Eos, Vol. 72, No. 41, October 8, 1991

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

EOS

VOLUME 72, NUMBER 41

OCTOBER 8, 1991

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Free Software Helps Map and Display Data

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Paul Wessel and Walter H. F. Smith

When creating camera-ready figures, most scientists are familiar with the sequence of *raw data → processing → final illustration* and with the spending of large sums of money to finalize papers for submission to scientific journals, prepare proposals, and create overheads and slides for various presentations. This process can be tedious and is often done manually, since available commercial or in-house software usually can do only part of the job.

To expedite this process, we introduce the Generic Mapping Tools (GMT), which is a free, public domain software package that can be used to manipulate columns of tabular data, time series, and gridded data sets and to display these data in a variety of forms ranging from simple x-y plots to maps and color, perspective, and shaded-relief illustrations. GMT uses the PostScript page description language, which can create arbitrarily complex images in gray tones or 24-bit true color by superimposing multiple plot files. Line drawings, bitmapped images, and text can be easily combined in one illustration. PostScript plot files are device-independent, meaning the same file can be printed at 300 dots per inch (dpi) on an ordinary laserwriter or at 2470 dpi on a phototypesetter when ultimate quality is needed. GMT software is written as a set of UNIX tools and is totally self contained and fully documented. The system is offered free of charge to federal agencies and nonprofit educational organizations worldwide and is distributed over the computer network Internet.

The original version 1.0 of GMT was released in the summer of 1988 when the authors were graduate students at Lamont-Doherty Geological Observatory, Columbia University. During our tenure as graduate students, L-DGO changed its computing environment to a distributed network of UNIX workstations and we wrote GMT to run in this environment. It was successful at L-DGO and soon spread to many institutions in the United States, Canada, Europe, and Japan.

The current version 2.0 reflects the many changes and new features we have implemented since the original release and addresses some of the minor shortcomings of the first version. Version 2.0 benefits from the many suggestions contributed by users of the first version, and includes 20 new tools, five new projections, and many other new, more flexible features. GMT 2.0 provides Earth scientists with a variety of tools for data manipulation and display, including routines to sample, filter, compute spectral estimates, and determine trends in time series; grid arbitrarily spaced data, perform mathematical operations (including filtering) on two-dimensional data sets both in the space and frequency domain, sample sur-

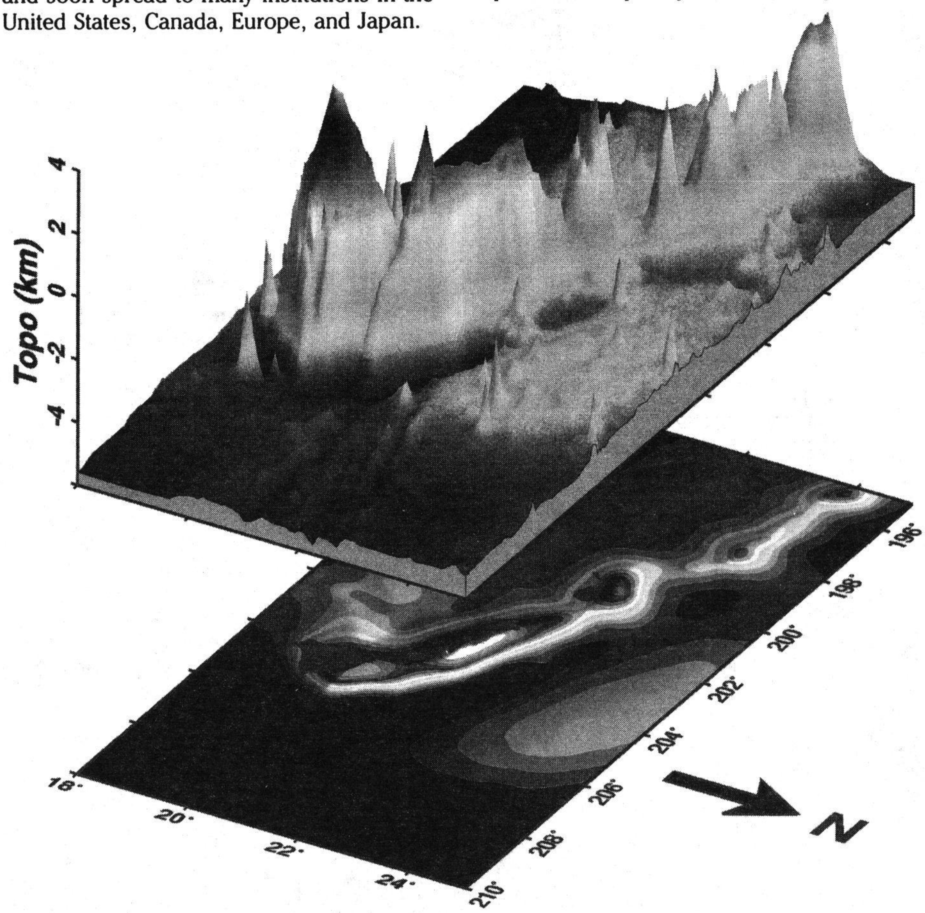

Fig. 1. Layer cake illustration of the bathymetric expression and the altimetric seasurface height of the Hawaiian island chain. The composite color figure was created with GMT and converted to a 2300 x 1800 x 24-bit rasterfile on a SUN Sparcstation 1 using the GMT utility psto24 (which requires SUN's xnews application). This rasterfile was subsequently plotted out on a Canon CLC-500 color laser copier to yield 300-dpi resolution. [*Original color image appears in the back of this volume.*]

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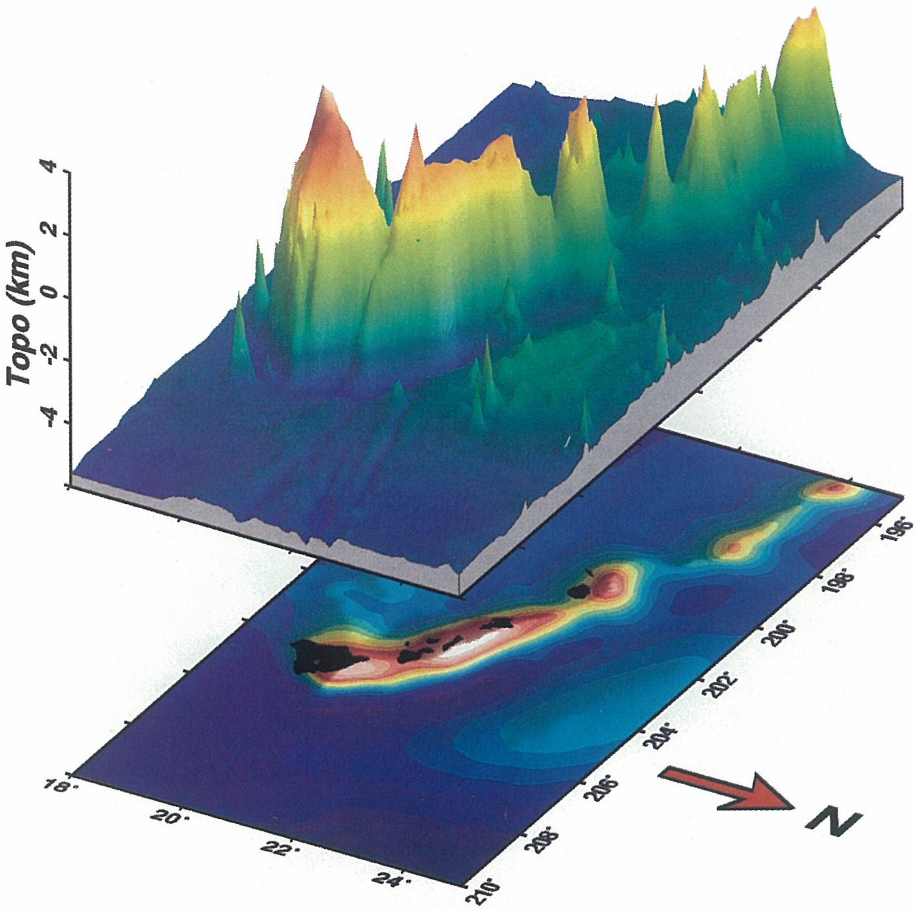

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faces along arbitrary tracks or onto a new grid; and find trend surfaces. The plotting programs will let the user make linear, $\log_{10}$, and x^a-y^b diagrams, polar and rectangular histograms, maps with filled continents and coastlines (choosing from seven common map projections), contour plots, mesh plots, monochrome or color images, and artificially illuminated shaded-relief and three-dimensional perspective illustrations.

GMT is written in the highly portable ANSI C programming language [*Kernighan and Ritchie*, 1988] and may be used with any hardware running UNIX, possibly with minor modifications. In writing GMT we have followed the modular design philosophy of UNIX: The *raw data → processing → final illustration* flow is broken down to a series of elementary steps; each step is accomplished by a separate GMT or UNIX tool. Benefits of this modular approach are that only a few programs are needed, each program is small and easy to update and maintain, each step is independent of the previous step and the data type and can therefore be used in a variety of applications, and the programs can be chained together in shell scripts or with pipes, thereby creating a process tailored to a user-specific task. The decoupling of the data retrieval step from the subsequent processing and plotting is particularly important, since each institution will typically have its own data base formats. To use GMT with custom data bases, one has only to write a data extraction tool that will put out data in a form readable by GMT (discussed below). After writing the extractor, all other GMT modules will work as they are.

GMT makes full use of the PostScript page description language [*Adobe Systems Inc.*, 1990] and can produce color illustrations if a color PostScript device is available A top-of-the-line color printer is not needed to take advantage of the color capabilities of GMT; several companies offer imaging services where the customer provides a PostScript plot file and gets color slides or hardcopies in return. Furthermore, general purpose PostScript raster image processors (RIPs) are now becoming available, allowing the user to create raster images from PostScript and plot these bitmaps on raster devices like computer screens, dot-matrix printers, large format raster plotters, and film writers. Because publication costs of color illustrations are high, GMT offers 64 common bit and hachure patterns, including many geologic map symbol types, as well as complete graytone shading operations. Additional bit and hachure patterns may also be designed by the user. With these tools it is possible to generate publication-ready monochrome originals on a common laserwriter.

GMT is thoroughly documented and comes with a technical reference and cookbook that explains the purpose of the package and its many features and provides numerous examples to help new users quickly become familiar with the operation and philosophy of the system. The cookbook contains the shell scripts that were used for each example; PostScript files of each illustration are also provided. All programs have individual manual pages that can be installed as part of the on-line documentation under the UNIX *man* utility. In addition, the programs offer friendly help messages that make them essentially self-teaching; if a user enters invalid or ambiguous command arguments, the program will print a warning to the screen with a synopsis of the valid arguments.

The processing and display routines within GMT are completely general and will handle any (x,y) or (x,y,z) data as input. For many purposes, the (x,y) coordinates will be (longitude, latitude), but in most cases they may be any other variables, such as wavelength or power spectral density. Since the GMT plot tools will map these (x,y) coordinates to positions on a plot or map using a variety of transformations (linear, log-log, and several map projections), they can be used with any data that are given by two or three coordinates. In order to simplify and standardize input and output, GMT uses two file formats only. Arbitrary sequences of (x,y) or (x,y,z) data are read from multicolumn ASCII tables, that is, each file consists of several records in which each coordinate is confined to a separate column. This format is straightforward and allows the user to perform almost any simple (or complicated) reformatting or processing task using standard UNIX utilities such as *cut, paste, grep, sed and awk*. Two-dimensional data that have been sampled on an equidistant grid are read and written by GMT in a binary "grdfile" using the functions provided with the netCDF library (a free, public-domain software library available separately from the University Corporation of Atmospheric Research [*Treinish and Gough*, 1987]). This XDR- (External Data Representation) based format is architecture independent, which allows the user to transfer the binary data files from one computer system to another. GMT contains programs that will read ASCII (x,y,z) files and produce gridded files. One such program, *surface*, includes new modifications to the gridding algorithm developed by *Smith and Wessel* [1990], using continuous splines in tension.

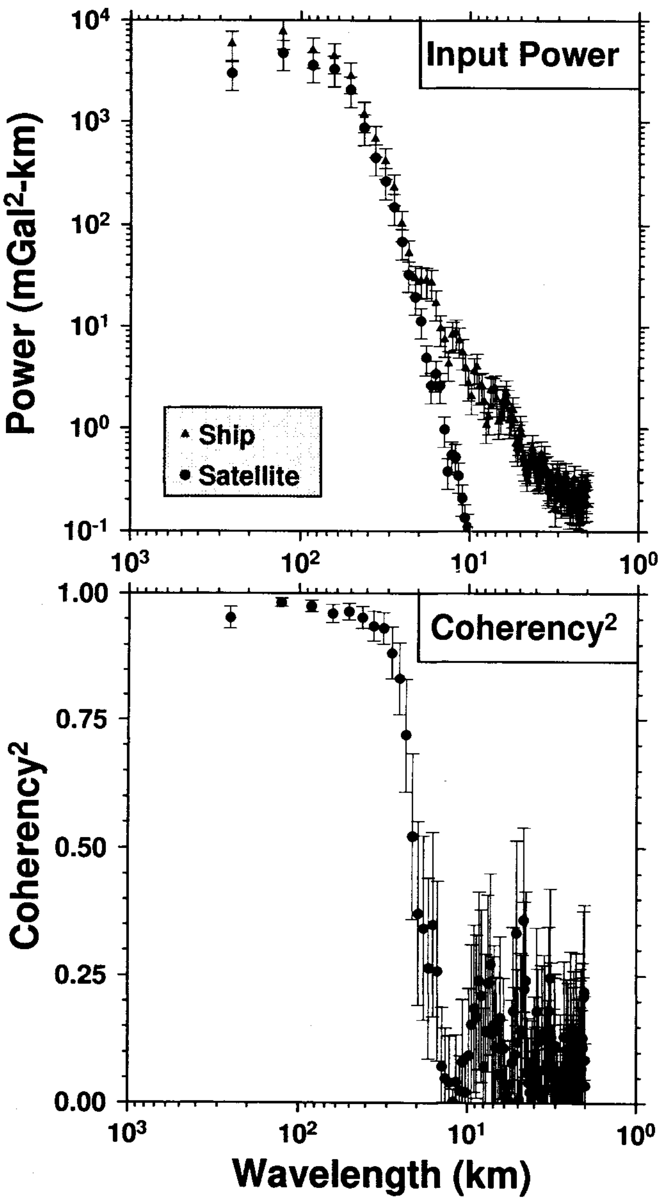

Fig. 2. Two $\log_{10}$ diagrams showing a spectral comparison between gravity anomaly estimates from ship gravity observations and Geosat altimetry. The composite black and white figure was created with a shell script running GMT programs that drew the symbols, axes, annotations, and legends. The illustration was printed on a 400-dpi laserwriter.

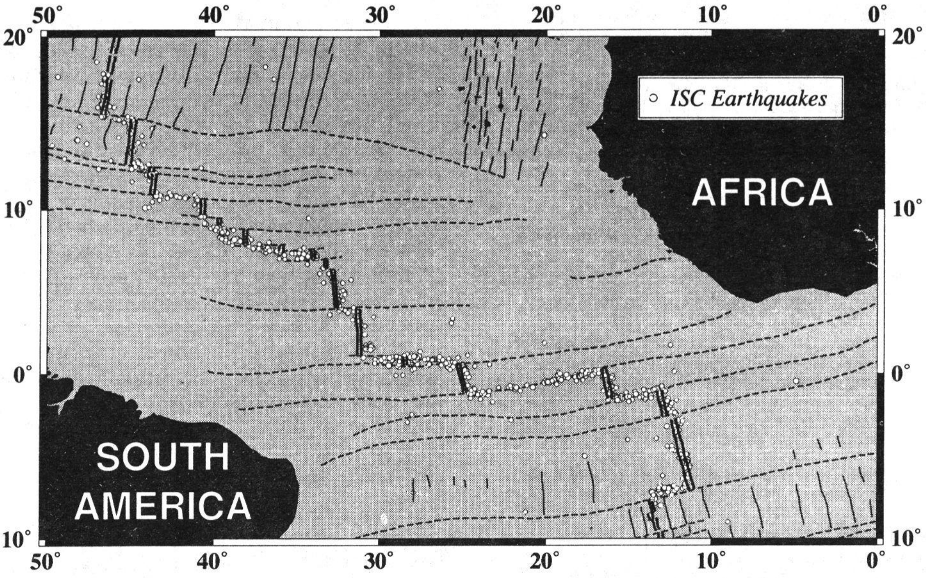

Fig. 3. Mercator basemap of the equatorial Atlantic Ocean. The continents were plotted using one of 64 available fill patterns. Several separate calls to psxy added the lines and earthquake symbols. The GMT utility pstext was used to overlay the labels. The final figure was printed on a 400-dpi laserwriter.

Most of the programs will produce some form of output that falls into four categories. Several of the programs may produce more than one of these types of output.

1. *One-Dimensional ASCII Tables*. For example, a (x,y) series may be filtered and the filtered values are output. ASCII output is written to the standard output stream.

2. *Two-Dimensional Binary netCDF "grdfiles."* Programs that grid ASCII (x,y,z) data or operate on existing grdfiles produce this type of output.

3. *PostScript*. The plotting programs all use the PostScript page description language to define plots. These commands are stored as ASCII text and can be edited should you want to customize the plot beyond the options available in the programs.

4. *Reports*. Several GMT programs read input files and report statistics and other information. Nearly all programs have an optional "verbose" operation, which reports on the progress of computation. All programs feature usage messages, which prompt the user if incorrect commands have been given. Such text is written to the standard error stream and therefore can be separated from ASCII table output.

To illustrate how GMT works, we present three case examples taken from our own research. The first example (Figure 1) shows a composite color plot displaying both the topography of the Hawaiian island chain and the Geosat sea-surface height viewed from the northeast. The bottom layer is a shaded-relief color image of the sea-surface height using a 1-m contour interval where each interval was assigned a fixed color. Variations in color within each interval are due to the artificial illumination from a light source due north. On top of this image we have plotted the outlines of the Hawaiian islands in black to mask out the Geosat data over land where it is not defined. To illustrate the bathymetry in the same region, we have superimposed a three-dimensional, illuminated perspective view of the ETOPO-5 data set [*National Geophysical Data Center*, 1988]. Here, color changes occur continuously as a function of both bathymetry and degree of artificial illumination. The complete illustration highlights several features of the Hawaiian Ridge: In the foreground of the bathymetry we clearly see the many strands of the Molokai fracture zone disappearing into the flexural moat. Furthermore, the flexural arch on the northern side shows up well in both images. This example uses four GMT tools: *grdraster* extracts the geoid height and topography grids from local data bases, *grdview* makes the color perspective views, *psxyz* makes the perspective draw and fill of the land areas, and *pstext* plots the title.

Our second example (Figure 2) shows an entirely different type of illustration made with GMT. In this case, we are comparing ship track gravity and Geosat-derived gravity. The upper panel in the figure is a log-log plot of the power spectra of the two data sets, and the lower panel shows the coherency between the two. We see that for wavelengths >20 km, the coherency is greater than 0.5, and the two spectra look similar. In this band, the ship power is generally somewhat higher than the satellite power, but the two are the same within one standard deviation. Figure 2 is drawn with the GMT tools *psxy* and *pstext*, which are used to plot the spectra and plot and annotate the inset box. However, not visible here is the fact that many additional GMT tools have been used to prepare this figure. The original data used in this figure were ASCII tables of (longitude, latitude, gravity) along ship and satellite tracks. We made this figure in several steps: we found the best fitting great circle to the satellite (x,y,g) data; projected each data set to (d,g) data, where d is a distance along the great circle; resampled these data equidistantly in d using an Akima spline; performed a cross-spectral analysis; and made the plot shown in Figure 2. GMT tools used were: *fit_circle*, *project*, *sample1d*, *spectrum1d*, *psxy*, and *pstext*.

The final example (Figure 3) illustrates how GMT can be used to create the type of location map that is often needed. The Mercator map shows the equatorial Atlantic Ocean, where we have plotted the location of earthquakes reported to the International Seismological Center. The solid and dashed lines are isochrons and fracture zones, respectively, taken from *Cande et al.* [1989]. Anomaly 1 isochrons were plotted with a wider pen, making the mid-ocean ridge easy to identify. The continents were added using the *pscoast* tool; the lines, symbols, and text were plotted using *psxy* and *pstext*. These examples show that GMT can run the whole gamut from simple monochrome x-y plots to complicated, three-dimensional perspective color illustrations. In our examples the GMT tools were used as commands to the shell interpreter, but could also be spawned from within other applications or user interfaces. An example of a graphical interface that can be configured to chain together a large number of GMT modules has been presented by *Davis* [1990].

The GMT-system is available over Internet at no charge. To obtain a copy, connect to kiawe.soest.hawaii.edu (Internet address 128.171.151.16) using anonymous ftp and copy the binary compressed tar archive "gmtv2.0.tar.Z" from the pub/gmt directory. Uncompress the file and extract its contents at your local site:

```
my_box% ftp 128.171.151.16
Name: anonymous
Password: <use your e-mail address as a
  password>
ftp> cd pub/gmt
ftp> binary
ftp> get gmtv2.0.tar.Z
ftp> quit
my_box% zcat gmtv2.0.tar.Z | tar -xBf -
```

The tar archive contains information on how to install GMT on your hardware platform. It also contains a license agreement and registration file. Users who fill out and return this form will be put on an electronic mailing list and kept informed about bug fixes and upgrades. For those who cannot access the package over the network we can arrange to send it on a 9-track tape (1600/6250 bpi) or data cartridge in QIC-24 or 8-mm format for small fee to cover tape, handling, and shipping expenses. The compressed tar archive is about 3 megabytes, so we cannot accommodate floppy disk requests. If you must order a tape, include return address and a send check for $100 payable to University of Hawaii to Paul Wessel, SOEST, 2525 Correa Road, Honolulu, HI 96822. For more information on how to obtain GMT, send e-mail to gmt@soest.hawaii.edu or a letter to one of the authors.

GMT has served a multitude of scientists very well, and their responses have prompted us to develop these programs even further. It is our hope that the new version will satisfy these users, as well as attract new users. We present this system to the community in order to promote sharing of research software among investigators in the United States and abroad.

(School of Ocean and Earth Science and Technology contribution 2660.)

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Panel Calls for Smaller EOS, Caution on Data System

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A review panel has apparently dealt the decisive blow to the use of massive platforms for NASA's Earth Observing System. The engineering review panel, chaired by Edward Frieman, director of Scripps Institution of Oceanography, also urged NASA to cooperate with the Departments of Defense and Energy and the National Oceanic and Atmospheric Administration to get EOS off the ground as quickly as possible. The panel also expressed considerable skepticism about EOSDIS, the system's vast information system.

Frieman discussed the panel's findings on September 26 before the House science committee's subcommittee on space. The panel, charged by the president in March 1991 with reviewing the platform configuration and launch sequence of EOS, released its report on September 23.

Ralph Hall (D-Tx.), the subcommittee's chair, endorsed the division of EOS into smaller components. "If we break these payloads up into smaller chunks, we may lose $2 million but we won't lose $2 billion if something went wrong," he said.

The review committee supported the deployment of EOS instruments on several satellites that could be launched sooner than a large platform and fixed or replaced faster if they failed. The smaller-component approach would also offer more fiscal flexibility with the uncertain budgets NASA is facing.

Frieman admitted that a scaled-down EOS would not meet all of NASA's science objectives. "The committee recognizes that some science is lost from the original $16 billion program, since some of the original instruments will be delayed and some may never fly," the report said. But the new program could get off to an earlier start and benefit more from technical innovations because of its greater flexibility.

Lennard Fisk, NASA's associate administrator for space science, said at the hearing that the agency fully supported the committee's recommendations. "The reality is that we are on a fast track to reconfigure this program on intermediate size spacecraft," he said.

NASA had pressed strongly for large platforms earlier this year, arguing that they would enable simultaneous measurements that are vital to answering climate change questions. At the hearing, Fisk said that simultaneity was still a key concern and that the project would now have to work harder to achieve it by flying some satellites in formation.

Hall and other members of the space subcommittee asked extensive questions about the launch options for EOS. Originally, only the small Delta and large Titan IV were available on the West Coast, where satellites must be launched to attain the polar orbit required for global mapping. The Air Force may soon prepare an intermediate size facility for Atlas rockets at a West Coast location, however.

The review panel only learned about the new option in the midst of its discussions, Frieman said, and the possibility further swayed the panel to recommend a reconfigured EOS. The panel took the position that "the flight of EOS instruments on intermediate and smaller platforms launched with Atlas and Delta class and smaller rocket boosters is a better option." In any case, Fisk argued, the EOS instruments have to be selected before the launch vehicle is chosen.

The review panel also called for NASA to expand participation in EOS to other U.S. agencies so that policy questions about climate change could be answered sooner. "You can't hold NASA's feet to the fire and say deliver earlier information" without providing the resources for it to do so, Frieman said.

The panel advised particular caution about EOSDIS, calling for "NASA to proceed slowly with plans to put implementation into the hands of a single industrial contractor." NASA says it plans to select a contractor for the data system in May 1992. The panel also said that the data system must be revamped to suit the new satellite program it will support. "EOSDIS should not develop a life of its own," it warned.

The panel did not fully review the data system, argues Jeff Dozier, EOS project scientist. He calls its recommendations on the system "inconsistent"—on the one hand, he says, the panel supports NASA's emphasis on proceeding with the EOSDIS prototype, yet it also advises the agency to proceed cautiously on naming a contractor.

At the hearing, Hall showed concern about whether NASA would actually embrace the review panel's recommendations for EOS. Frieman agreed that his panel would reconvene to evaluate implementation of the recommendations.—*Lynn Teo Simarski*

Congress Sets NASA, NSF Budgets for 1992

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Space Station Freedom emerged a clear winner from the House and Senate conference on September 26, which was Congress's final action of the year on the NASA budget. Selected members from the appropriations committees of both houses ironed out a compromise between the Senate and House budget bills that cover NASA and the National Science Foundation.

The conference report, as the compromise is called, followed the general approach of the Senate rather than that of the House in funding NASA for FY 1992. NASA will receive $1.4 billion less than the $15.7 billion requested by the president.

Freedom was fully funded at $2.028 billion for FY 1992, although spending on the station was capped at $2.25 billion for 1993. The conference temporarily abolished the caps that the Senate had established for many other NASA programs, while directing the agency to prepare its own caps.

The conference took $28.9 million from the Cassini Upper Stage, resulting in a 1-year schedule slip. The Senate had completely cancelled the Comet Rendezvous Asteroid Flyby, a related project. The conference, however, restored CRAF while somewhat paradoxically deleting $117.3 million from CRAF/Cassini and observing that Germany will likely pay for part of the mission.

Other cuts included $60 million from the Advanced X-ray Astrophysics Facility, the full $15.9 million for the Space Infrared Telescope Facility, the full $11 million for the Orbiting Solar Laboratory, and $2.2 million from the $29.4 million request for Gravity Probe "B." The conference added $22.5 million to the Mars Observer mission's $54.4 million request to cover unanticipated cost overruns.

The budget request for the Earth Observing System sustained a $65 million cut, $15 million more than the Senate had deleted. The full request of $82.6 million for EOSDIS, the project's data system, was granted. EOS's baseline was capped through the year 2000 at $11 billion, confirming the Senate's reduc-