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). With our proposed mechanical design approach for the radar electronics, the instrument can potentially be accommodated on a number of different applicable platforms. Upon surveying the capabilities and availabilities of UAVs and MPVs, the ALTAIR UAV and the Proteus aircraft 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 the radar configuration along with some of the trade studies for the platform and instrument.

I. 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[‡]. 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.

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.

II. 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 ±15° 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.

Fig. 1 illustrates the desired flight track and radar electronic pointing capability desired for airborne repeat pass observations.

‡ http://www.earth.nasa.gov/visions/stratplan/index.html

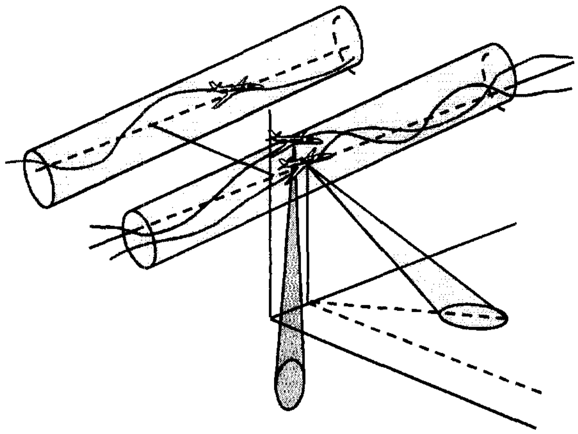


Fig. 1. To support efficient collection of repeat pass radar interferometry data the platform must be able to fly the same trajectory within a specified tube illustrated above in the tube with the red and blue aircraft. Since the yaw or crab angle of the aircraft can change between repeat pass lines 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 tomograhic 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.

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 ±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

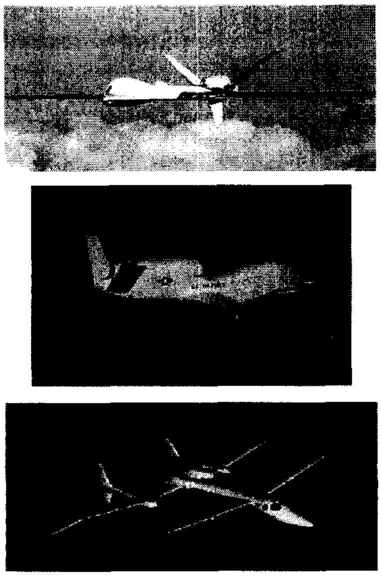
A. Survey of UAV Capabilities

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 Fig. 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. The manufacturer of the Proteus, Scaled Composites in Mojave, CA estimated that the construction of a new Proteus would cost between $10-$12 million. On the other hand, NASA signed a $10 million 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.

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.

Table 1. Platform Candidates

Plat-form	Alt (m)	Spd (kts)	L (m)	Wings (m)	Rng (nmi)	Pay-load 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
[redacted]						
Altus I	13,700	70	6.71	16.76	24 hrs	150
Altus II	19,800	70	6.71	16.76	24 hrs	150
[redacted]						



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

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

III. RADAR SYSTEM

The proposed radar for the UAV platform is a miniaturized polarimetric L-band radar for repeat-pass interferometry with options for single-pass 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 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.

Based on the science objectives and UAV platform characteristics, 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.

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 ±15° 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°.

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	Sample Rate	180 MHz
PRF	350 Hz	Inter-Pulse Period	2.857 ms
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 μs	Available Data window	2.817 ms
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	5.6 W	Duty Cycle	1.4 %

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

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. We will also describe the hardware configuration and 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.

A. 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 msec
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:	350 Hz (interleaving H and V transmit polarizations)
Altitude:	13.7 km
Ground speed:	100 m/s

B. 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.

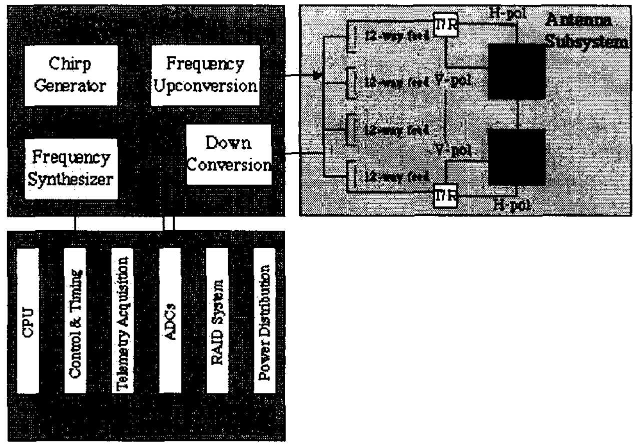


Figure 3. Simplified instrument block diagram of the L-band Repeat-Pass Interferometer.

The RFES generates the system clock and necessary local oscillator frequencies for the instrument, and performs the transmit chirp generation, frequency up-conversion, filtering, and amplification during signal transmission. The RFES also controls the routing, down-conversion, and filtering of the radar return signal and the calibration signal.

Using signals phased locked to the system clock, the DES performs overall control and timing for the radar. This includes the autonomous instrument control based on the flight plan. The DES digitizes the received echo, generates packets with this data and telemetry acquired from throughout the instrument, and routes the packets to on-board data storage.

The antenna subsystem performs beam steering, 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.

C. Estimate of Power, Weight, Volume

The estimated D.C. power for the L-band polarimetric RPI is just over 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 40 kg. The remainder of the radar electronics in the payload bay should weigh less than 175 kg (approximately 20 kg for the RFES, 65 kg for the DES, and 90 kg for cabling, power distribution, INU, GPS, etc.).

D. 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.

E. 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.

F. 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.

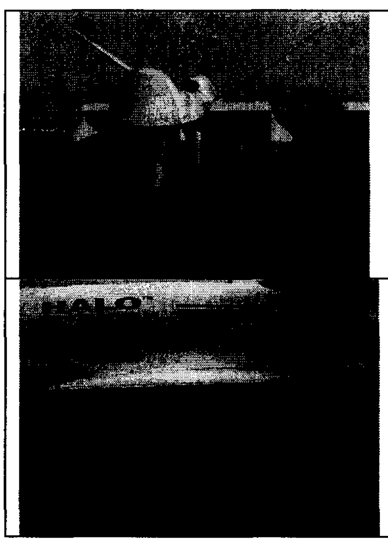
G. High Frequency Cross-Track Interferometry Option

High frequency XTI and polarimatric 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.

IV. MECHANICAL CONFIGURATION

The requirements for reconfiguration to support the addition of potential options or operation on a number of different platforms dictate that the UAVSAR mechanical design provide the necessary flexibility. In discussions with engineers from General Atomics and Scaled Composites, we learned of the different equipment pods that had been designed and manufactured for the Altair and the Proteus with the purpose of hosting instruments such as UAVSAR. Fig. 4 shows both the Altair and the Proteus with their associated equipment pods mounted.

The physical dimensions of the pod for each aircraft are quite different. The pod for the Proteus provides a useable are that is basically a tube of 3.8 meters in length with a 1 meter diameter. The Altair pod is far less spacious, and provides for the electronics a useable rectangular area of 0.61 meter by 0.61 meter by 1.52 meter.



ALTAIR UAV:. Showing equipment pods located under the wings on either side of the fuselage for center of gravity purposes

Proteus Aircraft: Showing equipment pod under aircraft on the fuselage center line.

Fig. 4. Candidate Plaaatforms with Equipment Pods

Our baseline plan is to configure the UAVSAR electronics such that they can be mounted in the smaller of the two pods (i.e., the Altair pod), with the active array antenna mounted to the external skin of the pod for the repeat pass configuration. Mounting this pod under the wing of the Altair would be relatively straight forward, once design of the required cable harness through the wing mount points is defined. On the Proteus, this pod would be mounted under the aircraft on the center line of the fuselage for the repeat pass configuration. Since the mounting points on the Proteus will be different than those for the Altair, we anticipate the need to fabricate mechanical fixtures to adapt the Altair pod to the Proteus mounting points.

As an additional benefit, use of the smaller of the two pods should make it easier to mount the UAVSAR instrument to other potential aircraft that may become available in the future. We anticipate that this pod could be fitted for mounting on a number of different aircraft platforms, although the mechanical fixtures to adapt the Altair pod to the mounting points would most likely be unique for each different aircraft type.

V. HARDWARE MINIATURIZATION

Past airborne radar hardware development activity at JPL has typically involved multiple racks of equipment within the passenger cabin of the aircraft. Examples of these past activities are the initial development, upgrades, and maintenance of AIRSAR on the NASA DC-8 and the development of GeoSAR on the Earthdata International Gulfstream G-II. For these instruments, a significant portion of the available cabin area was reserved and actually necessary for the implementation of the radar electronics. As discussed in a previous section, the UAVSAR electronics is baselined to be contained in an equipment pod with usable area dimensions of 0.61 meter by 0.61 meter by 1.52 meter. In order to house the UAVSAR electronics within this area, the hardware implementation will need to be very different than that used for AIRSAR and GeoSAR. For reference, Fig. 5 shows a view of the GeoSAR equipment rack configuration within the cabin of the Gulfsteam G-II. Fig. 6 shows the baseline equipment layout of the UAVSAR electronics within the area available in the Altair equipment pod.

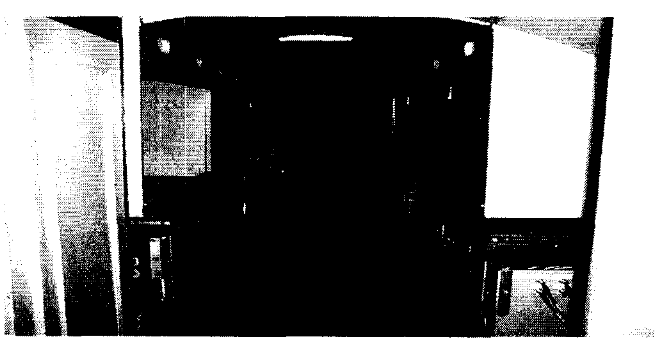


Fig. 5. GeoSAR Equipmnet Racks in the Gulfstream G-II

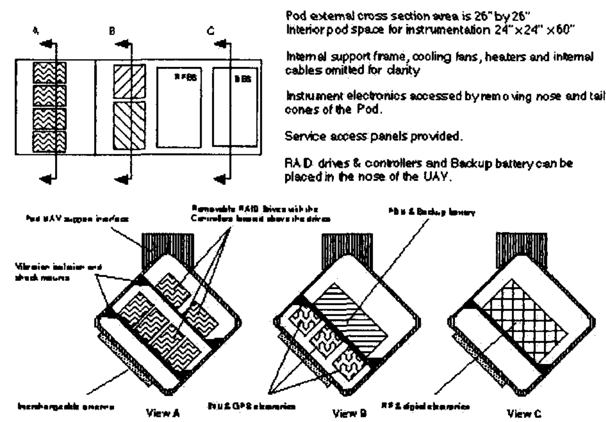


Fig. 6. Baseline Layout of Equipment in the Altair Pod

For some time now, most of the JPL radar digital electronics hardware has been implemented on custom designed VME cards housed within VME enclosures. It is only in the very recent past that we have implemented radar RF electronics hardware with this VME card approach. By using the VME based implementation of both the digital and RF radar electronics, we have generated equipment layout designs for the different UAVSAR options in the Altair equipment pod. As shown in Fig. 6, the complete DES will be housed in a single VME chassis enclosure, and the complete RFES will be contained in a separate VME chassis enclosure. With this approach there is adequate area remaining in the Altair pod to mount the power distribution electronics, battery backup system, removable RAIDs with their controllers, the INU and GPS receivers, and the instrument cable harness.

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