# IDENTIFICATION OF REQUIREMENTS AND SOURCES FOR GLOBAL DIGITAL TOPOGRAPHIC DATA

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## ABSTRACT

Many of the physical processes being studied by global change researchers are affected by land surface topography and consequently topographic data are an important requirement for these investigations. Remotely sensed data, especially those that will be collected by the instruments of the Earth Observing System, require significant correction to remove topographic effects. Although some requirements are met by existing topographic data, there are serious data shortages that will affect global change science. The interdisciplinary and multitemporal nature of global change research requires that remotely sensed data be processed using a consistent, highly accurate global topographic data base so that information extracted from these data for different areas and times can be compared quantitatively. Cartographic and remote sensing sources for the generation of new topographic data exist or are planned and will be helpful for fulfilling these requirements. More consistent use of accuracy statement terminology by data users and producers is necessary to better compare the requirements with existing or future data sets.

## INTRODUCTION

Topographic data are required by many researchers investigating global change. Many of the physical processes of interest to global change researchers are controlled by the topography of the land surface. Additionally, many of the remote sensing products used in characterizing global change require significant processing to be useful for quantitative analysis, and these corrections (atmospheric, radiometric, and geometric) rely on knowledge of the topography.

The Earth Observing System (EOS), part of NASA's Mission to Planet Earth, has wide-ranging requirements for topographic data. The U.S. Geological Survey's EROS Data Center (EDC) is one of the distributed active archive centers of the EOS Data and Information System (EOSDIS) and is responsible for managing data related to land processes. The functions of the EDC as an archive center are to receive, process, archive, and distribute data for EOS research. In support of the EOSDIS Version 0 implementation, the EDC is acquiring and archiving existing earth resources data sets, both remotely sensed and ancillary, and making them available to EOS researchers for algorithm and model development in the prelaunch stage of the EOS program. In the area of topographic data, staff at the EDC is striving to improve access to suitable digital topographic data for EOS applications. A significant aspect of this activity is the documentation of the topographic data requirements of the EOS investigators.

## BACKGROUND

General requirements for topographic data have been described and the many applications of digital topographic data are well established in the scientific literature. As the study of environmental change becomes more focused on global scale processes, the need for geographically referenced spatial data with global coverage (especially topography) has been recognized.

The U.S. Global Change Research Program (USGCRP) involves nine Federal Government agencies. USGCRP activities are coordinated by the Committee on Earth and Environmental Sciences (CEES). In a CEES report "The U.S. Global Change Data and Information Management Program Plan" (CEES, 1992), topography (absolute height) was listed as a land surface parameter having "high importance" for documenting and understanding

* Work performed under U.S. Geological Survey contract 1434-92-C-40004.

global change. Surface structure (slope and aspect) was listed as having "substantial" importance. The lack of global coverage for both of these parameters was noted.

The land cover working group of the International Geosphere-Biosphere Program has recommended the creation of a global data set with 1-kilometer resolution derived from advanced very high resolution radiometer data. The data set would be useful for studying land processes related to global change. The proposal to create such a data set is described in the report "Improved Global Data for Land Applications" (IGBP, 1992). The procedures recommended in this report require topographic data to produce surface reflectance images through radiometric calibration and atmospheric correction. First-order corrections, which compensate for gross changes in elevation that cause variation in atmospheric transmittance and scattering, such as a Rayleigh scattering correction, require only general elevation models. However, correction of localized radiometric and atmospheric effects on a pixel-by-pixel basis, such as those caused by slope and aspect, requires elevation models with much higher resolution and accuracy. Geometric correction is also identified as an important requirement. In areas of high relief, topographic data are needed for terrain correction so that images from different orbits can be precisely coregistered to minimize misregistration errors in the compositing process.

The National Research Council has recently reported on the status of multidisciplinary hydrologic science (Committee on Opportunities in the Hydrologic Sciences, 1991). Included in its report is a discussion of data collection, distribution, and analysis. Topography was identified as the most important surface factor affecting hydrologic processes. In the same report it is noted that data of adequate accuracy for quantitative modeling are available for only a small portion of the global land surface and that appropriate data for the polar ice sheets are also lacking.

In 1988, a topographic science working group organized by NASA produced a document that describes the diverse applications of topographic data, summarizes existing data, describes the techniques for acquiring new data, and makes recommendations for producing a global topographic data set (Topographic Science Working Group, 1988). This report provides an invaluable source of information on how topographic data are used in the study of physical processes. The requirements in this report are expressed as a range of scales. A global data set of moderate resolution (approximately 1,000-meter horizontal resolution and 10- to 100-meter vertical resolution) is identified as the first requirement. This global data set should be supplemented by a regional data set with higher resolution (100-meter horizontal and 1- to 10-meter vertical). Local sites would require very high resolution data (10-meter horizontal, 0.1- to 1-meter vertical). The report states that data with high vertical accuracy are essential. Many of the topographic variables (slope, aspect, and slope length) useful for the study of regional and local scale processes are derived from local differences reflected in a digital elevation model (DEM). Any "noise" in a DEM will be emphasized by the differencing operations used to calculate these variables, thereby reducing their usefulness. The report also notes the critical need for topographic data over the Greenland and Antarctic ice sheets. Data with greater vertical and horizontal accuracy are needed for studies of ice dynamics and mass balance. A recommendation in the report is that the acquisition of a consistent global topographic data set should be a high priority for NASA. Such a data set should be acquired with a combination of radar altimetry, laser altimetry (for polar regions), and synthetic aperture radar (SAR) interferometry.

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 digital topographic data sets that vary widely in resolution and coverage. Digital data with a horizontal resolution better than 500 meters are publicly available for only 10 percent of the global land surface.

## EOS REQUIREMENTS

EOS is NASA's main contribution to the USGCRP. EOS is composed of a series of remote sensing satellites, an associated data and information system, and a global change research program. The long-term global observations made by EOS sensors will enable the assessment of hydrologic, biogeochemical, climatological, and geophysical processes (Asrar and Dokken, 1993). Such observations will facilitate a greater understanding of fundamental physical processes and the interactions among them.

Topographic data requirements for EOS may be divided into two categories: data needed for instrument product generation and data needed by interdisciplinary science investigators for modeling physical processes. The use of topographic data and its derivatives will be pervasive throughout EOSDIS because six EOS instrument teams have identified a need for topographic data to produce standard products. Four of these instruments will be launched on the first EOS platform in 1998. Additionally, 11 of the 29 interdisciplinary science principal investigators have listed topographic data as required for their investigations.

### Instrument Data Processing

Topographic data are required for processing EOS sensor data to generate products. Geometric, radiometric, and atmospheric corrections require knowledge of the elevation and terrain characteristics, such as slope and aspect, of the land surface. The interdisciplinary character of EOS investigations and the interrelated nature of sensor observations compound the importance of topographic data. For example, a particular higher level data product, such as leaf area index, needed by an investigator may not require topographic data to be produced, but calibrated data from individual EOS sensors used as input for the generation of that higher level product do require corrections based on topography. This "algorithm dependency" propagates the effect of ancillary data through the process of EOS data product generation. The unavailability of topographic information required for atmospheric and radiometric preprocessing would preclude the generation of higher level products because the input sensor data would not be calibrated to the proper degree of accuracy.

Three instruments, all scheduled for launch on the first EOS morning sun-synchronous platform, AM-1, will be the primary sensors for collecting global data for the study of land processes. The Moderate-Resolution Imaging Spectroradiometer (MODIS), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and the Multi-Angle Imaging SpectroRadiometer (MISR) will collect data that will require topographic corrections. **Table 1** lists some of the important parameters for MODIS, ASTER, and MISR.

Topography will affect the geometric characteristics of MODIS data by causing the relief displacement of pixels. The relief displacement of pixels becomes more pronounced as scan angle increases or pixel resolution increases. Simulations of the effect of topography on MODIS data conducted using the ETOPO5 data base of global topography (National Geophysical Data Center, 1988) have shown that approximately 30 percent of the global land surface will induce a terrain relief displacement error of more than 1 pixel for MODIS 1-kilometer pixels (Muller and Eales, 1990). For MODIS 250-meter pixels, over 60 percent of the land surface has relief sufficient to cause a 1-pixel displacement. The relief displacement is less at nadir and small scan angles, thus, much higher relief is required to produce a 1-pixel shift. However, it is important to correct pixels at all scan angles because data from the entire MODIS field of view (±55°) will be processed. **Table 2** lists the terrain elevations that would cause a terrain relief displacement in MODIS data equal to 1 pixel at various scan angles.

Terrain correction, or the removal of relief displacement, to create an orthoimage requires the use of a DEM during image resampling. Analysis has shown that a DEM grid spacing of twice the nadir pixel size is required to perform appropriate terrain correction (Muller, 1993). For MODIS, this results in a requirement for elevation data with horizontal grid spacings of 500, 1,000, and 2,000 meters for 250-, 500-, and 1,000-meter pixels, respectively. Many of the MODIS land products will be used for multi-temporal analysis in which highly accurate coregistration is imperative. Terrain correction using accurate DEM's ensures the required coregistration quality.

An analysis of the factors contributing to MODIS geolocation error by Hubanks and Fleig (1993) included an examination of the impact of uncertain terrain height information. Many factors affect the error in the calculated location of a MODIS pixel, including uncertainty of the sensor's position and attitude. The accuracy of topographic data used to reference the elevation for a given Earth location also affects the overall error. The vertical error of a DEM causes error in the overall geolocation in the cross-track direction, and as the scan angle increases, the geolocation error due to DEM error increases. At a scan angle of about 40° the geolocation error and DEM error reach a one-to-one correspondence (1 meter of DEM error leads to 1 meter of geolocation error). Geolocation error can also be expressed as a fraction of a pixel. For example, elevation data with a 100-meter vertical error leads to a maximum geolocation error of more than 5 percent of a 1,000-meter pixel. Comparatively, elevation data with a 30-meter vertical error causes a geolocation error of less than 2 percent of a pixel for all scan angles. Although a global elevation data set with such vertical accuracy does not presently exist, this analysis points out the improvements in calculated Earth locations of MODIS pixels if highly accurate data are used for geolocation processing.

Topography will significantly affect the radiometric properties of MODIS data. Atmospheric and radiometric corrections to remove these topographic effects are essential for MODIS products being used in multitemporal studies, especially vegetation indexes, land cover, and surface temperature products. Different levels of radiometric correction lead to varying requirements for topographic data, and the goal is accurate retrieval of "at surface reflectance." The first level of correction adjusts the atmospheric path length due to gross changes in elevation. More detailed corrections account for localized topographic effects such as illumination differences due to slope and aspect, reflection from adjacent terrain, and subpixel shadowing (Teillet and Staenz, 1993). These pixel-by-pixel corrections, especially those that account for subpixel phenomena, require highly accurate topographic data with grid spacing finer than that of the image. The radiometric processing requirements for MODIS 250- and 500-meter pixels would be met by a global DEM with 100-meter horizontal grid spacing, 30-meter vertical accuracy, and a slope accuracy of 1° to 3°. For 1-kilometer MODIS pixels a global DEM with a 500-meter grid spacing, 100-meter vertical accuracy, and 5° slope accuracy is required (Running, 1993).

ASTER will provide numerous high-resolution geophysical data sets of the land surface. The multispectral, high-spatial-resolution data will be an important complement to other coarser resolution sensors onboard the EOS AM-1 platform. Several factors contribute to ASTER requirements for topographic data: the design of the sensor, its off-nadir imaging capability, and the high-spatial-resolution products that measure phenomena influenced by topography (surface radiances and temperatures).

ASTER is a unique sensor in that its visible and near infrared (VNIR), short wavelength infrared (SWIR), and thermal infrared (TIR) bands are collected by three separate radiometer subsystems. This configuration leads to a requirement for band-to-band coregistration among telescopes as part of product generation. Additionally, the SWIR bands require within telescope registration. The individual SWIR detectors are spaced far enough apart that a slight parallax between bands will result. The current specification for the SWIR bands calls for a registration accuracy of 0.2 pixels between bands. Elevation data with an accuracy on the order of 500-meters are required to ensure that SWIR band coregistration meets specification.

ASTER will have the capability to point off-nadir (cross track) up to ±8.5° for the SWIR and TIR bands and up to ±24° for the VNIR bands. This off-nadir viewing geometry leads to geometric distortions in higher relief areas. To create planimetrically correct products the terrain relief distortions must be removed with a DEM. **Table 3** lists the elevation that would cause a displacement equal to 1 pixel. The angles of 2.4°, 10.9°, and 25.9° represent the approximate look angle at the far edge of a 60-kilometer swath centered at nadir, 8.5°, and 24° off-nadir, respectively.

The radiometric calibration and atmospheric correction of ASTER data must take into account the influences of topography. As with MODIS data, different levels of correction will be required. A general knowledge of the base elevation is required to adjust the atmospheric path length, and a more detailed representation of the topography is required to account for local illumination differences. Procedures currently employed require knowledge of the slope to within ±5° for slopes less than 20°. This accuracy allows for a 3-percent error specification for calculated radiances to be met. The slope accuracy, or slope resolution, is dependent on the relative vertical accuracy and the horizontal grid spacing of a digital topographic data set (Harding, 1992). The relative vertical accuracy is the point-to-point accuracy within a particular data set. Slope resolution assumes that the adjacent elevation grid points used to calculate slope are both in error by the maximum specified point-to-point accuracy, but the errors are opposite in sign. The required relative vertical accuracy to meet a 5° slope accuracy specification are 0.65 meters for a 15-meter pixel, 1.3 meters for a 30-meter pixel, and 3.9 meters for a 90-meter pixel.

The geometric correction requirements for MISR are similar to those of MODIS data. The pixel displacements for some MISR data will be even more severe than that of MODIS data as MISR will collect data with off-nadir view angles up to ±70.5°. Additionally, MISR data will be collected through nine separate cameras, and removal of terrain effects is important for band coregistration. **Table 4** lists the terrain elevation that will cause a relief displacement equal to 1 pixel for the various MISR pixel sizes and view angles. The MISR data will be resampled with a DEM, thus producing a terrain corrected product. Statements from the MISR team indicate that topographic data with a 100-meter grid spacing and 30-meter vertical accuracy will be adequate for geometric correction processing (Diner, 1993). MISR data will also require topographic data for radiometric correction processing, but the definitive requirements are not yet known.

Interdisciplinary Science Investigations

The interdisciplinary science teams have specific requirements for topographic data and derivatives as input to physical process models. The solid Earth panel of the EOS investigators working group has noted that "...topography is perhaps the single most important land surface characteristic that determines the climatic, hydrologic, and geomorphic regimes" (Isacks and Mouginis-Mark, 1992). The interdisciplinary studies of the processes that affect global climatic change emphasize the need for a global topographic data base. The solid Earth panel also recognized the need to increase access to existing data and it endorsed the acquisition of new data with existing and planned remote sensing missions.

Eleven EOS interdisciplinary science teams have specifically identified topographic data as required input. The required resolution, accuracy, and coverage vary widely as they reflect the diversity of the science investigations. Generally, the topographic data requirements for EOSDIS product generation are more stringent than those of the interdisciplinary science investigations, so if EOSDIS requirements are met then the needs of the science investigators will be satisfied as well.

Effect of Data Unavailability

Because of the extensive use of topographic data in product generation and interdisciplinary science investigations, the lack of appropriate data at any stage will have a sequential effect and higher level products or model results will be degraded. Various levels of topographic information are required, ranging from coarse-resolution global data for atmospheric sensors to high-resolution data with meter and centimeter level vertical accuracies for local and regional areas.

A serious effect of topographic data unavailability is that most EOS data products are dependent on multiple types of input data, sometimes including data from other EOS instruments. Thus, the importance of topographic data for the generation of a first-level product is emphasized in the generation of all higher level products down the product generation flow. For example, if MODIS level-one products are not geolocated accurately enough to allow for accurate terrain correction (orthoimage generation) all subsequently derived products will suffer from degraded spatial accuracy. This misregistration is especially serious for vegetation indexes and other products that require multitemporal images as input. There are similar implications for ASTER level-one data that require topographic information for coregistration among and within telescopes. Any band misregistration error would be propagated through derived higher level products. Another example of algorithm dependency is found with the MISR land surface products that require MODIS directional reflectances (which requires a DEM as input) for validation. Also, MODIS land cover products, which will be used widely in EOS investigations, are dependent on the accurate generation of several products incorporating terrain data.

## ACCURACY STATEMENTS

In any discussion of topographic data, both in specifying requirements and in describing data sets, it is important to use terminology correctly. The terms "resolution" and "accuracy" are sometimes used interchangeably, which is unfortunate because each represents a unique property of topographic data. Topographic data generally have two accuracies reported, horizontal and vertical.

The term resolution is sometimes used to refer to accuracy. Although they are clearly related, it is incorrect to equate the two. For raster elevation models the horizontal resolution may be referenced as the cell size, grid spacing, or posting interval. Accuracy describes how close a measurement is to truth. It relates the measurement to an established standard reference. The horizontal accuracy of topographic data is related to grid spacing. Because terrain features are generalized in the surface represented by a raster elevation model, it is difficult to measure the accuracy directly from a DEM to any greater degree than the grid spacing (U.S. Geological Survey, 1990). The horizontal accuracy reported for topographic data usually refers to the positional accuracy of features on the source material (image or map).

Horizontal accuracy may be reported as a statistical error probability. Circular error (CE) represents the probable maximum displacement of a point's horizontal position from its true position (combining errors in both the x and y directions). The circular error is usually stated with a 90-percent confidence interval. This may be interpreted as follows: 90 percent of all points will meet or exceed the stated accuracy; or alternatively, for all points tested, 90 percent of the time the true location falls within a circle that has a radius equal to the stated accuracy and is centered on the grid location (Defense Mapping Agency, 1990). Horizontal accuracy is also frequently reported as the mean error expressed as the root-mean-square error (RMSE), or the statistical standard deviation of the measured errors. The RMSE is often used to report the locational error of geocorrected images.

For topographic data, vertical resolution is often confused with vertical accuracy. The vertical resolution, or sampling interval, of most elevation data sets is one unit of measure, (1 meter, 1 foot, or 1 centimeter). In other words, adjacent grid values may differ by as little as the vertical resolution, but this does not imply that an individual grid value is accurate to within that resolution. For example, a DEM can contain elevational differences as fine as 1 meter (the vertical resolution), but for any one grid point the actual terrain elevation at that location may differ by 7 meters (the vertical accuracy). Vertical accuracy for topographic data relates the stated elevation to the true elevation with respect to a vertical datum, usually mean sea level. Vertical accuracy is often reported as linear error (LE) at the 90-percent confidence interval, which means that 90 percent of the points in a data set have a true elevation that is within ± the stated vertical accuracy. The RMSE has also been used to characterize vertical accuracy.

The vertical quality usually reported for elevation data is the absolute accuracy that includes all the effects of systematic and random errors. For many applications the point-to-point, or relative accuracy within a certain data set, is more important than the absolute accuracy. The relative vertical accuracy accounts for just the random error measurements in a data set (Harding, 1992). Studies of slope dependent processes require very accurate slope measurements. Slope is usually calculated from raster elevation models by analyzing the local differences among adjacent grid points. Any random error contained in neighboring elevation measurements decreases the relative (point-to-point) accuracy and thus degrades any calculated slope. To better characterize the uncertainty of surface slope calculated from gridded elevation data, a measure of slope resolution can be used. The slope resolution is based on the horizontal resolution and the relative vertical accuracy. Slope between adjacent elevation points in a DEM cannot be calculated to any better accuracy than the slope resolution.

Consistent use of terms to refer to the accuracy of topographic data is important in order to correlate stated DEM requirements with existing or future data sets.

Accuracy describes the overall quality of a measurement, and resolution relates to the quality of the operation by which the measurement was obtained. It is also important to realize the distinction between describing accuracy with CE, LE, and RMSE metrics. To fully describe a topographic data set the following properties should be listed: horizontal resolution (grid spacing or cell size), absolute horizontal accuracy (CE or RMSE identified), absolute vertical accuracy (LE or RMSE identified), and, if known, the relative vertical accuracy.

## STATUS OF EXISTING TOPOGRAPHIC DATA

Even though a large amount of digital topographic data in the form of DEM's is available, coverage of the global land surface is inconsistent. The ETOPO5 data base, which has elevations posted every 5 arc minutes (approximately 10 kilometers) for all land and sea floor surfaces, is the highest resolution topographic data with global coverage that is publicly available. The ETOPO5 data set is distributed without restriction by the National Oceanic and Atmospheric Administration through its National Geophysical Data Center.

The Defense Mapping Agency (DMA) has produced digital terrain elevation data (DTED) for much of the global land surface, with coverage concentrated in the northern hemisphere (Jenson 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 meters). For locations above 50° north or south latitude the longitude spacing between adjacent elevation posts increases. The published accuracy of DTED is 130-meter horizontal (CE at 90 percent) and ±30-meter vertical (LE at 90 percent) (Defense Mapping Agency, 1986).

The DTED data base could serve as a valuable source of topographic information for global change science, but access to data 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.

The U.S. Geological Survey offers several levels of products for coverage of the United States. The country is completely covered by 3 arc second DEM's. Higher resolution DEM's with a 30-meter posting are available for about 50 percent of the continental United States.

## ALTERNATIVES FOR TOPOGRAPHIC DATA GENERATION

It is clear that existing data do not adequately fulfill the requirements imposed by EOS. A variety of sources for generating new topographic data exist or are under development. Consequently, the use of each of these sources for helping to meet the EOS requirements by launch of the EOS AM-1 platform in 1998 varies. Data are also needed before the launch for processing existing sensor data and for the development and validation of product generation algorithms.

### Cartographic Sources

The Digital Chart of the World (DCW), a vector data base produced by DMA, was created 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 (Danko, 1992). The Antarctic portion of the DCW was derived from the 1:2,000,000-scale Jet Navigation Chart series to complete total land coverage. The topographic information in the DCW is contained in several hypsography layers. The primary contour interval on the ONC's is 1,000 feet, with some supplemental contours at a 250-foot interval found in areas below 1,000 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.

Staff at the EDC have investigated the use of DCW hypsography and drainage data for the generation of gridded (raster) elevation models (Jenson and Larson, 1993). The feasibility of such processing was established over several test sites, and to date the resulting DCW grids have compared favorably with generalized higher resolution data sets. Raster data are being produced at a grid spacing of 30 arc seconds (approximately 1 kilometer). The surface interpolation procedure incorporates drainage information to perform "drainage enforcement," which results in an elevation model of higher quality and accuracy (Hutchinson, 1989). The EDC has begun production processing of the DCW data for the continent of Africa with the goal of eventual global coverage. Although many applications require topographic data with a resolution greater than 1 kilometer, this data set will be useful for many studies, especially those which require global or regional coverage at resolutions higher than that currently provided by ETOPO5.

Digital hypsography data of variable scale exist for selected areas of the globe. For example, Canada has digital vector topographic data derived from 1:250,000-scale sources available for the entire country (Energy, Mines and Resources Canada, 1990). Energy, Mines and Resources Canada also distributes 1:50,000-scale data for selected areas, and countrywide coverage is projected to be completed by the year 2000.

Processing of high-resolution digital hypsography data to create raster DEM's may be important for meeting some specific EOS requirements. Although it is not practical to create high-resolution global DEM coverage in this manner, data for specific regions or local sites can be generated.

Remote Sensing Sources

Optical stereo images are the most common remote sensing source employed for the generation of topographic data. Stereo aerial photographs have been the most widely used source for the production of topographic maps for many years. Digital stereo satellite images are another important source of topographic information. When stereo SPOT images became available in 1986, the possibility of generating topographic data from satellite images on a routine basis became a reality. Although SPOT is not a true mapping system because it does not acquire "simultaneous" stereo images, the availability of stereo satellite data spurred significant advances in image processing techniques aimed at automating the extraction of elevation data.

The Japanese Earth Resources Satellite (JERS-1) also carries an optical stereo sensor. Unlike SPOT, JERS-1 does collect simultaneous stereo images in the along-track direction. Large amounts of JERS-1 stereo data are not yet available but the use of the data as a source for DEM's has been demonstrated (Shimada, 1992).

Several satellite stereo sensors are planned for launch later this decade. The Advanced Visible and Near-Infrared Radiometer is a Japanese sensor scheduled for launch in 1996. The High Resolution Multispectral Stereo Imager, proposed for Landsat 7, and ASTER and MISR, on the EOS AM-1 platform, will collect simultaneous stereo images suitable for DEM generation. Stereo optical images will remain an important source for providing the topographic data required by EOS. Processing techniques are operational and relatively mature, and new sensors will increase the availability of suitable images.

SAR interferometry is a technique that uses two antennae with a known baseline separation to collect stereo radar images. Instead of measuring parallax between the images, the difference in phase between the radar returns is measured for each pixel. The phase difference is proportional to the difference in path length from each antenna to the surface and is thus influenced by elevation. A phase difference image is generated by registering the two SAR images and then performing cross correlation. Contours in the phase difference image correspond to contours of topographic height. By incorporating platform position and attitude information and (or) control points the phase differences are converted to terrain heights to create a DEM. Development of SAR interferometric techniques is an active research area. European Remote-sensing Satellite (ERS-1) SAR data have been used successfully to generate highly accurate DEM's (Prati and others, 1992).

A satellite mission carrying an interferometric SAR system has been proposed, and NASA has established a working group to analyze options. Several possible configurations have been presented for the Global Topography Mission (GTM), also known informally as Topsat. One configuration includes dual spacecraft orbiting at a controlled separation distance to maintain the required baseline. Each satellite would carry an L band radar. An alternative mission configuration calls for two Ka band radar antennae on one platform. The predicted accuracy of elevation measurements from both configurations is less than 6 meters.

The use of SAR interferometry has great potential for providing very accurate topographic data. Experiments with ERS-1 data have shown that elevation data with a vertical accuracy of 5 meters can be produced, and further advances should allow the production of data with an accuracy of better than 2 meters. Another major advantage of the technique is that cloud cover and illumination conditions do not affect data acquisition. It has been estimated that global coverage of interferometric SAR data could be acquired in 6 months by the proposed GTM.

## SUMMARY AND RECOMMENDATIONS

The topographic data requirements imposed by EOS instrument teams and interdisciplinary science investigations vary widely. Some requirements are met by existing data, but there are definite data shortages for numerous areas and applications. Ideally, a high-resolution, highly accurate DEM data base with complete coverage of the entire global land surface is the solution. A data base with a 100-meter grid spacing and an absolute vertical accuracy of 30 meters, which is technically feasible with current technology, would fulfill many requirements, including all geometric correction and geolocation requirements for MODIS and MISR data. Some radiometric correction requirements, especially those of higher resolution ASTER data, would not be met by such a data set.

A data base with the required detailed, accurate, and consistent global coverage does not exist, and it is unlikely that it will exist before the EOS AM-1 launch. Therefore, existing data must be used to the maximum extent possible, and future sources of topographic data must be evaluated to determine their usefulness for providing data that match the known requirements as closely as possible. Further study is required on the topographic data requirements of EOS, and one of the most important areas is algorithm dependency. Such analysis will produce the best understanding of the impact on science if specific data requirements are not met in the proper time.

Existing topographic data does fulfill some EOS requirements, although none of the useable data bases has complete global coverage. The 1-kilometer gridded elevation data derived from the DCW will be adequate for first-order atmospheric corrections (those that adjust for gross changes in atmospheric path length). DTED have the resolution and accuracy to meet the requirements for geolocation, geometric correction, and most radiometric processing of MODIS and MISR data. Generalized DTED would be more than adequate for coregistration of ASTER SWIR bands, and the DCW grids may even be adequate. The DTED data base, covering almost 70 percent of the global land surface, has the characteristics which match most closely to the globally consistent elevation data set that is required.

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Table 1.--Sensor parameters for MODIS, ASTER, and MISR.

| Sensor | Spectral bands | Pixel size (meters) | Field of view (degrees) | Swath width (km) | Maximum repeat cycle (days) |
|---|---|---|---|---|---|
| MODIS | 2 | 250 | ±55 cross track | 2,300 | 2 |
| | 5 | 500 | | | |
| | 29 | 1,000 | | | |
| ASTER | 3 | 15 | ±24 cross track | 60 | 16 |
| | 6 | 30 | ±8.5 cross track | | |
| | 5 | 90 | | | |
| MISR | 4 * | 250 (nadir) | ±70.5 along track | 364 | 9 |
| | | 275 | | | |
| | | 550 | | | |
| | | 1,100 | | | |

* Four bands for each of 9 cameras for a total of 36 channels.

Table 2.--Elevation (in meters) that causes 1-pixel displacement in MODIS data.

| Pixel size (meters) | Off-nadir scan angle (degrees) | | | | |
|---|---|---|---|---|---|
| | ±10 | ±20 | ±30 | ±40 | ±50 |
| 250 | 1,319 | 706 | 530 | 477 | 501 |
| 500 | 2,639 | 1,412 | 1,060 | 954 | 1,003 |
| 1,000 | 5,281 | 2,826 | 2,122 | 1,910 | 2,008 |

Table 3.--Elevation (in meters) that causes 1-pixel displacement in ASTER data.

| Sensor subsystem | Pixel size (meters) | Look angle (degrees) | | |
|---|---|---|---|---|
| | | ±2.4 | ±10.9 | ±25.9 |
| VNIR | 15 | 323 | 73 | 35 |
| SWIR | 30 | 646 | 146 | |
| TIR | 90 | 1,938 | 437 | |

Table 4.--Elevation (in meters) that causes 1-pixel displacement in MISR data from off-nadir cameras.

| Pixel size (meters) | Off-nadir view angle (degrees) | | | |
|---|---|---|---|---|
| | ±26.1 | ±45.6 | ±60 | ±70.5 |
| 275 | 491 | 211 | 78 | 5 |
| 550 | 982 | 422 | 157 | 10 |
| 1,100 | 1,965 | 844 | 313 | 20 |