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MULTIDIMENSIONAL SAR SATELLITE IMAGES – A MAPPING PERSPECTIVE

by

Mika Karjalainen

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Abstract

In this thesis, the use of Synthetic Aperture Radar (SAR) satellite images in potential mapping applications areas in Finland was studied. SAR is an active sensor using the microwave region of the electromagnetic spectrum in its pulses. Microwaves penetrate clouds, smoke and dust without noticeable attenuation, enabling all-weather and night-and-day satellite imaging. Because cloudiness is very common in Finland, SAR is of importance for monitoring purposes. Recently, the number of SAR satellites has increased notably. First, SAR images can now be acquired more frequently than before. Second, SAR images can be acquired in multiple polarization channels, different frequency bands and various imaging geometries using several satellites. As the dimensionality of SAR data increases, it can be expected that more automatic and sophisticated processes are needed.

The objective was to study streamlining of mapping processes based on SAR satellite images. First, automatic matching of remote sensing images and existing vector maps was studied. Second, multidimensional SAR satellite images were used in selected mapping applications. Example cases include agricultural monitoring (dual-polarimetric Envisat ASAR), detection of buildings (Radarsat-1 SAR), detection and verification of building subsidence (ERS-1 and ERS-2 SAR), and forest biomass mapping (ALOS PALSAR).

The results showed that it may be possible to use existing vector maps to refine the geocoding parameters of SAR images. According to the ground check points, accuracy of around 2 pixels was achieved in the image-to-map co-registration. When Persistent Scatterers SAR Interferometry (PSI) subsidence rates of individual buildings were compared with the levelling measurements, RMSE of 0.82 mm/year was achieved. At its best R^2 values of 0.55 and 0.72 were obtained for crop biomass and forest above ground volume estimations respectively. Crop species were classified with the overall accuracy of 75%. Building detection percentages varied between 13% and 98%, depending on the orientation of the building wall and building height.

The author believes that the results might show commercial potential and have a socioeconomic impact, providing the prices of SAR images decrease. PSI could be used to monitor subsidence of urban areas operationally. SAR satellite is the only way to monitor wide agricultural areas in Finland, even though the results are somewhat poor. In the case of forests, SAR enables more frequent update of forest information when compared to airborne laser scanning. SAR images might have potential in detection of changes in urban areas, especially in the remote areas of the world. The future of SAR satellites appears promising because more satellite systems will be launched in the next ten years.

Keywords Synthetic Aperture Radar, Mapping, Multidimensional Data Analysis, Geocoding	
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Tiivistelmä

Tutkimuksessa selvitettiin synteettisen apertuurin tutkan eli SAR-tutkan (Synthetic Aperture Radar) käyttöä erilaisissa kartoitussovelluksissa Suomessa. SAR on aktiivinen kuvauslaite, joka käyttää sähkömagneettisen säteilyn mikroaaltoaluetta. Koska esimerkiksi pilvet ovat SAR-tutkalle läpinäkyviä, on kuvaus mahdollista kaikissa sääolosuhteissa. Viime aikoina SAR-satelliittien lukumäärä on kasvanut huomattavasti. Kuvia saadaan aikaisempaa useammin, mutta samalla myös monilla polarisaatiokanavilla, eri taajuusalueilla ja vaihtelevilla kuvausgeometrioilla. Kun SAR-kuvadatan määrä kasvaa, tarvittaneen yhä automaattisempia ja hienostuneempia prosesseja kuvien käsittelyyn.

Tavoitteena oli tutkia SAR-satelliittikuviin perustuvien kartoitusprosessien suoraviivaistamista. Ensimmäiseksi tutkittiin SAR-kuvien geokoodauksen automaattista parantamista olemassa olevien vektorimuotoisten kartta-aineistojen avulla. Toiseksi SAR-kuvia käytettiin muutamissa valikoiduissa kartoitustehtävissä, joita olivat maatalousalueiden monitorointi Envisat ASAR-kuvilla, rakennusten tunnistus Radarsat-1 SAR-kuvilta, rakennusten painumisen havaitseminen ERS-1 ja ERS-2 -kuvilta sekä metsän biomassan kartoitus ALOS PALSAR-kuvilta.

Tulosten mukaan vektorimuotoisia kartta-aineistoja voitaneen käyttää SAR-kuvien geokoodausparametrien parantamiseen. Tarkistuspisteiden perusteella päästiin noin 2 pikselin yhteensovitustarkkuuteen kuva- ja vektoriaineistojen välillä. Kun pysyvien sirottajien SAR-interferometrian painumatuloksia verrattiin yksittäisten rakennusten osalta vaaitustuloksiin, saatiin RMSE-arvoksi 0,82 mm/vuodessa. Viljakasvuston biomassan estimoinnissa saatiin parhaimmillaan R^2-arvoksi 0,55. Metsien tapauksessa maanpinnan yläpuolisen tilavuuden estimoinnissa saatiin R^2-arvoksi 0,72. Viljakasvien tunnistaminen onnistui 75 prosentin kokonaistulkintatarkkuudella. Rakennuksia pystyttiin löytämään 13–98 prosentin todennäköisyydellä riippuen rakennuksen seinän suunnasta ja rakennuksen korkeudesta.

Tulosten perusteella SAR-kuvilla saattaa olla kaupallista potentiaalia ja yhteiskunnallista vaikuttavuutta, kunhan kuvien hinnat laskevat riittävästi. Pysyvien sirottajien menetelmää voisi käyttää kaupunkialueiden painumien operatiivisessa tarkkailussa. Vaikka maatalouden osalta tulokset olivat heikkoja, on SAR silti ainoa keino laajojen maatalousalueiden monitorointiin. SAR-kuvat mahdollistavat metsien ajallisesti tiheämmän havainnoinnin verrattuna esimerkiksi lentokonekäyttöiseen laserkeilaukseen. Kaupunkialueilla SAR soveltunee parhaiten muutosten kartoitukseen – etenkin maapallon syrjäisillä seuduilla. SAR-satelliittikuvien tulevaisuus vaikuttaa lupaavalta, sillä uusia satelliitteja laukaistaan vielä lisää seuraavan kymmenen vuoden aikana.

Asiasanat Synteettisen apertuurin tutka, kartoitus, moniulotteisen tiedon käsittely, geokoodaus	
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Preface

This thesis has been prepared at the Finnish Geodetic Institute in the department of Remote Sensing and Photogrammetry. First, I would like to thank my supervisors Prof. Risto Kuittinen and Prof. Juha Hyyppä for the opportunity to work with such interesting research subjects during my years at the FGI. Second, I would like to thank all my colleagues at the FGI, especially Lic.Sc. Kirsi Karila, Lic.Sc. Harri Kaartinen, and Lic.Sc. Ulla Pyysalo for their valuable contribution to the publications included in this thesis. Third, the members of the coffee and tea club of the FGI are highly appreciated for all non-scientific discussions, which, I think, were an essential part of the scientific writing process. Fourth, I would like to express my gratitude to Prof. Dr.-Ing. Olaf Hellwich and Dr. Yrjö Rauste for their thorough pre-examination and comments. Furthermore, I would like to thank Tekes, the Jenny and Antti Wihuri Foundation, European Space Agency, Japan Aerospace Exploration Agency, and Canadian Space Agency for the financial and data support.

My first hands-on experience with SAR images occurred somewhere in 1995. Back then, my knowledge of SAR images and processing of satellite images in general was fairly narrow. I had only a few SAR images, which were unfamiliar to me. However, I was surprised with the visual richness of the false colour SAR images, which I combined from the multi-date acquisitions. Since then, new SAR satellites with finer spatial resolution and enhanced imaging capabilities have been launched, and more detailed maps can be produced. I am glad to be able to summarize some of my key findings in this thesis. However, there is still a lot to learn as new and challenging SAR technologies and methodologies are emerging all the time.

Finally, I would like to thank my wife Kirsi for her patience during the writing process and my children Elina and Matias for giving me the endurance to cope with the loneliness of scientific writing.

Kirkkonummi, 25th March, 2010

Mika Karjalainen

Contents

List of Publications

This thesis consists of an overview and of the following publications, which are referred to in the text by their Roman numerals.

I Karjalainen, M., Hyyppä, J., Kuittinen, R., 2006. Determination of exterior orientation using linear features from vector maps, The Photogrammetric Record, 21(116):329-341.

II Karjalainen, M., 2007. Geocoding of Synthetic Aperture Radar Images Using Digital Vector Maps, IEEE Geoscience and Remote Sensing Letters, 4(4):616-620.

III Karjalainen, M., Kaartinen, H., Hyyppä, J., 2008. Agricultural Monitoring Using Envisat Alternating Polarization SAR Images, Photogrammetric Engineering & Remote Sensing, 74(1):117-126.

IV Karjalainen, M., Hyyppä, J., Devillairs, Y., 2003. Urban Change Detection in the Helsinki Metropolitan Region Using Radarsat-1 Fine Beam SAR Images, In Proceedings of the 2nd GRSS/ISPRS Joint Workshop on Remote Sensing and Data Fusion over Urban Areas 2003, p. 273-277.

V Karila, K., Karjalainen, M., Hyyppä, J., 2005. Urban Land Subsidence Studies in Finland Using Synthetic Aperture Radar Images and Coherent Targets, The Photogrammetric Journal of Finland, 19(2):43-53.

VI Karjalainen, M., Pyysalo, U., Karila, K., Hyyppä, J., 2009. Forest Biomass Estimation Using ALOS PALSAR Images in Challenging Natural Forest Area in Finland, Proceedings of ALOS PI 2008 Symposium, Island of Rhodes, Greece, 3-7 November 2008, ESA SP-664, Unpaginated CDROM, 5 pages.

Author's contribution

In all publications, previously unreported results have been presented. Publications **I**, **II**, **III**, and **V** are peer-reviewed. Publication **IV** is a conference article, which was published in the IEEE publication series. Publication **VI** is a conference article, which was published in the Special Publications series of the European Space Agency. The author's contribution to publications is described in the following.

Publication I was solely written by the author. Moreover, the software prototype was developed and the results were analyzed by the author. Prof. Risto Kuittinen initially proposed the study of automatic image orientation based on existing land parcel maps. Prof. Juha Hyyppä encouraged to publish the result and supervised the writing process.

The author was solely responsible for **publication II**.

In **Publication III**, the author's responsibilities were SAR image processing, methodology development, and data analysis. The publication was written solely by the author. Lic.Sc. Harri Kaartinen mainly carried out the field surveys. Prof. Juha Hyyppä was the supervisor of the project.

Publication IV was written solely by the author. The author also carried out SAR image processing and all data analysis. Mr. Yannick Devillairs carried out the field surveys and Prof. Juha Hyyppä was the supervisor of the project.

Publication V is a result of a collaborative study. The author designed the study, acquired SAR images and contributed to the preparation of the article. Lic.Sc. Kirsi Karila carried out the PSI processing and was the lead author of the article. Prof. Juha Hyyppä was the supervisor of the project.

In **Publication VI**, the author's responsibilities were processing of SAR images, data analysis, and the writing of the paper. Lic.Sc. Ulla Pyysalo processed the ALS data and calculated the Canopy Height Model. Lic.Sc. Kirsi Karila carried out the interferometric processing of the PALSAR images. Prof. Juha Hyyppä was the supervisor of the project.

List of Abbreviations

AGV	Above Ground Volume
ALS	Airborne Laser Scanning
DEM	Digital Elevation Model
DTM	Digital Terrain Model
ESA	European Space Agency
FGI	Finnish Geodetic Institute
GCP	Ground Control Point
CHM	Canopy Height Model
GIS	Geographic Information System
GPS	Global Positioning System
GSD	Ground Sampling Distance
IMU	Inertial Measurement Unit
NLS DEM25	National Land Survey Digital Elevation Model, 25 m grid size
PolINSAR	Polarimetric SAR Interferometry
PSI	Persistent Scatterers SAR Interferometry
SAR	Synthetic Aperture Radar
RADAR	Radio Detection and Ranging
RAR	Real Aperture Radar
RMSE	Root Mean Square Error
RPC	Rational Polynomial Coefficients
SRTM	Shuttle Radar Topography Mission
UTM	Universal Transverse Mercator
YKJ	Finnish Uniform Coordinate system
WGS84	World Geodetic System

1 Introduction

1.1 Motivation

According to Lillesand and Kiefer (1994) remote sensing can be defined as ″the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation.″ Consequently, remote sensing is a great tool for mapping large areas simultaneously from an airplane or a satellite. The early development of remote sensing satellites was closely related to military intelligence of the two rivalling superpowers in the 1950's. The first satellite images of Earth were acquired by Explorer-6 (USA) in 1959. The first meteorological satellite, TIROS-1 (USA), was launched in 1960. The spatial resolution of these pioneering satellites was very low compared to modern satellites such as GeoEye or WorldView, with the resolution of a few tens of centimetres.

If the visible light region of the electromagnetic spectrum is used in satellite imaging, cloudiness presents serious difficulties. For example, in Finland clouds hamper the acquisition of optical satellite images very effectively. However, in some situations satellite images are needed with a very short response time. The answer to that challenge is Synthetic Aperture Radar (SAR). SAR is an active remote sensing instrument capable of acquiring images from the target area with fine spatial resolution. The development of Radar (Radio detection and ranging) systems started in the beginning of the 20th century. In 1904, a German researcher, Christian Hülsmeyer, was issued the first patent for describing the operation principles of a radar-like device. The most significant innovation with respect to the fine spatial resolution of imaging radars occurred in 1951, when Carl Wiley (USA) invented the idea of Doppler beam sharpening.

Classified military projects pioneered in carrying out SAR research, but civilian versions were developed at the same time. The first commercial airborne radar images were acquired in the USA in the 1960's. The first Earth orbiting satellite equipped with a SAR system was Seasat, which the USA launched in 1978. The SAR system was damaged 106 days after the launch, but the Seasat satellite was still able to collect data, which proved the importance of satellite-borne SAR systems in the mapping of the Earth's surface. After Seasat, many SAR satellites have been launched with constantly improving quality of the acquired imagery. SAR images have been used in several application areas, such as topographic mapping, generation of DEMs, forestry, agriculture, geology, geodynamics, hydrology, oceanography, ice mapping, snow mapping, land use, and land cover mapping (Henderson and Lewis, 1998).

The most beneficial features of SAR over optical imaging sensors are its all-weather and day-and-night imaging capabilities. SAR is an active imaging sensor and uses the microwave region of the electromagnetic spectrum. Therefore, SAR images can be acquired through clouds, dust and smoke. The military need for such an imaging system is self-evident.

> *"The pre-dawn launch Monday of a new reconnaissance satellite further establishes Israel as one of the world's superpowers in space, and grants it an important further intelligence advantage over its rivals. The primary intelligence contribution of the TECSAR satellite, manufactured by Israel Aerospace Industries, lies in improving capabilities of intelligence gathering and coverage over Iran… "* (Haaretz.com, the online edition of Haaretz Newspaper, 21 January 2008)

> *"…GulfSAR is a high-resolution active satellite that can see through clouds or work day or night thanks to its ground-reflecting radar. Its low inclination angle means it will be ideally placed to cover the Middle East, covering a maximum latitude of plus and minus 43 degrees… The constellation will eventually consist of four satellites with two being launched in 2013 and the others the following year. The constellation will mean that an area can be revisited between in between one and four hours…"* (Arabian Aerospace Online News Service, 11 December 2009)

SAR can provide important information for civilian applications too. The way that microwave radiation interacts with an imaged target differs dramatically from the interaction of visible light. Therefore, SAR can provide unique information, which would probably not be obtainable by any other means. For example, the techniques of SAR interferometry allow the generation of coarse DEMs from even the most remote areas in the world. Differential SAR interferometry can be used to detect even sub-centimetre rates of subsidence and uplift of the Earth's surface (Masonnet and Feigl, 1998, Ferretti et al., 1999, 2000). Using a SAR satellite constellation, it is possible to acquire images from any area in the world within the response time of a few hours. Hence, SAR images can be used to rapidly plan emergency relief operations in crisis situations such as earthquakes (Gamba et al., 2007).

In the past few years, the number of SAR satellites has increased. At the same time, the number of possible polarization channels, possible imaging geometries, and imaging frequencies has increased as well. More new satellites, even constellations such as the COSMO-SkyMed system, have been and will be launched in the near future (Fagioli et al., 2006). Thus, multidimensional SAR images can be applied to remote sensing applications more operationally than a decade ago. However, as the amount of SAR data is growing, it would be advantageous if some parts of the SAR processing chain (see Figure 1) from raw data to final product could be carried out as automatically as possible.

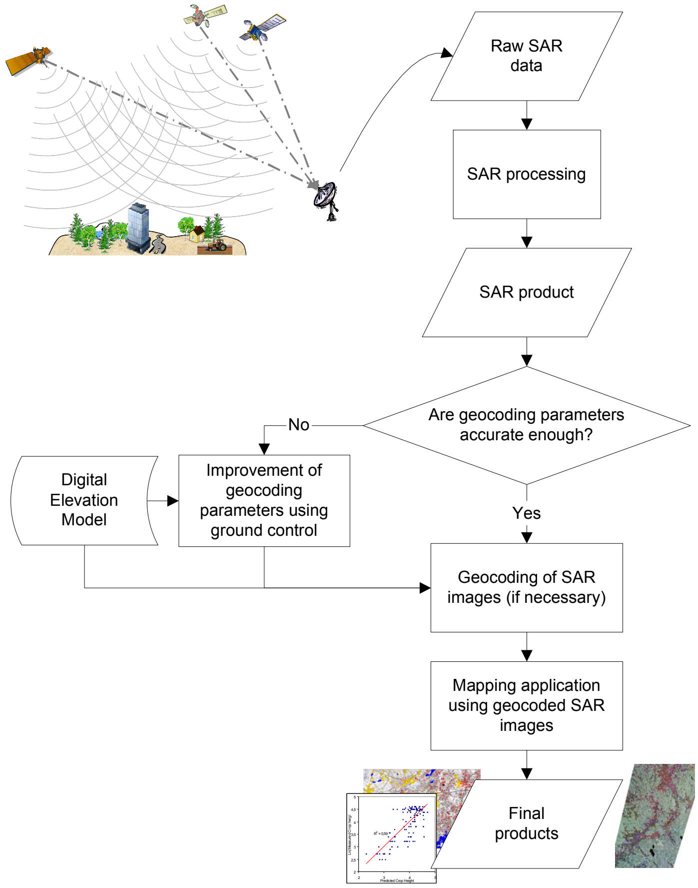

Figure 1. Basic processing chain for SAR images.

In reality, the processing chain is much more complex and includes many processing tasks. However, relatively high-level automation can be achieved. The first stages, from the image acquisition to a SAR product, are typically carried out by the ground segment of the satellite mission. SAR processing, in which image products are generated from raw SAR signal data, can be carried out by the user, but specific and typically expensive software is needed. Therefore, most of the users order images as SAR products, which are processed to a desired processing level such as a Single Look Complex, Detected, Ellipsoid Geocoded, or Terrain Geocoded. The processing level depends on the requirements, available software, and skills of the user.

The next stage shown in Figure 1 is geocoding, in which SAR images are transformed from the sensor coordinate system to the map coordinate system (such as UTM map projection) to be used in conjunction with existing digital maps. The ground segment of the satellite system is able to carry out the geocoding process very accurately nowadays. However, there might be geometric mismatches with respect to the existing digital maps due to the inaccuracies of the orbital parameters of the satellite and the applied DEM. Moreover, the geocoding process may be a chargeable service. Thus, one might want to carry out the geocoding process or refine the supplied geocoding parameters by oneself. However, in practice, the geocoding process is a laborious and manual process and should be automated as much as possible.

In the final stage of the processing chain in Figure 1, there is a mapping application process, which basically would create final products such as false colour type images, thematic maps, charts, and tables for the end-users. Some of the end-users may not want to know the fine details of the SAR processing, geocoding and physical models; they might only want the representation of the multidimensional data in a more familiar format – typically as a map. Obviously, the mapping application process should be as automatic as possible, similar to the geocoding process, but typically some user-interaction is required. In order to create a feasible mapping application, a lot of research and development is needed.

1.2 Hypothesis

It can be expected that the dimensionality of satellite images which are used in SAR based applications increases noticeably in the future. The hypothesis of this study is that some mapping applications in Finland may benefit from the multidimensionality of SAR satellite images and that the basic SAR processing chain presented in Figure 1 could be further automated.

1.3 Objectives of the study

In order to increase the automation level of the SAR processing chain from the user's perspective, there are essentially only a few tasks that could be improved. The aspects of image acquisition, the data transmission to the ground station, and the processing of raw SAR were beyond the scope of this study, and have thus been omitted. Moreover, the construction of seamless image mosaics, which is an important part of creating good quality wide-area SAR image mosaics, was excluded from the study objectives. Consequently, the following research objectives were set:

1. to study the automation of geocoding of remotely sensed images with special emphasis on SAR sensors and to develop a prototype software, which actually carries out the geocoding process, and
2. to evaluate the usability of multidimensional SAR satellite images in different mapping applications keeping in mind that the processes should be easily repeatable and automated.

The first objective was studied independently, because it is a prerequisite for the second objective. It was supposed that multidimensional SAR satellite images would be applied in the future. Therefore, SAR images should be, first, co-registered with each other, and second, geocoded on the map system, as automatically and accurately as possible. In order to facilitate the automation, the use of existing digital maps as reference data was studied.

The second objective concerned the visualization of the final products. There is still a huge gap between bleeding edge SAR methodologies and potential end-users in Finland. The aim was to study the fusion of multidimensional SAR images with existing digital maps and ancillary field measurements in order to create as comprehensible final products as possible for the end-users such as decision makers.

1.4 Structure of thesis

This thesis consists of a summary and six original publications. In Chapter 2, the state of the art of SAR satellite systems with respect to the research objectives is reviewed. The materials and methods used are summarized in Chapter 3. Publications I and II discuss the aspects of automation of image geocoding using existing map data. Publications III, IV, V, and VI deal with possible mapping applications, in which multidimensional SAR data could be used in Finland. The mapping applications discussed may benefit from the fact if applied images could be automatically geocoded. In Chapter 4, the results of the original publications are summarized. Finally a discussion and conclusions are presented in Chapter 5.

1.5 Contribution

In general, there is a wide interest in the scientific community in automatic geocoding of remote sensing images, of which one possible approach, namely, the use of existing digital maps, is presented in this thesis. With respect to SAR images specifically, automation in geocoding can be expected to speed up the processing of SAR images and potentially reduce the amount of time-consuming manual work. Such a method might be of interest to the developers of commercial remote sensing software packages.

In Finland, there are only a few operational users of SAR images. The main reason is the cost-effectiveness of other methods. For example, in the case of mapping of built-up areas, digital aerial images and ALS are superior when compared with SAR images. However, the results of this thesis could promote the usage of SAR satellite images in new areas of mapping applications.

2 Review

2.1 Synthetic Aperture Radar

SAR is an active instrument capable of acquiring images in fine details through clouds even at night-time from a distance of several hundreds of kilometres. In simplified terms, SAR operates by transmitting a short pulse of microwave radiation and then recording the backscattered signal from the illuminated area. The antenna footprint is the area that the transmitted pulse illuminates on the Earth's surface. For a SAR satellite, the width of the illuminated area of a single pulse is in the order of few kilometres. However, using SAR processing techniques the spatial resolution of around 1 metre can be achieved currently (see the example in Figure 2).

Figure 2. Masala, Finland, seen by TerraSAR-X satellite (Image data 2008-2009 © DLR, multitemporal images, nominal resolution: 2.0 m (ground range) and 2.3 m (azimuth), High Resolution Spotlight Mode, Dual polarization).

The fine spatial resolution of SAR is based on the creation of a long virtual antenna (wide synthetic aperture), which analogously to optical sensors enables better resolution than a smaller aperture. The synthetic aperture is founded on the following basic assumptions: (1) the SAR antenna is mounted on a moving platform, (2) the location and velocity of the platform is known, and (3) the transmitted and received radiation is phase-coherent (Lacomme et al., 2001). As the platform moves on its trajectory, a time series of signal data (range lines) is recorded. Any point target on the ground is visible for a certain period of time, which depends on the footprint width and the velocity of the platform. It is then possible to trace the path of a point target from the signal data. The point target tracing is called focusing and is an essential part of SAR processing. In reality, SAR processing is not as easy as it sounds and is actually a field of its own in scientific research (see for example Hein, 2004).

Spatial resolution, i.e. the smallest object it is possible to detect from an image, is probably one of the most important characteristics of any remotely sensed image. The spatial resolution of SAR images can be handled in two separate directions: (1) range and (2) azimuth. An informative explanation of the spatial resolution of SAR is given, for example, in Schreier (1993). In the range direction, which is perpendicular to the velocity vector of the platform, the spatial resolution is determined by the duration of the transmitted pulse. One would like to use as short pulses as possible in order to increase the resolution, but in reality the design of such a SAR system capable of creating short enough pulses with required power is difficult. However, the range resolution can be increased using pulse modulation techniques. The most common approach is the Linear Frequency Modulation, for which the slant range resolution given is:

$$\textit{Slant range resolution} = c / (2B_r) \qquad (1),$$

where c is the speed of light and B_r is the band width of the transmitted pulse. The resolution in ground range coordinates is obtained by dividing the slant range resolution by $sin\Phi$, where Φ is the look angle of the SAR antenna. The greater the bandwidth is, the better the range resolution. In civilian satellite-borne SAR systems, slant range resolutions of around one metre can be obtained (Keydel, 2007, Düring et al., 2008, MDA, 2008, Fagioli et al., 2006).

In the azimuth direction, the spatial resolution is slightly more complicated to clarify. The key parameter in determining the azimuth resolution is the width of the antenna footprint on the ground, which depends on the 3 dB aperture of the SAR antenna and the range (the distance between the SAR antenna and the Earth's surface). In the simplest case, also known as Real Aperture Radar (RAR), the azimuth resolution can be approximated using the following formula:

$$\textit{Azimuth resolution}_{RAR} = (\lambda R)/L \qquad (2),$$

where λ is the wavelength of the transmitted radiation, R is the range, and L is the physical length of the antenna (aperture). One can quickly calculate that the azimuth resolution of satellite-borne RAR would be very poor – in the order of kilometres. However, SAR processing techniques can be applied, and then the azimuth resolution becomes:

$$\textit{Azimuth resolution}_{SAR} = L/2 \qquad (3).$$

This is the famous SAR resolution equation, and its derivation is given in several SAR books (see for example Schreier, 1993 or Lacomme, 2001). One can observe that the azimuth resolution does not depend on the wavelength nor range, but only on the length of the antenna. Contrary to RAR, a smaller physical antenna (=smaller aperture) produces better resolution. It should be noted that modern SAR systems are able operate in a so-called spotlight mode as well. In the spotlight mode, the pulses are directed to the target area for a longer period of time, which increases the length of the synthetic antenna, consequently enhancing the azimuth resolution even more. Nowadays, in satellite-borne SAR systems, azimuth resolutions of around one metre can be achieved (Keydel, 2007, Düring et al., 2008, MDA, 2008, Fagioli et al., 2006).

A focused SAR image is a two-dimensional representation of the spatial variation of the backscattering characteristics of the illuminated area. In addition to being a ranging sensor, SAR records the amplitude and phase components of the received signal.

The amplitude component corresponds to the strength of the received signal, which is a function of the SAR system parameters and target properties. For example, one could try to extract the value of soil surface moisture from SAR data (Dubois et al., 1995). The amplitude component is the one that is most commonly used in SAR based applications due to its effortless exploitation in GIS and in remote sensing software packages. Typically, the amplitude component is converted into a so-called backscattering coefficient (also known as σ^0, sigma zero, or sigma nought), which corresponds to the strength of the backscattered signal per unit area on the ground. Basically, σ^0 enables the quantitative comparison of multidimensional SAR images. However, the comparison is not straightforward because the backscattering coefficient depends on, on the one hand, SAR system parameters (wavelength, polarization, look angle), and on the other hand, the target properties (dielectric properties, geometry, surface roughness) (Dobson et al., 1995, Kasischke et al., 1997). Moreover, SAR images contain speckle, which complicates the extraction of information. Speckle originates from the coherent nature of the transmitted radiation and it causes variations to the backscattering coefficients of the pixels of the virtually uniform target area. Speckle can be reduced by means of multilook processing or by using specific speckle filters (Lee et al., 1994). Another approach to tackle speckle is to apply areal averaging, which is particularly useful in cases where the boundaries of the investigated targets are known, in targets such as agricultural parcels (Schotten et al., 1995). Even though speckle is typically considered as noise from the point of view of the image's visual quality, image speckle and target texture could be used to distinguish land-use classes (Ulaby et al., 1986).

Unlike the amplitude component, the phase component of an individual SAR image is totally random. However, the phase component is the essential part of interferometric and polarimetric SAR processing. The phase difference of two slightly dislocated SAR images, also known as SAR interferogram, corresponds to the elevation variations (Crosetto and Pérez Aragues, 1999). In SAR polarimetry, the phase difference of different polarization states (for example HH and VV) can be used to determine the scattering mechanisms within the study area (Cloude and Pottier, 1996). Differential SAR interferometry enables the detection of movements in the range direction (Massonnet and Feigl, 1998). Promising results have been achieved by combining the methods of interferometry and polarimetry (PolINSAR (Papathanassiou and Cloude, 2001) or SAR tomography (Reigber, 2002)). However, in order to use the phase component, SAR images are typically delivered as so-called Single Look

Complex products. Thus, more specialized software and more skilled users are required for the image processing. This hampers the spread of interferometric and polarimetric methods to a wider group of users.

2.2 Multidimensionality of SAR satellite images

In the case of SAR images, Oliver and Quegan (2004) defined the multidimensionality of data as follows: "Multidimensionality arises in SAR data whenever the same scene is imaged in several channels, which may be separated by differences in polarization, frequency, time, aspect angle, or incidence angle".

Due to the frequent imaging capability, multi-temporal SAR satellite images can be obtained easily. In the case of a single satellite, the time interval between the possible acquisitions depends on the repeat cycle of the orbit. In Finland, the time interval is shorter than in Southern Europe due to the characteristics of the polar-orbiting satellites. Using a constellation of SAR satellites, such as the COSMO-SkyMed system, the imaging frequency can even be in the order of a few hours, which puts constraints on the planning system of image acquisitions, data transmission and SAR processing (Bianchessi and Righini, 2008). However, multi-temporal SAR images with high temporal resolution have strong potential in applications such as change detection and monitoring of various dynamic earth processes (Colesanti et al., 2003, Pacifici et al., 2008).

SAR sensors operate at a specific frequency band of electromagnetic radiation. Even today, military codes for the frequency bands are commonly used in the classification of SAR systems (see Table 1). Nowadays, all civilian SAR satellites operate at a single frequency band. Therefore, multi-frequency SAR images can be obtained only by using different satellite systems. Multi-frequency SAR images are beneficial in many application areas, for example in forestry, where the fusion of X and P band data is expected to provide more detailed information about forest biomass than single band systems do (Hyde et al., 2007).

Table 1. Band codes of SAR frequencies (Schreier, 1993).

Band code	Frequency (GHz)	Wavelength (cm)
P	0.225-0.39	133-76.9
L	0.39-1.55	76.9-19.3
S	1.55-4.2	19.3-7.1
C	4.2-5.75	7.1-5.2
X	5.75-10.9	5.2-2.7
K	10.9-36.0	2.7-0.83
K_u	10.9-22.0	2.7-1.36
K_a	22.0-36.0	1.36-0.83
Q	36.0-46.0	0.83-0.65
V	46.0-56.0	0.65-0.53
W	56.0-100.0	0.53-0.3

Polarization is a property of electromagnetic radiation and defines the direction and magnitude of the vibrating electric field (Henderson and Lewis, 1998). In the case of SAR, linearly polarized radiation is commonly used. SAR antennas are capable of transmitting and receiving two linear polarization components, which are defined in relation to the antenna orientation as vertical (V) and horizontal (H) components. Hence, there exist four transmission and reception alternatives: HH, HV, VH, or VV. For example, depending on the convention used, VH means that the radiation is transmitted in V polarization and received in H polarization. Importantly, all polarization channels typically have different backscattering values for the same target area (except HV and VH, which should be equal in the monostatic case). Thus, multi-polarization images, by default, provide better results than single polarized SAR systems. For example, the benefits of multi-polarization SAR images are evident in the case of crop biomass estimation (McNairn and Brisco, 2004, Karjalainen, 2008).

In addition to SAR channels separated by time, frequency, and polarization, it is possible to view the target area using various imaging geometries. The incidence angle defines the angle at which the radiation hits the target. The side-looking imaging geometry of SAR is described in more details in Chapter 2.3. The aspect angle refers to the azimuth angle (or point of the compass), from which the target area is imaged. It is well known that the variation in the incidence angle causes noticeable changes in the observed backscattering – particularly in non-vegetated areas (see for example Chen and Wang, 2008). The aspect angle plays an important role in the detection of urban structures and extraction of 3D models of buildings (Bolter, 2001, Bamler and Eidener, 2008). In the case of a vegetated area, the effect of incidence and aspect angles on the backscattering coefficient is not as significant as in the case of a non-vegetated area. In the case of satellite-borne SAR systems, only certain incidence or aspect angles are possible depending on the orbit of the satellite and the latitude of the target area.

SAR image channels are typically correlated to some extent, depending on the time interval, target properties, and SAR system parameters. For example, SAR images that are acquired on consecutive days and in similar weather conditions are plausibly highly correlated. On the other hand, for example in the case of agricultural crops, the total backscatter observed by different frequency bands radars depends on the sizes of the target components such as ears, leaves and stems of the crops. Therefore, multi-frequency SAR images can be considered as non-correlated in most cases. It is a matter of careful study to find out the most suitable SAR channels for the mapping application in question.

2.3 SAR imaging geometry and geocoding

SAR typically uses side-looking imaging geometry, because the ground range resolution becomes infinitely large when the look angle is 0° (nadir). The SAR imaging geometry can be handled in the range and azimuth directions independently. The range direction is the direction in which the pulses are transmitted. The azimuth direction is parallel with the direction of the velocity vector of the platform (satellite). SAR imaging geometry in the range direction can be described with the angles depicted in Figure 3, where Φ is the look angle, β is the depression angle, and θ is the incidence angle (Henderson and Lewis, 1998). The incidence angle depends on the topography, and surface normal should be taken into account when local incidence angles are calculated.

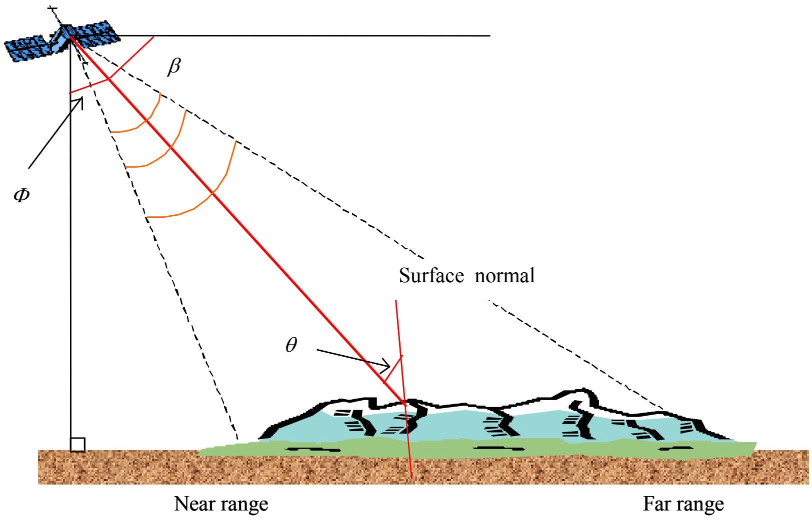

Figure 3. SAR imaging geometry in range direction.

The side-looking imaging geometry causes distortions on the SAR image in the range direction. In the case of flat areas, the distance ratios on the image and map plane remain the same. But, due to the topography, SAR images contain distortions, which should be corrected before images can be used simultaneously with existing maps or other images. The basic types of SAR image distortion are depicted in Figure 4.

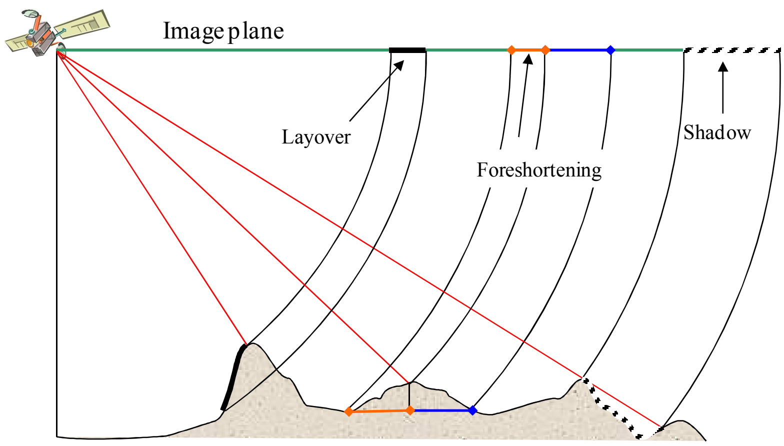

Figure 4. SAR image distortions.

The displacement of a point target on a map plane can be significant, if elevation variations are not considered in the correction process. Figure 5 shows the amount of displacement (ΔGr) of a point target on a map plane as a function of elevation error (H) and the look angle (Φ). The displacement is particularly significant in low look angles. For example, a displacement of about 10 meters can be measured if the look angle is 25° and elevation error is 5 metres in Figure 5.

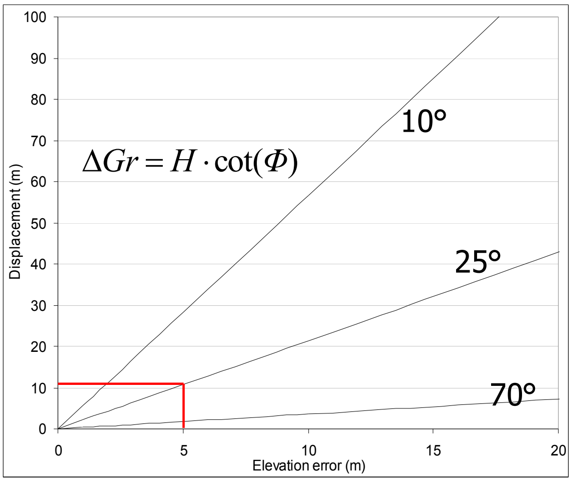

Figure 5. Displacement due to the elevation error.

Consequently, the correction of image distortions plays a very important role in the multidimensional SAR image analysis – particularly if various imaging geometries are used. The correction process is commonly called geocoding, but some synonymous terms exterior orientation, georeferencing, and geometric calibration could be used as well. Basically, the purpose of the geocoding process is to transform any image (in this case a SAR image) from the sensor image coordinate system *(x, y)* to the map coordinate system *(X, Y)* such as UTM. Once images are geocoded, it is then possible to overlay images taken at different times, from different perspectives, and with different sensors in order to carry out, for example, change detection, mapping, map updating, image mosaicing or stereo plotting (Zitová and Flusser, 2003). It should also be noted that the elevation information (*Z* coordinate) is very important in order to correct image distortions such as those presented in Figure 5.

In general, there are three approaches to carrying out the geocoding process, using either (1) non-physical, (2) rigorous, or (3) hybrid models. Non-physical models are able to transform coordinates between the object and the image space, but it is usually not possible to directly perceive the location, movement, or pose of the sensor in the object coordinate system (Toutin, 2004). A good example of a non-physical geocoding model is the affine transformation:

$$\begin{pmatrix} x = a_0 X + a_1 Y + a_2 \\ y = b_0 X + b_1 Y + b_2 \end{pmatrix} \quad (4),$$

where coefficients a_0-b_2 are unknown and can be calculated using GCPs and their corresponding image coordinates. As can be perceived, the *Z* values are not included in the 2D affine model. Therefore, image distortions remain in the geocoded image. Recently, geocoding models based on the Rational Polynomial Coefficients (RPC) have gained a lot of popularity. Zhang and Zhu (2008) used the RPC model to geocode TerraSAR-X and COSMO-SkyMed SAR images, and a very high geometric accuracy was obtained. However, it should be also noted that the RPC model is a non-physical one.

The second approach, rigorous models, uses physical parameters to model the propagation of the electromagnetic radiation between the object and the image coordinate systems as exactly as possible. A good example of a rigorous model is the collinearity equations model of the perspective camera, in which the 3D location and pose of the camera are explicitly written in the equations. In the case of SAR images, the rigorous geocoding model can be described with the system of the following three equations (Curlander, 1982):

$$
\begin{gathered}
f_{DC} = 2\left(\dot{\vec{s}} - \dot{\vec{p}}\right)\cdot\left(\vec{s} - \vec{p}\right)/\lambda\left|\vec{s} - \vec{p}\right| \\
R = \left|\vec{s} - \vec{p}\right| \\
\frac{\vec{p}_X^{\,2} + \vec{p}_Y^{\,2}}{(R_e + h)^2} + \frac{\vec{p}_Z^{\,2}}{R_p^2} = 1
\end{gathered}
\qquad (5),
$$

where λ is the wavelength, f_{DC} is the Doppler frequency shift, *R* is the measured range by the SAR sensor, $\vec{p}$ and $\dot{\vec{p}}$ are the position and velocity vectors of a ground point, $\vec{s}$ and $\dot{\vec{s}}$ are the position and velocity vectors of the SAR sensor, R_e is the radius of the Earth at the equator, R_p is the polar radius of the Earth, and *h* is the elevation of the target relative to the reference ellipsoid. $R_p = (1-f)(R_e+h)$ where *f* is the flattening factor of the reference ellipsoid. The first equation is called the Doppler equation, and the second, the range equation. The third equation is the Earth model equation. Using these three equations it is possible to carry out coordinate transformations between object and the image coordinate systems. The unknown parameters in the range and Doppler equation system are the location and velocity of the SAR sensor as a function of time.

In the third geocoding approach, some kind of hybrid of non-physical and rigorous sensor models is applied. An example in the case of SAR images can be found in Huang et al. (2004), where the hybrid model is based on a simple polynomial function, but uses elevation values to correct displacements rigorously.

The determination of the unknown transformation parameters is the key problem in using any geocoding model. In principle, there are two approaches to determine the unknowns: (1) direct geocoding or (2) space resection. In direct geocoding, GPS and IMU systems are used to determine the unknowns directly. Direct geocoding is more feasible in the case of rigorous sensor models, where these physical parameters are written explicitly in the transformation equations. Space resection actually refers to the photogrammetric solution of exterior orientation parameters, but is used in this context to mean that the geocoding parameters are calculated afterwards from 3D GCPs and their corresponding image coordinates. The accuracy of the direct geocoding can be acceptable in many cases, but if very high geocoding accuracy is desired then additional refinement of the geocoding parameters may be required. For example, Fraser et al. (2005) needed only a few GCPs to enhance the existing RPC models of the optical satellite images.

The use of GCPs in the determination of the unknown geocoding parameters is typically very reliable, but usually GCPs have to be measured manually, which is laborious, and thus, very time-consuming. Therefore, there is interest in localization of GCPs by automatically using existing geocoded images or digital maps. In principle, the automation methods can be divided into area-based or feature-based methods. In the area-based methods, such as image correlation techniques, previously geocoded or simulated SAR images can be used as ground control. Kwok et al. (1990) studied automatic methods to combine SAR images as wide-area mosaics. In favourable conditions, image correlation provides excellent results and even sub-pixel geocoding accuracies have been achieved for Radarsat-1, ERS and Envisat satellite SAR images (Lauknes and Malnes, 2005, Cheng, 2006). The feature-based methods use basic mapping entities (points, lines, and polygons) in geocoding. One can find these mapping entities in existing vector-type digital maps. The idea of using map entities in mapping processes is not a new one (Masry, 1981), and the use of linear features in photogrammetric resection was introduced in 1988 (Mulawa and Mikhail, 1988). At the same time, similar approaches were applied in the field of image processing (Liu and Huang, 1988). However, the major problem is the automatic localization of these features from remote sensing images. The use of digital maps in automatic geocoding of SAR images is challenging due to the speckle that can be observed. Rignot et al. (1991) discussed the use of features in automated multisensor registration. Line and polygon type map features have been used in the case of automatic SAR image geocoding (Dare and Dowman, 2001, Hellwich et al., 1996, Tupin et al., 1998). According to my knowledge, feature based techniques have not been utilised in leading remote sensing software packages.

2.4 SAR based mapping applications

2.4.1 Overview

Mapping can be defined in many ways. Encyclopædia Britannica describes mapping as: "any prescribed way of assigning to each object in one set a particular object in another (or the same) set" (Encyclopædia Britannica, 2009). In this thesis, the term mapping is understood as a method which uses remote sensing images (specifically multidimensional SAR satellite images) in order to create various final products such as false colour images, thematic maps, charts, or tables. The range of mapping applications is very broad, and probably can never be fully automated. A mapping application could be based on the use of a SAR amplitude image, which is displayed in GIS software in order to rapidly delineate simple map features such as a road network or rivers (Dell'Acqua et al., 2009). More complicated mapping processes involve user interaction and sophisticated classification methodologies (Bruzzone et al., 2004). A mapping application might also be based on an inversion model, which would have been created using ground reference measurements and simulation studies. For example, biophysical parameters could be estimated from multidimensional SAR images using techniques based on amplitude information, interferometry, polarimetry, or on some feasible combination of different techniques (Dobson et al., 1995, Blaes and Defourny, 2003, Engdahl and Hyyppä, 2003, Le Toan et al., 1997). There are many application areas where SAR images have been used in the past. However, many of these application areas are beyond the scope of this thesis. Therefore, the cases of built-up environment, forests, and agriculture, which were considered as the main research areas of the Finnish Geodetic Institute related to the SAR images, are described in more detail in the following chapters.

2.4.2 Mapping the built-up environment

According to Statistics Finland (2009), the built-up environment represented about 60% of the national wealth of Finland in 2005. Nearly one third of the wealth is connected directly to the buildings. The share of built-up environment of the national wealth has increased during the last ten years, indicating a rapid increase in the value of real estate. Hence, the remote sensing of built-up environment is very important and may have a significant socioeconomic impact.

What would be the contribution of SAR satellite images to the mapping of the built-up environment? It is clear that SAR images are not able to compete with digital aerial images and laser scanning in large-scale mapping, which have the scale that is required for representing the built-up environment. In the past ten years, laser scanners have evolved from cumbersome measuring devices into high-level imaging instruments capable of creating remarkably accurate 3D representations of a built-up area. Mobile mapping systems and methods integrating digital aerial images with ALS have revolutionized the creation of virtual city models, and the list of possibilities appears endless. SAR images seem to be way behind the requirements. The power of SAR is in its response time and repeatability, which enables rapid mapping (Dell'Acqua et al., 2009). However, the information content of SAR images in the case of urban area mapping is a bit vague. Dowman and Morris (1982) have already studied the use of airborne SAR images in large-scale mapping. The results were reasonably promising. However, it was evident that not all cartographic objects were extracted successfully. In some cases some buildings could be observed quite easily from the images, while other buildings were not visible at all. The visibility of a building depends heavily of the orientation of the wall in relation to the aspect angle of the SAR acquisition. In literature, this phenomenon is referred to as the Cardinal effect (Henderson and Lewis, 1998). For example, in the Helsinki metropolitan area, over 90% of the buildings in a favourable orientation in relation to the aspect angle were detected, but fewer than 20% were detected in the cases where the orientation angle was perpendicular to the favourable orientation (Publication IV). Hence, it can be assumed that SAR images are not of interest to Finnish mapping authorities and to private mapping companies in the mapping of urban areas. Nevertheless, SAR images can be used in the mapping of remote areas, where other more accurate methods are unavailable (Henderson and Xia, 1997). Moreover, the rapid imaging response is particularly significant in cases of natural or geological hazards, disasters, and emergencies such as tropical cyclone, flooding, earthquake, or volcano eruption, which may cause significant damage in urban areas. SAR images could be used to evaluate the scale of the impact, to help organize relief efforts and operations, and to aid in emergency relief in general (Chini et al., 2009, Gamba et al., 2007).

In medium-scale land-use mapping (scales near 1:50000), the time series of SAR images may be beneficial. Basic land-use classes (such as water, built-up, and forested areas) can be distinguished (Strozzi et al., 2000, Matikainen et al., 2006). Bugden et al. (2004) described a process model for generating land-cover maps from SAR products. In the SAR interferometric process, a side-product called coherence is calculated. Coherence is a measure of correlation describing the quality of the interferograms. Urban areas are more stable targets than forested areas with respect to microwave radiation.

Finally, probably the most important application and the first commercial breakthrough of satellite-borne SAR is Persistent Scatterers SAR Interferometry (PSI). Using a long time series of SAR images, it is possible to detect subsidence or uplift of the Earth's surface in the order of millimetres. Persistent scatterers are point targets that remain stable with respect to microwave radiation, i.e. the coherence is high. Forested areas may lose the coherence within a few hours, but urban structures remain stable for a very long period. In PSI, multiple interferograms are calculated, persistent scatterers are located, and the effects of atmosphere and DEM are cancelled. The result is a distribution of persistent scatterers and their rate of vertical subsidence or uplift. Recently, a massive number of research papers have been published on PSI. The method was originally developed by an Italian team of researchers (Ferretti et al., 1999, 2000).

2.4.3 Forest mapping

In Finland, about 76% of the land area is forested, which is the highest percentage amongst the European countries (Parviainen et al., 2007). Forests have a large impact on the Finnish economy and environment. The Finnish national forest inventories have been based on systematic sampling in field surveys, in which aerial and satellite images and various maps have been used for additional data. In general, the inventory results are accurate, but they lack detailed information, which might be helpful for paper companies in planning wood supplies. Airborne Laser Scanning (ALS) has proven its significance and superiority in forest inventories and is already operationally used in wood supply planning (Hyyppä et al., 2008). However, ALS is somewhat expensive when very large areas are considered, and the repeatability is not very good either (mapping of the whole of Finland might take 10 years or so). Therefore, there is a space in the process chain of forest inventories that could be filled using satellite-borne SAR images.

The amplitude of the backscattering is correlated with the forest biomass, particularly when long wavelengths of the L or P bands are used (Le Toan et al., 1992, Rauste, 2005). On the other hand, the scattering in the X band occurs mainly in the branches of the trees. Interferometric coherence has also been found to be highly correlated with forest stem volume (Askne et al., 2003). However, both the amplitude and coherence signal seem to saturate at some point of the stem volume, and the volume above the saturation point cannot be observed. Recently, the fusion of ALS and SAR data has been studied in order to increase the estimation accuracy and the repeatability of inventories as well as to allow wide-area forest mapping (Walker et al., 2007, Nelson et al., 2007).

2.4.4 Mapping agricultural areas

Agriculture can be regarded as the most basic industry. On the one hand, farmers supply food for the rest of the population, and, on the other, agriculture provides raw material to other industries. About one third of the world's population works directly in agriculture. Trading in agricultural products may also have a major impact on the economy of countries, especially on the developing ones. Therefore, remote sensing could provide significant information in order to optimize production and in trade-related issues. There is also growing public interest in biofuels and in reduction of eutrophication and carbon emissions, which is likely to further encourage the use of remote sensing techniques.

In general, the utilization of remote sensing in agriculture can be categorized into the following application areas: mapping of yield losses, mapping of the area under cultivation, estimation or prediction of crop yield, crop species interpretation, precision farming, and control of agricultural subsidies. In this context, the main benefit of SAR is its all-weather imaging capability because the applied images should preferably be acquired in the certain stages of the crop growth. In addition, SAR enables mapping of large areas almost simultaneously, which would be unrealistic with optical satellite images due to the cloudiness in Finland.

There has been a wide range of studies of agricultural remote sensing based on SAR satellite images, and this research field is well summarized in Wooding et al. (1995). Potential applications include rice yield estimation (Le Toan et al., 1997), crop species classification (Saich and Borgeaud, 2000, Schotten et al., 1995), and crop biomass estimation using interferometric coherence (Blaes and Defourny, 2003). Multidimensional SAR images are expected to increase the feasibility of applications

(McNairn and Brisco, 2004). However, the problem of extracting crop biomass related parameters from SAR images has proven to be a challenging one. Therefore, the fusion of SAR images and laser scanning may have potential in the near future similar to the case of forest inventories (Karjalainen, 2008, Lumme et al., 2008).

2.5 Past and current satellite-borne SAR systems

2.5.1 Civilian satellites

In this context the term civilian refers to SAR missions, from which detailed technical information is available in public. The list of past and current satellite-borne SAR systems is given in Table 2. Additionally, there have been shuttle-borne SAR missions, which have produced remarkable data. These include the SIR-A, SIR-B, SIR-C, and SRTM missions (Rabus et al., 2003, Farr et al., 2007).

Table 2. List of civilian satellite-borne SAR systems (Kramer, 2001, Düring et al., 2008, Rosenqvist et al., 2007, Fagioli et al., 2006).

Satellite	Time period	Frequency band	Polarization	Nominal spatial resolution	Incidence angle range	Swath width
Seasat (USA)	1978 (106 days)	L	HH	25m	20°	100km
Kosmos 1870 (Russia)	1987-1989	S	HH	25m	16-60°	20-35km
Almaz-1 (Russia)	1991-1992	S	HH	13-20m	25-60°	2*172km
ERS-1 (ESA)	1991-2000	C	VV	30m	20-26°	100km
JERS (Japan)	1992-1998	L	HH	18m	32-38°	75km
ERS-2 (ESA)	1995- (not fully functional at the moment)	C	VV	30m	20-26°	100km
Radarsat-1 (Canada)	1995-	C	HH	8-100m	20-60°	45-500km
Priroda in MIR Space Station (Russia)	1996- (Mir destroyed in 2001)	S, L	HH, VV	50m	35°	50km
Envisat (ESA) (http://envisat.esa.int/)	2002-	C	HH, VV, HV and VH (dual polarimetric)	30m	15-45°	100km
ALOS (Japan) (http://www.eorc.jaxa.jp/ALOS/)	2006-	L	HH, VV, HV and VH (fully polarimetric)	7-100m	8-60°	40-350km
TerraSAR-X (Germany) (http://www.dlr.de/terrasar-x)	2007- (TanDEM-X in 2009)	X	HH, VV, HV and VH (fully polarimetric)	1-16m	15-60°	10-100km
COSMO-SkyMed (Italia) (http://www.telespazio.it/cosmo.html)	2007- (three satellites have been launched)	X	HH, VV (dual polarimetric	1-100m	20-55	10-200km
Radarsat-2 (Canada) (http://www.radarsat2.info/)	2007-	C	HH, VV, HV and VH (fully polarimetric)	3-100m	10-60°	20-500km

One can easily notice that there has been a significant improvement in image characteristics during the lifetime of SAR satellites. For example, the spatial resolution is nowadays in the order of one metre. TanDEM-X satellite, which is a successor to TerraSAR-X, enables single-pass SAR interferometry from these two satellites (Krieger et al., 2007).

2.5.2 Military satellites

In addition to civilian SAR satellites, there have been numerous military satellite-borne SAR systems. The information about these satellites is limited and vague because detailed information is highly classified. SAR-Lupe is a German constellation of SAR satellites consisting of five similar satellites (Keydel, 2007). The first SAR-Lupe satellite was launched in 2006, and the spatial resolution of the SAR images is presumably in the order of one metre. Lacrosse (sometimes referred to as Onyx) is a military SAR satellite system from the USA (Vick, 2005). The first Lacrosse satellite was launched in 1988, and the last one in the series of five satellites was launched in 2005. Practically no information at all is available about the Lacrosse system. COSMO-SkyMed is an Italian constellation of SAR satellites (Fagioli, et al., 2006). The COSMO-SkyMed system is partially a civilian mission, but also includes military aspects which are not very well known. At the moment, there are 3 COSMO-SkyMed satellites in the space. TecSAR is an Israeli SAR satellite, which was launched in early 2008 (Naftaly and Levy-Nathansohn, 2008). The technical details of the TecSAR system are not known, but presumably the most advanced SAR components have been used in it. India and Japan also have their own military SAR satellites in order to monitor regional security threats. In 2007, Japan launched the Information Gathering Satellite (IGS-4A), which includes a Very-High-Resolution SAR system. In April 2009, India launched their RISAT-2 satellite, which contains a SAR system similar to that of the TecSAR satellite. The common features in all military SAR systems are their rapid imaging response and fine spatial resolution. Futuristic plans include cartwheel constellations, bi-static imaging operations, geosynchronous radar transmitters, and several receiving antennas (Keydel, 2007). These new features will probably emerge in civilian SAR satellite systems some day in the future.

3 Material and methods

The SAR satellite images and ancillary data used in this thesis are listed in Table 3. More details about the applied SAR satellites can be found in Table 2.

Table 3. Materials used in publications.

Image data	Reference data
Radarsat-1 fine beam (**II, IV**) *GSD: 6 m *Frequency band: C *Polarization: Single-pol (HH)	*Water boundaries from Landsat imagery (**II**) *Height information from NLS DEM25 (**II, IV**) *Check points from NLS Topographic Database (**II**) *Building map from Blom kartta Ltd. (former FM-kartta) (**IV**)
ERS-1 and ERS-2 AMI (**II,V**) *GSD: 12.5 m *Frequency band: C *Polarization: Single-pol (VV)	*Water boundaries from Landsat imagery (**II**) *Height information from NLS DEM25 (**II, V**) *Check points from NLS Topographic Database (**II**) *Levelling data from Turku city (**V**)
Envisat ASAR (**II, III**) *GSD: 12.5 m *Frequency band: C *Polarization: Dual-pol (VH/VV)	*Water boundaries from Landsat imagery (**II**) *Ground control points from Topographic maps (**III**) *Height information from NLS DEM25 (**II, III**) *Check points from NLS Topographic Database (**II**) *Parcel boundaries from the National Land Parcel Identification System (**III**) *FGI field surveys of test parcels (**III**)
ALOS PALSAR (**VI**) *GSD: 20 m (Quad-pol) *GSD: 10 m (Dual-pol) *Frequency band: L *Polarization: Quad-pol (HH,HV,VH,VV) *Polarization: Dual-pol (HH,HV)	*Ground control points from NLS Topographic Database (**VI**) *Height information from NLS DEM25 (**VI**) *ALS based Canopy Height Model (**VI**)
RC-30 aerial imagery (**I**) *False color film *GSD 0.4 m, Flying height 5000 m Note! Automation of geocoding was initially tested using aerial images	*Parcel boundaries from the National Land Parcel Identification System (**I**) *Height information from NLS DEM25 (**I**) *Signalized ground control points (**I**)

SAR images were geocoded into the Finnish Uniform map coordinate (YKJ) system, except in Publication VI, where UTM/WGS84 system was used. YKJ is the old nation-wide map coordinate system of Finland and it is based on the Gauss-Krüger projection and Hayford ellipsoid. At the moment, Finland is in a transition phase to start using the Universal Transverse Mercator (UTM) based global grid coordinate system in nation-wide applications. NLS DEM25 is the Finnish nation-wide DTM with the grid size of 25 m. NLS DEM25 was used, first, to determine the height information (Z value) for the GCPs, and second, in the orthorectification process of the geocoded images. The vertical accuracy of NLS DEM25 can safely be expected to be less than 5 metres, which is adequate in geocoding of the SAR satellite images used in this thesis. In PSI studies (Publication V), the levelling surveys of the Real Estate Department of Turku were used as reference data. In agricultural studies (publication III), ground surveys were carried out simultaneously with image acquisition. The most important and practically measurable parameters of the soil surface and vegetation were measured. In mapping of urban areas (Publication IV), the reference building map was acquired from the Blom kartta Ltd. (former FM-kartta). The building map also included the height of the buildings. In the forest mapping study (Publication VI), ALS based Canopy Height

Model was used as a reference data for the estimation of forest above ground volume using ALOS PALSAR images. In SAR geocoding studies, manually digitized 3D check-points were used as a reference data.

The applied methodologies are listed in Table 4. It should be noted that the list of methodologies is not comprehensive, but merely indicates the main methods used in the publications.

Table 4. Summary of used methodologies and SAR data dimensionalities.

		Data dimensionality				
		Multi-temporal	**Multiple polarizations**	**Multiple frequency bands**	**Multiple incidence angles**	**Multiple aspect angles**
Used methodologies	**Building detection/ mapping**	**IV**	**-**	**-**	**IV**	**IV**
	Automatic Geocoding	**II**	**II**	**I vs. II (optical vs. SAR)**	**II**	**-**
	Crop/forest biomass estimation	**III, VI**	**III, VI**	**-**	**III**	**-**
	SAR interferometry	**V, VI**	**VI**	**-**	**VI**	**-**
	SAR polarimetry	**VI**	**VI**	**-**	**VI**	**-**
	Data classification	**III**	**III**	**-**	**III**	**-**

4 Results

4.1 Automation of geocoding process

4.1.1 Publication I

In publication I, the objective was to study automatic exterior orientation of aerial frame images using existing digital vector maps. Even though GPS and IMU systems provide very good approximations for the exterior orientation parameters (or geocoding parameters) of the remotely sensed data nowadays, these parameters can be unreliable due to the broken GPS signal or drifting of the IMU system. Therefore, it could be advantageous if geocoding could be automatically verified and possibly refined using existing map information as ground reference data. The method proposed in Publication I was based on the line scanning technique, which was aimed to be very fast (in the order of a few seconds) and fully automatic. The line scanning technique projects the line segments from the vector map one by one on the image plane and tries to locate the actual position of the line segment on the image using cross-profiles. The method uses only well located line segments in the determination of new parameters. Thus, it tolerates coarse digitising errors in vector maps to some extent and can exploit only partially visible line segments (due to the shadows or occlusion). Prototype software was developed and the method was tested using both nadir and oblique aerial images. According to the tests the aerial images were robustly oriented to coincide with vector maps i.e. the best matches between images and vector maps were found. However, it should be noted that the absolute accuracy of the exterior orientation parameters with respect to the object space coordinate system depends solely on the accuracy of the vector map. For example, if the vector map is shifted in relation to any other map data, this shift is directly visible in the resulted orientation parameters. In this case, however, the automatically derived exterior orientation parameters were found to be well comparable with the parameters derived from well-defined signalised GCPs.

4.1.2 Publication II

The geocoding information of the SAR satellite images of the previous generation (ERS-1, ERS-2, Radarsat-1, and Envisat) was rather poor without additional precise orbit information. For example, it is possible to apply precise orbits to ERS and Envisat satellites, but this information is typically available a month after the acquisition. In publication II, the objective was to refine the geocoding information of SAR images using existing digital vector maps. The line scanning technique, which was developed in Publication I, was extended to be applicable for SAR images as well. Again, the method projects the line segments on images and tries to locate them from the images using cross-profiles. However, in the case of SAR images it was not possible to use the coplanarity equation in the determination of geocoding parameters as in the case of aerial frame images. Therefore, the displacements of the projected and located line segments were used to create so-called virtual GCPs. Because line features contain matching information only in the across-direction of the lines, the geocoding process had to be performed iteratively by gradually minimizing the dislocations. Tests were carried out for ERS-1, Envisat, and Radarsat-1 SAR images using vector map consisting of boundaries of water bodies, which are usually well detectable in SAR images. In general, the main requirement of the method is that at least some of applied line segments should be detectable on the images. For example, it would be useless to apply the method for SAR images covering only forested area. According to the test, the accuracy of the automatically geocoded images was in the order of 1-2 pixels when a rigorous SAR sensor model was used. The accuracy estimate was calculated using independent check points derived from digital maps. The accuracy of 1-2 pixels corresponds to the nominal spatial resolution of these SAR satellites; thus, the result was seen as successful.

Publications I and II resulted a prototype version of the software capable to automatically refine the geocoding parameters of SAR images (and other type of remote sensing image geometries as well). Additionally, the prototype software outputs the automatically located GCPs and their image coordinates into a text file, which could be later processed using commercial software packages such as Socet Set software. The graphical user interface, in case of SAR imagery, is represented in Figure 6.

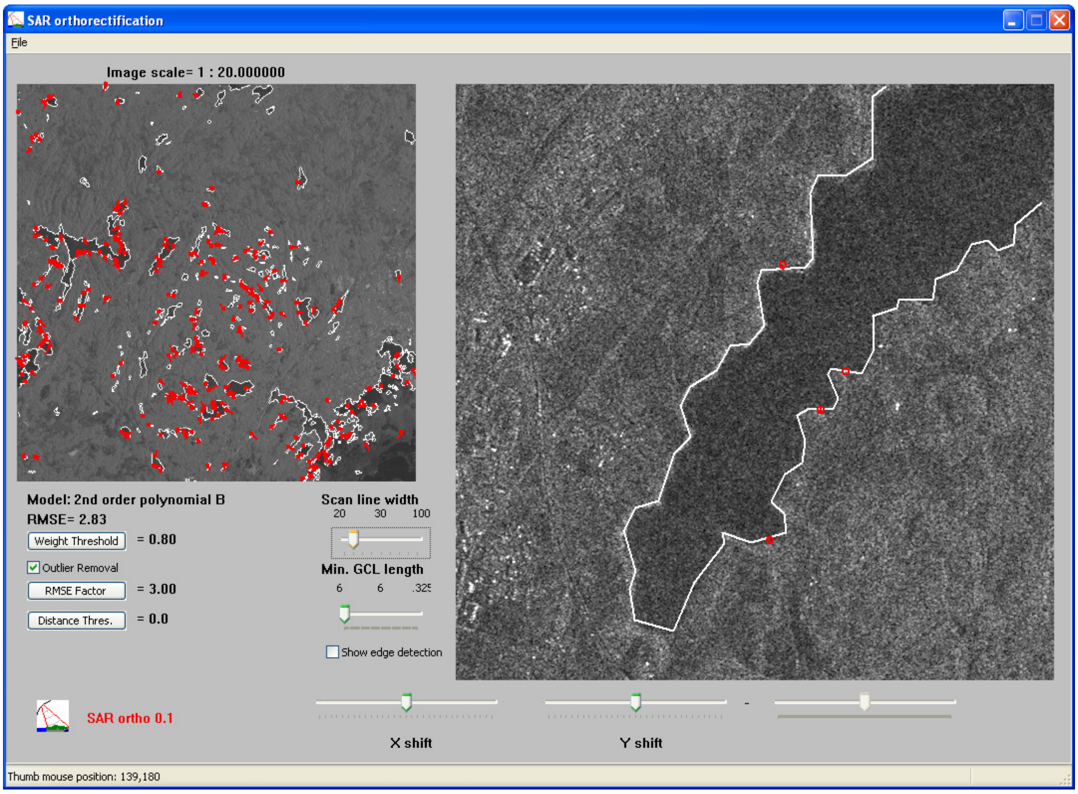

Figure 6. Graphical user interface of prototype software.

4.2 Processing multidimensional SAR satellite images

4.2.1 Publication III

Cloudiness is very common in Finland. Therefore, the frequent imaging capability of SAR satellites could be useful in monitoring of agricultural areas in Finland. In publication III, the suitability of high temporal resolution Envisat SAR satellite images in agricultural monitoring was studied with special emphasis on crop species interpretation and crop biomass estimation. In the study, the practical aspects of monitoring of agricultural areas were underlined and not the physical modelling of SAR backscattering of crop canopy. The test set consisted of 12 dual-polarization (VV/VH) Envisat SAR images. The basis of the reference data was the Finnish Land Parcel Identification System, which consists of the boundaries of the base parcels. The information of the true crop species for each parcel was obtained from the Ministry of Agriculture and Forestry of Finland. Additionally, field surveys were carried out simultaneously with the image acquisitions in order to obtain ground truth for the evaluation of the biomass estimation capability. In field surveys, only those characteristics of soil and vegetation parameters were measured, which were possible to measure as effortlessly as possible without destructing any crops. All studies were carried out at the parcel level, i.e. average SAR backscattering was calculated for each test parcel. This way the effect of SAR speckle was reduced. The results showed the overall classification accuracy of 75% for the crop species interpretation. The cumulative addition of images improved classification in the beginning of the growing season, but after the beginning of August the accuracy did not improve anymore. In the case of biomass estimation, SAR information was used to predict the crop height using multiple linear regression modelling. In the best case, where soil surface parameters were used as additional information, the coefficient of determination of 0.55 for the crop height and SAR signal was achieved (Figure 7).

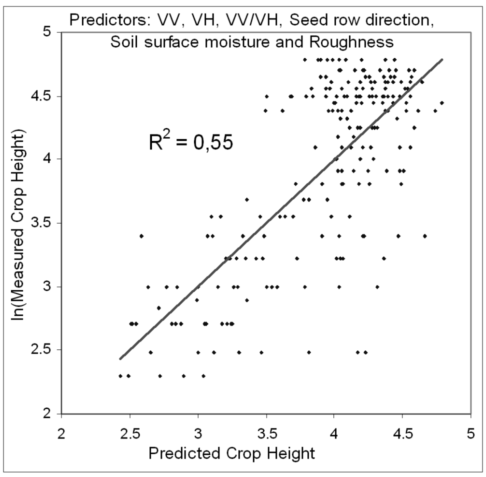

Figure 7. Scatterplot of the measured versus predicted crop heights using the multiple regression model.

There was clear correlation between the measured and the predicted crop height even though the R^2 value was relatively poor. The dual-polarization capability of Envisat SAR was found as beneficial feature in both classification and biomass estimation cases when compared with the use of single-polarization information only.

4.2.2 Publication IV

In publication IV, the feasibility of mapping of urban areas using fine resolution SAR images was studied. The test set consisted of 7 Radarsat-1 SAR images acquired in Fine-beam mode and aspects of multi-temporality, multiple incidence and aspect angles were included. The feasibility of mapping of urban areas was studied by determining the percentage of detectable buildings on SAR images. An automatic method for detecting buildings on SAR images was also developed. Then, the automatically detected buildings were compared to a real building map. The building map was created by FM-Kartta (nowadays Blom Kartta Oy) by means of photogrammetric stereo plotting. The heights of the buildings were also included in the building map. Moreover, a smaller set of 122 buildings was created in order to study if the roof type or material, for example, has any effect on the detectability of buildings from SAR images. In summary, the results were expected, although the additional test set of 122 buildings was too small to draw any concrete conclusions. The orientation of the building wall in relation to the SAR aspect angle had a very strong impact on the building visibility (Figure 8).

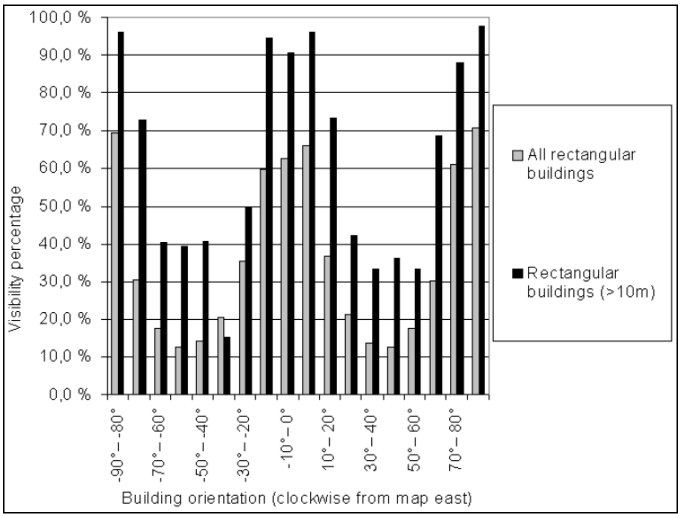

Figure 8. Building visibility on SAR images as a function of building wall orientation.

For example, in the case of buildings with height over 10 metres and facing one wall perpendicularly to the SAR aspect angle, the resulting detection percentage was over 90%. On the other hand, in the case of small houses with unfavourable wall orientation in relation to SAR aspect angle, less than 20% of the buildings were detected.

4.2.3 Publication V

The use of persistent scatterers SAR interferometry in the detection of urban subsidence has gained a lot of popularity throughout the world after the first results produced by Ferretti et al. (1999). Ground subsidence is a well-known problem in Finland also, but extensive information about the phenomenon is usually missing. Local authorities and private companies carry out levelling surveys to monitor certain buildings that are, for example, historically remarkable. Therefore, any subsidence information provided by PSI could be valuable to local authorities or owners of the buildings. In publication V, the goal was to evaluate the usability of PSI in Finland. The cities of Helsinki and Turku were selected as test areas and a time series of ERS-1 and ERS-2 SAR were obtained through a Category-1 project of ESA. However, the comparison of subsidence rates of PSI and levelling was only possible in Turku, where the levelling surveys were more comprehensive than in Helsinki. Moreover, the Turku case is very favourable for testing the accuracy of PSI based methods, because the rate of the subsidence has been very stable throughout the years. The Coherent Target Monitoring software module developed by the Vexcel Canada (nowadays owned by the MDA Geospatial) was used in the PSI analysis. The Real Estate Department of Turku provided us with levelling surveys. In total, there were 10 buildings, for which both PSI and levelling subsidence rates were available. The number of coherent targets (PSIs) and levelling benchmarks varied from one building to another, but nevertheless, there were several points for comparison for each building. According to the results, very good agreement of the PSI subsidence values in comparison to levelling measurements was achieved. An example of two buildings is presented in Figure 9. When all 10 test buildings were considered, the RMSE of 0.82 mm/year between PSI and levelling subsidence rates was obtained.

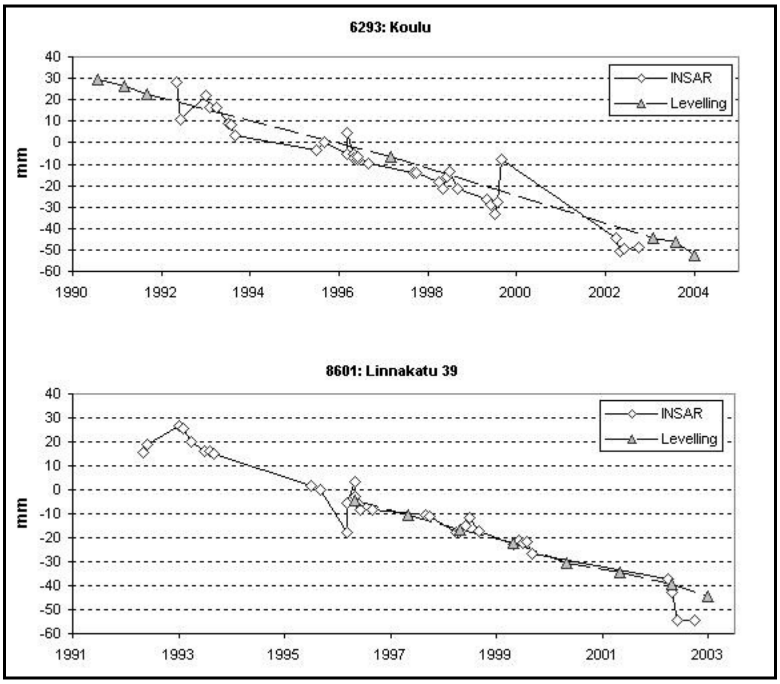

Figure 9. Comparison of PSI and levelling subsidence rates for two buildings in Turku.

4.2.4 Publication VI

ALS has established its position as a reliable data source in forest inventories in Finland. However, at the moment the repetition frequency of ALS in nation-wide surveys is rather poor – maybe 10 years or so. Thus, SAR satellite image could have potential in forestry, namely in updating the inventories or change detection. In publication VI, the Quad and Dual polarization ALOS PALSAR images were used in mapping of a forested area in Finland. The test area was located in the Nuuksio national park in Southern Finland, which mainly consists of mixed forests in their natural conditions. Therefore, the test area can be characterized as a challenging one with respect to the use of SAR images. Reference information was obtained from Optech ALS data with the point density of $3/m^2$. ALS data was used to create a Canopy Height Model (CHM) by subtracting the ground elevation values from the canopy elevation values. Then, CHM was used to estimate the Above Ground Volume (AGV) for 111 manually digitised forest stands, which were located at as flat areas as possible in order to cancel the effect of topography on the SAR backscattering values. Even though AGV is not directly related to the stem volume, it seems that it is possible to estimate stem volume relatively accurately (Hyyppä et al., 2008). In total, 2 Dual polarization and 3 Quad polarization ALOS PALSAR images were used. In addition to the amplitude information of SAR backscattering, polarimetric descriptors (alpha-entropy-anisotropy decomposition) were calculated. In the case of Dual polarimetric images, the interferometric coherence between the two images was calculated also. Then, SAR descriptors were used to estimate the LIDAR based AGV using multiple linear regression modelling. The results showed relatively good correlation between the AGV and SAR signal. In the cases of Dual and Quad polarization images the R^2 values of 0.53 and 0.72 for the AGV estimation were achieved respectively. The scatterplot of estimated and LIDAR based AGVs in the case of Quad polarization SAR descriptors is presented in Figure 10.

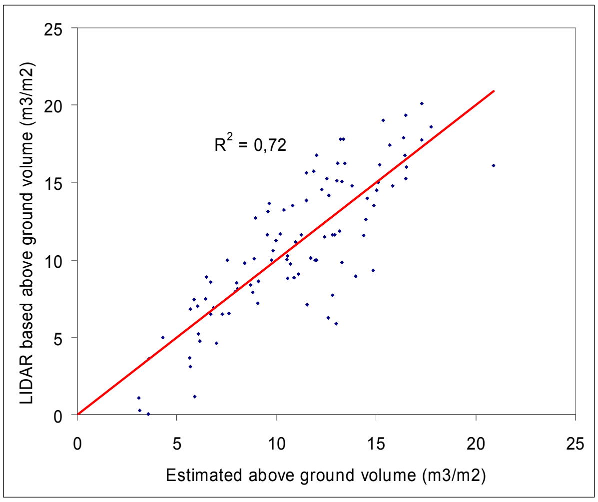

Figure 10. Scatterplot of estimated (Quad polarization PALSAR data) and LIDAR based AGV.

5 Discussion and conclusions

5.1 Geocoding of satellite SAR images

The number of SAR satellites has increased noticeably in the last few years, and it can be assumed that even more satellites will be launched in the future. In order to use SAR images in mapping applications they have to be precisely registered with each other, and at least for visualization purposes, with existing digital maps.

The problem of image-to-image registration in the case of nearly similar images has already been worked out, and in commercial remote sensing software packages there are area-based matching algorithms, which automatically produce tie-points (Heipke, 1997). Image-to-image tie-points can also be used for SAR images. It has been demonstrated that SAR images can be automatically registered with each other very precisely in order to create wide-area mosaics (Kwok et al., 1990, Rignot el al., 1991). Moreover, previously geocoded SAR images or synthesized SAR images from DEMs can be used to geocode new SAR images to the map coordinate system (Werner et al., 2002, Sheng and Alsdorf, 2005, Lauknes and Malnes, 2005).

Image-to-map registration, which can be used to automatically generate GCPs needed in the calculation of the geocoding parameters, is a more challenging problem than image-to-image registration. Recent developments in the geometric processing of SAR satellite images have nearly made geocoding obsolete from the end-user point of view. Ager and Bresnahan (2009) reported that the range measurements and the orbit of the TerraSAR-X satellite are routinely known with such a high accuracy that the resulting error on the ground is less than a metre if the DEM of the target area is available and used. It has also been shown that satellite SAR images could be even used in the geocoding of other satellite images or in the correction of old topographic maps (Gonçalves and Dowman, 2002, Liu et al., 2004). However, from the reliability point of view, it would be reasonable to at least check the geocoding accuracy and possibly to refine the geocoding parameters. For this purpose the use of existing digital maps might be beneficial.

In this thesis, a new approach to image-to-map registration is presented. The method is based on line features, which are derived from digital vector maps. Automatic line matching produces GCPs and their corresponding image coordinates, which are then used to calculate the geocoding parameters for SAR images. The prototype software was able to cope with Radarsat-1, ERS-2, and Envisat SAR images with the accuracy around the nominal spatial resolution of the SAR systems. Somewhat similar approaches based on line features for automatic SAR-to-map registration have been presented earlier. Dare and Dowman (2001) used polygon and line features derived from SPOT satellite images to register SAR and SPOT images. They were able to automatically locate tie-points between images, thus enabling a fully automatic geocoding process. However, the accuracy in the range direction was poorer than in the azimuth direction due to the lack of a rigorous SAR sensor model. Krüger (2001) studied the problem of registration based on the line segments and also successfully tested the method with SAR images. Balz (2006) used 3D wire-frame models of buildings to create a synthesized SAR image, which was then used in the geocoding of real SAR images. The Balz method is particularly beneficial in urban environments, where layover and shadow distortions are dominantly visible in SAR images. Habib and Alruzouq (2004) presented a method based on parametric line features, which was capable of registering multisensoral image data. Although the use of line features in automatic geocoding of remote sensing images has been demonstrated in many scientific studies, according to my knowledge they are still non-existent in major commercial remote sensing and photogrammetric software packages. I believe that the main obstacle is that the line feature based methods are not mature enough to really tackle all sensor types, various sources of digital maps, and temporal changes (for example, conditions of snow and no-snow are very challenging). And this obstacle applies to the method proposed in this thesis as well.

5.2 Mapping applications based on SAR satellite images

In this thesis, various mapping applications based on SAR satellite images were studied. A common characteristic in all cases was the multidimensionality of applied SAR data. In these studies, the emphasis was put on the practical aspects of the possible applications, i.e. how SAR satellite images could be exploited in mapping processes as effortlessly as possible and operationally without high extra costs such as field surveys.

The most promising technology considering the operational use seems to be PSI, which provided very accurate rates for ground subsidence of buildings in the Turku case. There are commercial software packages which are able to carry out PSI processing nearly automatically. The main advantage is that PSI offers a wider picture of the subsidence phenomenon than traditional levelling measurements. If the costs of SAR images were to decrease in the future, a PSI application could be used operationally to monitor urban areas in Finland. Similar results for urban subsidence have been reported all around the world (see for example Colesanti et al., 2003, Ferretti et al., 2007). However, special caution should be used in the interpretation of PSI results without a-priori information. Raucoules et al. (2009) compared eight PSI methods in the same test area and concluded that non-linear subsidence was problematic and there were deviations in the PSI and levelling subsidence rates when the subsidence rate was more than 2 cm/year in the consecutive SAR images. Moreover, SAR interferometry and PSI have potential in monitoring natural hazards, for example, monitoring faults to predict earthquakes (Funning et al., 2007). In Finland, such natural hazards are non-existent, but there might be potential to apply PSI methodology to monitor nuclear plant areas (Karila et al., 2008).

SAR satellite images have been studied in various agricultural applications, and in the 1990's it seemed that there might be even potential for operational use (Wooding et al., 1995). In Finland, due to the cloudiness, SAR satellite images could have a significant role in operational monitoring of agricultural areas. However, the results of the use of Envisat Dual-polarization SAR images in Finland were not very convincing. The overall classification accuracy of the crop species was 75%, which most likely would be inadequate for the use of the Ministry of Agriculture and Forestry in monitoring. Satalino et al. (2009) also used Envisat Alternating Polarization SAR images (HH/VV) and obtained accuracies in the same order for wheat and non-wheat classification. On the other hand, in the light of the crop biomass estimation results, SAR images could be used to estimate crop growth and potential yield to some extent. Le Toan et al. (1997) were able to achieve very good agreement with rice biomass and the ERS-1 SAR signal, but the estimation problem in the case of cereal crops in Finland has proven to be more challenging (Karjalainen, 2008). More detailed information about soil surface and vegetation would be required in order to increase the biomass estimation accuracy. Thus, the use of optical satellite images and more SAR channels (multi-frequency and polarimetric images) would be required in order to improve the estimation results (McNairn et al., 2009).

In the case of forests, there are similar challenges to be faced as in the case of agriculture. It is possible to estimate the stem volume to some extent using SAR backscattering information, but at some point of the stem volume estimation the SAR signal saturates, and the accuracy of the estimates is rather poor (Le Toan et al., 1992, Rauste, 2005). However, by using SAR satellite images it is possible to create, for example, stem volume maps more frequently and for wider areas than with ALS. Therefore, SAR can be considered as an interesting alternative and worth studying in the case of forest mapping. In this context, global single-pass interferometric SAR missions (such as SRTM) and tandem SAR missions (such as TanDEM-X) seem very promising (Kellndorfer et al., 2004, Düring et al., 2008).

In the case of mapping of urban areas, SAR is known to have limitations. First, the layover and shadow distortions and speckle on SAR images complicates visual interpretation. Second, due to the Cardinal effect some of the buildings are completely invisible on SAR images. Therefore, fairly experienced operators are needed in the visual interpretation of SAR images. In this thesis, automatic detection of buildings from Radarsat-1 SAR images was studied and some general guidelines for detection success in various cases in Finland were created. According to the results, the detection proved least reliable in the case of residential areas with small apartment houses. However, in densely built urban areas the detection of buildings with respect to the reference data set was highly successful. In order to maximize the detection of buildings, multi-aspect SAR images are needed. Bolter (2001) summarized that four views should be enough for most buildings. In problematic areas, the use of interferometry and polarimetric SAR interferometry would most likely increase the detection percentage as well (Matikainen et al., 2006, Shimoni et al., 2009). The Radarsat-1 images used in this study were not suitable for interferometric processing, however. In the light of the results, it seems evident that SAR satellite images cannot compete with digital aerial images and ALS in large-scale mapping. Due to the frequent imaging capability and the high revisit time, the future SAR satellite systems could provide crucial information in the cases of natural or non-natural disasters. However, in the case of mapping of urban areas one should keep in mind the overall constraints of SAR images on detecting buildings and possibly damaged structures.

In this thesis, Radarsat-1, ERS-1, ERS-2, Envisat, and ALOS satellites were used. However, the FGI is participating in the scientific projects of the new SAR satellites: TerraSAR-X AO and Radarsat-2 SOAR. The quality of SAR satellite images has increased in many ways. For example, the Spotlight SAR imaging mode of TerraSAR-X satellite allows a spatial resolution in the order of one metre, which enables the change detection of smaller targets. Radarsat-2 and ALOS PALSAR acquire Quad-polarization images routinely. Using all these SAR satellites, multi-frequency (X, C, and L band) images can be obtained with more flexible imaging geometries than earlier. Hence, in order to create simplified final products for the potential end-users, processes must be as automatic as possible in mapping applications. A possible simplified processing chain based on the methodologies studied in this thesis is presented in Figure 11.

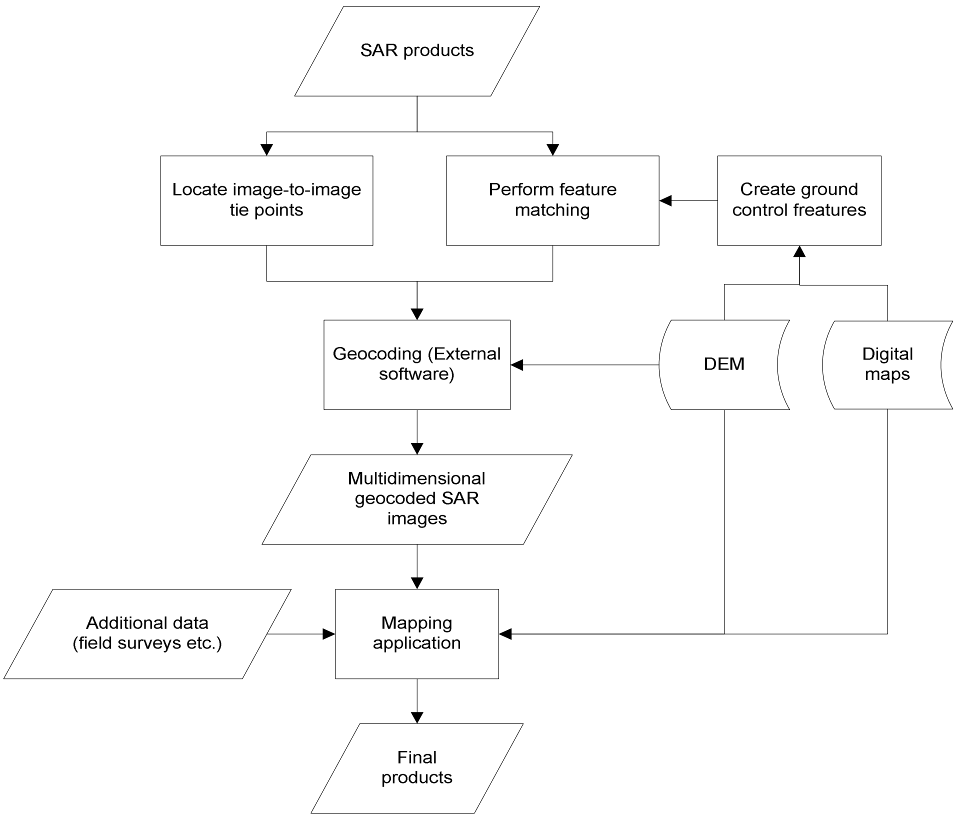

Figure 11. A processing chain for SAR products to create final products.

The processing chain in Figure 11 applies to the case where the input SAR products are so-called detected products (amplitude images). In the case of raw or SLC images (interferometric or polarimetric SAR methods), the processing chain would be dramatically different. Applying the methodologies studied in this thesis, it would be possible to create mapping applications, which would process input SAR products to a final product nearly autonomously. However, a lot of research would be still required to actually implement such an application. Moreover, the selection of appropriate input SAR products (the most suitable timing of image acquisitions, frequency, polarization, imaging geometry) is not a trivial task.

6 Summary

In this thesis, there were two main objectives. First, automatic refinement of the geocoding parameters of remotely sensed images, with a special emphasis on SAR satellite images, was studied. The aim was to develop prototype software for carrying out the geocoding process. Second, the usability of multidimensional SAR satellite images in selected mapping applications was studied.

The main results of the thesis are summarized in the following:

1. Geocoding of SAR satellite images
   - An automatic method for geocoding SAR images using existing vector maps (image-to-map matching) was developed.
   - When a rigorous SAR sensor model was used, the RMSE of around 2 pixels was achieved for test images based on independent check points. The accuracy is close to the nominal spatial resolution of the SAR images used.
   - Prototype software to carry out the geocoding was developed. The software includes functions to export image-to-map tie-points to commercial software packages, such as Socet Set.
   - Due to the recent development in the direct orbit determination of the remote sensing satellites (geolocation accuracy of TerraSAR-X is around one metre), the need for such a refinement algorithm is decreasing. However, the developed method could be used in the automatic verification of the geocoding accuracy.
2. Mapping applications based on SAR satellite images
   - When using Envisat Dual-polarization SAR images (C band), the overall crop species classification accuracy of 75% was obtained and the coefficient of determination of 0.55 was achieved for the crop biomass estimation in the test area in Finland. The results appeared to be in line with earlier scientific studies. The dual-polarization capability of Envisat SAR provided beneficial information when compared to the use of single-polarization signal only. The results show some potential, but are hardly good enough for the purposes of the Ministry of Agriculture and Forestry in Finland. The estimation of crop biomass could be beneficial in the future due to the increasing interest in precise information of crop production – not only in Finland, but globally as well. However, it seems that more detailed information about soil surface and vegetation is needed in order to get more reliable estimation results using SAR images.
   - Multidimensional Radarsat-1 images were used to analyse the visibility of buildings in SAR satellite images in the Helsinki metropolitan area in Finland. In the residential areas with low apartment houses, the building detection percentage was less that 20% even though images with multiple aspect angles and incidence angles were used jointly. On the other hand, tall buildings (over 10 metres high) facing one wall towards the SAR satellite were detected with a percentage of over 90%. In the light of these results, the information content of Radarsat-1 SAR images (C band) seems to be vague for urban mapping

purposes even though SAR images with multiple aspect angels were used. Therefore, aerial images and ALS are superior in large-scale mapping of built-up areas. Taking into consideration these limitations, SAR satellite images could provide crucial information, for example, in the cases of natural and non-natural disasters due to the frequent imaging capability.

- The use of Persistent Scatterers SAR Interferometry was studied in order to detect ground subsidence in urban areas. According to the results based on multitemporal ERS-1 and ERS-2 SAR satellite images (C band), very accurate subsidence rates of individual buildings in Turku city in Finland were achieved compared to the levelling surveys of the same buildings (RMSE of subsidence rates was 0.82 mm/year). The results were similar to the earlier scientific findings, but in this case it was proved that the PSI techniques are also applicable in Finland, where snow and forests present challenges to the use of multitemporal SAR images (repeat-pass SAR interferometry). Therefore, PSI could be used operationally to monitor urban areas in Finland, even though the use of PSI technology does not eliminate the need of levelling in terms of reliability.
- Forests are of high importance to Finland. ALS is already used operationally in forest inventories in Finland and it seems very unlikely that SAR can compete with ALS in terms of the accuracy of the required forest parameters. However, SAR satellite images provide the means to map wide areas nearly simultaneously more frequently than ALS. When ALOS PALSAR Dual and Quad polarization images were used in the estimation LIDAR based Above Ground Biomass, the coefficient of determination of 0.72 was achieved in the best case. According to the results, Quad polarization images worked better than Dual polarization images in the estimation; thus, the multi-polarization capability seems to be beneficial in this case. In the future, tandem SAR interferometry (TanDEM-X) seems to be an interesting option in forest monitoring as it might provide the Canopy Height Model in a way similar to ALS.

Despite the limitations of SAR satellite images in the mapping applications discussed, it seems that the results of both geocoding and possible mapping applications show some potential. It was possible to automate the geocoding process of the SAR satellite images further than in the existing commercial remote sensing software packages. However, the geocoding software is still a prototype, and is not intended for operational use. For example, the use of digital vector maps requires a lot of pre-processing in GIS software. Moreover, it was assumed that there are some control features that can be automatically located from the SAR images, which is not true for all SAR images (in the case of forest or sea, for example). The developed method could also be applied to improve the geocoding parameters of existing vector maps (and other satellite images as well) using SAR images as accurate reference data. All discussed mapping applications benefited from the exploitation of multidimensional SAR data. However, it is not possible to generate conclusive rules for how the most appropriate imaging configuration for each mapping case should be selected. For sure, agricultural applications benefit from high temporal resolution and urban mapping from multiple aspect angles. But, it is very difficult to determine the minimum set of SAR images which would fulfil all the needs from the viewpoint of end-users, who are not specialist in the field of SAR images.

The future of SAR satellite systems in relation to geocoding and the discussed mapping applications appears promising. It would be interesting to continue studies with the new SAR satellite systems (TerraSAR-X, Cosmo-SkyMed, and Radarsat-2): for example, taking into to account the high geometric accuracy of TerraSAR-X images, is there still a need for further improvement of geocoding parameters using existing map data? It seems that SAR satellite images can be used as reference data in geocoding other remote sensing images. The enhanced spatial resolution, the Quad-polarization capabilities, the joint use of different satellites, SAR interferometry, SAR polarimetry, and the fusion with ALS data are interesting topics for future in the context of mapping application areas discussed in this thesis.

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