Do we really observe internal gravity waves and tides in altimeter data ?

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ABSTRACT

In the past years, several reports claimed pronounced manifestations of internal M_2 tides [1,2] and, more generally, of baroclinic inertia-gravity (BIG) waves [3,4] in sea surface height variations observed by satellite altimetry. The reported SSH amplitudes caused by these high-frequency baroclinic motions are in the range of several centimeters. The estimates [1,2] have been confirmed by numerical modeling of internal tides [5,6]. Both the altimeter measurements and the numerical model results are reviewed in this talk. We also present standard theoretical estimates of the SSH amplitude based on vertical profiles of the Brunt-Vaiasalia frequency and ocean current velocities measured in a few regions, and show that such estimates yield SSH amplitudes not exceeding 20 percent of the altimeter-based values. This large discrepancy raises the following questions: Have the numerical models and all known altimeter-based estimates of the SSH signal associated with internal gravity waves greatly exaggerated the actual signal? Or, is our present theoretical understanding of the basic physics of BIG waves missing something important ?

Theoretical expectation for SSH amplitude

In the absence of backround flows in a horizontally uniform field of water density, the amplitude of the ocean current velocity, $\widehat{U}$, near the surface and the SSH amplitude, $\widehat{\zeta}$, are related by [Ref: textbook knowledge]:

$$\widehat{U}^2 = \frac{\omega^2 + f^2}{\omega^2 - f^2} \, \frac{g^2}{C^2} \, \widehat{\zeta}^2 \quad , \tag{1}$$

where C is the Kelvin speed (≈ 3 m/s for the 1st baroclinic mode), ω is the wave frequency, and f is the Coriolis frequency.

With the internal tide current under 4 cm/s, Eq.(1) yields $\widehat{\zeta}$ below 1 cm.

Altimeter-based estimates of SSH amplitude

Estimated values of the SSH amplitude $\widehat{\zeta}$ due to internal M_2 tide, found in [1,2], are about 3 to 5 cm.

Estimated values of the SSH amplitude $\widehat{\zeta}$ of BIG wave motions due to the entire spectrum of internal gravity waves, including tides, as found in [3,4], are about 1 to 10 cm.

Estimation of SSH amplitude using observations on currents' velocities

Assuming horizontally uniform density field and zero background flows, the shallow-water equations yield an eigenvalue problem for the vertical profiles of pressure, density, and fluid velocities amplitudes. In particular, the profile of the vertical velocity amplitude is found from

$$\partial^2_{zz}\widehat{w} + \frac{\rho_* N^2}{\rho_0 C^2}\widehat{w} = 0, \qquad (2)$$

with boundary conditions $\widehat{w}(-H_0) = 0$, $\widehat{w}(0) = 0$.

Amplitude eigenfunctions for pressure, vertical velocity, and SSH are related by

$$\begin{aligned}
\widehat{p} &= \frac{i\rho_0 C^2}{\omega}\psi(z) && (a)\\
\widehat{\zeta} &= \frac{iC^2}{g\omega}\psi(0) && (b)\\
\psi &= \partial_z \widehat{w} && (c)
\end{aligned} \qquad (3)$$

In a similar way, one can express the horizontal velocity amplitudes in terms of $\widehat{w}(z)$. The following figures illustrate our field data analysis.

Table 1. Ocean current meter measurements employed for data analysis

Station	Lat	Lon	Depth m	Start	End	No. of levels	Sampling rate, min	Institution
1	27.998 N	151.948 W	5300	07/08/82	07/11/83	10	15	SIO
2	25.532 N	28.953 W	5670	10/15/92	06/16/93	11	15	WHOI
3	41.972 N	152.007 W	5150	07/18/82	07/07/83	7	15	SIO
4	31.170 S	30.537 E	2498	03/03/95	04/13/95	10	30	SOC

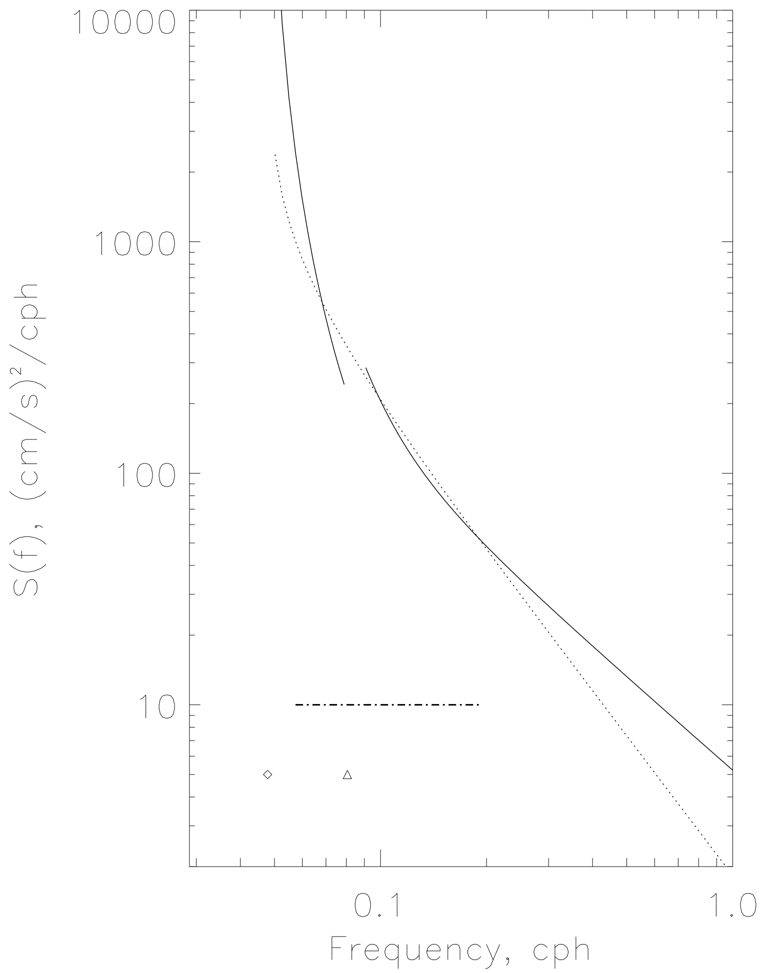

Figure 1: Theoretical spectra [7] of kinetic energy for 35° latitude and 3 m/s Kelvin wave speed. Solid curves: The case of the direct energy cascade for two values of the spectral flux, Q, of wave energy: for the lower-frequency range, the value of Q is 0.1 that for the higher (post-tidal) frequency range. Dotted curve: the Garret-Mink spectrum. The diamond and triangle represent the Coriolis and the semi-diurnal M_2 tide frequencies, respectively. The horizontal dash-dot line marks the frequency range within which the theory [7] is valid. The corresponding wavelengths are 340 and 58 km. The internal M_2 tide wavelength is 166 km.

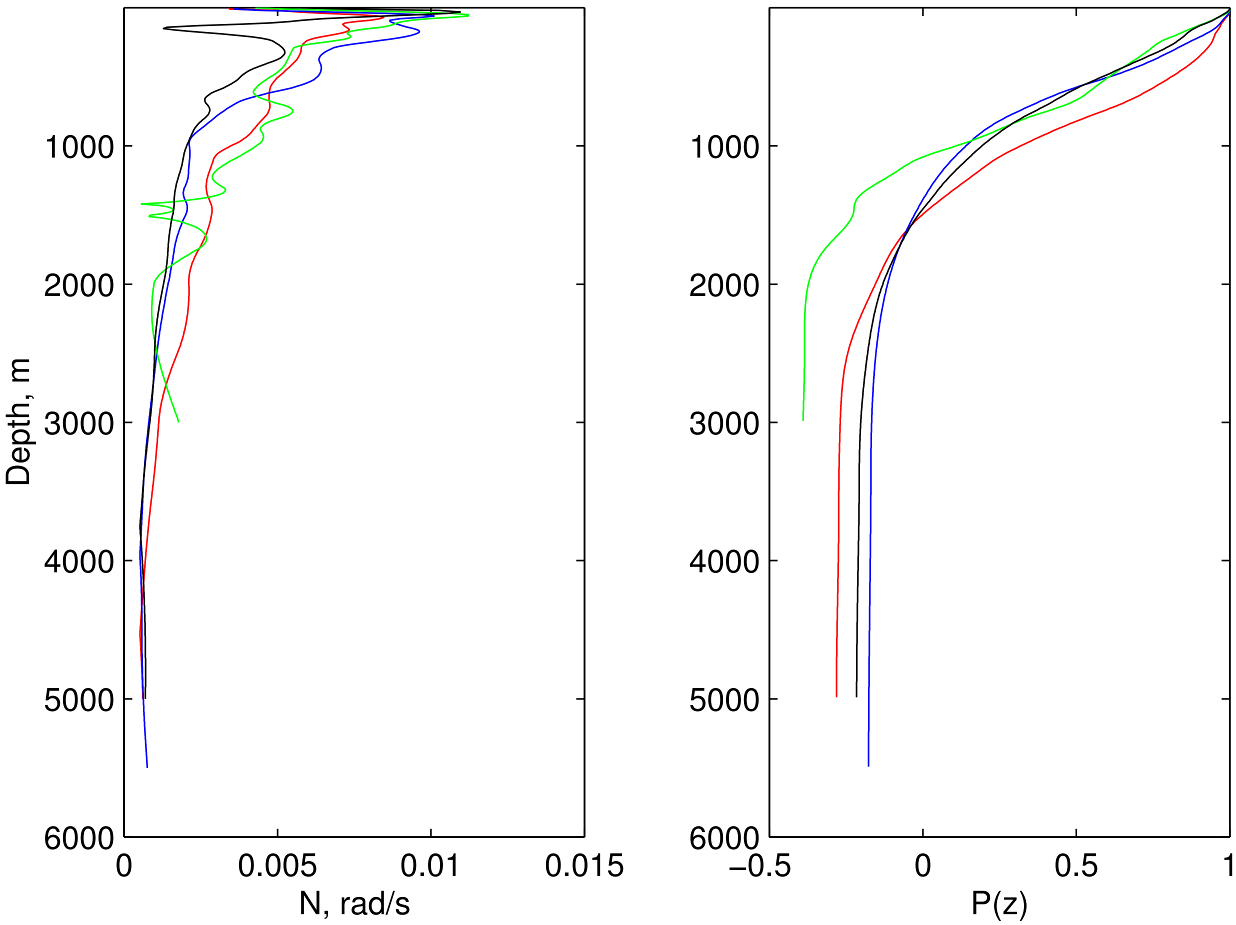

Figure 2: Vertical profiles of the buoyancy frequency (left panel) and pressure amplitude for the first baroclinic mode (right panel). Blue curves: Station 1. Red: Station 2. Black: Station 3. Green: Station 4.

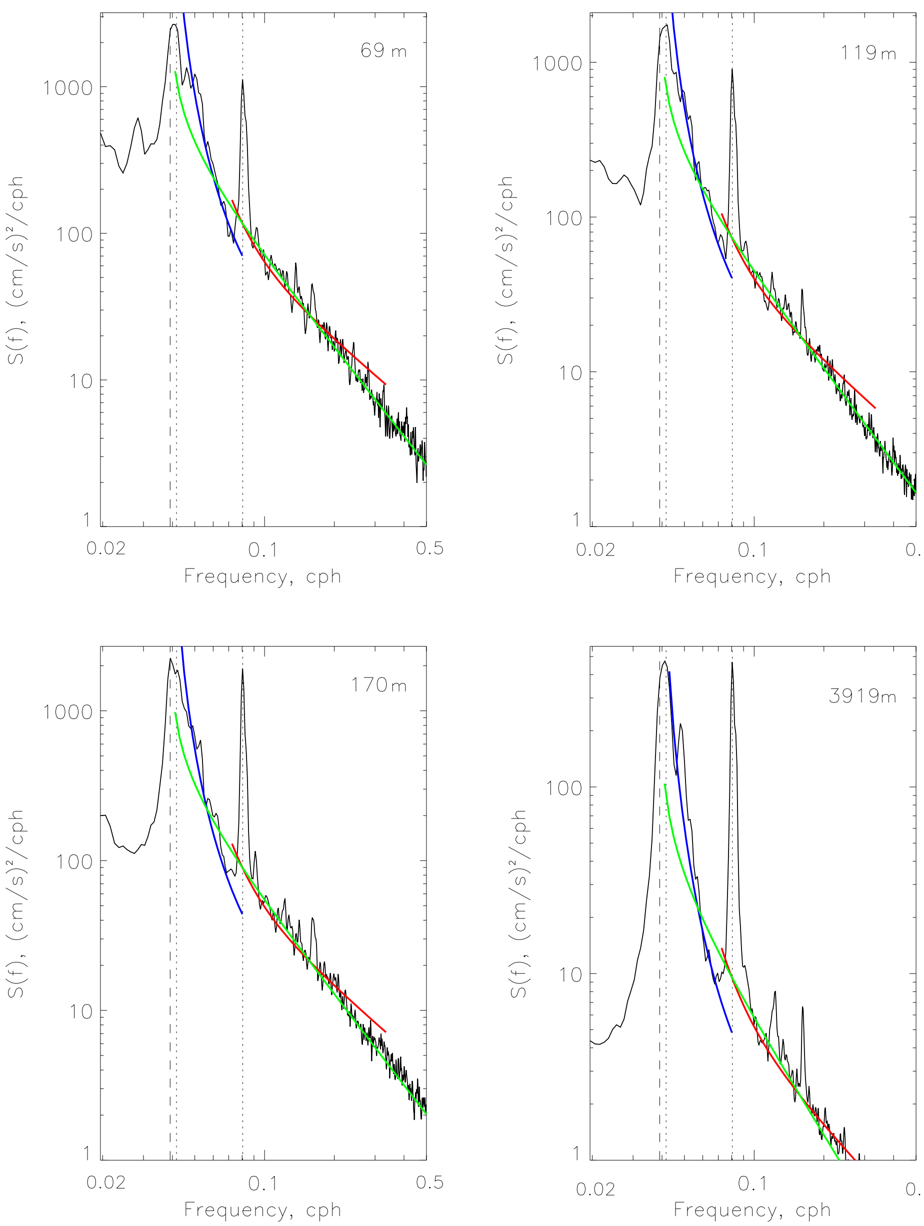

Figure 3: Observed and model spectra of horizontal velocity fluctuations for Station 1, at depths indicated in the upper right corner of each plot. Red and blue curves: theoretical spectra from [7] estimated separately for the high- and low-frequency subranges. Green curves: G-M spectrum. Vertical dashed lines mark the Coriolis frequency. Two vertical dotted lines correspond to diurnal and M_2 tides.

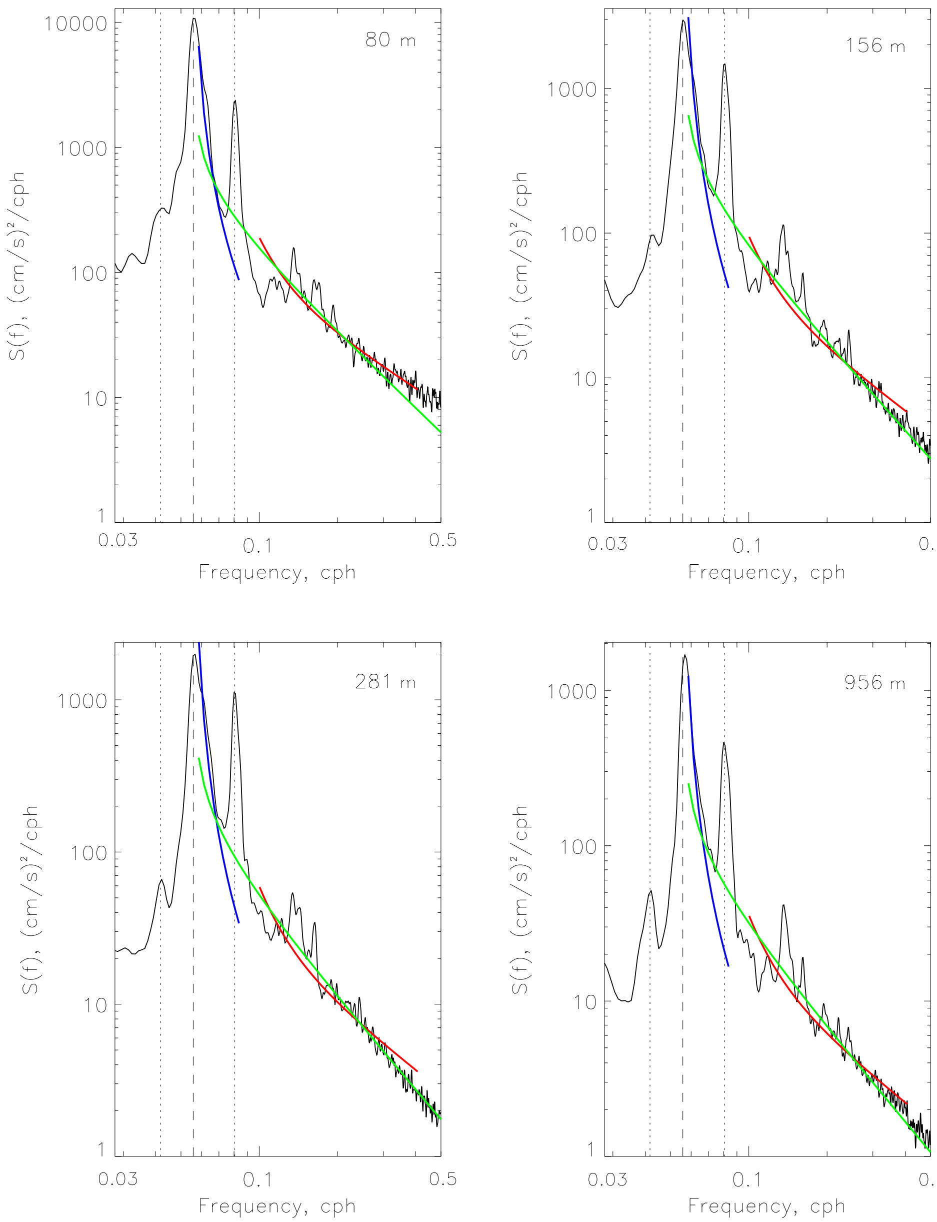

Figure 4: Observed and model spectra of horizontal velocity fluctuations for Station 3. All notations are the same as in Fig.3.

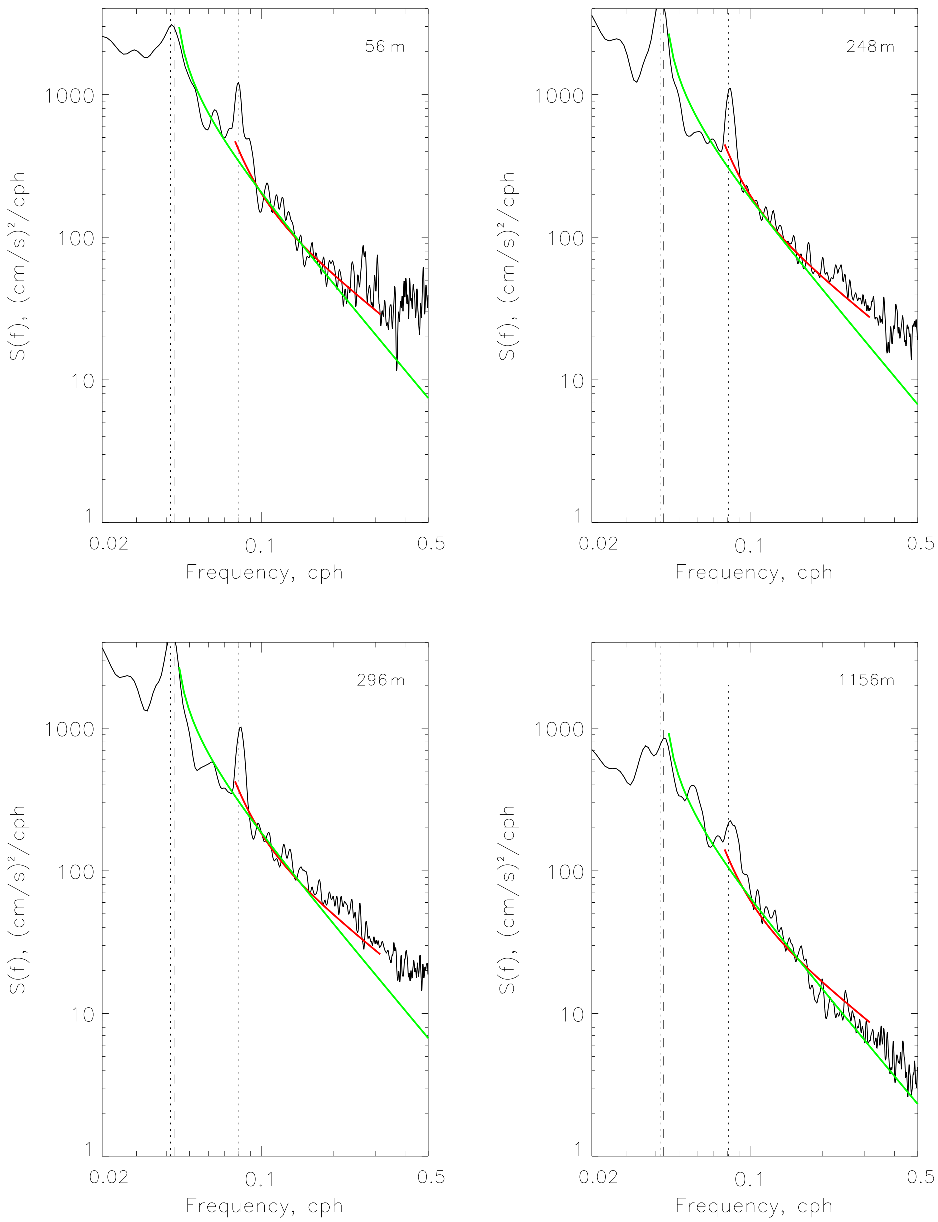

Figure 5: Observed and model spectra of horizontal velocity fluctuations for Station 4. All notations are the same as in Fig.3.

CONCLUSIONS

1. Analysis of ocean current meter measurements in the framework of standard linear theory indicates that: (1) Velocities of M_2 internal tide at sea surface do not exceed 3 cm/s. (2) Velocities of BIG waves representative of the entire wave spectrum do not exceed 5 cm/s. The corresponding (maximum) amplitudes of SSH oscillations predicted by standard theory do not exceed 1.5 cm.

2. The SSH amplitudes of these motions estimated based on altimeter data are much greater than the predicted values. Those estimates have been confirmed by at least two independent numerical modeling studfies [5,6] (for internal M_2 tide).

3. Either our altimeter-based estimates and numerical modeling results yield greatly exaggerated values, or the simplifications employed in standard theory are unjustified to produce correct values.

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