Skylab Earth Resources Experiment Package (EREP): Sea Surface Topography Experiment

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The S-193 Skylab radar altimeter was operated in a round-the-world pass on Jan. 31, 1974. The main purpose of this experiment was to test and "measure" the variation of the sea surface topography using the Goddard Space Flight Center (GSFC) geoid model as a reference. This model is based upon 430,000 satellite and 25,000 ground gravity observations. Variations of the sea surface on the order of −40 to +60 m were observed along this pass. The "computed" and "measured" sea surfaces have an rms agreement on the order of 7 m. This is quite satisfactory, considering that this was the first time the sea surface has been observed directly over a distance of nearly 35,000 km and compared to a computed model. The Skylab orbit for this global pass was computed using the Goddard Earth Model (GEM 6) and *S*-band radar tracking data, resulting in an orbital height u ainty of better than 5 m over one orbital period.

Introduction

THE S-193 Skylab radar altimeter was operated in a round-the-world pass on Jan. 31, 1974 over a ground track starting off the coast of Brazil and ending in the Caribbean Sea. This long arc of almost 1 rev or approximately 35,000 km has provided, for the first time, a basis for a comparison along one ground track on the Goddard geoid (approximately the sea surface) and the geoid as "measured" from space using the Skylab altimeter.

Figure 1 shows the ground track of the Skylab superimposed on the Goddard geoid. The purpose of this experiment was twofold: 1) to "test" and/or "measure" the variation of the sea surface topography along the Skylab ground track using the Goddard gravity field GEM 6[1] and the Goddard geoid[2] as a reference, and 2) to evaluate the capability of the altimeter to operate over much longer arcs than was done previously.[3]

The Wallops Skylab instrument 3-6 originally was designed to operate in short predetermined modes that sequence through a routine of data-taking, calibration, and automatic turnoffs. Therefore, the mission had to be run in a series of short altimeter arcs containing gaps where height measurements were reinitialized (see Fig. 1). A revolution was chosen to maximize tracking coverage over the oceans and to obtain a good orbit. A good orbit here means an orbit with small height errors, that is, better than 5 m, as mentioned. No specific attention was paid to the along- and cross-track errors, since those errors will not influence the results presented. This means that the detected ocean surface features may be in error in longitude and latitude by, say 50 to 80 m, which is not significant.

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Analysis and Results

Analysis and evaluation of the experimental altimeter data were accomplished by comparing these data with "computed" altimeter values. These "computed values" are the differences of the satellite geocentric position $r(xyz)$ and the Goddard geoid $R(xyz)$ (see Fig. 2).

The sea surface topography consists of a time-varying and a constant part. The latter can be considered the geoid. The time-varying portion is due to tides, currents that introduce geostrophic height variations of the ocean surface, storm surges, pileups, etc. This component is, in general, on the order of 1 to 2 m. The ocean surface, except for tidal, current, and wind effects, etc., follows an equipotential surface. The equipotential surface of the Earth which most nearly corresponds to mean sea level is commonly referred to as the geoid. The geoid is irregular in shape because of the variation of the mass and density distribution within the Earth. In order to describe the geoid mathematically, an ellipsoid is adopted which best fits the geoid. The separation of the geoid above or below the reference ellipsoid is defined as the geoidal undulation N(see Fig. 2). A good estimate of N can be derived from the altimeter measurements when the satellite orbit is assumed as a reference. The relationship between geoidal undulations and the satellite altitude measurements is given by

$$r \doteq H + (N/\cos\delta) + R_{ell} + \Delta = H + R_{geoid} + \Delta$$

where

r = geocentric radius vector to the satellite
H = altimeter height measurements
N = geiodal undulation
R_{ell} = geocentric radius vector to the reference ellipsoid
R_{geoid} = geocentric radius vector to the geoid
Δ = time-varying part of the sea surface topography
δ = angle between the geocentric radius vector to the satellite and the normal to the ellipsoid

It is evident from the equation that any radial orbital errors will propagate directly into errors in the geoid height N.[9] Particular attention therefore was paid to minimize these errors in the required orbital computations. Two rs make the determination of accurate Skylab orbits a difficult task. First,

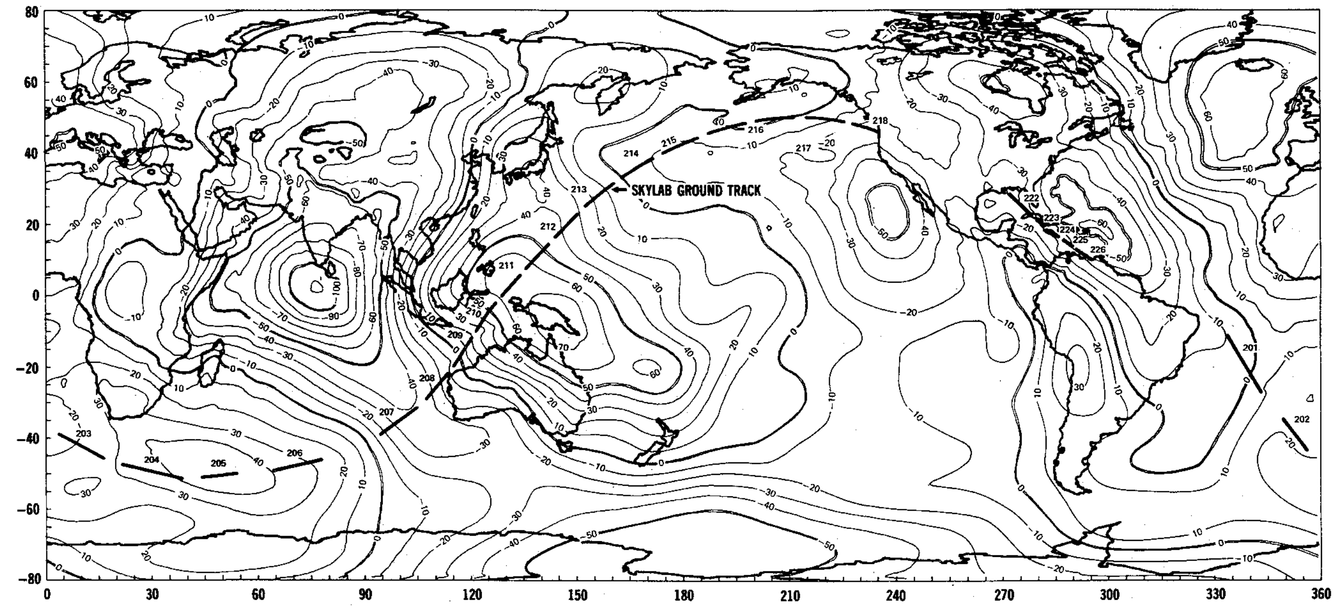

Fig. 1 NASA Goddard Space Flight Center gravimetric geoid (a_e = 6378. 142 km; GM = 398,600.9 km^3/sec^2; $1/f$ = 298.255).

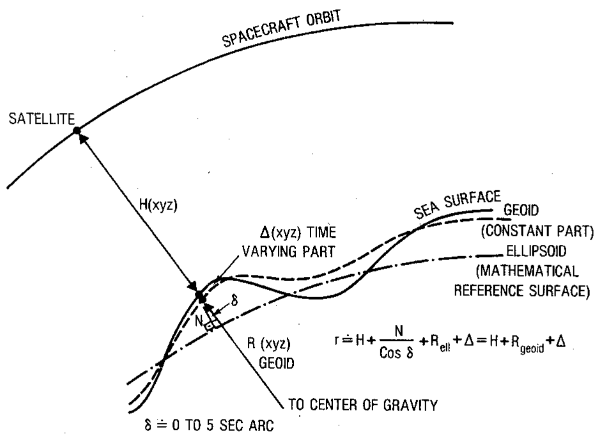

Fig. 2 Sea surface topography measured with satellite altimetry.

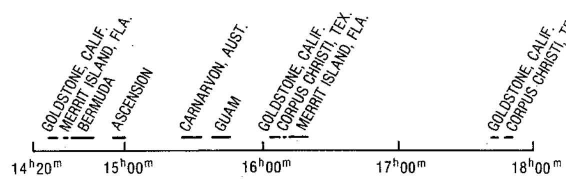

Fig. 3 Tracking data used for Skylab-4 globe orbit computation.

the altitude of the Skylab orbit is rather low, namely, 440 km, and thus the atmospheric drag has a large effect on the satellite orbit accuracy obtainable. Secondly, thrusting is used for spacecraft maneuvers both before and after the altimeter data are acquired which will cause further errors in the orbit.

Orbit error analyses have shown that, in order to minimize systematic errors effects due to drag, thrusting, and geopotential, the length of arc fitted should be kept as short as possible. The arc length chosen for orbit determination on the "around-world" pass was apprtely 3½ hr. The tracking data were provided by the Goddard Space Flight Center, Unified S-band System (USB). Figure 3 shows the tracking station distribution used. For orbit determination, only the two-way average range-rate data provided by the USB system were used. These data were averaged over 60 sec, resulting in a two-way Doppler error of approximately 3.7 cm/sec.

In order to assess the accuracy of this computed orbit, an error analysis was made of the orbit determination process for

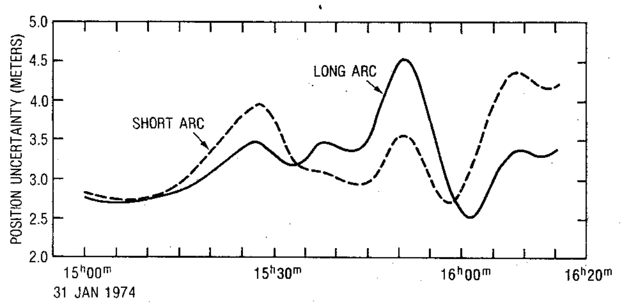

Fig. 4 Skylab-4 radial orbit uncertainties from error analysis.

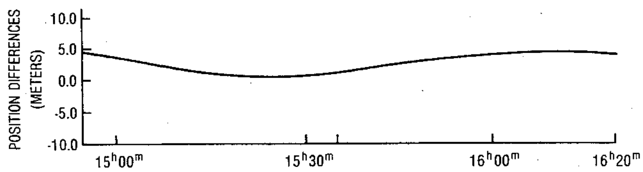

Fig. 5 Skylab-4 Fig. 5 Skylab-4 radial position differences between long-arc and short-arc orbits.

this particular data set. Figure 4 is a plot of the estimate of the radial orbital errors due to noise, drag, gravity field and station survey. The error curve of Fig. 4 labeled "long arc" (~3 hr) is a plot of the expected uncertainty based on all of the tracking data shown in Fig. 3. The curve labeled "short arc" (~ 90 min) is a plot of the expected uncertainty if the orbit is determined by omitting the last passes of tracking data from California and Texas. These two curves illustrate that one can obtain an orbit that minimizes errors in a specific area of interest. Error studies are certainly important, and they are being used in our investigations; however, caution must be exercised in their interpretation, since it is very difficult to compare "computed" errors with real ones.[8] Using the "overlap" method,[7,8] the "long-arc" and "short-arc" orbits based upon actual tracking data were compared as a further means of assessing the magnitude of the orbit errors. These differences are presented in Fig. 5. Overall, the 3-hr arc seems to be preferable. However, if individual subsets of the data are to be studied, the orbit determination process can be optimized for that particular region.

Analyses of artificial Earth satellite orbital perturbations have provided the long-wavelength components (greater than

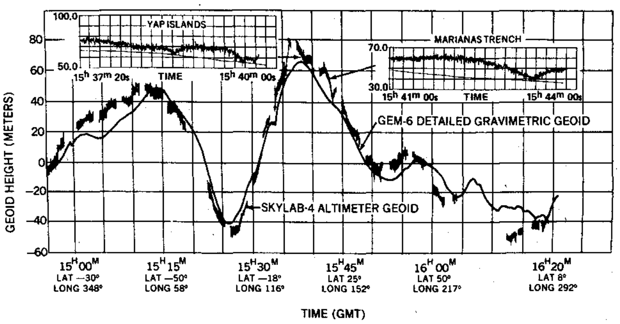

Fig. 6 Comparison of Skylab-4 altimeter geoid and the GEM-6 detailed gravimetric geoid.

3000 km) of the geoidal undulations N on a world-wide basis.[1] In order to provide a more accurate representation, particularly with respect to the wavelengths shorter than those resolvable with satellite observations (less than 3000 km), the Goddard geoid presented in this paper has been computed by integrating $1° \times 1°$ surface gravity data through Stokes' formula in an area of $20° \times 20°$ centered on the computation point.[2]

Analyses made to estimate the precision of the GSFC gravimetric geoid demonstrated that a high correlation exists between the precision of the geoid and the availability of surface gravity data and satellite observations. For example, in the North Atlantic, where surface data and satellite observations were relatively abundant, the errors in N are in the range of ± 2 m. In the South Atlantic and South Pacific, where data are less abundant, the errors are generally in the 5- to 10-m range. Thus, the detailed geoid seems to be sufficiently accurate in most parts of the world to be used as ground truth for a first global evaluation of radar altimeter probing of the sea surface. Altimeter data can be used further to grossly test long-wavelength geoidal undulation errors of various published satellite gravity models. Assuming that the altimeter data are correct, as proven in areas of the world where the geoid is known better, the undulations in the southern hemisphere, where observations are lacking, thus can be evaluated.

Figure 6 presents the geoid profile based upon the global altimeter pass along with detailed gravimetric geoid profile computed using the Goddard GEM 6 model. The overall level of agreement is quite good. The rms difference between the altimeter-derived profile and the profile derived from the gravimetric geoid is in the order of 6 to 8 m. These differences are due to errors in the computed orbit, the gravimetric geoid, and radar altimeter system. Differences as large as 20 m can be observed in some areas. These differences are attributable primarily to a lack of surface gravity data in the computed gravimetric geoid along this particular ground track, as well as to the presence of very short-wavelength features not modeled in this geoid. For example, large differences are noted in Fig. 6 when Skylab crossed the Yap Island and the Marianas Trench. Both of these features are represented by very large gravity anomalies. These features were not in the gravimetric geoid, since these areas lacked sufficient coverage with surface data. In other areas of Fig. 6, the differences are due to long-wavelength errors in the satellite-derived models, as well as the uncertainty in the altimeter determination of the geoidal undulations. In the region of $-30°$ lat, $348°$ long to $-50°$ lat, $58°$ long, the bulk of the differences probably can be attributed to long-wavelength errors in the gravimetric geoid, since Figs. 4 and 5 indicate that orbit uncertainty is expected to be less than 5 m during this time.

It is evident, therefore, from the preceding discussion that the rms difference of 6 to 8 m between the gravimetric geoid and the global pass of altimeter data is largely due to uncertainty in the gravimetric geoid along this particular ground track. Thus, the precision of the altimeter data is estimated to

Conclusions

Previously published analyses have shown that the satellite altimeter could detect rather small variations of th surface topograp)say, 15 m deep, 150 km wide) such as the Puerto Rico trench and sea mounts. Features ois nature generally were not easily detectable with other techniques, used in the past. As a result of the analysis of the "around-the-world" pass, additional conclusions have been drawn.

1) The Skylab altimeter has been quite successful in measuring directly the long-wavelength (4000 km) undulations of the geoid to within a few meters. It should be noted, however, that variations of the sea surface topography due to currents, tides, winds, etc., have not been taken into consideration because they are too small (1 to 2 m) to be detected yet.

2) Numerous short-wavelength (~ 100 km) features such as the Marianas Trench and the sea surface variations near the Yap Island have been observed directly for the first time.

3) The orbit determination process can be designed so as to minimize orbit uncertainties over certain areas of interest. It should be noted, however, that the Skylab tracking data are rather limited. In this respect, we are looking forward to a considerable improvement in orbit determination accuracy by using GEOS-C, the first NASA altimeter spacecraft which was launched in April 1975 into a much more stable orbit of 800 km.

4) Finally, this new satellite-borne altimeter system will provide a global homogeneous set of data which can be used to study short-period dynamic ocean processess, e.g., ocean currents and tides.

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