

## AN L-BAND SAR FOR REPEAT PASS DEFORMATION MEASUREMENTS ON A UAV PLATFORM

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### ABSTRACT

We are proposing to develop a miniaturized polarimetric L-band synthetic aperture radar (SAR) for repeat-pass differential interferometric measurements of deformation for rapidly deforming surfaces of geophysical interest such as volcanoes or earthquakes that is to be flown on a unmanned aerial vehicle (UAV) or minimally piloted vehicle (MPV). Upon surveying the capabilities and availabilities of such aircraft, the Proteus aircraft and the ALTAIR UAV appear to meet our criteria in terms of payload capabilities, flying altitude, and endurance. To support the repeat pass deformation capability it is necessary to control flight track capability of the aircraft to be within a specified 10 m tube with a goal of 1 m. This requires real-time GPS control of the autopilot to achieve these objectives that has not been demonstrated on these aircraft. Based on the Proteus and ALTAIR's altitude of 13.7 km (45,000 ft), we are designing a fully polarimetric L-band radar with 80 MHz bandwidth and a 16 km range swath. The radar will have an active electronic beam steering antenna to achieve a Doppler centroid stability that is necessary for repeat-pass interferometry. This paper presents some of the trade studies for the platform, instrument and the expected science.

### INTRODUCTION

The solid earth science community is seeking earth deformation measurements at a variety of scales, from seconds to decades. The NASA Solid Earth Science Working Group has recommended an observational program that includes both airborne and spaceborne capabilities and this is reflected in the NASA Earth

Science Enterprise strategic plan<sup>‡</sup>. Ultimately, scientists would like to have earth deformation measurements on an hourly basis with global access, objectives best supported by a spaceborne high-orbit (e.g. geosynchronous) constellation of repeat-pass interferometric SAR satellites. The recommended first step in this observational program is a low-earth-orbit deformation satellite with a repeat period of roughly one week. The sub-orbital radar program enters the Earth Science Enterprise plan as a key supplemental capability, providing repeat-pass measurements at time scales much smaller than one week, potentially as short as twenty minutes.

Understanding the time varying nature of rapidly deforming features such as some volcanoes and glaciers or deformation from post seismic transients requires observational sampling intervals of a day or less to capture and model such events. In addition to providing unprecedented temporal detail of deformation of dynamic processes, the suborbital radar will be a testbed for understanding the observational needs for how rapid repeat observations would be acquired. This is a capability that the currently operational NASA AIRSAR system has demonstrated but cannot practically support for science experiments in its current configuration due to lack of track repeatability and beam pointing limitations.

A proposal was submitted to the NASA 2002 Instrument Incubator Program (IIP) to develop a repeat pass measurement capability as an augmentation to the existing AIRSAR system. NASA accepted the proposal but directed that the proposed capability be fielded on a UAV or MPV platform to support the long term interests of the airborne science community and that the first year effort be devoted to developing a radar system design and implementation plan.

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Nominally when designing a new sensor system, an “optimal” design based on observation objectives is generated subject to various constraints imposed by physics, engineering or costs. The design of this system is not well constrained at this point since actual availability and capability of the platform(s) on which the system may be hosted are still unresolved and the full range of science applications that must be supported by the sensor is still being decided. Thus it is not possible at this point to prescribe a well defined optimality metric from which an optimal design would result. This paper presents an interim design for the sensor based on expected platform availability and capability as discussed in the first section with inherent flexibility to accommodate a range of applications as envisioned by a panel of scientists convened by NASA to set priorities.

### **PLATFORM SELECTION**

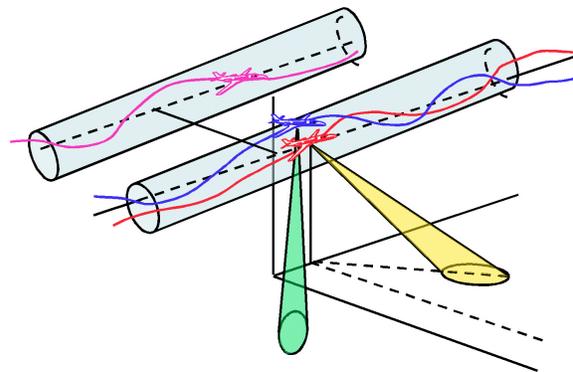
Reliable collection and processing of airborne repeat pass radar interferometric data for deformation measurements imposes additional platform and radar instrument constraints on a UAV platform not normally required by standard SAR imaging systems. The platform needs to fly within a 10 m diameter tube (with a 1 m goal). This provides a small repeat-pass baseline desired for deformation measurements as well as an ability to fly the same path multiple times with multiple time scales for reliable acquisition of the desired science data. Flying trajectories this accurately requires real-time platform position knowledge with sub-meter accuracy. Such position accuracy is possible based on previously developed real-time GPS platform position determination capability (20-50 cm) that then must be interfaced with the platform flight management system (FMS). The radar modifications required to support repeat-pass deformation measurements include:

- Radar should support electronic steering of antenna beam with 1° accuracy over a range of  $\pm 15^\circ$  in azimuth so that the repeat pass pointing requirements can be achieved for a wide variety of wind conditions aloft.
- Electronic steering of antenna must be linked to the inertial navigation unit (INU) attitude measurements with an update rate capability of less than one second.
- L-band is required to maintain interferometric coherence over large repeat time observation intervals and coupled with maximal allowed bandwidth of 80 MHz have the largest possible critical baseline.

Figure 2 illustrates the desired flight track and radar electronic pointing capability desired for airborne repeat pass observations.

One of the main tasks for fielding the new system is selection of a platform from the currently operational UAV or minimally piloted vehicles (MPV) that meet the following requirements.

- Operate in a variety of weather conditions
- Operate from conventional airports
- Operate above 12,000 meters to avoid commercial traffic and reduce turbulence
- Maintain a flight path with positional accuracy of  $\pm 5$  meters
- Has a minimum range of 2000 nautical miles
- Has a minimum payload capacity of 300 kilograms
- Has a minimum payload volume of 1 cubic meter
- Has a minimum 2,000 watts of DC power available for the payload
- Support over-the-horizon up/downlink
- Able to mount an external, side-looking, active array antenna (0.5m by 2.0m) without obstruction



**Figure 1.** To support efficient collection of repeat pass radar interferometry data the platform must be able to fly the same trajectory within a specified tube illustrated above in the tube with the red and blue aircraft. Since the yaw or crab angle of the aircraft can change between repeat pass lines the radar will use an electronically scanned antenna to compensate for the different aircraft yaw angles between passes. Additional science such as very high resolution topographic mapping or tomographic imaging studies may also be supported by flying well defined baselines illustrated by the magenta aircraft flying on a trajectory displaced by a fixed amount from some reference trajectory.

Studies during the next year supporting platform selection and radar design are briefly described below.

The first step in selection of a suitable platform was a survey of the available UAV platforms and their capabilities. This survey determined the target UAV platforms to be used for the design and cost estimate of the L-band radar system.

Survey of UAV Capabilities

Identified in Table 1 are the potential UAV platforms and their characteristics that are currently available to both civilian and military government agencies. In this table, we have used a subset of the UAV requirements specified in the previous section to narrow down the choices of UAV platforms. The criteria we used were the loiter altitude, the true air speed, the range, and the payload weight.

As indicated by asterisks next to the platform name in Table 1, there are 3 platforms suitable for L-band repeat-pass interferometry: the Global Hawk, the Altair, and the Proteus UAV shown in Figure 2. The Global Hawk UAV is developed to provide intelligence, surveillance, and reconnaissance (ISR) capability in support of the joint combatant forces worldwide during peace, crisis, and wartime operations. The \$35+ million UAV is still in the checkout phase and is not likely to become available for scientific experiments in the near future. NASA’s Environmental Research Aircraft and Sensor Technology (ERAST) program has conducted some flight tests with both the Proteus UAV and the Predator-B UAV. Between the two UAVs, the Proteus is the larger and more capable platform. However, the Proteus currently requires a two-person crew for landing and takeoff. In addition, there is only one Proteus aircraft available for scientific experiments. Experiments are conducted on a first-come first-serve basis. NASA or other government agencies fund most of the payloads. The availability of the aircraft for radar experiments will probably be limited. On the other hand, NASA signed a contract with General Atomics in early 2000 for the development of two enhanced Predator-B UAVs (ALTAIR) to perform high altitude Earth science missions. Flight tests for the ALTAIR UAV began in Spring 2003. The ALTAIR is based on General Atomics Aeronautical Systems, Inc.’s (GA-ASI) family of UAVs with over 35,000 flight hours in deployments for scientific, military, and civil applications. Hence, the availability and reliability of the ALTAIR is likely to be higher than the Proteus aircraft.

**Table 1.** Platform Candidates

Platform	Alt (m)	Spd (kts)	L (m)	Wings (m)	Rng (nmi)	Payload weight (kg)
Global Hawk*	19,800	400	13.4	35.36	9,000 30 hrs	900
Predator-A	7,620	> 70	8.23	14.84	400	204
ALTAIR*	13,700	220	8.23	14.84	32 hrs	340
Altus I	13,700	70	6.71	16.76	24 hrs	150
Altus II	19,800	70	6.71	16.76	24 hrs	150
Proteus*	19,800	450	17.2	23.6	9,000 24 hrs	900
DC-8*	12000	400	47.8	45.1	5400 12 hrs	•

In light of the NASA requirement to replace the NASA DC-8 and ER-2s with UAVs and the Proteus aircraft to support Earth Science missions, we need to design a radar system that is capable of data acquisition on both the ALTAIR UAV and the Proteus aircraft with minimal modifications. This will provide more flexibility for scheduling imaging radar missions.



**ALTAIR UAV:** Enhanced Predator-B produced by General Atomics Aeronautical Systems, Inc. for NASA



**Global Hawk UAV:** Produced by Northrop Grumman Corporation for DARPA, DARO, and USAF



**Proteus Aircraft:** Operated by Scaled Composites in Mojave. One-of-a-kind platform

**Figure 2.** Three aircraft platforms are currently being considered to host the UAVSAR radar. Global Hawk and Altair are UAVs while Proteus is a MPV.

An important aspect of repeat pass interferometry is the ability to control the flight track. Studies will

determine the ability of each platform to fly within the required tube of 10 m (and desired tube of 1 m). These studies will evaluate the intrinsic performance of each platform as is, i.e. without modification to FMS, and the ability of a pilot to fly the Proteus aircraft (piloted) along desired flight tracks with an on-course indication display in the cockpit. Trying to maintain an aircraft flight track within a narrow tube has proven to be very taxing on the pilots and typically cannot be maintained for long duration missions, but it may be more achievable in the Proteus at the prescribed altitudes. Determination of the software and/or hardware modifications and cost that would be required to the FMS, including modifications to support data ingestion of real-time GPS-determined state vectors into the FMS are key components of the platform selection process.

#### The “Enhanced” Predator-B Aircraft: The ALTAIR

The ALTAIR is a derivative of the fully operational Predator UAV and is developed specifically for scientific and commercial applications that require large payload capacities with operations to 15,850 m (52,000 ft). The jet-powered turboprop ALTAIR can remain airborne for 32 hours. Equipped with fault-tolerant avionics, the ALTAIR is an extremely reliable and stable platform to meet a variety of mission scenarios. The ALTAIR is being developed at GA-ASI’s flight operations facility in El Mirage, California adjacent to Edwards Air Force Base, under the supervision of NASA Dryden’s ERAST UAV program. From the ALTAIR Experimenter’s Handbook we found much of the information needed for initial design of a L-band radar.

The ALTAIR aircraft specifications are:

- 1) Wingspan: 26.2 m (86 ft)
- 2) Length: 11.0 m (36.2 ft)
- 3) Height: 3.6 m (11.8 ft)
- 4) Maximum payload: 300 kg (660 lb)
- 5) Maximum altitude: 15,850 m (52,000 ft)
- 6) Air speed: 60 – 200 knots
- 7) Endurance: 32 hours above 12,192 m
- 8) Maximum ferry range: 5170 nm
- 9) Power: 9 kW main, 4.5 kW backup (The UAV requires 2 kW)
- 10) Payload bay size: 46 ft<sup>3</sup>
- 11) Safety: triple redundant control module, dual flight controls, dual electrical power systems, Traffic Avoidance and Collision Alert System (TCAS), ATC voice relay, mode 3C transponder, NASA approved flight termination system (FTS).

- 12) Navigation: remotely-piloted or fully-autonomous with three integrated INU and three Differential GPS units (optional P-code GPS)
- 13) Data link: C-band line-of-sight, Ku-band SATCOM over-the-horizon, or airborne relay.
- 14) Shipping size: fits inside a C-130 aircraft (64”W x 437” L x 78” H)
- 15) Payload bay is not pressurized.

#### ALTAIR Flight Path Stability

In discussions with the GA-ASI engineers, we determined that a flying altitude of 13.7 km (45,000 ft) is nicely suitable for repeat-pass interferometry because flying at this altitude will allow us to reduce the air turbulence and eliminate conflicts with commercial air traffic. For repeat-pass interferometry, we require the platform to be capable of maintaining a flight path within 10 m tube in the worst case, and preferably within a 1 m tube to minimize the affect of topography on the deformation signature, avoid excessive geometric and volumetric decorrelation and generate a consistent quality deformation signal over regional areas to be mapped. The ability to control the flight path of an aircraft depends on the dead-band of the control surfaces used to maneuver the aircraft and is directly proportional to the servo gain of the control surfaces. Typically, the aircraft will use low servo gain while cruising and high servo gain for auto-landing to have tight control of the flight path for a smooth landing. According to GA-ASI, at 13.7 km (45,000 ft) altitude, the ALTAIR UAV can maintain a path within a 30 ft (9 m) tube plus GPS-induced error with low servo gain. If high servo gain is used, this tube can be reduced to 5 ft (1.5 m). The ALTAIR is equipped with three Novatel Differential GPS receiver, which provide 1 m vertical accuracy directly or 20 cm vertical accuracy with the aid of ground reference stations (RG-20). Alternately, JPL’s real-time Gypsy DGPS software is capable of delivering position measurements with better than 10 cm accuracy with satellite broadcasted corrections.

We have discussed a plan to assess the ALTAIR’s flight path accuracy with GA-ASI, and this involves:

- 1) Performing an upgrade to the ALTAIR’s differential GPS to receive RG-20.
- 2) Flight test the track position in differential GPS mode with regular servo gain at 13.7 km (45,000 ft).
- 3) Repeat flight test with high servo gain.

### ALTAIR Antenna Location(s) and Baselines

The antenna size of the L-band radar will be 1.6 m in length (i.e. in the fuselage direction) by 0.5 m in the vertical direction. We can mount the antenna(s) flush on the side of the aircraft or at the hard points underneath the wings. The hard points underneath the wings are located 144" (3.7 m) apart, which provides sufficient baseline for single-pass cross-track interferometry (XTI). The length of the UAV provides a 3 to 4 m baseline for L-band along-track interferometry (ATI) depending on the antenna length.

### ALTAIR Operational Scenario

The ALTAIR may be remotely-piloted or fully-autonomous. Remote operation is facilitated in the Ground Control Station (GCS) via line-of-sight communication (C-band) within 125 nautical miles, satellite communication (Ku-band), or airborne relay. The GCS incorporates a trailer that houses pilot workstations, payload workstations, and administrative support equipment. The ground crew consists of 7 people for an 8-hour flight (2 pilots, 2 mechanics, 1 engineer, 1 team lead, and 1 technician). Permission over air space is granted on a case-by-case basis by the FAA and this process typically takes 60 days.

### The Proteus Aircraft

The Proteus aircraft is a very lightweight (6000 lb without payload and fuel) experimental aircraft that requires two pilots (or one pilot and a mission specialist) to operate. The aircraft could become a UAV if more funding is available for further development. Because it is a manned aircraft, the Proteus is certified by the FAA to take off and land at any airport equipped with a 6000-ft runway. However, it does require a large hangar for storage because the lightweight aircraft can be easily damaged by strong winds or heavy storms. The Proteus can fly in most weather conditions that a typical aircraft flies except for icing on the wings.

The Proteus aircraft is an unusual looking aircraft with a canard configuration and a pair of vertical tailplanes mounted on booms extending back from the rear wing (see Figure 2). The Proteus aircraft specifications are:

- 1) Aft wingspan: 23.6 m (77.6 ft)
- 2) Canard span: 16.7 m (54.7 ft)
- 3) Length: 17.2 m (56.3 ft)
- 4) Height: 5.4 m (17.6 ft)
- 5) Maximum payload: 900 kg

- 6) Maximum altitude: 18,593 m (61,000 ft)
- 7) Air speed: 220 knots at 13.7 km (45,000 ft)
- 8) Endurance: 8 to 10 hours (pilot restriction)
- 9) Maximum ferry range: > 2000 nmiles
- 10) Payload power: 11.2 kW (28 V-dc)
- 11) Payload size: limited by the pod size, which can be as big as 10 m x 1.2 m x 1.2 m
- 12) Navigation: Garmin GPS receiver and Boeing's GPS stabilized INU with a 1 Hz update rate (attitude is updated at 10 Hz).
- 13) SATCOM link: via INMARSAT (2400 baud); via Iridium (9600 baud).
- 14) Standard payload pod is not pressurized. Pressurized pod would double the pod cost.

### Proteus Flight Path Stability

At a flying altitude of 13.7 km (45,000 ft), the Proteus aircraft is flown manually by the pilot. The ability to stay within a 5 – 10 m tube at this altitude is heavily dependent upon the accuracy of the real-time DGPS (which the Proteus currently does not have) and the skills of the pilot. In order to reliably fly within a 5 –10 m tube, and preferably within a 1 m tube for reasons discussed above, we would have to install a real-time DGPS receiver on-board the Proteus with real-time feedback to the pilot, and most likely also a new flight management system and/or avionics to allow the Proteus to be flown by auto-pilot at 13.7 km altitude. This is an issue that requires resolution before we proceed to design a radar system for the Proteus platform.

We are currently proceeding with a plan to conduct an experiment in conjunction with Scaled Composites and NASA Dryden Research Center to do the following:

- 1) Provide flight profiles (position and attitude) flying straight lines at 13.7 km to assess the stability of the flight path at altitude.
- 2) Install JPL's real-time DGPS receiver and software onboard the Proteus and develop a pilot's display to allow him to fly by the DGPS position and altitude.
- 3) If the flight path stability requirement cannot be met by (2), then investigate the avionics and/or flight management system needed to achieve the requirement.

### Proteus Antenna Location(s) and Baselines

The Proteus aircraft provides many options for mounting the L-band antenna(s). For a single-antenna system, the most obvious option is to mount the antenna

on the side of the payload pod. This will minimize power loss and integration time. For an along-track interferometry system, it is possible to mount two L-band antennas at either end of the 10-m long payload pod to achieve a 7 m physical baseline. Alternatively, the fuselage of the aircraft could provide about a 10 m physical baseline. For single-pass cross-track interferometry, the two antennas could be mounted on either tailplanes on the aft-wings to provide a physical baseline of about 7 m.

### Proteus Operational Scenario

The Proteus aircraft is operated by a pilot and a co-pilot who could provide minimal support to the payload, such as power cycling the instrument. Hence, radar operation has to be completely automated with self-diagnostic capabilities built into the system. A satellite link is available typically via INMARSAT with a low data rate of 2400 baud to provide limited communication with the radar instrument from the ground. On deployment, the Proteus aircraft crew consists of the two pilots and the crew chief (to service the aircraft). Permission to fly over air space is granted by the FAA similar to any manned aircraft, which is logistically easier than the Predator UAV and does not require the 60 day lead time allowing for rapid response to geophysical events of interest.

### RADAR SYSTEM

The proposed radar for the UAV platform is a miniaturized polarimetric L-band radar for repeat-pass and single-pass interferometry with options for along-track interferometry and additional frequencies of operation. The radar will be appropriate for use both with existing radar testbed platforms as well as for installation on an UAV. Such a system will demonstrate key measurements both to NASA including:

- Precision topography change for monitoring earthquakes both during and after a seismic event, for monitoring volcanic activity and for monitoring human-induced surface change such as subsidence induced by oil or water withdrawal, or other displacements of the surface from tunneling activities.
- Polarimetric interferometry, which can provide NASA with measurements of forest structure and sub-canopy topography.
- Polarimetric tomography, mapping in detail the vertical structure of a vegetated area.

- Along-track interferometry, which can be used to monitor surface currents in coastal regions as well as moving targets.

The philosophy of the radar design is as follows: the design should be modular, compact, light-weight, and adaptable to the UAV and other airborne platforms. The design should also be flexible so that this radar platform may serve as a testbed to demonstrate new radar technology and techniques.

Repeat-pass interferometry (RPI) for surface deformation requires precise knowledge of motion and location, stability of the baseline to within a 5 – 10 m tube, and stability of the attitude in order to have Doppler centroids from two data passes to agree to a fraction of a beamwidth for adequate coherence. Precise knowledge of motion and location is provided by the high precision INU and real-time differential GPS receivers. Doppler centroid stability can be achieved by along track electronic beam-steering up to  $\pm 15^\circ$  linked to the INU attitude angle measurements. This dictates the radar design to utilize an active array antenna with transmit/receive (T/R) modules and phase shifters with a beam steering angle resolution of better than  $1^\circ$ .

An important selection criterion for the platform is its suitability for hosting a L-band radar and possible future upgrades to the system. As this SAR will be operated on a UAV, there will be no radar operator. Based on a data file provided by flight planning software, the UAVSAR will automatically initiate data takes at the appropriate locations throughout the flight. This approach was implemented on GeoSAR (a radar interferometric mapping system designed and built by JPL and currently operated by Earthdata International which is hosted on a Gulfstream II aircraft) with good results. Because of the autonomous requirement, this instrument must include BIT (Built In Test) capability and be able to determine failure at the unit level. A modular approach to delineation of logic functions in the instrument will assist in the addition of potential options in the future. Because the instrument is designed for modularity, reconfiguration for the addition of potential options or installation on a different platform should be feasible. The goal is to be able to fly on either an ALTAIR or a Proteus aircraft.

Based on the Proteus and ALTAIR's altitude of 13.7 km (45,000 ft), we designed a fully polarimetric L-band radar with 80 MHz bandwidth and 16 km range swath. This radar has an active electronic beam steering

antenna to achieve Doppler centroid stability that is necessary for repeat-pass interferometry.

In the following sections, we will outline the radar design for the L-band polarimetric RPI radar and its expected performance. We will also describe the hardware configuration and potential opportunities for technology demonstration. We will then discuss two add-on options: the L-band cross-track or along-track interferometer and a high frequency (C, X, or Ku)-band polarimetric and cross-track interferometric radar.

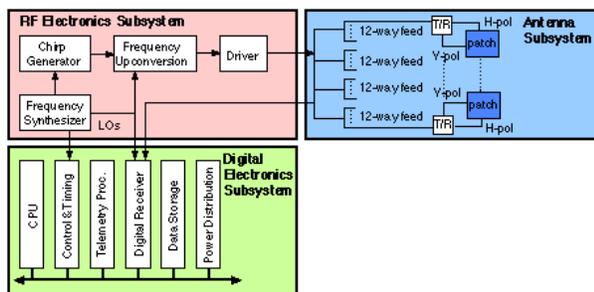
### Instrument Overview

Based on the science objectives and UAV platform characteristics, the key parameters of the radar design include:

Frequency:	1.26 GHz (0.2379 m)
Bandwidth:	80 MHz
Pulse duration:	40 $\mu$ sec
Polarization:	Fully polarimetric
Interferometry:	Repeat-Pass
Range swath:	16 km
Look angle:	30° - 60°
Transmitter:	2.0 kW peak power
Antenna size:	0.5 m x 1.6 m with electronic beam steering capability
PRF:	1600 Hz (interleaving H and V transmit polarizations)
Altitude:	13.7 km
Ground speed:	100 m/s

### Hardware Configuration

The radar instrument is made up of three major subsystems: the RF electronics subsystem (RFES), the digital electronics subsystem (DES) and the antenna subsystem. Figure 3 is a simplified instrument block diagram of the L-band radar.



**Figure 3.** Simplified instrument block diagram of the L-band Repeat-Pass Interferometer.

The RFES performs the transmit chirp generation, frequency up-conversion, filtering, and amplification during signal transmission. The RFES also controls the routing of the radar signal and the calibration signal.

The DES performs overall control and timing for the radar, frequency down-converts and digitizes the received echo, and routes the data to on-board data storage. The dual-channel digital receiver employs two high-speed analog-to-digital converters (ADCs) capable of handling L-band signals to perform sub-harmonic sampling of the radar echoes. Filtering is performed by the digital filters implemented on field-programmable gate arrays (FPGAs). This approach saves cost, mass, and power while provides tremendous flexibility in the frequency selection of the digital filters. The sub-harmonic sampling technique is frequently used in the communication industry at lower frequencies. The recent availability of high-speed ADCs capable of handling L-band signals makes this technique feasible for radar applications, but has not yet been demonstrated with SAR systems.

The antenna subsystem performs beam steering, transmission, and high power amplification on transmit and low noise amplification on receive. The antenna is a dual-polarization corporate-fed planar phased-array with 4 x 12 T/R modules and phase shifters for electronic beam steering from radar pulse to pulse. The peak transmit power for each T/R module is 40 W and the combined power of the 48 T/R modules is approximately 2.0 kW. Typical efficiency for L-band solid state amplifiers (SSPAs) is 40 %. On the transmit end, there will be a polarization switch to direct the transmit signal to either the H or V-polarization feed of the antenna element. On the receive end, each T/R module will have two receiver front-ends (pre-select filter, high power limiter, and low-noise amplifier) to accommodate radar echoes from both the H and V-polarizations.

### Estimate of Power, Weight, Volume

The estimated D.C. power for the L-band polarimetric RPI is just under 1 kW when the radar is transmitting. This is well within the capacity of the ALTAIR UAV or the Proteus aircraft. The standby D.C. power should be on the order of 150 W. The active array antenna should weigh less than 80 kg since each T/R module weighs about 0.5 kg. The remainder of the radar electronics in the payload bay should weigh less than 100 kg (approximately 20 kg for the RFES, 30 kg for the DES, and 30 kg for cabling, power distribution, etc.).

## Radar Upgrade Options

We have assessed the possibility of adding L-band along-track or cross-track interferometry on both the Proteus and ALTAIR platforms. The performance and cost of the L-band interferometry options are heavily dependent on the placement of the second antenna on the aircraft. Other hardware changes for interferometry would be the addition of some extra switches in the switching network, and the necessary timing signals for controlling these switches. Further study is needed to determine these parameters.

### L-band Cross-Track Interferometry Option

L-band cross-track interferometry may be achieved by placing two antennas at the hard points underneath the wings of the ALTAIR, which are 3.7 m apart. The expected height accuracy should be better than 3 m, which is a significant improvement from the AIRSAR's L-band interferometer height accuracy of 5 to 10 m. For the Proteus aircraft, the two antennas could be mounted on either tailplanes on the aft-wings to provide a physical baseline of about 7 m to achieve a height accuracy of about 1 m. Polarimetric XTI may be achieved if both the antennas are dual-polarized and H & V polarized pulses are transmitted in an interleaving manner.

### L-band Along-Track Interferometry Option

L-band along-track interferometry may be achieved by placing two antennas at the front end and tail end of the platform respectively. For the ALTAIR, the maximum physical baseline is 3 to 4 m depending on the length of the antenna. This is significantly shorter than the AIRSAR's physical baseline of 20 m and is not likely to be a viable mode for this platform. For the Proteus aircraft, the physical baseline is 7 to 10 m depending on whether we mount the antenna pairs on the payload pod or the fuselage of the aircraft. This antenna separation should be viable for L-band ATI.

Addition of a second frequency radar would be more involved than the addition of an interferometric capability. For the second frequency radar, it would be necessary to add: An additional Up-Converter unit, an additional Switching Network, an additional antenna panel, a pair of additional receivers for down-conversion and a pair of additional digital channels to the digital system. This option could be implemented in the Proteus aircraft without modifying the anticipated mechanical packaging approach. In order to implement

this option in the Predator-B aircraft, it is quite possible that a more efficient mechanical packaging approach would need to be pursued.

### High Frequency Cross-Track Interferometry Option

High frequency XTI and polarimetric capability are key components of the hydrology discipline, which could be used to measure snow wetness, river level changes, etc and cold land processes, which could be used for ice thickness and ice age determination. This capability would require a pair of antennas, a pair of receiver front-ends to down-convert the signal to an L-band signal, an additional pair of L-band digital receivers, an additional chirp generator card with frequency up-conversion to the desired frequency, and added on-board data storage.

### Technology Demonstration

As a radar technology test-bed for NASA ESE, the implementation of this new system presents several opportunities for technology demonstration. For example, to our knowledge, the sub-harmonic sampling digital receiver has never been implemented for radar applications before. It is also conceivable to integrate the digital receiver with the back-end of each T/R module element, thus distributing the receiver function among the T/R modules to reduce transmission loss while increasing redundancy and flexibility of the system. Furthermore, it is also conceivable to replace the bulky cable harness between the antenna subsystem and the data storage subsystem in the payload bay with light-weight fiber-optic cables. Both of these two concepts have tremendous advantages for space-borne radar systems.

### Performance Estimation

Detailed radar design trade-offs were performed using JPL's System Performance Analysis Tool Design System (SPAT). The key parameters of the radar design are summarized in Table 2. The antenna size was traded-off against T/R module power to satisfy the sensitivity requirement of the radar. The range swath of 16 km was selected based on the 3-dB beamwidth of the raised-cosine weighted range antenna pattern, the data rate, and system performance.

**Table 2.** Parameters for the L-band Radar System

Altitude	13.7 km	Platform Velocity	100 m/s
Frequency	1260 MHz	Wavelength	23.79 cm
Elevation boresight	48 deg	Azimuth Boresight	0 deg
Bandwidth	80 MHz	Clock Rate	180 MHz
PRF	1600 Hz	Inter-Pulse Period	625 $\mu$ s
Beam-limited Swath	16.9 km	Swath Width	16 km
Near Range Look Angle	30 deg	Far Range Look Angle	60 deg
Pulse Duration	40 $\mu$ s	Available Data window	585 $\mu$ s
Noise Temperature	600 K	System Losses on Receive	-6 dB
Total T/R Module Peak Power	2 kW	System Losses on Transmit	-7 dB
Average Radiated Power	24 W	Duty Cycle	6.4 %

Detailed description of selected parameters follows:

Noise temperature – receiver noise temperature including the front-end pre-select filter, the high-power limiter, and the LNA.

System losses on receive – includes receive antenna inefficiency and receive path loss from the antenna to the receiver.

Total T/R module peak power – total peak RF power of the T/R modules before efficiency is taken into account.

System losses on transmit – includes T/R module inefficiency, transmit path loss, and transmit antenna inefficiency.

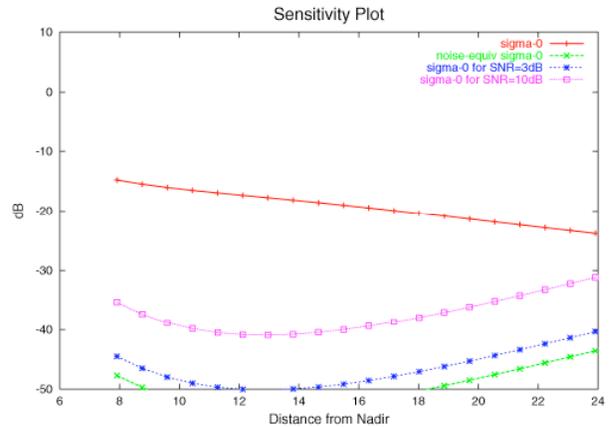
Average radiated power – (T/R module peak power + system losses on transmit) \* duty cycle

A summary of the performance parameters across the data swath is shown in Table 3. There are no significant range and azimuth ambiguities. The relatively low data rate of 136.4 Mbps can be easily handled by a RAID system with a tape backup or DVD-RAM archiving system. The total data volume for an 8-hour flight is expected to be less than 350 GB. The power consumption is well within the capacity of the ALTAIR UAV or the Proteus aircraft.

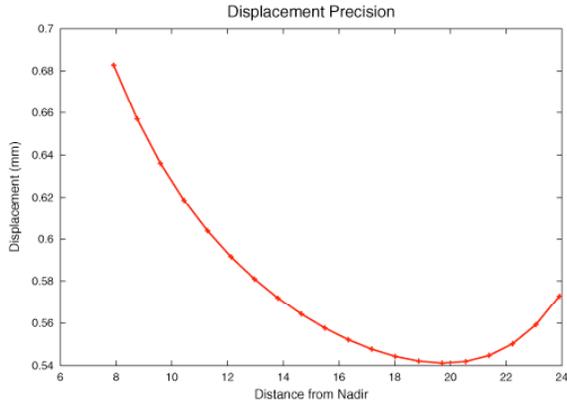
**Table 3.** Radar Performance Parameters

Performance Parameter	Value
Maximum Displacement Error	0.2671 mm
Maximum Noise Equivalent $\sigma_0$	-40.53 dB
Minimum SNR	11.84 dB
Maximum Range Ambiguity	-71.32 dB
Worst Cross-Track Resolution (1-look)	4.487 m
Along-Track Resolution (1-look)	0.7796 m
Data Rate	136.4 Mbps

Figure 4 is a sensitivity plot showing the  $\sigma_0$  for various Signal-to-Noise ratios. The green curve in the plot shows the estimated noise-equivalent  $\sigma_0$  of the system as a function of range in swath. The red line shows the theoretical  $\sigma_0$  of soil as a function of range swath. The estimated SNR varies from over 25 dB in near range to about 15 dB in far range. Figure 5 shows the estimated displacement error as a function of range swath with repeat-pass interferometry for change detection. The plot shows that the displacement error is worst at near range at just under 0.3 mm. The displacement error is dominated by system noise (thermal and quantization); other sources of error such as volumetric decorrelation due to vegetation cover do not seem to have a significant effect on the precision of the displacement measurement.



**Figure 4.** Sensitivity plot showing  $\sigma_0$  for soil (red curve). The green curve is the noise-equivalent  $\sigma_0$  of the system. SNR is the difference between these curves. The other two curves show the minimum  $\sigma_0$  to achieve SNRs of 3 dB and 10 dB.



**Figure 5.** Plot of the displacement error as a function of range using the L-band radar for repeat-pass interferometry for change-detection.

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