Earth Observation with SAR Satellite Formations: New Techniques and Innovative Products

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ABSTRACT

This paper discusses the use of small satellites for future radar remote sensing applications. After a short introduction, we give first an overview of the TanDEM-X mission to be launched in autumn 2009. Here, special emphasis is put on the demonstration of innovative synthetic aperture radar (SAR) imaging techniques. Then, novel SAR configurations are introduced which make synergistic use of multiple small satellites flying in close formation. Performance examples demonstrate their unique capabilities for advanced Earth observation applications. Among these opportunities are the generation of digital elevation models with decimetre accuracy, the monitoring of ocean currents, and the measurement of small vertical displacements from snow accumulation, vegetation growth, and thawing permafrost soils. Challenges associated with the use of small satellites are pointed out and solutions to overcome them are presented.

1. INTRODUCTION

The development of small, reliable, and low-cost satellites employing miniaturised electronics and micro-electromechanical components, the rapid advancements in lightweight unfurlable antenna technology, and the progress in accurate orbit determination open new opportunities for Earth observation with radar. One promising direction is the synergistic use of multiple small satellites that work in consort to acquire scattered signals from multiple view angles. The simultaneous data reception by such a distributed antenna configuration enables new radar imaging modes and the generation of highly innovative Earth observation products. This paper summarizes the manifold opportunities arising from the use of small satellites for future radar remote sensing applications.

2. SAR IMAGING WITH SMALL SATELLITES

The eye of a radar system is its antenna. All state-of-the-art SAR satellites (including TerraSAR-X) employ a single fixed antenna beam during the reception of a scattered radar echo. As a result, the antenna gain is low, especially at the swath border, and a high transmit power is needed to obtain wide swath coverage. In order to reduce the power demands, an innovative SAR architecture has been suggested in [1], combining a deployable lightweight reflector antenna with a digital feed array as schematically illustrated in Figure 1. This combination enables the cost-efficient generation of a narrow and high-gain antenna beam that is steered in real-time to the varying direction of the arriving radar echo. Hence, less transmit power is required to obtain the same image quality. Besides many other advantages, this innovative SAR concept allows for the use of a smaller satellite bus. The improvement is especially pronounced for shortwave radar systems (e.g. X-, Ku- or Ka-band), where a large gain is achieved with rather small antennas.

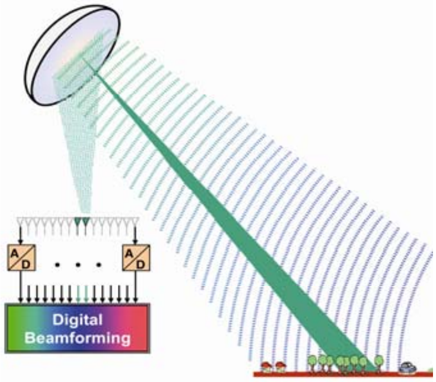

Figure 1: Digital beamforming with reflector antennas (cf. [1])

3. SATELLITE FORMATIONS AND CONSTELLATIONS

3.1 Bistatic and Multistatic SAR

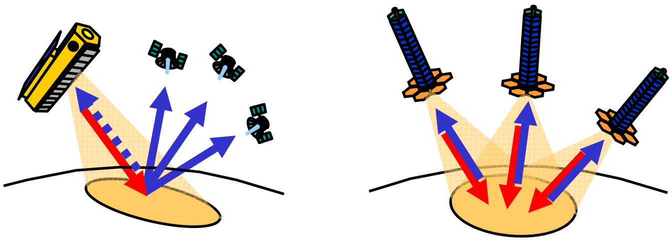

Figure 2: Semi-active (left) and fully-active (right) multistatic SAR satellite formations.

Bistatic and multistatic synthetic aperture radar operates with transmit and receive antennas mounted on separate platforms. Such a spatial separation has multiple advantages, increasing the capability, reliability and flexibility of future SAR missions and generating new, unique data products [2]. Bi- and multistatic SAR systems may be further divided into semi-active and fully-active configurations. Semi-active configurations combine an active illuminator with one or more passive receivers as shown in Figure 2 on the left. The separation of the transmitter from the receiver hardware allows for the use of low-cost microsatellites for signal reception, thereby enabling the cost-efficient implementation of a sparse array SAR with multiple baselines. In a fully active configuration, each radar has both transmit and receive capabilities as illustrated in Figure 2 on the right. Fully active systems can be operated in multiple modes, thereby providing increased flexibility, easy phase synchronization, and higher redundancy [3]. An example of a fully-active configuration is TanDEM-X which will be the first ever flown bi- and/or multistatic SAR mission in space [4].

3.2 TanDEM-X

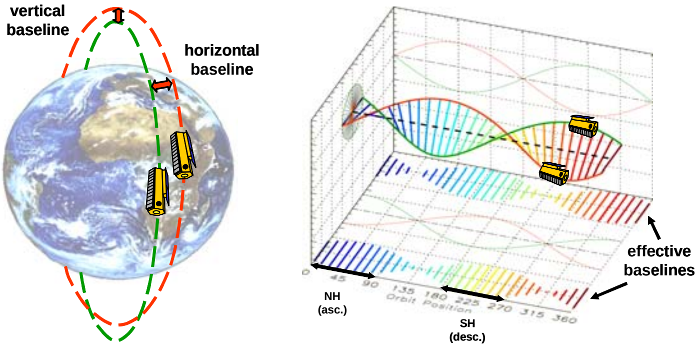

Figure 3: Helix satellite formation for TanDEM-X. Left: orbital arrangement. Right: cross-track baselines as a function of the argument of latitude for one orbital period.

TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurements) is a highly innovative spaceborne radar interferometer mission that will be launched in autumn 2009 [4]. The primary objective of TanDEM-X is the generation of a world-wide, consistent, timely, and high precision digital elevation model (DEM) as the basis for a wide range of scientific research, as well as for commercial DEM production. The global TanDEM-X DEM is specified with a 2 m point-to-point height accuracy at a 90% confidence level and a 12 m horizontal posting, by this exceeding the accuracy of available global DEMs by at least one order of magnitude. DEMs with even higher accuracy can be generated on a local scale. The high accuracy of TanDEM-X is achieved by extending the TerraSAR-X mission by a second, almost identical satellite flying in close formation with TerraSAR-X as illustrated in Figure 3. Both satellites will then act as a large single-pass radar interferometer with the opportunity for flexible baseline selection. This enables the acquisition of high quality cross-track and along-track interferograms without the inherent accuracy limitations imposed by repeat-pass interferometry due to temporal decorrelation and atmospheric disturbances. Besides the primary goal of the TanDEM-X mission, several secondary mission objectives based on along-track interferometry as well as new techniques with bistatic and multistatic SAR have been defined which represent an important and innovative asset of the mission. TanDEM-X will be implemented in the framework of a public-private partnership between the German Aerospace Center (DLR) and EADS Astrium GmbH, as for TerraSAR-X.

3.3 Advanced SAR System Concepts and Applications with Small Satellite Receivers

3.3.1 Multi-baseline DEM generation

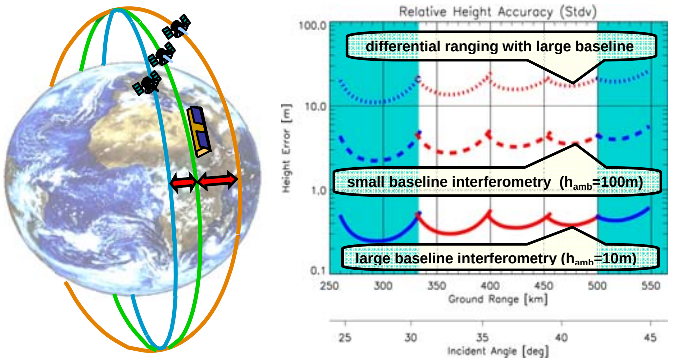

Figure 4: Multibaseline single-pass SAR interferometry in the Trinodal Pendulum configuration (left) and predicted DEM performance for large and small baselines (right).

The height sensitivity of a spaceborne SAR interferometer is significantly improved by increasing the distance between the satellites. However, a large baseline is also associated with a low height of ambiguity which is defined as the vertical distance between two points that yield the same interferometric phase value. A lower height of ambiguity is hence well suited to increase the sensitivity, but it means also that it becomes more and more difficult to resolve phase ambiguities in the phase-to-height conversion process. To avoid such difficulties, TanDEM-X uses only a rather large height of ambiguity of 30 to 40 m which corresponds to less than 5% of the maximum possible baseline length [4]. Future satellite formations with more than two receivers allow for the simultaneous acquisition of multiple SAR interferograms in a single satellite pass as illustrated in Figure 4. Their combination enables a reliable resolution of ambiguities and by this the cost-efficient acquisition of a global DEM with decimetre accuracy [3].

3.3.2 Satellite Tomography

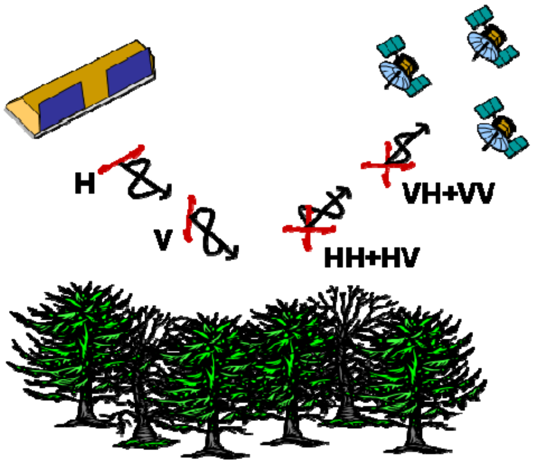

Figure 5: Polarimetric SAR interferometry (Pol-InSAR) enables the systematic mapping of vegetation height and its density.

A further unique feature of radar remote sensing is its ability to map the 3-D structure of semi-transparent volume scatterers like vegetation, sand, ice and snow on a global scale from space. A first step into this direction is polarimetric SAR interferometry (Pol-InSAR) which combines the power of cross-track interferometry for accurate height measurements with the capability of SAR polarimetry to separate signals from different scattering mechanisms [5]. This combination enables the measurement of fundamental 3-D structure parameters like vegetation height and density. Another opportunity is the simultaneous acquisition of digital terrain and surface models which provide complementary information for many scientific and commercial applications. The use of more than two receiver satellites enables even the acquisition of 3-D tomograms. This allows not only for a full volumetric imaging of natural scatterers in the bio-, geo- and cryosphere, but it has also high potential for an accurate 3-D mapping of urban and other anthropogenic environments and their changes.

3.3.3 Velocity Measurements of Natural and Man-Made Objects

Multistatic SAR satellite formations provide a unique opportunity for wide-area along-track interferometry (ATI), which compares the phase of two or more complex SAR images acquired in identical geometries but separated by short time intervals. The evaluation of the phase difference enables the measurement of millimetric displacements within adjustable time intervals from a few milliseconds up to several seconds. The ATI technique is hence well suited to observe the dynamics of a variety of processes on the Earth surface. Examples are the measurement of ocean and tidal currents, the observation of sea ice drift, and wide-area traffic monitoring. Large along-track baselines are required for accurate measurements of slow movements, while short baselines are required to avoid ambiguities in case of higher velocities. An acquisition with multiple along-track baselines is hence of great help to resolve ambiguities and enables highly accurate measurements over a wide velocity range.

3.3.4 Frequent Monitoring and Change Detection

The revisit times of current spaceborne SAR sensors – ranging from several days to several weeks – will not suffice for important upcoming applications like systematic traffic monitoring, coherent change detection, risk and disaster management, etc. Satellite constellations have the potential to shorten the revisit times substantially. However, the use of multiple conventional SAR satellites is also associated with high costs. An alternative is the employment of passive receive-only satellites in conjunction with, e.g., a geostationary illuminator [2]. No transmit equipment is needed for the receivers, which reduces the instrument weight and power demands, and enables the use of a small, light-weight and low-cost satellite bus. Hence, more receivers can be launched for the same budget and the revisit times are reduced without a cost explosion.

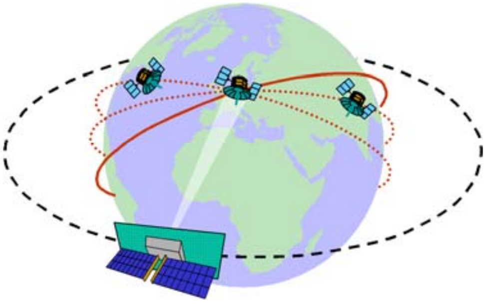

Figure 6: Frequent monitoring with a bistatic SAR satellite constellation.

4. CONCLUSIONS

This paper provided a short overview of the manifold opportunities arising from the combined use of multiple small satellites for innovative radar remote sensing applications. The focus was on the acquisition of novel bio- and geophysical data products by bi- and multistatic SAR formations and the examples in this paper represent only a small subset of the opportunities arising from the coherent combination of multiple SAR images. A further dimension of observation will be provided by combining a set of multistatic SAR acquisitions in time. Such a multi-dimensional time series provides a unique observatory to monitor a multitude of dynamic process in the biosphere (e.g. forest and agricultural vegetation growth), cryosphere (e.g. ice structure change and snow accumulation), lithosphere (e.g. vector deformation due to tectonic movements, subsidence and thawing permafrost soils), and hydrosphere (e.g. ocean current changes). By this, radar will provide important information to understand, predict and better deal with the upcoming challenges in a rapidly changing world and environment.

5. REFERENCES

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