Comparative View of Antenna/RF Subsystems between SIR-C and NISAR L-band SAR Systems for Wide-Swath Imaging

Yuhsyen Shen
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, USA
yshen@jpl.nasa.gov

Scott Shaffer
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, USA
Scott.Shaffer@jpl.nasa.gov

Abstract—In 1994, SIR-C demonstrated ScanSAR, a mode of operating the SAR system that has become the "standard" implementation for wide-swath spaceborne imaging SAR systems. The NISAR SAR instruments introducing a new SAR architecture for wide-swath imaging call SweepSAR which is expected to have similar success. This paper compares the Antenna and RF subsystem design and the technology utilization considerations between the SIR-C planar phased array SAR system using the ScanSAR technique and NISAR off-set reflector with phased array feed using the SweepSAR technique.

Keywords—SAR System Architecture; SAR Antenna Subsystem; ScanSAR; SweepSAR; Digital Beam Forming; SIR-C; NISAR; L-band SAR System

I. Introduction

The Spaceborne Imaging Radar-C (SIR-C) Mission with the NASA/JPL-provided L-band and C-band SAR systems and DLR-provided X-band SAR system flew on the Space Shuttle Endeavour in April 1994 (STS-59) and again in October 1994 (STS-68) [1]. SIR-C's L/C-SAR systems were the fourth generation of NASA/JPL SAR instruments, a most capapable successor to those previously flown on SEASAT (1978) [2], SIR-A (1981), and SIR-B (1984), all of which had been as a series of progressive technological demontrations of spaceborne SAR instrument architecture and technologies, and exploration of SAR data for science applications. The NASA-ISRO SAR (NISAR) Mission's L-band SAR system, previously studied under DESDynI/Tandem-X Mission [3], can be considered the fifth version of NASA/JPL SAR instrument, incorporating system architecture and technologies that have been studied and developed since SIR-C radar systems were built.

The SIR-C L/C-band SAR systems were fully polarimetric and utilized plannar active phased array antennas with operational cabilities for StripSAR, ScanSAR, SpotlightSAR modes of data acquisition. The SIR-C SAR system architecture and operation capabilities have remained as the prevalent architecture of spaceborn SAR sytems that have flown after SIR-C. (Later, the SIR-C C-band and X-band SAR hardware was augmented – adding a 60m deployable boom and two outboard antennas, C-band and X-band, to the tip of boom and baseline metrology systems, to form a dual-frequency fixed baseline interferometrier that was flown as the SRTM/X-SAR mission in February 2000 (STS-99), collecting data for constructing global land topographic elevation map.)

Forcusing on being able to collect wide-swath SAR data in short repeat cycles (12 days), the NISAR L-SAR system, also fully polarimetric, adopts a new system architecture, using an offset reflector with array feed antenna to implement the first wide-swath SweepSAR technique in data acquition. ISRO adds a similar set of S-band S-SAR electronics and feed to share the same reflector to implementing SweepSAR technique, makes NISAR Mission carrying a dual frequency (L/S) SAR system, more capable and more beneficial to sciences than a single frequency system [4].

This paper compares the differences and presents the pros and cons between the SIR-C L-SAR system design and technologies vs. the NISAR L-SAR system design and technologies. Sec. II describes the SIR-C ScanSAR technique and NISAR SweepSAR technique and its effects of SAR system design. Sec. III describes the specific design of SIR-C anteana subsystem and NISAR antenna subsystem, their design considerations and effects on system sensitity performance. Sec. IV describes other differences besides the antenna subsystem between the SIR-C and NISAR radar hardware. Sec. V lists some of drawbacks on flight system (spacecraft) of using a large reflector with arrayed feed for which mitigation is required. Sec. VI provides summary of the comparison.

II. Adoptation of SweepSAR and the use of Reflector/Feed Antenna for NISAR

For wide swath imaging, the SIR-C SAR instrument implemented the now conventional ScanSAR mode of data acquisition [1]. By using an electronically steerable phased array antenna, SIR-C was able to scan the antenna beam in elevation angle over several consecutive subswaths in time (by the control of phasing of the phased array) cyclically over the entire swath. (See ScanSAR technique in left part of Figures 1 and 2.)

The ScanSAR mode is subject to the constraints that the time of the cyclic period over which the beam has to return to the same subswath must be less than the time it takes for a target to pass through the azimuth beamwidth (the synthesized aperture), lest an along track gap occur. Because this time is split between each of the subswaths within a scanning cycle, each subswath only sees a fraction of the full azimuth beamwidth, thus reducing azimuth integration gain and degrading the resolution from that which could be obtained with full azimuth synthesized aperture. However, because each beam illuminates a subswath, it is designed that the return echoes of that subswath is contained within the radar transmit inter-pulse period (IPP), not crossing over to the next IPP.

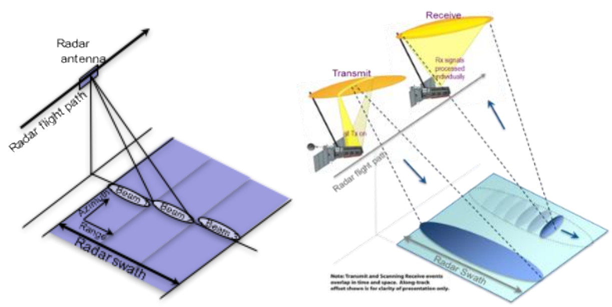

Figure 1: Wide-swath imging using SIR-C ScanSAR technique (left) and NISAR SweepSAR technique (right)

The concept of SweepSAR for wide swath imaging was studied by DLR [5] and later joined by JPL. Various system architectures were also studied by DLR [6][7]. Based on that concept, JPL and DLR performed a joint DESDynI/Tandem-L study which concluded that using a reflector with an arrayed feed is more cost effective than using a planar phased array. (See SweepSAR technique in right part of Figures 1 and 2.)

The SweepSAR technique achieves wide swath imaging by illuminating the entire swath with a broad beam in elevation and allowing the returned echoes to traverse over several interpulse periods. The broad transmit elevation beam is actually achieved by the composition of several narrower elevation sub-beams (L-SAR uses 12 sub-beams, S-SAR uses 24 sub-beams), with each sub-beam (like a pencil-shape beam) pointing at at a subswath with overlap at approximately the 3dB points on the antenna patterns. Transmit pulses are radiated on all beams at the same time and propogate through each sub-beam to illuminate the full swath. The echo returns to the radar and is received by the over-lapping beams, but since each consecutive sub-swath is pointed farther away, the returned echoe is broadened in time, traversing over 3 IPPs. Since the echo returns from the lower look angles arrive first, then gradually progess to the higher look angles, the echo appears to sweep over the array feed (thus the term SweepSAR).

In comparision to the ScanSAR technique, in which a wider elevation beam (elliptical beam) scans in time over several subswath with a fractional dwell time in azimuth but with echoes contain within an IPP, the SweepSAR technique has the advantage of gaining full azimuth aperature intergration time as the elevation sub-beams are illuminated on every pulse.

However the long echo from one pulse lasting over several IPPs and overlapping with the echoes from the next few pulses have to be contended with. First the echoes from each transmit pulse must be tracked precisely to determin their return time. Second, the long echo lasting more than an IPP upon receive is interrupted by the transmit pulse gating to protect the receiver, resulting in the received echoes having "transmit gaps" while the radar continues to transmit pulses. To address this, the NISAR L-SAR design includes an operational option to dither the PRFs by which different PRFs cycle through the duration of one azimuth aperture integration time, spreading the gaps of the received echoes over different ranges in the image where they will be filled in by adjacent pulses, as opposed to operating at a constant PRF which would place the transmit gaps at the same ranges in each pulse and produce gaps in the processed images. Serveral PRF dithering schemes have been studies and implemented, each adding slightly different artifacts to the now ungapped images [8]. The L-SAR radar dither sequence is table driven and can be uploaded during flight should other sequences prove to be more useful.

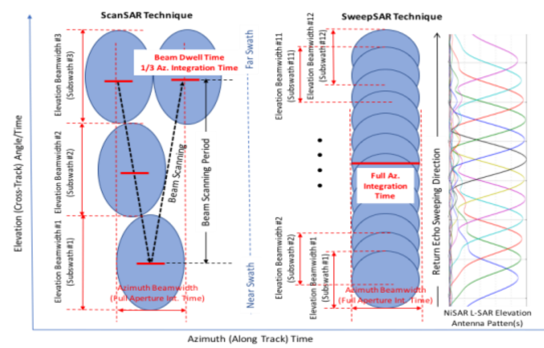

Figure 2: Simplified schematic for ScanSAR beam scanning (left) and SweepSAR subswath (sub-beam) sweeping over arrayed feed unpon return (right). The ScanSAR technique loses azimuth integration time; the SweepSAR technique needs to address overlapping sub-beams by digital beam forming.

Lastly, the long echoes are a concatenation of sub-echoes from subswath illuminated by each overlapped sub-beam in elevation and when the echoes sweep through the arrayed feed, the sub-echoes will be intercepted by more than one radiating element because each sub-beam is overlapped in beamwidth with its neighboring beams, leading to the sub-echoes being received by more than one receive channel at a time, which if combined without the proper phase and weighting would lead to loss of signal level (losing sensitivity) in the overlapped portions of the subswaths. NISAR implements a digital beam forming scheme to rectify the overlapped subswath echoes received by neighboring receive channels and sum them up coherently [7][14].

III. SIR-C L-SAR AND NISAR L-SAR ANTENNA TECHNOLOGY COMPARISON

The most obvious technology difference of SIR-C and NISAR L-band SAR systems is the antenna subsystem: SIR-C uses an active phased array antenna whereas NISAR uses an offset reflector with an arrayed feed. In the early study phase of the mission, JPL commissioned an independent assessment of implementation risk and cost effectiveness of using an active phased array antenna vs. a reflector with arrayed feed, factoring in technology availability. The independent study corroborates the JPL internal study conclusion that a reflector with array feed is the more attractive technology available for both implementation risk and cost.

The SIR-C L-band active phased array antenna consists of 2 (elevation) x 9 (azimuth) panels to form a 3.0m (elevation) x 12.0m aperture [5][6], shown with radar electronics in Figure 3. Each panel consists of 9 sticks of dual polarization radiating elements on the surface, and, for each polarization, 7 T/R modules plus phase-shifters and weighted microstrip feeds, providing beam steering and additional beam tapering. Additional coax corporate feed (two for each polarization and one for panel internal testing.) connecting the panels to form a full aperture and interfacing with the radar drive/receive electronics.

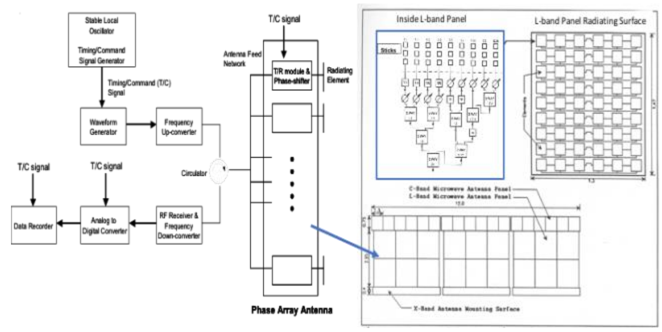

Figure 3: SIR-C L-SAR planar active phased array antenna configuration (right) and radar electronics functional block diagram (left). From [6].

The whole antenna contains many more T/R modules than the NISAR feed with more complicated feed networks, but offers (1) azimuth (along track) steering capability (for Spotlight SAR mode demonstration which NISAR is not required), (2) in-panel panel test monitor capabilities (which NISAR L-SAR does not implement), and (3) system performance that is less susceptible to T/R module failures.

The NISAR off-set Reflector with Array Feed Antenna include a 12m (diameter) offset light weight reflector, ~9m boom (when deployed) and an ~2m arrayed feed consisting of 2 (azimuth) x12 (elevation) dual polarization radiating elements arranged as 6 tiles mounted on a support structure [6]. A functional representation or the radar system is shown in Figure 4. To compare with SIR-C planar active phased array antenna system, the T/R modules must be included. As shown in Figure 4, there are 12 H-pol T/R modules and V-pol T/R modules connected to the arrayed feed, each H-V paring of T/R modules connecting to each of the 12 dual-pol radiating element forming a dual-pol sub-beam upon reflecting from the reflector.

With this antenna architecture, it is relatively easy to share a single reflector between both radar instruments, just adding another array feed at that radar frequency, which is exactly what NISAR has done, having an S-band array feed mounted on the same feed structure sharing the same reflector. This is, arguably, the most advantageous of this antenna architecture over the planar active phased array architecture, and is the enabler of NASA and ISRO collaboration [4]. Due to the use of fewer T/R modules, in comparison to the number of T/R modules used in planar active phased array antenna, this architecture provides much saving in mass and complexity in RF signals distribution.

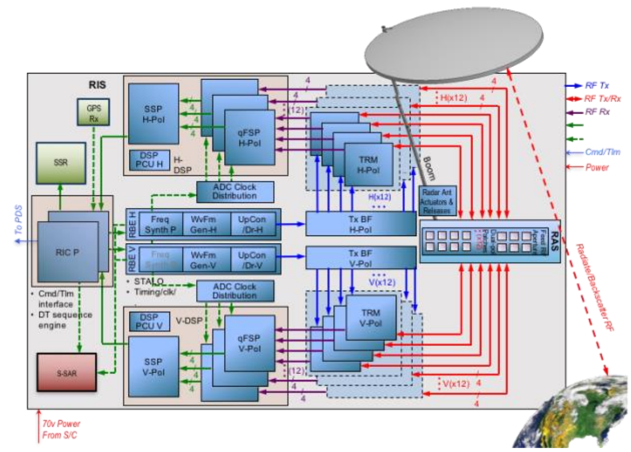

Figure 4: NISAR L-SAR Functional Block Diagram, showing the antenna subsystem consists of the 12m reflector, ~9m boom, ~ 2m 12-subbeam L-band Feed, and, to compare with SIR-C antenna.

However, the use of fewer T/R modules, one for each sub-beam, makes the system more vulnerable to T/R module failure, losing one T/R module will significantly reduce the SNR over one sub-swath, or for L-SAR case, 1/12th of the full swath. The antenna system, unlike SIR-C antenna, also does not have azimuth steering capability, and because the arrayed feed is laid out, only the radiating element of center sub-beam is close to the focal point of the offset reflector, all other sub-beams are off focal point. This has some effect on sub-beam efficiency with the center sub-beam having slightly better gain than those off centered sub-beams. To support dual frequency implementation, the lateral separation of the L-band feed and S-band feed leads to the L-SAR beam and S-SAR beam squinted slightly in azimuth (along-track) in the opposite direction of the azimuth mechanical boresight. Lastly the array feed and structure are within the field of view of the reflector, affecting the secondary antenna pattern and efficiency and contributing to multipath interference. The number of sub-beams, spacing between radiating elements, placement of L-SAR feed and S-SAR feed, and minimization of feed blocking effect have gone under numerous iterations and optimization to arrive at the current configuration being implemented.

From the radar equation, SAR system sensitiviy is a multipication of transmit antenna gain (or effecive area), radiated power from the antenna, and receive antenna effective area, with the same given frequency for a given scatterer at a given range. For SAR, the duration of a target exposure to the antenna beam being used for integration (or aperture synthesis) not only providing sharpening the azimuth resolution but also increase the integration gain for the target. For comparison, consider a scatter at the range center of the full swath, at the peak gain of the SIR-C beam and NISAR subbeam. The NISAR 12m reflector aperture area is about 3 times as large of the SIR-C 3mx12m aperature, which means the engergy spread unpon radiation is more concentrated and more energy collected from backscattering, resulting in NISAR system (two-way) ~ 9 times better than the SIR-C system in sensitivity. And SIR-C ScanSAR dwell time in azimuth is only about 1/3 of NISAR SweepSAR azimuth integration time, given that the systems have same azimuth beamwidth. So from an aperture size and usage viewpoint, the NISAR SweepSAR system is a factor of ~27 (~14dB) better over SIR-C ScanSAR-operated systerm in sensitivity over that target. Furthermore, for the sensitivity of the SIR-C ScanSAR-operated system peaks over the target at the electrical boreight of the beam and graduadually reduces until the 3dB point of the elevation pattern, after which the beam moves to the next subswath (which creating the scalloping effect in the image between subswath before antenna pattern correction), whereas NISAR SweepSAR system designs the antenna to illuminate the entire swath uniformly (with overalapping sub-beams) and uses digital beam forming to regain the sensivity in the overlap between subswath (with overall, not having the scallopped effect across track). This can account for the NISAR SweepSAR sensitivity being better over off-peak subswath than SIR-C ScanSAR, as much as a factor of ~4 (~6dB) for the target at the edge of the subswath. However, for the peak of each subswath, SIR-C ScanSAR-operated system bears nearly the whole power from the the T/R modules (4,400W) to the target, while NISAR SweepSAR would be the power from a single T/R module (120W). So from the transmit power aspect, the SIR-C ScanSAR-operated system is a factor ~35 (~15dB) better than the NISAR implementation. With the above "crude" compartive estimate, not counting the efficiency and loss of the antenna systems, of sensensity contributing factors using the system's parameters of both systems, that the NISAR ScanSAR system has a bigger aperture and full integration time of the azimuth aperture than the SIR-C system, but less transmit power illuminating the subswath, we conclude that the NISAR system senstivity is ~1dB lower than the SIR-C system at the peak antenna gain over the subswath but gets better toward the edge of the subswath and becomes 5dB better at the far edge of the SIR-C subswath. Over the entire swath, the NISAR system can be ~ 3dB, on the averge, more sensitive than SIR-C system, if flown at the same altitude.

Note the above comparison uses high level system parameters, not by performing a simulation using the acutal antenna patterns or including the efficiency/loss of respective antennas. Also note that for both systems increasing the transmit power for each T/R modules would increase the sensitivity, but how much more transmit power can be achieved may be limited by thermal considerations.

IV. Other NISAR L-band SAR Design and Technology Changes from SIR-C L-band SAR

For the NISAR L-SAR system to have sufficient sensivity, inspite of advantage of the more efficient use of a larger reflector aperture and more azimuth integration time, high power transmit/receive (T/R) modules must be used. The NISAR L-T/R modules employ high density/efficiency GaN devices as the high power amplifier, transmiting as much as 120W peak power to each of the 12 arrayed feed elements per polarization. The L-T/R modules are also designed to include serveral calibration signal routing paths and phase shifters, to allow for monitoring the entire set of T/R module stability and if necessary applying phase adjustment to invidual T/R module to ensure unformity of electrical path of the T/R module sets [11]. The NISAR L-SAR T/R module functional signal routing is shown in Figure 5.

That high power T/R modules feeding into the array feed tiles also requires more careful considerations in the feed tile design, including thermal and multipaction considerations [12].

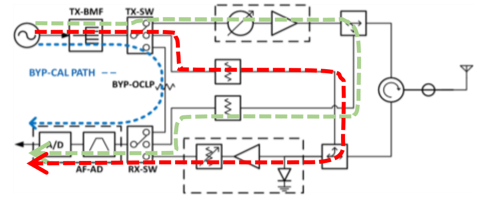

Figure 5: NISAR L-SAR TRM module calibration signal routing: green Tx-Cal, red Rx-Cal, blue Bypass.

Another difference between NISAR L-SAR system and SIR-C L-SAR system is in the receiver front end (after the T/R modules). SIR-C system down converted the received L-band RF signals to an intermediate frequency before the data was digitaized (see Figure 3 of SIR-C system block diagram); whereas the NISAR system does direct digital downconversion of the L-band RF signals from the T/R modules; high speed ADCs inside each Quad-First Stage Processor sample the data at 240MHz and forward it to the FPGA based DSP to perform bandpass filtering and first stage digital beam forming (see Figure 4 of NISAR sysem block digram). Since the RF signals are directly digitized at the front-end of the receiver right after the T/R module receive, the entire receiver chain is a digital procesing system [13], including first stage baseband filtering, calibration estimation, digital beam forming, to second stage digital beam forming, data compression, and data packaging. A digital receivr is considered more stable, more predicable, and more flexible than an analog receiver.

NISAR L-SAR system adds capabilities in (1) transmitting split-spectrum waveforms, transmit two spectrally separated but concatenated pulses, for ionospheric correction and (2) operating in compact-pol mode (by which the SAR system tranmits in right-hand or left-hand circular plarization but receives in veritical and horizontal polarization) and quasi-Quad pol mode (by which the H-transmit and V-transmit are in different chirp bandwidth). These are new capabilities that SIR-C L-SAR system had not implemented.

V. Other Issues of using Reflector+Arrayed Feed Antenna

While using a reflector with arrayed feed for SweepSAR techinque has several advantages, it does have some drawbacks at flight system level, in comparision to a direct radiating planar active phased array antenna. Below is the list of these drawbacks as we have learned from current NISAR implementation:

(1) The antenna subsystem structure, including the reflector, boom and arrayed feed structures, is more susceptable to thermal-eleastic distortion antenna optical geometry, affecting antenna pattern and pointing long-term stability.

(2) The arrayed feed structure directly within the field of view of the reflector not only reduces the efficiency of the antenna but also induces more multipaths which may contribute to additional ambiguty and noise in SAR performance.

(3) High power near-field radiation from high power T/R modules transmitting thru the L/S-feeds directly, or reflected by the reflector/boom structure, may impose the flight system electronics to needing better EMI protection.

(4) The antenna structure (reflector and boom) would be exposed to high power dual frequency radiation when L-SAR

and S-SAR simultaneous transmitting out of the feeds, possibly inducing passive intermodulation products which may affect other non-radar electronics performance.

(5) The 12m reflector once deployed will block some S/C sensors's field of view, needing reorient or relocation those sensors.

(6) The antenna system during and after deployment is a cantilever system mechanically, which can be more demanding on the spacecraft's attitude control capability to maintain pointing stability.

These drawbacks have minor effects on SAR system performance; they are more flight system configuration issues. The NISAR team has addressed all these drawbacks.

VI. Summary

The NISAR L-SAR system, by adopting SweepSAR technique, choose to implement a reflector with arrayed feed antenna that departs from the conventional planar phased array antenna used by SIR-C L-SAR system and other spaceborne SAR systems that uses ScanSAR for wideswath imaging. This article, by comparing SIR-C implemention of ScanSAR and NISAR implemenetation of SweepSAR, shows the differences in design considerations and technology usages. For a mission that just requires wideswath imaging, the NISAR SAR system proves to be more efficient and more effective having better sensitivity by comparing SIR-C system paramters operated in ScanSAR mode and NISAR system parameters for SweepSAR technique, if both systems are flown at the same altitude. But NISAR requires higher power T/R modules and feed to handle higher power and it complicates the radar receiver design and puts a higher demand on on-board processing throughput. Furthermore the presence of the reflector with feed can pose as drawbacks in affecting other flight hardware adversely, for which mitigation would be required and for which NISAR teams have addressed.

Acknowledgment

The authors would like to thank SIR-C and NISAR system design teams at JPL whose design and technology utlization for these two radar systems are included in this paper. The authors were members of SIR-C implementation team and members of current NISAR design and implementation team. As the NISAR SAR design stems from a NASA/DLR joint DESDynI/Tandem-L Mission Study, the authors would like to acknolwdge DLR team members of the study team for their contribution to the architectural concept and early design specifications. This paper was prepared at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the U.S. National Aeronautics and Space Administration.

References

[1] R. L. Jordan, B. L. Huneycutt, and M. Werner, "The SIR-C/X-SAR Synthetic Aperture Radar System," IEEE Transactions on Geoscience Remote Sensing, vol. 33, no. 4, pp. 829-839, July 1995.

[2] R. Jordan, "The Seasat-A Synthetic Aperture Radar,", *Special Issue on the SEASAT-1 Sensors*, IEEE Journal of Oceanic Engineering, Vol. OE-5 Nr. 2. April 1980, pp. 154-164.

[3] A. Freeman, G. Krieger, P. Rosen, M. Younis, W. Johnson, S. Huber, R. Jordan, A. Moreira, "SweepSAR: Beam-forming on receive using a reflector-phased array feed combination for spaceborne SAR," Proc. Radar Conference 2009, Pasadena, CA.

[4] P. Rosen, Y. Kim, H. Eisen, S. Shaffer, L. Veilleux, S. Hensley, "A Dual-Frequency Spaceborne SAR Mission Concept," Proc. IEEE IGARSS 2013, Melbourne, Australia, pp. 2293-2296, 2013.

[5] B. Huneycutt, "Spaceborne Imaging Radar – C," IEEE Transaction on Geo. Sci. and Remote Sensing, Vol. 27, No. 2, pp. 164-169, March 1989.

[6] Y. Kim and R. L. Jordan, "Spaceborne SAR Antennas for Earth Science," Chapter 6 in *Spaceborne Antennas for Planetary Exploration*, edited by W. Imbriale, Wiley Interscience, 2006.

[7] G. Krieger, N. Gebert, M. Younis, F. Bordoni, A. Patyuchenco, A. Moreira, "Advanced Concepts for Ultra-Wide-Swath SAR Imaging," EUSAR 2008, pp. 31-34, Friedrichshafen, Germany, 2008.

[8] G. Krieger, M. Younis, N. Gebert, F. Bordoni, A. Patyuchenco, A. Moreira, "Advanced Concepts for High Resolution Wide-Swath SAR Imaging," EUSAR 2010, pp. 524-527, Anachen, Germany, 2010.

[9] M. Vilano, G. Krieger, and A. Moreira, "Staggered SAR: High Resolution Wide-Swath Imaging by Continueous PRI Veriation,", IEEE Trans. GEosci. Remote Sensing, Vol. 52, No. 7. Pp. 4462-4479, July 2014.

[10] N. Chamberlain et al., "The DESDynI Synthetic Aperture Radar Array-Fed Reflector Antenna," 2010 IEEE International Symposium on Phased Array Systems and Technology Proceeding, pp. 381-386 , Walham, MA.

[11] J. Hoffman, "High-Efficiency, Digitally Calibrated TR Modules Enabkubg Lightweight SweepSAR Architectures for DESDynI-Class Radar Instruments," NASA Earth Science Technology

[12] P. Focardi, P. R. Brown, "NISAR L-Band Feed Antenna Tiles, Preliminary Design," 2016 IEEE International Symposium on Antennas and Propagation (APSURSI) Proceeding, pp. 1379-1380, Fajardo, Puerto Rico.

[13] C.-L. Chang, S. Shaffer, N. Namsuwan, S. Li, C. Lin, V. Duong, B.Volain, K. Vines, M.-W. Yan, K. Wheeler, "NISAR L-band Digital Electronics Subsystem–Multichannel System with Distributed Processor for Digital Beam Forming and Mode Depent Filtering," IEEE Radar Conference, Philadelphia, 2016.

Yuhsyen Shen received his Ph.D. in electrical engineering from the University of Pennsylvania in May 1987 and joined JPL Radar Science and Engineering Section in June 1987. Since then he has served in technical leadership positions and program/project management positions at JPL. Most of the positions are with radar-related projects, including Airborne SAR, SIR-C/X-SAR, SRTM/X-SAR, CloudSat, AQ/SAC-D, and most recently RapidScat on ISS. He also served as deputy program manager/systems engineering manager for NASA's Deep Space Network and deputy division manager for JPL Communications, Tracking and Radar Division, during which time he got involved in space telecom network systems engineering and oversaw flight telecom subsystem implementation. He was JPL DESDnyI/Tandem-L Study Lead and since 2013 he has been NISAR Project chief engineer at JPL.

Scott Shaffer received a B.S. degree in electrical engineering from the University of California, Davis in 1984, and a M.S degree in the same field from the University of California, Los Angeles in 1986. Since joining the Jet Propulsion Laboratory, Mr. Shaffer has worked on numerous airborne and spaceborne radars including Magellan, SIR-C, SRTM, UAVSAR, and Cassini. He was also the cognizant engineer for the landing radars on Pathfinder, MER, and Phoenix. Since 2013, he has been lead systems engineer for the NISAR DSI/L-SAR System.