Updating GeoSAR for Full-pol Interferometric Capability

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***Abstract*— GeoSAR is a single pass, dual frequency (X-band and P-band) interferometric mapping radar designed to map both top vegetation canopies and the terrain beneath the canopy. This system was developed from 1998-2003 as a joint effort of NASA JPL and EarthData under sponsorship of DARPA and NGA. The system is flown on a G-II aircraft and maps 10-12 km swaths simultaneously on both sides of the aircraft to generate high quality DEMs and imagery at both X-band and P-band. The system was later augmented with a nadir-pointing lidar profiler system to generate highly accurate control points that can be used in generating large area mosaics. Over the last 5 years the field of polarimetric interferometry has shown great utility in mapping the top of canopies and the underlying terrain with a great deal of accuracy at both L-band and P-band. This paper discusses an upgrade of the GeoSAR dual-pol (HH, HV) P-band interferometer to a fully polarimetric interferometer (HH, HV, VH, VV). We present both hardware and processor changes to the GeoSAR system needed for fully polarimetric interferometric operation.**

I. Introduction

GeoSAR is the result of a 5-year (CY1998–2003) joint development effort[1] between Caltech's Jet Propulsion Laboratory (JPL) and EarthData. JPL led the GeoSAR system design and integration into the aircraft. EarthData developed a highly automated commercial production center for processing deliverable product data. EarthData provides commercial mapping services using the GeoSAR system. Subsequent modernization of the radar system was performed by EarthData and Technology Service Corporation (TSC) under sponsorship of NGA. A more complete description of the original system can be found in [1], [2]. This paper describes some of the technical innovations of the original 160MHz bandwidth dual-frequency second-generation interferometric synthetic aperture radar (IFSAR) mapping system and the considerations and constraints for updating this system to full-pol interferometric operation.

II. GeoSAR System Description

A. GeoSAR Airborne System Integrated into Gulfstream-II Aircraft

The GeoSAR system as currently configured is integrated into a Gulfstream-II jet aircraft, which has an endurance of over four hours and a cruise speed of 230 m/s (450 kts) at altitudes up to 12 km MSL (40 kft). The Gulfstream-II has a wing span of 20 m, which supports simultaneous dual-sided, single-pass, X-band and P-band interferometric mapping.

GeoSAR single-swath performance parameters are summarized in TABLE-1. Single-swath performance refers to GeoSAR's mapping capabilities *prior* to multiswath mosaicking and application of ground control data. Single swath performance is applicable to relatively flat open terrain. Post-mosaic accuracy can considerably improve single-swath performance.

Fig-1 shows the location of the P-band and X-band antennas. As the aircraft traverses along a flight line, the GeoSAR system simultaneously collects single-pass interferometric X-band and P-band data in swaths of 10–12 km on each side of the aircraft, as shown in Fig-2.

[1] Sponsored initially by DARPA and later by the National Geospatial-Intelligence Agency (NGA)

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TABLE I. GeoSAR Nominal Performance

Parameter	X-band	P-band
DEM Height Accuracy (RMSE)*	First Surface	Foliage Dependent
Single Swath	0.5 to 1.2 m (relative)	1–3 m (Relative)
Mosaic	~1 m (Absolute)	2.5-5 m (Absolute)
DEM Posting	3 m	5 m
Planarmetric Accuracy (RMSE)*	1.25 m (Relative)	1.25 m (Relative)
Post Mosaic w/GPS/lidar control	<2.5 m (Absolute)	4 m @ 10 km Altitude (Absolute)
Ground Swath Width*	10–12 km, Each Side	10–12 km, Each Side
Radar Look Angles	25–60 deg	25–60 deg
Polarization	VV	HH HV
Pixel Size (Draped over DEM)	1.25–3 m	1.25–5 m
* Terrain, slope and foliage dependent		

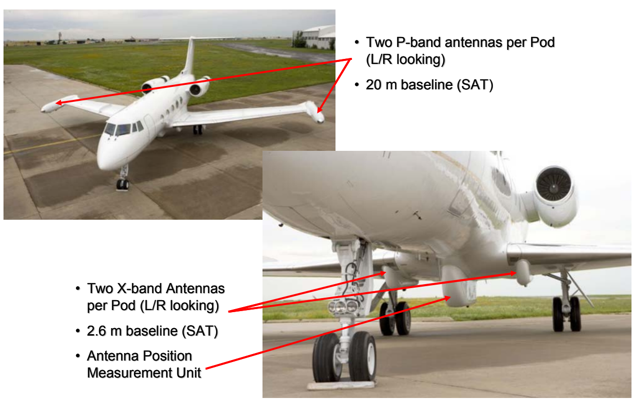

Fig-1 GeoSAR X-band and P-band antenna locations

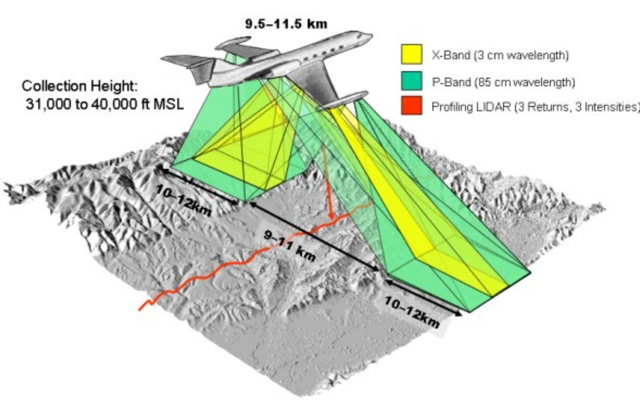

Fig-2. GeoSAR dual side acquisition geometry

Between the swaths on either side of the aircraft lies the ~10 km nadir coverage gap, which is filled by adjacent flight lines. The nadir gap is inherent in the synthetic aperture radar imaging principle. These adjacent lines generate overlapping swaths, which in turn generate acquisition redundancy (typically ~ 4:1) to ensure complete coverage, even in steep terrain.

B. Airborne Component

A high-level view of the radar system as currently integrated into the G-2 is shown in Fig-3. Subsystems 1–7 and 16–20 form and control the dual-sided X-band radar. Subsystems 8–15 and 16–20 form and control the dual-sided, dual-pol P-band radar. Subsystem 17, GeoSAR Data Processor (GDP) uses a single FPGA to integrate the functions of radar signal digitization, data formatting and multiplexing, and central timing and control. Subsystems 22–24 capture auxiliary aircraft and antenna position and motion.

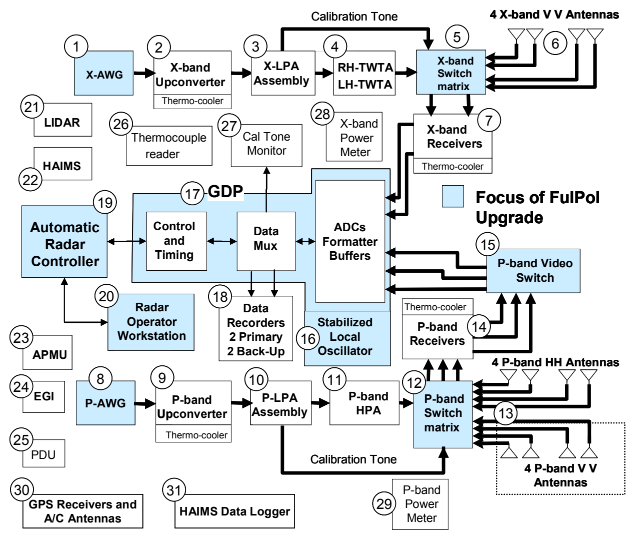

Fig-3. GeoSAR Hardware Block Diagram, Airborne Component

Subsystem 23 is the Antenna Position Measurement Unit (APMU) and provides direct measurements of the P-band antenna location (two angles and one range per side. Subsystem 31 is a data logger for recording 1200Hz data from the High Accuracy Inertial Measurement Systems (HAIMS, subsystem 22). A HAIMS unit is mounted on each antenna truss supporting the wing-mounted P-band antennas and provides auxiliary antenna motion and attitude information. The HAIMS data logger and the HAIMS unit are manufactured by Sandia National Laboratories and are proprietary to them. Subsystem 21 is a lidar profiler adapted from a 3-return, 3-intensity Leica ALS40. This subsystem operates at altitudes of 40 kft MSL and provides ~50 cm nadir samples of terrain height at ~5 cm post. The lidar profiler is used for mosaicking and ground control. Subsystem 25 is the power distribution system that converts aircraft generator power to conditioned power for all the remaining subsystems.

The direct-to-disc data recording rate is 380 MB/S at 10 bits/sample, block compressed (128-samples/block) linearly to 8-bits. Timing and control for the current system is FPGA driven. The radar is currently configured with 14 channels implementing dual baseline operation for both X-band (6 channels) and P-band (8 channels). X-band and P-band are concurrently acquired, with the left/right looks interleaved at a 500 Hz/side (max) PRF per channel using four minor frames per major transmit interval.

Single-pass, full-pol interferometry requires transmission and reception from two antennas in two polarizations. Transmission/reception diagrams are used to designate how the polarimetric data is acquired. Fig-4 diagrams the possibilities. The circle (node) corresponds to an antenna, e.g., H1 corresponds to horizontal polarization for antenna one, V2 corresponds to vertical polarization for antenna two. The arcs connecting the nodes correspond to backscattered transmitted energy, the tail being the transmitting antenna, and the head being the receiving antenna. In general, the backscattered energy from each transmitted pulse can be received by each of the four antennas, therefore if all antennas are used (sequentially) for transmission and all antennas are used (simultaneously) for reception, then a maximum of 16 raw data channels are available for recording. For a two sided system such as GeoSAR, this means that 32 data channels are available for acquisition. Due to recording bandwidth limitations GeoSAR records a subset of this data.

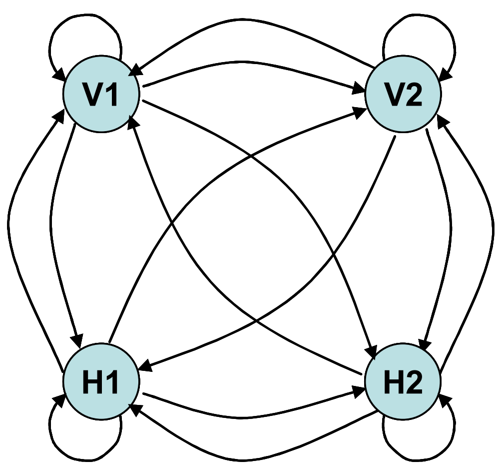

Fig-4. Transmission/reception diagram for a single pass full-pol interferometric system

Fig-5 shows the transmission/reception diagrams for the *current* dual-pol system. Note, the cross-pol P-band channel for antenna 2 (V2, cross axis looking) is not recorded, and X-band is VV only, due to antenna design limitations.

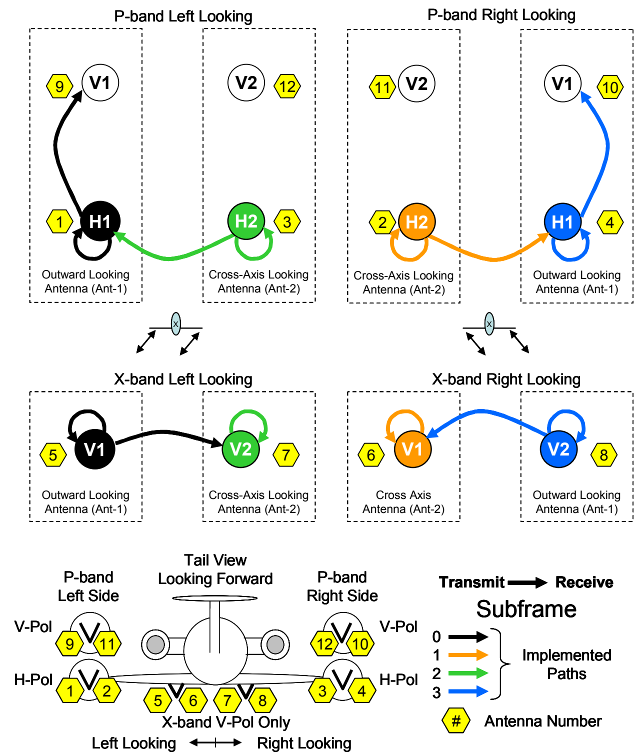

Fig-5. Current GeoSAR transmission/reception diagrams

III. Upgrading for Full-pol Capability

A. Airborne Element

P-band is particularly well suited for deep foliage penetration. Additionally, it is well known [12] that full-pol data has much greater ground height reconstruction and terrain feature classification capabilities and GeoSAR would significantly benefit from a full-pol upgrade.

With this in mind, under NGA sponsorship[2], a systems study was performed to determine additional P-band polarization modes that should be and could be implemented, given practical hardware constraints associated with a legacy system. New capability was balanced against implementation risk and system downtime. The constraints included: (a) no increase in recording bandwidth, (b) no major hardware architectural changes, (c) no increase in the simultaneously collected data channels, (d) support for the legacy dual-sided acquisition mode, (e) retain dual-band capability, and (f) a maximum of three months of down time for the upgrade.

[2] GeoSAR System Improvement Program, Agreement NMA201-00-9-1001

Seven modes of operation are being implemented: (1) current legacy capability, (2) 3-pol dual sided (X-band SAT),[3] (3) 3-pol dual sided (X-band PP), (4) 4-pol Left looking, (5) 4-pol right looking, (6) counter clockwise circle, and (7) clockwise circle. Modes 6 and 7 are special spotlight modes used for all aspect angle full-pol imaging (noninterferometric), single side, noninterferometric 4-pol, double PRF on P-band. The upgrade necessitates replacing the P-band antenna switch to incorporate a path to the vertically polarized inboard antennas. The upgrade also includes replacing the two legacy arbitrary waveform generators (AWG) from 8 bits/sample to a single unit with 14-bit/sample, integrating the stable local oscillator (StaLO) onto the FPGA controller board, and increasing the number of ADCs from four to five. The latter will dedicate a separate ADC to each receiver. Representative transmission/reception diagrams for the new P-band modes are shown in Fig-6.

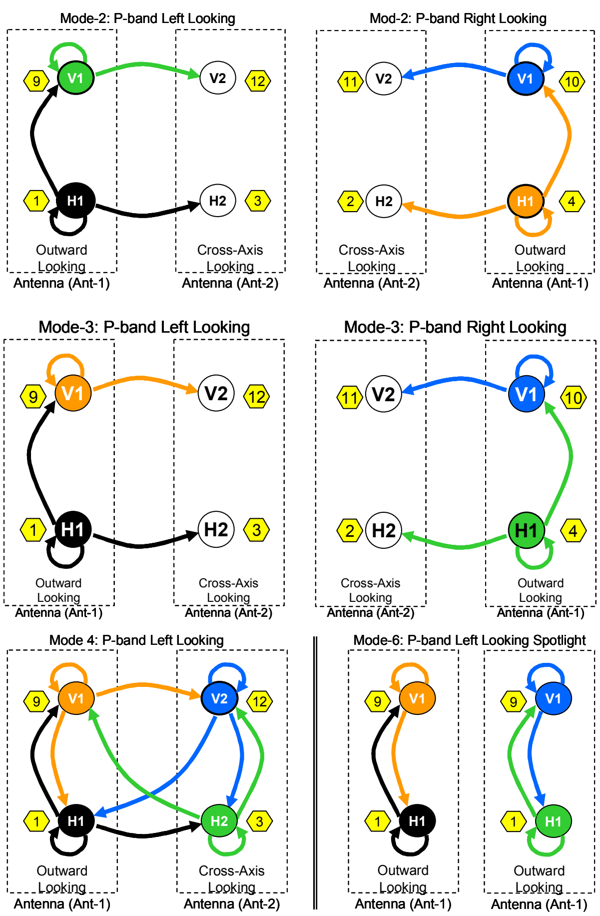

Fig-6 GeoSAR Full-pol Transmission/Reception Diagrams

[3] SAT: Single Antenna Transmit, physical baseline; PP: Ping-Pong, double baseline

Note, the upgrade constraint kept the number of minor frames at four to keep the along-track range line spacing at ~0.5m. Acquisition of this additional data will require a future addition of a 4^{th} P-band receiver, and additional recorder bandwidth.

B. Ground System Updates

New acquisition modes require new corresponding ground processing modes. The full-pol upgrade requires changes to the following ground processor functions: (1) mode-dependent ingest of the raw phase history data (since only 14 data channels are available for recording, the processor channel sets are mode dependent), (2) generalizing the motion measurement solution to include the antenna phase center locations for all the antennas for each of the modes, and (3) generalizing the interferometric processor to handle the additional interferometric full-pol channels. Examination of the transmission diagrams (Fig-5) shows that the 3-pol modes (2 and 3) are not cross-pol interferometric—they are only HH and VV interferometric.

Within the USA, utilization of P-band by GeoSAR is on a secondary, noninterference basis. The current system is designed to accommodate arbitrary transmit waveform notching to accommodate this regulatory restriction. Airborne field measurements made in CY2000 showed that GeoSAR induced electromagnetic interference (EMI) to ground receivers using vertically polarized receiving antennas may increase by as much as 10dB. Therefore, the notching requirements for full-pol transmission (transmit vertical) will likely require some modification of the notching methodology to prevent interference to primary users.

IV. Radiometric and Polarimetric Calibration

Interferometric calibration of a fully polarimetric P-band SAR system proceeds similarly to a single-channel polarimetric SAR [3]. Radiometric and polarimetric calibration are however more general, and in fact should prove somewhat easier to accomplish since direct measurement of the four polarizations can be made. This should yield calibration accuracy improvements over the current dual polarimetric system.

In the current P-band system, which collects HH and HV polarizations and only HH interferometrically, polarimetric calibration is hampered by incomplete sampling of the scattering matrix. Using trihedral calibration targets, it is possible to achieve accurate radiometric calibrations of both the X-band VV and P-band HH channels. Complete removal of polarimetric impurity from the HV channel in a dual-pol system using only external calibration is not possible. Even at its best, the external calibration scheme for the HV channel will still contain a VV component scaled by the system cross-talk. GeoSAR is designed to minimize internal cross-talk [4] and thereby alleviates this issue to some extent. However some of the cross-talk is external, and results from antenna polarization isolation and from multipath on the aircraft, the latter being angle dependent and may require sophisticated modeling to remove.

External polarimetric calibration of the HV channel in a dual-pol SAR system is further hampered by the need to use depolarizing targets. Traditionally these are dihedral reflectors, which must be aligned rotated 22.5^{o} about boresight at the elevation determined by the local incidence angle. This is difficult to achieve even at high frequency, and for a permanent calibration site. At P-band the problem is exacerbated by the requirement that the targets be electrically large in order to be sufficiently bright. Even for very large targets the scattering response of the target in azimuth is narrow and this limiting factor must be taken into account in the calibration process.

To overcome these problems Fugro EarthData is currently engaged in the design and testing of a new type of trihedral target with depolarizing capabilities. The target is essentially a standard trihedral with one surface replaced with a waveguide that preferentially reflects and transmits linear polarizations [5]. The result is a target with a wide scattering pattern that does not require rotational alignment, but which provides a depolarizing signature for polarimetric calibration. Such targets have recently been tested at X-band by the Navy Research Laboratory [6], but this is the first time that the technology will be tested at low frequency.

To achieve the correct limit for the geometrical-optics/physical-optics (GOPO) model of target scattering to be accurate requires at P-band a target of extremely large dimension, perhaps 9 m or more on a side. In practice it is not possible to deploy such large targets, especially during campaigns in remote parts of the world. Targets must be used that are smaller than might be desired, and therefore their responses must be modeled at the desired frequencies and orientations, and this requires the use of EM scattering codes and/or the use of measurements on scaled conducting models at higher frequencies [7], [8].

Collection of the full scattering matrix information permits full polarimetric calibration using a combination of natural and artificial targets. Using the observed polarimetric coherence for natural clutter, plus the additional use of only trihedral targets, one can obtain a full polarimetric calibration solution [9], [10], [11]. This technique removes the need for dihedral or depolarizing artificial targets, although it does require some level of assumption regarding polarimetric correlations for natural clutter.

A portable P-band calibration target, Fig-7, has been constructed with a side length of 2.2 m and consists of a steel framework supporting a perforated aluminum sheet. Performance, weight and ease of manufacture and deployment were taken into consideration in the design process.

Fig-7 A P-band 2.2 m trihedral calibration target.

With the calibration of a fully polarimetric, interferometric SAR, comes the potential to exploit PolInSAR [12] techniques for tree canopy and ground height reconstruction. A fully polarimetric GeoSAR has the added advantage of single-pass interferometry, which will eliminate the uncertainty associated with temporal decorrelation over natural targets. At the same time a fixed baseline of 20 m (single antenna transmit) or 40 m effective baseline (ping-pong) at P-band limits the sensitivity of the system to polarimetric volumetric decorrelation which is exploited in PolInSAR. Thus the first post-calibration exercises with GeoSAR II will involve the investigation of the suitability of the system for PolInSAR and polarimetric coherence optimization, the benefits of which will be improved ground-height estimation for topographic mapping: one of the main applications of the GeoSAR technology.

V. Acknowledgments

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References

[1] Rodriguez, Richard M Goldstein, "Synthetic aperture radar interferometry," Proceedings of IEEE, Vol 88, No. 3, March 2000.

[2] "The GeoSAR Airborne Mapping System," IEEE International Radar Conference

[3] P. A. Rosen, S. Hensley, I. R. Joughin, et al., "Synthetic aperture radar interferometry," Proc. IEEE, vol. 88, no. 3, pp. 333-382, 2000.

[4] K. Sarabandi and F. T. Ulaby, IEEE Trans. Geosci. Remote Sensing, "A convenient technique for polarimetric calibration of single antenna systems," 28, #6, pp. 1022-1033, 1990.

[5] D. R. Sheen, E L Johansen, L P Elenbogen, and E S Kasischke, "The gridded trihedral: A new polarimetric SAR calibration reflector," IEEE Trans. Geosci. Remote Sensing, 30, pp. 1149-1153, 1992.

[6] T. L. Ainsworth, "Design, modelling and analysis of gridded trihedral reflectors for dual-polarization calibration," IEEE Trans. Geosci. Remote Sensing (submitted).

[7] L. Pastore, "Imagerie Radar par Synthese d'ouverture en basse frequence," PhD Thesis Dissertation, Paris X Sevres-ville-d'Avray, University France, 2003.

[8] H. Cantalloube et al., "Polarimetric repeat-pass interferometric airborne UHF SAR data acquisition and calibration," Proceedings PolInSAR05, 2005.

[9] J D Klein, "Calibration of complex polarimetric SAR imagery using backscatter correlations," IEEE Trans. Aerosp. Electron. Syst. 28, 183-194, 1992.

[10] S Quegan, "A unified algorithm for phase and cross-talk calibration of polarimetric data – theory and observations," IEEE Trans. Geosci. Remote Sensing, 32, pp. 89-94, 1994.

[11] Thomas L. Ainsworth, Laurent Ferro-Famil and Jong-Sen Lee, "Orientation angle preserving a posteriori polarimetric SAR calibration," IEEE Trans. Geosci. Remote Sensing, **44**, 4, April 2006.

[12] S R Cloude and K Papathanassiou, "Polarimetric SAR interferometry," IEEE Trans. Geosci. Remote Sensing, **36**, 4, pp. 1551-1565, 1998.