Instrument Commissioning timeline for NASA-ISRO Synthetic Aperture Radar (NISAR)

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Abstract— **The NASA-ISRO Synthetic Aperture Radar (NISAR) is a joint collaboration between NASA and India's national space agency, the Indian Space Research Organization (ISRO). This Earth-orbiting radar mission, which will be launched from Sriharikota (India) in December 2021 in a near-polar, sun-synchronous orbit, is designed to systematically and globally study solid Earth, ice masses, and ecosystems.**

Following NISAR's launch, the first 90 days will be dedicated to performing 'in-orbit checkout', or the 'commissioning' period, during which there will be a step-by-step buildup in capability to full observatory operations. Activities performed during commissioning will be aimed at demonstrating the full functionality of the radar instruments (L-band and S-band), the reflector antenna, spacecraft and flight systems, characterizing and confirming their nominal performance within specifications. All ground systems and infrastructure, including Ground Data Systems (GDS), Science Data Systems (SDS) and Mission Operations Systems (MOS), as well as the compatibility of all system interfaces, will be tested and validated. Calibration strategies for monitoring instrument stability will be tested during initial instrument calibrations.

The scheduling of these initial instrument calibration activities takes into account factors like the satellite orbit and attitude after launch, requirements on specific instrument configurations for operation, required ground targets and the corresponding number and frequency of overflight times during a satellite repeat cycle (12 days). A timeline for NISAR instrument checkout that takes into account these factors and constraints is presented in this paper.

TABLE OF CONTENTS

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1. INTRODUCTION

The mission concept for the NASA-ISRO Synthetic Aperture Radar (NISAR) is derived from the DESDynI-Radar mission (Deformation, Ecosystem Structure and Dynamics of Ice), which was one of the four Tier 1 missions recommended by the National Research Council (NRC) in the 2007 Earth Science Decadal Survey [1]. NISAR will be launched on ISRO's GSLV Mark-II launch vehicle in 2021 in a near-polar, sun-synchronous orbit, and will be carrying two radar instruments: NASA's L-SAR (L-band SAR, 24 cm wavelength) and ISRO's S-SAR (S-band instrument, 12 cm wavelength). The radars will employ a SweepSAR technique to attain a large swath (> 240 km) for global data collection via a repeat orbit of 12 days in duration [2]. The main objective of the NISAR mission is to enable studies of the *causes* and *consequences* of land surface change on Earth. Multiple scientific and applications disciplines will benefit from and utilize data from this mission, including solid Earth deformation, ecosystems, cryospheric studies, natural disasters and hazard assessment [3, 4]. The NISAR flight project entered Phase C (implementation phase) in August 2016.

In-orbit checkout or commissioning is one of the key critical phases in the early lifetime of any mission. This period usually occurs right after launch and early operations for Earth science missions, and after planetary orbit insertion for deep space missions. This phase allows operations teams to power on spacecraft and payload components for the first time, characterize and calibrate their performance, transition the observatory from initial injection orbit after launch to the final science orbit through orbit-raising and correction maneuvers, and in general, prepare the observatory in space and all ground systems for collecting science data during nominal operations.

The commissioning phase for NISAR is divided into four sub-phases, starting with 'Initial Checkout', during which spacecraft and flight engineering systems will be powered on and calibrated. This will be followed by the 'Reflector Boom Assembly (RBA) Deployments' sub-phase. 'Spacecraft checkout' will follow the RBA deployment, during which the GPS subsystem will be turned on, and orbit-raising maneuvers will be executed to transfer the observatory from the initial injection orbit after launch to a science-like orbit (within 5-10 km of the NISAR Reference Science Orbit (RSO)). The final sub-phase of commissioning will be 'instrument checkout' during which the observatory will reach the RSO, both the L-SAR and S-SAR instruments will be powered on, and their performance will be characterized and calibrated. Figure 1 shows the NISAR observatory, with the components contributed by NASA and ISRO highlighted.

This paper provides an overview of the commissioning timeline for NISAR. The sub-phase of commissioning called instrument checkout, its timeline, strategy to be employed and a plan of all activities required to calibrate the two radar instruments on NISAR, will be described in detail and are the main focus of this paper. Out of a total of 90 days assigned for NISAR commissioning, 66 days will be allocated to checkout of the L-SAR and S-SAR instruments onboard the spacecraft.

Section 2 of this paper outlines the overall mission timeline and phases currently planned for NISAR. The commissioning timeline for NISAR is the focus of Section 3, with each of the sub-phases briefly described, along with a comparison of commissioning durations with key Earth-orbiting radar satellites. Section 4 provides an in-depth discussion of the instrument checkout sub-phase and factors affecting development of its timeline. The current baseline timeline for instrument checkout during commissioning is also presented in Section 4. Finally, Section 5 summarizes the results presented in this paper.

2. NISAR MISSION TIMELINE

Four mission phases have been defined to simplify description of the different periods of activity during the NISAR mission. These phases are: launch, commissioning, science operations, and decommissioning. Epochs may be referred to with respect to the date and time of launch as "L+" or "L-" for time periods either after or prior to the time of liftoff respectively. Figure 2 and Table 1 provide a high-level overview of the NISAR mission timeline and the different phases.

Launch Phase

The NISAR Observatory will be launched from ISRO's Satish Dhawan Space Centre (SDSC), also referred to as Sriharikota High Altitude Range (SHAR), located in Sriharikota on the southeast coast of the Indian peninsula, on the Geostationary Launch Vehicle (GSLV) Mark-II expendable launch vehicle contributed by ISRO. The target launch readiness date is 28 December 2021. The launch sequence encompasses the time interval that takes the observatory from the ground, encapsulated in the launch vehicle fairing, to after separation, and ends with the completion of solar array deployment and the observatory in an Earth-pointed attitude and in two-way communication with the ground. Only components critical to the successful operations and health and safety of the observatory are powered on during this phase.

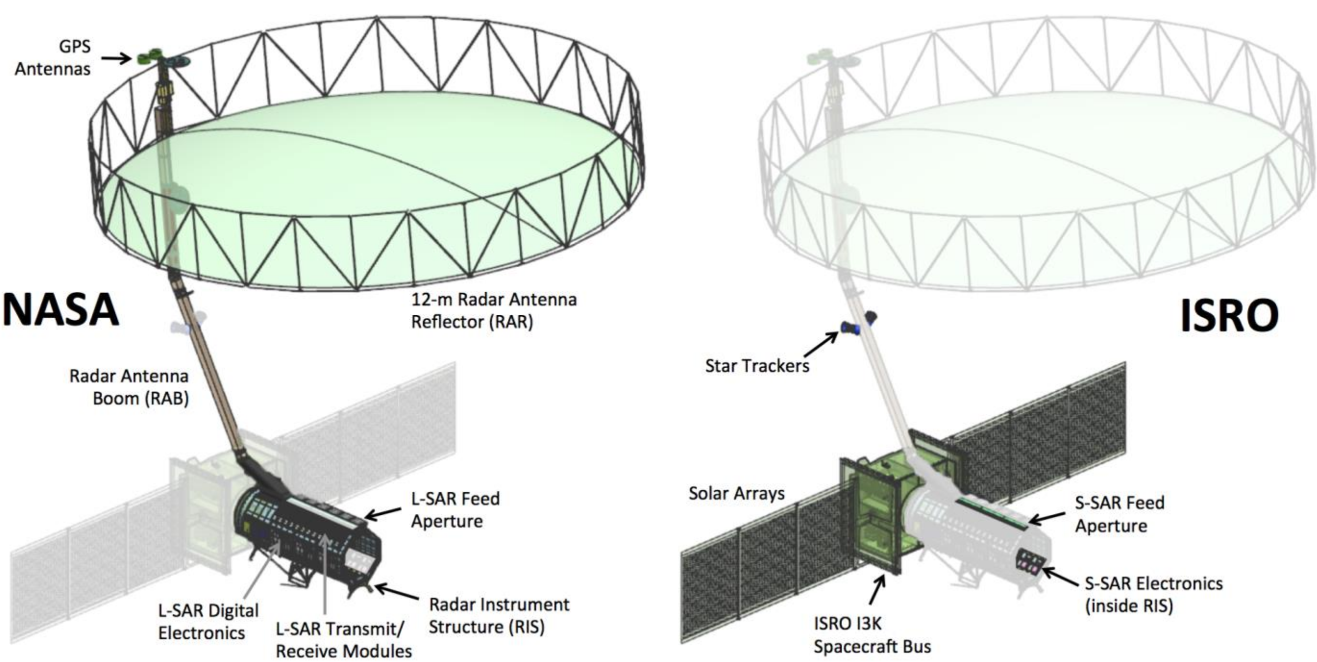

Figure 1. NISAR observatory, with NASA and ISRO contributions highlighted

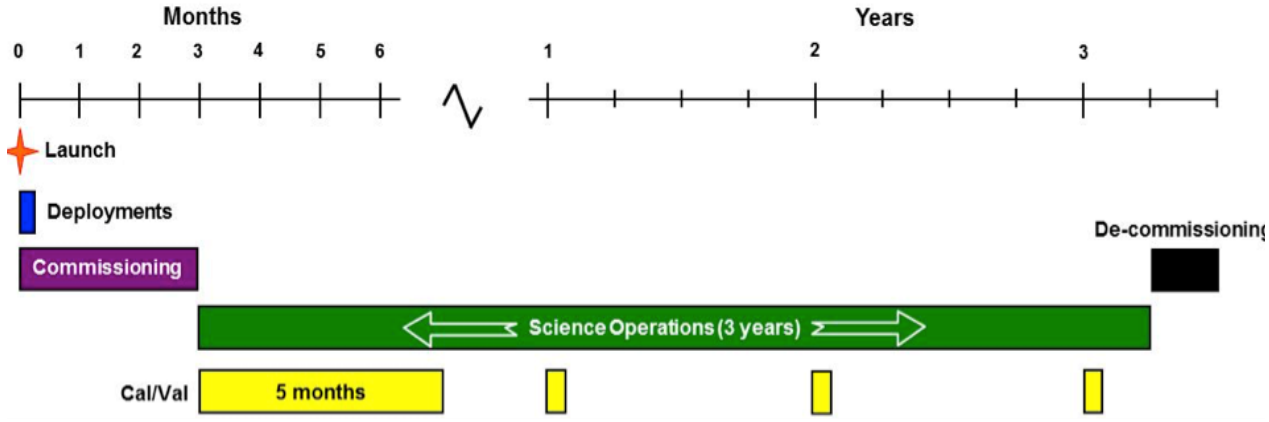

Figure 2. Mission timeline and phases for NISAR

Commissioning Phase

The first 90 days after launch will be dedicated to Commissioning, or In-Orbit Checkout (IOC), the objective of which is to prepare the observatory for science operations. Commissioning is divided into sub-phases of Initial Checkout (ISRO engineering systems + JPL Engineering Payload checkout), Deployments, Spacecraft Checkout and Instrument Checkout. The commissioning phase is described in greater detail in Section 3.

Science Operations

The Science Operations Phase begins at the end of Commissioning and extends for three years and contains all data collection required to achieve the Level 1 science objectives. During this phase, the science orbit will be maintained via regular maneuvers, scheduled to avoid or minimize conflicts with science observations. Extensive Calibration and Validation (Cal/Val) activities will take place throughout the first 5 months, with yearly updates of 1-month duration.

The observation plan for both L- and S-band instruments, along with engineering activities (e.g. maneuvers, parameter updates, etc.), will be generated pre-launch via frequent coordination between JPL and ISRO. This plan is called the “reference mission”; the science observations alone within that reference mission are called the “Reference Observation Plan” (ROP). This schedule of science observations will be driven by a variety of inputs, including L- and S-band ground target maps, radar mode tables, and spacecraft and ground-station constraints and capabilities. This schedule will be determined by JPL’s mission planning team, and the project will endeavor to fly the reference mission which includes these science observations exactly as planned pre-launch (accommodating for small timing changes based on the actual orbit). Periodic updates are possible post-launch which will lead to a new reference mission.

Routine activities performed during science operations phase for NISAR will include Orbit Maintenance Maneuvers, science observation planning and acquisition, data-downlink, continuous pointing of the Solar Array to maximize power, continuous zero-doppler steering of the spacecraft, and periodic yaw-turns to shift from left-looking vs right-looking attitudes to support phases of science observations.

Decommissioning Phase

Decommissioning phase begins after the 3 years of primary science operations have concluded if the mission is not extended. This phase extends for 90 days. NASA deorbit and debris requirements are not applicable for NISAR, however the project must comply with ISRO's guidelines to safely end the mission. ISRO adheres to the IADC Space Debris Mitigation Guidelines, IADC-02-01, Revision 1, September 2007 [5].

3. NISAR COMMISSIONING TIMELINE

The NISAR Commissioning Phase takes place after the Launch Phase, is 90 days in length, and prepares the observatory for science operations. Commissioning is divided into sub-phases of Initial Checkout (ISRO engineering systems + JPL Engineering Payload checkout), Deployments, Spacecraft Checkout and Instrument Checkout. Philosophically, the sub-phases are designed as a step-by-step buildup in capability to full Observatory operations, beginning with the physical deployment of all deployable parts (notably the boom and radar antenna, but not including the solar arrays which are deployed during Launch Phase), checking out the engineering systems, turning on the radars and testing them independently, and then conducting joint tests with both radars operating.

Table 1. NISAR mission phases. L refers to Launch.

Mission Phase	Start Date	Duration	Boundary End State
Launch	December 2021 (L - 24 hours)	1 day + ~40 min	Spacecraft in target orbit, power positive, in two-way communication
Commissioning	L + ~40 minutes	90 days	All systems ready to begin science data collection
Science Operations	L + 90 days	3 years	Mission objectives are complete
Decommissioning	L + 3.25 years	90 days	Spacecraft in disposal orbit and passivated

NISAR's 90-day commissioning period is similar in duration to that of other radar satellites. Table 2 provides an overview of the duration of commissioning and nominal science phase for some key radar Earth science satellites, including SMAP, SRTM, SWOT, ALOS-2 PALSAR-2 and Sentinel-1A. Similar to NISAR, all of these satellites (except SRTM) have a nominal science phase lifetime of a few years, preceded by a commissioning phase that lasted for 85-90 days [6-12]. The exception to this, SRTM, had a commissioning period that was 12 hours in duration, in proportion with the mission's overall lifetime of 11 days. Also, note that although Sentinel-1A's commissioning was originally scheduled for 90 days, it had to be extended for ~2.5 months to satisfy all requirements for SAR instrument calibration.

The entry criteria for beginning Commissioning Phase are:

- Solar Array assembly is deployed
- Spacecraft is in Earth-pointing attitude
- Two-way ground communications have been established
- Power-positive state has been confirmed

The objectives of the Commissioning Phase are:

- Confirm health and functionality of the spacecraft on its free-flying orbit after launch
- Ensure spacecraft reaches Reference Science Orbit (12-day repeat cycle within diamond) safely and maintains the RSO
- Demonstrate full functionality, characterize and confirm nominal performance within specifications for Radar instruments (L-SAR and S-SAR), spacecraft, flight systems, Engineering Payload, Reflector Boom Assembly
- Check operability and compatibility of all system interfaces (between spacecraft, engineering payload, L-SAR & S-SAR payloads, GDS, SDS, MOS)
- Checkout and validate all ground systems (GDS, SDS & MOS) and infrastructure (for command generation, downlink data captures, and downlinked data processing)
- Perform initial instrument calibrations and monitoring instrument calibration stability
- Evaluate adequacy of mission operational capabilities, including staffing and procedures, for science operations

Satisfaction of these objectives is used to define the exit criteria for the commissioning phase.

Figure 3 provides an overview of the commissioning timeline, along with additional details on durations of sub-phases, evolution of spacecraft attitude and orbit during the commissioning phase.

Table 2. Commissioning phase durations for some key Earth-orbiting radar satellites

Mission name	Launch date	Science Phase duration	Commissioning duration
Soil Moisture Active Passive (SMAP) [6,7]	Jan 31, 2015	3 years (planned; currently in science phase)	90 days
Shuttle Radar Topography Mission (SRTM) [8]	February 11, 2000	11 days	12 hours
Surface Water Ocean Topography (SWOT) [9]	April 2021	3 years (planned)	85 days
Advanced Land Observing Satellite-2 (ALOS-2) with PALSAR-2 (Phased Array L-Band Synthetic Aperture Radar) [10]	May 24, 2014	5 years (planned; currently in science phase)	90 days
Sentinel-1A [11,12]	April 3, 2014	7 years (planned; currently in science phase)	90 days (had to be extended by ~2.5 months to finish all SAR calibration tasks)

Initial Checkout

Initial Checkout sub-phase begins right after the end of Launch phase (after launch plus a few hours), from the 2nd orbit, and lasts for 5 days. Prior to the beginning of this sub-phase, the solar arrays must have been already deployed, the spacecraft should be in an Earth-pointing attitude, two-way ground communications should have been established and power-positive state should be confirmed. Beginning of this sub-phase marks the beginning of the Commissioning phase. ISRO Engineering systems (including propulsion, GNC, power, telecom and thermal systems) and JPL Engineering Payload (all components except the GPS, including the Payload Data System, Power Distribution Unit, Pyro Firing Assembly, Solid State Recorder and Ka-band telecom link) are powered on and checked out during this sub-phase, ending with the spacecraft being ready to begin deployments. Pyros are fired within the first few hours of initial checkout to release redundant launch restraints on the Reflector Boom Assembly (RBA) to minimize thermal cycling stress. S-band OD/ tracking will be available after the first 2 days, and will enable Conjunction Monitoring and Mitigation (CMM) analysis and decisions on making Risk Mitigation Maneuvers (RMM) to avoid collisions with other satellites and orbital debris.

Deployments

The main objective of this sub-phase is to deploy the Radar Antenna Boom (RAB) and the Radar Antenna Reflector (RAR) safely and nominally. This sub-phase follows initial checkout and is allocated a total of 5 days, with a subsequent 1 day allocated for RAR detensioning activity, which may follow non-deployment activities such as orbit-raising maneuvers.

Spacecraft Checkout

The Spacecraft Checkout sub-phase starts on day 11 after launch and lasts for 6 days. The GPS (part of the JPL Engineering Payload) is power on and checked out. Repeated testing of the Ka-band telecom link using all ground stations is continued during this sub-phase. Orbit-raising maneuvers are executed to start transitioning the observatory from the initial injection orbit after launch to the Reference Science Orbit (RSO).

Instrument Checkout

The Instrument Checkout sub-phase follows the Spacecraft Checkout sub-phase during the Commissioning phase. It starts on day 17 after launch in the current timeline and continues for 66 days. The main objective of activities performed during this sub-phase is to power on the L-SAR and S-SAR instruments, characterize their performance and carry out initial standalone and joint calibrations for both the instruments. Also, the observatory will achieve the Reference Science Orbit (RSO) through continued orbit-raising maneuvers, followed by orbit-maintenance maneuvers that are performed during this sub-phase.

4. DEVELOPMENT OF INSTRUMENT CHECKOUT TIMELINE

Prerequisites

A number of prerequisites or entry criteria need to be satisfied before beginning checkout of the L-SAR and S-SAR instruments onboard NISAR:

• Spacecraft should be power positive and switches for survival heaters for the instruments should have been enabled (closed)

• Ka-band antenna should be deployed and gimbal performance should be within specifications

• Download of SSR-recorded data should have been established

• GPS should be on and providing GPS clock

• Spacecraft, JPL Engineering payload and Reflector Boom Assembly should be operating nominally, within specifications

• ISRO S-band tracking stations (Bangalore (primary), Lucknow, Biak, Antarctica (Bharati), Mauritius) should be available for instrument checkout communications

• Ka-band stations available for instrument checkout communications should include Alaska (ASF), Svalbard (KSAT), Punta Arenas, ISRO Shadnagar and ISRO Antarctica (Bharati)

• Any open issues in progress (for example, ground station being out of service, incorrect spacecraft attitude, personnel availability conflicts, etc.) should not be in conflict with beginning instrument checkout

Types of instrument checkout activities

The initial activities performed during the first few days of instrument checkout will be focused on initial power-on, functional and interface validation for both the L-SAR and S-SAR instruments. The L-SAR instrument is powered on in stages called standby configurations, which correspond to different power states for the instrument. The instrument power on begins with activation and checkout of the Radar Instrument Computer (RIC) and the RF Back-End (RBE) components. Telemetry from the RIC is monitored to confirm the presence of the 10MHz clock and timing signals, and the Stable Local Oscillator (StaLO) frequency is verified to be stable at the nominal value. Connectivity between the RIC and the SSR is verified. Next, the Digital Signal Processor (DSP, a combination of quad First Stage Processors (qFSPs) and Second Stage Processors (SSPs)) is activated and checked out. DSP self-test datatake is performed, and the same data are also sent to the SSR and downlinked to the ground so a bit-true comparison can be made on the ground with data collected during Integration and Test (I&T). This is followed by activating and checking out the Transmit Receive Modules (TRMs). As part of the TRMs checkout, the RIC collects a number of different types of datatakes, including a Receive-only, Bypass Cal, Low Noise Amplifier (LNA) cal, Receive cal and minimum duration datatake. Next, the Radar transmitter self-test checkout is performed and the TRMs are enabled in groups of 1, 4, 8 and 12 consecutively, to verify good transmit calibration signal for all the TRMs. Engineering telemetry for the instruments and the spacecraft will be monitored at this time, with no science data being collected yet.

Initial power on for the instruments will be followed by a joint health checkout, during which compatibility validation for the two instruments will be performed.

Standalone calibrations will follow the joint health checkout. The L-SAR instrument team has identified 10 types of calibrations that need to be performed. All of these activities are tied to ground calibration targets. Most only take a few minutes of operation but require observation of multiple

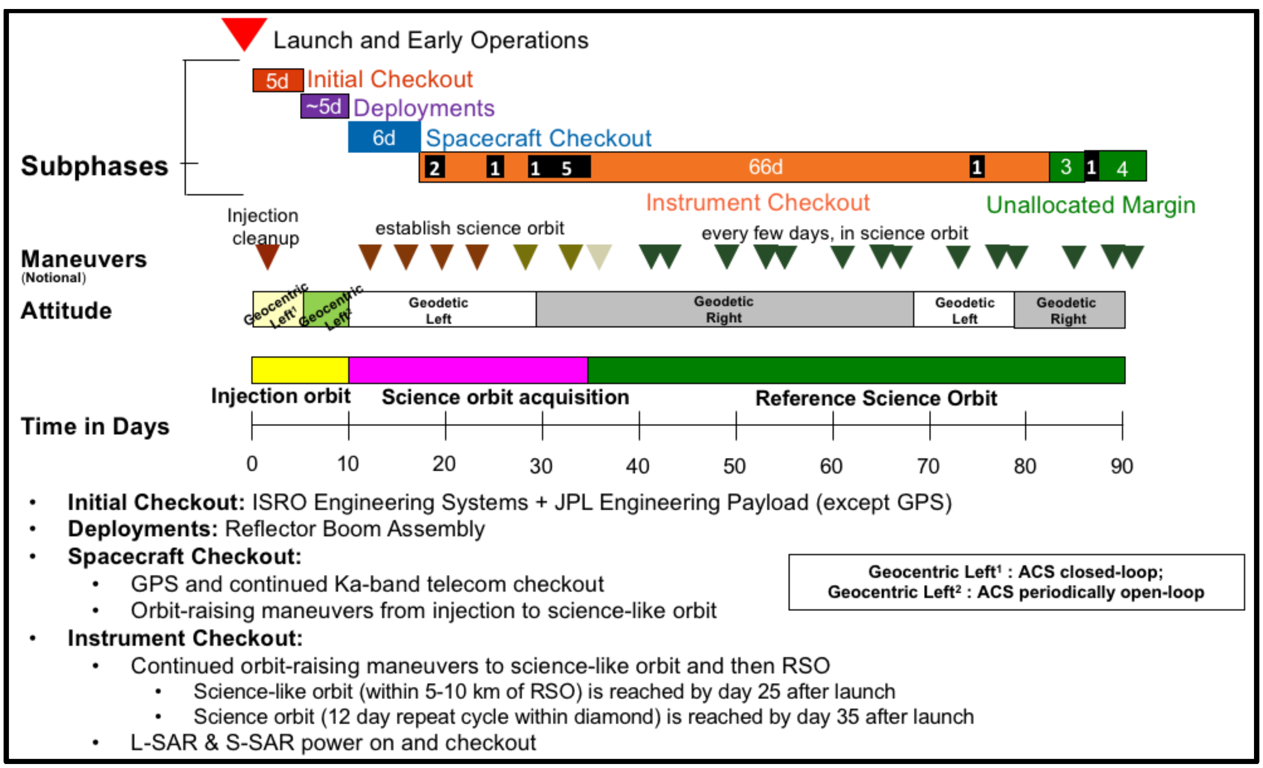

Figure 3. Sub-phases of NISAR Commissioning Phase

ground targets. The 10 types of instrument calibrations can be divided into two categories: calibrations that affect *data collection in space* versus those that affect *data processing on ground*.

The calibrations that affect how the instrument on the spacecraft collects data lead to uplinks of updated instrument parameters to the spacecraft. If available time during commissioning is constrained for any reason, these instrument calibrations must be performed at a minimum during commissioning. These include:

• Thermal noise calibration: Receive only test (skip transmit pulse) to measure power due to background thermal noise and scene brightness temperature variation

• Turning on each prime radar mode for the first time: Checking formatting, data rates, throughput, power, temperatures, etc.

• Digital Beam Forming (DBF) calibration: Calibrate imagery in overlap area between beams by calculating ratio of gain/amplitude of one beam with respect to another

• Antenna pattern verification: Compare ground-based (pre-launch) antenna pattern with antenna pattern observed post-launch by calculating parameters like Peak Gain, Peak Angle, Range and azimuth resolution, Peak Sidelobe ratio (PSLR), Integrated Sidelobe ratio (ISLR)

• Antenna pointing calibration: Measure difference between actual and expected antenna pointing by comparing measured Doppler centroid to expected Doppler centroid

• Time Delay calibrations (common time delay, differential time delay, time tag calibrations): Time delay due to internal electronics; or time delay between different polarimetric channels

The second type of calibrations are those that affect data processing by leading to changes in ground processing parameters. These calibrations can be performed during the 5-month science calibration/validation phase, in case of limited time available during commissioning. These calibrations include:

• Radiometric calibration: Calibrate accuracy with which an image pixel can be related to target scattering characteristics by comparing observed radar cross-section with theoretical/expected radar cross-section

• Cross-talk calibration: Measure channel imbalance (amplitude and phase) between H and V channels on receive and transmit; Leakage of co-polarizations into cross-polarizations is measured

• Polarimetric phase calibration: Measure co-polarization and cross-polarization channel imbalance

• Geometric calibration: Calibrate accuracy with which the position of an image pixel can be registered to an Earth-fixed grid, by measuring location and spatial resolution of point targets in geo-coordinates versus radar coordinates

• Split-spectrum calibration: Determine correction to be applied for ionospheric effects (by measuring Total Electron Content (TEC))

The standalone calibrations will be followed by a period of joint calibrations during which joint modes that utilize both the L-SAR and S-SAR instruments will be exercised and tested.

Spacecraft orbit and attitude considerations

The NISAR baseline orbit was selected to satisfy scientific and programmatic requirements, and has the following characteristics: 747km altitude, 98.4 degrees inclination, sun-synchronous, near-polar, dawn-dusk (6 PM ascending node), and a total repeat cycle of 173 orbits in 12 days. NISAR's 747-km altitude orbit consisting of 173 orbits/cycle will allow for global coverage every 12 days.

During science operations, NISAR will fly within a diamond-shaped orbital corridor defined for each of the repeat cycle’s 173 orbits and tied to the rotating Earth [13]. This corridor is defined to enable accurate correlation of science observations from pass-to-pass and cycle-to-cycle, supporting assessment of changes in the science targets. The dimensions of the diamond were calculated as an upper bound on acceptable error produced by a non-zero baseline between successive passes over a ground target.

The initial activation (power on) of the instruments can be performed in a science-like orbit (within 5-10 km of RSO). However, the standalone and joint calibration activities can only be performed after the satellite has reached the RSO.

The NISAR spacecraft and flight systems are being designed to allow operation in either left or right-looking spacecraft look directions. The current baseline observation strategy calls for the nominal look direction to be right-looking, with the left-looking attitude used for 2 months every year to provide a more comprehensive coverage of land ice in Antarctica, a region of interest for the cryosphere discipline scientists.

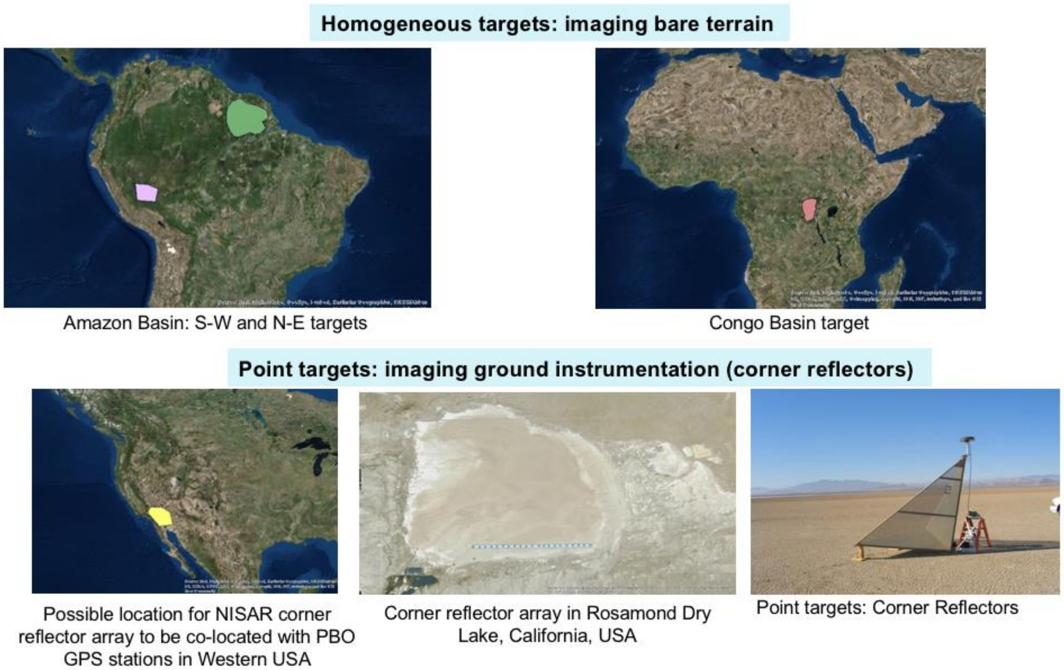

Figure 4. Calibration ground targets for NISAR L-SAR instrument

The initial power on activities can be performed using any look direction. The observatory will be in a left-looking geometry after launch, and currently there are no yaw flips scheduled before beginning instrument checkout, so the initial power on activities will be conducted in a left-looking attitude. Majority of the instrument standalone calibrations will be performed in the nominal right-looking geometry for the spacecraft, and a small subset of these (Digital Beam Forming, Antenna Pattern Verification, Antenna pointing calibration, Radiometric calibration, Cross-talk calibration, Polarimetric phase calibration) will be repeated for the left-looking geometry. Three 180-degree yaw flip maneuvers will be executed during the instrument checkout sub-phase to perform the switch between right-looking and left-looking attitudes to perform instrument calibrations.

Calibration ground targets

Instrument calibrations require data collection over specific ground targets, which include a mix of homogeneous/distributed and point target sites for NISAR. Homogeneous/distributed targets are those for which the radar backscatter is expected to not vary significantly over time, with the instrument being used to image the bare terrain at these sites. Based on radar imagery from other missions and historic trends of minimal deforestation and flooding, NISAR's science and instrument team members have selected three such homogeneous targets for calibration: two sites within the Amazon basin in South America and one site within the Congo basin in Africa. The Amazon basin, in particular, has been used for instrument calibration by other spaceborne radar missions also, including the Japanese Space Agency's (JAXA) ALOS-2 PALSAR-2 instrument as well as ISRO's RISAT-1. Point targets are the second type of ground targets that will be used for instrument calibration for the NISAR mission. These are sites where ground instrumentation in the form of corner reflector arrays will be installed prior to launch and will be imaged by the instrument. NASA's L-band airborne radar instrument, Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR), currently uses a corner reflector array installed in the Rosamond Dry Lake (California, USA) as a calibration site. The NISAR project plans to install corner reflectors co-located with GPS stations within the Plate Boundary Observatory (PBO) network in the Western United States prior to launch, to be used for calibration during commissioning. Figure 4 shows the locations of these calibration sites for NASA's L-SAR instrument.

ISRO has also proposed some preliminary ground targets for calibration of the S-SAR instrument. Similar to NASA's proposed calibration sites, ISRO's proposed sites also include a mix of homogeneous (Amazon basin) and point targets (corner reflector arrays in India and Antarctica).

Calibration requirements and interdependencies

The requirements for performing NISAR instrument calibrations involve a mix of modes and targets, which vary for each calibration type. For some of the calibrations like the Digital Beam Forming (DBF) calibration, diagnostic modes different from the science modes will be used. For each of the instrument calibrations, the radar payload team provides

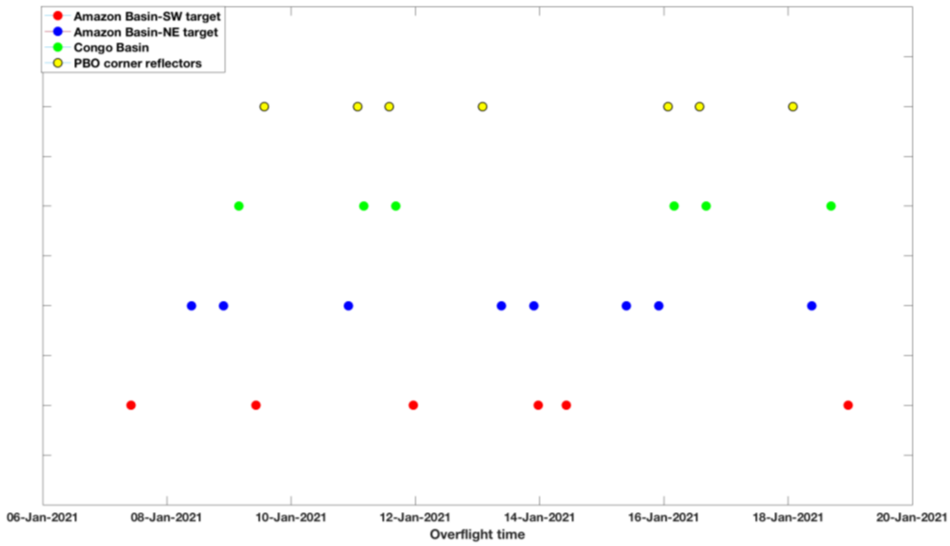

Figure 5. NISAR overflight times for proposed instrument calibration sites over a representative 12-day repeat cycle

requirements on radar modes to be used, ground calibration sites to be imaged, number and duration of datatakes to be collected, and whether to repeat the calibration or not for both left and right-looking spacecraft geometries. This information, combined with the knowledge of overflight times of NISAR satellite passes over the calibration sites over a 12-day cycle (Figure 5), is used for scheduling various calibrations and developing the instrument checkout timeline. Table 3 provides a listing of requirements by calibration type, and Figure 6 shows a graphical view of interdependencies between timing and sequence of L-SAR calibrations.

Antenna pointing calibration will also be performed during this sub-phase and has some unique requirements. This calibration needs to be performed 3-4 times for both left and right-looking spacecraft geometries. Pointing calibration datatakes will be spaced 3-4 weeks apart. Each of these datatakes requires one day's (~14 orbits) worth of collected radar data, ACS data, thermal data, accelerometer data and GPS data. The spacecraft will undergo dithering during pointing calibration datatakes, as a result of which no other activities can be performed simultaneously. Pointing calibration can only be performed after the spacecraft has reached RSO (~ 35 days after launch), and the first datatake must be at the start of radar operations. The first time for conducting this measurement and following correction attitude command is important as most of the alignment errors get corrected at this point. The first three pointing calibrations will be performed during commissioning (2 right-looking and 1 left-looking), while the remaining 3-5 datatakes will be collected during the 5-month cal/val phase.

Mission Planning challenges in scheduling timeline for instrument checkout

Scheduling activities for two radar instruments, that need to perform the same set of calibrations, presents a challenge in optimizing the instrument checkout timeline for NISAR. Commissioning activities during the instrument checkout phase for NISAR need to be scheduled in a manner to be able to accommodate calibrations for both NASA's L-SAR and ISRO's S-SAR instruments, while at the same time, maintaining a healthy margin in the overall timeline. Moreover, the Amazon basin is a common site of interest for the calibration of both instruments, with one of the proposed S-SAR calibration sites in the Amazon overlapping with one of NASA's sites. Preliminary analysis shows that scheduling alternate acquisitions of the common calibration site for the L-SAR and S-SAR instruments will satisfy the calibration requirements for both instruments. Furthermore, the L-SAR instrument cannot be transmitting and should be in idle state when the S-SAR instrument is being calibrated and vice versa. Details of the S-SAR checkout timeline are still being developed and interleaving of L-SAR and S-SAR calibrations will require a more thorough analysis in the future.

Another aspect that makes the scheduling challenging is the variability in expected timing of the observatory achieving the Reference Science Orbit (RSO). ISRO will be responsible for planning and executing maneuvers to raise the observatory from the initial injection orbit to the final RSO for collecting science data. The number, type and magnitude of maneuvers will be planned by ISRO, and will depend on the actual injection orbit. ISRO has studied a few variations of injection and developed maneuver plans to reach RSO, spanning approximately 9 days (to a maximum of 15 days) after deployment of the Reflector Boom Assembly is finished, implying that the RSO could be achieved as early as day 25 after launch. Delays in finishing deployments could push this milestone further. JPL's Current Best Estimate (CBE), based on analysis done by NISAR's mission design and navigation team, is that the observatory could reach the

Table 3. Requirements for performing NISAR L-SAR instrument calibrations

Calibration	Radar modes	Ground target	Number of datatakes	Duration of individual datatake	To be repeated for left and right-looking?
Thermal	5 Prime modes (all bandwidths)	No specific target	2 for each mode	~ 1 min	Yes
Digital Beam Forming	1) Diagnostic mode 1 2) Diagnostic mode 2 3) Science mode	1) Radar-bright targets 2) Homogeneous + point 3) Homogeneous target	1) 44 (4 for each pair of beams (11 total) for both H and V channels 2) 3 for homogeneous targets + 1 for point target 3) 1 for homogeneous target after uplinking new DBF coefficients	~ 2 mins	Yes
Antenna Pattern verification	1 mode (20+5 MHz DP)	Homogeneous+point	5 for each target	~ 1-2 mins	Yes
Radiometric	5 Prime modes (all bandwidths)	Homogeneous+point	3 for each target	~1-2 mins	Yes
Cross-talk	Only quad-pol modes	Homogeneous+point	same data as collected for radiometric cal	same data as collected for radiometric cal	Yes
Polarimetric	Only dual-pol & quad-pol modes	Homogeneous+point	same data as collected for radiometric cal	same data as collected for radiometric cal	Yes
Geometric	5 Prime modes (all bandwidths)	Point targets	same data as collected for other cals	same data as collected for other cals	Yes
Differential Time Delay	5 Prime modes (all bandwidths)	Homogeneous+point	same data as collected for other cals	same data as collected for other cals	Yes
Common time delay+time tag	5 Prime modes (all bandwidths)	Point targets	same data as collected for other cals	same data as collected for other cals	Yes
Split-spectrum	All modes with split-spectrum	Homogeneous+point	same data as collected for other cals	same data as collected for other cals	Yes
Antenna Pointing	Diagnostic high data-rate mode	No specific target	6-8, spaced 3-4 weeks apart	1 day	Yes

RSO 35 days after launch, assuming a 1-sigma dispersion from the target injection orbit (the estimate changes to as late as 50 days in the case of a 3-sigma deviation from the target injection orbit). Although the exact timing of when the RSO is reached will not affect the initial power on activities for the instruments, it will influence the start of standalone calibrations which can only be performed after reaching RSO.

Once the observatory reaches the RSO, Orbital Trim Maneuvers (OTMs) will be performed to offset major perturbing forces including gravity of the Sun, Moon, and atmospheric drag. At a minimum, one OTM and one clean-up maneuver are scheduled for each 12-day repeat cycle; occasionally, these scheduled maneuvers may be waived due to expected yearly variations in the perturbing forces. At the height of the predicted solar cycle in 2024, OTMs may occur as frequently as once every two days. The early OTMs after reaching RSO, will have to be interspersed in between instrument checkout activities. Although OTMs are planned to be performed over oceanic passes (when no calibration datatakes are to be collected), sufficiently accurate Ka-band antenna pointing and observatory thermal stabilization will have to be re-established quickly after an OTM is completed, to be able to support instrument checkout. Some padding might have to be included in the timeline to accommodate loss of downlink opportunities of calibration acquisitions due to pointing inaccuracies after a maneuver.

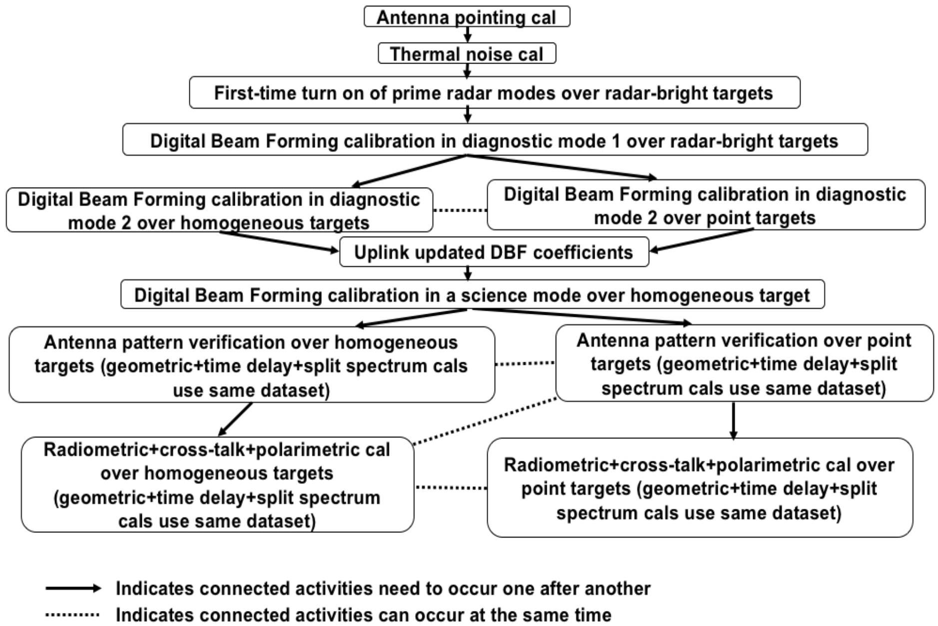

Figure 6. Graphical representation of interdependencies between timing of L-SAR calibrations

Finally, another factor that will lead to variations in the instrument checkout timeline over the next few years until NISAR's launch in 2021, is the inclusion of additional instrument calibration ground targets. In addition to the existing NASA and ISRO calibration sites, it is expected that more point target sites (corner reflector arrays) will be available for NISAR instrument calibration by the time of launch through collaborations with universities, scientists and research groups. Scheduling acquisitions over these new ground targets, as they become available to the project, will lead to incremental changes in the timeline over the next few years.

Timeline for NISAR instrument checkout during commissioning

The instrument checkout phase during commissioning for NISAR is planned to last for a total of 66 days (day 17-82 after launch). Figure 7 shows the overall timeline for L-SAR checkout (note that this timeline does not yet include S-SAR checkout activities). The first 11 days (day 17-28) are dedicated to L-SAR initial power on activities, followed by the first spacecraft yaw flip on day 29 to change the look direction from left-looking to right-looking. One buffer day is allocated as a margin after every yaw flip. The first yaw flip is followed by 5 days (day 30-34) of unallocated margin, since L-SAR standalone calibrations can only begin after the observatory reaches RSO (CBE day 35). Once the observatory reaches RSO, the first calibration to be performed is antenna pointing calibration, which requires one entire day of data collection. Right-looking standalone calibrations follow this from day 36-73, with another antenna pointing calibration interspersed on day 64. The spacecraft look direction is then switched to left-looking by performing a yaw flip on day 74. A left-looking antenna pointing calibration follows on day 75, with the remaining left-looking calibrations to be carried out on days 76-82. Three days of unallocated margin follow (day 83-85). A final yaw flip during commissioning is then performed on day 86 to change the observatory attitude to right-looking in preparation for beginning nominal science operations. The last 4 days of commissioning are accounted as unallocated margin (day 87-90). Overall, the L-SAR checkout timeline is well-ventilated with a total of 18 days of margin (12 unallocated + 6 allocated) built into it.

5. SUMMARY

The NASA-ISRO Synthetic Aperture Radar (NISAR) satellite will be the world's first dual-frequency radar Earth mission, and the first collaboration of this scale between NASA and ISRO. The scientific fields of study of solid Earth deformation, ecosystems and cryosphere, will benefit tremendously from the global mapping of the Earth every 12 days by the two instruments onboard this satellite.

NISAR's commissioning phase will be 90 days in duration, and will include a sub-phase of instrument checkout during which initial calibrations for the L-SAR and S-SAR radar instruments will be performed and calibration strategies, that will be continued into the following 5-month long calibration/validation phase, will be developed. Initial power on activities will be followed by standalone and joint calibrations, including Digital Beam Forming, Antenna

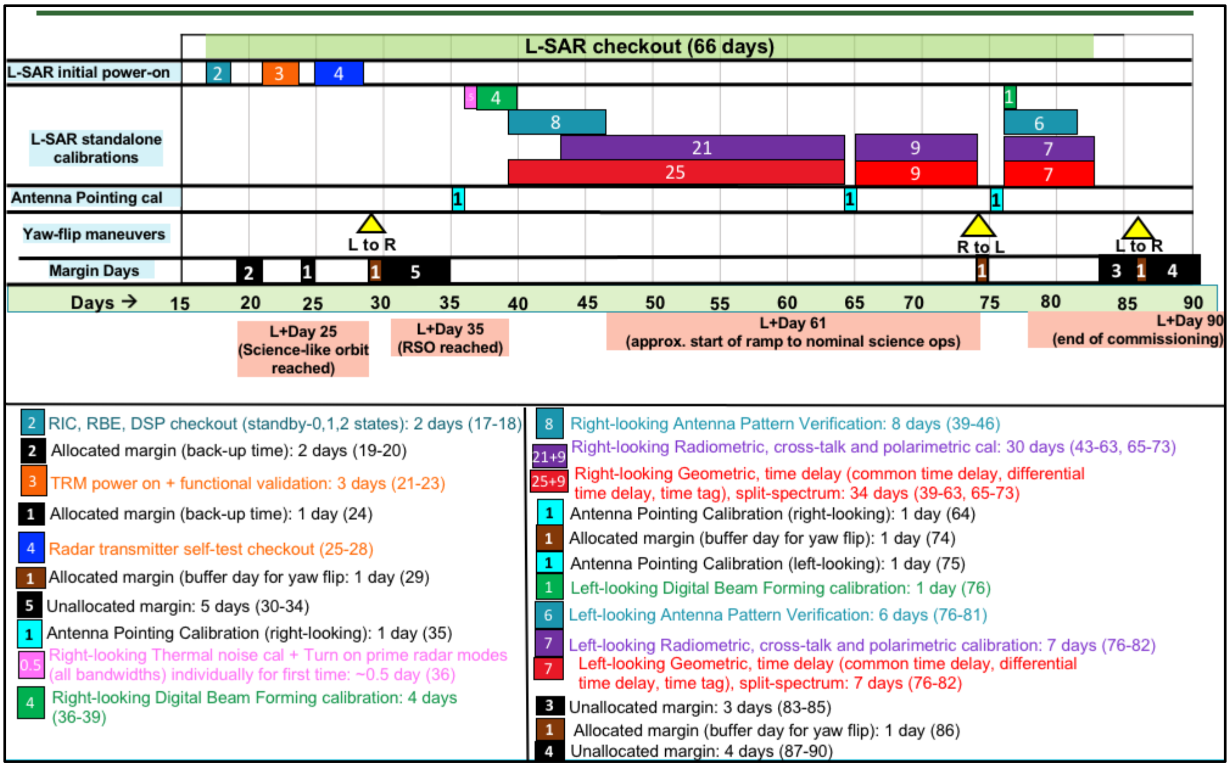

Figure 7. Timeline for NISAR L-SAR instrument checkout during commissioning

Pattern Verification, Antenna pointing calibration, radiometric, cross-talk, polarimetric phase, time delay, geometric and split spectrum calibrations. Both homogeneous/distributed and point targets (corner reflector arrays) will be imaged to assist with instrument calibrations. The current baseline timeline for instrument checkout is presented in this paper.

Future work to be done on this topic will include interleaving L-SAR and S-SAR checkout activities in the commissioning timeline for NISAR. The current timeline does not take into account differences in time zones and thus prime shifts between the JPL and ISRO teams. The effect of this factor, along with staffing assumptions, needs to be evaluated and accordingly incorporated in the timeline. The frequency of ground-in-the-loop operations (uplink/downlink contacts needed; time for data analysis and processing) also needs to be better understood and its effect on the timeline investigated. Finally, as additional calibration ground targets become available for the NISAR project, data acquisitions over them will have to be scheduled in the instrument checkout timeline.

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REFERENCES

[1] Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, Ed. by Committee on Earth Science and Applications from Space, National Research Council, National Academies Press, ISBN 978-0-309-10387-9, 2007.

[2] Hoffman, James P. Shaffer, Scott and Perkovic-Martin, Dragana (2016) NASA L-SAR instrument for the NISAR (NASA-ISRO) Synthetic Aperture Radar mission. Proceedings of the SPIE, Volume 9881, id. 988108 8 pp., doi: 10.1117/12.2228489

[3] Rosen, Paul A. et al. (2015) The NASA-ISRO SAR mission - An international space partnership for science and societal benefit. 2015 IEEE Radar Conference (RadarCon), Arlington, VA, 2015, pp. 1610-1613, doi: 10.1109/RADAR.2015.7131255

[4] Rosen, Paul A. et al. (2017) Global persistent SAR sampling with the NASA-ISRO SAR (NISAR) mission. 2017 IEEE Radar Conference (RadarConf), Seattle, WA, 2017, pp. 0410-0414, doi: 10.1109/RADAR.2017.7944237

[5] IADC Space Debris Mitigation Guidelines, IADC-02-01, Revision 1, September 2007. http://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf. Accessed 25 Sep. 2017

[6] Tung, Ramona H. (2016) Development of effective and efficient operations for NASA's Soil Moisture Active Passive mission. 2016 IEEE Aerospace Conference, Big Sky, MT, USA, doi: 10.1109/AERO.2016.7500588

[7] "Timeline". https://smap.jpl.nasa.gov/mission/timeline/. Accessed 24 Sep. 2017

[8] Farr, Tom G. at el., (2007) The Shuttle Radar Topography Mission. Reviews of Geophysics, 45, RG2004, doi:10.1029/2005RG000183.

[9] Chen, Curtis et al., (2017) Status of HR Data Coverage during the fast-sampling phase. SWOT Science Team Meeting, June 26-28, 2017. Toulouse, France. Accessed from https://swot.oceansciences.org/docs/jun17_stm_15_chen.pdf on 24 Sep. 2017.

[10] Arikawa, Yoshihisa et al., (2014) ALOS-2 launch and initial checkout result, Proc. SPIE 9241, Sensors, Systems, and Next-Generation Satellites XVIII, 92410T (11 November 2014); doi: 10.1117/12.2067157; http://dx.doi.org/10.1117/12.2067157

[11] Schwerdt, Marco et al., (2010) In-Orbit Calibration Plan of Sentinel-1. 2010 8th European Conference on Synthetic Aperture Radar (EUSAR), Aachen, Germany.

[12] "Operational Ramp-up phase" https://sentinel.esa.int/web/sentinel/missions/sentinel-1/data-distribution-policy/operations-ramp-up-phase, Accessed 20 Sep. 2017

[13] Sweetser, Theodore H., Vincent, Mark A. and Hatch, Sara J. (2014) Shootin' the Pipe around the World: Orbit Design and Maintenance for L-Band SAR Radar Interferometry, AIAA/AAS Astrodynamics Specialist Conference, AIAA SPACE Forum, (AIAA 2014-4117)

BIOGRAPHY

Priyanka Sharma *received a B.E. in Manufacturing Processes and Automation Engineering from Delhi University (Netaji Subhas Institute of Technology), New Delhi in 2006. She then received her Ph.D. in Planetary Sciences from the University of Arizona's Department of Planetary Sciences/Lunar and Planetary Laboratory (LPL) in 2012. Her Ph.D. thesis was focused on investigations of the geomorphology, topography and surface roughness of Saturn's largest moon, Titan, using Cassini radar data. She first joined JPL as a Caltech Post- Doctoral Research Scholar in 2013, and analyzed UAVSAR data to monitor subsidence in California's Sacramento-San Joaquin Delta. She is currently a member of the Mission Engineering and Planning Group at JPL, and works as a Systems Engineer in Mission Planning on the NISAR project. She has also worked on formulation studies of robotic precursor missions for future human missions to Earth's Moon, Venus orbiter/lander mission concept, and landing site selection studies for Mars 2020 and future lunar missions.*

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