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DETERMINATION OF OCEAN GEODETIC DATA FROM GEOSAT

The major objective of the GEOSAT satellite is to collect a dense set of high-quality radar altimetry measurements over the world's oceans. The measurements are then processed to obtain ocean geodetic data, geoid heights, and vertical deflections and are combined with other data to provide operational support to Navy and Department of Defense missions. This article outlines the procedures used at the Naval Surface Weapons Center's Dahlgren Laboratory in making the transition from radar altimeter measurements to ocean geodetic data.

INTRODUCTION

Satellite radar altimetry for ocean geodetic purposes has reached maturity with GEOSAT. GEOS-3[1] and Seasat,[2] the predecessors of GEOSAT, were launched in 1975 and 1978, respectively. GEOS-3 proved the concept of ocean geodesy measurements by satellite radar altimeters and acquired a significant set of data. Seasat obtained improved accuracy by using newer technology and data processing, but it experienced a complete power failure after only three months in orbit, an inadequate length of time to acquire a sufficiently dense set of measurements to meet Department of Defense ocean geodetic requirements. GEOSAT was launched in March 1985 and benefited by carrying a further improved radar altimeter (see MacArthur's article elsewhere in this issue) and improved orbit-determination and data-reduction procedures.

The radar measures the distance from the radar antenna electrical center to the instantaneous sea surface as averaged over the footprint width (several kilometers). The size of the effective footprint depends on sea state as well as the length of the radar pulse. In order to obtain a mean sea surface with respect to a reference surface, the orbit and many system and environmental corrections must be calculated; they are shown in Fig. 1. The Naval Surface Weapons Center (NSWC) uses the WGS84 reference ellipsoid as the reference surface for GEOSAT. The mean sea surface thus obtained will approximate the geoid (equipotential surface), differing from the true geoid by measurement noise, errors in the corrections, and oceanographic effects (currents, thermal–salinity gradients, etc.). The orbit errors have been significantly reduced from the Seasat values as the result of improved gravity models and improvements in the Doppler tracking network; this will be discussed further in the next section. While most of the environmental corrections are made just as they were for Seasat, there have been improvements in the tide model and data-editing procedures, and the magnitude of the ionospheric cor-

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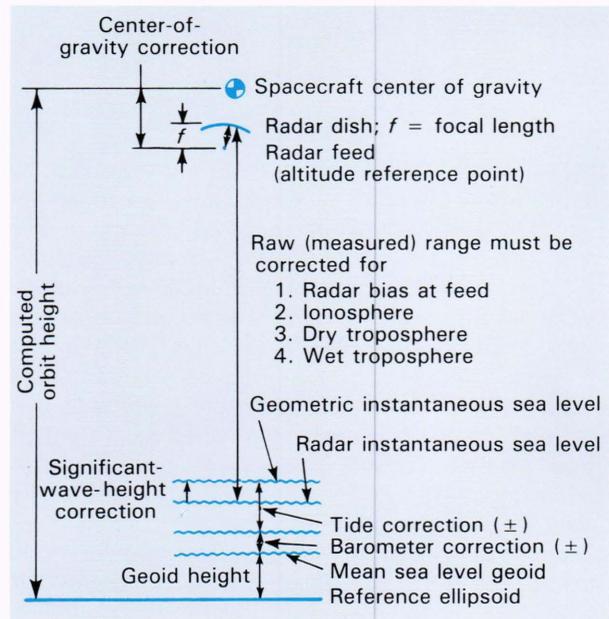
Figure 1—Altimeter data reduction.

rection is less than it was for Seasat. We do not have enough information worldwide to make intelligent corrections to remove the oceanographic errors. The section entitled Computation of Geodetic Data outlines the data sources and procedures used to derive the geodetic data products.

DOPPLER ORBIT COMPUTATIONS

The ephemeris of the GEOSAT satellite is computed in two-day spans using observations made by the combined TRANET/1502-DS Doppler tracking network (Fig. 2). The Magnavox 1502-DS receivers have more stable oscillators than were used in previous satellite receivers.

The computed orbits are based on Doppler measurements made on the continuous-wave signal generated by the spacecraft at 150 and 400 megahertz. Two frequencies are used to correct for first-order ionospheric effects

Figure 2—GEOSAT Doppler tracking network.

on the signal. Observations are made at 50 sites distributed worldwide, resulting in about 225 station passes each day. The data observed on each pass are used to determine two components of the position of the satellite at the time of its closest approach to the station; these are often called navigation errors.[3] One component is the station–satellite range (the "radial error"), and the other is along the velocity vector of the satellite (the "tangential error"). While orbit computations are actually based on least-square fits made to range differences computed from the observed Doppler counts, the navigation errors provide a diagnostic that is useful in evaluating and interpreting the quality of the orbit fit.

Orbits are computed using the Doppler observations in the NSWC Celest Computer Program described by O'Toole.[3] The technique is an iterative one of weighted least squares where the data are edited and weighted within the program. Trajectories are formed by directly integrating the equation of motion in the inertial frame. The force equation has components resulting from the gravitational effects of the earth, sun, moon, solar radiation pressure, thrust, and atmospheric drag. The latest Defense Mapping Agency Earth Gravity Model is used in the orbit computation. The value used for the earth's gravitational constant is 398600.5 kilometers cubed per seconds squared. The Doppler observational data were corrected to the center of mass of the satellite with the use of the following corrections to the antenna offset from the center of mass:

Radial component	$= -2.9840$ meters
Along-track component	$= 2.2548$ meters
Cross-track component	$= 0$ meter

The estimated error of the height of the satellite is less than 1 meter rms, with the principal component of the error having a wavelength equivalent to the orbital period of the satellite.

COMPUTATION OF GEODETIC DATA

This section describes the procedure for computing the best estimated along-track geoid heights and vertical deflections. The procedure entails the computation of environmental corrections, elimination of spurious data points, separation of data over land/ice and water, computation of subsatellite position and velocity, computation of sea-surface heights, and application of spacecraft system and environmental corrections. In addition, it uses an adaptive Kalman smoother to obtain the best estimated along-track geoid heights and vertical deflections. Figure 3 shows the procedures described below under the subheadings Inputs, Corrections, Preprocessor, and Adaptive Kalman Smoother.

Inputs

The major inputs to the procedure are Sensor Data Record tapes, Doppler precise orbits, climatology data, tide constants, coastline coordinates, and sunspot numbers. The Sensor Data Record tapes provide the altimeter heights, spacecraft system corrections, and other auxiliary information and are received from APL by messenger biweekly. Doppler precise orbits are used in the computation of subsatellite position and velocity and sea-surface heights. The worldwide climatology data (temperature, atmospheric pressure, and partial pressure of water vapor) are transmitted daily from the Fleet Numerical Oceanography Center, Monterey, Calif., over the Naval Oceanographic Data Distribution System. Algorithms for computing barotropic, wet, and dry tropospheric refraction corrections require the climatology data. The tide amplitudes and phases are computed using the Schwiderski model,[4] and the results are used in the determination of the tide correction.

The Central Intelligence Agency World 2 Database of coastline coordinates was used to generate a masking grid for separation of land/ice and water data. The database

DMA/AC - Defense Mapping Agency/Aerospace Center
DMA/HTC - Defense Mapping Agency/
                 Hydrographic Topographic Center
FNOC - Fleet Numerical Oceanography Center
GDR - Geophysical Data Record
IGDR - Intermediate Geophysical Data Record
NAVOCEANO - Naval Oceanographic Office
NSWC - Naval Surface Weapons Center
SDR - Sensor Data Record
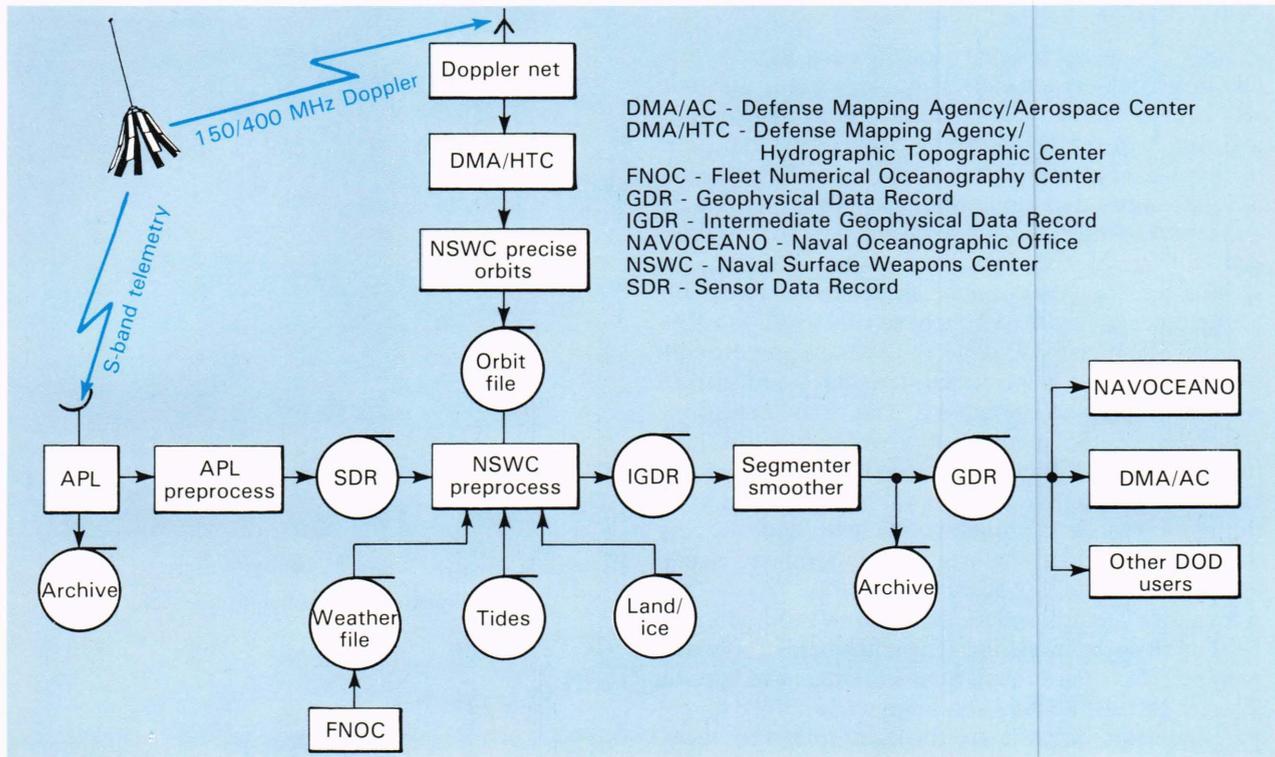
Figure 3—GEOSAT data flow.

was acquired from the Naval Oceanographic Office, Bay St. Louis, Miss. The ionospheric refraction model requires the predicted monthly sunspot numbers acquired from the National Oceanic and Atmospheric Administration's National Geophysical Data Center, Boulder, Colo.

Corrections

The altimeter height, determined by calculating the time required to transmit the radar signal from the spacecraft to the ocean surface and return, is corrected for environmental, instrument, and spacecraft system errors. Corrections for instrument and spacecraft errors are provided on the Sensor Data Record tape and are described in the System Interface Control Document.[5] Environmental corrections include wet tropospheric refraction, dry tropospheric refraction, barotropic pressure loading, ionospheric refraction, and ocean and solid earth tides. The barotropic, wet, and dry tropospheric models employ the climatology fields provided by the Fleet Numerical Oceanography Center. In instances where climatology data are missing, standard values are used in the models. The ionospheric refraction correction is computed using a model scaled by the monthly average sunspot numbers.

Preprocessor

The altimeter heights are preprocessed, then combined with the orbit heights and environmental corrections to give the sea-surface heights that are input to the Kalman smoother. Preprocessing involves the separation of land/ice and water data and the elimination of spurious al-

timeter heights. Data separation is accomplished by using the coastline coordinates masking grid derived from the Central Intelligence Agency World 2 Database, and land/ice and water data are stored as two different data files. The land/ice data are used for topographic studies, and the geodetic products are generated from the water or ocean data.

Four tests are used in the elimination of spurious altimeter heights: boundary values for heights, boundary values for standard deviation of heights, status of the automatic gain control, and status of the mode word. A sliding linear least-squares fitting procedure is applied to the heights to remove any spurious heights undetected by the previous tests. The significant wave height and the automatic gain control are processed by a procedure similar to the one for the heights.

Adaptive Kalman Smoother

The sea-surface heights, separated by satellite revolutions and divided into time-continuous segments, are inputs to an adaptive nonsteady-state Kalman smoother. The smoother is based on a third-order Markov process[6] and was adapted for the altimeter by C. J. Cohen as given in Appendix A of Ref. 7. An adaptive algorithm[8] was used to provide improvements to the set of a-priori smoother parameters, autocorrelation distances, geoid height variance, and noise standard deviation. The Kalman smoother produces the final geodetic products, best estimated along-track geoid heights, and vertical deflections in time-continuous segments. These are written to tape and comprise the filtered geodetic data records sent to users.

ACCURACY

NSWC analyzes selected geodetic data derived from GEOSAT both as a means of quality control for data sent to users and to determine the nature, magnitude, and source of residual errors in the geodetic data. The methods used in these analyses are (a) self-consistency at intersections and along repeat or near-repeat tracks and (b) comparisons with independent data such as those derived from shipboard gravimetry, where available. The spectral content receives particular attention, since many of the potential error sources have characteristic wavelengths. The numerical results of these analyses are classified and cannot be presented here, but a few general statements may be of interest. The orbit error (long wavelength), although much improved over the orbit error in Seasat, continues to be the largest. Techniques based on intersection analysis will minimize that error in the final geodetic products. The lower solar activity during GEOSAT results in smaller ionospheric errors, and the large database acquired over the 1½-year time span allows all atmospheric errors to be reduced in the final products by averaging. The magnitudes of oceanographic effects (such as current systems) have become a larger part of the total error budget. Since we do not have enough information worldwide to correct for them, the GEOSAT geoid will have strong oceanographic signals aliased into it. To start attacking the aliasing, the worldwide dynamic-anomaly heights were computed using the Levitus[9] model for each GEOSAT data point and included on the along-track data file. Figures 4 and 5 (with all numbers removed for classification reasons) are examples of small-area geoid height contours and three-dimensional surface projections of the GEOSAT geoid.

SUMMARY

Observations from over 6000 revolutions of GEOSAT (over 360 million observations) have been reduced to along-track geodetic data (geoid heights and vertical deflections) using the system of computer programs described above. These data have been examined graphically and distributed to the Defense Mapping Agency Aerospace Center, St. Louis, Mo.; the Naval Oceanographic Office, Bay St. Louis, Miss.; and other specified Department of Defense users. Analysis has shown the quality of the geodetic data to be outstanding. The oceanographic effects aliased into the geoid are now the predominant uncorrectable error sources, but GEOSAT may give researchers the data that could lead to accurate modeling (and therefore allow removal from the GEOSAT geoid) of the oceanographic signals. At the end of the geodetic mission, an orbit change is planned, and GEOSAT will commence the Oceanographic Exact Repeat Mission (see the article by McConathy and Kilgus elsewhere in this issue).

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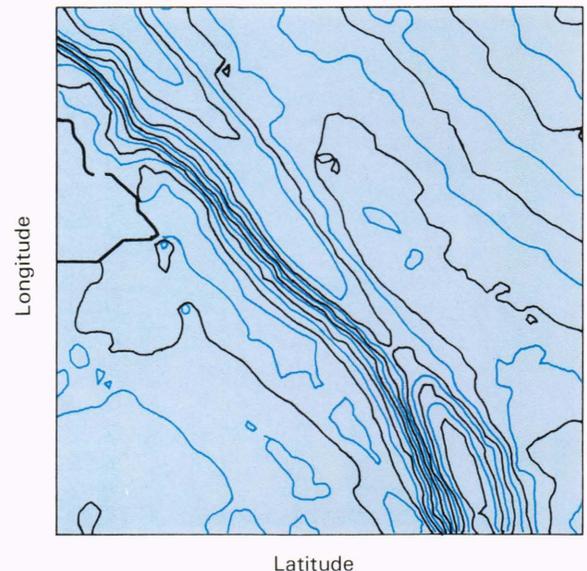
Figure 4—Geoid height contours.
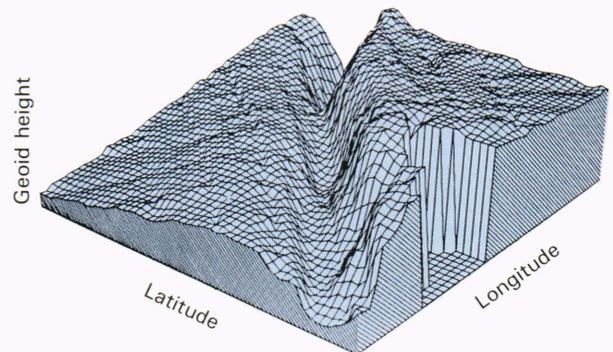
Figure 5—Sample geoid surface.

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