NASA L-SAR Instrument for the NISAR (NASA-ISRO) Synthetic Aperture Radar Mission

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ABSTRACT

The National Aeronautics and Space Administration (NASA) in the United States and the Indian Space Research Organization (ISRO) have partnered to develop an Earth-orbiting science and applications mission that exploits synthetic aperture radar to map Earth's surface every 12 days or less. To meet demanding coverage, sampling, and accuracy requirements, the system was designed to achieve over 240 km swath at fine resolution, and using full polarimetry where needed. To address the broad range of disciplines and scientific study areas of the mission, a dual-frequency system was conceived, at L-band (24 cm wavelength) and S-band (10 cm wavelength). To achieve these observational characteristics, a reflector-feed system is considered, whereby the feed aperture elements are individually sampled to allow a scan-on-receive ("SweepSAR") capability at both L-band and S-band. The instrument leverages the expanding capabilities of on-board digital processing to enable real-time calibration and digital beamforming. This paper describes the mission characteristics, current status of the L-band Synthetic Aperture Radar (L-SAR) portion of the instrument, and the technology development efforts in the United States that are reducing risk on the key radar technologies needed to ensure proper SweepSAR operations.

Keywords: Radar, beamforming, SAR, NISAR, SweepSAR, L-SAR

1. INTRODUCTION

The proposed L-SAR instrument for the NISAR mission concept was endorsed in 2007 by the United States' National Academy of Sciences as a Tier 1 mission that is essential for the study of earth science over the coming decades. At that time, this mission was dubbed DESDynI (Deformation Ecosystem Science and Dynamics of Ice) and was a combined L-SAR and LIDAR (Light Detection and Ranging) mission. The mission was refocused as a SAR-only concept, and this L-SAR instrument successfully passed its Mission Concept Review (MCR) gate and is currently in Phase B development.

Phase A studies focused on technological risk reduction and mission concept modeling. Now in Phase B, key elements of the radar electronics are being prototyped and tested as full instrument requirements are being finalized.

At the core of the proposed L-SAR instrument would be a highly capable L- band SAR system. This SAR would ride on a dedicated, high power, precisely pointed spacecraft capable of high downlink rates, which would be provided by ISRO—the Indian Space Research Organization. L-SAR would fly in a repeatable orbit with short revisit times of 12 days or less, depending on location. The frequent SAR observations would be combined via interferometric processing to detect changes in various physical properties, which are discussed next. By analyzing interferometric observations over several years, randomly varying measurement errors are drastically reduced and very small changes become detectable. Polarimetric capability enables additional scientific observations, including estimates of biomass. ISRO is providing the S-SAR, or S-band Synthetic Aperture Radar, for the proposed joint mission.

This joint mission has a proposed launch date in 2020.

2. SCIENCE OBJECTIVES

The Earth's surface changes on very rapid scales and human interaction with our environment and ecosystems has had noticeable effects on the carbon cycle, such as melting of the ice caps and global climate change. These changes are not currently tracked continuously and some changes cannot be detected on the small scales available from current technologies being deployed on the ground or from space. DESDynI L-band SAR, now NISAR's L-SAR, was recommended by the National Academy of Sciences in 2007 [2] to address all of the above. The NISAR mission would

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contribute to our understanding of processes that drive changes in five areas: 2-D Solid Earth Displacement; 2-D Ice Sheet & Glacier Displacement; Sea Ice Velocity; Biomass & Disturbance; Cropland, Inundation Area.

The key science questions to be investigated by NISAR [2]:

- Dynamics of Ice: Ice sheets, Glaciers, and Sea Level
  - Will there be a catastrophic collapse of the major ice sheets, including Greenland and West Antarctic and, if so, how rapidly will this occur?
  - What will be the resulting time patterns of sea-level rise?
  - How are alpine glaciers changing in relation to climate?
- Ecosystems and Biomass Change
  - How do changing climate and land use in forest, wetlands, and agricultural regions affect the carbon cycle and species habitats?
  - What are the effects of disturbance on ecosystem functions and services?
- Solid Earth Deformation: Hazard Response
  - Which major fault systems are nearing release of stress via strong earthquakes?
  - Can we predict future eruptions of volcanoes?
  - What are the optimal remote sensing strategies to mitigate disasters and monitor/manage water and hydrocarbon extraction and use?
- Coastal Processes: India
  - What is the state of important mangroves?
  - How are the Indian coastlines changing?
  - What is the shallow bathymetry around India?
  - What is the variation of winds in India's coastal waters?
- In order to achieve near-global coverage and short repeat intervals, the swath of the instrument must be quite wide. DSI would achieve swaths greater than 200 km, using a new technique called SweepSAR, described in the following section and in much more detail in [3,7]. To estimate biomass and biomass changes (Ecosystems Structure), DSI would require polarimetric radar measurements [7]. This would require DSI to transmit and receive on orthogonal polarizations, which complicates the radar design, due to increased azimuth ambiguities, increased demands on the hardware, since dual-pol Transmit-Receive Modules (TRMs) and dual-pol antenna feeds are required, as well as significantly increases the data processing and downlink data rates, due to the additional polarization's data. Much higher accuracy of the radar's amplitude response is also required in order to derive the biomass from the polarimetric returns.

3. L-SAR INSTRUMENT

The instrument concept hinges on the challenging requirements of measuring solid earth deformation on the order of 1 mm/year, glacial displacement on the order of 100mm over sub-annual sampling periods, approximately 100m/day sea ice velocity, biomass estimates on the order of 20 Mega-grams per Hectare (Mg/Ha), and approximately 80% classification accuracy of disturbance and crop, inundation areas. To address these challenges within realistic budgetary goals, an L-band SweepSAR concept was developed. L-SAR's SweepSAR conceptual drawing is shown Figure 1.

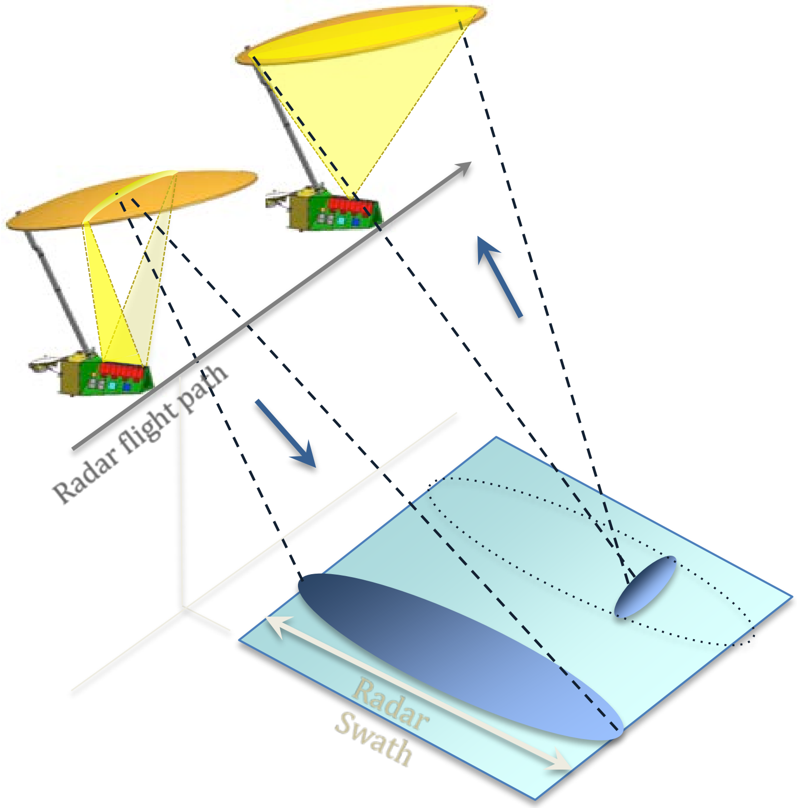

Figure 1 SweepSAR scan-on receive technique is implemented using an array-fed reflector antenna, which enables wide swath operation with high resolution [3,7].

On transmit, the array elements are aligned in phase, which focuses the beam and sub-illuminates the reflector, as shown in the left spacecraft drawing of Figure 1. This produces a wide beam on the ground, enabling imaging of a very wide region. If such as beam were to be used on receive, however, it would lead to radar returns from to wide of a region to discriminate properly, or range ambiguities. To avoid this, each array element independently digitizes the radar return. A single element illuminates the entire reflector, which produces a smaller swath on the ground. Each array element is sensitive to a different portion of the transmitted swath, and each does not suffer the same extent of range ambiguities. The benefit of this architecture is that it can image a very wide swath, without excessive range ambiguities, and without building a massive 12-meter by 12-meter phased array. This architecture does require onboard beamforming, which presents challenges in the digital processing and data rates, as well as imposes unique challenges on the onboard calibration system.

The independent channels must each be aligned in phase and amplitude in order to be beamformed properly, and due to constraints on downlink bandwidth, this beamforming must be accomplished on-board. Since the amplitude and phase information of each element is lost in the beamforming process, the calibration must also be performed onboard. Therefore, each channel's transmit and receive paths must be calibrated onboard and in near real-time. Fortuitously, this can be accomplished since each channel is already independently digitized. By taking advantage of this, and of advances in high speed digital processing, each channel's phase and amplitude, during transmit and receive, can be independently estimated and corrected.

3.1 L-SAR Concept Design and Trades

DSI would take advantage of SweepSAR techniques that enable wide swath operation without sacrificing resolution, unlike other SAR techniques, such as ScanSAR. DSI is still in the planning stage of instrument design and trade-studies.

3.2 L-SAR Array-Fed Reflector Subsystem

Conventional SAR systems trade resolution for swath and are unable to satisfy both requirements of wide swath and high resolution. The limiting factor is usually the large antenna dimension required. Digital Beam Forming SAR (DBF SAR) techniques have been developed to overcome some of these limitations, however they have usually been aimed at smaller wavelength systems (C-, X- and Ka-band) and while these are very useful at higher frequencies, they do not lend themselves easily to lower wavelength applications [4].

A unique adaptation of the technique discussed in [4] has been made for longer wavelength antenna systems, such as L-band, where a reflector antenna is fed by a one-dimensional array feed [1,8] as shown in Figure 1. During transmit events, all of the feed elements illuminate the reflector resulting in a wide beam being formed while during receive only a subset of the feed elements are active, which produces a narrower beam. Due to the geometry of the antenna to the illuminated scene, the return signals 'sweep' through elevation, illuminating only a subset of receivers. This makes use of a larger area of the reflector on receive, increasing gain. On receive the signals from different beams are combined digitally on-board the instrument after passing through the Transmit Receive Module.

The proposed antenna system for DSI is an array-fed reflector of up to 13 m in diameter depending on the volume and mass that will be constrained by basic launch vehicle payload fairing dimensions.

3.3 L-SAR Transmit/Receive Modules

The array feed elements are fed by Transmit Receive Modules (TRMs) that distribute and amplify the L-band signal to form the transmit beam. On receive the backscattered echoes are filtered and amplified by the TRMs before being digitized independently and subsequently recorded.

Since the transmit signals must combine coherently at the reflector means that the TRMs need to have very stable transmit phase and amplitude properties and need to be able to compensate for systematic changes that would significantly affect the gain of the transmitted signal. On the other hand since the Digital Beamforming is occurring in real-time on- board the instrument it is essential to have accurate knowledge of system's behaviour at short time-scales.

At times where accurate knowledge of the system's characteristics are required at very short-time scales for operation, the traditional calibration techniques, which either utilize temperature sensors strategically placed at thermally dynamic spots or sample and downlink a copy of the transmitted waveform, become unusable. The temperature sensors cannot provide information on short-time scales or on drifts unrelated to temperature changes, while the downlink and on-board storage capacity of a multi-TRM system make it technologically challenging to process frequent updates of the waveforms on all TRMs. To overcome these issues, digitally calibrated TRMs were proposed where both the transmit and receive knowledge of each TRM state can frequently be monitored on-board and updated as necessary.

The concept of the digitally calibrated TRMs is depicted in Figure 2.

The digital subsystem in this case is an integral part of the TRM closing the loop on acquiring the knowledge of the system state and being able to control the TRMs to a different state in order to ensure proper beam steering [6].

3.4 L-SAR Digital System Calibration

Digital calibration is a relatively novel solution for monitoring and operating a multi-TRM system and is an integral part of the DSI operation. It closes the control loop for transmit phase and amplitude stability while it also produces estimates of the receive chain's gain and phase changes throughout mission lifetime.

The integrated TRM and digital subsystem comprise a full digital calibration loop (see Figure 2), where the TRM responds to controls fed from the digital calibration to adjust its transmit characteristics while the digital subsystem constantly updates the present state of the RF module in its DBF coefficients' estimates. This makes for a highly adaptable and autonomous digital/RF design that provides knowledge of the system within tenths of dBs/degrees and control capabilities of approximately 1 dB in power and a few degrees in phase (limited by flight-qualified hardware capabilities).

3.5 SweepSAR Airborne Technology Demonstration

The SweepSAR technology was demonstrated in the first airborne implementation of the technique using a Ka-band architecture. A frequency scaled instrument was used to allow for the reflector, which is a required component of

SweepSAR, to fit in an aircraft instrument bay. A system with 8 receive and one transmit channel was built to emulate proposed SweepSAR DESDynI technique using scaled geometry [5,9].

The airborne system was deployed from a NASA DC-8 aircraft and flown over Edwards AFB, where corner reflectors were deployed for instrument calibration and over urban Palmdale area.

Digital Beamforming was performed in non-real time environment due to limitations of the existing hardware. An image from this demonstration is shown in Figure 3.

Figure 3. SweepSAR airborne demo, beamformed image of area of the lake bed with corner reflectors.

The data collected over 12 flight lines is an invaluable resource that will be used in evaluation and demonstration of the real-time digital processing algorithms.

4. SUMMARY

The proposed DESDynI SAR Instrument is expanding the trade-space of radar instrument concepts and pushing the boundaries of high-level integration of digital and RF subsystems in order to achieve very precise assessments of system's behaviour.

DESDynI mission concept would provide continuous science measurements that would greatly enhance understanding of geophysical and anthropological effects in three science disciplines. Trades in instrument architecture implementations and partnership discussions are producing a set of options for science community and NASA to evaluate and consider implementing late in the decade.

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