Dynamics and Control Issues for Future Multistatic Spaceborne Radars

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Abstract

Concepts for future spaceborne radar systems are being developed which rely on the transmitter and receiver(s) being carried on separate spacecraft. The potential advantages include lower cost than current spaceborne radars and improved measurement capability. This paper reviews two currently proposed systems: GNSS reflectometry (GNSS-R) and a geosynchronous synthetic aperture radar constellation (GeoSAR).

GNSS-R uses reflections of signals from GPS (and Galileo when available) to measure the height and state of the ocean surface. The receiver is typically in a low Earth obit (LEO) and provides global coverage. GeoSAR uses a radar receiver in geosynchronous orbit (slightly displaced from geostationary but still with a period of 1 day). The radar sees a fixed region of the Earth and is able to integrate signals over long periods to obtain a satisfactory signal-to-noise ratio. If several receiver spacecraft are used simultaneously the time to obtain an image can be reduced in proportion to the number of spacecraft used.

The principles of these two systems are described and then requirements applying to the system dynamics and control are derived. For GNSS-R the requirements are relatively easy to achieve (coarse pointing and only basic orbit control). GeoSAR's requirements are more demanding although the environmental disturbances at geosynchronous orbit height are significantly smaller than in LEO. For GeoSAR the most demanding requirement is the need for centimetre-level orbit measurements to allow aperture synthesis to be implemented.

Introduction

During the 1990s spaceborne radar became an established civilian Earth observation technique. ESA's ERS-1 mission was followed by ERS-2 as well as Radarsat-1 (Canada) and the US Shuttle Radar Topography Mission. The present constellation of spaceborne radars includes further follow-on missions such as Envisat. Radar observations complement the more conventional visible band sensors by providing images which depend on the surface structure and moisture content (dielectric constant) rather than just the visible colour. Spaceborne radar is also usually a coherent imaging technique and signal phase as well as amplitude is measured. Some of the most dramatic radar images are based on this phase information and show, for example, detailed topographic measurements (Figure 1) or the centimetre-scale deformation of the Earth's surface around an earthquake zone (Figure 2). Two (or more) radar

Figure 1: These fringes based on the radar phase measurements can be interpreted as topographic contours for the area around Vesuvius. The image was obtained by combining two ERS SAR images interferometrically [1].

images with good quality phase measurements are required for these interferometric products; the phase data in a single image is never of direct practical use.

One of the difficulties with conventional spaceborne radar is the cost and complexity of the spacecraft with its payload. The antennas are typically large ($\geq$ 10 m^2) and heavy (e.g. the ASAR antenna on Envisat has a mass of 750 kg), high power is needed for the transmitter, and huge data quantities are generated and require extensive processing. Another problem with early systems was the poor temporal repeat frequency. ERS-1 and -2 were in 35-day repeat orbits because of the narrow (100 km) imaged swath width; this allowed typically 2-4 images per 35 days. More recent radars have wider, steerable swaths but even this only reduces the typical repeat time to a few days.

Several approaches are being pursued to develop lower cost radar systems, including work on lightweight antennas and novel radar system architectures. Some novel architectures concern *multistatic* systems, where the transmitter and receiver are at different locations, and there may be more than one transmitter or receiver. This paper concerns two novel architectures being investigated at Cranfield, which are:

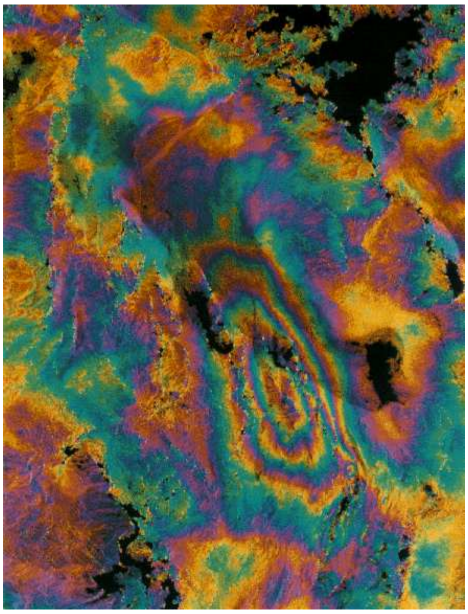

Figure 2: Surface displacement associated with the May 17, 1993 Eureka Valley earthquake in a remote section of eastern California, measured interferometrically using data from ERS-1. One fringe represents 28 mm of range change. Concentric rings just below the image's centre show subsidence of up to 9.5 cm [2].

1. Geosynchronous radar systems (using one or several spacecraft in geosynchronous orbit; referred to as GeoSAR) [3, 4]. These have the potential to provide near-continuous coverage of large areas of the Earth's surface. A large antenna is required (e.g. 50 m^2), and conventional radar images with a resolution of 100 m can be obtained several times a day if required.

2. Systems using reflected signals from GPS satellites (and GNSS in general) [5, 6, 7]. This technique is referred to as GNSS-R (GNSS-Reflectometry) and is effectively a multiple-beam radar altimeter. Typical parameters are: antenna size = 1 m^2, spatial resolution = 10 km, and repeat images can be provided every few days.

This paper discusses some of the principles of these two radar architectures and issues deriving from them. The next section outlines the relevant principles, and then the dynamics and control issues derived from them, especially the length scales and corresponding timescales relating to measurement and control, are discussed in the remainder of the article.

Principles of spaceborne radar

An understanding of radar principles is needed to design GeoSAR and GNSS-R systems (Stimson [8] gives an excellent introduction to the principles of radar). Techniques like aperture synthesis and interferometry impose particular requirements on the system.

GNSS–R uses a backscatter radar technique like conventional radar altimeters. The dominant reflected GNSS signal is centred on the specular reflection direction and the receiver detects this (Figure 3). Over land surfaces the reflectivity in the specular direction is much lower than over the oceans; the only currently proposed applications for GNSS-R are over oceans . The specular reflection is centred on the *glistening point* which is a well-defined region except over very rough seas.

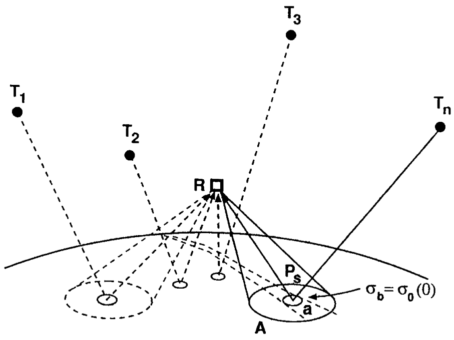

Figure 3: Principle of operation of GNSS-reflectometry. The receiver spacecraft (R) uses near specular ocean surface reflections of GNSS signals (T_i are the transmitter spacecraft) [5].

Imaging spaceborne radar systems are usually more complex than visible-band imagers since the motion of the antenna is an integral part of the imaging process. This is because a technique known as *aperture synthesis* is used: this allows a small real aperture to obtain the spatial resolution of a much larger aperture. Without aperture synthesis spaceborne radars with practical antenna sizes of several metres would only be capable of a spatial resolution of 10’s of km or worse.

One further issue for spaceborne radar is the antenna. The antenna is a crucial component of the system and ideally should have a large area and low mass. These requirements tend to conflict, and it is likely that future antenna designs will have to be regarded as flexible structures for the purposes of spacecraft attitude manoeuvring.

Aperture synthesis

The need for aperture synthesis is based on the diffraction limited resolution of an aperture. The angular limit is approximately the aperture diameter divided by the wavelength of the radiation used. Thus for typical parameter values (wavelength, λ = 10 cm, orbit height h = 500 km) the real aperture resolution is 5 km (for an aperture length of 10 m), and to achieve 5 m resolution an aperture length of 10 km is needed.

However, with a *coherent* imaging technique like radar where the transmitted phase is deterministic and the phase of the received signal can be measured relative to that transmitted, it is possible to synthesize the image which could be obtained using an aperture much larger than the physical aperture. The real aperture is moved along the length of the aperture to be synthesized and the complex received signal (amplitude and phase) is measured at each point. This effectively measures the wavefront across the synthesized aperture, and then the synthesized wavefront can be “focussed” by appropriate signal processing (rather than conventional optics or a parabolic radar antenna) to achieve the desired resolution.

An assumption which underlies the aperture synthesis technique is that the target does not change during the time that the image is acquired. In practice the atmosphere and target are not frozen: turbulence and weather patterns affect the atmosphere and the Earth’s surface changes over a wide range of timescales due to processes including crop growth and weathering (Table 1). A conventional radar image from low Earth orbit is acquired over a period of 1 s; some of the geosynchronous radar concepts involve signal integration over periods of minutes or hours; any changes during these periods can result in loss of image quality. Also, for many of the interferometric radar products there should also be no change in the scene between the times at which the two images are acquired. *Coherence* is a concept which quantifies the degree of unmodelled change in the signals.

For spaceborne radars, the satellite’s orbit carries the real aperture along a path allowing the synthesised aperture to be several kilometres long. Figure 4 illustrates the imaging situation. In principle, there could be several real apertures recording the signals in parallel - this will reduce the total time required to form the image. For perfect focussing, the wavefront across the synthesized aperture must be measured to an accuracy much smaller than a wavelength (along the aperture’s line of sight). In practice there are several mechanisms which can corrupt the phase measurement (these are also identified in Table 1):

1. Uncertainty in the true aperture position relative to the ideal synthesized aperture (only the *relative* position uncertainty in the measurement along the aperture’s line of sight matters - a measurement bias common to all positions is much less significant),
2. Refractive index irregularities in the atmosphere (principally in the ionosphere and troposphere),
3. Changes in the target (surface) during the acquisition of the image.

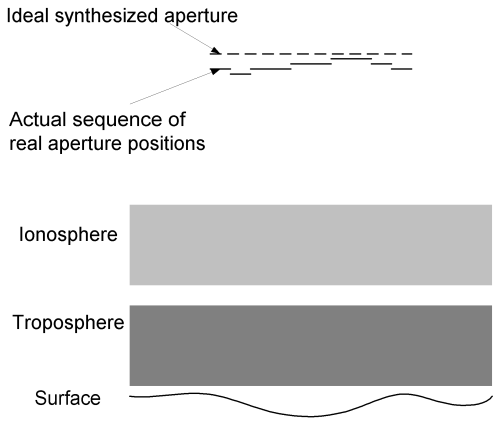

Figure 4: Schematic representation of the SAR imaging situation showing regions where phase uncertainties can arise.

Coherence

Coherence is a key concept which quantifies the degree to which phase variations remain systematic (and therefore usable). For the (complex) backscatter measured at two points (z_1, z_2), the coherence (γ) is defined as

$$\gamma = \frac{E\left(z_1 z_2^*\right)}{\sqrt{E\left(z_1 z_1^*\right) E\left(z_2 z_2^*\right)}} \tag{1}$$

The expectation function $(E())$ is usually evaluated as an average. By definition, the magnitude of the coherence lies between 0 and 1. All modellable phase variations should be removed and the coherence is calculated based on the remaining un-modelled phase variation.

Coherence can be interpreted as a physical parameter. For example if z_i represent the complex backscatter coefficient of the Earth's surface for two different images (labelled $i = 1, 2$) then the magnitude of the coherence calculated for a particular region of the image is a measure of the fraction of the radar power scattered by static elements of the scene. Thus over thick vegetation or a water surface (where the surface can change radically between two images) the coherence magnitude is near zero, and over a bare soil or urban scene the coherence magnitude can be close to one.

For interferometry there are two significant timescales: (1) the period over which a single image is acquired (typically seconds to hours), and (2) the time between the acquisition of the separate images (typically days to months). Interferometric product quality depends on changes over both these timescales.

System element	Possible mechanisms
Satellite orbits	Imprecise (relative) orbit knowledge
Atmosphere	Refractive index variations *Ionosphere*: electron number density variations *Troposphere*: Turbulence and weather patterns affecting atmospheric humidity (water vapour) and liquid water content (cloud droplets)
Surface	Surface backscatter changes e.g. vegetation movement due to wind, soil drying, dense traffic movements, rain, freeze / thaw vegetation growth, landslips, etc.

Table 1: Sources of phase uncertainty for SAR imaging with geosynchronous satellites

Interferometry

Some of the most valuable radar products are based on interferometry. For interferometry to be possible the two radar images must have high coherence. As well as this requiring the surface not to have changed between the two images it also requires that the two images be taken from almost exactly the same viewing direction. The maximum across-track separation of the two orbits is known as the critical perpendicular baseline (b_{crit}) and is defined as [9]

$$b_{\mathrm{crit}} = \frac{\lambda B R \tan\theta}{c} \tag{2}$$

where λ is the radar wavelength, c is the speed of light, B is the range bandwidth, R is the slant range distance to the target, and θ is the local incidence angle corrected for surface slope. For useful interferometric imaging, the actual perpendicular baseline should be no more than 10-20% of the critical baseline.

Issues for dynamics and control

For both the geometries considered, the satellite orbit / constellation is a key part of the measurement system. If aperture synthesis is to be performed then measurements (accurate to a fraction of a wavelength over the integration time for the synthetic aperture) of the relative positions of the real aperture(s) during image formation is needed.

Pointing requirements are not particularly strict for either system because antenna beamwidths are relatively broad.

GNSS-R

The main requirements relating to system dynamics and control for GNSS-R concern the choice of satellite orbit to provide suitable coverage of the Earth's surface. Some concepts are based on a constellation of receiver spacecraft and so there needs to be maintenance of the constellation geometry. It is not necessary to have precise knowledge of the orbital positions.

Geosynchronous SAR

GeoSAR is more demanding than GNSS-R. To enable aperture synthesis it is necessary to have good knowledge of the relative positions of the real aperture during imaging. If a single receiver spacecraft is used then the natural orbital dynamics and the small size of the perturbations (e.g. *fluctuations* in solar radiation pressure) mean that the receiver track can be known to very good relative accuracy.

The orbit measurement problem becomes more difficult if a formation of spacecraft is used since the relative positions of the separate spacecraft must also be known. The greatest accuracy is required along the slant range (from the radar to the target); lower accuracy is needed in the two orthogonal directions. From orbits near the geostationary height, the angular width of the Earth's disk is $17.4°$. Assuming the imageable area is half this width $8.7°$, then the position accuracy required perpendicular to the slant range is a factor $1/\sin(8.7°/2) = 13$ less demanding than the slant range accuracy (determined by the change in viewing angle between the centre and edges of the imaged area).

There are two aspects to the problem of measuring slant range accurately with multiple receivers: (1) measurement accurate to a fraction of a wavelength to allow correct phase compensation for image formation, and (2) measurement accurate to a fraction of the range resolution (so that signal from the same target point can be correlated between the different receivers). To enable image formation, a position error of an integer number of wavelengths along the line of sight to the target is not significant, but the fractional part of the wavelength must be known accurately. It may be that a reference target or transponder in the target area can most easily provide the slant range accuracy.

Orbit / constellation design is needed for GeoSAR. This is coupled with the radar design since the ground track and velocity affect the radar's resolution, data acquisition, and signal processing as well as its coverage. Interferometry requires satellite orbits to repeat within a tolerance of the critical perpendicular baseline defined above (2).

Timely delivery of services is increasingly important to users. Since the orbit data are a crucial part of the imaging system (especially for a formation of spacecraft) the relevant orbital measurements are also required in near real-time.

Discussion

Of the two novel spaceborne radar configurations discussed, GNSS-R is under study for potential missions later this decade, and is not demanding in terms of system dynamics or control.

GeoSAR is a more long-term project requiring further technical development to make it practical. There are significant areas of uncertainty about several aspects of the system concept, including system dynamics and control. The most challenging issues are raised when a formation of spacecraft is used, in fact many of the challenges are similar to those raised by missions such as Darwin [10] although the longer wavelength used by GeoSAR relaxes the constraints. A large aperture is likely to be required to collect enough signal power and this brings further challenges since the antenna is likely to be relatively flexible (to enable low mass).

Scale	Requirement / process	Remarks
Length	Fraction of wavelength	Accurate relative position knowledge is required for aperture synthesis
	Fraction of range resolution	Allows signals to be correlated between different receivers
	Interferometric baseline	Satellite orbits must be well within b_{crit} (2) for interferometry
Time	Aperture synthesis	Consistent phase accuracy is needed to synthesize the aperture
	Image formation	Require consistent phase information across whole image to permit interferometric processing
	Interferometry	Two or more images are needed with high coherence between them
	Service provision	Users value timely data highly

Table 2: Summary of length and time scales defined by the GeoSAR imaging process which relate to system dynamics and control. In general, consistent position accuracy is required over the corresponding timescale. The length scale requirements are especially demanding if a formation of spacecraft is used to improve temporal resolution.

Conclusions

The article discusses two novel concepts in spaceborne radar and issues relevant to system dynamics and control. The two concepts are GNSS-R and GeoSAR. Of the two GeoSAR raises the greater challenges, especially if a formation of spacecraft is used to reduce the time taken to acquire an image for aperture synthesis. The GeoSAR imaging process defines several length and time scales which are summarised in Table 2.

Acknowledgements

This work draws on contributions from and discussions with students at Cranfield University; it is a pleasure to acknowledge their role: Elisaveta Bobolina, Davide Bruno, Kajal Haria, Libby Jackson, Cassie Lee, Giuseppe Ottavianelli.

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