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Deep Sea Tides Determination From GEOS-3

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Introduction

One of the outstanding problems of geophysics is the global determination of the oceanic tide. The coastal tide can be markedly different from the oceanic tide due to the influence of bottom topography (Redfield, 1958). Many measurements exist of the coastal tide, but few are known in the deep sea. If a radar altimeter on a satellite could adequately detect deep-sea tides (NASA, 1969), the need for sea-floor pressure gages could be significantly reduced. Zetler and Maul (1971) showed that it was possible to retrieve the most important tidal amplitudes and phases from a simulated satellite altimeter in the presence of noise which was larger than the signal. A practical test of this concept was performed using the GEOS-3 altimeter data and is reported herein.

Geometry of the measurements is shown in Figure 1. Height of the spacecraft above the ellipsoid and the corrected altitude measurement are provided by the NASA Wallops Flight Center; details of the tracking techniques and microwave propagation corrections are given in Leitao, et al. (1975). For the purposes of this report, the oceanic tide will be considered the temporal variability of the sea-surface height at a particular location in certain tidal frequencies (see again Fig. 1). Perturbations in the sea-surface height due to wind waves, swell, quasi-geostrophic currents and eddies, and to steric changes are considered along with tracking and propagation inaccuracies, to be noise.

Test site for this experiment is the GEOS-3 calibration area off the east coast of the United States. Surface truth for the
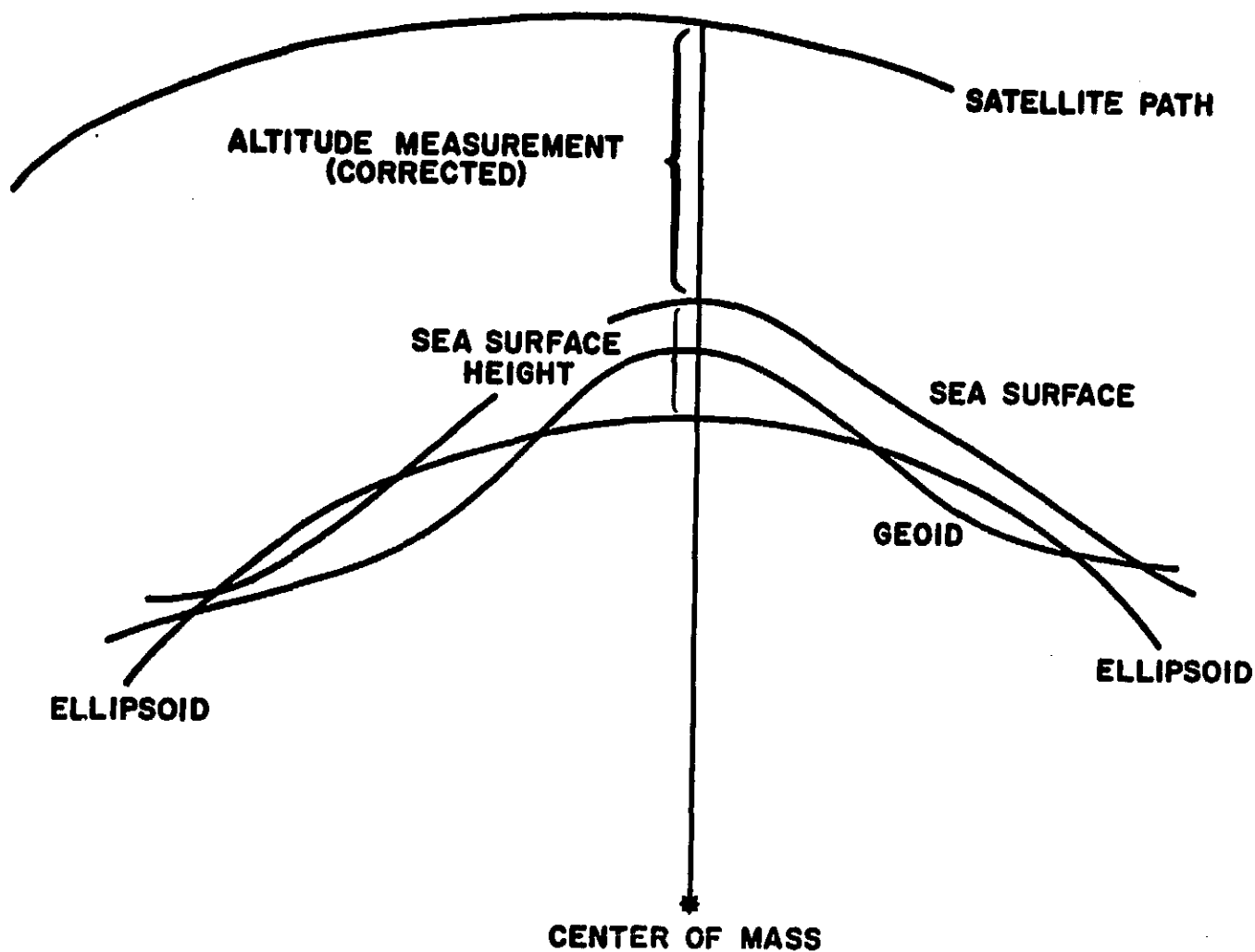
Figure 1. Skematic of the measurement geometry. Height of the space-craft above the reference ellipsoid is determined from tracking data; altitude measurement is from the corrected radar alti-meter data. Note that the ellipsoid, the geoid, and the sea-surface vary independently of each other.

observation of oceanic tides does not require concurrent measurements if

the amplitude and phase of the tidal constituents are well known. For

the GEOS-3 calibration area, Mofjeld (1975) developed an empirical tidal

prediction model; development of that model was part of this contract.

Mofjeld's model, when compared with a deep-sea tide gage within the GEOS-3

calibration area, had a standard deviation of $\pm$ 3 cm. The amplitude of

the tide in this area is approximately 60 cm. Signal to noise ratio due

to inaccuracies in the model is 20:1, which is adequate for this analysis.

To analyze altimeter data for tides, the calibration area was

divided into $1^{o}x1^{o}$ squares of latitude and longitude. Referring again

to Figure 1, consider a $1^{o}x1^{o}$ square centered on the vertical line

connecting to the center of mass. An altimeter measurement of the sea

surface taken at another point along the curve of the ellipsoid within

the $1^{o}x1^{o}$ square will be subject to a difference due to the combination

of the slope of the geoid and the slope of the tidal wave. It is desired

to relate each measurement within the $1^{o}x1^{o}$ square to the center; this

can most simply be accomplished by neglecting geoid and tidal effects,

if they are small enough.

Mofjeld's (1975) model shows that for an area even as large as

$5^{o}x5^{o}$, the error due to assuming a uniform areal rise and fall is less

than $\pm$ 5 cm in the GEOS-3 calibration zone. Marsh and Vincent's (1974)

gravimetric geoid shows a broad minimum in the vicinity of $30^{o}N$, $70^{o}W$

(Fig. 2); geoidal variance is about $\pm$ 1 m in a $5^{o}x5^{o}$ square here, and

this variance is within the noise range that Zetler and Maul (1971)
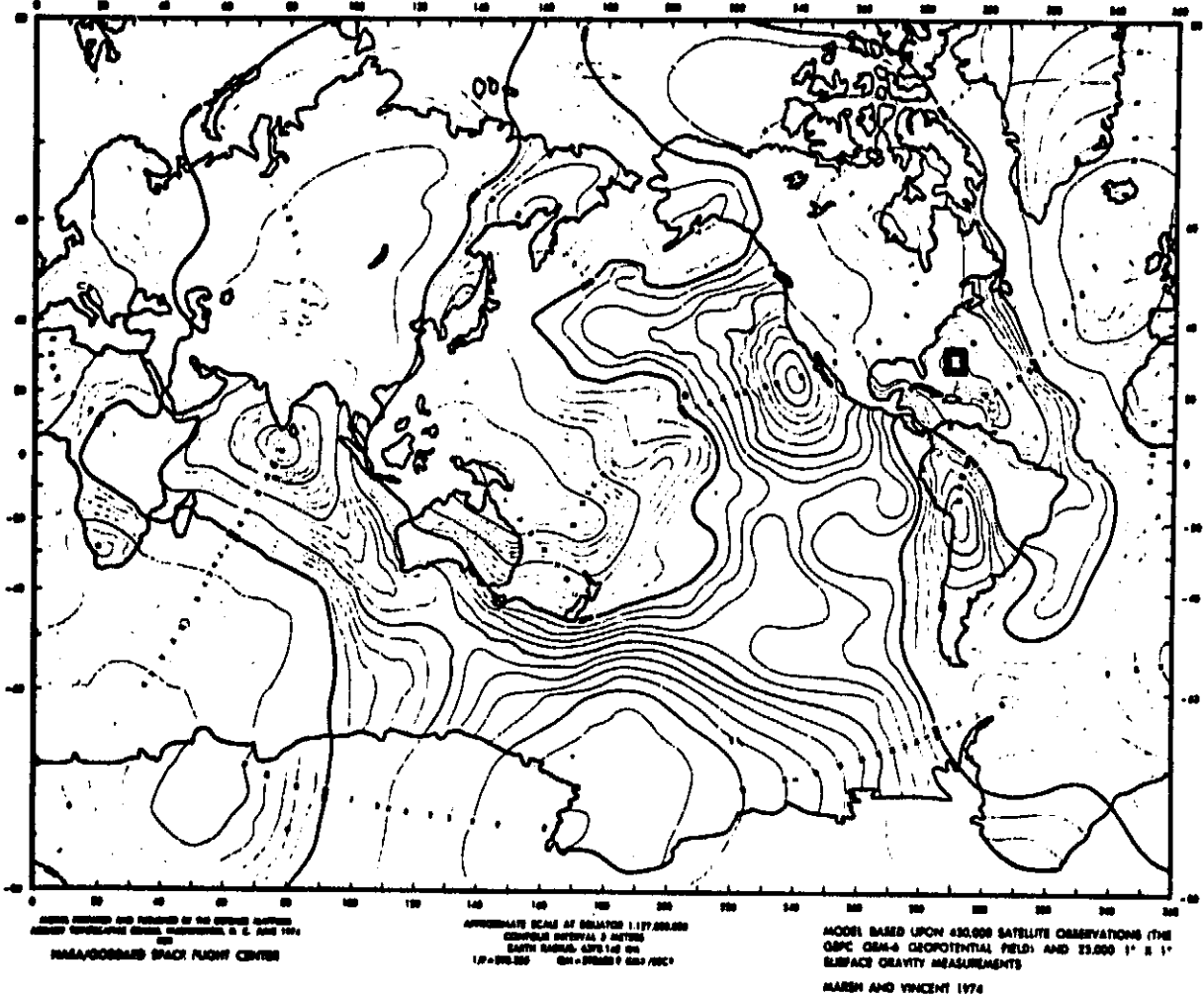
Figure 2. NASA's Goddard Space Flight Center detailed gravimeter geoid based on the work of Marsh and Vincent (1974). Center of the analysis region used herein is marked by a rectangle near $29.5^{\circ}N$, $70.5^{\circ}W$ ($289.5^{\circ}E$).

successfully retrieved the tides. Bottom topography (Bush, 1976) is quite uniform in this region (known as the Hatteras Abyssal Plain), which supports Marsh and Vincent's calculations. Finally, a deep-sea tide gage (Zetler, et al., 1975) was located at $28^{\circ}08'$N, $69^{\circ}45'$W, and the amplitudes and phases of the tidal constituents are well known. Based on these facts, the $5^{\circ}x5^{\circ}$ square centered on 29.5°N, 70.5°W was chosen for the analysis, and to first order, it is assumed that the tides and geoid are uniform.

Data Management and Processing

Initially GEOS-C data were received in one of two formats: the 7-track binary packed decimal, and the 7-track card image BCD. These formats existed until January, 1977 when the binary 7-track format was replaced by the binary 9-track format. The 7-track BCD formatted tape was eliminated. Seventy-one (71) 9-track tapes were received. The final mailing of 20 tapes was received in late August, 1977. Nine more tapes were received on 29 September, 1977. These had been sent to an incorrect address and were forwarded by the recipient.

These 71 tapes were difficult to read and necessitated the option that parity and frame count errors be ignored on reading. On reading a record, the format indicator was unpacked to determine the data rate. This determined which number was a valid altimeter status word for that record. All status words were then compared to this standard, and for all data rates each sample had to be valid in order for that record to be acceptable.

The latitude and longitude were then unpacked and, if in the calibration area, were accepted. The various parameters were then unpacked. All these data were arranged chronologically and ready for analysis.

The summary report computer printout distributed by Wallops Flight Center indicates that 357 days of data were acquired and distributed. These data varied from one to ten orbit segments per day; the elapsed time between the first and last data tape is 18 months. There are then no data for one third of the time these tapes cover. The elapsed

time in that portion of the calibration area represented by the $5^\circ \times 5^\circ$ shaded box (Fig. 3), is 498 days. There are 97 days for which data are available in this area and a total of 148 separate data points within the 97 days. These points are scattered throughout the $5^\circ \times 5^\circ$ area.

Both high and low intensity mode data were used in this study in order to have adequate samples. Whenever a pass crossed any $1^\circ \times 1^\circ$ box, all altimeter values in that pass were averaged, and that single averaged value was considered a measurement of the sea-surface height (see Fig. 1). Each average includes an error due to variations in the tides and the geoid across each $1^\circ \times 1^\circ$ box. Maximum range of the geoid in any $1^\circ \times 1^\circ$ box in the $5^\circ \times 5^\circ$ area (Fig. 3) is 1 meter, the average value being approximately 0.2 meters. In summary, the error introduced by averaging a pass across a $1^\circ \times 1^\circ$ box (tidal and geoid), is no more than ±0.5 m, and for the most part is ± 0.15 m.

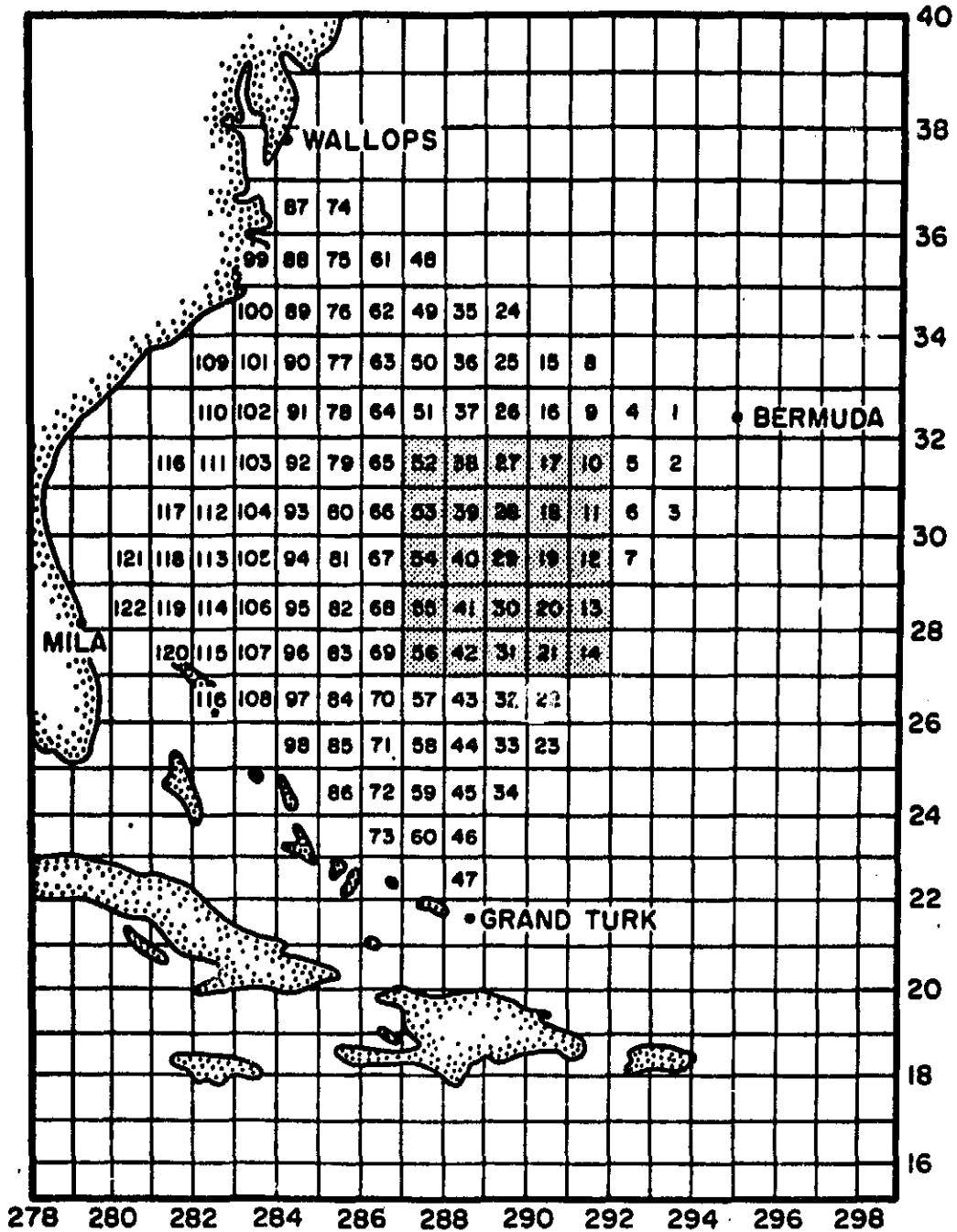Figure. 3. $1^{o}x1^{o}$ squares of latitude and longitude in the GEOS-3 calibration area. Analysis region used herein is lightly shaded. The deep-sea tide gage used as surface truth was located in box number 20.

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Data Analysis

Analysis of the GEOS-3 altimeter data for ocean tides was per-
formed using two independent methods, both of which are least squares
techniques. The methods of Zetler et al. (1965) have been applied
to a simulation of this problem (Zetler and Maul, 1971) and require
no further verification. Another technique derived by Vanicek (1971)
is also applied, but since it is not well known to the oceanographic
community, it was tested with simulated tidal data.

Consider a time series of the form

$$H(t) = H_o + \sum_i A_i \cos (w_i t - \phi_i) \tag{1}$$

where the height (H) of the tide at time (t), is the sum of the mean
value (H_o) plus a series (i) of cosine terms with amplitude (A),
frequency (w), and phase (ϕ). From well known trignometric identities
equation (1) may be written

$$H(t) = H_o + \sum_i C_i \cos (w_i t) + \sum_i S_i \sin (w_i t) \tag{2}$$

where $A^2 = C^2 + S^2$ and $\phi = \tan^{-1} (S/C)$.

A time series using equation (1) was generated for the M_2, S_2, N_2,
O_1, and K_1 tides, and C, S, and ϕ given in equation (2), and the variance
spectra were calculated by Vanicek's (1971) method using the program
of Wells and Vanicek (1977). In order to simulate randomly acquired

data, a random number generator (R) on the interval (0,1) was used

to degrade the data generated by equation (1) progressively until

100%, 90%, 80%...10% (R = 1, 0.9, 0.8,...,0.1) of the original data

remained. Results of those calculations are given in Table 1.

Listed at the top of Table 1 are the original input values for

the five constituents and the mean value. Record length is 2160

hours (3 months), and ϕ = 0 for all inputs. The least squares analysis

is within a few tenths of a percent of the input data when 100% of the

original data are used (row 1.0). Even when only 10% of the original

data are input (row 0.1), the maximum error in amplitude is 0.6% and

the maximum error in phase is 3°. Thus, for a geophysical process

where the frequency is well known, randomly spaced gappy data sampled

without regard to the Nyquist theorem can be successfully analyzed.

If the frequencies are unknown, Vanicek's (1971) technique is

still useful. Figure 4 is a variance spectrum for the semi-diurnal

species input as before (Table 1). The ordinate in Figure 4 is the

percentage variance, defined as

$$\frac{A_i^2}{\sum_i A_i^2} \tag{3}$$

and the abscissa is the period. It is clear that the spectrum using

100% of the data (dotted line) and the spectrum computed from 10%

of the data (solid line) are quite similar. There are no errors in

period, and the maximum error in percentage variance is 5% which occurs

Table 1

$$H(t) = H_o + \sum_i C_i \cos \omega_i t + \sum_i S_i \sin \omega_i t$$

$$\Sigma t = 2150 \text{ hrs}$$

| Ran. No.	H_o	O_1 (25.82^h)		K_1 (23.93^h)		N_2 (12.66^h)		M_2 (12.42^h)		S_2 (12.00^h)	
		C	S	C	S	C	S	C	S	C	S
Input	100	1	0	3	0	7	0	10	0	5	0
1.0	99.999	0.999	0.051	2.998	-0.113	7.003	0.013	10.000	-0.080	4.996	-0.007
0.9	100.000	0.999	0.051	2.998	-0.113	7.003	0.013	10.001	-0.080	4.996	-0.007
0.8	99.999	0.999	0.050	2.998	-0.113	7.003	0.013	9.999	-0.080	4.998	-0.008
0.7	99.998	0.997	0.050	2.998	-0.113	7.002	0.014	9.999	-0.079	4.993	-0.007
0.6	99.999	1.000	0.049	2.997	-0.113	7.003	0.013	10.001	-0.080	4.994	-0.007
0.5	100.000	0.999	0.053	2.996	-0.112	7.002	0.013	9.999	-0.078	4.996	-0.007
0.4	100.002	1.002	0.048	2.997	-0.112	7.001	0.015	10.003	-0.079	4.997	-0.006
0.3	99.999	0.398	0.048	3.002	-0.115	7.001	0.011	10.003	-0.081	4.995	-0.007
0.2	99.998	0.992	0.051	2.998	-0.117	7.001	0.013	10.004	-0.080	5.003	-0.010
0.1	100.000	0.999	0.054	3.000	-0.120	7.004	0.014	9.996	-0.077	4.994	-0.006

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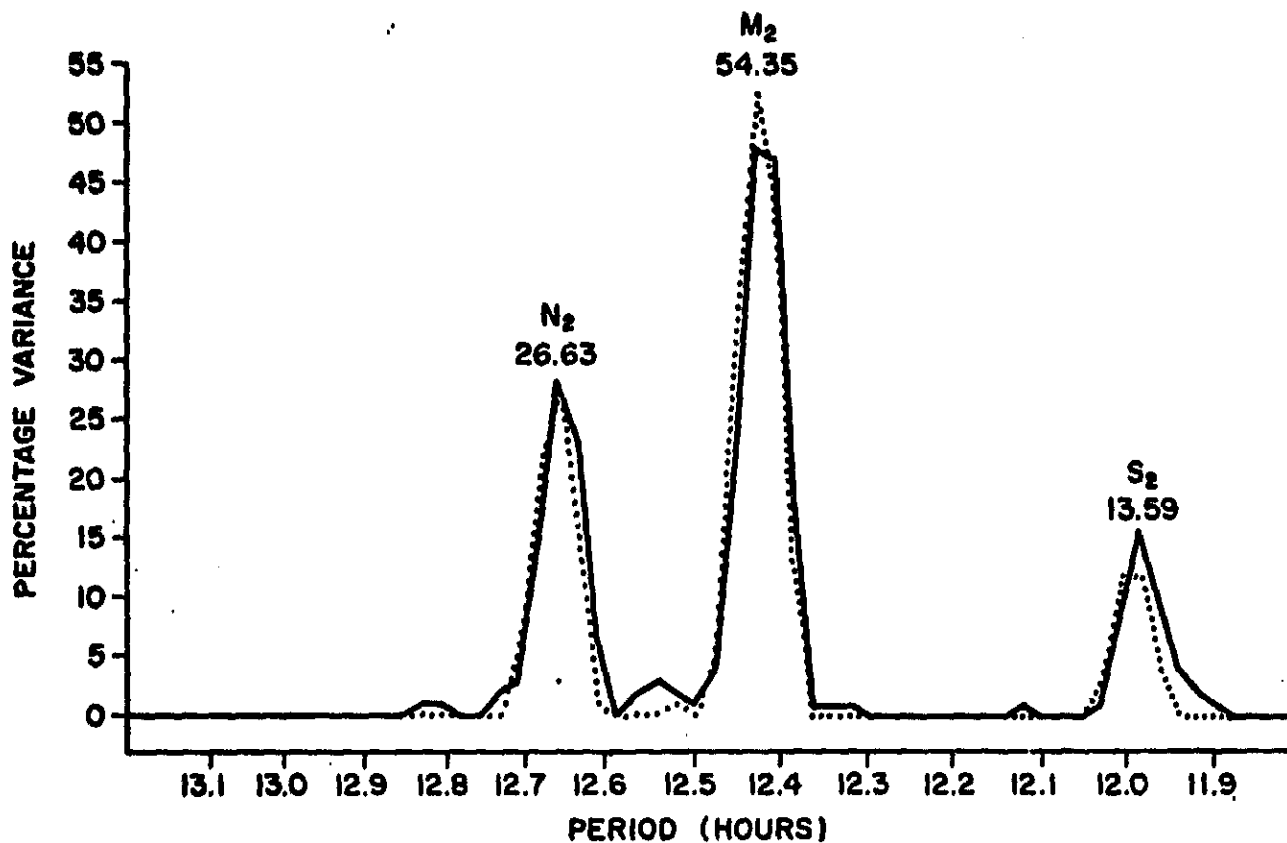
Figure 4. Comparison of the variance spectrum for the semi-diurnal
constituents using least squares analysis. Dotted line
used 2160 hourly values; solid line used 10% of the 2160
values randomly chosen. Theoretical values of the percentage
variance age given below their identifying constituent ab-
breviation.

in the M_2 constituent. Thus, if the signal to noise is low (there being no noise in this example), it appears that an unknown period can be detected, and then once detected, its amplitude and phase calculated.

The analysis techniques tested above were applied to the GEOS-3 data in the calibration zone. It should be noted that the calibration zone is typical of oceanic regions, and imposes a reasonable test. The number of observations would be increased by using a higher latitude site; the signal to noise would also be impaired by choosing an area with large tidal range. The intent herein is to question the applicability of GEOS-3 data for determining the global tide, rather than a proof of concept.

Results

Table 2 summarizes the calculations using the methods of Vanicek (1971) and Zetler et al. (1965); the known tidal constituents from Zetler et al. (1975) are listed at the bottom of the table. Tabulated are the amplitudes in meters, and the phases in degrees (relative to 0000 GMT, 1 March , 1975). The number of samples in each area size is based on 18 months of data. The average number of samples is 1.5 per month in each $1^{\circ} \times 1^{\circ}$ square (Zetler and Maul (1971) used more than 9 samples per month in their analysis which was based on different orbital parameters). Sparcity of samples undoubtedly contributes to the poor agreement between predicted values and observed in the GEOS-C data.

In most cases (Table 2) the GEOS-C derived amplitude is an order of magnitude more than the values reported by Zetler, et al. (1975). The phase calculations are equally uncorrelated. Comparisons of the two analysis methods (see $5^{\circ} \times 5^{\circ}$ rows) show some consistency in the calculation of amplitude (within 93%), but the phases are poorly related.

The correlation is graphically displayed in Figure 5. Observed sea-level heights from GEOS-3 are plotted along the ordinate, and the values predicted due to ocean tides by Mofjeld's (1975) model are along the abscissa. The range of the tide (signal) is at best an order of magnitude less than the measurement variability (signal + noise). Thus, the tidal signal to noise ratio is approximately 0.1, which is seven times smaller than assumed by Zetler and Maul (1971) in their successful theoretical analysis. Table 3 summarizes the

Table 2

Vanicek (1971)

Area Size	No. Samples	S_2	M_2	N_2	K_1	O_1
				Ampl./Phase		
$1°x1°$	26	1.92/75.9	1.55/32.2	1.59/27.6	2.02/81.5	1.25/36.9
$2°x2°$	58	0.46/12.1	1.52/294.4	0.37/327.6	2.05/75.9	1.0/42.4
$3°x3°$	92	0.98/69.3	1.67/347.1	0.739/3.2	2.11/85.8	.96/337.2
$4°x4°$	119	1.24/42.5	1.83/1.7	0.577/29.8	2.16/280.0	.476/338.8
$5°x5°$	148	.81/20.6	1.35/315.5	0.75/18.8	1.86/303.4	.91/86.4

Zetler et al. (1965)

Area Size	No. Samples	S_2	M_2	N_2	K_1	O_1
				Ampl./Phase		
$1°x1°$	26	.49/166.8	1.21/330.2	1.39/133.7	1.98/99.5	1.43/132.4
$2°x2°$	58	.48/354.6	1.49/279.1	.39/209.3	2.25/94.7	.96/179.6
$3°x3°$	92	1.01/309.6	1.63/228.4	.71/310.0	2.11/89.0	.95/249.0
$4°x4°$	119	1.20/335.4	1.85/215.4	.37/277.5	2.13/78.1	.49/251.1
$5°x5°$	148	.78/337.8	1.31/231.8	.62/307.8	2.01/70.2	.96/271.6

Zetler et al. (1975)

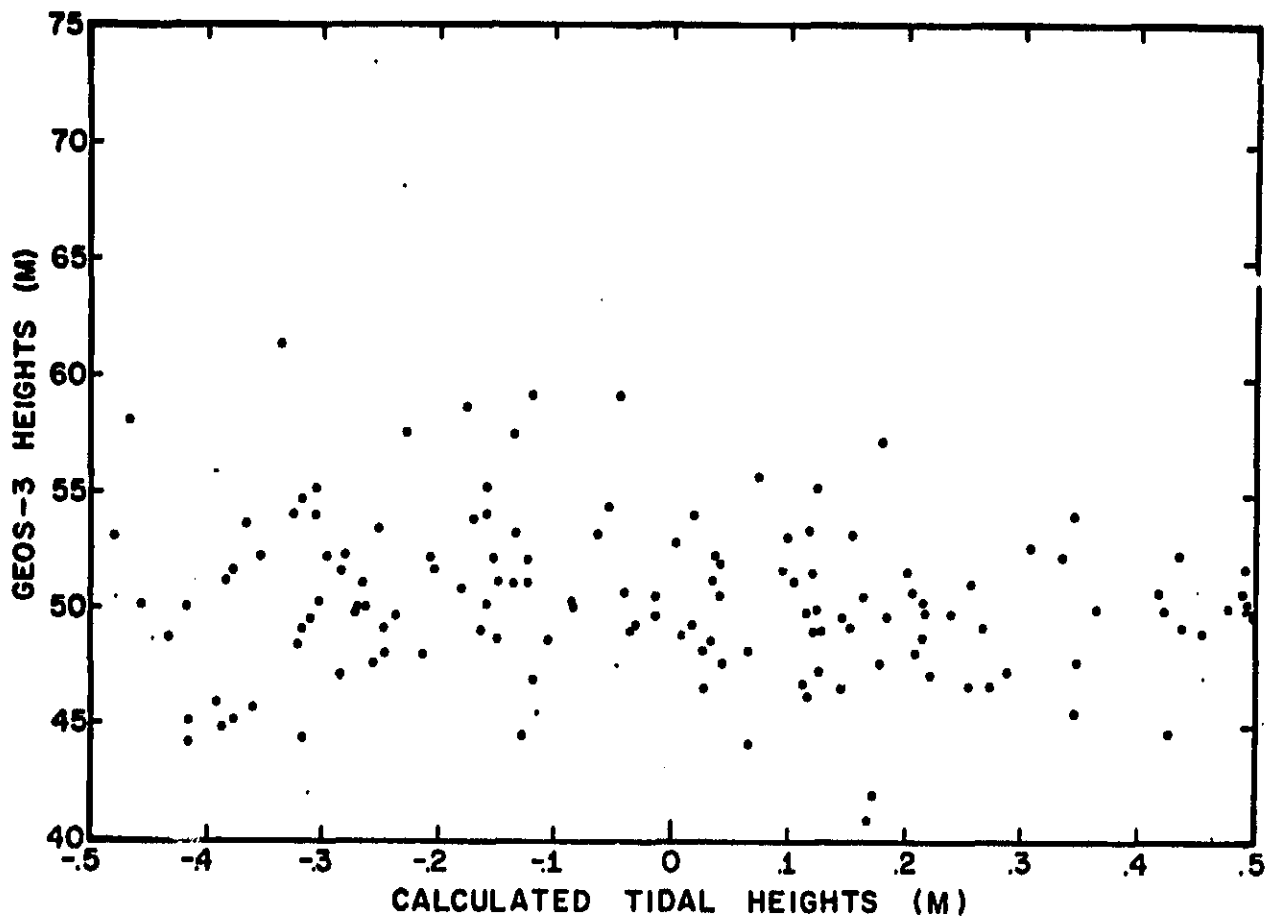| S_2	M_2	N_2	K_1	O_1
		Ampl./Phase		
0.071/30.8	0.345/0.6	0.080/339.8	0.077/194.7	0.061/197.6

Figure 5. Comparison of tidal height observed by the GEOS-3 altimeter versus computed tides (Mofjeld, 1975) in the 5°x5° calibration area. Observed values are corrected for atmospheric effects but not for spatial variation in the geoid.

variance of sea-level height above the ellipsoid from the GEOS-3 altimeter in the $5^\circ \times 5^\circ$ square shaded in Figure 3. Mean height of sea-level in this $5^\circ \times 5^\circ$ square is 50.7 (± 1.3) meters below the ellipsoid. The low standard deviation is in agreement with the Marsh and Vincent (1974) gravimeter geoid (cf. Fig. 2), and confirms that geoid variability does not significantly contribute to the inability of the GEOS-3 data to discriminate the oceanic tide.

However, to further insure that geoid variability is not important, the calculations summarized in Table 2 were repeated after subtracting the Marsh and Vincent (1974) geoid. That is, the Vanicek (1971) and Zetler et al. (1965) techniques were applied to the temporal term

$$H(t) = h_{ss} - h_g \qquad (4)$$

where h_{ss} is the GEOS-3 determined height of the sea-surface above the ellipsoid, and h_g is the height of the Marsh and Vincent 5'x5' geoid. The results of those calculations were essentially identical to the results summarized above, leading to the conclusion that the GEOS-3 data, in the form provided, is not useful for observing ocean tides.

As a final test of using GEOS-3 altimeter data to study temporal variability of the sea-surface, the percentage variance spectrum (cf. Equation 3) was computed for the $5^\circ \times 5^\circ$ calibration area. Tidal frequencies have been removed in this application of Vanicek's (1971) least squares technique. Because of the signal to noise analysis above, it is difficult to have a great deal of confidence in this spectrum. However, some

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Table 3

Mean and standard deviation of the GEOS-3 height of sea-level above the ellipsoid in the 5°x5° calibration area (see Fig. 3).

1°x1° Box	Number of Points	Mean (Meters)	Std Dev (Meters)
10	24	-48.6	±3.9
11	24	-50.9	±6.8
12	22	-51.1	±7.1
13	28	-49.6	±7.1
14	34	-49.7	±2.8
17	36	-50.6	±5.9
18	33	-51.3	±6.1
19	26	-52.0	±3.3
20	26	-50.9	±3.3
21	31	-51.2	±3.7
27	27	-51.1	±2.7
28	35	-51.3	±3.2
29	33	-51.5	±3.6
30	28	-51.8	±3.8
31	24	-52.4	±3.5
38	30	-51.2	±3.9
39	32	-51.7	±3.1
40	35	-51.5	±3.8
41	32	-51.3	±4.0
42	28	-50.7	±4.7
52	31	-51.4	±4.2
53	31	-51.6	±4.3
54	29	-50.3	±3.5
55	31	-47.6	±7.2
56	34	-47.2	±9.6

features are common to a similar analysis of Gulf Stream meanders made from infrared measurements by Maul, deWitt, Yanaway, and Baig (in preparation). The numerous spectral peaks with a period of a fortnight or so and less are commonly reported in the oceanographic literature. At 38 days, a strong peak (Fig. 6) is evident, which is probably due to the 37 day cycle in the GEOS-3 orbit. The most intriguing peak, however, is at 56 days. Hansen (1970) noted that the average periods of Gulf Stream meanders is about 1½ months, which is close to 56 days, and Maul et al. noted this too in their spectra of meanders. This raises the interesting possibility that sea-level in the Sargasso Sea pumps up-and-down in response to the meanders, as well as to other forcing.

Conclusions

The GEOS-3 altimeter data as processed by the NASA Wallops Flight Center were analyzed for deep-sea tides in the calibration area of the western North Atlantic Ocean. It was found that the signal to-noise ratio of the data was about 0.1, and that only one observation every four days was available in a $5^{\circ} \times 5^{\circ}$ latitude & longitude area for the 18 months analyzed. Using two independent methods, the tides could not be resolved. Tidal variability will not detract from geoid determination if data averaging is used, however, other error sources such as orbit determination, altimeter correction, or mean (steric) sea level will influence the accuracy of the marine geoid.

The consistency of the calculated tidal amplitudes (Table 2) raises the question of tidal frequency errors in the tracking of GEOS-3. If there are undetectable errors of these frequencies in the data, it may never be possible to do deep-sea tide determinations with
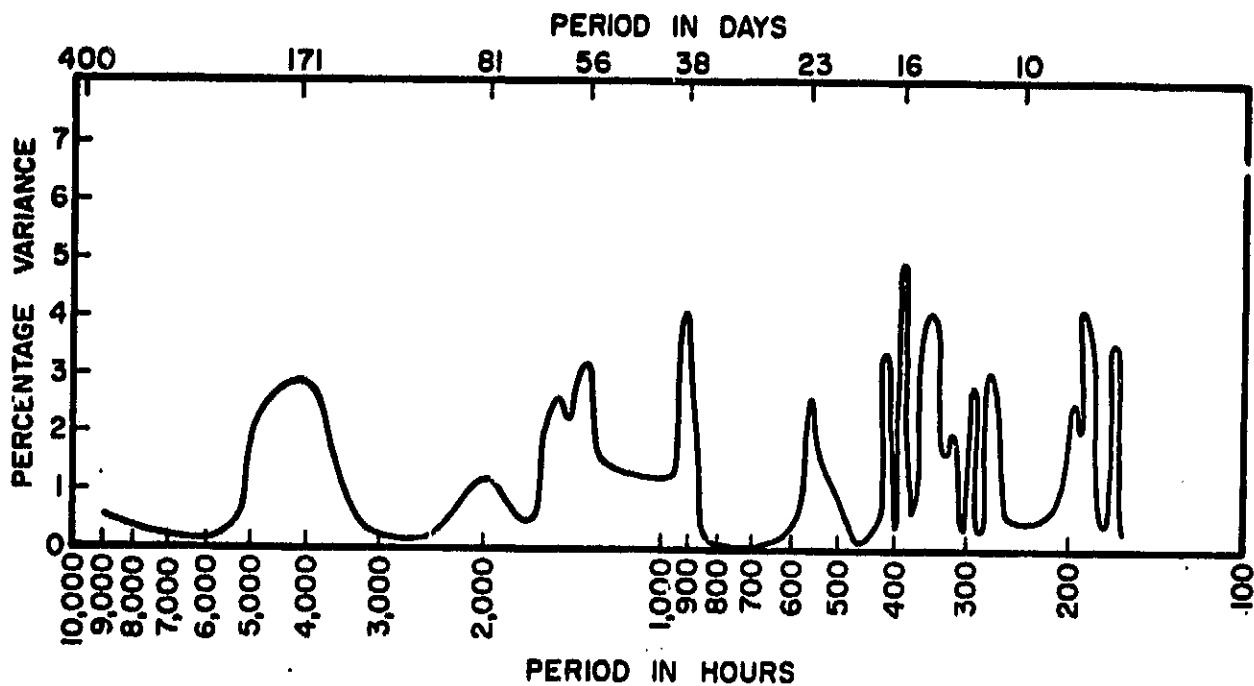
*Figure 6. Percentage variance of sea-surface heights in the 5^ox5^o
calibration area as a function of period in hours. Note
the variance at 38 days.*

future vehicles such as SEASAT-A. The average of the standard deviations given in Table 3 is ±0.5 m of which can be attributed to variations of the geoid and oceans tides. SEASAT-A's radial orbit determination error is specified as ±2 m; unless that can be improved upon by a factor of at least 2, it does not seem possible to extract tides from that data either, unless a refined approach is taken.

Refinement of the approach used herein forms the basis for suggestions for further research. From conversations held at the GEOS-3 Principal Investigator's Meeting (November, 1977) it appears that better orbit determinations would give the most marked improvement in the signal to noise ratio. Thus, a new analysis of the spectrum of variability (cf. Fig. 6) would identify known periods, such as the 37 day cycle, which could be filtered out. If filtering etc. increases the signal to noise by half an order of magnitude, it is reasonable to expect that the ocean tides would be observed. Success does not seem possible with these GEOS-3 data, but with improvements in the orbit determinations, SEASAT-A is still a viable contender.

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15. Supplementary Notes

16. Abstract

GEOS-3 altimeter data in a 5°x5° square centered at 30°N, 70°W were analyzed to evaluate deep-sea tide determination from a spacecraft. The signal to noise ratio of known tidal variability to altimeter measurement of sea level above the ellipsoid was 0.1. A sample was obtained in a 5°x5° area approximately once every four days. The randomly spaced time-series was analyzed using two independent least squares techniques, but it was not possible to retrieve the amplitude and phase of the M_2, S_2, N_2, O_1, or K_1 constituents.

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