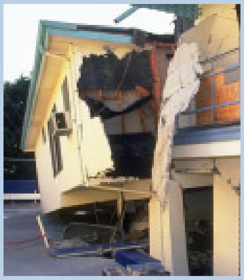
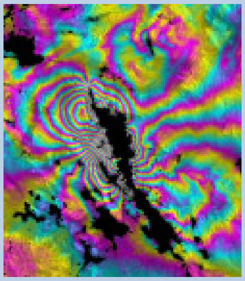
GESS

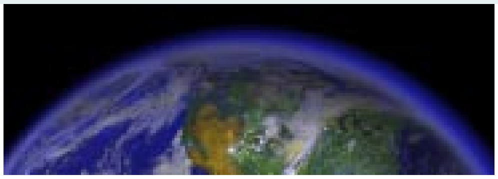
GLOBAL . EARTHQUAKE . SATELLITE . SYSTEM

A 20-YEAR
PLAN TO
ENABLE
EARTHQUAKE
PREDICTION

MARCH 2003







Enhanced Low-Earth Orbit

CHAPTER THREE

The GESS enhanced low-Earth orbit concept, or LEO+, proposes the operation of one or more L-band SAR systems at an altitude of approximately 1325 km, significantly higher than those of most current SAR platforms. The higher platform altitude affords a wider visible area to the sensor: two 800-km swaths, each comprising seven subswaths, from 300 to 1100 km on either side of the satellite ground track. The large viewable area enables the system to access the entire Earth quickly, reducing the interferometric repeat period to six days and allowing for much finer InSAR temporal resolution than is available from other current or pending SAR missions. The higher altitude also offers better orbit stability, another important consideration for repeat-pass interferometry. A LEO+ mission could be flown using existing conventional technology, though the system would require a slightly larger antenna and greater power than LEO SAR systems.

The radar would be capable of generating high-resolution single-subswath images in a standard stripmap mode and provide lower-resolution, wider-swath images from multiple subswaths in interferometric ScanSAR mode. In stripmap mode, the five-look image resolution would be 30 × 30 m or better. The interferometric surface-displacement accuracy would depend mainly on the temporal correlation properties of the surface under observation, as well as on atmospheric effects, but with appropriate calibration and post-processing, nominal line-of-sight displacement accuracies better than 1 cm can be achieved. The instrument would acquire right-looking and left-looking data on ascending and descending passes, so it would be possible to synthesize 3-D maps of surface displacement from multiple interferograms with different viewing angles. Over targeted areas, a high-resolution 3-D displacement map comprising ten or more individual images could be generated in under 12 days, and global maps generated annually.

System Parameters

The radar would transmit 10 kW of peak power from a 3.5 × 13.5 m aperture L-band (24 cm wavelength) antenna that is mechanically steered to a fixed position looking either to the left or the right of the platform direction of motion. Each subswath on a given side would be illuminated through ±10° of electronic beam steering. Because the system performance would degrade somewhat with increasing slant range and incidence angle, the inner four subswaths (1–4) on each side are denoted "primary beams" while the outer three subswaths (5–7) are denoted "extended beams." Across the entire swath, the ground incidence angle varies from 15° to 47°. Instrument parameters and performance measures for each subswath are summarized in Table 3.1.

A split-spectrum approach would be employed for ionospheric correction (see Payload Description for further detail) so that transmitted pulses occupy two distinct subbands of the 80 MHz L-band frequency allocation. The subband pulse bandwidth would be 20 MHz in subswaths 3–7, while the steep incidence angles in subswaths 1 and 2 would require a somewhat larger total bandwidth in order to maintain the required ground-range resolution. (Because the surface would also reflect more radar energy at steep incidence angles, SNR performance would not be sacrificed.) The pulse repetition frequency would be nominally around 1200 Hz.

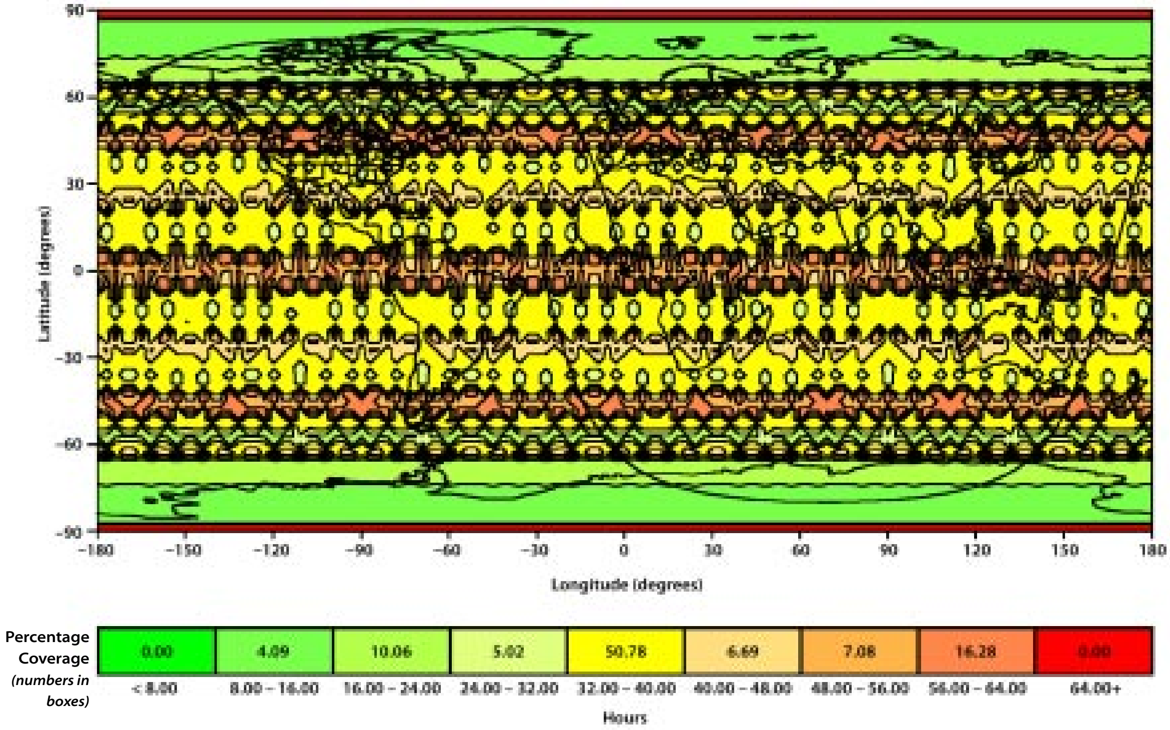


Figure 3.1
The maximum revisit time for any given spot for a single LEO+ SAR at approximately 1325 km altitude and 100° inclination, with a six-day repeating ground track. The percentage of the Earth's surface that would be revisited within a given time frame is given in the legend below.

Table 3.1 LEO+ beam summary.

	1	**2**	**3**	**4**	**5**	**6**	**7**
Ground Range from Nadir (km, near/far)	300/450	445/595	590/740	735/835	830/930	925/1025	1020/1090
Look Angle (deg, near/far)	12.7/18.5	18.4/23.7	23.5/28.4	28.2/31.1	31.0/33.6	33.5/36.0	35.8/37.4
Incidence Angle (deg, near/far)	15.4/22.6	22.3/29.1	28.8/35.0	34.8/38.6	38.4/42.0	41.8/45.2	45.0/47.2
Transmit Power (peak, kW)	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Pulse Duration (μs)	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Bandwidth (MHz)	17.0	12.0	10.0	10.0	10.0	10.0	10.0
Polarization	HH	HH	HH	HH	HH	HH	HH
Pulse Repetition Frequency (Hz)	1240	1191	1233	1178	1224	1176	1220
Ground Range Resolution (m, near/far)	28.8/19.9	28.5/22.3	26.9/22.6	22.7/20.8	20.9/19.4	19.5/18.3	18.4/17.7
Single-Look Azimuth Resolution (m)	6.0	6.3	6.0	6.3	6.1	6.3	6.1
Minimum SNR Assuming Model Soil Surface (dB)	10.4	9.8	9.6	11.1	11.0	10.3	10.3
Maximum Range Ambiguity Level (dB)	–35.0	–36.0	–29.5	–32.8	–26.8	–23.7	–20.1
Maximum Azimuth Ambiguity Level (dB)	–22.1	–20.9	–21.8	–20.4	–21.7	–20.5	–21.5
Data Rate (Mb/s)	142.7	124.6	128.6	95.2	105.9	107.8	84.9

Orbit, Coverage, and Constellations

The satellite would be launched into a nearly circular, sun-synchronous terminator orbit at an altitude of 1325 km and an inclination of 101°; this orbit has a six-day repeating ground track (Figure 3.1). The satellite would be controlled under tight attitude and trajectory constraints in order to facilitate repeat-pass interferometric processing. Given the satellite orbit and the capabilities of the radar instrument, 85% of the Earth's surface would be viewable by the satellite within 24 hours, and 100% of the surface would be viewable within 60 hours. This quick-response capability of the SAR could provide timely data in the crucial hours and days following an earthquake or other natural disaster.

A constellation of identical satellites in phased, node-spaced orbits could provide even shorter interferometric repeat times and event-response times (see Figure 3.2).

With a constellation of four satellites, the interferometric repeat period could be reduced to 36 hours, and an image of any point on the Earth could be formed by at least one satellite within about 12 hours of an event (or six hours for 85% accessibility). Multiple satellites could also be placed at different orbital inclinations in order to enhance the achievable 3-D surface displacement accuracy. That is, while near-polar orbits are required to provide Earth coverage at high latitudes, they do not offer much diversity in viewing angle at very low and very high latitudes. Hence, in equatorial regions of the Earth for example, the north–south component of surface displacement could not be very accurately determined. Therefore, in addition to the satellite(s) inclined 101°, one or more satellites could be placed in lower-inclination orbits in order to increase the orthogonality of the directions from which different areas are mapped (Figure 3.3).

A more ambitious constellation of 36 satellites could reduce the interferometric repeat time to four hours and could allow most points on the Earth to be imaged within around two hours or less.

Instrument and Operational Modes

Each satellite could be operated in both high-resolution, single-subswath stripmap modes and wide-area, multiple-subswath interferometric ScanSAR modes (100-m resolution at eight looks). Note that in the interferometric ScanSAR modes, the instrument would need to be timed such that corresponding ScanSAR bursts are aligned between successive orbit passes. This mode of operation has not been demonstrated, but we expect that it is feasible.

If the instrument collects data for one-third of the time it is over land, its operational duty cycle would be approximately 10% on average,

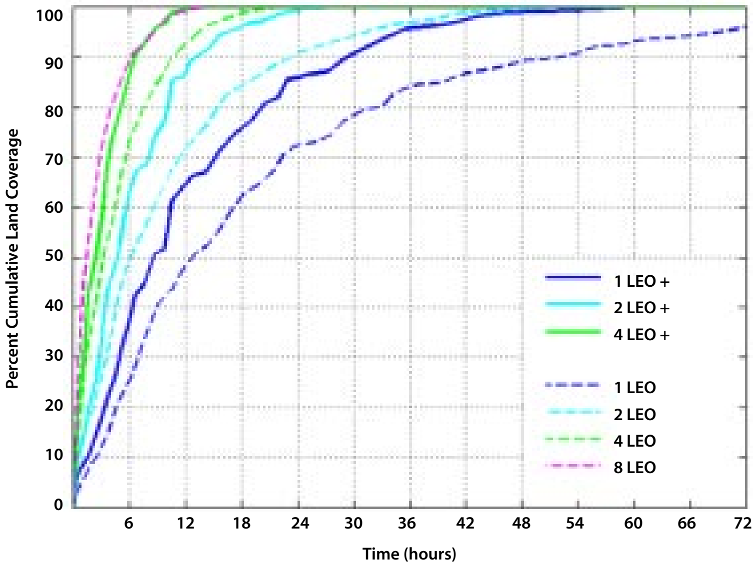


Figure 3.2
A comparison of cumulative land coverage by different LEO and LEO+ constellations. A four-satellite LEO+ constellation covers 90% of the Earth in six hours.

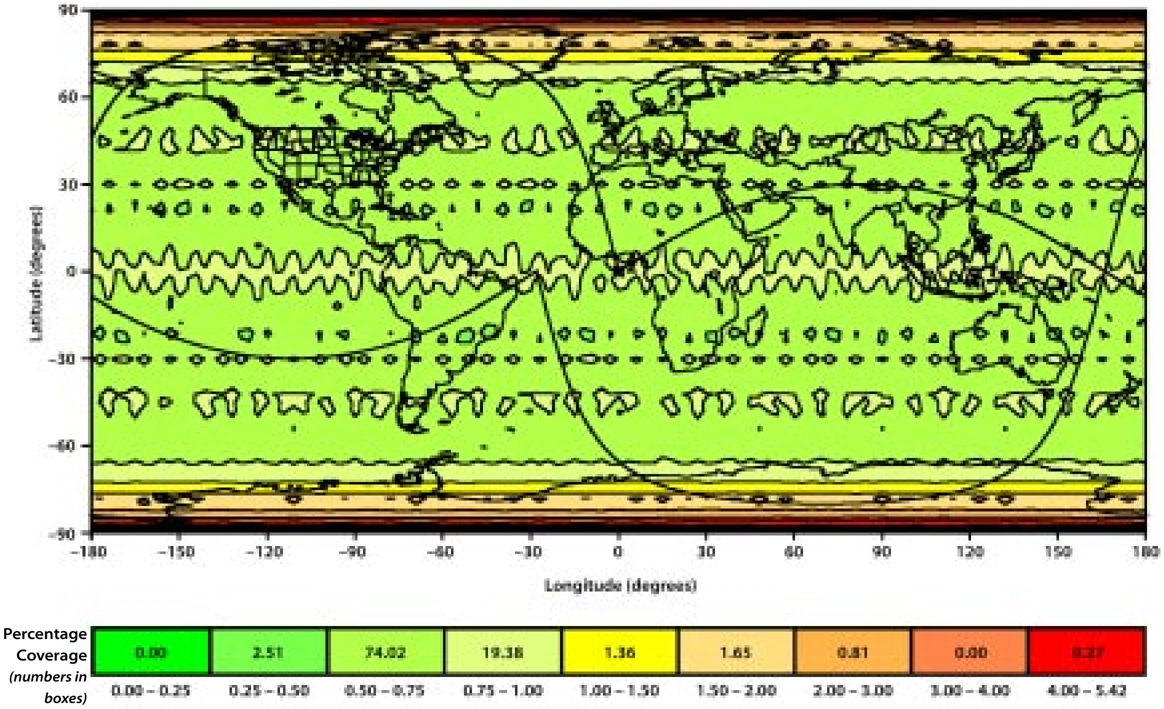


Figure 3.3 Maximum 3-D accuracy from two LEO+ satellites at 101° and 30° inclinations, assuming 1 cm line-of-sight displacement.

though the duty cycle might be significantly higher for some orbits. Each year, the instrument's operational plan would most likely include the collections of different global data sets in various high- and low-resolution modes for archive in an interferometric library (see Table 3.2).

The satellite would also be tasked to collect data as frequently as possible from important seismogenic areas, such as Southern California and other parts of western North America, in addition to other seismogenic zones in South America, Asia, the Mediterranean, and others.

A typical six-month operational plan might consist of 36 days spent acquiring a global, low-resolution, primary-beam, interferometric ScanSAR data set, and 144 days spent acquiring four to six high-resolution maps of western North America and two to three high-resolution maps of other key areas. As possible, data would also be acquired over other areas to fill in coverage for global high-resolution maps.

The ground resolution depends on which operational mode is in use. The ground resolution for both primary (1-4) and extended beams (5-7) is 30 m in stripmap mode, and 100 m in ScanSAR. The number of looks available also changes for different modes both across and between subswaths. The primary beams have five looks in stripmap mode, and 14 in ScanSAR mode; while the extended beams have five looks in stripmap mode, but 18 looks for ScanSAR. The ground swath for each beam can be calculated from the ground range values in Table 3.1. For stripmap mode, the ground swath in beams 1-7 in kilometers is: 150, 150, 150, 100, 100, 100, 70. In ScanSAR mode, however, the primary-beam ground swath is 535 m, and the extended-beam ground swath is 260 m. Additional instrument parameters do not vary for subswath or operational mode:

- RF peak power is 10 kW
- Average orbit duty cycle is 10%
- Peak DC power is 3816 W

An illustration of the operational modes and beams is shown in Figure 3.4.

Performance

While the studied system parameters do not represent a final, fully optimized design, they maintain a signal-to-noise ratio of at least 10 dB over the entire visible area, assuming a model scattering profile for a soil surface and incidence angles determined by a nominal spherical Earth. The preliminary design yields a range ambiguity level below –30 dB in the primary subswaths and –20 dB in the extended subswaths, and an azimuth ambiguity below –20 dB in any subswath. Note also that the overall performance is generally better in the middle of a subswath than at its edges, and that the subswath widths can be increased slightly if reduced performance is acceptable in the extended areas. For the stripmap modes, the nominal along-track (azimuth) resolution would be 6 m, and the nominal cross-track (range) resolution projected onto the ground would be 30 m or better. Performance parameters are summarized in Table 3.1, referenced previously in the System Parameters section.

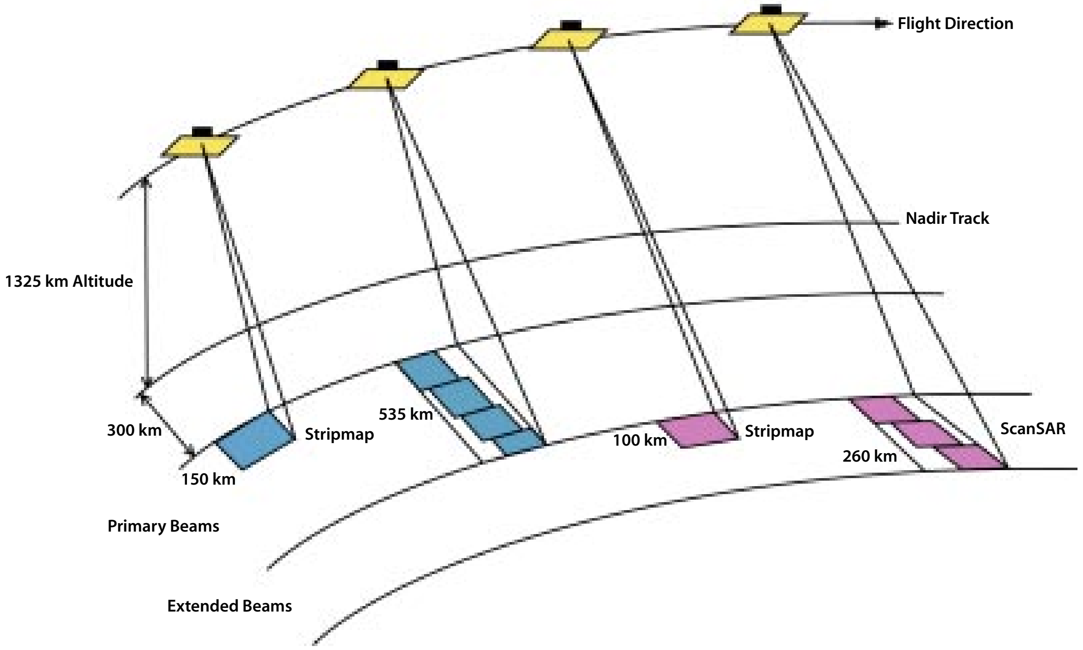
The interferometric displacement accuracy of the system would be highly dependent upon the properties of the surface and the atmosphere at the time data is acquired. Under ideal conditions, line-of-sight displacement accuracies of a few millimeters might be possible from a single interferogram at 30 m resolution, but the performance would degrade considerably in the presence of temporal decorrelation or atmospheric variability. Temporal decorrelation comes about when, rather than bulk displacement, the surface exhibits random change that makes the interferometric phase noisier.

Decorrelation-induced phase noise tends to become more severe as the temporal baseline is increased, but it can also be reduced through averaging, either spatially or over multiple interferometric pairs. Atmospheric artifacts result from the spatial and temporal variations in the effective radar signal path length related to changes in the propagation properties of the troposphere and ionosphere. These artifacts are more difficult to remove,

Global Primary-Beam ScanSAR	(6 days) * (2 sides) / (0.333 over-land duty cycle)	36 days
Global Extended-Beam ScanSAR	(6 days) * (2 sides) / (0.333 over-land duty cycle)	36 days
Priority-Area Primary-Beam Stripmap	(6 days) * (2 sides) * (4 beams)	48 days
Priority-Area Extended-Beam Stripmap	(6 days) * (2 sides) * (3 beams)	36 days
Global Fill-In Primary-Beam Stripmap	(6 days) * (2 sides) * (4 beams) (Targeted Area Time) (0.333 over-land duty cycle)	96 days
Global Fill-In Extended-Beam Stripmap	(6 days) * (2 sides) * (3 beams) (Targeted Area Time) (0.333 over-land duty cycle)	72 days

Table 3.2
LEO+ operational modes.

Figure 3.4 LEO+ operational modes.



but some mitigation strategies are possible (see the Atmospheric Mitigation section in Chapter 5). We expect that average-case accuracies of a few centimeters or better would be possible from a single interferogram, and that these accuracies might be reduced to the subcentimeter level with the proper combination of multiple data sets. (This underscores the need for an InSAR mission that can acquire large amounts of data over short time periods for targeted areas.) We also expect subcentimeter 3-D displacement accuracies for regions between ±30-70° latitude, though as described previously, one of the 3-D displacement components may be indeterminable for other latitudes if data are acquired only from satellites at the same near-polar orbital inclination.

Data Rates and Volumes

The average instantaneous data rate of the satellite would be approximately 105 Mb/s, so assuming a 10% instrument duty cycle, the data volume collected each day would be about 950 Gb, or 119 GB. Over five years, the satellite would collect more than 200 TB of data that would need to be archived. For downlink and instrument-storage sizing, the maximum instantaneous data rate of 320 Mb/s and a 25% instrument duty cycle would yield 250 Gb of data per orbit. See the Ground Data System section in this chapter for more detail.

Payload Description

The LEO+ mission described here consists of an L-band SAR instrument on a dedicated spacecraft. The radar antenna, consisting of ten lightweight rigid panels and antenna deployment structure, comprises the majority of the radar instrument's 640 kg mass (including 30% contingency). The radar sensor electronics subsystem, which generates the transmit waveform and receives the return echoes, include the RF electronics, data handling electronics, and timing and control electronics.

Radar Sensor Electronics

The Radio Frequency (RF) electronics perform the transmit chirp generation, upconversion, filtering, and amplification during signal transmission (Figure 3.5). They also provide amplification, downconversion, and filtering of the received echo. The instrument uses the full 80 MHz frequency allocation by transmitting and receiving a single linear polarization (HH) chirp in two frequency subbands (split-spectrum) with 70 MHz separation to permit ionospheric corrections similar to the L1/L2 GPS approach. The aggregate bandwidth of both subbands is up to 20 MHz.

Subharmonic sampling will be used to combine the two subbands into a minimum-rate data stream using the least amount of hardware. An NCO-based direct digital synthesizer (DDS) generates multiple chirp waveforms in a small and power-efficient package. Solid-state power amplifiers (SSPAs) are used as the radar transmitter. SSPA technology is very mature at L-band, and several hundred watts to several kilowatts of RF power (over relatively narrow bandwidths) can be readily achieved. For an active phased-array architecture, the transmit power is generated using transmit/receive (T/R) modules distributed on the antenna. In this configura-

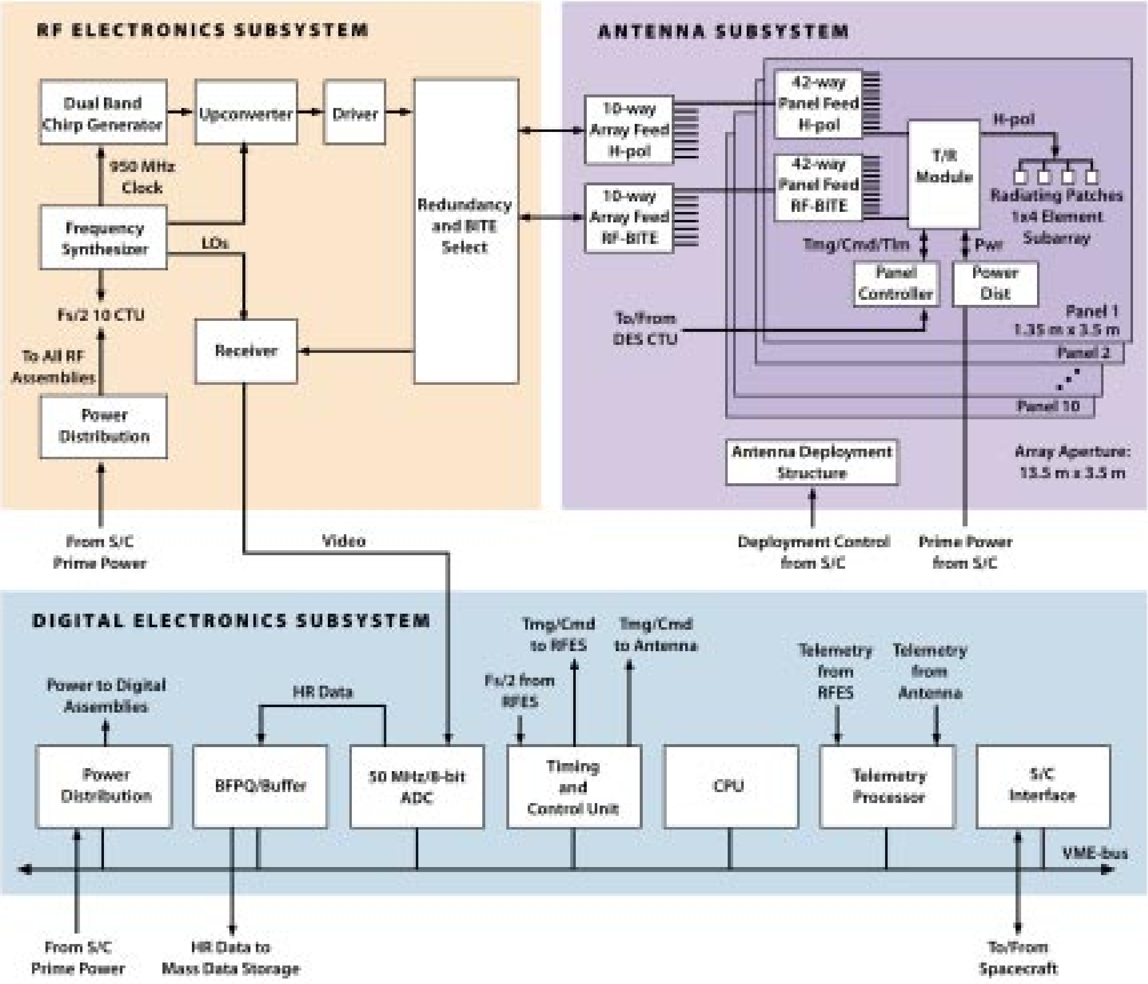


Figure 3.5
Radar electronics for the LEO+ SAR payload.

tion, we assume roughly 25 W per module, where 420 modules are distributed along the array to achieve the 10 kW minimum transmit power. The front-end electronics control the signal routing of the primary, redundant, and test/calibration signals. The receiver downconverts the echo received from the antenna and frequency translates the two split-spectrum subbands using a subharmonic sampling technique to produce two concatenated frequency bands at range-offset video. Gain control provides high dynamic range. These signals are then routed to the data handling system for digitization and storage.

The data handling hardware consists of the high-speed analog-to-digital converter (ADC), data buffer and block floating-point quantizer (BFPQ). For the subharmonic sampling receiver, the ADC sample clock is only required to be 50 MHz, with an analog bandwidth of 80 MHz, sampling at 8 bits per sample. The BFPQ converts the 8-bit data to 4-bit data and the buffer reduces the peak data rate to interface with the solid-state recorder (SSR). Formatting includes embedding a synch word, frame count, and spacecraft data (GPS, time) into the data stream. Only one high-rate data channel is required.

The radar control, timing, and telemetry hardware includes a central processor unit (CPU), telemetry processor, spacecraft interface module, radar control and timing unit (CTU), and power module. A dedicated CPU is implemented to control and manage the instrument functions and data flow. This approach ensures a simple interface to the spacecraft and aides in ground testing of the instrument. While the CTU generates deterministic subsecond timing parameters, the CPU controls operations for time scales greater than one second (ScanSAR control parameters, radar mode, data flow). The dedicated CPU will be able to easily handle the control algorithm to calculate and store in a look-up table the beam position for ScanSAR operation. Based upon the command word generated by the CPU, the CTU generates the timing signals necessary to control the radar, including pulse repetition frequency (PRF), receiver protection and gain control, antenna phase shifter settings, and data window position.

The radar electronics will be housed in two separate chassis, one for the RF electronics and one for the digital electronics. Each subsystem has its own dedicated power distribution unit to convert the raw spacecraft voltages to the required DC voltages and to condition and distribute them to the subsystems. Full block redundancy of the radar electronics is implemented to achieve the five-year mission lifetime. The RF electronics consist of primary and redundant subassemblies and the Redundancy/Built-In-Test select switch matrix, each packaged in a separate shielded enclosure. Surface-mount RFIC/MMIC technology in microstrip circuits ensures cost-effective, low-mass packaging. The digital electronics will reside in a standard VME chassis. Standard VME architecture enables the use of several existing commercial-off-the-shelf (COTS) hardware assemblies to reduce cost and risk. These include the CPU board, the Telemetry Processor Board, the spacecraft I/O interface board, and the power distribution and conditioning board. The custom digital hardware uses FPGA technology to reduce size and power while increasing flexibility of the design.

Radar Antenna

The antenna performs the beam steering and transmission function as well as high-power amplification on transmit and low-noise

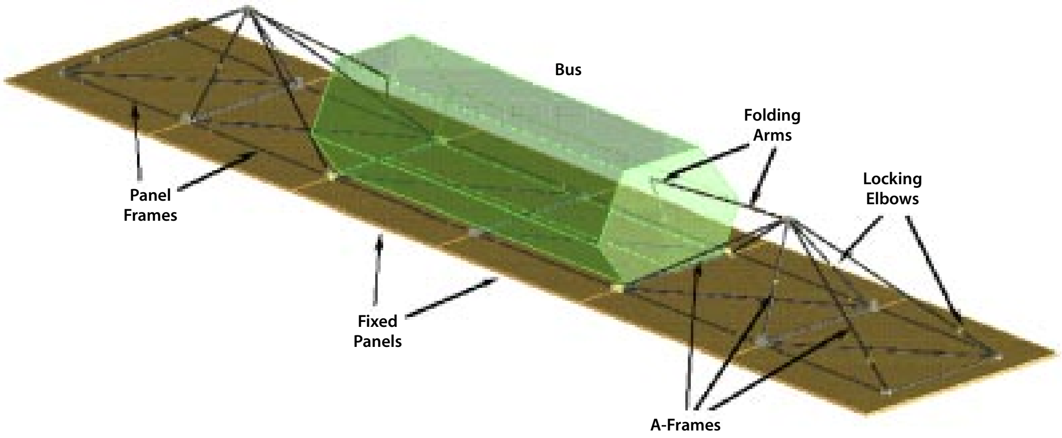


Figure 3.6
LEO+ deployed antenna using a RADARSAT-2 modified truss structure.

amplification on receive. The antenna is a corporate-fed planar phased array with deployable antenna structure (Figure 3.6). The use of many distributed T/R modules on the antenna provides inherent redundancy since random failures of the T/R modules result in a graceful degradation of radar performance. The Antenna Subsystem consists of the RF aperture (antenna panels) and the deployment structure. When stowed, the antenna is folded into ten panels, each measuring 1.35 m × 3.5 m. The antenna width (3.5 m) was selected such that it could be accommodated in several existing launch vehicles. The radiating elements consist of half-wavelength microstrip patch radiators. To minimize grating lobes, an element spacing of 0.7 λ is selected so there are 21 (elevation) × 80 (azimuth) radiating elements in the full array. The radiating elements are single polarization (HH) and combined into 1 (elevation) × 4 (azimuth) element subarrays that are each driven by a single transmit/receive (T/R) module. The T/R modules, with integrated 4-bit phase-shifters, are distributed over each antenna panel to achieve elevation steering as well as to minimize losses. The 420 T/R modules are organized in panels, which contain 21 (elevation) × 2 (azimuth) T/R modules (42 modules). This configuration enables one phase shifter per elevation element. Although there is no azimuth steering requirement, the antenna does have the capability of limited azimuth scanning. To facilitate ground testing and in-flight performance monitoring, an RF Built-In Test Equipment (BITE) capability is included in the T/R module. A small portion of the transmit signal is coupled to a BITE port and routed to the receiver to monitor the transmitter performance of the antenna. Alternatively, an in-band caltone signal can be routed through the BITE feed and coupled into the T/R module's LNA to test the receive portion of the system. This calibration feature can be implemented as either a special test sequence during a non-data-taking mode or else incorporated directly into the data-taking mode. A broadband corporate feed network distributes the RF signals to and from the antenna elements. The coaxial array feed distributes the RF signals to each panel. Within each panel is a microstrip panel feed to distribute the RF signals to each subarray. Conventional multiwire harness cabling distributes the DC power and control signals to each panel.

Table 3.3
Instrument mass and power for GESS LEO+ mission.

	QUANTITY	MASS (KG)	PEAK DC POWER (W)	STANDBY POWER (W)	ORBIT POWER AVG (W)
Antenna Subsystem		**433.0**	**2783.3**	**13.3**	**278.3**
T/R Modules	420	43.0	2066.7	0.0	
Panels (Aperture, Panel RF Feed, Frame, Hinges)	10	298.0	0.0	0.0	
Antenna Panel Electronics	10	10.0	160.0	10.7	
Antenna DC–DC Converters	67	10.0	556.73	2.7	
Antenna Array RF Feed	—	10.0	0.0	0.0	
Antenna Power and Control Cabling	—	15.0	0.0	0.0	
Deployment Structure	1	47.0	0.0	0.0	
Interface Structure and Launch Support	s/c	0.0	0.0	0.0	
Actuators and Release Mechanisms	s/c	0.0	0.0	0.0	
Thermal Blankets (MLI)	s/c	0.0	0.0	0.0	
Radio Frequency Electronics Subsystem		**29.0**	**91.1**	**11.1**	**9.1**
Chirp Generator	2	2.0	12.0	0.0	
Frequency Synthesizer	2	3.0	20.0	10.0	
Upconverter	2	2.0	7.0	0.0	
Driver	2	4.0	28.0	0.0	
Receiver	2	2.0	3.0	0.0	
Red and BITE Select	1	1.0	12.0	0.0	
Power Distribution	2	3.0	9.1	1.1	
Housing, Cabling, and Misc.	1	12.0	0.0	0.0	
Digital Electronics Subsystem		**31.0**	**61.3**	**41.3**	**6.1**
Timing and Control Unit	2	2.0	7.0	7.0	
ADC/Buffer	2	3.0	10.0	0.0	
BFPQ	2	2.0	6.0	0.0	
CPU	2	2.0	10.0	10.0	
Telemetry	2	2.0	10.0	10.0	
S/C I/F and Data Formatter	2	2.0	6.0	6.0	
Power	2	3.0	12.3	8.3	
Housing, Cabling, and Misc.	1	15.0	0.0	0.0	
Radar Total		**493.0**	**2935.7**	**65.7**	**293.5**
30% Margin		147.9	880.7	19.7	88.1
GESS Radar Total w/ Margin		**640.9**	**3816.4**	**85.4**	**381.6**

The antenna structure is a deployable truss structure, which provides both support and strength to the panels and maintains flatness of the full array. The structure and deployment mechanisms must be reliable and lightweight and must deploy such that the antenna is flat, structurally stiff, and thermally stable. The flatness requirement of the antenna is one-sixteenth of a wavelength (1.4 cm) to minimize antenna pattern distortion. Two competing truss structures are suitable for this application. A modified deep-truss structure (as used in Seasat and RADARSAT-2) has extensive heritage and is considered relatively low risk. The edge-truss structure offers a very compact stowed envelope although it is less mature technologically. Both are very lightweight and can meet all GESS structural requirements. The spacecraft provides the interface, launch support structure, and thermal blankets. The instrument mass and power are shown in Table 3.3.

Heritage

While the instrument is based on existing technology, it represents a major leap forward in measurement capability. The GESS L-band SAR instrument derives much design and hardware heritage from its SIR-C predecessor. SIR-C experimentally validated several new SAR techniques including ScanSAR, spotlight SAR, and repeat-pass interferometry. Technology development activities following the success of SIR-C have focused on reducing the mass, power, and cost of similar instruments to enable a future free-flyer. The Advanced Radar Technology Program (ARTP) in collaboration with LightSAR demonstrated numerous L-band SAR component technologies with significant reductions in mass and power. Many of these technologies can be implemented in the GESS LEO+ mission for cost and risk reduction. For instance, based on LightSAR prototyping activities related to the antenna panel, T/R module, and structure, the total antenna mass density is projected to be roughly 10.2 kg/m^2, which is a significant improvement over the SIR-C L-band panels (23 kg/m^2) and the SRTM C-band outboard antenna (20 kg/m^2).

Mission Design

The design of the LEO+ mission is summarized below. Overall objectives and subsystem requirements were defined, and traded against, to achieve this baseline design. The LEO+ spacecraft block diagram showing the subsystems is illustrated in Figure 3.7. The five-year mission duration requires the use of functional redundancy in design. In order to mitigate overall risk, the spacecraft design uses full redundancy. The original LEO+ study used a launch date of July 2006, which corresponds to a technology cutoff date of 2003. This means that all technology items must be at a TRL of 6 by the beginning of Phase C/D. Another constraint is that the spacecraft must survive through the short eclipse seasons that occur each year. The power systems were designed to meet that requirement. Additionally, the LEO+ orbit radiation environment is somewhat more harsh than LEO. For study purposes, we assumed a radiation value of 24 krad behind 100 mils per year, with a radiation design margin of two. The current mission was designed for the use of a Delta II launch vehicle. The spacecraft would need either a two-axis gimbal High-Gain Antenna (HGA) or two antennas. These gimbals are required to permit continuous data taking without much performance degradation.

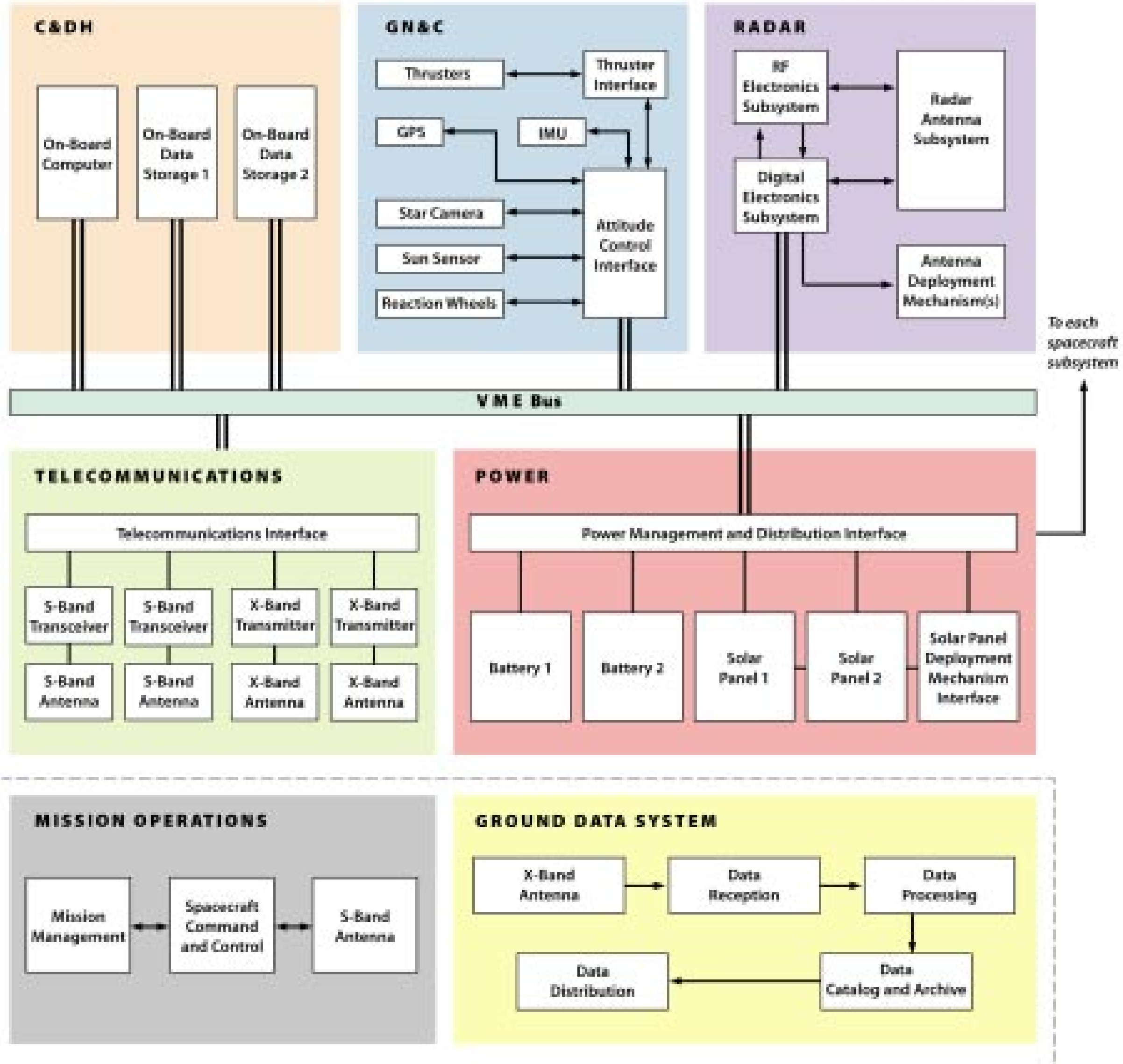


Figure 3.7 LEO+ spacecraft block diagram showing the subsystems.

Spacecraft Description

The LEO+ system concept has been formulated to keep overall costs low by using existing commercial designs (hardware and software) to the maximum extent possible. Applying this approach to the entire end-to-end system design has kept the spacecraft requirements in a range that can be satisfied by any one of several readily available satellite busses that can be obtained from industry. To minimize cost and development schedule, the approach is to use existing designs with limited modifications to support the mission characteristics. The system design requires the bus to provide the following functions:

- Radar instrument commanding
- Antenna deployment initiation command
- Onboard storage of radar data
- Data handling capacity to accommodate instrument peak data rates
- Data downlink for instrument telemetry
- Global Positioning System data
- Radar instrument power
- Attitude and articulation control
- Capability to handle large instrument

MISSION OBJECTIVE

- mm-level surface change detection accuracy per year (cm-level for any given interferometric pair).
- Six day repeat coverage.
- Global accessibility.
- Five-year mission duration.

MISSION AND INSTRUMENT CHARACTERISTICS

- L-band frequency.
- Single polarization.
- 200-m orbit tube radius.
- Left/right-looking, sun synchronous.
- Up to 20 MHz combined bandwidth split in the 80 MHz available L-band bandwidth to mitigate ionospheric delay problems.
- Incidence angle range 15.4–47.2°.

ORBIT DESIGN

- Baseline six-day repeat orbit of 1325 km.
- 6 am/6 pm orbit baseline.

ATTITUDE CONTROL SUBSYSTEM (ACS)

- Pitch and yaw pointing control to within ±0.05° (180 arcsec), 3 sigma. Roll pointing control to within ±0.1° (360 arcsec), 3 sigma.
- Pitch and yaw pointing knowledge to within ±0.025° (90 arcsec), 3 sigma. Roll pointing knowledge to within ±0.05° (180 arcsec), 3 sigma. These are half of the pointing control requirement.
- Pointing stability to within ±10 arcsec/sec, 3 sigma per axis. This supports the pointing control requirements.
- Repeat orbit position to within 200 m, 3 sigma.
- Real-time orbit position knowledge to within 20 m, 3 sigma, which supports the repeat orbit position requirement.
- Slew about the roll axis through 64° within 5 or 10 minutes.

COMMAND AND DATA SUBSYSTEM (CDS)

- 100 Gbits / orbit average.
- Two orbits storage.
- 150 Mbps data rate.

INSTRUMENT POWER

- 10 kW peak RF output.
- 2936 W DC input in science mode, 66 W in standby mode (3816 W with 30% uncertainty, 85 W with 30% uncertainty).

STRUCTURES

- SAR antenna consists of rigid honeycomb panels with back-up truss, 13.5 × 3.5 m deployed, stowed in 1.35 × 3.5 × 1.5 m assuming 10 panels.
- 433 kg mass estimate (current best estimate with no contingency) for SAR antenna panel.
- Total instrument mass estimated to be 493 kg, including the RF antenna and data electronics boxes (641 kg with 30% contingency).

TELECOM

- Support a minimum data rate of 105 Mbps (preferably 320 Mbps using two channels at 160 Mpbs), into 11.3 m ground stations in South Dakota (EROS Data Center), Alaska (Alaska SAR Facility), with Svaalbard, Norway as backup.
- Provide a low-rate S-Band TTC link.

PROPULSION

- Provide 143 m/s of velocity for a 1500-kg spacecraft (based upon assumed bus mass and Team X estimates).
- Provide 20 kg for miscellaneous attitude control functions.
- Unload reaction wheels if necessary. Normal unloading is by torquer bars.
- Provide initial tipoff rate reduction during launch.
- Provide many very small orbit correction maneuvers similar to TOPEX.
- Functional redundancy.

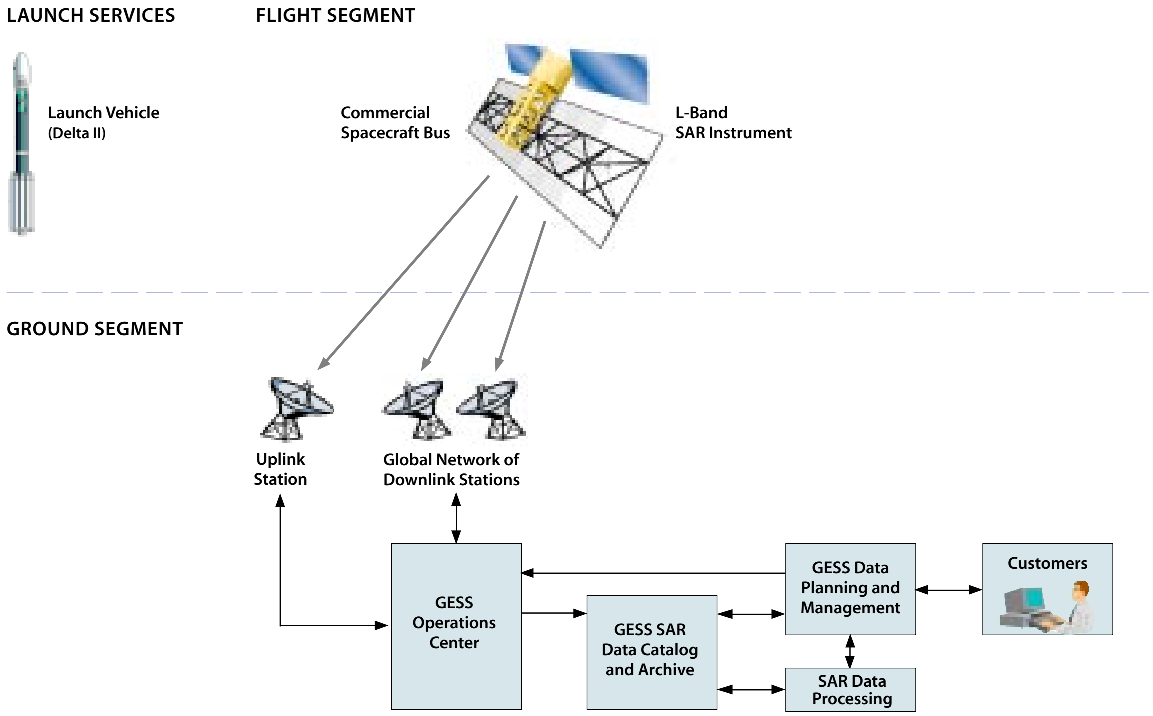


Figure 3.8 System elements for launch, flight, and ground operations.

A survey has been completed that indicates several manufacturers can supply satellite busses that meet or exceed the LEO+ requirements with little or no modifications to existing designs. All of the busses surveyed have substantial flight heritage and utilize space qualified components and technologies. Some of the available busses are production-oriented designs that will provide substantial cost and schedule efficiencies. The cost-saving approach for selecting a bus for nominal design requires that the bus requires little modification, has substantial space flight heritage, is compatible with multiple launch vehicles, has redundancy and sufficient margins to accommodate unexpected changes in the designs, uses radiation-hard standard or commercial parts when possible, and has well-defined interfaces to allow parallel development and testing of the instrument.

Launch Vehicle

The LEO+ launch vehicle will be obtained by the NASA Expendable Launch Vehicle Office and provided to the project using NASA ELV Office procurement and quality assurance processes. The NLS-Medium launch vehicle (Delta II) was assumed, as it can place the spacecraft into the desired orbit (Figure 3.9). A Delta IV would provide ample mass and volume margin.

Assembly, Test, and Launch Operations (AT&LO)

Once the LEO+ system design is complete and has passed the critical design review (CDR), production of the major elements will proceed concurrently. The spacecraft bus, radar instrument, and ground segment systems and their components will complete a rigorous test program during development and build-up for flight. All subsystems will be thoroughly tested prior to delivery to AT&LO (Figure 3.10). The objectives are to verify system level requirements, functional interfaces, and nominal performance of the integrated flight segment configuration in flight-like conditions.

The main objectives for AT&LO are:

- Provide an integrated, test validated, flight-ready space segment consisting of the spacecraft bus, radar instrument, and launch vehicle, which is capable of being launched on the scheduled launch date.
- Plan and implement traceable, repeatable, and comprehensible test activities.
- Demonstrate an ability to support the spacecraft and the mission objectives with functionally validated ground operations and data processing systems.

The AT&LO program shall test or demonstrate the following:

- Compliance of the integrated flight segment with system-level design and functional requirements.
- Nominal flight segment performance in ambient and expected environmental conditions (of launch and flight), with baseline representative operational sequences; and, predictable performance in selected contingency conditions.
- Compatibility with the launch vehicle and launch systems interface requirements.
- Compatibility with the ground segment and operations systems.
- Verified spacecraft capability to receive and process commands, and to clock out execution time for commands or command sequences that cannot be fully tested in ambient/ground environments.

In addition to traditional integration and test support, the AT&LO organization will also support a postlaunch on-orbit commissioning phase to checkout and calibrate the end-to-end flight and ground system. The AT&LO activity will conclude upon completion of the operational acceptance review, which occurs at the end of the commissioning phase.

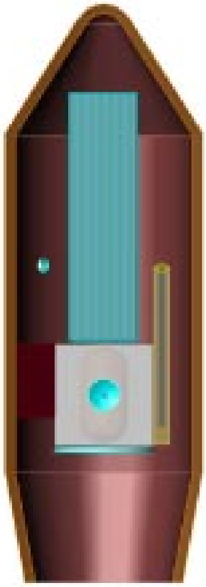


Figure 3.9
The LEO+ payload in stowed configuration in a Delta II launch vehicle fairing.

AT&LO Approach

The AT&LO approach targets several areas, including the early use of a system testbed to evaluate and confirm avionics architecture and end-to-end Information System design in order to avoid surprises and risks later in integration and testing (I&T). The spacecraft bus manufacturer will be responsible for the spacecraft bus I&T, and will deliver a fully integrated and tested bus. The radar system I&T would follow the incremental build and test approach. Final flight element I&T would be conducted at the spacecraft bus contractor facility. No thermal/vacuum tests at system level, no post-environmental antenna deployment test, and only limited mechanical/integrity verifications

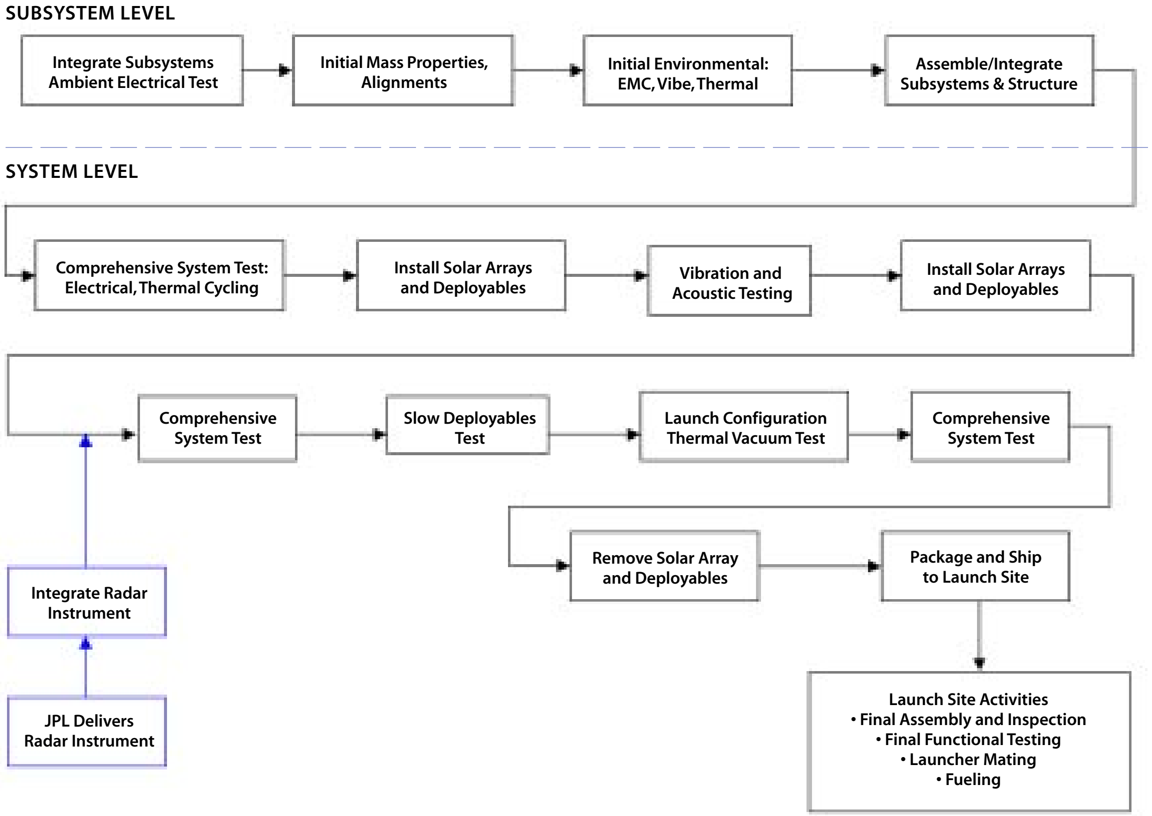


Figure 3.10 Satellite integration and test flow.

are assumed. There will be maximum use of system engineering in other WBS elements. The launch will be from the Western Test Range (Vandenberg Air Force Base).

Ground Data System and Products

The GESS Ground Data System (GDS) is designed to support the disaster management community (Figure 3.8). Specifically, the data latency for disaster response is two hours or less for time-tagged raw data and six hours or less for Level 1 data products, which could be utilized directly by the disaster response teams. Two downlink stations are planned to capture all the raw data being acquired, the EROS Data Center (EDC) in South Dakota and the Alaska SAR Facility (ASF). The Svaalbard Ground Station in Norway will serve as a backup downlink station. EDC would be the central data archiving and processing center, whereas another center, such as JPL, would serve as the GDS development site and backup data archiving and processing facility. JPL would have the capability to handle both the standard data product delivery as well as special event product generation. Level 0 product generation may be done at the downlink station and transmitted directly to the users when needed to reduce the data transmission overhead via EDC.

In the following section, we will summarize the ground data system requirements and corresponding design impact on the GDS for the LEO+ mission. We will describe the output products based on inputs from the seismology community. Next, we describe the external interfaces to the GDS and the distributed software architecture. The distributed nature and scalability of the GDS architecture designed for the LEO+ mission can be easily expanded to support a geosynchronous mission. We describe the hardware architecture of the GDS, which is composed entirely of commercial off-the-shelf (COTS) products.

Ground Data System Requirements

Based on the functional requirements for the LEO+ mission, the ground data system requirements and design impacts are summarized in Table 3.4.

Data Product Definitions

Two primary user communities with different requirements will be supported: those with radar processing capabilities, and researchers relying on geophysical Level 2 products. The former group of users would request the raw radar data to process themselves. In addition, they will need ancillary data for the purpose of calibration such as the removal of atmospheric effects. The second group of researchers who have no interest or capability to process their own radar data prefer to work directly with the geo-coded differential interferograms to extract the deformation measurements. Therefore, as shown in Table 3.5, the data products are defined to serve both of these user communities.

All level data products have accompanying metadata, which includes the ancillary data and quality, calibration, and processing parameters. Quick-look data (without corrections) will also be available. Ancillary data needed for processing includes:

- Satellite orbit information derived from onboard GPS
- Ground reference GPS (from mission operations)
- Atmospheric path delay model (from meteorological services)
- Ground truth data (from external sources) necessary for calibration

Browse products will be generated for all Level 1a, 1b, and 2 products. Ancillary data may be bundled with any level data product delivery.

Ground Data System Interfaces

The GESS GDS is an integrated SAR processing, product delivery, and archiving system. The GDS interfaces with the following components:

- Spacecraft operations
- Science users
- Program management
- Algorithm developers and calibration engineers
- Ancillary data sources

The high-level GDS boundaries and external interfaces are shown in Figure 3.11.

Spacecraft operations provide satellite-tasking information (instrument on/off times and modes) to the GDS. This information is catalogued, used for internal processing and made available via a Web-based GIS interface (interactive map) and subscription. It also provides ground station tasking and downlinked data. Science users access the GDS through a Web portal. This portal provides product and processing request capability, as well as other features such as data mining and education and outreach. Program management accesses the GDS through a Web portal to view metrics and provide processing priorities etc. Algorithm developers submit basic algorithms and refinements through a Web-enabled configuration management interface. The GDS actively acquires and ingests ancillary files required for product processing.

Table 3.4 Ground data system requirements. Based on the functional requirements for the LEO+ mission, the ground data system requirements and design impacts are summarized here.

REQUIREMENTS	**DESIGN IMPACT**
At least two downlink stations	Distributed system architecture Secure and reliable network connections Process raw data at more than one location
Duty cycle up to 20–25%	200–250 Gbits of data per orbit Parallel processing environment Distributed high-speed storage devices
13 orbits per day and six days in a repeat cycle	Online real-time data storage over 30 TB of data Six days' worth of data available on line
Fast downlink (320 Mbps) required	Network upgrades at ASF and Svaalbard Identify other possible stations
Single Data Archiving Center with a backup site	Develop operational concepts with EDC Design near online storage devices Use of DVD and high density magnetic media with jukeboxes
System interfaces to those with radar processing capability and individual researchers without the capability	Develop capability to interface with various data access methods Fault tolerance with real-time data deliver Support special orders of various level products
Access to ancillary data	Negotiate interfaces with ancillary data providers Develop redundant interfaces during emergency
Level 0 in compliance with EOS-HDF	Develop metadata standards Participate in HDF version 5 development
Latency for time-tagged raw data is 24 hours	320 Mbps downlink reception capability
Latency for calibrated data products is six days	Parallel/Beowulf/clustered processors Smart online data management system Reliable interfaces to ancillary data repositories
In emergency, two hours for raw and six hours for Level 1	Capability to handle special processing
Easy to use user interface	Data mining Web interfaces to access data Single interface to access all data levels Data and metadata standards
Five-year mission lifetime	Reliable system maintenance and upgrades Develop cost-effective operational concept

Table 3.5
Data products definitions.

LEVEL	DEFINITION
0	Reformatted raw signal data with associated radar headers.
1a	Processed single-look complex (SLC) data, browse imagery from multi-look SLC data, browse interferogram generated with most recent data-take from archive, and associated radar headers.
1b	Interferogram and correlation map with associated radar headers.
2	Calibrated three-dimensional displacement map in standard map projections.
Ancillary data	Satellite orbit information derived from onboard GPS data and ground reference GPS stations (from mission operations), atmospheric path delay model (from meteorological services), and any ground truth information (from external source) necessary for calibration. May be bundled with any level data product delivery.

Software Architecture

The software architecture supports a distributed implementation allowing for any number of receiving stations to be integrated into the system. In addition, this architecture is scalable in order to meet the performance requirements of a LEO+ mission or a geosynchronous mission. Additional designs may also be studied. Alternate architectures such as a direct broadcast approach may be viable, if data quality and calibration can be ensured.

The current design will allow for one or more ground data systems to be deployed. All ground systems will contain the same software, and will be configured to archive products long term at the EDC, the central data archiving center. The EDC will contain that master catalog of data products acquired throughout the mission and will include both online and offline storage of the data products and metadata. Ground receiving stations will be capable of receiving the products, performing basic data processing, and archiving the products at the EDC.

The product catalogs will be designed to reside on one or more hosts allowing scalability in the catalog. A typical scenario would be to build three product catalogs representing L0, L1, and L1+ data products. The data products will be stored on a network attached storage (NAS) file system so that the data products always appear local to the system creating an online archive.

Two key user interfaces will be created. The science user interface will allow scientists to enter product requests. Requests for previously captured data takes will be processed and products staged for download by the data distribution function. Requests for products that have not been acquired will be recorded by the system and scheduled for notification and distribution to the user once acquired. In addition, an operational user interface will also be created which will allow system operators to manage the data system.

In addition to the principal site of EDC, the software will also support the creation of a replicated site in the event that the EDC is unavailable. The replicated site will allow for products to be archived and queried at that site should the EDC be unavailable. The replicated site will contain a short-term “online” archive. Should the archive be unavailable, products will be captured by the replicated site, and then moved to the EDC once available. The site will also contain a master copy of the catalog indicating what products are available in the system.

Hardware Architecture

The GDS hardware system is composed of COTS products utilizing COTS operating systems. The hardware architecture is scalable in order to meet the performance requirements of a LEO+ mission or a geosynchronous mission. The physical interface between co-located machines is a high-speed switched network, now specified as Gigabit Ethernet but soon to be 10× Gigabit Ethernet. The design is also adaptable to the new InfiniBand architecture, a high-speed I/O protocol that is five times or more faster than the 10× Gigabit Ethernet, when it becomes widely available. Ground stations and the processing centers communicate through the Internet at the highest available bandwidth connections provided by the NASA Integrated Services Network (NISN) or commercial providers. The hardware system supports fully distributed processing, access, and control. The database is fully mirrored at an off-site location and is continuously updated. The main repository and archive for the database, online processed products, and long-term archived L0 product will be centralized at EDC. Mirror sites and Web caching at multiple locations will facilitate periods of high demand access to processed products.

Operational Scenario

The GESS GDS is fully responsive to the published operational scenarios. The GDS will be operated and serviced by EDC once the GDS system is delivered. The operational

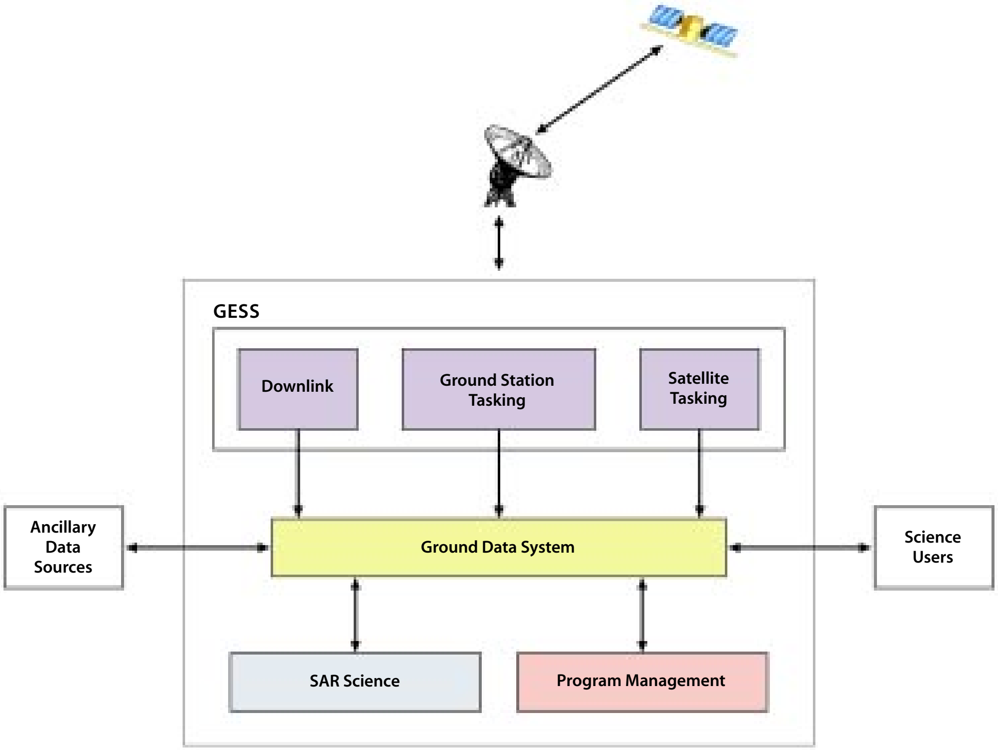


Figure 3.11
Ground data system boundaries and interfaces.

and service concepts will follow the current model of EDC.

Through the GDS Science and Management interfaces, processing priorities will be set (as in the case of the response to a targeted seismic event) and the processed products from the various mapping campaigns will be segregated into virtual collections for distribution and browsing (Table 3.6).

Geosynchronous GDS

To scale the GDS to support a geosynchronous mission essentially increases the duty cycle from 25% to 100% radar on-time. This increases the procurements and downlink costs significantly and would more than double the cost of the LEO+ system described here.

Table 3.6 Ground data system operational scenarios.

FIRST 6 MONTHS	
14 days	Checkout
36 days	ScanSAR Global
36 days	ScanSAR Extended Beams Global
48 days	High-resolution (Strip) Targeted areas
48 days	High-resolution (Strip) Extended Beam Targeted Areas
Total 182 days	

RECURRING 6 MONTH SCENARIO	
36 days	ScanSAR Global
144 days	High-resolution (Strip) Target Areas

Mission Cost

The total mission cost for the LEO+ system is in the range of $400–500 million. The JPL Project Design Center (PDC), also known as Team X, which is a concurrent engineering process for proposal development and mission definition, developed the spacecraft and mission costs. The Team X subsystem engineers used grass-roots estimates and parametric models to estimate the costs. The basis of the L-band SAR instrument is a grass-roots estimate developed by experts from the JPL Radar Science and Engineering Section. The following assumptions apply to the costs:

- All costs are in FY02 $M.
- The mission starts in September 2003. The mission launches in August 2006.
- Phase A is nine months, Phase B is 12 months, Phase C/D is 25 months, and Phase E is 60 months.
- This is a Class-B mission using commercial and military 883B parts.
- It will have full redundancy for a five-year mission duration.
- The spacecraft will be supplied by industry and built as a protoflight. The instrument will be built by JPL.
- Phase A, B, C, D, E will have 30% reserves. There is no reserve on the launch vehicle cost.

These cost study results should be considered a departure point for more in-depth study. By iterating the science requirements with the user community, and the mission design with mission architects, significant cost reductions may be available. Identifying descope options is an important first step in this process. Additional cost savings, as well as additional mission value, should be explored through partnerships with other government agencies (such as NPOESS, DoD) and international programs, including ground stations and flight elements.

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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