InSAR

Interferometric Synthetic Aperture Radar

Concept Study Report

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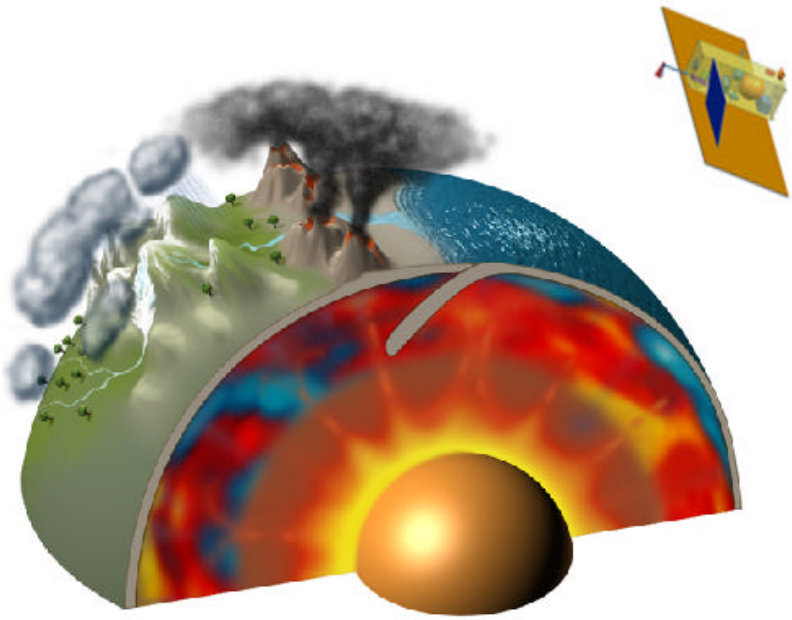

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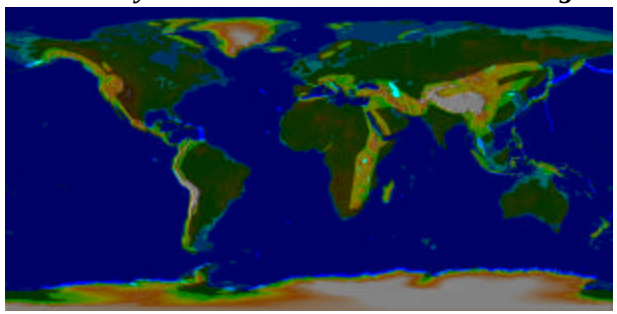
InSAR

Potential Partners

Interferometric Synthetic Aperture Radar

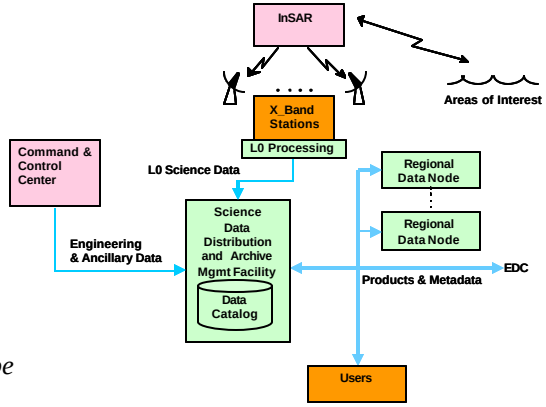
Mission Objective: *The InSAR mission objective is to provide the first dedicated spaceborne interferometry mission to precisely map Earth surface deformation due to tectonic, volcanic, and glacial processes. The resulting data will uniquely allow characterization and quantification of underlying processes enabling predictive models.*

Preliminary InSAR Fundamental Science Targets



Science Objectives:

- *Characterize and understand strain changes in tectonically active areas leading to and following major earthquakes*
- *Characterize three dimensional magma movements leading to better prediction of volcanic eruptions*
- *Assess the impact of ice sheet and glacier system dynamics on sea level rise and characterize temporal variability*



Operations:

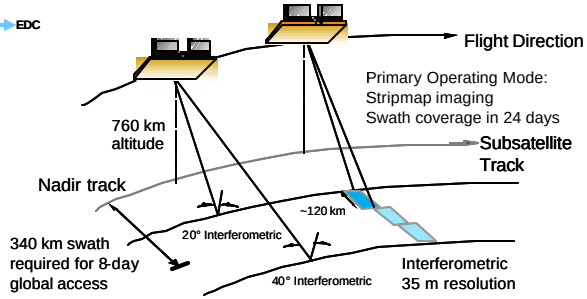
- *Simple 8-day repetitive mission cycle*
- *Two S/X-band Ground Stations*
  ASF and Svalbard
- *Selected ground automation*
- *Distributed processing architecture*

Mission Requirements:

- *5-year lifetime*
- *10-minutes of data per orbit (average)*

Navigation and Orbit:

- *Sun synchronous 6am/6pm*
- *760 km, 98.5º*
- *250 m diameter orbital tube*

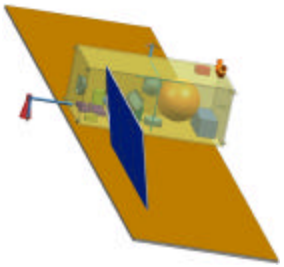


Project Implementation:

- *JPL instrument electronics build*
- *Commercial spacecraft bus; antenna panels, structure, and deployment mechanism*
- *Precision GPS as GFE to spacecraft bus contractor*
- *JPL I&T of phased-array antenna and radar electronics*

Measurement Technology:

- *Repeat pass radar interferometry*
- *3-D vector deformation by observing*
  - *while pointing to the left and right*
  - *on ascending and descending orbits*



Flight System:

- *Enhanced RSDO Catalog bus*
- *GPS for Precision Orbit Determination/Nav.*
- *Selected-to-full redundancy*
- *Mass* — *1350 kg wet (CBE + cont.)*
- *Downlink* — *300 Mbps X-band*
- *Storage* — *256 Gb minimum*
- *Maneuvers* — *0.1°/sec left/right pointing*
- *Pointing* — *0.04° 3-sigma yaw/pitch*
  0.25° 3-sigma roll

Launch System:

- *Delta II 2920-10*
- *3150 kg to 760 km*
- *57% Launch Margin*
- *April 2009, VAFB*

Payload System:

- *L-band single-polarization (HH) radar*
- *Split spectrum for ionospheric correction*
- *Full redundancy of radar electronics*
- *Stripmap, High-Resolution and ScanSAR Modes*
  - *Primary operating mode – Stripmap Mode (continuous strip-mapping with 3 possible beams)*
- *13.8 m x 2.5 m antenna aperture*
- *Deployable antenna structure*
- *Mass* — *600 kg (CBE +30%)*
- *Power* — *1800 W peak (CBE +30%)*
- *Data rate* — *130 Mbps average (CBE)*

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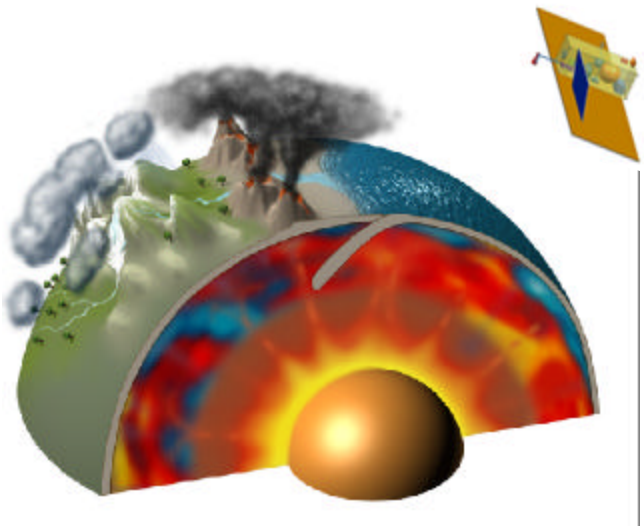

Program/Focus Area:

ESE / Solid Earth

Mission/Operations Scenario

Orbit:	
Type	LEO-SS
Altitude (km)	760
Inclination (deg.)	98.44
Nodal Crossing Time	06:00 AM
Orbit Period (min.)	100.0
Eclipse Period (min.)	17.77
Repeat Period (days)	8

Mission Parameters:	
Mission Duration (yrs.)	5
Launch Date (month/year)	April '09

Technologies:	TRL	Type
L-band SAR	5	Enabling
Deployable Antenna	5	Enabling

Science Objectives:

- Characterize and understand strain changes in tectonically active areas leading to and following major earthquakes
- Characterize three dimensional magma movements leading to better prediction of volcanic eruptions
- Assess the impact of ice sheet and glacier system dynamics on sea level rise and characterize temporal variability

Public Impact:

Improved global maps of earthquake and volcanic hazards, and strategies for mitigating injury and property damage (e.g., prioritization of building & bridge retro-fitting); improved predictions of global sea level rise

Programmatic Objectives/Constraints:

Payload Description:

L-band single-polarization synthetic aperture radar

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1.0 Introduction

The mission architecture described in this Concept Study Report is driven by and based on three key assumptions. It is assumed for this study that the InSAR project starts in FY 05, that there are no international collaborations, and that a Delta II 2920-10 launch system is made available for an April 2009 launch of InSAR.

The current InSAR mission architecture utilizes a commercial spacecraft bus; phased-array antenna panels, structure, and deployment mechanism(s). The instrument electronics and precision GPS (Global Positioning System) would be a JPL build with the GPS hardware being GFE (Government Furnished Equipment) and provided to the spacecraft bus contractor. Integration and Test (I&T) of the phased-array antenna and/or antenna panels with the radar electronics would be performed at JPL while the Flight System I&T would be performed at the spacecraft bus contractor facilities.

1.1 Task Summary

The objective of this study was to accelerate the InSAR mission concept definition task by identifying development options, performing trade studies, and completing technology readiness assessments. The tasks completed as a result of this effort are listed in the subsections below.

1.1.1 Science

The science efforts included investigation of several optional deformation mapping objectives including “rapid” response, coastal hazards, and mountain glacier dynamics, which are discussed in the Science Investigation Section. The InSAR science target areas have been reassessed and refined resulting in a science target document. An effort to refine the InSAR Science Requirements has been undertaken to document a set of clearly defined and verifiable science requirements. In addition, various operational scenarios have been investigated including utilizing a ScanSAR Mode as the primary operating mode to facilitate the development of a global baseline; as well as the possibility of changing revisit frequency on-orbit to make possible the study of fast moving mountain glacier ice.

1.1.2 Technical Implementation

Previous SAR studies were reviewed (ECHO and LightSAR) to capture Lessons Learned and any previous deficiencies that could benefit the InSAR effort. Development of a Preliminary Project Requirements Document was begun to capture a clearly defined verifiable requirements set – a living document to be archived for future use/reference in developing InSAR mission architectures. Radar system studies and design trades were performed, including but not limited to, development of a spreadsheet-based InSAR design tool with key hardware specifications that allow feedback to the hardware design, development of a radar system functional requirements document, and numerous design trades (analysis to derive orbital tube

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requirement, analysis on ScanSAR interferometry; and radar performance analysis of the three principal InSAR beams and interferometric ScanSAR) to establish instrument requirements. Radar hardware electronics development activities were performed including an internal Technology Assessment Workshop to assess past technology developments and plan for InSAR technology investments, and development of radar electronics prototypes (L-band RF Transceiver, AD-9858 NCO-based Digital Chirp Generator, Atmel TS8388 Analog to Digital Converter and 1:8 Demux, Xilinx FPGA-based Block Floating Point Quantizer, and a high speed data acquisition system) to raise the TRL. The instrument architecture was then refined to utilize the new hardware technologies. An orbital tube memo was developed to quantitatively describe the 250 m orbital tube requirement. Industry surveys of Ball Aerospace (surveyed for spacecraft bus and phased-array antenna capability), Spectrum Astro (surveyed for spacecraft bus capability), Lockheed Martin (surveyed for phased-array antenna capability), and Vexcel (surveyed for repeat orbit interferometry processing capability) were performed. A preliminary trade of on-ground vs. on-spacecraft maneuver determination was performed. GPS requirements definition, development plan and cost to meet navigation and precision orbit determination requirements were carried out. An assessment of the orbit maintenance and orbit determination requirements to maintain the 250 m orbital tube was done. In addition, various launch system options were performed including payload fairing volumes and dual payload architectures.

1.1.3 Management

A Project WBS and WBS Dictionary was developed to Level 4 for all subsystems with the Payload System WBS developed to Level 5 and Radar System Engineering and Radar Electronics WBS developed to Level 6. A Project Master Schedule was created and an Environmental Compliance Launch Approval Status System (ECLASS) form was completed (required of Pre-Phase A missions to assess their specific National Environmental Policy Act (NEPA) requirements). All Project Systems (Project Management, Project System Engineering, Safety and Mission Assurance, Science [including Education and Public Outreach], Payload System, Flight System, Mission Operations System, and Launch System) were investigated and planned for to a level of fidelity consistent with a Pre-Phase A mission architecture.

1.1.4 Cost and Cost Estimating

Utilizing the Project WBS, cost estimation was performed for the L-band InSAR mission development. The costs for each JPL WBS element were supplied by those who will be responsible for delivery. A grassroots or bottom-up method was used to develop the InSAR cost estimate excluding procured items (spacecraft bus and phased-array antenna). Costs for procured items (spacecraft bus and phased-array antenna) were based on actual costs of analogous missions and vendor input. Two Mission Operations System (MOS) options (a commercial company provided MOS and JPL MOS) were investigated and costed.

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1.2 InSAR Baseline and Options Summary

The following figure depicts the current InSAR baseline mission architecture on the left and InSAR options studied on the right. The baseline and options are discussed in detail in their respective Sections of this report.

Figure 1-1. InSAR Baseline and Options

InSAR Baseline Architecture

- Science Objectives
  - Characterize and understand strain changes in tectonically active areas leading to and following major earthquakes
  - Characterize three dimensional magma movements leading to better prediction of volcanic eruptions
  - Assess the impact of ice sheet and glacier system dynamics on sea level rise and characterize temporal variability
- Flight System
  - Enhanced RSDO spacecraft bus
  - 256 Gbits min on-board storage
  - 300 Mbps X-band science downlink
  - Left/right pointing
  - 5-year mission lifetime, with selected-to-full redundancy
  - GPS for Precision Orbit Determination/Nav
- Payload System
  - Procured phased-array antenna panels, structure, and deployment mechanism(s)
  - 13.8 m x 2.5 m antenna aperture
  - L-band single polarization (HH)
  - Full redundancy of radar electronics
  - Stripmap, High-Resolution and ScanSAR Modes
    - Primary operating mode – Stripmap Mode (continuous strip-mapping with 3 possible beams)
  - Power – 1800 W peak (CBE + 30%)
  - Mass – 600 kg (CBE + 30%)
  - Data rate – 130 Mbps average (CBE)
- Navigation and Orbit
  - 250 m diameter orbital tube
  - Sun-sync 6am/6pm, 760 km, i = 98.5^{0}
  - 8-day exact repeat
- Operations
  - 10 min average data per orbit; 24-hr latency
  - High-latitude X- band receiving stations – ASF & Svalbard
  - Distributed Vexcel processing software – Focus™ & Phase™
  - Selected ground automation
- Launch System
  - Delta II 2920-10

InSAR Options Under Study

- Science Options
  - "Rapid" response deformation mapping objective
  - Coastal hazards deformation mapping objective
  - Mountain glacier dynamics mapping objective
  - ScanSAR Mode (100 m resolution) as primary operating mode
    - Global baseline mapping
  - Stripmap Mode (35 m resolution) as secondary mode
- Spacecraft Bus Options Studied
  - Spectrum Astro – SA-200HP
  - Ball – BCP 2000
  - Astrium – Flexbus
  - Team X – mission specific bus/industry labor rates/longer data takes
- Phased-Array Antenna Options Studied
  - Ball/ABLE Engineering
  - Lockheed Martin
- Payload System Options
  - ScanSAR Mode as primary operating mode
  - Stripmap Mode (35 m resolution) as secondary mode
  - Multiple operational altitudes/repeat intervals
- Navigation and Orbit
  - Various repeat frequency scenarios
    - 2-day -> 9-day
    - 9-day -> 2-day
    - 2-day -> 9-day -> 2-day
- Operations
  - Increased data volumes (instrument on-time)
  - Ka-band – Safety Net
  - X/Ka-band – ASF & Svalbard/Safety Net
  - Specific data product development in coordination with Science Team and E/PO
    - Web-based Portal - on demand processing
    - Distributed server side processing at regional data nodes using ROI_PAC
    - Scheduled processing of high demand products as part of ingestion pipeline
  - Data mining and analysis support

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2.0 Science Investigation

2.1 InSAR Mission Objective

The InSAR mission objective is to provide the first dedicated space-borne interferometry mission to precisely map Earth surface deformation due to tectonic, volcanic, and glacial processes. The resulting data will uniquely allow characterization and quantification of underlying processes enabling predictive models.

2.2 Science Objectives

Within this mission objective are three distinct science objectives:

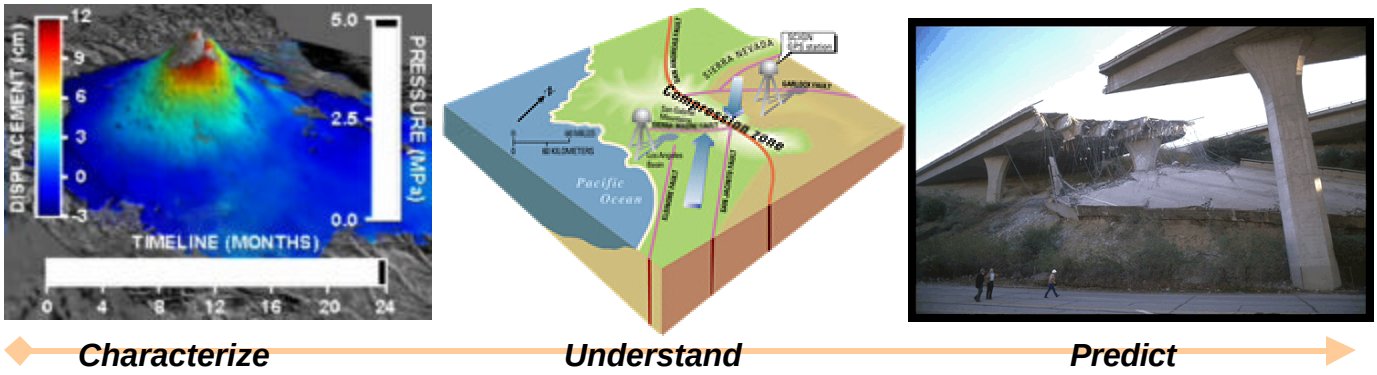
- Characterize and understand strain changes in tectonically active areas leading to and following major earthquakes.
- Characterize three dimensional magma movements to understand volcanic processes, leading to better prediction of eruptions.
- Assess the impact of ice sheet and glacier system dynamics on sea level rise and characterize temporal variability.

InSAR will return an enabling dataset to *characterize, understand and predict: tectonic deformation/earthquakes, volcanic activity, cryosphere change, and coastal subsidence.* Deformation measurements from InSAR will allow scientists to *characterize* surface deformation related to ice, coastal processes, and crustal deformation, deepening *understanding* of processes responsible, which, when coupled with modeling will permit *prediction* of future changes and events, minimizing their impact.

2.3 Science Community Justification

Surface deformation is the key measurement to characterize, understand, and ultimately predict consequences and natural hazards from volcanoes, earthquakes, ice and sea-level changes, and other solid earth phenomena.

Figure 2-1. Surface Deformation Measurement is Key



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The need for a dedicated InSAR satellite to monitor and measure crustal deformation has been intensively studied and repeatedly endorsed by the scientific community:

> In the next 5 years, the new space mission of highest priority for solid Earth science is a satellite dedicated to interferometric synthetic aperture radar (InSAR) measurements of the land surface at L-band. Such a mission would address the most urgent objectives in the areas of plate-boundary deformation, land-surface evolution, ice and sea-level change, volcanism, and mantle dynamics (Living on a Restless Planet: Solid Earth Science Working Group Report, 2002, p. 59).
>
> A space based system for monitoring crustal deformation is the logical next step to achieve revolutionary advances in earthquake science needed to develop a better predictive capability (Global Earthquake Satellite Study Report, 2003, p.14).

InSAR responds to solid Earth questions posed by NASA, NSF and the Earth Science Community:

> INSAR was identified as the highest priority measurement by the Solid Earth Science Working Group Report (SESWG-p.59).
>
> The Global Earthquake Satellite Study Report recommends: "A space based system for monitoring crustal deformation is the logical next step to achieve revolutionary advances in earthquake science needed to develop a better predictive capability (Global Earthquake Satellite Study Report, 2003, p.14). They go on to urge development of 'InSAR Everywhere All the Time' within 25 years.
>
> The major NSF funded EarthScope project now underway to understand crustal processes in the western US, consists of four measurements, three of which are currently funded by NSF. InSAR is the fourth and key spaceborne measurement required yet unsatisfied.
>
> Earthquakes and volcanic eruptions have caused the greatest natural disasters in history, yet the processes by which these events occur are poorly understood. Predictions will not occur without understanding.
>
> Cryospheric changes and sea level rise have the greatest potential impact on civilization on the medium term. Global inventory of ice budgets lack required precision and temporal/spatial coverage. Recent discoveries highlight our ignorance. Trillions of dollars of coastal infrastructure and communities are at risk.

Frequent, high precision, geographically comprehensive, surface deformation measurements are practical only via a dedicated InSAR satellite.

2.4 Meeting the InSAR Mission and Science Objectives

InSAR derived geographically comprehensive *maps of deformation due to tectonic,*

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volcanic, and glacial processes at required sensitivity, spatial resolution and temporal frequency are required to meet the InSAR Science Objectives. The InSAR mission and systems must be designed to collect the InSAR data required to precisely map Earth surface deformation over time through frequent observations over a five year mission lifetime. Because InSAR measures only line of sight (LOS) changes in spacecraft-to-ground distance related to surface deformation, InSAR measurements from multiple directions are required to determine the actual surface displacement vectors.

These objectives can only be achieved via a dedicated spaceborne radar interferometry mission.

2.5 Primary Science Targets

InSAR primary science targets are tectonic areas, volcanoes, and the cryosphere. Our understanding of earthquake, volcanic, cryospheric, and many other processes is severely limited by spatially sparse and/or temporally infrequent deformation data. Geographically comprehensive measurements of surface deformation measured over sufficient time (5 years) to characterize the underlying driving phenomena are required.

The following InSAR primary science targets have repeatedly been endorsed by the science community (e.g. ECHO, LightSAR mission objectives, SESWG and GESS reports, NSF funded Earthscope project, etc.).

2.5.1 Tectonically Active Areas

Earthquakes and volcanic eruptions cause great damage and have caused the greatest natural disasters, yet the processes by which these events occur are poorly understood. Useful prediction will not occur without understanding. GPS and InSAR studies to date have revealed the crust behaves in unanticipated ways. What are the rates and spatial distribution of tectonic deformations and how do these relate to the earthquake process?

2.5.2 Volcanic Areas

More than 600 potentially active subaerial volcanoes are known. Recent research with space-based data has revealed that many volcanoes previously believed inactive are deforming, and other unanticipated deformations have also been observed. What are the rates and spatial distribution of deformation related to volcanic processes and magma movement, and how do these relate to the eruption process?

2.5.3 Cryospheric Processes

The cryosphere and sea level rise have the greatest potential impact on civilization on the medium term. Global inventory of ice budgets lack required precision and coverage. Recent discoveries highlight our ignorance. InSAR data during the mission life of the GRACE gravity mission will greatly help separate components of sea level rise related

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to glacial melting vs. thermal expansion (steric component of sea level rise). What are the rates and spatial distributions of ice sheet and glacier system dynamics, and how do these relate to sea level rise?

2.6 Science Operational Scenario

All InSAR science objectives require baseline InSAR data against which to measure change. Therefore, baseline InSAR data for primary target areas should be collected as soon as possible in the mission (see target maps below). InSAR data will be collected from four directions over all targets to determine surface vector displacements. The primary science target data will be collected in a routine manner (see target maps below).

Subsequent to the Calibration and Validation period, raw InSAR signal data will be made available to the scientific community via the internet within 24 hours (TBR) of downlink. Higher level data processing and analysis will be performed by the investigators utilizing a project provided data processor. The current InSAR baseline plan utilizes a commercial company, like Vexcel, for development and provision of the InSAR processing package and for s/w support. JPL will produce basic deformation products for E/PO during the course of the mission and develop procedures/select entities for emergency requests following earthquakes / storms, etc. InSAR data will be archived long term at the USGS EDC.

2.7 Data Processing Approach

Historically, interferometric SAR products have been largely produced by individual PI's using raw signal data. Interfermoetric SAR raw signal data is best processed by individual PI's according to specific research goals, e.g. time period of observation, average all interferograms or sequence, highest spatial resolution or spatially average for better SNR, etc. Therefore, InSAR plans to provide both the raw data and the processing software/support to investigators to be processed individually according to their specific research goals. This approach is most responsive to the investigative community. An approach that developed specific InSAR products would simply not satisfy the investigative community as it would not address all, or even most of the individual PI's research goals. In addition, a Project supported processing effort that attempted to provide products that addressed each investigative community's needs would not be cost effective.

The project will enable sophisticated users by providing access to InSAR raw data and the JPL developed ROI-PAC processor. New users would be developed/supported by providing a web-based simple path to raw data and a commercial graphic-user-interface processing software package. In addition, the science users would have access to software support.

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2.8 Observational Frequency

2.8.1 Observational Frequency Requirements for Earthquake/Tectonics, and Volcanoes

InSAR data for the tectonically and volcanically active western US will be acquired at every opportunity (>90% acquisition success) for the duration of the mission. InSAR data for the volcanically active western US, Aleutians, and Hawaii will be acquired at every opportunity (>90% acquisition success) for the duration of the mission. Foreign tectonic and volcanic targets will be imaged at least once from four directions every three months for the duration of the mission.

2.8.2 Cryosphere Observational Requirements

InSAR data for Antarctica and Greenland will be acquired at every opportunity (>90% acquisition success) during first, third, and fifth winters. InSAR mapping of Antarctica and Greenland will be designed to yield at least 5 complete deformation mappings per winter.

2.8.3 Targets of Opportunity

The InSAR mission and systems will be designed as to not preclude rapid targeting of developing natural disasters (e.g., targeting at first opportunity after the event), and targeted at every subsequent opportunity for the duration of the emergency.

2.9 Science Target Coverage at 10 Minutes of Data per Orbit

The current InSAR baseline design allows for collection of 10 minutes of data per orbit on average. This satisfies the basic science coverage requirement, however, additional instrument on-time would greatly improve the scientific return by effectively reducing the revisit intervals and the time required to return the deformation mapping data. Options are being assessed that include increased instrument on-time. The following maps illustrate the primary science targets and describe the coverage possible at the baseline 10 minute per orbit average data collection.

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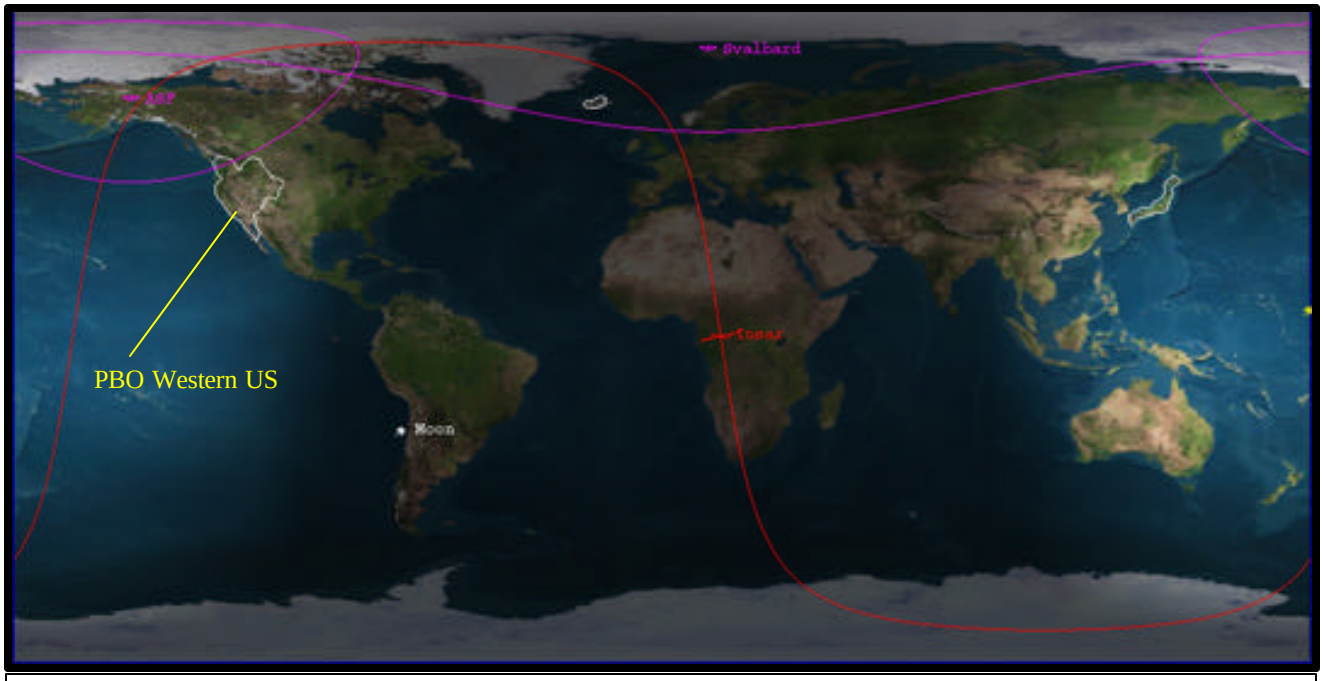
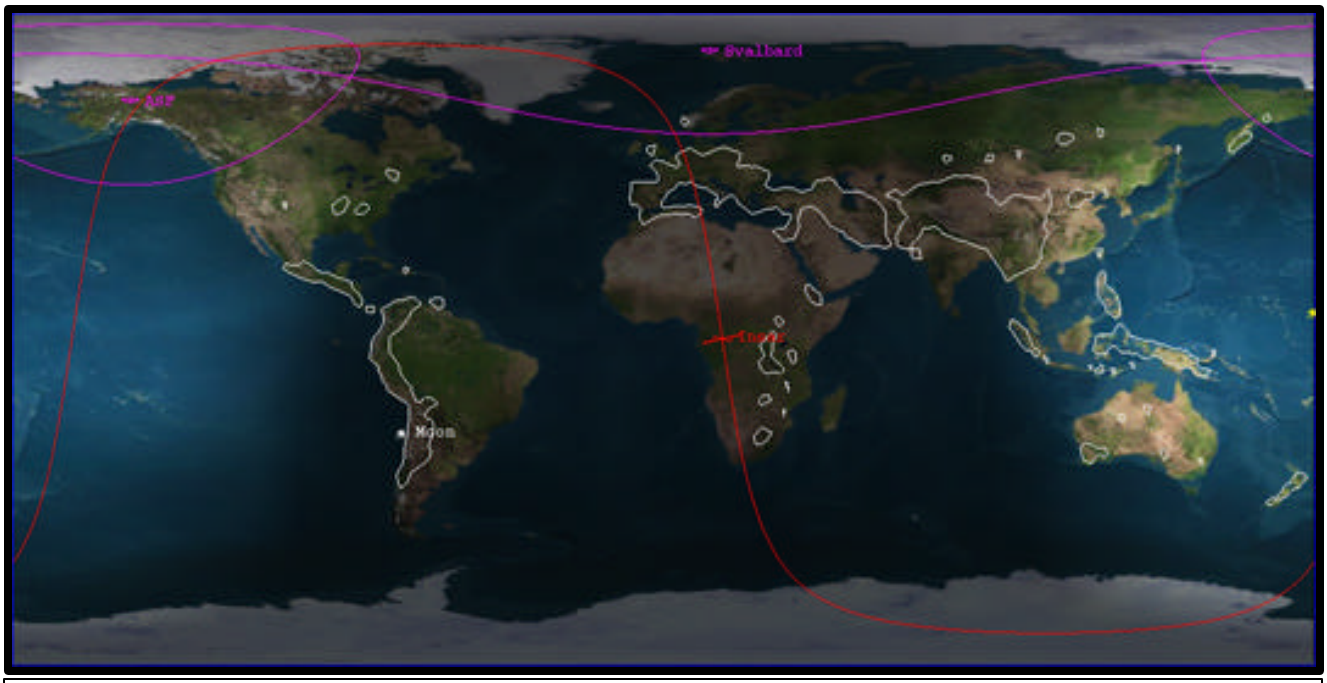
Figure 2-2. Highest Priority Target: Plate Boundary Observatory (PBO) Region US



- Currently planned InSAR coverage area of the Western US PBO is outlined in white
- Complete coverage from 4 directions is possible every 48 days

Figure 2-3. Active Earthquake and Volcanic Areas



- Currently planned tectonic and volcanic target areas are outlined in white
- Complete coverage from 4 directions is possible every 75 days

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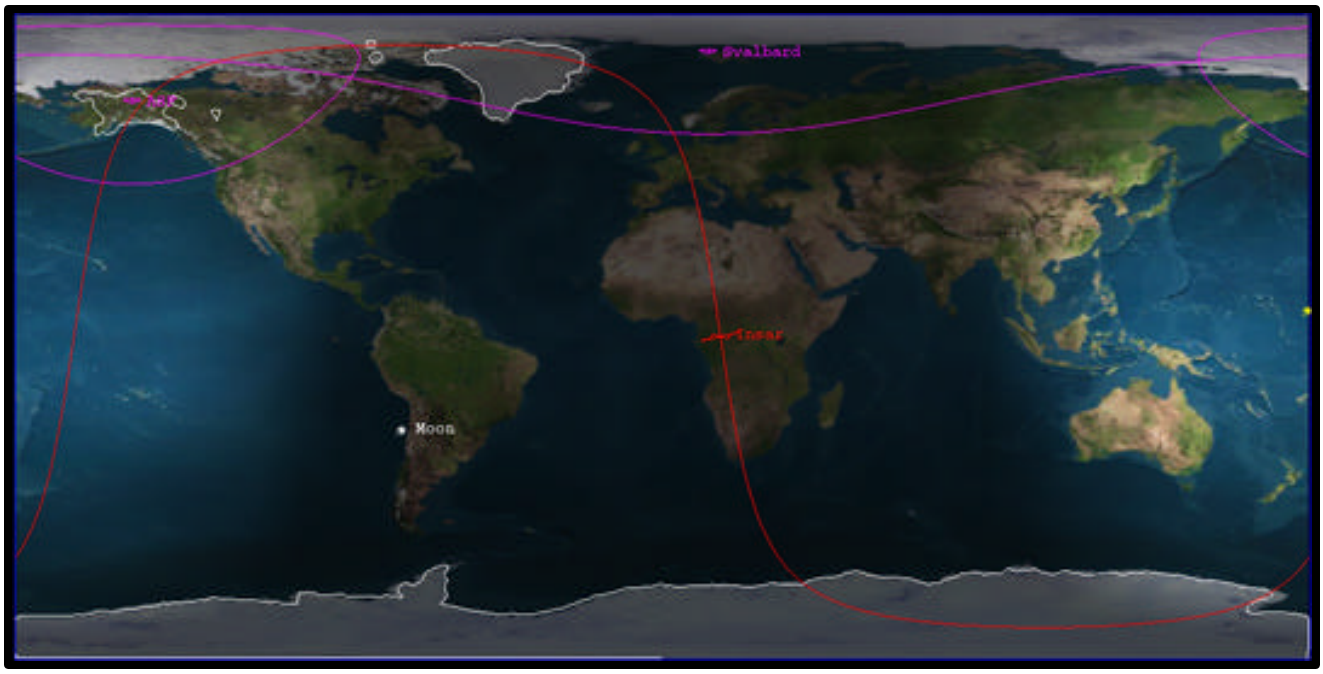
Figure 2-4. Cryosphere-Glacier and Ice Targets



- Currently planned cryosphere target areas are shown outlined in white
- Complete coverage from 4 directions is possible every 48 days local fall/winter only

2.10 Optional Science/Science Targets and Operational Scenarios

2.10.1 Optional Science/Science Targets

InSAR Measurements for Homeland Security and DTRA (Defense Threat Reduction Agency): Surface deformation related to oil and water extraction, subway tunneling, and mining activities has been measured using Interferometric SAR. There is great potential for InSAR applications to the detection of subsurface activities. This application would require long term observations, observations of known targets for calibration/validation, and an 80 MHz bandwidth for high resolution.

InSAR Measurements for Gulf Coast Subsidence: What are the rates and spatial characteristics of coastal subsidence, how does this relate to coastal environmental change, coastal infrastructure, public safety, and homeland security? Coastal processes, particularly subsidence, conspire with sea level rise to place trillions of dollars of infrastructure and communities at risk. Regional, high precision subsidence and decorrelation measurements will aid risk assessment, mitigation, and severe storm response and recovery.

The primary InSAR target area would be the US Gulf Coast of Louisiana, adjacent

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Texas and Mississippi. This area would be a good proof of concept area.

The Gulf Coast near the Mississippi River is subsiding due to the load of river sediments. Inundation occurs due to combined subsidence, fluid withdrawal, sediment compaction, and sea level rise. Some areas are subsiding at up to 3 cm/yr. Plackerman's Parish is below sea level. Port Fourchon and other critical infrastructure is at risk. GPS and conventional surveys provide a precise but spatially and temporally incomplete understanding of the problem. The Louisiana Spatial Reference Center (LSRC) is the research and data center for coordinated work with other agencies including NOAA and the NGS, and is interested in InSAR application to this problem.

InSAR data would need to be collected at every opportunity over the target area (90% acquisition success). The target area would cover from approximately Houston Texas to Pascagoula Mississippi, ~700 km east-west and ~400 km north from the Gulf Coast. The InSAR Project would provide standard InSAR data availability (raw data and processor) and the data would be processed by LSRC (Louisiana Spatial Reference Center).

InSAR Measurements for Areas of Destruction: Can InSAR decorrelation maps provide useful data for areas of destruction related to earthquakes, fires, severe storms, floods, landslides, or other major disasters? This option would require identification and targeting of specific areas on orbit with baseline and post event InSAR data during the mission. Events outside of the primary science target areas would not necessarily have baseline data available for analysis unless a global land surface InSAR data effort were made.

InSAR Measurements for Regional Crustal Deformation and Gravity: What is the relationship between regional crustal deformation and gravity? GRACE data may provide a unique opportunity for simultaneous analysis and modeling. This option would require regional InSAR mosaics (an InSAR mosaic capability is under development), an Antarctica suitable target, and augmentation of ongoing GRACE studies.

InSAR Measurements for Soil Moisture: InSAR measurements could be used to complement the Hydros mission. Interferograms of soils have been shown to be a partial function of moisture content, which can be tested/developed against Hydros data. This option would require observations of Hydros calibration targets at appropriate times.

InSAR Measurements for Vegetation Biomass Mapping via Non-zero Baseline Orbit: This option would require the InSAR satellite be initially inserted into an orbit 1 km displaced from the baseline "deformation" orbit. The resulting interferograms of vegetated areas would provide data for deriving tree heights and for profiling forest vertical structure. Twenty-four days in this orbit in ScanSAR Mode would provide a global vegetation data set. The additional topographic data could also be used in the generation of baseline mission deformation interferograms.

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2.10.2 Optional Operational Scenarios

ScanSAR: Most tectonic and volcanic science objectives are better served with lower spatial resolution but higher temporal resolution ScanSAR data. In this option ScanSAR would be the primary operating mode for InSAR, however, stripmap and high-resolution modes would be retained.

Increased Instrument On-time: At 23 minutes (TBR) instrument on-time per orbit (on average); all primary science targets could be imaged from 4 directions every 48 days with the 100 km stripmap swath width, or every 16 days with the 350 km ScanSAR swath. The ability to beat down tropospheric effects is a function of the number of observations; therefore, this option would greatly improve that capability.

Changing Revisit Frequency On-orbit: SIR-C results show rapidly moving mountain glaciers can decorrelate in 3-4 days. Mountain glaciers are rapidly moving and melting, are a poorly constrained contributor to sea level rise, and are difficult to study due to inaccessibility. Mountain glacier science could be greatly enhanced by more frequent InSAR measurements. Several mission design options are being investigated that would address this. One such option would require the InSAR satellite be inserted temporarily into a 3-day repeat orbit, moved to an 8-day repeat for the main mission, and then returned to a 3-day repeat for final observations.

Global Land Surface Measurements: InSAR and GPS data to date have yielded repeated surprises about the mobility of the earth's crust. Other unanticipated phenomena may be observed if global data are collected and studied by curiosity driven scientists. This would require global land surface InSAR data four times per year utilizing the ScanSAR mode.

2.11 Science Requirements

ECHO Heritage, SESWG/GESS reports and Earthscope project documents justify and elucidate principal InSAR science observational requirements. The following requirements are from a preliminary set of high-level requirements being developed for future InSAR missions.

Mission Lifetime Requirement: The InSAR mission and systems shall be designed to perform the Nominal Science Mission science data collection in 60 months of operation including Calibration and Validation.

The temporal scale of non-catastrophic deformation events is years. While capture of an earthquake would be assured in approximately 3 years time, the temporal scale of non catastrophic events (slow deformation related to tectonics, volcanoes, and temporal variability of the cryosphere) is >3 years and is undersampled. In addition, studies to date show unanticipated deformation before and after seismic events related to the style of tectonics and local conditions that may not be captured with a mission lifetime of less than 5 years. As an example, the Northridge region continued to deform for >2 years

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after the earthquake. A five-year mission duration allows for sufficient observing history to detect slow movements in the presence of noise due to tropospheric and ionospheric variations. Adequate InSAR sampling on the order of 5 years or more is required to understand these processes.

Ionospheric/Tropospheric Noise Reduction Requirement: The InSAR orbit shall have an ascending node at the 6 am terminator.

This is a 6 am / 6 pm nodal crossing orbit. A 6 am/6 pm nodal crossing time is required to minimize ionospheric effects and tropospheric moisture variability in the data.

Repeat Pass Requirement: The InSAR orbit shall be an exact repeat orbit with a repeat frequency of $\leq$ 9-days.

Repeat frequencies greater than 9 days would introduce surface decorrelation errors and would not allow surface unfolding events to be captured. SIR-C results show rapidly moving mountain glaciers can decorrelate in 3-4 days. Shorter revisit times are highly desirable, but must be balanced with the requirement for global access. Note: A ScanSAR true 8-day repeat at 100 m resolution would be ideal for most science observations.

Minimum Swath Width Requirement: The InSAR mission and systems shall be designed for a minimum swath width (single beam) of $\geq$ 100 km in the primary operating mode.

Phenomena to be observed have ~100 km scale: large earthquakes and volcanoes, and the cryosphere. As an example, the deformation related to the Landers, Kern County and Owens Valley events extended beyond 70 km. Swaths less than 100 km will not capture a snapshot of phenomenon at one time.

Pixel Resolution Requirement: The InSAR mission and systems shall be designed for approximately 25-100 m Interferometric SAR pixel resolution.

Spatial complexity of faulting during earthquakes and localized volcanic phenomena during eruption sequences requires 25 m pixel size, while 100 m resolution is adequate for slow deformation phenomena.

Geolocation of Slant Range Pixel Spacing Requirement: The InSAR mission and systems shall be designed for geolocation of slant range pixel spacing to 0.2 pixel.

Precise location and distribution of phenomena is required.

Post-Processing Surface Displacement Detection Requirement: The InSAR mission and systems shall be designed to enable post-processing detection of vector deformation rates of $\leq$ 2 mm per year (single component accuracy) over 50 km with 100 km swaths averaged over the 5-yr nominal mission subsequent to the Calibration

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Validation period.

A goal of 1 mm per year displacement over 50 km with 100 km swaths was identified by the SESWG (SESWG. P. 31). Slower phenomena such as fault creep and glaciers require this sensitivity.

The following table depicts the science requirements traceability to instrument and mission functional requirements at the highest level.

Table 2-1. Science Traceability Matrix

Science Objectives – Fundamental	Scientific Measurement Requirements	Instrument Functional Requirements	Mission Functional Requirements
Understand strain changes leading to and following major earthquakes	Globally distributed measurement of vector deformation rates to 2 mm/yr (single component accuracy), with position accuracy of 5-10 mm at 35-100 m resolution over a 5-year mission.	Swath size 1. Larger than 100km Accuracy 1. L-band radar for high coherence 2. Split-spectrum for ionospheric correction 3. Noise equivalent s_0 smaller than –24 dB Accessibility 1. 30 minutes of on-board storage for global accessibility within ground station constraints 2. Electronic beam steering in range Calibration 1. GPS for baseline knowledge and for orbit control Mission duration 1. 5 years	Vector measurement 1. Ability to image left and right for vector measurements Accuracy 1. Orbit maintenance to repeat-track to within 250m for high coherence 2. Precise orbit determination 3. Instrument pointing to better than 0.05 deg. (1 sigma) 4. Frequent observations over a site to average out tropospheric and other noise sources Mission duration 1. 5 years
Characterize three dimensional magma movements to predict volcanic eruptions	Globally distributed monthly measurements of deformation with 5-10 mm accuracy. Frequent measurements during eruptions.	As above (no additional requirements)	As above plus Accessibility 1. 8 day repeat orbit for frequent monitoring of eruptions
Assess the impact of ice sheet and glacier system dynamics on sea level rise and	Ability to map vector ice motion for Greenland and Antarctica to 1 m/yr (single component accuracy). 5 year mission to study	As above (no additional requirements)	As above plus Accuracy 1. 8 day repeat to avoid temporal decorrelation & aliasing of fast motion Accessibility

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Science Objectives – Fundamental	Scientific Measurement Requirements	Instrument Functional Requirements	Mission Functional Requirements
characterize temporal variability	temporal variability and infer ice sheet mass balance.		1. Polar orbit & left/right looking capability to image both poles
Science Objectives - Experimental	**Scientific Measurement Requirements**	**Instrument Functional Requirements**	**Mission Functional Requirements**
Assess the impact of mountain glacier system dynamics on sea level rise and characterize temporal variability	Ability to map vector ice motion of mountain glaciers to 1 m/yr over scales of 200 km and greater.	As above (no additional requirements)	As above plus Accuracy 1. 2 day repeat to avoid temporal decorrelation & aliasing of fast motion Accessibility 1. Polar orbit & left/right looking capability to image both poles 2. Ability to change revisit frequency on-orbit

2.12 Mission Success Criteria (Science Floor and Descopes)

All primary science targets require baseline data to be collected as soon as practical. A principal operational descope is to reduce the frequency of coverage after initial interferograms for all high priority areas are assessed. It may be reasonable to reduce frequency of coverage for slow deforming or lower priority areas. However, tropospheric noise will degrade the data as repeat frequency is reduced.

Earthquake/tectonic science requires baseline data for tectonically active areas to be collected as soon as feasible in the mission. The current InSAR mission architecture would cover the western US Plate Boundary Observatory areas at every opportunity. A potential descope would be to cover only the most actively deforming PBO areas on every opportunity (e.g., the western half of the PBO). The implications of this descope are that some earthquake creep events and volcano deformation events would be missed.

Volcanology requires baseline data for all volcanoes to be collected as soon as feasible in the mission. The current InSAR mission architecture would collect data for all 600 volcanoes on each observational opportunity. A potential descope would be to reduce the temporal coverage guided by initial data analysis.

Cryosphere science requires baseline data for all cryosphere targets to be collected the first winter as soon as feasible in the mission. The current InSAR mission architecture

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would collect data over the cryosphere science targets every opportunity during first, third and fifth winters. A potential descope would reduce the temporal observation for areas demonstrated to be slow moving.

The current InSAR mission architecture is for a five-year mission lifetime. A 3-year mission lifetime is a possible descope, but limits science by limiting the temporal observations of long-term processes. A 3-year mission would observe significant earthquakes, but would miss significant pre/post event deformation. Northridge continued to deform for >2 years after the event in 1994. Temporal observations of aseismic tectonic processes would be limited (8 years of Central Mojave Shear Zone observations led to new discovery). In addition, volcano observations would be limited (Etna inflation>eruption cycle can exceed 3 years). Recently documented deformation of dormant volcanoes needs longer term study.

Table 2-2. Potential Mission Descopes

De-scope Item	Savings		Impact on Science
	M$	Kg	
3-year vs. 5-year mission lifetime	20-30	≤150	Limits temporal observations of long term processes
Delta 2420-10 vs. Delta 2920-10	5-10	N/A	None assuming mass can be constrained without impact to science
Single instrument mode (ScanSAR)	TBD	TBD	100 m resolution capability only
On-orbit reduction in temporal observation	TBD	N/A	Selected limitation of long term processes
Non-phased-array antenna	TBD	TBD	TBD

Note: Savings are derived from subsystem expertise and best judgment. Mission descopes were not studied in detail.

2.13 Calibration and Validation

Initial Cal/Val will occur during a 3-month commissioning phase. This will be followed by an initial report and data release. Investigators will have access to InSAR data from this point forward. Full validation will require 1 year of observations to fully quantify the tropospheric and ionospheric delays. A complete validation report with metrics will be made available to community after full validation. This will allow refinement of observations made up to that time.

2.14 Science Management

The following table lists the proposed InSAR Science Team. Not all individuals named below have been contacted regarding their support of the InSAR effort.

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Table 2-3. Proposed InSAR Science Team

Team Member/Affiliation	Proposed Role/Responsibility	Capabilities/Experience
Internal Science Team		
Ronald Blom/JPL	Science Coordinator	
Andrea Donnellan/JPL		earthquake geophysics/modeling
Ian Joughin/JPL		cryosphere/glaciers
Eric Rignot/JPL		cryosphere/glaciers
Paul Rosen/JPL		geophysics/engineering
Frank Webb/JPL		geophysics/GPS
Paul Lundgren/JPL		volcanology
External Science Team		
Tom Jordan/USC-SCEC		
Bernard Minster/SIO-IGPP		
Gilles Peltzer/UCLA/JPL		
David Sandwell/SIO		
Paul Segall/Stanford		
Mark Simons/CalTech		
Wayne Thatcher/USGS		
Howard Zebker/Stanford		
Maria Zuber/MIT		
John Rundle/UCD		
Brad Hagar/MIT		
Zhong Lu/USGS		volcanology
Roy Dokka/LSU		coastal processes

2.15 External Science Review Results

The external science review has not occurred; however, the current InSAR mission architecture is based on considerable scientific heritage from previous InSAR mission studies. Essential tectonics, volcanics, and cryospheric requirements and objectives were derived from the ECHO proposal, Solid Earth Science Working Group (SESWG) Report, and the Global Earthquake Satellite Report (reports available at: http://solidearth.jpl.nasa.gov/).

2.16 Plans to Resolve Open Science Issues

Nearly all science objectives are better met with more frequent revisits at 100 m resolution, so the question (Should the primary operating mode be ScanSAR?) must be answered. Discussions are underway with scientists. Ice and volcanology have responded that they would prefer an 8-day repeat ScanSAR as a baseline option if suitable specifications can be achieved.

The size and composition of the Science Team needs to be negotiated. Discussions at JPL are ongoing and are to be followed by discussions with potential science team members.

Should other experimental InSAR science targets (As described in the Optional

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Science/Science Targets and Operational Scenarios Section) be added to the mission objectives? These additional targets would require additional resources on the satellite (e.g., >10 min of instrument on-time per orbit), and therefore, each experiment needs to be evaluated for mission impact vs. potential science return.

2.17 InSAR Science Summary

Solid Earth science, and cryoscience have an immediate, well documented, need for InSAR measurements. InSAR measurements provide data that will enable scientists to characterize, understand, and predict phenomena related to earthquakes, volcanic, and cryosphere activity. These phenomena have direct impact on society, and greater understanding can save lives and dollars. Existing radar satellites are demonstrably inadequate for achieving these goals due to the wrong frequency, inadequate repeat interval, poor orbit control, etc. Science requirements demand an L-band, split spectrum radar system with frequent revisit capability and broad area coverage.

The recent earthquakes in Bam, Iran, and San Simeon, California highlight the need for a dedicated InSAR satellite. Nearly two months post events, no interferograms are available to the scientific community, nor to the earthquake recovery agencies. Furthermore, any pre-event deformation, and details of sequences post event deformation are unmeasured. Post event deformation in the Northridge earthquake, much of it aseismic, provided essential information on the fault physics and processes.

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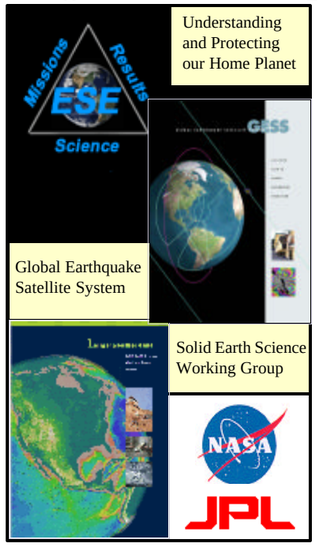
Foldout 1. Science Requirements Flow: ***InSAR will return an enabling dataset to Characterize, Understand and Predict: Tectonic deformation/earthquakes, volcanic activity, cryosphere change, and coastal subsidence. InSAR Mission/Science Objectives are in direct response to Programmatic/Science Community need***

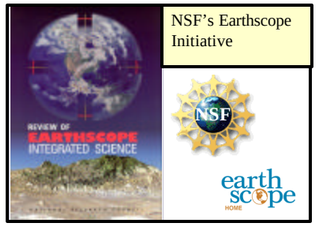
Programmatic Support



Understanding and Protecting our Home Planet

Global Earthquake Satellite System

Solid Earth Science Working Group



NSF's Earthscope Initiative

The Earth Science Enterprise mission: *to understand and protect our home planet by using our view from space to study the Earth system and improve prediction of Earth system change.*

The ***Global Earthquake Satellite System*** *lays out a plan to enable Earthquake forecasting over the next two decades. Increasingly frequent InSAR observations are required.*

The ***Solid Earth Science Working Group****, an independent panel of scientists,* ***recommends InSAR as the highest priority measurement.***

The NSF funded ***Earthscope*** *Initiative now underway* ***calls for an InSAR mission as a critical component*** *of the Earth laboratory.*

InSAR Motivation

InSAR Mission Objective

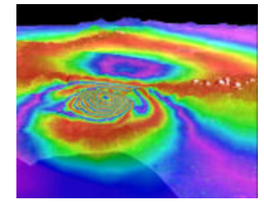
Mission Objective: *The InSAR mission objective is to provide the first dedicated spaceborne interferometry mission to precisely map Earth surface deformation due to tectonic, volcanic, and glacial processes. The resulting data will uniquely allow characterization and quantification of underlying processes enabling predictive models.*

Within this mission objective are three distinct science objectives

1. Characterize and understand strain changes in tectonically active areas leading to and following major earthquakes.
2. Characterize three dimensional magma movements to understand volcanic processes, leading to better prediction of eruptions.
3. Assess the impact of ice sheet and glacier system dynamics on sea level rise and characterize temporal variability.

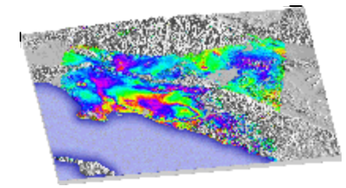
Deformation measurements from InSAR will allow scientists to characterize surface deformation related to ice, coastal processes, and crustal deformation, deepening understanding of processes responsible, which, when coupled with modeling will permit prediction of future changes and events, minimizing their impact.

Characterize



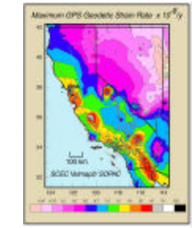
InSAR mission

Understand



Solid Earth modeling

Predict



Event forecasting

To meet the InSAR science objectives the following high-level scientific measurement requirements must be met. These high-level scientific measurement requirements flow down into instrument and mission functional requirements.

Table F1-1. High-level Scientific Measurement Requirements

Scientific Measurement Requirements
Globally distributed measurement of vector deformation rates to 2 mm/yr (single component accuracy), with position accuracy of 5-10 mm at 35-100 m resolution over a 5-year mission.
Globally distributed monthly measurements of deformation with 5-10 mm accuracy. Frequent measurements during eruptions.
Ability to map vector ice motion for Greenland and Antarctica to 1 m/yr (single component accuracy). 5 year mission to study temporal variability and infer ice sheet mass balance.

Table F1-2. High-level Instrument Functional Requirements

Instrument Functional Requirements
Swath size • Larger than 100km
Accuracy • L-band radar for high coherence • Split-spectrum for ionospheric correction • Noise equivalent s_0 smaller than –24 dB
Accessibility • 30 minutes of on-board storage for global accessibility within ground station constraints • Electronic beam steering in range
Calibration • GPS for baseline knowledge and for orbit control
Mission duration • 5 years

Table F1-3. High-level Mission Functional Requirements

Mission Functional Requirements
Vector measurement • Ability to image left and right for vector measurements
Accuracy • Orbit maintenance to repeat-track to within 250m for high coherence • Precise orbit determination • Instrument pointing to better than 0.05 deg. (1 sigma) • Frequent observations over a site to average out tropospheric and other noise sources
Mission duration • 5 years
Accessibility • 8 day repeat orbit for frequent monitoring of eruptions • 8 day repeat to avoid temporal decorrelation & aliasing of fast motion • Polar orbit & left/right looking capability to image both poles

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3.0 Education and Public Outreach

3.1 Education and Outreach Plan Summary

The InSAR mission Education and Outreach Plan will package the eagerly awaited science data in a public-friendly palate and bring it to the attention of the American people. The activities are designed to reach a broad spectrum of people using such mass audience reaching methods as television and radio, as well as more personable methods such as a Professional Development series for teachers, to scholarships for students.

Considering other federal agencies such as FEMA and USGS have all ready created excellent products, the InSAR outreach plan will not be recreating similar products. Instead, ***the focus will be on the interaction with the people – engaging them, informing them and educating them***. We plan on promoting the educational and outreach materials of the other agencies to encourage the general public's overall interest.

During our activities, we will especially stress the significance of the mission as a value-added technology for the people. It is important that we start demonstrating the "Science for Society" component of NASA and highlight not so much through dollars saved, but rather how the science and technology are really a part of their everyday life. We will also work with the DAAC to promote the use of the InSAR data within the science/academic communities as well as potential entrepreneurial opportunities.

3.2 Rationale

As a part of a public agency, NASA/JPL has a responsibility to report on the content and results of their activities to the American people, both for their information and application. NASA's direction to do this is contained in the 1958 Space Act that directs the agency to "provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

The InSAR Mission study's Education and Public Outreach plan must support the NASA mission statement – "To understand and protect our home planet, To explore the Universe and search for life, To inspire the next generation of explorers."

Specifically, the InSAR mission will contribute programs that subscribe to the new NASA criteria called "Exemplary Program Criteria", which include: Customer Focus, Content "as only NASA can", Pipeline – Science Technology Engineering Mathematics (STEM), Diversity, Evaluation, and Partnerships/Sustainability.

3.3 Goals and Audience

Our goals are derived from Goal 6 and 7 of the NASA Strategic Plan, which are to "Inspire and motivate students to pursue careers in Science, Technology, Engineering

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and Mathematics (STEM)" and to "Engage the public in shaping and sharing the experience of exploration and discovery", respectively.

The targeted audiences are the groups designated by the NASA ESE Outreach & Communications Plan and the NASA Plan for Earth Science Education. In Education, the targeted audiences are the students and teachers. In Outreach and communications, the targeted audiences are, in order of importance: The General Public, The Stakeholders and The Peers.

3.4 Activities

The planned activities for the InSAR mission will be put into three categories:

Public Affairs: This is the area where we need to work closely with NASA Headquarters to coordinate our efforts. Public Affairs include all media related events including television, radio, print and Internet, public services and appearances.

- **Goal 7:** Engage the public in shaping and sharing the experience of exploration and discovery.
- **Intended audience:** General Public, Stakeholders, Peers
- **Purpose:** All activities are the status quo methods used to generate media attention if there is breaking news or to encourage desired media coverage. The visualizations/ animations can be used on television or as a part of a talk. The science writer support is a dedicated effort to maintain interest on the mission and science through interest stories.
    - Scheduled and Breaking News Press Releases
    - Live Shot Campaigns
    - Video file productions
    - Earth Science Update Productions
    - Science Visualization/Animations
    - Pre-Launch Campaign
    - Science Writer support

Outreach: This is the area where there is the most overlap because of the broadness of the targeted audience- the general public. All efforts in outreach would include activities that would touch on both public affairs and education; however, it is also traditionally the weakest area. With renewed efforts from NASA Headquarters to deliberately present the unified "ONE NASA" presence, all outreach efforts must communicate the NASA Mission to the general public.

- **Goal 7:** Engage the public in shaping and sharing the experience of exploration and discovery.
- **Intended audience:** General Public, Stakeholders, students and teachers
- **Purpose:** All activities are creative vehicles to highlight InSAR science. We are stressing the human element in the science to encourage participation in the people.

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- Earth Science Ambassadors- a group of science experts trained to promote Earth Science and give talks, interviews and be the "faces" of Earth Science.
- "The Accidental Explorer" series- Documentary style that will follow a scientist in what he/she does on the job, showing why it's a challenge but still cool and fun!
- Earth & Sky Radio- 60 second interviews with the working scientists
- Interchangeable Display/Exhibit featuring how InSAR studies fit into the different NASA ESE science focus areas
- Website- NASA Earth Watch- What is NASA learning about our home planet? Specifically from InSAR data, we can show earthquake updates showing the stress changes. This will be an interactive page to replace the current JPL Earth Homepage.
- NASA Kids Science Files production- Joint production with Langley.
- NASA Earth Science Museum Alliance- An ongoing effort to bring more Earth Science and its activities/trainings to museums across the country
- Support for Outreach Coordinator

Education: The current administration has raised the importance of Education for the agency to a new level when they created the Education Enterprise or Code N. All activities must map to the Code N initiatives and specific Code Y Programs and will be subject to the Exemplary Program Criteria. The InSAR mission's educational activities will forge a STEM pipeline by creating a path to encourage and support students' growing interests. The specific activities will provide opportunities at targeted grade levels that will: first, engage young students and inspire them to explore math and sciences; second, motivate the students to take math and science classes and especially provide first hand experiences of what it is like to work as a scientist or engineer; then, once they have chosen to pursue advanced studies in STEM, supporting them in their efforts through research opportunities and grants.

- **Goal 6:** Inspire and motivate students to pursue STEM careers.
- **Purpose:** Provide educational activities for students and their teachers where there is a direct interaction with scientists as role models. Activities are also aligned for continued engagement from the youngest grade levels to the post graduate levels-forging an InSAR pipeline to STEM careers. InSAR science data and its use will be introduced to the students and teacher, infusing NASA content into the classrooms.
    - Imagine yourself a Geoscientist Camp through Southern California Earthquake Center (SCEC)- Weekend immersive event where students will experience first hand what it's like to be and work like a geoscientist. Activities will be grade specific, starting at 6th grade-12th grade.
    - K-12 Teacher Professional Development Series at the NASA Education Resource Centers/Aerospace Education Specialists Program Workshops- The series is aimed at educating teachers on InSAR science and how to use of data in the classroom as necessary for their curriculum. Teachers will be rewarded credits towards ongoing education or if they are seeking

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a Masters Degree.
  - Wings of Education- A JPL chapter of the EAA Young Eagles Program where the students will learn about ground truthing to remote sensing, followed by an opportunity to fly with a volunteers pilot to gain a new perspective of their world.
  - GLOBE- Students gather ground data, input onto internet, sharing and analyzing results from other students and scientists around the world.
  - NASA Undergraduate Student Researchers Program (USRP)
  - NASA Graduate Student Researchers Program (GSRP)
  - National Research Council (NRC) Resident Research Associateship (RRA) Programs

3.5 Dissemination & Evaluation

Dissemination: Since the focus of the plan is on the interaction with people, the dissemination of our messages and products will be through all the listed activities where we meet the intended audiences. We will also request products and materials from the other agencies, making them available during the planned activities. In particular for the science peers, we will work with the DAAC and support the science conferences to further publicize the science data.

Evaluation: To objectively measure the success and effectiveness of the activities and programs, evaluation for our three categories will be conducted by:

- **Public Affairs:** Evaluation will be done on the collected metrics from the various media domains- Television, radio, print and Internet. The collected metrics will be plotted and analyze to see where certain campaigns may or may not have been successful. Furthermore, time incremented milestones will be set to make sure we are on target with our efforts.
- **Outreach:** Evaluation will be done via direct feedback from the participants and an independent company who will evaluate the programs and be able to suggest ways where we can make improvements.
- **Education:** Evaluation will be done according to feedback from participants as well as the NASA Code N Exemplary Program Criteria.

3.6 Management

At JPL, Education and Outreach falls under the responsibility of the Public Engagement Program. The Earth Theme Lead is the manager of the Earth Science Public Engagement office and will therefore be responsible for managing all aspects of the InSAR mission Education and Outreach plan including implementation, execution and maintenance of the budget. The dedicated outreach coordinator reports to the Theme lead and will work closely with the project in executing the plan and the education and outreach activities. The current Earth Public Engagement team will also support InSAR mission efforts when necessary, especially during events when we promote Earth System Science. The science writer will also report to the Theme lead but will

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coordinate efforts with the Earth Science Media Relations lead. They will share the responsibility in **initiating** Public Affairs efforts. The Education Officer from the JPL Education office will work with the Theme Lead and dedicated outreach coordinator in realizing the logistics and executing the educational activities. He/she will also initiate any new efforts or opportunities on behalf of the public engagement office.

3.7 Budget

From the debut of mission to Pre-Launch, the funding in Education & Outreach will be to support necessary efforts to promote the mission and pre-launch efforts. Contrary to past practices and in accordance with the NASA ESE Outreach and Communications Plan, more than 75% of the E&PO budget must be maintained *for after launch.*

3.8 Plans to Resolve Open E&PO Issues

This plan deliberately did not address the Small, Disadvantaged and Small, Veteran-owned business, Minority Institution Involvement and Commercial opportunities because they need to be coordinated with other current ongoing NASA efforts.
Any Small, Disadvantaged and Small, Veteran-owned business opportunities must be coordinated with the SBIR office at JPL and NASA Headquarters. Minority Institution Involvement will be handled in the outreach and educational efforts as dictated by the NASA Strategic Plan. Commercial Opportunities will be handled by the Data Users workshops and conferences managed by ESIP. We will need to coordinate efforts with them and also provide training.

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4.0 Payload System

4.1 Summary of Radar Instrument Activities

A summary of the various design, analysis and development activities that were completed under the InSAR design study task is presented below. A more detailed description of the results is presented in subsequent sections.

4.1.1 Radar System Studies and Design Trades

A spreadsheet-based InSAR design tool has been developed. Key hardware specifications have been incorporated into the system design tool to give feedback to the hardware design. A functional requirements document is under development. Numerous design trades have been conducted to establish instrument requirements: 1) Analysis to derive the orbital tube requirement for the platform; 2) Analysis on ScanSAR interferometry; and 3) Radar performance analysis of the three principal InSAR beams, interferometric ScanSAR, and seven high resolution InSAR beams; 4) Hardware design specifications such as data rate, transmit/receive chain specifications, and phase and frequency stability requirements.

4.1.2 Radar Hardware Electronics Development

An internal technology assessment workshop was held in October, 2003. The purpose of this workshop was to assess past technology developments and identify common radar components suitable for additional technology investment by InSAR. This was accomplished by surveying past technology investments and new candidate technologies to understand adaptability to InSAR as well as other planned missions such as Aquarius, WSOA, Hydros and potentially UAV SAR. Based on the results of this workshop, the development of the following radar electronics prototypes was initiated to raise the TRL: 1) L-band RF Transceiver; 2) AD-9858 NCO-based Digital Chirp Generator; 3) Atmel TS8388 Analog-to-Digital Converter and 1:8 Demux; 4) Xilinx FPGA-based Block Floating Point Quantizer (BFPQ). In addition, the instrument architecture has been refined to utilize the new hardware technologies.

4.1.3 Radar Testbed

An InSAR Radar Testbed has been developed to demonstrate the radar components developed in an end-to-end test environment. In addition to the radar components mentioned above, the testbed includes a high-rate data acquisition system, Labview-based user interface and a fiber-optic delay line. The testbed is a functional single-string radar where new components can be inserted into the signal flow with only minor modifications to standard interfaces. The testbed is designed with sufficient data acquisition capability to characterize performance with some limited display and analysis options for quick-look results. The testbed is located in JPL's building 300 Room 222 with 588 sq. ft. of dedicated lab space. A demonstration of the Radar Testbed was completed on July 9th, 2004. The Payload System Foldout provides a

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block diagram of the radar testbed and shows key components of the system. Future upgrades include improvements to the timing and control interface and completion of the data quality analyzer to include data analysis capability.

4.2 Instrument Requirements and Design

The science measurements set the design requirements on the instrument and mission. The following discussion illustrates the connection between the science requirements and the instrument performance. Single-component and change rate accuracies required to meet the science objectives define the instrument performance and observing strategy. Earthquake and crustal stress measurements are the most demanding in terms of measurement accuracy (single component accuracy of 2 mm/yr) and change rate (deformation accuracy of 5-10 mm at 35-100 m resolution over a 5-year mission), and therefore, drive the instrument design.

The troposphere (the dominant error source) and ionosphere are two sources of error in measuring deformation with InSAR. The instrument is designed to contribute less error than either of these two error sources; and the five-year mission duration will allow for sufficient observing history to detect slow/small movements in the presence of noise due to tropospheric and ionospheric variations.

The current instrument design requirements required to meet the InSAR science measurement objectives are listed below:

- L-band to minimize temporal decorrelation in regions of appreciable ground cover
    - Two sub-bands separated by 70MHz to allow correction of ionospheric effects
- Viewable swath width larger than 340 km to obtain complete global access
    - Based on an eight day revisit frequency – this baseline orbit was chosen to balance temporal decorrelation with required swath coverage
- Ground resolution better than 35 m to characterize fault geometries
- Noise equivalent $\sigma_\circ$ better than -24 dB to map radar-dark regions (see next figure)
- Azimuth ambiguity better than -20 dB to suppress along track ambiguous signals
- Range ambiguity better than -25 dB to suppress cross track ambiguous signals
- Electronic beam steering to minimize spacecraft interactions for acquisition and allow ScanSAR operation
- Data rate less than 140 Mbps to avoid data loss in the link to S/C SSR (to be reviewed)
- Single polarization

The current instrument requirements on the Flight System and mission are listed below:

- Orbit maintenance within a 250 m tube (one-sigma required, three-sigma goal) to ensure interferometrically viable scenes
- Onboard GPS for cm-level orbit and baseline knowledge to improve calibration
    - Orbit knowledge: $\leq$10 cm (post-processing) using GPS ground analysis

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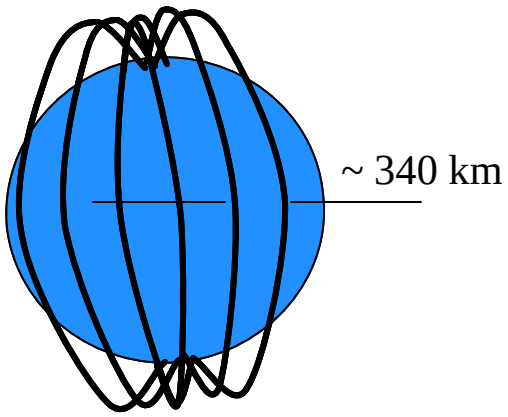
- 5-year life time to achieve measurement accuracy
- Pointing:
    - Instrument pointing is chosen to minimize antenna gain loss when steered to zero-doppler.
        - 0.04° 3-sigma yaw/pitch (1/20 Azimuth beamwidth)
        - 0.25° 3-sigma roll (1/20 Elevation beamwidth)
- Maneuvers:
    - Spacecraft right/left rolling capability to make vector measurements
        - Left/right pointing at 0.1°/sec (10 min changeover between +/- 30°)

4.2.1 Global Access and Viewing Geometry

The current InSAR baseline eight-day sun-synchronous orbit at 760 km altitude yields a separation of ~340 km at the equator between adjacent nadir tracks, as shown in the following figure. In order to meet the requirement for complete global access the InSAR Payload System will be designed such that the accessible area (viewable swath) is greater than or equal to 340 km.

Figure 4-1. Adjacent Nadir Track Separation at Equator



The Payload System will be capable of electronically steering between same-side sub-swaths. In addition, the satellite will be capable of performing left-right roll maneuvers such that the Payload System can view science targets from both sides of the platform.

A summary of the relevant radar instrument characteristics is given below.

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Table 4-1. Radar Instrument Characteristics

Item	Value/Summary
Sensor type	Synthetic aperture radar
Frequency and polarization	L-band single-polarization (HH)
Signal-to-noise ratio	Noise equivalent sigma naught less than –24 dB
Swath width	Larger than 340 km (viewable) to obtain global access
Bandwidth	80 MHz (maximum) and split spectrum capability to perform two sub-bands processing for ionospheric correction
Instrument modes	Stripmap (3 possible beams), High-Resolution and ScanSAR
Antenna aperture	13.8 m x 2.5 m (with distributed T/R modules)
Antenna incidence angle	From 20-deg to 40-deg (electronic beam steering)
Transmit power	3.5 KW
Antenna structure	Deployable
Data acquisition duty cycle	10 min/orbit average (200 W average power per orbit)
Radar electronics redundancy	Full redundancy (with cross-strapping) of radar electronics for 5-year mission lifetime
Instrument mass	600 kg including 30% contingency
Instrument DC power	1800 W peak (during data take) including 30% contingency
Instrument data rate	130 Mbps average

4.3 Measurement Technology and Instrument Modes

With the exception of the high-resolution mode, the observing bandwidth is split into two parts, 15 MHz and 7 MHz which “bookend” the L-band 80 MHz bandwidth allocation. The purpose of this is to provide observations which can be used to reduce the effect of the ionosphere on the deformation measurements. That is, correction for ionospheric effects may be possible by observing the same target using two slightly offset frequency bands, where the offset is chosen to be as wide as possible to provide the most sensitive estimates of ionospheric effects without falling outside of the L-band frequency allocation.

The Payload System is an L-band H-pol (1.25 GHz) system designed for repeat pass interferometry. 3-D vector deformation will be achieved via observations in left and right-looking modes and observations on ascending and descending passes/orbits. There will be three modes for the instrument. These are:

Stripmap Mode: The Stripmap Mode (15 & 7 MHz, split spectrum), currently the primary operating mode for InSAR has a resolution of 35 m. In this mode one of three beams, each with a swath width of ~120 km, can be utilized at any one time. Although the actual spacecraft revisit time is dependent upon other Flight System and mission resources/constraints, the Stripmap Mode viewable swath (all 3 beams combined) allows for complete global access in 8 days and complete global coverage in 24 days.

High-Resolution Mode: The High-Resolution Mode is an 80 MHz mode that trades swath coverage for increased resolution (10 m). One of seven beams may be chosen in this mode; each with a swath width of ~40 km. Operation in this mode would be in lieu of the primary 35 m resolution Stripmap Mode and would be performed intermittently at the request of the Science Team when targets of interest requiring higher resolution are identified.

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ScanSAR Mode: The ScanSAR Mode (15 & 7 MHz, split spectrum), in the current InSAR baseline, is an experimental mode. (An option to utilize ScanSAR as the primary operating mode in lieu of the Stripmap Mode is currently being assessed.) At the cost of resolution (resolution for this mode is 100 m); all three beams of the accessible swath can be collected at once to achieve a single-pass 350 km swath which can be used for interferometry. The data rate would not be appreciably different, but resolution would be affected due to the along-track sub-sampling, as well as the SNR. That is, the SNR would become a function of the along-track position, and would be significantly degraded at the large squint angles due to loss in the azimuth beam pattern and the increase in the azimuth ambiguity ratio. Furthermore, due to the need for the co-alignment of bursts between passes, the SNR performance would become a permanent function of the observing geometry and hence linked to the geography, making deformation measurements in one part of a region consistently less accurate than measurements in another part of a region. Yet ScanSAR interferometry offers a method of obtaining large regional coverage over short revisit periods. Operation in this mode would be in lieu of the primary 35 m resolution Stripmap Mode and the current InSAR baseline plan includes operation in this mode for limited time periods only.

The observing geometry for the satellite platform and the relative swath sizes for the three modes are shown below. The near range incidence angle is 20 degrees (18 degree look angle) and the far range incidence angle is 43 degrees (37 degree look angle). Relevant parameters for the fundamental InSAR modes are given in the following table. These are the three beams of the Stripmap Mode, a ScanSAR Mode, and a 80 MHz High-Resolution Mode. The mean data rate for the system will be 130 Mbits/second.

Figure 4-2. InSAR Radar Modes

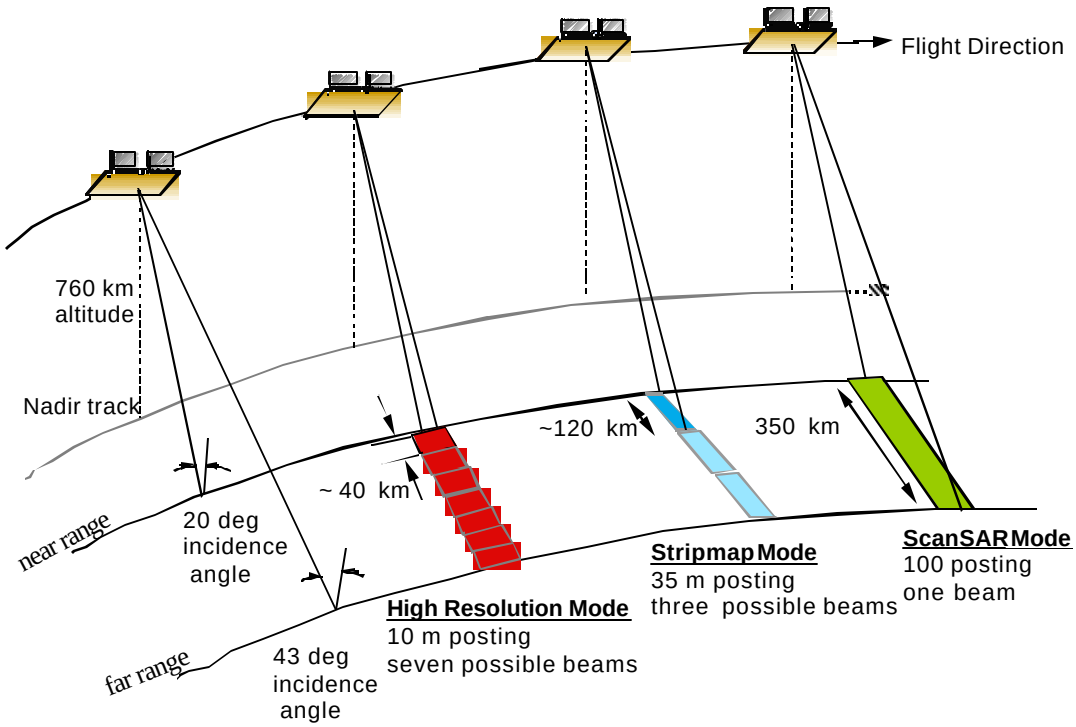

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Table 4-2. Instrument Mode Parameters

Parameter	Near	Mid	Far	ScanSAR	Hi-Res
Bandwidth	15 +7 MHz	15 + 7 MHz	15 + 7 MHz	15 + 7 MHz	80 MHz
Swath Width	130 km	120 km	120 km	350 km	25 to 35 km
PRF	1351 Hz	1271 Hz	1180 Hz	1180 to1351 Hz	1100 to 1300 Hz
Look Angle	18 to 26 deg	26 to 32 deg	32 to 37 deg	18 to 37 deg	18 to 37 deg
Coverage	248 - 378 km	370 - 490 km	480 - 600 km	248 to 600 km	248-600 km
Ground-range Resolution	21.5 m	16.7 m	14.3 m	14 to 22 m	3 to 5 m
Azimuth Resolution (4-look)	24.7 m	27.4 m	30.8 m	~75 m	25 to 30 m
Average NEσ_0	-31 dB	-32 dB	-31 dB	-31 dB	-25 to -30 dB
Azimuth Ambiguity	-26 dB	-22 dB	-21 dB	-28 dB	-25 to -30 dB
Worst Case Range Ambiguity	-30 dB	-25 dB	-30 dB	-25 dB	-23 to -30 dB
Average Radiated Power	143 W	170 W	160 W	-	166 W
Data Rate	118 Mbits/s	128 Mbits/s	139 Mbits/s	~130 Mbits/s	130-140 Mbits/s

4.4 System Design and Performance

The following table lists the performance details for the three standard InSAR beams (near-, mid-, and far-beams). Swath width, PRF (Pulse Repetition Frequency), etc. vary for each beam to maximize the overall performance. The maximum data rate for the three beams is 139 Mbits/second. The mechanical boresight for all three beams is the same and electronic steering is used to choose between the three beams. Noise equivalent sigma nought (NEσ^o) performance is worst at swath edges and improvement in NEσ^o is the subject of ongoing analysis. ScanSAR combination of all three beams will yield roughly the averaged behavior over the three beams and produce a data rate of 130 Mbits/second.

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Table 4-3. Radar Instrument Performance Details

Parameter	Near	Mid	Far	Requirement
Swath Width (km)	130	120	120	350 km w/10km overlap
PRF (Hz)	1351	1271	1180	
Mechanical Boresight Angle (deg)	30	30	30	
Minimum Look Angle (deg)	18	25.6	31.6	
Maximum Look Angle (deg)	26.1	32.2	37.2	
Range to Midswath (km)	829	886	949	
Start Coverage (km) from Satellite Nadir Track	248	370	480	
Stop Coverage (km) from Satellite Nadir Track	378	490	600	
Ground-range Resolution (m) (15 MHz BW)	21.7	16.8	14.5	< 35 m
Azimuth Resolution (m) (4-look)	24.7	27.4	29.0	< 35 m
Minimum NE σ^0 (dB)	-34	-35	-34	
Maximum NE σ^0 (dB)	-24	-24	-26	< -24 dB
Worst Case Azimuth Ambiguity (dB)	-26	-22	-23	< -20 dB
Worst Case Range Ambiguity (dB)	-30	-25	-30	< -25 dB
Average Radiated Power (W)	143	173	160	
DC Power (W)				
Data Rate (Mbits/sec) (15+7 MHz)	118	130	139	

4.4.1 Noise-Equivalent Sigma Naught (s_0) Goal

The reflection from a scene depends in part on the target type. The minimum return occurs over smooth, dry surfaces. Target models were used to set the minimum system SNR (Signal-to-Noise Ratio); soil is most likely target (shown below); desert and ocean surfaces (not shown) are the worst case targets. Sea-ice is to later be included as a potential target type.

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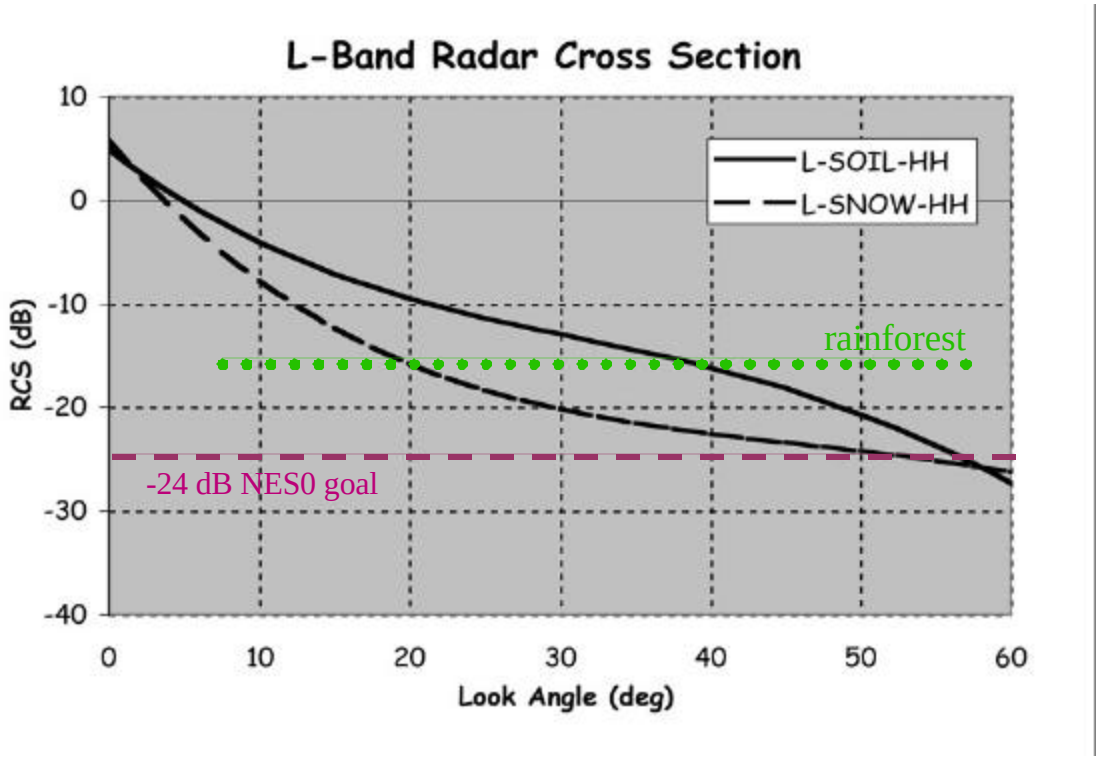
Figure 4-3. Noise-Equivalent Sigma Naught Goal – L-Band Radar Cross Section



4.4.2 Tropospheric Delay Affecting Instrument Performance

The dominant error source for repeat-pass inteferograms is due to path delay variations through the troposphere. The ionosphere is also a potential source of error, but is likely to be less of an error than the troposphere. The magnitude of variations is dependent upon the time- and length-scale of the observations. A dense network of GPS receivers located in Southern California can be used to estimate the variations that will affect repeat-pass InSAR observations.

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Figure 4-4. Tropospheric Delay Affecting Instrument Performance

4.4.3 Tropospheric Effects on Differential Path Length

The following figure shows path length variation measurements through the troposphere using data from the Southern California GPS Network over seven day periods. The path length variations depend, in part, on the length scale between GPS receivers. Increasing the length scale increases the atmospheric delay. Variations as a function of length scale are plotted relative to published theoretical results (Treuhaft and Lanyi 1987), Goldstein (1995), and a mean curve fit through the data (see solid line with 1-sigma bracket, interpolating the measured data). A solid red line is used to show the InSAR measurement accuracy design goal of 5 mm. The InSAR instrument hardware design is such that it will, under most circumstances, contribute less error than that induced by the troposphere.

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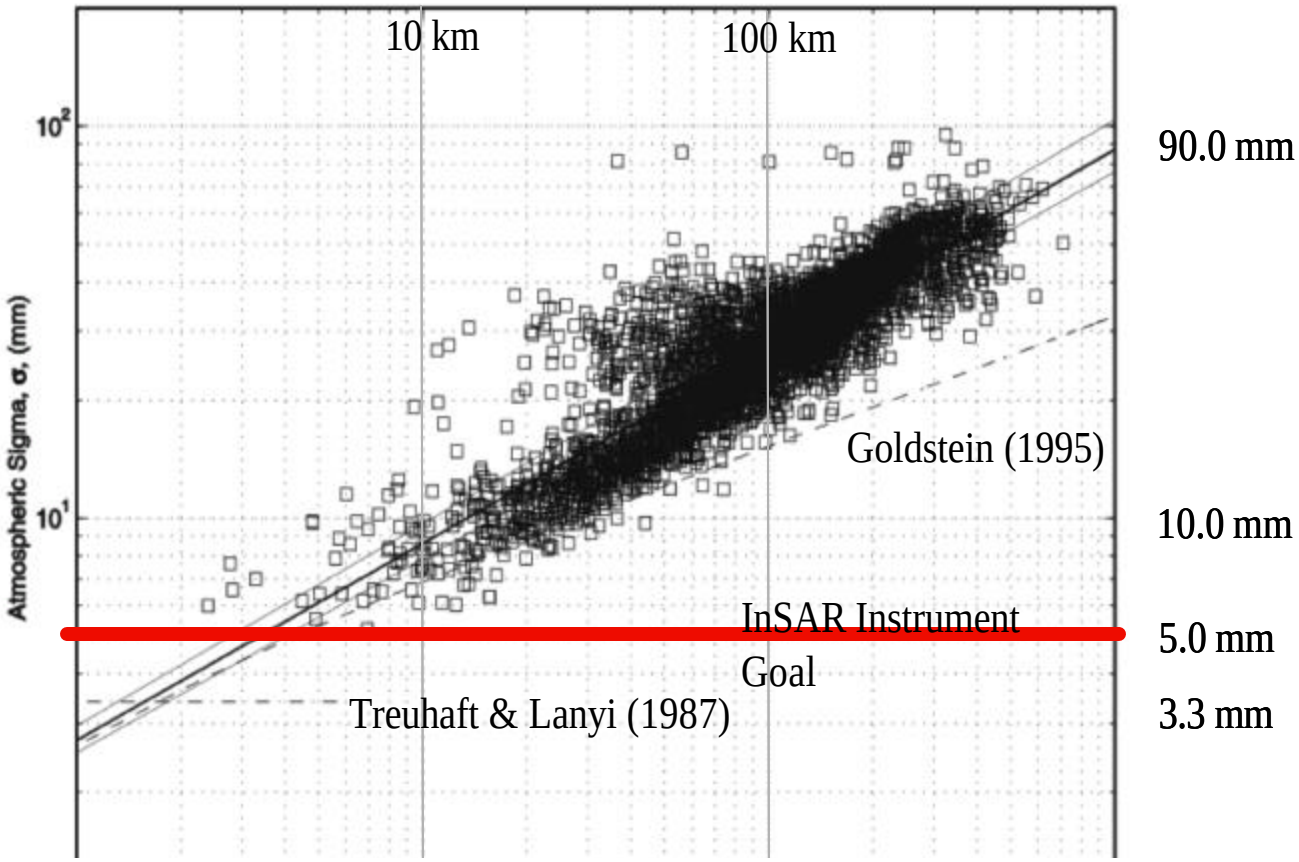
Figure 4-5. Tropospheric Effects on Differential Path Length



Modified from: Emardson, Simons, and Webb, "Neutral atmospheric delay in interferometric SAR applications: statistical description and mitigation," JGR 108(25), 2003. Note: Data taken from Southern California GPS Network. Seven day difference between observations, which are zenith looking (0 +/- 15 degrees) one way path delay.

4.4.4 Tropospheric and Instrumental Error Effects on Observing Period

The following figure/analysis assumes a worst-case scenario where tropospheric effects must be mitigated by averaging interferograms. The actual error induced by the troposphere may be less, depending on observing conditions and the algorithm used for reducing the tropospheric delays. Measurement goals for Glaciology and Solid Earth Science are plotted as points on the plot with axes for Deformation Rate Accuracy requirements and the length scale for the observations. Assuming an eight day repeat cycle and the tropospheric errors measured by the Southern California GPS network plotted in the previous figure, it is possible to estimate the observing period required to meet the accuracy requirements for various targets. The instrument hardware measurement accuracy is independent of the length scale and is designed to be accurate to within 5mm for any pair of interferograms.

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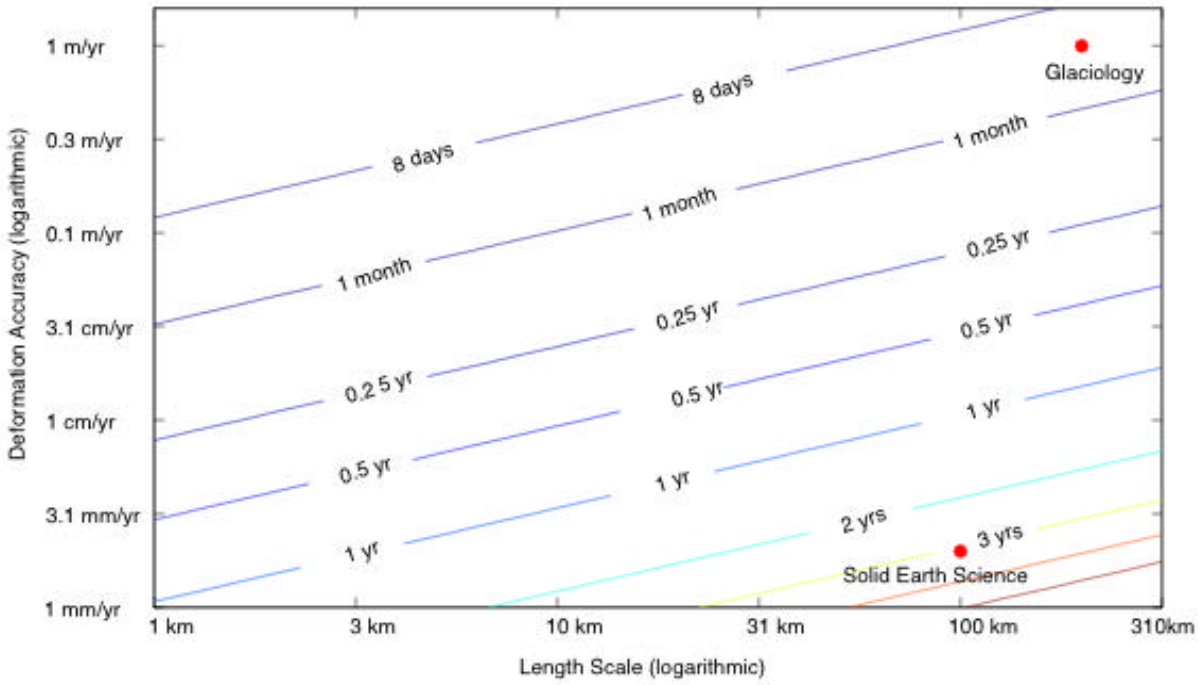
Figure 4-6. Tropospheric and Instrumental Error Effects on Observing Period



4.4.5 Orbital Sensitivity to Deformation

Radar and SAR can measure the distance to targets very accurately. Repeat pass observations can be used to detect slight changes in the distance to the target which can be interpreted as displacement of the target in the line-of-sight direction. Baseline separation between the observations will induce a topographically sensitive measurement. This effect, and the desire to eliminate it, sets the limit on the orbital tube which defines the repeat-pass requirements for the instrument. In the following, the formula for determining the target displacement as a function of the measured phase, ϕ, the look angle, θ, the baseline, B, and the baseline orientation angle, α, is shown. Note that in this case, the topographic component represented by the second term in the boxed equation, is regarded as a source of error.

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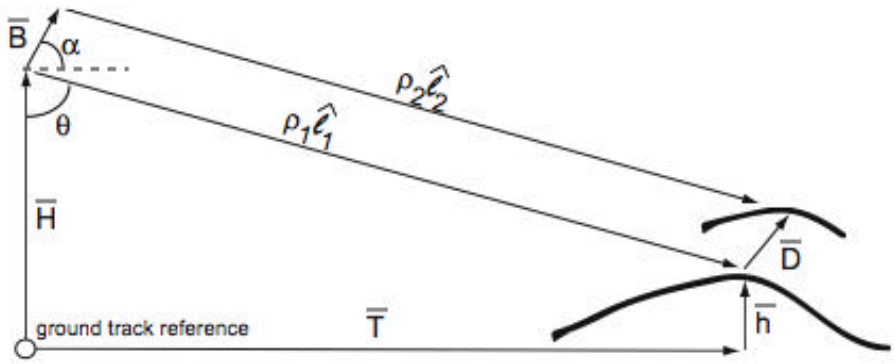
Figure 4-7. Observing Sensitivity to Deformation

$$D_{\parallel} = \hat{l}_1 \cdot \overline{D} = f\,\frac{l}{4p} + B\sin(q - a)$$



$$r_1 = \overline{T} \cdot \hat{l}_1 + \overline{h} \cdot \hat{l}_1 - \overline{H} \cdot \hat{l}_1$$

$$r_2 = \overline{T} \cdot \hat{l}_2 + \overline{h} \cdot \hat{l}_2 + \overline{D} \cdot \hat{l}_2 - \overline{H} \cdot \hat{l}_2 - \overline{B} \cdot \hat{l}_2$$

$$C_N = \frac{\langle E_1 E_2^* \rangle}{\sqrt{\langle |E_1|^2 \rangle \langle |E_2|^2 \rangle}} = g e^{jf}$$

$$f = 2k(r_2 - r_1) \approx 2k\hat{l}_1 \cdot \left(\overline{D} - \overline{B}\right)$$

Note: Observed interferometric phase is sensitive to the surface deformation projected onto the look direction.

4.4.6 Error Budget

The error budget for the instrument can be determined by differentiating the deformation equation above with respect to the various system parameters. The goal for the maximum error contribution from the instrument is for it to be less than 5 mm. Among the contributing error sources such as phase noise (ϕ), and the wavelength error (related to the STALO [Stable Local Oscillator] stability), is the error induced by errors with respect to the viewing geometry. These viewing geometry errors can be minimized by minimizing the separation between flight tracks of the InSAR platform. That is, minimizing the baseline, B. Given that the instrument measurement requirements are to be <5 mm per interferometric pair, we next split the error into its constituent sources in the following figure.

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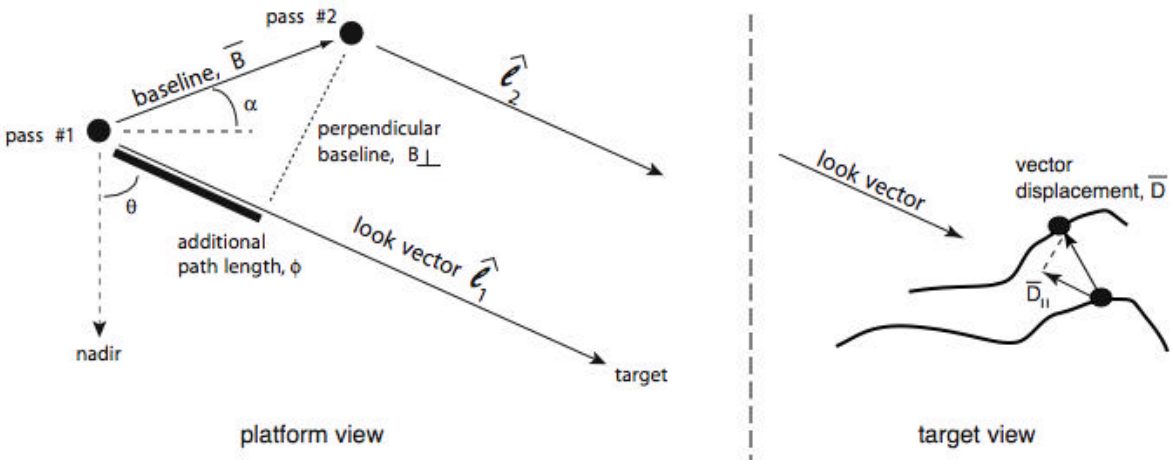
Figure 4-8. Error Budget – Differentiating the Deformation Equation

$$s_{D_{\parallel}}^{2} = \left(\frac{\P D_{\parallel}}{\P f}\right)^{2} s_{f}^{2} + \left(\frac{\P D_{\parallel}}{\P l}\right)^{2} s_{l}^{2} + \left(\frac{\P D_{\parallel}}{\P B}\right)^{2} s_{B}^{2} + \left(\frac{\P D_{\parallel}}{\P q}\right)^{2} s_{q}^{2} + \left(\frac{\P D_{\parallel}}{\P a}\right)^{2} s_{a}^{2}$$

$$s_{D_{\parallel}}^{2} = \left(\frac{l}{4p}\right)^{2} s_{f}^{2} + \left(\frac{B}{l}\sin(q-a)\right)^{2} s_{l}^{2} + s_{B}^{2} + \left(\frac{B\cos(q-a)}{r\sin q}\right)^{2} \left[s_{h}^{2} + s_{H}^{2} + \cos^{2} q\, s_{r}^{2}\right]$$



4.4.7 Orbital Tube Requirement

The tolerance of the orbital tube is set in part by the amount of error considered acceptable in the measurement and the knowledge of the observing geometry. Assuming a ten meter error in the knowledge of topography, the impact of increasing the baseline can be determined. The orbit tube is set by assuming both left- and right-looking geometries. This creates an orbit tube requirement that is symmetric about the nadir look direction. The plot in the following figure shows 15, 10, and 5 mm errors that would be induced in the deformation estimates due to a 10 meter inaccuracy in the measurement of topography. The diameter at the narrowest part of the orbit tube is approximately 250 meters. Orbital tube geometry and dimension is set by knowledge of the look angle (i.e. topography) and baseline decorrelation. Shown below is the error induced in the deformation measurement due to a 10 m accuracy in the surface topography.

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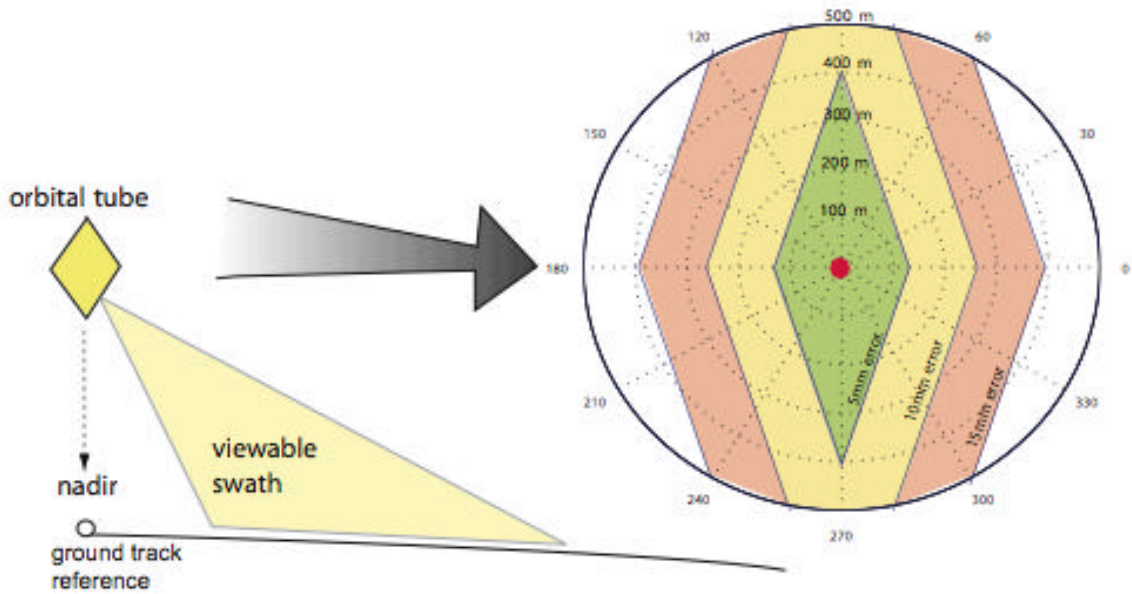
Figure 4-9. Orbital Tube Requirement – Error Induced in Deformation Measurement (10 m Surface Topography Accuracy Assumed)



$$D_{\|} = \hat{l}_1 \cdot \overline{D} = f\,\frac{l}{4p} + B\sin(q - a)$$

4.4.8 Instrumental Error Sources

In addition to errors induced by inaccuracies in the knowledge of the viewing geometry, are phase noise and wavelength related errors which affect the overall accuracy of the deformation measurement. The following figure shows the measured interferometric correlation in the complex plane. The magnitude of the measured correlation, γ, is a measure of the phase noise, the temporal decorrelation and the volumetric decorrelation of the measurement. The phase of the measured correlation, γ, is what is used in the deformation equation for determining the surface deformation in the along track direction. The figure illustrates how increasing phase noise decreases the accuracy of the interferometric phase measurement.

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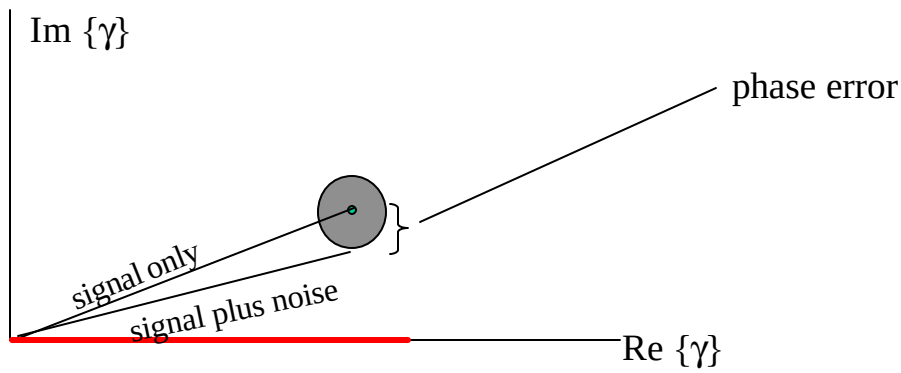
Figure 4-10. Instrumental Error Sources

$$D_{\|} = \hat{l}_1 \cdot \overline{D} = f\frac{l}{4p} + B\sin(q - a)$$



$$s_f^2 = \frac{1 - g_{obs}^2}{2Ng_{obs}^2} \qquad g_{obs} = g_{SNR}g_{geom}g_{temporal}g_{vol} \qquad g_{SNR} = \frac{S}{S+N}$$

Note: Instrumental phase noise will affect the accuracy for measuring deformation.

4.4.9 Contributing Sources to Measurement Phase Noise

There are a number of sources which contribute to measurement phase noise. These are as follows: integrated Side-lobe Ratio (ISLR) for the point target response; range (including nadir return) and azimuth ambiguities in the image; thermal noise; quantization noise induced by data compression; and baseline decorrelation. Phase noise can be controlled by controlling the dominant sources of this phase noise. The methods for ameliorating the phase noise for each of the above error sources are listed in the following table.

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Table 4-4. Methods of Controlling Measurement Phase Noise

Phase Noise Source	Method of Control
ISLR	Interpulse jitter and STALO stability
Range Ambiguities (including nadir return)	Pulse timing and antenna steering, antenna dimensions, antenna weighting
Azimuth Ambiguities	Processing bandwidth and PRF, antenna dimensions
Thermal Noise	Effective noise temperature, transmit power, antenna dimensions
Quantization Noise	Quantization bits, downlink data rate
Baseline Decorrelation	Orbit tube, bandwidth

4.4.10 The InSAR Beams

For the InSAR standard observing mode, data will be collected from one of three beams which compose the total “viewable” swath (350 km wide). In what follows, for each beam, a plot of the total signal to noise ratio over the extent of the swath covered by the beam is plotted. The L-band soil target backscattering cross section dependence on look angle that was used for calculating the SNR can be found in the Noise Equivalent Sigma Nought Goal Section and Figure of this report. Also listed in the figures below are relevant parameters which specify the configuration and performance of the instrument. Following the figures showing total SNR and the instrument parameters for each beam are figures illustrating displacement error as calculated by the equation for displacement error described in the Error Budget Section of this report. In addition to the total displacement error, the two principal contributing components to the total displacement error are shown as well. These are: 1) the displacement error from instrument-induced decorrelation (or phase noise), and 2) the displacement error from topography (or knowledge of the topography) to within 10 m. The latter of these errors is related to the orbit tube, and can be improved by reducing the navigational accuracy of the platform or increasing the accuracy of the topographic knowledge. The decorrelation error from system noise, by contrast, can be controlled through the design of the instrument.

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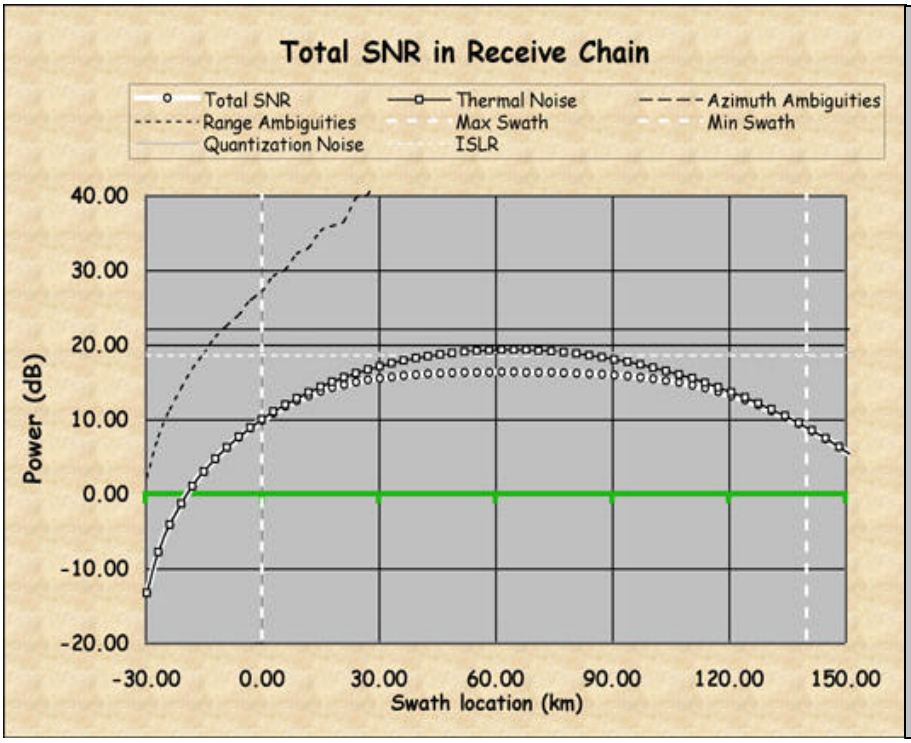
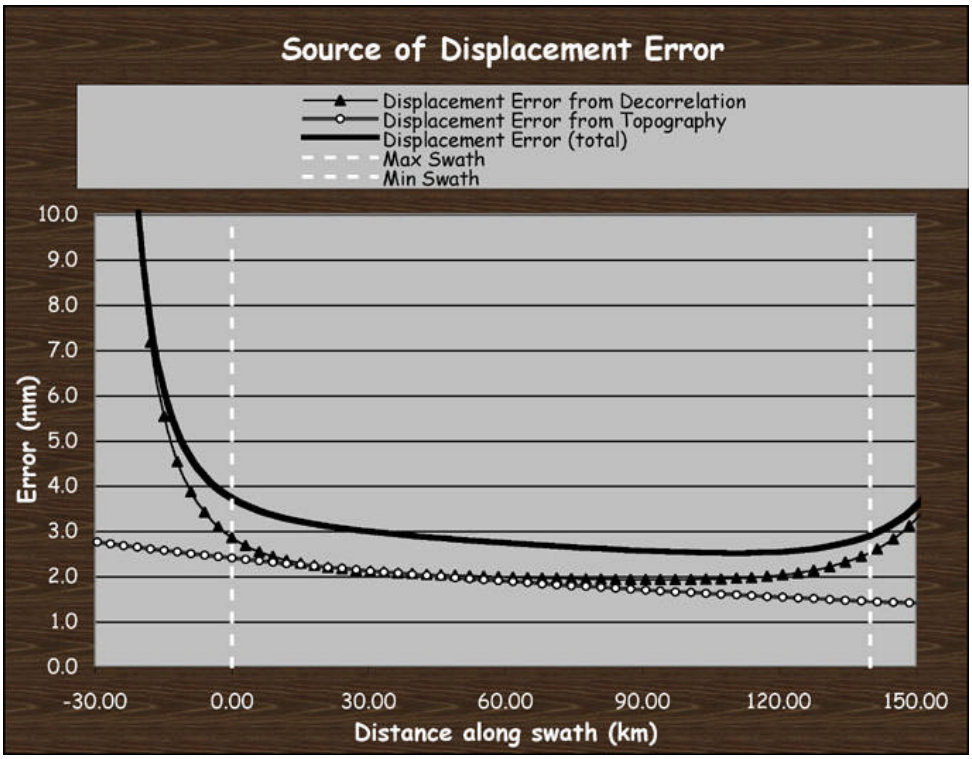
Figure 4-11. InSAR Beam 1 – Total SNR



- Imaging from 248-388 km past nadir (140 km swath).
- 18^0 to 26^0 look angle
- 3.4kW power
- 40 usec pulse
- (15+7) MHz BW
- 53 MHz sampling
- 800K effective noise temp
  - -19 dB ISLR
- 14 of 18 elements used on transmit, Hamming weighting on return.
- 13.8 m x 2.5 m aperture
- 740 usec interpulse period
- 1347 Hz PRF
- 127 Mbits/sec

Note: As shown above, InSAR Beam 1 errors are dominated by thermal SNR and ISLR.

Figure 4-12. InSAR Beam 1 – Displacement Error



Note: InSAR Beam 1 displacement accuracy is ~ 3 mm across the 140 km

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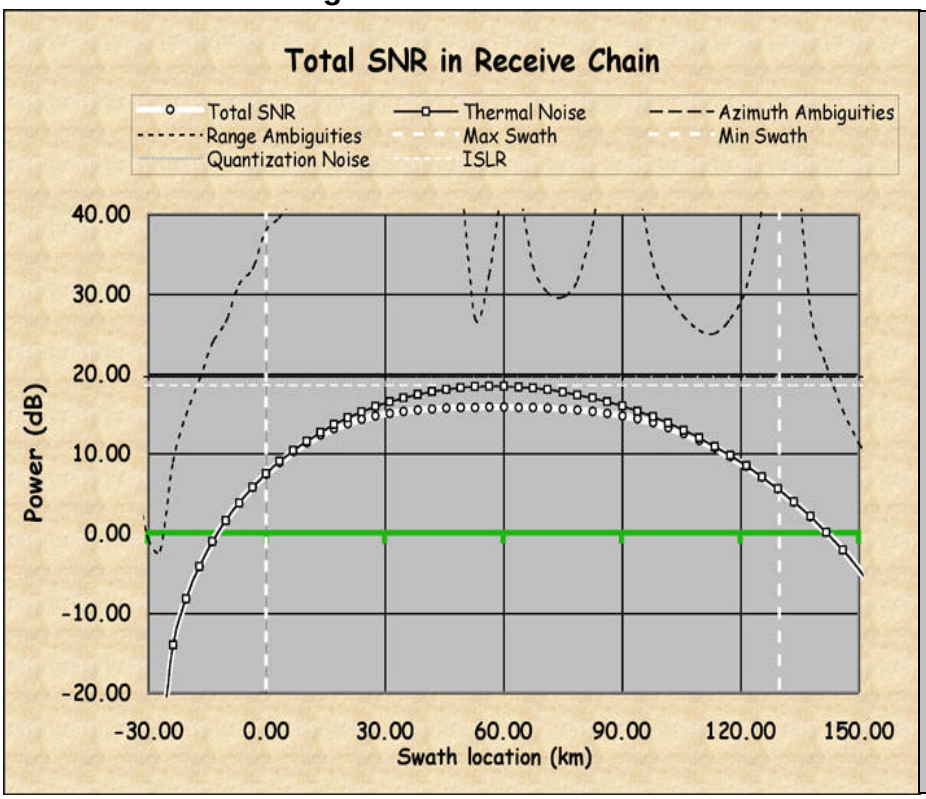
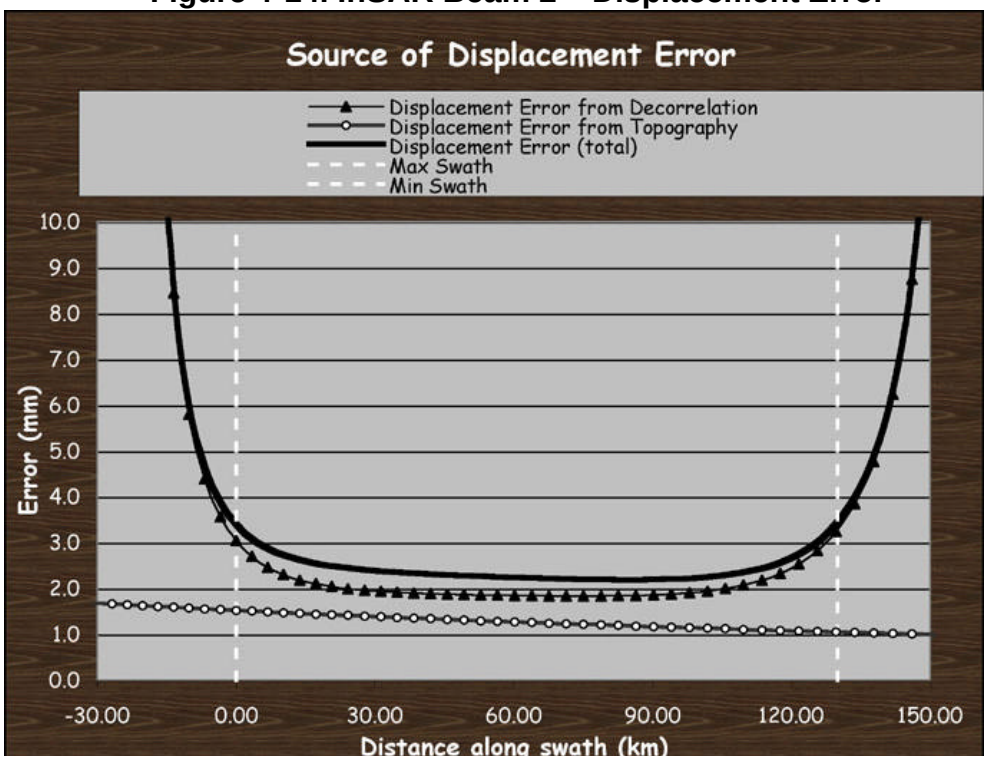
Figure 4-13. InSAR Beam 2 – Total SNR



- Imaging from 370-500 km past nadir (130 km swath).
- 25.6^0 to 32.6^0 look angle
- 3.4kW power
- 40 usec pulse
- (15+7) MHz BW
- 53 MHz sampling
- 800K effective noise temp
- -19 dB ISLR
- full aperture used on transmit, cosine weighting on receive
- 13.8 m x 2.5 m aperture
- 791 usec interpulse period
- 1252 Hz PRF
- 138 Mbits/sec compressed

Note: As shown above, InSAR Beam 2 errors are dominated by thermal noise.

Figure 4-14. InSAR Beam 2 – Displacement Error



Note: InSAR Beam 2 displacement accuracy is ~ 2.5 mm across the 130 km swath; Nadir return in receive window removed by antenna null

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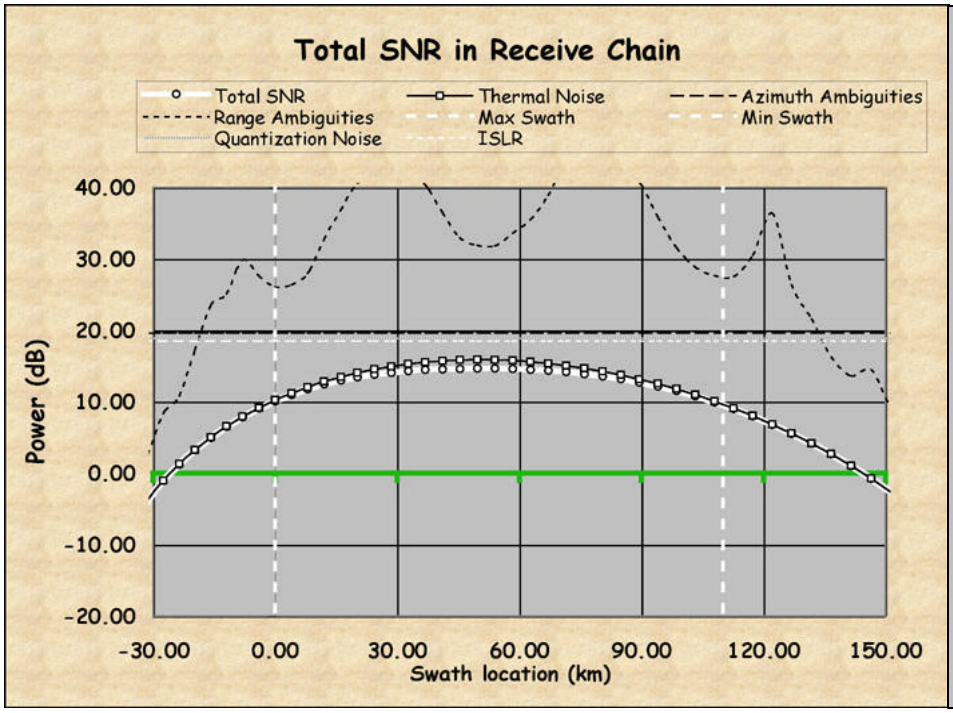
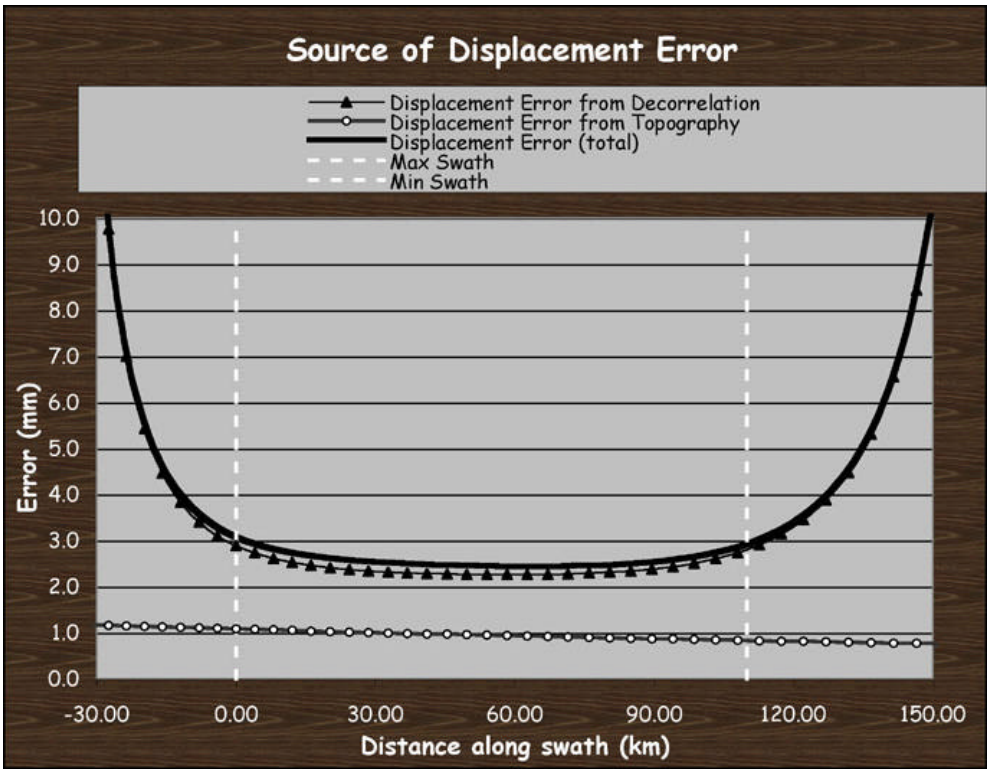
Figure 4-15. InSAR Beam 3 – Total SNR



- Imaging from 490-600 km past nadir (110 km swath).
- 32.2^0 to 37.2^0 look angle
- 3.4kW power
- 40 usec pulse
- (15+7) MHz BW,
- 53 MHz sampling
- 800K effective noise temp
- -19 dB ISLR
- full aperture on transmit, cosine weighting on receive
- 13.8 m x 2.5 m aperture
- 791 usec interpulse period
- 1176 Hz PRF
- 128 Mbits/sec compressed data rate

Note: As shown above, InSAR Beam 3 errors are dominated by thermal

Figure 4-16. InSAR Beam 3 – Displacement Error



Note: InSAR Beam 3 displacement accuracy is ~ 2.5 mm across the 100 km

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4.5 Payload System Description

The previous discussion linked the science requirements to the instrument performance. In this section we present the InSAR instrument design which responds to the radar performance requirements discussed in the previous sections. A review of the radar hardware components which can be used to achieve the instrument performance is then described including the technical maturity.

A block diagram of the InSAR radar instrument, along with other details on the instrument design and performance, can be found in the Payload System Foldout. The InSAR instrument payload is composed of three fundamental subsystems. These are:

RF Electronics Subsystem (RFES): Responsible for frequency synthesis and generation of the linear-FM (chirp) signal and its up-conversion to the carrier frequency (L-band); generation and routing of the system calibration tone; and downconversion of the received L-band echo to offset-video for digitization.

Antenna Subsystem: Responsible for the network distribution (feed) of the chirped carrier signal to the antenna elements, phase shifting to adjust elevation antenna steering, transmit power amplification, radiating antenna elements, and low noise amplifiers for the receive signal which is routed through the antenna feed to RFES for downconversion.

Digital Electronics Subsystem (DES): Responsible for the sampling of the offset video signal, digital filtering of this signal to extract only in-band chirp signal, compression of the digital signal from N bits to M bits (nominally, N=8, M=4), formatting of the range line data and appending of header data to each range line, and final buffering of the signal prior to storage on the spacecraft's data storage system (nominally 256 GBytes deep for holding science data). The DES is also responsible for coordinating the InSAR instrument timing and control, through the Command, Timing and Control Interface and the Flight Computer which communicates with the spacecraft's GPS and navigational systems via the spacecraft's 1553 communications bus.

4.6 Radar Instrument Mass and Power Budget

A current best estimate (CBE) for the radar instrument mass and power budget is detailed in tabular format on the Payload System Foldout. The Antenna Subsystem (consisting of the antenna aperture, the T/R modules and other antenna electronics, and the antenna support structure) dominates both the mass and power budgets for the overall Payload System by about a factor of ten. A 30% contingency is carried to give a CBE for the weight and power for the total InSAR Payload System of 597 kilograms and 1758 Watts respectively.

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4.7 Payload Accommodation

Several instrument configurations have been studied including previous SAR designs (e.g., the ECHO design). The ECHO design utilized the Astrium spacecraft bus, had a baseline antenna size of 2 m x 13.8 m, and was designed to fit within the Dnepr launch vehicle fairing. To increase the performance margin the InSAR mission is baselining a larger SAR antenna compared to ECHO. The Spectrum Astro SA-200HP bus was examined for the InSAR mission. The resulting preliminary Flight System configuration included accommodation of the larger (2.5 m x 13.8 m) InSAR antenna and met the Delta II 2920-10 payload fairing volume constraints. The Ball Aerospace BCP 2000 bus was also examined for the InSAR mission. This configuration included the larger SAR antenna (2.5 m x 13.8 m) and preliminary analysis indicates the design can meet the Delta II 2920-10 payload fairing volume constraints. Previous studies and the InSAR industry survey effort give high confidence in the ability to accommodate the InSAR payload on a commercial spacecraft bus.

4.8 Radar System Architecture

Shown in the figure below is a block diagram of the receive chain, which is broken up into subcomponents to illustrate the basic system architecture. After reception, amplification and downcoversion, the analog signal is digitally sampled and digitally filtered (nominally into two bands; a 15 MHz band a 7 MHz band). The two receive bands are decimated in time then compressed using a block floating point quantizer (BFPQ) to reduce the data rate. If a split spectrum approach is used, the two data streams are also concatenated, one after the other to form the rangeline data stream. Appended to this stream as a 1 kByte header is the GPS and relevant spacecraft data (such as attitude, etc.) which will be used in processing. The science data is stored on the spacecraft bus solid state recorder (SSR) until the next available opportunity for downlink to the ground station.

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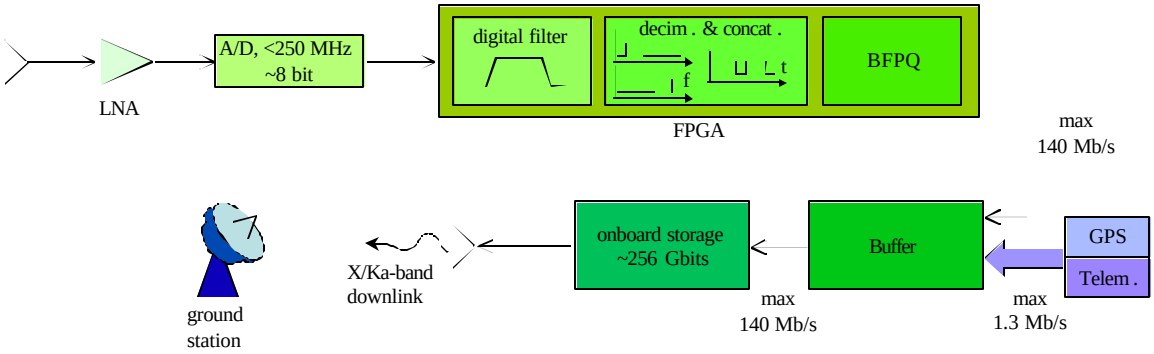
Figure 4-17. Payload System Receive Chain



4.9 Payload System – Subsystem and Component Discussion

A technology survey was conducted to assess past technology investments and new candidate technologies to understand adaptability to InSAR. What follows is a brief review of the key radar hardware components under consideration for InSAR.

4.9.1 Antenna Subsystem

The Antenna Subsystem analysis consists of the results of an industry survey for determining the current best estimate of the relevant power efficiency and weight characteristics of available systems. High TRL antenna technology can be used to achieve the InSAR requirements with low implementation risk and sufficient mass and power margin. Emerging lightweight antenna technologies are also being developed that can further reduce antenna mass and power. Results of this survey have shown that the current systems at high TRL will meet InSAR hardware requirements to remain within the mass and power budgets allocated to this subsystem.

The candidate antenna technology is a honeycomb microstrip patch array consisting of 9 panels deployed with a lightweight deployment structure. Each panel includes a radiating aperture and microstrip panel corporate feed network; distributed T/R modules (20-30 Watts Tx, >40% efficiency, <3dB NF Rx, 6-bit phase shifter, 6-bit attenuator); coaxial array feed, signal and power distribution harness; array controller, and DC-DC converters. The antenna mass density is <12 kg/m^2 (panels + deployment structure).

4.9.1.1 Antenna Mechanical Subsystem

The InSAR candidate antenna mechanical subsystem technology is an ABLE Engineering design (see following figure) based on the flight truss for RadarSat-2. The truss members have M55J graphite epoxy Ø1.0 inch X 0.050 inch walls and bonded titanium fittings. One DC brushless planetary gearmotor per wing is used to deploy the

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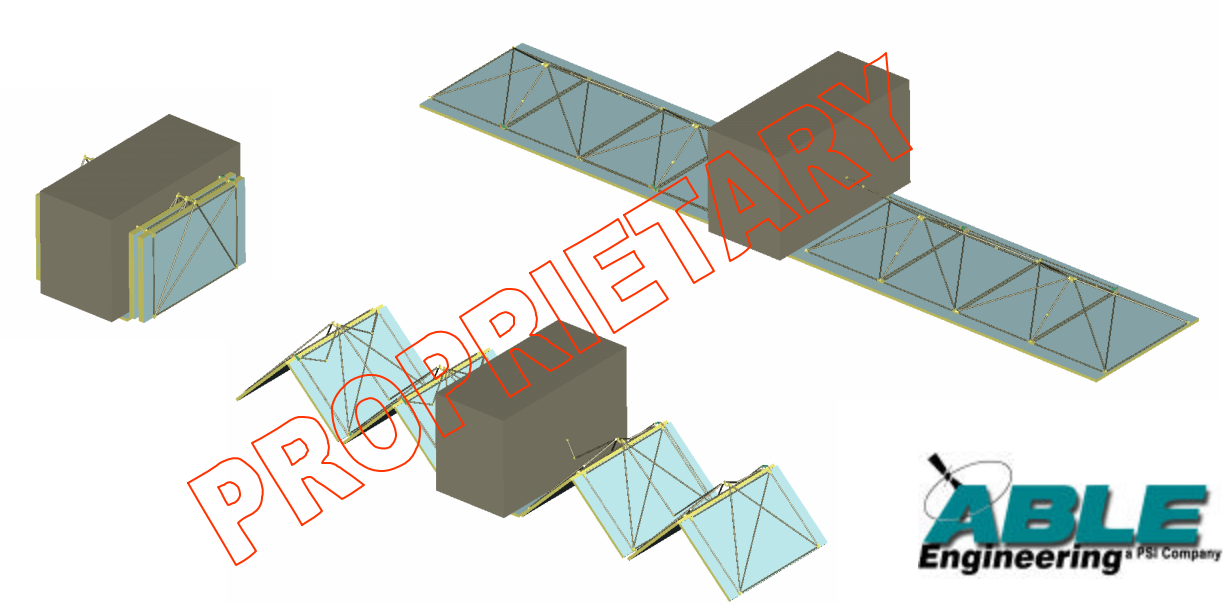
truss. The system uses redundant drive electronics and redundant windings in the gearmotors. The truss mass is 82 kg (CBE), including motors and drive electronics. The current antenna design is a nine panel design consisting of two deployable wings (consisting of 4 panels each) and a fixed center panel. The fixed center panel/support structure mass is 24 kg (CBE) and each of the additional 8 panels have a mass of 19.8 kg (CBE).

Figure 4-18. Candidate Antenna Subsystem Deployment Depiction



4.9.1.2 High Efficiency L-band T/R Module

The T/R module is a key component in the radar antenna. The T/R module performs power amplification and phase shifting of the L-band carrier signal on transmit; and low noise amplification phase shifting on receive. It also includes amplitude control on receive to allow an amplitude taper if desired.

JPL is currently developing high-efficiency (>60%) 30 Watt L-band T/R modules using high-efficiency Class-E/F amplifiers (see figure below) under funding from the Earth Science Technology Office (ESTO) Advanced Component Technology Program (ACT). This high-efficiency T/R module was breadboard demonstrated in 2003 and is currently rated at TRL 4. Future improvements include increasing efficiency, miniaturizing packaging and addressing space-qualification. Currently, a miniaturized prototype is to be developed and completion by October 2004 is expected. Lower efficiency (~30-40%) T/R modules (at TRL 6) can be commercially purchased. The InSAR hardware design assumes a conservative T/R module minimum efficiency of 30% to calculate DC power requirements.

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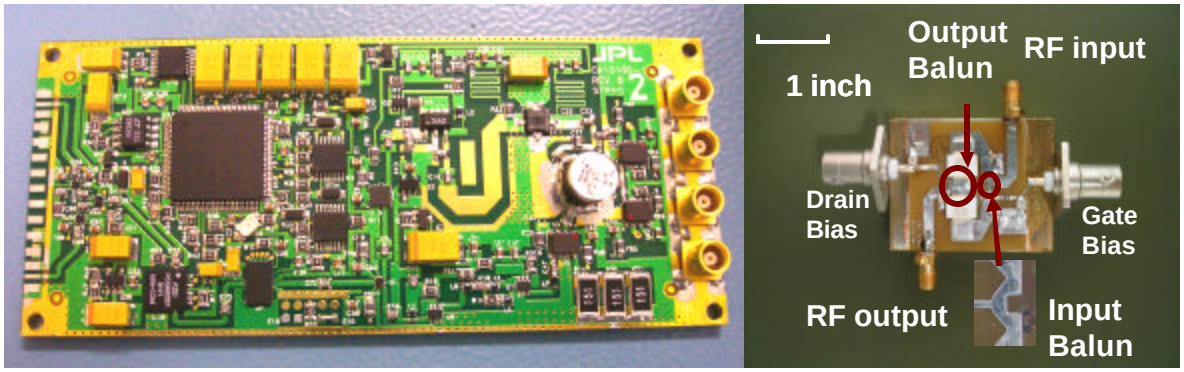
Figure 4-19. 30W T/R Module Prototype and 35 W Class-E/F Power Amplifier developed under the ACT Program



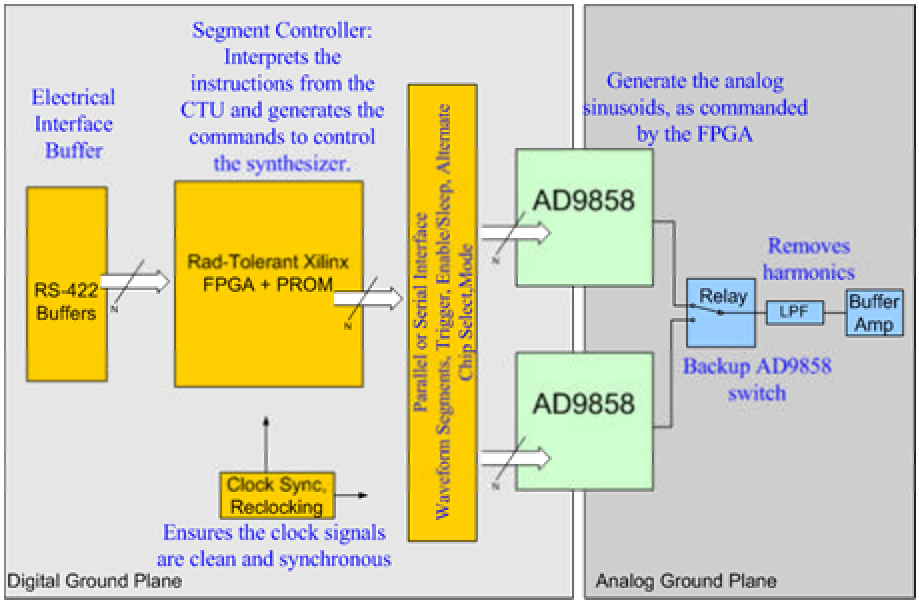
35W PA with 70% drain efficiency

4.10 Radio Frequency Electronics Subsystem (RFES)

4.10.1 Digital Chirp Generator

The Digital Chirp Generator (DCG) is constructed from a DDS (Direct Digital Synthesizer) which includes an NCO (Numerically Control Oscillator) with an integrated DAC (Digital Analog Converter), and a controller, such as an FPGA (Field Programmable Gate Array). The FPGA commands the DDS to generate the various required chirp and continuous wave signals in proper sequence. The concept depicted below integrates an FPGA, which acts as an interface and waveform sequence controller, with redundant DDSs, a selection switch, filtering to remove the DAC harmonics, and a buffer amplifier to provide reasonable output power.

Figure 4-20. Digital Chirp Generator with Integrated FPGA



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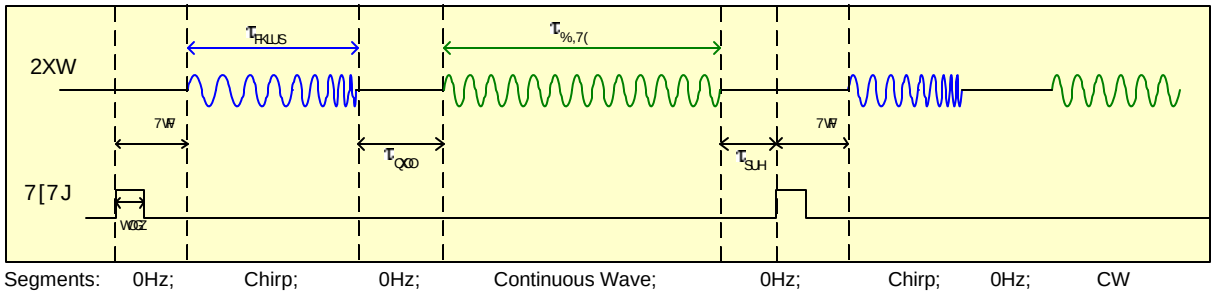
By adding an FPGA to the Direct Digital Synthesizer, one creates a segment-based synthesizer, where each segment is part of the transmitted waveform (see figure below). By passing a Start Frequency and a Delta Frequency, one may generate a chirp or a continuous wave signal. (Delta Frequency for CW is 0 Hz.)

Figure 4-21. Transmitted Waveform



We completed a survey of DDS parts that would meet our requirements for InSAR and other radar missions. Two candidate DDS technologies for the digital chirp generator have been investigated. The first was the moderately high DC power (15 W), high TRL (6) design using the STEL-2375B GaAs DDS, which is currently being developed for the WSOA project. The second candidate technology is a low DC power (3 W), lower TRL (4) design using the AD9858 CMOS DDS. Both of these DDS technologies will satisfy current InSAR hardware requirements. The InSAR study (in cooperation with other development programs) is advancing the TRL of both of these candidate technologies. Down selection will occur prior to mission start.

The AD9858 was very attractive since it is low cost, low power, programmable and has performance specifications comparable to the STEL-2375B. The two primary issues with the AD9858 were the radiation susceptibility and the reliability of the part. We opted to purchase a large number (360 pieces total) of the AD9858 as potential flight parts (pending radiation and reliability test results). The parts were procured by the JPL Parts Specialist as flight parts and have been stored in the JPL Flight Stores. These parts are now available for use by InSAR and other projects to develop their own semi-custom digital chirp generators. For InSAR, we have completed the design, fabrication and test of a DCG prototype using the AD9858. This component will be integrated in the InSAR Radar Testbed in the future. We expect that the external interfaces might change, and some analog components might change to meet various mission requirements, however, the majority of the design will be agile and customizable through straightforward changes in the firmware.

Another aspect of this effort was to perform radiation testing on the AD9858 to determine what the linear energy transfer (LET) level is that causes single-event-latchups (SEL) events, since it is well known that CMOS technology is prone to single-event-latchups. Second, radiation testing was conducted to determine the TID level that this part could survive and operate without serious degradation in performance. A major factor in the testing of this part is the fact that these types of testing are generally valid only for the

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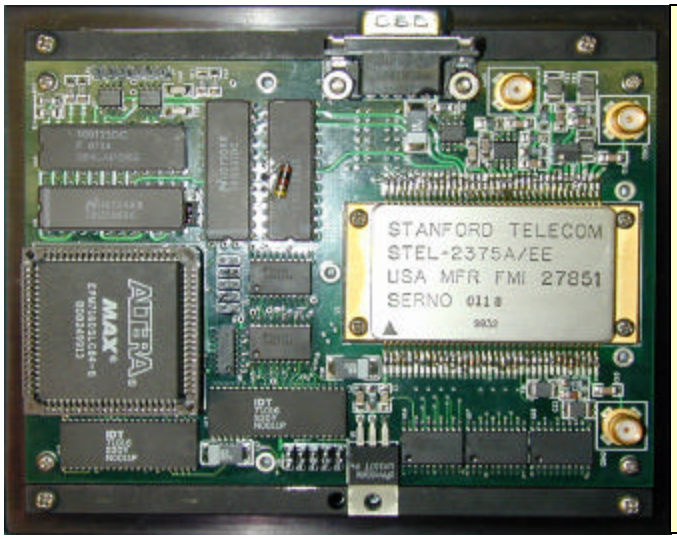
devices from the same semiconductor wafer, as the physical characteristics, such as circuit trace thickness, may vary considerably between wafer lots. Therefore, we purchased a large number (120 pieces each) from three different lots to get a statistical sampling across lots, and the have parts to use in flight should any of the lots prove to be acceptable for flight.

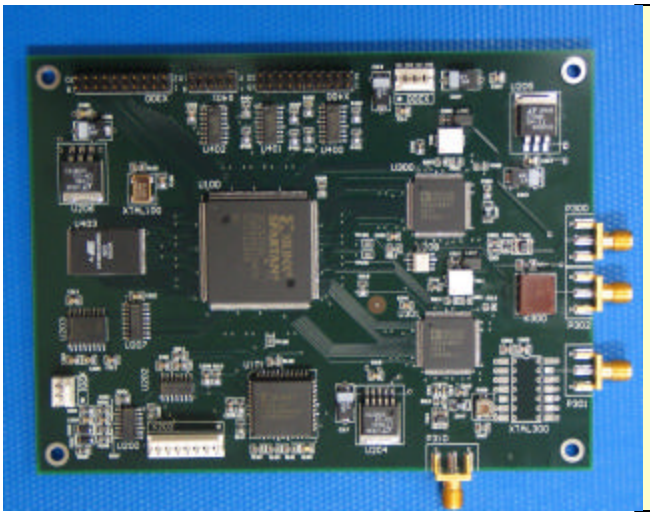
Since we anticipated that these devices would be susceptible to SELs, our prototype board contains a primary and redundant AD9858. Should one device suffer a catastrophic SEL, that device could be powered off, and the back-up powered on. While both parts will suffer some degradation due to the ambient radiation, the SEL effect is only an issue for powered components. In this way, we further reduce the chances of a fatal SEL.

Figure 4-22. STEL-2375B High-Speed GaAs NCO-Based Digital Chirp Generator



- STEL-2375B GaAs NCO, 400 MHz max BW, 40 dB SFDR, 15 W DC
- Currently at TRL 6. Prototype built and tested, airborne validated. STEL-2375B received preliminary acceptance by WSOA project. EM completion by Jan 05.
- This part is baselined for WSOA. InSAR will track its development.

Figure 4-23. AD-9858 Low-Power CMOS NCO-Based Digital Chirp Generator



- AD-9858, CMOS NCO, 400 MHz max BW, 40dB SFDR, 3 W DC.
- Currently at TRL 4. Prototype demonstrated in lab. Preliminary radiation testing of NCO completed. Reliability assessment is planned.
- 360 flight parts procured (3 lots) and may be used for InSAR pending radiation/reliability results.

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4.10.2 L-band Transceiver

The L-band Transceiver takes the IF chirp generated at 142.5 – 222.5 MHz and upconverts it to L-band (1220 – 1300 MHz) with a local oscillator of 1440 MHz (thus inverting the spectrum). Using this high-side LO mixing scheme produces no mixing intermodulation products in the L-band chirp. In the Receive chain, it is desirable to avoid requiring very sharp filters since they are more sensitive to phase vs. temperature variations, and are more bulky. So, the L-band filter is generous and its purpose is to only limit possible interference and noise into the receiver. With an LO of 1320 MHz (again inverting the spectrum) the resulting baseband frequency range of 22.5 to 102.5 We chose an offset video frequency range of 22.5MHz to 102.5MHz to be digitized at 250MSps. The high oversampling ratio enables the actual band shape to be determined by the digital filters, whereas the low pass filter (LPF) after the mixer is only required to filter the mixing image and reduce the noise into the digitizer. Digital filtering would provide consistent and temperature independent performance and also enables selection between multiple filter parameters as required by the different operating modes of the radar. Post digital filtering, the data will be decimated appropriately, in order to minimize the data rate out. This is an acceptable trade-off since the digitizer bandwidth was still realizable with commercial devices and the decimation performed by the digital filters would eliminate the excess bandwidth.

The RF transceiver also includes T/R switches to diplex the transmit and receive signals such that a single feed to the antenna can be used. These T/R switches also enable a calibration signal to be injected into the receiver chain for a Built-In-Test (BITE) capability. The noise figure was optimized to the extent that a moderately low noise amplifier (LNA NF<2dB) was selected but the front-end switches were selected for their good isolation and acceptable loss. The LNA also has a sufficiently high intercept point to avoid saturation when configured in the back-end of the system. A programmable attenuator was incorporated to provide adequate dynamic range in the event that the terrain echo amplitude varies significantly. Components were selected according to the following guidelines: radiation hardness (i.e., GaAs or related technology), small size, and low power. Care was also taken to minimize parts count and part type, thus minimizing the cost of parts upscreening to qualify for space-flight environment.

The TRL of the L-band Transceiver is 6. The module was designed, built and tested in a laboratory environment. Detailed testing of the module included: (a) frequency response (passband ripple, out-of-band rejection, amplitude and phase linearity over frequency); (b) transmit and receive isolation; (c) receiver gain compression; (d) local oscillator (LO) power sensitivity; (e) receiver recovery time from saturation; and (f) receiver noise figure. The figures below shows the block diagram and photos of the actual hardware of the RF transceiver that was designed and built under internal R&TD funding and later tested under the InSAR study task. It is miniature (15.5x6x2.2cm), lightweight (270g), low power (<3W) and rad-hard (GaAs).

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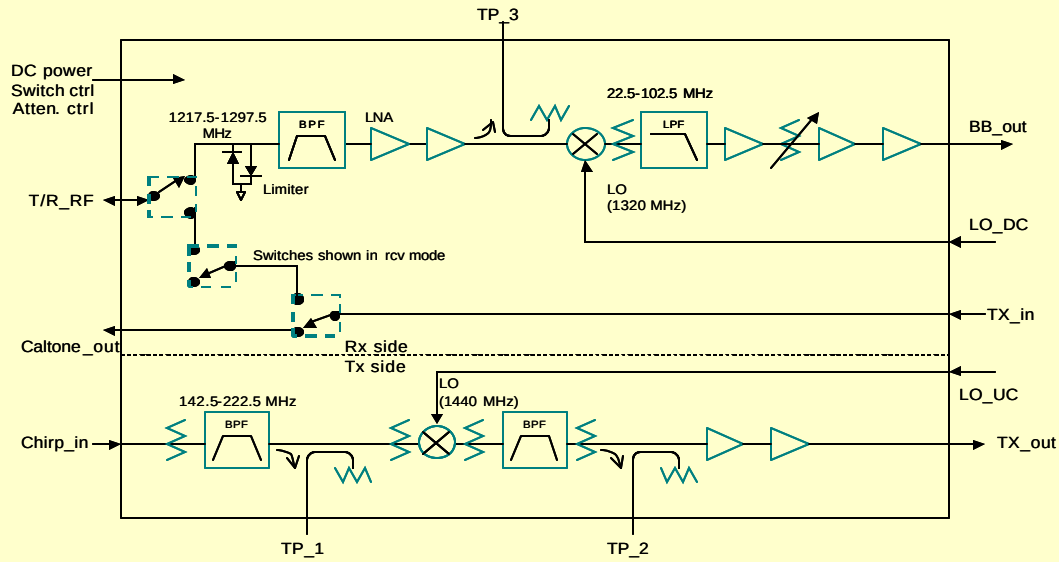
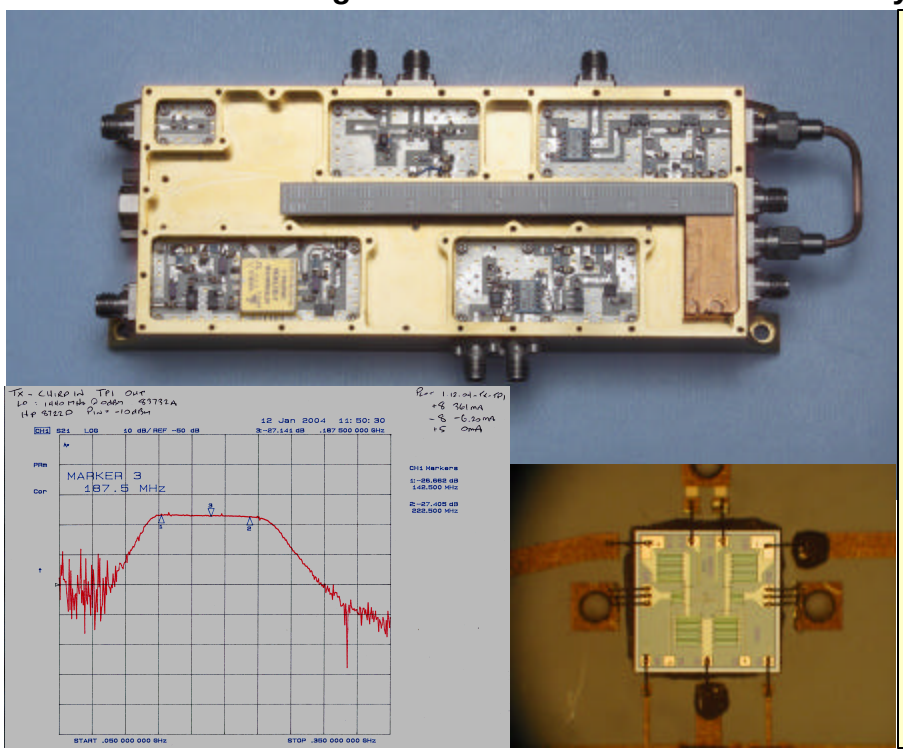
Figure 4-24. L-Band Transceiver Block Diagram



Description:
Provides all RF functionality between Digital Subsystem and T/R module:
- Up/downconversion; Signal amplification; Gain control; Caltone routing;
- Is miniature, low power, and rad hard

Key features:
- High-side LO mixing scheme produces no in-band intermodulation products on transmit chirp
- Good image rejection with single mixing stage on receive
- Bandwidth selection (split spectrum or 80 MHz) using digital filters eliminates need for sharp (and bulky) RF filters sensitive to phase and temperature variations

Figure 4-25. L-Band Transceiver Prototype



Key Specifications:

- Bandwidth: 80 MHz
- Rx Gain: 94 dB max (15 dB programmable attenuator, 1 dB steps)
- Rx Output 1 dB compression: 17.5 dBm
- Tx gain: 15.5 dB
- Tx output power: 16 dBm
- Tx/Rx isolation: 97 dB
- Power dissipation: < 3 W
- Rad hard RF electronics
- Hybrid/SMT miniature package (270 g)

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4.10.3 Frequency Synthesizer

The frequency synthesizer uses a STALO as a reference to provide system clock signals and local oscillator frequencies for signal upconversion and downconversion. The design approach for the synthesizer is picked with consideration into the number of frequencies required, their harmonic relationship, power and size constraints, spectral purity, reliability etc. Typically a phase locked oscillator (PLO) is chosen since it provides several benefits: arbitrary frequency selection; the design can be duplicated with minor modifications for the different frequency outputs required; it is low power, high reliability, and has high spectral purity. As an alternative, a step recovery diode can be used to generate harmonics and the desired harmonic can be filtered and amplified. This approach limits the frequency choices, is power inefficient and may have reliability issues related to power dissipation. The phase locked loop (PLL) multiplier is a phase locked loop that has its bandwidth optimized for best phase noise/spur performance for a fixed frequency output. This approach is appropriate when stringent performance requirements demand it, although this custom approach is more costly. InSAR has baselined a PLO-based Frequency Multiplier for maximum flexibility, scalability and lowest implementation risk and cost.

Table 4-5. Frequency Synthesizer Approaches Considered

Phase Locked Oscillators (PLO)	Phase Locked Loop (PLL) multipliers	Step Recovery Diode (SRD) multipliers
- Arbitrary frequency selection - Scalable design to other frequencies, powers - High spectral purity - Reliable and low risk - Moderate power consumption - Proven design (TRL 6)	- Performance (phase noise/spurs, power) optimized for fixed frequencies - Lower power - Custom design - Less adaptable to other applications	- SRD generate harmonics where desired harmonic is filtered and amplified - Limited frequency choices - Power in-efficient - Reliability concerns

4.11 Digital Electronics Subsystem

4.11.1 Data Handling System

The high-rate data handling system consists of an 8-bit analog-to-digital converter (ADC), demultiplexer, digital filters, signal compression (through BFPQ), data formatters and buffers. An 8-bit, 250 MHz A/D converter with >80 MHz analog bandwidth is used to generate the digital signal. The higher (than Nyquist) sampling frequency is chosen to allow some margin in the design of the digital filters. The digital filter may be either a pair of filters at the band edges (15 & 7 MHz bandwidth) for split spectrum processing, or a single 80 MHz filter. The block floating point quantizer (BFPQ) will take-in blocks of data (nominally 128 samples) and compress them from M to N bits per sample. Each block of data will have, nominally, a 5 bit exponent (with 3-bit error correction code) for carrying the multiplicative exponent for the current block of data.

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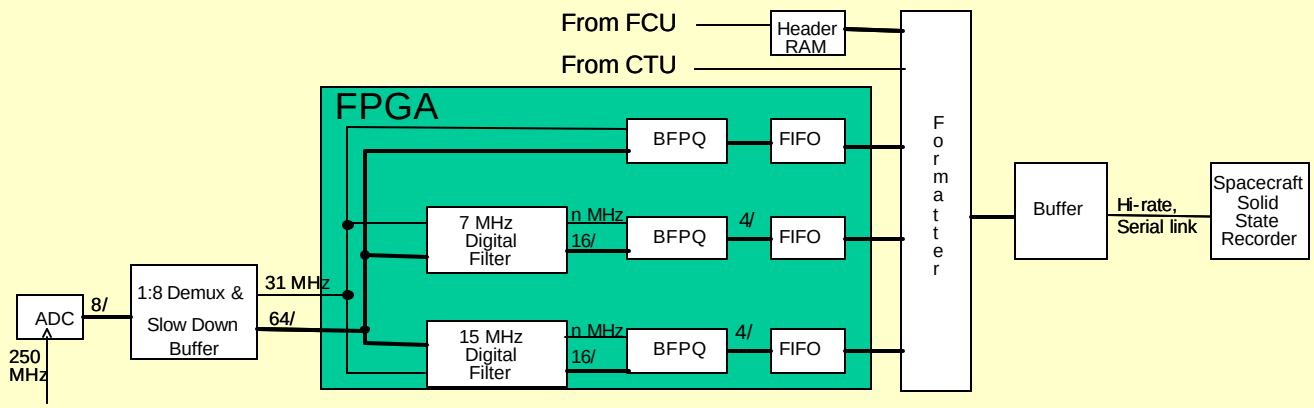
Figure 4-26. Data Handling System Block Diagram



Description:

- 8-bit A/D converter with >80 MHz input bandwidth and 250 MHz sampling rate
- Demux and buffer to slow down data rate to FPGA clock rates for digital filtering or BFPQ (Block Floating Point Quantizer)
- Digital filter eliminates bulky analog filter banks and allows programmability and flexibility. Parameter requirements linked to Matlab simulation and then translated to Verilog code to program the FPGA.
- The BFPQ performs m-bit to n-bit data compression.
- Buffer and formatter inserts header information and formats data for transfer to SSR

4.11.2 Science Acquisition ADC

A high sampling rate ADC (Analog-to-Digital Converter) was investigated for conversion of the analog offset video receive signal into a digital stream. The goal was to identify a fairly high speed, low power ADC for InSAR science data acquisition. A minimum sampling rate of 250 MHz is required to sufficiently sample the bandwidth. Two candidates for the ADC have been identified, one from Fairchild Semiconductor and one from Atmel. The Fairchild ADC has been dropped as a candidate due to concerns about the component passing radiation testing and parts availability. The Atmel part is at TRL 4 and has a maximum sampling rate of 1 Giga-sample per second. This device is being evaluated at JPL and ongoing efforts will work to increase its TRL.

The Atmel TS8388 (see figure below) is an advanced high speed bipolar technology 8-bit ADC with a maximum sampling rate of 1 GSps and a power consumption of 3.6 W. This ADC is a higher power part than the Fairchild SPT ADCs that was also investigated, but the Atmel TS8388 is radiation tolerant and there are no concerns with regard to part availability in the future. A companion 1:8 DeMux part (Atmel TS81102G0), which can be clocked at lower speed (with reduced power consumption), will be used in conjunction with this ADC. A prototype board for the Atmel TS8388 has been designed, built and currently being tested. It is anticipated that full characterization of the Atmel ADC circuit board in the InSAR test bed will be completed by the end of August 2004.

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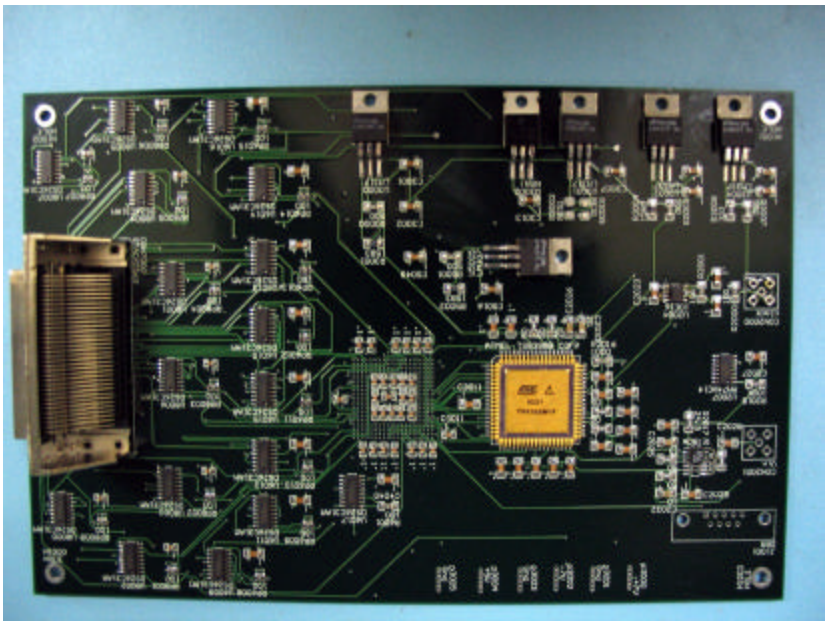
Figure 4-27. Atmel TS8388 Analog-to-Digital Converter Prototype



4.11.3 Digital Filtering

The InSAR digital filtering objective is to use a *bandpass decimation filter* to select a desired subband with arbitrary bandwidth and center anywhere within the available spectrum, and for data rate reduction. Digital filtering was selected for stability, controllability and large-scale integration. The digital filters are stable and not affected by temperature or the manufacturing process. All aspects of the digital filter are controlled by software. In addition, the filters have large memory, massive parallization and high performance.

The InSAR digital filter must be flexible, reconfigurable, and scalable once in orbit to adapt to new requirements. It must have a real-time capability with TBD InSAR required performance and accuracy. It must interface smoothly with the radar electronic system. It must fit within the prerequisite component allocation/constraints of size, weight, and power. It must have a minimum mission lifetime of 5 years and degrade gracefully. The digital filter must be tolerant to the space radiation environment at the specified orbital altitude. The subsystem must be realizable and low-risk (in terms of performance, development schedule, cost, and on-orbit maintainability). The filter must be upgradable and modular in design to allow for future functionality to be easily added.

The current digital filtering challenges are finding an efficient design methodology, optimizing the architecture, obtaining a high data rate, high throughput, scalability, flexibility, modularity, all in a space qualified implementation.

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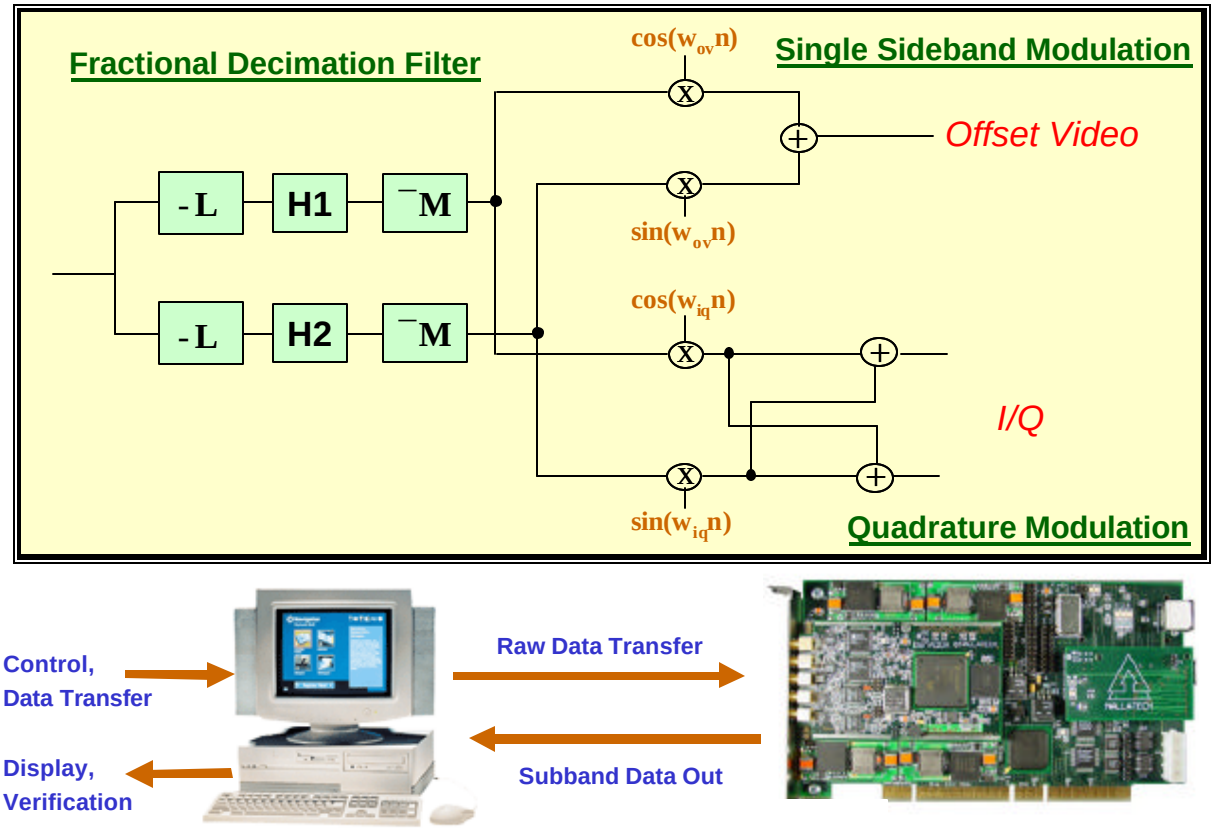
Figure 4-28. Digital Filter – Approach & Demonstration Plan



4.11.4 Block Floating Point Quantizer (BFPQ)

The BFPQ performs m-bit to n-bit data compression. Each block has an exponent sample that describes a multiplicative factor by which all samples in the block are scaled. The resulting data stream has the quantization noise characteristic of a properly scaled n-bit system with the dynamic range of an m-bit system. For InSAR the baseline is 8:4 bit compression, although other values are possible.

An early prototype developed by ARTP used the Xilinx XC4005-5 FPGA which performed a near 2 to 1 data compression (8-bit to 4-bit) at an input data rate of 15 MBps. The prototype was demonstrated on AirSAR and is currently at TRL 4. The previous prototype required redesign of the algorithm and implementation using Verilog and current Xilinx FPGAs. InSAR has completed the redesign of the algorithm with a new generalized M:N compression algorithm for maximum flexibility:

- (m,n) compression, $1 \le n \le m \le 16$
- Variable block size, maximum 256 total samples/block
- Prefer powers of 2, if possible
- 5-bit exponent with 3-bit error-correcting code

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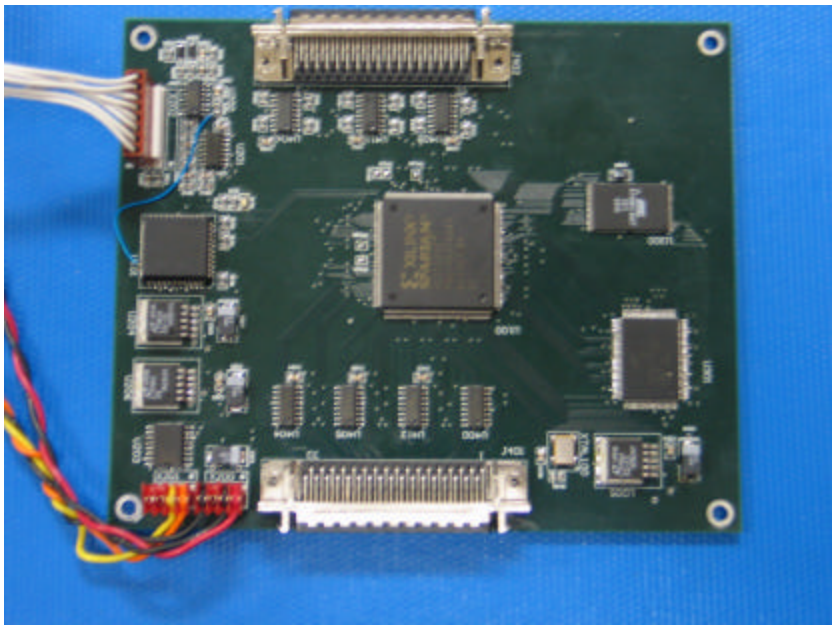
Figure 4-29 Block Floating Point Quantizer (BFPQ) Protoype



The InSAR Block Floating Point Quantizer, BFPQ, decreases the amount of on-board data storage required and therefore the science data rate by decreasing the number of bits per sample in such a way as to maintain an adequate dynamic range. The InSAR BFPQ algorithm is programmable such that from 8 to 16 bits per sample can be compressed to from 15 to 1 bits per sample (but obviously the number of bits out is less than the number of bits in). There is also a straight through mode. The highest input sample data rate that this BFPQ can handle is 167 MSamples/second, which is more than enough for InSAR. The data rate slow down from the 250 MHz output of the ADC is handled by the digital filters using the data window to control the slowdown. The BFPQ can interface directly with the ADC (in straight through mode) or with the digital filters as baselined for InSAR.

The new InSAR BFPQ algorithm has been designed, reviewed and published. The algorithm has be implemented in an FPGA and a custom board has been designed, built and tested. Three complete BFPQ board were built and tested stand-alone. The detailed design including schematics, BFPQ source code, and design description have been documented. Future work will include a more complete test of the BFPQ to test all BFPQ functions at several data rates and verification in the Radar Testbed.

4.12 Ground Support Equipment

The Radar Testbed includes several key pieces of ground support equipment (GSE) that are being developed for InSAR. The data quality analyzer (DQA) is a commercial-off-the-shelf (COTS) data acquisition system with custom firmware provided by an FPGA. A thermally-controlled fiber optic delay line provides a stable round-trip delay

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path to enable an end-to-end radar measurement capability. Labview is being used to control the testbed components and test equipment.

4.12.1 Data Quality Analyzer (DQA)

The Data Quality analyzer (DQA) acquires and stores high-rate data from the flight instrument. The DQA accepts high speed data (250 MBps), generates and attaches a header, and stores up to 10 seconds of data for analysis. This data will then be stored in a PC for later analysis. The DQA will have a generic interface to the ADC to allow for multi-mission support.

The SIR-C DQA operated at 5.6 MBps. This DQA will run ~50 times faster. Various DQA approaches have been investigated. A Logic Analyzer approach lacks memory depth and speed, but will be used initially to verify digital filter operation. A "bufferless" option was investigated, but direct write of high speed data to disk array was not feasible. The current approach is to buffer 10 seconds of data in high speed RAM using a commercially available Xilinx II Pro development board from AvNet. The board provides the following interfaces; RS-422, AvBus, and PCI bus. The board contains a Xilinx II Pro 2VP30 FPGA. The DQA is commanded from a PC, through a serial interface. The PC loads a counter in the DQA with current spacecraft time. The DQA then keeps spacecraft time internally. Part of the command from the PC is a start time. When the start time matches the DQA kept time, data collection begins.

The FPGA has a fixed amount of on chip RAM. This RAM is split into two banks. Each RAM bank can store one IPP worth of data. The data is ping-ponged between two banks of on-chip memory. The data then gets attached to its header and sent to the memory controller. Data is then written to one of two banks of on board DDR memory. The current board contains 1 GB of on board DDR. This allows the DQA to capture 6 seconds of data with a 250 MSPS ADC. After the data take is completed, the data is sent to the PC over the PCI bus. It is written to a hard disk for later evaluation. The header contains a PRF counter, a PPS counter, spacecraft time, and some other status values. The data block consists of a sync word, a header, and the high rate data. Timing is simulated using commercial test equipment. This equipment will be controlled using LabView.

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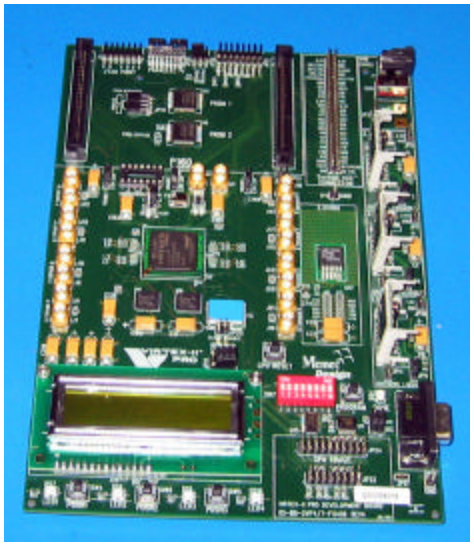
Figure 4-30. Data Quality Analyzer



4.12.2 Fiber-Optic Delay Line

When testing a radar system, it is very useful to be able to simulate the round-trip time delay of the transmitted chirp from the space borne radar transmitter to the ground and back to the radar receiver. This enables using the flight instrument's transmitter and receiver for various performance testing (such as stability and end to end functionality), rather than incorporating a substitute receiver or transmitter that may not have the fidelity of the flight instrument. As part of the Testbed development, we developed a 100 microsecond stable fiber optic delay line (FODL) using a 20 Km fiber optic link and a custom-designed thermally controlled housing. The link bandwidth is 11 GHz, however our stability testing was performed at L-band. We achieved phase stability of 0.32 deg. over 10 minutes. Other key characteristics of the delay line are a reasonable insertion loss, mass, and cost.

A block diagram of the FODL is shown below, along with a photograph of the actual hardware built. The key components of the FODL are the fiber optic transmitter which includes a laser and a modulator, the fiber optic delay line and the photo-detector. We inherited a few high performance lasers, modulators and photo-detectors from the Wide Swath Ocean Altimeter project of which we were fortunate to select a laser transmitter and a photo-detector to suit our requirements. A detailed design document and users manual was developed so this key piece of test equipment can be rebuilt at very low cost.

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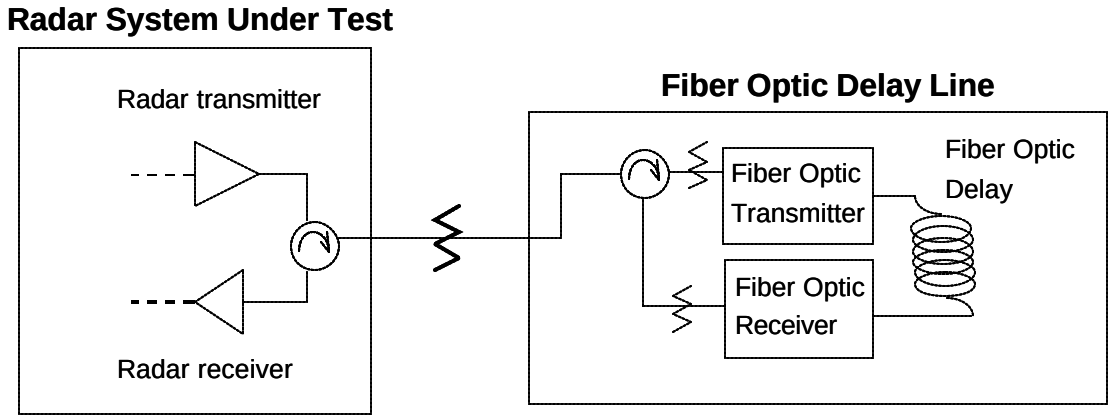
Figure 4-31. Fiber-Optic Delay Line block diagram and hardware



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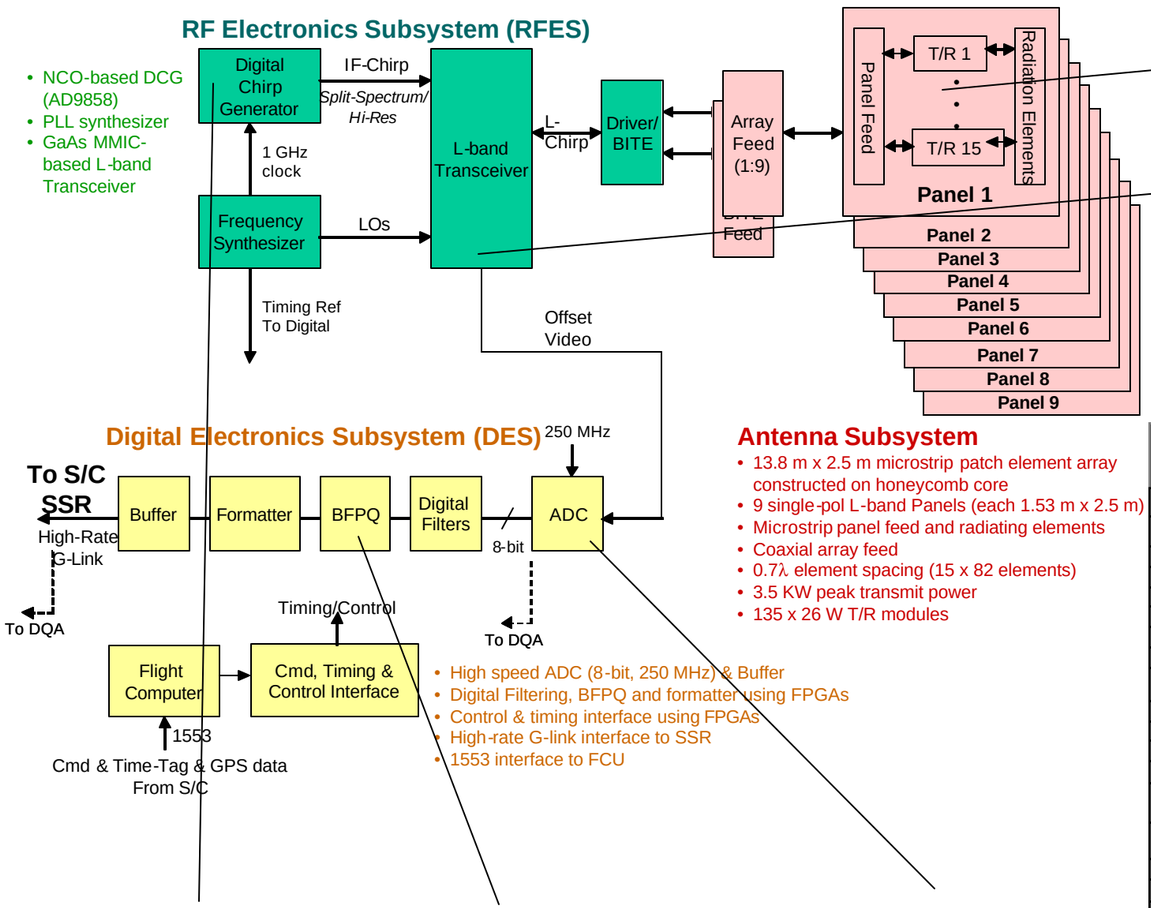
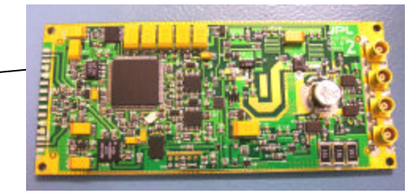
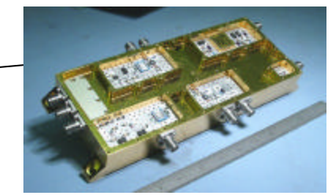
Foldout 2. Payload System: ***InSAR's L-band single-polarization (HH) radar utilizes three instrument modes (Stripmap, High-Resolution and ScanSAR), split spectrum ionospheric correction, and has full redundancy of radar electronics. High TRL technologies can be used to achieve the InSAR requirements with low implementation risk and sufficient mass and power margin.***

Figure F2-1. InSAR Payload System Block Diagram







Antenna Subsystem

- 13.8 m x 2.5 m microstrip patch element array constructed on honeycomb core
- 9 single-pol L-band Panels (each 1.53 m x 2.5 m)
- Microstrip panel feed and radiating elements
- Coaxial array feed
- 0.7λ element spacing (15 x 82 elements)
- 3.5 KW peak transmit power
- 135 x 26 W T/R modules

Table F2-1. Payload System Mass and Power Budget

Item	Qty	Unit Mass (kg)	Mass CBE (kg)	Mass Contingency (%)	Mass Contingency (kg)	Unit Power (W)	Power CBE (W)	Power Contingency (%)	Power Contingency (W)	Heritage
Antenna Subsystem			**414**		**124**		**1250**		**375**	
Antenna Aperture			**302**	**30%**	**91**	**1250**	**1250**	**30%**	**375**	**M**
Panels (honeycomb structure & radiating aperture)	12		160			0	0			M
T/R Modules			54			960	960			M
Panel Power & Control Units (PCU)			27			240	240			M
DC feed			6			0	0			L
Array RF feed			31			0	0			L
CPDU	1		24			50	50			M
Antenna Structure			**112**	**30%**	**34**	**0**	**0**	**30%**	**0**	**M**
Extendable Support Structure	2		76				0			H
Launch Restraints			15				0			L
Center Structure			15				0			L
Actuators			6				0			H
Radar Electronics			**45**	**30%**	**14**	**103**	**103**	**30%**	**31**	**M**
Radar Timing & Control	2	0.7	1.4			5	5			M
Frequency Synthesizer	2	1	2			10	10			M
Chirp generator	2	1	2			25	25			H
Driver Amplifier	2	1	2			12	12			L
BITE monitor	2	1	2			10	10			L
L-band Transceiver	2	0.8	1.6			5	5			M
ADC/Buffer	2	1	2			5	5			M
BFPQ/Formatter	2	0.7	1.4			5	5			M
RF Redundancy Select	1	1	1			5	5			L
RF Power Distribution	2	1.2	2.4			17	17			L
Digital Power Distribution	2	1.2	2.4			4	4			L
Electronics Housing	1	8	20			0	0			L
Cabling	1	5	5			0	0			L
Payload (Radar) Totals			**459**		**138**		**1353**		**406**	

Total Payload (Radar) Power w/ 30% Contingency **1758 W**
Total Payload (Radar) Mass w/ 30% Contingency **597 Kg**
Standby Power **100 W**

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5.0 Flight System

5.1 Unique InSAR Flight System Characteristics

5.1.1 Mission and Navigation Design

To ensure high correlation of SAR measurements and interferometrically viable scenes, the spacecraft must be maintained within 125 m of its reference orbit (navigated within a 250 m tube). This orbital precision will be met via use of frequent (up to three times per week) small maneuvers and precision-GPS data. The InSAR orbit will be determined using data from a precision GPS receiver built by JPL and provided to the spacecraft vendor. (The GPS program at JPL began in the early 80's and has continued to manifest itself in a succession of record-breaking achievements for mission such as TOPEX/POSEIDON, SRTM, SAC-C, CHAMP, Jason-1, and GRACE.) The maneuvers can be easily computed on the ground using existing institutional navigation software and will be uplinked to the spacecraft once a day.

5.1.2 Payload Accommodation

Due to the large stowed volume of the deployable SAR antenna, the InSAR flight system configuration will be mainly driven by the accommodation of the antenna inside the launch vehicle fairing volume. Though several preliminary InSAR flight system configurations have been studied that meet Delta II 2920-10 payload fairing volume constraints; reduced heritage and the potential for increased risk due to a volumetrically constrained redesign will be carefully considered as part of the mission trade space. (There are no payload fairing volumetric margin design criteria identified in JPL's Flight Project Practices or Design Principles.)

Regardless of spacecraft bus utilized, the InSAR flight system dry mass will be comprised of approximately 50% or greater science Payload components (radar instrument and phased-array antenna [SAR antenna, T/R modules, structure and deployment mechanisms]). All commercially available spacecraft buses studied will require structural adaptations to accommodate the mass and volume of the deployable SAR antenna. However, structure subsystem redesign of commercially available spacecraft buses is required of most, if not all, missions and is typically included in vendor's estimates/planning.

The relatively large instrument average data rate of 130 Mbps (CBE) and peak power requirement of 1800 W (CBE +30%) requires additional data storage, downlink capability, and power system enhancements over standard commercially available spacecraft buses. However, the upgrades (upgrades in the Command and Data Handling subsystem, Telecom subsystem and Power subsystem) required for InSAR are well within the modifications typically made to commercially available spacecraft buses.

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5.2 InSAR Study – Flight System Constraints

5.2.1 Use of Proprietary Data Provided by Industry

Several spacecraft bus options (Spectrum Astro's SA-200HP, Ball's BCP 2000, and Astrium's Flexbus) have been studied as a result of the InSAR Industrial Survey and through review of previous SAR studies. In addition, phased-array antenna providers (Ball/ABLE Engineering and Lockheed Martin) have also been visited during the InSAR Industrial Survey. Due to the proprietary nature of the data provided by industry inclusion of design detail in this report would preclude distribution beyond a very limited audience, therefore, InSAR flight system design detail provided in this report will be limited to JPL's Team X data.

5.2.2 Obtaining Information from Industry

A potential exists for protest and limiting of competition during a future InSAR Request For Proposal (RFP) process if contracts were let with a select few for more detailed (subsystem and component level) flight system design information. However, the preliminary information provided by Industry thus far provides high confidence in Industry's ability to support an InSAR mission, and though may differ slightly, is well supported by JPL's Team X design detail.

5.3 Survey of Industry Capability

5.3.1 Spacecraft Bus Options Studied

As a result of the InSAR Industry Survey, several spacecraft bus options have been studied and identified as potential options satisfying InSAR requirements. A comparison of the commercially available standard (without modification) spacecraft bus options investigated (Spectrum Astro's SA-200HP, Ball's BCP 2000, and Astrium's Flexbus) is illustrated in the following figure. All spacecraft bus options studied can be modified to support an InSAR mission, however, selection of the system requiring the least modification would most probably result in comparably reduced risk and cost. As shown, and independently verified during the InSAR Team X study, the standard Spectrum Astro SA-200HP appears to most closely match InSAR mission requirements. It is important to note that the two key unique flight system characteristics (payload mass and volume) are most closely accommodated by the Spectrum Astro SA-200HP bus.

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Figure 5-1. Spacecraft Bus Options Studied

Characteristics Most Closely Matching InSAR Requirements are Depicted in **Bold** *Italics*

- **Ball – BCP 2000**
  - Lifetime > 5 years
  - Max Payload Mass = 380 kg
  - Payload Power < 285 W (average)
  - Data Storage ≤ 200 Gbits
  - Max Payload Volume = 2.1 m^3 (external)
- **Astrium – Flexbus (Growth Vers.)**
  - Lifetime = 5 years
  - Max Payload Mass ~ 500 kg
  - Payload Power ~ 600 W (average)
  - ***Data Storage = 256 Gbits***
  - Max Payload Volume = Unknown
- **Spectrum Astro – SA-200HP**
  - ***Lifetime ≥ 6 years***
  - ***Max Payload Mass = 800 kg***
  - ***Payload Power = 650 W (average)***
  - Data Storage ≤ 100 Gbits (payload)
  - ***Max Payload Volume = 5.5 m^3 (external)***

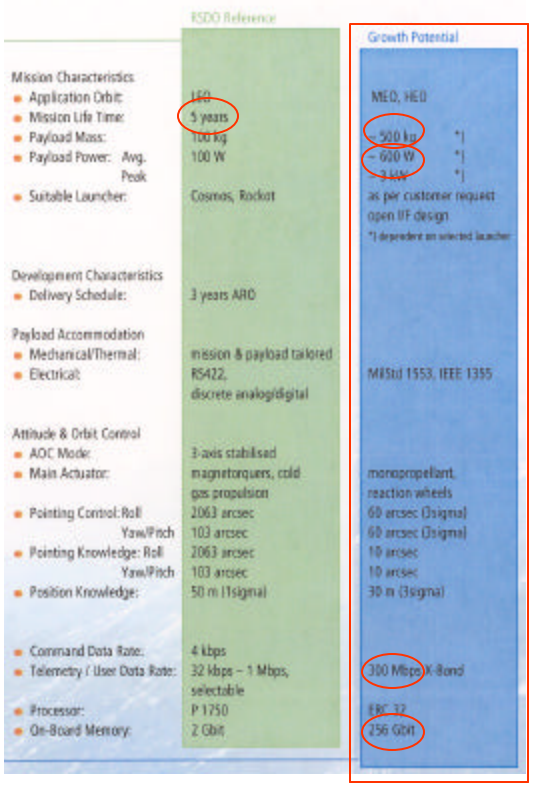
Potential Issues

- Previous studies identified issues with stowed volume and CG
- ITAR (International Traffic in Arms Regulations)
- Requires growth beyond planned growth potential

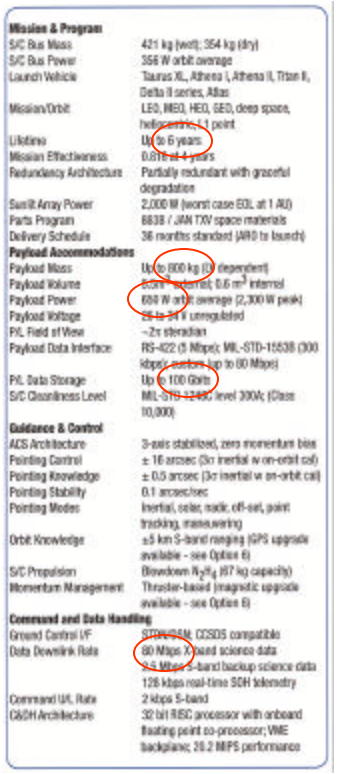
All Spacecraft Bus Options Studied Can be Modified to Support an InSAR Mission

Item	*BCP 2000 Performance*
Launch Vehicles	Taurus, Athena, Titan II, Delta II, COSMOS SL-8, Long March
Design Life	>5 years achieved with redundant architecture
Orbit Options	400 to 900 km, 0 degrees to sun synchronous
Geolocation	<10 to 23 m (3-sigma) after ground processing
Operations	Simultaneous data acquisition by pay-load(s) and data transmission capability
Onboard Storage Capacity	Scalable up to 200 Gbits
ADCS Approach	3-axis stabilized, star tracker/IRU/ reaction wheels, C/A Code GPS
Pointing Accuracy	25 microradians per axis
Pointing Knowledge	<15 microradians per axis
Pointing Stability	<10 microradians per second
Agility (along and track)	Time to re-point and stabilize the cross spacecraft for data acquisition: Maneuver of 10 degrees in 20 seconds Maneuver of 50 degrees in 45 seconds
Communications Payload Data Housekeeping	320 Mbps X-band S- or X-band from 4 to 256 Kbps 2 Kbps S-band uplink
Propulsion	Anhydrous Hydrazine (N_2H_4) blowdown
Spacecraft Mass	642 kg (wet)
Maximum Payload Mass	380 kg (nominal orbit)
Maximum Payload Power	<730 W continuous, <952 W sunlit, <285 W eclipse (orbital average)
Maximum Payload Volume	82x115x218 cm excluding accom-modation for payload electronics
Delivery Time	<24 months depending on amount of customization required and inventory status; additional systems can be deliv-ered every 4 months after the first unit.

Note: Numerical ranges reflect orbit altitude options (400 km to 900 km)



	RSDO Reference	Growth Potential
Mission Characteristics		
Application Orbit:	LEO	MEO, HEO
Mission Life Time:	5 years	
Payload Mass:	100 kg	~ 500 kg *)
Payload Power: Avg.	100 W	~ 600 W *)
Peak		~ 3 kW *)
Suitable Launcher:	Cosmos, Rockot	as per customer request open IF design
		*) dependent on selected launcher
Development Characteristics		
Delivery Schedule:	3 years ARO	
Payload Accommodation		
Mechanical/Thermal:	mission & payload tailored	
Electrical:	RS422, discrete analog/digital	MilStd 1553, IEEE 1355
Attitude & Orbit Control		
AOC Mode:	3-axis stabilised	
Main Actuator:	magnetorquers, cold gas propulsion	monopropellant, reaction wheels
Pointing Control: Roll	2063 arcsec	60 arcsec (3sigma)
Yaw/Pitch	103 arcsec	60 arcsec (3sigma)
Pointing Knowledge: Roll	2063 arcsec	10 arcsec
Yaw/Pitch	103 arcsec	10 arcsec
Position Knowledge:	50 m (1sigma)	30 m (3sigma)
Command Data Rate:	4 kbps	
Telemetry / User Data Rate:	32 kbps – 1 Mbps, selectable	300 Mbps X-Band
Processor:	P 1750	RISC 32
On-Board Memory:	2 Gbit	256 Gbit



Mission & Program	
S/C Bus Mass	421 kg (wet); 354 kg (dry)
S/C Bus Power	356 W orbit average
Launch Vehicle	Taurus XL, Athena I, Athena II, Titan II, Delta II series, Atlas
Mission/Orbit	LEO, MEO, HEO, GEO, deep space, heliocentric, L1 point
Lifetime	Up to 6 years
Mission Effectiveness	0.976 at 4 years
Redundancy Architecture	Partially redundant with graceful degradation
Sunlit Array Power	2,000 W (worst case EOL at 1 AU)
Parts Program	8838 / JAN TXV space materials
Delivery Schedule	36 months standard (ARO to launch)
Payload Accommodations	
Payload Mass	Up to 800 kg (S/C dependent)
Payload Volume	3.0 m^3 external; 0.6 m^3 internal
Payload Power	684 W orbit average (2,300 W peak)
Payload Voltage	28 to 34 V unregulated
P/L Field of View	~2π steradian
Payload Data Interface	RS-422 (5 Mbps); MIL-STD-1553B (300 kbps); ethernet (up to 80 Mbps)
P/L Data Storage	Up to 100 Gbits
S/C Cleanliness Level	MIL-STD-1246C level 300A; (Class 10,000)
Guidance & Control	
ACS Architecture	3-axis stabilized, zero momentum bias
Pointing Control	± 16 arcsec (3σ inertial w on-orbit cal)
Pointing Knowledge	± 0.5 arcsec (3σ inertial w on-orbit cal)
Pointing Stability	0.1 arcsec/sec
Pointing Modes	Inertial, solar, nadir, off-set, point tracking, maneuvering
Orbit Knowledge	±5 km S-band ranging (GPS upgrade available - see Option 6)
S/C Propulsion	Blowdown N_2H_4 (87 kg capacity)
Momentum Management	Thruster-based (magnetic upgrade available - see Option 6)
Command and Data Handling	
Ground Control I/F	STDN/DSN, CCSDS compatible
Data Downlink Rate	80 Mbps X-band science data 2.5 Mbps S-band backup science data 128 kbps real-time SOH telemetry
Command U/L Rate	2 kbps S-band
C&DH Architecture	32 bit RISC processor with onboard floating point co-processor; VME backplane; 26.2 MIPS performance

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From the RSDO catalog of commercial buses (http://rsdo.gsfc.nasa.gov), the Spectrum Astro 200HP appears to be the closest match for the InSAR mission. From this standard bus, the following upgrades are necessary to meet the InSAR requirements:

- Major re-design of the Propulsion Subsystem to add a de-orbit thruster and increase the propellant load,
- Upgrade in the CDS subsystem to increase the data storage from 100 Gbit to 256 Gbit,
- Update in the Power Subsystem to change the configuration to a single wing design, go to a larger battery that can handle slightly higher rates,
- Upgrade in the Telecom Subsystem to increase the data rate from 80 Mbps to 300 Mbps. This is available as an option on that bus,
- Small upgrade of the ACS Subsystem to resize the reaction wheels for meeting the same pointing capability with a larger antenna and a larger mass,
- Total redesign of the Structure Subsystem, which is typically included in the vendor's estimates.
- Total redesign of the Thermal Subsystem per these upgrades.

Future studies should consider the potential for reduced spacecraft bus and phased-array antenna design heritage and the potential for increased cost/risk associated with a configuration constrained to the 3 m Delta II fairing. During the Industry Survey a CG (center of gravity) issue was identified with the heritage BCP 2000 configuration. Though both the Ball and Spectrum Astro spacecraft can be modified to satisfy the InSAR requirements, the heritage rectangular bus configuration (offered by most spacecraft bus providers) may prove to be inappropriate for the size and mass of the phased-array antenna considering the volume constraints of the Delta II.

5.3.2 Phased-Array Antenna Options Studied

As a result of the InSAR Industry Survey, two potential phased-array antenna providers were visited and potential options were identified that would satisfy InSAR requirements. Lockheed Martin has completed and is in the process of significant phased-array technology Research and Development and offers great potential for significantly reduced mass and volume. The Ball Aerospace/ABLE Engineering design presented would utilize Ball phased-array antenna panels and ABLE Engineering antenna structure and deployment mechanisms. Ball and ABLE Engineering offer heritage (from SIR-C and RadarSat-2) in design and the potential for reduced cost and risk.

Lockheed Martin's Research and Development (R&D) activities offer potential for significantly reduced mass and enhanced packaging. However, the current InSAR Flight System design has a 57% launch margin on the Delta II 2920-10 and at present the lower TRL of these technologies present comparably higher risk and cost.

The Ball Aerospace antenna aperture studied, as a result of the InSAR Industry Survey, has SIR-C heritage (similar L-band panels were flown on SIR-C). In addition, the ABLE

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Engineering design is based on a proven structure and deployment mechanism with RadarSat-2 heritage. This heritage and previous experience offers the potential for reduced risk and cost.

5.4 Flight System High-Level Design Requirements

The InSAR mission and systems shall be designed for a 5-year mission lifetime to capture the slow deformation related to tectonics, volcanoes, and the temporal variability of the cryosphere. InSAR is a Class B/C mission. Based on the class and lifetime, this mission will require selected-to-full redundancy.

As previously mentioned, to ensure high correlation, the spacecraft must be maintained within 125 m of its reference orbit (within a 250 m tube).

The InSAR mission and systems shall be designed to collect a minimum of 10 minutes (on average) of data per orbit – maximum of 15 minutes. Increased instrument on-times are under investigation. The data latency requirement is 24 hours.

This study assumes a launch date of April 2009, but because this is an Earth-orbiting the launch date is very flexible. The 2009 launch date corresponds to a technology cutoff date of 2006, meaning that all technology items must be at a TRL of 6 by the beginning of Phase C/D, which occurs in 2006.

The InSAR mission and systems shall be capable of left/right rolling (+/- 30°) from nadir. The current roll rate and frequency being designed to is 0.1°/sec (10 min changeover between +/- 30°) from nadir, as often as twice per orbit. The InSAR Flight System shall be controlled to 0.04° 3-sigma yaw/pitch (1/20 Azimuth beamwidth), and 0.25° 3-sigma roll (1/20 Elevation beamwidth). This corresponds to a knowledge requirement of at least 0.025 degrees

5.5 Flight System Design

5.5.1 Summary

The Team X Flight System concept verifies the validity of mass and power estimates presented in InSAR industry survey designs.

The spacecraft is 3-axis stabilized using star trackers for attitude determination and reaction wheels for attitude control, with magnetic torquers to unload the wheels. A BlackJack GPS system is used for orbit determination. (At this high altitude, with an antenna presenting its side to the velocity direction, there is no significant drag. The key attitude perturbation comes from the gravity gradient.) The spacecraft propulsion system is a blowdown hydrazine system. A total of 80 m/s are required to maintain the orbit precisely over the lifetime of the mission. This is achieved using eight 4.5-N thrusters. In addition, a 70 m/s delta-V maneuver is required for de-orbit, performed by a

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22-N thruster. The spacecraft is powered by a 5.4 m^2 one-wing, one-axis gimbaled GaAs triple junction solar array sized to accommodate the maximum duration of data taking, even in eclipse, with a 23 deg cosine loss. Eclipse operation is ensured by a 76 A-hr NiH_2 battery, sized by the higher charge/discharge rate. Data is processed in a redundant commercial PC750, and stored with ample data storage margin in a solid-state recorded (SRR) of 256 Gbit capacity. Telemetry and commands are handled by an S-band telecom system with redundant transponder, while science data downlink requires the use of an X-band system, with redundant transmitter.

The design for the spacecraft follows JPL's Design Principles with regards to mass and power contingency. These principles require a 2% contingency on mass for existing hardware, 10-15% contingency on mass for an inherited design and 30% contingency on mass for a new design. In addition, additional contingency has been added above that to reach a total of 30% growth contingency in both mass and power.

The Mass Equipment List for the InSAR Flight System, below, is followed by a discussion of each of the Flight System Subsystems excluding the Payload Subsystem. A Mass and Power summary table can be found on the Flight System Foldout.

Table 5-1. Flight System Mass Equipment List

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	TRL
Instrument								
SAR radar	1	459.000	459.000	30%	596.700		1353.0	
Attitude Determination and Control System								
Sun Sensors	8	0.005	0.037	10%	0.040	0.0	0.0	9
Star Trackers	2	2.500	5.000	10%	5.500	9.0	9.0	9
Magnetic Torque Rods	3	2.100	6.300	10%	6.930	3.7	3.7	9
Magnetometers	2	1.017	2.034	10%	2.237	0.8	0.8	9
GPS Receivers	2	3.000	6.000	10%	6.600	14.0	14.0	9
GPS Antennas	3	0.100	0.300	10%	0.330	0.0	0.0	7
Gyroscopes /IRUs	3	1.600	4.800	10%	5.280	7.5	7.5	9
Reaction Wheels	4	7.000	28.000	10%	30.800	105.0	22.0	9
Drive Motors #1	2	0.500	1.000	10%	1.100	8.0	5.0	9
Drive Motors #2	1	2.000	2.000	10%	2.200	18.0	10.0	9
Gimbal Drive Electronics	2	0.990	1.980	10%	2.178	3.6		9
Torquer Drive Electronics	2	0.360	0.720	10%	0.792	4.0		9
Command and Data System								
Broad Reach PPC 750	2	5.000	10.000	30%	13.000	25.0	12.5	6
SEAKR 256 Gbit SSR	1	14.500	14.500	30%	18.850	60.0	30.0	9
Power								
Solar Array	1	19.876	19.876	30%	25.838			9
Ni-H2 (IPV) Battery	1	57.822	57.822	30%	75.169			9
Chassis	1	1.750	1.750	30%	2.275			0
Array Switching Boards	1	0.800	0.800	30%	1.040			9
Load Switching* Boards	1	0.800	0.800	30%	1.040			9
Thruster Drivers Boards	2	0.800	1.600	30%	2.080			9
Pyro Switching Boards	1	0.800	0.800	30%	1.040			9
Converters* Boards	6	0.800	4.800	30%	6.240			9
Battery Control* Boards	1	0.800	0.800	30%	1.040			9
Diodes Boards	1	0.800	0.800	30%	1.040			9
Propulsion								
Gas Service Valve	1	0.230	0.230	2%	0.235			
Temp. Sensor	1	0.010	0.010	5%	0.011			

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Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	TRL
Liq. Service Valve	1	0.280	0.280	2%	0.286			
LP Transducer	2	0.270	0.540	2%	0.551			
Liq. Filter	1	0.400	0.400	2%	0.408			
LP Latch Valve	3	0.350	1.050	2%	1.071			
Temp. Sensor	10	0.010	0.100	5%	0.105			
Lines, Fittings, Misc.	1	2.000	2.000	50%	3.000			
Monoprop Main Engine	1	0.517	0.517	10%	0.569			
Monoprop Thrusters	8	0.330	2.640	10%	2.904			
Fuel Tanks	1	19.958	19.958	30%	25.946			
Structures								
Primary Structure	1	98.876	98.876	30%	128.539			6
Secondary Structure	1	13.455	13.455	30%	17.492			6
Instrument Interfaces	1	46.000	46.000	30%	59.800			6
Solar Array Actuator	1	4.700	4.700	30%	6.110			6
Solar Array Latch /Release	1	1.600	1.600	30%	2.080			6
Antenna Articulation Mechanism	1	4.700	4.700	30%	6.110			6
Antenna Boom	1	2.700	2.700	30%	3.510			6
Integration Hardware & MHSE	1	6.921	6.921	30%	8.998			6
Balance Mass	1	9.499	9.499	30%	12.348			6
Adapter, Spacecraft side	1	19.832	19.832	30%	25.781			6
Cabling Harness	1	48.014	48.014	30%	62.418			7
Telecomm								
X-MGA (19dBi) MER	1	0.600	0.600	30%	0.780			9
S-band omni TECOM	1	0.255	0.255	30%	0.332			9
S-band 2W xpnr (STDN)	2	3.700	7.400	12%	8.288	23.8	23.8	7
X-band Transmitter (160mbps/channel, or 320 mbps total)	2	4.091	8.182	12%	9.164			7
Additional Hardware	1	6.000	6.000	30%	7.800			9
Thermal								
Multilayer Insulation			7.347	30%	9.551			6
Thermal Surfaces			0.532	30%	0.691			7
Thermal Conduction Control			1.217	30%	1.582			6
Heaters /Thermostats			2.9	23%	3.57	143.7	71.9	7
Temp Sensors		1	0.6	10%	0.66			
Thermal Radiator (Unit Area)			1.35	30%	1.755			

5.5.2 Structure Subsystem

Although the spacecraft will be based on an existing commercial bus (Spectrum-Astro SA-200HP), it is expected to be a new structural design requiring a customization of the mechanical design and structural configuration. Thus, the structure mass was estimated parametrically, based on the masses of the other subsystems which the structure supports, plus specific identified substructures, components and mechanisms. The cabling harness mass estimate is based on historical factors times the mass of the separate electrically connected subsystems and mechanisms, with adjustments as warranted.

Delta II fairing volumetric considerations will be crucial in developing the Flight System design. The SAR antenna is 13.8m x 2.5m and configured such that the long dimension can be split into either 6 or 9 panels. Telecommunications antennas (and any other

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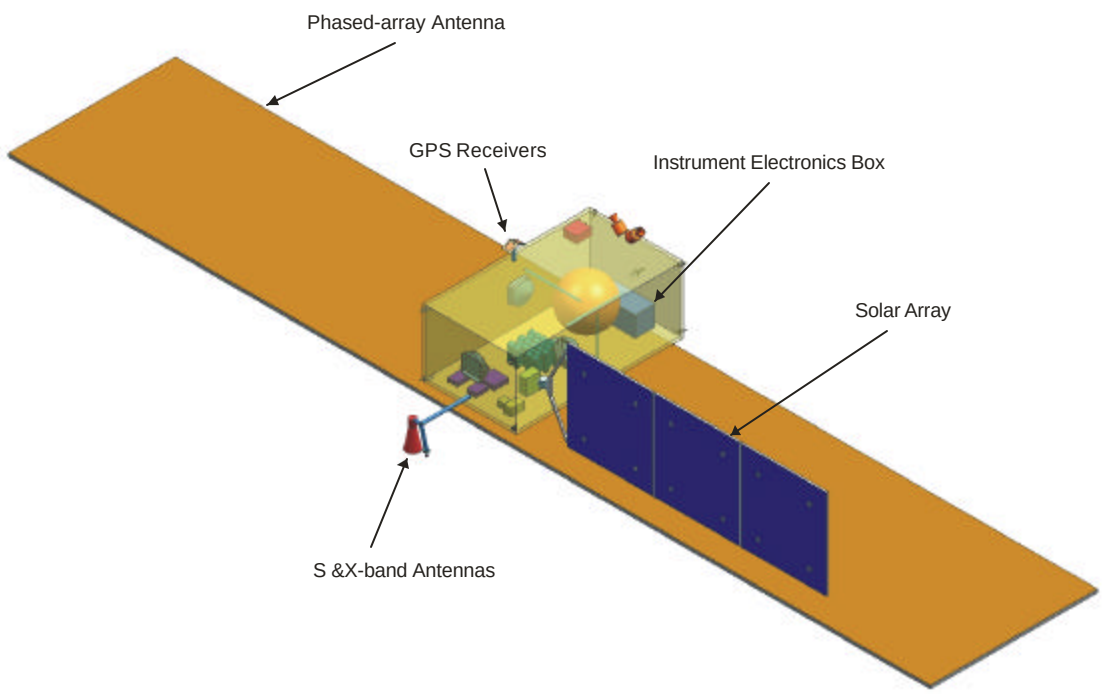
components) must not project forward of the plane of the SAR antenna, and therefore, will require stand-off booms. For gravity-gradient purposes the bus mass must be kept close to the SAR panels.

SAR is slant-pointing (+/- 30°) with the lengthwise panel direction parallel to the velocity vector. The solar array is also parallel to the velocity vector and will have single-axis articulation. Antennas will also be articulated, but in 2-axes. Both antennas (an X-band horn and an S-band quadrifilar) will be located on a single platform.

Figure 5-2. Flight System Configuration



5.5.3 Command and Data Handling Subsystem

The Command and Data Handling Subsystem (CDS or C&DH) is responsible for overall control of the spacecraft using the primary onboard computer. The CDS is responsible for processing commands sent to the spacecraft, generating and sending spacecraft engineering data, managing the transmission of science data, and keeping control and watch over the health of the entire spacecraft.

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The CDS interfaces with all parts of the spacecraft, but the primary interaction for control purposes is with the power subsystem and the attitude control system. The CDS commands and monitors the control of power onboard the spacecraft. The CDS also works with the attitude control subsystem to maintain the required pointing of the spacecraft for propulsion, cruise, and science observations. Also, the CDS controls the spacecraft radio transmitters and receivers.

A major function of the CDS is spacecraft fault protection. The CDS monitors sensors placed throughout the spacecraft for detect anomalous conditions which could jeopardize the ability of the spacecraft to maintain control of itself or which could affect the fidelity of scientific observations. Whenever a problem is detected, the CDS activates an appropriate response to correct the situation and either return to normal operation or enter a safe state until ground controllers can analyze the problem and send commands required to return the spacecraft to nominal operation.

The CDS subsystem is designed for 15 minutes maximum data taking per orbit. The design is based on using a commercial spacecraft bus with a fully-redundant computer, 100 Mbps maximum data rate for recording, and 300 Mbps maximum data rate for playback. The design assumes 10 to 14 science downlinks per day and is based on a BRE 750 commercial CDS with a SEAKR 256 Gb SSR. A redundant CDS is used and data storage will be designed to accommodate missed passes.

5.5.4 Power Subsystem

The Power Subsystem must support operations up to 20% of the 100-minute orbit, limited science during eclipse and must support science and downlink simultaneously. The maximum eclipse period is 17.6-minute and occurs over the North Pole. Trajectory analysis of science targets elicits the need for 5.9 minutes of operation during eclipse.

The solar array is assumed to be a rigid panel for reduced cost. The cells are assumed to be advanced triple junction, 28% efficient cells. The configuration is a single wing mounted aside the bus with single axis articulation, resulting in +/- 23 degree off pointing seasonally. Solar array gimbaling could be three ways depending upon the contractor selected. A contractor without gimbals as an option could take the combined 23 and 30 degree loses. A contractor with a single axis gimbal available on the bus could use a simple 23 degree loss. A contractor with heritage dual axis gimbals could eliminate all loses and fly a slightly smaller array.

The power electronics selected are close to what a commercial bus would offer. The Power Electronics would utilize 6U boards, COTS Power Converters, dumb solid-state switches, and would be functional redundant.

The battery design is an IPV (individual pressure vessel) single string battery with 22 cells. The single string design is assumed to use cell bypass devices to achieve fault tolerance. This assumption needs to be reviewed given peak power requirements as a single fault could result in a reduction in eclipse operating capability late in life. The

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battery is sized by eclipse science operations and as sized will handle a full 6 hours at launch down to 73% DOD. The DOD of the battery for the eclipse science orbit is 29%. The sizing used here is power based, with a 1.2 C rate for 15 minutes maximum Battery sizing is for the eclipse operating mode discharge rate. A smaller battery might be fitted based on typical energy based sizing.

5.5.5 Propulsion Subsystem

The Propulsion System is a simple blowdown monopropellant hydrazine system consisting of one 22N main engine to provide de-orbit delta-V, and eight 4.5N thrusters to provide RCS and orbit trim delta-V. Based on an InSAR initial mass of 1,350 kg and a total mission delta-V of ~150 m/sec the total propellant load is 117.7kg, including residual. The hydrazine tank is 36.2cm in diameter and the Propulsion System dry mass is 19.7kg (CBE).

5.5.6 Attitude Control Subsystem

InSAR is a 3-axis stabilized spacecraft using reaction wheels for fine pointing and magnetic torque rods for unloading excess wheel momentum. Thrusters would be used to provide control torque during initial deployment (in particular, to null out tip-off rates), for safe mode, during orbit maintenance delta-V maneuvers, and when the reaction wheels are not available. The baseline configuration for the reaction wheels is a pyramid of 4 wheels. All wheels would be in use during normal operations and are sized to complete the mission using any 3 out of 4 wheels. The baseline configuration includes 3 orthogonal magnetic torque rods with high reliability and redundant torque coil driver electronics. A redundant magnetometer is used to sense the direction and magnitude of the Earth's magnetic field. Precision star trackers and gyros are used for stellar inertial attitude determination. The star trackers would be anti-boresighted with the antenna. Coarse analog sun sensors and precision gyros are used for safe mode and during initial deployment. The high gain antenna (HGA) is attached to the bus via a gimbal with 2 DOFs. One large solar arrays is attached to the bus via a gimbal with 1 DOF. The ACS baseline includes two Black Jack GPS receivers and 3 Ashtech patch antennas. The Black Jack should be capable of providing real-time accuracy to within a 20-meter (3 sigma) error radius using P-code. Black Jack may include internal redundancy; in that case, the number carried should be reduced to one.

5.5.7 Telecommunications Subsystem

The Telecommunications Subsystem must support a 300 Mbps X-Band downlink to ASF and Svalbard ground stations. Two-way communications are needed at S-Band for engineering telemetry, command and tracking. The nominal engineering data rate is from 32 kbps up to 1 Mbps. Redundant electronics with single antennas at S and X-band will be used. Both antennas will be placed on the same 2 axis gimbaled platform to point at the ground stations during passes. The gimbaled platform will compensate

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for the spacecraft roll angle and ground station to nadir angles. Further configuration study is needed to verify that one boom is sufficient to resolve the viewing angle issues between the science antenna and the telecom antennas.

The X-Band link margin at max range is 9.5 dB to the 11.3m station at ASF while the S-Band link margin (1 Mbps) at max range is 19 dB to the 11.3m station at ASF.

The system includes 2 X-Band QPSK transmitters with internal 6W power amplifier, 2 S-Band STDN transponders with internal 5W power amplifier, 1 X-Band MGA (18dBi), 1 S-Band quad helix (3 dBi), 2 switches, and cabling. Future study will consider an additional S-Band antenna on the opposite side of the spacecraft for safe mode communications.

Spectrum issues at X-Band will have to be examined, a higher level modulation scheme or shaped pulse modulation may be required to increase roll off of the spectrum - ground receivers will have to be compatible with the chosen modulation scheme. In addition, a filter may have to be employed at the output of the transmitter to protect the next higher band.

5.5.8 Thermal Subsystem

The Thermal Subsystem maintains the flight elements within specified temperature limits for all flight modes. The stressing modes for InSAR are Radar operation and telecom operation. Given the sun-synchronous orbit with a 6 AM – 6 PM nodal crossing the environmental inputs are relatively constant, which simplifies the thermal design. The design uses passive thermal control with electric heaters for sensitive elements and possible differences in operational modes. Further there is an eclipse during some of the orbits, and can be accommodated with a small increase in heater power. The design of the telecom system shows a 66 watt transponder thermal dissipation, which necessitates a thermal radiator, which will require a thicker skin over a part of the bus. This design assumes that the transponder is mounted on the skin, and requires heater power to keep the transponder above minimum non-operate temperature. The passive elements of the thermal control system are multilayer insulation (MLI), thermal surfaces, thermal conduction control, a thermal doubter (for Telecom), and temperature sensors. Electric heaters, both commanded and thermostatically controlled will be required for propulsion elements and batteries.

5.5.9 Software Subsystem

This Section covers the development of the flight software, but does not include Ground, Visualization, Simulation, GSE and GDS. The software architecture is based on QuickScat, and will utilize a high degree of heritage from that mission. The flight software part includes, for example, software required to interface, command and control the various subsystems of the flight system (e.g., AACS, CDS) and instruments and payloads (though only the part that is not embedded in instrument or payload hardware). The term “flight software” here not only covers the flight software design and development, but also covers management, system engineering, test bed(s), fault

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protection, integration and test effort required to complete the flight software product. However, it does not cover science investigative and other software delivered with the instruments or payloads (which is covered under Instruments/Payloads), control algorithm design and analysis (covered under ACS), or the operating system and device driver level software effort (covered under CDS). The project software engineering part includes, for example, development of software policies and practices, software requirements, design, implementation, test issues, flight/ground tradeoffs, and project interface to independent verification and validation (IV&V).

We are assuming flight software inheritance from several previous missions of similar design and purpose. The reusability is estimated at 50% design level and 25% code level, which is a high estimate, but we consider this justified given that the missions are very similar in function, science requirements, and operational modes. However, to be considered inherited, software must be reused *without modification of any kind*. New adaptations of existing components are *not considered* inherited.

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Foldout 3. Flight System: *The Team X Flight System concept verifies the validity of mass and power estimates presented in InSAR industry survey designs.*

Table F3-1. Flight System Mass and Power Summary

Subsystem	Mass (kg)			Power (W)				
				Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
	Mass (kg)	Subsystem Contingency	Mass (kg) +Contingency	Science in Eclipse (5.9 min)	Science in Sun (8.6 min) Telecom on	Eclipse no Science (11.5 min)	No Telecom No science (73.5 min)	Launch +3hr Anomaly
Payload								
Instruments	459.0	30%	596.7	1353.0	1353.0	50.0	50.0	50.0
Payload Total	459.0	30%	596.7	1353.0	1353.0	50.0	50.0	50.0
Bus								
Attitude Control	58.2	10%	64.0	141.7	141.7	141.7	141.7	20.4
Command & Data	24.5	30%	31.9	85.0	85.0	85.0	85.0	25.0
Power	89.8	30%	116.8	108.5	115.1	24.9	24.7	11.9
Propulsion	27.7	27%	35.1	12.7	12.7	12.7	12.7	12.7
Structures & Mechanisms	188.5	30%	245.0	0.0	0.0	0.0	0.0	0.0
S/C Adapter	19.8	30%	25.8	0.0	0.0	0.0	0.0	0.0
Cabling	48.0	30%	62.4					
Telecomm	22.4	17%	26.4	4.5	114.5	4.5	4.5	39.5
Thermal	15.6	28%	20.0	71.9	64.7	89.8	86.2	35.9
Bus Total	494.6	27%	627.3	424.2	533.7	358.6	354.8	145.4
Spacecraft Total (Dry)	953.6	28%	1224.0	1777.2	1886.7	408.6	404.8	195.4
Subsystem Heritage Contingency	270.4	28%						
System Contingency	15.7	2%						
Spacecraft +Contingency	**1239.7**			**2310.3**	**2452.7**	**531.2**	**526.2**	**254.0**
Propellant & Pressurant	106.0							
Spacecraft Total (Wet)	**1345.7**							
Launch Vehicle Capability	**3220.0**							
Launch Vehicle Margin	**1874.3**							
Spacecraft Mass Margin	**1874.3**							

Figure F3-1. Flight System Stowed

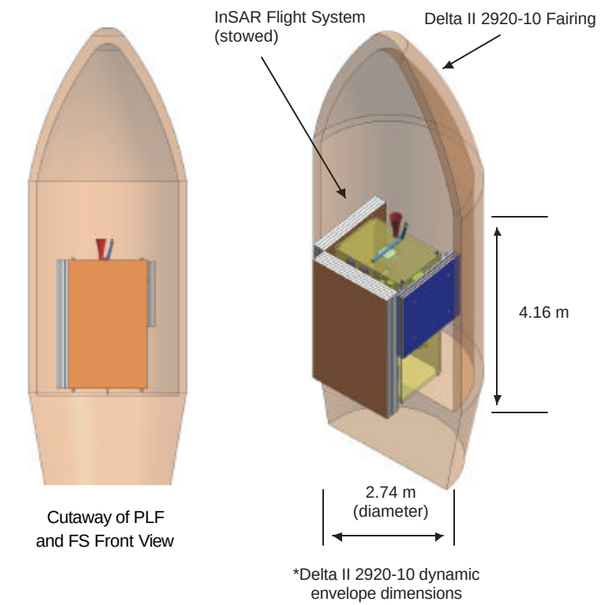

Figure F3-2. Flight System Deployed and Bus Detail

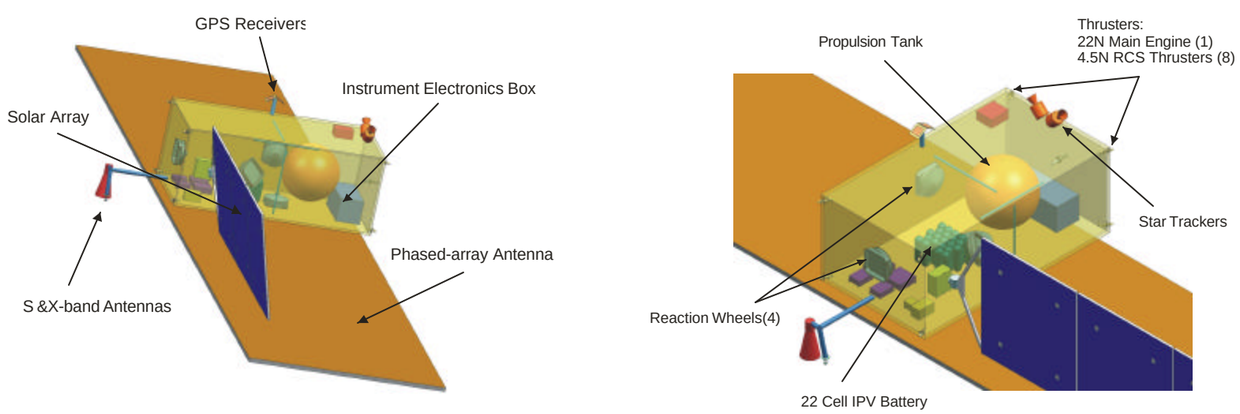

Table F3-2. Mission Parameters

Mission Parameter	Requirement/Performance
Payload I&T Site	JPL
Flight System I&T Site	Industry
Launch Site	Vandenberg Air Force Base
Instrument Supplier	JPL
Spacecraft Bus Supplier	Industry (RSDO)
Hardware Models	Protoflight S/C, EM instrument
Tracking Network	ASF and Svalbard
Payload Pointing (3 sigma)	Roll +/- 30 deg from nadir, max twice per orbit, within 5 min (0.04 deg yaw/pitch, 0.25 deg roll)
Type of Propulsion System	Monopropellant
Radiation Total Dose	25 krad behind 100 mils alum., with an RDM of 2 added
Heritage	SIR-C, SRTM for the radar; RSDO catalog bus
Mission Orbit	Syn-synchronous 6am/6pm, 760 km, 98.5 deg inclination
Navigation	8-day repeating groundtrack, within 125 m
Delta-V	150 m/s (69 m/s orbit maintenance, 11 m/s injection correction, 70 m/s for deorbit
Technology Cutoff	2006
Redundancy	Selected
GPS	20 m accuracy real-time, 10 cm accuracy post-knowledge
Total Mission Data Volume	2E+09 Mbits
Return Data Rate	300 kb/s
Instrument Data Rate	130,000 kb/s
Mission Duration	5.0 years
Stabilization	3-Axis
Pointing Control	180 arcsec
Pointing Knowledge	90 arcsec
Pointing Stability	1 arcsec/sec
Data Storage	256 Gbits

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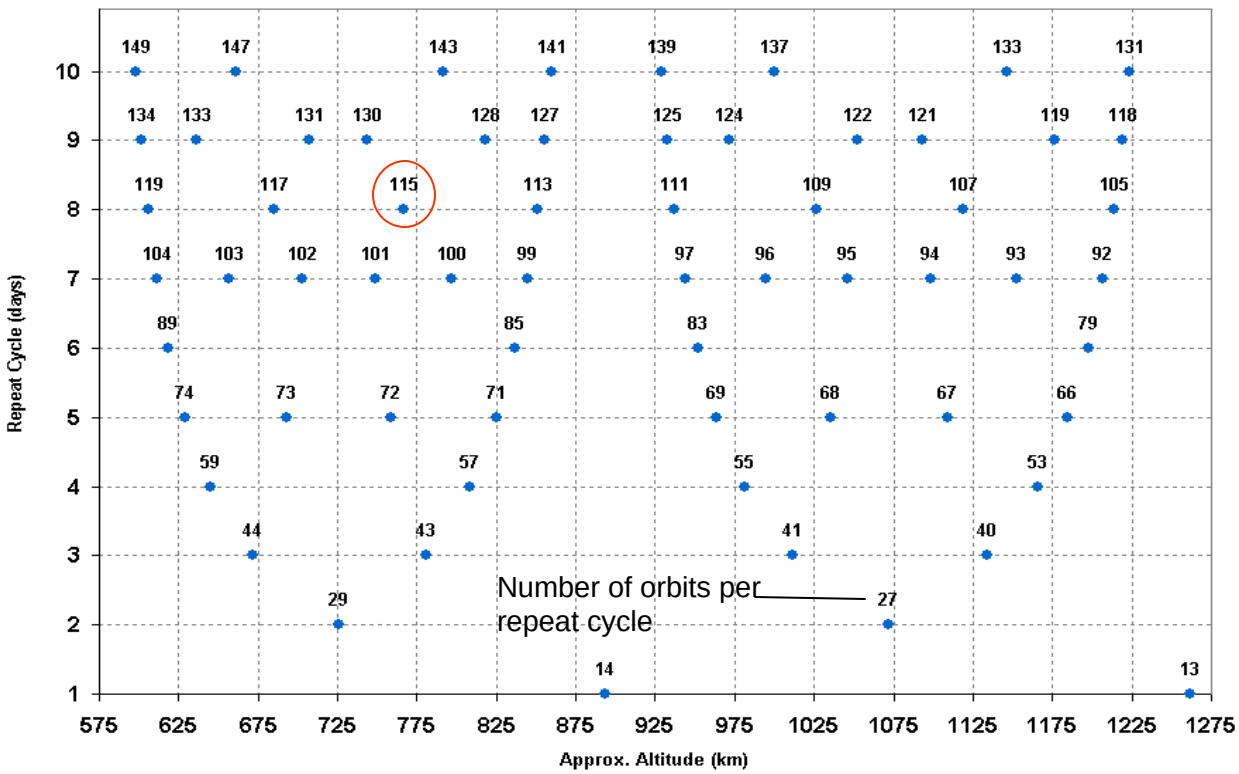
5.6 Mission and Navigation Design

5.6.1 Sun Synchronous Repeat Orbits

Only a discreet number of possible repeat orbits exist. Differing altitudes and number of orbits per repeat cycle greatly impact Payload System design. Higher orbits have less drag and require less delta-V for orbit maintenance. However, as altitude increases the number of orbits per cycle decreases, which may require more power/mass to maintain the same coverage at the same instrument resolution. Similarly, as the repeat cycle decreases (e.g., from 8 to 7-days) the number of orbits in a repeat cycle goes down, which, again, may require more power/mass to maintain the same coverage at the same instrument resolution.

The InSAR selected orbit (depicted in the figure below and circled in red) is a result of the science requirement for a frequent revisit interval (e.g., ≤9-day exact repeat) and optimization of Payload and Flight System performance. There are 115 orbits per 8-day repeat cycle for this orbit.

Figure 5-3. Sun Synchronous Repeat Orbits



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The InSAR Flight System launches on a Delta II 2920-10 from Vandenberg Air Force Base to a 760 km Sun-sync 6 am /6 pm orbit with an inclination of 98.5 degrees (corresponding to an 8-day repeat ground track) in April of 2009. A maximum of 3,220 kg can be launched into this orbit. The maximum eclipse period for this orbit is 17.6-minute and occurs over the North Pole. The longest data-take in eclipse was determined to be 5.9 minutes based on regions of interest.

The orbit maintenance constraints require that the spacecraft remain in the orbit to a precision of 250 meters. Tidal perturbation (cross-track) and drag make-up (along-track) maneuvers can be easily computed on the ground using existing institutional navigation software. Along-track maneuvers will have to be performed up to three times per week. Cross-track maneuvers will have to be performed up to once per week. Delta-V for the mission is divided into 3 groups: 1) 11 m/s is reserved for injection correction; 2) 69 m/s is reserved for orbit maintenance; and 3) 70 m/s is reserved for the deorbit maneuver at the end of the mission.

5.7 Flight System Options Investigated

5.7.1 Increased Instrument On-time

During the InSAR Team X study the potential to increase instrument on-time was investigated to discover knees in the curve and subsystem drivers associated with increased data taking over the 10 minute InSAR baseline. The study suggested an increase is possible with small impacts to the Flight System's Command and Data Handling and Power Subsystems. A potentially larger impact would be to the Mission Operations System and Ground Data System (MOS/GDS) which needs further investigation.

Based on an orbital average time over ASF and Svalbard stations (combined) of 27 minutes, a total of 216 Gbits can be downloaded with each orbit. The current InSAR baseline of 10 minutes of data taking per orbit amounts to 78 Gbits per orbit. At 23 minutes of data taking this number increases to a total of 179 Gbit/orbit. This change, more than doubling the instrument on-time, fits well within the ground station capability. Flight System modifications include going from a 256 Gbit SSR to a 512 Gbit SSR, additional solar array area, small increases in propulsion and structure amounting to approximately $5M – a seemingly reasonable option at this level of analysis.

5.7.2 Changing Revisit Frequency On-orbit

To potentially better minimize surface decorrelation, capture unfolding events, beat down tropospheric effects, and to assess the impact of mountain glacier system dynamics on sea level rise (SIR-C results show rapidly moving mountain glaciers can decorrelate in 3-4 days) the option of decreasing repeat cycle (e.g., from 8 to 2-days) and changing repeat cycle on-orbit is under investigation.

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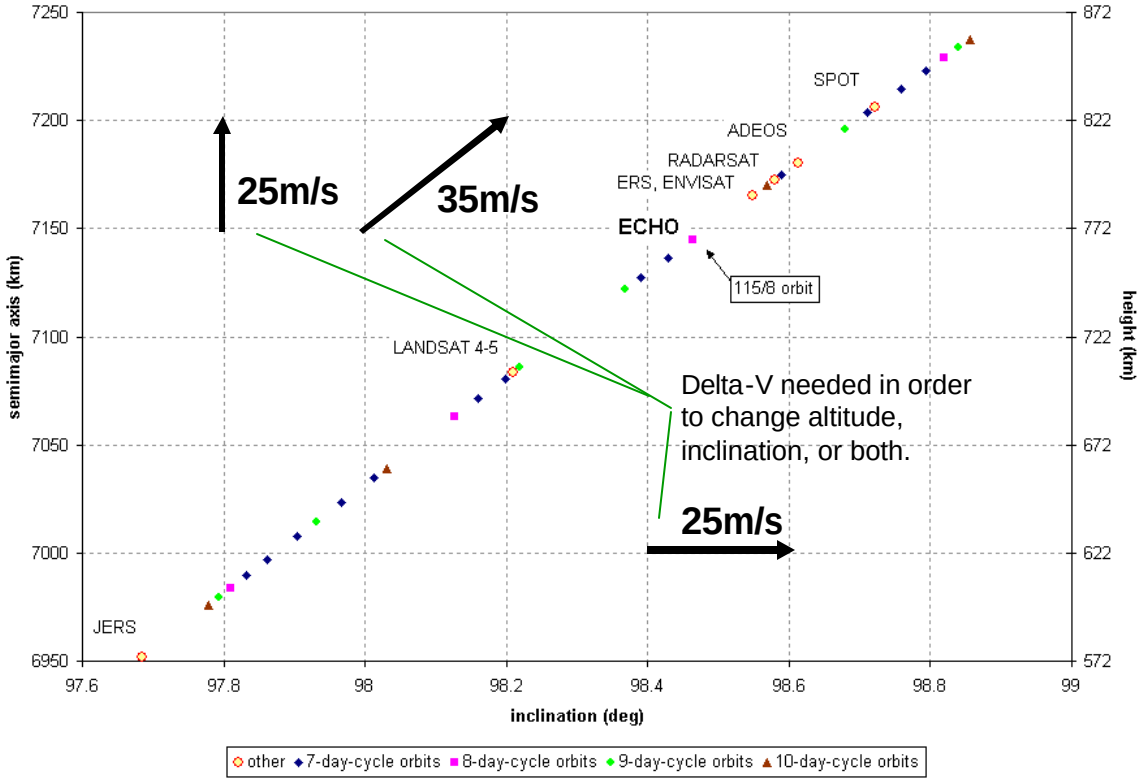
Changing the repeat cycle is expensive in terms of Delta-V (as depicted below). Both the inclination and the altitude need to be changed in order to maintain sun-synchronicity, and therefore, a certain level of optimization is required. The total Delta V estimate for the 5-year mission (including de-orbit [70 m/s]) is approximately 150 m/s. To include a single on-orbit repeat cycle change in the baseline InSAR mission would increase the propellant loading by approximately 30%.

Figure 5-4. Delta V Needed for Altitude/Inclination Change



There are significant potential scientific benefits associated with decreasing the orbital repeat cycle (e.g., from 8 to 2-days). However, by establishing a revisit frequency of 9-days as the baseline nominal orbit would enable moving to a 2-day repeat cycle by reducing the propellant required to make the orbit change by $\geq$50% over the current baseline 8-day revisit frequency orbit (as can been seen by the following figure). In addition, moving to either of the 9-day repeat cycles identified below would offer a lower altitude and higher number of orbits per repeat cycle, which would provide performance benefit to the Payload System and to a lesser extent the Flight and Launch Systems.

Several operational scenarios are under investigation by the Science and Mission Team. One option would be to begin the mission in a 9 or 8-day repeat orbit and move to a 2 or 3-day repeat at the end of the nominal mission. This scenario would be dependent upon the resources available after the nominal mission has been achieved minus resources required for deorbit. Though resource dependent this “best effort” approach would be the most cost effective and least impacting option. Other options

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include expanding the nominal mission to include changing repeat frequency as many as two times during the mission. For example, the mission could begin in a 2-day repeat orbit to establish a baseline, move to a 9-day repeat orbit for the nominal mission and move back to the 2-day repeat near end-of-mission.

The most economical options, in terms of delta-V required, for the on-orbit revisit frequency change scenario would be a mission architecture that utilizes an 8-day nominal mission orbit and a 3-day enhanced orbit. As shown in the figure below this appears to be the optimal selection when balancing required delta-V and the Science Community desire for more frequent revisits.

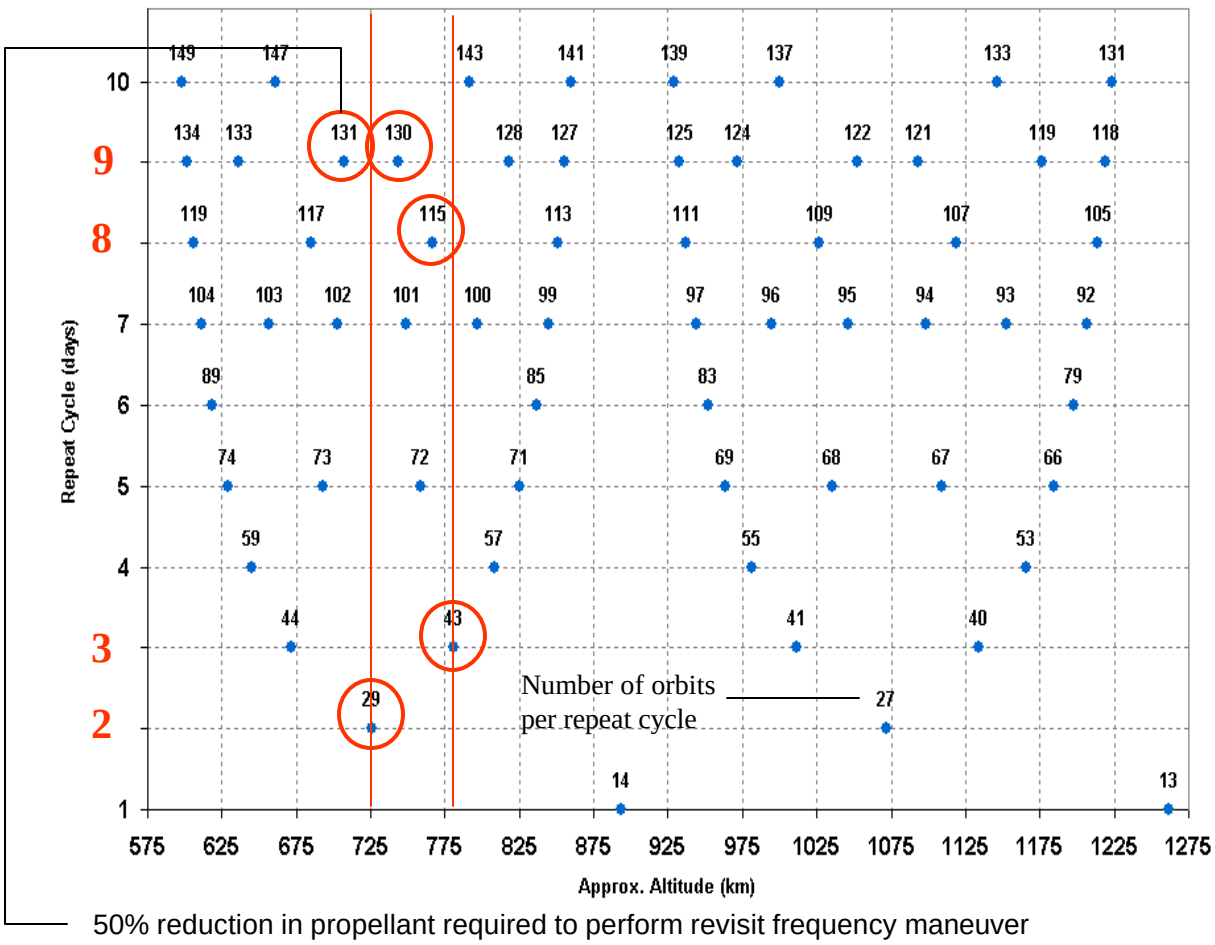

Figure 5-5. Orbit Selection and Propellant Savings – Changing Revisit Frequency

To insert the Flight System into a new repeat orbit timing is critical. When the Flight System is in the ground track that over flies the science target or is in a ground track that is optimized for over flight/maximum coverage of multiple science targets (e.g., mountain glaciers) transition to the new repeat would be initiated. This means that it could take up to one cycle (8 days assuming the original orbit is an 8 day repeat) before the change in repeat frequency could be initiated. Most likely it would be less than the

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duration of the original repeat cycle, because in the original cycle (8-day repeat) every point on the ground is at least visible twice, once in an ascending track and once in a descending track (high latitude targets may be visited more often). At this point two maneuvers would be executed near the ascending and descending nodes of one orbit, to get the change in semimajor axis and inclination required. The maneuvers have a size of about 5 m/s each and an execution error of about 2%. Approximately 4 hours later touch up maneuvers would be performed near the ascending and descending nodes of the orbit. The typical touch-up maneuver size is 100 mm/s (2% of 5m/s) and again has execution errors of about 2%. Approximately 5 hours later final touch-up maneuvers (one or two), with a typical size of 2 mm/s would be performed. Next overflight of the target should happen approximately one day later.

Going back to the original orbit and ground track would take a little more time, because the exact phasing would need to be considered, so instead of doing semimajor axis and inclination changes in one orbit, it may need to be split to allow for phasing corrections. Although the decision to go back to the original orbit could be given at an opportune time, so there is a probability that no more than 10 days would be required to get back into the original orbit.

The delta-V needed to go from various repeat frequency orbits and back is shown in the following table. As shown on the previous figure, the 8-day (115)/3-day (43) scenario is the most cost effective in terms of delta-V/propellant needed.

Table 5-2. Delta V Required for Various Revisit Frequency Changes

Maneuver	Delta-V Required
From an 8-day (115 revolutions) orbit to a 3-day (43 revolutions) repeat orbit and back:	
For the semimajor axis change:	7.3 m/s (2 times 3.6 m/s plus touch ups)
For the inclination change:	7.8 m/s
If the maneuvers can be combined:	10.8 m/s (2 times 5.3 m/s plus touch ups)
Total going there and back:	21.6 to 30.2 m/s (combined vs. independent maneuvers)
Total time to implement: ≤ 11 days (0-8 days prior to initiating maneuver, ~20-24 hrs to perform maneuvers, and 2 day for over flight of target within the orbital tube)	
From a 9-day (130 revolutions) orbit to a 2-day (29 revolutions) repeat orbit and back:	
For the semimajor axis change:	9.8 m/s (2 times 4.8 m/s plus touch ups)
For the inclination change:	11 m/s
If the maneuvers can be combined:	14.8 m/s (2 times 7.2 m/s plus touch ups)
Total going there and back:	29.6 to 41.6 m/s (combined vs. independent maneuvers)
Total time to implement: ≤ 11 days (0-9 days prior to initiating maneuver, ~20-24 hrs to perform maneuvers, and 1 day for over flight of target within the orbital tube)	
From an 8-day (115 revolutions) orbit to a 2-day (29 revolutions) repeat orbit and back:	
For the semimajor axis change:	22 m/s (2 times 10.7 m/s plus touch ups)
For the inclination change:	25 m/s
If the maneuvers can be combined:	33.2 m/s (2 times 16.3 m/s plus touch ups)
Total going there and back:	66.4 to 94 m/s (combined vs. independent maneuvers)
Total time to implement: ≤ 10 days (0-8 days prior to initiating maneuver, ~20-24 hrs to perform maneuvers, and 1 day for over flight of target within the orbital tube)	

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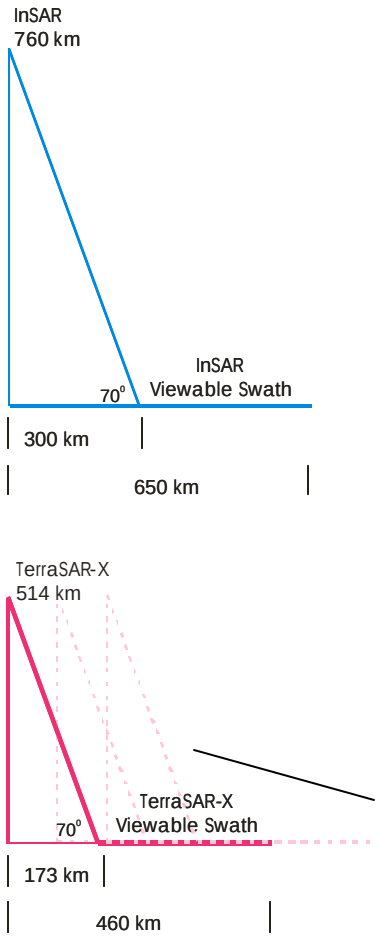
5.7.2.1 *Combining Measurements to Reduce Acquisition Intervals*

A study was performed to assess the potential of reducing SAR acquisition intervals by combining measurements from two SAR spacecraft. For this exercise the specific mission assessed, in combination with InSAR, was TerraSAR-X. As shown below, the differing orbits of TerraSAR-X and InSAR cause the instrument swaths to overlap only when the spacecraft nadir tracks are between 127 and 190 km apart.

Figure 5-6. Orbital Parameters and Overlapping Swaths



- InSAR
  - The orbit is circular, 760 kilometers above the equator, sun-sync, with an 8-day repeat. The accessible area extends from 300 to 650 kilometers on both sides of the groundtrack.
- TerraSAR-X
  - The orbit is circular, 514 kilometers above the equator, sun-sync, with an 11-day repeat. The accessible area is defined by an incidence angle between 20 and 45 degrees on both side of the groundtrack, which equates to an accessible area extending from 173 to 460 kilometers on both sides of the groundtrack.

If the TerraSAR-X nadir track is offset between 127 and 190 km it will be within the InSAR swath.

Analyses were performed by selecting a set of targets on the Earth and computing the times when the targets are within InSAR's accessible swath. An interval of +/- 1 (2,3,6) hours around those times was then searched for TerraSAR-X accessibility for the same targets. The number of pairs (InSAR + TerraSAR-X) found was recorded for each target and each separation threshold (1,2,3 or 6 hours) and is illustrated in the following figure.

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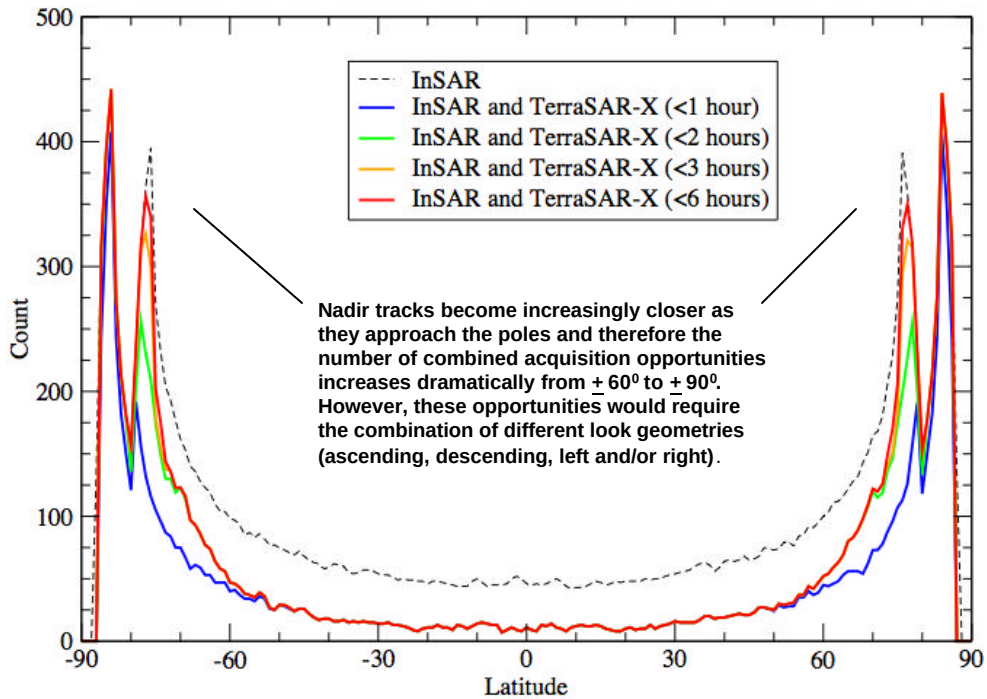
Figure 5-7. Combined Acquisitions Over 88 Days



The analyses showed that complete global access with 1hr acquisition separation every 88 days is possible. Any specified science target could be accessed every 11 days on average or every 36 days (worst case) with a 1hr combined acquisition measurements. Increasing the maximum temporal separation between InSAR and TerraSAR-X acquisition does not increase the number of useable pairs below 60 degrees latitude. Between 60 and 80 degrees latitude, combining pairs that are up to 3 hours apart double the number of useable acquisitions. Going beyond 3 hours does not provide any significant improvement.

5.7.3 Global Land Surface Measurements

Acquiring a global set of data at the beginning of the mission would allow the creation of an interferogram in response to an event outside the targeted areas. Using the ScanSAR mode, the total on-time required to get 2 global maps (left and right looking) is 11,730 minutes. This dataset could be acquired before the main data collection phase, or continuously by designing a system with more capability than required by the nominal (baseline) mission. Assuming that the radar operates 10 minutes per orbit, as planned, is focused on creation of a global baseline map and that the on-time is equally spread between the 115 orbits of an 8-days cycle, it would take 80 days to complete the map. Using actual on-time per orbit would take 104 days to get the data from the busiest orbits with a 10 minute per orbit constraint.

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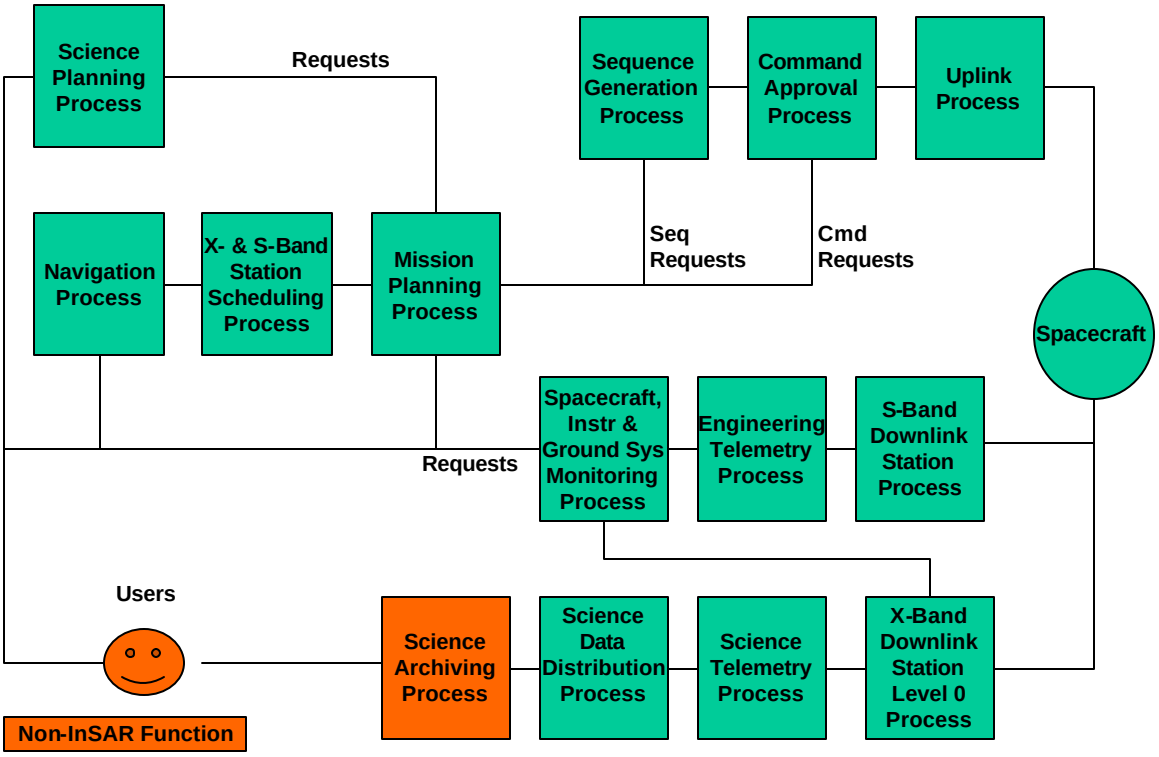
6.0 Mission Operations System

6.1 InSAR MOS Summary

The following diagram shows the major MOS (Mission Operations System) functions and processes:

- The uplink process takes science requests from users and coordinates them with engineering activities to produce a mission plan. An uplink sequence is developed, approved, and sent to the spacecraft.
- The downlink process takes engineering data from the ground stations, monitors spacecraft health and safety, and provides the data for detailed analysis.
- Science data is retrieved from the ground stations, processed at JPL, cataloged, archived, and provided to science users.

Figure 6-1. InSAR MOS Summary Flow Diagram



6.2 MOS Operational Concept

Two S/X-band Ground Stations are used for command uplink and simultaneous engineering & science downlinks. The prime station is the Alaska SAR Facility (ASF) near Fairbanks, Alaska. It has one prime and one backup antenna. The second station is the NASA Ground Network station at Svalbard, Norway.

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Ground station passes will occur once per orbit for ~10 minutes per pass. Science data will be downlinked on X-band for ~4 minutes during each pass at 300 Mbps. Total raw science data is 147 Gbytes / day. (This is based on 10 min of "data takes" per orbit at 130 Mbps of data from the radar.) The nominal plan is to downlink 75% of the data via ASF and 25% via Svalbard. Engineering and science data will be FTPed to JPL at 10-20 Mbps over TBD data lines.

Global Positioning System (GPS) data will be used for Precision Orbit Determination (POD) and quick look Navigation (NAV) orbits. In support of Launch and Early Orbit (LEO) tracking, NASA Ground Network (GN) S-band ground stations are used for command uplink and engineering telemetry downlink.

6.3 Flight/Ground Interfaces

The X-band science downlink data rate is 300 Mbps, the S-band engineering downlink is between 8-32 Kbps. The spacecraft must have enough onboard storage to retain science data for 12 hours and engineering data for at least 48 hours. Both X-band and S-band downlinks will use Consultative Committee for Space Data Systems (CCSDS) telemetry formats and be Reed-Solomon (RS) coded. The command uplink will be ~4 Kbps and use CCSDS formats. Guaranteed command delivery will be assured by the use of Command Operations Protocol #1 (COP-1) or equivalent protocols. The spacecraft must have enough on-board sequence command storage for two weeks of normal operations. Also, the on-board command sequence must be able to be modified by the ground after it is uplinked.

6.4 MOS Team Overview

The InSAR MOS will consist of the following Teams:

The ***Mission Management Team*** manages all MOS activities and approves all commands sent to the spacecraft.

The ***Science Planning Team*** coordinates science data "takes" with the science community and outputs sequence and individual command requests.

The ***Mission Control Team*** performs all real-time spacecraft monitoring and commanding. It establishes the spacecraft/ground data links, transmits all command files, receives and processes engineering telemetry data including alarm checking, and monitors health and safety of the spacecraft, including the instruments. Operations are performed by a 12 hour/7 day on-site flight team staff (24 hour/7 day for the first 6 months) using a combination of manual and automated processes.

The ***Sequence Generation Team*** integrates sequence inputs from science planning, instrument maintenance, spacecraft maintenance, navigation, and ground station schedules into a coordinated sequence of events and an uplink command file. Each sequence takes three weeks to generate and executes for one week, so multiple

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sequences are in generation in parallel. Sequences are made up of "standard blocks" including science data collection, ground station passes, routine spacecraft and instrument activities, and periodic spacecraft and instrument maintenance activities. The Team also requests and negotiates ground station schedules. *(The sequence generation process is able to make changes to a sequence due to high-priority science requests after the sequence has been uplinked to the spacecraft.)*

The ***Navigation Team*** determines the spacecraft orbit and generates detailed maneuver plans to maintain that orbit within requirements. It generates the POD and other orbit products, and outputs sequence and individual command requests to other teams.

The ***Spacecraft Analysis Team*** analyzes and performs trending of spacecraft telemetry information, responds to spacecraft anomalies, and outputs routine or contingency requests to other teams. The Team is staffed under a support contract with the spacecraft builder.

The ***Science Data Processing Team*** monitors receipt of science data from the ground stations, performs Level-0 processing, generates and maintains online science data catalogs, processes and sends science data to regional data nodes, and sends data to archive centers (Eros Data Center (EDC) and TBD).

6.5 MOS Requirements Drivers

The following requirements and design issues have major effects on the MOS designs, staffing, and costs:

The number and size of science observations and the number and size of high priority observations. Due to the very large amount of science data that must be received and processed each day, significant increases in the average amount of data taken on each orbit or in the "high-priority" data could result in additional ground station passes and/or increased data line rates needed to get the data back to JPL.

The frequency and turn-around time of science replanning due to high priority events. Frequent or rapid modifications to approved command sequences to respond to "high-priority events" could require increased MOS staffing.

The following are MOS requirements on the spacecraft design:

6.5.1 Spacecraft Design and Ease of Use

- Simultaneous S-Band uplink, S- and X-Band downlink are required.
- Standard CCSDS frame/packet telemetry and command formats, guaranteed command delivery protocol (COP-1 or equivalent).
- On-board data storage memory size of 512 Gbits. Provides 12 hours of storage

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before overwriting. Two Partitions – “high-priority” and “normal”, with ability to select partition for reading/writing by ground or sequence command.

- Sequence memory for up to 2000 commands with ability to modify sequence after loading.
- Translation thrusters on “back” and “side” of spacecraft to allow drag-makeup maneuvers and inclination adjust maneuvers without large attitude turns. (Drag-makeup maneuvers are needed 2-3 times / week. Inclination maneuvers are needed ~1 / week.)

6.5.2 GPS Receiver Data Content and Field of View

- The spacecraft GPS receiver shall provide continuous dual-frequency pseudorange and carrier, and navigation solutions. Data must be transmitted to the ground at each ground station pass.
- GPS antenna mounting on the spacecraft shall be such as to maximize the unobstructed field of view and minimize multipath effects.

6.5.3 Spacecraft Real-Time Command & Telemetry System

- The spacecraft contractor must provide a real-time command/telemetry system that will support automated operations. Automation scripts must have access to real-time telemetry and be able to perform all functions that can be performed by an operator. Automation scripts must be able to notify on-call personnel via telephone paging in the event of spacecraft or ground alarms.

6.6 Implementation Approach

With the intent to defer MOS/GDS designs and subsequent reviews to allow maximum possible maturity of science and flight system requirements and designs: The MOS/GDS Preliminary Design Review (PDR) will be conducted independently of and delayed from the Project PDR. (Approximate date = Mid-February 06.) Similarly, the MOS/GDS Critical Design Review (CDR) will be conducted separately from the Project CDR. (Approximate date = Mid-February 07.)

The Spacecraft System contract must include: Spacecraft Analysis Subsystem and Spacecraft Analysis Team support. Spacecraft Real-time Command and Telemetry Subsystem. MOS automation scripts must be developed jointly between the Spacecraft System Contractor and MOS personnel.

MOS/GDS Implementation Plans will specify required system and subsystem documentation, reviews, implementation approach, etc. JPL standards will be followed in all areas. The MOS/GDS will provide representatives on the project level Design Team.

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Design of the MOS/GDS will be led by MOS and GDS engineers and performed by a Design Team with representatives from all MOS/GDS elements. Subsystem implementation and team planning will be monitored and reviewed by the same Design Team.

Work Breakdown Structure (WBS) elements and Work Agreements (WAs) are constrained by the following: Development activity accounts should be terminated approximately 6 months after launch. Operations and maintenance activity accounts should be initiated no earlier than approximately 6 months before launch. Funding for those two categories of activities originates in separate UPNs. Mission Operations Management functions are assumed to be included in WBS element 01. Mission Operations Command Assurance function is assumed to be included in WBS element 03.

6.7 Navigation

InSAR will be navigated so it is always no more than 125 meters away from a reference Earth-fixed trajectory. Two main natural perturbations require that maneuvers will have to be performed to keep the spacecraft inside this 250 meter diameter tube:

- Tidal (3-body) perturbations will produce an annual change in the inclination of the orbit. These perturbations will need to be compensated for with up to weekly cross-track maneuvers at the equator, with a cost in delta-V of about 9 m/s per year. The inclination perturbation is very predictable and a plan for maneuvers can be easily prepared weeks or months in advance.
- Drag will decrease the orbit period and consequently move the trajectory eastwards. Along-track maneuvers will have to be performed, up to three times per week, to maintain the spacecraft in the tube, with a cost in delta-V of only a few mm/s depending on the level of solar activity. These maneuvers will also be used to maintain the altitude and the frozen eccentricity. The drag perturbation is more difficult to predict, but solar and geomagnetic activity predictions for up to one week should be accurate enough to prepare the maneuver plan.

All these maneuvers can be easily computed on the ground using existing institutional navigation software. They can be recalculated daily in an automated fashion considering all applicable constraints and uplinked to the spacecraft once a day. Comparing the updated maneuver plan with the previous can be used as an easy validation step. On-board automation would require additional development, validation, and maintenance costs and may also increase risk and fuel expenditure.

6.7.1 Drag-free Ground Track Walk at the Equator

Even in absence of drag, because of the eccentricity of the Earth orbit around the Sun and the Moon tidal effect, small maneuvers would be needed to maintain the spacecraft inside the 250 m tube.

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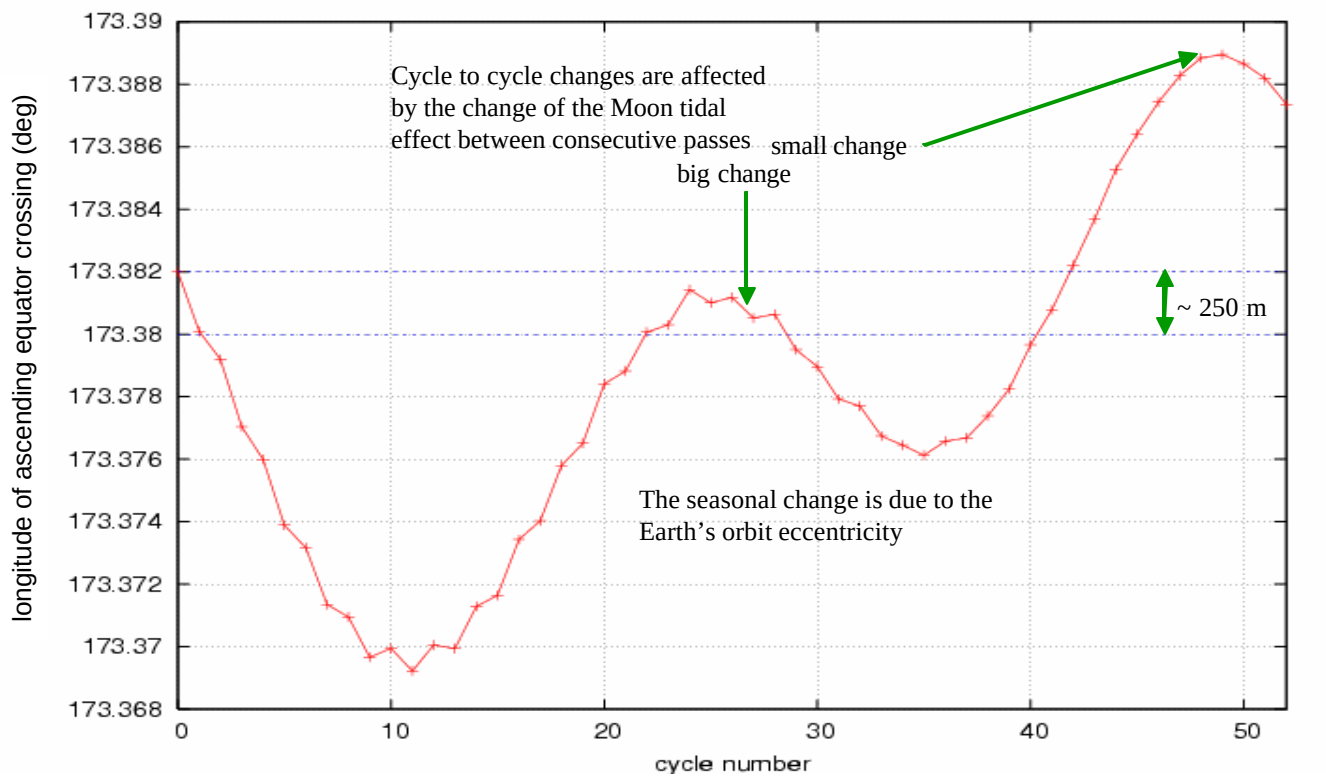
To control the ground track walk at the equator in absence of drag we would need to expend only about 10 mm/s per year in along-track maneuvers.

Figure 6-2. Drag-free Ground Track Walk at the Equator



6.7.2 Drag-free Inclination Walk

It is much more expensive to control the ground track walk at the poles. The change in tidal effects is going to change the effective J2 and, consequently, the inclination of the orbit. To control the ground track walk at the poles in absence of drag we need to expend about 9 m/s per year in inclination change (cross-track) maneuvers.

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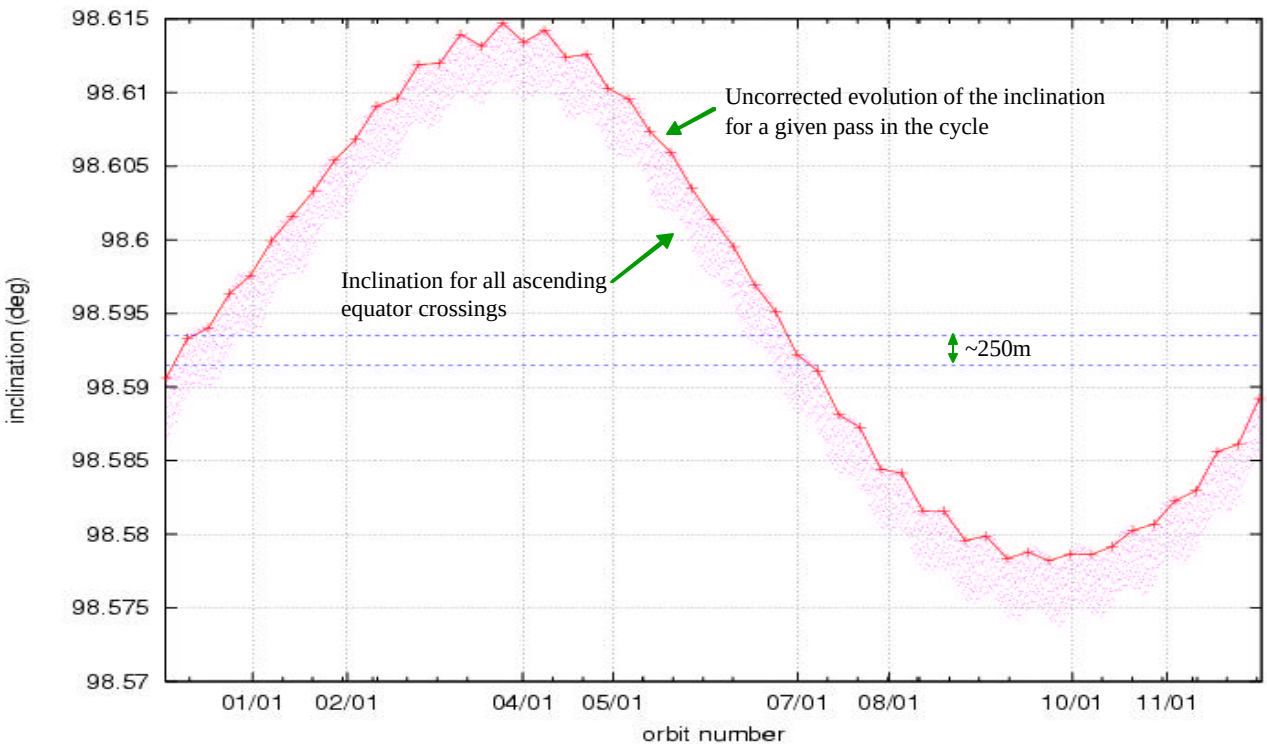
Figure 6-3. Drag-free Inclination Walk



6.7.3 Drag Compensation

Atmospheric density depends on location (altitude, latitude, and solar time), season, and solar activity. The solar activity level can change the atmospheric density by a factor of 10 or more and considering drag is a function of the atmospheric density and the spacecraft frontal-area to mass ratio the delta-V required to compensate for drag is highly dependent upon solar activity, as shown below.

Table 6-1. Annual Delta-V Needed to Compensate for Drag

Solar Activity	Delta-V Required
High solar activity	1 - 5 m/s
Medium solar activity	0.2 - 1 m/s
Low solar activity	0.04 - 0.2 m/s

6.7.4 Precision Orbit Determination

The InSAR orbit will be determined using data from a precision GPS receiver. The GPS antenna mounting shall be such as to maximize the unobstructed field of view and minimize multipath effects. As such, solar arrays and other structures should not be

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located in the field of view of the GPS antennas.

The GPS receiver may provide real-time position and velocity data to the spacecraft bus, so it can be used to point the solar array or to calculate the optimal attitude.

Data from the GPS receiver, continuous dual-frequency pseudorange and carrier and navigation solutions, shall be transmitted to the ground at least once a day, so it can be used to verify receiver health, support operational navigation and support precise orbit determination.

Operational orbit determination will be performed as frequently as the GPS data is downloaded, employing a robust automated system using the best available GPS orbits and clocks, a simple dynamic model, and solar flux and Earth orientation values to fit the data and predict the trajectory for navigation purposes.

POD (Precision Orbit Determination) will be performed once a day, fitting more than 24 hours of GPS data and high quality GPS orbits and clocks, with a more sophisticated dynamical model. Precise orbits will be delivered to users together with the best trajectory prediction estimate for the next 24 hours.

The system will be highly automated, but it may require fine-tuning post-Launch to achieve the best possible accuracy.

6.8 MOS Automation

Routine operations for each orbit will be performed automatically by ground automation. Downlink of engineering and science data will be performed by ground automation commanding once the real-time system has confirmed good data links with the spacecraft. Receipt of science data at the station, FTP to JPL, and routine processing by the DPS should all be automatic with ground automation monitoring the data flow and processing. MOS personnel will perform any special activities during one 12 hour shift each day. This includes any non-standard Ground Station scheduling, ground anomaly handling, and special science or engineering commanding.

Since mission control staff will not be available 24/7 to resolve anomalies, there is significant risk of occasional “normal priority” science data losses. High-priority data will be protected in a separate on-board memory region which will not be erased until the receipt of this data has been verified on the ground.

6.9 Ground Data System

The following diagram shows the major elements and data flows of the InSAR GDS (Ground Data System). Descriptions of each element follow the diagram.

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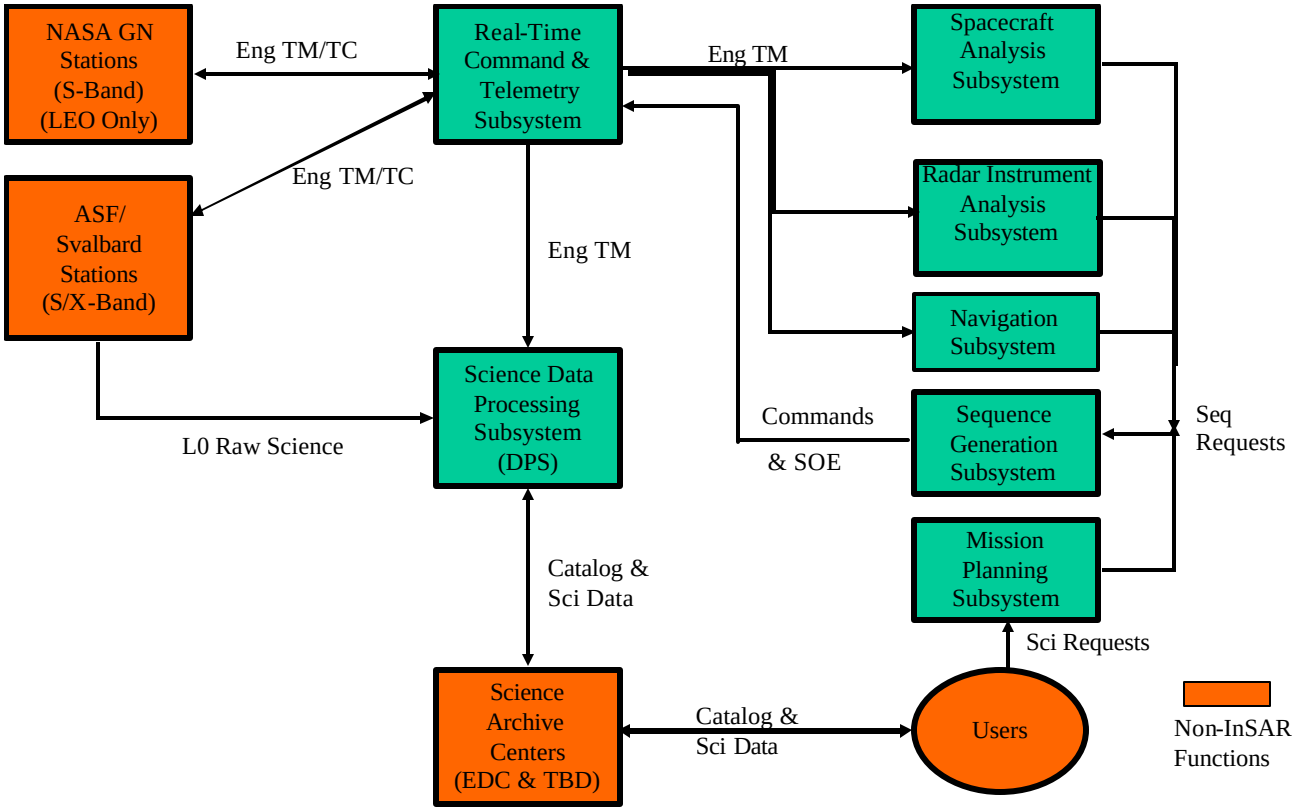
Figure 6-4. InSAR Ground Data System Diagram



6.9.1 GDS Subsystem Descriptions

NASAs GN Stations: NASA GN (Ground Network) stations at Poker Flats, Alaska (PFF), and Wallops Island, Virginia (WFF), will be used for engineering data uplinks and downlinks during Launch and Early Orbit (LEO) support.

ASF/Svalbard Stations: The Alaska SAR Facility (ASF) and the NASA GN Station at Svalbard, Norway (SGS), will be used for all engineering and science data downlinks and all command uplinks during normal mission operations.

Real-Time Command and Telemetry Subsystem: Real-time command and telemetry processing will be performed by a highly automated processing system to be provided by the spacecraft contractor.

Sequence Generation Subsystem: JPL institutional capabilities will be used for this subsystem: SEQGEN, SOEGEN, SFOSGEN are some of the programs that will be

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configured for our use. TBD software for Ground Station scheduling will be generated based on the existing Jason Project scheduling tools.

Mission Planning Subsystem: This subsystem will provide the tools needed to prepare science “data take” requests.

Spacecraft Analysis Subsystem: This subsystem will be provided and operated by the spacecraft contractor, and will support spacecraft anomaly and trend analysis, maneuver command generation, etc.

Radar Instrument Analysis Subsystem: JPL institutional radar instrument capabilities will form the basis for this subsystem, and will support anomaly and trend analysis of the radar instrument.

Navigation Subsystem: JPL institutional NAV capabilities will form the basis of this subsystem.

Ground Communications Network: NASA Input-Output Network (IONET) will provide secure communications between JPL and the NASA GN S-band stations. Engineering & science data transmission between the S/X-band stations, JPL, Regional Data Nodes, and Science Archive Centers (EDC & TBD) is TBD.

6.9.2 Data Processing System Overview

The InSAR DPS (Data Processing System) will provide the infrastructure to enable archiving, processing and distribution of the science data for the InSAR mission. It will support various topologies that enable archiving and distribution via a multi-center architecture where geographically distributed data nodes are able to capture, process and distribute data that is regionally oriented. A virtual system will be constructed that integrates all the nodes despite the physical distribution of both the software components and data products. This will include local and permanent archiving, discovery and access to distributed science data, software and infrastructure to support data processing and tools to manage the deployed system. A multi-tiered software architectural approach will be followed which will enable connection to InSAR data via middleware so that InSAR can share data with other earth science initiatives.

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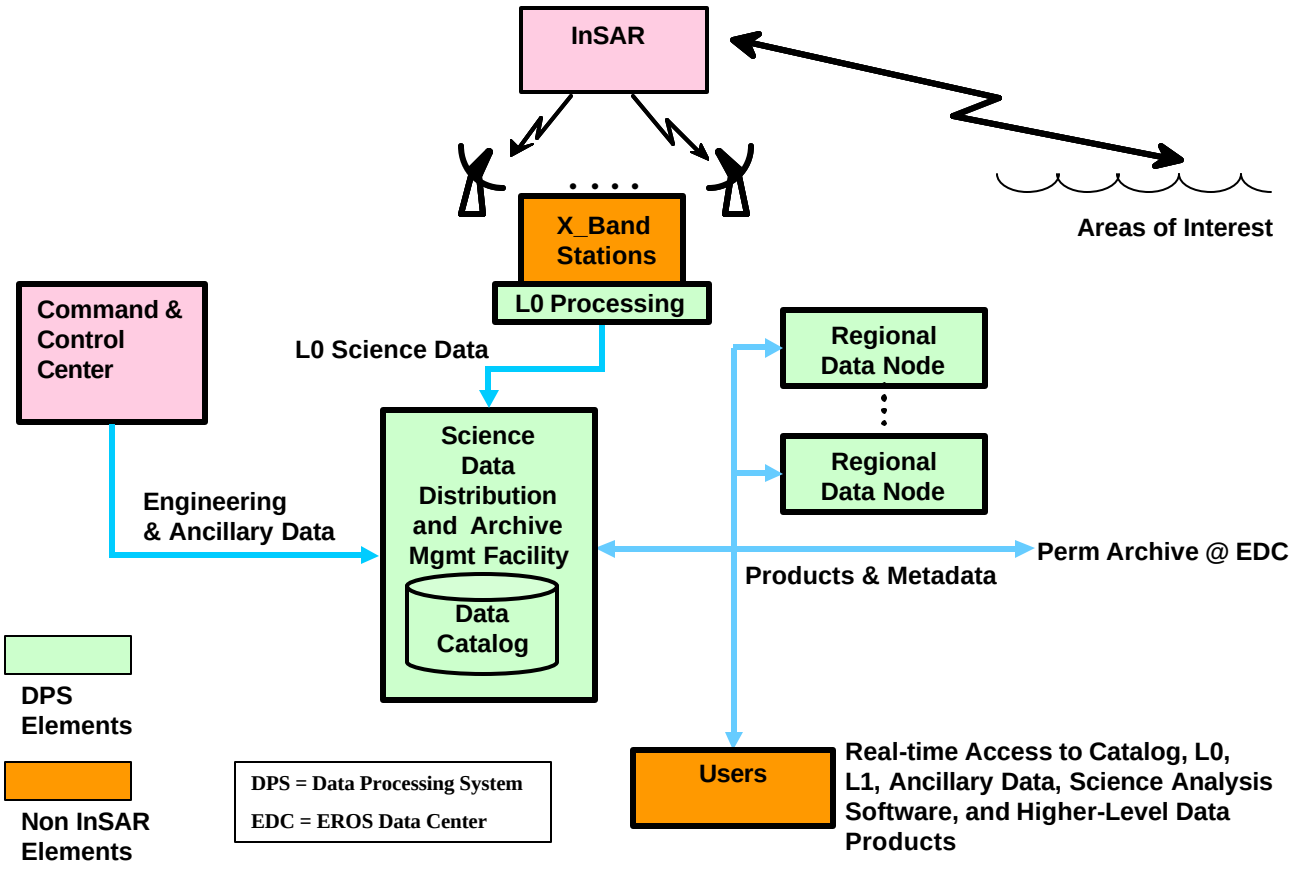
Figure 6-5. InSAR Science DPS Architecture Diagram



6.9.3 DPS Pipeline Architecture

The DPS architecture will provide a pipeline architecture that connects and manages data from the X-band stations to a Science Data Distribution and Archive Management Facility at JPL to Regional Data nodes distributed across the United States. A centralized data catalog will be developed to catalog and manage information regarding the physical data products managed at the independent data nodes and the EDC archive. Each of the data products sent to the data nodes will follow an ingest process which will capture metadata associated with the data product in the InSAR data catalog. This will include not only metadata to describe the data product, but also information on how to access the data product including information about the access mechanism (i.e. protocol, etc). This metadata will provide sufficient definition of the product so that it can be used to later query and mine for the InSAR repositories.

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6.9.4 DPS Data Distribution

Regional data nodes will provide short term archiving for InSAR data products for a period of up to six months. These regional data nodes will serve as distribution points for the InSAR data defined by regional boundaries within the data. Data products will be maintained on-line enabling faster data acquisition through a realtime web-based discovery tool. Access to data products will be provided through published distributed system interfaces that enable access via a client/server "grid-like" architecture. Middleware will be deployed which will plug into these protocols and support the development of science tools that can access the distributed data products as well as enable interoperability with other earth science data systems. The system will enable cataloging and distribution of any InSAR data product that the project feels should be included as part of the science data sets.

6.9.5 DPS Data Processing

Creation of "raw data" products will occur at the ground stations prior to distribution. The data products will be archived and distributed via the regional data nodes as well as the permanent archive at EDC. Processors (both the commercial and ROI_PAC processors) will be made available for download by scientists, which will provide desktop processing of the raw data products. Due to the number of possible processing combinations, standard data products beyond L0 will not be automatically processed. However, the DPS infrastructure will also support the ability to plug-in specific on-the-fly processing or enable a data processing center (as an enhancement). Specific on-the-fly processing could be incorporated in multiple ways. First, the data ingest function at a regional data node could perform processing as part of the data movement and registration process. Second, the software middleware which enables data process access and distribution can be augmented to perform server-side processing as part of the request for the product (as mentioned under the ROI_PAC web interface discussion). Both of these options are deemed as enhancements to the baseline.

6.9.6 DPS Data Archiving

Long term data archiving will be provided by the Eros Data Center (EDC). In addition, short term archives will be maintained for a period of six months both at the Science Data Distribution and Archive Management Facility at JPL and the regional data node. All archived data products will be registered within the InSAR data catalog. Engineering and ancillary data will also be captured and archived at the Science Data Distribution and Archive Management Facility at JPL.

6.9.7 DPS Baseline Requirements

Data Acquisition: The DPS shall capture all of the InSAR science and telemetry data

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files successfully down-linked to the Ground Stations.

Data Processing: The DPS shall process all of the successfully received InSAR science and telemetry data files to the space agency standard Level 0 product (CEOS format). The DPS shall provide public access to required ancillary files and algorithms for processing the DPS-generated Level 0 files to Level 1.

Data Management: The DPS shall catalog all captured InSAR science and telemetry data files down-linked to the Ground Stations. The DPS shall catalog all Level 0 product files it produces. The DPS shall distribute all DPS-generated Level 0 product files appropriately to designated regional access nodes.

Data Archiving: All DPS-generated Level 0 files shall be accessible from a DPS-managed archive (the regional data nodes) for at least 6 months. All DPS-generated Level 0 files shall be distributed to the designated long-term archive. The DPS shall distribute all of the successfully down-linked InSAR science and telemetry data files to the designated long-term archive.

Data Distribution: The DPS shall provide public access to all DPS-generated Level 0 product files. The DPS shall provide tools for the public to generate higher level data products from the DPS-generated Level 0 products.

6.9.8 DPS Potential Enhancements

On-Demand Processing: Users who desire higher level products for a specific geographical region can request the processing of those products via a web-based portal. The portal will accept the request in terms of the data product desired (time range, geographical region, etc.) while the details of the actual processing are hidden. The central catalog will provide the necessary information for locating the input files, triggering the requested processing and delivering the final products to the user. The processing will occur at the regional data nodes using ROI_PAC.

Retain Processed Data Products at Regional Data Nodes to Minimize Reprocessing of High Demand Products: Higher level products generated by on-demand processing requests will be retained at the regional processing node while demand for those products are high. This will create an intelligent “cache” that will cut down on the amount of processing required for frequently requested regions and products.

Scheduled Processing of High Demand Products as Part of the Ingestion Pipeline: Designated geographical regions of high interest will be automatically processed to higher level products at the regional nodes. These products will be made available to the public through the web-based portal and possibly, via a subscription service. The baseline DPS infrastructure will make it relatively trivial to “link” in new processing as part of the automated ingest of the level 0 product.

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Data Mining and Analysis Support: Users will be able to plug-in their data mining and analysis tools to the DPS for data discovery. Product metadata stored in the central catalog and DPS-provided APIs will provide the ability for the user to locate and retrieve the data products of interest. In addition, feature detection and other mining agents will be designed in such a way as to generate additional metadata describing the product to aide knowledge discovery. These agents will be executed at "ingest" time of the level products to support build-out of a knowledge-base where the metadata can be searched.

6.9.9 Science Data Processor Overview

Science Data Processor Approach: ROI_PAC (existing JPL software for repeat pass interferometry data processing) will be used for the cal/val process, validation of the "public" processor (as defined below), and the algorithm development such as the split spectrum processing algorithm for ionospheric compensation. ROI_PAC needs to be improved for the InSAR project. ROI_PAC is currently used by many reseachers in the world to process the existing SAR data such as ERS data. ROI_PAC may not be suitable for "public" use since the "help-desk" activity will be difficult to accomplish by the processor authors. A commercial processor will be used as the "public" processor to be distributed to and maintained for the public. The commercial processor development and maintenance will be funded by the project; however, the public does not have to pay for the service.

6.9.9.1 ROI_PAC

ROI_PAC Modification: ROI_PAC currently is a usable processor, having been used extensively to process ERS and JERS datasets, but is not InSAR-capable. There are some improvements that are necessary:

- Split-spectrum processing, for ionospheric effects removal
- The code must be cleaned up to make the interfaces uniform, to improve error handling, and add a mode which removes temporary files after use
- If ScanSAR becomes a mode for InSAR, then ScanSAR processing mode must be added

Additional modifications that would significantly improve ROI_PAC's speed and flexibility:

- Parallelize more modules in the code. Right now, only the processor ROI is parallelized to any extent, and a couple of very time-consuming processes, correlation and interpolation, could be speeded up significantly by parallelization
- Modify the Doppler estimation code to handle longer strip lengths, up to 500 km, and rapidly varying Doppler values
- In the same vein, extend the supported platforms to include Beowulf clusters, benefit from parallelized commodity computing

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For capable and experienced users, ROI_PAC would deliver excellent results. However, a wider audience with less radar experience would likely have a difficult time using ROI_PAC to obtain the desired displacement products.

Web Interface to ROI_PAC: There is an effort currently under way to add a web interface to ROI_PAC, which allows controlled parameter input, tracking of output logs, and error handling. It is called Wiglaf (Web Interface Generator and Legacy Application Façade), and it is a general web interface for running complex modular computational codes using Java applets and an Apache web server to control the processing. Wiglaf builds a script to control the process, and as long as the code has feedback on what it is doing, Wiglaf can display that, including monitoring log files that are being written by the computational process. The interface right now is a bit raw, and it requires quite a bit of infrastructure to run, but it is a GUI, and it does run ROI_PAC. Wiglaf could be an excellent way for a university department or company to offer up processing capability or even processed products as a service to users, rather than as a processor running standalone on a user's desktop.

6.9.9.2 Vexcel Processor

Vexcel has produced a very fine suite of tools for processing radar data from a variety of platforms: ERS, JERS, and Radarsat. Its Level 0 processor is already running at ASF and Svalbard. The combination of Vexcel's **Focus**™ SAR processor for SLC image generation and their **Phase**™ interferometric processor seems to work similarly to ROI_PAC. These programs have well-tuned Java-based GUIs which allow parameter selection, process monitoring and control, dumping of intermediate products for analysis, display functions, and batch script generation. The processor appears to have similar speed to ROI_PAC, which is not surprising since it uses similar algorithms. As with ROI_PAC, the SAR processor is parallelized, while the interferometric processor currently is not. The SAR processor currently runs on Sun, SGI, and Linux platforms, but the interferometric processor only runs on Sun and SGI. ROI_PAC runs on Sun, SGI, and Linux platforms. Both processors would need to be modified to do split-spectrum processing for ionosphere correction.

The Vexcel processor suite appears to be an excellent product which can be modified to process InSAR data. It has a very fine GUI and lots of documentation, as well as a worldwide support network to aid the less sophisticated user to obtain the desired DEM or displacement map. Its main disadvantages are its cost, and its current inability to run on commodity hardware.

6.10 MOS/GDS Options Investigated

6.10.1 SafetyNet

Current planning information suggests the SafetyNet design, which is to be operational in the 2008 timeframe, would include 150 Mbps Ka-band receivers with 45 Mbps ground network lines. Based on the orbital average time over station(s) of 27 minutes for

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SafetyNet, a total of approximately 243 Gbits of data can be downloaded per orbit. This performance is more than adequate for the InSAR baseline 10 minute (orbital average) instrument on-time. However, the Ka-band received signal-to-noise ratio (SNR) is more susceptible to large variations due to weather effects than is the X-band SNR and consideration should be given to the reliability of a Ka-band link due to weather (or rain fade).

6.10.2 TDRSS (Tracking and Data Relay Satellite System)

The GSFC Space Network Project (Space Network) hopes to have a Ka-Band Ultra High Rate data service which would provide Space Network customers with data relay services from their spacecraft to ground via TDRS-8, 9 or 10 up to 1.2 Gbps by FY'06. For NASA customers Space Network services are free at this time. However, the spacecraft would need a TDRSS compatible transceiver and gimbaled antenna in place of the X-band equipment chain.

6.10.3 Contracted MOS Option

Two options for MOS/GDS were costed. A JPL developed MOS/GDS with JPL providing primary operations support, and an option with JPL overseeing a contracted commercially developed MOS/GDS with the commercial company providing primary operations support. As a risk mitigation measure, a 30% reserve is carried on the commercial company MOS estimate for all mission phases.

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7.0 Launch System

Various launch system options have been investigated for InSAR in support of current and future trades to mitigate potential increased cost and risk associated with Delta II volumetric constraints and availability concerns. A range of viable launch system solutions are followed by a discussion of the Baseline Launch System and various options and analyses performed.

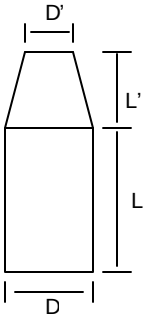
7.1 Delta Launch System Family

Several Delta Launch System configurations meet the performance requirements of the InSAR Mission (see table and figure below). The Delta Launch System configurations that bound the needed performance capability are the Delta II 2420-10, Delta II 2920-10 and Delta IV-M. These launch systems are described in more detail in following Sections.

The Delta II 2920-10 has been selected as the current Baseline Launch System for the InSAR mission as it appears to be the most resilient and cost effective approach. The 2920-10 offers significant room for mass growth and the potential to trade Flight System mass for cost. A decision could be made to utilize the Delta II 2420-10 in lieu of the 2920-10 (and the associated cost savings realized) at or around PDR if the mass margin is no longer needed.

Table 7-1. Viable Delta Launch System Configurations

Launch System	Performance (kg)	Margin	Dynamic Envelope Dimensions (m)				Cost (RY$)
			D	L	L'	D'	
2420-10	1950	31%	2.74	4.16	2.67	0.61	$78.9
2920-10	**3150**	**57%**	**2.74**	**4.16**	**2.67**	**0.61**	**$81.0**
Delta 4040	6740	80%	3.75	5.41	4.53	0.91	$140.0



Note: Assumes an InSAR mass of 1,350kg and a 760 km sun-synchronous orbit; Margin is calculated: (LV Capability-InSAR Mass)/LV Capability; Performance curves and assumptions; and cost sources and assumptions are listed in back-up material.

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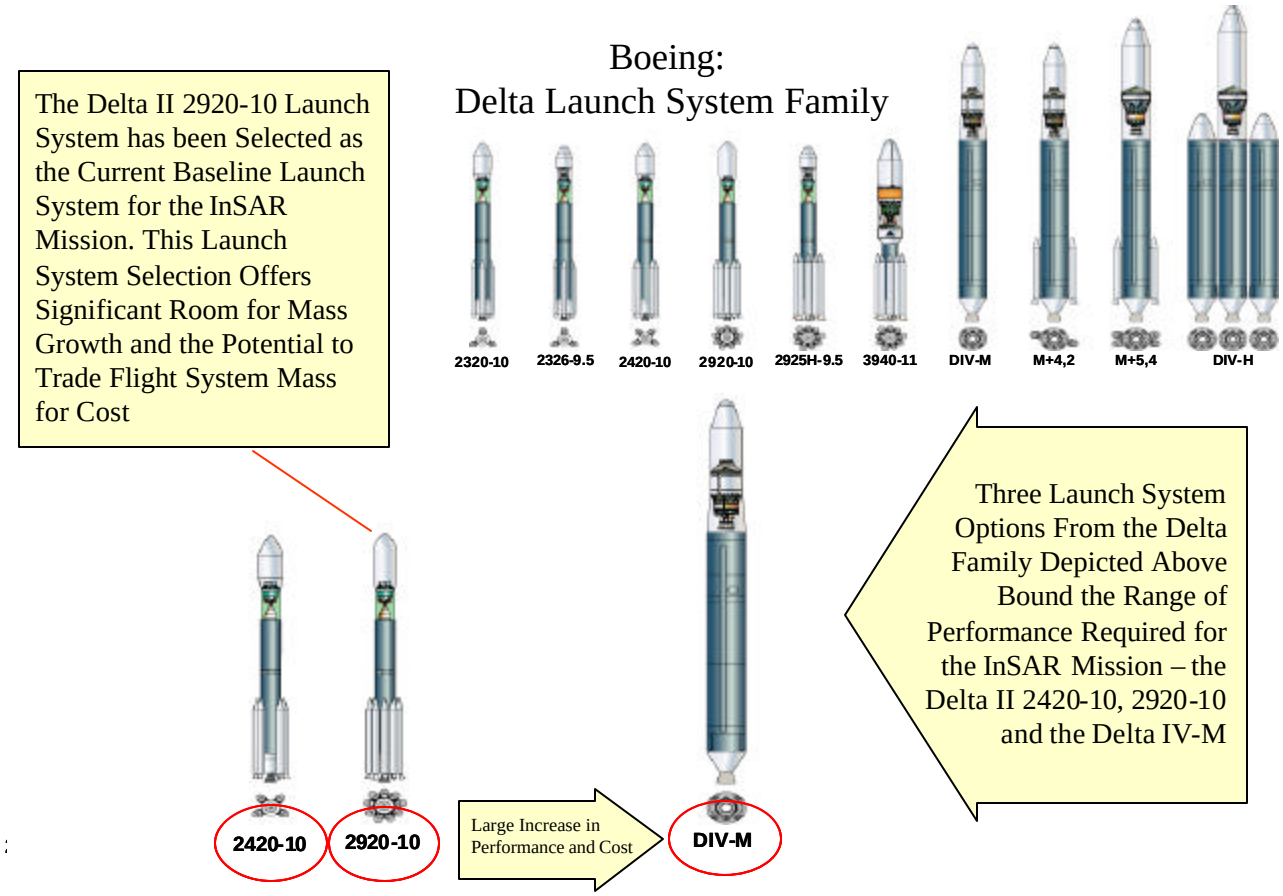
Figure 7-1. Viable Delta Launch System Configurations



7.2 Delta II 2920-10 Launch System Description

The major elements of the Delta II 2920-10 Launch System (depicted in the figure below) are the first-stage, the second-stage, and the payload fairing (PLF). The first-stage includes the engine section, liquid oxygen (LO2) tank, centerbody, fuel tank, and the interstage. The Delta II 2920-10 configuration includes nine solid rocket motors to augment first-stage performance. Six of these motors are ignited at liftoff; the remaining three are ignited in flight after burnout of the first six. The second stage propulsion system has a bipropellant engine that uses Aerozine-50 as fuel and nitrogen tetroxide as oxidizer. For two-stage missions like InSAR, the payload attach fitting (PAF) provides the interface between the second stage and the spacecraft

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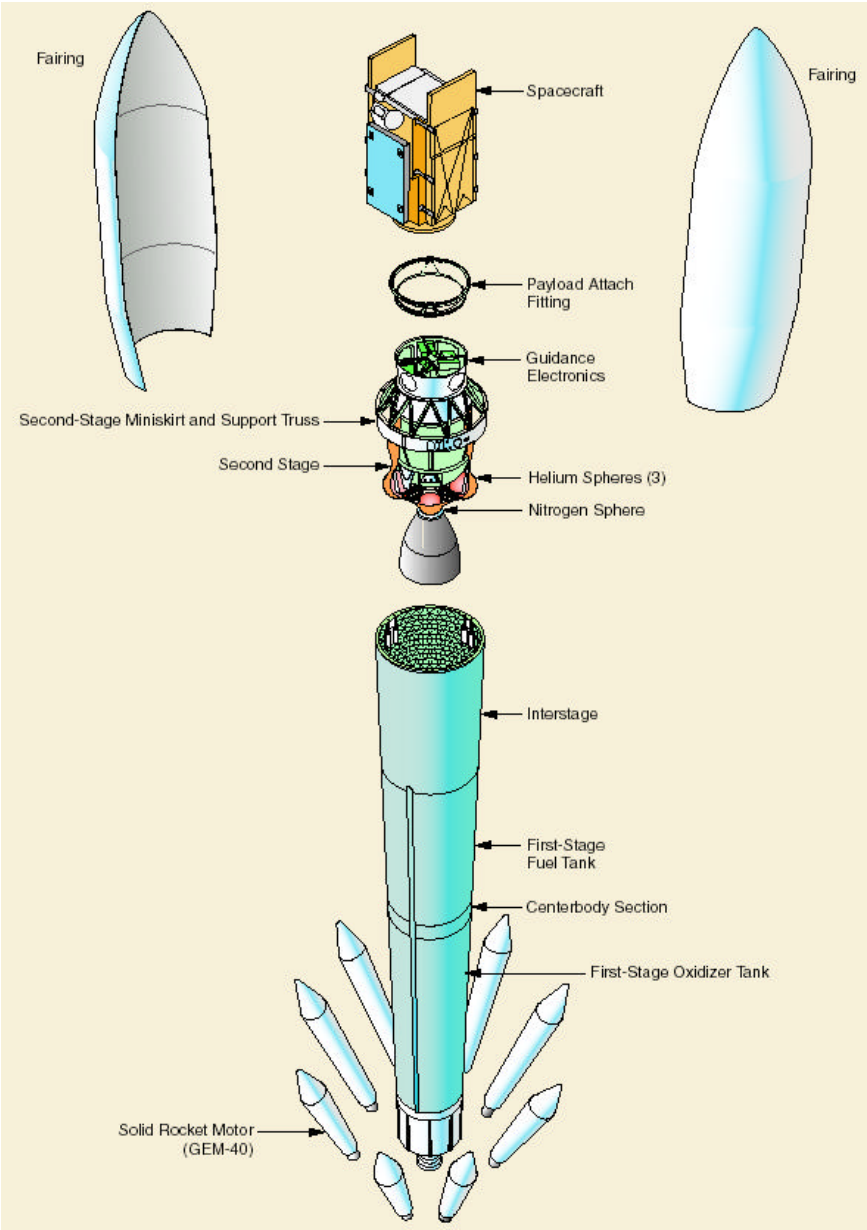
Figure 7-2. Delta II 2920-10 Launch System



7.2.1 Delta II 2920-10 Three Meter Payload Fairing

The Delta II 3.0-m (10-ft) fairings have been flight proven over many years. The payload envelopes presented in the following figure define the maximum allowable static dimensions of the spacecraft (including manufacturing tolerances) for the spacecraft/ payload attach fitting (PAF) interface. If the spacecraft dimensions are maintained within these envelopes, there will be no contact of the spacecraft with the fairing during flight, provided that the frequency and structural stiffness characteristics of the

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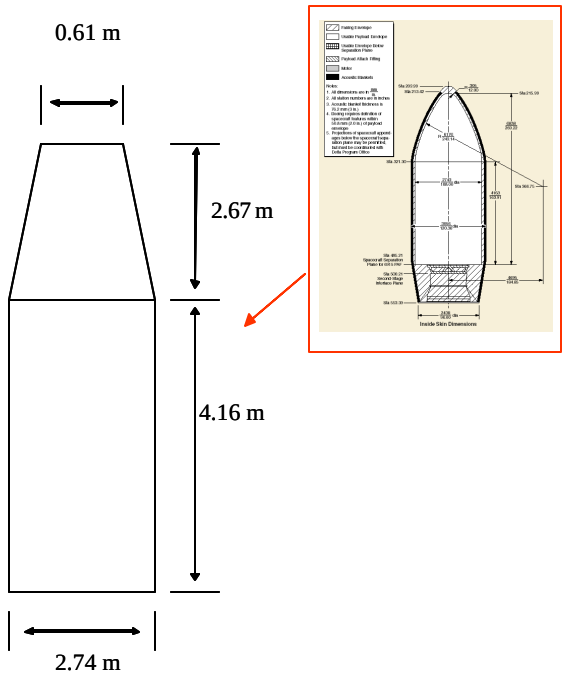
spacecraft are in accordance with the dynamic environmental limits specified. The envelopes include allowances for relative static/dynamic deflections between the launch system and spacecraft.

Figure 7-3. Delta II 2920-10 Three Meter Payload Fairing



7.2.2 Dynamic Launch Environment Data

The table below lists the Delta II launch and flight environments to which the spacecraft is exposed during launch. The frequency and structural stiffness characteristics of the spacecraft must be in accordance with the dynamic environmental limits specified.

Table 7-2. Delta II Launch and Flight Environments

Launch System	Acceleration g's (1) Axial/Lateral	Acoustic (2) db	Shock (3) 10^3 g's	Min S/C acceptable natural freq (Hz) (4)	
				Axial	Lateral
Delta II	6-8/2-4.5	142	3.0-5.5	>35	>15-20

(1) Dependent on the number of Launch System stages, Strap-on boosters, and payload mass. For low mass S/C, axial g's may be greater at burn-out of final stage (or Kick stage).
(2) Can vary 3 db depending on Launch System payload fairing acoustic blankets and S/C configurations.
(3) Maximum shock usually occurs at separation of the S/C from the Payload Adapter and is dependent upon Payload Attach Fitting and clampband preload, etc.
(4) Secondary structures may require higher minimum frequencies.

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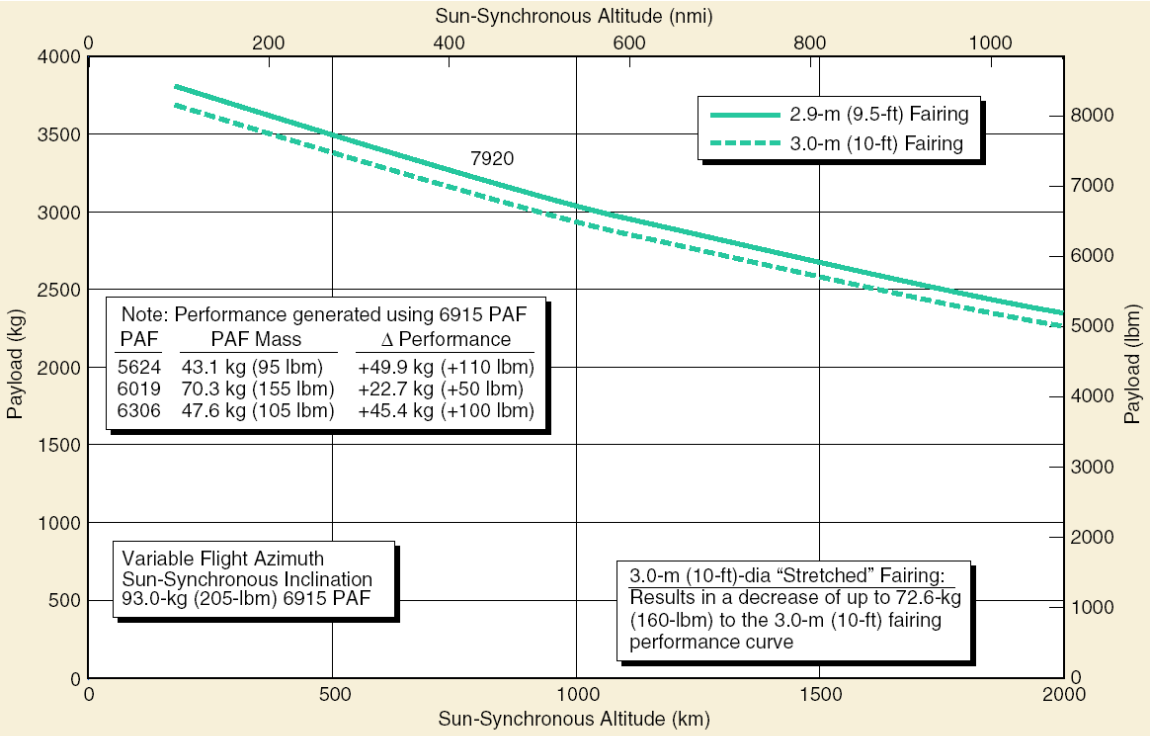
7.2.3 Delta II 2920 Sun-Synchronous Capability – VAFB

The current InSAR Flight System wet mass is 1,350 kg and the Delta II 2920-10 Launch System capability to the desired InSAR orbit is 3,150 kg (as shown in the following figure) providing a 57% mass margin.

Figure 7-4. Delta II 2920 Sun-Synchronous Capability from VAFB



Source: Delta II Payload Planners Guide, Oct., 2000.

7.2.4 Delta II Limited Availability

The production line for the Delta II is open and available for some new missions under the NASA Launch Services (NLS) procurement contract. This procurement is limited to 19 launch vehicles. Due to the number of missions proposing to launch in the 2009 - 2011 time frame, InSAR should request launch system allocation as soon as possible. KSC manager assessment of the likelihood of a Delta II not being available for InSAR is HIGH. The impact assessment is also HIGH (use of the Delta IV Launch System would increase costs considerably). A possible mitigation strategy would be to accelerate the launch system decision to the Phase A timeframe. A second option would be to join other missions requiring this capability after the 19 pack have depleted and request a second buy.

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7.3 NASA Launch Services

NASA Launch Services include the launch system, associated standard services, nonstandard services (mission unique options), all engineering and analysis, and minimum performance standards. NASA launch services also provide technical management of the launch service, technical insight into the launch system production/test, coordination and approval of mission-specific integration activities, mission unique launch system hardware/software development, payload-processing accommodations, and the launch campaign/countdown management.

7.4 Launch System Performance

The Delta II 2920-10 Launch System provides significant margin given the current InSAR Flight System mass estimate of 1,350 kg. As previously stated, a decision could be made to utilize the Delta II 2420-10 in lieu of the 2920-10 (and the associated cost savings realized) at or around PDR if the mass margin is no longer needed. As can be inferred from the following figure the Baseline Launch System (the Delta II 2920-10) has a launch mass margin of 57%, the Delta II 2420-10 has a launch margin of 31% and the Delta II 2320-10 has a launch margin of 16%, assuming the current InSAR wet mass of 1,350 kg.

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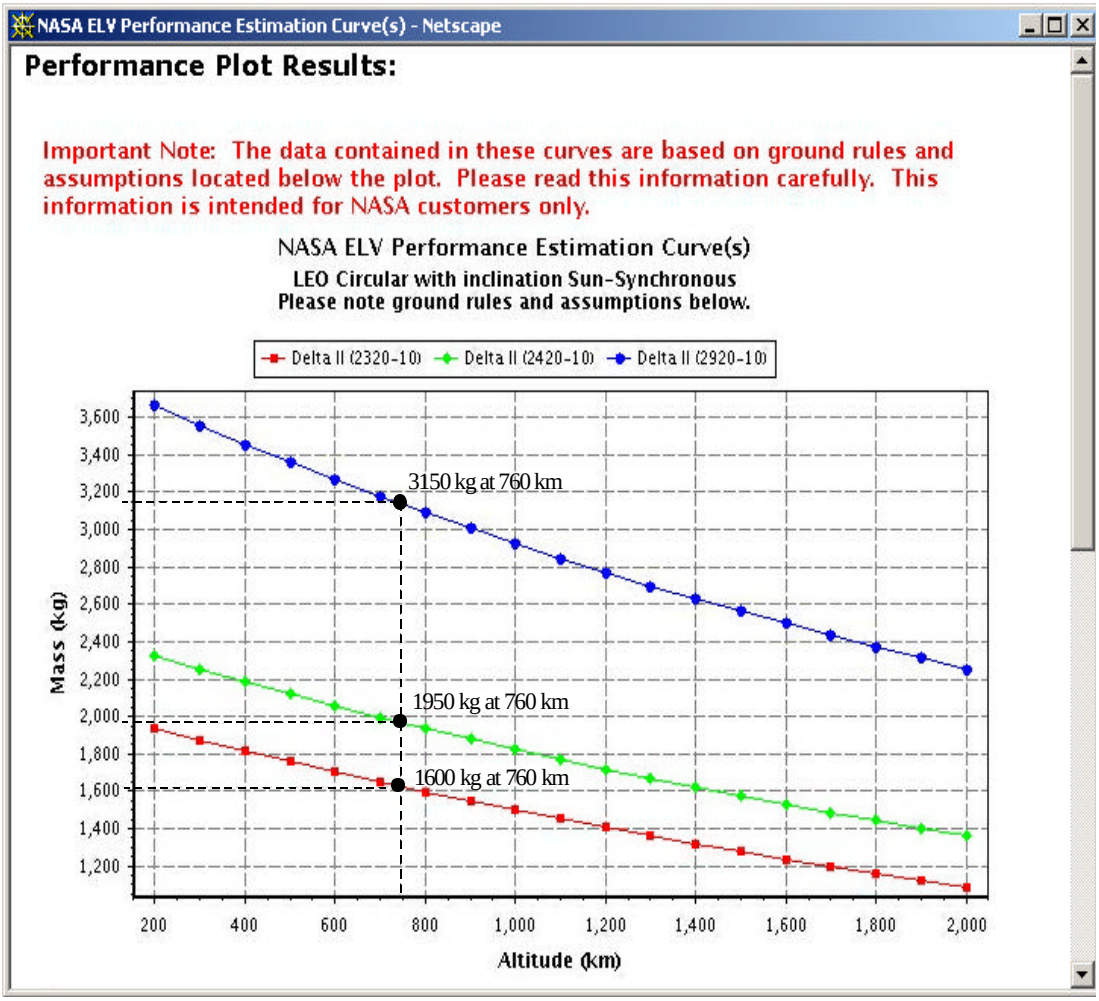
Figure 7-5. NASA ELV Performance Curve for the Delta II



Assumptions: All analyses assume a 99.7% probability of command shutdown, a 185 km (100nmi) park orbit attitude, and variable inclination – data last updated 5/15/02; Delta II (2320-10) analysis assumes a 6306 Payload Attach Fitting (PAF), 10-ft composite fairing would reduce performance; Delta II (2420-10) analysis assumes a 6306 Payload Attach Fitting (PAF), 10-ft composite fairing would reduce performance, configuration has not flown from Western Range and may require a significant increase in cost; Delta II (2920-10) analysis assumes a 6315 Payload Attach Fitting (PAF)

As can be inferred from the following figure, the Delta IV 4040 performance offers InSAR a mass margin of 80%. (The Atlas 401 performance is expected to be similar.) In addition, the Delta IV and Atlas 401 have 4-meter diameter payload fairings, which could provide for increased spacecraft bus and phased-array antenna heritage and associated cost/risk reduction.

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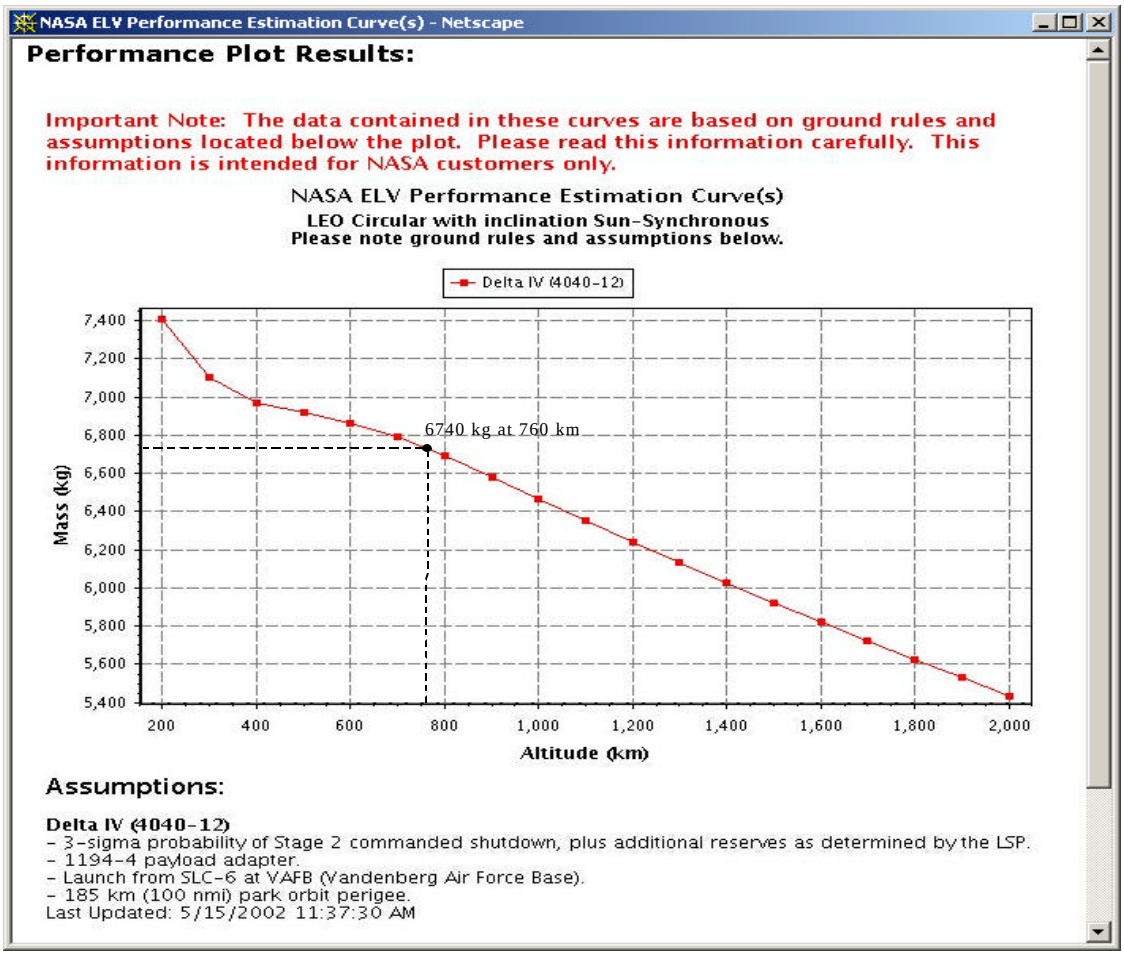
Figure 7-6. NASA ELV Performance Curve for the Delta IV 4040



7.5 Launch System Costs

Launch system costs for the range of InSAR options are shown in the table below. The Baseline Launch System cost of $81 M was provided by Code Y.

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Table 7-3. Launch System Costs

LV Configuration	Cost Data Source	RY ($M)				
		FY 06	FY 07	FY 08	FY 09	Total
Delta II 2320-10	KSC Advanced Planning Manager email dated 4/6/2003	6.6	30.0	27.3	13.4	77.3
Delta II 2420-10	KSC Advanced Planning Manager email dated 4/6/2003	6.7	30.7	27.9	13.6	78.9
Delta II 2920-10* (Baseline)	$81M estimate was provided by Code Y. Profile is an estimate and has not been concurred by HQ.	8.0	31.0	28.0	14.0	81.0
Delta II 2920-10* With modified fairing	This number is preliminary and requires further study.	--	--	--	--	118
Delta IV* 4040	New Frontiers AO: 10/03, launch date 6/09; Intermediate Class Vehicle	2.0	57.0	50.0	31.0	140.0
ALTAS V* 401	New Frontiers AO: 10/03, launch date 6/09; Intermediate Class Vehicle	2.0	57.0	50.0	31.0	140.0

*NOTE: All costs are estimated in real-year dollars (order year = Launch minus 30 months) based on current NLS contracts information. Costs assume a June 2009 launch date from CCAFS. The funding profiles provide for the launch service, nominal allocation for mission unique launch system modifications/services, Mission integration, launch site payload processing, range safety, telemetry and communications.

7.6 Launch System Options Investigated

As previously stated, various launch system options have been investigated for InSAR in support of current and future trades to mitigate potential increased cost and risk associated with Delta II volumetric constraints and availability concerns. The following options mainly focus on relaxing the currently existing volumetric constraints of the Baseline Launch System.

7.6.1 Potential Flight System Volumetric Growth Accommodation

To accommodate potential Flight System volumetric growth two options have been evaluated: 1) Baselining of a Delta IV/Atlas V (4 m fairing) Launch System; and 2) Width (diameter) modification of a Delta II fairing to allow margin for potential InSAR volumetric growth.

Launch system payload envelopes for all InSAR options are listed in the table below.

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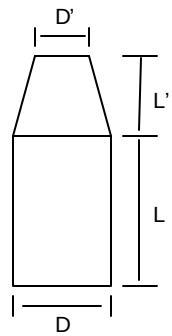
Table 7-4. Launch System Payload Envelopes – All Options

Launch System	Fairing Identification	Size of Dynamic Envelope (m/in)			
		D	L	L'	D'
Delta II	10 ft (3 m diameter)	2.74/ 108	4.16/ 163.9	2.67/ 105.3	0.61/ 24.0
Delta IV Medium (4,X)	4 m	3.75/ 147.6	5.41/ 212.9	4.53/ 178.2	0.91/ 35.9
Atlas V	4 m LPF	3.75/ 147.6	4.20/ 165.3	5.50/ 216.5	0.91/ 35.9



The input and recommendation received from KSC's Advanced Planning Manager regarding a Delta II fairing modification effort are enumerated below:

1. Modification of the diameter of a Delta II-10 3 m fairing may be possible and may be more cost effective than upgrading to an Intermediate Class (Delta IV 4040 or Atlas V) launch system with 4 m fairing.
2. Length modifications to 3 m fairing have been done ($14M cost), width modifications have not.
3. Rough cost estimate for modification of a Delta II 3 m fairing may cost in the range of $18M to $40M.
4. Issues with modification of existing fairing exist: CG, couple loads flight certification, control authority, increased risk, etc.
5. Given InSAR performance margin on a 7920, KSC recommends initiating a fairing width modification feasibility assessment (Feasibility assessment cost: $50k - $100k).

In analyzing the cost and risk impacts of the two options to accommodate a possible larger InSAR design, modification of a 3m fairing (though preliminary input suggest it may be more cost effective) introduces additional risk, and thus, if required, a Delta IV/Atlas V Launch System might be a better solution to volumetric growth. At this stage of the design, it is more feasible to constrain the spacecraft volume to a 3m fairing.

7.6.2 InSAR Dual Payload Existence Proof

The following quick look study investigated the possibility (in terms of launch system performance and payload fairing volume only) of launching two InSAR Flight Systems on a Delta IVH, Ariane 5, or an H-IIA Launch System. The payload characteristics assumed for the following existence proof are listed below and were based on a point design received during the InSAR Industry Surveys.

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Table 7-5. Dual Payload Existence Proof Point Design

Characteristic	Value
Diameter	2.7 m
Height	3.9 m
Payload mass	1,940 kg
Orbit	760 km, Sun-synchronous

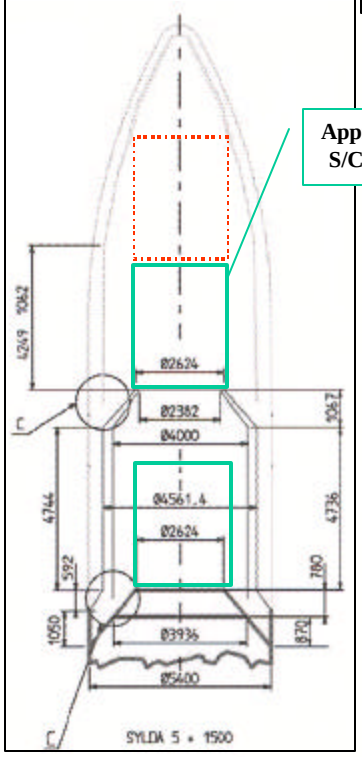
Launch system information was obtained through open literature collected and maintained on JPL's Launch Services Planning website. Results of the existence proof are as follows.

7.6.2.1 Delta IVH

The Delta IVH appears to provide adequate volume and mass performance for launching dual-InSAR spacecraft given the assumed payload characteristics above and assuming the SYLDA 5 +1500 fairing as a proxy for the to be developed Delta IVH DPAF-5 fairing.

Figure 7-7. Delta IVH Dual-Manifest Capability

SYLDA 5 Fairing



Given current assumptions, this configuration appears to provide adequate volume and mass performance for launching dual-InSAR S/C.

Delta IVH DPAF-5

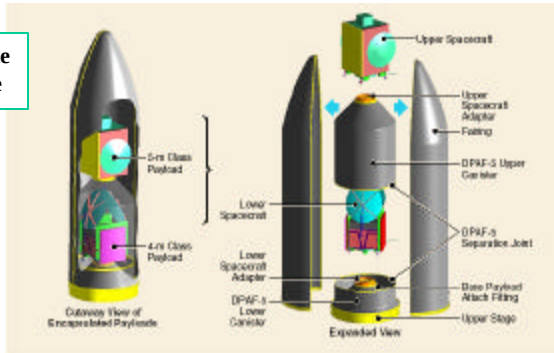


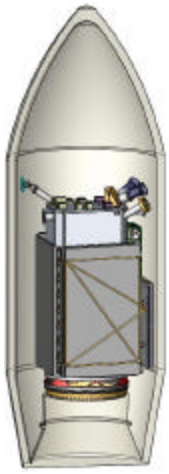
Figure 1-8. Delta IV Heavy Dual-Payload Attach Fitting (DPAF-5)

A 5-m composite fairing that is 19.1m (62.7 ft) long based on a slightly modified version of the flight-proven SYLDA-5 dual-manifest system.

Payload Fairing	Portion of fairing	Height (m)	Diameter (m)
DPAF-5 (SYLDA 5 + 1500)	upper	4.2*	4.5
	lower	4.7*	4.0
Delta IVH Capability: ~19,725 kg to 1,000 km, sun-sync (configuration dependent)			

*Height to first taper

Representative InSAR S/C in Delta II Fairing



Payload Characteristics

Diameter – 2.7 m

Height – 3.9 m

Payload Mass – 1940 kg

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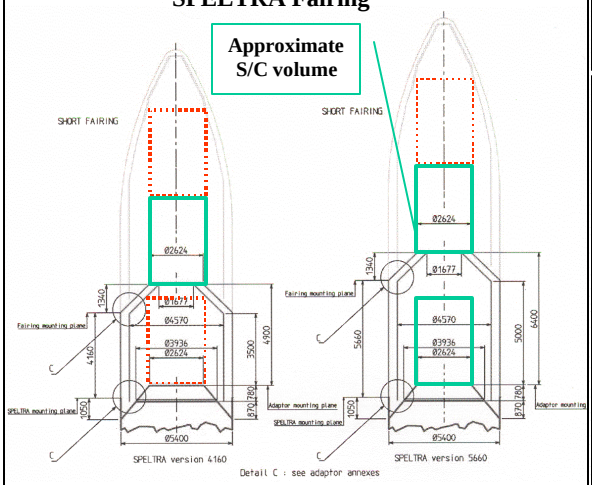
7.6.2.2 *Ariane 5*

The Ariane 5, utilizing either the SPELTRA 5660 or SYLDA 5 +900 Medium fairing, appears to provide adequate volume and mass performance for launching dual-InSAR spacecraft given the assumed payload characteristics above.

Figure 7-8. Ariane 5 Dual-Manifest Capability

SPELTRA Fairing



To provide adequate height margin (given the current S/C configuration) in the lower portion of the fairing the SPELTRA 5660 would most probably be required.

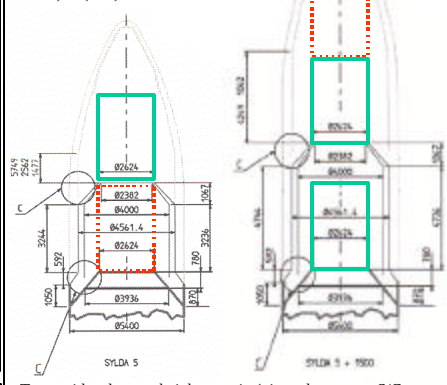
Payload Fairing	Portion of fairing	Height (m)	Diameter (m)
SYLDA 5 + 900M (SPELTRA 5660)	upper	1.6 (~5.0)*	4.5 (4.5)
	lower	4.1 (5.0)*	4.0 (4.5)
Ariane 5 Compatibility: ~10,000 kg to 800 km, sun-sync (configuration dependent)			

*Height to first taper

Given current assumptions, the Ariane 5 Launch System with the SPELTRA 5660 or SYLDA 5 +900 Medium fairing appear to provide adequate volume and mass performance for launching dual-InSAR S/C.

SYLDA 5 Fairing

The lower portion of the fairing can be extended by 0.3, 0.6, 0.9, 1.2 or 1.5 m.



To provide adequate height margin (given the current S/C configuration) in the lower portion of the fairing the SYLDA 5 +900 or larger fairing would be required.

The upper portion of the fairing can be extended via use of the medium or long fairing configurations. To provide adequate height margin (given the current S/C configuration) in the upper portion of the fairing the SYLDA 5 +900 Medium fairing would be required.

Representative InSAR S/C in Delta II Fairing

Payload Characteristics

Diameter – 2.7 m

Height – 3.9 m

Payload Mass – 1940 kg

7.6.2.3 *H-IIA*

The H-IIA, utilizing Model 4/4D-LC fairing, appears to provide adequate volume and mass performance for launching dual-InSAR spacecraft given the assumed payload characteristics above.

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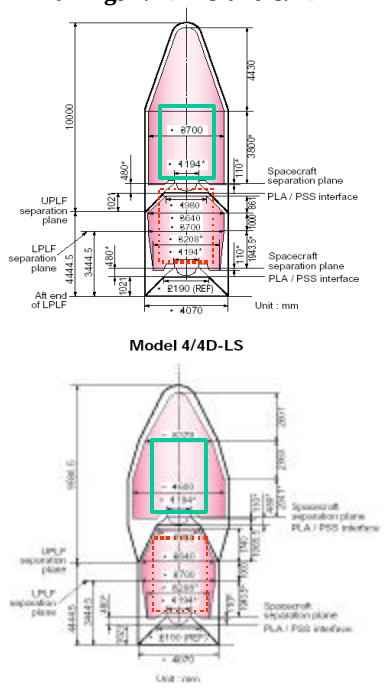
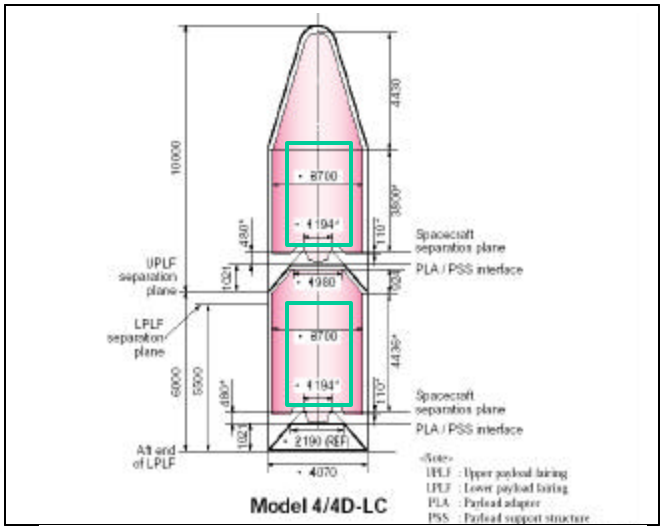
Figure 7-9. H-IIA Dual-Manifest Capability

Fairings 4/4D-LS and 5/4D



Given current assumptions, the H-IIA and Model 4/4D-LC fairing appear to provide adequate volume and mass performance for launching dual-InSAR S/C.



Payload Fairing	Portion of fairing	Height (m)	Diameter (m)
4/4D-LC	upper	3.8*	3.7
	lower	4.4*	3.7
HIIA Capability: ~4,400 kg to 800 km, sun-sync (configuration dependent)			

*Height to first taper

Representative InSAR S/C in Delta II Fairing

Payload Characteristics

Diameter – 2.7 m

Height – 3.9 m

Payload Mass – 1940 kg

7.6.3 Atlas V Launch System Family

Currently, the capability to launch the Atlas V Launch System from the West Coast does not exist, however, the Atlas V Launch System may be a viable option for InSAR based on the following recent communication with JPL Launch Vehicle Integration Engineers, Evolved Expendable Launch Vehicle site information and input from our KSC Advanced Planning Manager in the NASA Launch Services Program. There appears to be a distinct possibility of having the capability to launch an Atlas V from VAFB and meeting InSARs mission requirements. Based on the Air Force committing to launching 3 Atlas V's from VAFB in 2006 (1 in fiscal 06 and 2 in fiscal 07), assuming a worse case delay of 1 year, launch services should still be available for an InSAR launch from the West Coast. Given this information, we believe that an Atlas V can be considered in the InSAR trade space for launch systems. The Atlas V 40X configuration has performance capability in the range needed for the InSAR mission. This vehicle has performance similar to the Delta IV.

7.6.4 Delta III and Delta II 2320

The Delta III and Delta II 2320 were investigated but eliminated from further consideration. The Delta III does not have launch capability/availability from the West

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Coast and is being phased out. The Delta II 2320-10 Launch System was investigated early in the InSAR Mission Study as it met the performance requirements of an InSAR Flight System mass consistent with that proposed in the ECHO proposal. The capability of the Delta II 2320-10 does not provide adequate mass margin (only 16%) given the current InSAR Flight System mass; and constraining InSAR Flight System mass to meet Delta II 2320-10 performance capability would not be cost effective.

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8.0 Safety and Mission Assurance

8.1 Safety and Mission Assurance Summary

A comprehensive InSAR Safety and Mission Assurance (SMA) program, extending throughout the project life cycle, will be developed. This Safety and Mission Assurance approach will be consistent with the ISO 9000 documents and NASA's NPG 7120.5A/B. The approach will integrate applicable NASA/JPL Lessons Learned, JPL's Flight Project Practices, JPL's Design Principles and JPL's Safety and Mission Assurance Principles into the program. The program will also include mission assurance participation in the areas of risk management and mitigation, formal life cycle reviews, peer reviews and inheritance reviews of any inherited flight hardware and software. The SMA program will be tailored to the particular needs and specifics of the project and the mission. JPL will have the primary management and oversight of the integrated Safety and Mission Assurance Program, including the flight system and the Radar.

8.2 Mission Assurance Management

The InSAR SMA program will include a Mission Assurance Manager (MAM) for the development phase. The MAM will be responsible for coordination between the Project Office and the Office of Safety and Mission Success (OSMS). The MAM will develop and monitor SMA budgets and will be responsible for development and documentation of SMA requirements and the Mission Assurance Plan (MAP). The MAM will coordinate and oversee all work performed by other SMA disciplines. The MAM will coordinate insight/oversight efforts with the S/C Provider SMA program and will report at Project and line management reviews.

8.3 System Safety

The InSAR SMA program will include participation by the System Safety Office. System Safety will produce the System Safety Plan. Planning will be done by JPL to ensure that all hazards to personnel and critical hardware have been identified and controlled throughout the design and operation phases. At the start of the project, site visits and safety surveys will be performed for facilities that produce critical H/W and support equipment for JPL and its subcontractors. System Safety will participate in activities involving flight hardware and support equipment at JPL. System Safety will participate in all launch-site pre-launch activities.

8.4 Environmental Engineering

The InSAR SMA program will include participation from the Environmental Engineering discipline. JPL's Environmental Engineering team will create and approve the Environmental Requirements Document (ERD). These tailored requirements will include as a minimum: dynamics (launch environment), solar/thermal vacuum, electromagnetic compatibility, and natural space radiation. Design requirements and testing requirements will utilize robust margins appropriate to the mission

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characteristics. JPL's team will also support environmental test planning, test oversight and test reporting/review at JPL, for Radar, and at the S/C Provider. Experts within this discipline area will perform the NASA-required Orbital Debris analysis.

8.5 Reliability Engineering

The InSAR SMA program will include participation from the Reliability Engineering discipline. Reliability analyses consisting of worse case analyses, fault tree analyses (including system analyses conducted in conjunction with systems engineering and mechanical FTAs [Fault Tree Analyses]), FMEAs (Failure Mode and Effect Analysis), and parts stress analyses will be reviewed /performed per a planned, project coordinated, Reliability Assurance Plan. JPL will review and approve S/C provider and other external H/W providers' reliability analyses, and review/perform the analyses for in-house H/W, including Radar. A closed loop PFR (Problem Failure Reporting) system will be implemented with risk rating and thorough closure review. Red-flag PFRs will be tracked and reported at all major project reviews.

8.6 EEE Parts Engineering

The InSAR SMA program will include participation from the EEE (Electrical, Electronic, and Electro-mechanical) Parts Engineering discipline. JPL's team will develop an electronic parts plan by tailoring the JPL institutional Parts Program Plan (IPPR). JPL's team will review/audit and approve electronic parts lists and Non-Standard Parts upgrades (NSPARs) for the S/C Provider. JPL's team will review and approve electronic parts lists and NSPARs for the RADAR instrument. JPL's team will assist with electronic parts procurement for the in-house flight H/W. JPL EEE Parts Engineering team will perform a thorough review for GIDEP (Government-Industry Data Exchange Program)/NASA Alerts for applicability to InSAR parts.

8.7 Hardware Quality Assurance Engineering

The InSAR SMA program will include participation from the Hardware Quality Assurance (HQA) engineering discipline. Hardware Quality Assurance team will provide planning, on-site QA surveys, workmanship inspections at various assembly levels, configuration verification at beginning of major tests, End Item Data Package Reviews, and process verification, to help produce high quality hardware, spanning from early development of flight hardware through launch of the spacecraft. Requirements will be defined for the detection and correction of deficiencies or trends that may result in unsatisfactory quality of the flight hardware. HQA residents will be provided at Radar antenna contractor and S/C provider during their development phase. An HQA Plan will be produced that will be applicable to the RADAR instrument and the S/C Provider.

8.8 Software Quality Assurance Engineering

The InSAR SMA program will include participation from the Software Quality Assurance (SQA) engineering discipline. Software QA team will provide software development

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support tailored to the project software requirements. The SQA team performs a software development process risk assessment using criteria contained in JPL institutional standards and lessons learned. The SAQ team will provide recommendations pertaining to software development tasks, SQA activities and/or NASA IV&V facility support. The resulting tailored software quality approach will be documented in the Software Quality Assurance Plan.

8.9 Materials and Processes

The InSAR SMA program will include participation from the Materials and Processes (M&P) Engineering discipline. The M&P Engineer will produce a Materials and Processes Plan. All materials and processes will be qualified for the application for which they are used and will be submitted to the project's Materials and Processes Engineer for approval. The M&P Engineer will maintain a Materials Identification and Usage List (MIUL) and will update it on a regular basis.

8.10 Contamination Control

The InSAR SMA program will include participation from the Contamination Control (CC) Engineering discipline. Contamination Control will:

- identify mission susceptibility to contamination;
- identify potential sources of contamination
- establish contamination control requirements
- establish processes and procedures to insure appropriate contamination standards are maintained for the mission.

The Contamination Control requirements are levied on the RADAR instrument and the S/C Provider. Each InSAR hardware developer will generate a Contamination Control Plan in response to the project requirements. These plans will describe the approaches that will be implemented to minimize contaminates and their effects, cleanliness procedures, and monitoring activities throughout development, launch and flight operations.

8.11 Software IV&V

Per NPD 8730.4, software independent verification and validation (IV&V) will be performed by the NASA Fairmont IV&V Facility. The JPL IV&V Liaison will coordinate all initial interactions with the NASA IV&V team, the project team, Software Quality Assurance, Development MAM, etc. Ongoing software IV&V will be facilitated and supported by SQA during the design and development phase. A yearly assessment of complexity of flight S/W will be made by the JPL IV&V team and reported back to NASA. Recommendations pertaining to software development tasks, SQA activities and/or NASA IV&V facility support will be coordinated by SQA. Starting in FY '05, new projects do not need to directly budget for IV&V facility fees.

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8.12 Mission Operations Assurance

The InSAR SMA program will include participation from the mission operations assurance management discipline. The mission operations assurance discipline is a continuation of the JPL mission assurance program as the project transitions from development to flight operations. The approach is based on a teaming arrangement whereby JPL OSMS will provide oversight through an active Mission Operations Assurance Manager, who insures that mission risk is assessed during the critical operations and establishes a unique proactive mind set for operational problem solutions and problem avoidance. The OPS MAM will become involved several months prior to launch to participate in ORTs and become familiar with the mission. The JPL ISA (Incident Surprise Anomaly) System, which is a part of the JPL Unified Problem and Reporting System, will be utilized to report, track, risk rate, and trend all anomalies during the operations phase.

8.13 Plans to Resolve Open Mission Assurance Issues

The current SMA assumption is that the use of the GPS is non mission critical. If a full parts upgrade is required of the Blackjack GPS it must be planned.

The current SMA assumption is that the S/C provider will lead launch site operations. This assumption impacts JPL System Safety and HQA support. If a change to this assumption occurs (e.g., JPL leads launch site operations) it must be planned.

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9.0 Project System Engineering

9.1 InSAR Project System Engineering Summary

The InSAR Project System Engineer (PSE) will direct, coordinate, and monitor the system design and product development activities to ensure that the project's intended technical content is delivered by the project's system. The PSE will lead the Project System Engineering effort and report directly to the Project Manager as the "chief" technical advocate and technical spokesperson (for engineering) on the project. The PSE will lead the project's system engineering team and direct the overall design development from that position. The PSE coordinates the activities of the System Element Managers and their system engineers.

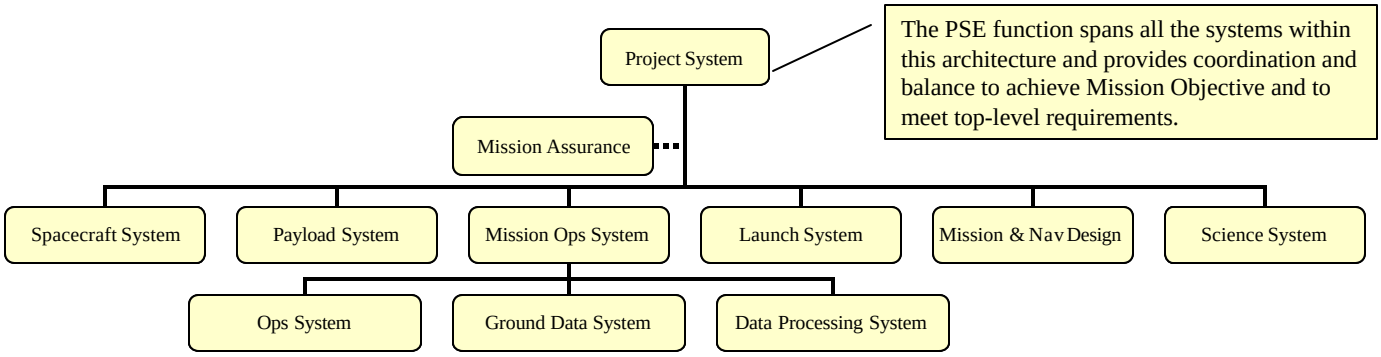
9.2 Project System Engineering Roles on InSAR

The PSE will interact with system users, i.e., the scientists, to determine their "objectives and requirements" and to translate those into engineering requirements. Based on this interaction, the PSE will establish the project's mission objective and top-level requirements, i.e., the Project Requirements (a.k.a. Mission and System Requirements) and oversee/act as negotiator during the development of lower tier requirements/ensure balance for the design effort/risks. The PSE will define functions within and boundaries between systems, and direct trade studies for issues that crosscut system boundaries. The PSE will monitor the system design and development processes; and lead the verification and validation processes. The PSE will also work interfaces with systems external to the project, e.g., the Launch System, etc.

9.3 InSAR Project System Architecture

The PSE will provide project-wide oversight of the design development and implementation activities to ensure compliance with requirements. The PSE also helps the Project Manager (PM) manage risks, support informed and timely decision-making, and direct and oversee the project's verification and validation. Depicted below is a proposed InSAR Project System Architecture which would allow the PSE to accomplish these functions.

Figure 9-1. Project System Architecture



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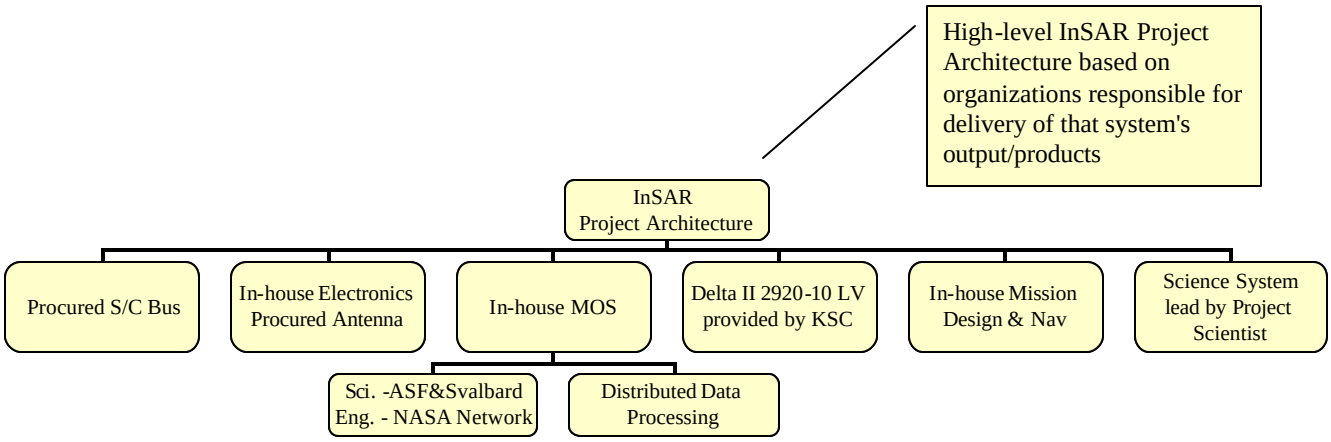
9.3.1 InSAR Project Architecture by "Doing Organization"

Per the current plan, organizations responsible for the provision of the project's systems are indicated below. Each of these organizations will have system engineering personnel to direct, coordinate, and monitor the system design and product development within their own system to ensure that allocated and derived requirements are met.

Figure 9-2. InSAR Project Architecture by *"Doing Organization"*



9.4 InSAR Semantics

The PSE is responsible for overseeing the development of the project's terminology enabling clear, consistent, unambiguous communications between systems and to ensure clear, consistent, unambiguous documentation of its technical data and written products. Terminology is defined within the context of the system engineering team by its members.

The following are preliminary examples of terminology specifically proposed for use on InSAR:

- Spacecraft = spacecraft bus and associated hardware
- Payload = radar instrument and phased-array antenna
- Flight System = spacecraft and payload
- Phased-array Antenna = SAR antenna, T/R modules, structure and deployment mechanism
- Mission Operations System (MOS) = operations, ground data, and data processing systems
- Launch System = launch vehicle and launch services (ground support equipment, etc.)

9.5 Requirements Development

Requirements development is a very important step and currently the top priority for

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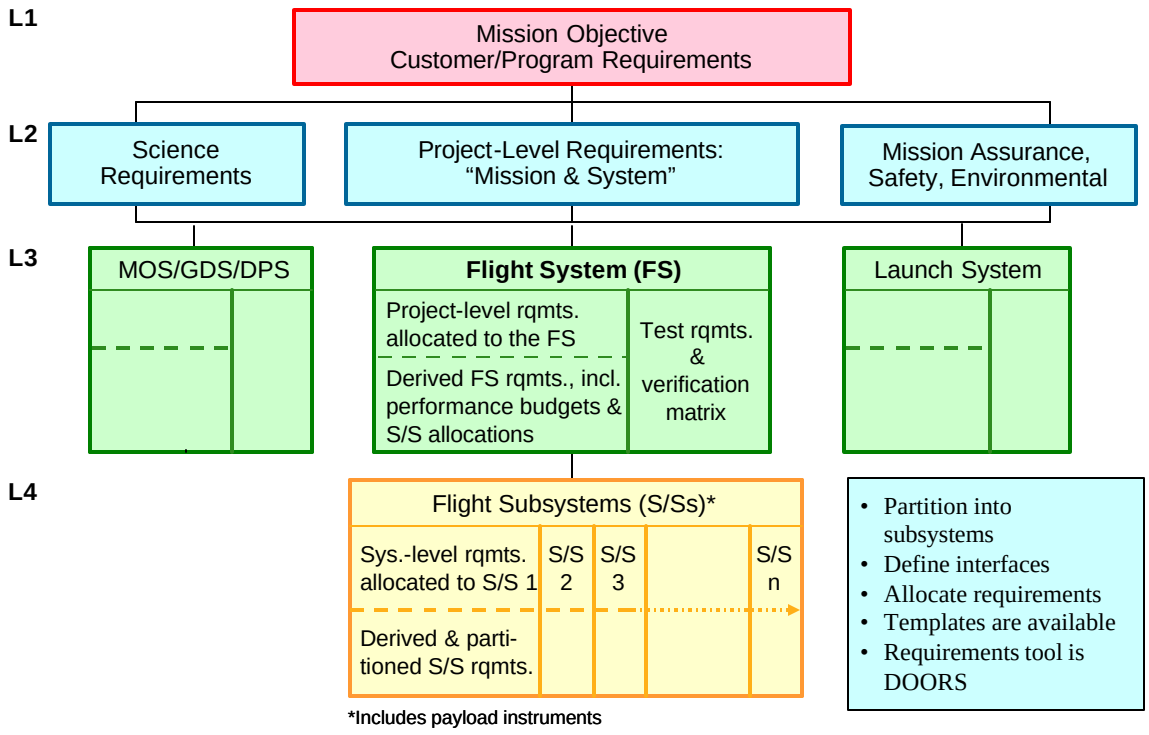
InSAR PSE. An InSAR Preliminary Requirements Document development effort is currently on-going. Requirements will flow down within the Requirements Hierarchy from the Mission Objective to lower and lower levels to define the project's technical scope. An example Requirements Hierarchy is shown below. Requirements describe what must be done (Functions), and, how well it must be done (Performance). Requirements (in conjunction with the design margins) bound the scope by telling the designer when to STOP. System engineering defines the appropriate design margins to be used and monitors the design's conformance. Frequently, system engineering will also define a margin depletion schedule, e.g., via the "Design Principles", for key system resources, e.g., mass, power, CPU thru-put, etc. System engineering will also conduct/direct Requirements Analysis to ensure the appropriate robustness and balance in the specification of a parameter. A Hierarchy of traceable requirements ensures that the project is building only what is necessary, i.e., no frivolous activities. A Hierarchy of negotiated requirements ensures balance in the system design. Requirements are the basis for the project's verification and validation efforts. Poorly written, unverifiable requirements mean lots of ECRs and waivers!

Figure 9-3. Example Requirements Hierarchy - A Flow-Down Pyramid



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9.6 Design Monitoring

Once a design solution is identified as satisfying the requirements, it will become the "baseline design" and serve as a reference for future development of more detailed, lower level designs within the baseline. Design decisions will be delegated to designers within the system being developed and decisions must provide:

- Compliance with technical requirements, including preservation of margins
- Compliance with interface requirements
- Compliance with project's implementation schedule
- Development cost within budget

The PSE will monitor the design process without interference to the system designer unless the system is unable to meet one of the above compliances.

9.7 High-Level Trades

System analysis and trades between different possible solutions within the design-space are done to define a "preferred solution" for the technical baseline. The InSAR Concept Study Report is a vehicle for such analyses and trades.

9.8 Verification & Validation

Verification is the process of certifying that the system (and its components) as built is compliant with all requirements. The PSE will define the criteria for certifying that the design is compliant with the requirements. Verification is a repetitive process which starts by asserting design compliance with less rigorous means, e.g., similarity, analysis, and ends by certifying, wherever possible, design compliance by test, measurement, and demonstration. The PSE directs and audits requirements verification. The PSE must determine how to deal with those elements with the system which are not compliant, i.e., the ECR or waiver process.

Validation is the process of certifying that the system as built will meet the mission objective and deliver the intended technical output/products. The PSE in conjunction with the SE team will develop the project's validation approach. Including, but not limited to, a list of system functions to be validated and how; what will be tested, simulated, and/or both; where it will be tested (e.g., I&T, field test, MOD test); and how it will be tested (e.g., aliveness, performance, endurance, etc.).

9.9 Risk Management

The first step in Risk Management is to identify and assess all risks to the project achieving success. The second step is to devise, where possible, a plan for mitigating risks should the risk be realized. Mitigation could include the allocation of schedule and/or dollar reserves. These steps are repeated as necessary. The PSE, MAM, and other SEs support the PM in making decisions that affect the project's risk exposure -

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because mitigation involves commitment of resources, it's ultimately the PM's decision.

The following table lists InSAR Project uncertainties. These are aspects of the current mission architecture that have been identified as having design uncertainty, lack of maturity, and/or potentially substantive risk. As the design matures, these uncertainties will either be retired or will be characterized as a mission risk (with quantification of probability of occurrence and level of impact) and an appropriate mitigation strategy developed. With additional maturity in design the remaining identified areas of uncertainty/risk will be used to form the Project reserves posture.

A key assumption driving the current InSAR mission architecture is that the Delta II 2920-10 launch system will be available for an April 2009 launch of InSAR. Feedback received from Kennedy Space Center personnel and JPL Launch Vehicle Integration Engineers suggest the probability of not getting one of the Delta II launch systems purchased during the recent NASA block-buy is high. As of February, 2004, the remaining 6 Delta II launch systems (of 19 purchased during the block-buy) were already approved and financed. However, Kennedy Space Center points-of-contact believe there is a high probability of another block-buy or another similar launch system becoming available. Efforts should be made as early as possible after Project approval to ensure InSAR is on the "Flight Planning Board Manifest", such that a Delta II 2920-10 launch system will be secured for an April 2009 launch.

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Table 9-1. Significant Uncertainties List

	Uncertainty	Mitigation Strategy	Impact	Likelihood
1	Instrument cost exceeds estimated allocation and margin	1. Build a radar electronics breadboard and conduct a technology survey of viable antenna options 2. Develop descope options 3. Limit number of operating modes	High	Moderate
2	Instrument mass/power growth exceeds allocation	1. Build a radar electronics breadboard and conduct a technology survey of viable antenna options 2. Develop descope options 3. Limit number of operating modes	High	Moderate
3	Antenna fails to deploy	Use heritage design with adequate Project oversight of array deployment Verification and Validation	High	Low
4	Spacecraft bus cost exceeds estimated allocation and margin	Design specificity in contract and requirements with adequate Project oversight and schedule reserve	Moderate	Moderate
5	Flight System design not compatible with Payload Fairing volume	Define an acceptable stowed configuration design with adequate Project oversight, schedule and cost reserve	Moderate	Low
6	Antenna is not delivered on schedule due to delay in RFP/contract start or funding profile doesn't match that of contractor	Use heritage design with adequate Project oversight and schedule reserve	Low/ Moderate	Low
7	Spacecraft bus is not delivered on schedule due to delay in RFP/contract start or funding profile doesn't match that of contractor	Use heritage design with adequate Project oversight and schedule reserve	Low/ Moderate	Low
8	Significant cost increase due to need for redesign of Ground Data System	Define an acceptable data distribution plan and obtain customer buy-in	Low/ Moderate	Very Low
9	X-band channel allocation inconsistent with data rate requirement	Apply for channel allocation early and re-plan if necessary	Low/ Moderate	Very Low
10	Significant cost increase to meet navigation requirement (250 meter tube)	Carry adequate cost reserve	Low	Low
11	Significant cost increase in GPS development	Carry/apply reserves or accept commercial GPS accuracy	Low	Low
12	Spectrum issues at both X-Band and Ka-Band have to be examined.	May push InSAR to different modulation schemes and less coding.	Low	Low

9.10 NEPA (National Environmental Policy Act) Status

JPL policy and procedures requires Pre-Phase A missions to complete an ECLASS (Environmental Compliance/Launch Approval Status System) Form in order to assess their specific NEPA (National Environmental Policy Act) compliance requirements. InSAR has completed this requirement and as currently envisioned InSAR's NEPA

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compliance requirements would be satisfied by qualification as a NASA Routine Payload. NEPA compliance cost, per doing organization agreement, will be covered under JPL Institutional Launch Approval Engineering funding at no cost to the project.

9.11 ODA (Orbit Debris Analysis) Status

The InSAR Flight System design currently includes a 22-N thruster and propellant for a 70 m/s delta-V maneuver required for de-orbit. Orbit debris analyses will be performed to ensure InSAR meets all applicable requirements. In addition, the PSE element of the project will ensure orbital debris expertise is brought on at the appropriate time such that the potential for re-design is minimized.

9.12 Plans to Resolve Open PSE Issues

The primary PSE open issue is Requirements Development. A preliminary InSAR requirements document needs to be developed and approved by the science team and other key stakeholders.

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10.0 Project Management

The InSAR Concept Study Report described herein is based on the following management implementation assumptions:

- InSAR project starts in FY05
- No international collaborations
- No financial contributions from other agencies
- Delta II 2920-10 launch system is available in April 2009
- R&A (Research and Analysis) component is funded separately

10.1 Management Processes and Plans

JPL has 25 years experience on SAR projects including SEASAT, SIR A, B, and C, and SRTM and will provide the overall project management for InSAR. The L-band InSAR management team is supported by well-known scientists selected by NRA, SESWG, and EarthScope. The implementation of the InSAR project will be based on detailed make/buy studies. The SAR antenna and the spacecraft bus will be procured. JPL will execute and manage contracts with subsystem contractors under a task order executed as part of the JPL-NASA contract. Contracts will be designed so that incentives are provided for on-orbit performance and successful data return. The NSF and USGS contributions will be decided during Phase A with input from and the concurrence of the Joint Steering Group (JSG) consisting of NASA, NSF, and USGS officials. The outcome will be formalized with a Memorandum of Understanding between participating agencies The InSAR management approach will be rigorous and based on JPL rules including EVM (Earned Value Management), NPG 7120.5, and ISO 9000 requirements. A rigorous technical risk management approach will provide for prudent use of cost and schedule reserves. A Resource and Margin Management strategy will be developed during Phase A based on the identification and management of appropriate margins in all major project resources, including launch mass and volume, spacecraft power, cost, schedule, and science margin. InSAR will ensure an effective use of reviews with particular emphasis on peer reviews. InSAR will utilize a rigorous review process in accordance with JPL D-10401 (JPL Guidelines for Reviews) Critical Milestone Reviews, Peer Reviews and Product Integrity Reviews by the line management of the organizations performing the work of the Project will be performed. Peer reviews will precede Critical Milestone Reviews, and will provide in-depth assessment of technical material.

10.2 Descoping Strategies

The PM (Project Manager) will control the expenditure of reserves. The PM will exercise descope options (in extraordinary circumstances) by working with JPL ESTD (Earth Science and Technology Directorate) senior managers, NASA OES (Office of Earth Science) managers, and the science team in order to maintain an appropriate level of reserves throughout the development cycle. The Science Section identifies the minimum science mission, descopes and their required timing.

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10.3 Reserves and Margins Management Strategies

The PSE (Project System Engineer) will define a margin policy and approach along with policies and guidelines for the allocation; tracking, redistribution and balancing of technically related resources.

JPL Design Principles incorporate the most recent lessons learned on the management of risk during the life cycle of a project, and will be embedded in our margin management strategy developed during Phase A. As the mission and system design reaches maturity, margins will be tailored to fit the InSAR risk management strategy. It will specify the project's commitment to maintaining a certain level of key reserves at development milestones, especially PDR, CDR and, beginning of system test. The PSE is responsible for implementing these policies amongst the Project systems. These resources are determined as part of the design process and continue to be negotiated with the systems throughout Project development.

10.4 JPL Workforce/Project Planning

Significant JPL in-house efforts in the '06 to '09 time period include MSL, SIM, JIMO, and LISA. InSAR workforce will be secured through line organization commitments and signed work agreements during the Formulation Phase. The following table illustrates the estimated JPL workforce required for the life of the mission by fiscal year assuming contracted mission operations support. There are currently no issues identified with required level or timing of workforce required for InSAR.

Table 10-1. JPL Estimated Lifecycle Workforce Plan – Contracted MOS Option

	Total Workforce Budget - WBS Breakdown by Fiscal Year (1 = Full Time Equivalent [work year])										
WBS Element	**FY 2005**	**FY 2006**	**FY 2007**	**FY 2008**	**FY 2009**	**FY 2010**	**FY 2011**	**FY 2012**	**FY 2013**	**FY 2014**	**Total**
01 Project Management	6.9	6.9	7.5	7.9	7.0	5.1	3.2	3.1	3.1	2.0	**52.7**
02 Project System Engineering	4.8	5.1	3.6	3.9	2.6	0.0	0.0	0.0	0.0	0.0	**19.9**
03 Mission Assurance	2.5	2.7	2.9	2.7	2.7	0.3	0.3	0.3	0.3	0.2	**15.0**
04 Science	1.0	1.0	1.0	1.0	6.3	1.0	1.0	1.0	1.0	0.7	**14.9**
05 Payload System	20.7	35.9	40.0	24.7	4.6	0.0	0.0	0.0	0.0	0.0	**125.8**
06 Flight System	7.2	7.4	6.7	6.7	3.5	0.0	0.0	0.0	0.0	0.0	**31.6**
07 Mission Operations System	5.0	9.3	13.7	14.5	10.0	4.3	6.2	6.2	6.2	5.9	**81.2**
08 Launch System	0.2	0.5	0.5	0.5	0.4	0.0	0.0	0.0	0.0	0.0	**2.1**
InSAR Total	**48.4**	**68.8**	**76.0**	**62.0**	**37.1**	**10.6**	**10.6**	**10.5**	**10.5**	**8.8**	**343.3**

The following table illustrates the JPL workforce required for the life of the mission by fiscal year assuming JPL mission operations.

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Table 10-2. Estimated Lifecycle Workforce Plan – JPL MOS

	Total Workforce Budget - WBS Breakdown by Fiscal Year (1 = Full Time Equivalent [work year])										
WBS Element	**FY 2005**	**FY 2006**	**FY 2007**	**FY 2008**	**FY 2009**	**FY 2010**	**FY 2011**	**FY 2012**	**FY 2013**	**FY 2014**	**Total**
01 Project Management	6.9	6.9	7.5	7.9	7.0	5.1	3.2	3.1	3.1	2.0	**52.7**
02 Project System Engineering	4.8	5.1	3.6	3.9	2.6	0.0	0.0	0.0	0.0	0.0	**19.9**
03 Mission Assurance	2.5	2.7	2.9	2.7	2.7	0.3	0.3	0.3	0.3	0.2	**15.0**
04 Science	1.0	1.0	1.0	1.0	6.3	1.0	1.0	1.0	1.0	0.7	**14.9**
05 Payload System	20.7	35.9	40.0	24.7	4.6	0.0	0.0	0.0	0.0	0.0	**125.8**
06 Flight System	7.2	7.4	6.7	6.7	3.5	0.0	0.0	0.0	0.0	0.0	**31.6**
07 Mission Operations System	10.7	15.5	22.2	24.1	30.5	20.1	20.4	20.4	20.4	20.1	**204.3**
08 Launch System	0.2	0.5	0.5	0.5	0.4	0.0	0.0	0.0	0.0	0.0	**2.1**
InSAR Total	**54.0**	**75.0**	**84.5**	**71.5**	**57.5**	**26.4**	**24.9**	**24.8**	**24.8**	**23.0**	**466.4**

10.5 Facilities and Equipment

Flight System I&T (Integration and Test) is currently planned to occur at contractor facilities. Current planning suggests SAF will most probably be booked from late 08 to late in FY09 for MSL. If contractor selection precludes InSAR flight system integration and test at contractor facilities the InSAR team will ensure appropriate timing of in-house InSAR I&T by closely coordinating with concurrent projects.

10.6 Risk Management Approach

InSAR Risk Management will be highly integrated with project system engineering efforts. The InSAR Project Systems Engineer will hold the key responsibility of Project Risk Engineering with close collaboration with the PM and MAM. The InSAR Risk Management planning and implementation will follow the JPL Risk Management Handbook, which contains a risk-management approach involving risk-planning, identification and assessment, decision making and tracking. A risk-management plan will be developed in the Formulation Phase and will include the contractors as active participants. Risk assessments of the project from the safety and mission assurance staff will be accompanied by its recommendations for risk mitigation and incorporated into the risk-management plan.

The Problem/Failure Reporting System will be utilized for the identification, tracking, closure, verification and status of problems and failures encountered.

10.7 International Traffic in Arms Regulations

Currently no foreign contractors or partnerships have been identified. However, an option does exist for the use of an Astrium spacecraft bus. If this option is selected, JPL and the PM will conduct relationships with international partners in accord with the U.S.

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International Traffic in Arms Regulations (ITAR) and the U.S Export Administration Regulations (EAR). The spacecraft bus would be obtained through a RSDO (Rapid Spacecraft Development Office) procurement. Since the launch is currently planned to be from the United States and the spacecraft bus would be a permanent import; an import license would not be required for the spacecraft bus. For integration purposes, NASA may need to transfer interface technical data to the foreign contractor, in which case a State Department export license for the technical data transfers would be filed. Since the InSAR phased-array antenna contractor would levy interface requirements on the spacecraft bus, they may need to interact with the potential foreign entity during the mission and may have to obtain a State Department export license.

10.8 Roles and Responsibilities

The PM is responsible to NASA for successful execution of the mission. The PM will plan, coordinate and monitor system design and implementation during all phases of the project. The PM is responsible for Project Planning, System Engineering, Progress Reporting Requirements and Interface Management, Risk Management, Mission Assurance, and Resource and Margin Management. The PM is advised by an Advisory Board consisting of TBD at JPL, and TBD Contractor Officials. Commitments with and contributions of civil agencies will be closely coordinated with the Joint Steering Group (JSG). All system managers report to the PM and decision making will occur at the lowest level possible. The PM is the final project authority for all decisions.

Figure 10-1. InSAR Project Preliminary Organization Chart

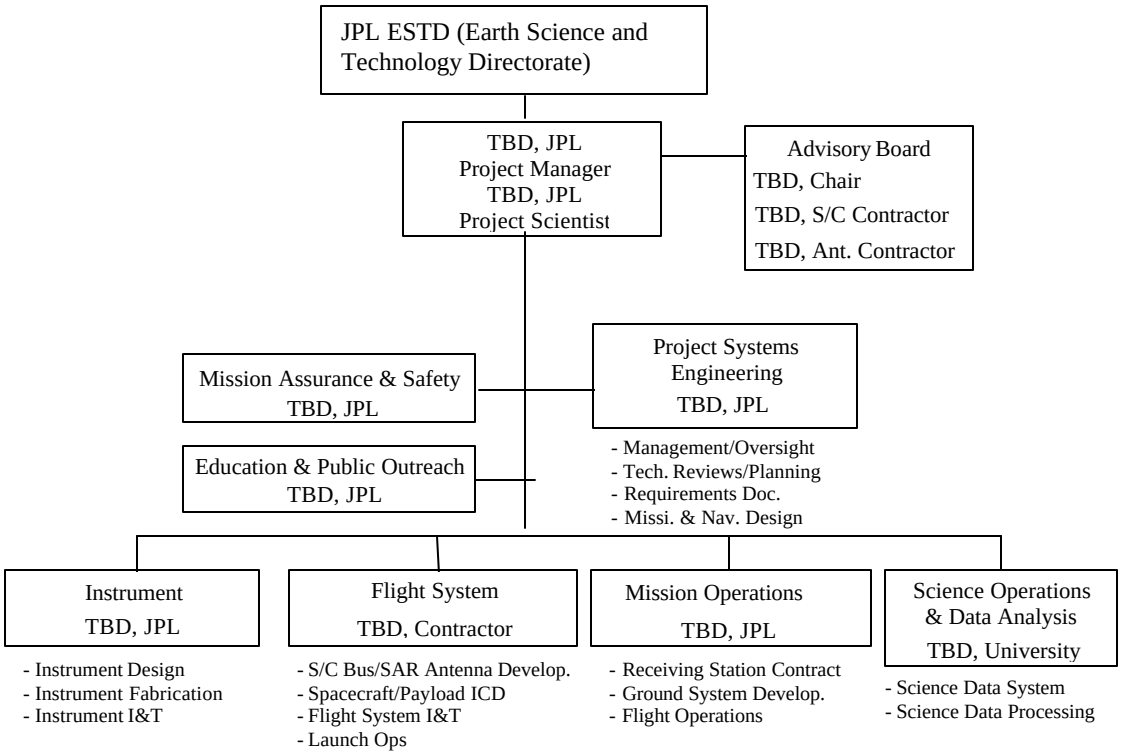

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Figure F4-1. Project Schedule

ID	Task Name	Start	Finish
1	**Milestones**	Fri 10/1/04	Fri 10/1/04
2	**Mission Phases:**	**Fri 10/1/04**	**Fri 4/30/10**
3	**Formulation**	**Fri 10/1/04**	**Sun 1/1/06**
4	Phase A	Fri 10/1/04	Tue 3/1/05
5	Phase B	Tue 3/1/05	Sun 1/1/06
6	**Development**	**Tue 1/3/06**	**Wed 4/8/09**
7	Phase C	Tue 1/3/06	Thu 1/3/08
8	Phase D	Thu 1/3/08	Wed 4/8/09
9	Operations	Wed 4/8/09	Fri 4/30/10
10	**Project Reviews**	**Tue 2/1/05**	**Mon 3/2/09**
11	PMSR	Tue 2/1/05	Tue 2/1/05
12	PDR/MCR	Mon 10/3/05	Mon 10/3/05
13	CRR/MCR	Mon 1/2/06	Mon 1/2/06
14	CDR	Tue 8/1/06	Tue 8/1/06
15	RTR	Tue 10/2/07	Tue 10/2/07
16	TRR	Wed 12/5/07	Wed 12/5/07
17	PER	Mon 6/2/08	Mon 6/2/08
18	ORR/PSR	Thu 1/1/09	Thu 1/1/09
19	MRR/LRR	Mon 3/2/09	Mon 3/2/09
20	**Radar Electronics**	**Fri 10/1/04**	**Mon 7/2/07**
21	Elec/Mech/Thermal design	Fri 10/1/04	Tue 8/1/06
22	Radar Electronics fab & test	Thu 12/1/05	Mon 7/2/07
23	**Radar Antenna**	**Wed 12/1/04**	**Mon 7/2/07**
24	RF/Electrical design	Wed 12/1/04	Mon 7/3/06
25	EM Antenna Panel fab & test	Thu 12/1/05	Tue 8/1/06
26	FM Antenna Panel fab & test	Thu 8/3/06	Mon 7/2/07
27	**Antenna Structure/Mechanism**	**Wed 12/1/04**	**Mon 7/2/07**
28	Elec/Mech/Thermal design	Wed 12/1/04	Tue 8/1/06
29	Antenna Structure fab & test	Mon 1/2/06	Thu 2/1/07
30	Antenna Deploy Mech fab & test	Mon 1/2/06	Mon 7/2/07
31	**Radar Instrument I & T (JPL)**	Tue 7/3/07	Wed 1/2/08
32	Schedule Reserve (3 months)	Thu 1/3/08	Thu 4/3/08
33			
34	**Satellite Development**	**Wed 12/1/04**	**Wed 1/2/08**
35	Interface Definition/Design	Wed 12/1/04	Wed 6/1/05
36	Design, Fab & Test	Tue 2/1/05	Mon 10/1/07
37	Schedule Reserve (3 months)	Tue 10/2/07	Wed 1/2/08
38	Satellite Testbed Integr & Test	Wed 11/1/06	Wed 8/1/07
39	**Satellite System I & T (TBD)**	Thu 1/3/08	Thu 1/3/08
40	Satellite Integration	Thu 1/3/08	Thu 7/3/08
41	Radar Integration	Fri 4/4/08	Fri 7/4/08
42	Environmental Testing	Mon 7/7/08	Tue 10/7/08
43	System Validation Test	Wed 10/8/08	Fri 12/5/08
44	Schedule Reserve (2 months)	Mon 12/8/08	Fri 2/6/09
45	**Launch Campaign**	Mon 2/9/09	Mon 2/9/09
46	Pack/Ship & Launch Ops	Mon 2/9/09	Tue 4/7/09
47	Launch	Wed 4/8/09	Wed 4/8/09
48			
49	**Mission Operation System**	**Wed 12/1/04**	**Fri 4/30/10**
50	MOS/GDS requirements & Design	Wed 12/1/04	Mon 6/5/06
51	MOS/GDS development & test	Wed 6/1/05	Wed 10/1/08
52	Shedule Reserve (6 months)	Thu 10/2/08	Wed 4/8/09
53	Flight operation (5 years)	Wed 4/1/09	Fri 4/30/10

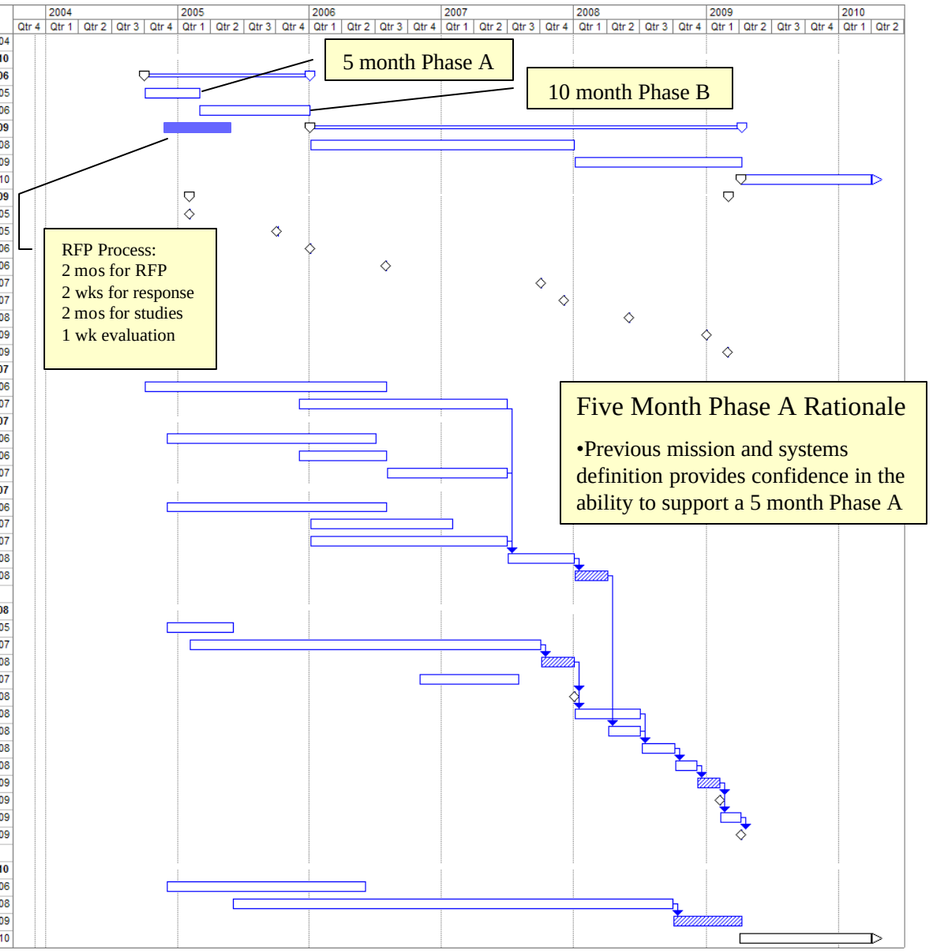
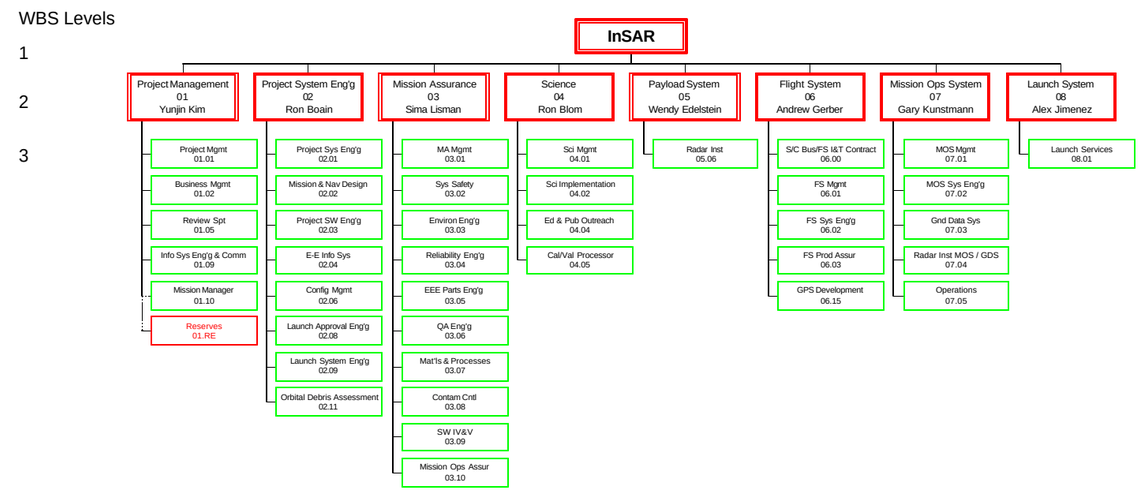


Figure F4-2. Project Work Breakdown Structure



- The InSAR Team has established a product-oriented WBS and corresponding organization to define clear decision making roles and lines of authority
- The plan for intersite delivery of WBS elements is for the instrument to be delivered to the spacecraft contractor, and for the flight system to be delivered to VAFB for launch
- The complete InSAR WBS and WBS dictionary are included in the study appendices

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