figure 3-6: Deviation of the calculated DEM from UAV images to the total station reference measurement of the building floor (example for the SLR and Pix4D software).

The root mean squared error (RMSE) of the point deviations to the floor plane (Table 3-5) further confirms that photo-based reconstruction can outperform estimated theoretical height accuracies from the normal stereo-case (Table 3-2). The SLR reveals lowest error mainly due to the best signal-to-noise ratio because of the largest pixel size. The more complex tools reveal best accuracy results. Highest errors are measured for the simple SfM tools, especially for the CC, which is due to the remaining distortion.

Table 3-5: Mean (mm) and RMSE (mm) of point deviation between reference measurement and photo based reconstruction using different software and camera types. Floor plane is used to assess accuracy. Corrugated plates are for precision assessment of dense matching. Thereby, PMVS is used by Visual SfM as well as Bundler and MicMac is used by APERO. Undistorted images are used within Bundler and Visual SfM.

	SLR			CSC				СС				
	Floor plane		Corrugations		Floor plane		Corrugations		Floor plane		Corrugations	
	Mean	RMSE	Mean	RMSE	Mean	RMSE	Mean	RMSE	Mean	RMSE	Mean	RMSE
Visual SfM	0.1	1.9	0.4	6.9	-0.8	2.8	-0-4	8.1	11.3	16.9	14.3	16.7
Bundler	-0.2	1.6	0.9	5.5	-0-4	2.0	0.1	6.8	-0-4	11.2	8.7	12.8
PhotoScan	-0.1	1.5	-1.1	6.1	-0-2	1.6	0.6	7.2	-0.7	1.8	-0.1	7.9
Pix4D	-0.3	1.5	-0.2	4.5	0.3	1.9	2.1	6.3	-0.3	2.0	0.0	7.0
APERO	0.4	3.0	-0.3	4.1	0.0	2.1	0.2	5.9	1.2	2.6	1.3	6.4

When evaluating deviations to the corrugation plates to evaluate dense matching, it is obvious that the RMSE is generally higher than the error of the floor plane, due to the influence of lateral errors on the height accuracy, which is negligible for the floor plane. Regarding the different cameras, the best surface representations are achievable with SLR, followed by CSC and finally CC, confirming the importance of signal-to-noise ratio again indicated by decreasing pixel size, respectively. The best dense matching performance was measured with MicMac. Point deviations for the corrugated plates between the reference mesh and DEMs generated with PhotoScan are significantly higher than for DEMs generated with the other complex tools, although height accuracy for the floor plane was the highest. This is because PhotoScan implements a filtering process, which cannot be disabled completely, leading to surface smoothing. Larger errors produced by the images from the CC in combination with the basic SfM tools, which use PMVS for dense matching, are due to the slightly remaining dome error. Concluding, in this study global and/or semi-global matching implementation (MicMac) achieves better surface representations than local (patch-based) matching implementation (PMVS).

3.3.3. Reconstruction of natural surfaces

The point deviations of the soil surface between the DEMs calculated from the UAV images and the reference DEM generated from TLS are illustrated with boxplots (Fig. 3-7).

The average of point differences reveals no systematic error. However, due to ICP registration between UAV and TLS data, possible existing shifts or rotations between both models are masked. More validity is expected from error analysis constituted by RMSE and boxplot extent, which both reveal magnitude of data noise. Point deviations larger than 4 cm are excluded for statistical investigation and hence considered as outliers, because greater differences are mainly due to vegetation residuals. Thereby, data is maximally

reduced by 1.5 %. Largest differences are visible for Bundler and VSfM (both dense matching with PMVS) utilising undistorted images. As for the building floor, images of the CSC were distortion-corrected, but this time intrinsic camera parameters are estimated with the local calibration field designed for field campaigns, which is captured immediately before the UAV flight.



Figure 3-7: Boxplots illustrating statistical analysis of point deviations of the UAV photo based reconstructed soil surface to the meshed DEM based on terrestrial laser scanning. RMSE is indicated with green values.

DEMs calculated with basic SfM tools and undistorted images reveal similar performance in surface representation as the more complex tools. MicMac (used after APERO for dense matching) seems to display the lowest noise, confirming results obtained from the corrugated plates (Table 3-5). Except for the original distorted images applied in basic SfM tools, RMSE values of the differently dense matched surfaces are within the range of the TLS device (7.5 mm according to Mulsow et al., 2004). However, better reconstruction performance of the UAV data is likely for soil surfaces, but cannot be detected due to noise within the TLS data, which increases with surface roughness because of the scan geometry and known given error sources, e.g. edge effects. Hence, it is not feasible to evaluate to which extent DEM generated with UAV data reaches possible accuracies estimated for the axes-parallel normal stereo-case (Table 3-2). Overall, error

analysis, revealing no significant large differences between the dense matching algorithms, should mainly be considered in relative terms.

Concluding, Fig. 3-8 allows for a visual assessment of the dense matching performance. With MicMac most details are visible (e.g. comparing scrub in the northern surface area). Pix4D displays likewise results. However, soil surface reconstruction with PhotoScan appears not as distinct (e.g. contrasting rills in the south-eastern surface area) compared to the previously mentioned solutions (coinciding with the results of the corrugated plates in Table 3-5) due to software-based smoothing, which is disadvantageous for soil erosion measurements. PMVS seems to calculate a slightly noisier DEM. Nevertheless, all investigated dense matching algorithms perform very satisfactory by displaying a high degree of detail, especially when the corresponding pictorial representation is kept in mind, which can be pioneering for geomorphological studies.



Figure 3-8: Results of different dense matching algorithms. Left image shows the exhibited clip of the soil surface area.

3.4. Discussion

3.4.1. Factors complicating photo-based reconstruction and dense matching comparison

When comparing different photo-based reconstruction and dense matching tools, it has to be considered that differently implemented algorithms as well as parameters complicate contrasting their performance. For instance, diverse geometric camera models are considered for self-calibration. Bundler and VSfM only estimate principal distance and two or one radial distortion parameters, respectively. In contrast, the more complex tools solve for a larger number of intrinsic camera parameters. Furthermore, basic SfM tools model one set of interior orientation parameters for each image (if distortion is being optimised) which may lead to over-parameterisation, while PhotoScan, Pix4D and APERO estimate one set of interior orientation parameters for the entire image block, which is more suitable in this study because every DEM is reconstructed with a single camera, whose geometry did not change significantly during image acquisition.

Dall'Asta and Roncella (2014) measure relative accuracy performance of SGM, MicMac and PhotoScan and their results coincide with this study, stating that these tools perform without large differences and that the inability to disable surface smoothing within PhotoScan causes local deviations.

3.4.2. Factors influencing the dome effect

Besides differing tools, a major impact on the accuracy and precision of 3D reconstruction is the axes-parallel UAV image configuration causing problems in the context of dome error within the calculated DEM if no GCPs are considered in the BBA (e.g. Bundler and VSfM).

3.4.2.1. Dome effect as a function of parameterisation

Wackrow and Chandler (2008) assign the dome error to a wrongly estimated lens model and show that dome magnitude increases with increasing false radial distortion calculation. Furthermore, James and Robson (2014) identify a linear relationship between the dome error and the uncertainty in radial distortion estimation. This study confirms the impact of the degree of wrong distortion estimation, e.g. due to an insufficient geometric camera model, because Bundler, which integrates two radial distortion parameters, results in lower dome magnitudes compared to VSfM, which only considers one parameter. Also, the complexity and/or degree of radial distortion seem to be relevant, causing larger domes for cameras with stronger distortions because of increasing false estimation of these distortion parameters. Wackrow and Chandler (2008) highlight the difficulty of calibrating an adequate geometric model with an unstable camera, which is also indicated in this study because CC reveals still remaining dome error for undistorted images. General importance of camera stability for data accuracy is also discussed by Rieke-Zapp et al. (2009).

Another possible influence on the dome error is the number of parameters, which are estimated by the SfM approach. Remondino et al. (2012) report unstable interior orientation calculation for Bundler and VSfM compared to more complex tools (PhotoScan and APERO), and relate their findings to the different consideration of the number of interior orientation parameter sets per image block as already mentioned above. Hence, unfavourable error propagation and over-parameterisation, especially for stable cameras during the image acquisition, can be the consequence, which is also assumed by Rosnell and Honkavaara (2012). When distortion-corrected images are used in the basic SfM tools, radial distortion is set to zero (or fixed), reducing the number of estimated parameters, which might be a further cause for minimisation of the dome error.

3.4.2.2. Dome effect as a function of image configuration

The possibility to integrate convergent images minimises this systematic error significantly (Wackrow and Chandler, 2008; James and Robson, 2014). However, in the field such image configurations are not realisable in all UAV operation situations.

Furthermore, the amount of overlap between images can influence the dome magnitude. In regard to dome error explanation of Wackrow and Chandler (2011), higher image overlap should decrease the dome error if one set of interior orientation parameters is calibrated for the entire image block. This is because the same object area is displayed within nearly same regions of the images and hence similar values of distortion correction are assigned to the corresponding pixels. However, highly overlapping images result in low baselines between adjacent camera positions and thus increasing glancing ray intersections. This is partly compensated for by high image information redundancy due to high numbers of overlapping images. Nevertheless, convergent image integration should be favoured, if possible, over highly overlapping axes-parallel image configurations to decrease subsequent processing resources.

3.4.2.3. Dome effect as a function of additional information within BBA

Consideration of GCPs within the process of image orientation minimises the systematic error of a DEM dome. James and Robson (2014) discuss the disadvantage of SfM tools that do not implement GCPs in the BBA. The same findings are confirmed in this study, because DEMs generated with PhotoScan without implementing GCPs reveal a dome in the models, just as Bundler and VSfM. That error is not eliminated until final refinement of the camera parameters is performed by an optimisation algorithm, which considers GCPs. Hence, the complex camera model itself, as implemented in PhotoScan, is not sufficient to avoid this systematic error.

3.4.3. Application to field data

The approach in this study shows that it is possible to use basic SfM tools and subsequent dense-matching for axes-parallel UAV image configuration with high precision if the camera is calibrated accurately enough immediately before or after data acquisition. Using distortion-corrected images can be extended to the complex 3D reconstruction software if no GCPs are available, which allows for flexible UAV applications under complicated terrain conditions, where GCP setup might be difficult and only direct orientation can be used for georeferencing. Furthermore, CSC reveals suitable stability, which is important for UAV missions due to the limited payloads.

Generally, comparison of different dense matching algorithms reveals soil surface reconstruction with very accurate surface representation, especially when (semi-)global matchers are implemented. Difficulties of soil surface reconstruction result from their rough nature, such as alternating areas of low texture within very complex regions. Modern photogrammetric methods facilitate topographic mapping, with high accuracy and precision, thus giving new perspectives into soil surface change detection studies.

3.5. Conclusion

Two different surfaces have been used to investigate the performance of 3D reconstruction from axes-parallel UAV images. First, the accuracy of DEM calculation from overlapping axes-parallel images was assessed in laboratory conditions. Secondly, a natural soil surface – originally evaluated for soil erosion studies – was 3D reconstructed in order

to evaluate the performance and surface representation. The following conclusions can be drawn from this study:

- (1) Applying three different cameras with different focal lengths as well as sensor and pixel sizes reveals that signal-to-noise ratio and ground resolution are essential factors influencing accuracy, with best performance for the SLR.
- (2) 3D reconstruction tools that implement complex geometric camera models as well as GCPs in the BBA show similar accuracies, resulting in accuracies at least as precise as estimated for the normal stereo-case. Furthermore, dense matching performs satisfactorily to represent natural soil surfaces.
- (3) Dome errors in the reconstructed DEMs are obvious for SfM tools that integrate simple geometric camera models and perform geo-referencing following relative image orientation, without GCPs in the BBA. The implemented algorithms fail to determine accurate parameters of radial distortion using axes-parallel UAV image configuration, without converging image sets.
- (4) It is possible to minimise dome error by applying distortion-corrected images from pre- or post-flight calibrated cameras, where convergent image configurations have been used. The only requirement is stable camera geometry and a temporary calibration field. This method can be extended to more complex reconstruction tools in the case of missing GCP information, for instance if only scale information is used for DEM referencing.

Measuring high resolution soil surfaces from UAV images for multi-temporal change detection and large field plots is a challenging task. However, these demands are realisable due to recent advances in platform technology and data processing algorithms, allowing for fast surface reconstruction with SfM and dense-matching tools.

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4. UAV photogrammetry implemented: high resolution soil surface change detection at hillslope scale

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Abstract: The fragile landscape of the north European loess belt is prone to soil erosion due to soil properties and intense land use of the fertile region. Exact measurement of surface changes with high temporal and spatial resolution over large areas is necessary to quantify and understand rill and interrill erosion processes. High resolution aerial imagery, acquired by an unmanned aerial vehicle (UAV), is used to automatically generate precise digital surface models (DSMs) of high spatial resolution by applying structure-from-motion image processing tools. During an investigation period of ten months, a 600 m² field plot is observed during four field campaigns. A stable reference system is established for multi-temporal comparison. The overall accuracy of the DSMs generated from UAV images is less than 1 cm, verified by comparison with terrestrial laser scanner (TLS) data. Furthermore, a method for automatic rill extraction and rill parameter calculation is developed, which enables objective rill description with cm-accuracy and -resolution. Soil surface roughness and rill development as well as volumetric quantifications are analysed for multi-temporal change detection. Surface changes during winter season are controlled by soil consolidation, crusting and sheet erosion. During rainy spring season sheet erosion and rill incision occur. Two thunderstorms in summer season cause dominant rill erosion. Erosion rills are more dominantly deepening than widening (from to 2 to 4 cm depth and from 17 to 23 cm width), resulting in average per rill erosion values of 0.03 and 0.07 m³ respectively. An orientation dependent lateral rill shift is revealed, implying rill widening in eastern direction due to dominant winds from the West. Volumetric quantifications indicate high erosion volumes, reaching up to 121 tha-1 during the summer events. Highest erosion volumes are due to rill erosion rather than interrill erosion.

Keywords: UAV, soil erosion, rill-interrill, automatic rill extraction, field scale

4.1. Introduction

Soil erosion is a driving factor for land degradation – especially in fragile landscapes dominated by loess. Due to the low clay and organic matter content, the silty soils formed in loess reveal low aggregate stability. Fast crusting is the consequence (Le Bissonnais et al., 2005). Crusts develop due to aggregate breakdown because of slacking and raindrop impact, which leads to surface sealing and subsequent infiltration decrease (Bresson and Boiffin, 1990; Valentin and Bresson, 1992; Le Bissonnais, 1996), contributing to increased runoff (Auzet et al., 1995). In addition to unfavourable soil properties, intense farming leads to frequent bare soil surfaces due to cropping cycles that are vulnerable to precipitation and runoff.

Soil erosion occurs due to rill and/or interrill erosion. On the one hand, interrill erosion is determined by soil detachment and lateral movement due to raindrop impact and shallow overland flow (Govers and Poesen, 1988; Beuselinck et al., 2002). On the other hand, rill erosion is a function of rill hydraulics and soil detachment due to soil shear stress overcoming as well as transport capacity (Govers et al., 2007). To investigate rill-interrill ratios and their development over time, area based measurements of soil surface changes are necessary but difficult to realise. Surface changes due to short term events have to be captured with very fine resolution. Furthermore, larger field plots should be examined and surface manipulation avoided to achieve a comprehensive view on soil changes (Faust, 1991). Established field methods (Stroosnijder, 2005) are representative for an entire field plot – e.g. gutters, cover only small areas – e.g. rainfall simulators (Agassi and Bradford, 1999), and are labour intensive – e.g. profilers (Casalí et al., 2006).

Methods from photogrammetry, which generate dense digital surface models from image data, are an interesting alternative to measure soil surface changes. They exhibit the advantage of high accuracy data and do not impact the surface. Using multi-image techniques, photogrammetry can provide automatically generated 3D object models of high precision and high spatial resolution (Maas and Kersten, 1997). Several authors already utilise stereo images in soil studies (Rieke-Zapp and Nearing, 2005; Jester and Klik, 2005; Heng et al., 2010). However, observations are solely made for small plots or under laboratory conditions. Only a few studies that use traditional photogrammetry are published because processing is challenging and expert knowledge necessary (Chandler, 1999). Recent advances in digital photogrammetry and computer vision resulted in the Structure-from-Motion (SfM) software tool, a technique for reconstructing threedimensional models from multiple images. Thereby, it is possible to rapidly produce high resolution digital surface models (DSMs) for large areas from (multi-)stereo images without expert knowledge in photogrammetry.

James and Robson (2012) are the first to use SfM for applications in geosciences, who additionally conducted accuracy investigations for differing object scales. Westoby et al. (2012) introduce a general workflow for topographic mapping with SfM. Additional geoscientific implementations are made recently. Castillo et al. (2012) use SfM to model gullys, James et al. (2013) estimate coastal erosion, Fonstad et al. (2013) measure fluvial topography and Bretar et al. (2013) volcanic terrains.

Beside its straightforward operation, the particular interest for SfM-techniques in geosciences is boosted by advances in the technology of unmanned aerial vehicles (UAVs). The development of low weight aircrafts, which are usually equipped with global positioning system (GPS) and inertial measurement unit (IMU), allows for organised flight planning. Hence, autonomous and frequent area monitoring is feasible. UAVs are equipped with different sensors ranging from ordinary consumer grade cameras to thermal cameras and hyperspectral cameras and recently even laser scanners (Colomina and Molina, 2014). Within photogrammetry, the technology has already been recognised for its potential in geosciences (Eisenbeiß, 2009).

UAVs depict a promising sensor platform for geomorphological studies. However, to date only areas with extensive erosion magnitudes have been monitored – i.e. gullys (Marzolff and Poesen, 2009; D'Oleire-Oltmanns et al., 2012; Peter et al., 2014) and landslides (Niethammer et al., 2012; Lucieer et al., 2013). Ouédraogo et al. (2014) were the first to use UAV data within soil studies. They observe a watershed under agricultural usage with a resolution of 1 m² and compare the results with terrestrial laser scanning (TLS) data.

So far, a multi-temporal soil surface change survey has not been done that estimates soil erosion rate at field scale with high resolution. In this study, we introduce the usability of a UAV to measure surface changes of short term erosion events for a large field plot with sub-centimetre accuracy. Furthermore, a method is introduced which allows for automatic cm-resolution rill extraction and parameter calculation (i.e. rill width, depth, cross section area) by applying methods from image processing and integrating local surface height information.

4.2. Material and Methods

4.2.1. Study area

The studied field plot is located in the fragile landscape of the Saxon loess province (Figure 4-1) as part of the north European loess belt. Wolf and Faust (2013) document constant changes of the landscape during the Holocene due to erosion processes. The dominant in-situ substrate is late Pleistocene loess. Higher stone concentrations of Palaeozoic shists are only present on the north eastern part of the field plot due to a nearby local outlier. The developed soil is a Luvisol, which is predominantly topped due to soil erosion. The grain size of the investigated soil is made of 20 % clay, 70 % silt and 10 % sand. The study area is affected by a temperate climate with an average annual temperature of 8.6°C and an average annual cumulative precipitation of 580 mm.

The study area is positioned within an active agriculturally used field of several hectares. The location of the field plot is on the upper part of a long hill slope. The plot is situated close to a local watershed to minimise the effect of concentrated runoff and to examine erosion resulting from splash as well as the initiation of runoff. The defined plot size amounts to about 600 m^2 ($20 \times 30 \text{ m}^2$). The longer field side is oriented in slope direction, which is aligned from South to North with the upper slope at the northern end. Slope averages 5.5° and has an elongated to slightly concave shape. In this study, four investigation dates are set that last in total over 10 months from October 2012 to July 2013. The field is freshly ploughed and harrowed one day before the first field campaign starts on 2 October 2012. The second field campaign follows on 22 April 2013.



Figure 4-1: Location of the study area. Photo illustrates the field plot (line of sight is south - north).

During the first and the longest investigation period of almost seven months the study area is exposed to precipitation with low intensities that amounts in total to 275 mm. At the end of winter occurs an exceptional long lasting snow cover until the beginning of April. The third field campaign is conducted on 13 June 2013. During the second investigation period of about two months a prolonged rainy interval is captured with a cumulative precipitation of about 150 mm within nine days (Figure 4-2). Daily values are not extraordinarily high, but the enduring precipitation results in a high magnitude of soil moisture and leads to intense flooding in the ambient environment. During the second study period precipitation amounts to 234 mm and is characterised by changing intensities. The last field campaign occurs on 24 July 2013. During the third investigation period of about one month two thunderstorms with high precipitation intensities and quantities of 50 and 25 mm are recorded.



Figure 4-2: Daily precipitation values for the first (1 October 2012-22 April 2013), second (22 April-13 June 2013) and third (13 June-24 July 2013) study period (SP).

Observing the soil surface state during the entire observation epoch, reveals that crusting is apparent (Figure 4-3). The freshly tilled soil has an initial fragmentary facies, whereas after winter season a depositional crust is formed, which degrades further during spring season.



Figure 4-3: Orthophoto clips of the same area illustrating development of crusts during the observation time.

4.2.2. Data acquisition

4.2.2.1. UAV

In this study, the UAV "Falcon 8" (octocopter) from Ascending Technologies is used for image acquisition. The platform is equipped with an active stabilising camera mount, which compensates for unwanted movements due to wind and system vibrations and therefore ensures sharp images as well as a constant downward viewing direction of the camera. Furthermore, the UAV records GPS and IMU data to allow for an autonomous flight to predefined camera positions (waypoints). At each waypoint the flight system remains until the image has been captured to avoid motion blur due to flying speed. Average flying height is between 8 and 11 m to guarantee a high ground resolution between 2 and 4 mm. About 100 images are taken to cover the field plot as well as some back-up area beyond to account for UAV drifts due to GPS inaccuracies and wind impacts. The images are taken with an overlap of 80 % in flight direction and a flight strip overlap of 60 %. Two different cameras are used (Table 4-1). During the first field campaign the UAV flies with the consumer grade compact camera Panasonic Lumix DMC-LX3. The camera is equipped with a zoom lens and is set to the wide angle of 5.1 mm. During the latter three field campaigns a compact system camera (Sony NEX 5N) with a fixed lens is utilised to ensure more stable inner camera geometry to improve digital surface model precision. The compact system camera permits less image noise due to a larger pixel size of 5 μ m (Table 4-1).

	Pixel size (µm)	Sensor size (mm ²)	Focal length (mm)	Ground resolution (mm)	Aperture
Panasonic	2	7.4 x 5.5	5.1	4	f4
Sony	5	23.5 x 25.6	16	2	f6.3-f8

4.2.2.2. TLS

Besides UAV measurements, a terrestrial laser scanner is applied to exploit its accuracy and reliability for error assessments of the aerial data. Because the field plot is situated within a constantly changing surrounding, stable references for accuracy examinations are missing. The rough soil surface impedes accuracy estimations, additionally. Therefore, the scanner is used as an independent control measurement. During every field campaign the scanner is located at four positions around the field plot to ensure complete area coverage. The scanner Riegl LMS Z420i works with the time-of-flight principle and is installed on a four metres high tripod to improve the viewing geometry onto the field plot. But even with the special tripod, the incidence angles decrease already to only 15° at a distance of 15 m. At that distance, the low incidence angle results in a laser spot size of 5 cm for a beam divergence of 0.25 mrad and scanner ray cross section emergence size of 1 cm. Hence, TLS accuracy has to be considered carefully. The registration of the four scanner positions during each field campaign is carried out with temporal tie points made of retro-reflective cylinders that are located around the study area and behind the scanner positions to ensure stable registration geometry.

4.2.2.3. Multi-temporal reference

A local stable reference system is defined for multi-temporal registration of the UAV data. As the region immediately enclosing the field plot is intensely used for farming, nearby stable reference points are missing. Therefore, new solid control points are set up by placing marking pipes to a depth of 60 cm (Eltner, 2013). A self-designed ground control point (GCP) is accurately fitted on top of each pipe, which can be removed and refitted after every campaign. Two different kinds of GCP are constructed adapting to the respective applied system (Figure 4-4). For the TLS the GCPs are made of retro-reflective cylinders with a diameter and height of 6 cm. These GCP are provided with an additional circular marker on top for a combined usage with the UAV images. Furthermore, additional GCPs are solely built for the aerial imagery, which are made of wood and also have a circular shape with a 5 cm diameter. In total, 17 GCP are located around the field plot and along a small path within the field plot (Figure 4-4).



Figure 4-4: Oriented image block from the first field campaign (02 October 2012) containing GCP location and GCP type. Image at the bottom illustrates the applied GCP.

To be able to check for potential changes of the reference system, the GCPs are measured with a geodetic total station during the first and last field campaign. A 3D-Helmert-transformation is performed to measure GCP stability during the entire study period of ten months. The resulting residuals at every GCP indicate a stable reference system except for one TLS-GCP, where the gap in horizontal direction amounts to 7 mm. This GCP is excluded from further data processing. The remaining points have an average residual of 1 mm in horizontal as well as vertical direction, which is within total station measurement accuracy.

4.2.3. DSM calculation

To obtain 3D digital surface models, 2D image information is processed with methods from photogrammetry and computer vision. The core of photogrammetric image data processing, with the goal of 3D object model generation, is a functional relation between 3D object points and 2D image points through the collinearity condition, which represents the standard pinhole camera model. Given two images with known orientation parameters (camera projection centre coordinates and viewing angles), this model can be used to determine 3D object point coordinates. Reversely, the orientation parameters of a camera can be determined from at least three GCPs.

To calculate a DSM from a large number of images, the following processing chain is common. First, homologous image points between images are matched automatically. Second, this information is used to reconstruct the camera orientation of all images, 3D object point coordinates and camera geometry in an iterative procedure. In contrast to classical photogrammetry software tools, SfM also allows for reliable processing of a large number of images in rather irregular image acquisition schemes (Snavely et al., 2007). Third, the resulting oriented image block (Figure 4-4) allows for a subsequent dense matching, where object coordinates are resolved for almost every pixel. Finally, georeferencing of the 3D model can be performed with a 3D-Helmerttransformation.

In our study, the SfM-software Pix4D (www.pix4D.com) is used to generate the DSM. The software is especially developed for UAV imagery. The resulting DSMs (Figure 4-5) have a resolution of 1 cm², which is below the image resolution (Table 4-1) because not every image pixel will be assigned an object point during dense matching.

In contrast to UAV image data processing, TLS directly delivers 3D information about the object of interest. However, some data processing is necessary as well. Vegetation is filtered

with the open-source software CANUPO (Brodu and Lague, 2012), which uses the complex three-dimensional characteristic of vegetation to classify vegetation and non-vegetation with a multi-scale measure. After vegetation has been filtered, the open source point cloud library (PCL) for C++ (Rusu and Cousins, 2011) is utilised for noise reduction and point thinning. First, a moving least square filter is used to smooth the surface. Afterwards, outliers (e.g. due to edge effects) are removed. Finally, the point cloud is down-sampled with a voxel filter. The resulting point density is about 1 point per 0.5 cm³.



Figure 4-5: DSM generated from UAV images for every field campaign.

In this study, information on the location of the filtered vegetation within the TLS data is used to produce a digital terrain model (DTM) from the DSM generated from the UAV images by clipping corresponding vegetation spots. However, in cases when additional TLS data is not given, other possibilities exist to achieve true ground data (e.g. Guarnieri et al., 2009). Gaps within the DTM due to vegetation spots are not further interpolated because change detection is to be conducted at the accuracy limit of the applied system, especially for estimates of low magnitude soil erosion. Interpolation of missing DTM cell values introduces additional interpolation errors which are difficult to measure.

4.2.4. Soil surface roughness

Soil surface roughness is an important factor for soil erosion because it influences runoff due to interaction with infiltration and local retention. Furthermore, roughness affects soil particle detachment due to flow dissipation at surface obstructions. Changes over time may give possible conclusions for changing erosion rates. The height information of a DTM allows for the extraction of different parameters representing roughness. Jester and Klik (2005) already utilised DTMs from images to estimate roughness.

In this study, plot elevation range (height range), root mean square height (RMSH), local RMSH (locRMSH) and tortuosity are chosen. Further possible roughness parameters, to analyse geomorphological issues with raster DTMs, are presented by Grohmann et al. (2010). Only local surface changes are of interest to roughness investigation. Hence, the DTMs are detrended to minimise the influence of global factors such as slope or field plot shape.

Plot elevation range is simple to determine, but has the disadvantage that it represents a global value and is prone to outliers. However, the parameter gives coarse information about the roughness of the field plot. The RMSH is more reliable due to considering all height measurements for the calculation. But the parameter also defines a global estimate of roughness.

The locRMSH suggested by Haubrock et al. (2009) accounts for local height changes and is independent of global surface characteristics because roughness is calculated by convolving with a kernel of a specific size. RMSH is calculated for small area patches moving over the DTM. Hence, absolute values are expected to be lower than global RMSH. Different kernel sizes ranging from 7 to 99 cm² are used in this study to account for scale dependencies of roughness. Haubrock et al. (2009) demonstrate that changing kernel extents can reveal different surface properties and processes. In this study, locRMSH is chosen for a kernel size of 31 cm² for further illustration because it captures rill as well as interrill properties. Additionally, the locRMSH is extended considering different roughness directions. Down slope and cross slope locRMSH are estimated separately by kernel sizes of 31 x 1 cm² and 1 x 31 cm² respectively to account for roughness changes in dip direction and transversely. Down slope roughness represents local water retention and runoff slowdown, while cross slope roughness accounts for flow concentration due to depression connectivity (Kirkby, 2001).

Finally, tortuosity is calculated (Smith et al., 2011). The parameter is the ratio between 3D and 2D area. Tortuosity needs no surface detrending because global surface characteristics are considered in 3D and 2D and therefore are eliminated by ratio calculation, which is also advantageous for comparison between different plot sizes. The higher the dimensionless value, the higher the roughness.

4.2.5. Rill extraction

To quantify and qualify rill development, it is necessary to evaluate general rill parameters. So far, rills needed to be extracted manually and hence with coarse resolution, high labour effort and/or limited to few rills only (e.g. Faust and Herkommer, 1995). An algorithm is introduced that allows for (semi-)automatic rill extraction. Therefore, edge detection methods from image processing are applied to the DTM, treating the height values of the surface raster as greyscale values of an image (Sui, 2002). Richter et al. (2013) implement a simpler version of this technique to extract a dune cliff.

The algorithm realises two crucial points. First, the Canny operator (Canny, 1986) is applied to extract the rill wall position. Second, the upper edge is calculated which defines the upper end of the rill wall. The method is executed in Python. Figure 4-6 illustrates the entire workflow to estimate rill parameters from automatically extracted rill edges.



Figure 4-6: Flowchart that illustrates the general workflow of automatic rill extraction for rill parameter estimation.

The Canny operator comprises several processing steps. First, surface smoothing is performed because the Canny edge detector is sensitive to noise. The original image *I* is processed by convolution with a Gaussian kernel G_{σ} .

$$I_{\sigma} = I * G_{\sigma} \tag{4-1}$$

$$G_{\sigma} = \frac{1}{2\pi\sigma} e^{-\frac{x^2 + y^2}{2\sigma^2}}$$
(4-2)

In this study, the standard deviation σ is defined with a value of 2.5. Afterwards, the image is convolved with the Sobel operator *S* in horizontal and vertical direction, which corresponds to calculating the first derivate of intensity changes of the raster values.

$$I_x = I * S_x \tag{4-3}$$

$$I_{\mathcal{Y}} = I * S_{\mathcal{Y}} \tag{4-4}$$

Maximum and minimum values correlate with steep slopes or edges. Besides the local gradient ∇I , the gradient direction α is determined.

$$\nabla I = \sqrt{I_x^2 + I_y^2} \tag{4-5}$$

$$\alpha = atan2(I_x, I_y) \tag{4-6}$$

The information about edge gradient and direction is used to perform a non-maximum suppression that leads to a thinned edge. Finally, hysteresis thresholding follows to mark and link confident edges by applying a high threshold, and pad weaker edges connected to confident edges by applying a low threshold. The result is a binary edge map.

The resulting Canny edges have to be processed manually to delete false detected rill walls. Furthermore, each rill side needs to be assigned interactively a corresponding rill, which is essential for the automatic upper edge detection.

Because the Canny edge position is located at the steepest wall slope, further processing is necessary. The upper end of the edge is important for rill parameters, e.g. rill width and depth. Otherwise, the depth of steep rills and the width of shallow rills will be underestimated (Figure 4-7). To detect the upper edge, height information in the Canny neighbourhood is considered. Every 1 cm a profile is extracted perpendicular to the Canny

edge. Along that profile the upper end of a rill wall is defined, where the slope changes significantly or falls below a predefined threshold.



Figure 4-7: Automatic rill extraction – difference between detected Canny edge and upper edge has consequences for the measured rill parameters (e.g. rill depth and width).

The resulting upper edge is noisy due to the chaotic nature of the surface. Clear edges do not exist and slope variations of differing magnitude occur along the rill wall within shortest distances. To smooth the upper edge, the Savitzky-Golay (Savitzky and Golay, 1964) filter is applied. The filter corresponds to a moving window in which a least square fitting of a polynomial is performed for every upper edge point f, resulting in a filtered point g.

$$g_{i} = \sum_{n=-\frac{l-1}{2}}^{n=\frac{l-1}{2}} c_{n} f_{i+n}$$
(4-7)

For a specific polynomial order and number of points l respective filter coefficients c_n exist. In this study, nine neighbouring upper edge points along the rill wall and a polynomial of the first degree are set. The filter has the advantage of preserving higher moments typical for irregular natural surfaces, while smoothing noisy edge trends.

Concluding, it has to be considered that the upper edge is only an approximation of the rill position due to the complex nature of the surface. But also for investigations in the field, it is not possible to determine the exact position of the rill top – even for larger and more obvious forms such as gullys. Thus, within this study a compromise is found (Figure 4-8).



Figure 4-8: Extract of hillshaded DSM for exemplary illustration of automatic extracted Canny edge and upper edge.

The following rill parameters are calculated for the extracted rills: width, depth, cross section area, roughness and volumetric changes (Figure 4-9). Rill width is defined by the length of cross sections generated orthogonal to the reference rill side and the consequent intersection at the corresponding rill side. Rill depth is the deepest point along the cross section. The cross section area is calculated by the sum of rill depths corresponding to the cross section. All described parameters are calculated for cross sections with a sampling distance of 1 cm. The rill roughness is estimated to consider possible influences of the former DTM surface structure on rill incision due to runoff impacts. Thus, the roughness parameters height range and root mean squared height (RMSH) are calculated for the surface of the DTM from 22 April 2013 within a defined rill buffer of 10 cm. Finally, volumetric changes within the rill are evaluated by extracting the sum of surface changes for each pixel multiplied with the pixel size.



Figure 4-9: Schematic illustration of the calculated rill parameter

4.3. Results

4.3.1. Accuracy assessment

Accuracy assessment of DSM heights can either be based on internal or external parameters (Maas/Kersten, 1997), with the latter being desirable. Internal precision parameters can be obtained by an analysis of the 3D point coordinate standard deviations obtained from the forward intersection for each surface point, though theory says that these internal parameters may sometimes be too optimistic. Error propagation theory applied to the normal case of a stereo image pair delivers a good estimate of horizontal accuracy σ_{XY} and vertical accuracy σ_Z for a specific flying height *H* (Kraus, 2007).

$$\sigma_{XY} = 0.29 \sigma_x \frac{H}{c_k} \tag{4-8}$$

$$\sigma_Z = 0.29 \sigma_x \frac{H^2}{Bc_k} \tag{4-9}$$

The equations are made under the assumption that the base *B* and focal length c_k are error-free. Furthermore, for measuring with an image accuracy σ_x of one pixel, a quantisation noise of 0.29 pixels is considered due to the conversion of a continuous signal to a discrete pixel value. During the first field campaign (compact camera) estimated errors averaged for flight altitudes between 8 and 11 m amount to 1 and 5 mm in horizontal and vertical direction, respectively. During the remaining field campaigns (compact system camera) errors amount to 1 and 4 mm, respectively. It has to be considered that the
accuracy estimates might be too pessimistic for 3D-point reconstruction from multi-view images, as the above formula applies to an image pair.

GCP residuals may also be used to assess precision (Table 4-2). The residuals indicate the remaining deviation between the GCP coordinates measured by the total station and those retrieved from the photogrammetric data processing. However, they are not representative for actual terrain surface points because they depend on the weighting of observations in the bundle adjustment. In this study, residuals amount between 1 and 3 mm and must be assumed to be too optimistic.

2 October 2012 22 April 2013 13 June 2013 24 July 2013 X (cm) 0.0 0.1 0.1 0.1 Y(cm) 0.0 0.1 0.1 0.1 Z(cm) 0.1 0.2 0.2 0.3

Table 4-2: GCP residuals after bundle block adjustment.

External precision parameters can be derived from a comparison with TLS data. Usually, external precision figures only allow for a thorough accuracy check, if the reference data has been obtained independently by a measurement technique providing a superior accuracy potential. In the case of TLS data, the latter is questionable due to several reasons. First, the geo-referenced TLS point cloud still needs to be registered by an iterative closest point (ICP) algorithm (Besl and McKay, 1992) to the DSM generated by the UAV images because the registration error of the TLS data is larger than of the UAV images. 3D fitting of the retro-reflective cylinder targets is more error prone than sub-pixel accurate image coordinate measurement of the GCPs. Also, GCPs could only be located in front of the scanner positions because the surrounding area was under active land use. This results in an instable referencing geometry. Second, TLS exhibits errors due to the unfavourable low viewing angle onto the field plot. The resulting large spot sizes cause noisy data, e.g. due to edge effects or blending of different distance values. Finally, to asses UAV data accuracy with TLS, it has to be considered that the points measured by SfM and TLS are not identical. For a comparison, they have to be interpolated to identical locations, introducing an additional interpolation error. Thus, the results obtained from a comparison with TLS data must be considered too pessimistic.

Nevertheless, TLS data is consulted as reference due to lack of alternatives (Eltner et al., 2013). Furthermore, due to the reliability of TLS data, systematic errors can be calibrated and random errors partly compensated by smoothing algorithms. TLS and UAV data

comparison is conducted with the open-source solution CloudCompare. The differences are estimated between the meshed models from the UAV images and the TLS point cloud (Table 4-3). The standard deviation of difference amounts between 4 and 8 mm. However, due to the limited adequacy of TLS as a reference, these accuracies are assumed to be on the pessimistic side. All DSMs from the UAV images are within the TLS accuracy of 1 cm, resulting from general system performance.

	2 October 2012	22 April 2013	13 June 2013	24 July 2013
std-dev _{TLS-UAV} (cm)	0.5	0.4	0.4	0.8

Interestingly, differences in accuracy between the compact camera (first field campaign) and compact system camera (remaining field campaigns) are not recognisable. It seems that instabilities of sensitive camera parts are either not as severely existent or compensated by the active-stabilising camera mount. Because one camera model is estimated by self-calibration for all images used for DSM generation, camera instabilities would be manifested in lower overall accuracy.

The estimated standard deviations are implemented in error propagation theory to calculate the accuracy of multi-temporal change detection (Brasington et al., 2003; Lane et al., 2003; Wheaton et al., 2010). The propagated error for the digital elevation model of difference (DoD) is estimated as well as the level of detection (LoD), representing the surface change for a given confidence interval defined by a probabilistic threshold. In this study, a combination of the DSM accuracy estimates from every field campaign is used. The differing standard deviations are mainly due to changing surface properties, alternating the influence on errors primarily within the TLS data that are difficult to estimate. Thus, averaging of the standard deviations of all investigation intervals is done. The final average error amounts to 5 mm, which is assigned to every DSM, resulting in a propagated error for the DoDs of 7 mm and a corresponding LoD for the 90 % confidence interval of 1 cm.

4.3.2. Multi-temporal change detection

Several parameters are considered for multi-temporal change detection, but a facile and fast; first qualitative analysis can be performed by visualising DoD maps for consecutive field campaigns (Figure 4-10).



Figure 4-10: Soil surface changes during the entire study period. LoD is 1 cm for 90% confidence interval. Circular gaps during the last two investigation periods represent vegetation and linear gap during the first two investigation periods represent a foot path to reach GCP positions.

Herein, different magnitudes of soil surface changes are obvious during the entire investigation period. During the first interval from 02 October 2012 till 22 April 2013 almost the complete field plot is affected. The soil surface is decreasing over large areas. The second, shorter investigation interval, lasting from 22 April 2013 till 13 June 2013, is characterised by laminar surface decline as well as linear concentrated surface decrease in rills. Only the north-eastern part of the field plot, which contains higher stone fragment contents, is nearly not changing. During the last study period (13 June-24 July 2013) solely the western part can be considered for change detection due to disturbing extensive vegetation cover on the eastern half of the field plot. The complex structure of vegetation causes strongly differing appearances from varying viewing angles, which interferes with image matching. Linear surface decreases of large magnitudes are dominant during the last study period. Though, rills are shifted laterally in eastern direction (Figure 4-11). Within the developed rill network, localised accumulation spots appear in rills or at the end of shorter rills. At the field plot bottom, also larger alluvial fans are present. However, during the entire investigation period of ten months elevated surface areas are negligible compared to surface subsidence.

Soil surface roughness, rill parameters and volumetric examinations are further parameters for multi-temporal change detection that are presented in the following (Figures 4-12 – 4-14).



Figure 4-11: Extract of DSMs from June and July 2013 to illustrate eastward rill shift. Arrows highlight exemplary rills. DSM has been filtered with methods from Fourier analysis to enhance rills.

4.3.2.1. Soil surface roughness

To quantify surface roughness, height range, RMSH, locRMSH and tortuosity are determined and compared over time. As expected, absolute values for locRMSH are considerably lower than global RMSH (Table 4-4) due to the contradictory influence of global surface characteristics. Height range values, which are additionally sensitive to outliers, are even higher. The applied kernel sizes, ranging from 7 to 99 cm², of the locRMSH show same tendencies of roughness change, which differs to findings from Haubrock et al. (2009), where different scales revealed different surface properties and processes. However, only locRMSH for the kernel size of 31 cm² is considered further because it captures rill as well as interrill surface properties in this study due to the particular average rill density.

	Height range	RMSH		Tortugaity		
	(m)	(mm)	Combined	Cross slope	Down slope	Tortuosity
02 October 2012	0.303	40	11.6	11.2	4.9	1.11
22 April 2013	0.251	38	8.2	7.8	3.5	1.05
13 June 2013	0.407	40	9.8	9.5	3.1	1.06
24 July 2013	0.663	37	16.9	16.3	4.6	1.12

Table 4-4: Different parameters representing surface roughness.

A comparison of the changes of all parameters reveals a roughness decrease during the first study period (02 October 2012-22 April 2013) and a subsequent increase, especially during the last field campaign in July 2013. Only the RMSH is decreasing because of the smaller study area (only western part of the field plot) compared to the previous field campaigns. Hence, unfavourable dependency of the global shape affects the roughness value because the field plot has a concave shape that cannot be removed by detrending. Tortuosity and locRMSH exhibit similar results because both parameters are less sensitive to global effects and more reliable for local roughness estimation. The locRMSH in down slope direction illustrates a continuing smoothing of the soil surface during the second study period (22 April-13 June 2013), which is in contrast to the other roughness parameters. Because rills are oriented down slope, the value reveals interrill changes more accurately. Height variations perpendicular to the rills are ignored and thus the influence of rills, which imply significant shifts in height. During the last study period (13 June-24 July 2013) down slope roughness.

At the beginning of the investigation, the soil surface is rough due to recent ploughing and harrowing, while surface roughness is high at the end of the investigation time due to the presence of deep rills. The exemplary profile in Figure 4-12 illustrates the initial surface smoothing till April 2013 and subsequent continuing roughness increase till July 2013.



Figure 4-12: Profiles of every field campaign to illustrate surface roughness changes. For information about the location of the profiles, view Figure 4-5.

4.3.2.2. Rill development

Rill investigations are performed for the final study period (13 June-24 July 2013) because during the last two field campaigns rill incision and deepening can be observed. Rill distribution within the field plot exhibits a high density. Perpendicular to the slope dip direction rills occur every 20 to 40 cm, representing the average distance of harrow discs. In Table 4-5 erosion and accumulation per rill as well as rill width and depth are averaged for the main rills with a length of at least 15 m. These rills capture almost the entire field plot length. Furthermore, only the western field plot is analysed to guarantee identical area coverage for consistent comparability. Mean rill width amounts to 17 cm in June and increases to 23 cm in July, while rill depth increases from 2 to 4 cm. Rills are more deepened than widened because rill depth increases by 100 %, whereas width increases only by 35 %. Rill deepening appears to be the dominant process. Average rill erosion volume amounts to 0.03 m³ (2.2 tha⁻¹) in June and increases significantly in July up to 0.07 m³ (5.9 tha⁻¹). Accumulation occurs in rills as well. In July, material deposition amounts to about 0.02 tha⁻¹.

	Erosion per rill (m ³)		Accumulation per rill (m ³)		Rill width (m)		Rill depth (m)	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
13 June 2013	0.03	0.02	6E-06	7E-06	0.17	0.03	0.02	0.01
24 July 2013	0.07	0.06	3E-04	4E-04	0.23	0.03	0.04	0.02

Table 4-5: Averaged erosion and accumulation per rill as well as rill width and depth for rills longer than 15 m.

Comparing the rill wall represented by the upper edge with the edge extracted by the Canny operator, a general underestimation of rill parameter values calculated with Canny edges is obvious. Average rill depth is about 1 cm smaller during the field campaign in June and 2 cm in July. Rill width is underestimated by 4 cm during both campaigns. However, the upper edge is yet an approximation of the actual position of the rill wall. Rill extraction becomes more accurate, the more distinct the edge is formed. Therefore, the results during the field campaign in July are more precise because rills are steeper and more pronounced. Furthermore, in June predominantly shallow rills are embedded in local depressions, inducing an overestimation of rill depth and width because the crest of the depression might be extracted instead of the upper end of the rill wall. DTM resolution influences rill extraction as well because too coarse grid resolution causes too smooth edge representation.

Correlations between different rill parameters are calculated and illustrated in Figure 4-13 for further investigation of rill development. All rills are considered. It is obvious that with increasing rill length erosion volume is increasing as well as rill width, depth and cross section area due to increasing catchment size and thus flow concentration. Growing transport capacity of runoff and hence more energy for rill incision results in distinct rill forming with an increasing rill width and depth which is reflected in a positive correlation with rill length. Accumulation volume also increases with growing rill length during the July campaign when the rills are deepening. Another positive correlation is detectable between rill depth and erosion, whereas correlation between rill width and erosion is negligible. Hence, the growth of rill depth is the primary factor for the loss of soil material, which is especially obvious during the last field campaign. Compared to the campaign in June, correlation between rill depth and erosion increases in July. Furthermore, the importance of rill depth adverse to width is indicated by higher positive correlation between cross section area and depth in June, which increases further in July.



Figure 4-13: Correlation between different rill parameters and their changes from June to July 2013. Number within each plot represents correlation coefficient.

Comparing soil surface roughness from the DTM previous to the rill development events reveals an influence of local height changes on rill erosion. Correlation is not as obvious during the field campaign in June, but becomes distinguishable in July. Considering Figure 4-5 (DSMs), the importance of roughness becomes even more apparent. Distinct rills are forming and deepening close to local above-average crests and/or within above-average depressions. This observation also confirms in a higher correlation of height range adverse to RMSH, which implies the significance of maximal height differences.

4.3.2.3. Volumetric changes

A quantitative measure to estimate surface changes are volumetric calculations. In this study, average surface changes and corresponding volume changes are estimated for the entire field plot and differentiated between rill and interrill areas. The cumulative rill-interrill area is smaller than the total field plot because the rill-interrill area is clipped to the beginning and end of rills. Hence, the "belt of no rill erosion" at the top and the alluvial fans at the bottom of the plot are neglected. The rill-interrill area ratio amounts to 1 and 1.3 for the measurements in June and July 2013 respectively.

To calculate volumetric changes, an average bulk density of 1.5 g cm⁻³ is assumed, which is typical for silty soils. To account for uncertainties in volume estimations due to DTM accuracy, quantities are measured for LoD of 1 cm, corresponding to 90 % confidence interval, and for LoD of 1.2 mm and 0.8 mm, corresponding to 95 % and 85 % confidence interval, respectively.

During the first study period, lasting from October till April, surface changes amount to 4.7 mm (Figure 4-14), corresponding to a volume of 70 tha⁻¹. However, volumetric measures should be considered carefully because changes might not relate to loss of material alone, but consolidation, crusting and local allocation processes as well – especially when observing a freshly ploughed surface. During the second study period, lasting from April till June, the surface subsided by 3 mm and 45 tha⁻¹ are lost. Erosion dominantly occurs in rills, but happens in interrill areas as well. Furthermore, accumulation increases. Figure 4-10 shows that areas of material deposition are primarily close to vegetation spots, which disturb and retain runoff. During the last study period (June till July) the highest erosion values are measured, amounting to 8.1 mm average surface decrease and about 121 tha-1 soil loss. The importance of rill erosion is growing compared to the former events because rill erosion increases by 60 % from June till July, while interrill erosion remains

constant. Accumulation values are also highest during the last study period (2.1 tha-1). The material is deposited at the bottom of the field plot, forming alluvial fans because adjacent vegetation at the bottom due to cultivation acts as a local dam for runoff. Within rills accumulation is growing as well.



□ 2.10.12 - 22.4.13 □ 22.4.13 - 13.6.13 □ 13.6.13 - 24.7.13

Figure 4-14: Positive (lower graph) and negative (upper graph) soil surface changes and corresponding volumes on the entire field plot and in rill and interrill areas. LoD is 1 cm (90% confidence interval).

Minimal changes in LoD have a significant influence on laminar changes. DTM accuracy is more relevant for the estimation of sheet erosion and levelling processes than rill erosion. During the first and second study period surface changes prevail in laminar form on the entire plot and hence errors are higher (24-26 %) than during the last event (10 %) when the rills are deepening. Accuracies of changes in the interrill area illustrate the importance of LoD even more. Also, accumulation exhibit higher uncertainties compared to erosion because material deposition predominantly occurs in lateral direction and at lower magnitudes. To estimate long-term soil surface changes, tracer measurement with the radio nuclide Cs-137 are performed. Within 50 years the surface has been eroded about 32 cm. Hence, short-term erosion events on un-vegetated surfaces, amounting to 3 mm and more, are supported by a mean annual erosion rate of 6 mm calculated from tracer measurement.

4.4. Discussion

4.4.1. Surface consolidation and crusting

During the first study period, lasting seven months (02 October 2012-22 April 2013), different processes influence the changes of the soil surface. At the beginning of the investigation the loosened and uncrusted soil inherits a low bulk density due to recent tillage (Hieke and Schmidt, 2013). Structural soil stability is low and soil erodibility is high, especially in the case of ploughed surfaces (Knapen et al., 2007). Hence, consolidation due to gravitation, causing collapse of particles because of their own weight and raindrop impact, is expected to be the main process shortly after tillage. Furthermore, degrading soil structure processes due to wetting and drying as well as freezing and thawing are expected. Decrease of soil surface heights and roughness is the consequence. Surface lowering and surface smoothing rapidly after tillage are observed by van Wesemael et al. (1996) and Knapen et al. (2007) as well.

Besides consolidation, surface crusting mainly constitutes to surface changes. Thus, the measured roughness decrease is also due to the filling of local depressions. The low intensity rain events during the winter season cause surface sealing because of the unstable soil aggregates. The sealed surface leads to higher runoff and hence erosion (Le Bissonnais, 2005). Possible loss of soil material during the first study period only happens due to sheet erosion because linear erosion forms are not detected. Other studies on sheet erosion in loess on bare surfaces measure distinct lower volumes (e.g. Le Bissonais et al., 1998). Therefore, it is assumed that sheet erosion is not the dominant process for the decrease of surface height in this study. Unfortunately, the data does not allow for a distinction between sheet erosion and surface lowering due to consolidation.

4.4.2. Sheet erosion and rill incision

During the second study period (22 April-13 June 2013) it is presumed that subsidence due to consolidation is not significantly existent anymore because the process only happens

rapidly after tillage (van Wesemael et al., 1996; Knapen et al., 2007). Other processes are responsible for surface changes. Soil properties are different, which is indicated by low roughness at the beginning of the second study period. Measured erosion volumes at rill and interrill areas emphasise that sheet erosion and the beginning of rill incision are dominant processes. The long lasting rainy season at the end of May and the beginning of June leads to high soil moisture content and possibly favours erosion due to changed soil surface conditions (Kuhn and Bryan, 2004; Faust, 2003). Of course, the immediate impact of precipitation is relevant as well. But especially rill incision seems to be induced by higher soil moisture content (Wirtz et al., 2012, Mancilla et al., 2005).

Although, most roughness values increase due to rill formation (Table 4-4), down slope roughness further decreases, which indicates continuing overall roughness decrease until rills are incised. Further soil degradation due to prolonged crust development might be a reason. The decreased roughness also increases chances for rill incision, which is observed by Mancilla et al., 2005.

Considering surface roughness and rill development, a positive correlation is detected between soil surface roughness during the field campaign prior to rill incision and the rill erosion in June and July. This circumstance is also visible when the DTMs are compared. Notably deep rills are forming close to higher harrow crests. These steeper and longer local slopes might increase runoff and flow velocity, which increases erosivity.

In the north-eastern part of the field plot almost no erosion is apparent compared to the remaining area (Figure 4-10). The reason is the higher stone fragment content in that region, which saves the surface from erosion due to the protection of the underlying soil and due to increase of macro-pores, leading to higher infiltration capacities (Poesen et al., 1994; van Wesemael et al., 1996). Almost no rills are present due to the dissipated and decreased concentrated runoff. Furthermore, rills are interrupted due to isolated vegetation cover, acting as obstacles that disrupt flow paths, eventually resulting in small accumulation spots.

Generally, rills develop along tillage tracks because they predefine the flow direction of runoff. The average rill distance reflects the gap between the harrow discs. Takken et al. (2001) already evaluated the importance of tillage for runoff pattern.

4.4.3. Rill erosion

Surface changes are highest during the last observation interval (13 June-24 July 2013) when only two thunderstorms with high precipitation intensities occurred on surfaces with low soil moisture content. Rill erosion is the dominant process, whereas sheet erosion is almost negligible. Studies from Smolska (2002) and Reijman and Brodowski (2005) observe higher importance of rill erosion for soils with high silt content in temperate climates as well. Also, Govers and Poesen (1988), Vandaele and Poesen (1995) and Cerdan et al. (2002) make that observation and additionally detect temporal variability of the rill-interrill erosion ratio. The importance of rill erosion is also reflected in the fact that only existing rills deepen while no new rills form, which is observed by Mancilla et al. (2005) as well.

Area based surface change detection reveals local accumulations in rills and complete expiring of rills in local alluvial fans within the rill network. The ending of rills in isolated depositions is most obvious in areas with the following characteristics. Rill density is low, rills are less deep and distinct, and the neighbouring surface preliminary to the rill incision is less rough. A possible explanation for the small alluvial fans is less concentrated runoff due to missing obstacles for concentration and thus shallower overland flow with consequent less flow shear stress, leading to lower erosion energy (Gómez and Nearing, 2005). In addition, minor rill depths can cause faster penetration of existing flow path, followed by runoff dissipation and flow velocity decrease. Higher infiltration capacities might be a further reason for the accumulation of alluvial fans (Bryan and Poesen 1989; Govers, 1987).

Accumulation in rills occurs only on the western side of the rill interior. A different cause might be given. During the first thunderstorm rills deepen and subsequently rill side walls collapse due to over-deepening, which is observed by Govers (1987). Wirtz et al. (2012) also notice the importance of bank failure for erosion rates. During the second thunderstorm the loose material is transported out of the system. Because the field plot is oriented in a north-south direction, yet another factor is relevant. The study area is located in the zone of prevailing westerlies, which implies that raindrops pre-dominantly hit the eastern rill side during precipitation. Hence, soil material is eroded primarily on the east side, which causes the observable accumulation pattern. This phenomenon also causes a principle detectable lateral shift of the erosion rills, i.e. rills widen in eastern direction only (Figure 4-11). However, rain from specific directions as the only possible source for an orientation dependent erosion process is not assumed. It is generally expected that when

rills are forming the influence of rain diminishes and the influence of rill hydraulics dominate due to increased flow depth (e.g. Govers et al., 2007; Beuselinck et al., 2002; Govers and Poesen, 1988). Eastward shift of concentrated runoff due to wind could be another, maybe complementing, explanation.

However, due to insufficient temporal resolution, rill erosion and accumulation processes are difficult to interpret because two precipitation events have been captured. But even if every thunderstorm could have been investigated separately, changing rain intensities during one rainfall do already influence erosion pattern.

4.4.4. Method uncertainties

Although, many studies exist that quantify rill and interrill erosion, comparison of absolute erosion values is not possible because different studies used different measurement methods as well as different plot sizes. Wirtz et al. (2012) already discussed the difficulty of comparing different rill erosion investigations. In this study, the field plot is relatively wide compared to usual plot sizes to increase the chance of capturing rills with the area based surface measurement. Previous studies prefer higher length-width ratios to be able to investigate larger slope lengths with higher runoff concentrations and because usual field methods – e.g. gutters – prevent wide plot sizes. Hence, it is possible that in this study the relationship between sheet erosion and rill erosion is overestimated compared to other studies because the upper hill part, which is more prone to sheet erosion due to splash and shallow overland flow, receives a higher weight in contrast to narrower plots, where the influence of runoff concentration increases with slope length. However, previous studies measure soil erosion at the field scale either at the outlet or with coarse resolution, i.e. punctual at selected rill cross sections. Only net losses are quantified. Hence, knowledge about local transport processes remains undisclosed. Applying UAV data enables new insights.

In this study, only bare soil surface in the highly erodible loess substrate is investigated, resulting in high erosion values. But even minor vegetation cover can hinder rill incision significantly. In other studies, rills are no more detected for vegetation covers larger 20% (Cerdan et al., 2002) and 40% accordingly (Govers, 1991). Thus, the possibility to compare our results with general erosion values for larger areas is limited. Cerdan et al. (2010) estimated erosion values of 2-10 tha⁻¹a⁻¹ in the West and Central European loess belt under different land use, but erosion estimations in most studies are considerably smaller. Even if

the results for bare soils only are considered (e.g. 80 tha⁻¹a⁻¹, Auerswald et al., 2009), a large difference to the measured values in this study, which amounts 166 tha⁻¹ in three months (22.04.-24.07.2013), remains. However, captured erosion values are solely representative for this investigated field plot due to its especially exposed and vulnerable position to erosion processes within a fragile landscape.

4.5. Conclusion

The application of UAV images to generate digital surface models with high resolution is an advantageous technique to quantify and qualify soil surface changes at field scales and possibly larger areas without disturbing the investigated plot. The DSMs have an accuracy of less than one centimetre. The accuracy of the reference net for multi-temporal observations amounts to one millimetre.

The obtained data enables new insights into rill and interrill erosion processes. Surface changes due to consolidation, crusting, sheet erosion and rill incision are observed and partly differentiated. A freshly tilled soil is abandoned to intense consolidation processes and sheet erosion due to low intensity precipitation events and snow cover as well as snow melt, leading to extensive surface subsidence. Changes of estimated soil roughness are attributed to crusting and subsequent rill formation. Also, detailed DSM examination indicates local rill ceasing in alluvial fans as well as accumulation in rills. Moreover, orientation dependent rill shifting is discovered, which is explained by dominant wind directions.

A method is developed that automatically extracts erosion rills with high accuracy and resolution. Hence, large areas and/or many rills can be examined fast and with low labour intensity. The method permits precise estimation of different rill parameters – i.e. rill depth, width and cross section area as well as per rill erosion and accumulation volumes. Calculated rill information reveals a strong correlation between rill depth and cross section area, which is confirmed by the fact that rill growth happens particularly due to rill deepening, which again is affirmed by a positive dependence between rill depth and erosion. Local surface crests and depressions are a further influence on the intensity of rill development, which is obvious when the roughness of the surface prior rill incision and the subsequent formed rills are compared.

In this study, soil surface changes are very high because a bare soil is considered, which is formed in loess, and because tillage practices are encountered, which support runoff. Rill erosion is the dominant process compared to interrill erosion. Extrinsic factors (amongst others precipitation amount and precipitation intensity as well as snow cover and snow melt) and intrinsic factors (amongst others soil aggregate stability, soil crusts, soil bulk density or soil moisture) influence surface changes, but cannot be distinguished. Hence, for further investigation of soil surface changes with high spatial and temporal resolution additional parameters relevant for soil erosion need to be measured.

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5. Synthesis

5.1. Synergetic fusion of TLS and UAV data

5.1.1. Error assessment

The evaluation and implementation of both HiRT methods results in explicit perception of achievable accuracies and resolutions depending on the observation distance and on the configuration of data acquisition. To assess the performance of TLS and UAV photogrammetry, TLS data is treated as model for comparison because of its error reliability as an established method. However, superior accuracy of the TLS data is not assumed. Different error values are specified decreasing with each chapter:

- Analysing TLS performance in chapter 2 (Eltner & Baumgart, 2015) reveals an error of 1 cm corresponding to the manufacturer's statement. This declaration is justifiable due to the confirmation by average point deviations between point clouds from different scan positions (average 12.3 mm according to Table 2-3, which closely corresponds to the propagated error of $\sqrt{1+1}$ cm for two models) and due to the evaluation of influences resulting from the setup conditions of the scanning device and corresponding point cloud characteristics (chapter 2.4.2.2).
- For the comparison of TLS to DEMs generated from UAV images a TLS error of 7.5 mm is assumed (chapter 3; Eltner & Schneider, 2015), which corresponds to redundant measurements of a plane made with the same device in an investigation by Mulsow et al. (2004). In chapter 3 the data acquisition configuration exhibits scan position density, which is significantly higher than within chapter 2. The RMSE of the TLS-UAV comparison for corrected surface models (Fig. 3-7) ranges between 8.1 mm to 9.8 mm.
- Deviations in chapter 3 are still significantly higher compared to the results of the hillslope study in Saxony (average error 5 mm) in chapter 4 (Eltner et al., 2015b), which is assumed to be due to higher roughness of the surface investigated in chapter 3 because the soil has solely been ploughed and not harrowed as in Saxony. Furthermore, a significant amount of vegetation resides at the study site in chapter 3. To contrast the UAV photogrammetry and TLS models in chapter 4, the TLS is not treated as the model for comparison but rather as a complementary device because both methods feature different error sources impeding the assignment of a superior method. Nevertheless, the averaged deviation between both methods can

be considered as suitable error estimation due to the usage of independent data acquisition schemes and data processing.

The implementation of TLS for soil erosion measurement at field scale highlights the relevance to consider scan geometry at almost horizontal surfaces. However, roughness is the other important influence to keep in mind (Brasington et al., 2012, Lague et al., 2013). The impact of roughness at the accuracy of soil surface change detection with TLS is inevitable because soil surfaces naturally exhibit complex topographies. This is confirmed by highest point deviations between UAV photogrammetry data and TLS data where the surface is especially rough (Fig. 5-1).



Figure 5-1: Relevance of soil surface roughness for data accuracy (field plot Andalusia – chapter 3; Eltner & Schneider, 2015). a) Surface clip with differing roughness; the rougher the soil the brighter the surface. The meshed surface corresponds to the UAV data. b) Point deviation (scale in m) between UAV photogrammetry and TLS point clouds. The displayed point cloud corresponds to the TLS data, which is colorized according to deviations to the UAV data.

Regarding roughness estimation, Milenković et al. (2015) illustrate that scanning device setup from more than one position, resulting in overlapping point clouds, reduces errors due to footprint effects significantly. Also in this thesis, each time data acquisition scheme was designed to achieve high scanning overlap, especially to assure high data density for smoothing and thus utilising information redundancy. However, unfavourable scan geometry can only be accounted for and hence improved at close distance to the scanner, which is also indicated by Milenković et al. (2015).

Different point characteristics across the field due the positional relation to the scanning device implies to prospectively consider spatially variable error estimates, e.g. after Wheaton et al. (2010), instead of global LoD values. For instance, close to the scanning device accuracy is assumed to be higher than in the middle of the investigated plot where

point density decreases and footprint increases significantly. However, e.g. Tarolli et al. (2012) and Prosdocimi et al. (2015) could also demonstrate the opposite; with decreasing resolution, which would correspond to decreasing point density, the error can decrease due to surface smoothing, which subsequently applies to the error as well. Thus, lower noise corresponds to stronger approximation of the surface within large footprints and larger point distances. However, if surface changes of small magnitudes are of interest, this resolution decrease is not preferable. Further investigations regarding spatially error behaviour are advisable if TLS is the chosen method for soil erosion measurement at field scale.

Systematic errors of the TLS data, which have been revealed by reference data (building floor surveyed by a total station) as well as by comparison between different scan positions (chapter 2.4.2), are also obvious when the TLS point clouds are compared to the UAV data, although the magnitude of point deviations due to random errors is significantly higher than the systematic error. The local peak of point deviations at a distance of about 7 m, specific for the TLS device used in this thesis, becomes more clearly distinguishable with the UAV photogrammetry DEMs than with the TLS data from different scan positions alone, which is due to less data noise and uniformly distributed point clouds within the UAV data (Fig. 5-2).



Figure 5-2: Correction of systematic errors evolving from the TLS data. Thereby, TLS points of the eastern scan position (field plot Andalusia – chapter 3; Eltner & Schneider, 2015) are compared to the respective meshed UAV photogrammetry DEM. Blue line corresponds to moving average of the point deviation. a) deviation before the correction and b) deviation after the correction.

In general, for the application of soil erosion assessment UAV photogrammetry outperforms TLS with the Riegl LMS-Z420i. DEMs calculated from overlapping UAV images allow for higher LoD than TLS DEMs due to better data resolution (which is especially relevant for surface roughness display due to its significance for soil erosion) resulting from low flying heights and due to more advantageous error propagation due to favourable line of sight. Thus, better error performance is rather due to the perspective at the area of interest and data acquisition configuration scheme than the method itself. For instance, if a scanner could be utilised on the UAV, comparison of accuracy performance between scanning and SfM can resolve in a completely different picture, which has already been shown for the opposite case in other studies where TLS and SfM photogrammetry utilised from similar terrestrial perspectives has been compared for close range applications, e.g. Smith & Vericat (2015), Prosdocimi et al. (2015) and Piermattei et al. (2015).

UAV photogrammetry itself is sufficient for scale independent soil surface measurement, e.g. high detail of rill and interrill areas. This is not the case for TLS that is suitable to survey rills and other higher magnitude changes but is at the performance limit regarding small forms, e.g. wash zones. Furthermore, rills are detectable with TLS but its precise description is yet inherited due to shadow effects that are not given for the UAV perspective (Fig. 5-3).



Figure 5-3: Illustration of the different rill representation depending on the data acquisition method (Saxony 24.07.2013, chapter 4; Eltner et al., 2015). a) Profile position, b) DEM from TLS, c) DEM from UAV photogrammetry. Rills within the TLS data are wider and shallower due to shadow effects, whereas UAV perspective allows for suitable line of sight to measure rills.

Also, after ICP registration point deviations between the designed reference data (building floor/calibration plot without obstacles) and the modelled DEMs are higher for the post-processed (i.e. smoothed) TLS data (1.5 mm) than for the UAV photogrammetry data (e.g. for the SLR amounting 1.3 mm with PhotoScan and 1.4 mm with Pix4D). Thereby, only a almost planar surface is considered and thus a relative increase of the DEM error of the TLS data compared to the UAV photogrammetry data assumed due to the discussed issues regarding increasing incidence angles. Therefore, concerning data resolution and accuracy, UAV photogrammetry has to be chosen over TLS in soil erosion studies at

hillslopes. Nevertheless, TLS is needed as an independent quality control, e.g. regarding the dome error, to increase data reliability.

5.1.2. Data registration

Complementary utilisation of UAV and TLS data due to synergetic information fusion is another option besides deciding for either one of the HiRT methods according to their performance. If data fusion is considered appropriate, precise co-registration between both datasets is a prerequisite. Thereby, five different approaches are possible:

- Signalised GCPs: An obvious solution can be signalised GCPs, which are distributed across the area of interest. They are used by both HiRT methods to register the data within the same coordinate system. However, GCP setup can be especially difficult in fragile remote areas.
- Manual target extraction in TLS point clouds: Although, SfM photogrammetry solely needs a small number of GCPs, compared to traditional photogrammetry, still a balanced point distribution is necessary (e.g. Smith et al., 2015). For that matter, TLS can serve as an appropriate supplement due to additional manual target extraction within the already scaled TLS point cloud that has been acquired from a safe distance. The usage of such targets (virtual GCPs) has been proven to be successful within another study involving gully observation from opposing lines of sight (more detail in Stöcker et al., 2015).
- Utilisation of 3D shapes: Another approach is the exploitation of similar surface topographies within the point clouds evolving from TLS and UAV photogrammetry, i.e. ICP algorithms (Besl & McKay, 1992).
- Feature extraction in (intensity) images: Furthermore, distinguishable features detected in the UAV images and corresponding features detected in TLS intensity images can be used to co-register both HiRT datasets (e.g. Liu & Stomas, 2012, Tong et al., 2015).
- Geometric feature extraction in images and point clouds: Finally, geometric features extracted in the UAV images and TLS point clouds (e.g. Meierhold et al., 2010) can be matched to convert UAV and TLS data into a joint system.

For the usage of complementary TLS and UAV data information to co-register the point clouds distinct and clearly identifiable surface points are necessary, which is a challenging constraint for complex soil surfaces that are captured from very different perspectives and with different sensors resulting in divergent soil surface appearances that applies especially to the TLS data source (Fig. 5-4). Issues regarding TLS accuracy as a consequence of unfavourable scan geometry are in particular relevant for rough surfaces rather than smooth objects (i.e. edge and occlusion effects). However, rough regions are usually the areas to search for prominent features.



Figure 5-4: Differing appearance of soil surface mainly due to different perspectives of the HiRT data sources (extract of the DEM 02.10.2012 of the Saxony study site). a) DEM from TLS, b) DEM from UAV photogrammetry, c) DEM from TLS overlaid on DEM from UAV photogrammetry, d) Difference between DEM from TLS and DEM from UAV photogrammetry (blue means TLS is lower). Especially, shadow and edge effects regarding the TLS data are relevant, i.e. leading to underestimation of ripple width and ripple frazzling (obvious in c).

Comparing UAV images to intensity images from TLS data of the device used in this thesis also implies disadvantages in the context of soil erosion applications due to solely low contrasts between the intensity information of the returned laser pulses. The natural soil surface is too homogeneous for sufficient intensity changes between varying object characteristics (Fig. 5-5).



Figure 5-5: Illustration of low intensity contrast on natural soil surfaces (field plot west, Andalusia – 11.09.2013, chapter 2; Eltner & Baumgart, 2015). a) Extract of an orthophoto. b) Corresponding extract of the intensity image generated from TLS point cloud (scan position 2).

5.1.3. Data fusion

If co-registration is performed successfully (in the case of soil erosion studies at gentle hillslopes this is mainly restricted to signalised GCPs), synergetic fusion of the HiRT datasets from different sources would be the next step. Thereby, the differing data acquisition geometries need to be considered as well as the surface topography, incorporating constraints according to the quality of the corresponding data. For instance, UAV image mismatching over surfaces of low texture or vegetated spots can be substituted by TLS data and TLS edge effects at rough surface regions and/or very high footprints can be compensated by UAV photogrammetry point clouds.

A conceptual workflow for synergetic data fusion is introduced (Fig. 5-6). First, mutual quality control is performed. On the one hand, a possible dome in the UAV photogrammetry DEM or DEM blunders due to false image matching are detected with the TLS data. On the other hand, certain systematic errors within the TLS point clouds are disclosed by the UAV data. Afterwards, the TLS data is utilised for vegetation filtering because of more reliable point classification due to specific point cloud appearance of plants. Filtering with UAV data is usually more problematic (chapter 4.2.3). Thus, points in the point cloud calculated by UAV photogrammetry are deleted if a defined distance to identified vegetation within the TLS point cloud is undercut, e.g. by exploiting kd-tree algorithms. In a next step, the DEM from the UAV data is used to estimate the surface topography to define threshold criteria, i.e. incidence angle and footprint according to each scan position, to filter the TLS point cloud corresponding to its point quality. Furthermore, roughness is calculated with the same DEM. The roughness constraint for the TLS data can be expanded considering isotropy (e.g. Snapir et al., 2014), which for instance is relevant for harrow and plough directions or rills oriented in similar directions down-slope. Finally, the filtered and corrected point clouds are merged into one dataset, possibly assigning different weights for post-processing.

HiRT data fusion for soil erosion studies at field scale is less relevant if one of the data sources is TLS with almost horizontal scan geometry and corresponding errors. However, this can change significantly for other applications with a more suitable perspective of the scanning device. Then, potential data gaps within the UAV data, e.g. due to overhangs, could be closed by additional TLS data. A further consideration of point quality regarding the acquisition scheme can be a subsequent measure to automatically generate a reliable and precise surface model.



Figure 5-6: Flowchart illustrating conceptual workflow for synergetic data fusion of UAV and TLS data to measure soil erosion with high precision.

Furthermore, although TLS is less suitable for soil erosion assessment at gentle hillslopes, it is not replaceable due to its constant error behaviour, which is in contrast to the errors evolving from UAV photogrammetry with its more complex calculation scheme. Besides, exploiting a TLS device working with the phase shift principle might already result in a better accuracy performance. Nevertheless, TLS receives only a small weight within the data fusion, but holds a high weight as an independent accuracy measure.

5.2. Sediment connectivity at hillslope scale

In Europe 25% of the territory is affected by soil erosion due to water (EEA, 2015). Thereby, erosion at arable land is especially high averaging 3.6 tha⁻¹a⁻¹ (and on bare surface 15 tha⁻¹a⁻¹) after Cerdan et al. (2010), who extrapolate rill and interrill erosion from field plot measurements considering land use, soil and topography but not rainfall (Fig. 5-7). They also reveal that erosion rates in the Mediterranean are higher at bare plots (with 32 tha⁻¹a⁻¹) compared to the rest of Europe (with 17 tha⁻¹a⁻¹) and are lower when the surface is under crop. However, Cerdan et al. (2006) further state the disadvantage of their method to being unable to display the high spatial variability of soil erosion. Thus, these erosion rates should be seen as values to estimate the relative dimension of soil erosion rather than providing absolute information, i.e. providing a qualitative and not quantitative assessment.

HiRT can be a suitable method to better assess the spatial diversity of soil erosion. Moreover, the utilisation of HiRT reveals sediment connectivity at agricultural used fields by assessing new perspectives. As a consequence novel observations at unprecedented scales are enabled. In two varying environments – a case study in the Mediterranean (Andalusia, chapter 2; Eltner & Baumgart, 2015) and a case study in the European loess belt (Saxony, chapter 4; Eltner et al., 2015) – soil particle relocation occurs in spatial and temporal interrupted manner.



Figure 5-7: Soil erosion map extrapolated from field plot measurements after Cerdan et al. (2010). Blue squares illustrate the position of the field plots in Andalusia and Saxony.

In both case studies, local barriers, i.e. across slope ridges and vegetation spots, cause disconnected erosion pattern (Fig. 2-10 and Fig. 4-14) due to deceleration of runoff (e.g. Cammeraat, 2004). Then again, connected sediment transport becomes obvious as well due to rill formation along the steepest slope and within pre-defined flow path from preceding soil working (e.g. Ludwig et al., 1995, Kirkby, 2001, Cerdan et al., 2002). However, at both study sites very different initial conditions are given that determine the process of soil erosion causing the large variation of measured rates (Table 5-1).

TLS allows for the assessment of sediment connectivity at field scale, whereas UAV photogrammetry enables corresponding observations at similar area coverage but with even higher resolutions, e.g. alluvial fans within the field plot due to expiring rills, which is solely rudimentary recognisable applying the LiDAR device. Nevertheless, both methods inherit the disadvantage of a LoD, which is still too low for resilient accumulation (and interrill) measurement due to rather laminar and dissipative occurring compared to concentrated rill erosion, leading to the possibly improper assumption that gross erosion almost equals the sediment yield (i.e. net erosion).

	Mediterranean case	European loess belt case study					
Measurement method	ent method TLS			UAV photogrammetry			
LoD [cm]	1.5	1.0					
Surface cover	Bare		Bare				
Pre-measurement soil working	Harrowed and ro	Harrowed and rolled			Ploughed and harrowed		
Main grain size/in situ substrate	Sand/Miocene calc. sa	andstone	Silt/P	leistocene l	loess		
Slope [°]	8	5.5					
Precipitation [mma ⁻¹]	540	624					
Field plot size [m]	20 x 50		20 x 30 10 x 3				
Precip. sum per study period [mm]	468	112	275	234	75		
Highest daily precip. [mm]	61	31	25	40	50		
Precip. days per study period	42	10	64	21	4		
Study period duration [days]	178	49	202	52	41		
Study period season	Autum./wint./sprin.	Autum.	Winter	Spring	Summer		
Surface height change [mm]	-0.2	-0.7	4.7	3.0	8.1		
Soil erosion [t per field plot]	0.7*	0.2	3.0*	1.9	2.6		
Soil erosion [tha-1]	10.0*	2.6	70.5*	44.8	121.5		

Table 5-1: Comparison of varying study area characteristics that are significant for soil erosion and corresponding differing soil erosion rates.

* value comprises consolidation as well as erosion

The different site specifications inherit any quantitative comparison of soil erosion rates. Furthermore, both study sites are solely treated as single case studies and do not claim any transferability at larger spatio-temporal scales or to be representative for the entire respective landscape. For instance, Vanmaerck et al. (2012) highlight that measurements at field plots overestimate soil erosion rates, due to usual choosing of erosion prone sites, compared to predicted soil erosion by models, which also consider a variety of land use. The plot design in particular is significant. In both case studies plots are exceptional wide but in Saxony the width to length ratio is even higher in contrast to the Andalusian field. This is relevant because Parsons et al. (2006) reveal that erosion increases with plot length and starts to decrease after a specific threshold range (7 m in their study), possibly leading to overestimating soil erosion at the shorter plot in Saxony. Field preparation works are also influencing the magnitude of soil erosion (Takken et al., 2001), with higher susceptibility at the plot in the European loess belt than in at the Mediterranean plot due to across slope harrowing at the latter and down-slop harrowing trails at the former study site.

Besides the different study site characteristics, the intentionally prevention of plant cover further highlights the necessity to regard observed soil surface changes detached from a holistic investigation of soil erosion. However, Ries (2010) displays for abandoned land that even if vegetation is present, considerable erosion is possible, e.g. due to grazing activities, and that at least 60% of plant cover is needed to decrease soil erosion significantly. Terrestrial SfM and recent terrestrial LiDAR devices, which are able to capture

multiple returns (e.g. Pirotti et al., 2013), can be promising tools to view around and under shrubs to facilitate erosion assessment at these locations with sparse vegetation cover.

Overall, the process of soil erosion is too complex and influencing factors are too varying to be understandable with two field plots only. Nevertheless, individual observations and qualitative statements regarding the process of soil surface changes due to precipitation and runoff and its variability in space and time are feasible.

Consideration of different spatial scales with the same HiRT method is in particular important for connectivity (hydrological and sedimentological) aspects. Amongst others, runoff usually occurs more often at smaller scales, for instance due to increasing influence of vegetation at larger scales causing dis-connectivity (Cammeraat, 2004). However, in both case studies wheel tracks can increase connectivity significantly (Cerdan et al., 2002). In Andalusia the trails become obvious due to compaction after passing of the engine, whereas in Saxony tracks, obliterated due to harrowing, reappear due to especially distinct rill formation in the former depressions.

Considering an even broader scale, different factors are relevant for erosion at catchment scale than for rill and sheet erosion at hillslope scales (de Vente & Poesen, 2005, de Vente et al., 2013, Brazier et al., 2011), leading to higher soil erosion at hillslopes than sediment yield in catchments amongst other due to the missing capture of gully erosion (Vanmaerck et al., 2012). Thus, UAV photogrammetry can help to close the gap between sediment yield measurements at the channel and erosion measurements at the field plots because larger erosion forms relevant for sediment connectivity, such as gullies (Poesen et al., 2003), are also measureable during the same data acquisition campaign capturing the hillslope (e.g. Stöcker et al., 2015). In addition, frequent monitoring with this method enlarges the temporal scale, as well.

5.2.1. Soil erosion in the Mediterranean case study

Generally, the Mediterranean is vulnerable to soil erosion amongst others due to low organic matter content, slow soil formation and thin soil profiles (e.g. Poesen & Hooke, 1997, Conacher & Sala, 1998, García-Ruiz et al., 2013). However, of course soil erosion rates depend on each site specific. For instance, Vanmaerck et al. (2012) detect low erosion rates in the Mediterranean, assumed due to stony and shallow soils (e.g. Seeger & Ries, 2008), compared to temperate regions, which is also argued by Cerdan et al. (2006), whereas at marl landscapes Cerdan et al. (2010) reveal very high erosion rates.

The Mediterranean field plot exhibits rather low erosion values at bare surfaces compared to the study by Cerdan et al. (2010), which considers interrill and rill erosion. Furthermore, observation indicates sediment dis-connectivity (e.g. Cammeraat, 2002, Fryirs et al., 2007, 2013) rather than connectivity at the hillslope amongst others due to acrossslope tillage leading to small ridges. Another reason can be the high infiltration capacity of the soil due to high sand contents leading to the need of high intensity precipitations to cause Hortonian runoff. Due to good percolation characteristics also for saturation excess runoff high precipitation intensities would be needed even if the soil moisture is already high at the study site. Furthermore, torrential rainfall events in the Mediterranean are characterised by short durations (Poesen & Hooke, 1997). Thus, rainfalls might not have been strong or long enough to cause hydrological and subsequent potential sedimentological connectivity due to insufficient soil detachment and/or insufficient sediment transport across the entire slope. Too short duration of rainfall events in regard to erosion patchiness is highlighted by Kirkby (2006). High daily precipitation values have been measured during the study periods. However, these do not reflect actual precipitation intensity.

Solely within wheel tracks potential for sediment connectivity are increased due to surface compaction and thus decrease of infiltration capacity (Basher & Ross, 2001), leading to mainly detachment-limited erosion. Nevertheless, for the case study in the Mediterranean measured low erosion at bare soil is assumed due to high infiltration capacities on sandy surfaces and temporally too short intense precipitation events.

5.2.2. Soil erosion in the European loess belt case study

The field plot in Saxony allowed more precise across-scale soil erosion assessment because erosion forms caused by different processes are clearly recognisable. In particular, interrill erosion due to raindrop impact as well as shallow overland flow and rill erosion due to concentrated runoff are displayed by the DoDs, setting the winter season aside to account for potential interference with soil consolidation. Spatial variability of soil erosion becomes apparent amongst others due to differing stone content at the study site leading to lower erosion rates, where higher rock fragments led to a stone cover and thus a decrease of runoff and increase of surface protection (e.g. Poesen & Lavee, 1994, Martínez-Zavala & Jordán, 2008). Furthermore, the importance of scale boundaries (e.g. Cammeraat, 2002) is identifiable by UAV photogrammetry because at the field plot bottom accumulation is surveyed. However, larger area coverage is needed to investigate the soil erosion process and its interlink between hillslope and e.g. adjacent channels.

Besides spatial difference, temporal variability of soil erosion is observable in several cases due to changes in sediment connectivity. For instance, eroded material is locally accumulated in rills, which is further transported during a subsequent strong precipitation event that causes even stronger loss of soil material (Table 5-1, summer event), emphasizing the significance of sediment supply as depicted by Bracken et al. (2015).

A special triggering event is apparent during late spring season. Due to enduring precipitation at the transition from May to June 2013 soil moisture is very high (Baumgart et al., submitted, Fig. 5-8) causing fast saturation excess runoff. Besides, infiltration capacity of the substrate is generally not as high as at the Mediterranean field plot. Within 10 days rained a quarter of the total annual precipitation, leading to severe floods in South and East Germany as well as Austria and parts of the Czech Republic (Grams et al., 2014). This event illustrates the non-uniform sediment movement in time and space (e.g. Fryirs, 2013, Bracken et al., 2015), when an exceptional wet period led to high erosion rates even during low intensity precipitation. Runoff concentration occurs, eventually leading to erosion rills covering the entire study site.



highest soil moisture value exceeded (new maximum) second highest soil moisture value exceeded no maximum exceeded

Figure 5-8: Soil moisture maps illustrating the exceptional high wetness of the soil in the late spring of 2013. a) soil moisture before enduring precipitation event (Schröter et al., 2013), b) soil moisture during enduring precipitation event (Stein & Malitz, 2013). Red rectangle shows location of study site. Reference for extreme soil moisture value are soil moisture values of the corresponding day from 1962 till 2012, i.e. 26th May for a) and 31st May for b). Illustration after Baumgart et al. (submitted).

A combined consideration of the spring and summer study period illustrates the temporally variable soil erosion because the rill incision after the triggering event (high soil moisture and enduring precipitation) facilitates sediment connectivity because hydrological connectivity and potential sediment yield are established faster in pre-defined flow paths (i.e. rills) with corresponding catchments (e.g. Auzet et al., 1995, Bracken & Croke, 2007) during subsequent rainfall events. Generally, the significance of event frequency and magnitude (Bracken et al., 2015) are recognisable. Small but more frequent events with typically lower sediment yield (Cammeraat, 2004), which are nevertheless effective due to curst formation (Bresson et al., 2006), are in contrast to solely two thunderstorms with highest erosion rates.

The temporal varying sediment connectivity is further recognisable due to significant roughness decrease (observable at the entire plot) due to crusting and thus lowering of surface retention of runoff, thereby enabling runoff also for low precipitation events and dry soils (Bresson et al., 2006). Generally, roughness decreases with prolonging runoff, because of aggregate destruction (e.g. Barthes & Roose, 2002) and erosion, and thus simultaneously a novel surface is created (Favis-Mortlock et al., 2000). The changing state of the soil surface in time due to progressive crusting influences the rill – interrill relation (Govers & Poesen, 1988), which is also the case in Saxony, increasing the importance of erosion rills in regard to the total soil loss. However, these findings are less reliable regarding interrill changes due to a yet high LoD (of 1 cm) of the UAV photogrammetry method. Thus, an important portion of potential surface change is superimposed by noise. Interrill and rill erosion are measured simultaneously with HiRT, but the former can be underestimated considerably.

5.3. Outlook

Unprecedented observations of soil surface changes after single precipitation events are enabled due to the high resolution and large area coverage of DEMs reconstructed from overlapping UAV images. If these surveys are complemented by methods capturing sediment yield (e.g. troughs), reliable differentiation between erosion and consolidation can be achieved or swell and shrink processes at sites with corresponding mineralogical background can be observed. Local changes of the soil surface after a single rainfall event are measurable at hillslopes with the HiRT method, e.g. directional rill erosion (influenced by wind-driven flow deflection and/or wind-driven raindrop impact at rill side walls), precise localisation of sediment sources and sinks, explicitly quantifiable rill expiring amidst the field plot, and individual rill behaviour in space and time. Besides investigating soil erosion at novel spatial scales, the fast and flexible data acquisition at large areas under field conditions enables a different look at the temporal scale, as well, i.e. varying sediment yield in time due to change of roughness and rill formation. Short-term event-based measurements and intra-annual as well as inter-annual study periods lasting several years are possible.

Future trend of soil erosion: Assessing the magnitude and frequency of soil erosion is an important concern in regard to the climate change because an increase of strong precipitation events is predicted (IPCC, 2014), which is significant for soil erosion because during such rainfalls high erosion rates occur. Thus, precipitation becomes more erosive (Pruski & Nearing, 2002, Nearing et al., 2004). Routschek et al. (2014) confirm the prediction of increasing precipitation intensity for the Saxonian loess belt with a local model. However, in the Mediterranean climatic predictions are yet more complicated because the local climate is especially sensitive to climate change at the global scale (Giorgi, 2006). A decrease in rain amount (Giorgi & Lionello, 2008) and an increase in rainfall intensity (Sanchez et al., 2004) are assumed. The increase in the average annual rainfall can lead to an increase of runoff (Imeson et al., 1998), e.g. due to decreasing vegetation cover if aridity increases (Lavee et al., 1998). Overall, the change of rainfall erosivity in the Mediterranean is spatial complex (De Luis et al., 2010).

However, projection of future erosion trends is difficult due to the principally high variability of soil erosion (e.g. Cerdan et al., 2010, Boardman & Poesen, 2006). High future estimates of relative changes can resolve in low absolute rates and vice versa (Mullan, 2013). Furthermore, soil erosion is not solely susceptible to precipitation characteristics. Another important factor is the type of land use (e.g. Bakker et al., 2008, García-Ruiz et al., 2015), whose change can influence soil erosion even stronger than changes in the rainfall character (Routschek et al., 2014, Paroissien et al., 2015).

Future trend of HiRT for soil erosion measurement: HiRT enables not just the measurement of soil erosion rates but also the visualisation of processes and thus permitting the investigation of process feedbacks and their relevance for sediment connectivity at hillslopes. At larger scales hillslope-channel-interaction can be assessed due to the high spatial resolution at unprecedented large area coverage. This can help to explain

the different rates of sediment yield at catchment scale and of soil erosion at hillslope scale because of different operative processes (e.g. de Vente & Poesen, 2005, Boardman, 2006, Vanmaercke et al., 2012) and due to different measurement methods at varying scales (García-Ruiz et al., 2015), indicating that no simple up-scaling is appropriate (e.g. Parsons et al., 2006). HiRT can be implemented at several scales to overcome this issue. In the future even greater areas can be digitally reconstructed due to the usage of greater flying heights and because of improved IMU and GPS devices for potential direct geo-referencing and thus decreased need for GCPs.

Increasing temporal resolution to observe soil erosion processes is expected, as well, for instance by implementing time-lapse methods (i.e. synchronised capturing of overlapping images at very high intervals), whose feasibility has already been demonstrated by James & Robson (2014b) for volcanological monitoring. This method can realise the observation of self-organising rill systems (e.g. Berger et al., 2010) and of changing micro-topography not just between events but also during the event potentially causing varying runoff and sediment yield during a single event (e.g. Favis-Mortlock et al., 2000).

HiRT is applicable over long-terms, keeping the soil still under agricultural usage due to the non-contact approach if a suitable reference is installed. This can promote reliable soil erosion measurement due to possible observation durations of at least 20 to 25 years, according to García-Ruiz et al. (2015), to comprise the high temporal soil erosion variability. Overall, the potential of spatio-temporal high resolution allows for addressing structural as well as functional sediment connectivity.

Future trend of HiRT for soil erosion modelling: The scale, at which soil erosion is assessed, is relevant for corresponding erosion models because usually models are developed for an explicit scale due to the restriction of erosion measurement methods (for model calibration and validation) at specific scales, highlighting the need for a model covering multiple scales and a corresponding data collection method (Brazier et al., 2006). The need for improved prediction models and suitable modelling concepts of soil erosion and sediment yield is there because a variety of models exist but still no optimum is reached, e.g. due to missing consideration of topography feedback, deposition and erosion with time (de Vente et al., 2013).
Landscape evolution models (LEMs) can be another option considering these issues, although these models depict simpler equations and are thought for larger spatio-temporal scales (Coulthard et al., 2012, de Vente et al., 2013). Coulthard et al. (2012) model soil erosion with a LEM integrating topography feedback and channel processes and achieve promising results. They further note that if HiRT is available, empirical data for the parameterisation of soil surface parameters within the erosion or landscape models might become obsolete (if grain size distribution is obtainable) due to the existing information regarding changes in micro-topography. HiRT as new input data utilised at different spatio-temporal scales can be a powerful tool to develop, calibrate and validate landscape and erosion models.

The feasibility, flexibility and straightforwardness of the method, utilised from aerial as well as terrestrial platforms, to describe the earth surface three-dimensionally will eventually lead to its implementation as a standard method also for long-term observations, potentially allowing for a novel evaluation of geomorphic processes.

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