Radiation of Internal Tides from the Hawaiian Ridge: Implications for the Large-Scale Tidal Energy Budget

[1]Brian Dushaw, [2]Peter F. Worcester, [2]Matthew A. Dzieciuch
[1]Applied Physics Laboratory, University of Washington, [2]Scripps Institution of Oceanography, University of California at San Diego

Applied Physics Laboratory
University of Washington

ABSTRACT

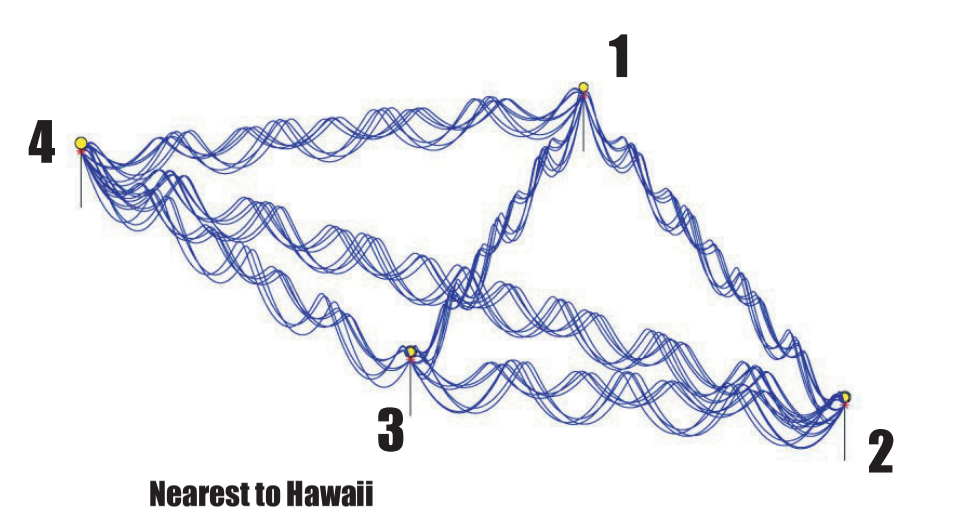
The Hawaii Ocean Mixing Experiment (HOME) Farfield Program was designed to quantify the energy radiated by low-mode baroclinic (internal) tides, and to measure the barotropic tidal currents and pressure to sufficient accuracy to stringently test barotropic tidal models. These measurements are important for constraining the tidal energy budget of the Ridge, in which the energy lost from the barotropic tide either radiates away from the Ridge as internal tides or is dissipated in the nearfield of the Ridge, driving ocean mixing. The HOME Farfield Program measured the radiation of internal tides using (i) moored tomographic arrays deployed north and south of the Ridge (ii) moored thermistors, and (iii) high vertical resolution measurements from R/P FLIP. These measurements were obtained in areas where altimetry and numerical models predicted intense radiation. The tomographic arrays were designed to measure the radiation of the lowest internal-tide modes over broad areas, while the moored thermistor data provide point-wise estimates of the internal tides. The in situ measurements of the internal tide indicate that the tidal field can be adequately modeled using a few wave numbers consistent with the dispersion relation. Simultaneously, estimates of the internal tide from altimetric data and models indicate that the tidal field consists of narrow "jets" of high energy, most likely resulting from the interference of several waves. Overall, the radiated mode-1, M2 energy is surprisingly weak: less than 1.5 kW/m, with relatively little incoherent energy. The rate of radiated energy varies considerably along the Hawaiian Ridge, however.

Barotropic tidal models based on altimetric data suggest that 18–25 GW of tidal power is lost from the M2 tide at the Ridge. Estimates of the M2 energy flux away from the Ridge as a coherent, mode-1 internal tide made from the tomographic data (roughly 3.4 GW) and from altimetric data (2.5 GW) are in approximate agreement. Extrapolating the tomographic data to include the M2 energy flux in all modes suggests that about 5.5 GW is radiated as coherent internal tides. The energy flux derived from the tomographic data is relatively weak compared to energy fluxes measured by other means in the nearfield of the Ridge, suggesting either significant dissipation (unlikely for mode 1) or loss of coherence in the first few hundred kilometers away from the Ridge.

BASICS

Sound travels faster in warm water than in cold water. By measuring the travel time of sound over a known path, the sound speed and thus temperature can be determined. Sound also travels faster with a current than against. By measuring the reciprocal travel times in each direction along a path, the absolute water velocity can be determined. Each acoustic travel time represents the path integral of the sound speed (temperature) and water velocity. As the sound travels along a ray path, it inherently averages these properties of the ocean, heavily filtering along-path horizontal scales shorter than the path length. A 1 °C change in temperature roughly corresponds to a 4 m/s change in sound speed, although this scale factor is somewhat temperature dependent. Over a 1000-km range, a depth-averaged temperature change of 10 m°C is easily measured as a 20-ms travel time change. (Munk, Worcester, and Wunsch, 1995)

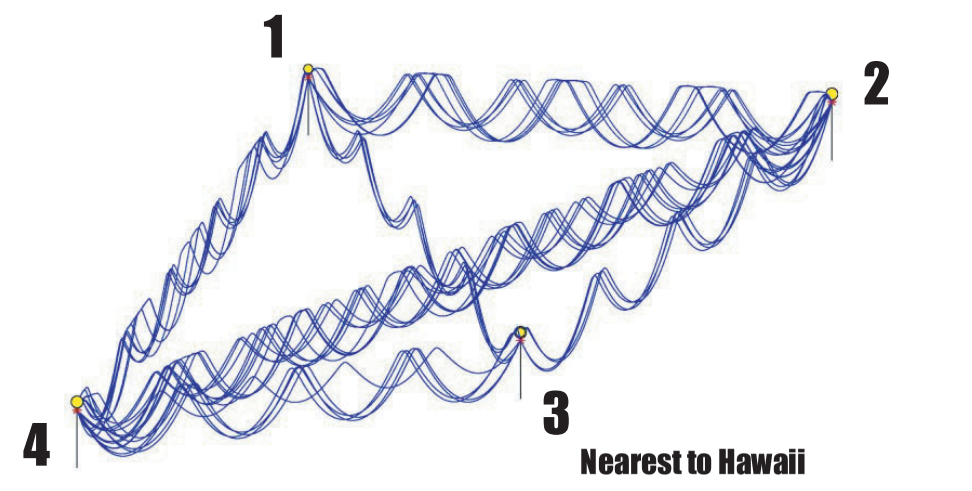
Northern HOME Tomography Array



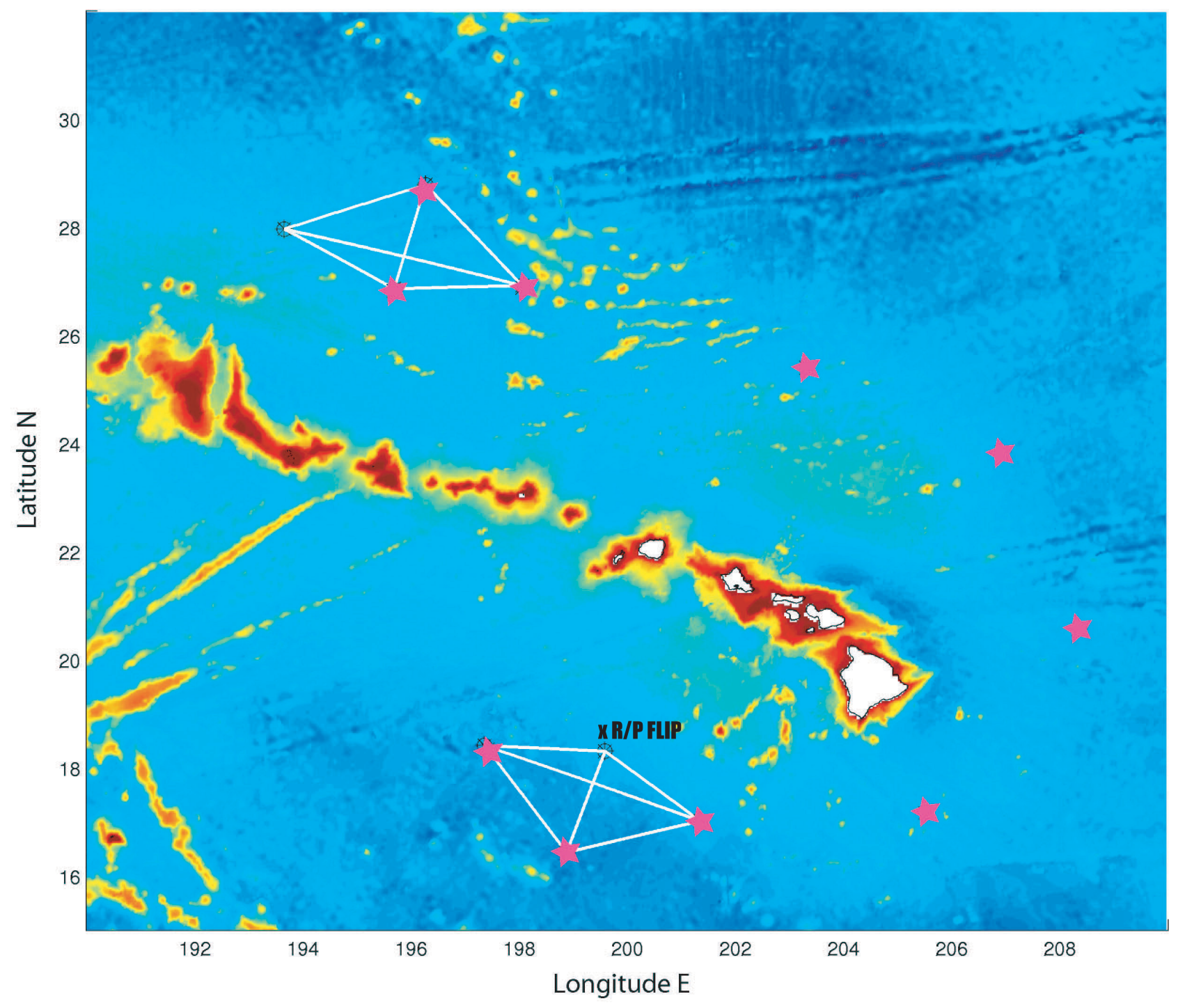
The figure above shows the resolved rays from the northern tomography array. The main diagonal of this array is about 450 km long, while the shorter diagonal is 225 km. From 4-8 rays were resolved on each path, adequate for the resolution of mode-1 variability.

By taking the sum of reciprocal travel times, the effects of current are canceled, leaving only the sound speed signals of the internal tides. The depth integrating nature of the acoustic ray measurements is a natural filter for the sound speed signals of mode-1 (similarly for barotropic current mode and the difference of reciprocal travel times).

Southern HOME Tomography Array

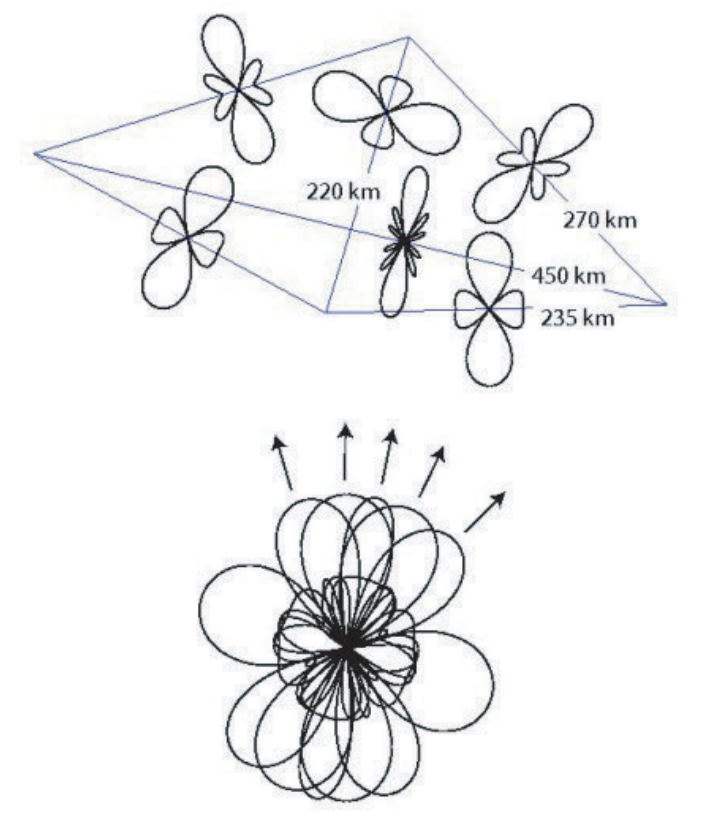


The northern array was deployed 500 km north of the Hawaiian Ridge in Spring 2001 for about 6 months. That array was recovered in September 2001, and redeployed 500-km south of Oahu for another 6 months. The array locations were chosen to be in regions suggested by altimetry and numerical models to have relatively intense internal tides.



ACOUSTIC ARRAY DESIGN

Beam patterns for 150 km wavelength.
0 to max. is 25 dB



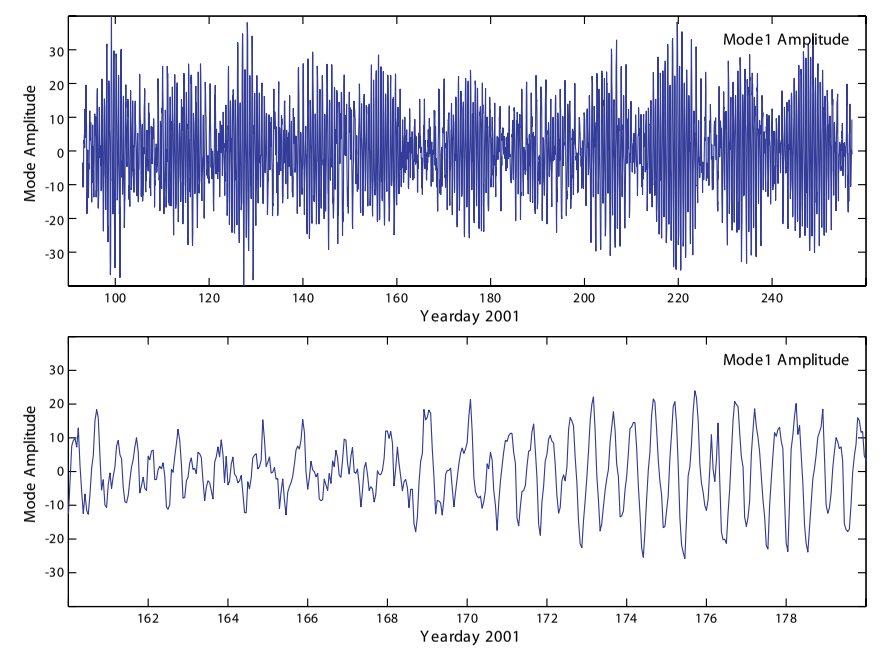
The diamond shaped arrays are designed to maximize the directional resolution of the array, given the cost limitation of four moorings. The top figure shows the beam patterns of each path within the array for mode-1 wavelength. The bottom panel shows the beam patterns brought together, showing that each path is roughly independent of the others. No attempt was made to measure the decay of mode-1 waves from the Ridge, because it was believed the decay is weak and the internal tide variabiility was so great as to swamp any attempt to measure decay. Instead, the resources of the array are optimized for wavenumber resolution.

MOORED THERMISTORS

Each of the tomography moorings was also instrumented with a set of thermistors to obtain a complementary, point-wise measurement of internal-tide variability. Only a limited number of thermistors (and microcats) was available, so the number of instruments varied from mooring to mooring. Some moorings had only 4 thermistors+microcats, but mooring 3 had 11 instruments. These 11 instruments from mooring 3 were used to derive time series of mode amplitude for the various modes using a weighted least squares fit. The time series for modes 1 and 2 are shown below.

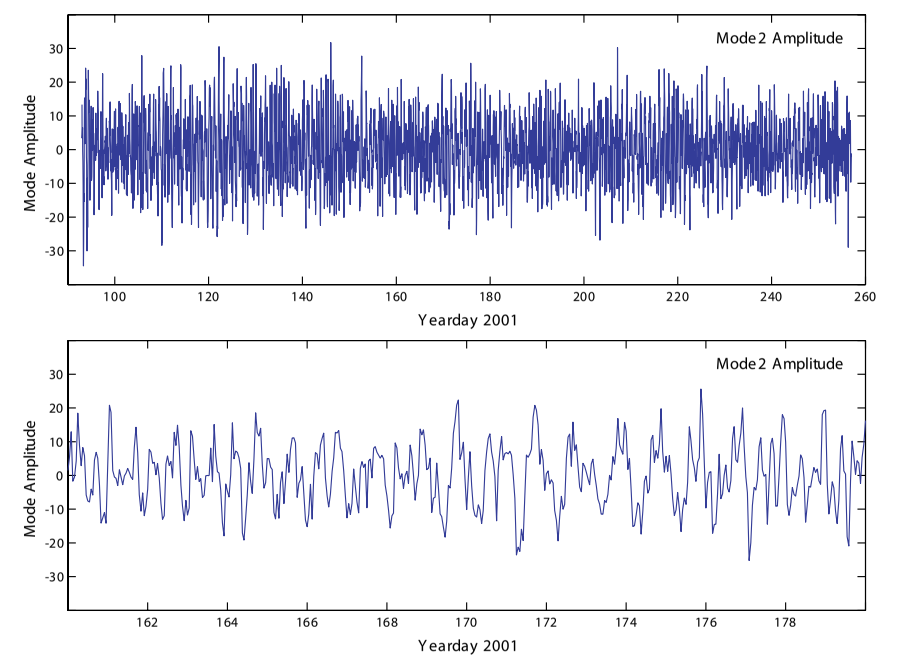
The other moorings did not have as many instruments as desired for adequate mode resolution. Further, by the time the southern array was deployed, many of the thermistors had been damaged, and the number of available instruments was further reduced. Resolution of modes on any of the southern array moorings is problematic.

Mode-1 Amplitude



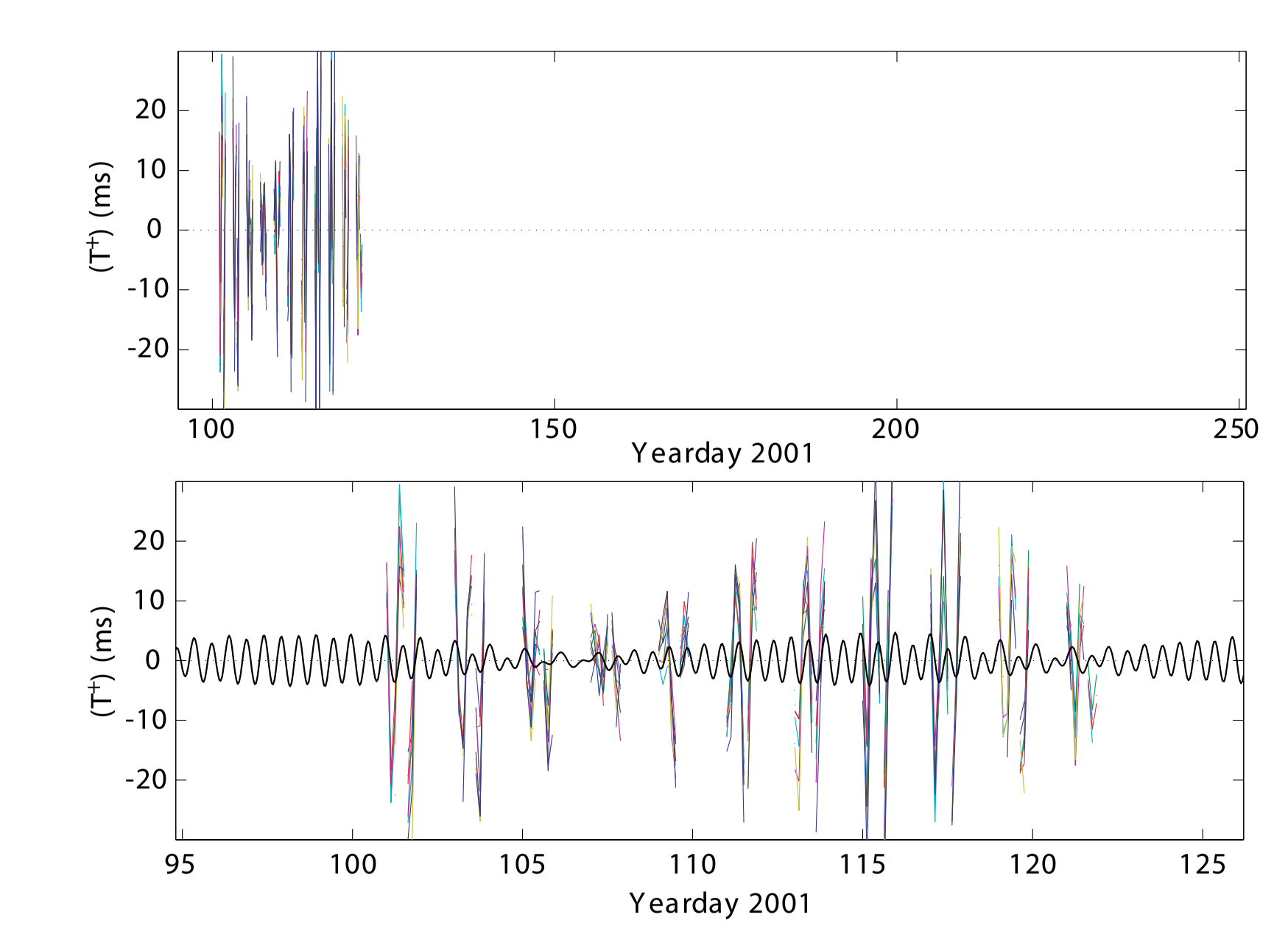
The tidal variability of mode-1 is predominantly phase-locked. A tidal analysis accounts for 70% of the variance. Note the clear spring-neap cycles in the time series.

Mode-2 Amplitude



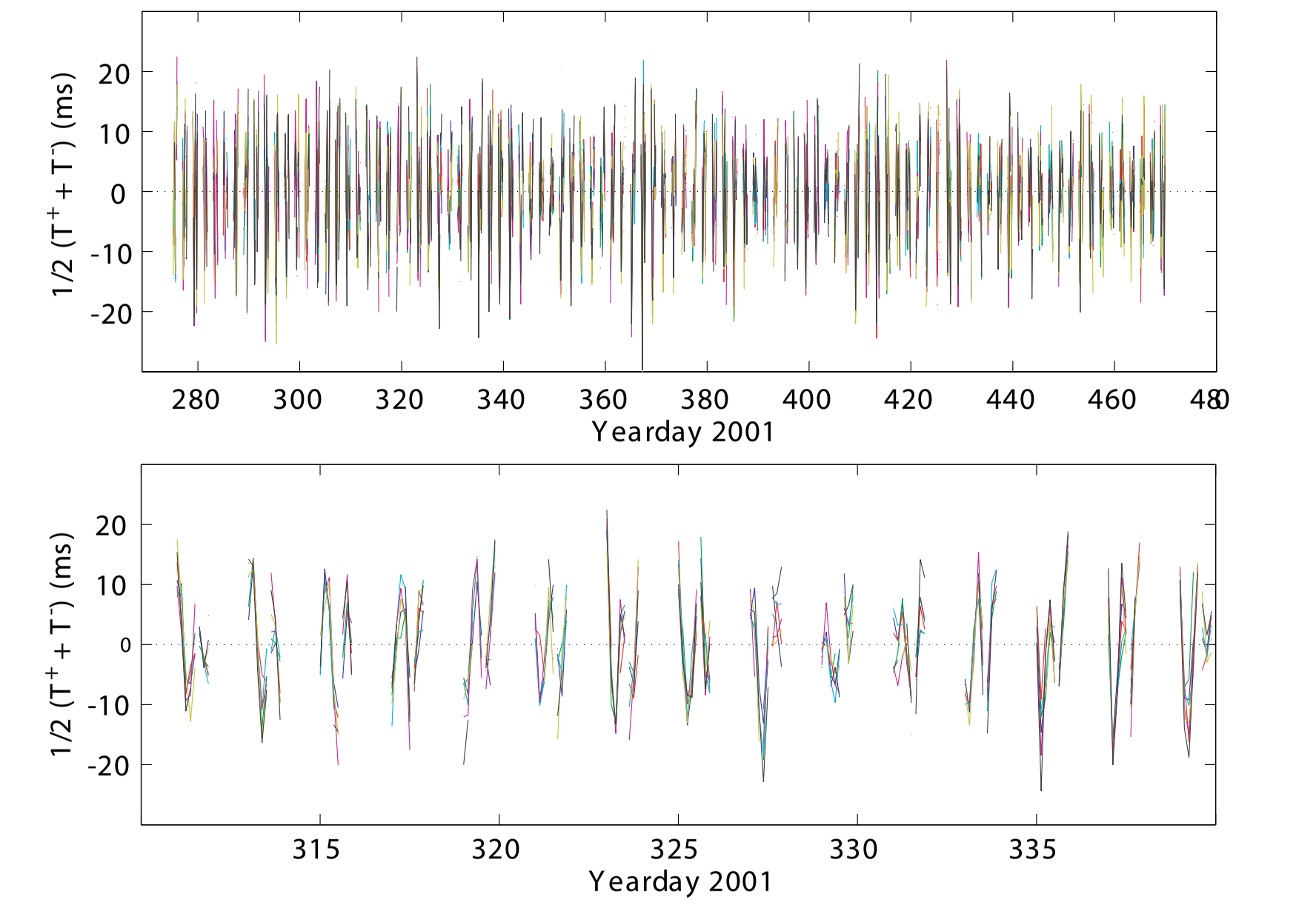
The tidal variability of mode-2 is not phase locked. A tidal analysis of this time series accounts for only 7% of the variance. It is unlikely that mode-2 variability will be resolved by satellite altimetry.

ACOUSTIC DATA



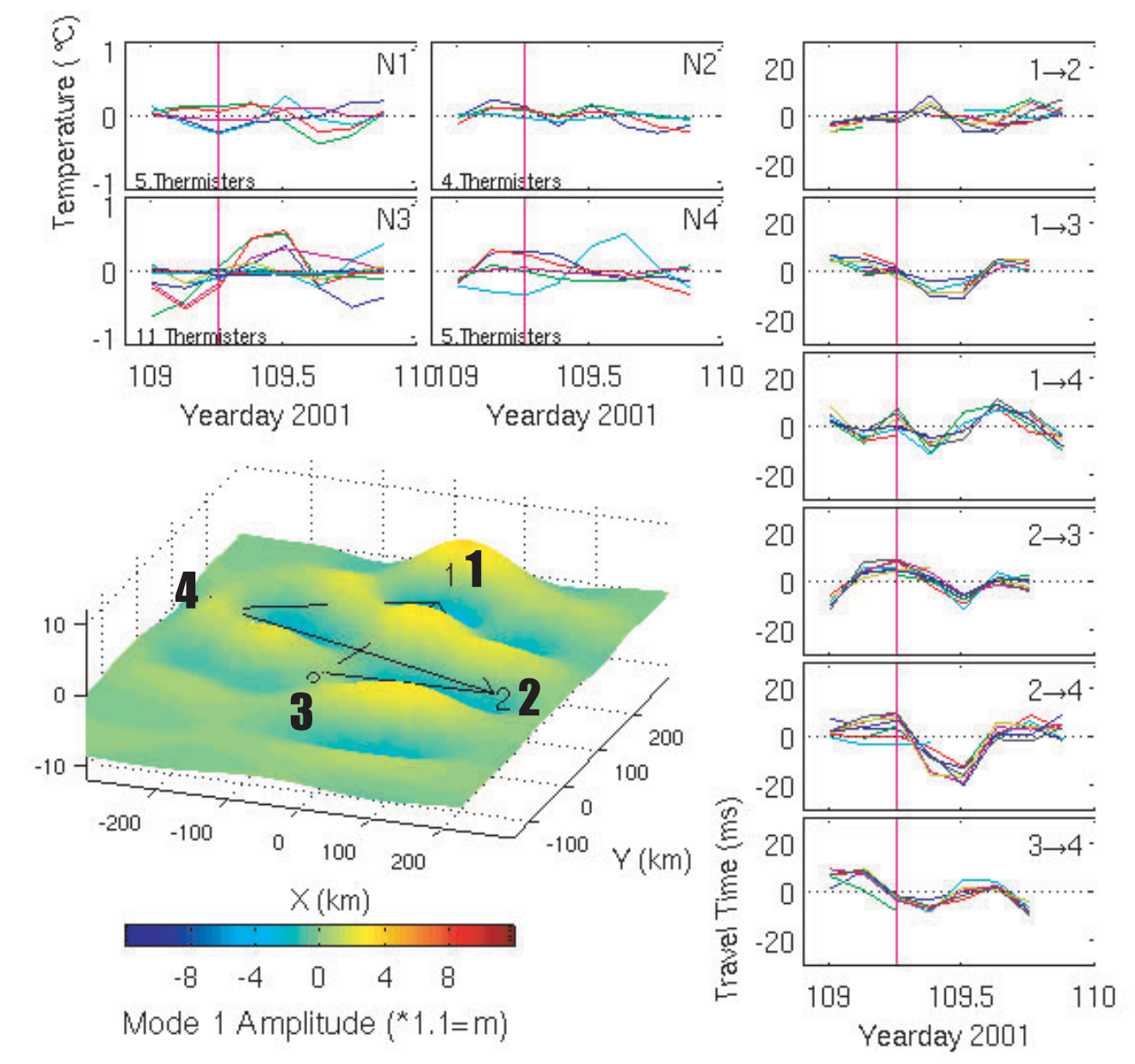
Time series of the one-way travel times from the main diagonal of the northern array. This array suffered from failures of the acoustic sources on moorings 2 and 4 after about three weeks of data were obtained. 21 days of data are just adequate to resolve the tides. Other paths have record lengths of about 150 days.

The time series show a fairly vigorous internal tide. The signals expected from the barotropic tide, which have been eliminated from these data, are shown in the black line of the bottom panel.



Time series of the sum of reciprocal travel times from the main diagonal of the southern array. The record lengths from the southern array time series are all about 200 days.

The time series show a fairly quiescent internal tide. Internal tides observed by the thermistors and acoustic transmissions of the southern array are fairly weak.



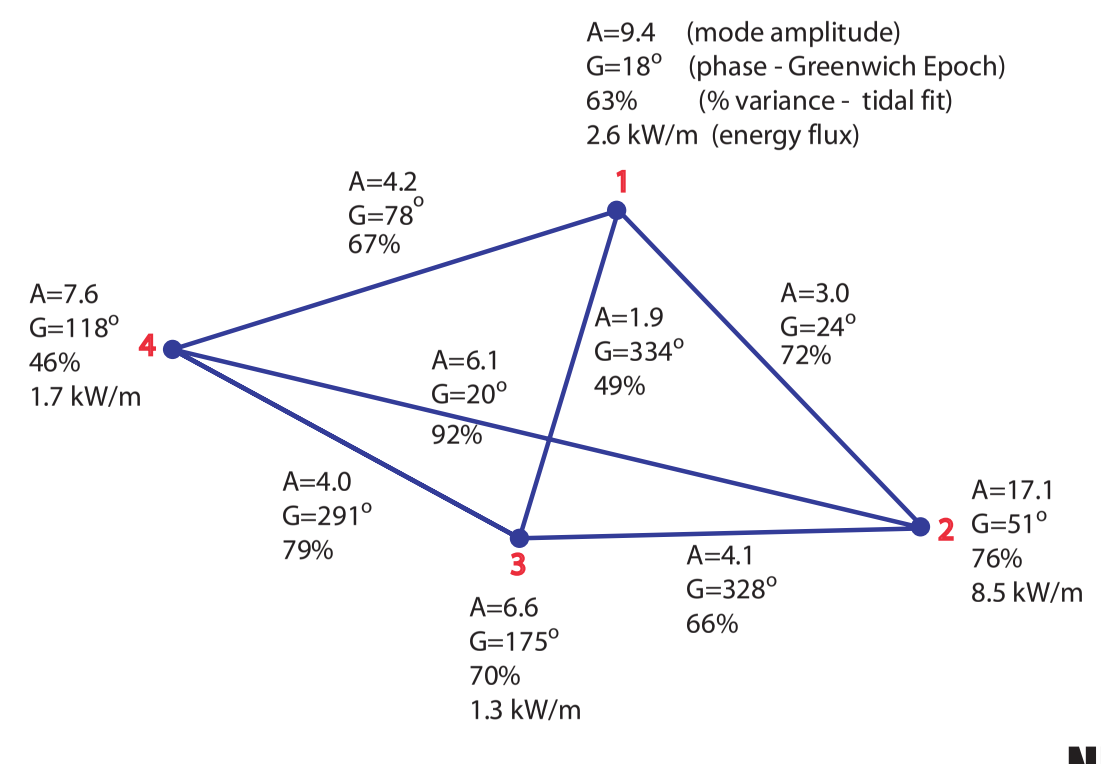
The travel times measured on each acoustic path and the thermistor time series obtained on the moorings can be combined using objective mapping techniques to estimate the state of the internal tide as a function of time. The surface above is the mode-1 amplitude over the northern array for a time of transmission on yearday 109 denoted by the vertical red line. The normalization of the modes are such that an amplitude of 1 corresponds roughly to 1 m internal displacement at mode maximum. Movies of this variability are fun and show propagation away from the Ridge but are not of much practical use.

The panel at right shows the travel times obtained on the acoustic path indicated; the signals are almost entirely mode-1. The four panels at upper left show the thermistor time series, which show significant variability from higher-order modes.

BASIC MEASUREMENTS

Mode-1, M_2 Amplitude, Phase and Energy Flux

HOME Northern Array

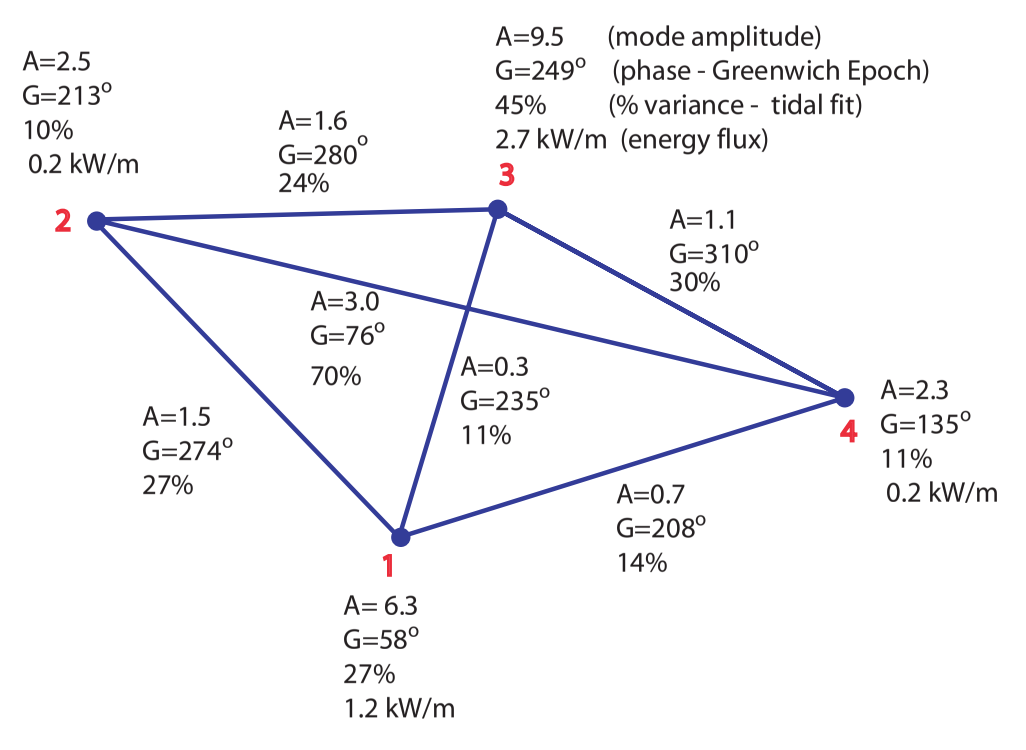


Unit amplitude has energy flux 12.1 W/m

	A	Energy Flux (W/m)
1->2	3.0	265
1->3	1.9	105
1->4	4.2	518
2->3	4.1	498
2->4	6.1	1079
3->4	4.0	461

NEED TO MAKE THE MAP!

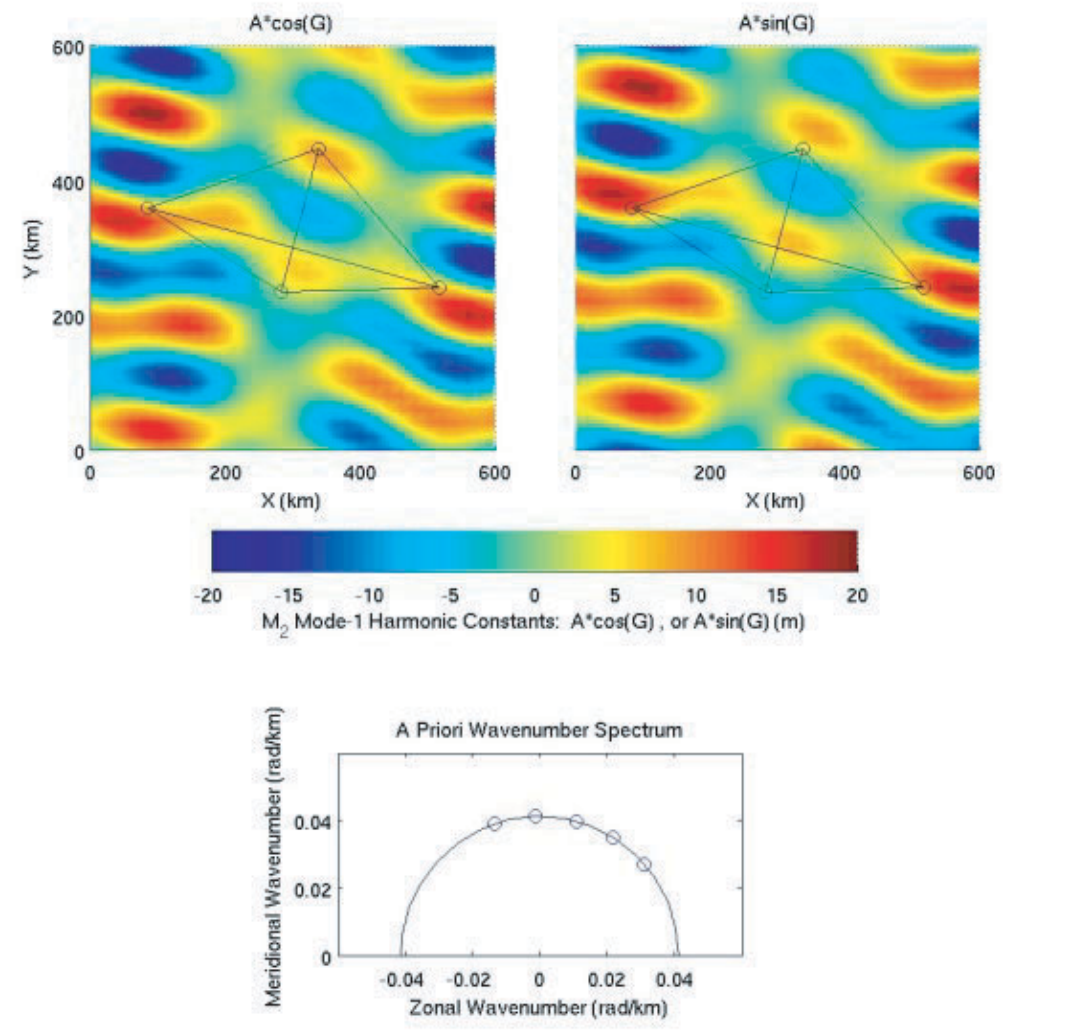
HOME Southern Array

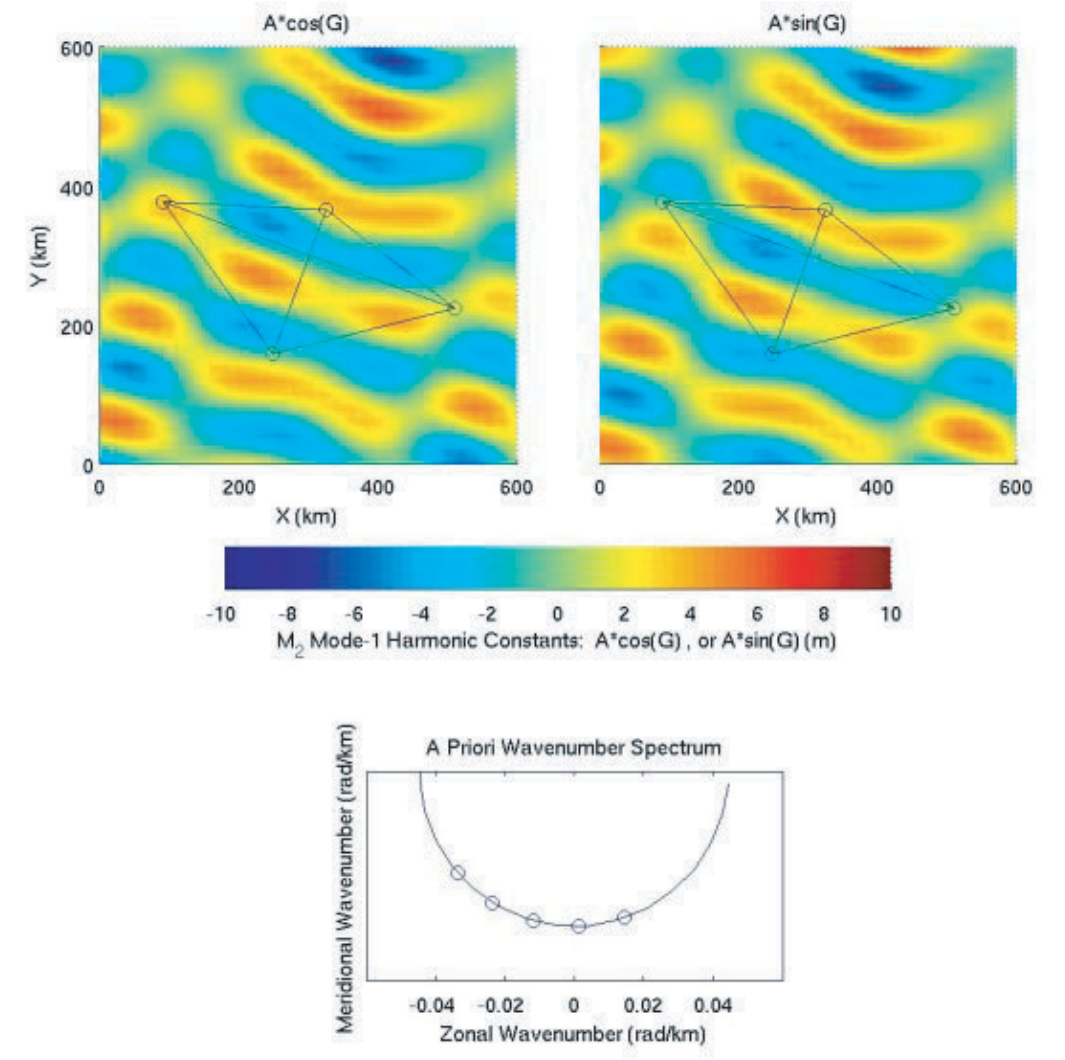


Unit amplitude has energy flux 30.0 W/m

	A	Energy Flux (W/m)
1->2	1.5	65
1->3	0.3	3
1->4	0.7	13
2->3	1.6	72
2->4	3.0	272
3->4	1.1	34

The two figures above show the results of tidal analysis of the acoustic travel times and the thermistor data for mode-1 variability and M_2 frequency. The acoustic results are variable and require an objective map to properly separate the various wavenumbers propagating through the arrays. The tidal analysis accounts for 50-70% of the variance of the tomography time series, showing the high temporal coherence of mode-1 internal tides. The thermistor results are highly variable; the northern array moorings obtained energy flux values of 2.6, 8.5, 1.3 and 1.7 kW/m, suggesting that the mode-1 field is a complicated interference pattern. Tides obtained on the southern array were fairly weak. In general, the weakness of the observed internal tide signals in both arrays was a surprise.



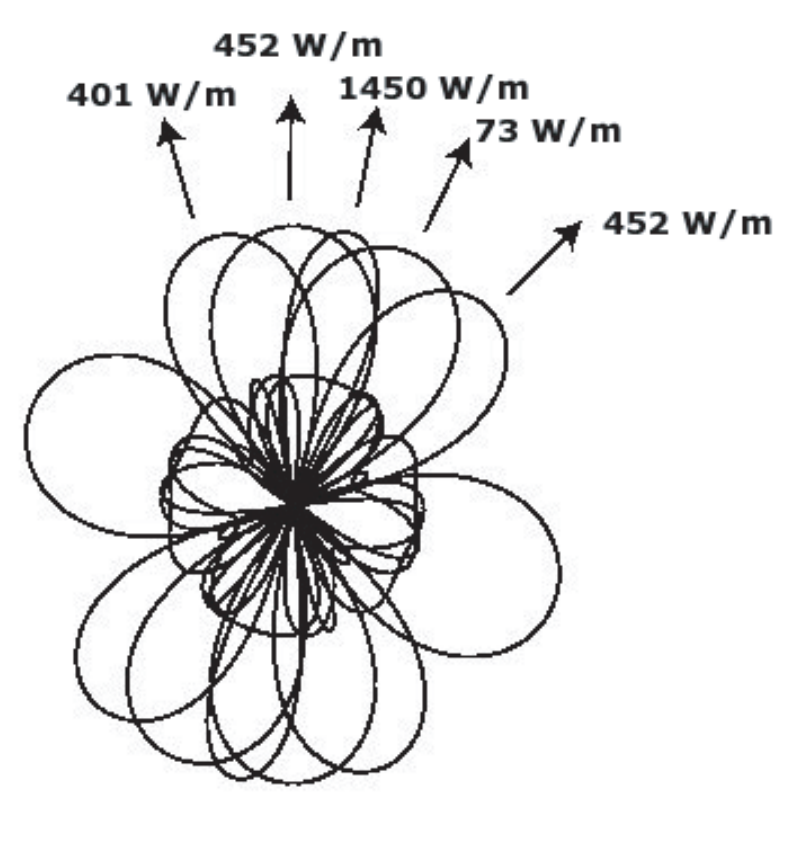


The model that is best to use in solving for the tidal field is not altogether obvious. In general, however models with different assumptions produce similar results within the tomography array. Perhaps the simplest model is that suggested by the original array design - 5 wavenumbers perpedicular to each of the acoustic paths. The above maps show the results of fitting those 5 wavenumbers to the acoustic and thermistor data in the top panels, and the prior "spectrum" in the bottom panel. Because only 5 wavenumbers are used (i.e., 5 delta functions in wavenumber space), the solution in physical space has considerable ringing.

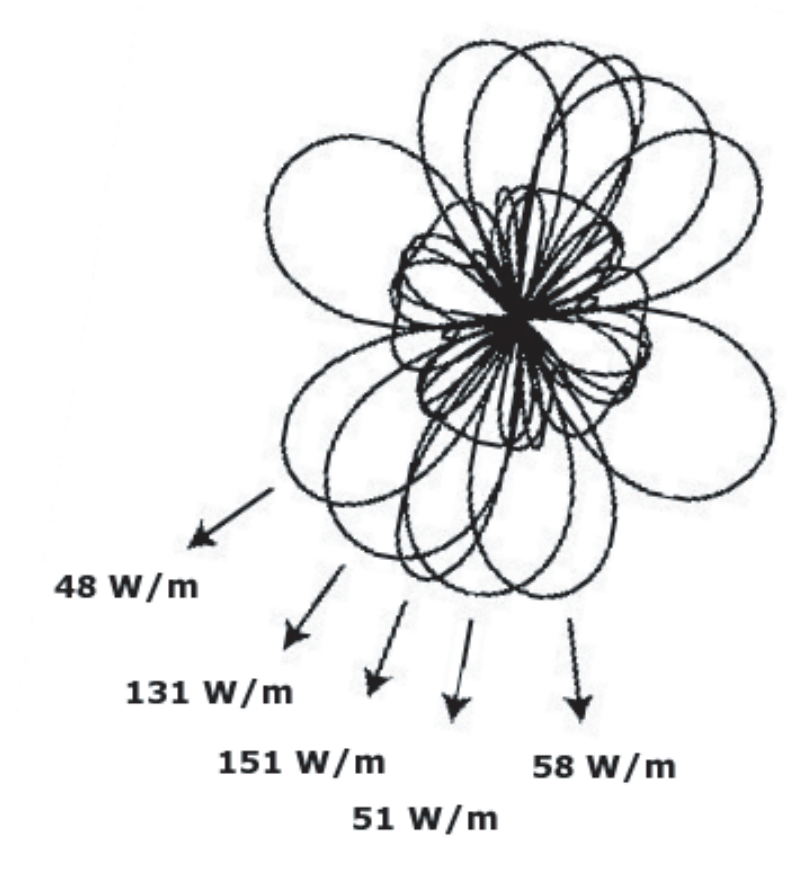
While this fit accounts for all of the acoustic data, it only accounts for most of the thermistor data. A model that accounts for the larger amplitudes of the thermistor data has not yet been devised. The issue suggests that the internal tide field is an interference pattern, with large variations and fairly short scales. To resolve such an interference pattern with point measurements is hopeless. The acoustic data produce more well behaved results, but inherently underestimate the energy of the internal tide.

One potential issue is the inability of the sparse thermistor arrays to properly separate the modes. On many of the moorings, there is certainly not sufficient resolution. However, if we accept that mode-1 is phase locked, while all other modes are not, then a tidal analysis of even a single thermistor would produce an accurate estimate of the harmonic constants for mode 1.

Northern Array



Southern Array

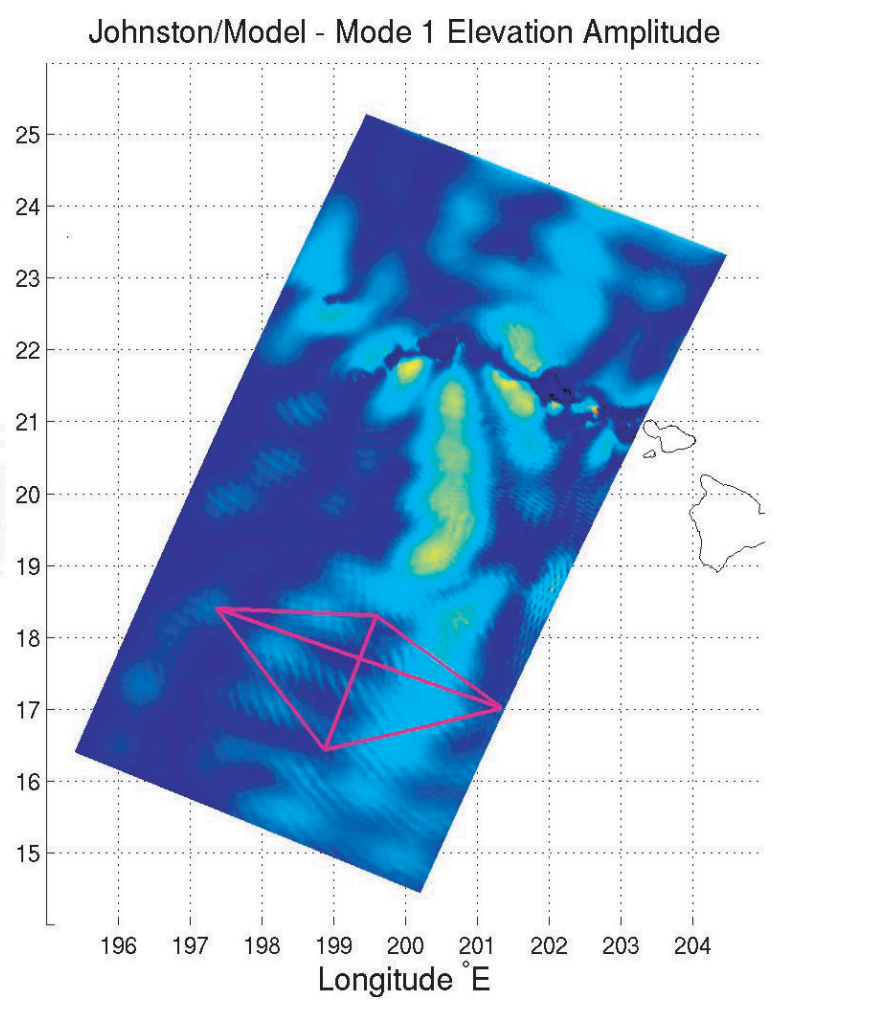


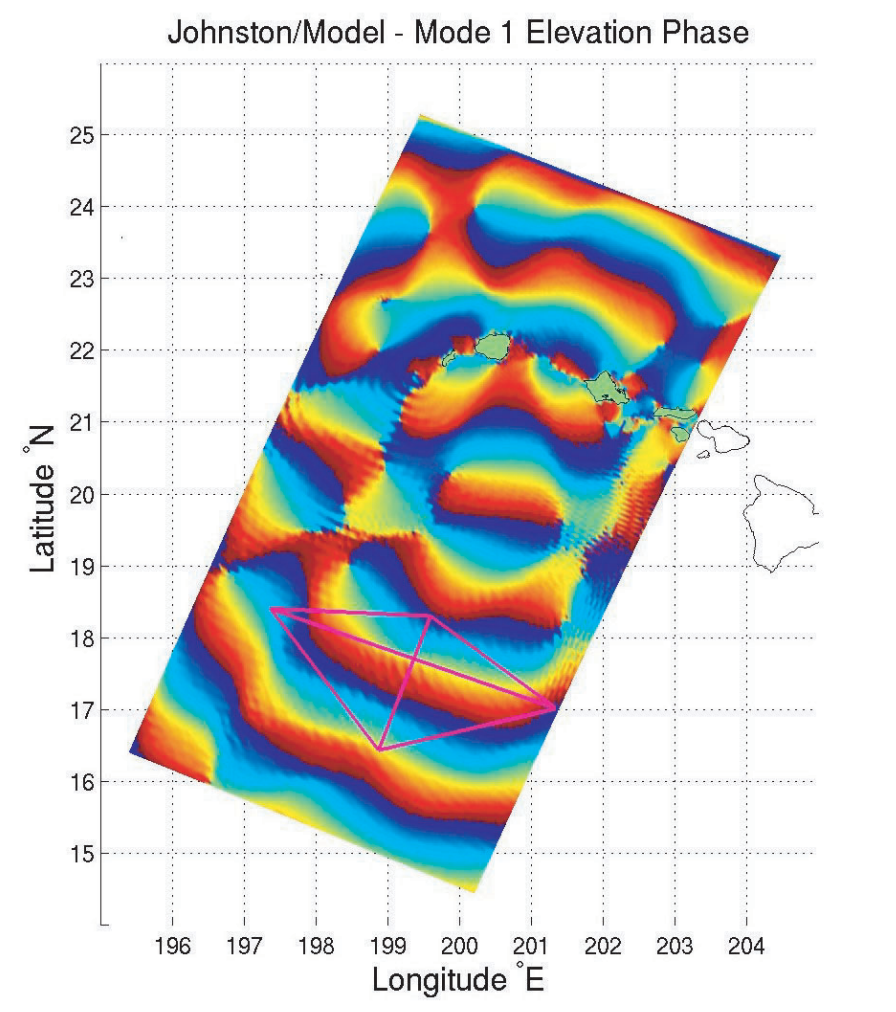
The mapping calculation described above naturally produces estimates of amplitude for each of the 5 wavenumbers, and these amplitudes can be used to calculate energy flux for each of the wavenumbers. This approach to the energy flux calculation is more accurate than just using the amplitude, or energy, obtained at a single point. The large 8.5 kW/m energy flux obtained on the N2 mooring is likely just a product of the interference pattern - at that point the internal tide happened to have a large amplitude because of the superposition of several or many wavenumbers. Energy flux calculated from <p'u'>,<p'v'> addresses this issue (e.g., a standing wave has no energy flux from <p'u'>, but it does have an amplitude), but velocity measurements are not available.

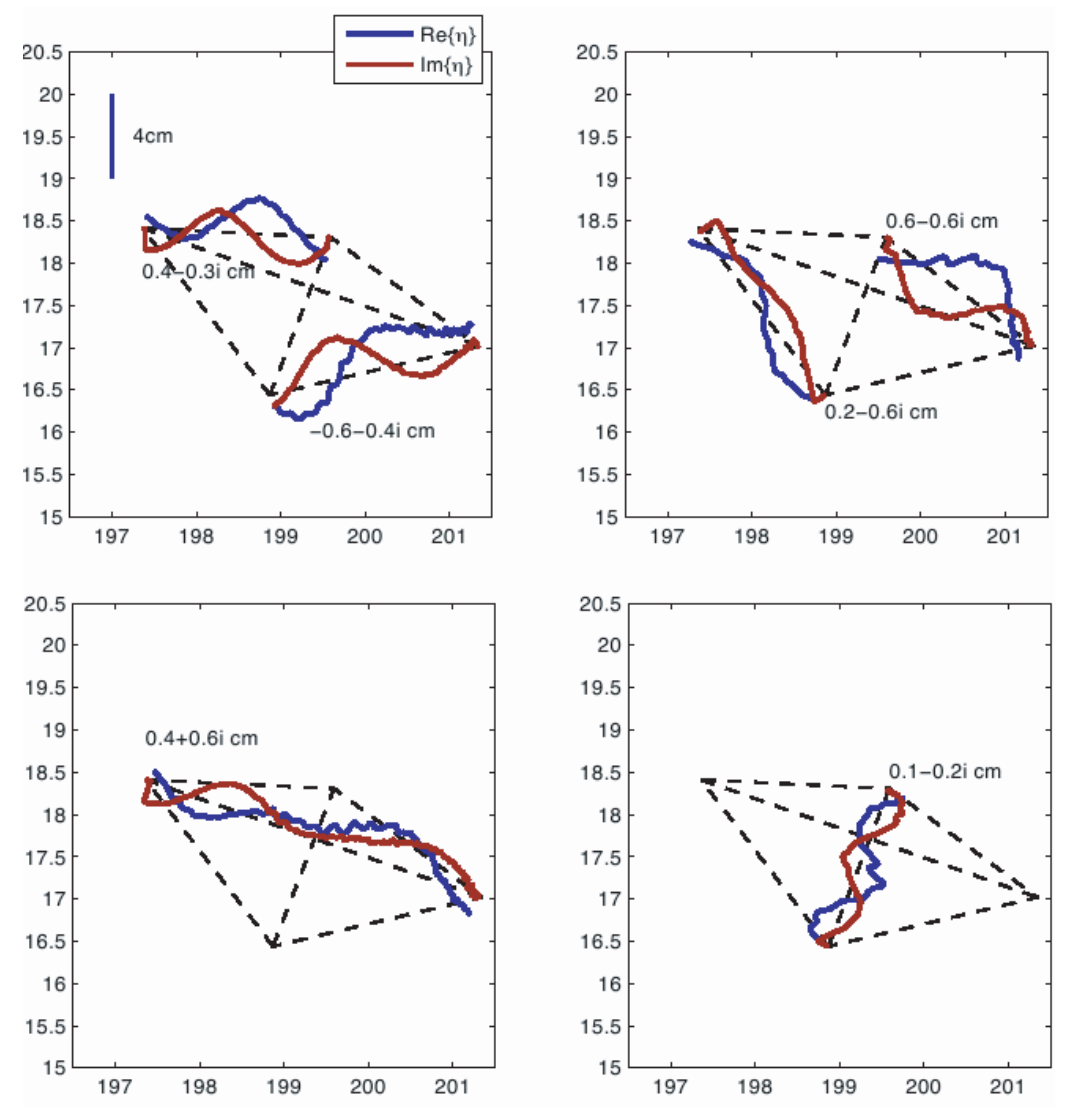
The values of energy flux obtained here are fairly small compared to values obtained in the nearfield of Hawaii (10-15 kW/m). The energy flux of the southern array is particularly small. While these values change somewhat if different models or assumptions are used, they do not change by very much, e.g., less than a factor of two.

COMPARISON WITH MODELS

The comparison between the thermistor and tomography measurements of mode-1 internal tides, and attempts to disentangle the various wavenumbers present through objective mapping techniques, suggest that comparisons with numerical models will be a useful aid in interpreting these data. The tomography data, because of its inherent averaging, appears to underestimate the internal tide, while the point measures of the interference pattern produce no clear picture of the internal tide (other than its variability). However, the data can be used to test the model to verify the model accuracy. Once verified, and adjusted through whatever means to better match the data, the model can then be used to perform the integration of energy flux leaving the Hawaiian Ridge. Modeling has been an essential component to the farfield project from the start. Although the tomography measurement appears to underestimate the internal tide, it is still a direct measurement, and making the equivalent measurement in the numerical models should produce values that match the data. This calculation is essentially an OSSE (Observing System Simulation Experiment), which is in progress. Upon completion of the OSSE, which will build confidence in the model, the model can be used to perform the total Ridge calculation. Model estimates provided by Shaun Johnston are shown here.







The figure to left shows the values of sea surface height along the various paths of the southern tomography array. Sea surface height is dominated by mode-1 internal tides. The various oscillations along the path are a product of the beam patterns of the acoustic paths - on most paths the internal tide variations will average to zero. The array is aligned such that the main diagonal is most sensitive to the waves, and the panel to lower left shows that the oscillations along the path are less, indicitive that the phase of the tide is somewhat more constant along the path, as the figure above shows.

The array is designed to resolve the wavenumber components of the field as much as possible, although the resolution is still limited.

CONCLUSIONS

1. Thermistor and tomography data show that mode-1 internal tides are phase locked. Thermistor data obtained at one point show that modes 2 and higher are not phase locked.

2. Mode-1 internal tide amplitudes were surprisingly weak. Maximum energy flux derived from the tomography data was 1.4 kW/m on the northern array (across the main diagonal) and 0.15 kW/m on the southern array (across the main diagonal). The weak values stem in part from the natural integration of the acoustic paths.

3. Amplitudes, and hence energy flux, obtained on the thermistor moorings were highly variable, and generally larger than those obtained on the tomography lines. This suggests that the salient feature of the internal tides near Hawaii is that they consist of an interference pattern, with multiple waves combining to form regions of large and small energy. The confined "beams" of internal tide energy seen in model and altimetry results are a product of this interference; they are not beams of energy in the traditional sense.

4. The original HOME farfield proposal explicitly relied on modeling to perform the extrapolation of the measured internal tide to the Hawaiian Ridge as a whole for comparisions to such things as the net barotropic tidal energy loss at the Ridge. The nature of the observed tidal field in the far field of Hawaii makes this modeling effort imperative.

LINKS

HOME Farfield: http://faculty.washington.edu/dushaw/HOME/
TOMOGRAPHY: http://faculty.washington.edu/dushaw/
(where you can also download this poster)

REFERENCES

Dushaw, B. D., P. F. Worcester, B. D. Cornuelle, B. M. Howe, and D. S. Luther, 1995: Barotropic and baroclinic tides in the central North Pacific Ocean determined from long-range reciprocal acoustic transmissions. J. Phys. Oceanogr., 25, 631-647.

Dushaw, B., 2002: Mapping low-mode internal tides near Hawaii using TOPEX/POSEIDON altimeter data. Geophys. Res. Lett., 29, 10.1029/2001GL013944.

Dushaw, B., 2003: Mapping and wavenumber resolution of line-integral data for observations of low-mode internal tides. J. Ocean. Atmos. Tech., 20, 1043-1059.

Dushaw, B., 2006: Mode-1 internal tides in the western North Atlantic Ocean. Deep Sea Res., in press.

Merrifield, M.A., P. E. Holloway, and T. M. Shaun Johnston, 2001: The generation of internal tides at the Hawaiian Ridge. Geophys. Res. Lett., 28, 559-562.

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