

## InSAR Microsatellite Constellations Enabled by Formation Flying and Onboard Processing Capabilities

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### ABSTRACT

The advancing development of low-cost small satellite platforms is a compelling driver for future remote sensing constellation missions. Multistatic interferometric synthetic aperture radar (InSAR) is a promising payload for such missions, potentially also in combination with additional remote sensing data. Significant challenges associated with using low-cost platforms for multistatic interferometric applications include the requirement of precise knowledge of the baseline distances between the spacecraft, and the high data volume generated (in the hundreds of megabytes per image), in light of the limited downlink capability of a microsatellite platform. To address these challenges, the Space Flight Laboratory (SFL) is making progress in a number of areas. CanX-4 and CanX-5 are a pair of identical nanosatellites designed by SFL, that will demonstrate formation flight in 2012 and enable future microsatellite constellation missions with sub-centimeter inter-satellite baseline knowledge. In regard to the data volume issue, it is observed that application-specific data requirements can be significantly smaller than the total amount of imagery collected. For example, the data required by a ground moving target indication (GMTI) mission may be limited to the position and velocity of targets, rather than entire images. Real-time image processing methods currently in development at SFL will enable onboard SAR focusing, automated image registration using precise orbit knowledge and frequency domain alignment methods, and interferometric image processing, allowing the downlink data volume to be reduced according to specific application needs. This paper discusses how CanX-4&5 technology together with real-time image processing approaches can be used to enable high performance sparse aperture missions on low-cost, small platforms.

### INTRODUCTION

The Space Flight Laboratory at the University of Toronto Institute for Aerospace Studies (UTIAS/SFL) is currently preparing two nanosatellite missions for launch – the CanX-4 and CanX-5 formation flight mission, and the BRITE constellation stellar photometry mission – which will demonstrate the technologies necessary for future remote sensing constellation missions. Interferometric synthetic aperture RADAR (InSAR) has been selected as a payload of interest for a future formation-flying mission, due to the need for baseline maintenance and knowledge. The mission concept of augmenting an existing SAR mission with interferometric capabilities is cost-efficient, adding capabilities for elevation mapping, temporal change detection, monitoring moving targets, and combining multiple received

images of the same target area for enhanced resolution using low-cost microsatellites.

InSAR involves imaging the same location from different receiver locations or in successive satellite passes over an area. Received signals are conjugate-multiplied to construct an interferogram, in which small differences in the received signal phase are then used to determine additional information about the imaged area. InSAR applications require precise position and attitude determination, as well as inter-satellite baseline maintenance capabilities<sup>1</sup>. Additionally, any proposed remote sensing mission concept must address restrictions of the microsatellite platform, specifically in limited downlink capability compared to the large data volume generated by a SAR mission (in the hundreds of megabytes per image).

If a large volume of remote sensing imagery is collected, on-board image processing could allow the data of interest – for example, changes detected between image passes, or the location of moving vehicles in the imagery – to be extracted and sent back to Earth, significantly reducing the volume of data transferred.

Herein we examine CanX capabilities and on-board image processing methods for a future multistatic InSAR microsatellite constellation. Inter-satellite baseline envelope requirements for potential InSAR applications (digital elevation modeling, super-resolution image formation, and ground moving target indication) have been described<sup>1</sup>. This paper focuses on CanX position and attitude determination capabilities, and their implications for on-board image processing methods.

### CANX TECHNOLOGIES

The CANadian Advanced Nanospace eXperiment (CanX) program at UTIAS/SFL provides low cost access to space using nanosatellites for research and development purposes. The Generic Nanosatellite Bus (GNB) is a 20-cm cubic form factor bus developed at UTIAS/SFL for scientific and technology demonstration missions, with nearly 30% of its mass and volume available for mission specific payloads. The upcoming CanX-4&5 mission and the BRITE constellation will both utilize the GNB for formation flight demonstration and stellar photometry, respectively. Technology demonstrated on these missions – namely, their position and attitude determination systems – will be an essential component of a future formation flying InSAR constellation.

#### *CanX-4 and CanX-5*

CanX-4 and CanX-5 are a pair of nanosatellites launching in late 2012, which will be among the first to demonstrate autonomous formation flight (Figure 1). The identical 7-kg 20-cm GNBs each contain key enabling technologies, including formation flying control algorithms, a commercial GPS receiver, a low-power inter-satellite communication system, the Canadian Nanosatellite Advanced Propulsion System (CNAPS), and a three-axis attitude determination and control system including six sun sensors, a magnetometer and three rate gyros for determination, and three orthogonal reaction wheels and three magnetorquer coils for control. The GPS and CNAPS have been validated in the CanX-2 mission<sup>2</sup>, which has recently surpassed three years of successful on-orbit operations. The attitude control system is currently operating successfully in AISSat-1, which launched in July 2010<sup>3</sup>.

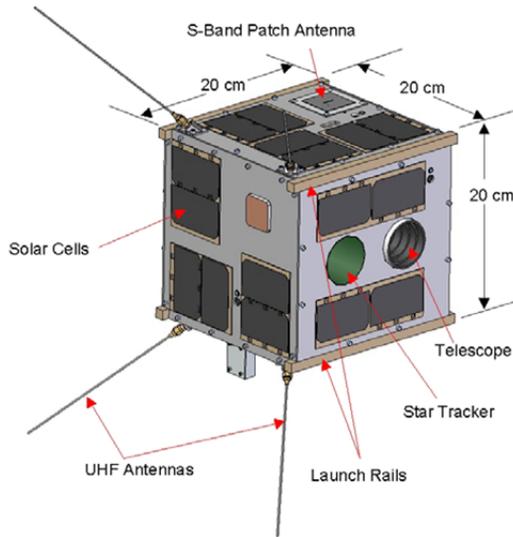


**Figure 1: CanX-4 and CanX-5 Formation Flight**

Over the duration of the mission, CanX-4&5 will demonstrate autonomous formation flight, with relative position determination accuracies better than 10-cm, and sub-meter position control. Of particular relevance to a future remote sensing formation flight mission, using single-point GPS processing the CanX-4&5 spacecraft will be able to determine their absolute position to an accuracy of 2-5 meters (RMS) and their velocity to an accuracy of 5-10 cm/s (RMS). Relative position and velocity will be determined within 2-5 cm (RMS) and 1-3 cm/s (RMS) respectively<sup>4</sup>.

#### *BRITE Constellation (CanX-3)*

BRITE (BRiGht Target Explorer) is a constellation of six nanosatellites from Canada, Austria and Poland, which will perform a photometry mission, measuring low-level oscillations and temperature variations of stars brighter than visual magnitude 4.0. The first pair of BRITE spacecraft will launch in Q4 of 2011. Each 7-kg 20-cm GNB (Figure 2) will carry the BRITE science instrument, a telescope with a 30-mm diameter lens and a 70mm focal length. The spacecraft's attitude will be determined using six sun sensors, a magnetometer, and a nanosatellite star tracker developed by Sinclair Interplanetary, Ryerson University, and UTIAS/SFL<sup>5</sup>. Three-axis attitude control and momentum dumping will be performed using three orthogonal reaction wheels (developed by Sinclair Interplanetary in collaboration with UTIAS/SFL) and three orthogonal vacuum-core magnetorquer coils.



**Figure 2: BRITE Nanosatellite Bus configuration**

The BRITE spacecraft's attitude determination and control performance, with arcminute attitude determination, attitude control accuracy better than 1.0-degrees, and 0.01-degree ( $3\text{-}\sigma$ ) attitude stability, represents a significant advancement over any other nanosatellite mission, and is the critical enabling technology for the science mission<sup>6</sup>.

### INTERFEROMETRIC SAR

SAR signals reflected from the same geographic location but received at different spatial locations exhibit phase variations which can be exploited in the process of SAR interferometry. The phase of the reflected signal is a combination of the phase proportional to the range to the target, and the phase due to the scattering characteristics of the target. If the images are coherent – that is, the scattering characteristics of the target are the same across both observations – then these contributions cancel and the phase difference between the received signals is dependent on the range-to-target difference between the receivers. The two received signals are conjugate multiplied, and the resulting interferometric phase can then be used to determine the height of ground terrain<sup>7</sup>.

Additional applications such as ground moving target indication (GMTI) and super-resolution image formation can be implemented similarly. In the case of GMTI, the interferometric phase observed from two receivers separated in the along-track direction is proportional to the velocity of moving objects on the ground, and in the case of super-resolution imagery, multiple complex images are coherently averaged to produce an image product with a higher spatial resolution than its contributors.

In all application cases, however, knowledge and maintenance of the baseline distance between receivers is paramount. Digital elevation modeling accuracy increases with baseline distance, but is bounded by an upper limit due to signal decorrelation, generally ranging between 1 and 10 km depending on signal wavelength. In the case of GMTI, the required baseline varies depending on the desired range of observable target velocities, ranging from meters to a kilometer depending on target speed and signal wavelength<sup>1</sup>. Super-resolution imagery requires long enough baselines (on the order of tens of kilometers) such that the received signals are decorrelated and the information in each received image is independent. CanX-4&5 will demonstrate the baseline maintenance algorithms enabling a future mission with these requirements.

If data processing is to be performed onboard the spacecraft, image processing requirements and their implications on spacecraft design requirements must be explored. Image processing steps necessary for a future InSAR constellation include the following:

*SAR focusing:* The received SAR signal reflected from a point target is distributed in both the range and azimuth directions. SAR focusing processes, such as the commonly used Range Doppler algorithm for continuously collected SAR data, focus the distributed signal onto a single pixel.

*Image registration:* Due to uncertainties in the position and orientation of the imaging sensor, the exact geographic position of the collected imagery is unknown. Image registration is the process by which images are automatically aligned such that pixels in one image geographically correspond to pixels in another image.

*Interferometric processing:* Interferometry utilizes small variations in the received signal phase from multiple images of the same target, acquired from different imaging geometries, to infer additional information about the target. The processing used is specific to the selected application.

Hardware and software architectures for onboard SAR focusing have been proposed<sup>8,9</sup>. Interferometric processing methods will be developed as necessary when the application for a future mission is identified. The design of the remaining image registration step depends on current CanX position and orientation determination capabilities.

## REGISTRATION

The image registration process can be broken down into two stages: *georeferencing*, in which spacecraft position and attitude sensors are used to determine the location of the image on the ground as closely as possible, and *registration*, in which an additional algorithm is used to more precisely align the images. The accuracy of the georeferencing stage depends on the position and attitude determination capabilities of the spacecraft. The quality of these measurements and their respective impacts on georeferencing accuracy then directly determine the complexity of the registration problem.

### Georeferencing

Direct georeferencing is the process of using knowledge of an imaging platform's position and orientation to determine the geographic locations of pixels in an image. A method of direct georeferencing for airborne imagers has been demonstrated<sup>10</sup>, using GPS and inertial navigation system (INS) data to determine aircraft position and orientation. In the spaceborne case, GPS is used for positioning and star trackers are used to determine platform orientation. Equation 1 describes the spaceborne SAR georeferencing equation for determining the geographic coordinates of image point  $i$  taken at time  $t$ , and is illustrated in Figure 3. Two frames of reference are needed: the geocentric mapping frame, and the body frame, which is centered on the imaging sensor. Terms are described below.

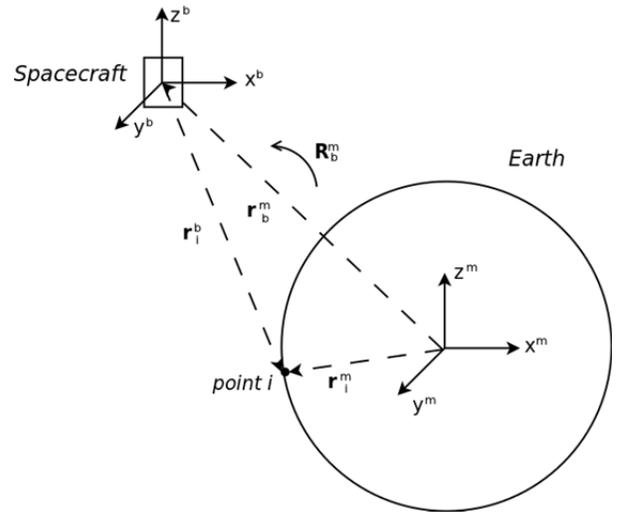
$$r_i^m = r_b^m(t) + R_b^m(t)r_i^b(t) \quad (1)$$

$r_i^m$  is a 3x1 column vector giving the location of image point  $i$  in the mapping frame.

$r_b^m(t)$  is a 3x1 column vector giving the location of the spacecraft at time  $t$  in the mapping frame.

$R_b^m(t)$  is a 3x3 rotation matrix between the body frame and the mapping frame, at time  $t$ .

$r_i^b(t)$  is a 3x1 vector from the imager to point  $i$  in the body frame at time  $t$ .



**Figure 3: Georeferencing Geometry: the measured spacecraft position and orientation are used to determine the geographic location of imaged points.**

In turn,  $r_i^b(t)$  depends on image scaling parameters as shown in Equation 2, where  $s_x$  and  $s_y$  are scaling factors to compensate for discrepancies between ground sampling distance (image spatial resolution) and the grid scale used in the mapping frame. In the case of SAR imagery, the GSD in the range direction (Equation 3) depends on signal bandwidth  $B$  and the speed of light, while the azimuth GSD (Equation 4) is a function of signal wavelength  $\lambda$ , range  $R$  to the ground target, and platform velocity  $V$  and imaging time  $T$  (the length of the synthetic aperture)<sup>11</sup>.

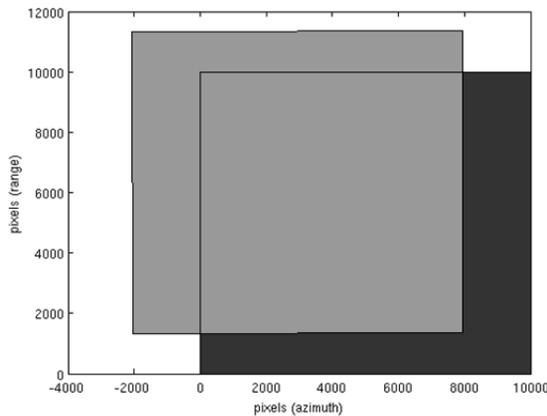
$$r_i^b(t) = \begin{bmatrix} s_x x_i \\ s_y y_i + z \tan \theta \\ -z \end{bmatrix} \quad (2)$$

$$\delta_r = \frac{c}{2B} \quad (3)$$

$$\delta_{az} = \frac{\lambda R}{2VT} \quad (4)$$

If direct georeferencing were a perfectly accurate method, images could simply be registered using georeferenced tie-points; however, georeferencing depends on the accuracy of the measured values in Equation 1, namely, the position and orientation of the spacecraft, which affect the accuracies of the positioning vectors and rotation matrix, as well as the scaling factors in Equation 2.

The effects of measurement errors on georeferencing results can be found by perturbing the measured spacecraft position and orientation in Equation 1. A future remote sensing constellation would rely on GPS technology from the CanX-4 and CanX-5 formation flight mission, and an attitude determination system from the BRITE constellation astronomy mission. The CanX-4 and CanX-5 GPS has a position determination accuracy of 2-5 meters (RMS) and a velocity determination accuracy of 5-10 centimeters (RMS)<sup>4</sup>, and the BRITE constellation star trackers have a 0.01-degree accuracy. However, the pitch and yaw measurements are much more accurate than the roll; mounting two star trackers orthogonally would allow an overall attitude determination accuracy equal to the pitch and yaw accuracies of 0.002 degrees<sup>5</sup>. Perturbing the measured position, velocity and attitude values has a negligible effect on scaling; the measured range resolution does not depend on these measurements, and the measured azimuth resolution varies by less than a millimeter when the GPS and star tracker measurements are perturbed. Errors in GPS and star tracker measurements do, however, induce noticeable georeferencing errors. Figure 4 shows the georeferencing error resulting from a platform position measurement error of 5m and an orientation error of 0.002 degrees.



**Figure 4: Georeferencing error: the dark rectangle is the area of a perfectly georeferenced image; the light rectangle is the same imaged area, but georeferenced assuming a 5m position determination error and a 0.002 degree attitude determination error.**

The orientation measurement error is the primary source of georeferencing error, and the effects of position and orientation measurement errors are to induce a translation and a small rotation in the georeferenced points. Reducing the orientation error greatly reduces the translation offset error, increasing

the amount of overlap between the perfectly georeferenced image and the error-georeferenced area. An additional image registration step will be necessary, but this example demonstrates that it will need to be suitable for correcting translations and small rotations between pairs of images, rather than more complex non-rigid transformations. It is important to note also that this analysis demonstrates the types of errors present in georeferenced imagery and does not constitute a required pointing budget, which would be determined by the application.

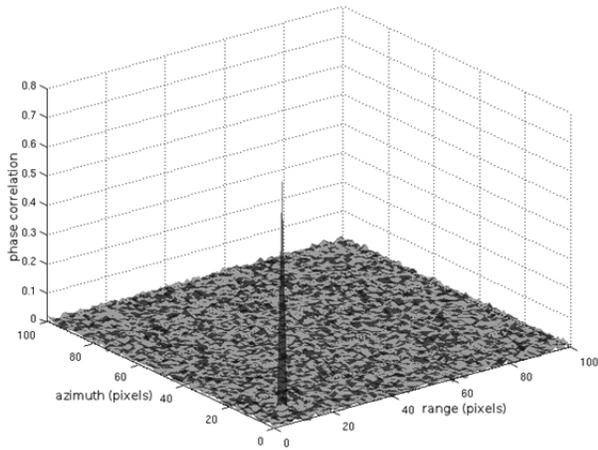
### Image Registration

Image registration of remote sensing imagery can be challenging due to varying illuminations, differences in reflectivity due to terrain changes or incidence angle variation, discrepancies between ground sampling distances, and varying feature characteristics at different wavelengths. Additionally, image registration methods must distinguish between static features that appear in different locations across multiple images due to varying imaging geometries, versus features that differ across images due to temporal terrain changes: the former features can be used to align the imagery, while the latter may be the subject of interest, such as vegetation growth.

The phase-correlation method, an area-based Fourier domain image registration method, has been implemented and demonstrated on SAR imagery at UTIAS/SFL for the purpose of future on-board implementation. Traditional area-based image registration methods maximize a cross-correlation metric in order to determine the most likely alignment between a pair of images. Fourier domain methods such as phase correlation utilize the shift property of the Fourier transform: when two images  $f$  and  $g$  are offset by a two-dimensional translation  $ux+vy$ , then the phase difference between the two images is equal to the phase of their cross power spectrum. Their Fourier transforms  $F(f)$  and complex conjugate  $F(g)^*$  are multiplied and normalized to calculate the cross power spectrum in Equation 5.

$$\frac{F(f)F(g)^*}{|F(f)F(g)^*|} = e^{2\pi i(ux+vy)} \quad (5)$$

Then, taking the inverse Fourier transform, the resulting function has a peak located at the translation offset necessary to register the two images. In an example, two cropped sections are taken from the same SAR image, offset from each other by 10 pixels in each direction. Figure 5 shows the resulting plot of the inverse of the cross power spectrum, with a peak at (10,10).

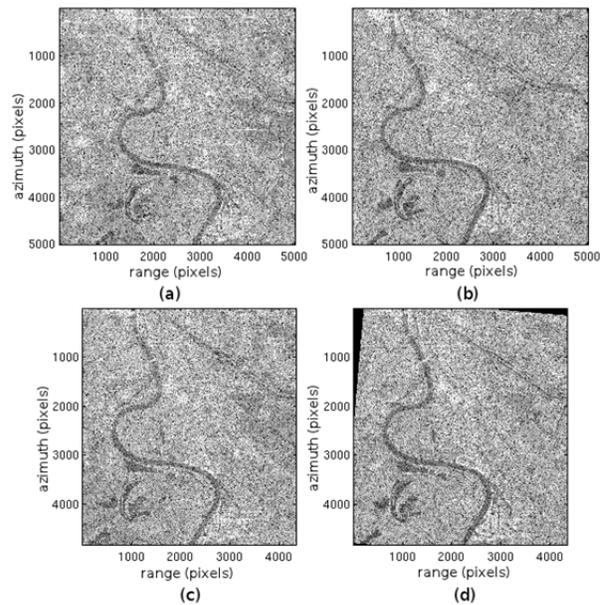


**Figure 5: Inverse Fourier transform of the cross-power spectrum, showing a peak at the x- and y-components of the translation between two images.**

Rotation and scale transformations can also be recovered if a log-polar transform is applied to both images: scale and rotation reduce to translational offsets, and can be recovered using the phase correlation method<sup>12</sup>. As such, this method is ideal for recovering the translations and small rotations present in georeferenced imagery.

Fourier domain methods are also particularly well chosen for registering remote sensing imagery, in that they are robust to noise that is present across a small range of frequencies, such as the types of illumination and reflectivity variations that are common in remote sensing imagery. Furthermore, methods such as phase correlation are well suited for onboard processing applications given that they can be implemented in hardware<sup>13</sup>.

In an example of this method, a pair of repeat-pass RADARSAT-2 C-band SAR images of Mannheim, Germany, are registered using the phase correlation method. The images were offset from each other by an unknown translation, and for demonstration purposes a small (5 degree) rotation was applied to one of the images prior to registration. Figure 6 shows the two original images, followed by the registered images, which have been rotated and cropped to show only the overlapping areas. Additional applications including cross-frequency SAR registration have been demonstrated<sup>14</sup>, and further validation of the image registration method will utilize GPS ground truth survey data.



**Figure 6: Registration of repeat-pass C-band SAR imagery: (a) and (b) show the two original images; (c) and (d) show the registered images, rotated and cropped to the overlapping area.**

On inspection, some features in Figure 6 vary between the two images. It is important to note that the registration method has aligned the images while preserving these varying features; such features are likely the result of changes in the terrain, such as vegetation growth, in the 6 weeks between image acquisitions.

Taking this example further, these changes between image acquisitions are an example of the type of feature that might be the object of study for a future remote sensing mission. After the images are registered, change detection algorithms can operate on the amplitude SAR images in various image representation domains to locate and classify these changes based on feature scale, for example<sup>15</sup>.

In additional application examples, the registered imagery can then be processed to identify the location and speed of moving targets such as ships traveling along a coastline, or sections of terrain that have changed elevation between passes. Performing the image registration and interferometric processing onboard reduces the amount of data transferred to Earth from multiple high-resolution images at several hundred megabytes each, to limited information such as the location and type of changes or targets detected.

## CONCLUSIONS

The BRITE constellation and CanX-4&5 will both demonstrate technologies developed at UTIAS/SFL enabling high-precision stellar photometry and autonomous formation flight, respectively. These technologies – attitude determination and control, absolute and relative position determination and control, and fuel-efficient formation flight algorithms – in turn enable future remote sensing formation flying constellation missions, for example augmenting an existing SAR transmitter with a constellation of microsatellite receivers for InSAR applications.

Interferometry relies on analysis of varying received signal phases, when SAR signals reflected from the same terrain are received by spacecraft separated by a baseline distance. The desired application determines the required baseline, which can vary from meters to tens of kilometers. Each additional receiver added to a constellation at a new baseline, maintained using CanX formation flight algorithms, enables additional interferometric applications.

On-board processing is a key component of any downlink-limited microsatellite platform collecting a large volume of remote sensing data, such as SAR imagery which can be hundreds of megabytes per image. Architectures for spaceborne on-board SAR focusing have been proposed; but on-board image registration remained unaddressed. Herein we have analyzed image georeferencing and registration methods, given CanX position and attitude determination capabilities, and have determined that errors in georeferencing using onboard position and attitude sensing are limited to image translations and small rotations. Therefore the phase correlation registration method, which can be implemented onboard in hardware, is sufficient for image registration and is demonstrated on sample SAR imagery. In turn, these methods will allow interferometric application-specific data to be extracted on-board, enabling future remote sensing constellation missions on a low-cost microsatellite platform.

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