The Global Topography Mission (TOPSAT)

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ABSTRACT

An earth orbiting space mission concept has been developed to produce a high resolution, high accuracy, global topographic data set using the Interferometric Synthetic Aperture Radar technique. The goal for absolute vertical accuracy is 2 to 3 m with 30 m horizontal resolution. The mission architecture uses two identical spacecraft flying in formation with L-band radars. The radar covers a 35 km swath, allowing the entire globe between +70° and -70° latitude to be covered in less than 3 months. The area between 70° and 83° would be covered by a Multi-Beam Laser Altimeter with 0.2 m vertical accuracy and 30m horizontal resolution. The radar baseline must be known very accurately to achieve the topography measurement goals and this is accomplished by the use of simultaneous Global Positioning System position measurements on the two satellites.

INTRODUCTION

Precise global topographic data for the earth's land masses and glacial and polar ice have been in great demand by geological and environmental scientists and map makers. NASA published a report in 1988 which collected the requirements of scientific topographic data users, assessed the then-current state of global topographic data, assessed the state of technologies to acquire data and made recommendations for the collection of global topographic data (Topographic Science Working Group, 1988).

A low earth orbit mission concept (TOPSAT) has been developed which would use Interferometric Synthetic Aperture Radar (InSAR) and a Multibeam Laser Altimeter (MBLA) to produce this data faster, with greater absolute accuracy and at lower cost than previous approaches.

The topographic data produced by TOPSAT can be the foundation of EOS data analysis and the database for future maps. TOPSAT will define the baseline height for glaciers and polar ice. Changes in the ice levels measured in subsequent years will confirm or deny one impact of global warming.

The Global Topography Mission will determine the heights of the earth's land surface to an absolute accuracy of approximately 2 to 3 m with 30 m horizontal resolution. The heights of polar ice sheets will be determined to an accuracy of approximately 0.2 meter.

1. BACKGROUND

Global topographic mapping systems have been studied for many years. But due to the high cost, the lack of technical maturity, and the risks associated with the many explored concepts, a system has not been developed.

Recently, an InSAR method was proven to be an effective topographic instrument and JPL has verified that GPS precision orbit determination is capable of calculating the absolute position of a spacecraft to better than 10 cm. In examining the error sources of the GPS data, it was determined that the relative position of two closely separated spacecraft can be measured to better than 3 mm. These two developments opened the door to a low risk, low cost, global topographic mission. This concept has two identical and conventional satellites carrying conventional L-band radar instruments operating as an InSAR.

The InSAR technique (Zebker, 1986) achieves its accuracy by a precise knowledge of the length and orientation of the "baseline", the vector between the phase centers of the two radar antennas forming the interferometric pair. The accuracy of all methods of InSAR at whatever radar frequency is proportional to the accuracy of baseline knowledge. Baseline orientation knowledge on the order of 1 arc-sec is consistent with approximately 2 m absolute height measurement accuracy. Other measurement error sources are also important but baseline knowledge determination tends to be the discriminator among different InSAR methods. The attraction of the L-band-GPS approach is that, with the long wavelength of L-band, the allowable baseline is long enough that the 1 arc-sec angle measurement is converted into a relative position measurement of a magnitude that can be performed with GPS. For smaller wavelengths, the required baseline is smaller and the relative position measurement accuracy is too small for GPS.

2. GPS BASELINE DETERMINATION

The achievement of 3 mm relative position accuracy between the two spacecraft relies on the knowledge of error sources that was gained from the TOPEX GPS Precision Orbit Determination experiment. This flight experiment has demonstrated absolute position determination for the TOPEX spacecraft to several centimeters (Bertiger, W. I. et al., 1993). This error is made up of four principal contributions: a) receiver thermal noise, b) multipath, c) GPS orbit knowledge and d) ionosphere delay. Receiver thermal error for a device such as was used on TOPEX is expected to be approximately one-third mm.

Relative position knowledge is all that is necessary to determine the length and orientation of the InSAR baseline. Absolute position determination, at much lower accuracy, is required to locate the measurement on the earth. By requiring only relative knowledge between the two spacecraft, and by assuming two geometrically identical spacecraft 1 to 2 km apart, the contributions of the last three errors are reduced from the centimeter level for best absolute position knowledge to the millimeter level for relative position knowledge. As all these errors are random and independent their root sum square is representative of a total combined error on the order of 2 mm. Further analysis of each error source will be done to increase confidence and assess performance margin. A ground experiment with various baselines from several hundred meters to several kilometers will be done to further reduce the perceived risk in using this new technique.

3. POTENTIAL TOPSAT CONCEPTS

A number of different mission architectures were studied. Most of these concepts have been examined before, however, to insure that no obvious superior concept is ignored a mini-review of them was performed. This is summarized below. The criteria used in the selection process were; total program costs, technical risk, relative performance, and schedule.

Three different methods of obtaining the InSAR data were considered and they are:

1)Repeat Pass Satellite

This is the simplest concept, using a single spacecraft with a SAR antenna to map the earth. Then the satellite maps the earth again with the observation baseline separated by 600 to 200 meters (for L-band). This seems a straight forward method, however, because the data is taken at different times, there is a significant decorrelation due to changes in the terrain. A relatively small physical change such as movement (soil heaving, plant growth, movement due to wind, etc.), and change in radar reflectivity (moisture content, surface frost, etc.) can cause a major change in data correlation between satellite passes possibly making the data useless.

The other major problem with repeat pass lies in the knowledge of the baseline vector between the radar locations on the two passes. The knowledge of the baseline vector is limited by the method of precision orbit determination in each orbit. The GPS and DORIS precision orbit determination systems were used to locate the TOPEX satellite to less than 10 cm. Using such a system on each leg of the repeat pass would yield a baseline vector knowledge greater than 10 cm. This is 30 times the 3 mm relative knowledge required to approach 2 m absolute height accuracy. Thus the absolute height accuracy for repeat pass methods approaches 60 m even with the best methods of precision orbit determination. At the lower altitude of TOPSAT relative to TOPEX, the DORIS precision orbit determination would not be able to perform as well due to less station visibility. Precision orbit determination relying on satellite dynamic modelling would also be degraded due to high drag.

Relative height accuracy could be much better when there are locally known reference points (tie-points). Thus repeat pass interferometry is limited in usefulness to local studies.

2)Dual Antenna Satellite

The second concept under consideration uses a single satellite with dual antennas (one antenna transmitting and both receiving SAR data) to obtain the InSAR data. This concept needs to operate at a high frequency to keep the antenna separation small. This need for a high frequency results in a small radar footprint (for practical levels of spacecraft power and data rate) and a sensitivity to rain. At Ka-Band, the antennas are required to have a separation around 12 meters or more. For lower frequency radars, the separation increases in proportion to wavelength. The small footprint requires precise alignment and pointing in orbit since both antenna footprints must almost completely overlap. A map obtained by narrow swaths (using a small footprint in the cross track direction) requires many orbits resulting in a relatively long mission. Knowledge of the orientation of the baseline vector between the two antennas to 1 arc-sec would be a major technological challenge. Both rigid body rotation and structure distortion would have to be measured to less than 1 arc-sec. For longer wavelengths than Ka, the boom required to separate the two antennas becomes longer and problems with structural distortion and baseline knowledge more severe. The dual antenna mission could not be implemented until the technology for 1 arc-sec baseline attitude determination is demonstrated.

3)Twin Satellite System

The third concept would utilize a twin satellite system where two conventional spacecraft work together as an InSAR. Frequencies from L-band to C were studied and only in the L-band case is the baseline long enough to use the GPS baseline determination method. This concept has the advantage of using relatively low cost, low technical risk satellites while obtaining excellent height accuracy. It also is insensitive to weather, and has a relatively short mission duration achieved by a 35 km swath width. In this concept, one satellite would transmit a signal that is received by both satellites. The two satellites must remain in proximity to each other (less than 1100 meters in the lag (orbit) (direction) so that the radar beams can be overlapped while maintaining the radar footprint along the velocity vector normal. The relative station keeping between the two satellites must be maintained to +/-460 meters. This is accomplished by using two identical spacecraft (to keep the drag identical) and navigating using GPS data.

The twin L-band satellite system is the only one that can be accomplished in the near term for modest cost.

4. MULTI-BEAM LASER ALTIMETER

All of the mission concepts include a laser altimeter on each satellite.

The MBLA is appropriate to determine topography in areas of lower relief because it cannot obtain the spatial coverage of a SAR. It will be used to determine ice sheet topography at latitudes greater than ±70° where the baseline between the two satellites has become too small for L-band radar. It has a swath width of 150 m and so it cannot obtain a complete map except near the poles where the coverage is dense. Away from the poles the MBLA obtains a contiguous line of points for comparison with the InSAR data. The lines of laser data from successive orbits are about 32 km apart at the equator.

The 150 m swath is made up of five 30 m spots from five lasers. Topographic data is extracted from each of the five spots which are contiguous along track.

In addition to providing surface height from measurement of the time of flight of the laser pulse, analysis of the return pulse waveform can provide information on surface slope, surface roughness, vegetation height, and surface reflectance at 1.06μm. The surface slope and vegetation height information can be used to correct the radar data or provide the only data in high relief terrain where the radar measurement is limited. The reflectance measurement is used in surface composition studies. The use of the laser altimeter and radar in combination provide complementary, synergistic and independent data. Because they are independent, they provide the potential for efficient and automated verification of the global radar data set.

The TOPSET mission design was described by Vincent, 1993. It will be briefly summarized here.

5. ORBIT CHARACTERISTICS OF CONCEPTS

Both the dual antenna and twin satellite concepts use a sun synchronous orbit operating near the terminator. The twin satellites operate at an altitude of 565 km and inclination of 97.6 degrees while the single satellite with dual antennas operates at an altitude of 400 km and inclination of 97.6 degrees. The lower altitude is required by the single satellite with dual antennas to maintain adequate height resolution. The height resolution is a function of antenna spacing and radar power. Because of the narrow antenna spacing the power at the target must be higher, requiring a lower operating altitude.

6. THE DUAL SATELLITE MISSION

The satellites are injected together into the 565 km orbit. After the correct orbit has been attained, the satellites are separated by a 1.2 m/s maneuver into two different orbit planes and at slightly different altitudes (a few meters). A good understanding of the satellite's flight properties will first be determined when the satellites are at a large lag distance. The differential drag experienced by the two satellites will be measured. The satellites will then be brought together to their operational lag distance. After radar calibration, the mapping phase will begin. After about 84 days, a full global map is obtained providing a topographic map of the land masses between ±70° latitude. By launching at the proper time of the year into a "6 AM-PM" sun synchronous orbit, two global maps can be obtained before entering solar occultation. The baseline mission is defined as the completion of 60 days of in-orbit checkout followed by two complete 84 day surveys for a total mission duration of approximately 8 months.

The second survey will fill in any gaps in the first. Data would be taken only on the ascending pass in the first survey because of limitations of on-board storage and downlink data rate. In the second survey, data could be taken on the descending pass so that the ground would be seen from the opposite look angle. This would help to locate errors in the data that are caused by high surface slope.

The MBLA would be used over the poles and when the radar is not on.

7. ORBIT CONFIGURATION

A baseline distance (the distance between the two satellites measured perpendicular to the velocity vector) of 800 m to 2000 m is required for proper single pass interferometric results. Figure 1 shows that the two orbits are identical except for a 2020 meter difference in the locations of the node crossings giving a baseline separation of 2000 meters at the equator and 800 meters at 65° latitude. Because the ground tracks are denser at the higher latitudes, good results can be obtained up to about 70° latitude despite the short relative separation. Coverage between ±70° includes almost all the land areas of topographic interest. By increasing the equatorial separation to 6 km, higher latitudes (about 80 degrees) could be covered in an extended mission. Mapping of regions from 70 to approximately 83 degrees will be accomplished by the laser altimeter.

8. NAVIGATION STRATEGY

After separation, one satellite is given a slight orbit raise so the two satellites will drift apart in the orbit plane. After a safe distance is obtained, both satellites are put in the same radius and a burn perpendicular to the orbit plane precesses one or both of the satellites' nodes along the equator until the proper 2020 meter separation is achieved. The navigation operation can be divided into orbit maintenance of the satellites and the more complex relative station keeping of the satellites. The GPS will be used for both purposes. The relative position knowledge system needed for radar baseline determination permits the precise navigation that is required to maintain the satellites at the proper separation.

In a comparative sense, the orbit maintenance requirements are less severe than the relative station keeping requirement. However, the atmospheric drag at this altitude will require both satellites to be raised on the order of 100 m at a maximum frequency of about 10 days. The orbit maintenance requirement is mitigated by the fact that the antennas can be tilted slightly to maintain the proper swath pattern on the ground. Nevertheless, the drag make-up maneuvers still have to be done accurately to avoid relative station keeping errors.

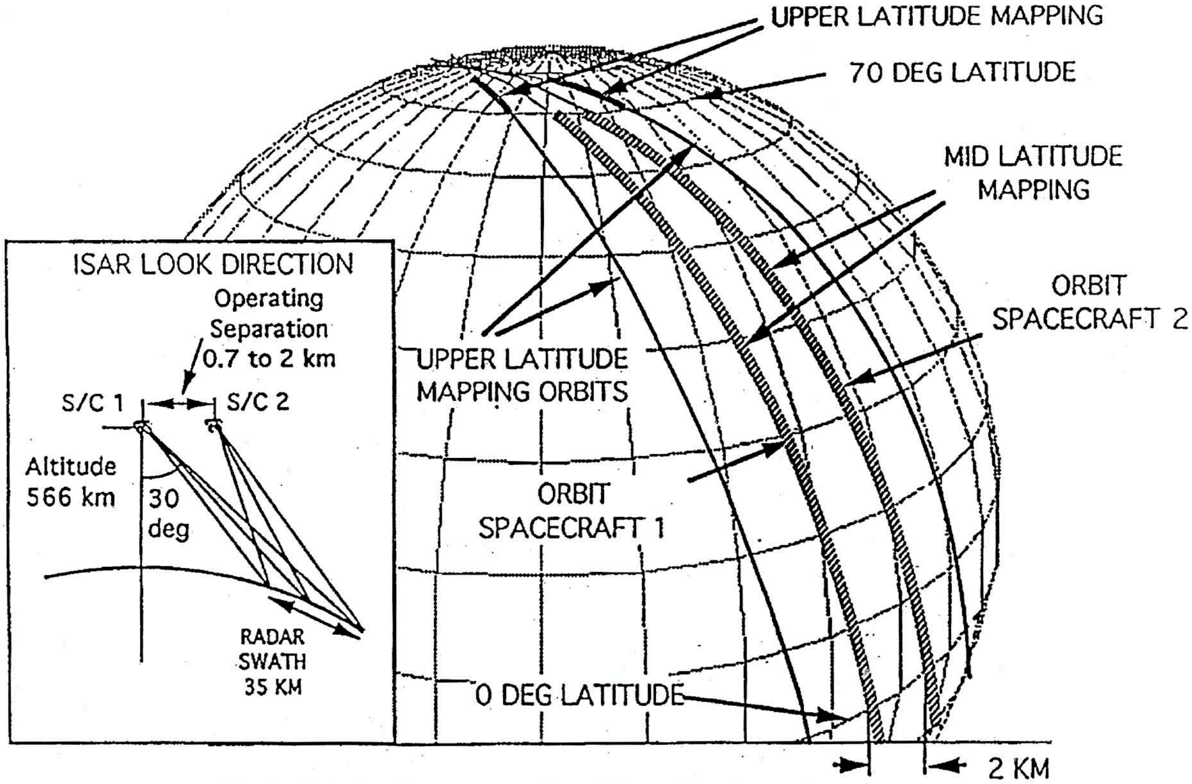

Fig. 1 - Twin Satellite trajectory for mid latitude and upper latitude coverage.

In between these drag make-up maneuvers there will be relative station keeping maneuvers to maintain the proper lag (separation in the orbit direction) distance. Preliminary analysis has indicated that the two major effects that contribute to lag changes are differential drag and the radial orbit difference induced by maneuver execution errors. The mission design requires that the two satellites be of identical construction, particularly in cross-sectional area and mass. A conservative 'a priori' value of 2% was assumed for the deviation of either satellite. The relative drag effect can be estimated to a high precision from early tracking results. The effects of relative drag can be, of a first order, compensated for by positioning the higher drag satellite in a slightly higher orbit (order of 1 meter).

9 FLIGHT SYSTEM CONCEPT

The baseline flight system consists of two identical spacecraft which carry identical L-band radar systems, laser altimeters, and GPS receivers. The major characteristics of the science payload are in Table 1.

Table I -TOPSAT Science Payload Characteristics.

	Mass (kg)	*Power (W)*	*Size (m)*	*Data Rate*
L-band Radar				
antenna	100		9x3.5x0.2	
electronics (ON)	200	694	$0.4m^3$	51 Mb/s
(STANDBY)		50		TBD
Laser Altimeter				
optical bench	75		1x1x1	
electronics (ON)	49	531	0.3x0.3x0.5	150 kb/s
(STANDBY)		207		22 kb/s
GPS Receiver				
antenna	1			
electronics	6	30	$0.01m^3$	1 kb/s
Total mass	**431**			
Max Power (Radar ON, Laser STANDBY) 931				
Maximum Data Rate				**52 Mb/s**

Both spacecraft can be launched on a single Delta II class vehicle. A possible configuration of the two spacecraft in the Delta shroud is in Figure 2.

The on-orbit configuration of one of the two spacecraft is shown in Figure 3. The radar antenna is deployable. The solar array is fixed to face the sun in the twilight, sun synchronous orbit. The laser altimeter points in the nadir direction. It includes two star trackers which must be pointed away from the sun and earth. The radar antenna points 30 degrees off nadir sideways to the velocity vector.

The radar mission requires that the baseline be known to an accuracy of 3 mm in any direction. This will be achieved by the use of the GPS receivers, one on each spacecraft, with antennas near the radar antenna phase centers. The GPS antennas must have a known and stable position with respect to the radar antennas. They must also have a clear hemispherical field of view to space so that a sufficient number of GPS satellites are constantly in view.

Multipath error arises from reflections of the GPS broadcast signal from different parts of the satellite (so that there is more than one path from the GPS transmitter to the receiver). This is minimized by having nothing on the satellite obstructing the hemispherical field of view of the GPS antenna. The remaining small multipath errors cancel out when they are identical on both spacecraft.

Another baseline determination error arises from the nonzero distance between the GPS antenna and radar antenna, combined with random spacecraft pointing errors. This is minimized by keeping the GPS to radar antenna distance small (less than 1 m) and providing pointing knowledge errors of less than 0.05 deg (1 sigma).

Spacecraft pointing control requirements derive from the need for both radar footprints to coincide on the ground and to control the ground coverage to avoid gaps. These requirements are in Table 2. They apply to each spacecraft independently.

Table II - TOPSAT Spacecraft Pointing Requirements.

- Controlled Pointing to Nadir +/-1° for radar swath control and laser altimeter
- Yaw Steering Profile of+/-3° to match drag profiles and overlap radar footprints
- Allowable attitude control error (1 sigma) to overlap radar footprints:

  Roll - 0.09°
  Pitch - 0.06°
  Yaw - 0.11°

- Allowable attitude knowledge error (1 sigma) due to GPS antenna distance from radar
  Roll, Pitch, Yaw - 0.05° for 1 m distance along worst axis

On-orbit RF-boresight pointing can be determined in flight from the radar data. Any mispointing would be taken out by biasing the spacecraft attitude in the required directions.

During the prime mapping mission of 8 months duration there will be no occultations. In the extended mission, when occultations begin, the radar mission is planned to be interrupted because of reduced solar power and the effect of occultation-caused thermal distortion on the radar antenna pointing. The spacecraft must provide enough power to

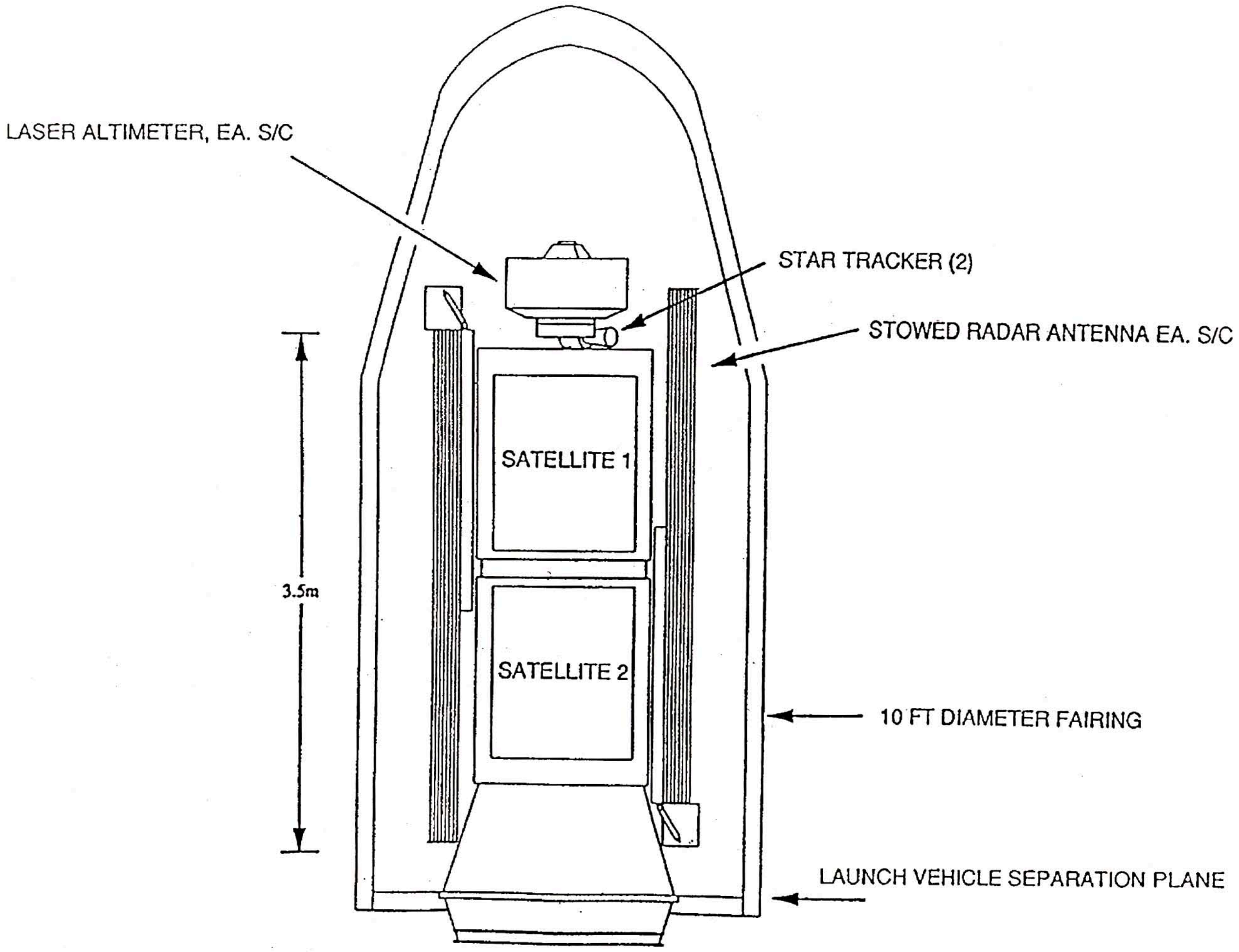

Fig. 2 - Twin spacecraft in launch vehicle shroud.

maintain a healthy state during the period of occultations until they end and an extended radar mission begins.

Each spacecraft must carry enough propellant to provide 20 m/s of delta-v. This will be used to achieve the initial orbits, to perform drag makeup and relative station keeping maneuvers during the prime mission as well as a possible extended mission. The relative station keeping maneuvers must be controlled to an accuracy of 0.05 mm/s to insure that the proper distance for collision avoidance is maintained

10. DATA STORAGE AND DOWNLINK

The radar produces data at a rate of 51.4Mb/s. This data must be stored on board for transmission to the ground. Ideally the data storage device would have a capacity of hundreds of gigabits to provide ground station scheduling flexibility and backup for missed passes and on-board failures. It would also be possible to read out any desired random block of data in the same order as it was recorded.

Presently no recording device meets the "desirements" of TOPSAT. 100 gbit tape recorders are expected to be available and the mission could be carried out with these. But they have the disadvantages of moving parts, reverse playback and difficulty in randomly addressing recorded data. 100 plus gbit solid state recorders, as are being considered for the EOS-AM platform, would better meet the needs of TOPSAT. Because SAR's are such prodigious producers of data there is almost no point where the amount of storage is considered enough. Any future developments in data storage technology will provide real value to TOPSAT and other future SAR missions.

There are two options being considered for data return. The prime option involves the use of 10 m, X-band ground stations located in Alaska and McMurdo which have frequent opportunities to see the spacecraft as well as additional coverage by 11 m DSN stations. The downlink radar

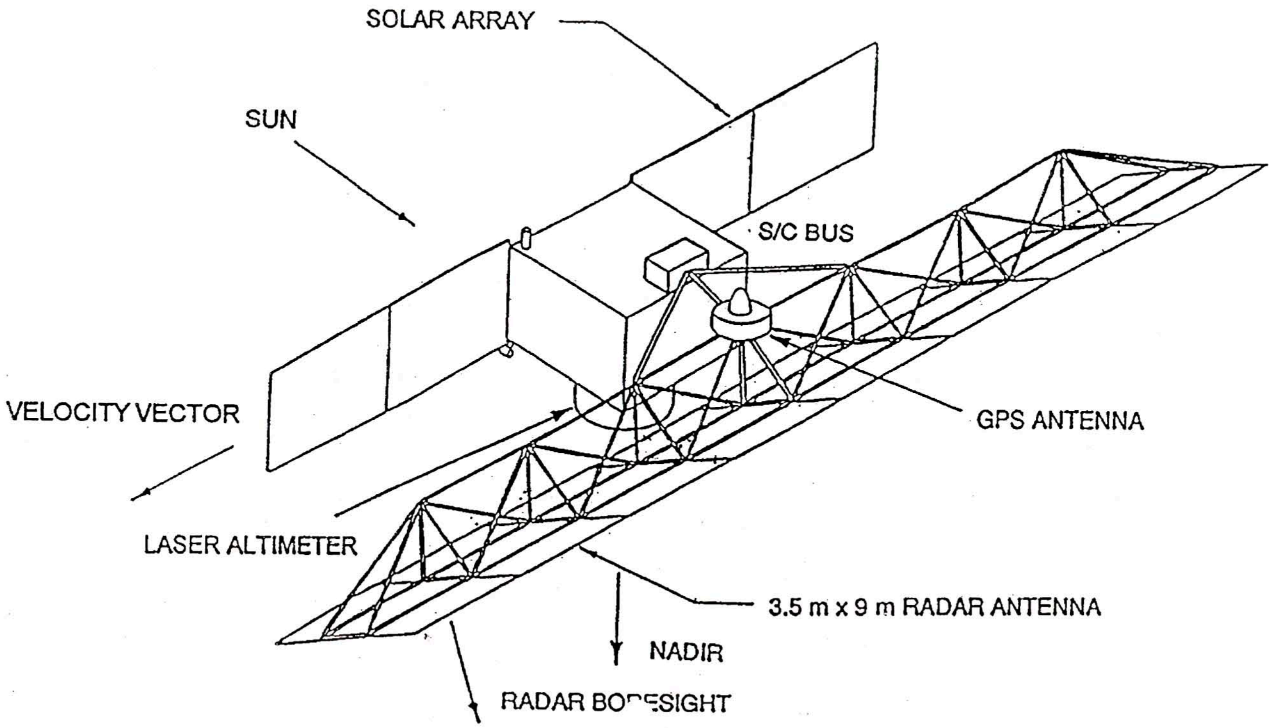

Fig. 3 - One of the twin L-band spacecraft in orbit.

and altimeter data rate would be at 85 Mbits/s. Downlink of GPS and spacecraft engineering data would be at a rate of 512 kbits/s by S-band to either the DSN 26 m network or the McMurdo station. Uplink would be at 2 kbits/s from the DSN 26 m stations.

The second data return option would use TDRSS K-band single access and a high gain antenna on one or both spacecraft. Normal uplink would also use TDRSS. There are several sub-options for data return in this case but each spacecraft should have a high gain antenna and be capable of downlinking to TDRSS. The disadvantages of the TDRSS option are that the steerable antennas would be varying source of differential drag between the two satellites as well as a varying source of multipath transmission of GPS signals to the GPS antennas.

11. DESIGN LIFE AND EXTENDED MISSION

The spacecraft would be designed for a prime mission of 8 months while carrying expendables for 3 years. This approach is consistent with the low cost nature of the project while providing the opportunity for an extended research-oriented mission. During the extended mission the baseline distance could be varied or the spacecraft could be flown in the same orbit to do along track interferometry. This technique can be used to study phenomena characterized by changes on short time scales, such as ocean currents.

CONCLUSIONS

Several different space mission architectures have been studied with the goal of acquiring global topographic data of the quality recommended by the Topographic Science Working Group. An architecture using two identical spacecraft with InSAR baseline determination by a GPS technique appears to be the lowest risk approach.

Future work will further refine the L-band mission architecture so that development risk can be minimized whenever a funding commitment is made. We will also keep abreast of technology developments that are important to either the choice of mission architecture or the cost and performance of the mission. Key technology areas are high capacity solid state recorders, high rate downlinks, high speed, low cost ground data processing, large, highly stable, deployable space structures, sub arc-sec attitude determination systems and low mass, low cost, space qualifiable radar equipment. Major efforts are now underway in NASA to reduce the cost of future space missions, including development, launch and operations phases. We will take advantage of these developments wherever applicable.

Finally, NASA desires to identify and encourage individuals and companies that can take the data NASA produces and add value to it to produce commercial products. To further this interest we will seek out those entities and consider their data needs in developing the details of the mission architecture.

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