The Global Topography Mission

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Abstract

An accurate description of the surface elevation of the Earth is of fundamental importance to many branches of Earth science. A number of working groups have considered the characteristics of the available digital topographic data base and found that there are significant deficiencies in available topographic data that severely limit existing and potential new scientific applications. Currently available global digital topographic data suffer from low spatial resolution and large vertical errors, Higher resolution and smaller errors characterize data sets for much smaller, local sites. New stereo-optical spaceborne systems are capable of producing high-resolution topographic data, but the limitations of cloud-cover and processing time may preclude the generation of a global data set by these methods. A joint NASA-Italian Space Agency working group concluded that the most feasible technique for obtaining a globally consistent, high-resolution digital topographic data set was radar interferornetry coupled with a laser altimeter and global positioning system receivers. A dual-satellite system was deemed most feasible, obtaining global coverage in 3 months. Horizontal resolution would be 30 m and vertical errors would be less than 5 m. Studies are continuing in ‘an effort to fully characterize errors, their sources, and strategies to minimize them. An area of particular attention is the technique of differential interferometry, which is sensitive to topographic changes of less than 1 cm.

Introduction

An accurate description of the surface elevation of the Earth is of fundamental importance to many branches of Earth science. Continental topographic data are required for studies of 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 (GCM) require topography as an important input,

A number of working groups (e.g. LPDAAC Science Advisory Panel, 1993; NASA Office of Space Science and Applications, 1991; National Research Council, 1990; Mueller and Zerbini, 1989; Task Group on Earth Sciences, 1988; Topographic Science Working Group, 1988; Committee on Earth Sciences, 1982) have considered the characteristics of the available topographic data base as well as existing and possible new scientific applications of high-resolution topographic data. Key findings of these previous groups are that there are significant deficiencies in available topographic data and that existing and potential new scientific applications are severely limited by these deficiencies.

In 1990 NASA and the Italian Space Agency (ASI) appointed a Joint Topographic Science Working Group to review previous reports and recommend a strategy for generating a high resolution data set consisting of accurate digital elevation measurements of the entire land and ice surface of the Earth in a single consistent reference frame. In this paper, we summarize the findings and recommendations of that Working Group, give the current state of digital topographic data, and detail a proposed strategy to acquire the needed data.

Summary of Global Topography Requirements

Figure 1 summarizes the horizontal and vertical resolution requirements for various disciplines. 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 cm) over the polar ice sheets is particularly important to enable mass balance studies. Here, high horizontal resolution is less critical because slopes are generall y 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 is 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 rnultiternporal 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. It is thus desirable to acquire data relatively quickly, ideally over a 1-2 year period or less, as opposed to building up a data base 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 continued for 3 years, changes over this period could be detected. Even if data acquisition ended after one year, future missions would benefit from a near-synoptic data base for comparison purposes, assuming sufficient accuracy. The ability to compare with future data sets maybe the most important constraint on the accuracy requirements of a topographic mission, as we cannot predict all possible future applications of a global, high resolution data set.

Currently Available DEM Data

Even though a substantial amount of digital topographic data are available, coverage of the global land surface is inconsistent. Many different mapping organizations around the world produce and distribute elevation data, and the available data vary widely in scale, accuracy, format, distribution policy, copyright, and royalty restrictions, and price. Wolf and Wingham (1992) reported on the status and availability of the world's digital elevation data. Their report describes the results of a survey of 352 mapping organizations from 64 countries. The report lists 50 different topographic data sets, both raster elevation models and digitized contours, that vary widely in resolution and coverage. Data with a horizontal resolution of better than 500 m are publicly available for only 10% of the global land surface.

ETOPO5

ETOPO5 is the highest resolution topographic data set with global coverage that is publicly available (Fig. 1). The ETOPO5 data set has elevations posted every 5 arc minutes (approximately 10 km) for all land and sea floor surfaces. ETOPO5 is distributed without restriction by the National Oceanic and Atmospheric Administration (NOAA) through its National Geophysical Data Center (NGDC). NGDC is currently updating ETOPO5 with some improved source data for certain areas, and the planned release date for the new version is early 1994.

Digital Chart of the World

The Digital Chart of the World (DCW) is a vector data base produced by the Defense Mapping Agency (DMA). It was produced by digitizing the 270 maps in the 1:1,000,000-scale Operational Navigation Chart (ONC) series, which represents the largest scale base map source having global coverage. The Antarctic portion of the DCW was derived from the 1:2,000,000-scale Jet Navigation Chart (JNC) series so that all land areas are covered, The topographic information in the DCW is contained in several hypsography layers. The primary contour interval on the ONCS is 1000 feet, and supplemental contours with an interval of 250 feet are found in areas below 1000 feet in elevation. Spot heights on the source maps have also been digitized into the DCW data base. Elevations of some larger inland water bodies are also included.

The U.S. Geological Survey (USGS) EROS Data Center (EDC) is processing the DCW hypsography data to produce raster data at a grid spacing of 30 arc seconds (approximately 1 km). The surface interpolation routine incorporates the DCW drainage layers to perform "drainage enforcement" which results in an elevation model of higher quality and accuracy (Hutchinson, 1989). EDC has begun production processing of the DCW data for the continent of Africa and portions of North and South America not covered by available higher resolution data with the goal of eventual global coverage. Although many applications require topographic data with a resolution greater than 1 kilometer (Fig. 1), this data set will be useful for some studies, especially those which require global or regional coverage at resolutions higher than that currently provided by ETOPO5. It will also serve as an interim global data set until higher resolution global data becomes available.

Defense Mapping Agency Data

DMA has produced digital terrain elevation data (DTED) for much of the global land surface, with coverage concentrated in the northern hemisphere (Jensen and Larson, 1993). DTED production continues with completion of a global data set anticipated in about 10 years. DTED have an elevation spacing of 3 arc seconds (approximately 90 m). For locations poleward of 50° north or south latitude the longitude spacing between adjacent elevation posts increases. The published accuracy of DTED is 130 m horizontal and ±30 m vertical (Fig. 1; Defense Mapping Agency, 1986).

The DTED data base is useful as a source of topographic information for some Earth science applications, but access to data for areas outside the United States is limited to agencies within the executive branch of the U.S. Government. Restrictions are also placed on the publication of derived products and research results. Distribution of the data is also limited by international agreements imposed by foreign governments who have cooperated with DMA on DTED production (Space News, 1993). Acting as an advocate for the science community, the U.S. Geological Survey has initiated a series of discussions with DMA aimed at facilitating the release and distribution of DTED, or generalizations of DTED, to civilian scientific users.

U.S. Geological Survey Data

The USGS offers several levels of products for coverage of the United States. The country is completely covered by 3 arc second DEMs (approximate y 90-meter horizontal resolution). Higher resolution DEMs with a 30-meter posting are available for about 50% of the continental United States (Fig. 1). There is also partial coverage by 2 arc second DEMs, and by Digital Line Graph (DLG) hypsography data which are digitized contour lines from 1:100,000 and 1:24,000 cartographic sources. Alaska is also mapped but the elevation spacing intervals are different. Complete coverage is available at 3 by 6 arc seconds (3 by 9 arc seconds north of 70). Parts of Alaska are also available at postings of 1 by 2 arc seconds and 2 by 3 arc seconds. All USGS DEM data are available through the USGS network of Earth Science Information Centers.

Other Data

Individual countries have produced elevation data for their areas of interest. DEMs exist for most of Western Europe, Australia, South Africa, and Japan. Parts of Antarctica, Canada, Australia, and New Zealand are covered by digitized contours. As is the case with all digital hypsography data, they are most useful after vector-to-grid conversion has been completed, since most applications using topographic data are also using other raster data layers such as remotely sensed images and thematic maps. Gridding of vector hypsography can be computationally demanding and very time consuming as in many cases the vector data need significant editing. There is also a wide choice of algorithms for surface interpolation and the quality of the output from them varies considerably.

Current Capabilities

Probably the only way a consistent, Earth center-of-mass referenced global digital topographic data set will be obtained is with a space-based technique. The synoptic view and controlled geometry of a space platform is unattainable by airborne techniques. Problems of air-space access are also non-existent with a space platform.

The capabilities of several space-based stereo-optical methods that are under evaluation for measurement of global, digital topographic data are also summarized in Fig. 1. These include SPOT (Système 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.

Panchromatic SPOT images acquired with 10 m pixels have been used since 1986 to produce DEMs of specific sites (e.g. Day and Muller, 1989). The cross-track pointing capability of SPOT allows the second image of the stereopair to be acquired as little as two days after the first. The cross-track look-angle can be up to ±27°, resulting in base-to-height ratios of 0-1. With suitable Ground Control Points (GCP), SPOT DEMs at 30 m spacing typically achieve 10 m RMS horizontal and vertical errors (Muller and Eales, 1990).

JERS-1 OPS data have been used in an experimental manner to produce DEMs (Shimada et al., 1992). With its nadir and 15.33° forward-looking sensors, it acquires near-simultaneous stereo coverage with a base-to-height ratio of 0.3. Nominal pixel size of the images is 18x24 m. Vertical error, with GCP, was found to be 60 m RMS. The proposed 1995 followon to OPS, AVNIR, will have cross-track stereo capability only, looking from ±40°, for a base-to-height ratio of 0.6. Its nominal image pixel size of 8 m may allow more accurate DEMs to be produced, provided good satellite attitude and GCP are available,

HRMSI, planned as a 1997 addition to Landsat 7, would have multiple along-track and cross-track imaging modes, Errors, using GCP, are estimated as 17 m vertical and 23 m horizontal. ASTER, another EOS instrument planned for 1998, would also have both along-track and cross-track modes with errors estimated as 15-20 m vertical and 8-15 m horizontal, using GCP.

For each of the current and proposed systems shown in Fig. 1, vertical bars show the range of vertical performance at the intrinsic horizontal grid size achieved by each method. As much as possible, performance ranges on the vertical accuracy chart (Fig. 1) incorporate both systematic and random elevation errors. For

DTED, the performance range is based on best-case to worst-case data quality reported by DMA for existing photogrammetrically derived data.

A comparison of data requirements versus measurement performance (Fig. 1) demonstrates that, except for GTM, none of the data sets or techniques meet the needs of the scientific disciplines. The closest, near-global data set, DTED has a relatively coarse 90 m horizontal grid size which is insufficient for disciplines classified as 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. Clearly, some use may be made of the data for studies of volcano morphology (Mouginis-Mark and Garbeil, 1993) and plate boundaries (Fielding et al., 1994; Burbank, 1992; Simpson and Anders, 1992), for interpretation of high resolution gravity and magnetic data, for global water balance studies, and regional studies of the elevation dependence of biomes. Progress is being made in these areas, mainly with released data for the US. Release of the full DTED data set would make possible global studies never before attempted.

The Joint Working Group also found that without GCP stereo-optical data cannot achieve even the vertical accuracies shown in Fig. 1, and that 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 data bases, namely the lack of consistency. 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, formats, map projections, and resolutions making it nearly impossible to produce a uniform data set or assess the accuracy of the resulting derived product.

The use of stereo-optical techniques for regional and possibly even near-global coverage has one major attraction: It can proceed with the use of existing or planned space systems. However, it is difficult to quantify rigorously all the costs and eventual application problems associated with cloud cover, degraded vertical resolution, and lack of statistical surface information inherent in a stereo-optical program.

Perhaps the major constraint on any stereo-optical approach is the existence of clouds in the Earth's atmosphere. Several studies have been conducted in the past two decades to determine the actual coverage that can be expected from orbital photography, using data from Landsat, various manned orbital flights, weather satellites, high-altitude aircraft, and ground observations (e.g. Warren et al., 1986; Hahn et al., 1987; Minnis, 1989). Many areas of the globe are cloud-covered much of the time (especially high-relief, 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 hours), 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.

Data from 10 years of ground observations of clouds were compiled by Hahn et al. (1987) and maps generated and published in Warren et al. (1986). Maps were produced showing total cloud cover amount (Fig. 2a) and frequency of occurrence of completely clear sky for 5x5° areas averaged seasonally over daylight hours (Fig. 2b). Using these data, Harding et al. (1993) derived the climatological probability for a nadir cloud-free line of sight (CPncflos) as a function of latitude (Fig. 3), This figure implies that a long period of time would be required to obtain two optical images of many areas of the Earth, particularly if the images were acquired at separate times, as in the case of SPOT and other cross-track stereo imagers.

Recommendations of the Joint Topographic Science Working Group

Because of the lack of currently available global digital topographic data at the required resolution and accuracy and the low probability that a stereo-optical approach can furnish those data, the Joint Topographic Science Working Group concluded that a relatively new technique, radar interferometry, coupled with a laser altimeter would be required, By providing its own illumination at a wavelength long enough to penetrate clouds and rain, the interferometer would help guarantee a global, uniform high-quality topographic data set. The Global Topography Mission (GTM) would include a radar interferometer (INSAR) to obtain rapid (less than 6 months), high resolution (30 m) and high vertical accuracy (less than 5 m) global height measurements, a Multi-Beam Laser Altimeter (MBLA) for high vertical accuracy (less than 1 m) height measurements in low-relief terrain (especially the polar ice caps) and vegetation height and surface roughness estimates in selected areas, and Global Positioning System (GPS) receivers for accurate (~ 10 cm) spacecraft tracking to ensure that the data are acquired in a consistent, Earth center of mass reference frame. The mission can be accomplished within the framework of NASA's "Earth Probe" program and be ready to launch in the 1998-2000 time frame. It is anticipated that NASA and ASI will each contribute approximately one half of the total cost of the mission,

GTM will generate a data set equivalenttoa1:100,000 topographic map over the entire globe. The best resolution of global digital coverage is currently limited to a horizontal resolution of about 5 km (ETOPO5, Fig. 1). GTM will improve this by more than two orders of magnitude, GTM will improve the horizontal resolution of contiguous northern hemisphere coverage by more than a factor of three, and the vertical accuracy by factors of 1.5-3 (in low-relief terrain) to more than an order of magnitude (in high-relief terrain). For much of the southern hemisphere the quality of topographic data will improve by one or two orders of magnitude or more. In some areas of the Earth, GTM will provide the first measurements of surface height ever made.

GTM will generate several ancillary data sets of scientific interest. A complete global radar image will be obtained as a byproduct of the radar interferometer height measurements. Radar images contain information on surface roughness at the cm-m scale and the dielectric constant of the surface, a quantity related to surface soil moisture content. This information is important in many studies in hydrology, ecosystems and land-atmosphere interaction. Over ocean surfaces, radar backscatter and decorrelation can be used to study sea-surface dynamics. The laser altimeter will also obtain sub-pixel information on surface roughness in addition to vegetation height estimates and regional reflectance information over land and ice surfaces at 1 μm wavelength.

GTM Instrument Descriptions

Interferometric SAR techniques have been described in several recent publications (e.g. Zebker and Goldstein, 1986; Evans et al., 1992). Briefly, the technique employs two radar systems; one transmits a radar signal and both receive the echo (Fig. 4). Since the two antennas are separated by a baseline, B, at an attitude determined by angle α, a phase delay, ϕ, which is dependent on the height of the target, z, is introduced between the echoes received by the two antennas. Knowledge of B, α, ϕ, and the radar wavelength λ, allows calculation of the height of the target (Fig. 4).

There are three basic methods of producing interferometric radar data: Repeat-Pass, Single-spacecraft, and Dual-spacecraft, So far, only repeat-pass interferometry has been accomplished from space, but prototype airborne systems have been used to test all three techniques. Repeat-pass interferometry was first demonstrated with Seasat SAR images over 10 years after the data were acquired (Gabriel et al., 1989). Subsequent work with ESA's ERS-1 orbital SAR has shown the utility and some of the disadvantages of the technique. For repeat-pass interferometry to work, the SAR must return on a later orbit to nearly the same point in 3-dimensions as a previous orbit. The difficulty in doing this prevents most orbits from being within the maximum baseline distance: about 600 m for ElW-l. Coulson (1992) showed that only about 10% of ERS-1 pairs had a small enough baseline fro interferometric processing. Additionall y, if too much change has occurred on the surface, the two images will not be correlated well enough to obtain the phase-difference information. Work with Seasat and ERS-1 has shown that some areas in Alaska changed too much in as little as three days for interferometric measurements whereas sites in the Mojave Desert remained correlated over 35 days or longer (Zebker and Villasenor, 1992). Estimates based on the amount of Earth's surface covered with forests, shrubs, or subject to freezing ground indicate that 30-50% of the Earth's land surface is unsuitable for repeat-pass interferometric measurement of topography. The limitations in orbit control and surface changes led to the rejection of repeat-pass interferometry as a potential technique for global topographic mapping.

A single satellite with two antennas appears to be a simple option for topographic mapping, but the desire for a relatively small structure drives the design to high frequencies. At frequencies in the Ka-Ku bands (15-30 GHz; 1-2 cm), a boom of 12-20 m in length would be required for the horizontal and vertical accuracies recommended by the Topographic Science Working Group. In addition, knowledge of the relative baseline orientation would be required at better than arc-second levels. These two requirements are currently technologically challenging. Further, the high frequencies would require relatively large amounts of power, unless more efficient transmit/receive technology could be developed, At current levels, this would limit the swath to approximately 10 km, increasing the time required for a complete global DEM to over 1 year. Finally, high frequency radar signals are known to be attenuated and scattered by rain. This may cause the loss of some data in areas experiencing heavy rainfall.

A dual satellite system allows the use of lower frequencies, thus removing the rain problem and increasing the swath width with existing technology. Baseline orientation knowledge in the arc-second range is also easier to accomplish for the larger baseline, and can be accomplished with dedicated Global Positioning System (GPS) receivers. These factors, and consideration of spacecraft safety drives the design to lower frequencies, with L-band (1.2 GHz, 25 cm) being the highest frequency with good safety margins.

The GTM project has concentrated detailed studies on the twin-spacecraft L-band approach (Table 1). The near-polar orbit allows access nearly to the poles, but the fact that the baseline distance between the two spacecraft changes as a function of latitude limits the use of INSAR to between 70° N and 70° S latitude. This is because the baseline, which is at its maximum of 2 km at the equator, decreases to the minimum usable (about 700 m) at those latitudes. Above those latitudes, the MultiBeam Laser Altimeter (MBLA) discussed next, will play a primary role. In an extended mission, however, the baseline could be increased to allow INSAR data to be acquired up to 82° N and S.

When it comes to producing DEMs from the raw data, the three approaches to INSAR described above share the same problems, most of which are related to the side-looking geometry inherent in imaging radars. The re-projection of the slant-range geometry to true ground-range produces a "stretching-out" of resolution elements on slopes facing the radar. This means that resolution is lower on these slopes. Worse, slopes that are steeper than the radar look-angle will "layover", causing loss of information in that area, The converse is also true:

steep slopes facing away from the radar will have lower SNR, causing large errors or blunders in phase-difference determination or will be in shadow, causing loss of data. These problems have analogs in the stereo-optical domain in shadows and distortions away from the principal point, but are exacerbated by the relatively larger look angles (about 30° for GTM) in radar systems.

Another problem shared by INSAR and optical techniques is the measurement of topography in vegetated regions. Both techniques sense the top of dense canopies, while most users desire measurement of the underlying ground surface. As discussed below, the MBLA may be used for corrections in selected areas,

The Multi-Beam Laser Altimeter (MBLA) measures the round-trip time-of-flight for pulses emanating from a distributed array of 5 laser emitters, providing continuous, direct measurements of surface elevation in a narrow swath directly beneath the spacecraft, Optical backscatter from the Earth's surface is collected by a telescope and array detector. On-board digitization of the return waveform at the nsec level also permits assessment of sub-pixel surface roughness and vegetation height (Fig. 5). The laser pulse transmitter uses efficient, long-life solid-state sources with demonstrated lifetimes adequate for a several-year mission, much longer than required.

MBLA will provide 5 high-resolution (30 m) adjacent pixels with excellent vertical accuracy, (approaching 20 cm) over low-slope regions, including the polar regions where the near-polar orbit of GTM allows dense spatial sampling. The 5 beams will produce a "swath" 150 m wide below each spacecraft. Since the 2 spacecraft have ground tracks that are separated by 2 km at the equator to O near the poles, the two swaths will generally be separated by a small amount. In addition, subsequent passes of the pair of spacecraft are currently planned to be about 30 km apart at the equator, again decreasing to O near the poles. In order to minimize power and data-rate requirements, the MBLA will be operated only on descending orbital passes while the INSAR will be operated, at least in the first cycle, only on ascending orbits. These constraints will produce many narrow MBLA swaths crossing the INSAR swaths between 70° N. and S. latitudes. Poleward of 70° latitude, since the MBLA swaths converge, the coverage increases to over 15 %. The area poleward of about 82° latitude will be inaccessible to both MBLA and INSAR.

Radar-Laser Synergism

There are scientific and engineering advantages that accrue from having these two complementary instruments present on the same platform. From a scientific standpoint, the radar will provide complete global coverage and will do so rapidly regardless of cloud cover, This gives us the opportunity to monitor certain time-varying features. On the other hand, the extremely high vertical accuracy of the laser altimeter is an ideal attribute for polar ice sheet applications. The laser data can also be acquired from slopes of any steepness, For regions of very low slope the magnitude and orientation of surface slopes can be difficult to measure accurately. For such low slope regions the laser data will yield highly accurate measures of slope magnitude (to better than 1°) and orientation with its narrow swath. The wider swath of the radar will allow slope estimates over an entire region at somewhat reduced resolution. The combination of high accuracy and complete coverage afforded by the two systems will enable accurate modeling of surface and subsurface water flow.

Reflections from surface elements at varying heights within the laser footprint cause the reflected laser pulse to be spread in time. The resulting time-distribution of returned laser energy for a single laser pulse is thus a measure of the height distribution of surface elements within a single footprint, for example providing important information on sub-pixel roughness which is a useful parameter in analysis of atmosphere/surface interactions. For open vegetation canopies, pulse shape analysis may provide information on both canopy and ground elevations, yielding a measure of vegetation height (Fig. 5). This is an important parameter in analysis of vegetation productivity and may be used to correct radar determinations of surface height which are most sensitive to the top of the canopy.

An additional component of synergy between the radar and laser systems is that each yields a distinct but complementary image of the surface that is directly coregistered with the height measurements. The image of 1μm reflectivity provided by the laser system and the image of backscatter provided by the radar will permit direct association of the height measurements with specific surface features identified in the images.

In addition to the complementary scientific data obtained by both the laser and interferometric systems, it is helpful to have simultaneous measurements by both systems for calibration purposes. Although the laser swath width is narrow, good horizontal coverage will be achieved in the polar regions given the polar orbit of the system and complete radar-laser comparisons can be conducted. At lower latitudes the laser system will be used to provide high-accuracy topographic swaths to complement the radar interferometer data in selected regions.

For any surface elevation measurement from space, the largest source of systematic error is due to uncertainty in platform orientation, The laser and radar systems monitor in different look directions. Since the effect of orientation errors depends in part on look direction and since many points on the Earth's surface will be measured at least once by each system, the systematic errors in the two measurements will be largely independent. In effect, each system can provide tie points over land or water to help understand and remove the effect of attitude errors in the other system. Note that the performance estimates (Table 2) have not assumed this synergism or any resulting reduction in systematic error due to platform orientation and thus are conservative.

The major source of random error for each system is signal to noise ratio, which strongly depends on surface brightness for the radar sensor, or albedo for the laser sensor. Since, in general, we expect little correlation between these two surface characteristics, the two sensors will make complementary measurements in terms of their random errors. Laser pulse returns will be achieved from slopes of any magnitude, providing heights for the rare terrestrial slopes of greater than 30° not measurable by radar interferometry. The laser altimeter ranging data will also provide an unambiguous, highly accurate measure of surface height that can be used to resolve any ambiguities associated with radar phase unwrapping.

In summary, the combined radar-laser measurements will help to reduce systematic errors in both systems, as well as contribute measurements of surface height, surface roughness, 1 μm reflectivity, radar backscatter and derived measures of slope magnitude and orientation that will be an invaluable means to quantify and model Earth surface processes.

Current Activities

Several studies are being conducted in order to address the problems described above. These are making use of ERS-1; the JERS-1 SAR; a prototype airborne INSAR system called TOPSAR, which was added to the NASA/JPL AIRSAR (Zebker et al., 1991); and a prototype airborne laser altimeter called ATLAS (Harding et al., 1993). Both ERS-1 and TOPSAR operate at C-band (5.4 GHz, 5.5 cm) and do not fully simulate GTM L-band data, but JERS-1 is L-band and a prototype L-band system is being designed for addition to the AIRSAR/TOPSAR system,

The ongoing studies include INSAR/laser altimeter synergism, use of overlapping and crossing INSAR paths for steep slopes and DEM verification, and tests of INSAR in built-up areas. INSAR/laser altimeter synergism is being tested with data sets from TOPSAR and ATLAS obtained over the Walnut Gulch experimental watershed in Arizona, the Death Valley topographic test site, and to be acquired as part of the BOREAS experiment in Canada. These data will be used to determine strategies for using MBLA data to verify GTM INSAR data and the limitations of laser altimetry for use in determination of vegetation height. Since the interaction of the higher frequency C-band radar with vegetation is greater than the planned L-band, additional studies are being conducted with JERS-1 SAR orbital repeat-pass data and with repeat passes of AIRSAR, which may provide multiple wavelength comparisons. Additional studies will be conducted as soon as the L-band TOPSAR is available.

Crossing TOPSAR swaths have already been used to produce DEMs that have been compared against one another and with an existing DEM in Ft. Irwin, California (Madsen et al., 1993), Crossing swaths of ERS-1 repeat-pass interferometry have been obtained over Death Valley and will be used to test strategies for spaceborne INSAR data acquisition, processing and DEM verification in high-relief areas. In addition, the effect of look angle will be evaluated with TOPSAR data spanning a range of angles and with existing DEMs, which can be used to produce slope-probability histograms. These data will be used to choose the optimum look angle for GTM INSAR. Overlapping swaths of TOPSAR data have been mosaicked, using algorithms that correct residual tilts through comparison of overlap areas and coast crossings, and an improved map of the Galapagos Island, Fernandina, produced (Fig. 6). The new data are already leading to new interpretations of the volcanic history of the island (Mouginis-Mark and Garbeil, 1993; Mouginis-Mark, pers. comm.). A thorough evaluation of error sources and amounts will be accomplished with these and other data sets.

Finally, the effects of buildings and metallic targets (fence lines, etc.) will be evaluated using ERS-1 data already acquired over Los Angeles, California and TOPSAR data of Washington, D.C. Double-bounces and point targets are expected to cause some difficulties in phase retrieval.

The primary mission of GTM is to acquire a global digital elevation model of the Earth's land masses and ice cover. This is anticipated to be completed approximately 1 year after launch, allowing for 2 complete cycles of coverage at one look-azimuth and 1 cycle from the crossing orbits. The DEM product will consist of approximately 300 GB of data. At the end of the primary mission, several potential extended mission objectives may be addressed. These include 1) widening the baseline to obtain INSAR data beyond ±70° latitude; 2) monitoring for topographic or radar-image changes; 3) moving one spacecraft into an orbit that follows the other, allowing motion-mapping via along-track interferometry; and 4) high-resolution mapping of topographic change by differential interferometry.

The last possibility, differential interferometry, is an exciting new technique that has been demonstrated to be capable of measuring topographic changes of less than 1 cm over broad regions (Gabriel et al., 1989; Massonnet et al., 1993). Success of the technique relies on the acquisition of repeat-pass INSAR data before and after the change, Comparison of the data cancels most errors, yielding a high] y accurate map of changes in the topography. So far, the technique has been used with Seasat data to show swelling of agricultural fields due to irrigation (Gabriel et al., 1989), and ERS-1 data to map changes caused by an earthquake (Massonnet et al., 1993) and the flow of a glacier (Goldstein et al., 1993). The differential technique has the same limitations as expressed earlier for repeat-pass interferometry and even the single-satellite or dual-satellite INSAR techniques would be subject to those limitations, though only 1 repeat would be necessary for them, vs. 3 for a repeat-pass system such as IRS-1. This unique capability of INSAR is being actively studied and new advances are expected in measurements of pre-eruption volcano swelling and potentially, pre-seismic strain in tectonically y active areas.

In order to make these new data types available to the scientific community for use and in the hope that feedback from the community will improve the product, **TOPSAR** data are available for a number of sites in the western U.S. and elsewhere. A complete list is available from Tom **Farr.** Laser altimeter data are also available through Dave Harding. The **TOPSAR** and ATLAS instruments are also available to NASA-funded investigators for flights over their sites. Information and Flight Request forms are available from NASA Ames Research Center (Code *OM),* or Dr. Miriam **Baltuck,** at NASA Headquarters in Washington, **D.C.**

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Figure Captions.

Figure 1. Summary of resolution requirements for various scientific disciplines compiled by the Topographic Science Working Group, currently available data sets, and potential capabilities of future instruments, including GTM.

Figure 2a. Map showing percent total cloud cover over land, averaged for December, January, and February. Numbers represent percent cloud cover in 5x5° blocks. Map from Warren et **al.** (1986).

Figure 2b. Map showing frequency of occurrence of completely clear sky in 5x5° blocks over land, averaged for December, January, and February and for daylight hours. Map from Warren et al. (1986).

Figure 3. Graph showing the **climatological** probability for a nadir, **cloud-**free line of sight **(CPncflos)** as a function of latitude.

Figure 4. The geometry of **INSAR** data acquisition. Transmission from one antenna (Al) is reflected from the ground, z(x), received at both antennas (Al, A2), and the phase-delay, δ, measured. Baseline length, B, and orientation, α, must be known accurately or control points will be needed to remove scale errors and tilts.

Figure 5. The shapes of the returned laser altimeter pulses are affected by the structure of the ground (slope, roughness) and by vegetation cover. If the cover is not complete, some laser energy reached the ground, producing multiple peaks in the return. Vegetation height measured in this way may be used to correct INSAR-derived topography for selected areas.

Figure 6. Mosaic of 4 TOI?SAR swaths over **Fernandina** Island, Galapagos. Color represents elevation; contour interval is 50 m. Intensity is modulated by one of the C-band radar images that were used to form the interferometer.

Table 1. Global Topography Mission parameters.

Interferometric Synthetic Aperture Radar

Frequency	1.2 GHz
Wavelength	25cm
Horizontal resolution	30 m
Vertical error	2-3 m
Swath width	35 km
Power	1.6 kW
Bandwidth	20 MHz

Mul ·-Beam Laser Altimeter

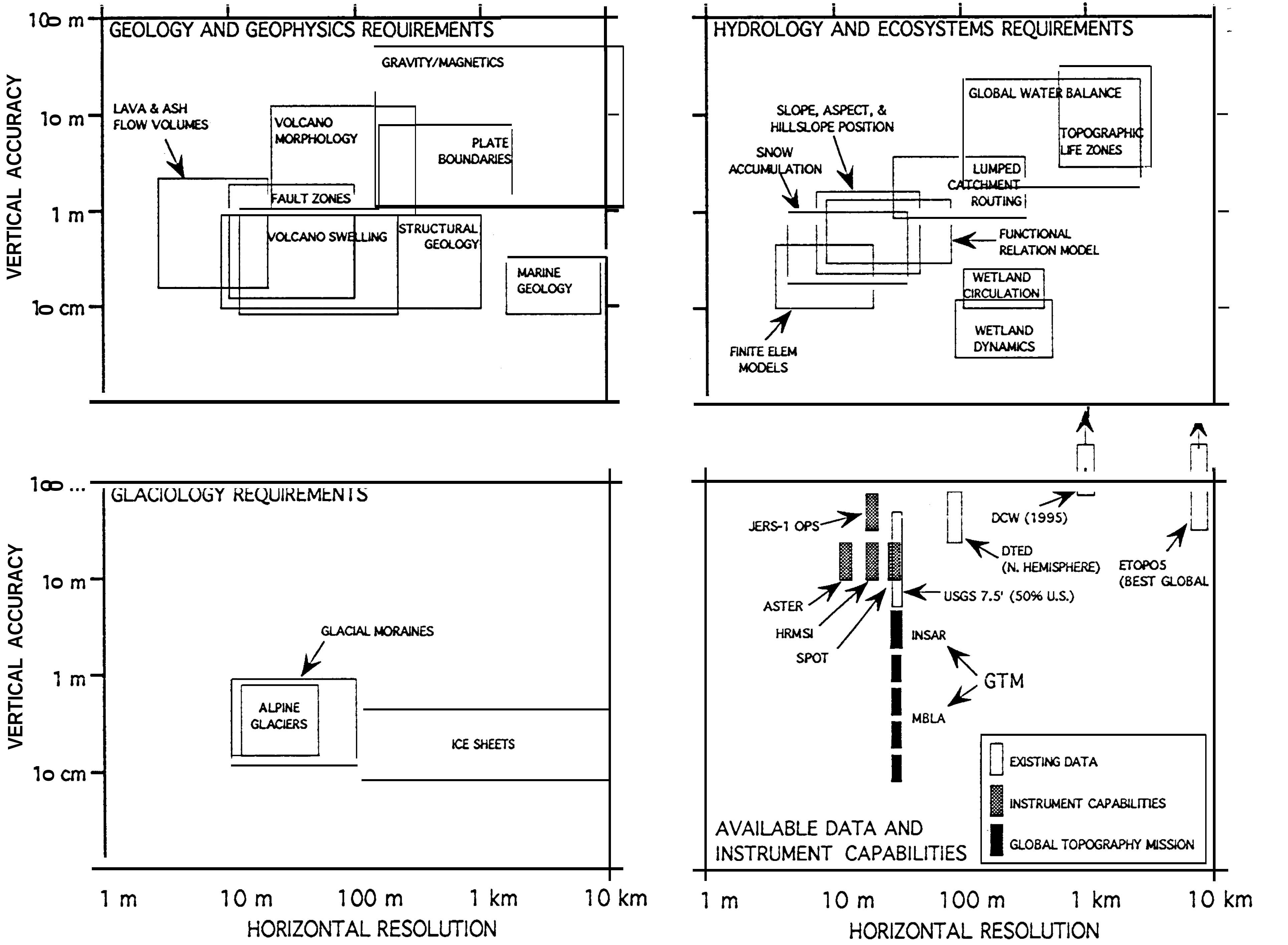
Wavelength	1.1 µm
Horizontal resolution	30 m
Vertical error	20 cm
Swath width	150 m
Power	500 w

Spacecraft

Altitude	565 km
Inclination	97.9°
Repeat interval	83 days
Data rate	102 MB/see
Mass	2600 kg

Table 2. Performance estimates for the INSAR and MBLA on GTM.

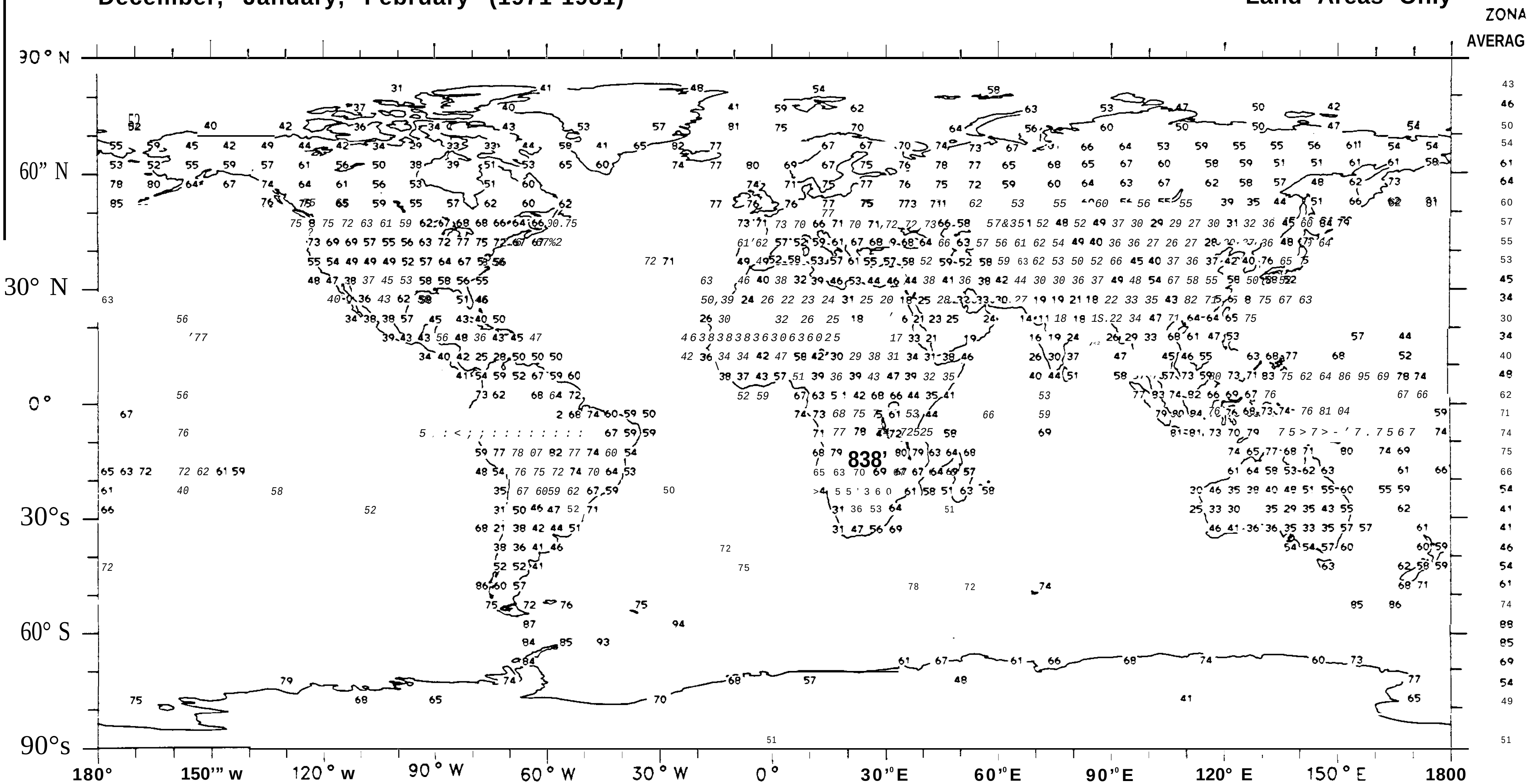
Vertical errors, m	Flat terrain	20° slope
Phase estimation error	1.56	2.54
Baseline error	*0.57*	*0.92*
Attitude error	0.98	1.60
Orbit height error	O.10	0.10
Other	*0.10*	0.16
RSS total	1.93	3.14
Horizontal (across-track) errors, m		
Phase estimation error	*0.90*	1.47
Baseline error	*0.33*	0.53
Attitude error	0.57	0.92
Navigation error	3.00	3.00
Other	*0.10*	0.16
RSS total	3.20	3.51
Horizontal (along-track) errors, m		
Orbit timing error	0.01	0.01
Navigation error	3.00	*3.00*
RSS total	3.00	*3.00*



Farr et. al Fig.

Average Total Cloud Cover (%)

December, January, February (1971-1981) **Land Areas Only**



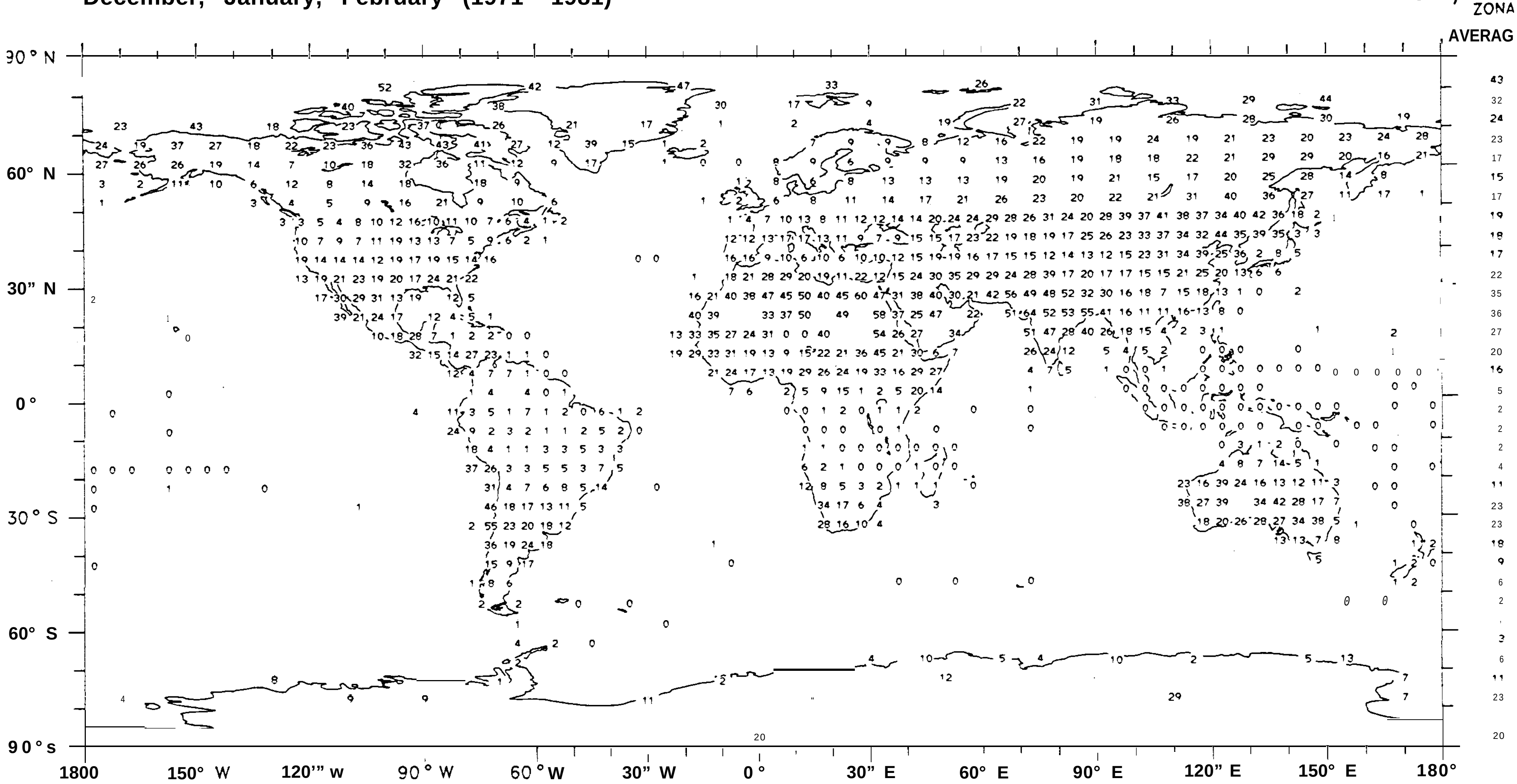
GLOBAL AVERAGE (LAND) 53 %

Farr et. al. Fig. 2a

Completely Clear Sky

Frequency of Occurrence (%), 6-18 LT

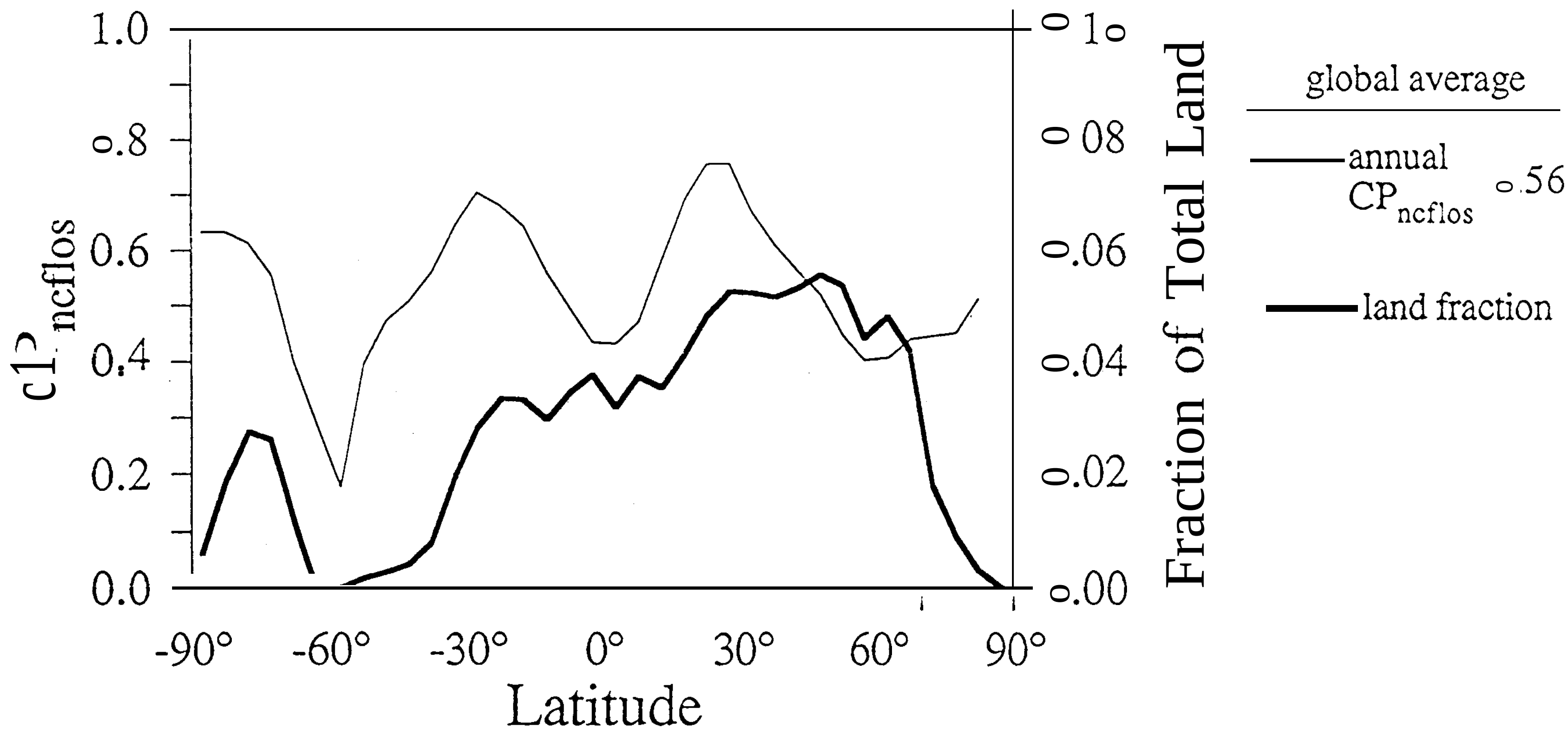
December, January, February (1971 -1981) — Land Areas Only



Farr et al. Fig. 2b

GLOBAL AVERAGE (LAND) 18%

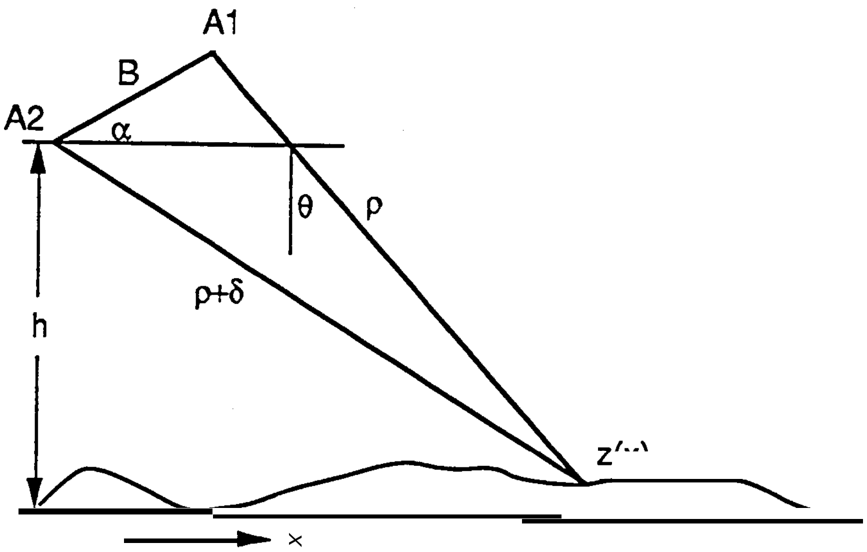
Annual Climatologic Probability of a Nadir Cloud Free Line of Sight (CP_{ncflos}) as a Function of Latitude



Farr et al. Fig. 3

NASA/GSFC March 9, 1991

SURFACE TOPOGRAPHY	$z(x)$
AIRCRAFT ALTITUDE	h
BASELINE DISTANCE	B
SLANT RANGE	ρ
LOOK ANGLE	θ
BASELINE ANGLE	α
PATH LENGTH DIFFERENCE	δ



RESULTING EQUATIONS FOR MEASURED PHASE ϕ, WAVELENGTH λ

$$\delta = \phi\lambda/2\pi \qquad (1)$$

$$\sin(\alpha-\theta) = ((\rho+\delta)^2 - \rho^2 - B^2)/(2\rho B) \qquad (2)$$

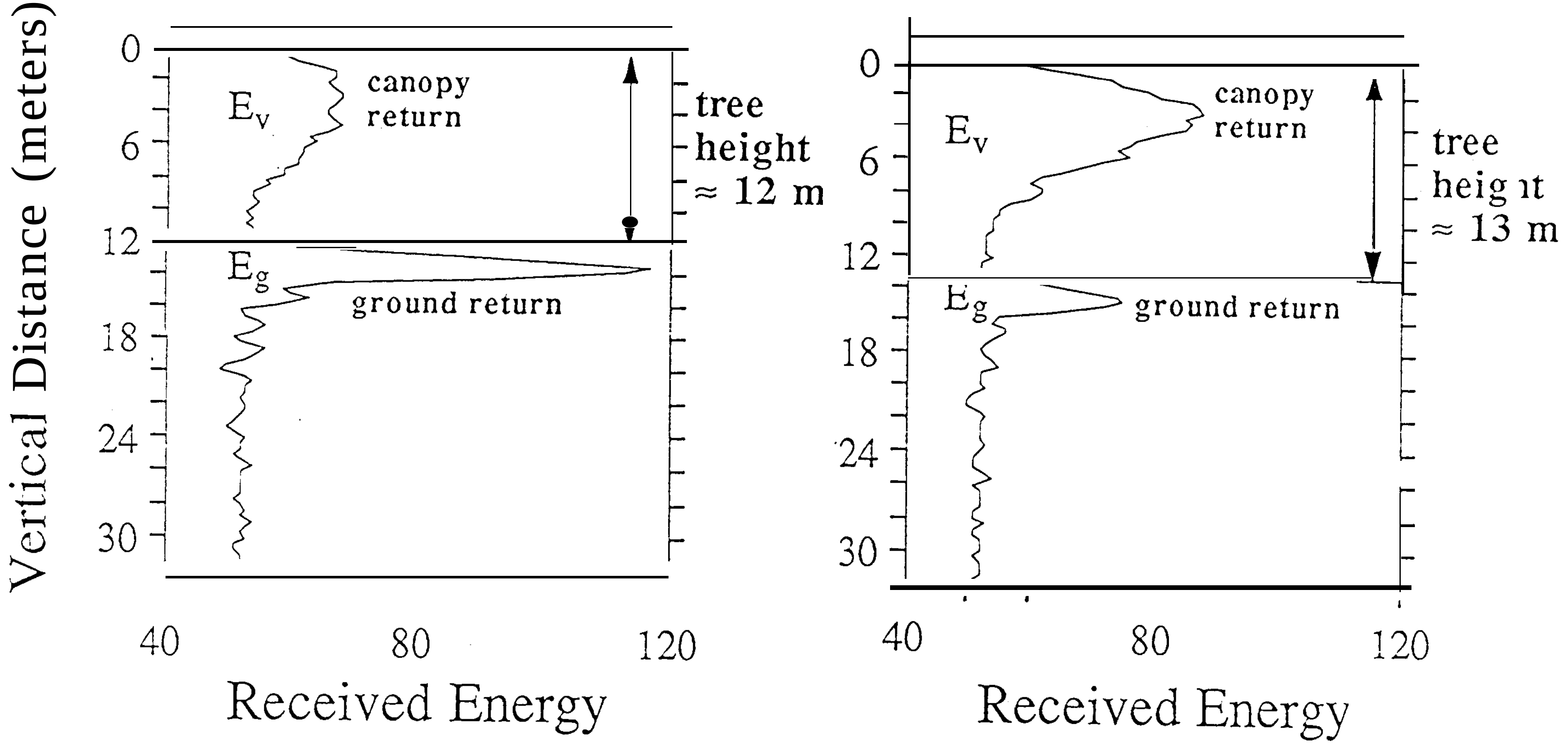
$$z(x) = h - \rho\cos(\alpha)\cos(\alpha-\theta) + \rho\sin(\alpha)\sin(\alpha-\theta) \qquad (3)$$

Farr et al. Fig 4

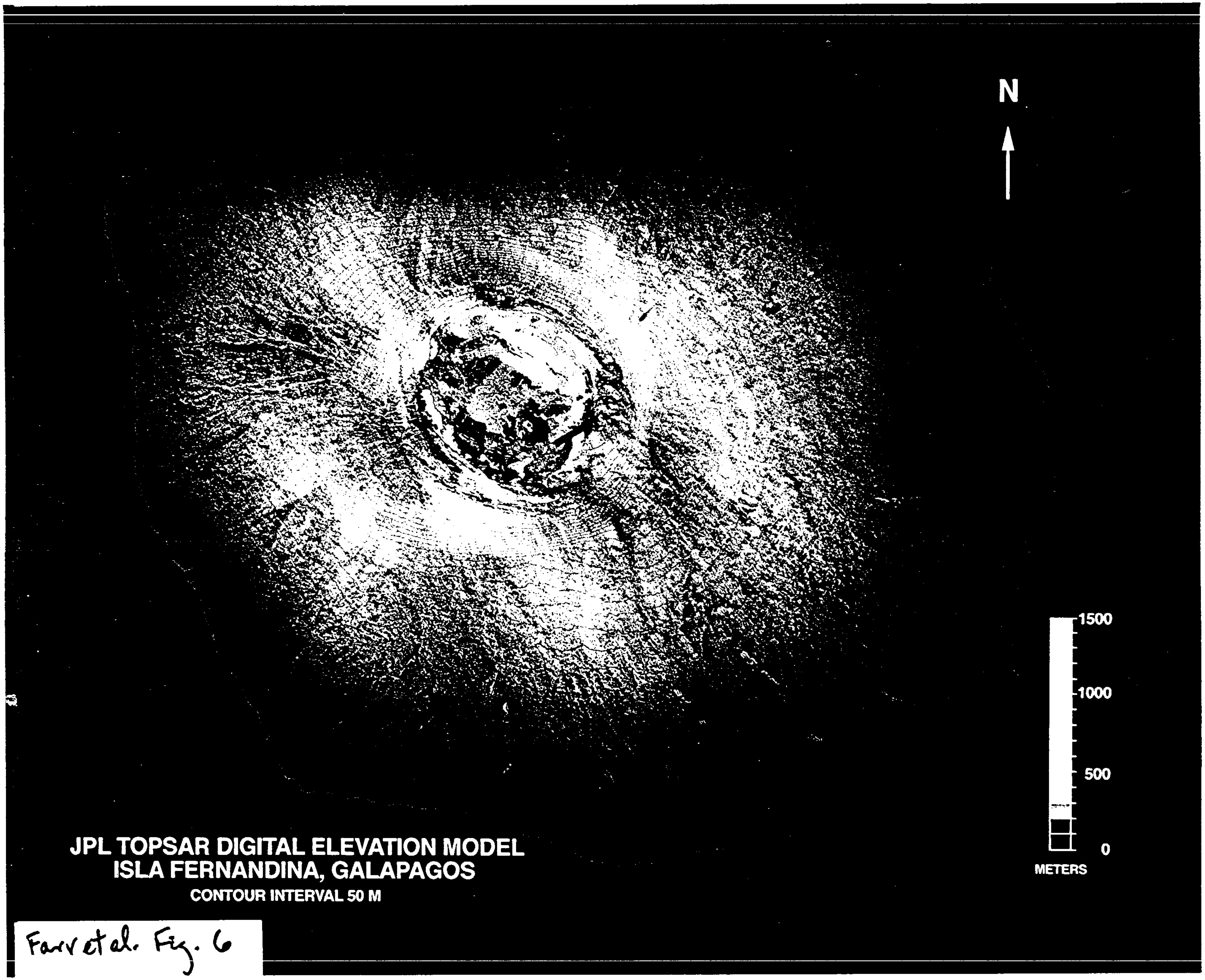
Laser Pulse Return Waveforms for Open Vegetation Canopy

(Mt. Humphreys, AZ)

4 meter diameter footprints



Farr et al. Fig. 5



Farr et al. Fig. 6