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Report of the NASA Workshop on Tidal Research

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Editors

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ABSTRACT

NASA, recognizing the importance of tides to the understanding of altimeter data, called together tidal experts from around the world to discuss the state of tidal research and the relationship of tides to altimeter data. The consensus was that tides should be recognized as a separate objective for altimetric research. An altimetric satellite such as TOPEX that is designed for separation of tidal signals in conjunction with surface measurements can significantly improve knowledge of the deep sea tide. Information gained in this way will be directly applicable to all other altimetric satellites.

Included in this report is a brief statement by each of the attendees on his current research.

ACKNOWLEDGMENTS

The editors would like to thank Dr. Larry McGoldrick for his unceasing support and work on behalf of this workshop, Dr. George Platzman for generously being host, and Dr. Dave Cartwright for his invaluable contributions to the content of this report.

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SECTION I

INTRODUCTION

Tides appear in many geophysical measurements. For the oceans, tidal dissipation could affect the circulation (Hendershott, 1981). In addition, tides couple with the Earth's magnetic field to produce variations in the Earth's electric field. For geophysics, a precise knowledge of the ocean tides would allow the structure of the ocean tide to be used as a known input function to be convolved with the Earth's structure. Depending on the intermediate dynamics, the resulting geophysical signal can be used to infer properties of the solid Earth. Tidal signals appear, for instance, in measurements of gravity, tilt, and strain. Also, Lambeck (1980) notes that tides are important to station locations, the Earth's moment of inertia and hence length of day, the secular retardation of the Earth's rotation, measurements of polar motion, satellite positions (both periodic and secular), and deceleration of the lunar longitude. Tidal loading is thought to drive a resonance of the Earth's core (Wahr and Sasao, 1981). Whether or not all of the deceleration of the Moon can be explained by tidal dissipation is of importance to whether or not gravity is a constant function of time and hence of importance to the history of the solar system's evolution.

Measurements of tides have been taken for hundreds of years. Major advances in the understanding of tides occurred with the discoveries of Newton, the hydrodynamical equations of Laplace and the harmonic analysis of Kelvin and Darwin. Historically, most measurements of the tide have been taken in coastal waters, based on commercial concerns. Extension of these measurements to the deep sea were initially empirical, e.g., the M2 charts by Harris (1904) and Dietrich (1944). More recently deep sea tides have been estimated by direct numerical calculation based on Laplace's tidal equations. Deep sea pressure gauges developed under the auspices of SCOR working group 27 are now capable of measuring the deep sea tide at any given location. Distribution of measurements throughout the world's oceans is still poor, however. The advent of satellite altimetry brings the promise of global coverage of the deep sea tide.

The purpose of this workshop, therefore, was to discuss the status of current research into ocean tides, and the impact future altimetric missions might have. Table 1-1 gives a list of the future altimetric missions that are proposed at this time. Each of these could provide valuable additional information about tides, the extent depending on the orbit of the satellite and the data quality.

Based on this, the rest of the report is divided into four parts. The first describes the effect of tides on altimeter data, the second concentrates on the impact of a sun-synchronous orbit, the third covers recommendations and conclusions drawn at the end of the workshop, and the fourth includes short contributions from each participant on the state of his current research.

Table 1-1. Ocean-Related Altimetric Satellites: Next Decade

Satellite	Sponsor	Sensor Complement	Launch	Status	Nominal Orbit	Comments
GEOSAT	USN	ALT	1984	Approved[a]	800 km, 108°	Geoid mapping mission
ERS-1	ESA	ALT, AMI, radiometer, wave spectrometer	1987	Approved	800 km, 98°, 3-day repeat	General ocean, sun-synchronous
Poseidon	France	ALT	1987?	Proposed	800 km, 98°, 26-day repeat	General ocean sun-synchronous
TOPEX	NASA	ALT + option for SCAT	1988?	Proposed	1300 km, 43°, 10-day repeat	Ocean circulation and tides
NROSS	USN/ NOAA	ALT, MR, SCAT (NOAA-D spacecraft)	1988?	Proposed (Proposed)	800 km, 98°	General ocean, sun-synchronous
ERS-2	ESA	ALT, SAR, SCAT?	1990?	Tentative	Undecided	General ocean
MOS-2	JAPAN	ALT, SCAT	1990?	Tentative	Undecided	General ocean

[a]Some data to be classified

REFERENCES

Dietrich, G., 1944. Die Schwingungssysteme der halb-und eintägigen Tiden in den Ozeanen, Veroeffentl. Inst. Meerskunde Univ. Berlin A41, 7-68.

Harris, R.A., 1904. Physical Hydrography. Manual of Tides - pt. IVb, Cotidal Lines of the World, in Report of the U.S. Coast and Geodetic Survey, Appendix 5, U.S. Printing Office, Washington D.C., 315-400.

Hendershott, M., 1981. Long waves and ocean tides. In B.A. Warren and C. Wunsch (Eds.), Evolution of Physical Oceanography: Scientific Surveys in Honor of Henry Stommel, The MIT Press, Cambridge, 292-341.

Lambeck, K., 1980. The Earth's Variable Rotation: Geophysical Causes and Consequences, Cambridge University Press, Cambridge.

Wahr, J.M., and T. Sasao, 1981. A Diurnal Resonance in the Ocean Tide and in the Earth's Load Response Due to the Resonant Free "Core Nutation," Geophys. J.R. Astr. Soc., 64, 747-765.

SECTION II

TIDES AND SATELLITE ALTIMETER DATA

The basic altimeter measurement is the distance from the altimeter feed horn to the ocean electromagnetic mean sea surface. Given knowledge of the position of the satellite, atmospheric corrections for the retardation of the radar beam in the atmosphere and an accurate time tag, the height of the ocean surface as a function of subsatellite position can be defined.

The initial concern here is the manner in which tidal signals appear in the altimeter data. Since one satellite cannot, in general, sample frequently enough to resolve tidal variations, the tidal signature will appear in the data at longer frequencies. It is useful to consider the effect of tides on altimeter data taken as part of a repeating orbit.

From the 1981 report of the Topex Science Working Group, the rate at which the orbital plane precesses is

$$\dot{\Omega} = -1.32 \times 10^{18}\, a^{-7/2} \cos i \text{ (SI units)}$$

where a is the geocentric height of the satellite and i is the orbital inclination. For example, for the SEASAT nominal orbit parameters of $a = 7178$ km and $i = 108^o$ one finds $\dot{\Omega} = 2.047^o$/day. In an Earth-based coordinate system $\dot{\Omega} = \dot{\Omega} - 0.9856$, or, for the SEASAT parameters, $\dot{\Omega}_e = 1.052^o$/day. For each tidal constituent, the daily rate at which the phase between the satellite and tide will shift will be

$$\Delta\phi = \frac{360(nT - 1) - \dot{\Omega}_e}{T}$$

where T is the tidal period and nT is that multiple of the tidal period nearest one day (in days); e.g., for M2, nT = 1.036 days. For a repeat period of P days, the rate at which the phase will shift will then be

$$\Delta\phi_p = P\Delta\phi \text{ (expressed from -180 to 180)}$$

The principal alias period, τ_p, will then be

$$\tau_p = \frac{360P}{\Delta_{\phi_p}}$$

Table 2-1 gives a few of the principal aliases for a Seasat orbit with a 3-day repeat period, a sun-synchronous satellite with a 3-day repeat period, a sun-synchronous satellite with a 26-day repeat period, a TOPEX orbit with a 3-day repeat period, and a TOPEX orbit with a 10-day repeat period. For TOPEX with $a = 7678$ km and $i = 63.43$, $\dot{\Omega}_e = -3.316$. Note that with a 10-day repeat period TOPEX cannot resolve variations less than 20 days.

The alias frequencies at which tides appear in the altimeter data are of critical importance both to analysis of tides and to separation of tides from other signals of geophysical interest. Separation of tidal species from each other and from other geophysical signals requires that the frequencies be distinct. For example, if two frequencies are separated by one cycle per year, then it will take a bare minimum of one year to separate them. If the tidal aliases are of very long period, then it will take a correspondingly long period to analyze for them.

There is another consideration to keeping tidal aliases as short as possible. The background continuum grows with frequency, and thus the longer the tidal alias period, the more difficult to separate the tide from the background "noise."

As Table 2-1 illustrates, orbits in the range from Seasat to sun-synchonous will have problems resolving the near-solar tides. There is no reason, however, why these satellites cannot be used to solve for the lunar tides: this question is discussed further in the next section. TOPEX, on the other hand, has relatively short alias periods for all the principal tidal frequencies and should therefore be ideal for separation of tides. The only drawback is the relatively low turning latitude of approximately 64°. There is no reason, however, why data from the many proposed altimetric satellites cannot be combined to produce a more accurate evaluation of the overall ocean tide. Because of the highly predictive nature of tides, tidal information from a satellite such as TOPEX can be used to aid other altimetric missions in the removal of solar tides.

It should be noted that at crossover points, i.e. where northward and southward bound ground tracks cross each other, the altimetric data will consist of samples from two interleaved principal aliases, with the phase between the principal aliases being a function of latitude and the orbit parameters. For a satellite with a nonrepeating groundtrack, each crossover will consist of two samples, one from each alias. For tidal constituents with a finite alias period, the phase relationship between northward and southward bound tracks will strongly depend on the specific order in which ground tracks are sampled.

For tidal constituents with a zero frequency alias, such as S2 for a sun-synchronous satellite, the phase relationship will be a constant function of latitude, and can therefore be described a priori. For S2, the phase change will be $360\Delta T/12$ where ΔT is the change in local time between the measurements. Frautnik (1983) has contributed the following calculation:

Table 2-1. Some Principal Alias Periods in Days

Contituent	Period, Days	Max Equilibrium Amplitude, cm	SEASAT, 3-day Repeat	ERS-1 Sun-synch., 3-day Repeat	Poseidon Sun-synch., 26-day Repeat	TOPEX, 3-day Repeat	TOPEX, 10-day Repeat
M2	0.51725	24.39	16.38	14.99	35.41	11.83	64.54
S2	0.500000	11.35	171.06			54.28	54.28
N2	0.527431	4.72	10.15	9.61	36.91	8.23	46.55
K2	0.498635	3.09	88.21	182.65	182.65	76.94	76.94
K1	0.99727	14.25	176.41	365.30	365.30	153.87	153.87
O1	1.07581	10.12	14.76	14.19	31.24	12.65	47.69
P1	1.00275	4.71	5795.38	364.64	364.64	83.83	83.83
Q1	1.11952	1.96	9.60	9.37	33.52	8.70	66.72

The amount of time from the latest ascending node crossing to the current satellite position is given by

$$\tau = \frac{P}{360} \sin^{-1} \frac{\sin\phi}{\sin(180-i)}$$

where ϕ is the satellite latitude, P is the nodal period, and i is the inclination of the orbit. The satellite longitude is then given by

$$\lambda = \lambda_o + \sin^{-1} \{\tan(90-i)\tan\phi\} - \omega_e\tau + \dot{\Omega}\tau$$

where λ_o is the longitude of the latest ascending node crossing, ω_e is the rotation rate of the Earth, and $\dot{\Omega}$ is the nodal precession rate. Finally, the local time of overflight can be found from

$$T = T_o + (\lambda-\lambda_o)24/360$$

where T_o is the local time of the latest ascending node crossing in hours.

Figure 2-1 gives the local time of overflight as a function of latitude for a sun-synchronous satellite at 800 km, assuming the ascending node crossing occurred at 12 noon local time. The S2 phase difference at a given latitude is then related to the change in local time of overflight by 30° per hour of time change between ascending and descending arcs. Except near the turning latitude, the rate of change of the S2 phase difference is slow, and thus data cannot be combined regionally to provide an estimate of the S2 tide. This leads to the considerations of the next section.

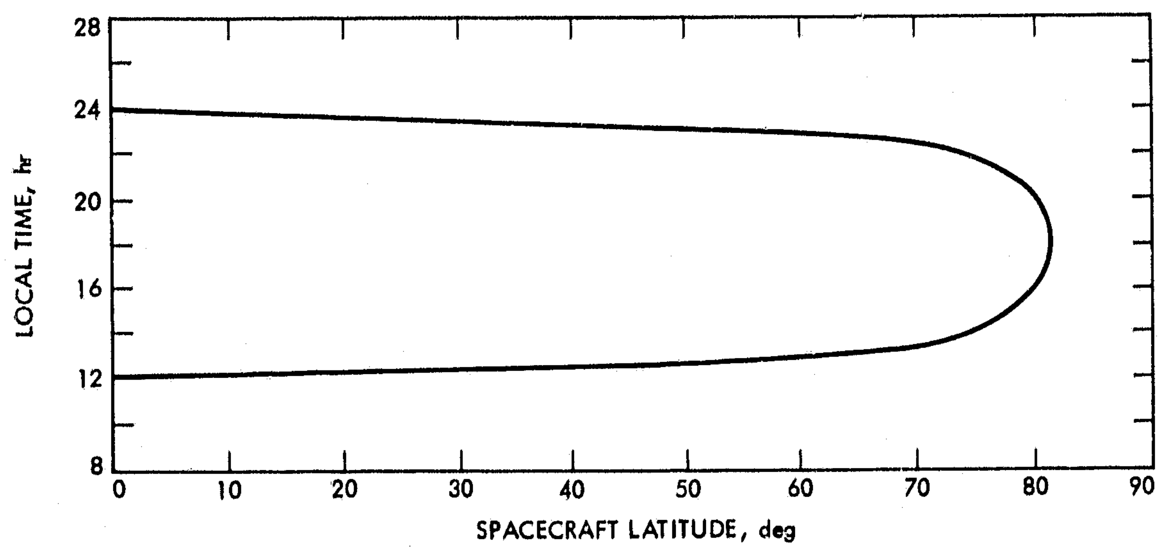

Figure 2-1. Local time versus spacecraft latitude for the northern hemisphere for a sun-synchronous satellite at 800 km elevation with the ascending node occurring at 12 noon local time (Frautnik, 1983).

REFERENCES

Frautnik, J.C., 1983, Jet Propulsion Laboratory, personal communication.

TOPEX Science Working Group, 1981, Satellite Altimetric Measurements of the Oceans, JPL Publication 81-4, Jet Propulsion Laboratory, Pasadena, California.

SECTION III

THE SUN-SYNCHRONOUS ORBIT

Because of power constraints and the requirements of other on-board instruments (such as the coastal zone color scanner), a number of altimetric missions are being proposed with a sun-synchronous orbit. As was discussed in Section II, such an orbit poses problems not only for analysis of the solar and near-solar tidal constituents, but also because of contamination of long-term variations in the data by the tides. In particular, K1 and P1 will be inseparable from each other and the annual cycle. Separation of K1 and K2 will require at least one year and preferably two or more. A practical strategy for working with these data sets was received by the editors from D.E. Cartwright. Since little can be added to this discussion, it is repeated verbatim below.

PRACTICAL STRATEGY

The above considerations are well known to those involved with satellite altimetry. A number of altimetric satellites currently being planned will be set deliberately to sun-synchronism for good reasons based on economy of solar power usage. How can one best make use of these potentially valuable altimetry data sets, despite the difficulties due to tidal aliassing?

In one approach, one may quite feasibly extract the purely lunar components such as M2, N2, O1, and Q1 by direct analysis, provided a year or more of data is recorded to enable separation of the daily and half-daily species. This should give good results at least for the dominant half-daily lunar tides in the Atlantic and Indian Oceans; separation may be more difficult in the Pacific Ocean, where the two species are of similar magnitude and relatively weak. Given less than a year's data, it would be better to subtract the weaker daily tides using a standard numerical model of adequate accuracy, then analyze the residuals for pure half-daily lunar components.

Oceanic tidal admittances are too variable to allow inference of the solar components from the lunar. A fair approximation may, of course, be obtained from numerical models, but the present considerations assume that these contain errors greater than the noise level of the system. Probably an accuracy of about 5 cm could be obtained from a numerical model of the solar tides. The situation is critical, because Table 2-1 shows that their alias frequencies, if not zero, coincide with seasonal frequencies of direct relevance to seasonal fluctuations of oceanic heat transport.

A second approach is to focus attention on, or wait for the results from TOPEX, which should enable resolution of solar tides as well as lunar ones. The best tidal results from TOPEX may ultimately be interpolated spatially and applied as complete corrections to the different grid spacing of the sun-synchronous data sets. The only areas in which this would not be possible are at high latitudes above the 65° limit of the TOPEX orbit. No doubt the reverse procedure could also be possible for the lunar tides, and in general an optimum solution could be adopted which makes the best use of all available data sets.

Because sun-synchronous satellites have logistic advantages, it has been suggested that one could be used to sample the solar tides at different phases and hence resolve them. To simplify the situation, consider a small segment of the Earth-track beneath a sun-synchronous orbit, along which the surface slope of the ocean may be represented by

$$S(t) = a_1(t)\cos 2\pi t + b_1(t)\sin 2\pi t + a_2(t)\cos 4\pi t + b_2(t)\sin 4\pi t + c(t)$$

where a_n and b_n contain constants and variable terms of frequency one cycle per year and its multiples, representing the daily and half-daily solar tidal element of the slope; $c(t)$ is the slowly variable element dependent on the steady circulation; and t is the time in solar days. The basic object is to estimate a_n and b_n and hence eliminate the solar tide to recover c.

A single satellite that passes the element at 0h local time determines, after higher frequency variations due to lunar tides have been eliminated, the quantity $(a_1 + a_2 + c)$. A second satellite on exactly the same track, 12 hours later, would similarly give $(-a_1 + a_2 + c)$. Together with the first satellite this gives estimates of a_1 and of $(a_2 + c)$, neither of which is much use on its own. $c(t)$ could be obtained, clearly, by averaging the signals from three sun-synchronous satellites at 0h, 8h and 16h local time, but these would not be sufficient to determine the four independent parameters of the solar tides. In general, five such satellites following an identical track would be required for unambiguous resolution of all parameters. Their precise timing would not be important, provided they were more or less evenly spaced. Such proliferation seems rather uneconomical when the whole system could in principle be solved from a single satellite altimeter at a more favorable orbital inclination.

SECTION IV

RECOMMENDATIONS AND CONCLUSIONS

After the presentations at the workshop, there was a general discussion of the future directions of tidal research and the role of altimetric measurements. Based on this discussion, the following recommendations and conclusions were readied. Since it was the consensus of the participants that a working group should be formed and these recommendations be considered more fully by the working group, the basic recommendations have not been expanded upon here.

RECOMMENDATIONS

1) An Indian Ocean study as a predecessor to TOPEX will be valuable as follows:

   a) Both for ground truth and as an aid to interpretation of TOPEX data.

   b) As a constraint for tidal modeling.

   c) In conjunction with Earth tide studies.

   d) Because the Indian Ocean is well suited for Earth tide calculations.

   e) Because of the presence of an anti-amphidromic region for the semidiurnal tides.

2) A working group should be formed to coordinate the Indian Ocean study and for the optimum use of TOPEX data.

3) Serious studies involving satellite measurements require in situ measurements.

4) Efforts at improving the state of the art in tidal modeling should be continued.

5) Strong emphasis should be placed on research using the upcoming satellite data to provide estimates of ocean parameters such as the location and amount of oceanic tidal dissipation and the magnitude of low-order tidal harmonics. Comparison with astronomically and satellite orbit derived values will be extremely useful.

6) These questions should be considered more fully by the working group.

CONCLUSIONS

1) Concerning upcoming satellite missions:

   a) Data from sun-synchronous satellites, such as from ERS-1, and data from high-inclination satellites, such as SEASAT, should be studied for nonsolar tidal constituents as far as possible.

   b) Sun-synchronous and other high-inclination satellites have the advantages of a high turning latitude, thus covering high-latitude regions not covered by TOPEX.

   c) TOPEX, however, has been designed to have tidal aliases that are both below one cycle/year and distinct from each other, thus aiding separation and analysis of tides.

   d) TOPEX, therefore, can serve as a focal point for tidal studies over the next decade.

2) The increase of the background continuum with period is very important for the study of tides from satellite measurements.

3) Trench areas and other severe tectonic regions should be avoided for detailed tidal studies.

SECTION V

INDIVIDUAL CONTRIBUTIONS

Each participant at the workshop was requested to provide a short contribution about his current research. These contributions have been collected in this section in purely arbitrary order.

Work on SEASAT Altimetry at the
Institute of Oceanographic Sciences, Bidston, United Kingdom
(Extract from paper presented at "SEASAT Over Europe"
Symposium, London, April 14-16, 1982)

D.E. Cartwright
Institute of Oceanographic Sciences
Bidston Observatory, Bidston, UK

Our work was divided into three distinct phases, each associated with a distinct sea area, as follows:

1. Removal of tides and meteorological effects from altimetry over the North Sea, as a contribution to the geoidal studies at I.A.G. Frankfurt and I.T.G. Hannover.
2. Study of residual errors and evaluation of semidiurnal tides from the altimetry of the Northeast Atlantic (5-30^{o}W).
3. Expansion of (2) with new JPL data set, and tidal evaluation for the central north Atlantic (30-60^{o}W).

In this paper, we briefly review researches (1) and (2) with references to more detailed accounts published elsewhere, and finally present some recent results from (3).

The North Sea

From the time of SURGE's formation in 1977, the major objective of its altimetry team has been an intensive study of the data from the North Sea as a test of the altimetric equation's validity. This study, which is now practically completed, made use of the accurate geoid available for the North Sea, the European satellite-tracking network, a good model for tides and weather-induced variations in sea level, and good coverage of coastal tide-gauges. The results (Lelgemann and Brennecke, presented at "SEASAT Over Europe" Symposium, 1982; multi-author paper in preparation) are very satisfactory, except for some uncertainty near the coast of Norway. Our part consisted in computing the dynamic deformation of the sea surface from a nearly geoidal surface, as one of the several elements in the altimetric equation.

Our calculations took account of:

1. the vertical tidal motion of the solid Earth,
2. the vertical marine tide relative to the solid Earth,
3. surges caused by wind stress and atmospheric pressure,
4. slow circulation and steric changes associated with movements of the Atlantic Ocean,

5. a quasi-static slope which balances the mean meridional gradient of atmospheric pressure, and
6. local steric differences caused by freshwater influx.

We ignored increments less than 0.05 m because several elements in the altimetric equation are only to decimetric precision. The Earth tide correction (1) was a straightforward calculation of the 'body tide' of the solid Earth, because loading and self-attraction from the M2 ocean tide in the North Sea has been shown to be less than 0.02 m (Baker, 1980).

Tides (2) and surges (3) were estimated to at least decimetre precision from a numerical model devised by Flather (1976, 1981) for the forecasting of floods and now used routinely by the UK Meteorological Office for this purpose. The tides calculated by global numerical models, though adequate in the deep ocean, are of poor accuracy in shallows such as the North Sea because of the small horizontal scale of such motions. Flather's model represents the principal components of the tides over the shelf seas more correctly, as free waves generated by the tides at the shelf-edge, which have been accurately measured by IOS (Cartwright et al., 1980). Shallow water effects are self-generated by a full complement of nonlinear terms used in the dynamical equations. Some small tidal constituents not included in the model, notably those of diurnal period, were added from an array of constants from an adequate tidal map. The dynamical effects of wind and pressure are computed in the model from an input array supplied by the 10-level weather forecasting model run by the UK Meteorological Office. These were not severe during the period of operation of SEASAT.

Estimation of steric slopes (6) was shown by some applications of Bowden's formula (Bowden, 1960) to typical density distributions in the North Sea to be negligible (less than 0.05 m) except in the extreme margins of the German Bight and near the entrance of the Baltic Sea and the Rhine river. We finally made a small correction to allow for (4) and (5), which occasionally on the order of 0.10 m, by fitting a least-squares plane surface to the low-passed sea levels measured at nine coastal stations round the North Sea (including Shetland), using for each individual datum the mean sea level recorded during a simultaneous year, corrected for the mean atmospheric pressure during that year. The year chosen for this reference datum was the only recent 12-month period during which all the chosen tide-gauges operated without obvious fault, namely the period October 1972-September 1973. We considered that geodetic information relating this surface to a true equipotential level was insufficiently reliable to attempt further reduction, but that the correction, if known, would probably amount to less than 0.1 m.

Figure 1 illustrates a typical set of dynamic 'corrections', calculated as described above, for the altimeter surface topography on the descending track of orbit no. 1158, crossing the North Sea from southern Norway to East Anglia and the English Channel from near Portland to Brittany. Points on the abscissae represent the passage over England. Similar corrections were made to all valid passes over the North Sea, and the results used in the overall altimetry exercise are described by Lelgemann and Brennecke in the proceedings of the "SEASAT Over Europe" Symposium.

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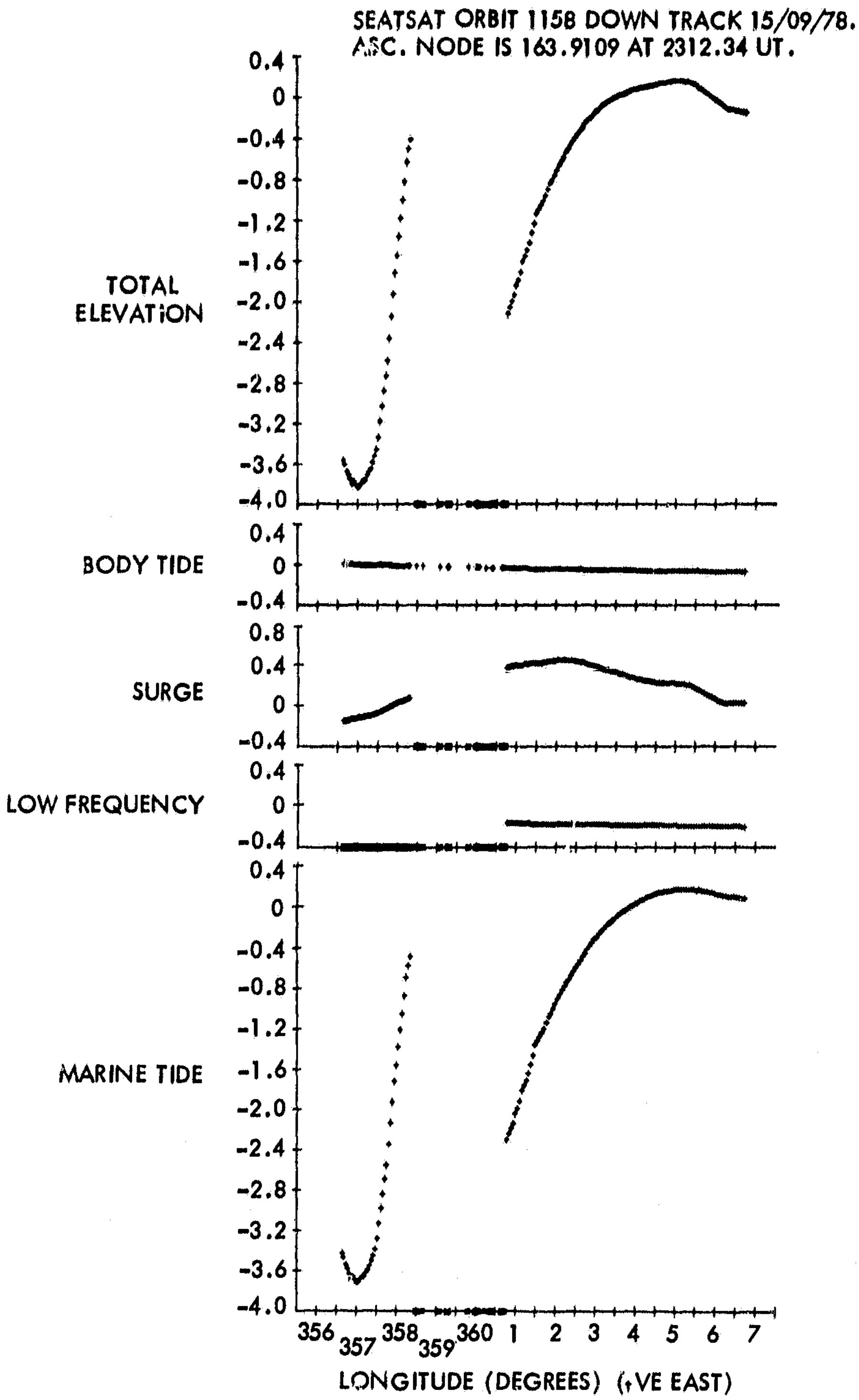

Figure 1. Computed increments in metres to altimetric sea surface recorded during SEASAT orbit no. 1158 over the North Sea and the English Channel, September 15, 1978. The bottom scale is in degrees of east longitude.

Preliminary Work on Northeast Atlantic

Our earliest work on the northeast Atlantic Ocean was based on the first edition of the SEASAT altimetry released to SURGE members, which was based on preliminary assessment of the orbital elevations by JPL. Our results are adequately presented in Cartwright and Alcock (1981), and we make only a brief summary here.

At first we applied corrections for the ocean surface topography in terms of known physical influences, as for the North Sea but with different techniques. The body tide of the solid Earth was calculated as before, but the oceanic loading effects are not negligible here. The loading tide was approximated simply by multiplying by (-0.04) by the local ocean tide, which was known accurately. In this area, the tidal signals supplied from the models of Parke and Hendershott (1980) or Schwiderski (1980) are probably adequate, but we calculated a complete tidal spectrum from our own maps of the area deduced from a major programme of measurements (Cartwright et al., 1980). Finally, weather effects in deep water were represented by the inverse barometer effect, using the good coverage of this area by six-hourly isobaric charts, and a possible small steric anomaly was corrected in terms of tide-gauge records at Cascais, Brest, Stornoway and Reykjavik.

Our statistical analysis of the altimetric topography, corrected for the above effects, during the period of repeated tracks (Bermuda orbit), confirmed what has probably been found by all investigators. The altimetric profiles show amazingly repeatable detail at short wavelengths, much of it correlated with bathymetric features, but there are evident errors in the orbital corrections at very long wavelengths, causing successive estimates of the surface height at any given point to vary within a range of 1-2 meters. The long wavelength errors may, however, be largely removed by pre-whitening operations, of which the simplest is working with the differences between surface elevation at two given points, L kilometers apart. The standard deviation of such pre-whitened measures is on the order of 0.1-0.2 m, which is certainly in the region at which one hopes to detect genuine oceanographic signals. For example, a dynamic change of 0.1 m in 1000 km at mid-latitudes is equivalent to a current of about 0.012 m/s, which is useful to be able to measure synoptically.

There being no interesting current systems which we could hope to resolve unambiguously in the northeast Altantic, we then proceeded to omit the semi-diurnal tidal correction from the altimetry and to attempt to recover it by analysis. Again, differences of elevation along the same repeated track had the lowest practical noise level, and it was particularly convenient to analyse the tidal component of differences in elevation between orbital crossing points. Plots of uncorrected data between such crossing points showed a reasonable semblance of an aliassed tidal variation of well over one period in the 25 days of repeated record.

A special technique of tidal analysis had to be devised whereby all tidal elements in the area were expressed in terms of a two-parameter response operator on a representative tidal variation, together with a third parameter (constant) to allow for the geoidal difference between each pair of crossing points. Forcing each of these parameters to sum to zero round every closed circuit of inter-crossing-point segments was a necessary and useful constraint on the overall solution.

Applying this procedure to the (then) total available data set, (after omission of a few obvious anomalies), covering a network of 18 segments, of which 12 were independent and the remaining six were determined by the zero-constraint, required solution of a 36 x 36 matrix. The resulting tidal-difference parameters were then converted to vectors of elevation at the crossing points themselves by addition of a single tidal vector for the known tidal elevation at one of the crossing points, derived from one of our bottom-pressure records. The array of M2 amplitudes and phases, so derived, agreed surprisingly well with the known tidal map of the area, considering the small sample of data used and its noise level. An expanded result is shown in Figure 2. This greatly encouraged the prospect of being able to use longer sections of future altimetry data to derive the tidal parameter for regions of the oceans where they are still very uncertain.

Recent Tidal Analysis for the Northeast Atlantic

With the arrival in 1981 of a global set of altimetry from SEASAT, newly edited by JPL, we decided to extend the method of tidal analysis outlined above to larger areas. Again, we were perforce restricted to the 'Bermuda' period of repeated ground tracks. Our procedure was the same, except that, for the atmospheric loading correction, in place of the barometric pressure array derived from UK sources, we used the FNWC data set supplied on the altimeter tape. Also, we omitted the steric correction based on tide-gauge data, because this would not, in general, be available in wider ocean areas. On the whole, there were fewer items of dubious data requiring elimination.

After applying the same method to precisely the same network of crossing points described earlier, and obtaining similar though not identical results, we expanded the network to include crossing points at about 32.8°, 7.7°, and 3.5°W longitudes and at 63.8° and 36.9°N latitudes. This entailed 39 x-point differences, of which 25 were independent, and 14 determined by constraints, leading to inversion of a 75 x 75 matrix of independent solution elements. The associated x-points are marked by circles in Figure 3, and the matrix of solutions for M2 is displayed in Figure 2.

As before, the 26 amplitudes and phases follow, by and large, the pattern known from the underlying tidal map, with amplitudes increasing eastwards towards the European shelf and phases progressing steadily northwards and westwards round the major amphidrome off the western side of the map. The reasonably good additional values at the x-point in the southeast corner are interesting because the vector-difference from the nearest x-point at 43.4°N has no constraint, owing to the absence of data from the x-point over northwest Spain preventing a closed loop. The evaluation of this difference is therefore independent of the rest of the array, and its satisfactory value is encouraging. Another area of interest is in the northeast corner, where the amplitudes and phases correctly represent the rapid changes round the secondary amphidrome east of Iceland.

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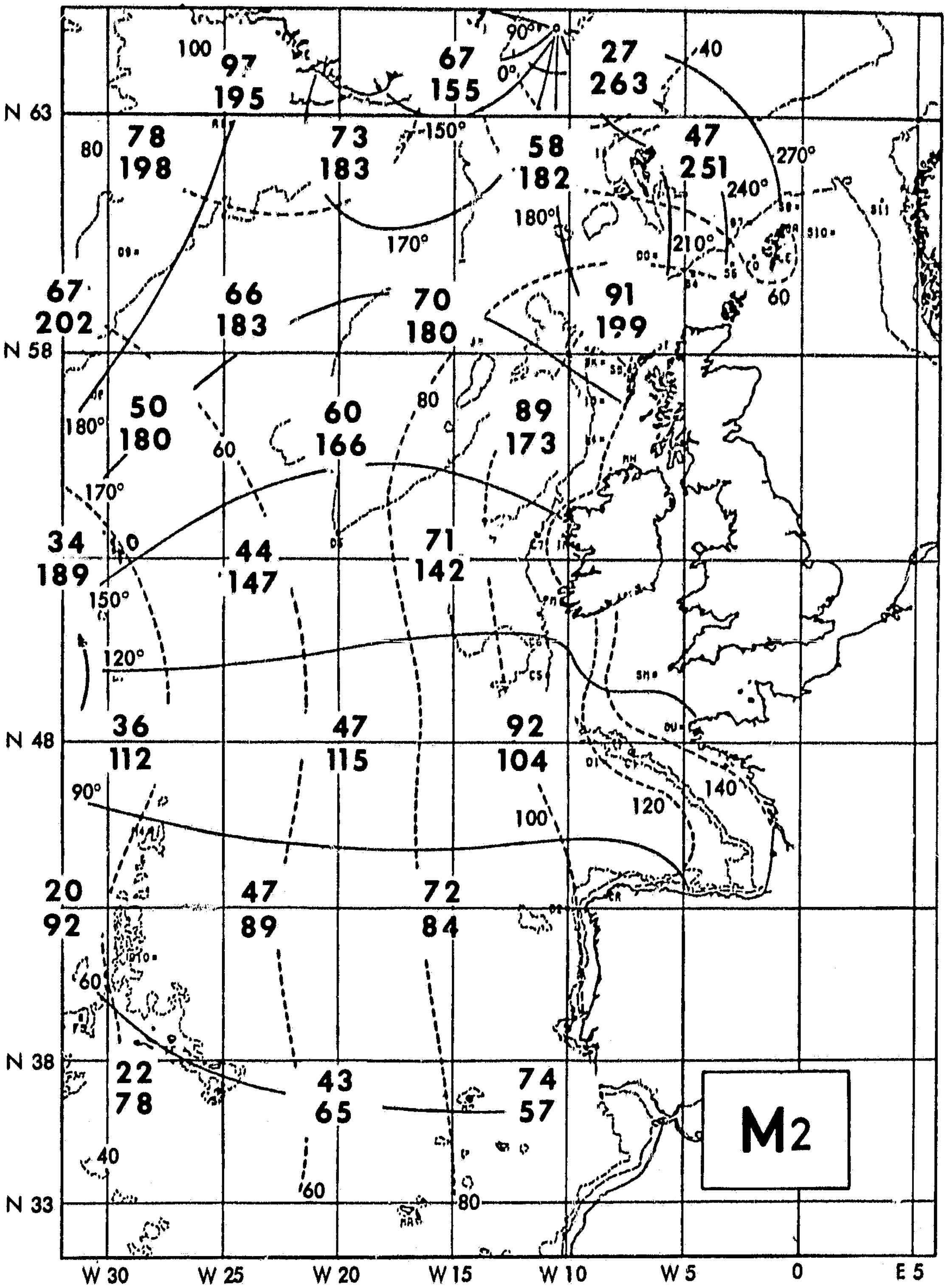

Figure 2. Large pairs of numbers denote amplitude in centimetres (upper) and phase lag in degrees (lower) of M2 tidal component at x-points of Bermuda orbit, deduced from altimetry by method described in text. The full-line contours are the true phase lags, the broken line contours amplitudes, derived from previous pressure measurements.

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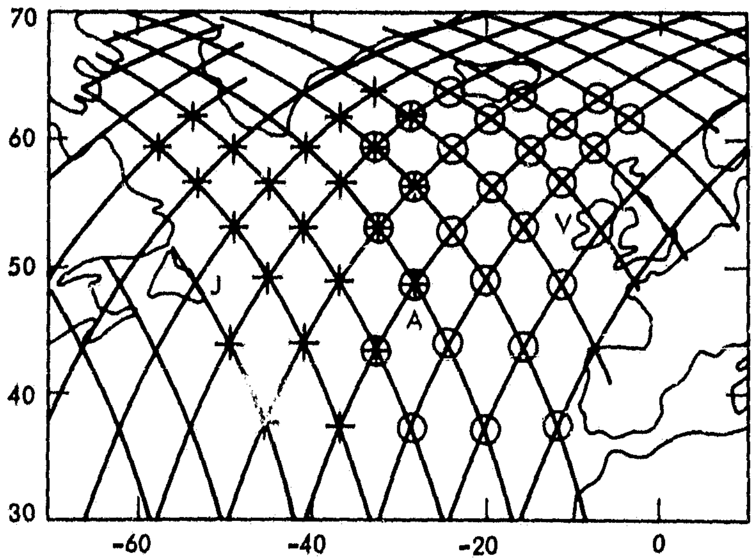

Figure 3. Earth-tracks of SEASAT over the north Atlantic during the Bermuda orbit period. Circles mark the cross-points used for the northeast array (Figure 3), and + signs mark the cross-points used for the central array (Figure 4). 'A' marks the point where tidal constants were supplied from measurements. V = Valentia, J = St. John's.

Extension to Central North Atlantic

Our most recent exercise in tidal analysis applies the procedure of the previous section to a more westerly sector of the north Atlantic, whose x-points are indicated by + in Figure 3. Six x-points are here used in common with our northeast array, partly in order to use the same tidal point (marked A) as origin for converting differences to elevations, and partly for a comparison test. The nature of the zero-constraints applied in our method results in a different solution for a given x-point difference vector according to the matrix array from which it was derived. To attempt solution for one huge array covering the whole north Atlantic would probably stretch the conditioning of the matrix of normal equations, although it would be worth considering when future altimeter data sets with longer time span and lower noise level become available. Besides this, the single vector used to parameterise the tides, necessitated by the present short span of data, is best referred to another tidal regime in the western Atlantic.

Whereas our tidal vectors in the northeastern array were referred to the tide at Valentia, southwest Ireland, for our array in the central north Atlantic we referred the vectors to the tide at St. John's, Newfoundland. Apart from that, the procedure was identical.

The results are displayed in Figure 4, superimposed on a tidal map transcribed from Schwiderski (1980). They are significantly less good than in our northeastern array. There is some qualitative agreement with the rapid change of phase as one passes the main amphidrome to the west and a correct increase in amplitude towards the north, but there are areas with errors of order 90 degrees in phase and 50 percent in amplitude, especially in the southern sector. It is possible that the geocentric tide as seen by the altimeter differs significantly from the Earth-relative tide plotted in the tidal map, especially in the position of the amphidrome, but this is only likely to make vector differences of a few centimetres amplitude. However, the main cause of deterioration is almost certainly the high noise level in the area of Gulf Stream meanders south of Newfoundland, clearly identified in the altimetry by Cheney, Marsh and Grano (1981), and by Menard (1981), accomplished by generally lower tidal signals than in our northeastern zone. Another possible source of error is the steep gradient of the geoid west of 30^{o}W, which would produce apparent errors in surface elevation related to slight lateral variation in the nominally fixed orbit. The latter source could be removed by further calculation.

Tidally-uncorrelated noise would be less harmful to tidal analysis as the time span of the data increases. However, Figure 4 usefully sets a limit to the amount of meaningful tidal data which can be extracted from the 25-day Bermuda orbit from SEASAT. We plan similar exercises restricted to the quieter areas identified by Cheney, March and Grano (1981).

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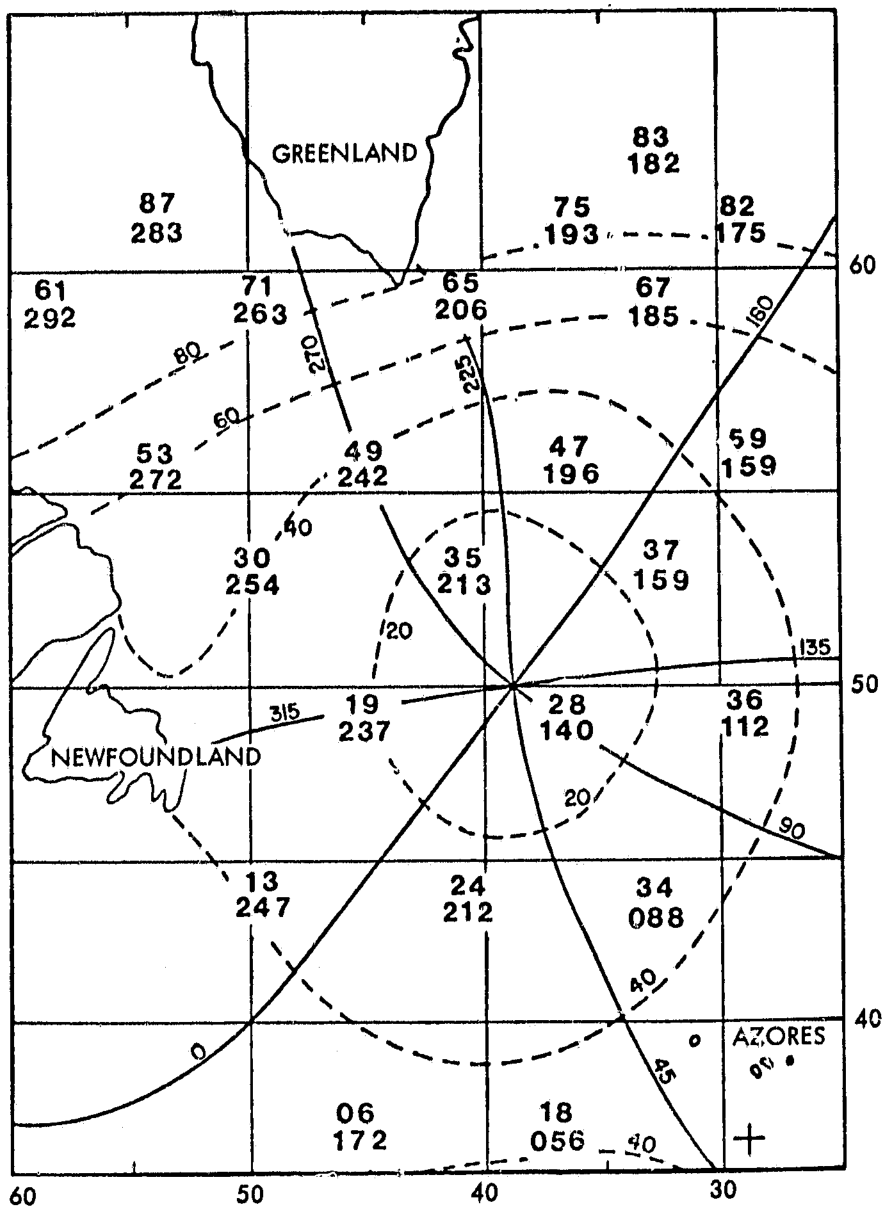

Figure 4. As Figure 2 for central north Atlantic, except that contours are from Schwiderski (1980).

REFERENCES

Baker, T.F., 1980. Tidal Gravity in Britain: Tidal Loading and the Spatial Distribution of the Marine Tide, Geophys. J. R. Astr. Soc., 62, 249-267.

Bowden, K.F., 1960. The effect of water density on the mean slope of the sea surface, Bull. Geodesique, 55, 93-96.

Cartwright, D.E., and G.W. Alcock, 1981. On the Precision of Sea Surface Elevations and Slopes From SEASAT Altimetry of the Northeast Atlantic Ocean, in J.F.R. Gower (Ed.), Oceanography from Space, Plenum Press, New York, 885-895.

Cartwright, D.E., A.C. Edden, R. Spencer, and J.M. Vassie, 1980. "The tides of the northeast Atlantic Ocean." Phil. Trans. R. Soc. London, A, 298, 87-139.

Cheney, R.E., and J.G. Marsh, 1981. SEASAT Altimeter Observations of Dynamic Ocean Currents in the Gulf Stream Region, J. Geophys. Res., 86, C1, 473-483.

Cheney, R.E., J.G. Marsh, and V. Grano, 1981. Global Mesoscale Variability From SEASAT Collinear Altimeter Data, EOS Trans AGU, 62, 17, 298.

Flather, R.A., 1976. A Tidal Model of the Northwest European Continential Shelf, Mem. Soc. Roy. Sci. Liege, 6 ser, 10, 141-164.

Flather, R.A., 1981. Storm-Surge Prediction Using Numerical Models, in M.J. Lighthill and R. Pearce, Monsoon Dynamics, Cambridge University Press, Cambridge, 659-687.

Gower, J.F.R. (Ed.), 1981. Oceanography from Space, Plenum Press, New York.

Kao, T.W., and R.E. Cheney, 1982. The Gulf Stream Front: A Comparison Between SEASAT Altimeter Observations and Theory, J. Geophys. Res., 87, C1, 539-545.

Lelgemann & Brennecke presented at "SEASAT Over Europe" symposium, 1982; in preparation.

Menard, Y., 1981. Study of Variability of Dynamic Ocean Topography West of the Mid-Atlantic Ridge, 30-55N, Annal. Géophys., 37, 1, 99-106.

Parke, M.E., and M.C. Hendershott, 1980. M2,S2,K1 Model of the Global Ocean Tide on an Elastic Earth, Marine Geodesy, 3, 379-408.

Schwiderski, E.G., 1980. Ocean Tides, Part II; A Hydrodynamical Interpolation Model, Marine Geodesy, 3, 219-255.

Synthesis of Ocean Tides by Normal Modes

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For the final phase of a study of oceanic normal modes, I have synthesized diurnal and semidiurnal tides of the world ocean. Sixty modes were used, in the period range of 8 to 96 hr. Although the modes are dissipationless, a variational treatment of Laplace's tidal equations permits the synthesis to include outward flux of energy across the boundary. The available friction parameter was adjusted to give a total flux of 3×10^{12} W for the M2 tide. The preliminary results (reported April 13, 1982, at the NASA Tides Workshop) placed the global Q at about 100, almost 10 times greater than generally received values. It also produced a frequency response with many modal peaks throughout the tidal bands. This overly energetic response was puzzling.

Subsequently (July 1982) I found that for a given dissipation there are <u>two</u> values of the friction parameter, one of which gives a high-Q response (the one on which I had been impaled!), the other a low-Q response. The latter Q is about 10 for M2 dissipation of 3.5×10^{12} W, and the corresponding tidal map resembles in most important respects published maps such as those of Accad and Pekeris (1978), Parke and Hendershott (1980), and Schwiderski (1980). Moreover, the frequency response at low Q conforms well to the "credo of smoothness" enunciated by Munk and Cartwright (1966).

References

Accad, Y., and C.L. Pekeris, 1978. Solution of the Tidal Equations for the M2 and S2 Tides in the World Oceans from a Knowledge of the Tidal Potential Alone, <u>Phil. Trans. Roy. Soc.</u>, A, 290, 235-266.

Munk, W.H., and D.E. Cartwright, 1966. Tidal Spectroscopy and Prediction, <u>Phil. Trans. Roy. Soc.</u>, A, 259, 533-581.

Parke, M.E. and M.C. Hendershott, 1980. M2,S2,K1 Models of the Global Ocean Tide on an Elastic Earth, <u>Marine Geodesy</u>, 3, 379-408.

Schwiderski, E.G., 1980. Ocean Tides, Part II; A Hydrodynamical Interpolation Model, <u>Marine Geodesy</u>, 3, 219-255.

Satellite Observations
and
Ocean Tides

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Geodetic parameters and orbit determination software have been improved significantly over the past few years so that accurate global observations of the ocean tidal effects are now possible. These observations are recoverable from direct measurements of the orbit perturbations of geodetic satellites by means of laser tracking data and also from radar altimeter measurements of the ocean topography.

For example, the total orbit perturbation of a typical geodetic satellite at an altitude of 1000 km due to the ocean tides amounts to almost 2 m in a 5-day orbital arc. This is a very large signal compared to the 10 cm accuracy of the laser tracking data. Numerous investigations have been carried out over the past several years for the recovery of ocean tidal parameters from orbital perturbation data. For example, some of the most noteworthy contributions to this field have been made by Cazenave and Daillet (1981), Daillet (1978), Cazenave, Daillet, and Lambeck (1977), Lambeck, Cazenave, and Balmino (1974), Felsentregger, Marsh, and Williamson (1978), and Goad and Douglas (1978). The most rigorous and accurate solution has been recently computed by Marsh, Lerch, and Williamson (1983) using direct analyses of the Starlette laser tracking data. The evolution of the mean orbit was used in all previous analyses. This recent solution has provided low degree and order values for K1, O1, K2, M2, S2 that are in good agreement with the Schwiderski (1980) and the Parke and Hendershott (1980) models (see also Yoder, 1982). Now that this new technique has been developed and proven, work is in progress to analyze additional data which will provide for the recovery of additional coefficients and also to include laser tracking data on SEASAT, Lageos and GEOS-3.

The satellite altimeter data provides a direct measurement of the location of the sea surface with respect to the spacecraft position. The tidal variations which at times are on the order of a meter are clearly visible in the data. The altimeter data from SEASAT has an accuracy of 5 cm; however, the location of the sea surface with respect to the center of mass of the Earth contains the orbit computation errors which currently amount to about 50 cm. These orbit errors have long wavelengths with the primary frequency being near once/revolution of the satellite. The long continuous arcs of SEASAT altimeter data provide an important data base for the separation of ocean tidal signals from the orbit error.

One technique which has been developed for the analyses of the altimeter data involves the use of sea height differences at the intersections of ascending and descending tracks. These intersection differences, called crossover differences, are due to the effects of temporal ocean height variability plus orbit error. The mean sea surface height at the crossover point will be the same for both passes at the crossover point and cancels out in the differences. During the lifetime of SEASAT, several million such crossover points were established. We have recently computed the geographic locations and crossover residuals for this data set. With such a long time record and global distribution of data it is believed that good separation between ocean tidal effects and orbit error can be achieved for this time period. These analyses are in progress.

References

Cazenave, A., S. Daillet, and K. Lambeck, 1977. Tidal Studies from the Perturbations in Satellite Orbits, Phil. Trans. R. Soc. London, Ser. A, 284, 595-606.

Cazenave, A. and S. Daillet, 1981. Lunar Tidal Acceleration from Satellite Data, J. Geophys. Res., 86, B3, 1659-1663.

Daillet, S., 1978. Détermination par Observation des Trajectoires de Satellites Artificiels des Ondes Semi-diurnes de la Marée Océanique: Application au Calcul de L'accélération Séculaire de la Lune, Ann. Geophys., 34(2), 79-87.

Felsentregger, T.L., J.G. Marsh, and R.G. Williamson, 1978. Tidal Perturbations on the Satellite 1967-92A, J. Geophys. Res., 83, 1837-1842.

Lambeck, K., A. Cazenave, and G. Balmino, 1974. Solid Earth and Ocean Tides Estimated from Satellite Orbit Analyses, Rev. Geophys. Space Phys., 12(3), 421-433.

Parke, M.E. and M.C. Hendershott, 1980. M2,S2,K1 Models of the Global Ocean Tide on an Elastic Earth, Marine Geodesy, 3, 379-408.

Schwiderski, E.G., 1980. Ocean Tides, Part II; A Hydrodynamical Interpolation Model, Marine Geodesy, 3, 219-255.

Yoder, C.F., 1982. Spherical Harmonic Decomposition of M.E. Parke's Ocean Tidal Models, JPL Engineering Memorandum 335-30, 27 pp. (A JPL internal document.)

Contribution to Report on NASA Tides Workshop

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Discussion of continuum

Some proposed tidal analyses have included much less frequent sampling so that a tidal frequency being sought is higher than the Nyquist frequency (two data points per cycle). The tidal frequency will then be aliased to a lower frequency, at which it can be identified and analyzed.

A Japanese oceanographer once proposed such a scheme, one that sampled every 35.5 hours. Using predicted, noise-free data, he then successfully analyzed the aliased frequencies of the principal tidal constituents. His method failed, however, with real data because with a Nyquist frequency of one cycle per 71 hours, the noise is maximized, being highest at extremely low frequencies and decreasing monotonically with increased frequency.

To summarize, the proposal to analyze at aliased frequencies is feasible but at a price, namely, decreased accuracy because of the higher continuum (noise); in some cases the signal will not be higher than the continuum, in which case the analysis results will represent noise rather than signal.

Analysis of Paired Tidal Stations

Studies have been suggested to use paired tidal records to determine variability in current normal to a line between two tide stations.

At one time I would have endorsed such a study enthusiastically; however, having been involved in what I originally thought was an optimum study (paired stations across the Florida Straits where the currents are on the order of 3 knots), I now have some doubts. We were quite sure that the station pairs, Miami-Bimini and Key West-Havana, would show a tilt upward to the right with increased speed and vice versa. Therefore cross-spectra analysis should show high coherence with a phase difference of 180°. The only good coherences we found had a zero phase difference showing the two stations rose and fell simultaneously, telling us nothing about variability in the current flowing between the stations.

This study, "Fluctuations of the Florida Current Inferred From Sea Level Records," by Wunsch, Hansen and Zelter, was published in Deep-Sea Research, 16, 447-470, 1969.

Acoustic Tomography

The suggestion has been made that the only alternative to satellite altimetry for monitoring variable elevations of the sea surface globally is a dense grid of anchored stations spanning the world's oceans. Similar claims have been made for ocean acoustic tomography, a joint research project of Munk (SIO), Wunsch (MIT), and Spindel (WHOI) (Deep-Sea Research 26, 123-161, 1979). In a more recent paper (now submitted for publication), Munk and Wunsch show that satellite altimetry and acoustic tomography complement each other, and "that a combination of these two disparate systems would be extremely powerful."

Contribution to NASA Tides Workshop Report

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It is still unclear whether the oceanic response to long period tidal forcing is equilibrium. Wunsch (1967), for example, has plotted admittance amplitude and phase for several Pacific tide gauge stations. His results suggested deviation from equilibrium, although the error bars make conclusions questionable. Numerical solutions (e.g., Schwiderski, 1982; Carton, 1982) of this problem in realistically shaped basins, suggest some regions are close to equilibrium while others are not. Considering the simplified frictional parameterizations employed in these models, it is compelling to understand the oceanic dissipation mechanisms and where they take place.

There is tremendous variability in ocean currents which is associated with mesoscale turbulence. The MODE data has shown the MODE region to contain considerable energy in time scales of 10 to 100 days and predominantly in the barotropic and first baroclinic modes. Since the oceanic response to the long period tides is also barotropic and on similar time scales, one must wonder what effects these eddies have in damping or exciting basin-wide vorticity modes. In order to better understand this, Myrl Hendershott and I have been looking at normal mode excitation in eddy-resolving numerical models.

We have obtained from Holland (see Schmitz and Holland, 1982) numerical simulations of quasi-geostrophic flow in 4000 km-square basins with (i) two layers, flat bottom, (ii) three layers, flat bottom, and (iii) two layers, random topography. We have decomposed the nonlinear flow into the linear normal mode solutions using appropriate orthogonality relations. For case (i) we found substantial excitation at the resonant frequencies, at least for the larger scale modes. The turbulence (which is localized in the western basin) apparently acts like a broadband energy source, since the wind forcing is steady.

We next intend to analyze cases (ii) and (iii). The three-layer simulation allows greater eastward penetration of the turbulence. We wish to see to what extent the stronger nonlinearity affects the widths of the resonant peaks. Case (iii) allows the presence of spacially locked linear modes and inhibits eastward energy transfers due to the topography. We intend to use Platzman's (1978) normal mode programs to solve for the linear modes in this case. Once we have analyzed all three cases, we will be in a position to decide which case would be best suited to add long period tidal forcing. Thus, we can get to the question of how close to equilibrium are the long period tides.

Doug Luther is in the process of preparing Pacific tide gauge records for normal mode analysis using Platzman's predicted modes. He intends to stack the records (i.e., lag them at the predicted phases, sum them, and then Fourier analyze) which, in principle, will suppress noise and bring out a peak at the predicted frequency if the mode is truly present. Thus, from the width of the peak, an estimate of the basin-scale dissipation rate can be made. This would give further insight into the long period tidal response question.

REFERENCES

Carton, J.A., 1982. The Long Period Tides in Closed Basins, to be published.

Platzman, G.W., 1978. Normal Modes of the World Ocean. Part I. Design of a Finite Element Barotropic Model, J. Phys. Oceanogr., 8, 323-343.

Schmitz, W.J., and W.R. Holland, 1982. A Preliminary Comparison of Selected Eddy-Resolving General Circulation Experiments With Observations, J. Mar. Res., 40, 75-117.

Schwiderski, E.W., 1982. Global Ocean Tides, Part X: The Fortnightly Lunar Tide (Mf). Atlas of Tidal Charts and Maps. Naval Surface Weapons Center Technical Report.

Wunsch, C., 1967. The Long-Period Tides, Rev. Geophys., 5, 447-475.

Synopsis of NSWC Ocean Tide Modeling

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The first phase of ocean tide modeling at NSWC has now been completed with construction of the leading eleven partial tides:

(M2, S2, N2, K2), (K1, O1, P1, Q1), and (Mf, Mm, Ssa).

All components are defined on a $1^{\circ} \times 1^{\circ}$ grid system with an estimated superposed tide prediction accuracy of about 10 cm in the open oceans. The estimate is substantiated by empirical tide data of equivalent accuracy from some 2000 gauge stations around and in the oceans. Since the known empirical data of the minor long-period tides (Mf, Mm, Ssa) are quite marginal in quantity and quality, the accuracy of these models may be somewhat questionable in certain ocean areas. Nevertheless, it must be mentioned that the applied hydrodynamical-interpolation technique failed to integrate consistently some earlier Pacific tide data into the model, but succeeded uniformly with all data which were recently reanalyzed by Luther for Mf and Mm.

The successful computation of harmonic ocean tides was essentially faciliated by the unique capability of the novel hydrodynamical interpolation to resolve realistically major distortions of ocean tides by continental shelves, narrow ocean ridges, and other bottom irregularities. Nevertheless, in coastal waters the accuracy of the tide models is naturally somewhat limited because of marginal empirical data, which are directly interpolated. Also, a $1^{\circ} \times 1^{\circ}$ grid system cannot resolve tides varying rapidly over short distances. In fact, many border seas are not modeled at all or display only crudely averaged empirical data. Finally, it must be mentioned that the time-stepping integration of the discrete ocean tidal equations was terminated when the tidal elevation field had reached a sufficiently periodic state. To foreclose expensive computer time, an analogously stringent condition was not imposed on the much more variable velocity field which, hence, cannot be assumed to have reached a similar uniformly periodic state.

To eliminate the shortcomings of our tide models and to improve their overall accuracy significantly, we are now calling for a worldwide drive for:

1. <u>Improved long-term gauge measurements (one year or more)</u> of ocean tides along all shores and at selected deep-sea points. Wherever possible, tidal velocities should also be measured.
2. <u>Accurate long-term satellite-altimeter measurements</u> of ocean tides, particularly in high-tide areas and in otherwise inaccessible regions.
3. <u>Improved multimode harmonic analyses</u> of all recorded long-term measurements, including radiation, noise, and other disturbances. Also the analysis should consider time variations of amplitudes and phases and include such additional partial tides as:

(Mf, Mm, Ssa, Mf′, Mtm), (J1, M1, K1′, O1′),

and (L2, T2, 2N2, μ2, ν2, M2′, K2′).

4. Refined normal-mode analyses of tidal resonances and other fundamental hydrodynamical properties of ocean tides.

5. Refined limited-area tide models of strong tidal variations particularly in border seas, bays, and other shelf regions.

6. Improved global ocean tide models with the goal to achieve a tidal height accuracy of 3 cm or better and a reliable realistic tidal velocity field in all waters, which are urgently needed in numerous applications of today.

Research on Ocean Tides

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The study of ocean tides is important because the tides not only introduce errors into the determination of geostrophic velocity but are also of considerable interest in their own right. Investigations of tides in ocean basins with realistic topography and coastal boundaries are in a very active stage now.

The numerical ocean tidal models currently available differ by several tens of centimeters in many areas of the world. The precision satellite altimeter measurements of the sea surface topography now provide the capability of assessing the accuracy of these models. As indicated in the report of the TOPEX science working group, the proposed altimetry mission will be capable of single-orbit accuracies with a $\pm$10 cm or less standard error over distances of 3000 km, assuming the error spectrum is white from 3000 to 30 km. Such accuracy should allow the observation and measurement of the ocean tides.

The development of tidal models and analysis of the potentially available accurate altimetric measurements should be closely coordinated to improve our understanding and description of ocean tides. Most of the present numerical models make extensive use of measurements which are obtained in awkward locations such as the coastal side of the continental shelves, bays, and estuaries, where shallow water effects are predominant, and use them with deep-sea tidal models. The number of bottom pressue gauges in the deep ocean is still small. Altimetric measurements in pelagic regions should alleviate these difficulties. Altimetric measurements of the tides in shallow seas should be useful in the determination of the friction parameters which consititute an open area of research in the present numerical models.

Conversely, the reduction of the altimetric data and its proper interpretation in the context of tidal effects is to some extent predicted upon a satisfactory nominal tidal model. The better the model the better the results of data reduction. Future development of numerical tidal models should proceed on a wide front:

1. Dynamical models yielding the natural modes of the ocean basins as well as the forced response should be developed in order to gain understanding of the basic dynamics involved.
2. The effect of friction, self-gravitation, and tidal loading merit continued investigation.
3. The modeling of long period tides should be developed beyond the present beginning stage.
4. Systematic procedures to extrapolate tidal data gathered at irregular invervals in space and time should be developed. These objective analysis techniques should circumvent many of the problems associated with uncertainties in physical parameters appearing in the dynamic formulations.

Deep Ocean Tide Determination--A Prospectus

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Our knowledge of ocean tides is severely limited by a lack of direct measurements in the deep ocean. There is a wealth of tide gauge data from the shores and estuaries of most developed countries and scattered islands in mid-ocean. These data are supplemented by data from a few bottom pressure gauges emplaced in deep water, and recently from land-based tidal gravity data (Kuo and Jachens, 1977). But modeling deep ocean tides from what are essentially boundary conditions cannot be expected to be accurate except in the vicinity of the measurements.

To assess the accuracy of tide models in the deep ocean, we need only review the tide model predictions in the northeast Pacific ocean. Since 1904, at least 20 different tide models have been constructed for this area. If we examine their parameters at a single point in deep water, say at about 34°N and 215°E, we may compare them with the JOSIE II bottom pressure gauge parameters reported by Irish, Munk, and Snodgrass (1971). Figure 1 shows the M2 amplitudes (arrow length) and Greenwich phase angle (arrow azimuth, CCW from East) predicted by these models for the JOSIE II station. M2 amplitudes predicted by these models range from 13 to 57 cm, and the Greenwich phase angles are spread over a range of 300 degrees, but cluster within 40° of the JOSIE II phase angle. These parameters have been extracted graphically from tide charts published in the literature, and as such they may have suffered transcription errors of as much as 10 cm in amplitude and 5° in phase. However, the importance of this diagram is not in the individual model parameters or their agreement with the bottom pressure gauge (16), but in their variation.

Since most of these predictions used the same measurements, the observed variation principally shows the effect of the different assumptions used in the modeling techniques. For example, models 5, 6, 8, 9, 10, 12, 13, 14, 15, 20, and 22 are numerical solutions of Laplace's tidal equations, using idealized assumptions for tidal dissipation: assumptions, such as nonideal coastline configuration, nonconstant ocean depth and dissipation, the presence of anomalous earth tides and ocean bottom loading effects, which can cause the tidal amplitude predictions to vary by a factor of three and cause amphidromes to rotate in the wrong direction (Perkeris and Accad, 1969). This sensitivity to variations in modeling technique is due to two factors: The near-resonance of the semidiurnal tide in this part of the ocean (Hendershott, 1973), and the lack of direct in situ measurements.

Bottom pressure gauges would provide ideal in situ measurements if they could be constructed and deployed cheaply. Since this is not likely, the next best alternative is to make use of the satellite altimeter data from existing satellite missions (GEOS-3 and SEASAT-1) and those planned for the near future (TOPEX and GEOSAT). The satellite altimeter measurement of sea surface height is referenced to the Earth's center of mass, and is thus free of assumptions of

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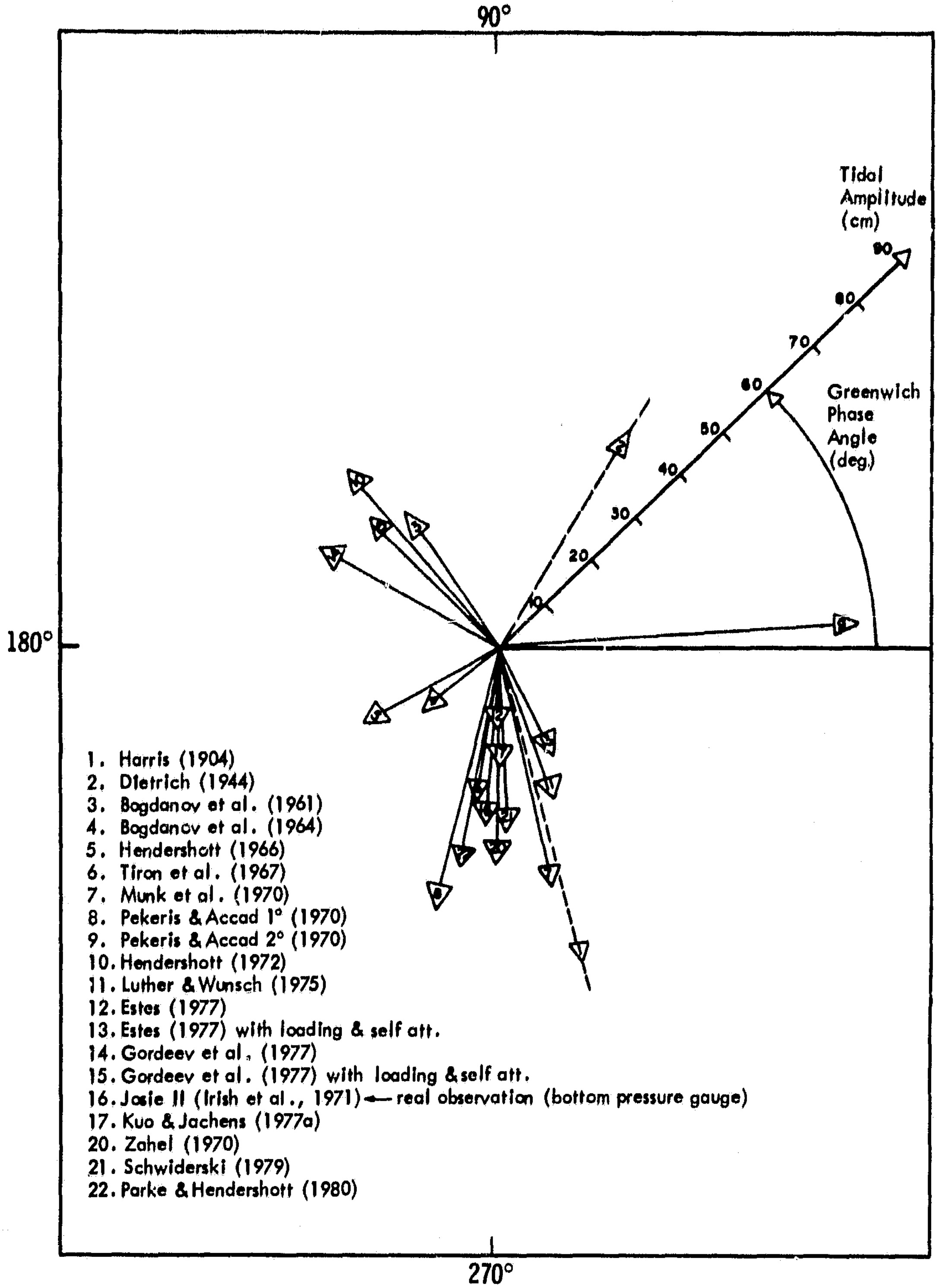

Figure 1. M2 amplitude (arrow length) and Greenwich phase angle (arrow azimuth, CCW from east) for tide models compared with the JOSIE II bottom pressure gauge (Irish et al., 1971).

bottom topography, Earth tides, crustal loading, and coastline geometry. In addition, satellite altimeter measurements can be made available at high density over all the world's oceans within a short time frame.

While satellite altimetry shows great potential as a tide measurement technique, it is not without problems. The simulation performed by Zetler and Maul (1971) indicating that the tidal signal could be spectrally separated from orbital error was contradicted by the poor GEOS-3 results of Maul and Yanaway (1978). Won and Miller (1978) attempted to mitigate the effect of orbit error by a simultaneous solution for geoid heights, tides, and orbit error biases, but found that the GEOS-3 altimeter noise error (30 to 70 cm RMS) was too high for reliable recovery of tidal parameters. Parke (1981) has demonstrated that the M2 tidal signal is strikingly evident in the more precise (6 to 15 cm RMS) SEASAT altimeter data, and Cartwright and Alcock (1981) have recovered M2 parameters in the eastern North Atlantic from SEASAT data. They used a priori knowledge of the tidal parameters at a local reference point to overcome the orbital error effects. Recently, Brown and Hutchinson (1981) demonstrated that fitting short arcs of altimeter data to a reference geoid removes orbit error sufficiently for a completely independent solution for tidal parameters. Using this correction, Brown (1982) has obtained a solution for the M2 tide parameters from 19 SEASAT passes near Cobb seamount in the northeast Pacific. This solution yields M2 tide parameters which are in fair to good agreement with those of a bottom pressure gauge on Cobb seamount. The amplitude is underestimated by about 40% but the phase angle agrees to within 2^{o}.

Problems yet to be solved in altimetric tide measurement are:

1. The limited amount of good quality altimeter data. SEASAT-1 provided only about 30 days of data suitable for tide determination, which is barely enough for observations of 20 different phases for a given tidal component. This is miniscule compared to the long time series normally used in harmonic analysis of tidal records.

2. The resonance of the repeating orbit with the tidal components. It is very desirable to have a repeating orbit in order to achieve a high density of measurements in a small local area. But with SEASAT-1, the repeat period was almost exactly three days, and was a close subharmonic of the K1, S2, and O1 components. As a result, the altimetric tide solutions are subject to unusually high aliasing between components. This is further aggravated by the shortness of the SEASAT data records.

3. The precision of the satellite altitude measurement. Even with the high precision provided by SEASAT-1, this is a limiting factor in our ability to locate and resolve tidal amphidromes.

In conclusion, the best prospect for improved ocean tide determination in the deep ocean is the use of satellite altimeter data from existing or planned future satellite missions. However, to maximize the utility of these data, it is important that the satellite orbit and mission be planned carefully.

REFERENCES

Brown, R.D., 1982. Ocean Tides Near Cobb Seamount From SEASAT Altimeter Data, J. of Geophys. Res., in press.

Brown, R.D., and M.K. Hutchinson, 1981. Ocean Tide Determination From Satellite Altimetry, in J.F.R. Gower (Ed.), Oceanography From Space, Marine Science, Vol. 13, Plenum Press, New York, 897-906.

Cartwright, D.E., and G.A. Alcock, On the Precision of Sea Surface Elevations and Slopes From SEASAT Altimetry of the Northeast Atlantic Ocean, in J.F.R. Gower (Ed.), Oceanography From Space, Marine Science, Vol. 13, Plenum Press, New York, 885-895.

Hendershott, M.C., 1973. Ocean Tides, EOS, Trans. Am. Geophys. U., 54(2), 76-86.

Irish, J., W. Munk, and F. Snodgrass, 1971. M2 Amphidrome in the Northeast Pacific, Geophys. Fluid Dyn. 2, 335-360.

Kuo, J.T., and R.C. Jachens, 1977. Indirect Mapping of Ocean Tides by Solving the Inverse Problem for the Tidal Gravity Observations, Ann. Geophys., T. 33, Fasc. 1/2, 73-82.

Maul, G.A., and A. Yanaway, 1978. Deep Sea Tides Determination From GEOS-3, NASA Wallops Flight Center, contractor report 141435.

Parke, M.E., 1981. Tides on the Patagonian Shelf From the SEASAT Radar Altimeter, in J.F.R. Gower (Ed.), Oceanography From Space, Marine Science, Vol. 13, Plenum Press, New York, 919-925.

Perkeris, C.L., and Y. Accad, 1969. Solution of Laplace's Equation for the M2 Tide in the World's Oceans, Phil. Trans. Roy. Soc. London, A, 265, 413-436.

Won, I.J., and L.S. Miller, 1978. Oceanic Geoid and Tides Obtained From GEOS-3 Satellite Data in the Northwestern Atlantic Ocean, NASA Wallops Flight Center, contractor report 156845.

Zetler, B.D., and G.A. Maul, 1971. Precision Requirements for a Spacecraft Tide Program, J. of Geophys. Res., 76(28), 6601-6605.

Open-Ocean and Shallow-Water Tides and Currents

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Through the finite element modeling in space and the finite differences modeling in time of tides and currents in the Atlantic Ocean and in the New York Bight at Columbia, it is clear now that the tides and currents in open oceans and in shallow waters can be resonably modeled to obtain meaningful results.

The present method complements the finite differences modeling in both space and time. However, the numerical results of tides and currents, obtained either by the method of finite differences or by the method of finite elements, must be experimentally verified in crucial areas.

At the Ninth International Symposium on Earth Tides, which was held in New York City last August, a resolution was passed that considering the tides, physical and satellite geodesy, astronomy, geophysics, meteorology, oceanography as well in space and ocean technology, the Permanent Commission for Earth Tides urgently recommends that a working group be formed to carry out a worldwide drive, principally for:

1. long-term tidal measurements of, if possible, at least six months in duration in oceans, continental slopes, and shelf seas.

2. improving the open ocean, slope, and shelf tides to an accuracy of 3 cm or better.

This resolution substantiates the importance of tidal measurements.

Ocean Tides and Satellite
Altimetry Data

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Altimeter data represents a single height value composed of a sum of contributions from geodesy, the atmosphere, and oceans (Tapley et al., 1982). The height value is inferred from the pulse travel time from the spacecraft to the ocean surface and back again. It is thus affected by instrument time delays, the position of the satellite, atmospheric time delays, the actual radial height of the sea surface, and the interactions of the pulse with the ocean surface. Separation of any one contribution to this measurement, such as tides, requires either distinct length or time scales or information from other sources. In addition, the problem is exacerbated by the usual irregular spatial sampling. Two of the largest problem sources for tidal solutions are the geoid and orbit errors. Figure 1 shows a gradient map of the mean sea surface (after Parke and Stavert, 1983). Typical large scale gradients are around 2 m per degree and can be as large as 5 m per degree over significant portions of the world. Thus, although deep sea tides are long length scale, in general one cannot directly combine height measurements over a spacing of greater than 2 km without creating an artificial time variation of greater than 10 cm based on geoid variations. Orbit errors cause problems because of their large amplitude and because length scales overlap with the deep sea tide. Marsh and Williamson (1980) have shown that the frequencies of orbit error due to errors in the gravity field will be sums and differences of 14.3 and 16.3 cycles/day. Errors at length scales less than 10,000 km should be less than 5 cm.

Analysis of tides from altimeter data involves a number of trade-offs. In shallow water, length scales of the tide can extend well below those of orbit error. On the other hand, resolution with existing data sets becomes poor. In the deep sea resolution improves, but separation becomes poor. Crossover data removes the problem of the geoid, but in general there are only two data points at each location.

Advantage should be taken of the fact that the shape of tidal admittances changes slowly in space. Cartwright et al. (1980) make use of this fact to improve tidal solutions from short bottom pressure gauge records in the northeast Atlantic by referring to a well-known reference station. Parke (1982) shows that with his models, tidal admittances change slowly in space throughout the world's oceans, with the most rapid changes in the south Atlantic and southeast Indian Oceans where length scales can be as short as 500 to 1000 km. Based on the above considerations, the following work is in progress:

1) Analysis on the Patagonia Shelf off Argentina. This is an ideal example of a shallow water case. The altimeter data is being used to distinguish between numerical models of the shelf, with an eye toward an improved estimate of shelf dissipation.

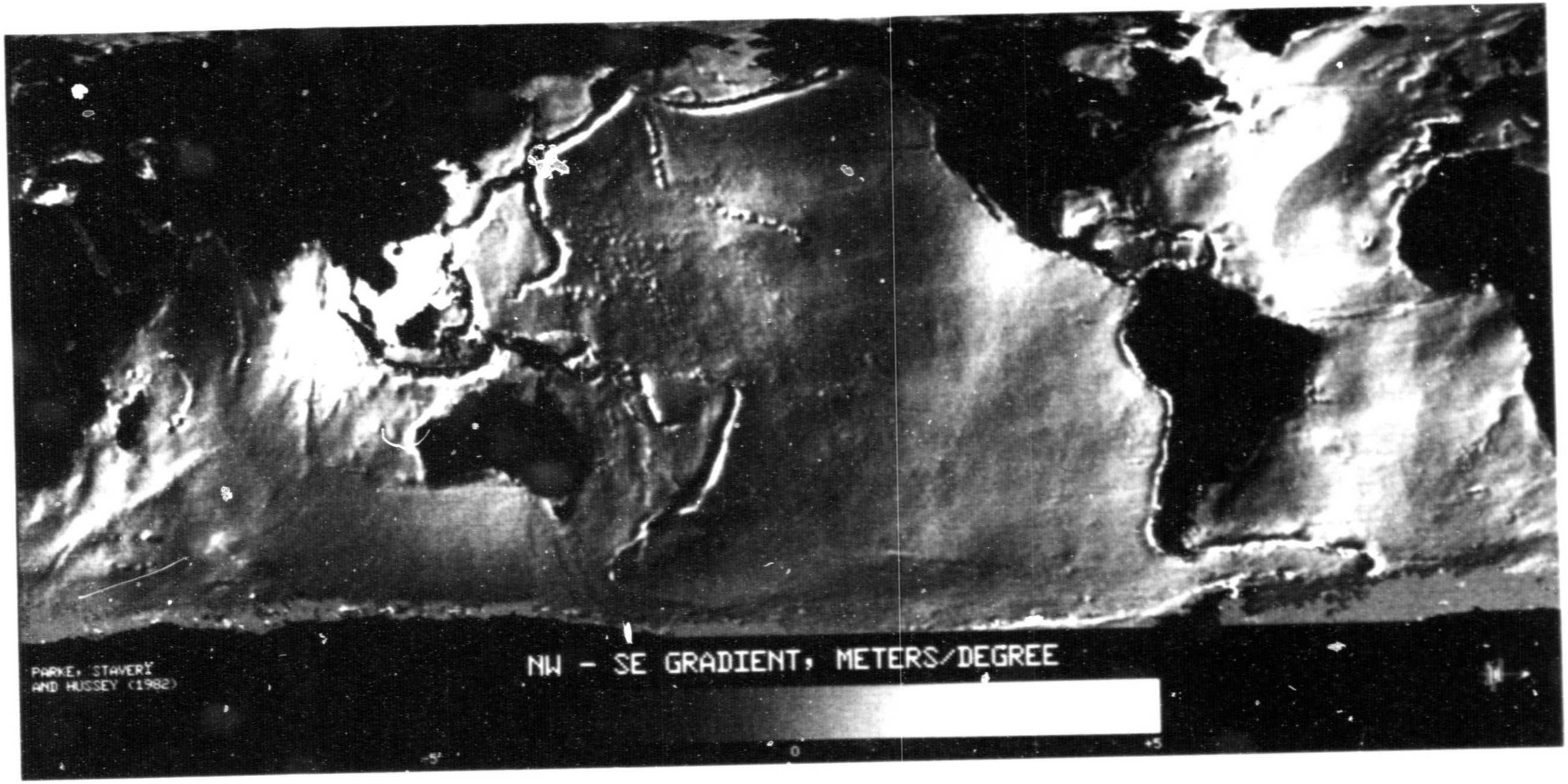

Figure 1. Topographic Relief From SEASAT Altimeter Mean Sea Surface, July 7 - October 10, 1978

2) A modified version of response analysis is being constructed to investigate the deep sea tide. The normal formation is modified to allow the shape of the admittances to vary slowly in space.

3) Several recent tide models are being compared with each other and with altimeter data to determine regional sources of disagreement, and, if possible, to determine the probable cause.

REFERENCES

Cartwright, D.E., A.C. Edder, R. Spenser, and J.M. Vassie, 1980. The Tides of the Northeast Atlantic Ocean, Phil. Trans. Roy. Soc. Lon., Series A, 298, 87-139.

Marsh, J.G., and R. Williamson, 1980. Precision Orbit Analyses in Support of the SEASAT Altimeter Experiment, JPS, XXVII (4), 345-369.

Parke, M.E., 1982. O1, P1, N2 Models of the Global Ocean Tide on an Elastic Earth Plus Surface Potentials and Spherical Harmonic Decompositions for M2, S2, and K1, Marine Geodesy, 6, 35-81.

Parke, M.E., and L.R. Stavert, 1983. Mean Sea Surface and Variability From the SEASAT Radar Altimeter, JGR, in press.

Tapley, B.D., G.H. Born, and M.E. Parke, 1982. The SEASAT Altimeter and its Accuracy Assessment, JGR, 87 (C5), 3179-3188.

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