ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

MAPPING BURIED ARCHAEOLOGIC SITES BY USING GEOMATIC TOOLS: ARCHAEOMATICS

Ph.D. THESIS

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<u>İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ</u>

SAKLI KALMIŞ ARKEOLOJİK ALANLARIN GEOMATİK ARAÇLARLA HARİTALANMASI: ARKEOMATİK

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Filiz KURTCEBE ALTIN, **a Ph.D.** student of ITU **Graduate School of Science Engineering and Technology,** student ID **501062607**, successfully defended the **dissertation** entitled "**MAPPING BURIED ARCHAEOLOGIC SITES BY USING GEOMATIC TOOLS: ARCHAEOMATICS"**, which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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FOREWORD

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ABBREVIATIONS

ALOS PALSAR	**:** Advanced Land Observing Satellite Phased Array type Lband Synthetic Aperture Radar
ALS	**:** Airborne Laser Scanning
ATM	**:** Airborne Thematic Mapper
AVNIR	**:** Advanced Visible and Near Infrared Radiometer
CASI	**:** Compact Airborne Spectrographic Imager
CW	**:** Continuous Wave
DEM	**:** Digital Elevation Model
DTM	**:** Digital Terrain Model
FBD	**:** Fine Mode Dual Polarization
FWF	**:** Fullwave Form
GIS	**:** Geographic Information Systems
GNSS	**:** Global Navigation Satellite System
GPR	**:** Ground Penetrating Radar
GPS	**:** Global Positioning Systems
IMU	**:** Inertial Measurement Unit
IPF	**:** Vienna University of Technology**,** Institute of Photogrammetry and Remote Sensing,
LBI	**:** Ludwig Boltzmann Institute
LIDAR	**:** Light Detection and Ranging
POS	**:** Positioning and Orientation System
PRISM	**:** Panchromatic Remote Sensing Instrument for Stereo Mapping
RADAR	**:** Radio Detection and Ranging
RS	**:** Remote Sensing
SAM	**:** Sayısal Arazi Modeli
SAR	**:** Synthetic Aperture Radar
SRTM	**:** Shuttle Radar Topography Mission
SYM	**:** Sayısal Yükseklik Modeli
UFG	**:** Institute for Prehistory and Early Mediaeval History
VIAS	**:** Vienna Institute for Archaeological Science

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SUMMARY

The increasingly intensive use of Airborne Laser Scanning (ALS) serves a variety of new promising applications. These applications can be related with any discipline, study area or project but all need a common point, topography/land information. Archaeology use information of earth topography from planning to the end of any project. Especially before an excavation it is essential to get information on land of archaeological area. The existing topography is used not only in planning stage but also in extracting archaeological information before excavation. These information are also helpful to sustain further studies and during analyzing the results.

Techniques used to get information from ground surface are the intersection points of Geomatics and Archaeology. Geomatics science include basically Remote Sensing, Photogrammetry, Geodesy, Surveying Techniques, Cartography, Land Management, methods and techniques. Geographic Information Systems is another tool of Geomatics for spatial data management and analyses.

Archaeology has utilized from Photogrammetry and Remote Sensing techniques for years. The essential issues from archaeological point of view are the existing remains over surface and the buried remains. Regarding existing remains over surface, optical images are used to detect, map and archive for years. Regarding the classical approach by using the signs over the surface (crop marks, soil marks, shadow marks) it is possible to detect anomalies. In a comparable way, like using ground penetrating radar data (GPR), hyperspectral or thermal images, old maps and other ancillary data, it is possible to extract and map the remains from ancient civilization in a rapid and accurate way. It is not an appropriate realistic approach trying to detect archaeological remains just by using one data source or method. All data acquisition technology and method have some weakness. Decision of data source due to financial aspects, time limitation, human sources, the technical requirements of data (accuracy, the size of area, active-passive, polarized, georeferencing etc.) is another important factor to get satisfying results in Archaeological studies. Considering buried archaeological remains, frequent method is using geophysical prospection methods. For example ground penetrating radar produces a large amount of data including valuable information for Archaeology. The visualized results are mainly in grey colours between black and white or coloured, namely "radargram": reflection profile of the ground surface. This method is useful to figure out the underground structure, although expertation is needed to understand and analyze these results. Regarding large areas it is an expensive and time consuming method. It is significiant to obtain data before during planning stage so it can be possible to interpret current situation of related topography. Remote sensing provide data for archaeology for that aim. In the past decades the importance of non-destructive prospection methods is growing. For cultural heritage protection and management, it is essential to find the most appropriate method that would be

less harmless to the remains. So just excavation is not one aim or method to study with archaeological remains. All the analyses would be helpful to decide further technologies and methods. The areas needs more analyses (i.e. need of geophysical prospection method) can be defined. For larger areas, another active remote sensing technology, Airborne Laser Scanning (ALS) or Radar technologies (Synthetic Aperture Radar-SAR) provide new opportunuties including newer information and further analyzing methods. The polarization property of radar technologies are in use especially for buried archaeological remains. There are studies in literature shows that the polarization properties can be discriminative to detect archaeological remains. On the other hand ALS is an active remote sensing technique and is a newly study area for Archaeological aims. ALS is used to produce topographic model (i.e. digital terrain models (DTM), digital elevation models(DEM)). DTM's generated from ALS data can be modeled by using shading, colouring or aspect properties. Analyses of these models are currently in use by archaeologists. The newer opportunity arose by using additional information acquired by ALS systems. The advantage of this new approach is to evaluate the radiometric calibrated ALS data by using reflectance values of related ground surface that could give an information regarding traces from buried archaeological remains. It is obvious that none of the data acquisition methods or any tools is the only one tool or method to obtain sufficient information especially regarding to extract buried remains. A colloborative approcah should be followed. Geomatics provides lots of tools from data acquisition to mapping the archaeological area. Earth Sciences is in use in geological, geophysical and in most of other analysis depending on the ground surface including underground properties. Without Informatics, it not possible to develop new opportunites in software in use or to provide the requirements of the statement (i.e virtual reality for city modeling, internet applications etc.). Therefore a new profession based on Geomatics and Earth Sciences; namely Arcaheomatics, is prior to utilize the opportunities of rapid improvement in tehnology and science.

SAKLI KALMIŞ ARKEOLOJİK ALANLARIN GEOMATİK ARAÇLARLA HARİTALANMASI: ARKEOMATİK

ÖZET

Son yıllarda Hava LiDAR (uçan platforma takılı lazer tarama) teknolojisi hızlı bir gelişim içindedir. Buna paralel olarak kullanıldığı alanlar da çeşitlenmektedir. Temel olarak topografyanın modellenmesinde kullanılan Hava LiDAR teknolojisi, mekansal veri ihtiyacına sahip pek çok disiplin tarafından kullanılmaya başlanmıştır ve Arkeoloji disiplini bu disiplinler içinde yer almaktadır. Özellikle kazı çalışmalarından önce ilgili arazi hakkında bilgi sahibi olmak kazı planlarının her aşaması için önemli bir yer tutar. Sadece kazı planlaması değil sonrasında de elde edilen verilerin değerlendirilmesi kısmında da mekansal veri önemli bir yer tutar. Mekansal verinin genel anlamda elde edilmesi, değerlendirilmesi ve analizi aşamalarında Arkeoloji ve Geomatik mühendisliği, birarada çalışan disiplinler halindedir. Geomatik mühendisliği, Uzaktan Algılama, Fotogrametri, Jeodezi, Ölçme Tekniği, Kartografya, Arazi Yönetimi ve elde edilen tüm verilerin bütünleştirilmesini ve analizini sağlayan Coğrafi Bilgi Sistemleri (CBS) konularında temel eğitimleri içerir. Fotogrametri, Uzaktan Algılama ve Ölçme Teknikleri, Arkeolojinin yıllardır kullandığı yöntem ve araçları içerir. Arkeolojik çalışmalarda kullanılan ölçme ve değerlendirme yöntemleri üç ana başlık altında toplanabilir;

1. Hava fotogrametrisi ve uydu teknolojisi,
2. Yersel ölçmeler (topografik ölçmeler, jeofiziksel yöntemler),
3.Arkeolojik yöntemler, yaklaşımlar ve elde edilen tüm veriler ışığında gerçekleştirilen analizler. Bu çalışmalar Hava Arkeolojisi (Aerial Archaeology) ve Arkeolojik Yüzey Araştırması (Landscape Archaeology) olarak da adlandırılabilmektedir. Hava arkeolojisi, tamamen Geomatik mühendisliği temel konularından hava fotogrametrisi ve uzaktan algılama teknik ve yöntemlerini içerirken, Arkeolojik Yüzey Araştırması hem Yer Bilimleri ile ortak gerçekleştirilen (GPR ölçmeleri vb.) hem de Arkeolojik yaklaşımlar ve diğer doğa bilimleriyle olan çalışmaları içerir.

Gerek topraküstü gerekse toprakaltı buluntuların ortaya çıkarılması, konumlarının belirlenmesi ve modellenmeleri için Fotogrametri ve Uzaktan Algılama yöntemleri uzun yıllardır kullanılmaktadır. Hava fotogrametrisi ve Uzaktan Algılama kullanılarak arkeolojik varlıkların belirlenmesi, bu detayların arazi yüzeyinde oluşturduğu anomalilerin yeni uzaktan algılama teknolojileriyle belirlenmesiyle mümkün olmaktadır. Uzaktan algılama tekniklerinin arkeolojik çalışmalar açısından bir önemli özelliği de, arkeolojik varlıkları tahrip etmeden belirlemeye olanak vermesidir. Özellikle son yıllarda, kazı çalışmaları esnasında arkeolojik değerlerin zarar görme olasılığını en aza indirgemeye yönelik yöntemler önem kazanmaktadır. Arkeolojik çalışmaların sadece kazı olarak değil kültürel mirasın varlığının ortaya konması ve bulunduğu yerde muhafazasının devamı için gerekli önlemlerin alınması şeklinde de algılanmaya ve kabul görmeye başlanmıştır. Bu doğrultuda seçilen tekniklerin bütünleştirilerek kullanılmasıyla elde edilen arkeolojik varlıkların,

konumları ve geometrik özellikleriyle üç boyutlu modelleri oluşturulabilmekte, sanal müzeler ve internet aracılığıyla da, sadece bilgisyarlarda değil her türlü kullanıcı ekranında paylaşmak mümkün olabilmektedir. Bu anlayışın da bir uzantısı olarak düşünülebilecek bir şekilde uzun yıllardır kullanılan optik görüntülerle toprak türünün değişimi, bitki boyları, renk farklılıkları, yerden fark edilemeyen ama hava veya uzay aracılığıyla belirlenebilen doğrusal (çizgisel) işaretler ve güneşin eğik açılarla geldiği sabahın erken saatleri veya akşam üstü saatlerinde yeryüzünde oluşan gölgeler kullanılarak toprakaltında gömülü bulunan arkeolojik varlıklar belirlenebilmektedir. Tüm bu sayılanlar bitkisel işaretler (crop marks), topraksal işaretler (soil marks) ve gölgesel işaretler (shadow marks) olarak üç sınıfa ayrılabilir. Gömülü arkeolojik varlıklar, tarlalardaki ürünlerde-bitki örtüsünün gelişiminde oluşturdukları farklılıklarla belirlenebilir. Örneğin bitkiler-ürünler, toprak tabakasının dibe doğru daha derin olduğu, bir engelle bölünmediği durumda daha iyi beslenir ve daha uzun olurken (positive crop mark) dipteki toprak tabakası arkeolojik kalıntılarla bölündüğünde üzerinde gelişen bitki ve ürünler, su kaybı nedeniyle daha az beslenirler, çok gelişemez, cılız kalırlar ve sarı bir renk alırlar (negative crop mark). Belirlenen bu izlerin arkeolojik bir anlamı olup olmadığı, eldeki diğer veri kaynakları ve tamamlayıcı bilgilerle karşılaştırmalı olarak değerlendirilmeler sonucu belirlenebilmektedir. Özellikle toprakaltındaki arkeolojik varlıklar için jeofiziksel yollarla elde edilmiş bilgiler (yer radarı, manyetik rezonans vb. yöntemler), hiperspektral veya termal görüntüler, Hava LiDAR verileri, ortofotolar, eski haritalar, arkeolojik diğer değerlendirme yöntemleri ile bütünleştirildiğinde daha hızlı ve daha doğru bir şekilde tarihi/kültürel varlıkların ortaya çıkarılması mümkün olabilmektedir. Özellikle toprakaltındaki arkeolojik varlıkların bulunması için tek bir yöntem veya teknoloji yeterli olmamakta, farklı veri kaynakları ve bilgilerin bütünleştirilmesiyle daha gerçekçi sonuçlara ulaşılabilmektedir. Finansal kaynaklar, çalışmanın ölçeği ve amacı, kullanılacak verinin belirlenmesinde öncelikli kriterleri oluşturur. Gömülü arkeolojik varlıklar özelinde bakıldığında, yer radarı (Ground Penetrating Radar, GPR) sıklıkla kullanılan bir jeofiziksel araçtır. GPR yer yüzeyi veya genel anlamda bulanık yüzeyler altında gömülü bulunan objelerin veya ara yüzeylerin (değişik toprak katmanları gibi) yerlerini belirlemek için kullanılmaktadır. Bu özelliği nedeniyle GPR, arkeolojik çalışmalarda, gömülü tarihi kültürel varlıkların tespiti için kullanılan bir radar tekniğidir. Bu çalışmalarda, GPR ve diğer teknikler yardımıyla (GPS, diğer jeofiziksel yöntemler) gömülü halde bulunan antik yapılara ilişkin kesitler ve profiller elde edilmektedir. Bu kesit ve profillerden hareketle yer altındaki diğer katmanların doğrultu ve eğimleri, süreksizlikler ve boşluk, kapı, duvar, mezar gibi antik yapı kalıntılarını belirlemek mümkün olmaktadır. Jeofiziksel yöntemler, uzaktan algılama yöntemine kıyasla daha küçük alanların incelenmesine olanak tanımaktadır. Gömülü varlıkların belirlenmesi açısından da oldukça etkili bir yöntemdir. Tüm kazı alanı için gerçekleştirilecek bir jeofiziksel yöntem, zaman ve maliyet konusunda kazı çalışmasına ciddi bir yük getirdiğinden, Uzaktan Algılama teknolojisinin kullanılması önem kazanmıştır. Özellikle aktif uzaktan algılama araçları, devamlı gelişen özellikleri ve farklı analiz seçenekleri sunmaları sayesinde Arkeolojik çalışmalar için yeni bir araç haline gelmeye başlamıştır. Aktif uzaktan algılama teknikleri kendi enerjilerini üretirler dolayısıyla güneş ışığına bağımlı olmaksızın günün her hangi bir saati için ölçme planlaması yapılabilir. Atmosferik koşullardan daha az etkileniyor olmaları da önemli bir üstünlüktür. Tezde de kullanılan Radar (Radio Detection and Ranging) ve Hava LiDAR aktif uzaktan algılama teknikleri içinde yer alır. Radar sistemleri temel olarak ürettikleri elektromanyetik sinyali hedefe yollar ve geri dönen sinyali alır.

Yollanan sinyalin gidiş-dönüş süresinden mesafe hesaplanır. Bunun yanısıra radar sistemleri, yansımanın yoğunluğu (intensity) ve yönüne ilişkin (polarisation) bilgi de sağlarlar. Yollanan ve geri dönen sinyalin yönünün bilinmesi, hedef veya ilgili yeryüzeyinin özelliklerinin anlaşılması açısından önemlidir. Arkeolojik çalışmalarda radar, özellikle kurak alanlarda geçmiş medeniyetlerin izleri olabilecek gömülü haldeki su kanalları gibi çizgisel izlerin bulunmasında kullanılmaktadır. Bunun yanısıra radar sistemlerinin bahsi geçen polarizasyon özelliği kullanılarak, gömülü arkeolojik varlıkların-alanların belirlenmesine yönelik çalışmalar da bulunmaktadır. Diğer aktif algılama sistemlerinden Hava LiDAR (Airborne Laser Scanning, ALS), son yıllarda Arkeolojik çalışmalarda kullanılan bir araç olmaya başlamıştır. Öncelikle Sayısal Arazi Modeli (SAM) ve Arkeolojik çalışmalarda önemli olan Sayısal Yükseklik Modeli (SYM) üretiminde sağladığı doğruluk ile bir üstünlük sağlayan Hava LiDAR radardan farklı olarak lazer ışınları kullanır. Lazer ışınları, hedefe gönderilir ve hedeften dönen yansıma değeri kaydedilir. Elde edilen bu SAM'ın, gölgelendirme, bakı ve yükseklik farklarına ilişkin özellikleri incelenerek gömülü arkeolojik alanlara ilişkin ipucu elde etmek mümkündür. Hava LiDAR özelinde olmasa da özellikle ortofotolar ve uydu görüntüleri kullanılarak üretilen SAM ve SYM arkeolojik çalışmalarda uzun zamandır kullanılmaktadır. İlgili arkeolojik alanda yapılacak herhangi bir çalışmadan önce mutlaka o alanın topografik modeli elde edilir. Elde edilen bu modelin günün farklı saatlerine ve farklı bakış açılarına göre gölgelendirme haritaları ve bakı haritaları üretilerek, çalışılacak topografyanın, toprakÜstünden fark edilebilecek anomalileri belirlenmeye çalışılır. Bunun için mutlaka ek veri kaynakları, tarihi haritalar-planlar, sözel bilgilerden de faydalanılır. Hava LiDAR'ın Arkeolojik çalışmalara katkı sağlayabileceği düşünülen ve tezde kullanılan diğer özelliği ise; 3 boyutlu konum bilgisine ek olarak, yollanan sinyalin genliği ve genişliği, yansıma (reflectance) değeri gibi özellikleri değerlendirilerek, yollanan sinyalin ulaştığı yeryüzü parçası (ağaç, çalılık vb.) veya obje (yapılar, yollar, elektrik direkleri vb.) hakkında bilgi elde edilmiş olmasıdır. Bu ek bilgilerin değerlendirilebilir hale gelmesi için kalibre edilmeleri gerekmektedir.

Tezde, Hava LiDAR verisinin radyometrik kalibrasyonu gerçekleştirilerek elde edilen yansıma sonuçlarının diğer veriler (radar ve ortofoto) ve bilgiler (şehir planı, tamamlayıcı bilgiler) ışığında değerlendirilerek toprakaltındaki kültürel mirasa ilişkin bir ipucu/iz bulunması planlanmıştır. Hava LiDAR verisi ile eşzamanlı yapılan spektrometre ölçmeleriyle kalibrasyon değerleri elde edilmiş olup bu değerler Viyana Teknoloji Üniversitei, Fotogrametri ve Uzaktan Algılama Enstitüsü'nden elde edilmiştir. Hava LiDAR uçuşu sırasında elde edilmekle beraber şimdiye dek Arkeolojik anlamda değerlendirilmesi düşünülmeyen ve her lazer impulsu için mevcut bulunan genlik, genişlik ve yansıma değerleri kalibre edildikten sonra elde edilen yansıma görüntüsünde, gömülü olduğu bilinen (yazılı belgeler, Carnuntum şehir planları doğrultusunda) arkeolojik kalıntılara ilişkin izler aranmıştır. Çalışma alanı olarak eski bir Roma şehri olan Carnuntum kullanılmıştır. Aşağı Avusturya denen güney kısımda, Viyana ve Bratislava'yı birleştiren anayolun ortasında bulunan bu eski Roma şehri eski bir askeri birliğin konuşlandığı bir yerleşmedir. Carnuntum'a ilişkin hava LiDAR verisinden, kalibrasyon sonucu elde edilen SAM, gölgelendirme ve yansıma sonuçları, ortofoto ve RADAR verileri ve şehir planı, tamamlayıcı diğer bilgiler (sözel-tarihsel) ışığında değerlendirilmiştir. Bu değerlendirme sonucunda aktif uzaktan algılama araçlarından biri olan hava LiDAR verisin sadece arazinin topografik modelini belirlemek için değil, arazinin yansıma değerlerinin ortaya çıkarılması için de kullanılabileceği ortaya konmuştur. Gerektirdiği uzmanlık yetisi gerçeğinin yanısıra birden fazla alanda sağladığı bilgi sayesinde Arkeoloji çalışmalarının özellikle kazı projelerinin planlanması aşamalarında hız katacağı, çalışmaya ilişkin her türlü kaynağın da optimum kullanımının planlanmasında faydası olacağı açıktır.

Çalışmanın geneli değerlendirildiğinde Arkeolojik çalışmalarda Geomatik Mühendisliği yöntem ve araçlarının kattığı değerin yadsınamaz düzeyde olduğu bir kez daha ortaya konmuştur. Bununla beraber Arkeoloji bilimi, Yer Bilimleri ve Bilişim teknolojilerini de yoğun ve etkileşimli bir şekilde kullanmak durumundadır. Özellikle gömülü arkeolojik varlıkların ortaya çıkarılması noktasında tek bir veri/bilgi kaynağı yeterli olmamaktadır. Bu durumda temelini Geomatik Mühendisliği ve Yer Bilimlerinden alan, Bilişimden destek alan ve tüm bu araç ve yöntemleri Arkeolojik çalışmaların ihtiyaçları doğrultusunda kullanma yetisine sahip yeni bir uzmanlık alanının varlığına ihtiyaç vardır. Arkeomatik adı verilen bu yeni uzmanlık alanının, lisanüstü bir çalışma olarak Geomatik Mühendisliği temelinde, Arkeolojinin ihtiyaç duyduğu diğer temel Yer Bilimleri ile ortak bir çalışma sonucu müfredat belirlenerek oluşturulması işlevsel olacaktır. Arkeolojinin ihtiyaç duyduğu mekansal veri eldesi, bu verinin işlenmesi, değerlendirilmesi ve arşivlenmesi için gerekli tüm teknik ve yöntemlerin daha hızlı ve etkin kullanımını sağlayacak böyle bir uzmanlık alanı küresel ölçekte bakıldığında, tarihi ve kültürel mirasın korunmasına önemli bir katkı sağlayacaktır.

1. INTRODUCTION

Geomatics Engineering models the Earth geometrically by using numerous techniques and methods in improvement. Moreover, the studies on spatial information in Geomatics, which covers data integration, analysis and management (i.e. Geographic Information Systems, CAD environments, digital image processing systems etc.), are required by the other disciplines related to spatial approach. In this context, Archaeology utilize Geomatic tools such as Tachymetry, Terrestrial or Aerial Photogrammetry, Terrestrial or Aerial Laser Scanning (LIDAR), Remote Sensing (RS), Global Positioning Systems (GPS) for extracting exploring, archiving and analyzing of cultural heritage including management from beginning to the end of archaeological project. Especially for the last decade, the improvement in Active Remote Sensing technologies, i.e. RADAR and LIDAR systems provide fast, accurate, and quantified information for Archaeology. Active systems are independent from Sun for illumination and are capable to acquire reflectance information of the illuminated Earth surface. The analysis and interpretation of these results concerning Archaeology also including subsurface Archaeology is a newly study area. The first hypothesis of this P.hD study is concentrated on the advantages of Active Remote Sensing methods and technologies in terms of buried Archaeological studies in a comparable way by using diverse data sources (i.e. Orthophotos, Hyperspectral Data, Ground Penetrating Radar studies, Archaeological methods and knowledge). On the other hand there are also some other disciplines (i.e. Informatics, Earth Sciences, Chemistry, Biology, History…) that Archaeology needs to collaborate with to get accurate and reliable Archaeological information. There is an existing study area, namely Archaeometry which is an interdisciplinary field between archaeology and natural and physical sciences (Url-1; Url-2; Url-3). The invention and usage of this approach can be dated at 19th century. Esin, 1984 (Url-4) mentioned that Aerial Archaeology including Terrestrial and Aerial Photogrammetry and Geophysical methods were in use to map surface and subsurface archaeological remains. Today, the rapid improvement in aerial and satellite technology support archaeological studies not just to map the archaeological heritage but to extract more information directly or indirectly on subsurface remains. Despite this definition, including Geomatics and Earth Sciences tools, the general inclination on the meaning of Archaeometry covers collaborative studies with natural and physical sciences. The second hypothesis is to put an emphasis to a new approach regarding Archaeological projects and the most important Earth related sciences for Archaeological aims, called Archaeomatics. The main components of Archaeomatics are, Geomatics, Archaeology, Earth Sciences and Informatics as depicted in Figure 7.1. These disciplines have some common study areas (e.g. GIS, programming, topographic modeling, aerial remote sensing etc.). For the last decade, the requirement of collaborative studies forces multidisciplinary cooperation (Campana and Francovich, 2003; Campana and Francovich, 2005; Turoğlu, 2006). The improvement in technology also supports collaboration approach regarding archaeology; from data acquisition to archiving, rapid and accurate technologies bring new area of specialization requirement in any archaeological project. Another important prefential approach is to prevent the existing cultural heritage both buried and (Campana and Francovich, 2007) over surface by using non-destructive technology and methods such as remote sensing even in different scale. Excavation can cause some damages beside its advantages in archaeology. Particularly, regarding to buried archaeological remains, if the location and existence of these cultural heritage are still unknown, the prior process is to analyze obtained information and extract these archaeological remains by using new technology and method before any excavation planning. There is lots of studies can be found in the literature, which integrate Geomatic and Earth Sciences tools following non-destructive methods to explore cultural heritage (Argote-Espino and Chávez, 2005; Di Iorio et al., 2008; Castaldo et al., 2009; Campana et al., 2009; Neubauer et al., 2009). The improvements in one discipline support and directly or indirectly affect the studies (results) of other disciplines. Bitelli (2012) pointed out importance of Geomatic tools and methods (from data acquisition to georeferencing) usage in Archaeology and he summarized integrated RS tools due to the properties of these tools and scale of the archaeological area. Consequently, Archaeomatics is the intersection set of these diverse disciplines, which has Geomatics in the center of overall study due to requirements of Archaeology. The main idea here is to point out the necessity of interdisciplinary planning and the requirement for a new area of specialization within a postgraduate study that can provide and support the requirements of any archaeological study. The studies on spatial information in Geomatics are required by the other disciplines related to spatial approach (Ipbuker, 2008). In this context, Archaeology use Geomatic tools for extracting exploring, archiving and analyzing of cultural heritage. Different surveying techniques can be used according to the financial situation and archaeological measurement scale, such as tachymetry, terrestrial or aerial photogrammetry, LIDAR, Radar, Global Positioning Systems (GPS), Global Navigation Satellite Systems (GNSS) for exploring, positioning, archiving and modeling for related cultural heritage. There is always a possibility to damage archeological remains during excavation. So especially in terms of subsurface archaeology, latest preferred approach is to decide on a non-destructive method as mentioned. Archaeology is also one of the first disciplines that used the benefits of remote sensing (Lillesand and Kiefer, 1994; Sever, 1990) tools as non-destructive technology. Remote sensing technology provides varied methodology including different instruments that will be chosen due to requirements and financial position of the intended archaeological project. There are two main prospection methods in archaeology, aerial archaeology and landscape archaeology. Landscape archaeology includes geophysical instruments such as Ground Penetrating Radar (GPR) that is near surface remote sensing platform and is not the main subject of this paper (Neubauer et al., 2002; Alpaslan and Ozcep, 2008; Lowry, 2009; Piro and Campana, 2012) and archaeological studies including field survey. Magnetic surveys, electromagnetic field surveys or methods by using infrared technology, it is possible to explore underground structure due to aim and plan of the project (Campana et al., 2006; Campana et al., 2009; Costello et al., 2007; Chapman et al., 2009; Dabas, 2009; Ekinci and Kaya, 2006). Geophysical methods provide reliable results but it is expensive for large areas and it takes much time (Safi, 2008; Aydın, 2004).Therefore it is preferred to use remote sensing technology for planning, then by evaluation of outputs it is more reliable and convenient to decide on the crucial areas for further land surveying methods. Aerial archaeology mainly covers all airborne and spaceborne technologies. From the invention of Photogrammetry, it is in use in Archaeological studies, for the last 30-40 years, the improvement in satellite technology also affects Archaeology (Doneus, 2001; Doneus and Neubauer, 1998). It can be inferred that almost every improvement in technology related spatial data acquisition and management has become an integrated part of archaeological studies.

Remote sensing in archaeology is used for several aims. The prior use is to explore the presence and location of the archaeological remains (such as ancient pathways, pipelines, cemeteries etc.). Lasaponara and Massini (2011 and 2012a) evaluated archaeology and remote sensing technology from visual interpretation to digital manipulation. They insisted on the increasing development in satellite technology and the use of this besides the products of Photogrammetry (Lasaponara and Massini, 2007). They mentioned about the traces obtained from images (airborne and spaceborne) used for buried archaeological remains extraction. The importance of being a non-destructive option is increasing the requirement and importance of RS as a data source including diverse technological options, such as different radiometric, spatial and spectral properties, enhancement and analyzing options (Lasaponara and Massini, 2012b). Lambers and Sauerbier (2006) used orthomosaics, satellite imagery, scanned topographical maps and DTM grid data in Peru-Nacka. They designed a conceptual data model for these data in GIS environment and after analyses; they investigated “Nacka Lines”. Rowland and Sarris (2007) insisted on benefits of multispectral remotes sensing in exploring subsurface archaeological remains. They used a wide variety of data from diverse sources, Compact Airborne Spectrographic Imager (CASI), Airborne Thematic Mapper (ATM), LIDAR and GPR. They mentioned that from visible to thermal portion of electromagnetic spectrum provides promising results for archaeological aims. Alexakis et al., 2009 studied Landsat ETM, ASTER, EO1 – HYPERION, IKONOS, air photos and GPS campaign results to explore Neolithic settlements and in the result they pointed out it was possible to obtain more results that are satisfactory by analyzing different data sources for detection of archaeological remains. GIS is also placed in archaeological studies. Especially for managing and analyzing, GIS is a widely used tool in archaeological studies for years in data integration and management of archaeological data obtained from various sources (Ciminale et al., 2009; Evans and Traviglia, 2012; Ozulu et al., 2007; Pappu et al., 2010; Petrescu, 2007).

The concentration on studies of active RS methods is a newly study area in archaeology. It is possible to utilize additional properties by using active RS besides conventional RS tools of archaeology (i.e. ortophotos, oblique and vertical photographs, LANDSAT, IKONOS, ASTER etc.). LIDAR is one of active RS tool that can be used (and in use partly) in terrestrial and airborne platforms for archaeological aims. The common usage of LIDAR is topographic modeling and orthophoto production (Aydar, 2006; Verhoeven et al., 2012). Feature extraction and data processing steps are important parts of LIDAR processing steps to obtain information on targeted objects and surface characterictics. Within this PhD thesis, Airborne Laser Scanning (ALS) term will be placed LIDAR. The prior use of ALS in archaeology is to get more accurate topographic model of the study area in a rapid way. It is possible to generate 3D model of terrain with ALS. Especially in dense forested areas by using ALS it is easier to produce DTM in a fast and high accurate way (Kraus and Pfeifer, 1998). The use of ALS in forested archaeological areas is also one of the ongoing studies. The acquired topographic model of the related terrain by ALS technology helps archaeological studies to understand the topography and explore archaeological remains in a non-destructive way (Doneus et al., 2008). Bennett et al. (2012) studied quantitatively comparable five visualization techniques (slope, aspect, two analysis of relief modeling and sky-view factor by Zaksek et al. (2011)) with ALS data for a better archaeological information extraction and interpretation. Trier and Pilø (2012) studied to trace ancient iron production sites and hunting systems. These systems are hidden as buried pits and they used ALS data to extract even small pits before any field survey. They constituted a methodology including normalization, threshold values of defined pit size and other possible attributes that can be helpful to extract these pits. They mentioned the importance of expertise during evaluation and interpretation of ALS data regarding these pits that can be visually inspected just by an "expert eye" on archaeology. Doneus et al. (2007) studied over archaeological area by using ALS next to conventional methods and obtained promising results, could be able to map lots of archaeological remains. Another challenging study area in ALS regarding archaeology is the reflectance properties of returned signals and interpretation of them. Studies over reflectance properties of LIDAR were started separately from archaeological aims, having an additional opportunity to get more information on surface characteristics. They insisted on the importance of various prospection methods on combining pieces of "archaeology puzzle". Pioneering studies on backscattering energy started with of Luzum et al. (2004). They pointed out the returned energy is affected from various properties (path length, surface roughness, atmospheric attenuation etc.) and if these are not corrected, it is not possible to compare properly data from different sensors, systems, regions and they conducted a normalization algorithm and process to ALS data. Wagner et al. (2004) presented physical principles of ALS systems depending on radar principles. They mentioned that except using very short wavelengths, LIDAR equation can be adapted from radar equation and backscattered energy can be evaluated. Kasaailanen et al. (2007) studied over radiometric calibration of physical attributes of LIDAR for more precise surface and target characterization. Kasaailanen et al. (2009) concentrated on the type of radiometric calibration of LIDAR data and concentrated on natural surface targets. Within these improvements, the newer opportunity was also studied in terms of archaeology. In conventional usage of ALS in archaeology, DEM-DTM generation, shaded relief of related topography and some visualization techniques implemented over these products are in use. Another inspiration of this PhD thesis is Lehner (2011), he studied over radiometric calibration of Schönbrunn castle area in Austria and evaluated the results regarding additional properties of fullwaveform ALS data. As well as LIDAR usage, there is another active RS tools which are in use in archaeological studies before LIDAR. While airborne methods provide good overview and prospection possibilities, the cost of mobilization are still considerable. Earth observation satellites provide an attractive alternative. Very high resolution optical imagery (e.g. 1m or 50cm GSD) is available and comparable to airborne images with respect to image quality. However, very high resolution images have a correspondingly small footprint in comparison to lower resolution images. Additionally, cloud cover and competing interests in image acquisition of different users, complicates obtaining imagery according to specific demands (e.g. during a certain phase of the vegetation period). Earth observation with microwaves is possibly an alternative. Microwaves are less influenced by atmospheric conditions. Synthetic Aperture Radar (SAR) is a relatively new technology used in archaeological studies. Elachi et al. (1984) studied with Shuttle Imaging Radar (SIR-A) images (L-band, HH polarization) of southern Egypt. They were able to extract the traces of drainage channels, faults, and terraces. From 1990's, there are studies around Guatemala by using various RS rechnology covering radar (Sever, 1998; Sever and Irwin, 2003) data to trace Maya culture. They also aimed to define the paleocahnnels –paleorivers to extract the settlement area and get clues the correlation between the environment and settlement of Maya's. Both studies also employ a lot of researches and academicians from universities, research institutes and NASA. Comer (2008) tried to characterize the different reflection of archaeological remains from other surface features. Patruno et al. (2009) used ALOS PALSAR, ALOS PRISM and orthophotos of related archaeological areas and evaluated the L-Band backscatter properties of PALSAR regarding to archaeological remains. The main aim of Blom et al. (2009) was to state the climatic chronology in Green Sahara region by using ALOS PALSAR L-band frequency, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Shuttle Radar Topography Mission (SRTM) data. By using all the data, they mentioned that they had an improved understanding about the effects of human being to environmental change. There are also some other studies insistent on the requirement of using different archaeological prospection techniques. Campana and Francovisch (2007) had several studies in that approach and they improved a surveying methodology for all the steps of an excavation plan considering by scale of the archaeological area.

The usage of both LIDAR and Radar (ALOS PALSAR and TerraSAR-X) data were studied over one of the biggest Roman legionary settlement in Carnuntum, Austria within PhD thesis. Web Atlas, orthophotos, city plan and ancillary information of the study area were evaluated in comparable analysis with LIDAR and Radar data.

2. GEOMATICS AND ARCHAEOLOGY

The main aim in archaeological studies is to explore the remains, to map these archaeological remains and analyze them to obtain more information on past civilizations. It is significiant and convenient to understand archaeological prospection methods in general for remote sensing and archaeology connection. *Aerial Archaeology* and *Landscape Archaeology* are two main prospection methods in archaeology. Aerial archaeology includes photogrammetry and remote sensing tehnologies whilst landscape archaeology covers field surveys (i.e. geophysical methods, GPS campaigns, tachymetry, leveling). Both Archaeological prospection methdos includes Geomatics tools. Archaeological studies is one of these disciplines discovered the importance and advantages of Photogrammetry and Remote Sensing next to geodetic surveying methods. Active remote sensing tools provide newer outcomes to analyze. Since the last two decade, commercially use of ALS and Radar is in increase, spatial data users from different disciplines and professions (as well as Archaeology) can benefit from this newer technique. DTM and DSM model generation and nowadays the additional properties obtained by active remote sensing systems provide new information for archaeological studies.

2.1 Active Remote Sensing

There are two classes of remote sensing sensors: passive and active sensors. Passive remote sensing sensors are dependent on Sun energy for illumination. On the contrary active remote sensing sensors are able to produce their own energy so measurement time is independent from daylight. Radar and LIDAR are two types of active systems used within the study.

Active microwave sensors, widely known as Radar, transmit an electromagnetic energy that they produced and receive the backscatter energy from the target (Wagner, 2010). Radar systems use microwaves that are less influenced by atmospheric effects. It is also possible to obtain data 24 hours a day. Radar data covers reflection properties of reference targets (objects or landscape) which provides significiant traces in detection archaeological remains (including buried remains) in comparison with other data sources (i.e. optical data, multispectral data, GPR data). Radar use radio waves to illuminate and collect the backscattered energy from target. The distance between sensor and target is calculated by using The time delay between the emission and return and the speed of radio waves.

LIDAR (Light Detection and Ranging, ALS) is the optical analogue of radar and use laser pulses for illumination. This is a newer active remote sensing tool for Archaeology. The possibility of producing DTM and DSM even in forested areas in an accurate and fast way is an important advantage in Archaeological studies. Moreover studies to utilize the additional properties of LIDAR provide more information on targeted area-object. The following sections are concentared on these two active remote sensing tools.

2.2 Airborne Laser Scanning

Airborne Laser Scanning (ALS - is also referred as LIDAR) is an active remote sensing measurement technique use short infrared pulses for obtaining information on earth's surface. Being an active remote sensing system is one of the advantages of ALS that means system produces and emits its own energy and does not have any dependency to sun radiation. Hence another advantage reveals; capability to measure day and night. The other advantage is generating topographical model of surface with a higher accuracy, even in forested areas. Generated model mainly includes lots of points namely "point cloud" (millions to billions of points up to the case study). Obtained data set including mass of points contains 3D coordinates per each point in the point cloud. It is also vital to know that, vertical accuracy (Z) is higher than planimetric (X,Y) accuracy. The acquisition is revealed stripwise and required model (i.e. DTM, hill shading, colored etc.) is produced to get and analyse. The emitted energy (very short laser pulse) is then reflected from the surface target and stored by the system.

The distance between the surface target and laser scanner, namely "range", is calculated from the travel time between emitted and received signal or the phase difference between transmitted and backscattered signals. The first method is currently used by pulsed lasers and the second one is in use by continuous wave lasers. Most of the existing ALS types are pulsed laser scanners. The subtype of pulsed lasers are discrete echo and fullwave form (FWF) laser scanner systems. FWF data set was analysed within this PhD thesis (Günay, A., 2006; Doneus et al., 2008; Doneus and Briese, 2006; Wehr and Lohr, 1999).

Before explaining ALS working principle, it is significiant to give information on components of ALS for a better understanding of overall mechanism.

Vital components (Figure 2.1, Figure 2.2) of ALS system are:

- Positioning and Orientation System (POS). POS covers:
    - Global Navigation Satellite System (GNSS), provides location information, and
    - Inertial Measurement Unit (IMU) provides orientation of platform. Both information is required for georefencing of point cloud and these establish the trajectory file.
- Laser scanner.
- Platform refers the vehicle where laser scanners and other instruments (storage media, POS) are mounted on, i.e helicopter for corridor mapping (highway and railway analysis, floodplain mapping), aircraft for large archaeological areas or for difficult topographic modelling like DTM generation in forested areas.
- Unit for data control/management and data storage.

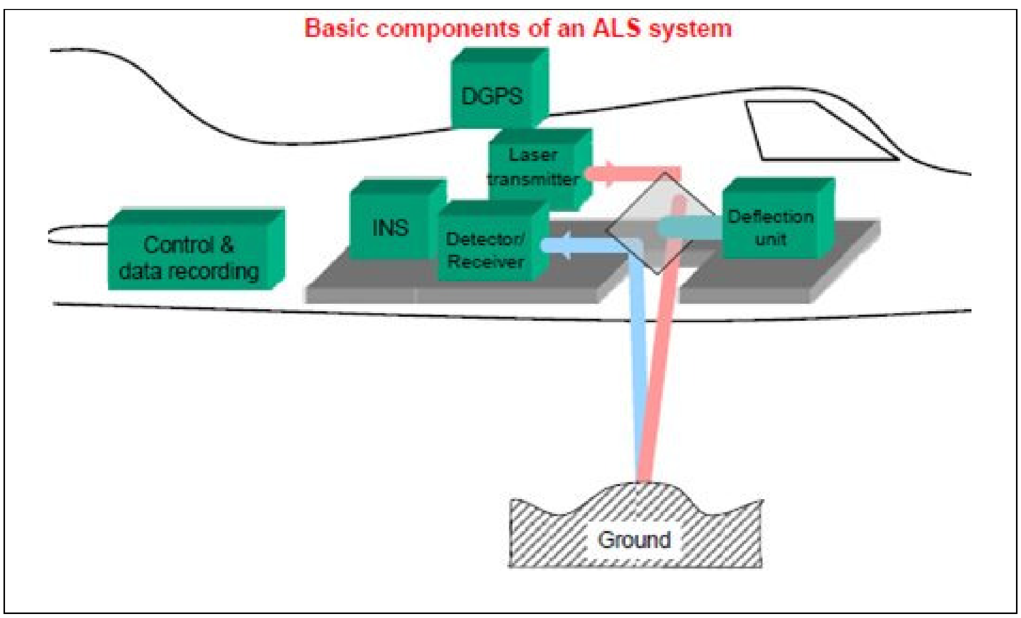


Figure 2.1 : ALS components (Brenner, 2006; Baltsavias, 2009).

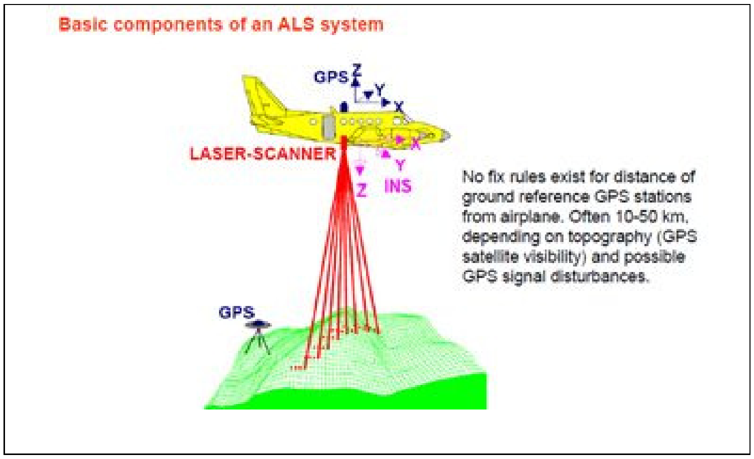


Figure 2.2 : Basic components of ALS (Baltsavias, 2009).

Laser scanner mostly operates on 1064 nm to 1550 nm (Near Infrared, NIR) portion of electromagnetic spectrum which is also convenient for eye-safety. This interval can be varied regarding to requirment of the study, i.e. for bathymetric studies 532 nm wavelenght is constituted because within this wavelength it is possible to penetrate water (Baltsavias, 1999; Brenner, 2006; Lehner, 2011; Campbell, 2006). Scanning mechanism is mainly divided into four types (Figure 2.3) as follow:

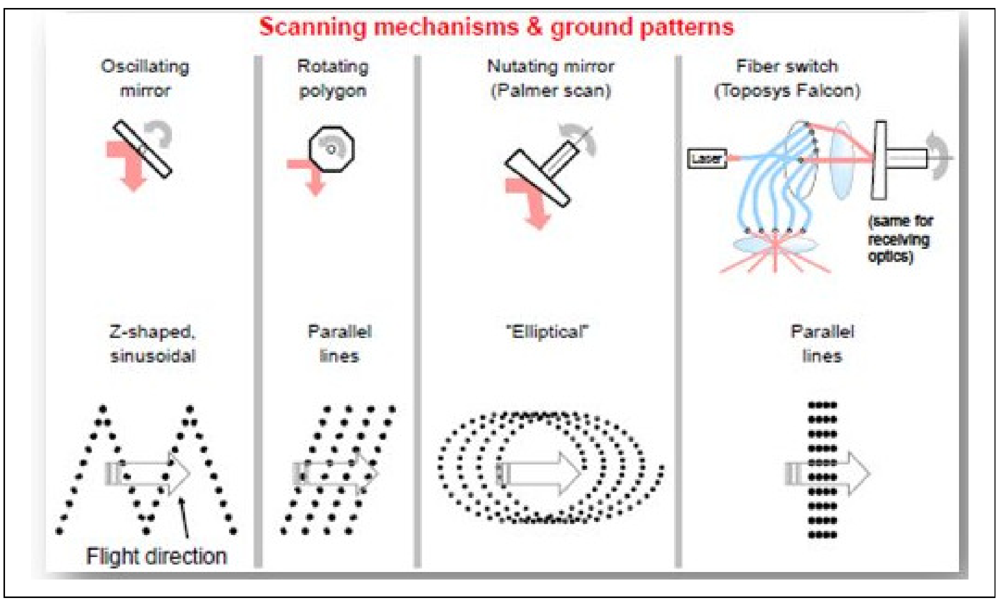


Figure 2.3 : General outlook to scanning mechanism (Brenner, 2006).

1. Oscillating mirror, here the system use an angular encoder. The scan results with Z-shaped or saw-toothed shape.
2. Rotating polygon, in this scanning type, scanned ground points constitute parallel lines.

3. Nutuating mirror (Palmer Scan), this type of scan results with overlapping elliptical pattern. Since there is an advantage to scan one single point two times, further processing steps become more complex (Mücke, 2008).
4. Fiber switch (Toposys Falcon). this mechanism results with paralell lines including circular scans (Petrie and Toth, 2008).

Laser scanning mechanism requires laser ranger for determining the distance (the range) between the emitted laser pulse (signal) and the received signal, namely "echo". Laser ranger produces and emits its own energy. Regarding to laser scanning property (pulse echo or continuouswave (CW)), the range between the scanner and target is calculated (Mandlburger et al., 2007; Mücke, W., 2008; Pfeifer and Briese, 2007; Lehner, H., 2011). Pulse echo systems use time of flight (TOF) for range determination between the transmitted very short laser radiation and received echo reflected from surface targets. CW systems measure the difference of phase between emitted and received continuous wave signal. CW laser is not the subject of this study. It is obvious in Figure 2.4 to understand the range measurement in pulse systems, the variable is time (t) where the phase difference is (Φ) the variable of CW laser systems.

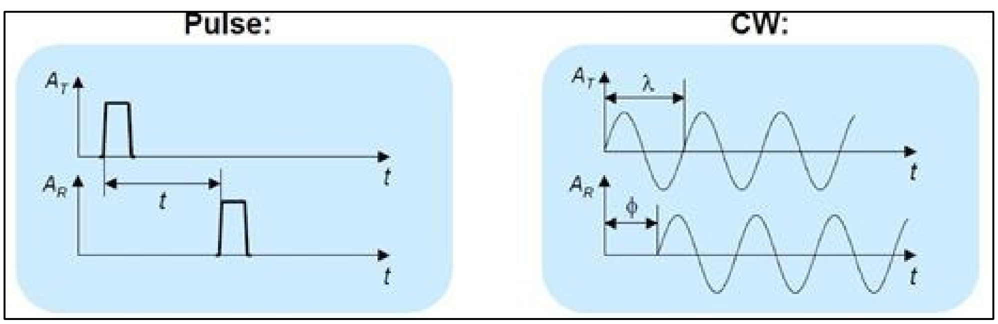


Figure 2.4 : Pulse (left) and CW (right) systems (Brenner, 2006).

Commercial ALS systems mostly use pulse echo systems and currently there are two types of ALS sensor systems, namely "discrete echo" and "fullwaveform". In discrete echo systems multiple echoes is emitted to the surface. Since the earliest echo within the received signals specifies the tree canopy (Figure 2.5), the last echo determines the ground. Others between first and last echoe refers to other natural or artificial surface targets Discrete echo systems analyze the return signal by using analogue detectors.

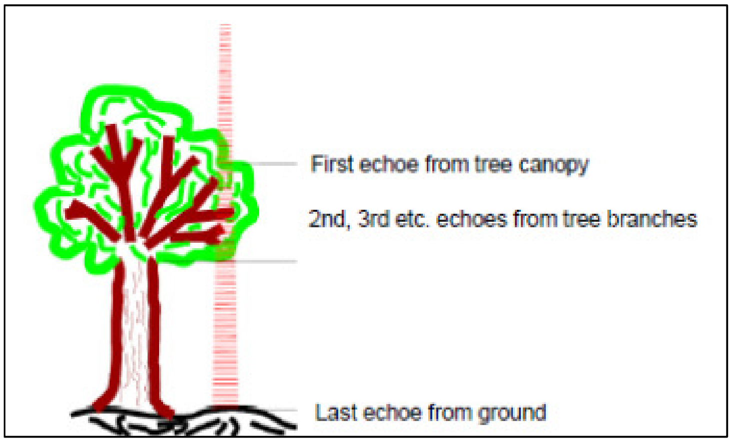


Figure 2.5 : Laser beam interaction with targets (Baltsavias, 2009).

Conversely fullwaveform systems digitize the all waveform of the received signal (Figure 2.6). Multiple echo acquisition by using fullwaveform provides more information on surface targets. Figure 2.6 shows the difference between fullwaveform and dicrete echo systems. The first received echo from the leaves of tree and this information is just stored with one single echo in discrete echo whereas multiple echoe is registered in fullwaveform that includes also widening property of tree. Next echoe is received from schrub and terrain respectively. Discrete echo system stores the echoe as one single shot but in fullwaveform systems signals are recorded as multiple echoe that means more information on surface targets. Another information is obtained on reflectance properties of received energy namely, "echo amplitude" and "echo width", both properties provides more information on surface characteristics. These properties is used within PhD thesis to get signs from terrain model for archaeological remain detection.

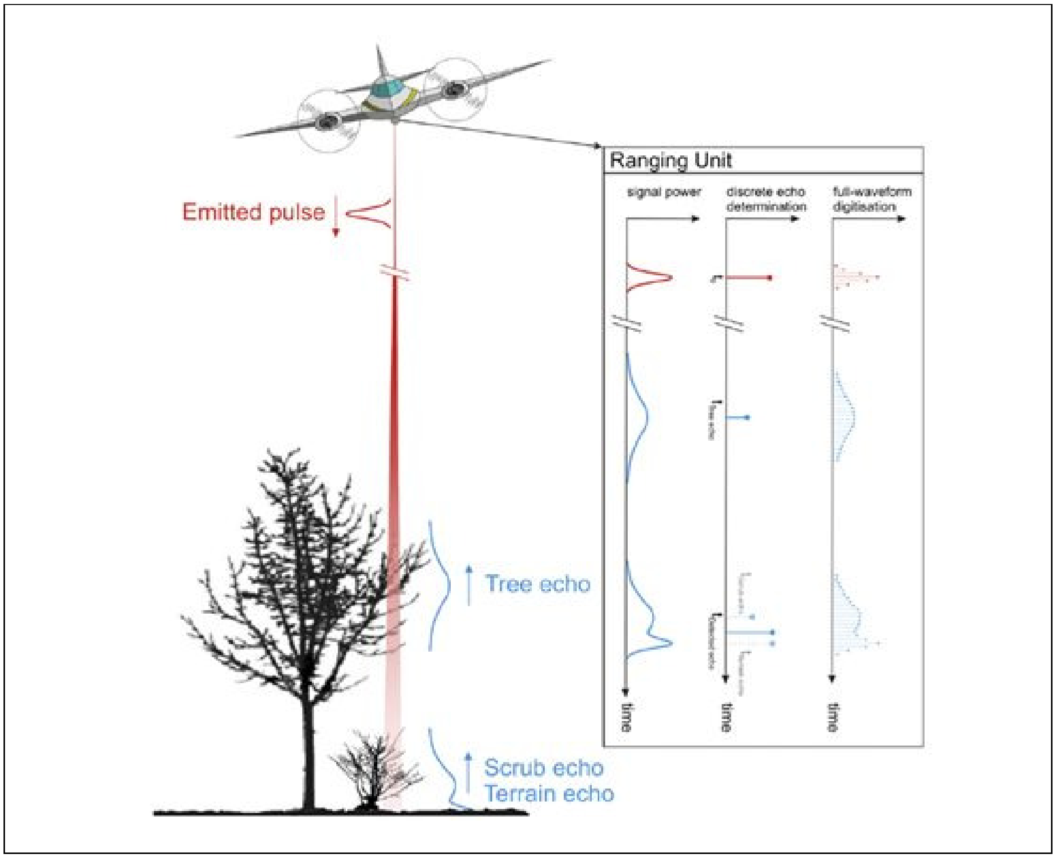


Figure 2.6 : Received echoe in FWF and discrete system (Doneus et al., 2008).

2.3 Microwave Remote Sensing

There are different portions of electromagnetic spectrum as mentioned in previous sections. In this remote sensing approach, microwave portion of electromagnetic spectrum is in use (Lillesand and Kiefer, 1994). The wavelength varies between 1 mm to 1 m. The distinctive properties of microwave remote sensing are being capable to generate its own illumination under all atmospheric conditions and able to make measurements both day and night without relying on sun energy (Woodhouse, 2006).

There are active and passive microwave remote sensing instruments. Additionally a classification based on sensor platforms can be useful to prove the wide variety usage of microvawe remote sensing in earth related objects or phenomenon. Airborne and spaceborne platforms are the main platforms. From archaeological point of view near surface remote sensing instruments like GPR is also using microwave energy to obtain information from subsurface features and can be mentioned as another platform as microwave use but it is not the main subject of this study.

Passive remote sensing sensors (passive microvawe radiometers) are used to measure microwave energy naturally emitted or reflected from Earth surface or atmosphere. The level of energy is quite low in radiometers and is useful to get information from atmosphere (clouds), terrain (humid regions), ice (glaciers) or rain. These sensors have very large wavelengths that results with very low spatial resolution and is limited to regional or global studies. This study relies on a regional application so it does not deal with passive sensors considering by these disadvantages. Active remote sensing sensors produce their own energy. By being independent from sun energy it is possible to plan a measurement in all atmospheric conditions and during 24 hours a day.

Active Radar systems transmit, receive and record the electromagnetic energy produced by the system itself. The background of the system is relied on the echolocation principle that is based on signal transmit and make measurements on the returned echo. If the speed of the transmitted signal is known, distance to the feature will be estimated by using measurements to the return time of the echo. It can be mentioned that the radar systems obtain two main information types: the distance information, by using time delay in return echo, and the properties of the echo such as polarization.

It is important to understand the radar basics to interprete images from that source. A transmitter, receiver and antennas are the basic components of the radar systems. The pulse from electomagnetic radiation is generated by radar sytem and sent to target by transmitter along antenna. Then the backscattered radiation from the target is obtained by the receiver. The processing step is executed with appropriate mathematical solutions through special software packages and signal processors (Mold, 2007).

The wavelength of the electromagnetic radiation in radar systems is longer than the other portions of EM (Figure 2.7). The measurement unit is in centimeters (1 cm – 1 m) in radar systems (Jong-Sen and Pottier, 2009) and varies between K and P considering by requirements of the study (Figure 2.7).

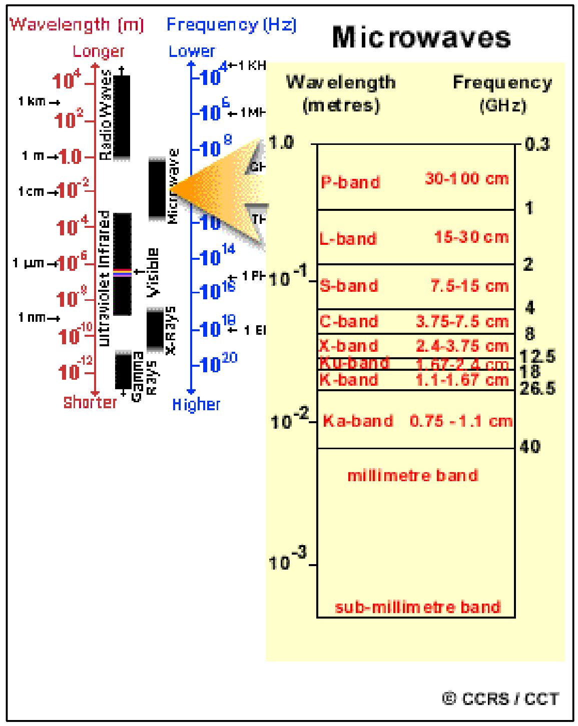


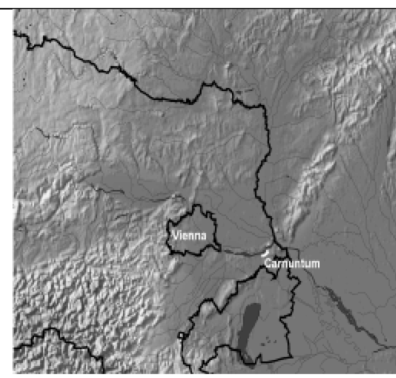
Figure 2.7 : Electromagnetic Spectrum and Microwave Portion (Url-5).

3. STUDY AREA AND DATA

3.1 Study Area

Carnuntum is most important ancient Roman settlement in lower Austria, which is located on the main road halfway between Vienna and Bratislava (Url-9) . The area (Figure 3.1) is characterized by the river Danube cutting through the foothills of the Carpathian Mountains in the east and its gravel-terraces forming a flat to slightly hilly terrain (Doneus and Scharrer, 1999). The main city was situated in the area between present-day Petronell-Carnuntum (civilian city) and Bad Deutsch-Altenburg (legionary city-military camp) with the area of 300 hectares (Figure 3.1a; Doneus and Scharrer, 1999; Url-1; Url-2).

a) Bad Deutsch Altenburg and Petronell parts of Carnuntum



b) General outlook to Carnuntum (Doneus and Scharrer, 1999)

Figure 3.1 : Carnuntum a)Legionary and Civilian parts,b) General outlook to Carnuntum.

The history of Carnuntum goes back to 2000 years. Velleius Paterculus is the first Roman historian who mentioned the city Carnuntum in the year 6 AD. After 1st century AD, Carnuntum got an increasing importance and became the capital of Pannonia (Gugl et al., 2008). One of the important trade routes, Amber Road was a bridge between upper Adriatic and Baltic crossed the Danube River near Carnuntum.

The oldest archaeological findings from the legionary city date from the middle of the 1st century A.D. (Url-5). The town situated before the camp (canabae legionis) had its own forum, thermal baths, an amphitheatre (first amphitheatre) and a temple district was discovered during the excavation (Url-2). The large thermal baths (palace ruin) was adapted for representative purposes. The amphitheatre (second amphitheatre) close to the Heidentor had a seating capacity of 13,000. Today two Roman aqueducts still carry water; they were made of bricks and it was even possible to walk in them. A temple district for the Roman state cult, monuments for the worship of the emperors Hadrian and Marcus Aurelius, a cult theatre, numerous altars and inscriptions were built on top of the Pfaffenberg hill. Finds are exhibited in the newly designed Museum Carnuntinum; archaeological park; Festival Art Carnuntum (Url-5).

After the second part of the 20th century, intensive archaeological studies over Carnuntum have been increased (Gugl et al., 2008). Especially Remote Sensing, Photogrammetry, and GIS are very useful concerning planning, excavation, modeling and analysing the archaeological area. Remote sensing technology provides varied methodology including different instruments that will be chosen due to requirements and financial support of any intended archaeological project. Archaeology is also one of the first disciplines that used the benefits of remote sensing (Lillesand and Kiefer, 1994; Sever, 1990). There are intense photogrammetry and remote sensing technology and method usage more than three decades in Carnuntum. The first aerial photos of Carnuntum were dated from 1930's, from the World War I period. The newer studies started in 1980's in University of Vienna (Doneus and Scharrer, 1999; Kandler et al., 1999; Doneus et al., 2008). Currently, University of Vienna, Vienna Institute for Archaeological Science (VIAS) and Institute for Prehistory and Early Mediaeval History (UFG) have major studies over Carnuntum covered by Ludwig Boltzmann Institute (LBI).

3.2 Application Data

ALS, Radar data (ALOS PALSAR and TerraSAR-X) and orthophotos are the three main data sources of the study.

ALS data, obtained from Institute of Photogrammetry and Remote Sensing, Vienna University of Technology. Data provider is Airborne Technologies and data acquisition date is 5th of June, 2010 by aircraft. The obtained flight plan includes 14 strips (Figure 3.2) over Carnuntum and 4 points/m^2 is provided. Planimetric data accuracy (relative) is ± 20cm, vertical accuracy is ± 7,5cm. Data coordinate system in ETRS 89 and UTM Zone 33. Flightline datasheet depicts more detail (Appendix A, including strips 301 to 308 and 110 to 116).

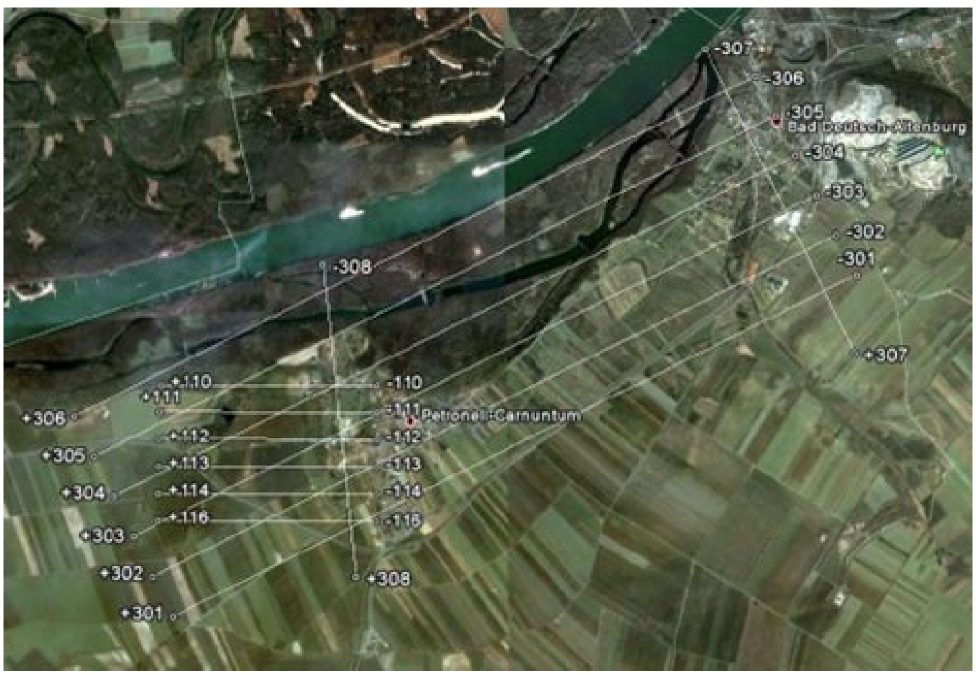


Figure 3.2 : Strips of ALS campaign from flight plan of Carnutnum (Airborne Technologies data sheet).

Data acquisition date of ALOS PALSAR is 03.05.2008, the process level is 1.1, the mode is Fine Mode Dual Polarization (FBD) with HH+HV polarization with 12.5 m pixel spacing.

TerraSAR-X was obtained from the TerraSAR-X Science Service System after an application procedure with a proposal depending on PhD thesis. Level 1B process level (including georeferencing) data with single HH polarization and 1.25 m pixel spacing. Data acquisition date is 14.11.2008. Orthophotos with 0.25 meter spatial resolution were obtained from the “Bundesamt für Eichund Vermessungswesen” (BEV). There were two orthophotos of Carnuntum with acquisition dates; 05.06.2000 and 17.08.2006 (Figure 3.3). Another source is the link to orthophotos of Carnuntum Niederösterreich Atlas (NÖ Atlas) and both orthophotos were used visually to compare and analyse due to extract archaeological remains (Url-9).

a) Dated June, 2000

b) Dated August, 2006

Figure 3.3 : Orthophotos of Carnuntum; a) Orthophoto, acquisition date June, 2000 b) Orthophoto, acquisition date August, 2006.

Ancillary information on Carnuntum from library, internet sources and previous studies including a vector map of Carnuntum obtained from Michael Doneus, were also used as complementary data sources (Jobst, 1983; Jobst, 2003; Url-2; Url-7).

During data processing and analyzing, different software were used. Radar processing steps were achieved by using ENVI (licensed to Institute of Remote Sensing and Photogrammetry Institute,Vienna University of Technology). The Next ESA SAR Toolbox (NEST) is a user friendly open source toolbox (Url-10) for reading, post-processing, analysing and visualising the large archive of data (from Level 1) from ESA SAR missions. NEST was used within some parts of image processing steps of Radar data.

ALS data process was implemented by using IPF software, OPALS, SCOP++ and GVE (Graphics Viewer Editor tool of SCOP) for point cloud visualization and editing in some parts of study. OPALS stands for Orientation and Processing of Airborne Laser Scanning data. It is a modular program system which aims to provide a complete processing chain for ALS data usage, consisting of small components (modules) grouped together thematically in terms of packages (from OPALS MANUAL). Modules used within Ph.D study is summarized in Table 3.1.

SCOP++ has been developed and continuously improved over the last 30 years in cooperation of INPHO GmbH, Stuttgart, and of Institute of Photogrammetry and Remote Sensing (I.P.F.), Vienna. SCOP++ is designed for interpolation, management, application and visualization of huge amount of digital terrain data and SCOP++ has central graphical user interface including the main graphics panel.

Table 3.1 : OPALS Modules within PhD thesis.

Module Name	**Functuonality**
Opals Datamanager	This module allows to access and manage huge data sets. All spatial data sets (eg. breaklines, formlines, borderlines or ALS point clouds) are primarily converted into Opals Datamanager Format (*.ODM) for further processing.
OpalsImport	OpalsImport module is a pre-requisite step for many OPALS application modules and currently covers the following formats: wnp/bwnp--- Winput files /Binary Winput files xyz/ bxyz---- xyz and bxyz files las-------LAS files (version: 1.0, 1.1, and 1.2) American Society for Photogrammetry and Remote Sensing(ASPRS) public interchange format for lidar point cloud data. sdw-----Riegl SDW files fwf------ IPF internal full waveform ascii format (version: 0.8, 0.9, 1.0, and 1.1)
OpalsCell	Derivation of raster models by accumulating selected features (min, max, mean, etc.) of a selected input data attribute (amplitude, echo width, etc.). Calculations for point density derivation that is one of the significiant concepts for defining ALS data quality, is achieved by using this module.
OpalsHisto	Generation of histograms and descriptive statistics (min, max, mean, r.m.s...) for either vector (ODM) or grid/raster data sets. The results are provided graphically (SVG plot file) or numerically (XML parameter file).
OpalsGrid	The aim of OpalsGrid is to derive digital surface models/digital terrain models (DSM/DTM) in regular grid structure using simple interpolation techniques.
OpalsAlgebra	OpalsAlgebra is a module to achieve process covers multiple input grid data sets (DTM mosaics, difference models, point density models ets.) and allows user defined formulas.
OpalsRadioCal	By using this module it is possible to perform an absolute radiometric calibration of ALS data. Outputs are the backscatter cross section, the backscattering coefficient and a diffuse reflectance measure for each laser return.
OpalsZColor	Color coded visualizations of grid models as geo-coded raster images are derived.
OpalsNormals	Local normals of each point or selected set of points are estimated by using OpalsNormals.
OpalsDifference	Derivation of difference grid models based on either two input grids or a single input grid and a horizontal reference plane.

4. METHODS

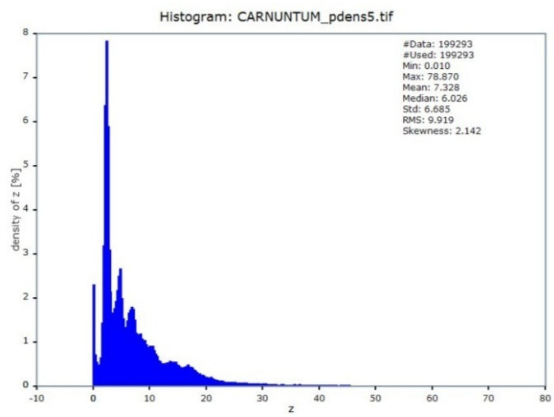
ALS data and processing steps due to archaeological remains is the distinguishing part of this PhD study, thus these process constitute the first part of analyzing stage. After ALS process, the following steps were followed: evaluation of orthophotos, radar data process and comparable analysis of all data sources.

4.1 Preliminary Analysis of ALS Data

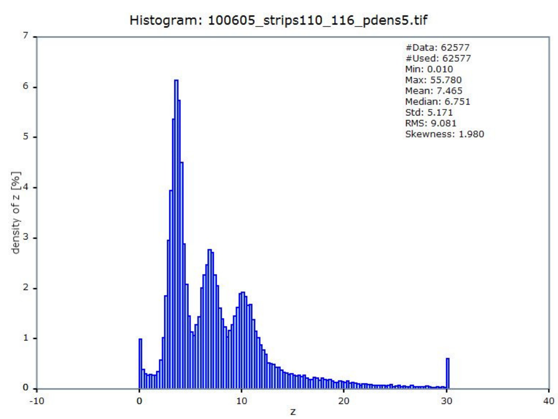
Preliminary step covers ALS data quality assesment. Quality of ALS data effects the accuracy of ALS data products (i.e. DTM). Herein three investigation way was implemented to ALS data (Karel et al., 2006; Mücke et al., 2010);

1. Point density of point cloud (OpalsCell Module),
2. Measurement noise (accuracy of measurement) (OpalsGridModule) and
3. Consistency of overlapping strips (OpalsDiff and OpalsAlgebra Modules).

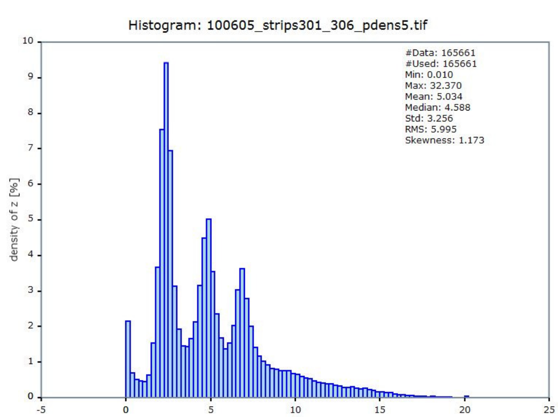
There are two blocks in the flight plan. Block including strips 301, 301, 304, 305 and 306 constitute the big block of Carnuntum and covers the all area. Smaller block consists strips 110, 111, 112, 113, 114, 116 and concentrated on Civilian city. Strips 307 and 308 are crossing strips. And the produced mosaic of all strips was called "Carnuntum". The first step was to import the all strips into Opals Datamanager by module OpalsImport. Obtained raw data format (*.sdw) was converted into Opals Datamanager (*.odm) format. *Point density* is the number of points per unit area (in our study unit is 1 square meters). Point density derivation of Carnuntum ALS data was implemented per each strip by using OpalsCell module; as well as point density of mosaic and point density of blocks. The promised mean point density of ALS data of Carnuntum is 4 points/m^2 by data provider. The result of generated histograms of point densities depict that the mean point density is 5 points/m^2. Figure 4.1 shows the histogram results of derived mosaic of all strips, big block and small block.



a) Point Density of all strips- CARNUNTUM



b) Point Density of Block 110-116



c) Point Density of Block 301-306

Figure 4.1 : Point densities of all of strips (a) and two blocks (b,c).

As depicted in the Figure 4.1, the resulting point density is around 6-7 points per square meters. Histograms were produced also stripwise and can be found in Appendix B. as a result of point density evaluation, it was ensured that the results covers the required point density (required 4 points/m^2). Additionally, the resulting point density distribution were depicted by using OpalsZcolor module and derived coloured maps of ALS strips, mosaic and blocks for a better understanding visually (Appendix C). The results in Appendix C covers the following colour interval (Figure 4.2). The light green is the expected/average value. Darker green tones define the higher value. Yellow and orange colour depict smaller point density value and red is used to define the areas including underflow point density value.

Value	Color	Comment
BG	194, 194, 194	background color
4.0	2, 91, 51	[this_class_bound, +Infinity) (overflow color)
3.0	45, 135, 47	[this_class_bound, next_larger_class_bound)
2.0	100, 165, 45	
1.0	161, 200, 40	**Expected density, accepted values**
0.75	242, 229, 12	[this_class_bound, next_larger_class_bound)
0.5	242, 161, 12	
uf	242, 12, 12	(-Infinity, next_larger_class_bound) (underflow color)

Figure 4.2 : Opals density palette.

In our study the results include expected point density. The underflow point density is occured mostly around the borders of the strips, forested areas and around Danube river.

Regarding the distribution of *accuracy of measurement* in height, sigma-z (standart deviation/accuracy of the interpolated height) was calculated for each strip in OpalsGrid module. These results (Appendix D) were also coloured by using difference palette of OPALS. Differences between (±1* expected standart deviation (STD)) is in gray tones. If it is higher, the multiplier with STD increases and is depicted with tones of green, from light to dark. And the overflow and underflow values are shown by dark colours (blue and red). The smaller values are colored by using yellow, then orange tones for intermediate values respectively (Figure 4.3).

Value	Color	Comment
BG	194, 194, 194	background color
5	0, 68, 144	[this_class_bound, +Infinity) (overflow color)
4	2, 132, 140	[this_class_bound, next_larger_class_bound)
3	41, 171, 136	
2	128, 219, 149	
1	208, 254, 202	
0	241, 241, 241	**Expected density, accepted values**
-1	240, 240, 240	[this_class_bound, next_larger_class_bound)
-2	255, 254, 182	
-3	249, 221, 63	
-4	249, 151, 63	
-5	235, 61, 0	[this_class_bound, next_larger_class_bound)
uf	153, 0, 0	(-Infinity, next_larger_class_bound) (underflow color)

Figure 4.3: Opals difference palette.

DTM generation by overlapping strips is required a check regarding c*onsistency*. There can be still systematic errors (calibration error, sensor orientation) even after DTM derivation so it is important to eliminate inconsistencies of data sets (Opals manual; Karel et al., 2006). Strip differences between overlapping strips are calculated and eliminated by using OpalsDifference and OpalsAlgebra modules. Calculated height difference bettween overlapping strips is scaled by given factor 0.03 (3cm) (Appendix E). This factor was chosed to point out the differences which were not visible to interperet in other executed scale factors, "1, 0.3, 0.6" and defult scale factor "0.06". Theoretically, the results are not supposed to include vegetation but the areas covered by shrub and low vegetation caused oveflow and underflow height difference values (more than ± 15 cm.) which still cannot be eliminated totally by using existing methods and software.

Quality assesment was completed with following acceptable results:

1. Point density is 5 points/m^2 , as promised by data provider.

2. Measurement noise (STD) of strips is around ± 3 cm in general. Because of vegetation effect, this value is calculated higher in some parts of strips.

3. Strip differences between overlapping strips is around ± (3-10) cm., but in some parts of strips, low vegetation increase the difference up to 15 cm.

The latter step with ALS data includes radiometric calibration that is the crucial part of reflectance analysis.

4.2 Radiometric Calibration and Reflectance Analyis of ALS Data

The first versions of ALS (discrete echo) systems are capable to measure the range (round-trip time) of laser pulse and to obtain the peak power of received energy, namely amplitude for each echo. Advanced FWF ALS systems have capabilities to capture higher number of intermediate echoes as a discriminative property than discrete echo systems and are able to capture whole waveform. Moreover, in FWF systems, it is possible to derive additional physical attributes of target surfaces; width and amplitude of each echo after a processing procedure. This information gives the possibility to classify the target classes and evaluate the properties of targets regarding to their backscattering mechanism, namely "backscatter cross section". The backscatter cross section is (in units of square meters) a measure of the electromagnetic energy intercepted and re-radiated by objects backwards towards the ALS sensor (Wagner et al., 2006; Briese et al., 2008). The backscatter cross section (4.5) is not only based on the peak power of received echo, but also includes all other target parameters e.g. the illuminated area A_i, the reflectivity ρ and surface scattering Ω (Briese et al., 2008; Lehner and Briese 2010; Lehner, 2011; Wagner et al., 2008a).

However, these physical attributes are influenced by various factors, e.g. backscattering properties of targets, beam divergence, flight parameters, atmospheric effects, topographic variations etc. (Höfle and Pfeifer, 2007; Wagner et al., 2008b). Before further evaluation of ALS data, radiometric calibration is essential for a better classification and comparable analysis from different sensors or data providers (Doneus et al., 2008; Wagner 2010). Within this PhD, (absolute) radiometric calibration method by using natural reference surface targets was achieved by following previous efforts and studies of IPF (Briese et al., 2008; Lehner and Briese, 2010; Lehner, 2011; Wagner et al., 2004). The formulation used for radiometric calibration is adapted from radar equation (Gaussian waveform decomposition) (4.1). Figure 4.4 shows a sample Gaussian decomposition of FWF ALS data. The peak power of received energy from four recorded echoes, namely "amplitude, $\hat{P}$" is depicted by red arrow. Echo width (blue) can be defined as sigma s_p or as full width at half maximum FWHM due to FWF processing method, in this PhD FWHM is valid. The relation between two terms is explained already in Lehner (2011). *R (green)* is the range from sensor to target. The black points in the figure show the Gaussian decomposition waveform, the black dashed line defines the Gaussian functions and the bold black line at the top of all points is the fitted Gaussian waveform model. Additionally within this study, the term intensity *I* is used as the area below the Gaussian curve of each echo, which is an integration of reflectance properties of related target within footprint, was depicted in filled area (orange) in Figure 4.4.

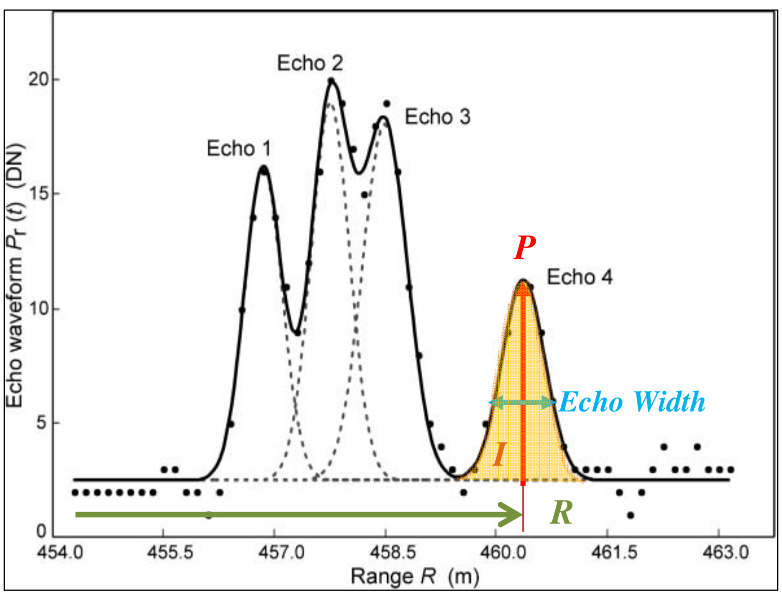


Figure 4.4 : Gaussian waveform decomposition (Wagner et al., 2008a).

The main formula based on Gaussian decompoisition for ALS data radiometric calibration (4.1) is composed of following parameters;

- P_r received power,
- P_t transmitted power,
- D_r receiver aperture diameter,
- R the range,
- β_t the laser beam divergence,
- σ backscatter cross section,
- η_{atm} and η_{sys} are the atmospheric transmission and sytem factor respectively.

$$P_r = \frac{P_t D_r^{\ 2}}{4\pi R^4 \beta_t^2} \cdot \sigma \cdot \eta_{sys} \cdot \eta_{atm} \tag{4.1}$$

In formula (4.2), backscattering cross section (σ) describes the all target parameters in surveyed area A_i, reflectivity ρ, and directionality of scattering.

$$\sigma = \frac{4\pi}{\Omega} \cdot \rho \cdot A_i \tag{4.2}$$

The unknown parameters in main formula are assumed as one constant, so-called calibration constant C_{cal} . In order to determine C_{cal}, the following formula is used; (4.3).

$$C_{cal} = \frac{\beta_t^2}{P_t D_r^2 \eta_{sys}} \tag{4.3}$$

For the first calculation of calibration constant, the required parameter is the backscatter cross section that can be estimated by using formula (4.2). The latter step is derivation of backscatter cross section for the whole data set.

In order to achieve this part, the main formula is adapted regarding to Gaussian waveform; the received power is proportional to amplitude and echo width (4.4) (Wagner, 2006; Lehner and Briese, 2010).

$$P_r = \hat{P}s_p \tag{4.4}$$

Therefore, backscatter cross section is,

$$\sigma = \frac{C_{cal} 4\pi R^4 \hat{P}s_p}{\eta_{atm}} \tag{4.5}$$

The same method (excluding system and atmospheric affects) was implemented within this PhD study. In the first step the calibration constant was calculated. Secondary the backscatter cross section and reflectance properties were derived by using calibration constant results.

This method requires reflectance properties of selected external reference targets in study area (Carnuntum). Thus, by using a spectrometer (Figure 4.5), simultaneous radiometric ground control measurement was performed by IPF, which was directly obtained from IPF and processed for radiometric calibration of Carnuntum ALS data.

Figure 4.5 : Measurement-spectrometer in Carnuntum(Ludwig Boltzmann Institute).

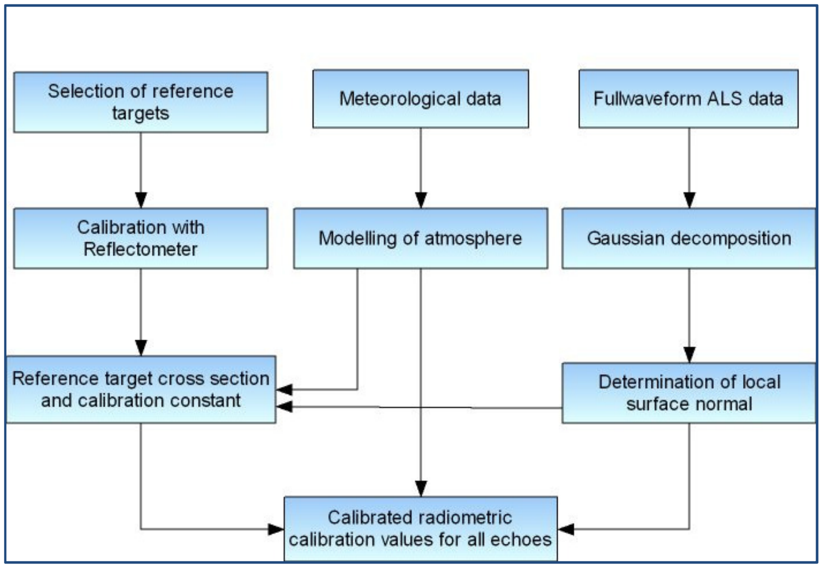


Figure 4.6 : Workflow of radiometric calibration.

Figure 4.6 depicts the main workflow of radiometric calibration, which was studied and summarized in Briese et al. (2008) and Wagner et al. (2006).

The radiometric calibration process was achieved by using strips overlapping natural surface targets. Three natural surface targets were chosen as two asphalt (number 1 and 3) and one pavement (number 2) surface shown with their approximate location in Figure 4.7.

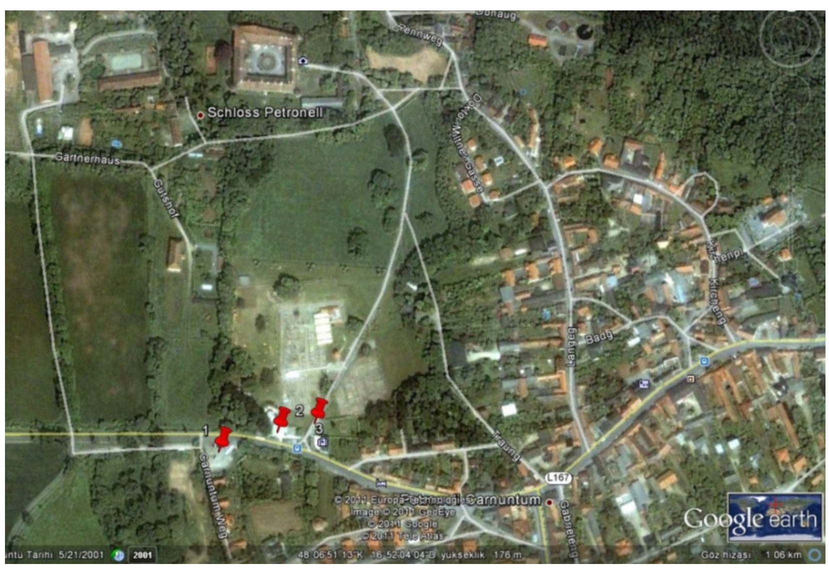


Figure 4.7 : Outlook to natural surface targets.

The location of these natural surface targets was depicted by using GVE software (Appendix F).

The crucial step is to perform reference target survey approximately at the same time with ALS flight campaign to get convenient reference information under the same weather conditions (Briese et al., 2008). During this data acquisition, both ALS flight and land survey was dated on 05.06.2010.

ALS data radiometric calibration process using natural surface targets was planned to achieve into four main steps based on OPALS (Lehner and Briese, 2010; Lehner, 2011). The modules and preferred parameters used within the study are as below:

1. **Module:** OpalsImport

   Parameters: -inf Test.sdw

   -iFormat sdw

   -outf Test.odm

   -Trajectory File -e.g. Test.asc- (obligatory)

2. **Module:** OpalsNormals

   Parameters: -inf Test.odm

   -normalsAlg robustPlane (user defined)

   -neighbours 8 (user defined)

   -searchr 2 (user defined)

   -searchMode d3 (in our case d3 mode is vital)

3. **Module:** OpalsRadioCal

   Parameters: -inf Test.odm

   -outf Test.txt

   -Region File -e.g. RefPolygon.wnp- (obligatory)

   -Reflectivity File -e.g. Reflectance.txt- (obligatory)

   (-atmosphericAtt NN) (optional, default = 0)

4. **Module:** OpalsRadioCal

   Parameters: -inf Test.odm

   -radioCal NN (obligatory)

(-atmosphericAtt NN) (optional, default = 0)

(-beamDivergence NN) (optional)

Within this study, some obligatory files of processing step were obtained from IPF:

- Trajectory File :P037_NoeHyperspektral_MGI_formated_opals.asc,
- Region File :AllTestfileds.wnp (Appendix F) and
- Reflectivity File :AllTestfiledsLambertian.txt

Additional and optional parameters such as file covers atmospheric effects or file for user defined beam divergence were not included in our study. The use of these parameters can be found in literature (Briese, 2008; Wagner et al., 2007; Wagner, 2010).

In the first step, ALS fullwaveform data (in Riegl Data format ".sdw") was converted into Opals Datamanager format (.odm) by using OpalsImport module. There are several ways to execute modules in Opals,

1. Command prompts (Unix or Linux shells as executables),
2. Python shells, and
3. By using C++ programs.

Command prompt usage option was chosen in this Ph.D study. Required command was written in script files by using Notepad and executed by using command prompt. The script file for data import is as follows:

:: opalsImport -inf (related folder)\082202.swd -iformat sdw -outf 082202.odm -trjFileP037_NoeHyperspektral_MGI_formated_opals.asc

For the rest of 13 strips similar scripts were executed.

Since most of the outputs were visualized by using additional software (e.g. SCOP++, GVE, ArcGIS, NEST, IrfanView) some of them were just used as inputs of the next step, e.g. the output of OpalsNormals module was just stored digitally and not have any visible result in its optional derivation but used as input for the next step, in Radiocal module (by using some other parameters in OpalsNormals it is optionally possible to visualize the calculated normal vectors).

The second step covers module OpalsNormals. The aim here to derive local fit plane for each echo within input ALS data and then derive the normal vector of each point. In the main formula of radiometric calibration, local incidence angle is calculated from the outputs of OpalsNormals module as follows:

:: opalsNormals -inf (related folder)\082202.odm -normalsAlg robustPlane -neighbours 11 -searchr 2 -searchMode d3

The intermediate step was to define the strips overlapped with selected natural surface targets. For that aim, it was visualized and analyzed the surface targets and whole strips to figure out the overlapping strips with surface targets in GVE software. As a result, seven strips were determined, strips 302-303-304-308-112-112-113, as overlapping strips with surface targets. The estimation of reflection property of Carnuntum ALS data requires mean/median calibration constants (in our case median value was used) calculated from these seven strips.

*In the third and fourth steps***,** radiometric calibration of data was performed by using RadioCal module. The reflectance properties of surface (reflectivity file) targets were taken into account in this step. The main script of RadioCal module is:

:: OpalsRadioCal -inf (related folder)\082202.odm -outf 082202.txt -calRegionFile AllTestfileds.wnp -reflectivityFile AllTestfiledsLambertian.txt

The first aim to calculate the median calibration constants for the strips overlapped with reference surface targets. For each 7 strip as mentioned in the previous paragraph, similar values as Figure 4.8 was obtained. The meaning of each value was defined in the caption part of Figure 4.8. In this figure from left to right x-y-z values, GPS, amplitude, echo width, received echo, returned echo, three column beam vector, range, three-column normal vector, reflectance, incidence angle and calibration constant for each echo were obtained.

By calculating the median calibration constants (the last column) obtained from seven strips (*in third step*), the value to calibrate the all point cloud was generated; median calibration constant value: 0.028492756033.

The latter part (*fourth step*) covers the use of calibration constant value for the whole ALS data set and RadioCal module to get the backscatter cross section, backscattering coefficients, incidence angle corrected value and reflectance properties of ALS data was performed. The scope of the thesis is concentrated on reflectance value so the other results could be a further study. The last command line in script of RadioCal module related the fourth step is executed for each strip and is as follow:

:: OpalsRadioCal -inf (related folder)\082202.odm -radioCal 0.028492756033

R1 Calibration constant

	x	y	z	gps	amplitude	echo width	receive echo	return echo	beam vector	beam vector	beam vector	range	normal vector	nV	nV	reflectance	incidence angle	Calibration constant
2	39300.45	330,550,307	177,073	548,911,356,169	16333	4,600	1	1	143,743	-226,727	756,779	802,983	0.009	0.017	1	0.3019	201,057	0.024925814654
3	39,300,738	330,549,653	177,071	548,911,356,162	18000	4,700	1	1	143,458	-226,073	756,780	802,749	0.014	0.008	1	0.3031	194,289	0.022236071235
4	39,301,304	330,548,352	177,063	548,911,356,148	19000	4,700	1	1	142,892	-224,771	756,789	802,290	0.020	-0.003	1	0.3044	186,419	0.021181865241
5	39,301,858	330,548,469	177,058	548,911,342,753	18267	4,700	1	1	142,904	-224,588	756,788	802,240	0.013	-0.004	1	0.3041	188,098	0.022014141143
6	39,301,019	330,549,004	177,068	548,911,356,155	17533	4,700	1	1	143,177	-225,424	756,784	802,520	0.019	0.004	1	0.3037	190,730	0.022886448694
7	39,301,579	330,549,107	177,063	548,911,342,761	16800	4,700	1	1	143,183	-225,227	756,783	802,465	0.015	0.003	1	0.3036	191,313	0.023880564295
8	39,302,458	330,548,524	177,050	548,911,329,359	17800	4,700	1	1	142,872	-224,342	756,790	802,168	0.012	-0.004	1	0.3041	188,303	0.022593228376
9	39,302,844	330,548,599	177,053	548,911,315,964	18733	4,700	1	1	143,049	-224,118	756,782	802,129	0.014	0.002	1	0.3037	190,306	0.021446267325
10	39,301,013	330,550,410	177,073	548,911,342,775	17800	4,800	1	1	143,749	-226,531	756,773	802,923	0.015	0.020	1	0.3019	200,742	0.021926693664
11	39,301,290	330,549,775	177,064	548,911,342,768	16600	4,600	1	1	143,472	-225,895	756,782	802,703	0.019	0.003	1	0.3037	190,656	0.024688019090
12	39,301,614	330,550,462	177,047	548,911,329,380	15667	4,700	1	1	143,714	-226,280	756,794	802,866	0.021	0.017	1	0.3025	197,410	0.025495669873
13	39,301,889	330,549,829	177,053	548,911,329,373	15667	4,700	1	1	143,439	-225,647	756,787	802,632	0.018	0.004	1	0.3036	191,052	0.025600553634
14	39,301,991	330,550,552	177,046	548,911,315,985	17067	4,700	1	1	143,901	-226,071	756,789	802,835	0.023	0.021	1	0.3023	198,962	0.023385857707
15	39,302,180	330,549,159	177,044	548,911,329,366	17333	4,700	1	1	143,149	-224,977	756,797	802,401	0.012	0.005	1	0.3033	192,808	0.023130732348
16	39,302,561	330,549,246	177,047	548,911,315,971	19200	4,700	1	1	143,332	-224,765	756,788	802,366	0.019	0.008	1	0.3034	192,438	0.020887632308
17	39,302,272	330,549,907	177,042	548,911,315,978	15867	4,600	1	1	143,620	-225,426	756,793	802,608	0.022	0.012	1	0.3031	193,917	0.025787996006
18	39,302,838	330,550,661	177,010	548,911,302,591	16600	4,600	1	1	143,620	-225,880	756,820	802,761	0.003	0.009	1	0.3024	198,148	0.024582111294
19	39,300,720	330,551,080	177,063	548,911,342,782	16800	4,700	1	1	144,042	-227,201	756,783	803,175	0.014	0.033	1	0.3004	208,041	0.023588645812
20	39,301,319	330,551,137	177,033	548,911,329,387	18000	4,500	1	1	144,009	-226,955	756,808	803,122	0.017	0.032	1	0.3007	206,608	0.023021006345
21	39,301,700	330,551,218	177,024	548,911,315,993	15200	4,600	1	1	144,192	-226,738	756,811	803,096	0.024	0.035	1	0.3008	205,873	0.026684778143
22	39,302,547	330,551,327	177,011	548,911,302,598	15000	4,600	1	1	143,911	-226,546	756,819	802,999	-0.002	0.014	1	0.3015	202,788	0.027106442634
23	39,303,696	330,548,701	177,020	548,911,302,570	19200	4,700	1	1	142,764	-223,920	756,810	802,050	0.000	0.005	1	0.3028	195,705	0.020866291181
24	39,304,266	330,548,778	177,050	548,911,289,175	15867	4,600	1	1	142,761	-223,697	756,774	801,952	-0.010	-0.003	1	0.3029	195,149	0.025812551879
25	39,303,123	330,550,012	177,024	548,911,302,584	15867	4,600	1	1	143,336	-225,231	756,807	802,515	0.003	0.008	1	0.3025	197,651	0.025740591749
26	39,303,410	330,549,354	177,024	548,911,302,577	17067	4,700	1	1	143,049	-224,573	756,806	802,279	0.001	0.004	1	0.3029	195,348	0.023465334934
27	39,303,693	330,550,086	177,040	548,911,289,189	14867	4,600	1	1	143,332	-225,005	756,784	802,430	-0.015	0.000	1	0.3023	199,018	0.027456957943
28	39,303,986	330,549,417	177,032	548,911,289,182	14533	4,500	1	1	143,040	-224,336	756,792	802,198	-0.015	-0.003	1	0.3026	196,775	0.028764596917
29	39,304,354	330,550,106	177,045	548,911,275,794	13933	4,600	1	1	143,236	-224,726	756,774	802,325	-0.007	0.001	1	0.3027	196,433	0.029347289445
30	39,304,643	330,549,445	177,039	548,911,275,787	14533	4,600	1	1	142,948	-224,064	756,780	802,094	-0.003	-0.002	1	0.3032	193,312	0.028200632617
31	39,304,922	330,548,807	177,048	548,911,275,780	17333	4,700	1	1	142,669	-223,426	756,771	801,858	0.001	-0.004	1	0.3036	190,844	0.023187276218
32	39,304,734	330,550,191	177,045	548,911,262,400	12867	4,600	1	1	143,421	-224,509	756,768	802,292	0.003	0.005	1	0.3029	195,261	0.031801952968
33	39,303,121	330,551,395	177,025	548,911,289,203	14667	4,600	1	1	143,904	-226,314	756,799	802,914	-0.016	0.004	1	0.3017	202,056	0.027742168266
34	39,303,416	330,550,722	177,029	548,911,289,196	15200	4,600	1	1	143,609	-225,641	756,795	802,669	-0.014	0.006	1	0.3017	201,680	0.026792897462
35	39,303,781	330,551,414	177,032	548,911,275,809	13133	4,600	1	1	143,808	-226,034	756,787	802,807	-0.004	0.004	1	0.3024	198,076	0.031069279939
36	39,304,070	330,550,755	177,031	548,911,275,802	13667	4,500	1	1	143,519	-225,374	756,789	802,571	-0.004	0.008	1	0.3022	199,567	0.030511426991
37	39,304,449	330,550,841	177,039	548,911,262,407	13800	4,600	1	1	143,706	-225,160	756,775	802,531	0.002	0.014	1	0.3020	200,494	0.029545944418
38	39,304,158	330,551,501	177,026	548,911,262,414	13800	4,500	1	1	143,996	-225,820	756,788	802,781	0.004	0.011	1	0.3023	198,958	0.030211770095
39	39,304,974	330,551,692	177,014	548,911,249,019	13267	4,500	1	1	143,747	-225,711	756,795	802,712	0.009	0.017	1	0.3020	200,542	0.031400674414
40	39,365,176	330,572,165	177,748	548,909,896,130	23533	4,800	1	1	140,736	-215,774	755,583	798,293	-0.011	-0.034	1	0.5152	176,148	0.028626687553
41	39,364,893	330,572,790	177,775	548,909,896,137	24400	4,900	1	1	141,019	-216,399	755,556	798,486	-0.003	-0.026	1	0.5149	177,167	0.027017749237
42	39,366,607	330,571,758	177,747	548,909,869,334	24133	4,800	1	1	140,439	-214,767	755,579	797,964	0.004	-0.019	1	0.5149	177,211	0.027921564682
43	39,367,727	330,571,427	177,735	548,909,855,932	22933	4,900	1	1	139,886	-214,134	755,588	797,706	0.002	-0.024	1	0.5156	174,804	0.028839877011
44	39,367,436	330,572,062	177,738	548,909,855,939	24933	4,600	1	1	140,176	-214,769	755,585	797,924	0.001	-0.015	1	0.5141	180,004	0.028160091627
45	39,365,871	330,572,246	177,773	548,909,882,736	25067	4,900	1	1	140,608	-215,554	755,555	798,184	-0.005	-0.029	1	0.5152	176,170	0.026333200807
46	39,366,310	330,572,407	177,764	548,909,869,341	23800	4,800	1	1	140,735	-215,417	755,562	798,175	0.005	-0.017	1	0.5145	178,443	0.028278029411
47	39,365,580	330,572,887	177,782	548,909,882,743	25867	4,600	1	1	140,898	-216,195	755,547	798,401	-0.000	-0.022	1	0.5146	178,316	0.027136158563
48	39,366,023	330,573,036	177,760	548,909,869,348	27000	4,700	1	1	141,022	-216,046	755,566	798,400	0.008	-0.012	1	0.5140	180,452	0.025414387928
49	39,365,287	330,573,529	177,784	548,909,882,750	28667	4,500	1	1	141,191	-216,837	755,545	798,625	0.008	-0.017	1	0.5146	178,164	0.025017904467
50	39,365,730	330,573,686	177,784	548,909,869,355	29533	4,600	1	1	141,315	-216,696	755,541	798,605	0.007	-0.036	1	0.5170	169,678	0.023868830190
51	39,366,854	330,573,344	177,758	548,909,855,953	26000	4,800	1	1	140,758	-216,051	755,565	798,354	0.001	-0.069	1	0.5208	156,476	0.026187396996
52	39,367,145	330,572,703	177,759	548,909,855,946	28133	4,500	1	1	140,467	-215,410	755,564	798,129	-0.001	-0.007	1	0.5127	184,864	0.025430088296
53	39,367,498	330,573,503	177,777	548,909,842,559	24733	4,900	1	1	140,682	-215,910	755,544	798,283	-0.017	-0.139	1	0.5254	136,438	0.027210494217
54	39,367,785	330,572,869	177,759	548,909,842,552	27000	4,500	1	1	140,395	-215,276	755,562	798,078	-0.013	-0.026	1	0.5140	180,130	0.026570055577

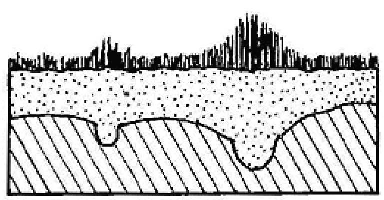
826ALL | 826_incidence | Sayfa3

Figure 4.8 : First step of radiometric calibration process for strip 302.

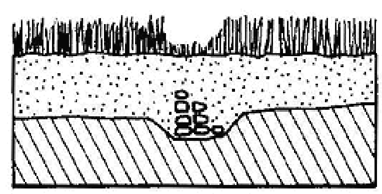
5. COMPARISON OF ALS AND OTHER DATA SOURCES

The scope of the PhD thesis is analyzing active remote sensing technology, based on ALS data to extract buried archaeological traces in a comparable way. The main method is radiometric calibration of ALS data to utilize the additional properties of FWF ALS data, “echo width” and “echo amplitude”. The reflectance property of ALS data was obtained after a series of applications by using these properties.

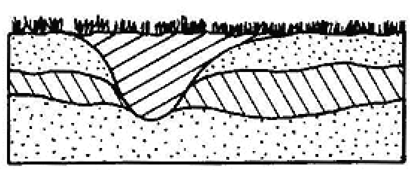
A huge amount of study regarding archaeological evaluation covers the analysis of photogrammetric products, i.e. orthophotos for years. As mentioned in the literature part, by using the orthophotos acquired at proper time (for DTM in leaf-off season or for crop marks before harvesting etc.) it is possible to trace ancient cultures by interpreting the signs arising from buried archaeological remains or by using the shadowing affects and/or DTM evaluation for extracting existing remains over the surface. As depicted in Figure 5.1a, if there is any hole in subsurface, the crops are healthier and longer over the surface because of more soil and water content.



a) Positive Crop Marks



b) Negative Crop Marks



c) Soil Marks

d) Shadow Marks

Figure 5.1 : Examples of crop marks (a,b); soil marks (c) and shadow marks (d).

Contrary if subsurface includes any structure, e.g. wall, part of settlement, the soil amount decrease and crop growth could be interrupted, and these are considered to be "negative crop marks" (Figure 5.1b). Different types of soils can result with different water content (Figure 5.1c). Shadow marks (Figure 5.1d) can occur areas showing the traces of deposits on the surface, deep ploughing is one of the reasons of this visibility (Url-8).

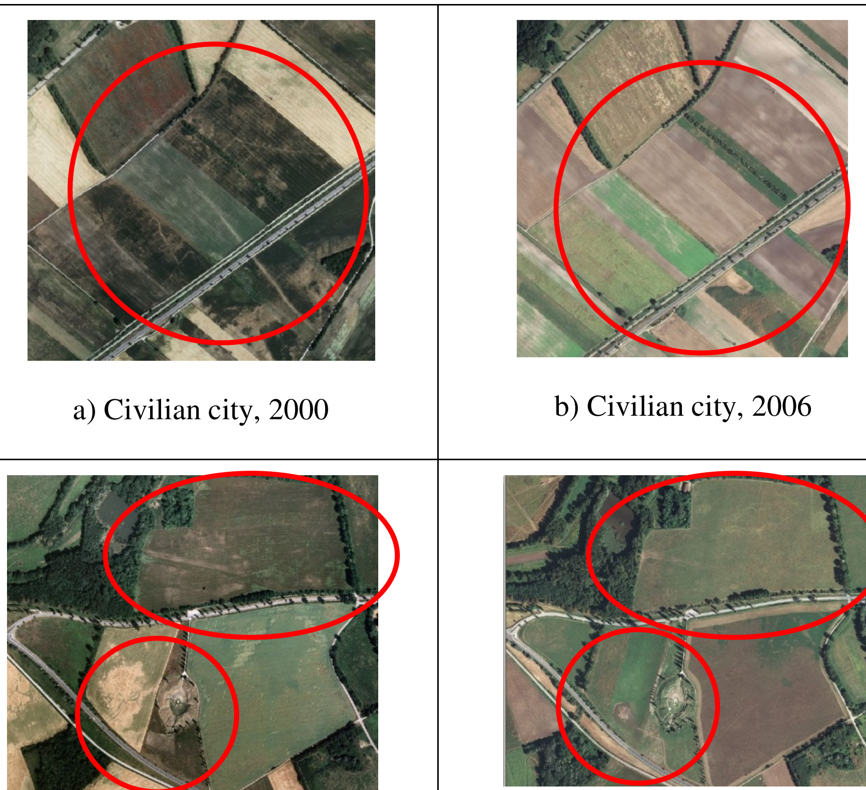
Archiving and producing (or update) the maps of existing archaeological remains are also one of the reasons of all these researches and studies. Currently, there are archaeological remains over the surface, such as thermal bath in civilian city and amphitheatres both in civilian and in legionary city in Carnuntum. The prior analysis is depended on visually analysis of existing orthophotos by comparing the legionary city plan (Jobst, 1983). Therefore*, the first analysis* was based on tracing crop marks and achieved visually by inspecting the orthophotos, ALS data ALOS PALSAR and TerraSAR-X radar images in comparison to legionary city plan of Carnuntum (Jobst, 1983; Michel Doneus) and Niederösterreich Atlas (Url-9). There are two orthophotos of Carnuntum belong to two different years, June 2000 and August 2006 (Figure 5.3). In the orthophoto acquired in year June 2000 (Figure 5.2), the subsurface archaeological settlement and ancient road in Bad-Deutsch Altenburg are clearly visible by crop marks (Figure 5.2a, Figure 5.3a and Figure 5.3c). This situation was checked by using the settlement plan of the legionary part (Figure 5.2b and Figure 5.4).

a) Ancient road, 2000

b) Legionary city plan

Figure 5.2 : a)Crop marks in orthophoto 2000 b)Carnutnum city plan from Jobst, 1983.

In orthophotos August 2006, the crop marks are not visible as orthophoto June 2000 (Figure 5.2b-d). It is most likely related to the harvesting time of the crops. This confirms that the acquisition time of the optical imagery plays an important role for identifying crop marks and detecting of subsurface remains (Figure 5.2).



a) Civilian city, 2000

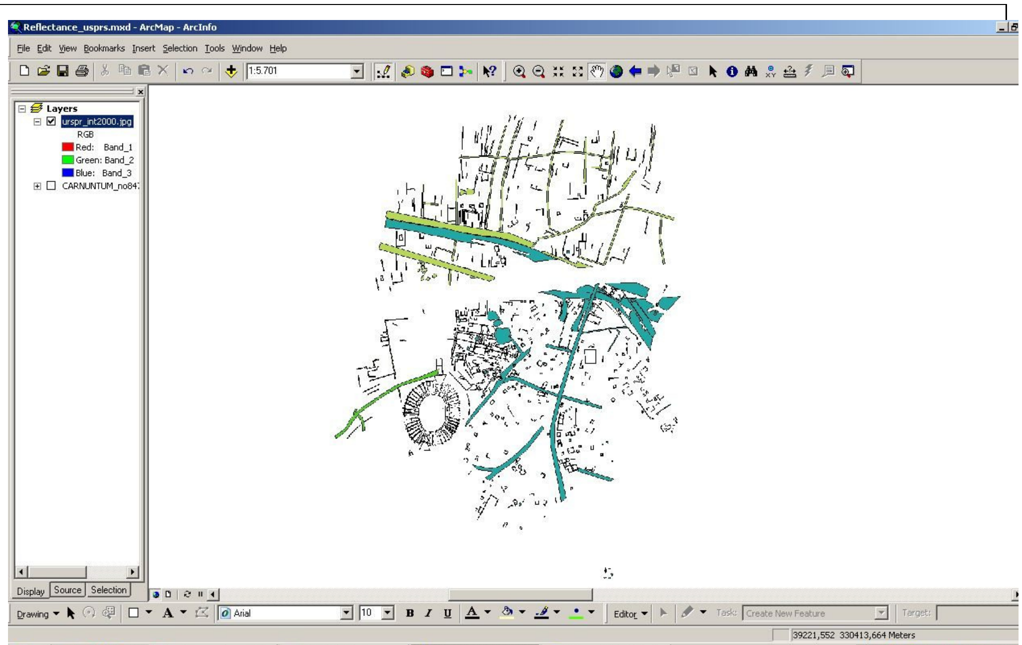
b) Civilian city, 2006

c) Civilian city, 2000

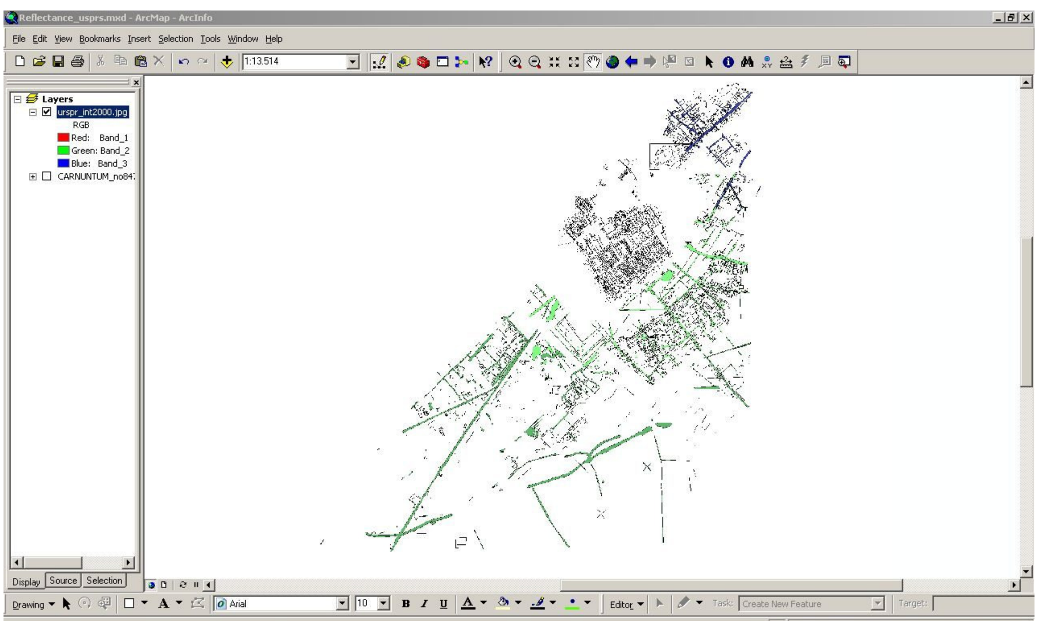
d) Civilian city, 2006

Figure 5.3 : Comparison of orthophoto 2000 and 2006.

Consequently, orthophoto belongs to 2006 was not used in comparable analysis of different data sources in latter steps of this PhD thesis. Additionally, Carnuntum city plan, which was obtained from Michel Doneus by face to face interview, was in use within the Ph.D study (Figure 5.4).



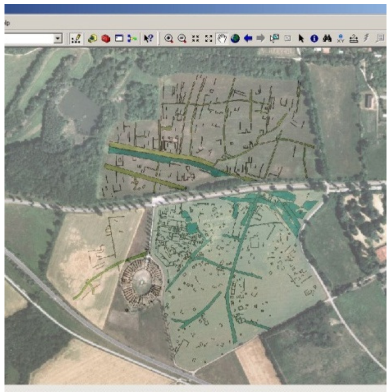
a) Civilian city part



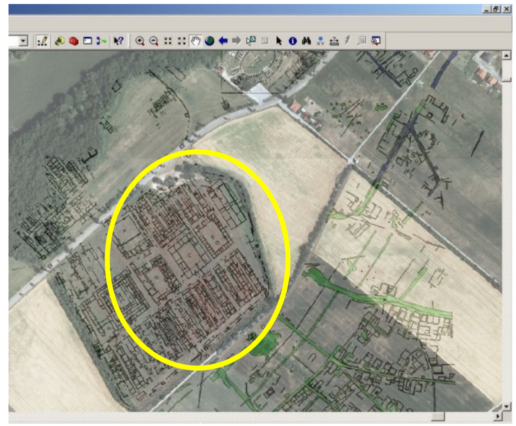
b) Legionary city part

Figure 5.4 : City plan digitized by using ancient plans and orthophotos.

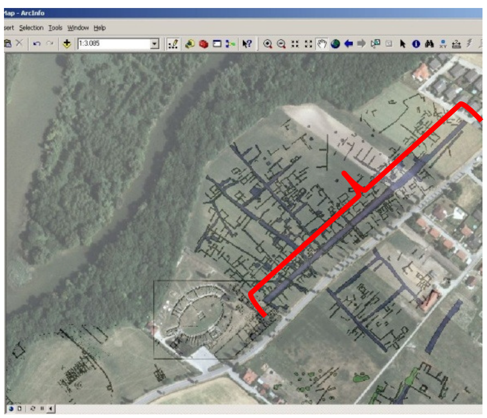
This vector plan covers integrated information from digitization of orthophotos, ancient Carnuntum city plan and ancillary information (books, archives etc.). This plan and obtained ancillary information were used to check the signs extracted from other data sources visually by using ArcMap (Figure 5.4).



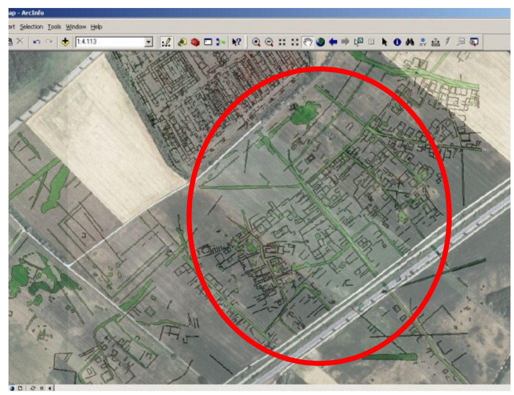
a) Civilian city



b) Legionary city, settlements



c) First amphitheatre



d) Legionary city, structures

Figure 5.5 : Overlapping areas in orthophoto 2000 and city plan of Carnuntum regarding crop marks.

In Figure 5.5, it is clearly visible the overlap traces of buried and existing remains between orthophoto from year 2000 and Carnuntum plan in different parts. Figure 5.5a shows the civilian city buried structures and 2nd amphitheater overlapping with the crop marks of orthophoto 2000 in most places, Figure 5.5b depicts less overlapping signs concerning crop marks but the red soil color is another trace to follow in legionary city-settlement area (yellow circle). Moreover, the old path (red bracket) and some other remains are also overlapped with crop marks in Figure 5.5c, Figure 5.5d covers some crop marks of buried structures around red circle.

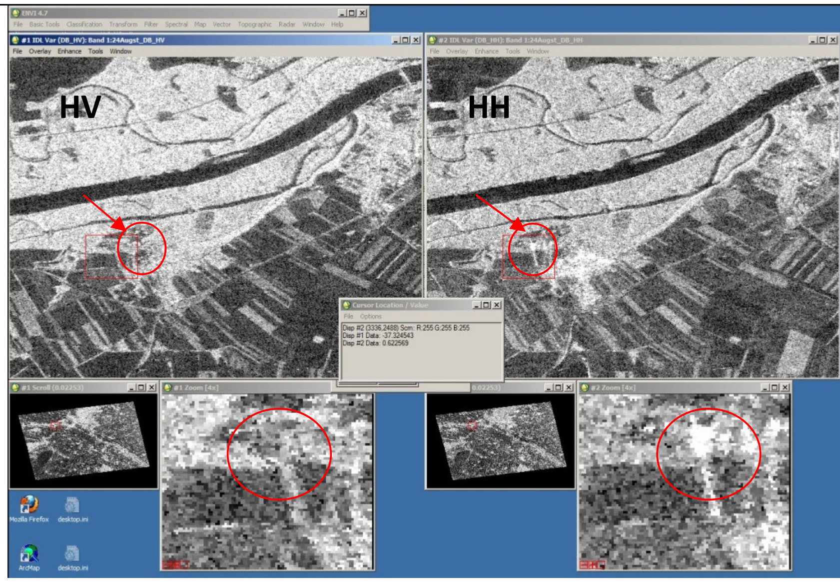
In every visual analysis within the PhD thesis, the Carnuntum plan was used as main data source to check the obtained results from other data sources. As a result of this step, it could be mentioned that one of the main analysis with orthophotos that has been in use for years in Archaeology and becomes a conventional data source, is still an important data source to trace ancient civilizations. Another important aspect is the importance of archiving ancient maps and plans as well as written documents to discover buried remains.

The second analysis of the thesis is based on comparing the traces from radar images (ALOS PALSAR and TerraSAR-X) with Carnuntum plan, Niederösterreich Atlas and orthophoto. The use of radar data are new data sources for Archaeological studies (especially in our country). ALS data is a newer data source so, the analyses of ALS in a comparable way constitutes the last analysis part of the thesis. ALOS PALSAR is the first radar data source studied for extracting buried remains in Carnuntum.

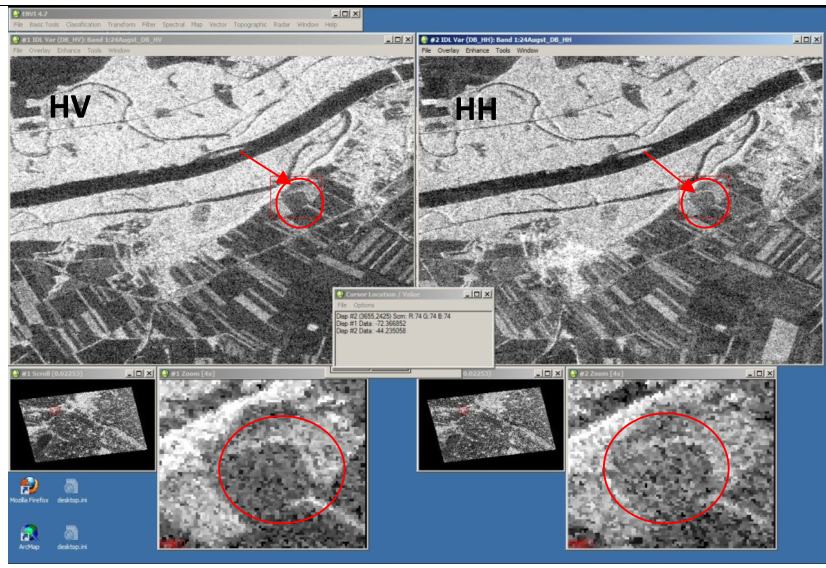
ALOS PALSAR data preprocessing steps were implemented in SARscape extension of ENVI (licensed to Institute of Remote Sensing and Photogrammetry Institute, Vienna University of Technology). The latter step covers the process to reduce the speckle effect and to improve the image interpretability of PALSAR images. Multilook tool was used and then geocoding was achieved in SARscape - ENVI. The common process step in radar studies for a more convenient visualization, converting the quantity of interested data in deciBels (dB) was achieved. Interactive Data Language (IDL) code was used for each polarization mode (HH and HV) individually. The equation for this purpose is as below, where $б_0$ refers the resulting radar image and β refers the radar image before the process (5.1).

$$(б_0) = 10*\log_{10}(\beta) \tag{5.1}$$

Then adaptive filtering options were achieved in ENVI software and the best result was obtained in "Local Sigma Filtering" with (3 × 3) window size (Figure 23). The differences between HH and HV polarization data are obvious in Figure 23. HH image is able to distinguish the distinct landscape types in a better way. As it seems in HV image, the existing modern settlement area seems like a part of the forested area but the backscatter differences is more detectable in HH image (Kurtcebe et al., 2010).



a) Thermal bath, Petronell



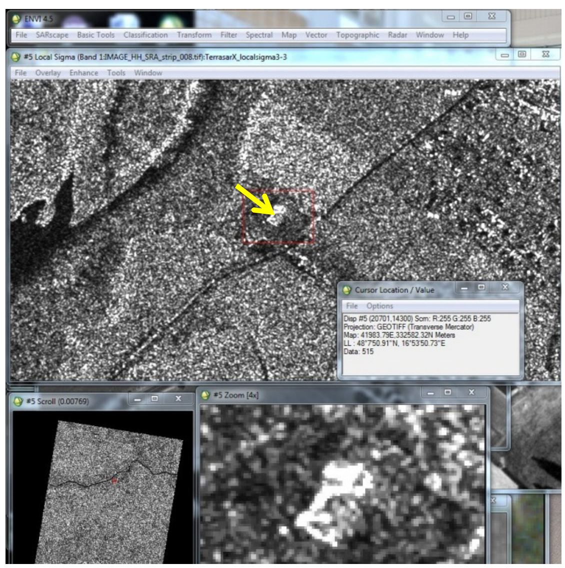
b) Legionary settlement, Bad-Deutsch Altenburg

Figure 5.6 : The result of Local Sigma Filtering after dB conversion.

In HH and HV radar images, around the first amphitheatre in Bad-Deutsch Altenburg and the thermal bath in Petronell (Figure 5.6a and Figure 5.6b) higher brightness values were identified in especially in HH polarization data. So the in latter steps HH polarization was used during analyses and comparison.

The second radar data source, TerraSAR-X HH polarized data was also converted to dB, which has higher spatial resolution than ALOS PALSAR.

a) 1st amphitheatre in ALOS PALSAR

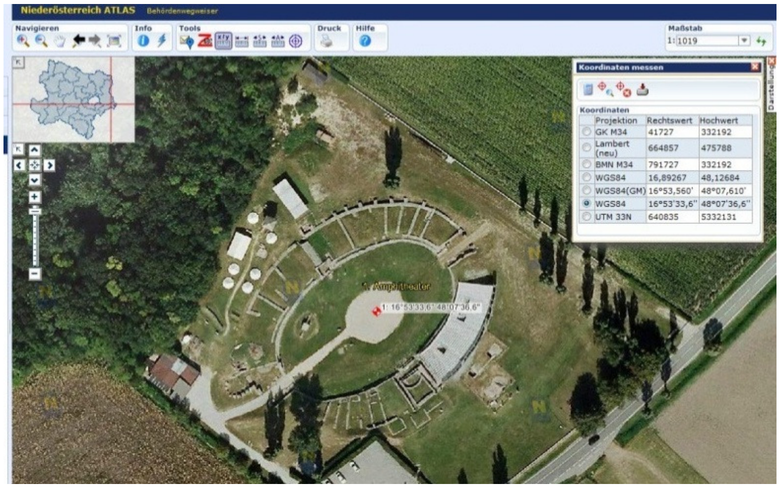


b) 1st amphitheatre in TerraSAR-X

Figure 5.7 : Trace of first amphitheater.

Firstly, depending on the location of existing archaeological remains (amphitheaters) was analyzed by using suspicious bright areas in both radar images. For that aim, the location of these areas was checked by comparing the obtained planimetric coordinates from radar data with the coordinates from Niederösterreich Atlas and Orhophoto 2000. The brighter areas in radar data are the traces followed and by using this approach, the coordinate of brightness in both radar data suspected to be a part of first amphitheater in legionary city was followed. The coordinate values are

(Figure 5.7a-b): ALOS PALSAR : Latitude: *48º 07' 48.12"* / Longtitude: *16º 56' 52.11"* TerraSAR-X : Latitude: *48º 07' 50.91"* / Longtitude: *16º 53' 50.73"*



a) 1st amphitheatre in Niederösterreich Atlas

b) 1st amphitheatre in Orhophoto 2000

Figure 5.8 : Coordinate comparison; 1st amphitheatre.

The coordinate values are (Figure 5.8a-b):

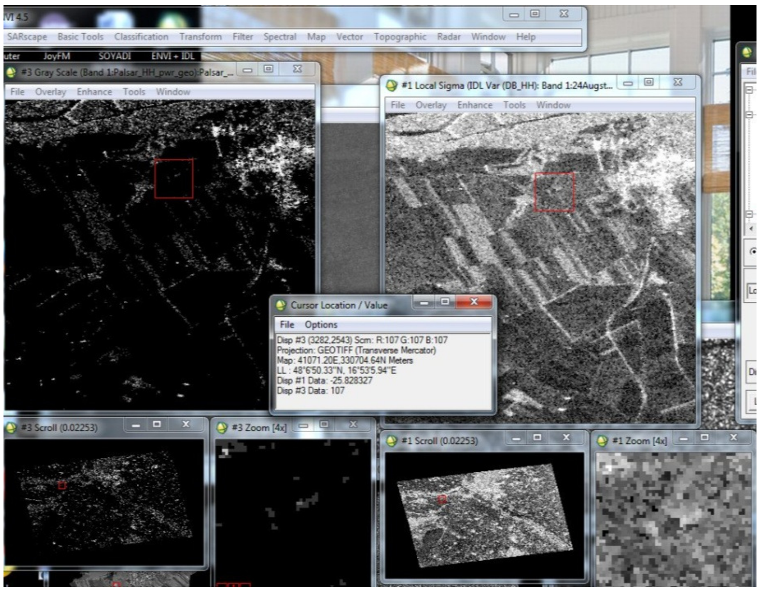
Niederösterreich Atlas : Latitude: *48º 07' 36.6"* / Longtitude: *16º 53' 33.6"*

Orhophoto 2000 : Latitude: *48º 07' 43.24"* / Longtitude: *16º 54' 14.79"*

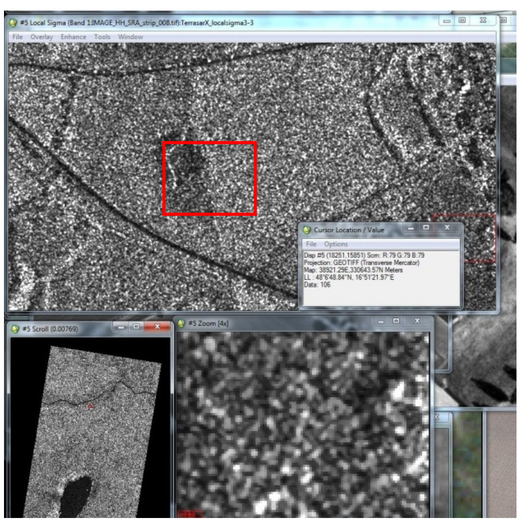
The second amphitheater was also analyzed in the same way. The coordinate of amphitheater results are obtained from radar images and then NÖ Atlas and Orthophoto 2000 respectively (Figure 5.9a-b and Figure 5.10a-b):

ALOS PALSAR : Latitude: *48º 06′ 50.33″* / Longtitude: *16º 53′ 5.94″*

TerraSAR-X : Latitude: *48º 06′ 48.84″* / Longtitude: *16º 51′ 21.97″*



a) 2nd amphitheatre in ALOS PALSAR

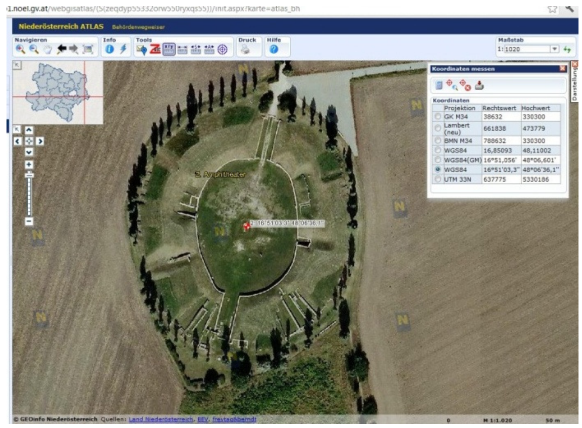


b) 2nd amphitheatre in TerraSAR-X

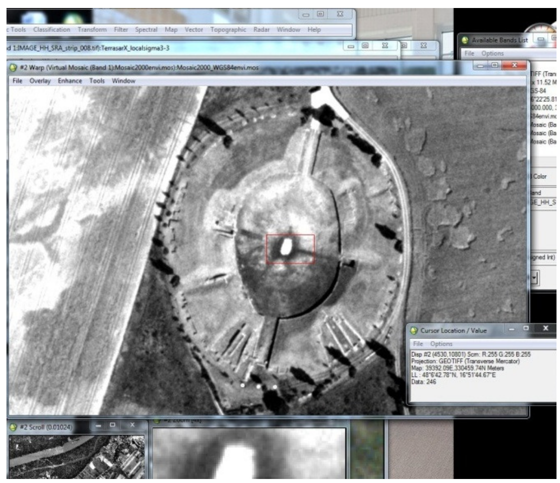
Figure 5.9 : Coordinate comparison; 2nd amphitheatre.

Niederösterreich Atlas : Latitude: *48º 06' 36.1"* / Longtitude: *16º 51' 03.3"*

Orhophoto 2000 : Latitude: *48º 06' 42.78"* / Longtitude: *16º 51' 44.67"*



a) 2nd amphitheatre in Niederösterreich Atlas



b) 2nd amphitheatre in Orhophoto 2000

Figure 5.10 : Coordinate comparison; 2nd amphitheatre.

Coordinates obtained from Orthophoto 2000 and NÖ Atlas were assumed as the base information regarding archaeological remains (here amphitheaters) above the ground. The comparable analysis of these base data and radar data is resulted with promising outcome. The coordinates matched up in seconds' degree Table 5.1).

Table 5.1 : Coordinates from Amphitheaters.

Data Sources	1.Amphitheater		2. Amphitheater	
	Latitude	Longtitude	Latitude	Longtitude
NÖ Atlas	48º 07' 36.6"	16º 53' 33.6"	48º 06' 36.10"	16º 51' 03.3"
ALS	48º 07' 38.31"	16º 53' 38.21"	48º 06' 37.72"	16º 51' 7.90"
City Plan	**48º 07' 38.19"**	**16º 53' 37.95"**	**48º 06' 37.83"**	**16º 51' 7.93"**
TerraSAR-X	48º 07' 36.46"	16º 53' 34.04"	48º 06' 35.92"	16º 51' 05.20"
ALOS PALSAR	48º 07' 36.72"	16º 53' 31.42"	48º 06' 36.34"	16º 51' 01.05"
Orthophoto	48º 07' 38.27"	16º 53' 37.93"	48º 06' 37.77"	16º 51' 07.87"

Another question reveals concerning polarization capability; if we have different polarization data (here HH and HV in ALOS PALSAR), is it possible to extract some traces belong to buried remains? After visual analysis of both HH and HV polarization, it was decided to use HH polarization because of its advantage of visual analysis as mentioned before. However, it was proceed from our study that by using the low spatial resolution radar data, it is not so applicable to trace buried archaeological structures even in HH polarization data without any other data source. It was visually identified that some suspicious bright areas which location is approximately matched up with ancient Carnuntum structures but it is not appropriate and feasible to define the exact location because of low spatial resolution. There are two traces, the first one belongs to the ancient road in legionary city-near 1st amphitheater, and the second trace approximately match up with a part of ancient structures buried in legionary city part of Carnuntum (Figure 5.11).

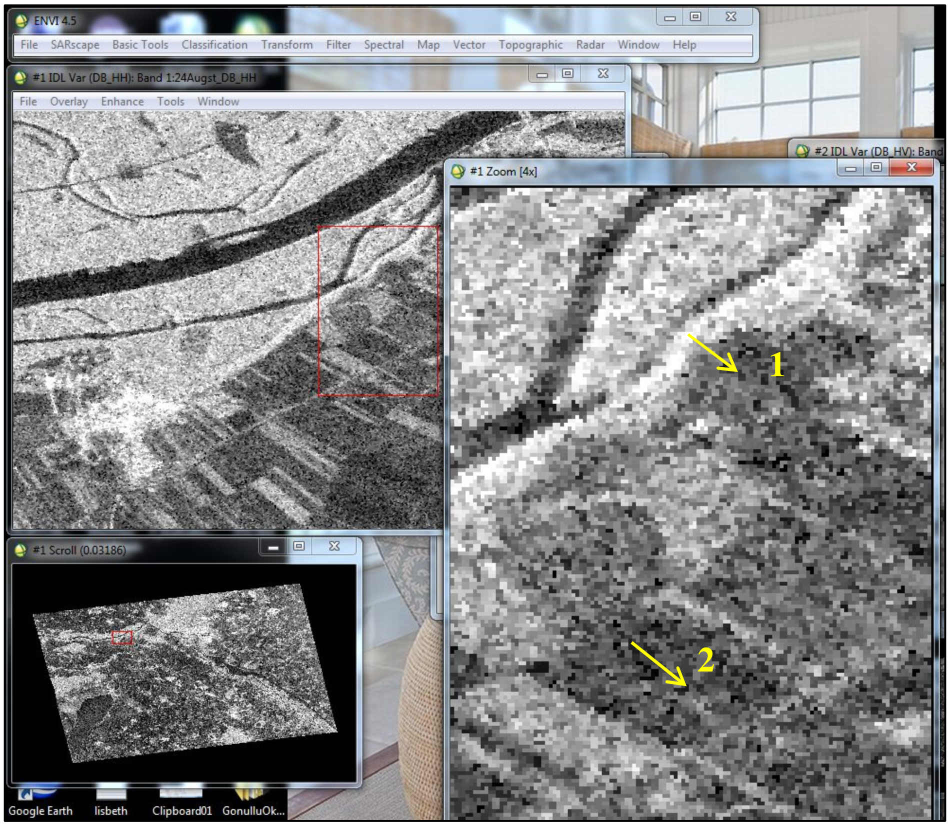


Figure 5.11 : ALOS PALSAR, archaeological traces.

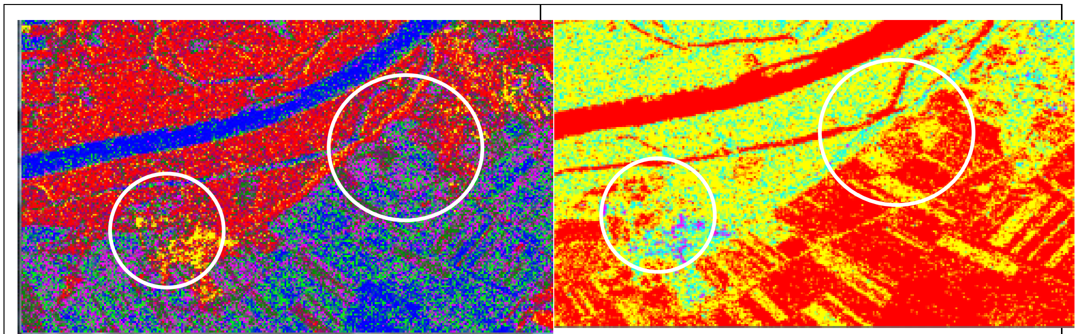
The main result obtained from the first analysis is the HH polarization data of ALOS PALSAR can be useful and can provide results more than the HV polarization data in terms of archaeology in similar topographies. For detecting individual features or remains having geometric dimesion less than 12.5 meters in size, spatial resolution of PALSAR is not enough. But for groups of buildings or for ancient settlement investigations in a region wide, ALOS PALSAR image is helpful as a complementary data considering by the different polarization option.

The other analysis was implemented to ALOS PALSAR data. The question here; except visual analysis, is it possible to get more results by using classification? *So, the third analysis* was achieved by implementing supervised and unsupervised classification techniques of ALOS PALSAR data. The Maximum Likelihood Supervised Classification by using two bands (HH-HV) of PALSAR was performed with using 7 classes as given in Table 5.2. KMeans Unsupervised Classification (Figure 5.12b) depicted more reliable result than ISODATA classification in terms of quantitiy of data that was classifed. The results of Maximum Likelihood Supervised

(Figure 5.12a) and Kmeans Unsupervised Classification have some common anomalies as depicted. Areas covered by circles exist some archaeological remains over ground and buried archaeological remains.

Table 5.2 : Classes in Supervised Classification.

Class	Color	Explanation
1	Red	Forest
2	Green(light)	Cropland 1
3	Green(dark)	Cropland 2
4	Magenta(dark)	Ancient settlement (known area)
5	Magenta(light)	Ancient settlement (known area)
6	Blue	Water body
7	Yellow	Current settlement area



a) Maximum Likelihood Supervised Classification

b) KMeans Unsupervised Classification

Figure 5.12 : Classification results of ALOS PALSAR.

Spatial resolution is higher in TerraSAR-X data (1.25m). This option provides advantage to utilize in evaluation of traces of archaeological remains. Similar processing steps were implemented (except classification) and comparing with ALOS PALSAR data and city plan, visually, it is possible to differantiate the amphitheatre easily. In ALOS PALSAR data visual analysis, it was hard to trace the buried structure of ancient city and only some brightness was obtained (Figure 5.11, 1st and 2nd arrows). In TerraSAR-X, comparing to obtained result of PALSAR in Figure 5.11 (1st arrow) and the city plan (Figure 5.4b), the bright area is wider which covers the buried remains (Figure 5.13, red rectangle).

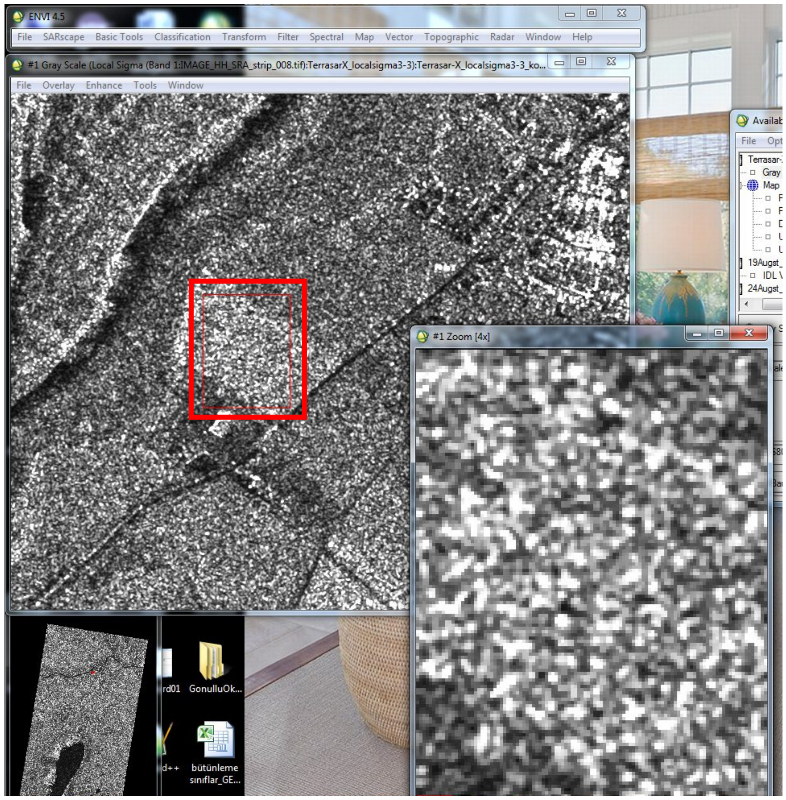


Figure 5.13 : TerraSAR-X, trace in legionary city.

The obtained results point out that despite it is still important to have additional data source to analyze the results, the new outcomes of radar technology provides promising results in topographies like Carnuntum. The usage of radar image mainly arose as a tool in arid areas to extract linear anomalies (i.e. paleochannels) but within the thesis, radar images reference the buried remains not as individual remains (i.e. artefacts) but as reflectance properties (brightness) in an area. The newer data source for archaeological studies is airborne laser scanning technologies. Since the main usage of ALS data is topographic modeling, analysis the additional properties of system is getting more important for different disciplines, such as archaeology. The main idea is analyzing the ALS data after radiometric calibration regarding to traces of buried archaeological remains. Therefore, *the last analysis* is based on evaluation of calibrated ALS data. The detailed radiometric calibration steps were explained in section 4.2. As mentioned, by using natural surface targets, the all ALS data strips were calibrated and reflectance result was obtained as well as other outcomes (backscatter cross section, backscattering coefficients etc.) by using gray palette for more convenient visual analysis (Figure 5.14).

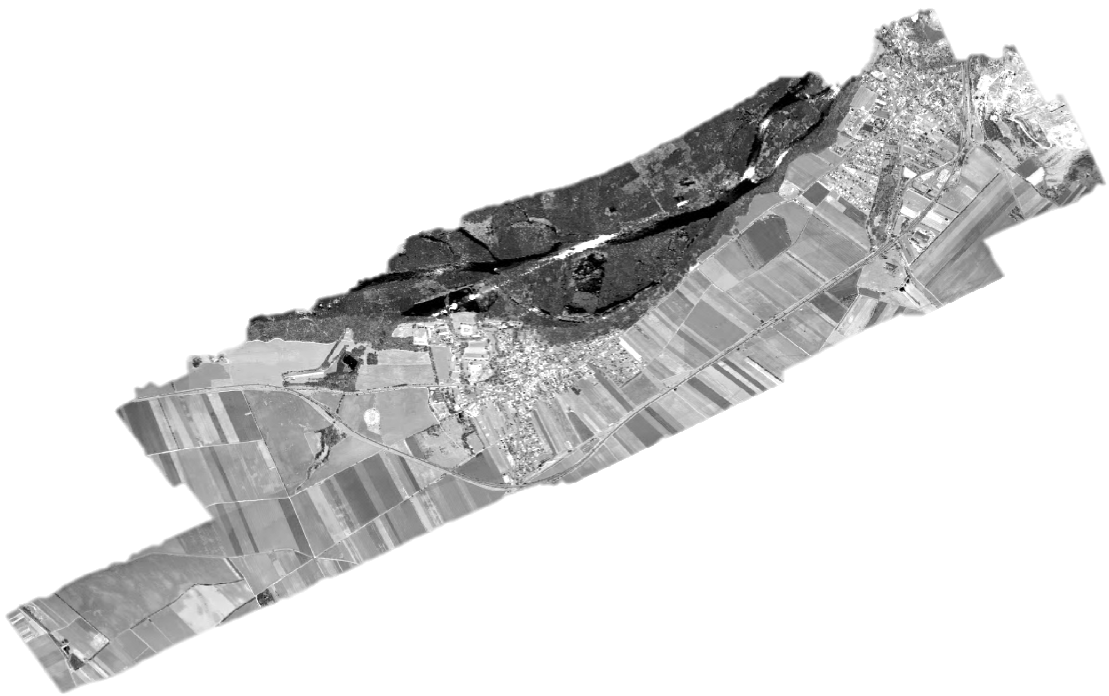
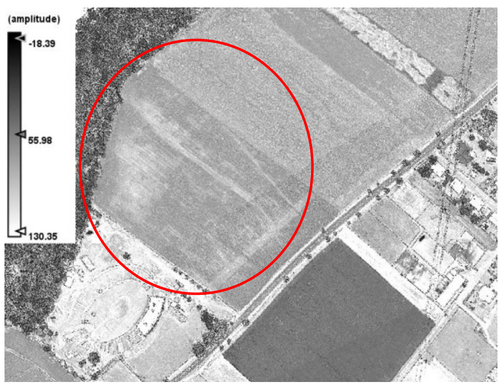


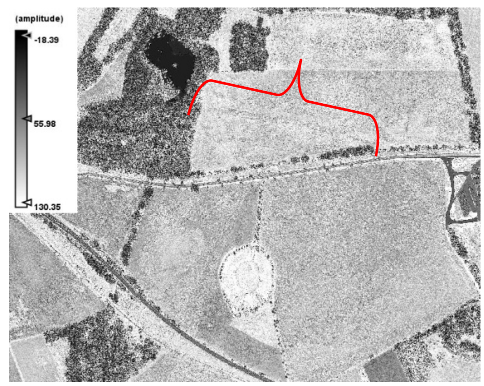
Figure 5.14 : Reflectance property of Carnuntum after radiometric calibration.

a) Reflectance result

b) Reflectance result



c) Filtered reflectance result



d) Filtered reflectance result

e) DTM-shading result of ALS data

f) DTM-shading result of ALS data

Figure 5.15 : Amphitheatre in legionary city (left side); amphitheater and surroundings in civilian city (right side).

The result of the process of whole Carnuntum is shown in Figure 5.15. Individual result of each 14 strips is in Appendix G.

Figure 5.15a depicts the first amphitheater in legionary city. Figure 5.15a and 5.15b show the main result after radiometric calibration. For a better interpretation, reflectance result was filtered by using different filtering methods (i.e. ENVI adaptive filters, NEST filters for detecting lines etc.). Visually better interpretable results, Figure 5.15c and 5.15d were obtained after filtering the reflectance result in NEST software by using Sharpen-High Pass filtering in 3×3 window size. The brighter areas, which are suspicious areas regarding buried remains of Carnuntum, are more visible in this result (within red circle and bracket).

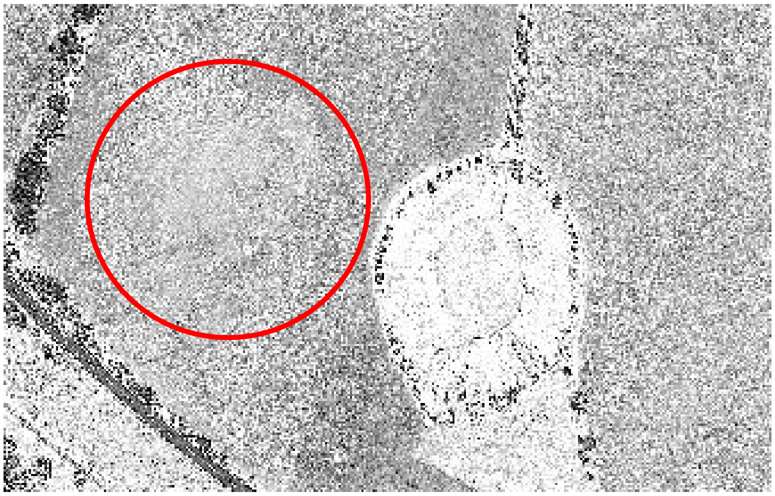
Most common conventional data analysis is based on evaluation of DTM and shaded relief of topography in archaeological studies. Differences in height will be a trace of ancient structure (settlement, tumulus etc.). Hill-shading related topography also a method to extract anomalies of topography. Figure 5.15e is the shaded relief of DTM of ALS data, which was generated in the first steps of ALS data processing. In visual analysis, amphitheater is detectable in Figure 5.15b but the traces of ancient road, which is more visible to naked eye (within red circle) in shaded relief of the same topography (Figure 5.15f), is not visible. On the contrary reflectance result (Figure 5.15a) includes the traces belong to buried remains within red circle whereas it is not possible to trace these signs in shaded relief result (Figure 5.15e). The linear anomaly in Figure 5.15b is easily detectable both in reflectance and in shaded relief results (red brackets in Figure 5.15b and Figure 5.15f). This anomaly refers to the ancient road depending on ancient city plan (Figure 5.4).

a) Shaded-DTM

b) Filtered reflectance result

Figure 5.16 : Comparison between reflectance and shaded-DTM results of Carnuntum.

Another trace of ancient structures is easily selectable in filtered reflectance result (Figure 5.16b). On the contrary, regarding the same signs and for the same topography, DTM is not effective and appropriate to trace buried structures (Figure 5.16a). Similar result is shown in Figure 5.15e; linear signs of buried structures are not visible in derived DTM. Nevertheless, amphitheater and some linear signs are visible in DTM (Figure 5.15f). Conventionally derived DTM and shading methods usage is useful in some parts of the topography, but the main process includes elimination of vegetation and regarding crop marks or soil marks, new approaches are required to analyze in a comparable way related areas in terms of archaeological studies. Another important point is; the area around Carnuntum is covered with field and ALS data was obtained in June, after the harvesting time. Especially in conventional studies, orthophotos should be taken just before the harvesting time to trace the crop marks. However, in ALS data (after radiometric calibration), even after the appropriate data acquisition period, it is still possible to extract crop marks.



a) Reflectance result (filtered)

b) Reflectance result

Figure 5.17 : Traces in reflectance result.

There is a brighter area in Figure 5.18a-b on the left side of second amphitheater (in civilian city). Similar brightness exists in different parts of reflectance result but when a comparable analysis was achieved by using ancillary information and plans, the anomaly seemed suspicious regarding buried remains. The brighter area is also visible as anomalies (linear in east and fuzzy shapes in northwest side of amphitheater) of topography in orthophotos (Figure 5.17b). The LBI-ArchPro team was suspicious about the linear anomaly was a part of the main road between the second amphitheater and some buildings on the eastern side. The western side has some shadowy area that was seemed like pointing out a large building. The team then surveyed the some parts of Carnuntum by GPR technique to investigate the profiles of underground (Url-11). In spring 2011, the results were announced that Gladiator school (Figure 5.18a) was found west-northwest side of second amphitheater as buried in 3 meters depth. (Url-12).

a) GPR results (Url-12)

b) Orthophoto 2000

Figure 5.18 : Buried remains of Carnuntum in orthophoto and GPR result.

6. RESULTS

The results obtained from comparison of all data sources can be summarized as follows:

1. The first result obtained from the study is the HH polarization data of Radar data can be useful and can provide results more than the HV polarization data in terms of archaeology in similar topographies to Carnuntum.
2. For detecting individual features or remains having geometric dimension less than 12.5 meters in size, spatial resolution of ALOS PALSAR is not enough. But for groups of buildings or for ancient settlement investigations in a region wide, ALOS PALSAR images are helpful as a complementary data considering by the different polarization option. All earth features, natural or man made structures are influenced from different polarization mode that can be a distinguishing property in archaeological studies. It was not studied over interefometric capabilities of ALOS PALSAR but it can be also an additional method to produce DTM of study area. This option can be also useful in comparison with other data sources in topographic modelling of the archaeological study area and can be used to investigate the archaeological remains.
3. TerraSAR-X has higher spatial resolution (1.25 m) but filtering results are not enough to give any exact location or geometry of any buried Carnuntum structres as well as ALOS PALSAR.
4. It is also important to choose the most appropriate data acquisition time. Since Radar instruments is functional in all weather conditions and 24 hour a day, the resulting data can be affected by the crop growth or by the dense vegetation. This affects will change the backscatter. So the seasonal affects in terms of related vegetation in study area should be considered carefully in the acquisition date of radar. However it is also functional to have temporal radar data to make a time series analysis.

5. Another aspect is that the study area (Carnuntum) is located near the Danube River and it is an agricultural area with forest and some modern settlements. Radar images are especially useful in arid areas, because the radar backscatter is sensitive to the water content in the soil. The second influential factor for the radar backscatter is the roughness of the terrain. It is thus not surprising, that in the supervised classification the water class and croplands were depicted as integrated areas.
6. ALS results can be evaluated in two parts: hill shaded DTM and reflectance result produced from calibrated ALS data. Produced DTM has some linear traces on buried archaeology just around the second amphitheater and covers the traces of existing amphitheaters. Hovewer after visual analysis, it was discovered that linear traces belong to buried ancient structures were extended in Carnuntum area more than traces in DTM result. Moreover amphitheaters can be identified visually. In addition to more accurate DTM, by using reflectance model of related area, it is possible to extract traces of buried remains.
7. Significiant another result gained from the study is, considering by the aim and the topography of the study area, it is more convenient and accurate approach to obtain data from different data sources or to make the archaeological plan in terms of different archaeological prospection technologies. Because it is significant to prove and support any individual data source in acomparable way, e.g. by using high resoluted images, orthophotos and plans of ancient culture and with ancillary data. It is recommended to obtain Orthophotos, Hyperspectral or Thermal data and Radar data next to ALS data due to the financial aspects and topographical properties of study area in macro or small scale projects. By analyzing these integrated data, more reliable and accurate results in terms of buried archaeological remains can be obtained.
8. For more objective comparison, coordinate match was checked by using two amphitheaters of Carnuntum by using all data sources (Table 6.1). from the center of amphithetaters, latitude and longtitude values were taken. It was easy to determine center of amphithetaters by using ALS, Orthophoto and NÖ Atlas and city plan. However in Radar images this selection was just executed on brighter areas, which were defined as traces of amphithetaers.

City plan coordinates were selected as main coordinates, which was obtained from Michel Doneus, archaeolog studies over Carnuntum for years. The difference is minimum in orthophotos. Then respectively, ALS, TerraSAR-X, NÖ Atlas and ALOS PALSAR have differences from minimum to maximum level. The reason of high coordinate difference can be several concerning Radar images. As mentioned, the visible higher brightness could be the trace of amphitheaters. Concerning ALOS PALSAR, this mentioned approach was followed but because of low spatial resolution, it was just possible to select the bright pixels that could be a part of another illuminated target covering similar reflectance nature. Despite higher resolution, in TerraSAR-X, second theater was partly selectable with its shape.

It was not possible to interfere base coordinate system in NÖ Atlas, this could be the reason of high diffrence in coordinates (especially in longtitude).

Orthophotos were supposed to be the same or have difference in centimeters or less, however the difference includes differences from 2 cm to 3 meters. Orthophotos are geo-corrected and georeferenced data. During the geometric correction and georeferencing, it is possible to effect and decrease the radiometric capability of Air Photos. The convetional usage of Air Photos in Archaeology can be a solution to this problem. Air photos can be evaluated on archaeological traces, then related workflow can be implemented for orthophoto production.

ALS data is the secondary data source on coordinate differences. It is an important factor to choose ALS data in Archaeology. Particularly, more accurate height derivation than planimetric coordinates is a significant option to evaluate the DTM for hidden archaeological remains (both surface and subsurface remains). Moreover, it was proved the usability of radiometric calibration of ALS data for buried archaeology. Especially to extract information on large areas, ALS provides rapid and accurate data for Archaeology.

It was mentioned that the city plan was digitized by using orthophotos and ancillary data source. This information was verbally obtained. Errors during digitization or georeferencing can effect the result. It is a posibility that the coordinates obtained from city plan were effected by such an error.

Table 6.1 : Coordinate differences.

Amphitheaters	City Plan Coordinates		Differences between city plan and other data sources									
			Δ Orthophoto		Δ ALS		Δ TerraSAR-X		Δ NÖ Atlas		Δ ALOS PALSAR	
			"	m	"	m	"	m	"	m	"	m
1st Amphitheater	φ	48º 07' 38.19"	0.08	2.4	0.26	7.8	1.73	51.9	1.59	47.7	1.47	44.1
	λ	16º 53' 37.95"	0.02	0.6	0.12	3.6	3.91	117.3	4.35	130.5	6.53	195.9
2nd Amphitheater	φ	48º 06' 37.83"	0.06	1.8	0.11	3.3	1.91	57.3	1.73	51.9	1.49	44.7
	λ	16º 51' 7.93"	0.0.6	1.8	0.03	0.9	2.73	81.9	4.63	138.9	6.88	206.4

7. CONCLUSIONS AND RECOMMENDATIONS

The conventional methods have been used in Archaeology for years are Geodetic surveying methods, Photogrammetry and Remote Sensing. Especially Aerial Photogrammetry and Remote Sensing provides detailed properties of the area. Moreover, concerning buried remains, orthophotos, oblique and vertical photographs are in use to get traces from the ground surface. In this PhD thesis, firstly this conventional approach was achieved by using orthophotos of Carnuntum from two different years. There are several signs/traces used to extract information from the images; crop marks, shadow marks and soil marks. It was possible to differentiate crop marks within PhD thesis but just by using one of the orthophotos (from year 2000) covering these crop marks. Depending on the data acquisition date, the crop marks can be visible or not. If the harvesting time is just before data acquisition, it is possible to get crop marks, but after the harvesting time, these signs get lost. The orthophoto from year 2006 is dated after the harvesting time so it was not adequate to analyze regarding to crop marks. The crop marks regarding to ancient city Carnuntum were easily revealed after visual analysis of the orthophoto 2000 (Figure 5.5). These crop marks are the hints of buried structures (roads, buildings) of Carnuntum and existing (over ground) amphitheaters are also selectable. The results of analysis were checked in comparable way by using Carnutnum plan and ancillary information. As expected from previous studies in the literature, the crop marks were matched with buried remains that are also visible in Figure 5.2 and Figure 5.5.

Active remote sensing is the main study area of the thesis. In addition to Photogrammetry, Remote Sensing is another significant tool for mapping, exploring, archiving and planning archaeological studies. Within this PhD thesis, Radar and ALS data were also analyzed regarding buried remains. Concerning Radar data, ALOS PALSAR and TerraSAR-X images were obtained. Previous studies with radar data mainly arose in arid areas regarding to archaeology. Nowadays, the additional radar properties have started to be studied, here polarisation of both radar data sources were analyzed on archaeologically investigated surface, especially concentrated on HH polarization. The first radar data was ALOS PALSAR including two polarization types; HH and HV. The study showed the HH polarization reveals more traces of ancient city. Despite its low spatial resolution, ground surface remains were identified and in some places, traces of buried remains can be extracted by using additional data source. Supervised and unsupervised classification techniques were implemented to radar data. The Maximum Likelihood Supervised Classification and KMeans Unsupervised Classification depicted result that is more reliable. There is an influential factor for the radar backscatter is the roughness of the terrain. It is thus not surprising, that in the supervised classification in ALOS PALSAR the water class and croplands were depicted as integrated areas (Figure 5.13). The latter radar data with higher spatial resolution, TerraSAR-X, HH polarization data was studied. The results do not include visible signs for analyzing concerning buried remains but covers the ground surface remains (amphitheaters). There are also some suspicious bright areas, which gives an impression just after a comparable analysis with other data sources (Figure 5.14). The study area (Carnuntum) is located near the Danube River and it is an agricultural area with forest and some modern settlements. Radar images are especially useful in arid areas, because the radar backscatter is sensitive to the water content in the soil. Despite this actual situation, polarization property of radar technology provides more information on related topography and further studies are required for better understanding this information. The second active remote sensing tool within the study is Airborne Laser Scanning. It is a newly tool regarding to archaeological studies comparing to other remote sensing tools. Preliminary studies based on the DTM generation and for the last decade, like radar tools, additional properties acquired by ALS systems have started to be one of the research areas to analyze archaeological remains. In addition to ALS data, spectrometer survey result to surface targets was obtained from IPF. Reflectance properties of Carnutnum ALS data was obtained after a series of process by using IPF software. Processed data later was coloured by using gray tones. The result is promising due to traces of buried remains. Despite, data acquisition was after harvesting, the signs are visible. The results were also compared with other data sources. Orthophoto and ALS results are similar to each other in terms of buried remains. Carnuntum plan and ancillary information was the first source for visual analysis. By using ground surface remains, the coordinate information was also checked between different data sources and they matched in seconds' degree.

The main question was the usage of active remote sensing tools for Archaeology, especially concentrated on calibrated ALS data. The prior result is, “yes, it is possible to use ALS data both in topographic modeling and reflectance properties of the topography”. This new opportunity provides the DTM with higher accuracy (±20cm planimetric/ ± 7,5cm vertical) accuracy and surface classification by using reflectance properties. Within PhD thesis, a study by using reflectance values for extracting buried archaeological remains was also investigated. The problem or secondary result is; if topography and ancillary information of the study area is not known sufficiently, any results of any data source cannot be evaluated alone properly by the interpreter. Therefore, considering by the aim and the topography of the study area, it is convenient and accurate approach to obtain data from different data sources and plan the archaeological study in terms of interdisciplinary approach. Comparable analysis of these different data sources result with a complementary and integrated outcome. By using these integrated data, more reliable and accurate results in terms of subsurface archaeological remains can be obtained. This integration and comparable data analysis requires a profession that is actually realized by personal efforts by learning from Geomatic fundamental tools (i.e. Geodesy, Cartography, GIS, GPS, Photogrammetry etc.) or by learning the basics of other disciplines archaeological studies required (Geophysical methods and tools, software programming etc.). The improvement in the technology and science force us to interdisciplinary approach. The lack of collaborative studies brings out to analyze the data and convert it to information/knowledge process. Regarding archaeological studies, this requirement is obvious. Archaeology utilizes different methods and technologies based on diverse disciplines to plan, manage, analyze and archive in lots of steps in any archaeological project. The prior ones are; Geomatics, Earth Sciences and Informatics next to Archaeological knowledge and its own tools. Archaeology use Geomatic techniques for years. These different techniques, methods and technologies of Geomatics are:

Land survey including GPS, Photogrammetry and Remote Sensing,

Cartography and GIS for evaluating and mapping even in different screens and different generalization techniques,

Land Management is a significant part of any project studies the land. On the other hand, for geophysical-geological or for any chemical-biological analysis Earth

Sciences is prior. Programming, virtual reality, computer graphics are very important in archaeological analysis and for remodeling ancient live. There is actually one integration part between Basic Sciences and Archaeology; Archaeometry. This approach represents a bridge between archaeology and the natural and physical sciences. This collaborative study area covers a wide variety of disciplines but mainly focused on cooperation between social and natural sciences including, museum curators to historians, provenance of ceramics and metals, DNA analysis etc. (Url-13; Url-14). However, this concept usually refers the analysis of natural sciences and excludes that there is also a requirement of "spatial data approach covering all related techniques, tools and management" of any archaeological study. Thus, a new postgraduate study (Figure 7.1) stemmed from spatial data profession (Geomatics and Earth Sciences) and specialized on Archaeological aspects is offered. This collaborative approach is prior to follow new technologies and scientific methods, which can be implemented regarding the requirements of any Archaeology study.

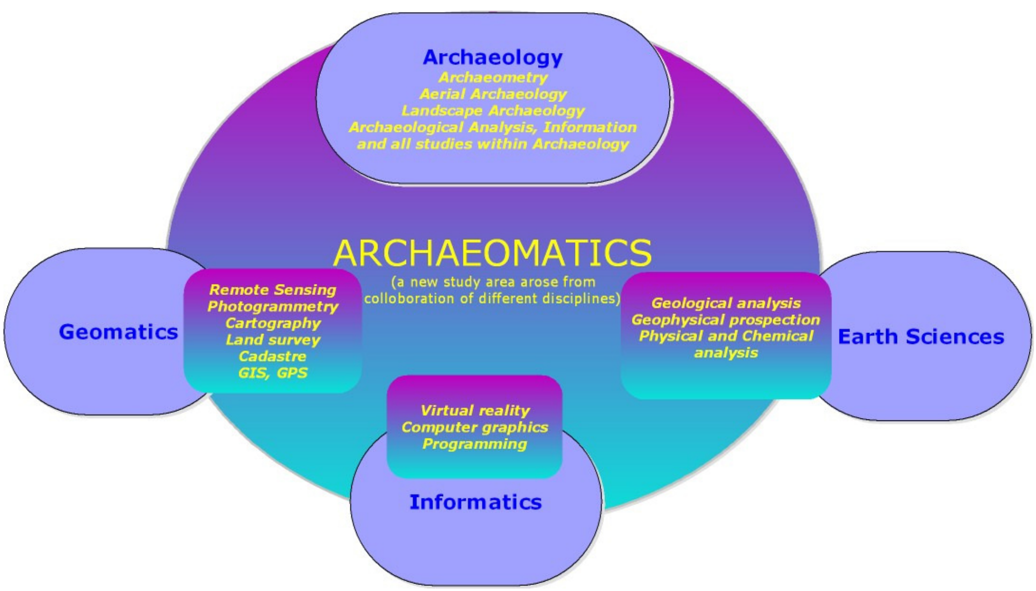


Figure 7.1 : Components of Archaeomatics.

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Url-10 <*http://nest.array.ca*>, date retrieved 02.06.2012.

Url-11 <*http://archpro.lbg.ac.at/* >, date retrieved 13.09.2012.

Url-12 **<***http://carnuntum.7reasons.at*>, date retrieved 13.09.2012.

Url-13 <*http://www.itarp.uiuc.edu/* >, date retrieved 14.09.2012.

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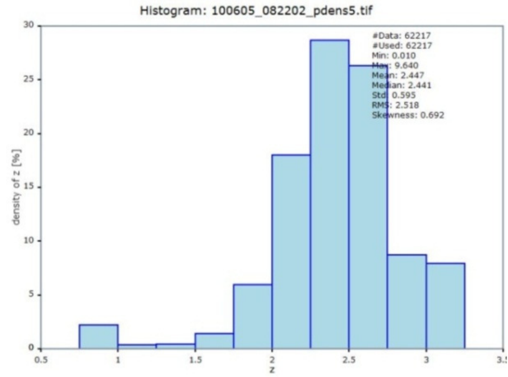
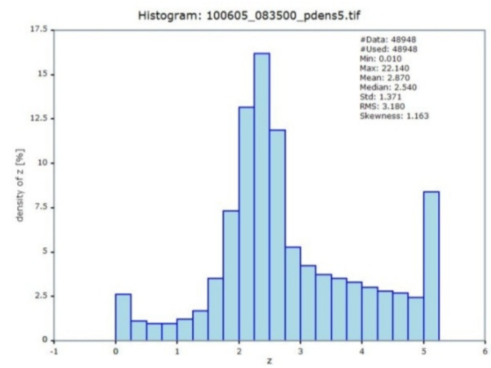
APPENDICES

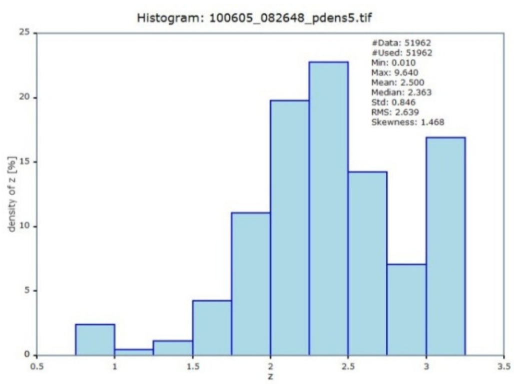
APPENDIX A: Histograms of ALS point density per strip.



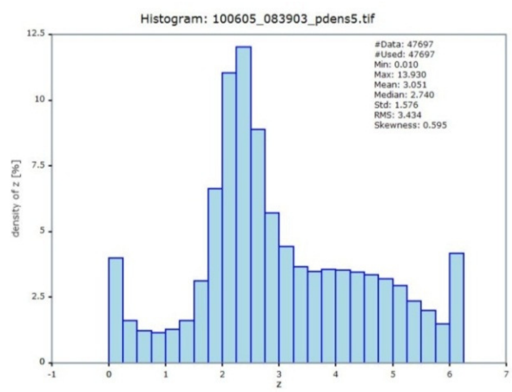
Point Density of Strip 301



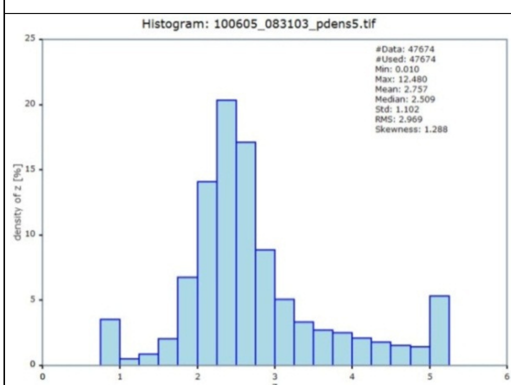
Point Density of Strip 304



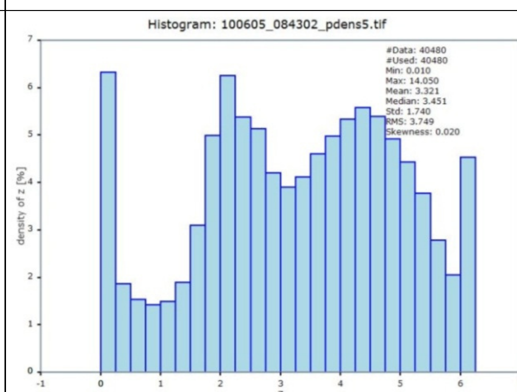
Point Density of Strip 302



Point Density of Strip 305

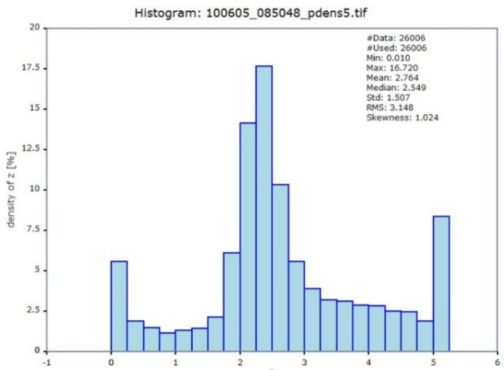


Point Density of Strip 303

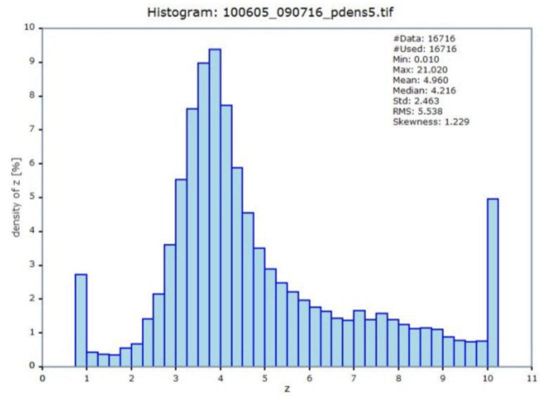


Point Density of Strip 306

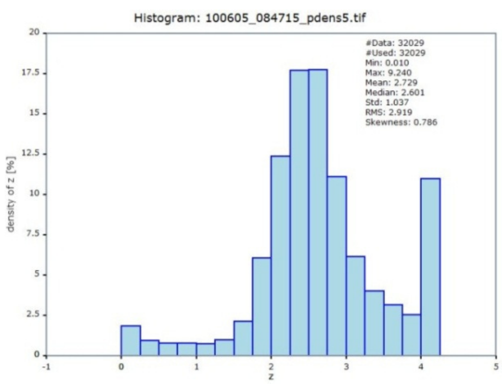
Figure A.1: Histograms of ALS point density per strip.



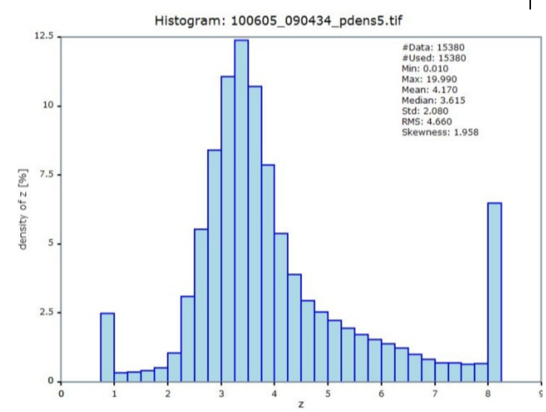
Point Density of Strip 307



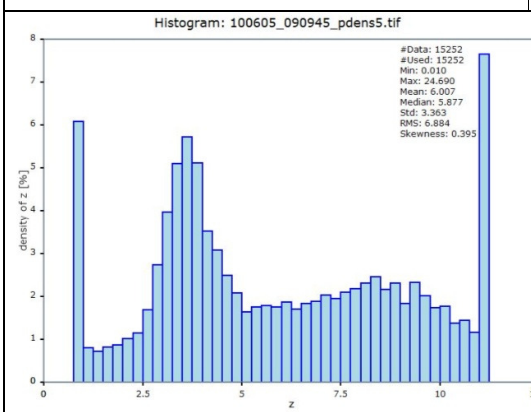
Point Density of Strip 111



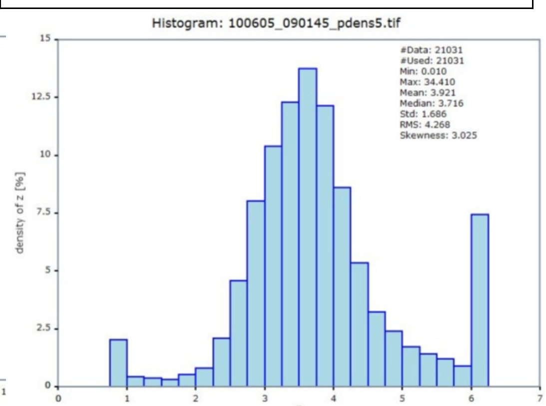
Point Density of Strip 308



Point Density of Strip 112

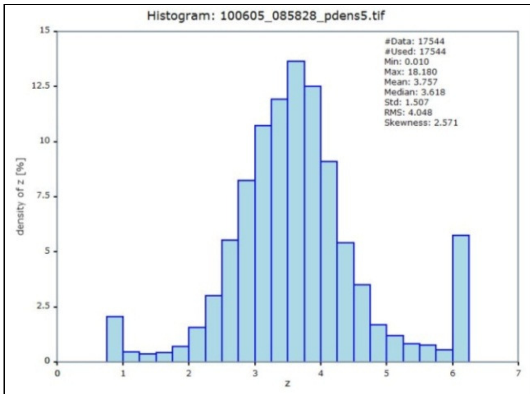


Point Density of Strip 110

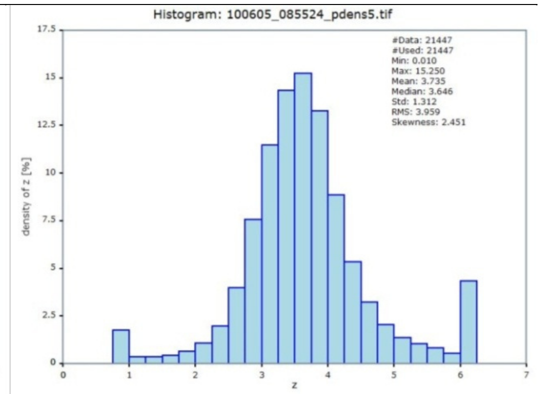


Point Density of Strip 113

Figure A.1 (continued) : Histograms of ALS point density per strip.



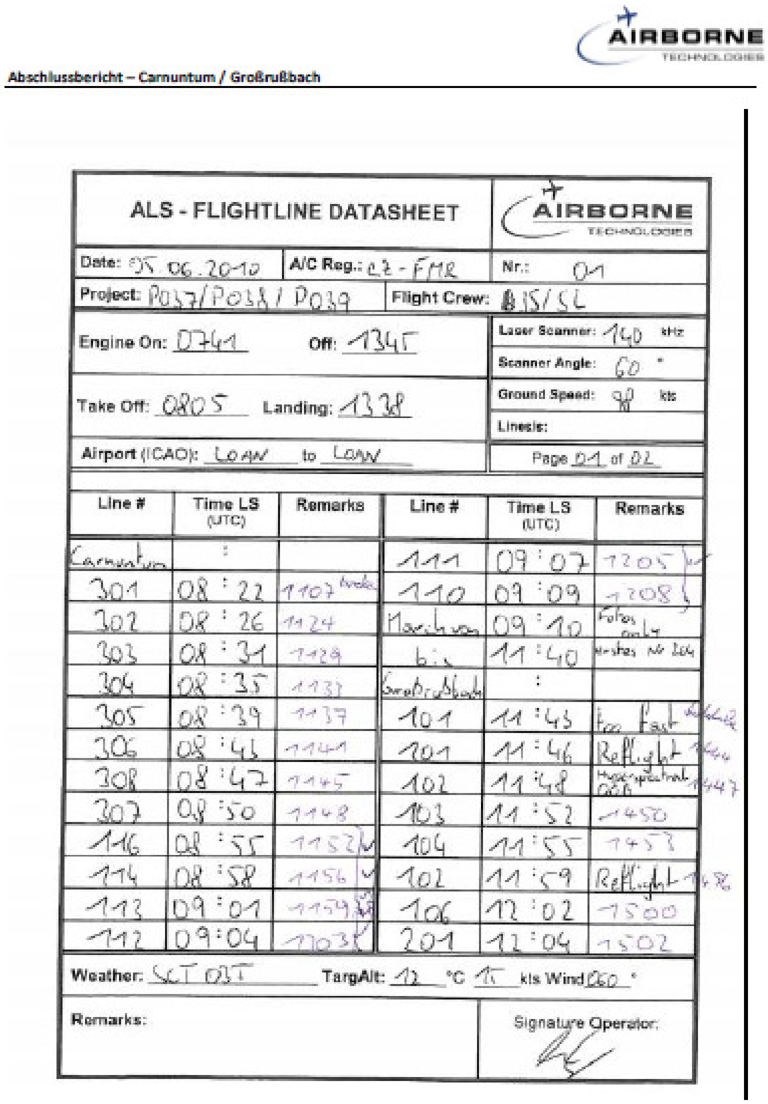
Point Density of Strip 114



Point Density of Strip 116

Figure A.1 (continued) : Histograms of ALS point density per strip.

APPENDIX B: Flightline data sheet.



Abschlussbericht – Carnuntum / Großrußbach

AIRBORNE TECHNOLOGIES

ALS - FLIGHTLINE DATASHEET

Date: 05.06.2010 | A/C Reg.: OE-FMR | Nr.: 01

Project: P037/P038/P039 | Flight Crew: [illegible]/SL

Engine On: 0741 Off: 1345

Laser Scanner: 140 kHz

Scanner Angle: 60 °

Take Off: 0805 Landing: 1338

Ground Speed: 90 kts

Line/s:

Airport (ICAO): LOAN to LOAN

Page 01 of 02

Line #	Time LS (UTC)	Remarks	Line #	Time LS (UTC)	Remarks
Carnuntum	:		111	09:07	1205
301	08:22	1107 [illegible]	110	09:09	1208
302	08:26	1124	Marchegg	09:10	Fotos only
303	08:31	1129	bis	11:40	[illegible] Nr 204
304	08:35	1133	Großrußbach	:	
305	08:39	1137	101	11:43	too fast [illegible]
306	08:41	1141	101	11:46	Reflight 1444
308	08:47	1145	102	11:48	Hyperspectral [illegible] 1447
307	08:50	1148	103	11:52	1450
116	08:55	1152	104	11:55	1453
114	08:58	1156	102	11:59	Reflight 1456
113	09:01	1159	106	12:02	1500
112	09:04	1203	201	12:04	1502

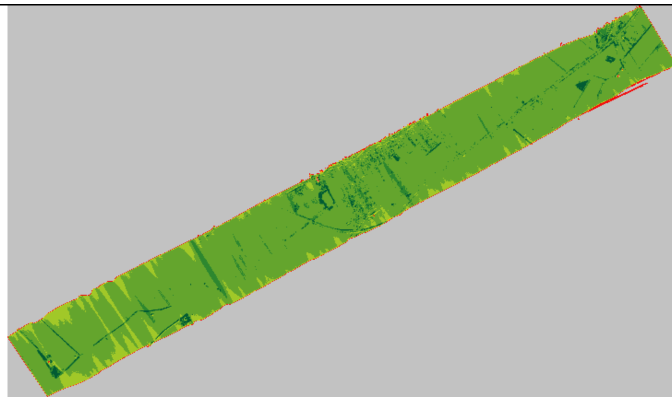
Weather: SCT 035 TargAlt: 12 °C 15 kts Wind 060 °

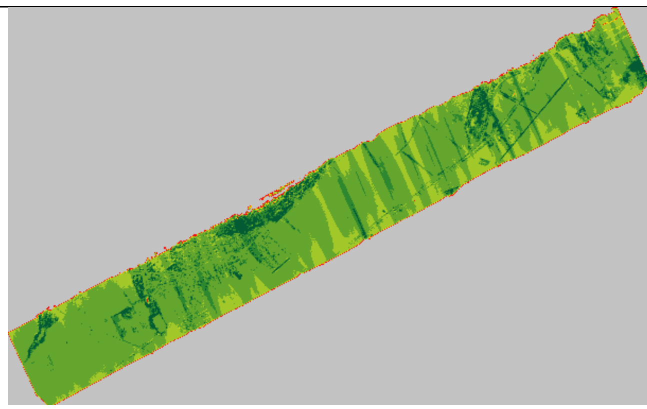
Remarks:

Signature Operator:

Figure B.1 : Flightline data sheet.

APPENDIX C: Coloured point densities per strip.


Point Density of Strip 301


Point Density of Strip 302

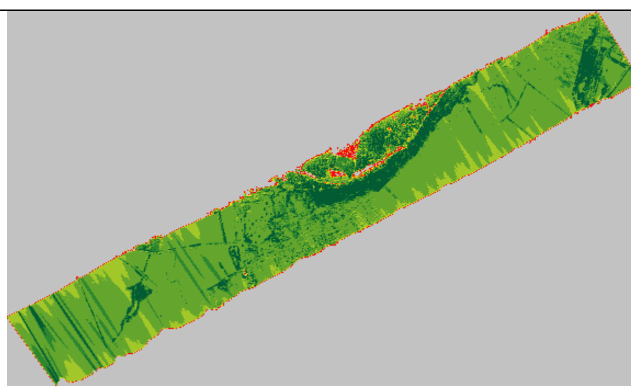
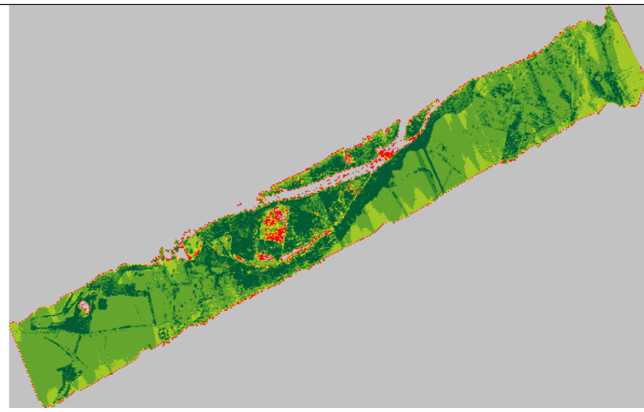
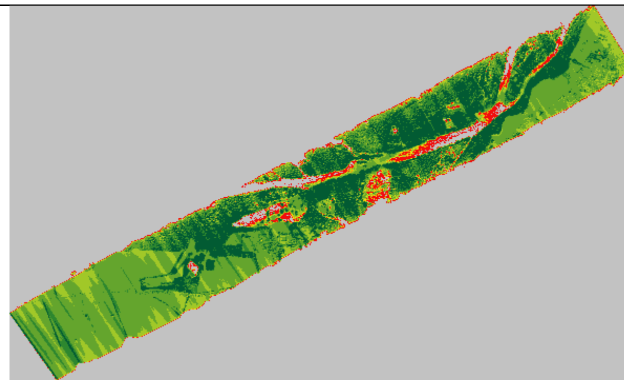

Point Density of Strip 303

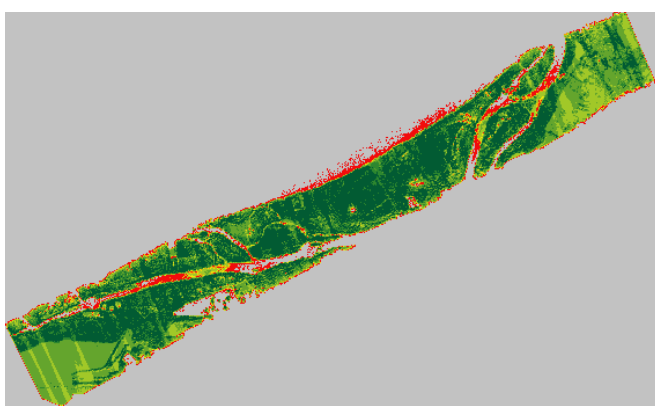
Figure C.1 : Coloured point densities per strip.



Point Density of Strip 304

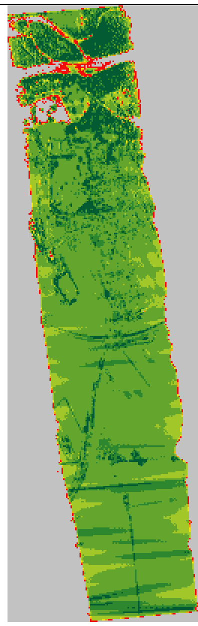


Point Density of Strip 305

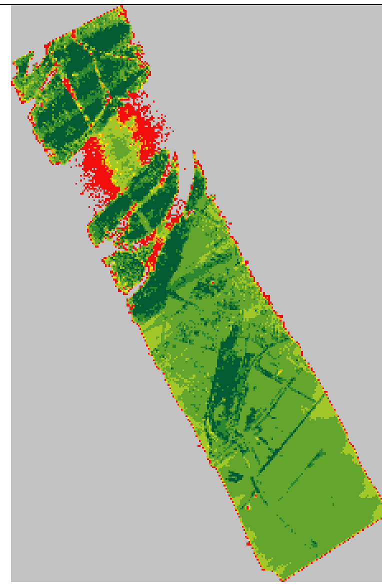


Point Density of Strip 306

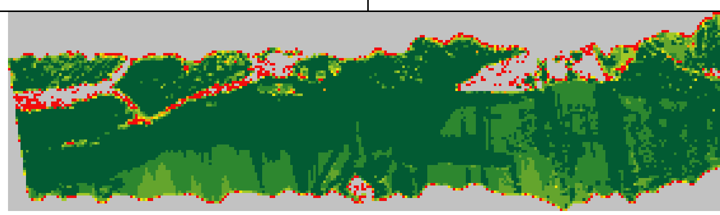
Figure C.1 (continued) : Coloured point densities per strip.



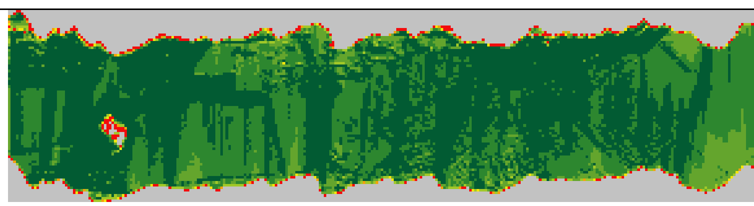
Point Density of Strip 308



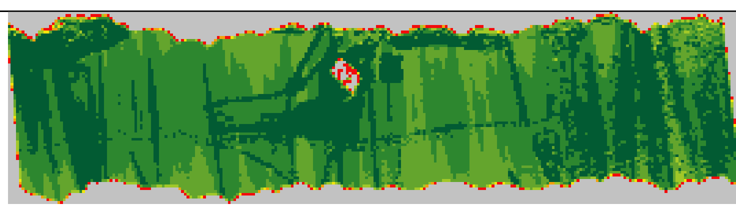
Point Density of 307



Point Density of Strip 110

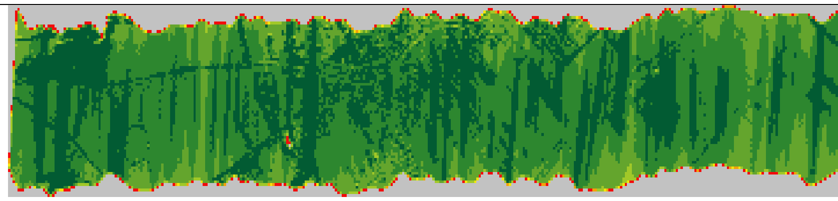


Point Density of Strip 111

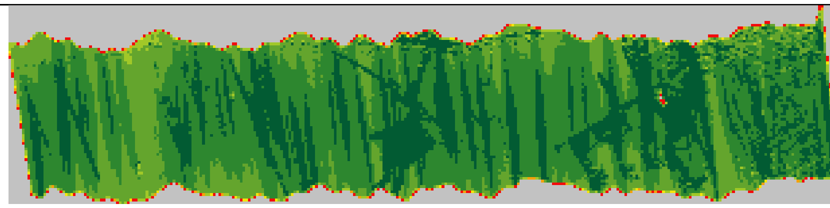


Point Density of Strip 112

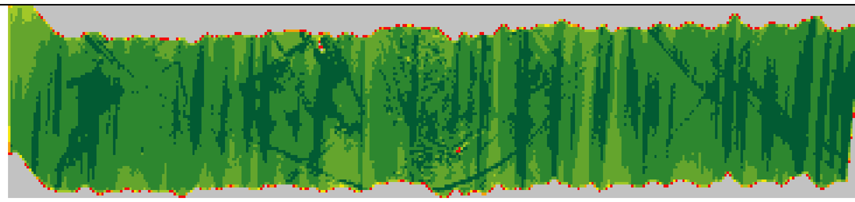
Figure C.1 (continued) : Coloured point densities per strip.



Point Density of 113



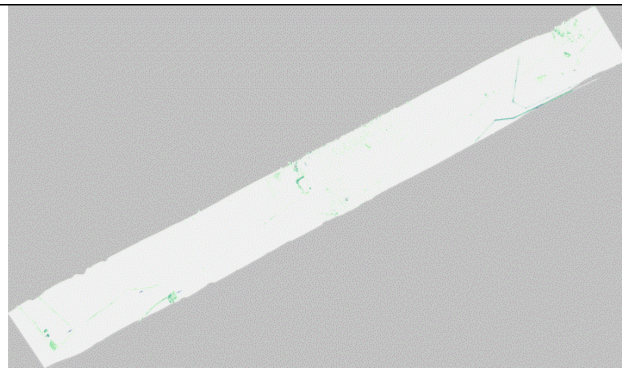
Point Density of Strip 114



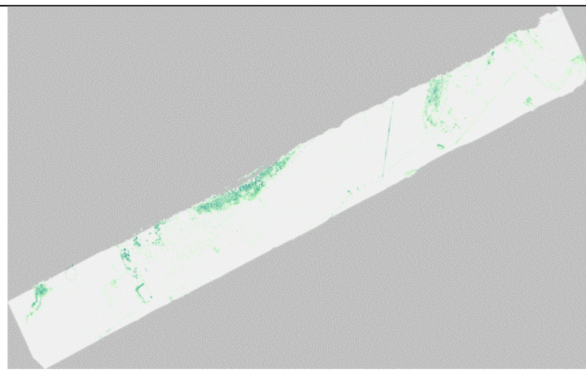
Point Density of Strip 116

Figure C.1 (continued) : Coloured point densities per strip..

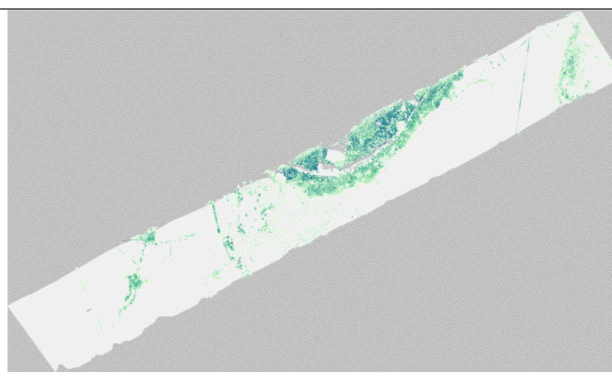
APPENDIX D: Coloured sigma-z results.



Sigma Z of Strip 301

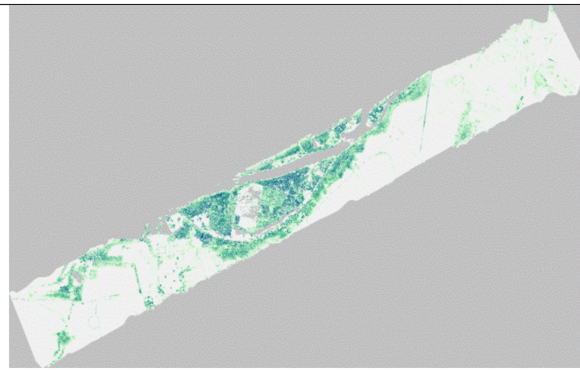


Sigma Z of Strip 302

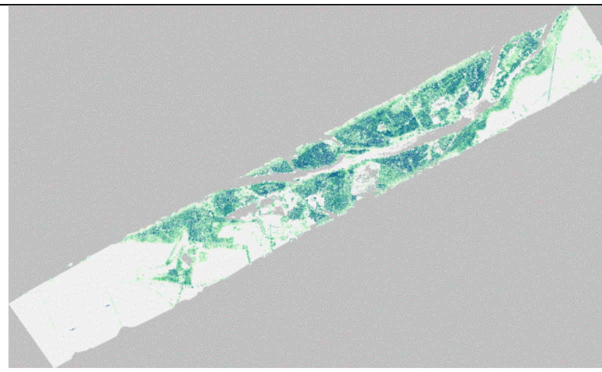


Sigma Z of Strip 303

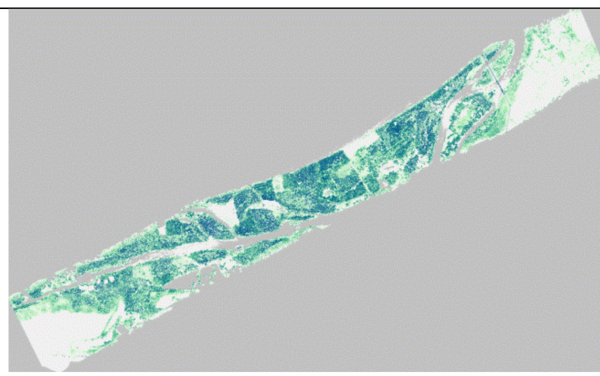
Figure D.1 : Coloured sigma-z results.



Sigma Z of Strip 304



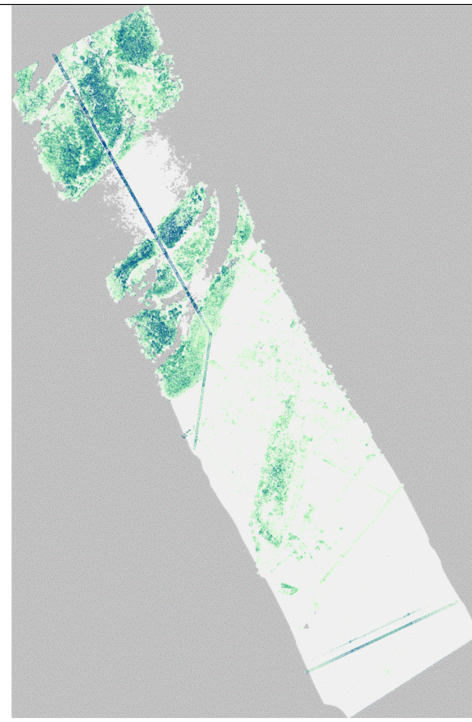
Sigma Z of Strip 305



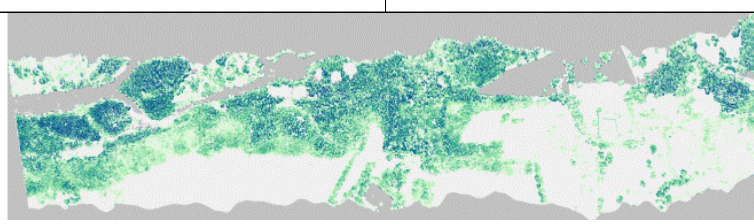
Sigma Z of Strip 306

Figure D.1 (continued) : Coloured sigma-z results.

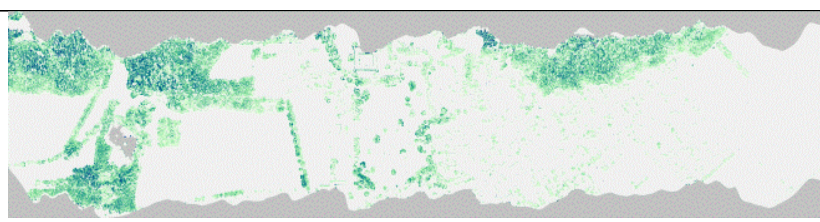
Sigma Z of Strip 308



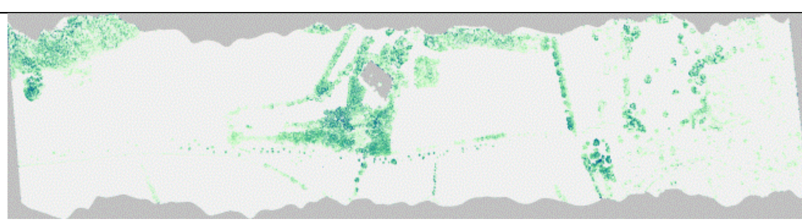
Sigma Z of 307



Sigma Z of Strip 110

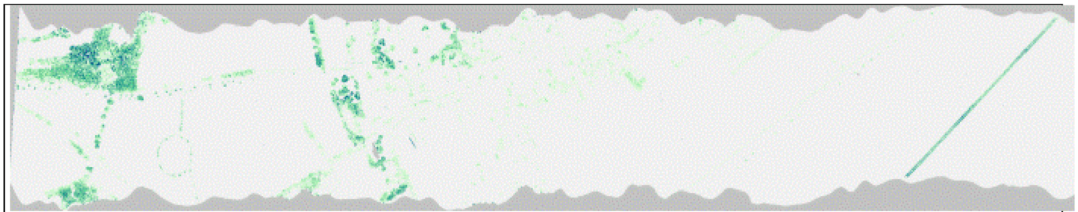


Sigma Z of Strip 111

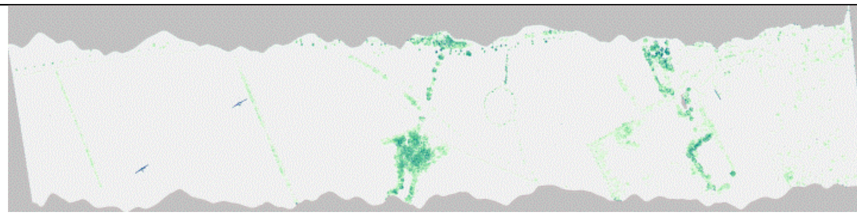


Sigma Z of Strip 112

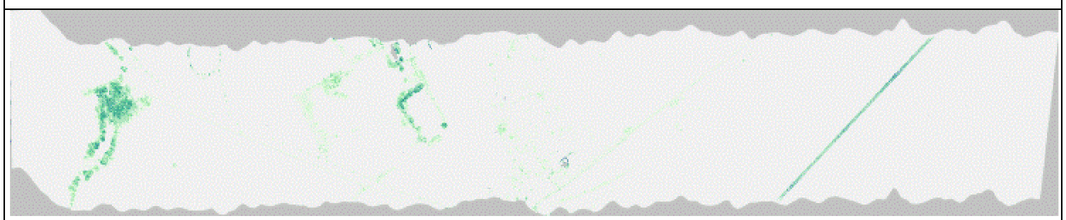
Figure D.1 (continued) : Coloured sigma-z results.



Sigma Z of 113



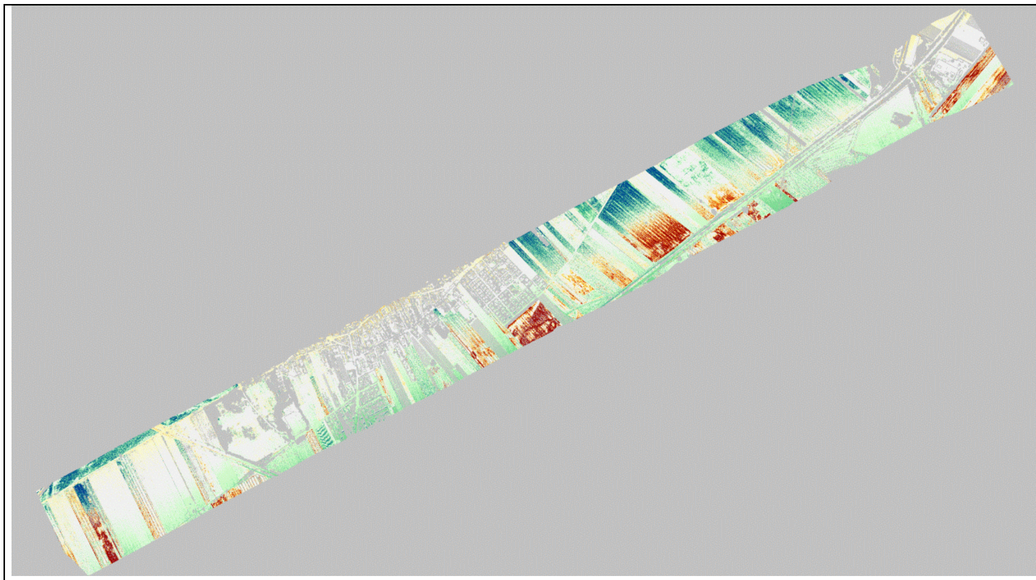
Sigma Z of Strip 114



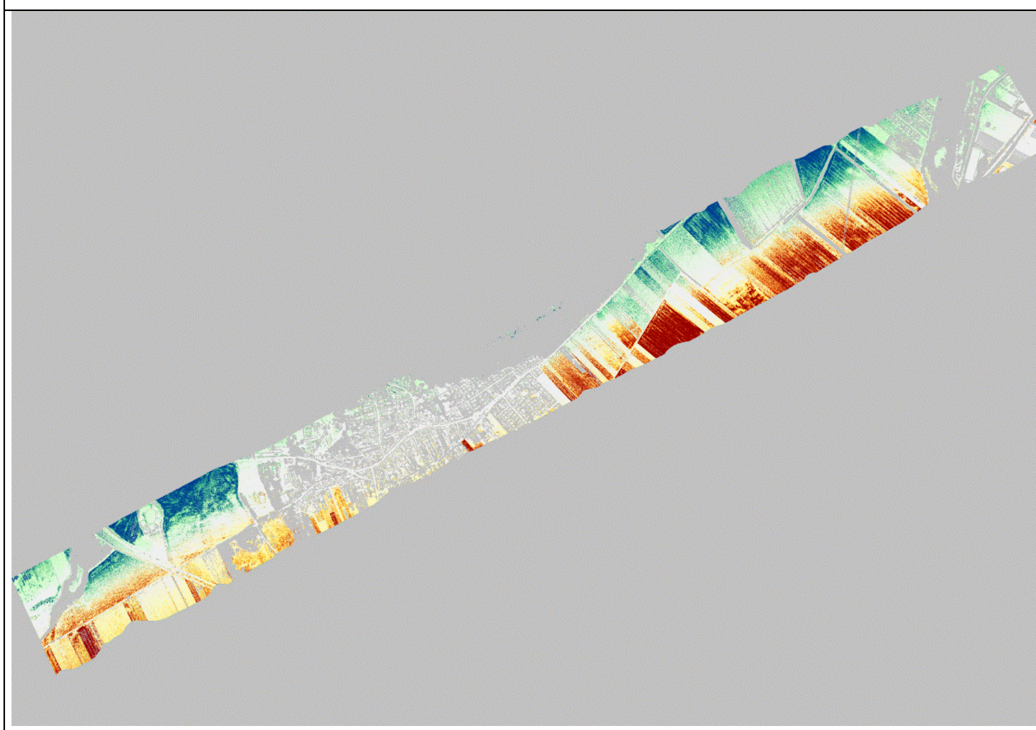
Sigma Z of Strip 116

Figure D.1 (continued) : Coloured sigma-z results.

APPENDIX E: Height difference between overlapping strips.

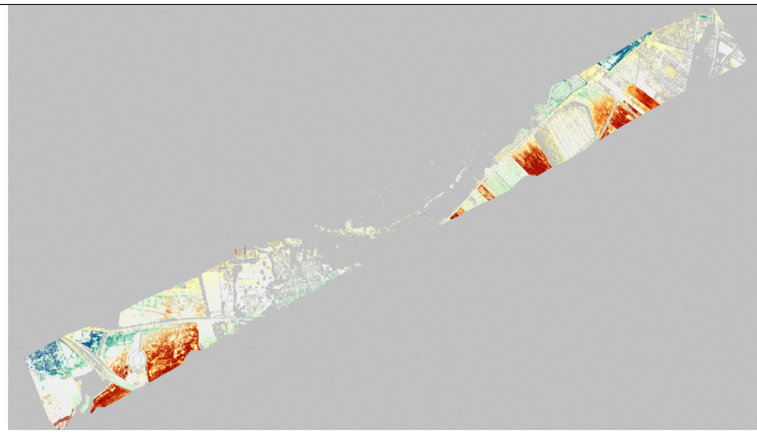


Masked strip differences between of 301-302

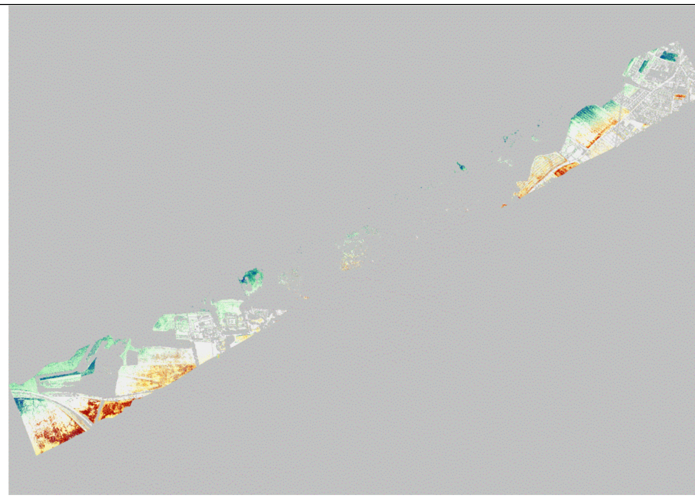


Masked strip differences between of 302-303

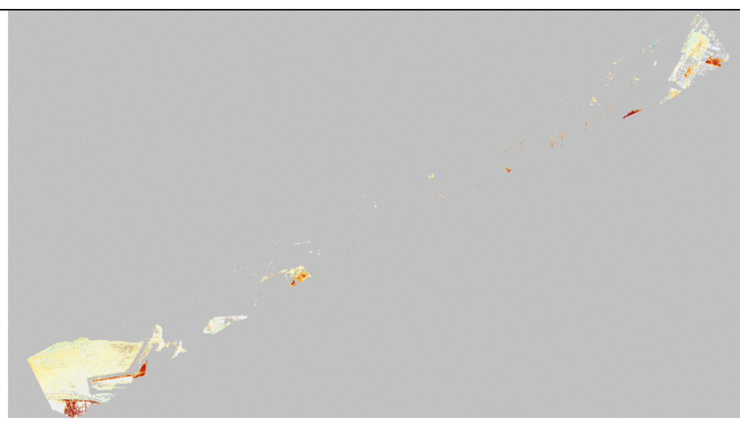
Figure E.1 : Height difference between overlapping strips.



Masked strip differences between of 303-304

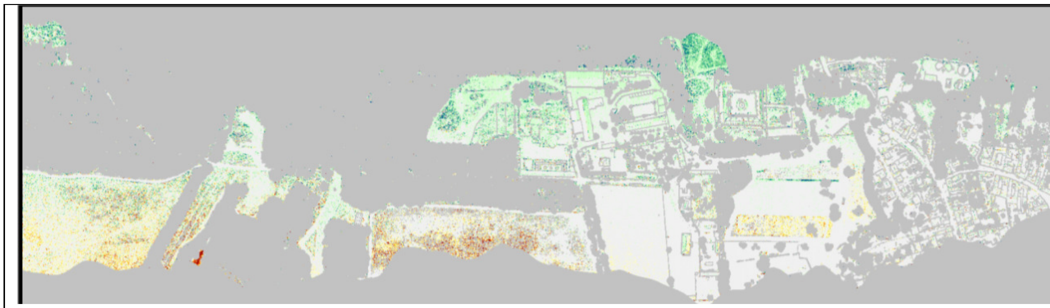


Masked strip differences between of 304-305

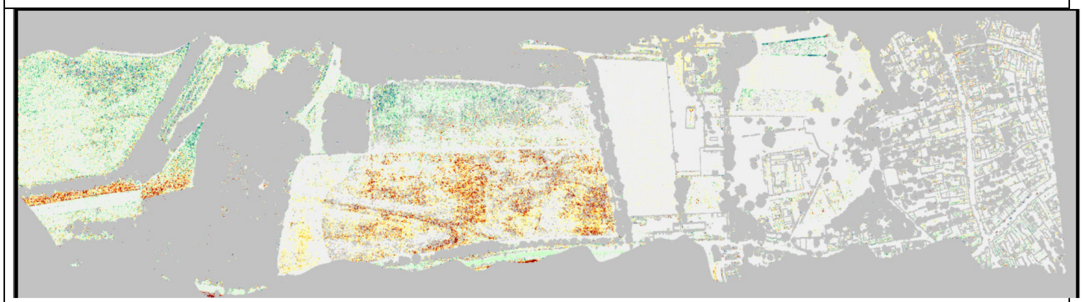


Masked strip differences between of 305-306

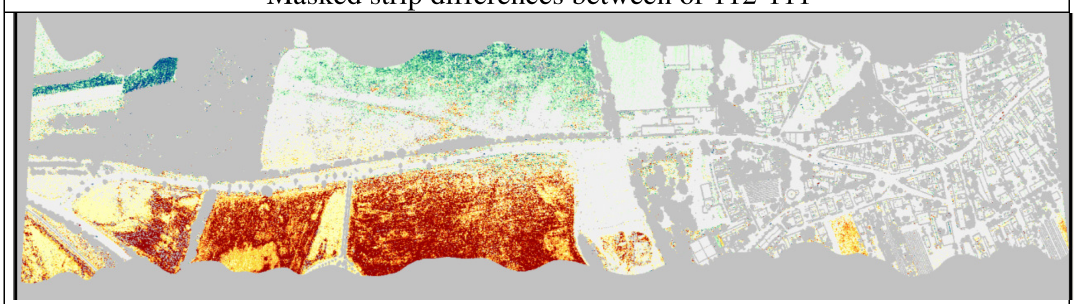
Figure E.1 (continued) : Height difference between overlapping strips.



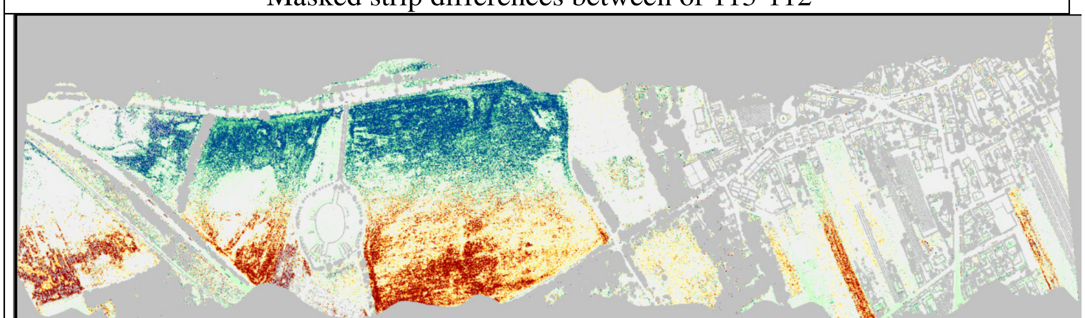
Masked strip differences between of 111-110



Masked strip differences between of 112-111



Masked strip differences between of 113-112



Masked strip differences between of 114-113

Figure E.1 (continued) : Height difference between overlapping strips.

APPENDIX F: Natural surface targets.

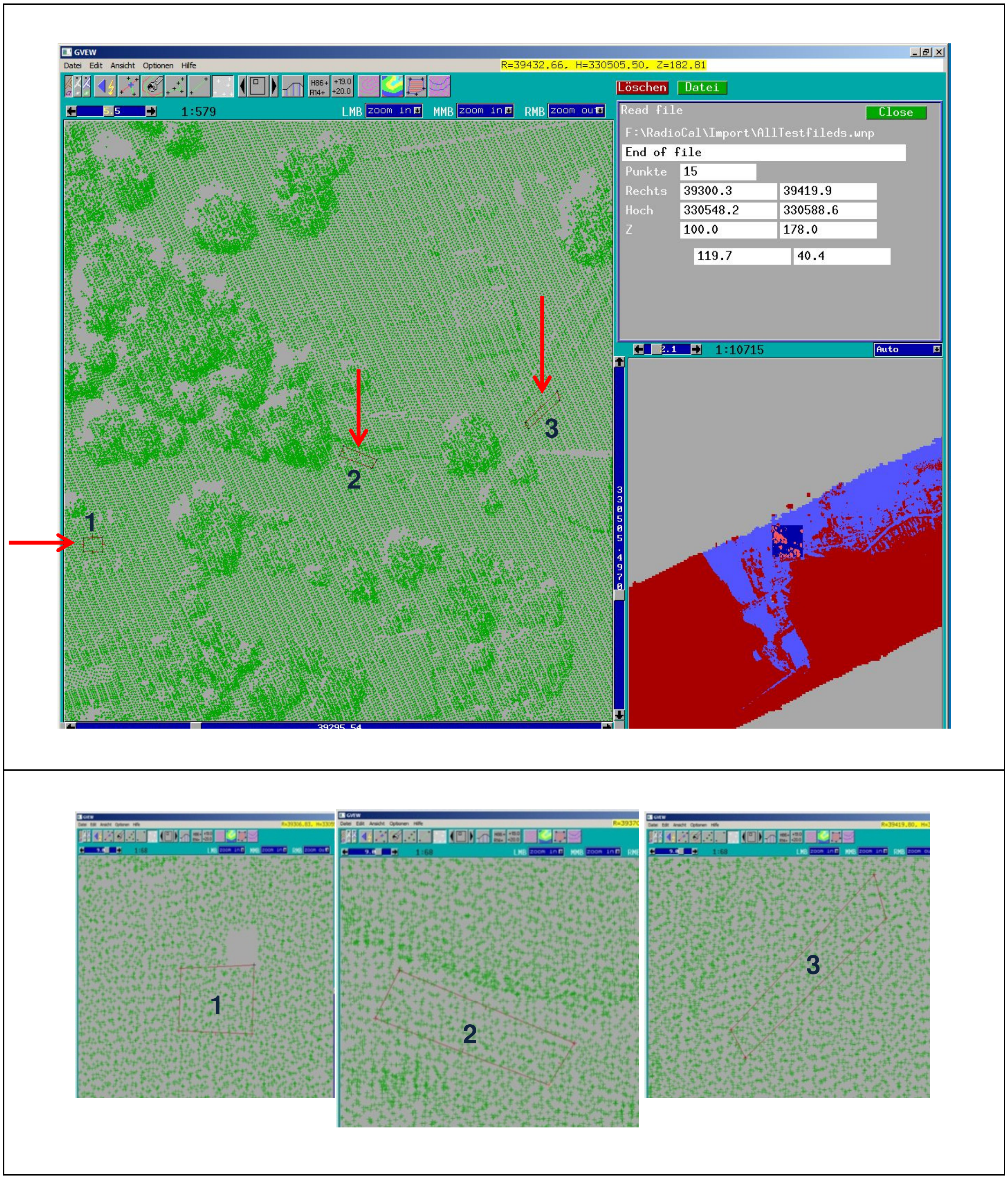
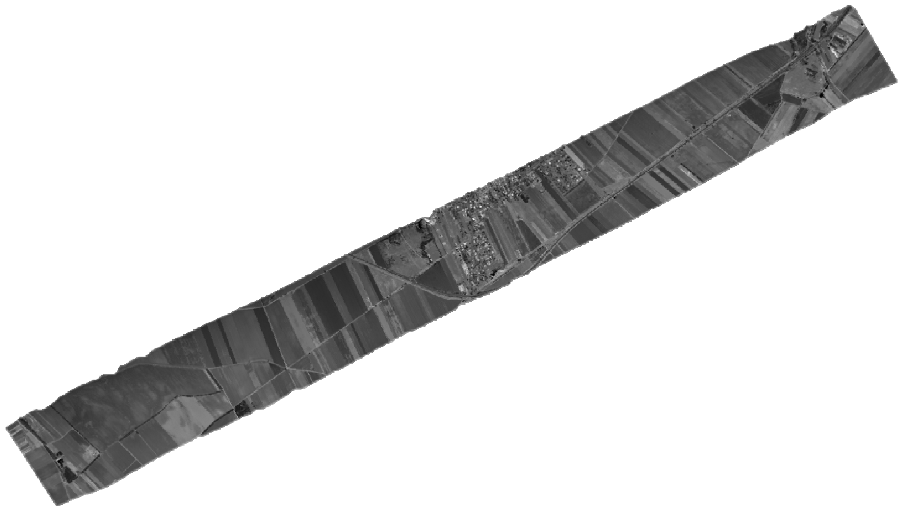
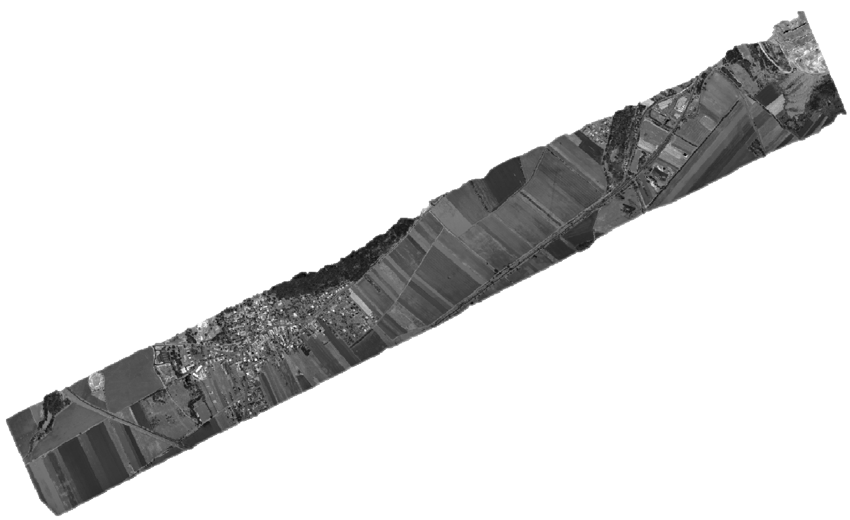


Figure F.1 : Natural surface targets.

APPENDIX G: Reflectance results.

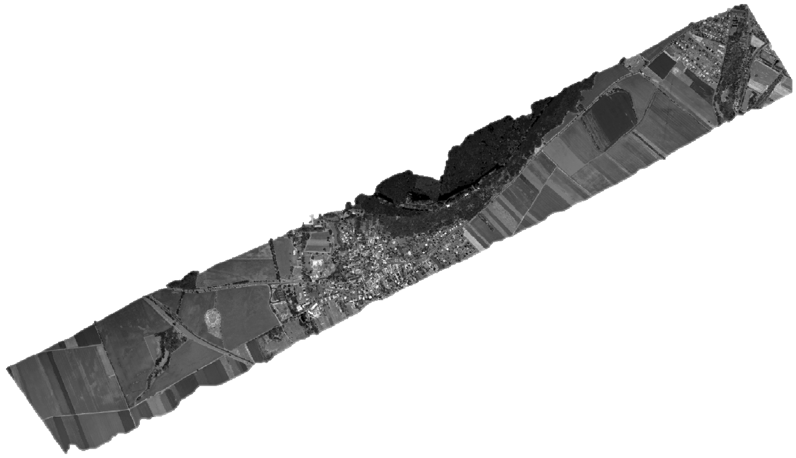


Reflectance result of Strip 301

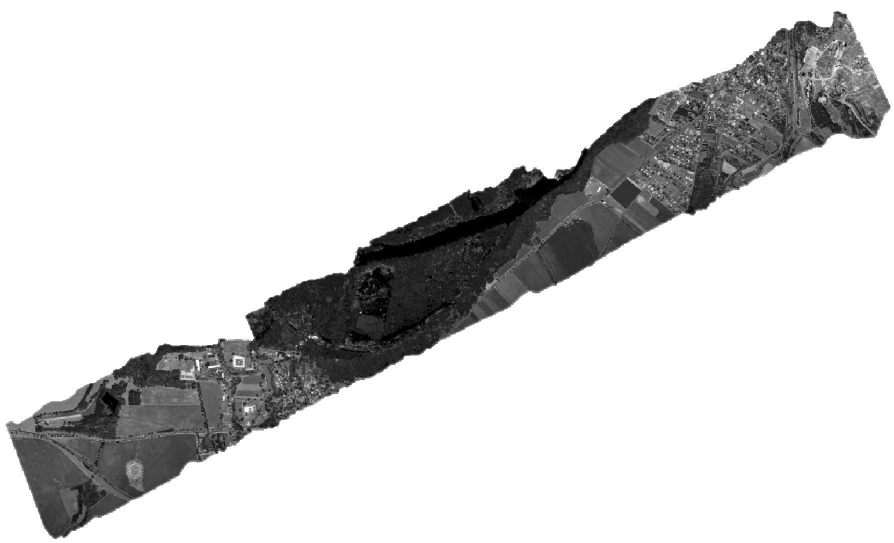


Reflectance result of Strip 302

Figure G.1 : Reflectance results.

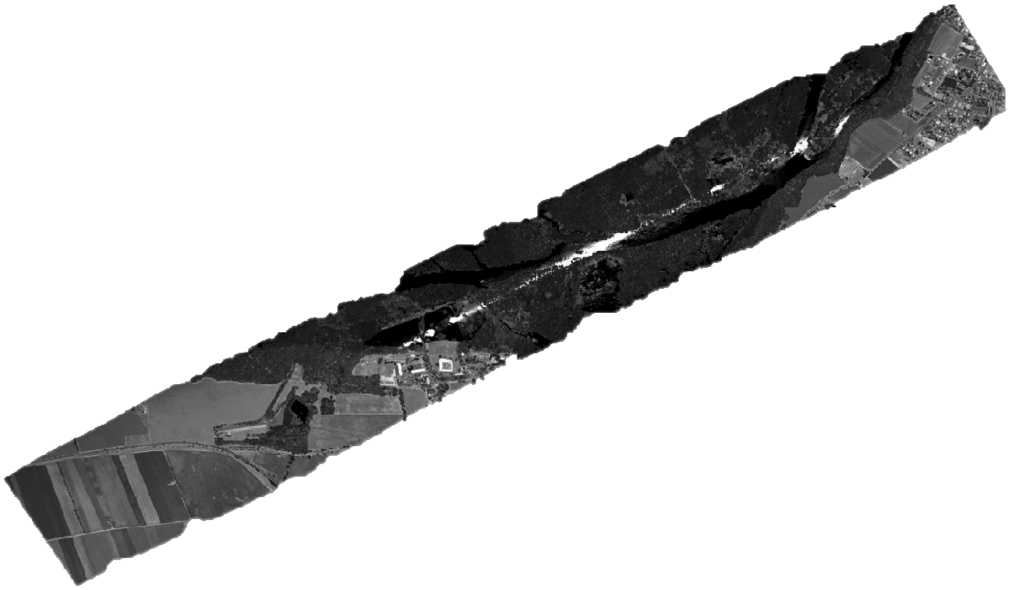


Reflectance result of Strip 303



Reflectance result of Strip 304

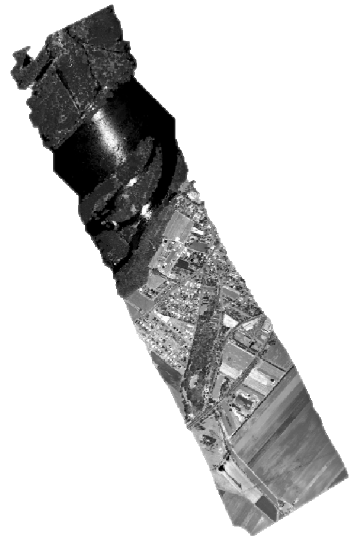
Figure G.1 (continued) : Reflectance results.



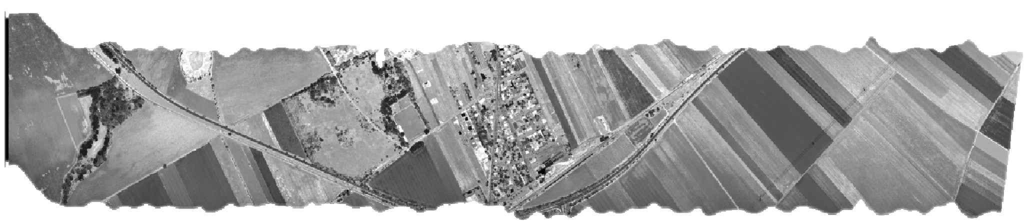
Reflectance result of Strip 305

Reflectance result of Strip 306

Figure G.1 (continued) : Reflectance results.



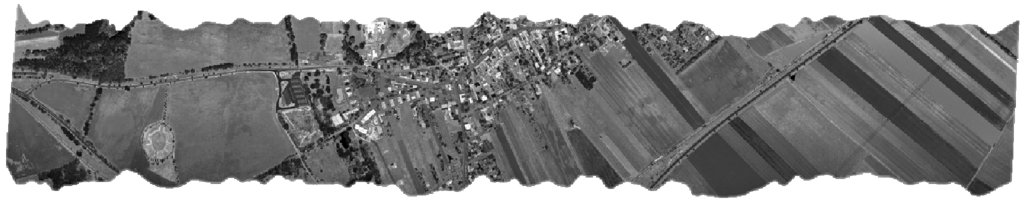
Reflectance result of Strip 307



Reflectance result of Strip 116

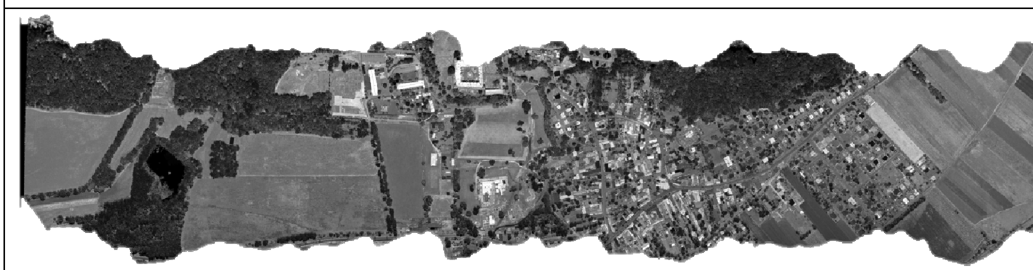
Reflectance result of Strip 114

Figure G.1 (continued) : Reflectance results.



Reflectance result of Strip 113

Reflectance result of Strip 112



Reflectance result of Strip 111

Reflectance result of Strip 110

Figure G.1 (continued) : Reflectance results.

CURRICULUM VITAE

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- (2006 - 2012) : Istanbul Technical University, Faculty of Civil Engineering, Geodesy and Photogrammetry Engineering, Division of Cartography.
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- Working as a Geodesy and Photogrammetry Engineer in Istanbul Technical University in a smart vehicle tracking system project.
- TÜBİTAK, 2224-Yurtdışı Bilimsel Etkinliklere Katılma Desteği ile bir hafta sure ile İtalya-Trento şehrinde "International Summer School, 3D modeling in Archaeology and Cultural Heritage" adlı çalıştaya katılım, 15-18 Haziran, 2009.
- İTÜ Araştırma Görevlileri Yurtdışı Destekleme Programı kapsamında, 2010 yılında 4 ay süreyle burs verilmesi ve Viyana Teknoloji Üniversitesi'ndeki çalışma (kişisel imkanlarla toplamda 8 ay sürmüştür.)

List of Publications:

PUBLICATIONS/PRESENTATIONS ON THE THESIS

- **Kurtcebe, F.**, Ipbuker, C., 2011: Active Remote Sensing for Archaeology, *25th International Cartographic Conference (ICC)*, 3-8 July 2011, Paris, France (accepted as oral presentation).

- **Kurtcebe, F.,** Pfeifer, N., Ipbuker, C., 2010. Remotely Sensed Archaeology: Recent Applications with "DAICHI"". *31st Asian Conference On Remote Sensing (ACRS)*, 1-5 November 2010, Vietnam, Hanoi (accepted as oral presentation).

INTERNATIONAL PUBLICATIONS

- **Kurtcebe, F.**,Ipbuker, C., "Active Remote Sensing for Archaeology", 25th *International Cartographic Conference (ICC),* 3-8 July 2011, Paris, France (accepted as oral presentation).

- **Kurtcebe, F.**,Pfeifer, N.,Ipbuker, C.,"Remotely Sensed Archaeology: Recent Applications with "DAICHI"", *31st Asian Conference On Remote Sensing (ACRS),* 1-5 November 2010, Vietnam, Hanoi (accepted as oral **presentation).**

- Dalgın, S., Ipbuker, C., **Kurtcebe, F**.,Direct Transformation of Map Coordinates, *24th ICC*, 15-21 November, 2009. Santiago, Chile (accepted as Poster Presentation)

- **Kurtcebe, F.**A System Approach on Spatial Epidemiology, Electronic *Proceedings of the First ICA Symposium on Cartography for Central and Eastern Europe, PhD/Master Forum* Ed. by Georg Gartner&Felix Ortag. 16-17 February 2009. Vienna, Austria. (CD) (accepted as oral presentation)

- Ulugtekin N.N., Dogru A.O., **Kurtcebe, F.** Studies in Cartography Division of Istanbul Technical University. *Electronic Proceedings of the First ICA Symposium on Cartography for Central and Eastern Europe.* pp: 535-54. Ed. by Georg Gartner&Felix Ortag. 16-17 February 2009. Vienna, Austria. (CD) (accepted as oral presentation)

- **Kurtcebe, F.**"A System Approach on Spatial Epidemiology", *Electronic Proceedings of the First ICA Symposium on Cartography for Central and Eastern Europe,* PhD/Master Forum (accepted as oral presentation).

- **Kurtcebe, F.,** Dogru, A.O., Ulugtekin, N., 2008. "GIS-based Epidemiological Studies at ITU". *ESRI Health GIS Conference*, Washington D.C., USA, 27-31 September 2008.

NATIONAL PUBLICATIONS

- Alkoy, S., **Kurtcebe, F.**, Doğru, A.Ö., Çatıker, A., Uluğtekin, N., Eskiocak, M., 2008."Aile Hekimliği Pilot Uygulamasının İkinci Yılında, Bolu'da Aşılama Hizmetlerinin Kalitesinin Lot Kalite Tekniği (LKT) ve Coğrafi Bilgi Sistemleri (CBS) ile Değerlendirilmesi", Ankara, *12. Ulusal Halk Sağlığı Kongresi*, 21-25 Ekim 2008.

▪ Alkoy, S., **Kurtcebe, F**., Doğru, A.Ö., Uluğtekin, N., Eskiocak, M., 2008."Aile Hekimliği Pilot Uygulamasının İkinci Yılında, Edirne'de Aşılama Hizmetlerinin Kalitesinin Lot Kalite Tekniği (LKT) ve Coğrafi Bilgi Sistemleri (CBS) ile Değerlendirilmesi", Ankara, *12. Ulusal Halk Sağlığı Kongresi,* 21-25 Ekim 2008.

CONFERENCES AND WORKSHOPS

▪ "Hava Kamerası ve LIDAR Teknolojileri Çözümler Çalıştayı", İTÜ Mimarlık Fakültesi Taşkışla, 13 Aralık 2011.
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▪ 31st Asian Conference On Remote Sensing ACRS, Vietnam, Hanoi, 1-5 November, 2010 (oral presentation).
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▪ YATA-TURK, Turkish Euro-Atlantic Youth Committee Conference: Bridge for Peace Istanbul 2010, ITU 2-5 February 2010 and organizing committee member in "NATO Information Week, 1-5 February 2010".
▪ International Summer School, 3D modeling in Archaeology and Cultural Heritage, Trento-Italya, 15-18 Haziran, 2009.
▪ Orta ve Doğu Avrupa Kartografya Sempozyumu, Viyana, Avusturya, 15 - 17 Şubat, 2009.
▪ 12. Türkiye Harita Bilimsel ve Teknik Kurultayı, 11-15 Mayıs 2009, Ankara, Türkiye.
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▪ 12. Halk Sağlığı Kongresi, 21-25 Ekim, Ankara, 2008.
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