APPLICATION OF GPS IN DISTRIBUTED SAR SATELLITE

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ABSTRACT:

In this paper, we proposed a new Distributed SAR Satellite(DSS) using one passive satellite with a dual receive antenna(DRA) flying in formation with an already existing conventional SAR satellite. Such system can provide either GMTI or INSAR functions or both. However, the complexities of DSS imaging increase due to the synchronization problems and Baseline estimation problem. Accuracy requirement for baseline estimation and synchronization are given. A method based on dual frequency GPS is introduced to solve the Baseline estimation and time & frequency synchronization problems of Distributed SAR Satellite.

1. INTRODUCTION

In many civilian and military applications of spaceborne SAR imaging, it is highly desirable to simultaneously monitor ground traffic and acquire a global DEM. Distributed SAR Satellite(DSS) operate with multiple receive antennas which are mounted on different satellites(Massonnet,2001). Powerful applications of DSS are single-pass cross-track interferometry(XTI) and along-track interferometry(ATI). The satellite orbits are designed such that the constellation provides a vertical and a horizontal baseline at the same time(Meyer,2005). So, this concept can be used for DEM and GMTI.

The DSS consists of master satellite with radar transmitter and receiver and one slave satellite with only receivers. Time & frequency synchronization error occurs because of the different formation flying platforms and different frequency sources. In INSAR processing the knowledge of accurate baseline length and orientation is important for DEM accuracy. The requirement of error of baseline measurement for creating accurate DEM is very stringent. Baseline estimation and Time & frequency synchronization are three key technologies for DSS(Matthias,2004).

2. SYSTEM DESCRIPTION

2.1 System Overview

In this paper, we considered the problem of Spaceborne INSAR and GMTI system and proposed a distributed satellite constellation using one passive satellite with a dual receive antenna(DRA) flying in formation with an already existing conventional SAR satellite. This novel proposed configuration operates in a 3 channel mode, thus can provide a combined XTI/ATI acquisition with across-track and long& short along-track separation (see figure.1). INSAR, or ATI, makes use of phase difference to measure topography or GMTI. Such system can provide either GMTI or INSAR functions or both. 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, thereby enabling improved and more accurate measurements over a wide spectrum of potential scatterer velocities. The combination of the different along-track baselines will be used for improved detection, localisation and ambiguity resolution in ground moving target indication (GMTI) and traffic monitoring applications.

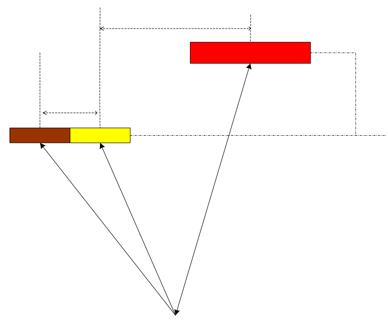

Figure 1. Combined XTI/ATI configuration

This approach is especially attractive, since it will enable a cost efficient and easy implementation for spaceborne sensor. Such system can provide either GMTI or INSAR functions or both, it has two acquisition modes: (1) Tri-baseline ATI mode,(2) Simultaneous INSAR and ATI mode.

2.2 Tri-baseline ATI performance

The basis of the ATI technique is that the interferometric combination of two complex SAR images of the same scene, acquired with a short time lag, is sensitive to the Doppler shift from the line-of-sight velocity of targets. The three SAR image

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complex images of the proposed tri-baseline configuration can be modelled as:

$$\begin{aligned} S_1 &= Z_{C1} + N_1 + Z_{T1} \\ S_2 &= Z_{C2} + N_2 + Z_{T2} \\ S_3 &= Z_{C3} + N_3 + Z_{T3} \end{aligned} \quad (1)$$

where Z_{C1}, Z_{C2} and Z_{C3} are the clutter processes representing the SAR complex images acquired from the three antennas, N_1, N_2 and N_3 are due to the presence of thermal noise at the receivers and Z_{T1}, Z_{T2} and Z_{T3} denote the SAR images of the moving target relative to the three interferometric antennas. ATI analysis exploits the correlation between the complex sample sets of the first aperture image, $S1$, and the second aperture image, $S2$, to produce the interferogram matrix

$$I = S_1 S_2^* = |S_1||S_2| \exp[j(\varphi_1 - \varphi_2)] \quad (2)$$

Where φ_1 and φ_2 are the phase angle of the first and second aperture images, respectively.

In presence of a moving target (in absence of noise and decorrelation effects), the interferogram phase angles $\psi = \varphi_1 - \varphi_2$ can be related to the line-of-sight component of the target velocity, v_r by

$$\psi = \frac{4\pi}{\lambda} \Delta R = \frac{4\pi}{\lambda} \cdot v_r \cdot \tau \quad (3)$$

Where λ is the radar wavelength, τ is the time lag. B is the distance between the two SAR antenna. For DSS, while A1 is transmitting, A1 and A2 are receiving from pulse to pulse resulting in an effective baseline of B/2. A moving target can then be detected by comparing the interferometric phase with a threshold.

$$v_r = \frac{V_{sat} \lambda \psi}{2\pi B} \quad (4)$$

	DRA ATI	DSS ATI
Along-Track Baseline	2.4m	150m
Signal to Noise Ratio	15dB	10dB
MDV	2.5m/s	0.15m/s
Vmax	59.37m/s	0.7919m/s

Table 1. short and long baseline performance

This novel proposed configuration can be adapted to the velocity range of the objects of interest. Short baseline and long baseline enables highly accurate velocity estimates for slow and fast object MTI (as shown in table 1). Hence, an acquisition with multiple long & short along-track baselines can enable improved and more accurate measurements over a wide spectrum of potential scatterer velocities.

2.3 INSAR

The goal of INSAR is to measure the difference in range between two observations of a given ground point with sufficient accuracy to allow accurate topographic reconstruction. Operational DEM generation will be performed through the interferometric phase and knowledge of the interferometer geometry (see Figure 2). Accuracy is obtained by careful measurement of the baseline length and orientation and the location of the platform relative to the reference coordinate system.

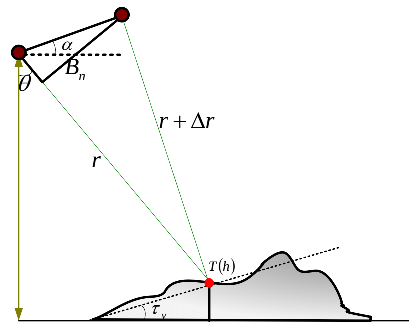

Figure 2. Geometry of the interferometer

A simplified expression for the target height h is

$$h = H - r\cos[\sin^{-1}(\frac{\lambda\Phi}{2\pi B}) + \alpha] \quad (5)$$

where h is the platform height (antenna altitude with respect to the WGS84 reference ellipsoid), r is the range, Φ is the measured interferometric phase, α is the baseline roll angle, λ is the observing wavelength, and B is the baseline length. For Distributed SAR Satellite the radar instrument provided data necessary to determine r and Φ, while a dual frequency GPS, measured the detailed shape of the interferometer, in essence (B, α)or (Δx, Δy, Δz).

Error source	Error Allocation	Δh(m)
α (arcsec)	2 arcsec	4.5m
B(mm)	8mm	4.56m
Platform position(m)	1m	1m

Table 2. Baseline estimation accuracy requirements

Clearly, errors in knowledge of the quantities in this equation impact the total INSAR performance. The propagation of a baseline uncertainty to a topographic height error has already been derived by Zebker and Goldstein (1986). The high sensitivity of the InSAR height on B, α and Φ puts extremely high requirements on the knowledge of these parameters. The trade-off between these errors was a large part of the mission design. Supposing effective across-track baselines B for high resolution DEM's is in the order of 1 km, Table 2 represents the error in elevation caused by errors of the INSAR system.

3. GPS APPLICATION

Dual frequency GPS are capable of eliminating the ionospheric signal errors and thus to make best use of the high accuracy GPS carrier phase measurements. Aside from space applications like real-time positioning, precise orbit determination, attitude determination of spaceborne sensors, dual-frequency GPS receivers are considered as practical and cost-effective system for precise baseline determination and time & frequency synchronization in DSS missions.

3.1 Position Determination

INSAR accuracy is obtained by careful measurement of the baseline length and orientation and the location of the platform relative to the reference coordinate system.

3.1.1 Baseline Estimation

In INSAR processing the knowledge of precise geometrical parameters of a DSS is essential. The precise baseline vector determination is based on direct evaluation of dual frequency GPS carrier phase measurements. Recent studies have demonstrated the usefulness of GPS receivers for relative positioning of formation flying satellites using dual-frequency carrier-phase observations(Meyer,2004). The analysis performed with GFZ's Earth Parameter and Orbit System utilizing an adapted GRACE configuration shows that a relative position knowledge of 1 mm can be achieved in most cases(Kroes,2005).

The measured position is that of the GPS antenna. Considering the impact of satellite attitude errors and uncertainties in both the GPS and the SAR antenna phase centre positions, Baseline estimation could be realized with 8mm accuracy(three axis).

3.1.2 Precise Orbit Determination

Precise knowledge of the orbit is required in order to obtain the required 1-m position determination. Furthermore, formation flying DSS also require an accurate real-time knowledge of the position. In accordance with INSAR applications, dual-frequency GPS receivers are also preferred for precise orbit determination and navigation of LEO spacecraft. Tracking Accuracy can reach: < 10m (real time); < 10 cm RMS (post-processed); velocity accuracy can reach:< 10cm/sec (real-time).

3.2 Time & Frequency Synchronization

Time & frequency synchronization error occurs because of the different formation flying platforms and different frequency sources. The phase coherence of different echoes, which is the key to SAR imaging and INSAR processing, must be guaranteed. Hence there must be higher requirement of the accuracy for time and frequency synchronization. For a DSS operation, some means must be provided to ensure that signals are received at the proper time and frequency.

3.2.1 Frequecny synchronization

Frequency synchronization is required to position the receive-only signal within the azimuth prefilter bandwidth, also the range shift of the impulse response will be dominated by deviations between the PRFs of the transmitter and receiver. Since the PRF is usually derived from the STALOs , the shift in slant range may be derived as

$$y \le \frac{2 \cdot \Delta r(t)}{c \cdot t} = \frac{2 \cdot r_g}{10 \cdot c \cdot t} \tag{6}$$

where r_g is the range resolution, c is the light velocity, t is the allowable payload working duration, y is the relative frequency deviation between the two STALOs . By solving formula (11), we get y<5E-11.

All required transmitter and receiver frequencies are generated from a stable local oscillator (STALO) by means of multiplication, division and phase-locked loops. The internal STALO with 5 x 10-E11 short term stability determines the short time stability which is required by master satellite SAR prcessing, while the long time stability is disciplined to the stability of the GPS satellites atomic clocks. The atomic clock onboard the GPS satellite has an accuracy of △f/f <10-14. As long as the receiver is locked to the GPS, the long time stability of STALO can reach 10E-11. In this way the highest possible coherency between master and slave satellite is ensured. Synchronising master and slave satellite internal time base to GPS timing is practical and cost effective.

In the case of GPS receiver unlock, the stability of the STALO unit will determine the drift due to aging and temperature changes. The idea way is to use atomic clock which is also disciplined to the GPS.

3.2.2 pulse-timing synchronization

Time synchronization includes pulse-timing synchronization and absolute time synchronization. Pulse-timing synchronization is used to synchronize the SAR data window start for the transmit/receive radar and the receive-only radar so that both radars can be triggered at a fixed time delay to meet the INSAR swath. Pulse-timing synchronization accuracy σ_r should be less than 0.01 times of the PRT (pulse repetition time) to provide sufficient overlap of swath, so σ_r < 2.5us is required.

GPS receiver outputs pulse-per-second (PPS) signal once a second. The rising edge of PPS which define each second start has an accuracy of 50ns. PPS signal is suitable for appropriate positioning of the data window and can be used for timing pulse transmission and range estimation for Distributed SAR Satellite. The receiver of slave SAR is always triggered at a fixed time delay after the signal is transmitted to compensate for the range difference between the distributed satellites.

3.2.3 bsolute Time Synchronization

Absolute time synchronization accuracy σ_T is also essential for DSS. Absolute time synchronisation needs to be used to trigger the data acquisition events and precisely timestamp the SAR acquisition data and baseline estimation data. σ_T should be less than 0.1 times of the PRT for application of triggering the data acquisition, $\sigma_T < 25us$ is required.

But for application of timestamping, the positioning error resulted by σ_T should be less than 0.1 times of the baseline measurement error. We can know from formula (7) , $\sigma_T <$ 263ns is needed.

$$\sigma_T \leq \frac{1}{10}\sigma_a / V_{st} \quad (7)$$

GPS absolute time synchronisation is qualified to precisely timestamp and trigger the data acquisition events. For GPS receivers the uncertainty in absolute time is in the order of 100ns, thus absolute time synchronization accuracy for DSS can reach 200ns.

4. CONCLUSION

In this paper, we proposed a novel DSS using one passive satellite with a dual receive antenna(DRA) flying in formation with an already existing conventional SAR satellite. Based on analyse and simulations, accuracy requirements for baseline estimation and time & frequency synchronization are given. A method based on dual frequency GPS is introduced. Baseline estimation could be realized by dual frequency GPS receivers with 8mm accuracy(three axis). Pulse-Timing synchronization is realized by GPS PPS signal and frequency synchronization is realized by the STALOs synchronized by GPS-receivers which could provide good frequency accuracy and long term stability. In this way the highest possible coherency between Distributed SAR Satellites is ensured. The new method is simple and practical and, most importantly, very effective. Future work would include the impact of oscillator phase noise and practical method of reduction of relative phase noise for DSS.

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