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R: An Integrated Airborne pping System

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A B C D E

Figure 1. CASMSAR is mounted on a Cessna Citation-II 500 aircraft (a). X-band antennas (b), P-band antenna (c), SAR cabinets (d), and POS (e) are the necessary ingredients.

- **Multiple polarizations**. The X-band SARs can collect data with HH polarization while the P-band sensor can collect data with quad-polarization (HH/HV/VH/VV). Through polarization synthesis, multi-polarization SAR information extraction can be achieved.
- **Interferometry combined with stereogrammetry**. Two X-band SAR sensors are used to construct a dual-antenna interferometer with a baseline of 2.198 m. The X-band SARs have cross-track InSAR map functionality while the P-band SAR can be operated with repeat-pass InSAR. Flexible viewing geometries allow for stereogrammetry from both X-band and P-band images, respectively. Equipped with a precise position and orientation system (POS), the fusion of interferometry and stereogrammetry techniques provide practical solutions to challenges in mapping difficult terrains (Zhang *et al*., 2010c; Lu *et al*., 2010).
- **High spatial resolution and wide swath**. CASMSAR utilizes strip-mode SAR imaging at multiple operation modes. It has the ability to acquire X-band interferometric SAR data at a resolution of 0.5- 5 m and P-band polarimetric SAR data at a resolution of 1- 5 m. The imaging swath can be up to 12 km.
- **High-precision map products**. When the relative flight altitude is less than 3 km, CASMSAR could meet the mapping accuracy required for products at a resolution of 0.5 or 1.0 m (1:10,000 scale). When the relative flight altitude is between 3 and 10 km, it could meet the requirement for products at a resolution of 2.5 or 5.0 m (1:50,000 scale).

In addition, CASMSAR employs a high-altitude aircraft, Cessna Citation-II, as the flight platform, and a high performance ground processing system. CASMSAR can achieve all-weather data acquisition and rapid data processing capabilities. Satellite-based differential GPS technology is adopted to achieve precise navigation of the flight path. State-of-the-art visualization technology with a rapid refresh rate and low latency is utilized to display the instantaneous flight line and its deviation from the planned path.

Table 1.Sensor parameters of the CASMSAR system.

Parameter	X-SAR Sensor	P-SAR Sensor
Operating frequency (GHz)	9.6	600
Available bandwidth (MHz)	400	200
PRF range (Hz)	1000 ~ 4000	500 ~ 800
Pulse peak power (kW)	4.0	1.0
Pulse width range (us)	8 ~ 22	15 ~70
Interferometric baseline (m)	2.198	N/A
Polarization mode	HH	HH, HV, VH, VV
Ground resolution (m)	0.5/1.0/2.5/5.0	1.0/2.5/5.0
Swath width (km)	2 ~ 12	3 ~ 11.5
Incidence angle (º)	37~63	33 ~53
Onboard electronics	2 cabinets, 2 antennas	1 cabinet, 1 antenna

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SAR Mapping Workstation

SAR mapping workstation (SMW) is CASMSAR's data processing and product generation system. It is China's first adaptation of SAR data processing and mapping software systems, utilizing InSAR, radargrammetry, polarimetric SAR technologies for mapping and image interpretation. Meanwhile, it also supports spaceborne SAR data processing from high-resolution images by Canadian RADARSAT-2, German TerraSAR-X, and Italian COSMO-SkyMed satellites.

CASMSAR SMW consists of SAR topographic mapping, polarimetric SAR land cover classification, multi-band and multi-polarization SAR information extraction, and interpretation and quantitative landscape parameter retrieval from SAR images and products. The detailed functionalities of CASMSAR SMW include:

- **Topographic mapping**. It is capable of generating digital elevation model (DEM) by the combination of interferometry and radargrammetry, producing digital orthophoto map (DOM) from X-band and P-band imagery, carrying out block adjustment using multi-images with sparse ground control points (GCPs), and extracting object-oriented topographic features in stereo mode (Toutin, 1995, Lu *et al*., 2007; Cheng *et al*., 2010).
- **Polarimetric SAR land cover classification**. It consists of various methods of exploring polarimetric SAR images such as target decomposition Pauli/Krogager/Freeman/Cloude decomposition), WishartH/α unsupervised and supervised classification, decision tree classification, data clustering and optimum clustering (Lee and Pottier, 2009).
- **Multi-band and multi-polarization SAR information extraction and interpretation**. It has the abilities to extract point, line and area elements, and fuse SAR and optical images (Zhang *et al*., 2010a-c, Lu *et al*., 2010).
- **Quantitative landscape parameter inversion**. It includes modules to estimate biophysical parameters of landscapes based on SAR images and backscattering modeling and polarimetric InSAR analysis (Cloude and Papathanassiou, 1998). The current functions consist of forest height retrieval, soil moisture inversion and snow cover parameter determination.

Technology Advancement

Several key technologies have been developed to map landscape topography and its characteristics in difficult terrains. These technical advancements have made it possible to optimize the processing of CASMSAR images for accurate product generation.

Integrated Techniques for Airborne SAR Data Acquisition

The irregular motion of the aircraft due to turbulence results in serious artifacts to SAR images. Highly accurate motion compensation and variable squint-angle imaging have been considered in CASMSAR. The key technologies include high-precision X-band interferometric baseline monitoring and correction, multi-channel receiver calibration and dual-channel motion compensation through phase-preserving algorithms, P-band large aperture motion compensation, and radio frequency interference suppression. The dual-band raw data are synchronized with POS data. X band interferometric and P band polarimetric SAR sensors, POS and the flight control and navigation system are integrated effectively to acquire synchronous and reliable SAR data. A highly accurate intelligent navigation system is designed for flight path management and control. CASMSAR provides 2- 4 views for every point on the ground to remedy SAR geometric distortions. Successive parallel flight lines allow about 50 percent overlap between neighboring swaths.

DEM Extraction Through Interferometry, Radargrammetry and Data Fusion

Severe layover and shadow artifacts make it difficult to obtain full topographic information in difficult terrains. In addition, decorrelation of interferograms and mismatch of stereo SAR images lead to degradation of map products. To cope with these difficulties, existing (low-resolution) DEM has been used for interferogram generation. Range and azimuth common-band filters that have taken into account the local topographic slopes have been implemented to improve interferogram coherence (Gatelli *et al*., 1994). Multi-angle radargrammetrics are combined to solve the problems due to layover and shadow. Parallax editing has been developed to make the registered stereo SAR images into zero-stereo pairs. More accurate parallax is obtained after editing. The final DEM is generated by fusion of DEMs from interferometry and radargrammetry based on SAR image pairs from multi-direction acquisitions. Multi-source DEM fusion is applied to generate satisfactory DEM products over difficult terrains.

DOM Generation Through Multiple Quad-Polarization SAR Images

In order to generate reliable DOM products over difficult terrains with severe geometric distortions, SAR images observed from several different looking angles should be merged. Color DOMs can be generated based on image mosaics from ascending and descending passes. In addition, image fusion through quad-polarized SAR images has been developed to create color DOMs (Zhang *et al*., 2010a). The processing module consists of two parts: one to detect and mask layover and shadow areas, the other to establish the rule of a decision tree for data fusion. Pixel values in layover and shadow areas can be replaced with the corresponding values from the opposite-looking SAR image to create artifact-free products.

Digital Line Graph (DLG) Generation Under Stereo-Mode

A stereo mapping system has been developed for DLG generation based on SAR images. It includes an intelligent SAR interpretation module, a SAR image stereo display and a geometric relocation module. Users can easily form stereo SAR image pairs for DLG production through the geometric location model. A single side-looking imaging model results in areas of shadow and layover. Thus multiple side-looking stereo pairs should be applied. In the process of stereoscopic image simulation, range-Doppler model or range-coplanarity model has been developed for SAR image orientation while slant range projection or central projection mapping has been applied for georeferencing (Cheng *et al*., 2010). In addition, stereoscopic pairs are constructed directly from original SAR images. Topographic features could then be collected and contours could be edited under the stereo mode. According to different characteristics of SAR data and mapping requirements, several methods of stereo model generation have been employed (Zhang *et al*., 2010), and more detailed information about landscape characteristics could be extracted.

Land Cover Classification with Multi/Quad-Polarization Images

Most of current SAR image classification methods are pixel-by-pixel based. Therefore, texture information of adjacent pixels has not been fully utilized to achieve highly accurate land cover classification. For this purpose, SAR image segmentation based on polarimetric and texture signatures have been developed. In order to avoid the effect of speckle noise and achieve high-accuracy land cover classification, a SAR classification method based on segmentation with multi/quad-polarization images has been developed (Yu *et al*., 2010; Liu *et al*., 2010).

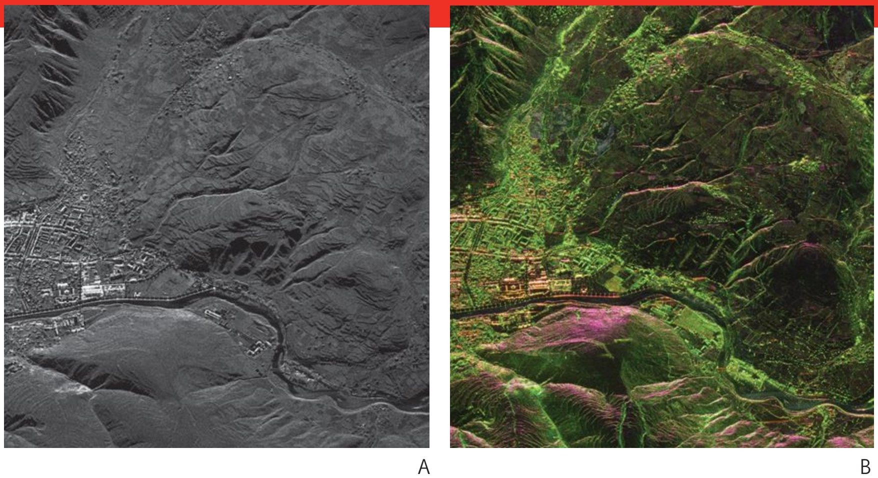

Figure 2. Examples of X-band (a) and P-band polarimetric (b) SAR images acquired by CASMSAR at a spatial resolution of 2.5 m at an altitude of 9771 m.

Block Adjustment Using Multi-Images with Sparse GCPs

It is difficult to acquire GCPs in western China. High precision geo-positioning has to be realized with sparse GCPs. Block adjustment is useful for reducing the required number of GCPs. A universal geometric model is necessary for block adjustment with multi-source SAR images. A rigorous geometric model for spaceborne and airborne SAR imagery has been constructed based on high-precision geo-position and sensor parameters. A range-coplanarity model such as the universal geometric model has been developed (Cheng *et al*., 2010). The geometric rectification model follows the rigorous mechanism of SAR imaging and is convenient for SAR image geo-positioning.

Capability Demonstration

After the completion of system integration of CASMSAR in 2009, a series of tests were conducted to carry out system calibration, product validation and accuracy assessment. CASMSAR flew over the Qinling Mountain and Hengduan Mountain areas, and was deployed for emergency response and disaster monitoring.

Qinling Mountain Area

CASMSAR acquired images covering approximately 1,200 km^2 in the Qinling Mountain area. The topographic height of this difficult terrain ranges from 300 m to 2500 m. Forty-one strips of X-band datasets were collected at altitudes of 3300 m, 6300 m, 8000 m and 10000 m with corresponding spatial resolutions of 0.5m (or 1 m), 2.5 m, 2.5 m and 2.5 m (or 5 m), separately. At the same time, 73 strips of P-band datasets were collected at altitudes of 3300 m, 6300 m, 8000 m and 10000 m with corresponding spatial resolutions of 1 m, 2.5 m, 5 m and 5 m, respectively. A large number of GCPs have been collected during the CASMSAR campaigns. A small percentage of GCPs were used for data processing while the remaining GCPs were used for accuracy assessment. Table 2 shows that CASMSAR is capable of generating DEM, DOM, DLG, and land cover products at scales of 1:10,000 and 1:50,000, respectively.

Hengduan Mountain Area

In less than five months, CASMSAR images of 109 flights have mapped mountainous areas of about 110,000 km^2, of which 30 percent was acquired at night time and 89 percent was under cloudy, rainy and snowy conditions. Success rate of data acquisitions was up to 95 percent. Figure 2 shows an example of the Hengduan Mountain dataset.

Airborne and spaceborne SAR images together with optical images have been applied to generate map products in the Hengduan Mountain area. A total of 480 map sheets (including DEM/DOM/DLG) at a scale of 1:50,000, covering around 190,000 km^2, have been produced. Independent quality verification and assessment have shown that the quality of DEM, DOM, DLG products is satisfactory at a scale of 1:50,000. Figure 3 demonstrates DEM products in the Hengduan Mountain area.

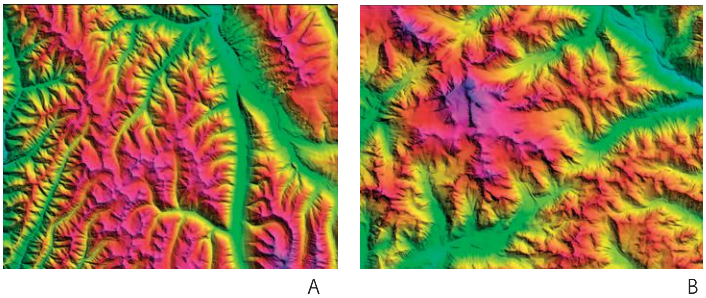

Figure 3. DEM products of Hengduan Mountain area at a scale of 1:50,000.

Emergency Response

A devastating earthquake of Ms 7.1 occurred in Yushu, Qinghai province of China on April 14, 2010. Shortly after the Yushu earthquake, CASMSAR was dispatched to test emergency response capability. X-band interferometric SAR data with spatial resolutions of 0.5 m and 1 m and P-band polarimetric SAR data at a spatial resolution of 1 m

Table 2. Accuracy assessment of map products from CASMSAR

Scale	DEM Error (m)	DOM Error (m)	DLG Error (m)	Elevation label point error (m)	Contour line error (m)
1:50,000	12.07	11.41	14.23	5.27	6.57
1:10,000	2.45	3.77	4.12	2.19	1.94

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were acquired, covering an area of 2,000 km^2 surrounding the epicenter. Image rectification, product generation, disaster situation interpretation and evaluation were rapidly generated through the CASMSAR mapping workstation, and provided to emergency response departments. They have proven critical in managing crises and saving lives.

At the end of March 2011, an aircraft was lost in the Tianshan Mountains of Xinjiang. The CASMSAR system flew over the crash site for 3 days, covering an area of 5,000 km^2 with 1 m X-band interferometric and P-band polarimetric images. CASMSAR products have identified several suspected incident locations, and facilitated the search and rescue efforts.

Summary

SAR mapping technology is the most effective remote sensing tool that offers all-weather, day and night operations in difficult areas. An airborne system enables rapid deployment and flexible data acquisitions. Hence, the airborne SAR system has become a high priority for Earth observation. Using state-of-the-art SAR technologies, the CASMSAR mapping system has been developed and applied to map difficult terrains over western China. With CASMSAR, DOM can be generated through image fusion with SAR images acquired from several different looking angles; highly accurate DEM can be produced using interferometry, radargrammetry, and DEM fusion; DLG can be generated with multi-direction SAR stereo image pairs; and maps of land cover and biophysical parameters can be produced by using multi-/quad-polarization images. It is no doubt that CASMSAR will play a critical role in landscape mapping and emergency response in China.

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