Mapping the World's Topography Using Radar Interferometry: The TOPSAT Mission

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Invited Paper

*Global-scale topographic data are of fundamental importance to
many Earth science studies, and obtaining these data is a priority
for the Earth science community. Several groups have considered
the requirements for such a data set, and a consensus assessment
is that many critical studies would be enabled by the availability
of a digital global topographic model with accuracies of 2 and
30 m in the vertical and horizontal directions, respectively. Radar
interferometric techniques have been used to produce digital ele-
vation models at these accuracies and are technologically feasible
as the centerpiece of a spaceborne satellite mission designed to
map the world's land masses, which we denote TOPSAT. A radar
interferometer is formed by combining the radar echoes received
at a pair of antennas displaced across-track, and specialized
data processing results in the elevation data. Two alternative
implementations, one using a 2 cm-λ radar, and one using a
24 cm-λ radar, are technologically feasible. The former requires
an interferometer baseline length of about 15 m to achieve the
required accuracy, and thus could be built on a single spacecraft
with a long extendable boom. The latter necessitates a kilometers-
long baseline, and would thus be best implemented using two
spacecraft flying in formation. Measurement errors are dominated
by phase noise, due largely to signal-to-noise ratio considerations,
and attitude errors in determining the baseline orientation. For the
2-m accuracy required by TOPSAT, the orientation must be known
to 1 arc-second. For the single-spacecraft approach, where attitude
would be determined by star tracking systems, this performance is
just beyond the several arc-second range of existing instruments.
For the dual-spacecraft systems, though, differential global posi-
tioning satellite measurements possess sufficient accuracy. Studies
indicate that similar performance can be realized with either
system.*

I. INTRODUCTION

An accurate description of the surface elevation of the
Earth is of fundamental importance to many branches of
Earth science, as has been detailed in the reports of several
working groups [1]–[4]. These studies have considered

the characteristics of the available topographic database as
well as existing and possible new scientific applications
of high-resolution topographic data. Key findings of these
groups are that there are significant deficiencies in available
topographic data, that existing and potential new scientific
applications are severely limited by these deficiencies, and
that ready availability of a worldwide digital elevation
model is a priority for these studies. The required character-
istics of the data set are that i) the data cover the majority
of the Earth's land surface, ii) all data be expressed in
a common coordinate system, iii) the data exhibit uniform
accuracy, and iv) the vertical accuracy and spatial resolution
of the model be approximately 2 and 30 m, respectively.

The development of interferometric radar systems for the
measurement of highly accurate digital elevation models
(DEM's) has by now been well-documented in the literature
[5]–[12]. The precision of the technique is now commen-
surate with conventional optical-stereo photogrammetric
procedures [13], while data reduction time is a small
fraction of that required by the optical-stereo instrument
systems, which follows mainly from the automated nature
of the radar data processing. In addition, because the radar
signals easily penetrate even dense clouds in the atmosphere
and are independent of solar illumination, there are also far
fewer restrictions on data acquisition times and geometries
from either airborne or spaceborne platforms.

Therefore, it is feasible to design a space mission ded-
icated to the acquisition of a global digital topographic
database at accuracies superior to existing elevation models,
including those described only in paper contour map format.
In fact, NASA has been studying such a mission for several
years to support many ongoing research programs and
the general science community. Consideration of accuracy,
facility of data reduction, and cost has led to the selection of
the interferometric radar technique as the leading candidate
for this mission, which we denote TOPSAT. The principal
TOPSAT goal is to map the topography of the entire Earth
in less than a year at an accuracy similar to that exhibited
by 1:50000 maps.

In this paper, we review the scientific need for global digital topographic data, including the requirements for the data set and a brief comparison of some data acquisition techniques. We then give a brief tutorial on the radar interferometric technique as applied to topographic mapping. This is followed by examples of the performance and application of such a system using data generated by TOPSAR, an airborne prototype of the space instrument, and also by repeat track analysis of data acquired by the ERS-1 radar satellite. Next, we present two possible designs of a spaceborne topographic radar system, one in which the interferometer is formed by using two antennas on a single spacecraft and one in which two platforms orbiting in formation are utilized. Finally, we present conceptual designs of the complete spacecraft systems needed to realize the TOPSAT mission.

II. SCIENCE RATIONALE

Digital topographic data are valuable among a wide community using maps on different scales for a variety of political, social, and scientific applications. In this section we will discuss quantifiable scientific studies enabled by large-scale, high-resolution elevation data. We then will present summaries of required accuracies for several discipline investigations. Finally, we will discuss several technologies used for generation of topographic data and show why the radar interferometric technique is the leading candidate for a spaceborne topographic mission.

Among the studies requiring continental topographic data are hydrology, ecology, glaciology, geomorphology, and atmospheric circulation. For example, in hydrologic and terrestrial ecosystem studies, topography exerts significant control on intercepted solar radiation, water runoff and subsurface water inventory, microclimate, vegetation type and distribution, soil development, and a host of additional interdependent parameters. The topography of the polar ice caps and mountain glaciers is important because it directly reflects ice-flow dynamics and is closely linked to global climate and sea-level change. Monitoring the amplitude of seasonal advance and retreat of mountain glaciers on a global basis and longer term trends of the polar ice sheets can give important information on the rate of global warming. Accurate mapping of the forms and slopes of young geomorphic features such as glacial moraines and feature offsets and scarps due to recent geological faulting can provide new information not only on the formative tectonic processes but also on the climatic and paleoclimatic processes contributing to their present form. Finally, models of the present and past general circulation of the atmosphere require topography as a fundamental input.

NASA has sponsored two working groups, the Topographic Science Working Group [3] and the Joint Topographic Science Working Group, to review previous panel reports and recommend a strategy for generating high-resolution, accurate digital elevation measurements of the entire land and ice surface of the Earth in a single consistent reference frame. The Joint Topographic Working Group, in particular, addressed horizontal and vertical resolution requirements for various disciplines. The working group report is still unpublished in its entirety, but we present a summary of their findings in Fig. 1 (private notes, authors Dixon and Zebker, who were participants in the group). This figure emphasizes the wide range (over several orders of magnitude) of requirements. Nevertheless, some common features stand out. First, several disciplines require very-high-resolution topographic data with horizontal resolution of a few tens of meters (approximately the resolution of current high-resolution space-based imaging systems such as Landsat TM and SPOT) and vertical precision of several meters or better. Acquisition of high horizontal resolution data with high vertical accuracy automatically satisfies all other lower resolution and accuracy requirements and thus is highly desirable. Vertical accuracy should not be significantly worse than vertical precision (we define the latter informally as the relative height uncertainty for adjacent pixels) to facilitate regional comparisons and comparisons of data taken at different times. High vertical precision (a few 10's of centimeters) over the polar ice sheets is particularly important to enable mass balance studies. Here, high horizontal resolution is less critical because slopes are generally lower, so widely separated measurements or averages over a few hundred meters do not, in general, cause large height biases.

Second, while high-resolution data are generally required only in specific regions, these regions may be located anywhere on the globe, and hence the data should be obtainable anywhere. This is virtually the same thing as a global requirement and demonstrates the desirability of space-based acquisition. However, if sensor power requirements, data rate, or ground processing time become significant cost drivers in a space-based mission, a compromise strategy for data acquisition and processing could be adopted whereby data are acquired or processed in high-priority regions first, building up a global data set more slowly. This approach must be traded off with the need in some applications to acquire a near-synoptic data set (see below).

The third requirement is in the area of multitemporal coverage for change detection and the related issues of synoptic coverage and accuracy. These are most critical for applications involving ice change and vegetation monitoring. While tree heights change slowly and are not usually the subject of topographic maps, the availability of temporally varying global height maps would permit global change studies such as forest destruction and regrowth. These ecological studies are not supported well by traditional mapping activities, but represent some of the new possibilities enabled by rapid global mapping technology. It is thus desirable to acquire data relatively quickly, ideally over a 1–2 year period or less, as opposed to building up a database more slowly, for example over a 5–10 year period as might be feasible with stereo-optical systems. It is feasible to acquire "near-synoptic" global data in 6 months with a radar interferometer. Seasonal or other shorter period effects will still have to be accounted for by modeling or other measurement. Obviously, if a global set could be acquired in 6 months, and the mission
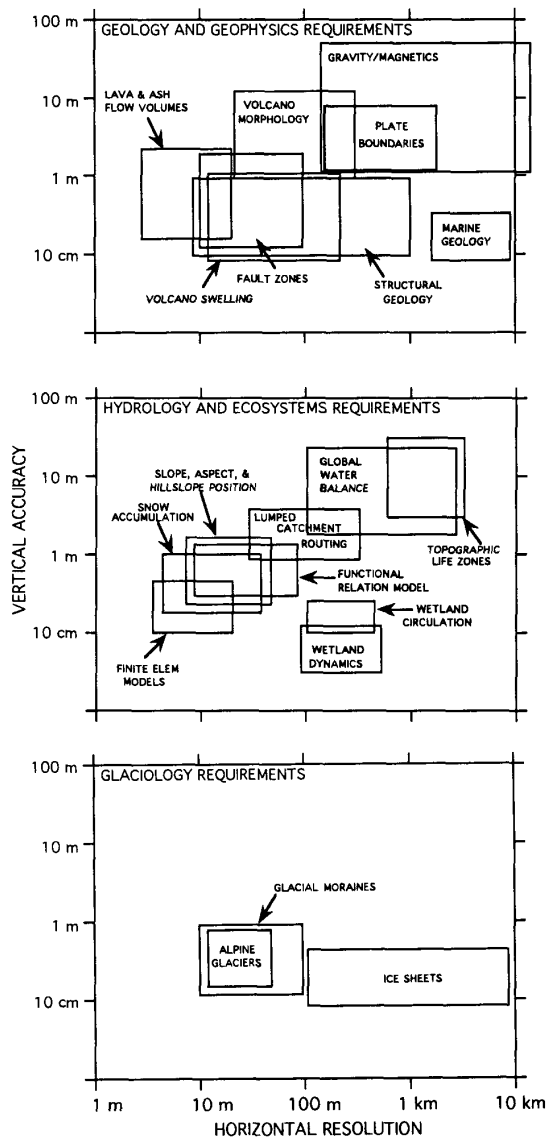
Fig. 1. Graphical depiction of horizontal and vertical topographic data accuracies required for several discipline studies. Each box represents a range of requirements for differing aspects of the studies.

implementations discussed below. The principle exceptions here are the polar ice studies, which do not require fine spatial resolution but do need very precise (10-cm scale) vertical accuracies for adequate calculation of ice volumes. These values, along with coverage needs, form the mission requirements.

The existing inventory of topographic data has been produced from a variety of regional and local data sets representing a potpourri of horizontal and vertical datums, accuracies, styles, map projections, and resolutions making it nearly impossible to produce a uniform data set or assess the accuracy of the resulting derived product. The best existing digital database is the Digital Topographic Elevation Data (DTED) produced by the United States Defense Mapping Agency. DTED have been produced for about 70% of the Earth's land surface, mostly in the northern hemisphere. Completion of a global data set, exclusive of the Greenland and Antarctic ice sheets, is anticipated by year 2005. Current production of DTED is accomplished by automated photogrammetry using classified orbital stereoscopic images. Previously, DTED were produced by traditional analog photogrammetry and by digitization from contour maps. DTED, although not classified, are limited in distribution to members of the Department of Defense and their contractors. This distribution policy is currently under review. The quality characteristics of DTED, taken from public-domain DMA product specifications for photogrammetrically derived data, are about 90-m spatial resolution and tens of meters accuracy in the vertical direction.

A comparison of data requirements versus measurement performance demonstrates that DTED quality does not meet the needs of most scientific disciplines. The relatively coarse DTED horizontal grid size is insufficient for disciplines requiring local digital topographic data. Even with spatial averaging, the poor vertical accuracy of DTED, which is due mostly to large systematic errors, also precludes its suitability for most regional and global scientific disciplines.

There are at least three possible technologies for generation of future topographic data on a global scale: i) optical-stereo instrumentation, ii) laser profiling instruments, and iii) radar interferometry. Of these, the optical-stereo approach has the advantage that it utilizes existing or planned satellite systems justified by a broad spectrum of applications. Currently these include SPOT (Systeme Probatoire d'Observation de la Terre), JERS-1 (Japanese Earth Resources Satellite) OPS (Optical System), AVNIR (Advanced Visible and Near-Infrared Radiometer) on the Japanese ADEOS (Advanced Earth Observing System), HRMSI (High Resolution Multispectral Stereo Imager) on Landsat 7, and ASTER (Advanced Spaceborne Thermal Emission and Reflection) on EOS. Depending on the exact system involved, spatial resolutions ranging from 20 to 40 m and vertical accuracies of 10–60 m may be achieved [14], [15].

It is important to note that these accuracies cannot be achieved without suitable ground control point knowledge, clearly an undesirable need for a global system. In addition,

continued for 3 years, changes over this period could be detected. Even if data acquisition ended after 1 year, future missions would benefit from a near-synoptic database for comparison purposes, assuming sufficient accuracy. The ability to compare with future data sets may be the most important constraint on the resolution and accuracy requirements of a topographic mission, as we cannot predict all possible future applications of a global, fine resolution, high-accuracy data set.

Examination of the figure above shows that many of the investigations would be enabled if elevation data at a vertical accuracy of 2–5 m and a spatial resolution of 30 m were available, requirements satisfied by the technological

truly global coverage is unlikely, even with a space mission, due to orbital limitations and the requirement for two cloud-free scenes with compatible imaging geometry. For these reasons, stereo-optical data would likely be acquired in a piecemeal fashion, slowly building up coverage from a variety of missions with different orbits, illumination conditions, and accuracies. Thus space-based stereo-optical data would suffer from one of the most vexing problems with existing digital topographic databases, namely the lack of consistency.

Perhaps the major constraint on any stereo-optical approach is the existence of clouds in the Earth's atmosphere. Many areas of the globe are cloud-covered much of the time (especially high-relief or tropical areas) and have never been photographed from space. This is not to say that such areas are cloud-covered all of the time. However, any sun-synchronous orbital platform is constrained to fly near local noon (±2 h), in order to minimize shadows and to ensure adequate solar illumination for passive optical sensors. Especially in tropical areas, cumulus clouds formed by solar heating of the ground and resultant convection generally start to form by mid-morning, severely limiting optical detection from sun-synchronous orbital platforms in certain locations.

The second approach is that of laser profiling, where one or more laser beams illuminate the Earth in a near-nadir direction to collect data directly beneath the satellite ground track. This approach has the advantage of very high vertical accuracy ($\approx$0.1–1 m), but the disadvantage that for practical implementations only a very narrow swath may be acquired at one time. For example, if a 30-beam laser were employed with each beam separated by 30 m, the swath would be less than 1 km and complete orbital coverage, with overlaps, would take over 4 years, stressing the performnace in terms of lifetime and efficiency of laser transmitters. It also requires that the orbit be controlled to about 50 m, a challenge in itself. Finally, although only a single pass is required over each region of the Earth's surface, the same atmospheric limitations noted for the stereo imaging affect laser performance.

We note here that there are certain studies, such as the polar ice volume measurements, for which the laser altimeter's high vertical precision and low spatial coverage are ideal, and an overall global topographic study would benefit from the inclusion of a laser instrument to permit the polar study.

The final approach, radar interferometry, achieves the required resolutions and accuracies in a reasonable mission lifetime without interference from clouds in the atmosphere. If a very short radar wavelength is employed, there remains the possibility of interference from severe storms, which, fortunately, are much more rare than clouds in the sky. We describe this approach in detail in the next section, concluding that interferometric radar promises the highest quality product in the shortest time. The remaining discriminator is of course cost, and implementation studies are now investigating the cost issue in detail. For the remainder of this paper, we will assume that there is no significant cost

advantage in selecting one of the optical approaches and will discuss only the radar implementation.

III. RADAR INTERFEROMETRY

A radar interferometer is formed by relating the signals from two spatially separated antennas; the separation of the two antennas is called the baseline. Radar interferometers have been realized in two ways. First, the two antennas may be mounted on a single platform. This is the usual implementation for aircraft systems [5], [6], [9], having the advantage of simultaneous observation (see below) but suffering from the disadvantage that the size of the airframe limits the achievable baseline. However, choosing a high operating frequency permits the baseline, measured in wavelengths, to be of sufficient length for meter-scale vertical accuracies. Second, synthetic interferometers have been formed by utilizing a single antenna on a satellite in a nearly exact-repeating orbit—the interferometer baseline is formed by relating radar signals on passes over the same site [7], [8], [12]. Even though the antennas do not illuminate the same area at the same time, if the ground is completely undisturbed between viewings the signals will be highly correlated and a spatial baseline may be synthesized. Here the choice of a baseline is limited only by orbit navigation accuracy, but the surface decorrelation properties must be considered. Topographic maps using this technique have been demonstrated [7], [16]–[18]. A third implementation, proposed for one possible implementation of the global spaceborne mission, is to utilize two spacecraft flying in formation. This has the advantage of obtaining arbitrary baselines while avoiding the temporal decorrelation phenomenon.

The performance of the radar interferometer depends on the radar instrument parameters, the orbit or aircraft attitude parameters, and the errors induced by the data processing and post-processing operations. For the repeat-pass implementation only, temporal decorrelation constitutes an important and in many cases the limiting error source in the operation of a topographic mapping radar. Zebker and Villasenor [18] investigated temporal decorrelation phenomena for the SEASAT 24 cm-λ (L-band) radar and were able to determine rates of decorrelation for several types of surfaces. A similar analysis of ERS-1 6 cm-λ (C-band) data [12] found that the decorrelation rates are often so much higher, and unpredictable, that the utility of the topographic maps derived from the radar measurements is limited. Therefore, the repeat pass implementation is a much less desirable candidate for global studies where complete coverage at uniform accuracy is required, and we will not consider it further here.

The theory of topographic mapping using radar interferometry has already been presented in some detail [6], [19], [20]—here we summarize the main results and establish notation. We note that for repeat pass imaging geometries, on each pass the radar acts as both a transmitter and receiver, therefore the path difference from each to a given point on the surface is twice what would be expected if a single spacecraft or aircraft with two physical antennas
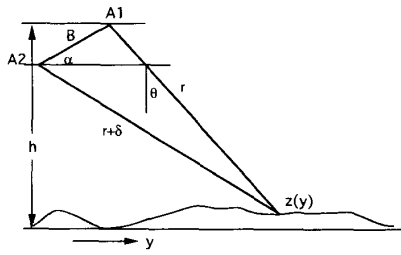
Fig. 2. Interferometer imaging geometry. Radar antennas $A1$ and $A2$ both illuminate the same patch of ground centered at $y = 0$. Incidence angles θ_1 and θ_2 result in phase offsets for all points P displaced by distance y of $y \sin \theta_1$ and $y \sin \theta_2$, respectively. Difference of these phases is measured interferometer phase.

were used. Thus some of the equations listed here differ from those in the references by a factor of two.

Given two antennas $A1$ and $A2$ as shown in Fig. 2, surface topography $z(y)$, the spacecraft altitude h above a tangent plane at the point of interest, the baseline distance B, the range to a point on the ground r, the look angle θ, and the angle of the baseline with respect to horizontal α, a radar signal transmitted from antenna $A1$ and received at both $A1$ and $A2$ will form an interferogram where the phase at each point is equal to the difference in path lengths δ. The measured phase of the interferometer is directly proportional to this distance, with the constant of proportionality $2\pi/\lambda$. Using the law of cosines we can determine the following equations for height as a function of these parameters:

$$\delta = \frac{\lambda \phi}{4\pi} \tag{1}$$

$$\sin(\alpha - \theta) = \frac{(r + \delta)^2 - r^2 - B^2}{2rB} \tag{2}$$

$$z(y) = h - r \cos \theta \tag{3}$$

where ϕ is the measured phase, and λ is the wavelength.

The above constitute a recipe for measuring topography with the interferometer. The two principal errors associated with the measurements arise from uncertainties in the measured phase and in the knowledge of baseline attitude. First, differentiation of (1)–(3) with respect to ϕ yields the error in height estimate as a function of the error in phase estimate

$$\sigma_z = \frac{\lambda r}{4\pi B} \tan \theta \sigma_\phi \tag{4}$$

where σ_z and σ_ϕ are the standard deviations of height and phase, respectively.

The second significant error source results from inaccuracies in knowledge of the interferometer baseline alignment. That is, it is impossible to distinguish a baseline angle knowledge error from a slope on the surface topography, and therefore extremely precise knowledge of the baseline geometry is required if absolute height estimation is needed. Again, differentiation but with respect to α yields

$$\sigma_z = r \sin \theta \sigma_\alpha. \tag{5}$$

Note that the error is independent of baseline length and depends only on attitude and range. This is a stringent constraint for spaceborne geometries where the range from the radar to the image swath can be many hundreds of kilometers. For TOPSAT's goal of 2-m accuracy the baseline orientation must be known to about 1 second of arc. We note that this requirement is for absolute accuracy only—relative height measurements corrected with ground control points to determine the absolute values do not require this accuracy. However, the additional costs associated with acquiring and integrating a worldwide ground control point data set probably outweigh the cost of the spacecraft systems needed to achieve arc second pointing knowledge.

Phase noise (4) in interferometric radar signals arises from several sources, including thermal noise, sampling and processing artifacts, and statistical correlation of the individual radar echoes before they are combined to form the interferogram. Thermal noise is of course minimized by using the greatest possible transmitter power and lowest noise receivers. Sampling and processing artifacts are a tradeoff between data system complexity and cost. All of these factors are well known in radar system design. However, for interferometric systems, the correlation property of the echoes represent a new factor limiting performance.

Decorrelation noise arises mainly from three sources, rotational, temporal, and baseline effects [18]. Rotation of the viewing angle between passes is important particularly when interferometric techniques are applied to satellites in crossing orbits [17], but these systems would never be practical for global mapping applications, and we will ignore this term here. Temporal decorrelation is important when the two radar echoes are not acquired simultaneously, as in the repeat pass technique, but as TOPSAT will likely be implemented using contemporaneous observations we can ignore that effect as well.

Baseline decorrelation results from viewing the surface at two slightly different angles and increases with increasing angle (or baseline). The correlation between echoes varies approximately linearly, decreasing from unity at zero baseline to zero at a critical baseline

$$B_c = \frac{\lambda r}{2R_y \cos^2 \theta} \tag{6}$$

where R_y is the ground range resolution and a nearly horizontal baseline, appropriate for orbital implementations, is assumed [18]. Thus a tradeoff is involved in any interferometer design—the baseline must be large enough to give sufficient phase sensitivity to height (1)–(3) yet small enough as not to introduce too much decorrelation noise.

The baseline length may be optimized by expressing the uncertainty in phase σ_ϕ as a function of thermal signal-to-noise ratio, processing parameters, and baseline parameters, as [19]

$$\sigma_\phi = \frac{\sqrt{1 - \gamma^2}}{\gamma \sqrt{2N_L}} \tag{7}$$

Table 1 TOPSAR and ERS-1 Radar System Parameters

Parameter	TOPSAR	ERS-1
Wavelength, m	0.0566	0.0566
Peak power, W	1000	4800
Pulse rate, Hz	600 nominal	1679 nominal
Pulse length, μs	5.0	37.1
Antenna length, m	1.6	10
Antenna width, m	0.11	1
Antenna gain, dB	25	43.2
Range bandwidth, MHz	40	15.55
Receiver noise temperature, K	2100	3700
Antenna baseline, m	2.58	variable
Baseline angle (α), deg	62.77	variable
Slant range resolution, m	3.75	9.6
Azimuth resolution, m	1.2	6.5
Platform altitude, km	8	790
Look angle, deg	20–65	23
Repeat interval, days	N/A	3, 35, 165

Table 2 Design Control Tables

Parameter	TOPSAR (dB/dBW)	ERS-1 (dB/dBW)
Peak power	30	36.8
Antenna directional gain	28	45.9
Antenna efficiency	−5	−3
$1/(4\pi)$	−11	−11
$1/R^2$	−80	−118.6
Illuminated area	53	78.4
$sigma^0$	−15	−15
$1/(4\pi)$	−11	−11
$1/R^2$	−80	−118.6
Antenna area	−8	10
Antenna efficiency	−5	−3
System losses	−8	−3
Oversampling gain	5	1.8
Total	−106	−110.3
Thermal noise (kTB)	−119	−120.0
Signal-to-noise ratio	13	9.7

where N_L is the number of radar "looks"

$$\gamma = \frac{1 - (B/B_c)}{1 + (1/\text{SNR})} \tag{8}$$

and SNR is the thermal signal-to-noise ratio.

It is worth noting that an active area of research in interferometric techniques involves the minimizing of baseline decorrelation at the expense of a loss of range resolution [8]. While in theory this is valid for flat surfaces, practical problems appear to limit its usefulness for practical systems. However, should the studies indicate that alternative processing could eliminate a major noise source, it would certainly be included in the data system design.

IV. Existing Radar Systems and Data Examples

In this section we illustrate interferometric radar principles by presenting data acquired by the TOPSAR airborne prototype topographic radar and by the ERS-1 radar satellite operating in a repeat pass mode. While TOPSAT would not be implemented by an ERS-1 repeat pass approach, the large areal coverage and global availability permitted by spacecraft systems is hard to appreciate by examining only aircraft strip maps, thus we include an example here.

The TOPSAR interferometric synthetic aperture radar system is implemented on the NASA DC-8 aircraft, where NASA /JPL also operates a multifrequency (P, L, and C bands), multipolarimetric radar (AIRSAR). The TOPSAR implementation uses much of the existing AIRSAR hardware. When in use, TOPSAR effectively replaces the C-band polarimeter instrument, but the remaining L- and P-band systems are undisturbed and operate together with the topographic mapper, producing simultaneous L- and P-band fully polarimetric, plus C-band VV polarization backscatter images in addition to the topographic product.

There are considerations specific to the TOPSAR environment which led to the existing design (Tables 1 and 2). The DC-8 airframe fuselage can support only a 2- to 3-m baseline without requiring significant modifications and this limits performance. The intrinsic range resolution of the AIRSAR is 3.75 m, thus the critical baseline at C-band from (6) is 150 m. The optimal baseline, balancing height sensitivity in the phase measurements and processing

feasibility, is about one tenth to one fifth of the critical baseline, or about 15–30 m. Clearly the airframe will not support an interferometer at the optimum baseline and we must settle for the largest baseline attainable. We therefore chose to mount one antenna below the existing P-band antenna fairing and the second at window level, yielding a 2.58-m baseline. Although this is a factor of ten less than optimum, reasonable performance is achieved.

The ERS-1 satellite contains several instruments, including the synthetic aperture radar. Since only one antenna is used on the spacecraft, we must rely here on repeat pass analysis to form the interferometer. This radar also operates at C-band and has somewhat lower performance in terms of signal-to-noise ratio and resolution as compared to the aircraft system. However, the swath width is over 100 km in contrast to the 10-km swath imaged by TOPSAR.

The main factors affecting topographic mapping performance for the ERS-1 repeat pass case are baseline length, baseline alignment, and temporal decorrelation of the surface. For ERS-1 the critical baseline from (6) is 1100 m, and best performance is realized for a baseline length near 200 m. ERS-1 has been operating in a 35-day repeat cycle for nearly 2 years and fortunately many revisits to a site have been possible. Derivation of a DEM requires selecting a pair from the set of available data with a usable baseline. The knowledge of the baseline orientation is about 3 mrad using the best available orbit reconstructions, yielding an absolute height error from (5) of 50 m. This is not useful for global studies, but given a set of ground control points a digital elevation model may be derived.

For a repeat pass implementation, it is important to minimize temporal decorrelation, and areas of the world with little surface change, such as deserts, are the best candidates for application of ERS-1 as a topographic measurement tool. Forests and other vegetated areas as well as areas subject to freezing and thawing will return radar echoes that are less well correlated due to changes during the 35-day revisit interval [12]. Again, since this radar was

Fig. 3. TOPSAR image of Walnut Gulch/Tombstone, AZ. Perspective from elevation measurements, brightness represents radar backscatter coefficient.

not designed specifically for interferometric applications, performance has not been optimized for topographic mapping. However, the application gracefully degrades with suboptimal geometry and under reasonable conditions of orbit alignment and surface temporal properties topographic maps may be derived.

We can estimate the system signal-to-noise ratio for each with the aid of a design control table (Table 2). Given the TOPSAR baseline parameters, assuming a nominal 200-m baseline length and horizontal alignment for ERS-1, and the signal-to-noise ratios we can then analyze performance of the interferometers. Equation (8) yields a phase noise of 2.8° and 9.1°, respectively, for the TOPSAR and ERS-1 systems; (4) then gives height uncertainties of 1.4 and 2.4 m, respectively.

Figure 3 illustrates a sample DEM acquired by TOP-SAR. Here the elevation data are used to generate a perspective view of Walnut Gulch experimental watershed near Tombstone, AZ; the amplitude at each point in the image is determined by the radar backscatter coefficient. Since the amplitude and the phase information are carried together in the data processor, precise alignment of the radar brightness and terrain information is maintained. This makes it relatively easy to reference the location of points in the DEM to a known coordinate system as many features are identifiable in the radar backscatter image.

Figure 4(a) is a TOPSAR image acquired over Ft. Irwin, near Barstow, CA. This was the site of a verification experiment [13] where TOPSAR data were compared with a very accurate DEM produced by the U.S. Army Topographic Engineering Center (TEC). The stated 1-m or better accuracy of the TEC reference DEM (shown in shaded relief representation in Fig. 4(b)) was ensured by using many ground control points. In Fig. 4(c) we plot an error map of the height difference between the TEC DEM and that obtained by TOPSAR. Peak errors approach 10 m, but for rms error the agreement is to the 1 m level in the flat regions and 2–3 m in the mountainous regions, as expected by the theoretical models.

TOPSAR shows its usefulness by acquiring data over regions of scientific interest for which the existing data are poor or nonexistent. One such region is the Galapagos Islands, which are remote and difficult to measure by conventional means, however are of great interest to the volcanology community. It is expensive to deploy aircraft with stereo cameras for extended lengths of time, which would be required to obtain complete cloud-free coverage over the entire islands. TOPSAR covered several interesting
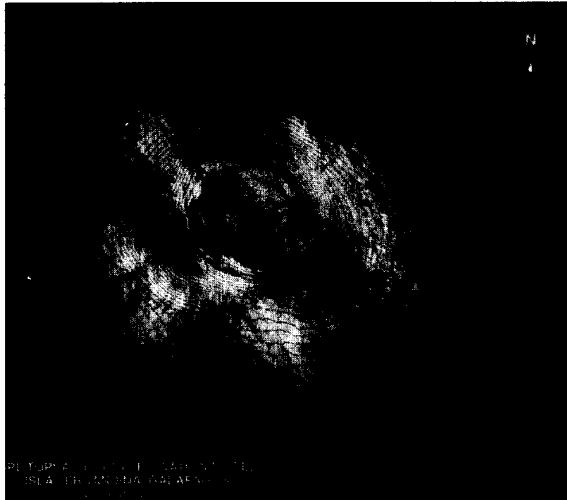

(a)
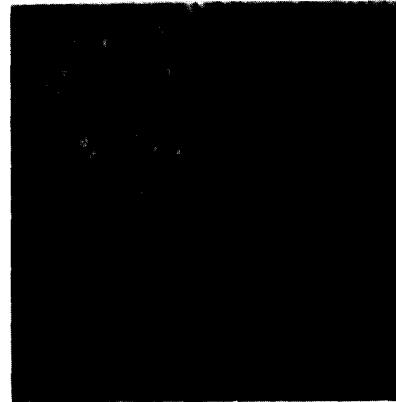
(b)
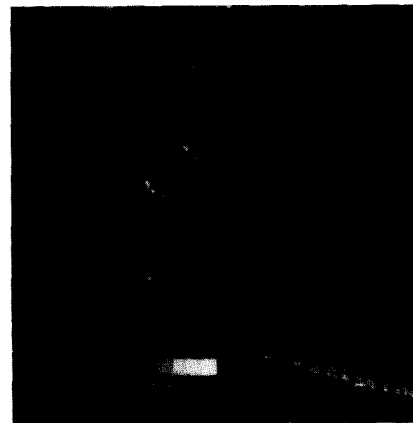
(c)

Fig. 4. (a) TOPSAR image of Ft. Irwin, CA. This was the site of a verification experiment that included a variety of terrains. A conventional stereo photogrammetric image was produced by the U.S. Army Topographic Engineering Center (TEC) as a reference. (b) Shaded relief representation of the reference TEC DEM. The TEC map does not cover all of the area in (a). (c) Error map of the difference between the TEC DEM and that from TOPSAR. Although peak errors approach 10 m, in an rms sense the agreement is to the meter level in the flat regions and 2–3 m in the mountainous areas.

islands in a matter of a few hours. In Fig. 5 we show a contour map derived from TOPSAR data over the Galapagos island of Fernandina. In this case there are no known elevation data of large parts of the island and for those data that exist the accuracy is not well characterized. This map is now the best available, and is in convenient digital format.

Fig. 6. ERS-1 interferometric digital elevation model of part of the Mojave Desert, CA. The bright, flat region in the foreground is the Pisgah lava flow, and the dark dry lake in the background is Drinkwater Lake.

Fig. 5. Contour map of Isla Fernandina, Galapagos Islands, derived from TOPSAR DEM. The contour interval is 50 m, and the brightness represents radar backscatter coefficient. This image consists of four parallel strips mosaicked together.

It consists of four strips mosaicked into a single image and covers an area of about 900 km².

As mentioned above, the principal advantages of spaceborne platforms are large areal coverage and global data acquisition. We have selected an interferometric pair of scenes acquired over part of the Mojave Desert in California, where little temporal decorrelation occurs and we chose two orbits separated by about 100 m in space. From these data we produced the ERS-1 digital elevation model shown in Fig. 6. This image is 40 km on a side, and represents a subset of a single swath of radar data. While we have not completed a detailed performance analysis of this scene, analyses on similar scenes [12] indicates that 5-m vertical precision at 40-m spatial resolution may be achieved if five ground control points are identified within the image and used to constrain the solution.

V. TOPSAT IMPLEMENTATION OPTIONS

In this section we present two possible spacecraft implementations that could satisfy many of the global topographic mapping requirements as described above. Each approach has its own limitations based on available technology. Thus many of the limits to performance described here result from details of the implementation rather than by shortcomings of the technique. However, both of the proposed implementations are feasible and are an appropriate starting point for a realistic system design.

If we eliminate repeat pass implementations as unreliable for a global mapping mission requiring contiguous, uniform data over much of the Earth, two alternatives for interferometric radar instrument designs remain: i) a single spacecraft with two displaced antennas, and ii) two spacecraft, each with a synthetic aperture radar, flying in formation to form the interferometer baseline. For each system, the basic limitations to interferometer performance

as described above remain. Signal-to-noise ratio must be maximized in the constrained spacecraft environment, the baseline must be of sufficient length to give the desired height sensitivity without causing too much baseline decorrelation, and the baseline attitude must be measured at the 1 arc second level.

The requirement to realize sufficient signal-to-noise ratio, coupled with technological limitations on transmitter efficiencies, practical device power ratings, and spacecraft prime power levels, translates into a need for a large antenna compared to the wavelength, producing a relatively narrow swath. The single-spacecraft design we present here (Tables 3 and 4) produces a 10.5-km swath after accounting for overlap in the mosaic process, and thus requires at least 241 days to map the world completely. A longer mapping cycle is more costly for two reasons: the design lifetime of the spacecraft must be longer and the operations phase of the mission lasts longer.

The single-spacecraft approach would achieve the required baseline lengths by mounting one or both of the antennas on a boom at a distance from the spacecraft. A boom would likely be limited to about 25-m length (see next section), therefore to form an adequate baseline the wavelength would have to be short, preferably 2 cm (Ku-band) or less. The effective boom length, however, can be doubled by "ping-ponging," or alternately transmitting from each antenna, at a cost of cutting pulse repetition rate and the average power per channel by a factor of two, which also increases azimuth ambiguities due to undersampling of the Doppler spectrum.

Baseline attitude determination would be achieved by measuring both the rigid body spacecraft attitude and the structural distortion between the two antennas. The spacecraft attitude can be measured by a star tracking system and the structural distortion by a laser metrology system. Of these two the measurement of spacecraft attitude to less than 1 arc-second is the more difficult. Current star trackers cannot measure absolute attitude to less than several arc-seconds, due to limitations in the trackers themselves, uncertainties in mechanical spacecraft flexure, and by limitations in absolute knowledge of star positions (private communication, S. J. Wang, JPL internal memorandum Jan. 10, 1994).

Several of the above limitations could be reduced by using two spacecraft to form the interferometer by flying in

Table 3 TOPSAT K_u- and L-Band Radar System Parameters

Parameter	K_u-band	L-band
Wavelength, m	0.02	0.24
Peak power, W	750	1600
Pulse rate, Hz	3800	2100
Pulse length, μs	60	50
Antenna length, m	5	9
Antenna width, m	0.65	3.5
Antenna gain, dB	49.9	38.4
Range bandwidth, MHz	20	20
Receiver noise temperature, K	700	600
Antenna baseline, m	25	800-2000 (variable)
Baseline angle (α), deg	30	0
Slant range resolution, m	7.5	7.5
Azimuth resolution, m	3.3	5.9
Orbit altitude, km	440	564
Look angle,	30	30
Orbit repeat interval, days	241	84

Table 4 TOPSAT Design Control Tables

Parameter	TOPSAR (dB/dBW)	ERS-1 (dB/dBW)
Peak power	28.8	32.0
Antenna directional gain	49.9	38.4
Antenna efficiency	-3	-3
$1/(4\pi)$	-11	-11
$1/R^2$	-114.1	-116.3
Illuminated area	75.8	84.2
$sigma^0$	-13	-20
$1/(4\pi)$	-11	-11
$1/R^2$	-114.1	-116.3
Antenna area	5.3	15
Antenna efficiency	-3	-3
System losses	-3	-3
Oversampling gain	2.1	2.1
Total	-110.3	-111.9
Thermal noise (kTB)	-125.2	-126.9
Signal-to-noise ratio	14.8	15.0

Table 5 TOPSAT Error Budgets (All values in meters.)

Parameter	K_u-Band Flat Terrain	K_u-Band Sloped Terrain	L-Band Flat Terrain	L-Band Sloped Terrain
Height errors, m				
Phase noise error	3.26	5.32	1.94	3.17
Baseline error	0.00	0.00	0.71	1.15
Attitude error	1.23	2.01	0.98	1.59
Orbit height error	0.10	0.10	0.10	0.10
Other	0.10	0.16	0.10	0.16
RSS total	3.48	5.68	2.29	3.73
Across-track position errors, m				
Phase noise error	5.65		3.36	
Baseline error	0.00		1.22	
Attitude error	2.13		1.69	
Navigation error	3.00		3.00	
Other	0.10		0.10	
RSS total	6.74		4.97	
Along-track position errors, m				
Orbit timing error	0.01		0.01	
Navigation error	3.00		3.00	

proper formation. Since the baseline can be much longer, a twin-spacecraft approach could utilize a much lower frequency, and hence technologically simpler, radar system (see Tables 3 and 4). We have chosen L-band with a wavelength of 24 cm as a nominal approach due to the relative technological maturity of the radar electronics—SEASAT, SIR-A, SIR-B, SIR-C, and the Japanese JERS-1 satellites all have L-band radar channels. Here we would navigate the two spacecraft in "parallel" orbits, identical except in node crossing, to form any desired baseline length. The baseline attitude knowledge requirement is still at the 1 arc-second level, but differential Global Positioning Satellite (GPS) techniques promise to determine the relative positions of the spacecraft to a precision of about 3 mm in all directions [21]. If the baseline length is nominally 1000 m, this translates to 0.62 second of arc, well within the requirements.

Successful measurement of the relative position of the interferometric antennas to an accuracy of 3 mm relies on extrapolation of current GPS system performance using knowledge of error sources gained from the TOPEX GPS precision orbit determination experiment. This experiment resulted in absolute position knowledge to the several centimeters level [22]. The total error was found to have four main sources: i) receiver thermal noise, ii) multipath effects, iii) satellite orbit knowledge limitations, and iv) ionospheric propagation effects. Since TOPSAT will require only the relative spacecraft positions at the very high precision, and since the spacecraft are identical in configuration and separated by only 1–2 km, the contributions of the last three error sources are reduced from the centimeter level to the millimeter level.

In the twin-spacecraft case, navigational complexity associated with two spacecraft orbiting within 1 km of each other, not to mention the additional cost of a second spacecraft, are the principal challenges. Spacecraft-to-spacecraft communications and synchronization are required and the data downlink problem may be more difficult. All of these problems can be solved with existing technologies, and the ultimate arbiter in the choice between one and two spacecraft will likely be the cost issue.

A complete error budget [19] for both implementations is shown in Table 5. Here we break down the total error into many components, only two of which (denoted height phase noise error and height attitude error) were described previously (4) and (5). Details of this procedure are beyond the scope of this paper, please consult the reference for more information.

Orbit Characteristics: Advantages accrue for both concepts if a sun-synchronous orbit operating near the terminator is utilized, as solar illumination remains constant for many months. The main advantages realized by this orbit choice are constant availability of power from the solar panels and few thermal shocks to the spacecraft. The twin satellites operate at an altitude of 565 km and inclination of

97.6° while the single satellite with dual antennas operates at an altitude of 440 km and inclination of 97.6°. The lower altitude is required by the single satellite with dual antennas to maintain adequate height resolution, since the height resolution is a function of antenna spacing and radar signal-to-noise ratio.

Navigation issues for the single-satellite implementation are straightforward and the major concern is to cover the entire Earth with a minimum of gaps. The twin-satellite mission design is more complex, involving two spacecraft; it has been described in detail [22] and will be summarized here. For 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 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, after which the satellites will be set at the operational lag distance. After a radar calibration period, the mapping phase will begin. A map of the land masses between ±70° latitude is obtained after about 84 days. By launching at the proper time of the year, two global maps can be obtained before entering solar occultation, the time when Earth shadows disrupt the sun's illumination of the spacecraft solar panels. 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.

Both implementations would be planned to conduct dual complete ground surveys. The second survey would fill in any gaps in the first. Data would be acquired 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 also 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.

Twin-Satellite Orbit Configuration: A baseline distance (the distance between the two satellites measured perpendicular to the velocity vector) of 800 to 2000 m is required for proper single-pass interferometric results. Figure 7 shows that the two orbits are identical except for a 2020-m difference in the locations of the node crossings giving a baseline separation of 2000 m at the equator and 800 m 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°) could be covered in an extended mission.

Data Storage and Downlink: The L-band radar design presented above produces data at a rate of 51.4 Mb/s per spacecraft, and the Ku-band radar at a rate of 64 Mb/s. These data must be stored on-board the spacecraft for transmission to the ground. Ideally, the data storage device would have a capacity of 100's of gigabits to
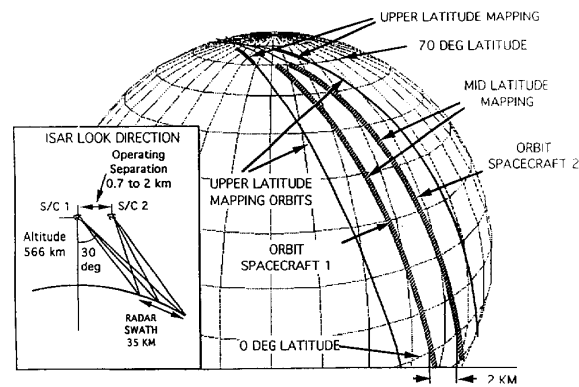

Fig. 7. Dual-satellite trajectory for mid latitude and upper latitude coverage. Note that the track separation is greatly exaggerated for clarity—the actual separation of 2 km at the equator would be too small to see at this scale.

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 TOPSAT required data rate and volume performance parameters. Although 100-Gb tape recorders are expected to be available in the next few years, they have the disadvantages of moving parts, reverse playback, and difficulty in randomly addressing recorded data. Solid-state recorders, which are being developed 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 main options possible for data return. One option involves the use of 10-m, X-band ground stations located in Alaska and McMurdo, Antarctica, which have frequent opportunities to see the spacecraft as well as additional coverage by 11-m DSN stations. The downlink radar and altimeter data rate would be at 85 Mb/s. Downlink of GPS and spacecraft engineering data would be at a rate of 512 kb/s by S-band to either the DSN 26-m network or the McMurdo station. Uplink would be at 2 kb/s from the DSN 26-m stations. The second data return option would use the TDRSS satellite system in a K-band single-access mode and employ high-gain antenna on the spacecraft. Even in this case, a large on-board recorder would be needed as TDRSS is run as a facility shared by many users, and is not always available. Normal uplink would also use TDRSS.

Other Mission Issues: The single-spacecraft approach relies on precise position and attitude knowledge and control of two radar antennas separated by a long structure. Occultation-induced thermal changes could disrupt the pointing control as well as causing lower orbit-averaged power availability. The orbit would be designed to minimize occultations but when they occur data collection may be interrupted. When the occultation periods end
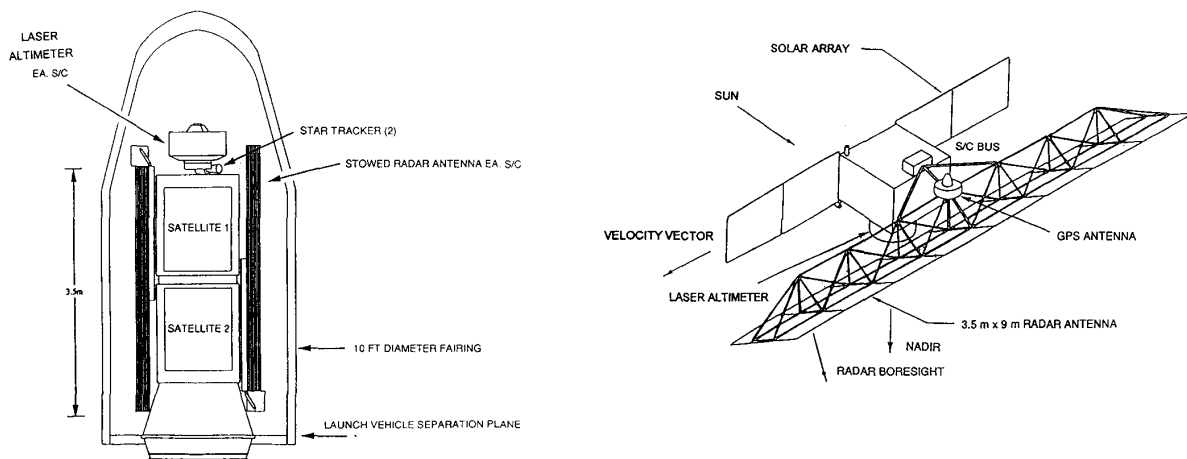
Fig. 8. Single-spacecraft configuration in launch vehicle shroud (left), and deployed (right).

the spacecraft is orbiting over a different set of ground tracks on the Earth, creating a gore in the map, and data acquisition could not be completed until the unmeasured regions become visible once again.

The overall mission could be enhanced, providing additional capabilities to a topographic mission, if a laser profiling instrument were included in the payload to enable polar ice volume studies. A practical design [24] has a swath width of 150 m and so cannot obtain a complete map except near the poles where the coverage is dense. Away from the poles the laser obtains a contiguous line of points for comparison with the radar data, both for validation and, if necessary, ground control point information. The lines of laser data from successive orbits in this approach are about 32 km apart at the equator.

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 to help constrain measurements of surface slope, surface roughness, vegetation height, and surface reflectance at 1.06 μm.

VI. FLIGHT SYSTEM CHARACTERISTIC SUMMARIES

We present here brief descriptions of the complete flight systems as driven by our radar implementation options above. While not strictly descriptive of the radar system itself, it is useful to examine the demand on spacecraft resources from any proposed implementation approach. The major characteristics of both the Ku-band and the L-band system are summarized in Table 6. Finally, we show possible spacecraft configurations for each option in Figs. 8 and 9. The single-satellite launch and on-orbit configurations are depicted in Fig. 8. For the case of the twin satellites, both spacecraft can be launched on a single Delta II class vehicle. A possible configuration of the two spacecraft in the Delta shroud and on-orbit is shown in Fig. 9.

In the case of the single spacecraft, the solar array would deploy once and then be fixed in position. There would

Table 6 Flight System Characteristics

	Single s/c	Twin s/c
Radar data rate	64 Mb/s	51 Mb/s (each s/c)
Radar power	922 W	694 W (each s/c)
Radar mass	250 kg	300 kg (each s/c)
Total flight system mass	1460 kg	2315 kg (both s/c)
Launch vehicle capability	3580	3420 kg
Launch vehicle margin	2120	1105 kg

also be a one-time deployment of the outboard antenna boom. The star tracking system would be located on the spacecraft near the radar antenna and a laser metrology system would be used to measure the position of the second antenna realtive to the spacecraft body. The twin-spacecraft implementation also is designed to have a one-time deployment of the radar antenna and solar array. The sun synchronous orbit allows the solar array to be fixed in position, decreasing cost, and increasing reliability.

VII. CONCLUSION

Global-scale topographic data are of fundamental importance to many Earth science studies, and obtaining these data are a priority for the Earth science community. Several groups have considered the requirements for such a data set, and a consensus assessment is that many critical studies would be enabled by the availability of a digital global topographic model with accuracies of 2 and 30 m in the vertical and horizontal directions, respectively. The necessity to acquire data globally in a time period of a year or less suggests that active microwave techniques, which are much less susceptible to atmospheric effects such as cloud cover than conventional optical techniques, are the preferred technology.

Radar interferometric techniques have been used to produce digital elevation models at these accuracies and are technologically feasible as the centerpiece of a spaceborne
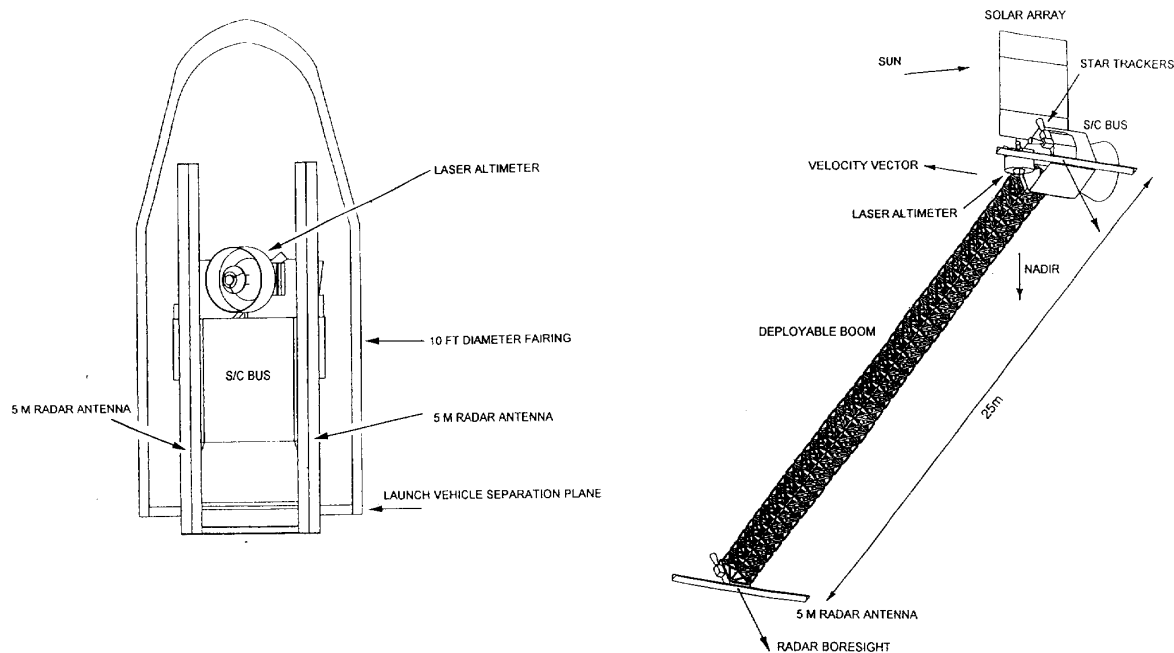
Fig. 9. Twin-spacecraft configuration in launch vehicle shroud (left), and deployed (right).

satellite mission designed to map the world's land masses. A radar interferometer is formed by combining the radar echoes received at a pair of antennas displaced across-track, and specialized data processing results in the elevation data. Two demonstration instruments, the TOPSAR airborne prototype and repeat track analysis of ERS-1 satellite data show that achieving the needed accuracies is feasible at modest cost. The accuracies of the prototype instruments depend mainly on signal-to-noise ratio of the radar echo and to knowledge of the precise imaging geometry

Two alternative implementations, one using a 2-cm-λ radar, and one using a 24-cm-λ radar, are technologically feasible. The former requires an interferometer baseline length of about 15 m to achieve the required accuracy, and thus could be built on a single spacecraft with a long extendable boom. The latter necessitates a kilometers-long baseline, and would thus be best implemented using two spacecraft flying in formation. Measurement errors are dominated by phase noise, due largely to signal-to-noise ratio considerations, and attitude errors in determining the baseline orientation. For the 2-m accuracy required by TOPSAT, the orientation must be known to 1 arc-second. For the single-spacecraft approach, where attitude would be determined by star tracking systems, this performance is just beyond the several arc-second range of existing instruments. For the dual-spacecraft systems, though, differential global positioning satellite measurements possess sufficient accuracy. Studies indicate that similar performance can be realized with either satellite system.

We have presented here preliminary mission concepts which have the potential to produce a global topographic data set in the near future at modest cost. The realization of

a TOPSAT mission requires selection of an implementation approach and its detailed design and construction. There are, however, significant open issues with respect to end-to-end mission design. Therefore, ongoing work emphasizes refining the system error budgets and system requirements, defining the mission implementation approach, and technology requirements, as well as examining efficient methods of ground data processing. None of these are technologically infeasible and it is quite likely that a mature concept can be selected in the near future.

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