On the radiational anomaly in the global ocean tide with reference to satellite altimetry

Solar tide
Air tide
Radiational anomaly
Satellite altimetry

Marée solaire
Marée atmosphérique
Anomalie radiationnelle
Altimétrie satellitale

David E. CARTWRIGHT[a] and Richard D. RAY[b]

[a] Borough House, Petersfield, Hampshire, GU32 3LF, Great Britain.

[b] Hughes STX, NASA/ Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

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ABSTRACT

The increasing precision of satellite altimetry in relation to tides justifies making a distinction between the gravitationally generated S_2 tide and its observed values in the ocean, which are affected indirectly by solar radiation. In view of the relatively high noise background, we propose a simplified form of response analysis in which the purely solar semidiurnal harmonics of the gravitational potential are modified by an arbitrary amplitude-factor R* and a phase lag r*. Analysis of a globally representative set of 80 tide-recording stations shows that the observed S_2 constituent is strongly coherent with its gravitational part deduced from lunar tides, with regression constants R* = 0.97, r* = 5.9°. The corresponding 'radiational' anomaly has a phase lag of 108° on the gravitational part, with amplitude ratio 0.105, very close to the values associated with the inverse barometric tide. The proposed analytical procedure should yield improved definition of S_2 and K_2 when applied to altimetry from either sun-synchronous or non-sun-synchronous satellites. This result is confirmed by comparing an analysis of 40 cycles of *Topex/Poseidon* altimetry with 'sea truth' from 30 open-sea tide-gage stations.

RÉSUMÉ

Anomalie radiative dans la marée océanique globale et altimétrie satellitale.

La précision croissante de l'altimétrie satellitale dans le contexte des marées justifie une distinction entre l'onde gravitationnelle S_2 et ses valeurs observées dans l'océan qui sont soumises indirectement au champ radiatif solaire. Compte tenu du bruit de fond relativement élevé, nous proposons, sous une forme simplifiée, une analyse de la réponse altimétrique dans laquelle les harmoniques semidiurnes purement solaires du potentiel gravitationnel sont amplifiées d'un facteur arbitraire R* avec un déphasage r*. L'analyse des constantes harmoniques tirées de 80 stations marégraphiques sélectionnées montre une forte corrélation entre la composante observée S_2 et sa partie gravitationelle déduite des marées lunaires, avec des constantes de régression R* = 0,97 ; r* = 5,9°. L'anomalie radiative correspondante est déphasée de 108° sur la partie gravitationelle, avec un rapport 0,105 en amplitude, valeurs très proches de celles qui sont associées à la marée barométrique inverse. La méthode analytique proposée devrait apporter une meilleure définition de S_2 et de K_2 dans son application à l'altimétrie, que les satellites soient hélio-synchrones ou non. Ce résultat est confirmé par la comparaison d'une analyse de 40 cycles d'altimétrie *Topex/Poseidon* avec les véritésmer de 30 stations marégraphiques au large.

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INTRODUCTION

Probably the most efficient way to extract parameters of the ocean tide from satellite altimetry is to evaluate the pointwise *admittance* to the tidal gravitational potential, assumed to be a smooth function of frequency across each species band. Such a method, commonly called a « response » method, was applied successfully to the « Geosat » altimetry by Cartwright and Ray (1990,1991), and more recently to the difficult case of *ERS-1* by Andersen (1993). The method is particularly useful in a repeated cycle of earth-tracks which aliasses a tide constituent into nearly zero frequency at every sampled global position, because the frozen constituent may then be recovered by inference from the admittance, which has been adjusted to fit other constituents with high frequency aliasses. Thus, Cartwright and Ray (1990) extracted good results for P_1, frozen by the Geosat orbit, and in a preliminary study Andersen (1993) appears to have obtained plausible results for S_2, frozen by the sun-synchronous orbit of *ERS-1*. The response method may also help to separate two constituents with close alias frequencies.

The enhanced precision of the altimetry and computed orbit for « *Topex/Poseidon* » further prompts us to pay attention to anomalous features of the apparent tidal admittance which were small enough to be ignored in the response analysis of noisier data sets, but relevant when an accuracy of 2-3 cm is demanded. Here, we shall ignore anomalies due to nonlinear processes, which affect tides only in shallow coastal seas. [A rationale for treating weak nonlinear effects in a response analysis is set out in Cartwright (1968)]. On the other hand, the so-called « radiational » anomaly, chiefly affecting S_2, appears to be present globally. Its effect is easily seen in good quality harmonic analyses of common tide-gage records by the phase lag of S_2 being usually greater than that of its higher-frequency neighbour K_2, whereas the general trend of phase lag across the gravitational admittance is to increase with frequency. (For an example, see Table 1.) The admittance amplitude is also slightly reduced at S_2.

This anomaly appears to be related in some way to solar radiation, and it is most likely caused by the response of the ocean surface to the global solar tide in atmospheric pressure, which is itself driven by thermal radiation absorbed at high level, (Volland, 1988). A contention by Godin (1989), that the observed anomaly at S_2 may be a result of friction, is inconsistent with the careful measurements in the deep ocean by Cartwright *et al.*, (1988), to be confirmed later in the present study. Godin's mechanism appears plausible in estuarine regimes, involving very shallow water and strong currents. However, such regimes notoriously show other effects of friction in the generation of harmonics by nonlinear interaction of the dominant M_2 with S_2 and N_2, resulting in obvious anomalies at μ_2 and L_2 respectively. Those nonlinear anomalies are undetectable in precise measurements from the open ocean, where the anomaly at S_2 is as evident as elsewhere globally.

In analysing about a year of conventional tide gage data, it is quite feasible to take account of the radiational anomaly, either by spectral analysis at $1 c.y^{-1}$ resolution or by allowing for a response to a *radiational potential* in addition to the gravitational response. The radiational potential differs fundamentally from the gravitational potential in being zero at night, but its spectrum near $2\ c.d^{-1}$, (Cartwright and Tayler, 1971, Table 6), is very similar to that of the gravitational potential of the Sun alone, without the lunar contribution to K_2. The two potentials are therefore strongly correlated, and attempts to separate the two potentials tend to show some degree of numerical instability, unless the noise level is very low or a very large sample population is available. Now, noise level at the low aliassed frequencies of satellite altimetry is considerably higher than that of unaliassed tide gage data, and the annual sampling rate at a given geographical position is only of order 10^2, compared with 10^4 for a typical tide gage record. So analysis in terms of radiational-cum-gravitational potentials of even the low-noise *Topex/Poseidon* would probably produce unacceptable « cross-talk » between S_2 and K_2.

Table 1

Constants for Reykjavik. (H, He in cm units)

	N	M	S	Sg	K
f	1.8960	1.9323	2.0000	2.0000	2.0055
He	12.1	63.2	-	29.4	8.0
H	26	131	51	56	15
G°	162	184	221	217	219

Rather than ignore the radiational anomaly altogether as previously, we here propose a simpler form of response analysis of satellite altimetry, which allows approximately for the mean anomaly at S_2 without introducing numerical instability. We propose generating the full gravitational potential by standard harmonic expansion, but to multiply the amplitude of S_2 (and its elliptical satellite T_2) by an arbitrary factor R^* and to retard their phases by an arbitrary increment r^*. We assume K_2 to remain unmodified, being largely lunar in origin. We shall show later that $R^* = 0.97$, $r^* = 5.9°$ makes a logical compromise. The slightly modified potential is to be used as a basis for a normal response analysis for three complex terms in each of species 1 and 2, similarly to that of Cartwright and Ray (1990). The harmonic constants for S_2 (and T_2 if required) may then be derived from the assumed smooth admittance-function by applying the same modifying factors. There is no evidence that the diurnal potential requires modification, since the principal diurnal anomaly is at S_1, which may usually be neglected.

In summary, we agree with a Reviewer that we have basically two scientific objectives in mind; 1: to improve definition of the ocean tides recovered from satellite altimetry; 2: to rationalise the comparison of data so derived with the fundamentally more accurate but scarce measurements supplied by *in situ* pressure gages. The discussion which follows is necessarily concerned with the technicalities involved in a practical solution.

DIRECT OBSERVATIONS

In order to test the feasibility of the above procedure, we abstracted the leading semidiurnal harmonic constants from

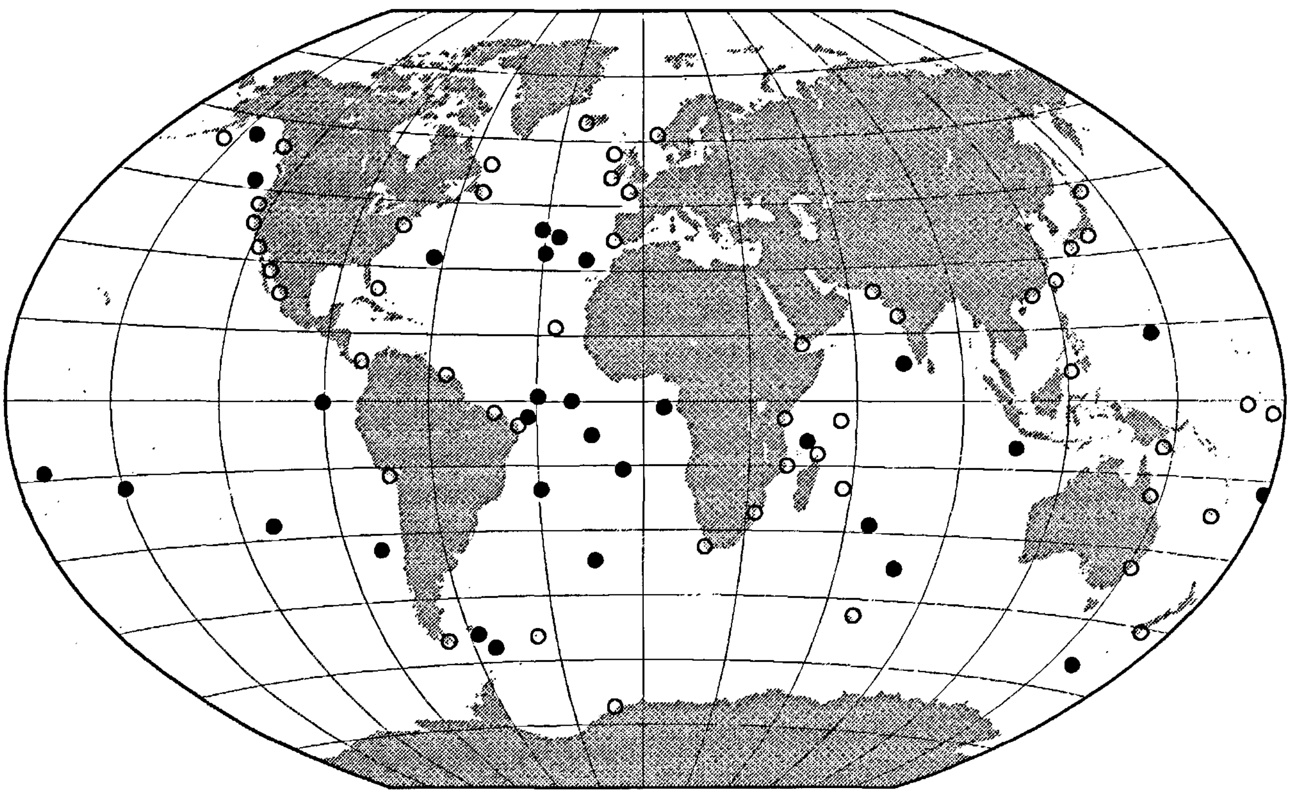


Figure 1

Positions of the 80 tide stations used for analysis of the radiational anomaly. Filled circles : positions also used for comparison with altimetry.

published analyses of long series of tidal data at 80 stations, reasonably well distributed over the global ocean between 65° North and 71° South. Their positions are shown in Figure 1. The main criterion used in selecting these stations was that the solar constituents S and K should be well resolved spectrally without inference from their gravitational relationship. This ideally calls for analyses based on about a year of the original data, or preferably several years, but 200-300 days duration was occasionally allowed in some bottom pressure records, which have lower intrinsic noise level than conventional surface gages. Some of the stations from the Hawaiian chain have many years of data, but were excluded on account of very low amplitude - less than 20 mm in K_2.

Most of the 348 *pelagic* stations published by IAPSO, (Smithson, 1992), are much shorter than 200 days and were therefore excluded, despite the good accuracy of their constants for S_2 and the lunar constituents. Some pelagic records of about a year's duration were also excluded because their published analyses were reportedly or implicitly based on a smooth admittance across the solar frequency band, essentially setting the radiational anomaly to zero. (Ironically, an old-fashioned harmonic analysis of the same data would have been more useful in the present context.) The majority of our 80 stations were therefore drawn from the standard compilations of the International Hydrographic Bureau, together with twelve carefully analysed Atlantic stations detailed in Table A of Cartwright *et al.*, (1988), three Indian Ocean stations from Pugh (1979), and some southern island sites whose constants were provided by the Proudman Oceanographic Laboratory, Bidston, U.K. and by the Australian National Tidal Facility, (Flinders University of South Australia).

Our procedure for evaluating the S_2 anomaly was the same as that described in Section 2(d) of Cartwright *et al.*, (1988), which is similar to that of Zetler (1971). We fitted 3-parameter splines exactly to the values of

$$(H1,H2) = (H / H_e) (\cos,\sin) G,$$

computed from the quantities (H,G) for the listed constituents N,M,K, as a function of frequency f $c.d^{-1}$, where H is the conventional station amplitude, H_e is the equatorial amplitude of the gravitational potential/g in the normalisation of Cartwright and Tayler (1971), and G is the station phase lag on the potential at the Greenwich meridian. The splines were used to provide estimates of the true gravitational tide (Hg,Gg) at the frequency f = 2.0 $c.d^{-1}$, for comparison with the listed constants (H,G) for S.

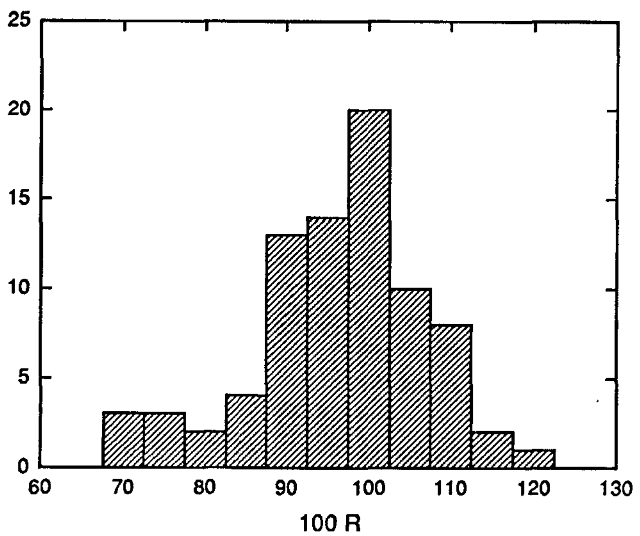
Table 1 lists the figures involved in such a calculation for Reykjavik, Iceland, a typical station except that its amplitudes are larger than average. The columns under N,M,S,K (suffix 2 understood) are the constants given for those constituents. The column headed Sg is the supposed gravitational part of S derived from the splines through N,M,K. For this station we see that R = 51/56 = 0.91; r = 221 - 217 = 4°.

Most tide gages, like Reykjavik, record a direct measure of sea surface elevation relative to land . Pelagic stations including some modern island stations such as Ascension, however, record variations of absolute pressure on the sea bed. Since we are concerned with surface elevation, these pressure variations should be modified slightly by subtracting the tide due to the local atmospheric pressure. For such stations, therefore, we first converted H from pressure units to surface elevation by dividing by (mean sea water density x g), then added to (H1,H2) for S the quantity

$$12 \cos^3 \theta \,(\cos,\sin)(111° - 2\phi) \text{ millimetres} \qquad (1)$$

θ = latitude, ϕ = east longitude), corresponding to the inverted pressure variation of the barometric tide, (Haurwitz and Cowley, 1973). The correction is quite trivial at high latitudes.

Figure 2 shows histograms for all individual estimates of R = H(S)/Hg and r = G(S)-Gg from the entire set of 80 stations. There is considerable spread, but the data are clustered symmetrically about the median values R = 0.975, r = 5.5°. Errors in the published constants for K must be an important source of scatter because of its frequently small amplitude (typically 2-8 cm) in relation to noise in the original sea level record, and because of strong dependence on K of the spline which determines Sg. Although usually quoted to the nearest millimetre and degree, confidence limits for K are typically about ± 3 mm and ± 3°, depending on location and duration of record. For H = 6 cm, these translate into 5 percent in R, 3° in r, comparable with the widths of spread in Figure 2.



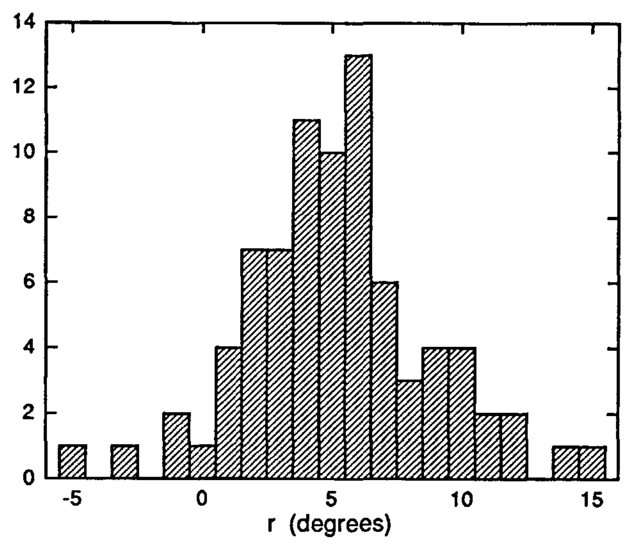


Figure 2

(upper) Histogram of the 80 values of amplitude ratio R.
(lower) Histogram of the 80 values of phase difference r.

MEAN STATISTICS

In order to obtain proper estimates for the mean relation (R*,r*) between S and Sg, we make a vectorial regression between the 80 pairs in terms of the following covariances (cm^2 units) :

$$c_{11} = \frac{1}{2} < H^2 > = 371.3, \qquad c_{22} = \frac{1}{2} < Hg^2 > = 389.4,$$

$$c_{12} = \frac{1}{2} < HHg \cos r > = 376.3, \qquad s_{12} = \frac{1}{2} < HHg \sin r > = 38.8,$$

where < > denotes ensemble averages. The vectorial mean estimates are then :

$R^* = \sqrt{c_{12}^2 + s_{12}^2}/c_{22} = 0.972$, and

$r^* = \arctan (s_{12}/c_{12}) = 5.89^*$, with coherence-squared equal to

$\gamma^2 = (c_{12}^2 + s_{12}^2)/(c_{11}c_{22}) = 0.990.$

So S and Sg are strongly correlated, as one should expect, and R* and r* are close to the median values of R and r respectively.

It is easily shown that the difference between a unit vector representing Sg, and one of amplitude 0.972 with phase lag 5.89° representing S, is a vector of amplitude 0.105 with phase lag 108°. This accords with previous estimates of the radiational S_2 tide, (Zetler, 1971; Cartwright *et al.*,1988), as an anomaly having about 10 percent of the amplitude of the computed gravitational tide with a phase lag in the region of 120°. (Table 3 of Cartwright *et al.*, defines « phase lag » as 360° minus the lag under discussion here, with values near 240°.) The present mean phase lag of 108° is very close to that of the inverse barometric tide, 111°, (equation 1), supporting yet again the hypothesis that the « radiational anomaly » is driven dynamically by the global S_2 air tide. Further, the amplitude ratio of 0.105 almost exactly equals the ratio of the equatorial amplitudes of the air tide, (water equivalent 12 mm), and the gravitational potential, (0.3863 × H_e = 114 mm), thus providing stronger confirmation of the close relationship. However, an exact dynamical theory would have to take account of the different variations with latitude, $\cos^2 \theta$ for the gravitational potential, but empirically $\cos^3 \theta$ for the air tide, (equation 1). We were unable to detect a significant variation with latitude from the present data.

Now, if we assume Sg to be correctly estimated from N,M,K, then the mean square error in sea surface elevation when S is inferred from Sg modified by (R*,r*) may be shown to be :

$$c_{11} + R^{*2}c_{22} - 2R^*(c_{12}\cos r^* + s_{12}\sin r^*) \qquad (2)$$
$$= 3.7, \text{ (rms 1.93 cm)}.$$

These values may be compared with the corresponding values if the correction were to be ignored, that is (2) with R*=1, r*=0, namely

8.0, (rms 2.83 cm).

In terms of satellite altimetry, the latter statistics may be said to apply to the case of a sun-synchronous orbit, for which virtually all observable variation in the solar frequency band comes from K_2, and S_2 has to be inferred from this variation. (In practice, there will be additional variability from the low signal: noise ratio and interference from the semi-annual tide Ssa). The correction (R*,r*) evidently has an advantage in terms of the reduced residual variance of (2), but the improvements in the mean amplitude and phase of S_2 are more important in geophysical terms.

For a satellite orbit which is not sun-synchronous, we may assume that the solar admittance is largely determined by S, from which Sg should be deduced by dividing H by R* and reducing the phase lag by r*. The resulting rms residual at K will then be roughly the above figures (1.93 cm or 2.83 cm) divided by the potential ratio Hg(S)/H(K) = 3.7. Such residual errors of less than 1 cm are of course trivial compared to other residual errors from the noise background, but again, the important advantage of applying (R*,r*) is to obtain a nearly correct global mean amplitude and phase for K_2. For example, maps for K_2 derived from the uncorrected gravitational admittances derived by Cartwright and Ray (1991) should be improved by dividing the amplitude by R* and subtracting r* from the phase lag. Even better results would have been obtained if the original Geosat altimetry had been analysed for a modified potential amplitude and phase for S_2 in the first place, as proposed here.

APPLICATION TO SATELLITE ALTIMETRY

As an application of the above procedure to actual satellite data, and as a demonstration that satellite altimetry has indeed advanced to where these small effects are detectable, we turn in this section to an analysis of data from the USA/France *Topex/Poseidon* satellite. Assessing the efficacy of a radiational adjustment requires a reliable comparison of data at both S_2 and K_2, so we will concentrate only on altimeter data falling near some of our present set of 80 « sea-truth » sites, (Figure 1). Altimetry with ground tracks passing near these sites from the first 40 repeat-cycles of *Topex/Poseidon* (approximately 400 days) was subjected to response-type tidal analyses, one with the modifications proposed here, and one without any adjustment for radiational effects.

The tidal signal in *Topex/Poseidon* altimeter data has already been studied by several investigators - see papers in « Special Issue » of J. Geophysical Research, Dec. 15, 1994. The overall data accuracy has been proven far superior to that of any previous altimetry mission, particularly in the accuracy of the radial ephemeris, with root-mean-square errors approximately less than 3 cm (Tapley *et al.*, 1994). (Of this 3 cm, we believe that only a few millimetres are likely to affect the tidal parts of the spectrum.) This removes the need for empirical adjustment to the orbit radius, a troublesome procedure which may itself introduce undesirable errors.

There are two altimeters aboard this satellite; data from only the Topex altimeter, excluding the Poseidon altimeter, were used here. This is an unfortunate but necessary sacrifice, caused by the current lack of a reliable determination of the range bias between the two instruments. Excluding the *Poseidon* altimetry loses about 10 percent of the data, somewhat more when collinear differences between repeat-cycles are formed, as explained below.

A large number of corrections must be applied to the raw altimetry, (Callahan, 1993); these are nearly standard and we will mention only those directly involving the tides. The « tidal corrections » applied were: (a) the « body tide », (b) the long-period ocean tides based on an « equilibrium » model, and (c) the solid Earth « load tide » derived from our own ocean tide model, (Cartwright and Ray, 1991). An « inverse-barometer » correction for atmospheric loading was also used; the atmospheric pressure data underlying this correction has been found to contain a small aliassed component of the S_2 air tide, which may induce errors less than 1 cm in the low-latitude altimetric tide.

Schrama and Ray (1994) discuss in detail the tidal aliasses and phase sampling imposed by the *Topex/Poseidon* orbital strategy. The outcome is that good tide resolution from less than about 100 repeat-cycles (i.e. <3 years), as here, requires sampling over rather wide bin-sizes, in order to include 2-4 adjacent earth-tracks, whence a wider distribution of phase information. In the present analysis we used bins of 7° in longitude × 3° in latitude, centred on each of the selected sites shown in Figure 1. This rather large bin-size inevitably blurs the tidal definition, so we restricted comparisons to widely open sea locations, excluding large islands and bathymetric features known to cause steep spatial variations in the surrounding tidal field. We also excluded any site for which the satellite analysis differed from the station constants for M_2 by more than 5 cm, as symptomatic of such steep variations or of altimetric interference from land. These criteria limited the number of test sites to the 30 stations denoted by filled circles in Figure 1.

Since the satellite's orbit is maintained to repeat its ground-track to ± 1 km in a repeat cycle of $\tau = 9.9156$ days, we eliminated geoidal variations by working with the variable

$$\Delta\xi(t) = \xi(t) - \xi(t+n\tau) \qquad (3)$$

where z(t) is an estimate of sea surface elevation at time t from the altimetry and orbital radius, and n is a small integer, optimally 3 for the present orbit. Our response-analysis then relates $\Delta\xi(t)$ to a similarly differenced tide-potential, (Cartwright and Ray, 1990).

Table 2 lists the mean statistics from comparison of the satellite solutions centred on the 30 selected stations with local harmonic constants for the four major constituents $(N,M,S,K)_2$. The rms differences of in-phase and quadrature components (HcosG, HsinG), comprising 60 independent values, are tabulated with and without the adjustment to the potential proposed in this paper. One sees that the N, M, S constituents are hardly affected by the adjustment, but the result for K is improved by $\sqrt{(0.71^2-0.64^2)} = 0.31$ cm. So, as predicted, for the non-sun-synchronous orbit of *Topex/Poseidon*, neglecting radiational effects maintains an adequate representation of S_2 at the expense of a relatively poor representation of K_2. Accuracy at K_2 (and to a slight degree S and M) is evidently improved by the adjustment.

Table 2

R.m.s. differences (satellite - sea-truth) in cm

	N	M	S	K
Without radiational adjustment	0.90	2.04	1.78	0.71
With radiational adjustment	0.90	2.03	1.77	0.64

As we noted earlier, the reduced error in K_2 is in some ways less important than the global improvement in its phase lag by some 6°. We therefore examined this phase improvement more directly, through the weighted mean phase discrepancy of K_2 at the 30 stations. (Values were weighted by their associated squared amplitudes up to an amplitude limit of 6 cm, since the effects of noise are obviously greater at low amplitude.) If G* denotes the « true » phase lag, and G the value estimated from altimetry, the results for the weighted mean (G - G*) are : 5.5 ± 1.3° for the analysis without radiational adjustment; –1.1 ± 1.3° with radiational adjustment. Thus, again as predicted, the mean error in phase is quite significant at 5-6° when the radiational anomaly is ignored, but effectively zero after the adjustment proposed in this paper.

We have not had the opportunity to examine the improvement in S_2 which would result from applying our adjustment to the altimetry of a sun-synchronous satellite, such as *ERS-1*.

CONCLUSIONS

The results from the global array of 80 good quality tide stations (Figure 1) show that, on average, the observed S_2 constituent has about 0.97 times the amplitude of the smooth-admittance gravitational S_2 tide, with its phase lagged by 5.9°. The corresponding anomaly of 0.105 times the gravitational amplitude with a phase lag of 108°, is remarkably close, at least near the equator, to the relation between the inverse barometric tide of Haurwitz and Cowley (1973), with maxima at 3 h 42 min am and pm in local time, and the gravitational potential, with maxima at 0 h and 12 h. This confirms a similar result of Cartwright *et al.* (1988), based on the Atlantic Ocean.

Assuming that noise will prevent an accurate independent assessment of both S and K harmonics or a reliable response to the radiational potential, we propose that altimetry should be analysed for a response to a modified gravitational potential, in which the S_2 constituent (and T_2 if used) has its amplitude multiplied by 0.97 and its phase lagged by 5.9°. A smooth admittance function to this modified potential will be better justified; the harmonic constants for S_2 can be adjusted accordingly; and the constants for K_2 will also be improved. The procedure is applicable to altimetry from both sun-synchronous and non-sun-synchronous satellite orbits. Our application to 40 cycles of *Topex/Poseidon* altimetry confirms the improvement in K_2 and shows that modern altimetry has low enough noise level to benefit from our approach.

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