EXTRACURRICULAR GEOPHYSICS

or

"When Instruments Pick Up Signals They Were NOT Designed to Record"

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EXTRACURRICULAR GEOPHYSICS

The occurrence of exceptional events, such as the 2004 Sumatra earthquake, occasionally gives rise to the recording of physical phenomena by instruments not designed for that purpose.

For example, a seismometer may record an air wave, a hydrophone may record a tsunami...

Such recording by *"unprepared" or "incompetent"* **instruments often times illustrates a physical coupling between the medium of the phenomenon and that where the instrument is supposed to operate.**

Such coupling being generally weak, requires a very large event (Sumatra, Maule...) to be detectable.

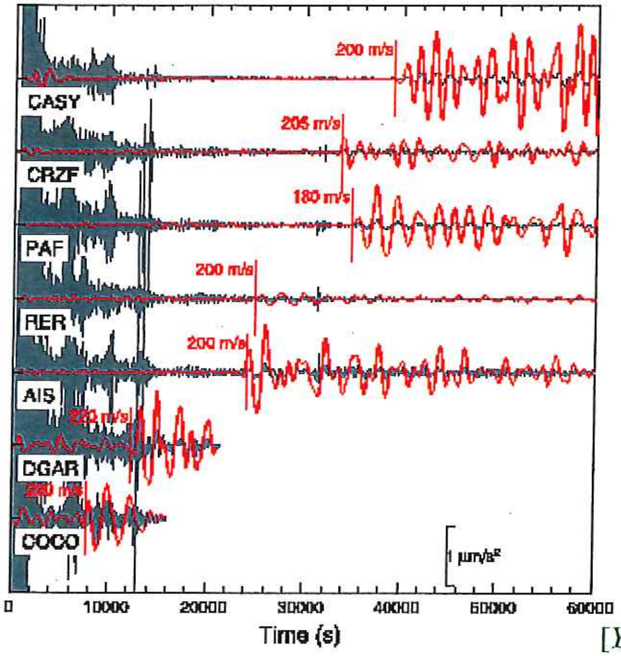
However, such instances of coupling are precious, since they shed light on some unsuspected properties of the physical waves and media involved.

SEISMOMETERS DETECT TSUNAMIS

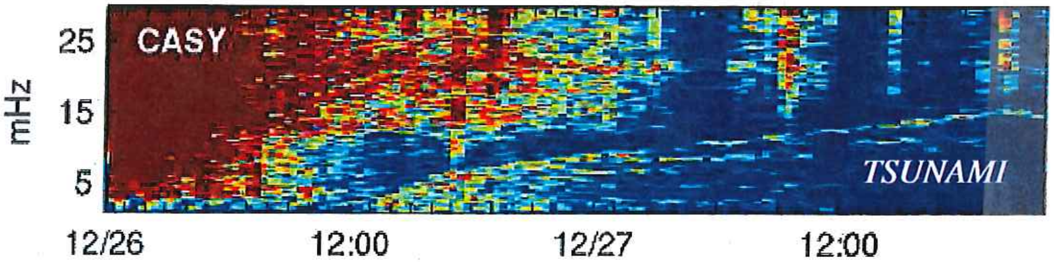
(The Seismic "DART" ?)

TSUNAMI RECORDED ON SEISMOMETERS

- Horizontal long-period seismometers (GEOSCOPE, IRIS...) record ultra-long period oscillations following arrival of 2004 tsunami at nearby shores [*R. Kind,* 2005].
- Energy is mostly between 800 and 3000 seconds
- Amplitude of equivalent displacement is **centimetric**



[*Yuan et al.,* 2005]



[*Hanson and Bowman,* 2005]

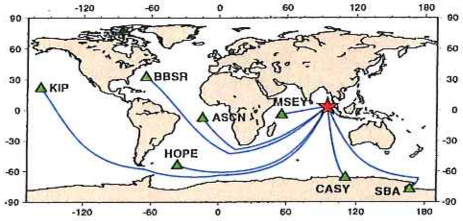
TSUNAMI RECORDED ON SEISMOMETERS (ctd.)

Enhanced Study [*E.A. Okal,* 2005–06].

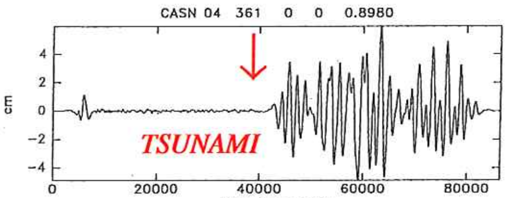
- *RECORDED* **WORLDWIDE** (On Oceanic shores)
- *HIGHER FREQUENCIES* (up to 0.01 Hz) *PRESENT* (in regional field)
- Tsunami detectable during **SMALLER EVENTS**
- *CAN BE* **QUANTIFIED**

SUMATRA 2004: TSUNAMI RECORDED ON SEISMOMETERS

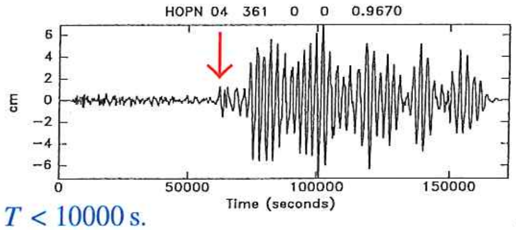
- Recording by shoreline stations is **WORLDWIDE** including in regions requiring strong refraction around continents (Bermuda, Scott Base).



Casey, Antarctica, 8300 km

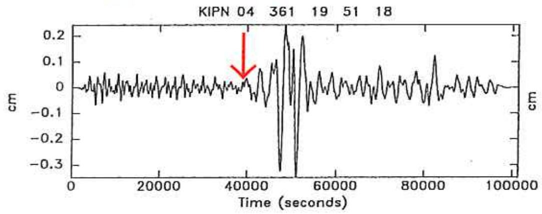


Hope, South Georgia, 13100 km

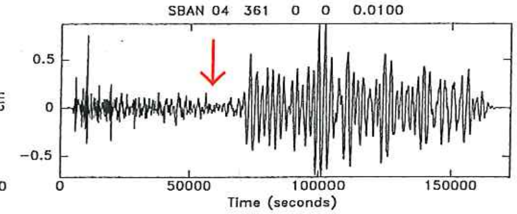


Filtered $100 < T < 10000$ s.

Kipapa, Hawaii, 27,000 km

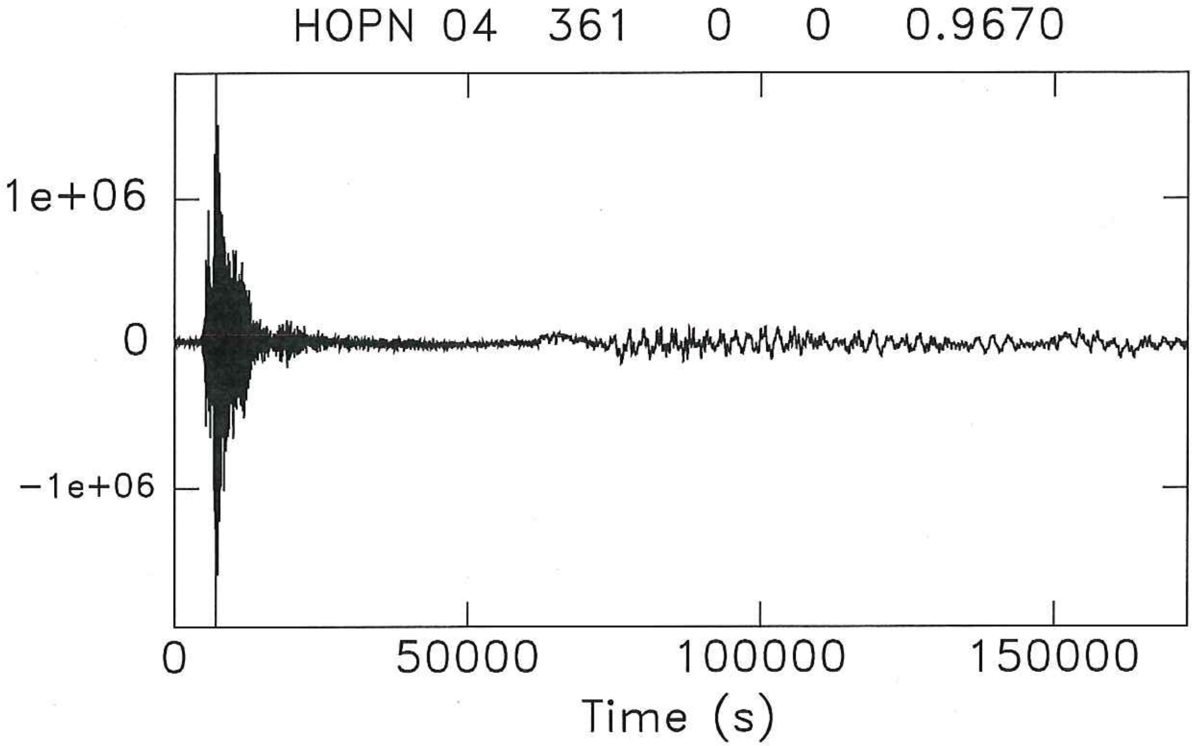


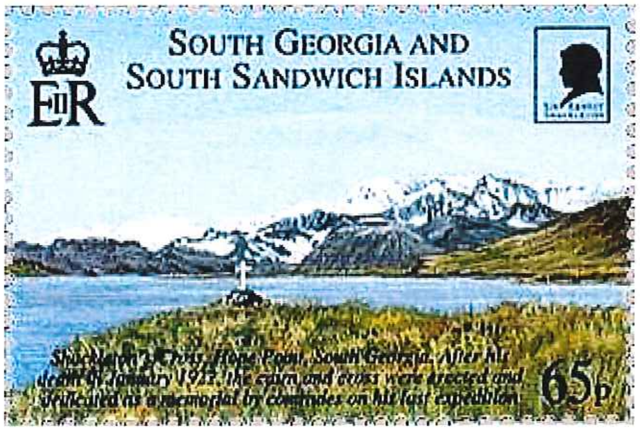
Scott Base, Antarctica, 10400+ km



- *On some of the best records, (e.g., HOPE, South Georgia), the tsunami is actually visible* ***on the raw seismogram!!***

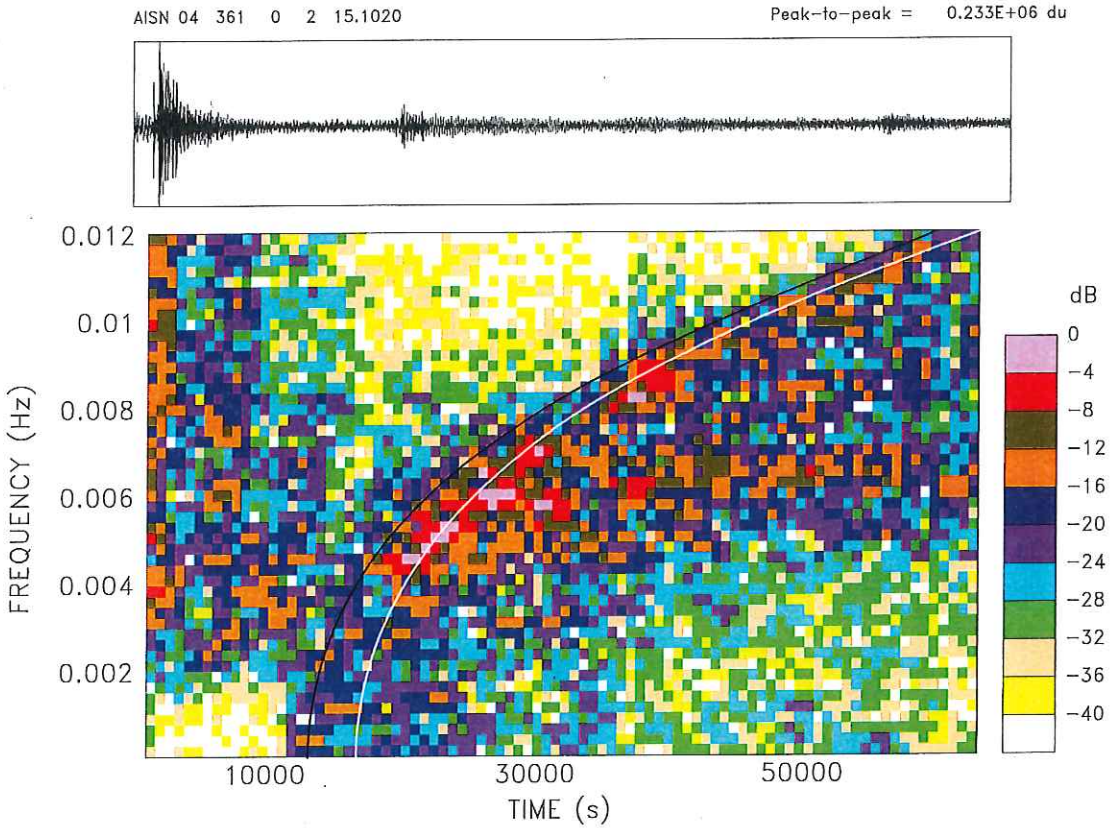
[But who "reads" seismograms in this digital age, let alone that of HOPE, South Georgia...]





Dispersed energy resolved down to $T = 80$ s.

Ile Amsterdam, 26 Dec. 2004

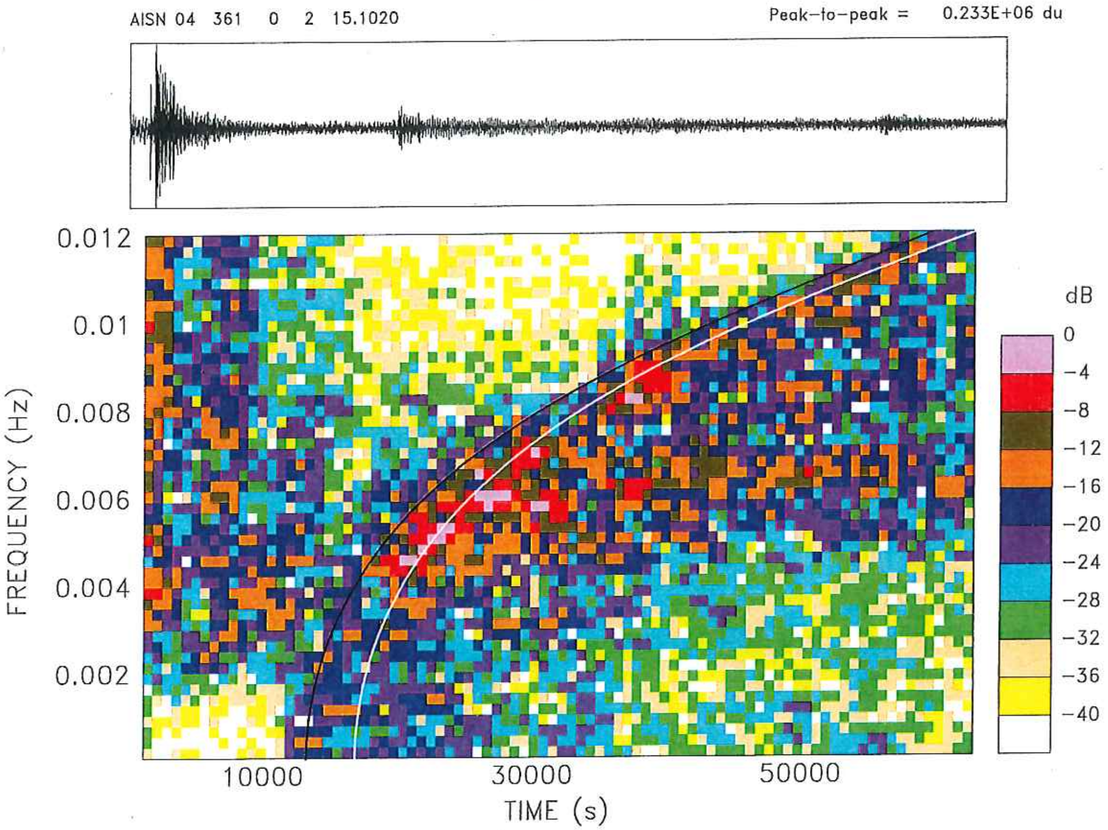


NOTE STRONG HIGH-FREQUENCY TSUNAMI COMPONENTS

CAN WE QUANTIFY SUCH RECORDS ?

Dispersed energy resolved down to $T = 80$ s.

Ile Amsterdam, 26 Dec. 2004



NOTE STRONG HIGH-FREQUENCY TSUNAMI COMPONENTS

CAN WE QUANTIFY SUCH RECORDS ?

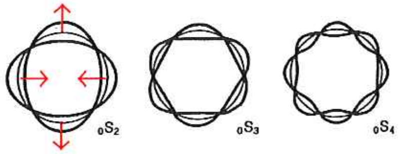
1. *USE NORMAL MODE THEORY*

TSUNAMIS: The NORMAL MODE FORMALISM

[*Ward,* 1980]

- At very long periods (typically 15 to 54 minutes), the Earth, because of its finite size, can ring like a bell.
- Such *FREE OSCILLATIONS* are equivalent to the superposition of two progressive waves travelling in opposite directions along the surface of the Earth.

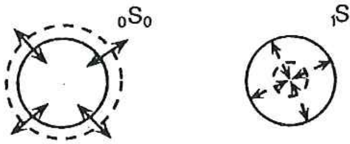
T = 54 minutes



"FOOTBALL Mode"

[After *Lay and Wallace,* 1995]

T = 21.5 minutes



"BREATHING Mode"

> *Ward* [1980] has shown that **Tsunamis come naturally as a special branch of the normal modes of the Earth,** provided it is bounded by an ocean, and gravity is included in the formulation of its vibrations.

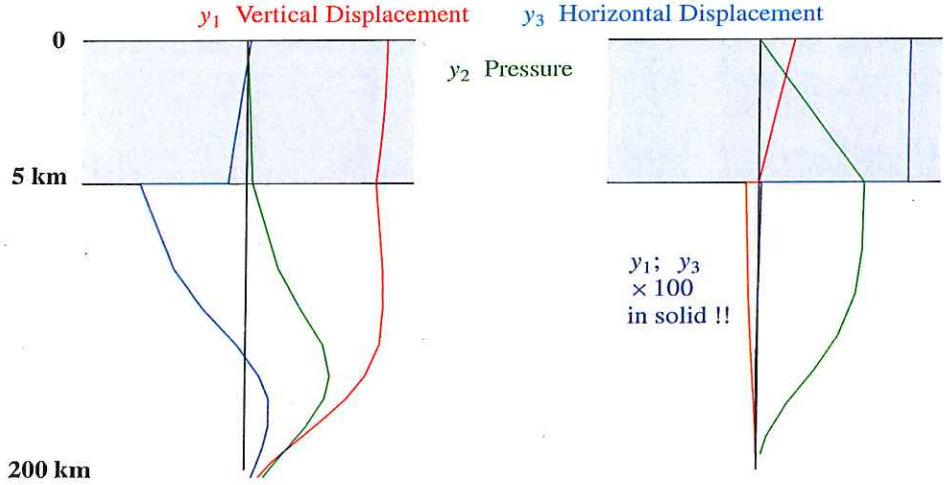
TSUNAMI as SPHEROIDAL MODE : STRUCTURE of the EIGENFUNCTION

Rayleigh Mode

$l = 200;\ T = 52\ s$

Tsunami Mode

$l = 200;\ T = 908\ s$



TSUNAMI EIGENFUNCTION is CONTINUED (SMALL) into SOLID EARTH

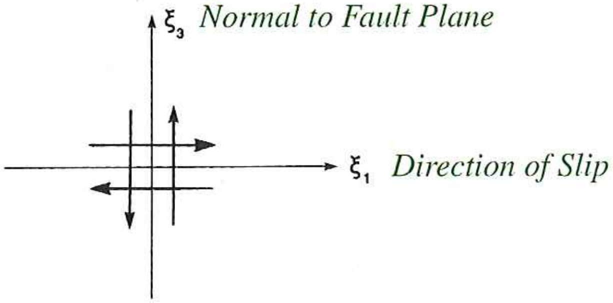
EXCITATION OF TSUNAMI in NORMAL MODE FORMALISM

- *Gilbert* [1970] has shown that the response of the Earth to a point source consisting of a single force **f** can be expressed as a summation over all of its normal modes

$$\mathbf{u}(r,t)=\sum_{N}\mathbf{s}_n(\mathbf{r})\left(\mathbf{s}_n^{*}(\mathbf{r_s})\cdot\mathbf{f}(\mathbf{r_s})\right)\cdot\frac{1-\cos\omega_n t\,\exp\left(-\omega_n t/2Q_n\right)}{\omega_n^2}\;,$$

the *EXCITATION* of each mode being proportional to the *scalar product of the force* **f** *by the eigen-displacement* **s** *at location* $\mathbf{r_s}$.

- Now, an *EARTHQUAKE* is represented by a system of forces called a ***double – couple***:



The response of the Earth to an earthquake is thus

$$\mathbf{u}(r,t)=\sum_{N}\mathbf{s}_n(\mathbf{r})\boxed{\left(\varepsilon_n^{*}(\mathbf{r_s}):M(\mathbf{r_s})\right)}\cdot\frac{1-\cos\omega_n t\,\exp\left(-\omega_n t/2Q_n\right)}{\omega_n^2}$$

where the *EXCITATION* is the *scalar product* of the earthquake's **MOMENT** ***M*** with the local *eigenstrain* ε at the source $\mathbf{r_s}$.

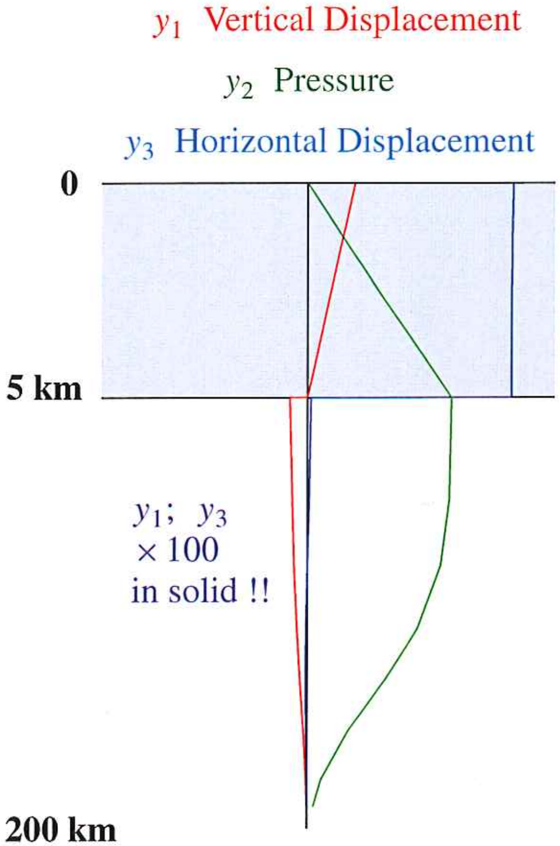
This formula is directly applicable to the case of a tsunami represented by normal modes of the Earth.

IMMEDIATE RESULTS

- Eigenfunction very small in Solid
  Requires ***HUGE*** *Earthquake*
- Eigenfunction decays slowly in Solid
  Depth has ***minimal influence*** *on tsunami excitation* ($h \leq 70$ *km*)
- y_3 present in solid. *All geometries,* ***including strike – slip*** *excite tsunamis.*

Tsunami Mode

$l = 200;\ T = 908\ s$



CAN WE QUANTIFY SUCH RECORDS ?

2. *MAKE SOME RATHER DRASTIC ASSUMPTIONS*

CAN WE QUANTIFY SUCH RECORDS ?

2. *MAKE SOME RATHER DRASTIC ASSUMPTIONS*

FORGET THE ISLAND *(or continent)* **!!**

QUANTIFYING the SEISMIC RECORD at CASY

- Assume that seismic record (*e.g.,* at CASY) reflects response of seismometer to the *deformation of the ocean bottom.*

FORGET THE ISLAND (or continent) !

- Use *Gilbert*'s [1980] combination of displacement, tilt and gravity;

Apparent Horizontal Acceleration (*Gilbert*'s [1980] Notation):

$$AV = \omega^2 V - r^{-1} L (g U + \Phi)$$

or (*Saito*'s [1967] notation):

$$y_3^{APP} = y_3 - \frac{1}{r\,\omega^2} \cdot (g\, y_1 - y_5)$$

- Use *Ward*'s [1980] normal mode formalism;

Evaluate Gilbert response on solid side of ocean floor, and derive equivalent spectral amplitude of surface displacement $y_1(\omega) = \eta(\omega)$.

- Use *Okal and Titov*'s [2005] Tsunami Magnitude, inspired from *Okal and Talandier*'s [1989] M_m ;
- Apply to CASY record at maximum spectral energy
  ($S(\omega) = 4000$ cm*s at $T = 800$ s).

→ Find **$M_0 = 1.7 \times 10^{30}$ dyn – cm.**

Published: 1.15×10^{30} dyn*cm [*Stein and Okal,* 2005; *Tsai et al.,* 2005]

Acceptable, given the extreme nature of the approximations.

→ Suggests that the signal is just the expression of the horizontal deformation of the ocean floor, and that

CASY functions in a sense like an OBS !!

QUANTIFICATION of SEISMIC TSUNAMI RECORDS

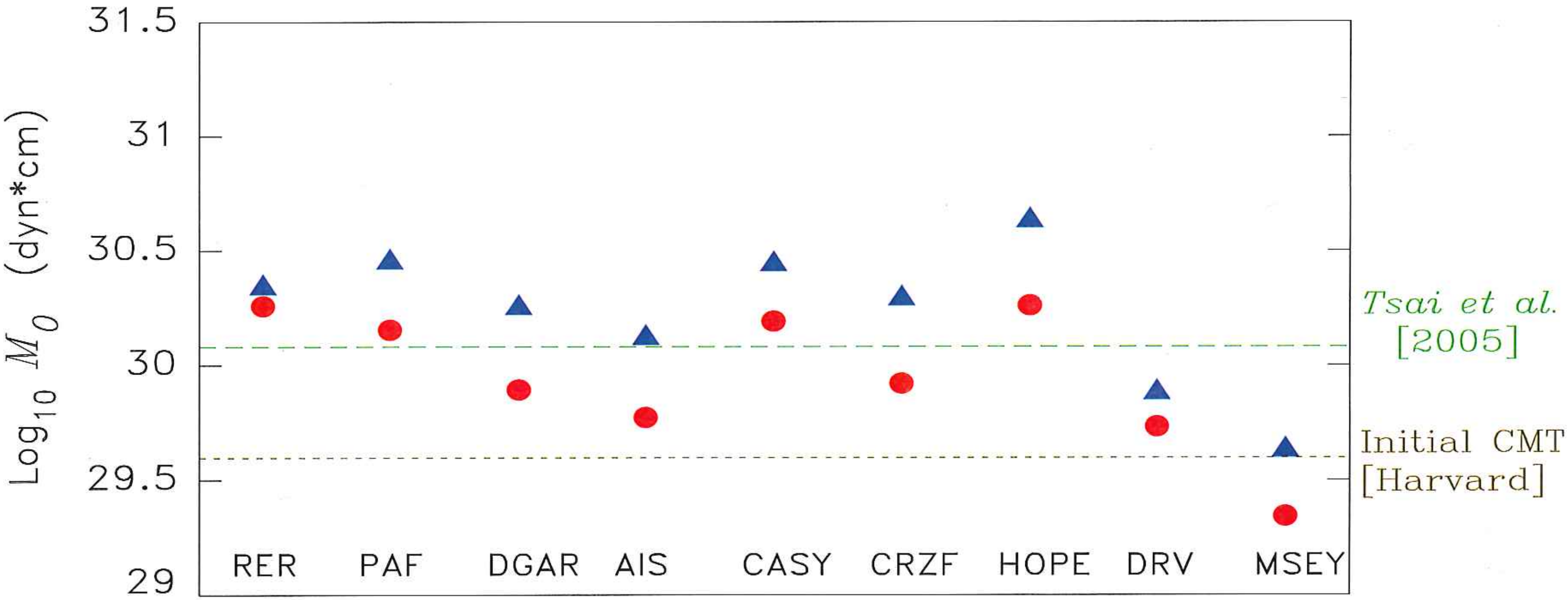
- Apply technique to dataset of 10 stations with direct great circle paths
- Use either Full Source computation (**Red Symbols**)

$$\overline{M_0} = 1.6 \times 10^{30} \text{ dyn} - \text{cm}$$

or M_{TSU} magnitude approach (**Blue Symbols**)

$$\overline{M_0} = 2.1 \times 10^{30} \text{ dyn} - \text{cm}$$

In good agreement with *Nettles et al.* [2005] and *Stein and Okal* [2005] (green dashed line)



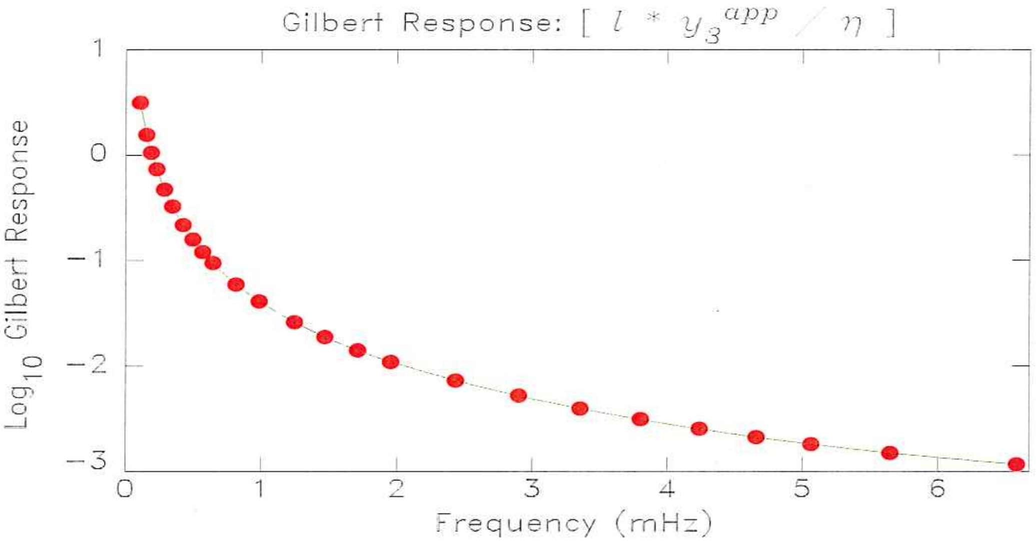
STATIONS

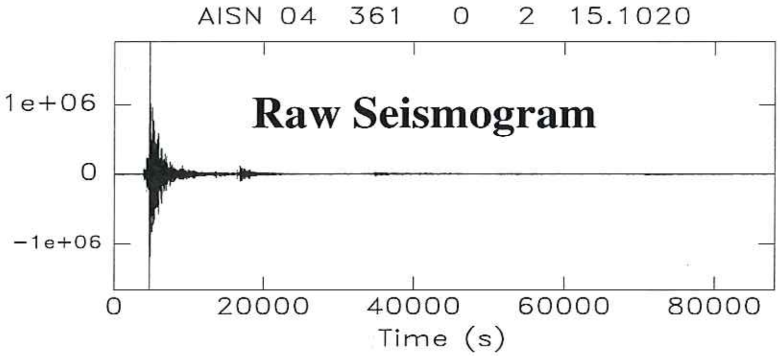
NOTE: DRV and MSEY affected by *substantial continental shelves*.

USING AN ISLAND SEISMOMETER AS A "DART" SENSOR?

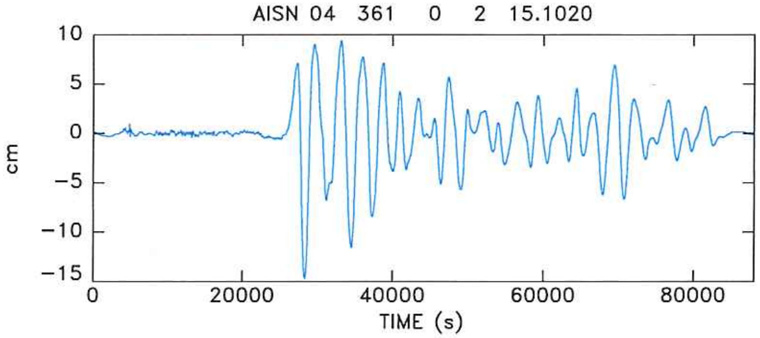
Example: Ile Amsterdam, 26 DEC 2004 (d= 5800 km)

- A horizontal seismometer at a shoreline location can record a tsunami wave.
- Once the instrument is deconvolved, we obtain an apparent horizontal ground motion of the ocean floor
- Further deconvolve the ***"Gilbert Response Factor"*** $[l\, y_3^{app} / \eta]$ and obtain the time series of the surface amplitude of the tsunami.
- The *G R F* can be computed from normal modes

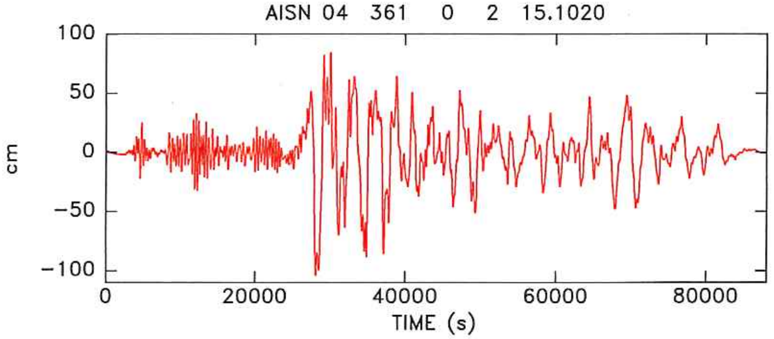




Deconvolve Instrument: **Apparent Ground Motion**



Deconvolve *GRF:* **"Tsunami Record"**

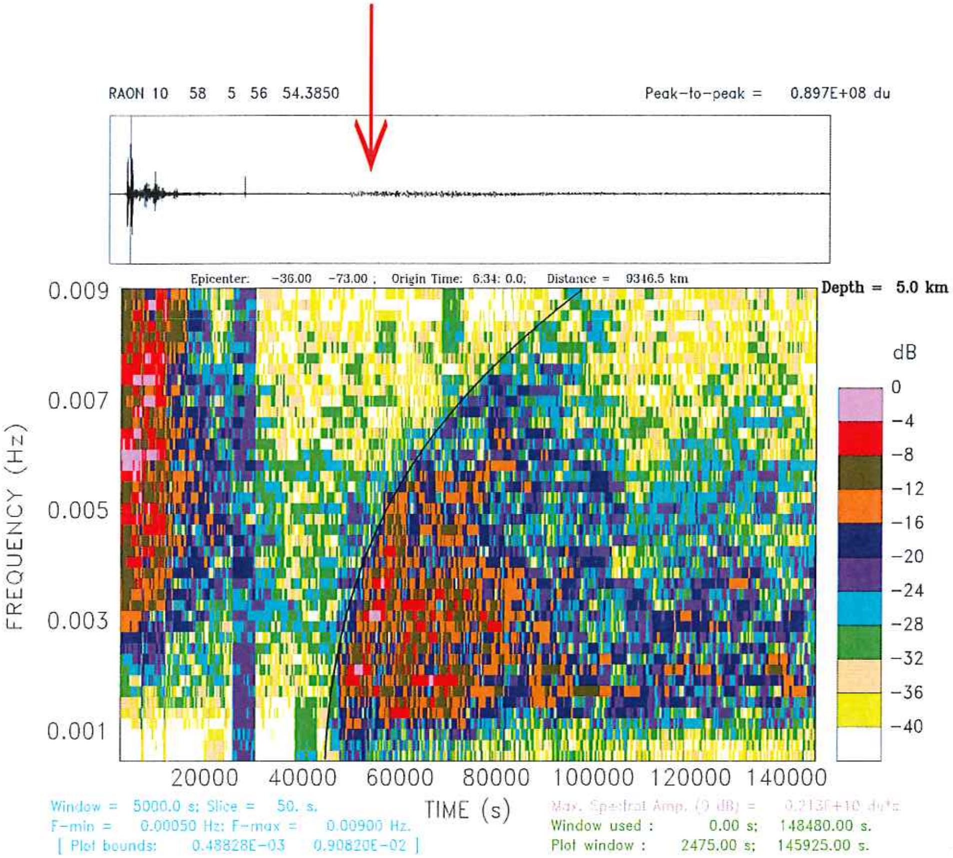


We find an amplitude $\eta \approx 80$ cm; Satellite Altimetry measured 70 cm in Bay of Bengal

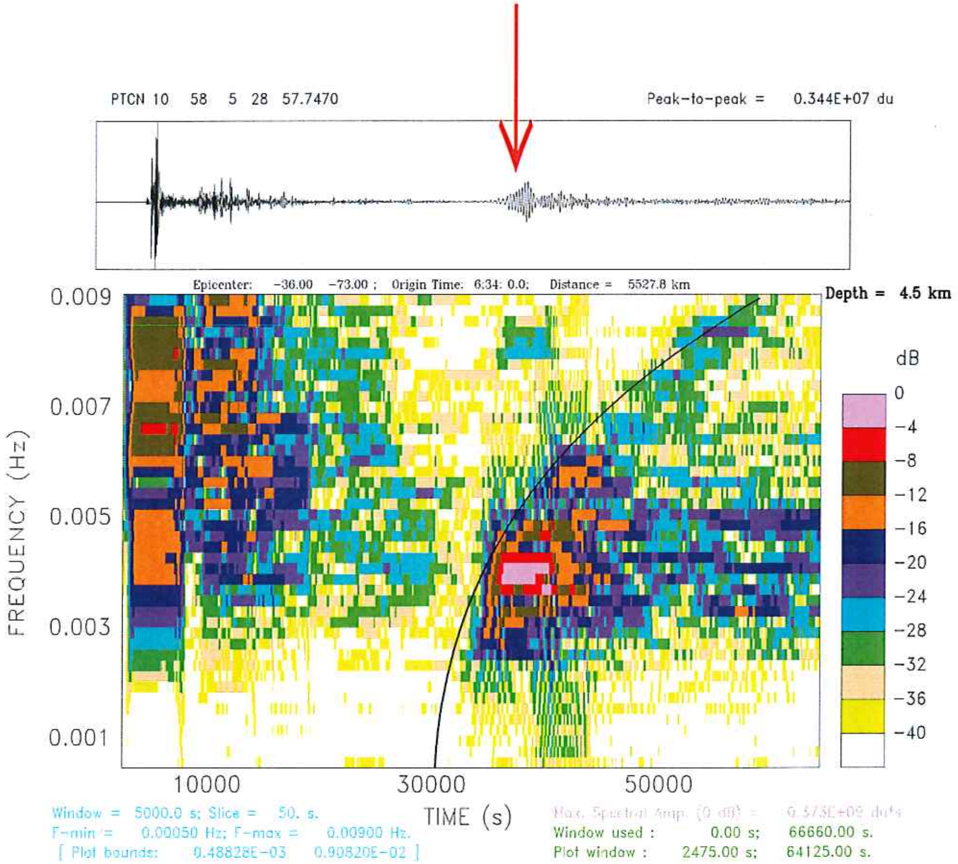
MAULE, CHILE, 27-FEB-2010

The spectacular records at Raoul Island and Pitcairn Island are clearly visible in the raw seismograms, without any processing.

RAO *Raoul Island, Kermadec Islands*

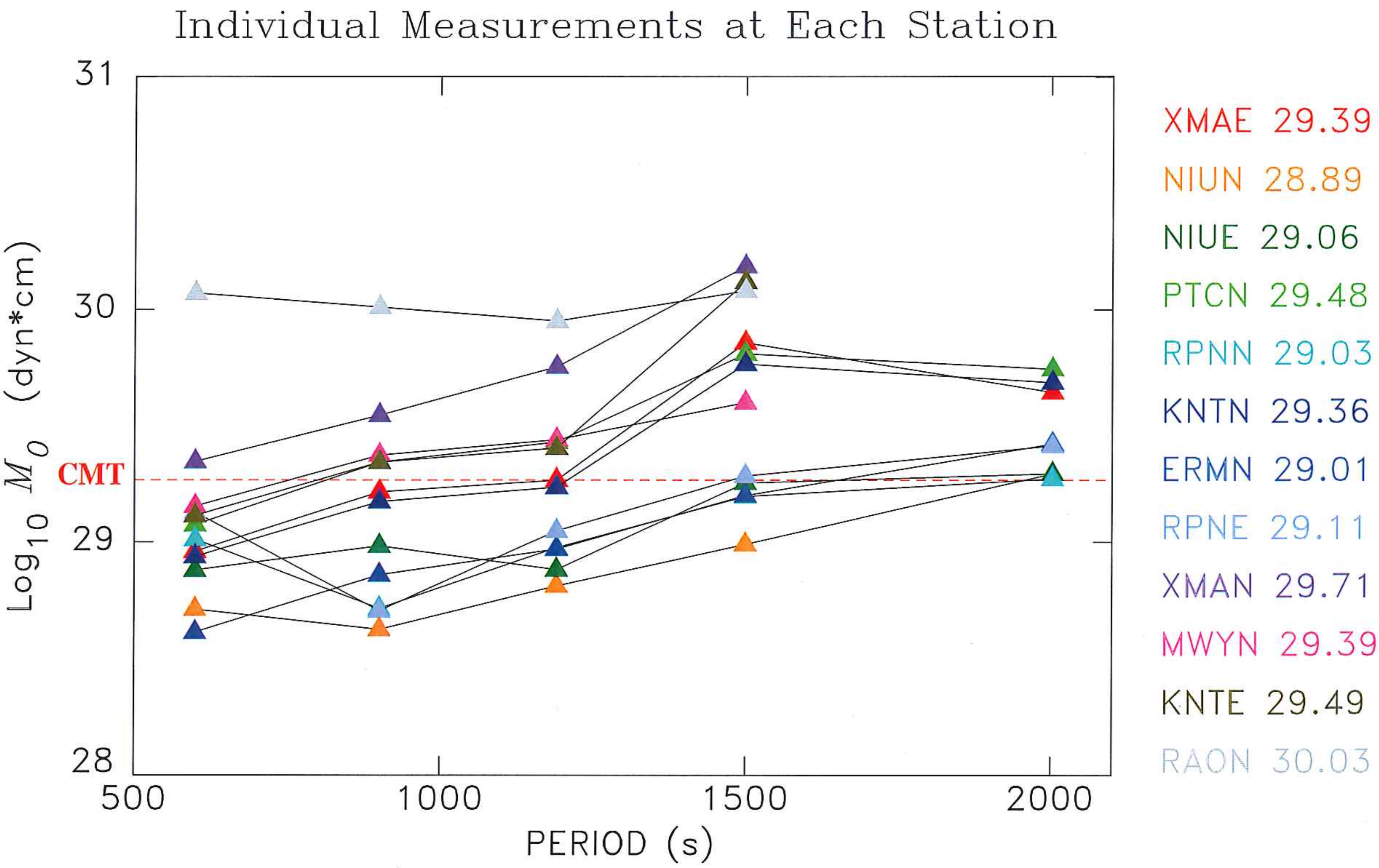


PTCN *Pitcairn Island, B.C.C.*

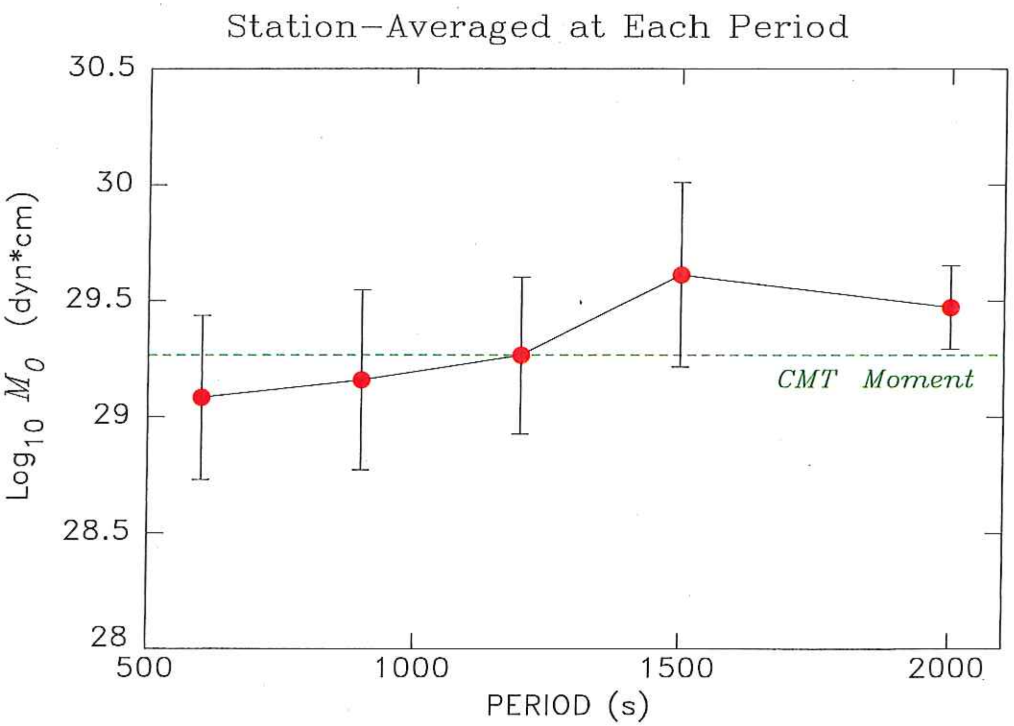


In this case, note the prominent high frequencies, which probably express a non-linear response of the structure of that small island (4.6 km^2).

→ *Using the previously described algorithm, we derive a seismic moment for the Maule event from the seismic records of its tsunami*



→ *In the 500–2000 s period range, the results are generally in agreement with the CMT scalar moment.*



This supports the finding [*Okal et al.*, 2010] *that the Maule earthquake is* **not a slow event**.

→ At higher frequencies (not shown), the results would depend on the response of the individual island structure.

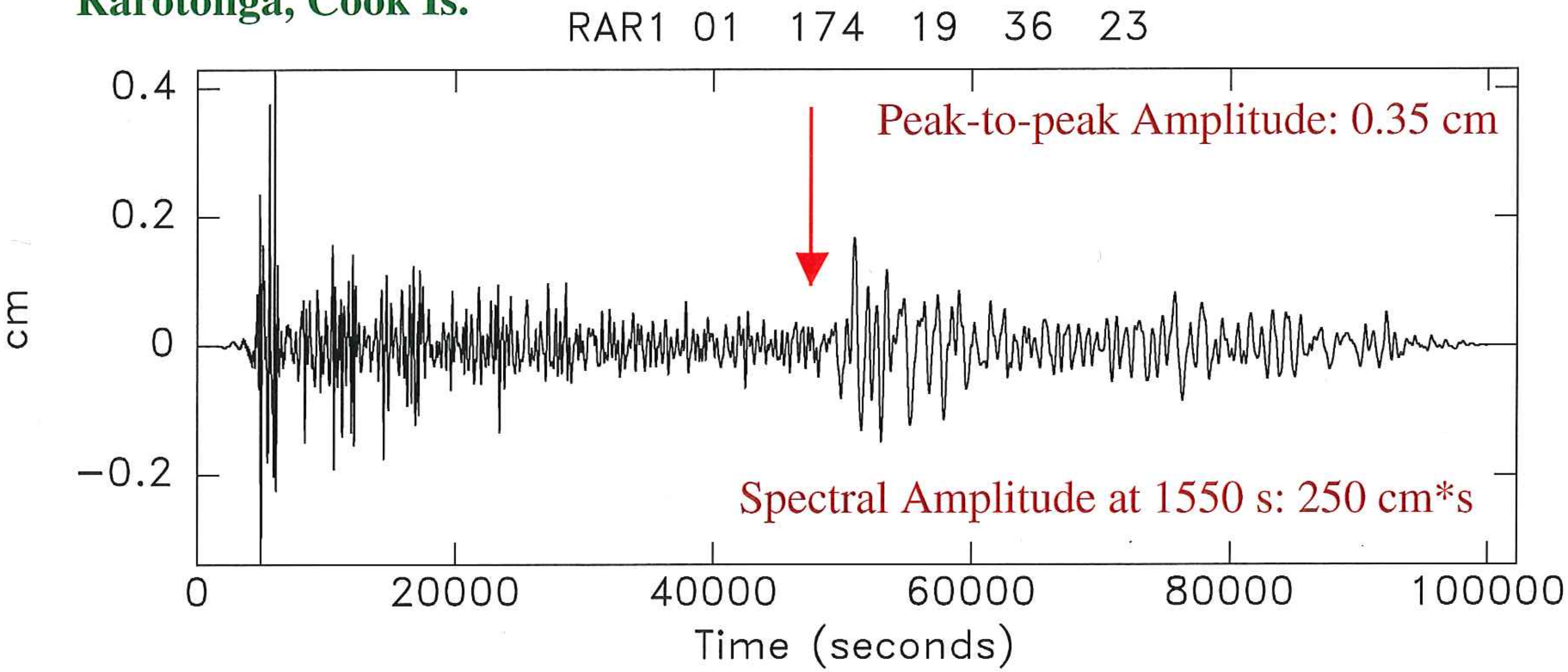
TSUNAMI DETECTED FOLLOWING SMALLER EVENTS

Camaná, Perú, 23 June 2001

Harvard CMT: $M_0 = 4.7 \times 10^{28}$ dyn-cm

FILTERED, Tmax = 10000. s; Tmin = 100. s.

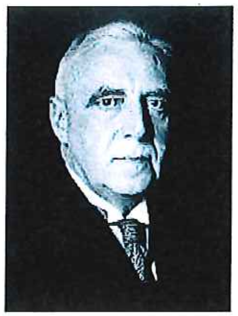
Rarotonga, Cook Is.



Peak-to-peak Amplitude: 0.35 cm

Spectral Amplitude at 1550 s: 250 cm*s

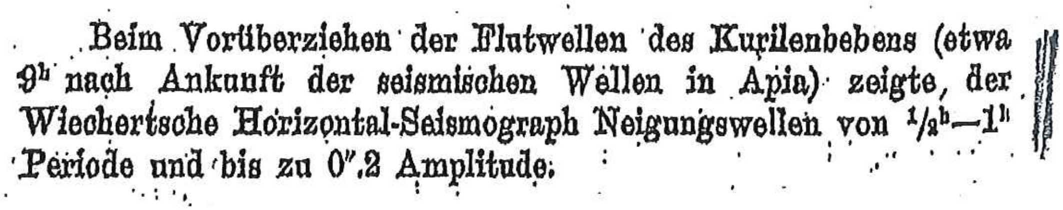
Computed Moment: $M_0 = 4.6 \times 10^{28}$ dyn-cm



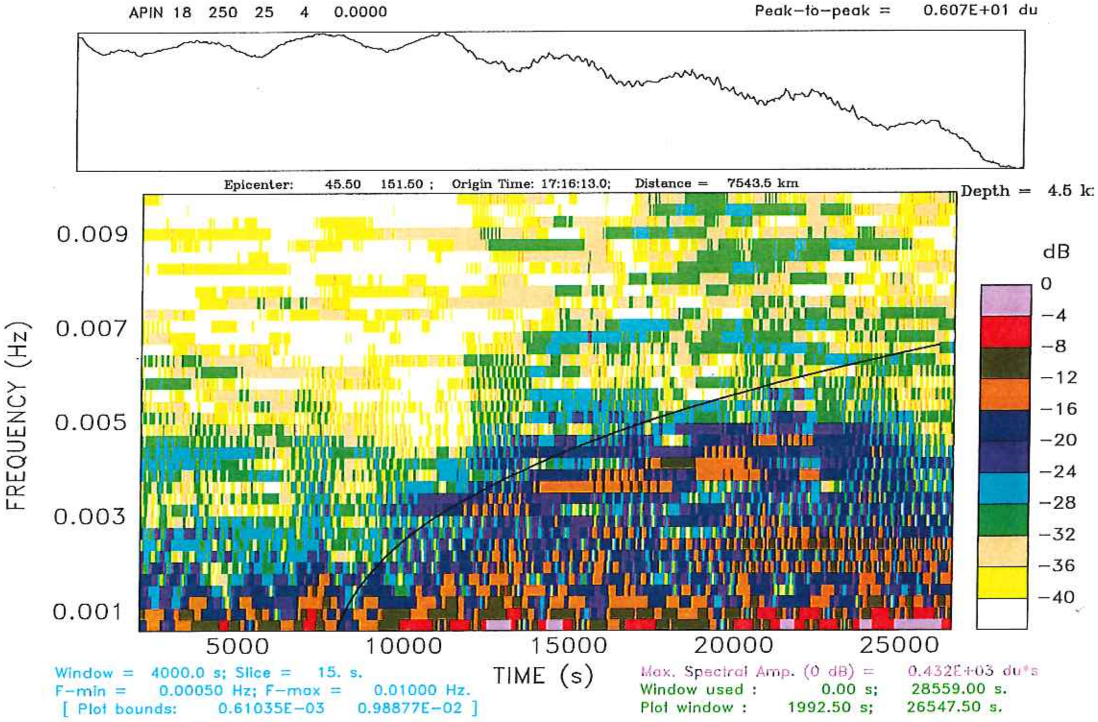
Or even... Kuriles, 07 SEP 1918

at Apia [*ex*–German] Samoa

as reported by *G. Angenheister* [1920]



Beim Vorüberziehen der Flutwellen des Kurilenbebens (etwa 9^h nach Ankunft der seismischen Wellen in Apia) zeigte der Wiechertsche Horizontal-Seismograph Neigungswellen von $^1/_2{}^h$—1^h Periode und bis zu 0″.2 Amplitude.



Window = 4000.0 s; Slice = 15. s.
F-min = 0.00050 Hz; F-max = 0.01000 Hz.
[Plot bounds: 0.61035E-03 0.98877E-02]

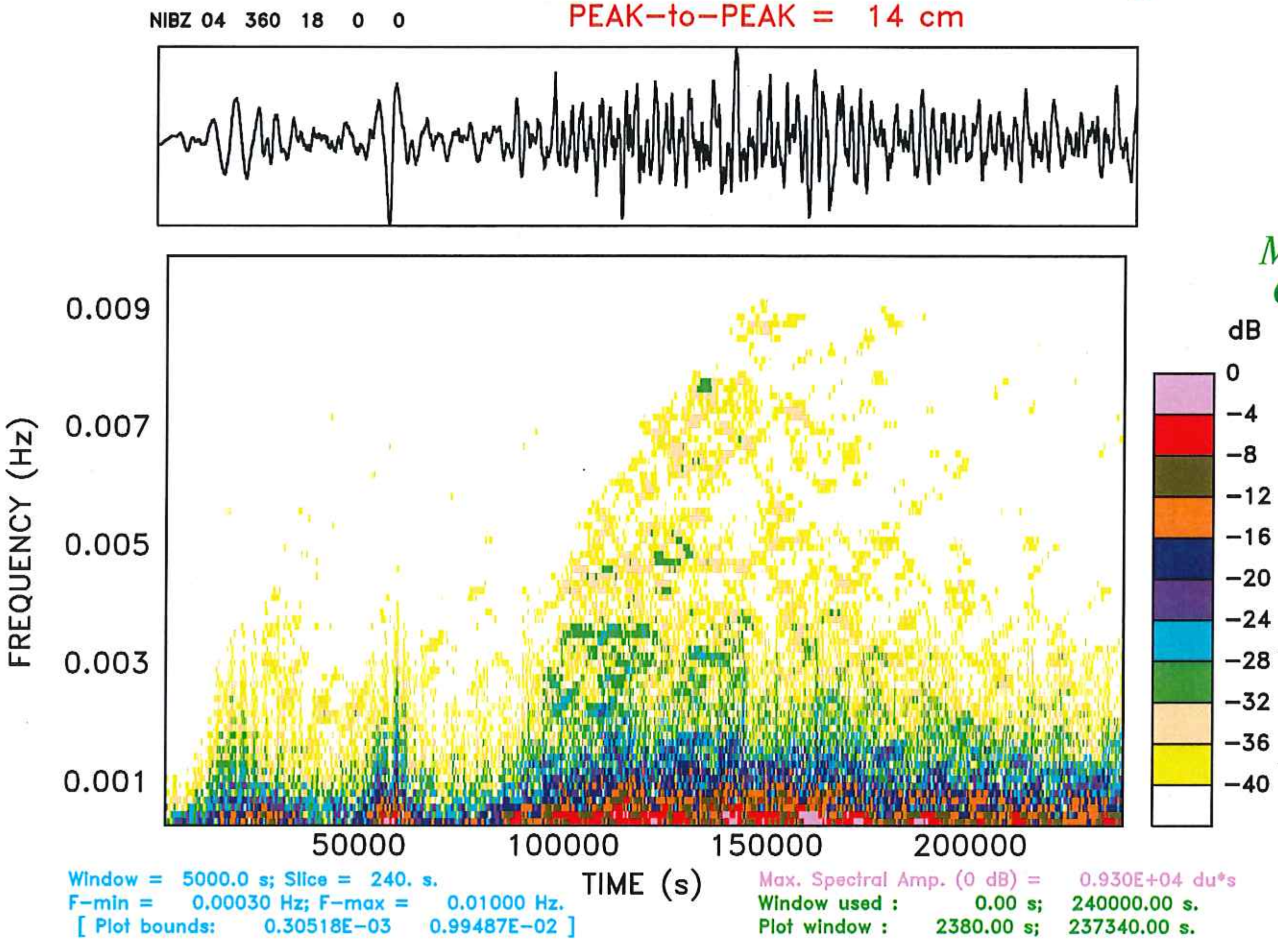
Max. Spectral Amp. (0 dB) = 0.432E+03 du*s
Window used : 0.00 s; 28559.00 s.
Plot window : 1992.50 s; 26547.50 s.

THE FLOATING SEISMOMETER

2004 TSUNAMI RECORDED on ICEBERGS

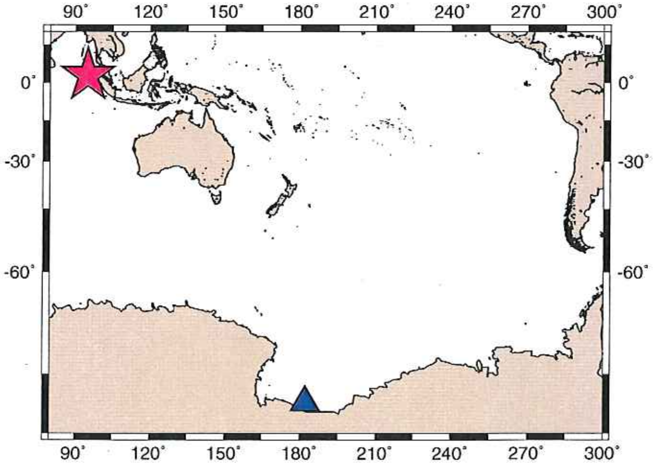
Since 2003, we had been operating seismic stations on detached and nascent icebergs adjoining the Ross Sea.

The tsunami was recorded by our 3 seismic stations, on all 3 components, with amplitudes of 10–20 cm.

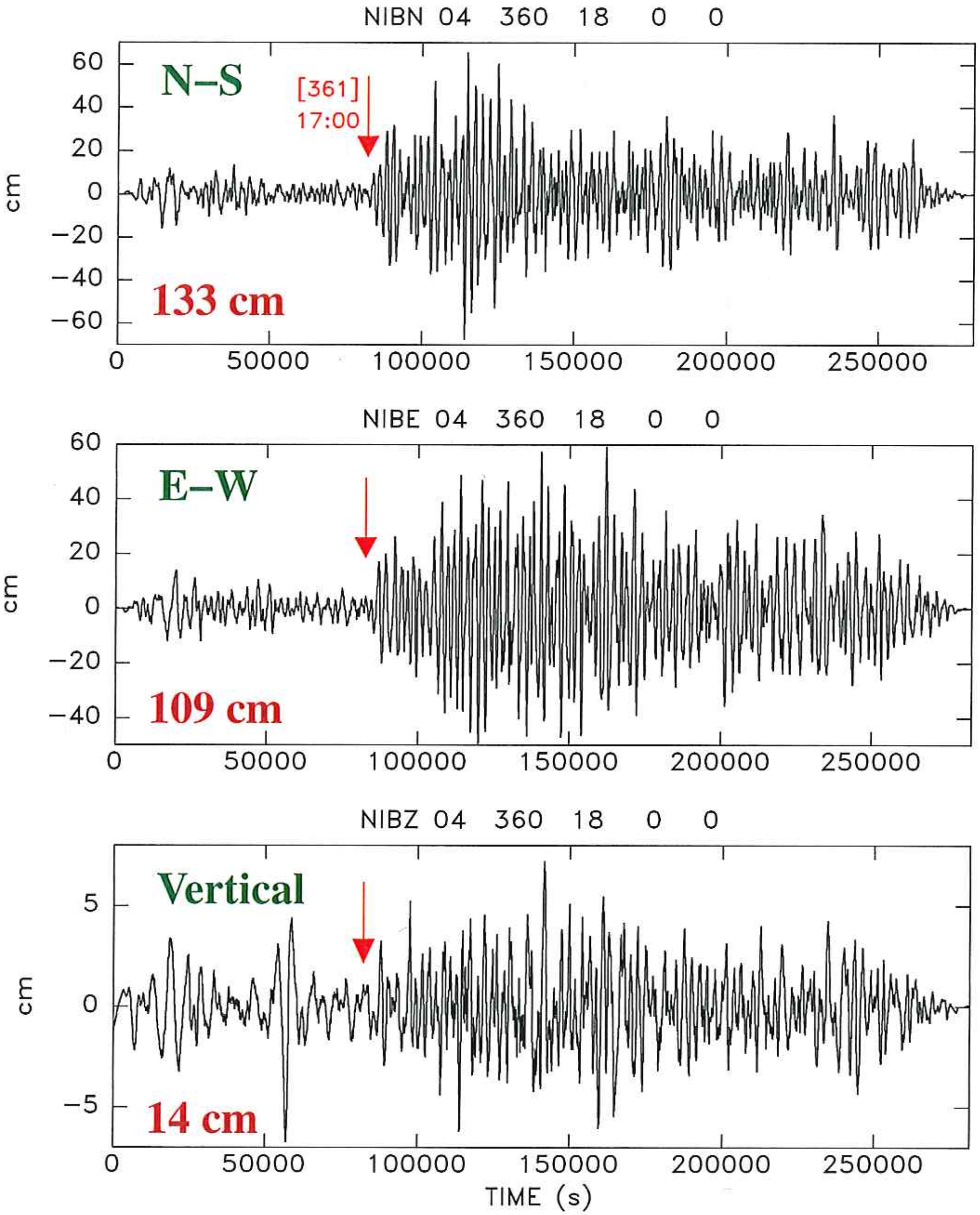


M.H. Okal

D.R. MacAyeal



Seismic recordings of 2004 Sumatra Tsunami on Iceberg
Nascent (NIB); *26 DECEMBER 2004*



This time, the iceberg (and the seismometer) float like a raft on the sea and **record directly the 3-dimensional displacement of the tsunami.**

In the Shallow-Water Approximation,

$$AR = \frac{u_x}{u_z} = \frac{1}{\omega}\sqrt{\frac{g}{h}}$$

Iceberg:

$T = 500$ s; $h = 500$ m $\quad AR \approx 11$

FIRST DIRECT MEASUREMENT OF HORIZONTAL COMPONENT OF TSUNAMI ON THE HIGH SEAS

ELLIPTICITY of TSUNAMI SURFACE MOTION

(Shallow Water Approximation)

$$AR = \frac{u_x}{u_z} = \frac{1}{\omega}\sqrt{\frac{g}{h}}$$

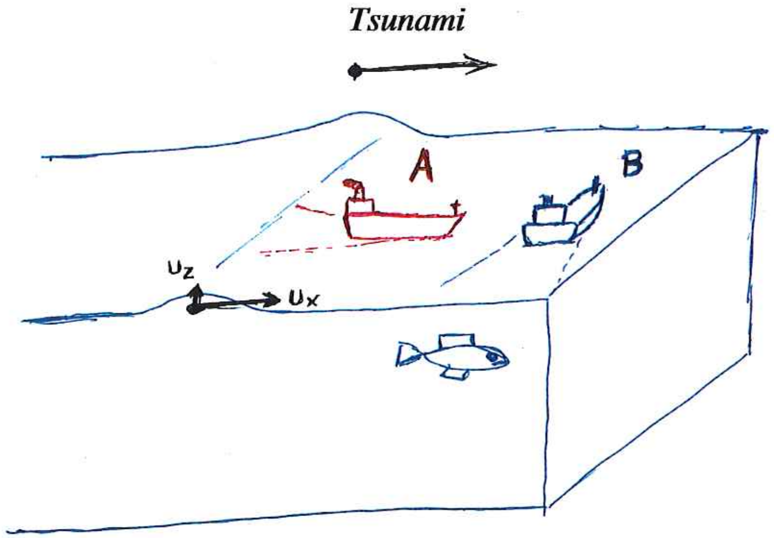
On the high seas ($T = 1000$–2000 s; $h = 2000 - 5000$ m),

AR can be typically between **10 and 25.**

Sumatra 2004: $u_z \approx 1$ m (JASON; seismic stations)

$u_x \approx 15$ meters ?

Conceivable to use GPS-equipped ships to detect tsunami.



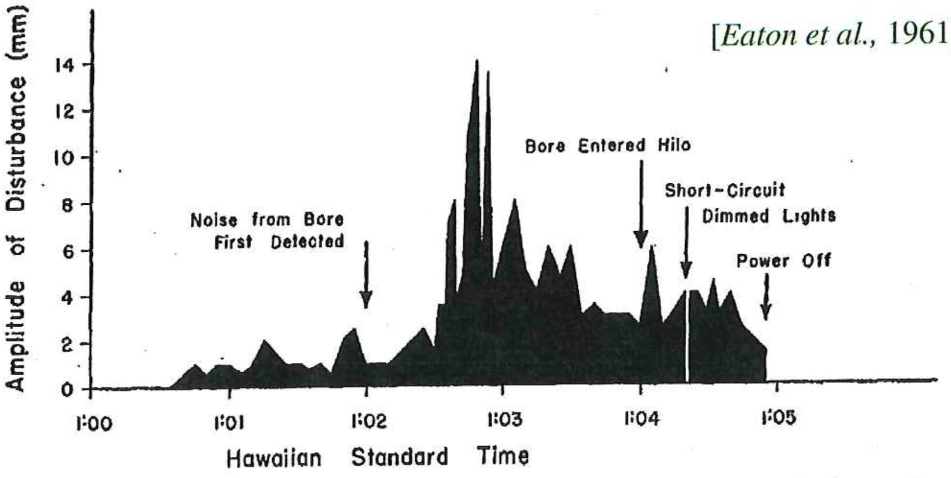
Ship A should see a perturbation in speed

Ship B would show a zig-zag in trajectory

YET ANOTHER FORM OF SEISMIC RECORDING OF TSUNAMIS...

Hilo, 23 May 1960 — Great Chilean Tsunami

- Impact of tsunami bore on island shoreline (during [maximum] third wave) was detected by standard short-period seismometer (redrawn as *envelope of disturbance*).



[*Eaton et al.*, 1961].

FIG. 7. Graph of the disturbance recorded by the Hilo seismograph while the destructive third-wave bore advanced through Hilo Bay.

→ The origin of the reported frequency of 2.5 Hz is unclear.

→ As is the nature of the wave(s) recorded by the instrument.

In the very shallow waters of Hilo Bay, the final approach of the water gravity wave will be much slower than even the acoustic wave from the formation of the bore,

which MAY (?) represent the strongest signal recorded.

THE OBS – OBH RELATIONSHIP

Ocean-Bottom Hydrophone operated as OBS

A simple generalization of body- and surface-wave theory in the presence of an oceanic layer shows that an ocean-bottom hydrophone can function as a seismometer, which will record

- Body-waves proportionally to ground velocity, *e.g.*, for *P* waves

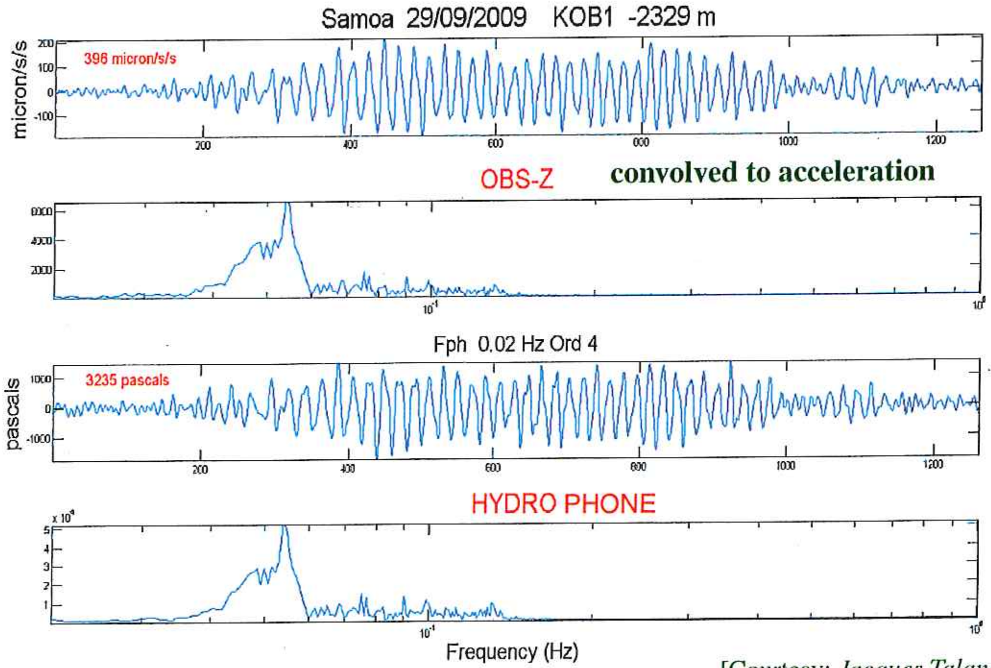
$$Z = \frac{P_s}{u_z} = \rho_l \, \alpha_l \, \omega$$

- Rayleigh waves, proportionally to *acceleration,* the response being itself proportional to the *thickness of the water column* (at long periods)

$$Z = \frac{P_s}{u_z} = \rho_l \, \omega^2 \, h$$

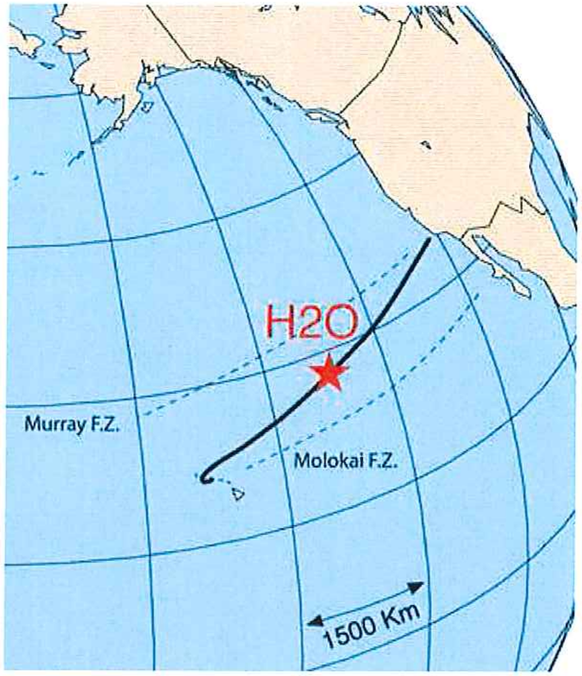
The latter is well verified using OBS and OBH records off the coast of Hokkaido

Samoa, 29 September 2009



[Courtesy: *Jacques Talandier*]

TSUNAMIS RECORDED ON O.B.S.

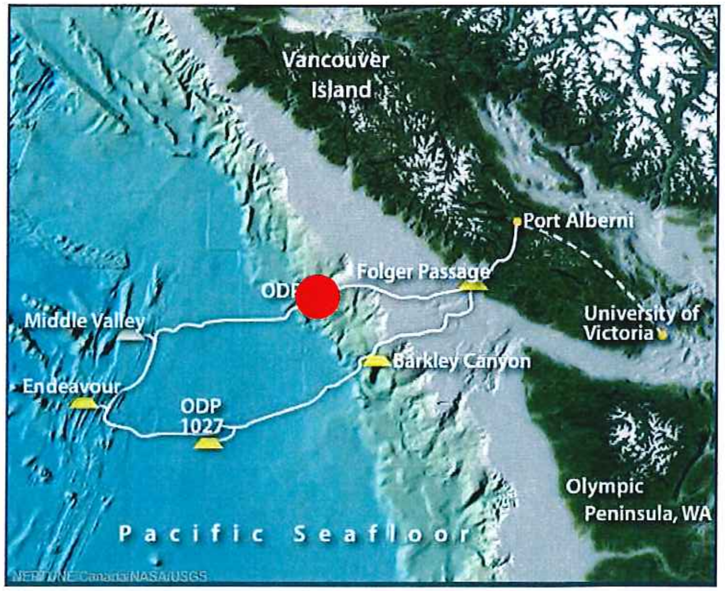


The mourning of H 2 O

5 October 1999 — 26 May 2003

The Rise of Neptune

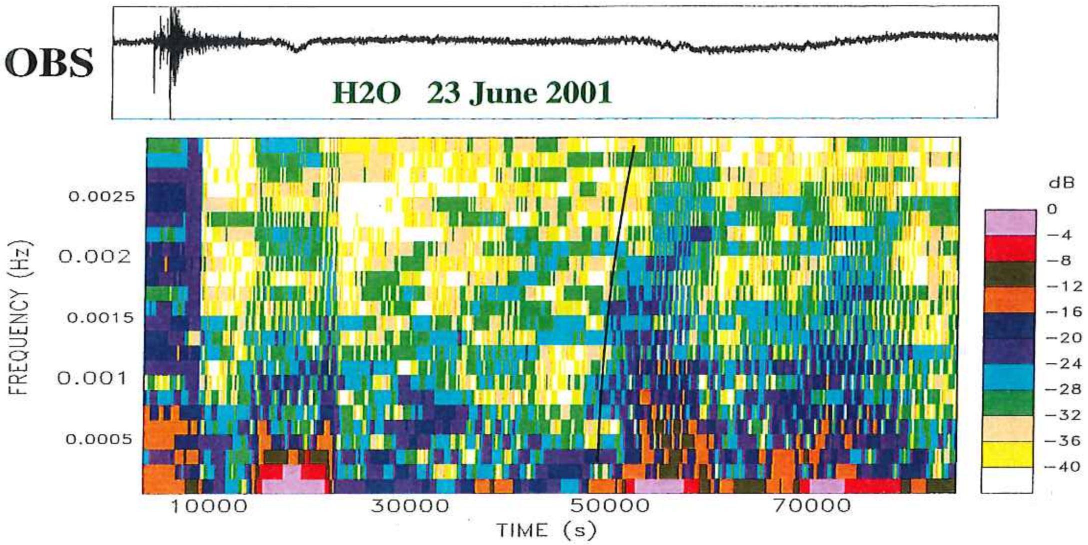
b. 13 October 2010

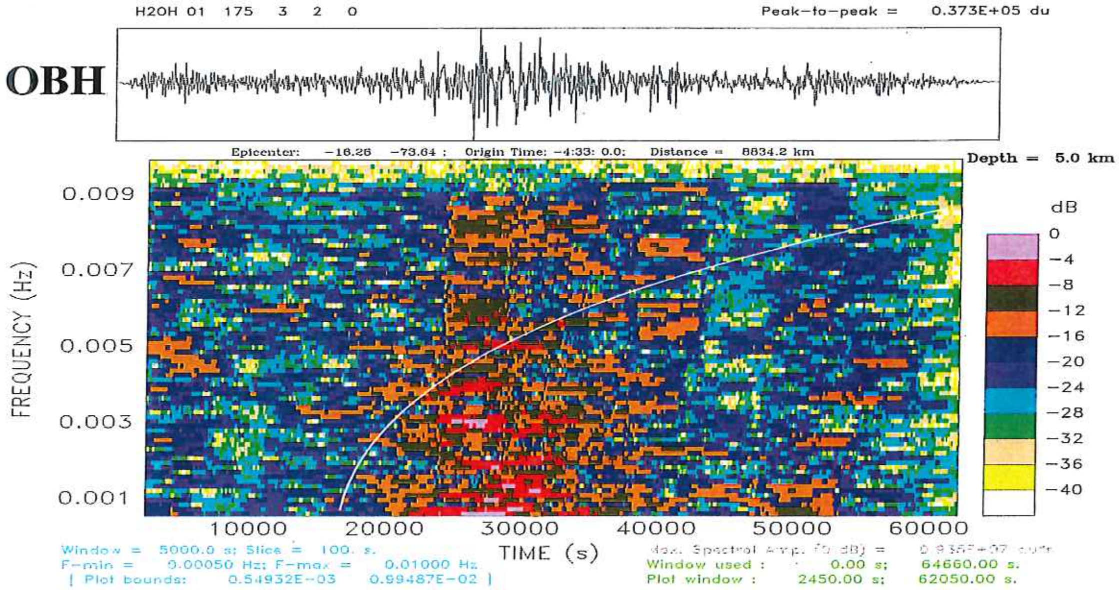


H2O: THE LONE TSUNAMI

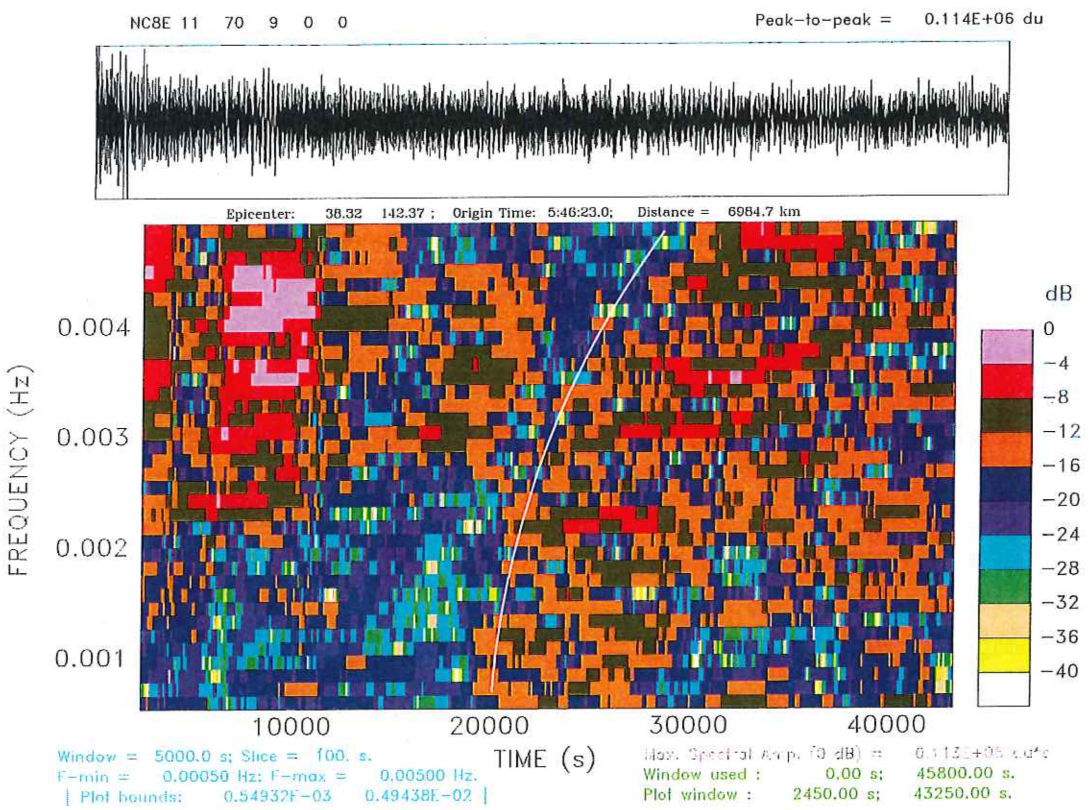
During its short operation, H2O recorded one significant tsunami: the Peruvian event of 23 June 2001.

While the event is clearly detected, both by the horizontal OBS and by the hydrophone, the recording characteristics are strongly non-linear, possibly raising doubt about the coupling of the instrument to the ocean bottom. At any rate, such signals cannot be quantified.





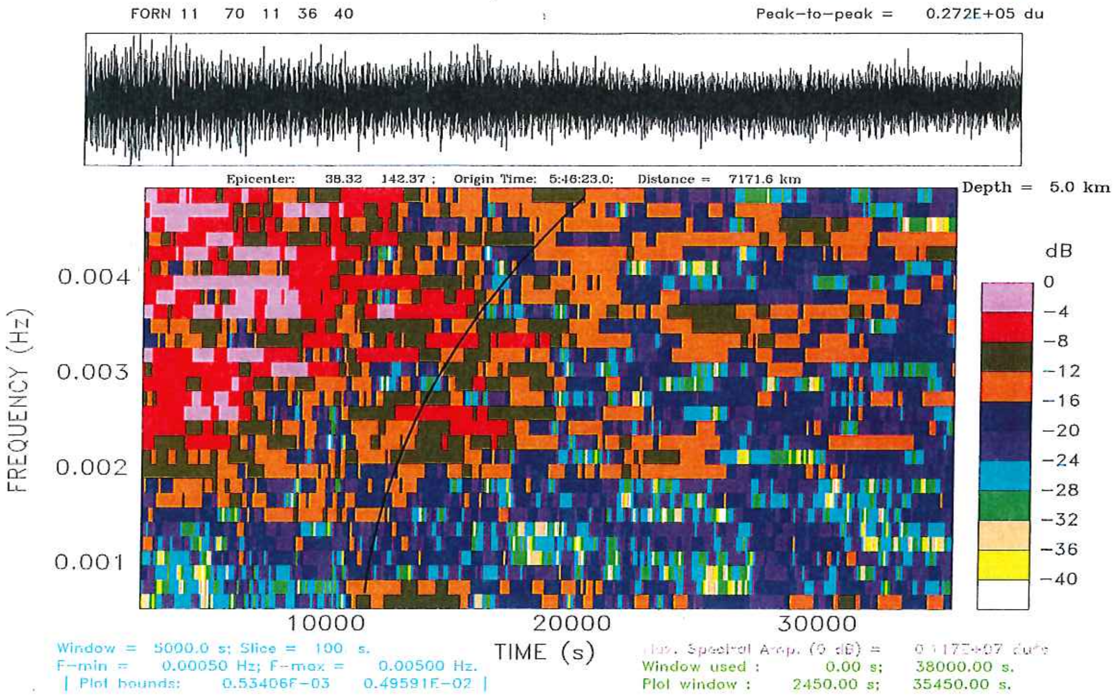
2011 TOHOKU TSUNAMI RECORDED at NEPTUNE



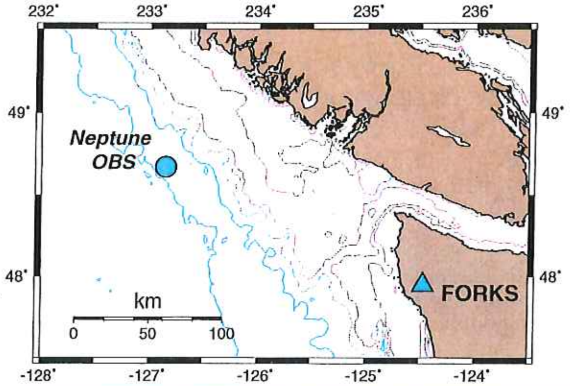
Inferred Moment: $M_0 = 3.3 \times 10^{29}$ **dyn*cm at 1130 s**

[NEIC *W* phase moment $= 4.0 \times 10^{29}$ dyn*cm]

2011 ONLAND RECORD at FORKS, Washington



Inferrred Moment: $M_0 = 5.3 \times 10^{29}$ dyn*cm at 1400 s



Note: "Least Bad station"

with relatively poor site:

5 km inland

35–km wide
continental shelf

YET, **General order-of-magnitude agreement with OBS value (and NEIC moment) validates argument that onland station functions as *de facto* O.B.S.**

CTBT HYDROPHONES

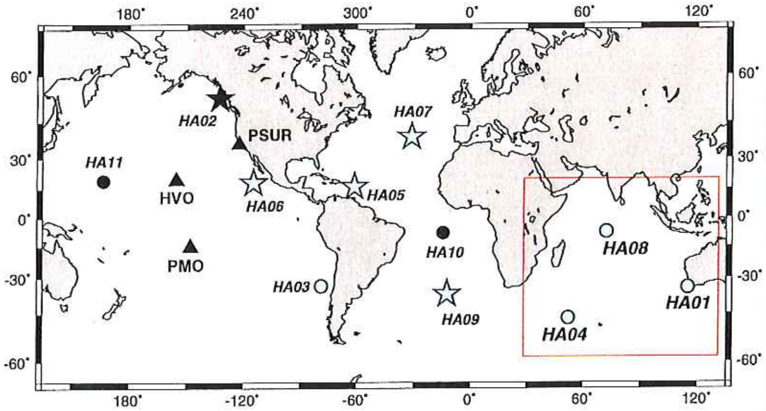
DETECT TSUNAMI

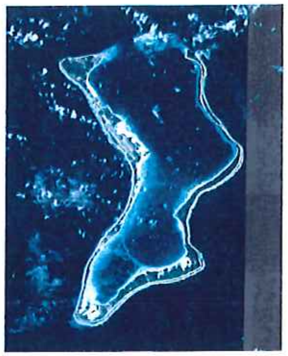
or

One Filter Too Many !

CTBT HYDROPHONE RECORDS

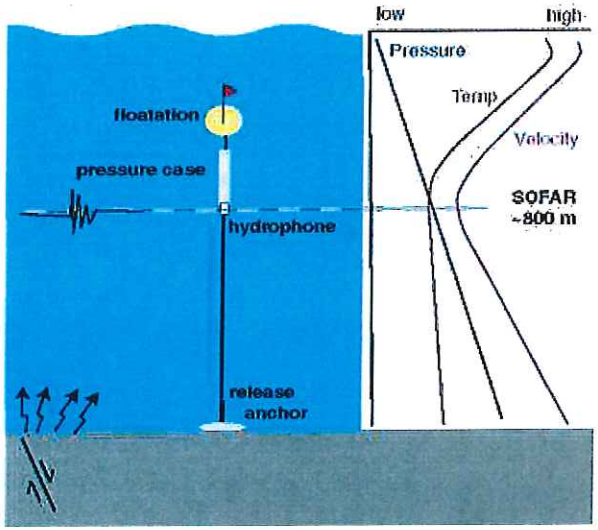
In the context of the CTBTO ("Test-Ban Treaty Organization"), the **I**nternational **M**onitoring **S**ystem comprises six hydrophone stations deployed in the SOFAR channel, including three in the Indian Ocean.





Diego Garcia, BIOT

Each station features several (3–6) sensors, allowing *beaming* of the array



[*M. Tolstoy,* Columbia University]

These instruments recorded not only the hydroacoustic (***"T"***) waves generated by the earthquake, but also its conventional seismic waves (Rayleigh), and most remarkably,

the tsunami itself.

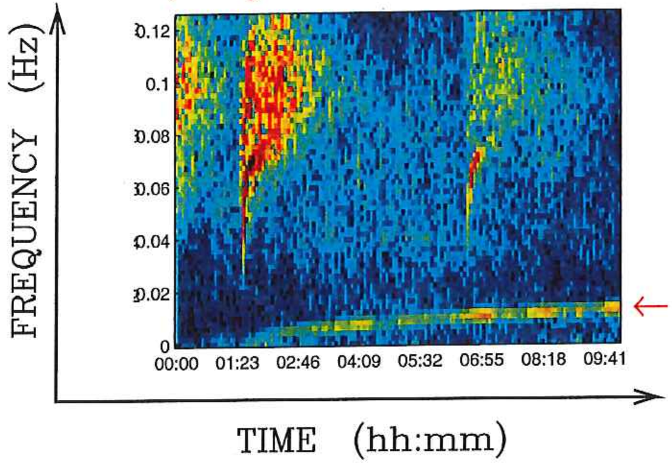
[*Okal et al.,* 2006]

TSUNAMI recorded by HYDROPHONES of the CTBTO

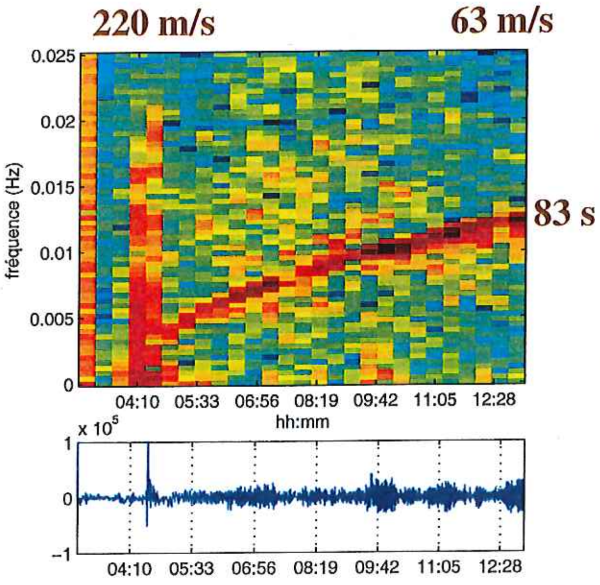
(hanging in ocean at 1300 m depth off Diego Garcia)

→ Instruments are severely filtered at infra-acoustic frequencies.

YET, they recorded the TSUNAMI!



← **Tsunami branch**



Note first ever observation of *DISPERSION* of tsunami branch at *VERY HIGH* [tsunami] frequencies in the far field

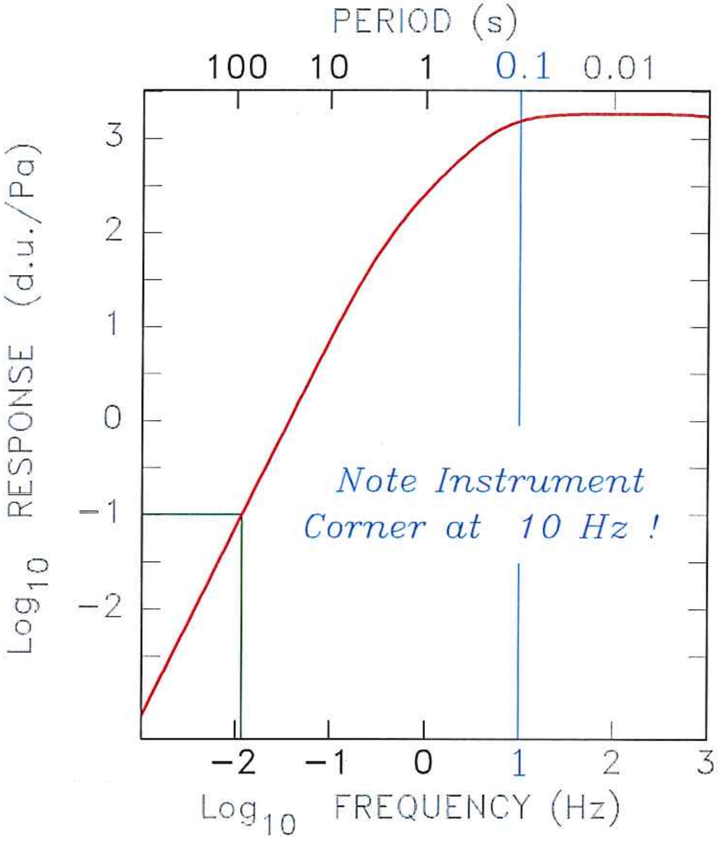
$$\omega^2 = g\,k \cdot \tanh(k\,h)$$

All of this on the high seas, unaffected by coastal response.

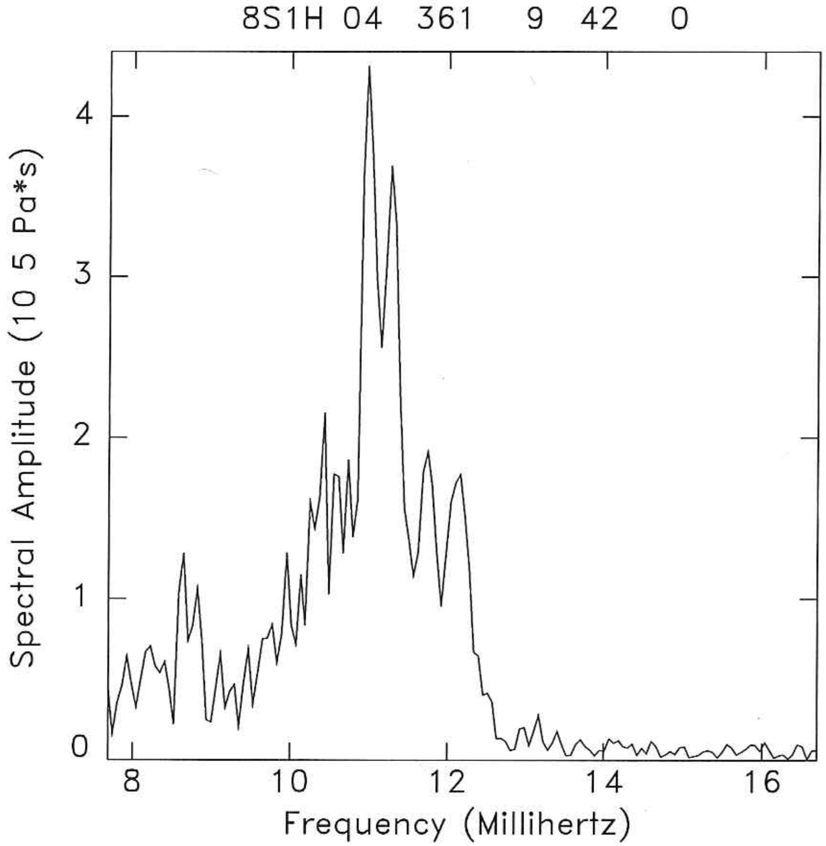
NOTE STRONG HIGH-FREQUENCY TSUNAMI COMPONENTS

Retrieving Seismic Moment from High-Frequency Tsunami Branch

- Use Hydrophone H08S1 from IMS at Diego-Garcia (BIOT)
- Deconvolve instrument and retrieve pressure spectrum



Note Instrument Corner at 10 Hz !



↓

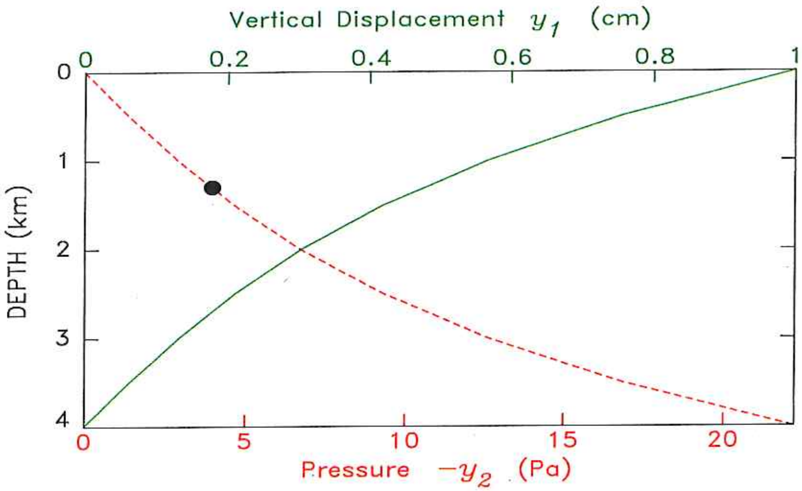
Note Instrument Response Down
by Factor 17,800 at 87 s.

$P(\omega) = 0.35$ MPa * s at 87 s

Retrieving Seismic Moment from High-Frequency Tsunami Branch (ctd.)

- Use *Okal* [1982; 2003; 2006] to convert overpressure at 1300 m depth (0.35 MPa*s) to surface amplitude η ,

outside classical Shallow-Water Approximation.



Structure of tsunami eigenfunction through water column outside S.W.A.

Find $\eta(\omega) = 78000$ cm*s at $T = 87$ s.

- Use *Haskell* [1952], *Kanamori and Cipar* [1974], *Ward* [1980], *Okal* [1988; 2003] in normal mode formalism to compute excitation coefficients.

Find $M_0 = 8 \times 10^{29}$ **dyn – cm**

ACCEPTABLE !

(Moment from Earth's free oscillations: **1 to** 1.2×10^{30} **dyn-cm**)

[*Stein and Okal*, 2005; *Nettles et al.*, 2005]

CONCLUSION: We understand ***QUANTITATIVELY*** the **excitation of the high-frequency components of the tsunami...**

TOAMASINA, Madagascar 26-DEC-2004

(a)

(b)

(c)

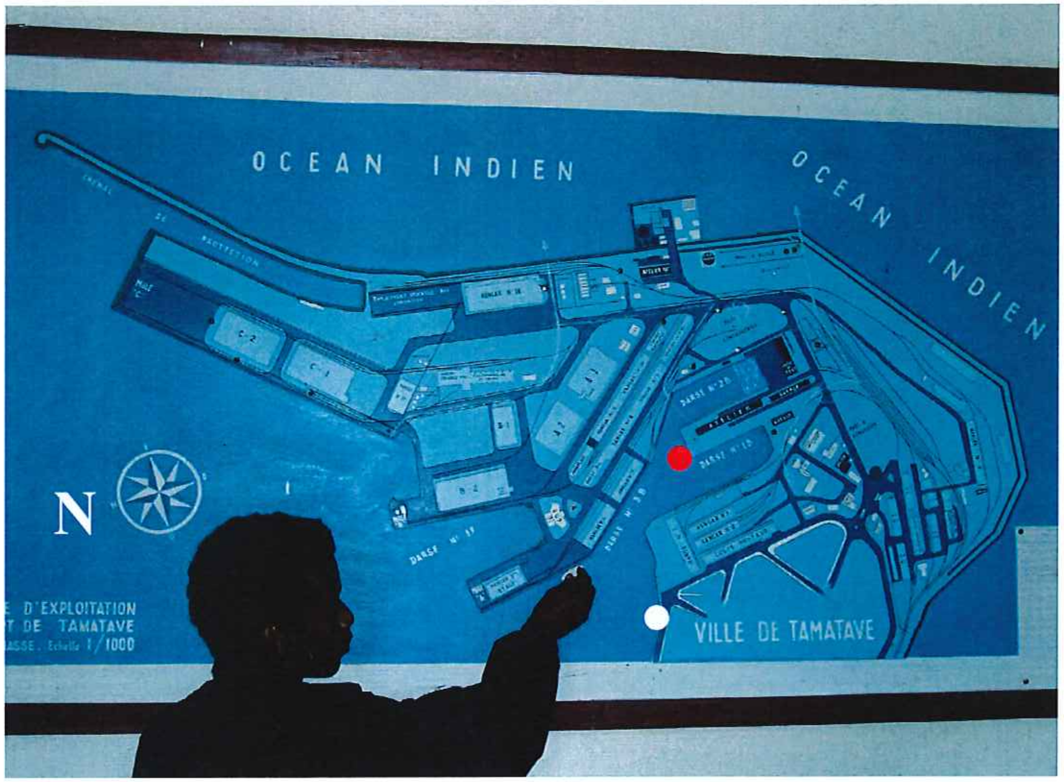


Figure 5. *(a):* The 50–m freighter *Soavina III* photographed on 2 August 2005 in the port of Toamasina. *(b):* Sketch of the port of Toamasina showing its complex geometry. *(c):* Captain Injona uses a wall map of the port (ESE at top) to describe the path of *Soavina III* from her berth in Channel 3B (pointed on map), where she broke her moorings around 7 p.m., wandering in the channels up to the location of the red dot (also shown on Frame *b*), before eventually grounding in front of the Water-Sports Club Beach (white dot; Site 17).

50–m SHIP BROKE MOORINGS around 19:00 (GMT+3), FOUR HOURS AFTER MAXIMUM WAVES

Preliminary modeling for Toamasina [Tamatave], Madagascar

[*D.R. MacAyeal,* pers. comm., 2006]

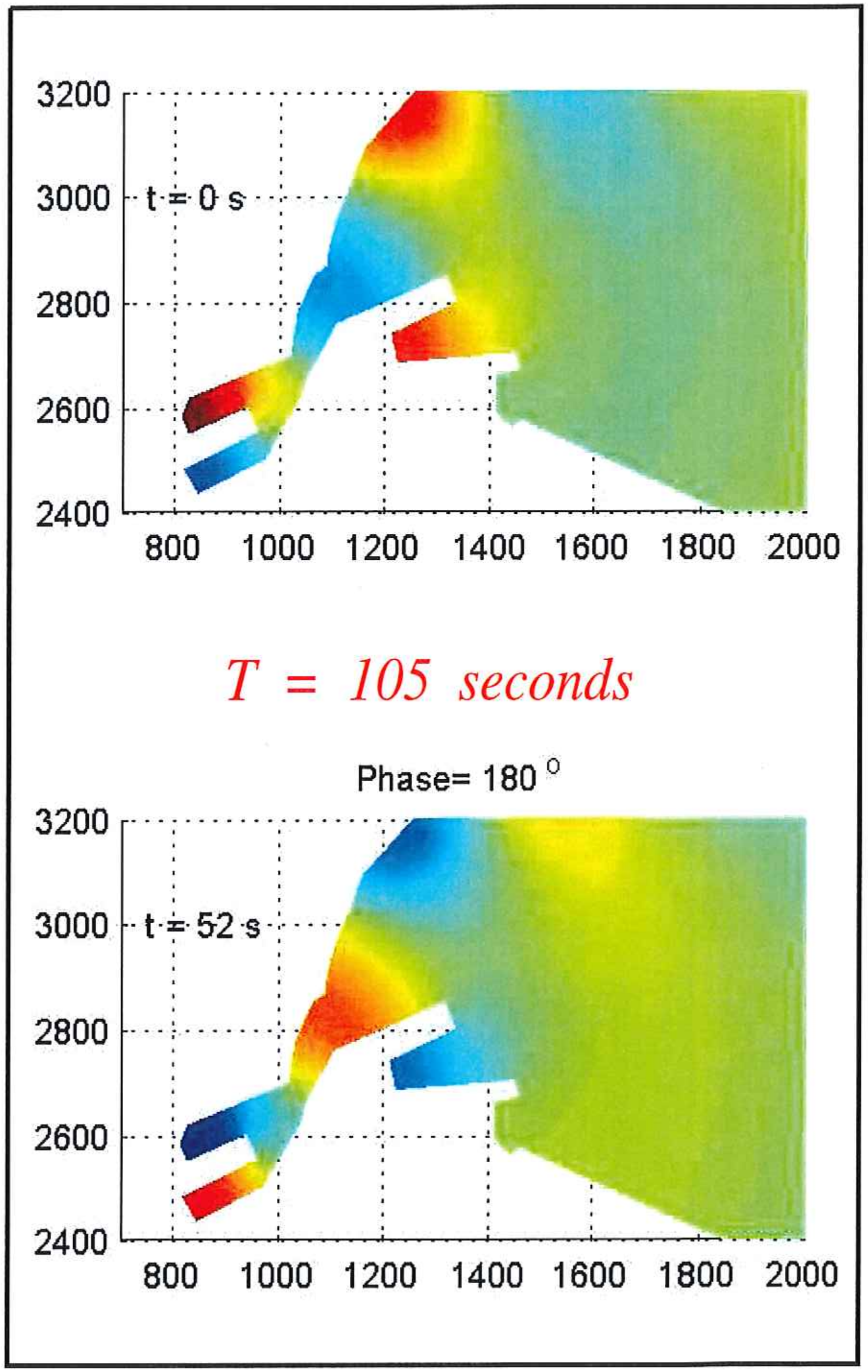
- Finite element modeling of the oscillations of the port of Toamasina reveals a fundamental mode of oscillation at $T = 105$ s, characterized by sloshing back and forth of water into the interior of the harbor, thus creating strong *currents* at the berth of *Soavina III*.

- At this period, the group velocity of the tsunami wave is found to be **97 m/s** for an average ocean depth of 4 km.

- This would correspond to an arrival at **16:55 GMT, or 19:55 Local Time**.

- This is in good agreement with the Port Captain's testimony

  "After 7 p.m. and lasting several hours"



T = 105 seconds

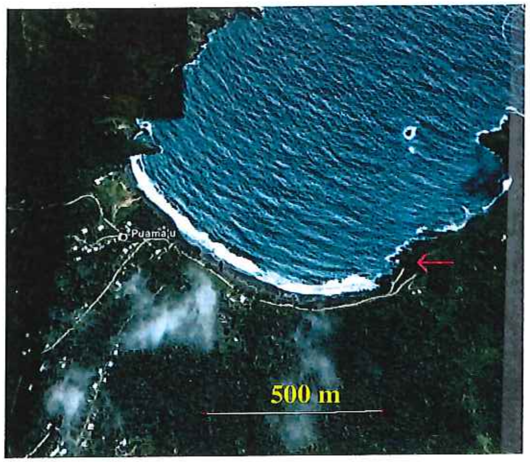
DELAYED HARBOR OSCILLATIONS ARE INDEED SYSTEMATIC

- **2004 Sumatra:**
  Le Port, Réunion
  Salalah, Oman
  Dar-es-Salaam, Tanzania
- **2006 Kuriles:**
  Crescent City, Calif.
- **2010 Chile:**
  Puamau, Marquesas
  Los Angeles, Calif.
- **2011 Tohoku:**
  Jayapura, Indonesia

They emphasize the subtle character of sounding an all-clear...

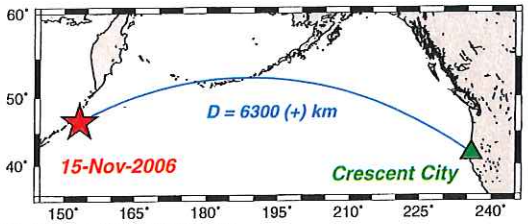
CHILE 2010: PUAMAU, Hiva Oa, Marquesas

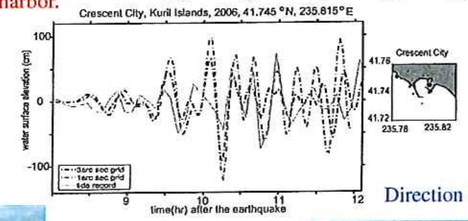
- In the village of Puamau, the Mayor reported that a launch from the supply ship *Ara Nui* was flung onto the wharf (*Arrow*; altitude 1.5 m) **around 2 p.m. local time,** *i.e.,* 2.5 hours after the all-clear, and 7 hours after the first arrivals.



2006 KURIL TSUNAMI DID SIGNIFICANT DAMAGE in CRESCENT CITY, California, TWO HOURS AFTER THE "MAIN" WAVES

- Harbor struck 8.5 hours after seismic O.T.
- Damage reached US$ 15 million
- Wave height reached 1.7 m (pk-to-pk) on local tide gauge
- Damage resulting from (i) beaming of some tsunami energy towards Northern California; (ii) non-linear amplification by bay and harbor.



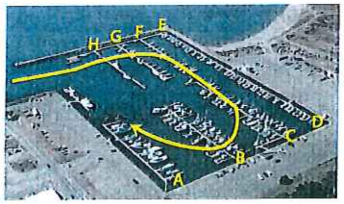


Tidal gauge record

[*Uslu*, 2007]

Damage to docks in harbor

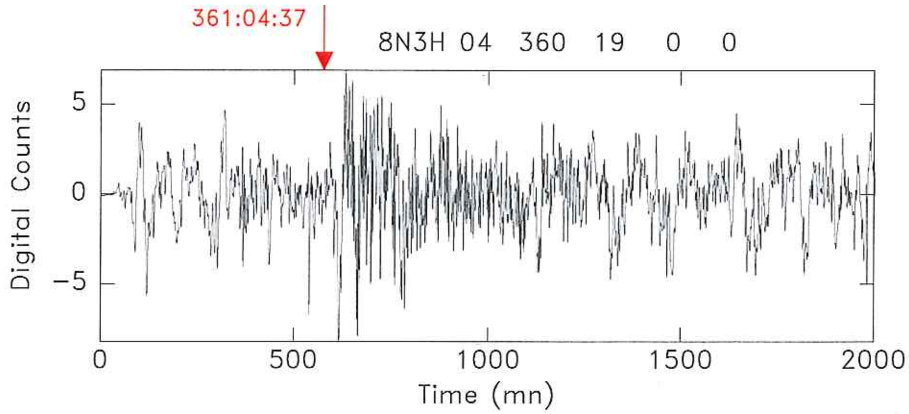
Direction of flow into harbor



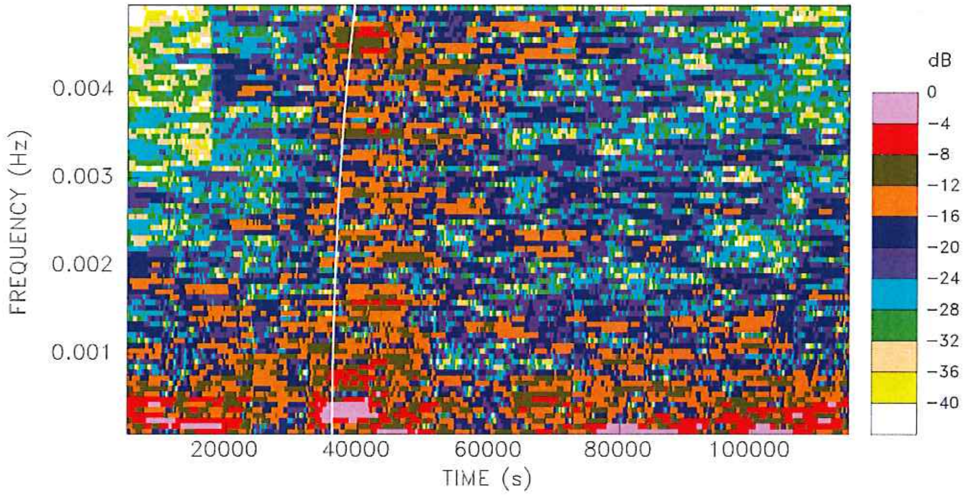
Docks H, G, F severely damaged

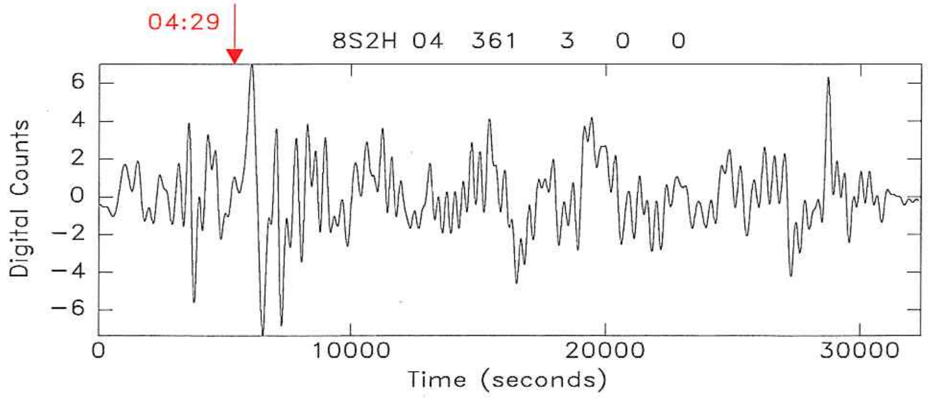
CLASSICAL TSUNAMI WAVES (S.W.A.) RECORDED BY HYDROPHONES

Diego Garcia, 26 December 2004

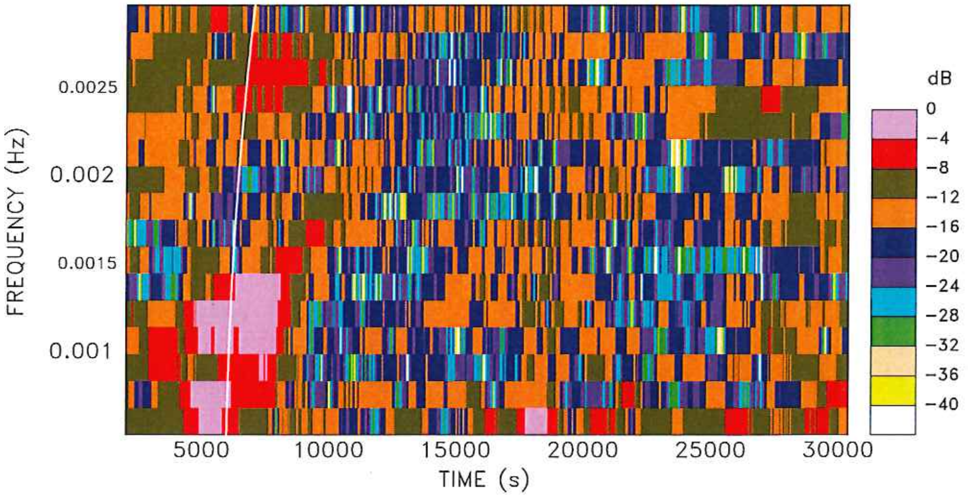


Northern Triad





Southern Triad

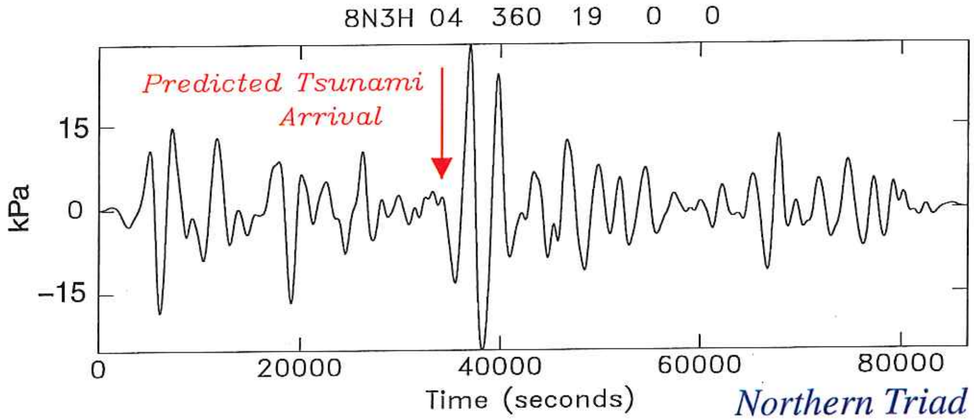


→ These long-period components (≥ 1000 s) are well recorded by the hydrophones.

COULD THEY BE QUANTIFIED ?

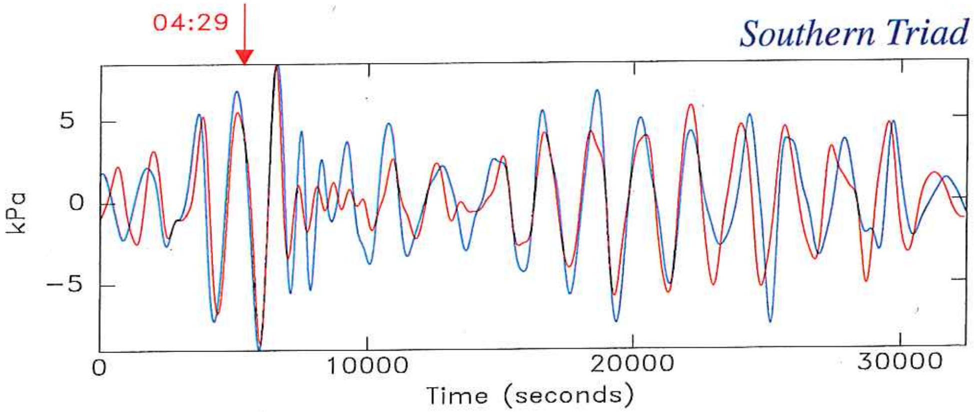
ATTEMPTING TO QUANTIFY LONG-PERIOD ($T \approx 3000$ s) TSUNAMI RECORDED BY DIEGO GARCIA HYDROPHONES

DECONVOLVED, Tmax = 10000. s; Tmin = 800. s.



Northern Triad

Southern Triad



HOWEVER, **the resulting overpressures (15 to 50 kPa peak-to-peak) are much too large as they would require tsunami amplitudes of 3 to 10 meters on the high seas.**

This is probably due to digital noise introduced by the extremely low response of the instrument at such long periods (10,000 times the filter's corner).

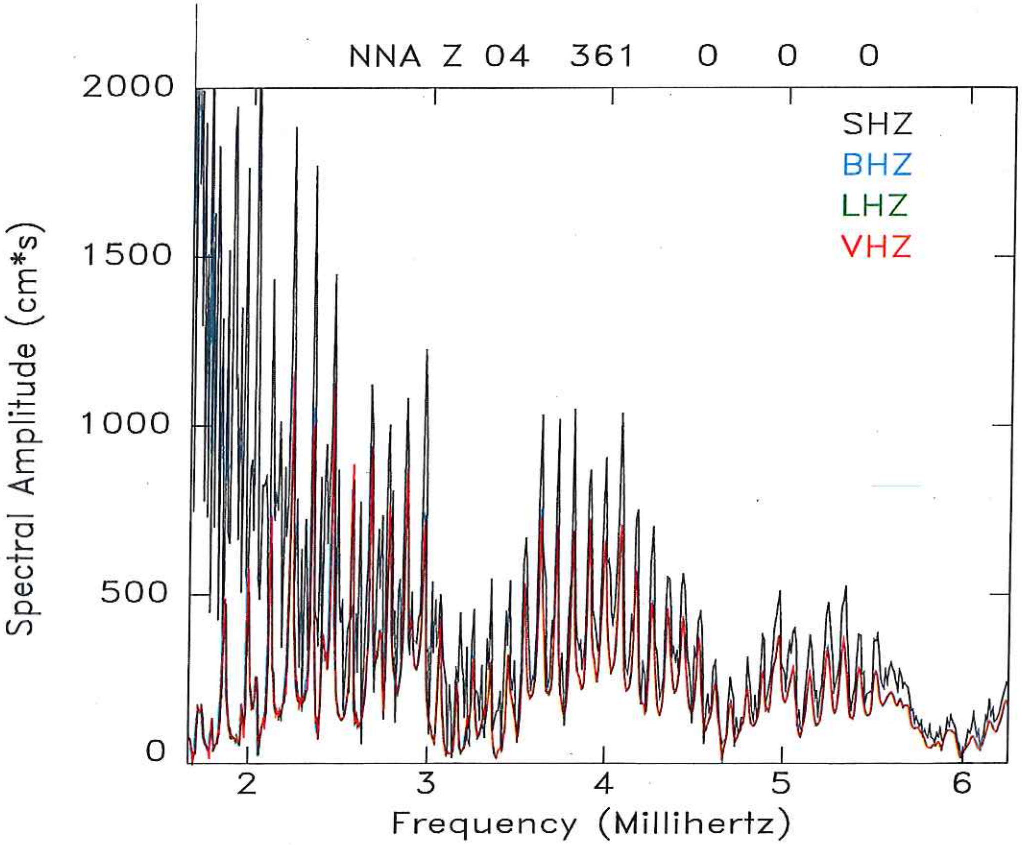
AFTER FILTERING, THE TSUNAMI SIGNAL SHOULD BE LESS THAN **1** *DIGITAL UNIT...*

THIS SUGGESTS AN INTERESTING TEST

What happens if we try to recover the Earth's normal modes from a Short-Period Seismometer ?

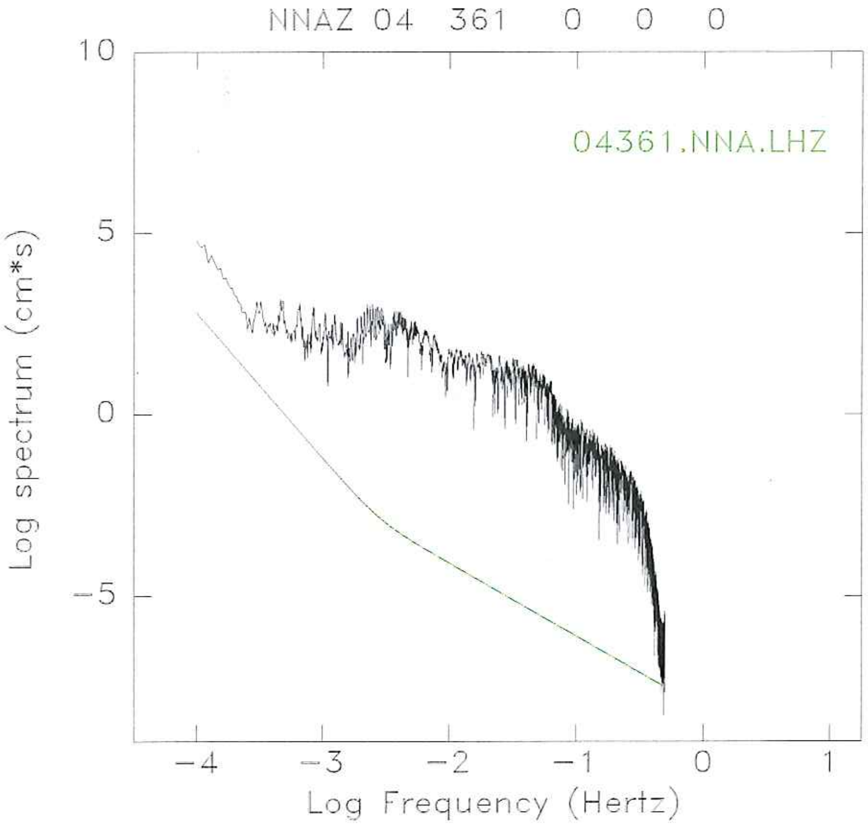
- We examine the spectra of the Sumatra earthquake (and the background noise) on VHZ, LHZ, BHZ and SHZ channels at the same station (NNA; Ñaña, Perù).

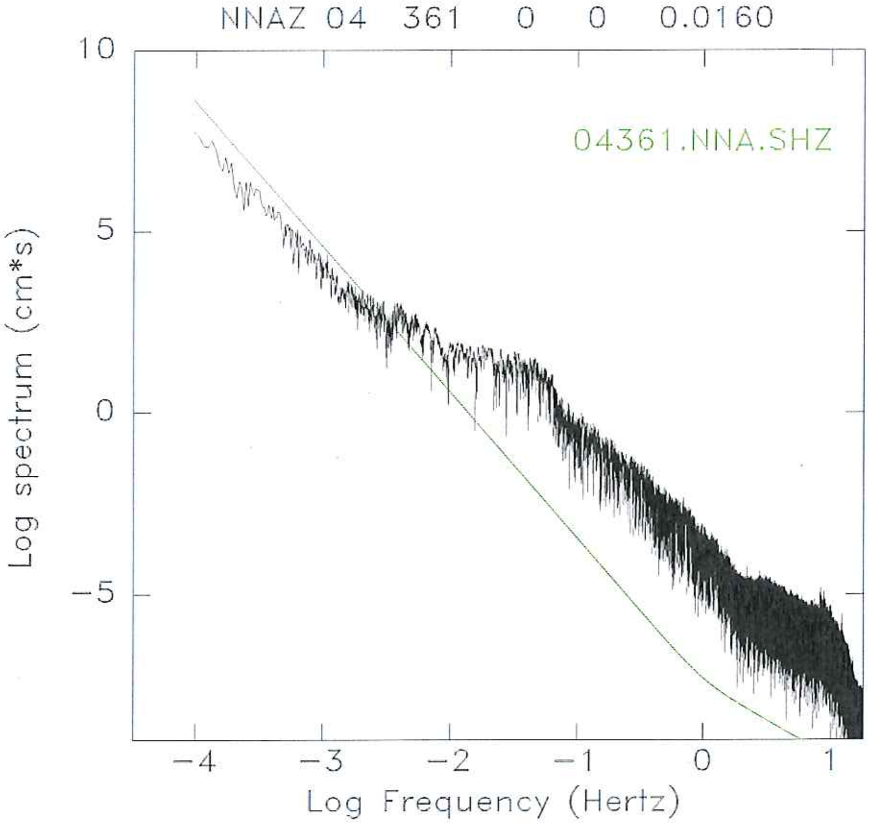
- We find that **VHZ**, **LHZ**, **BHZ**, *which share the same corner frequencies,* give exactly the same results (which allows the quantification of the modes), **while SHZ gives a beautiful spectrum (down to 2.5 mHz), but with spectral amplitudes too large by a factor ~ 1.5 .**



- We trace this effect to the fact that, at frequencies $f \leq 10$ mHz, the response of the SHZ instrument is so low, that an Earth's mode would be recorded with a time-domain amplitude of less than one digital unit.
- The spectral amplitude of a harmonic oscillation recorded with an amplitude of one digital unit is shown as the green line on the figures below.
- The resulting non-linearity introduced by this digital noise gives rise to a systematic bias overestimating the true spectral amplitude of the signal.

This is probably the origin of the excessive amplitude of the low-frequency components of the 2004 tsunami as recorded on the CTBT hydrophones.





FROM GROUND UP ...

or

Could Ionospheric Seismology

Help Tsunami Warning ?

IONOSPHERIC RADAR DETECTS SEISMIC RAYLEIGH WAVE 150 km UP !

Tokachi Oki — 16 May 1968

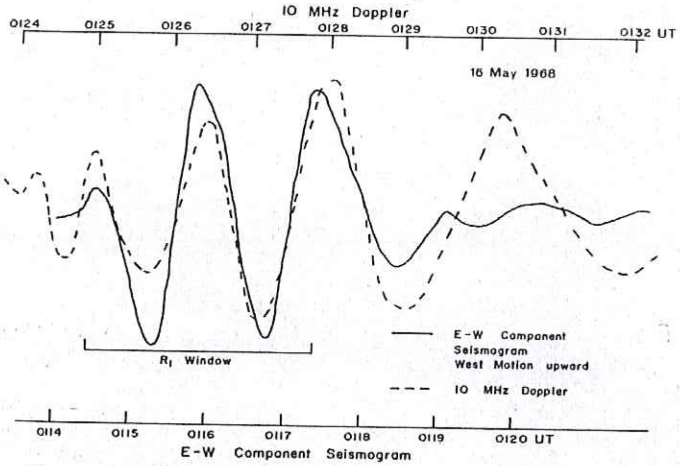
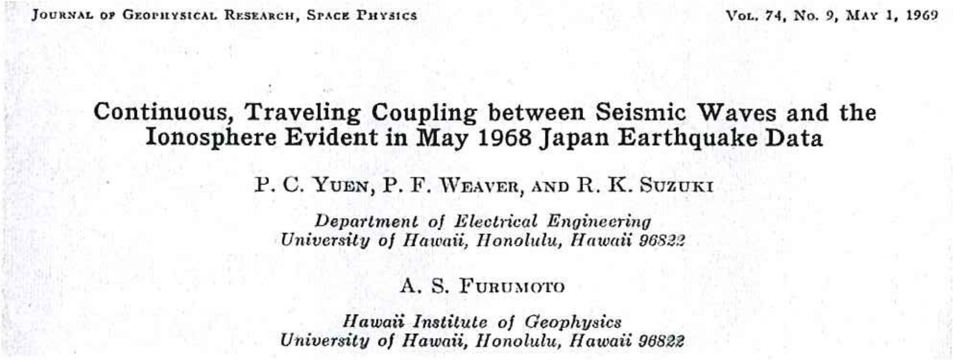


Fig. 5. Comparison of Doppler and longer-period seismogram data.



Journal of Geophysical Research, Space Physics Vol. 74, No. 9, May 1, 1969

Continuous, Traveling Coupling between Seismic Waves and the Ionosphere Evident in May 1968 Japan Earthquake Data

P. C. Yuen, P. F. Weaver, and R. K. Suzuki

Department of Electrical Engineering
University of Hawaii, Honolulu, Hawaii 96822

A. S. Furumoto

Hawaii Institute of Geophysics
University of Hawaii, Honolulu, Hawaii 96822

Kuriles, 11 August 1969

Detected in Hawaii

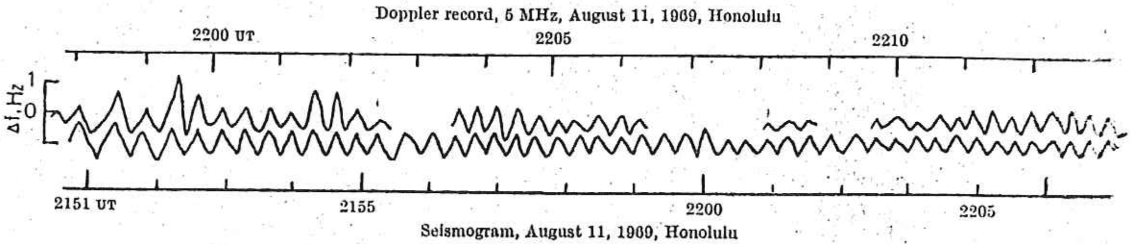


Fig. 2. Comparison of 5 MHz Doppler record and seismogram with expanded time scale.

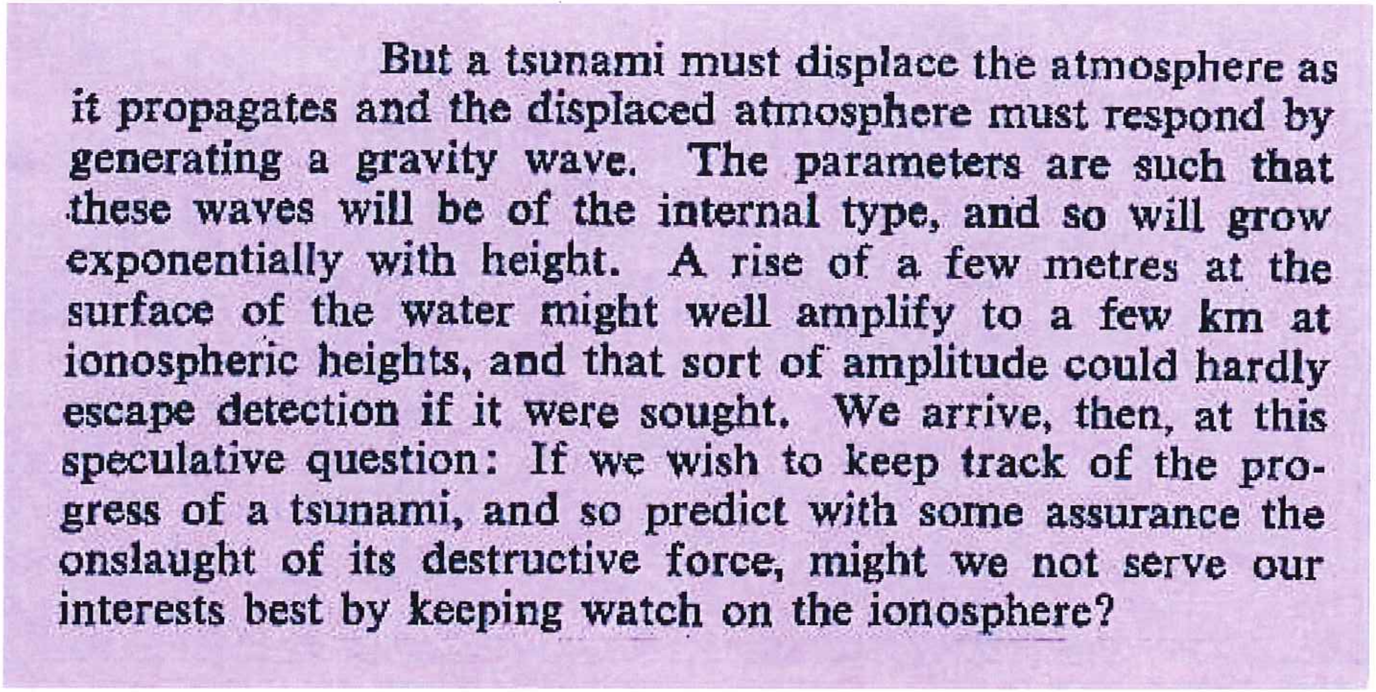
WHY and HOW ?

- Atmosphere is not vacuum... and so, Rayleigh waves do not stop at a free boundary, but rather are continued upwards in the form of an pseudo-gravity wave, whose phase velocity is forced to that of the main Rayleigh wave.

- Energy density decays exponentially upwards, but since *material density decays faster,* wave amplitude can actually **increase with height !** Radar detects variation in TEC due to perturbation of ionosphere.

WHAT ABOUT TSUNAMIS ?

- *Hines* [1972] speculates that the concept could be extended to tsunamis.



But a tsunami must displace the atmosphere as it propagates and the displaced atmosphere must respond by generating a gravity wave. The parameters are such that these waves will be of the internal type, and so will grow exponentially with height. A rise of a few metres at the surface of the water might well amplify to a few km at ionospheric heights, and that sort of amplitude could hardly escape detection if it were sought. We arrive, then, at this speculative question: If we wish to keep track of the progress of a tsunami, and so predict with some assurance the onslaught of its destructive force, might we not serve our interests best by keeping watch on the ionosphere?

Peltier and Hines [1976] elaborated on the subject, but

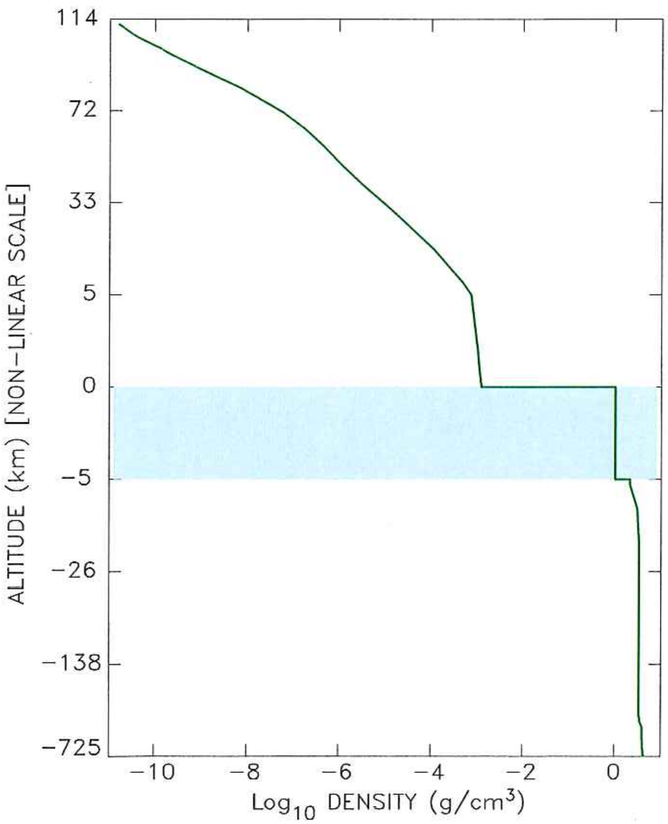
IT TOOK CLOSE TO 30 YEARS TO OBSERVE...

STRUCTURE of the TSUNAMI WAVE in the ATMOSPHERE

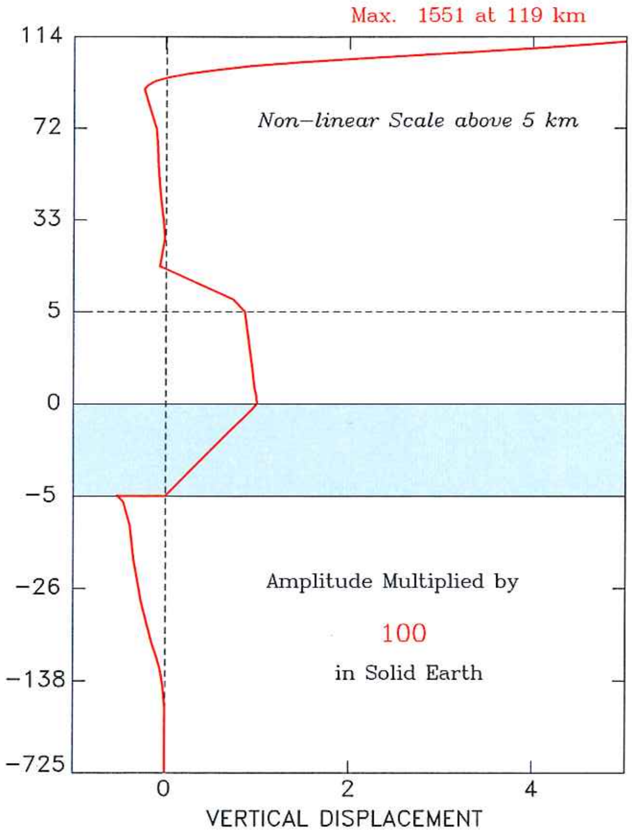
→ We compute the continuation of the tsunami wave both in the solid Earth and in the atmosphere using the generalized code "***HASH***" by *Harkrider et al.* [1974].

- Flat-layered model
- 5–km deep ocean
- Period ≈ 1000 seconds

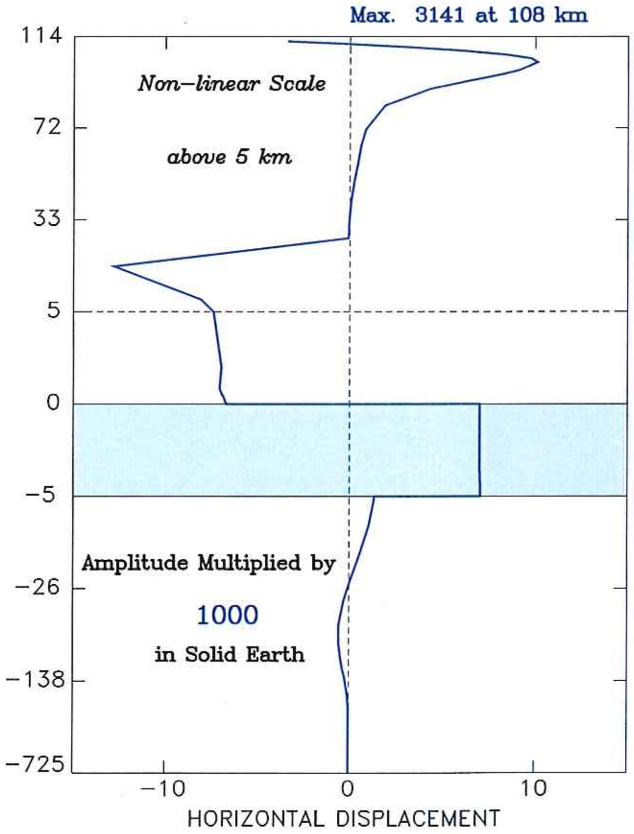
Density ρ



Vertical Amplitude



Horizontal Amplitude

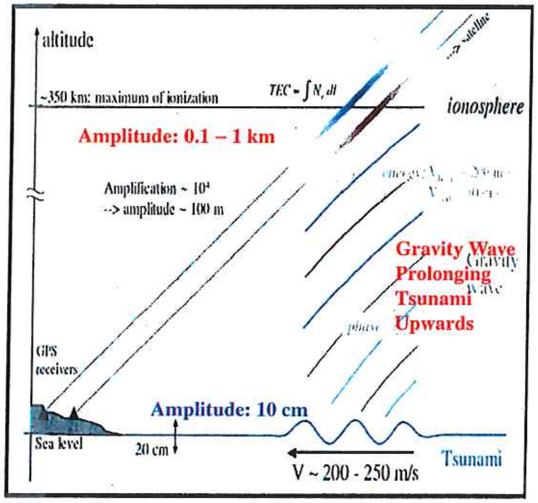


TOWARDS DIRECT DETECTION of a TSUNAMI on the HIGH SEAS

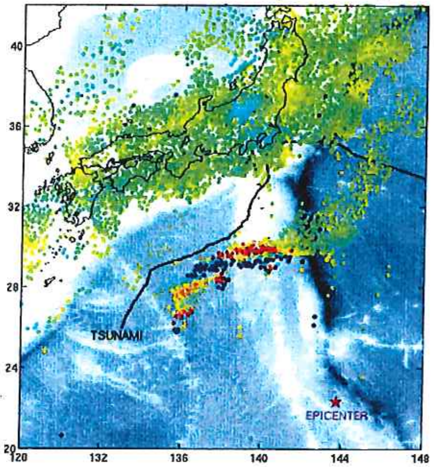
3. TSUNAMI DETECTION by GPS IONOSPHERIC MONITORING

J. Artru, H. Kanamori (Caltech); M. Murakami (Tsukuba); P. Lognonné, V. Dučić (IPG Paris) -- (2002)

- Ocean surface is not free boundary — Atmosphere has finite density
- Tsunami wave *prolonged* into atmosphere; *amplitude increases* with height.
- Perturbation in ionosphere (h = 150–350 km) detectable by GPS.



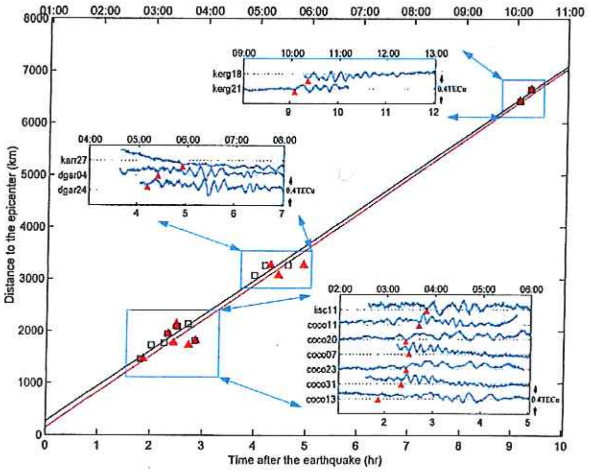
28 MAR 2000 -- 90 mn after earthquake

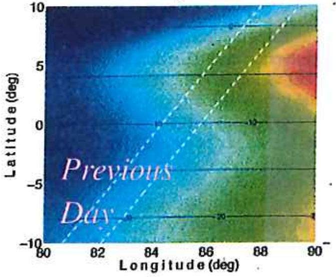


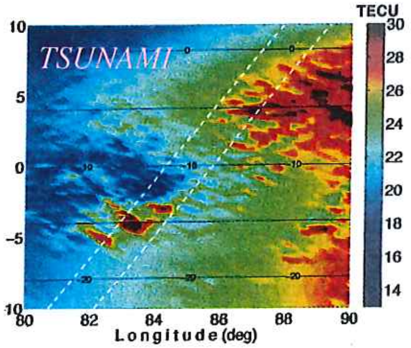
SUMATRA 2004

Perturbations detected in ionospheric **T**otal **E**lectron **C**ontent [*Liu et al.,* 2006]

Successfully modeled by *Occhipinti et al.* [2006].







Upon passage of the tsunami, the ionosphere may **glow in the visible...**

A map of this phenomenon was obtained by photography during night-time hours at Mauna Kea Observatory, Hawaii as the 2011 Tohoku tsunami was propagating across the Pacific Ocean [*Makela et al.*, 2011].

L13305 MAKELA ET AL.: IONOSPHERIC AIRGLOW TSUNAMI SIGNATURE **L13305**

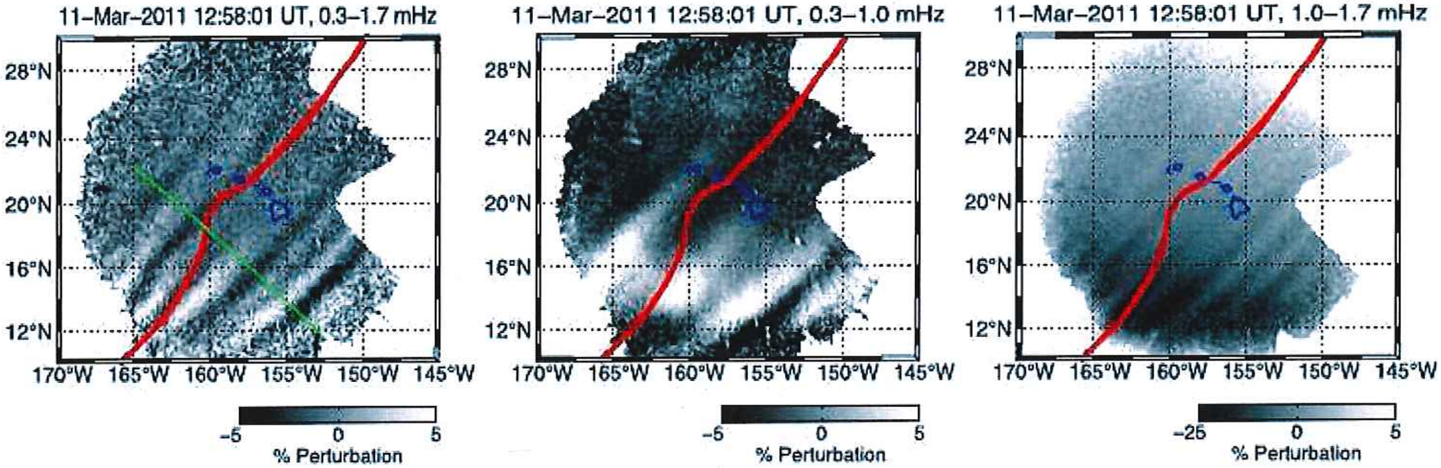


Figure 1. Example of 630.0-nm images processed using length-8 FIR filters with passbands of (left) 0.3–1.7 mHz, (middle) 0.3–1.0 mHz to highlight the 26.2-min period waves, and (right) 1.0–1.7 mHz to highlight the 14.2-min period waves. The red line in each image indicates the tsunami location at the time of the image. The green line in Figure 1 (left) indicates the line from which intensities were taken to construct Figure 2.

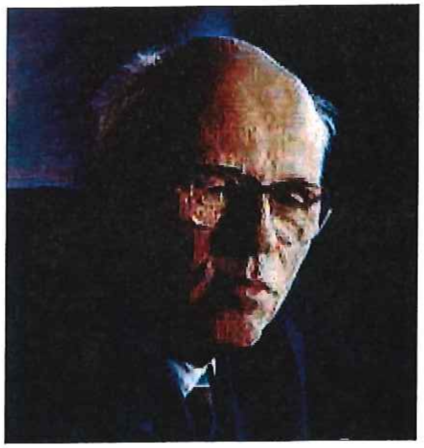
Detection of such visible perturbations may in the future be incorporated in tsunami warning procedures.

FROM AIR DOWN ...

or

Seismometers Listening

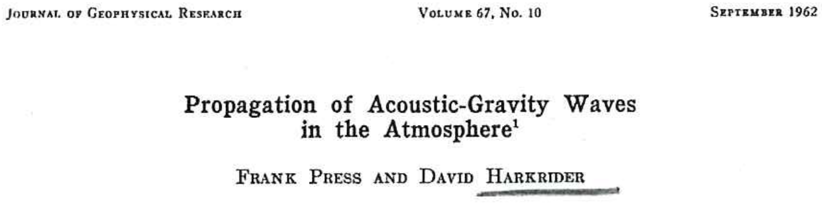
to Loud Sound !



SEISMOMETERS RECORD ATMOSPHERIC WAVES

Operation "Царь Бомба"

23 October 1961



JOURNAL OF GEOPHYSICAL RESEARCH VOLUME 67, No. 10 SEPTEMBER 1962

Propagation of Acoustic-Gravity Waves in the Atmosphere[1]

FRANK PRESS AND DAVID HARKRIDER

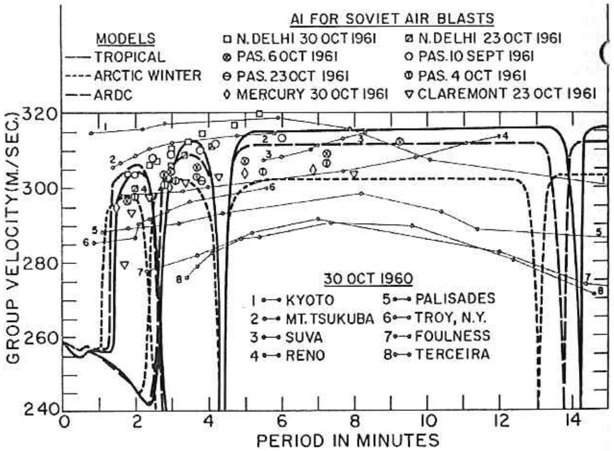


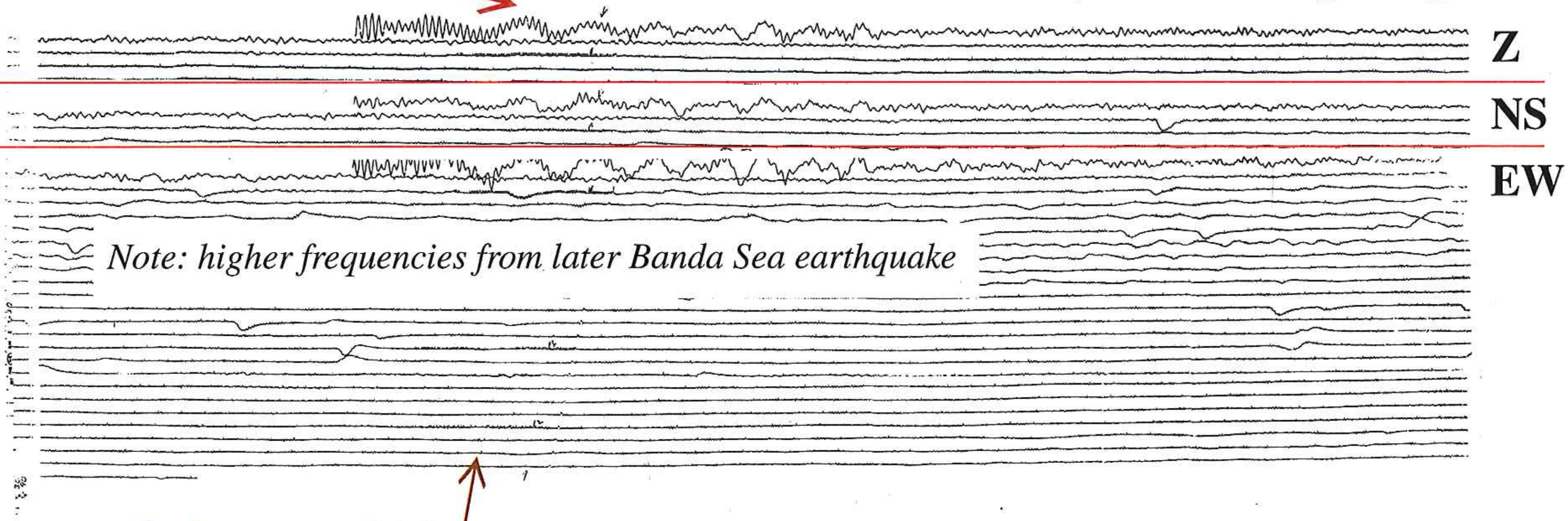
Fig. 18. Comparison of experimental group velocities for A_1 waves from Novaya Zemlya explosions with standard and extreme ARDC models. Data curves 1 to 8 from *Donn and Ewing* [1962].

Novaya Zemlya

25 Megatons

1st passage of Acoustic-Gravity Wave (A_1)

PASADENA, Press-Ewing Long-Period



Note: higher frequencies from later Banda Sea earthquake

2nd passage (A_2)

[Courtesy *D.G. Harkrider*]

SEISMOMETERS RECORD BOLIDE EXPLOSION

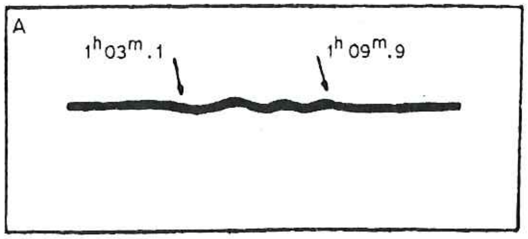
Tungunska (Siberia)

SOURCE PARAMETERS OF THE SIBERIAN EXPLOSION OF JUNE 30, 1908, FROM ANALYSIS AND SYNTHESIS OF SEISMIC SIGNALS AT FOUR STATIONS

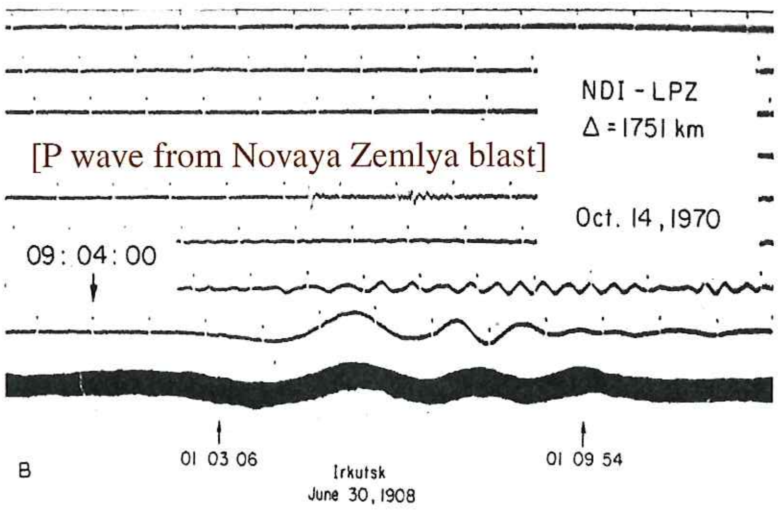
ARI BEN-MENAHEM

Phys. Earth Planet. Int., **11**, 1–35, 1975

30 June 1908 (n.s.)



Irkustsk, 1908
Air Wave



[P wave from Novaya Zemlya blast]

NDI (Lop Nor), 1970

Rayleigh
Air Wave

Irkustsk, 1908

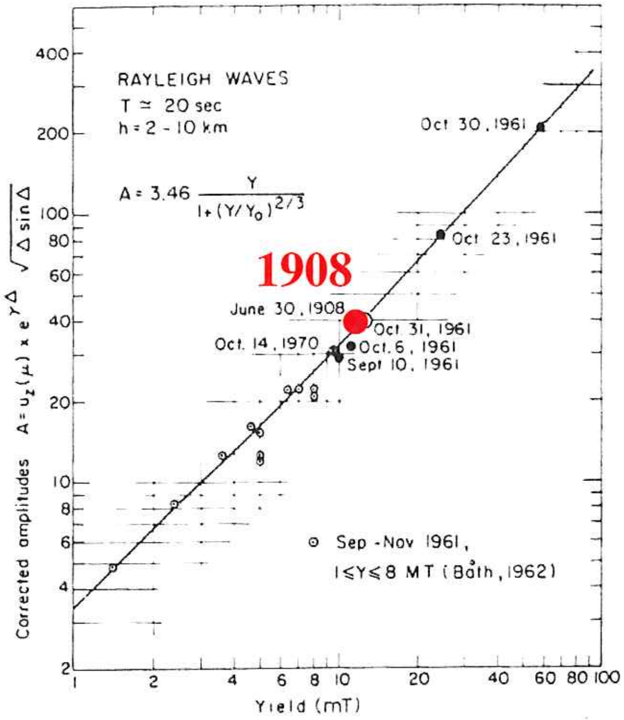
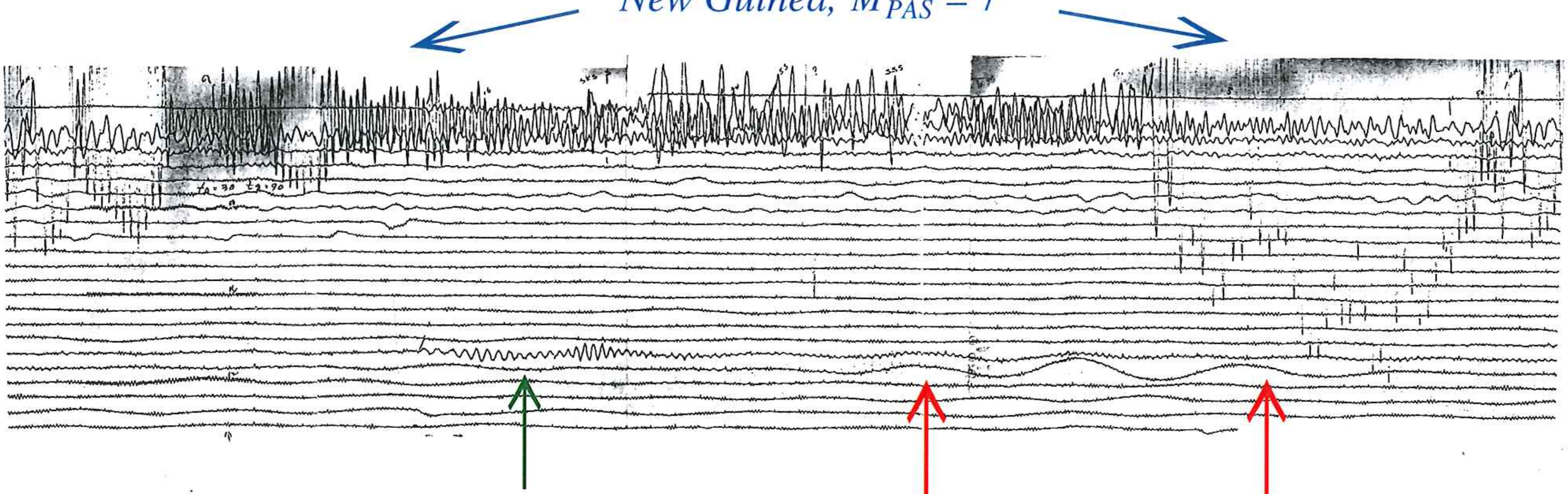


Fig. 12. Dependence of the Rayleigh-wave amplitude at 20 sec on the yield of the air explosion.

Yield from Body- and Rayleigh-wave modeling: **12.5 Megatons**

MYSTERY WAVES RECORDED ON L.P. SEISMOMETERS

PASADENA 02 MAR 1959 — *Press Ewing East-West*



New Guinea, $M_{PAS} = 7$

Banda Sea, $M = 6$

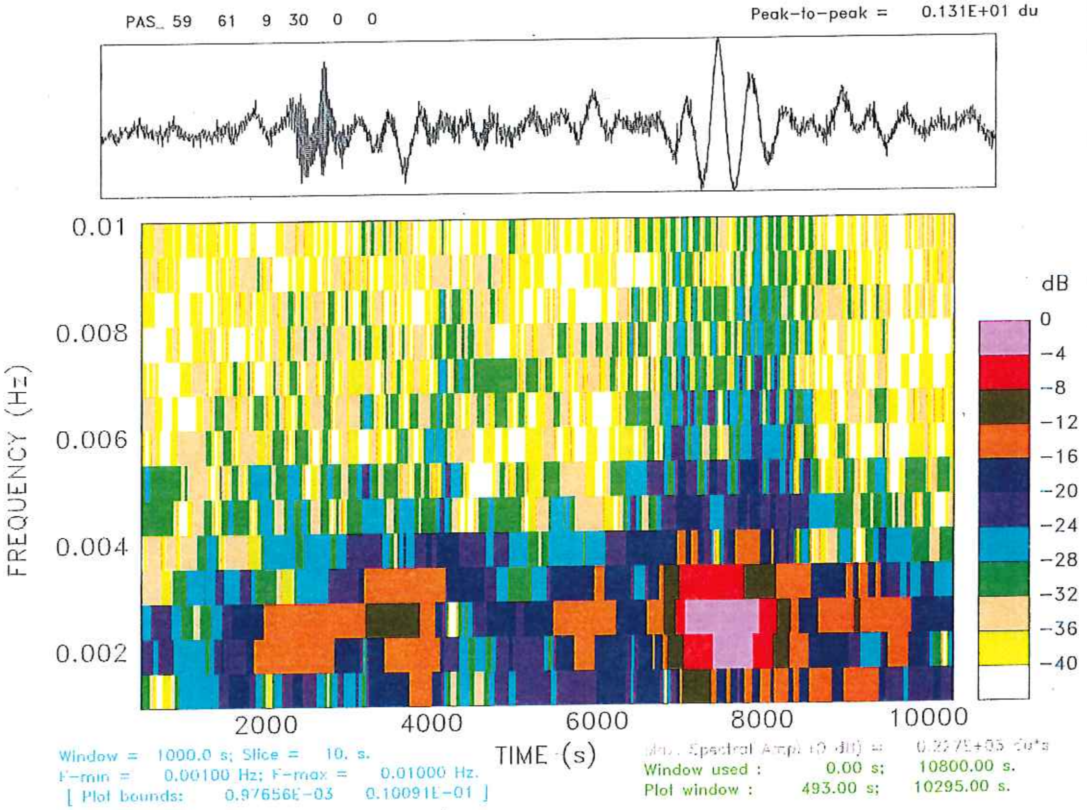
MYSTERY WAVE

The "Mystery Wave" is an extremely long-period oscillation ($T \approx 500$ s) recorded on all L.P. instruments at Pasadena, but absent at other stations.

THE MYSTERY WAVE (ctd.)

PASADENA — *02 MARCH 1959*

The "Mystery Wave" is reminiscent of atmospheric waves generated by large explosions (volcanic or man-made), nut none is known at the time.



IT IS NOT RECORDED ANYWHERE ELSE

THE MYSTERY WAVE : MORNING GLORY

- **2004:** *Tsai, Kanamori and Artru* crack the case of the mystery waves, showing that they are non-linear internal gravity waves, trapped by a temperature inversion inside the Los Angeles Basin, where they propagate at very slow speeds (5 to 25 m/s).

The morning glory wave of southern California

Victor C. Tsai, Hiroo Kanamori, and Juliette Artru
Seismological Laboratory, California Institute of Technology, Pasadena, California, USA

Received 21 May 2003; revised 26 September 2003; accepted 14 November 2003; published 13 February 2004.

TSAI ET AL.: LOS ANGELES MORNING GLORY WAVE

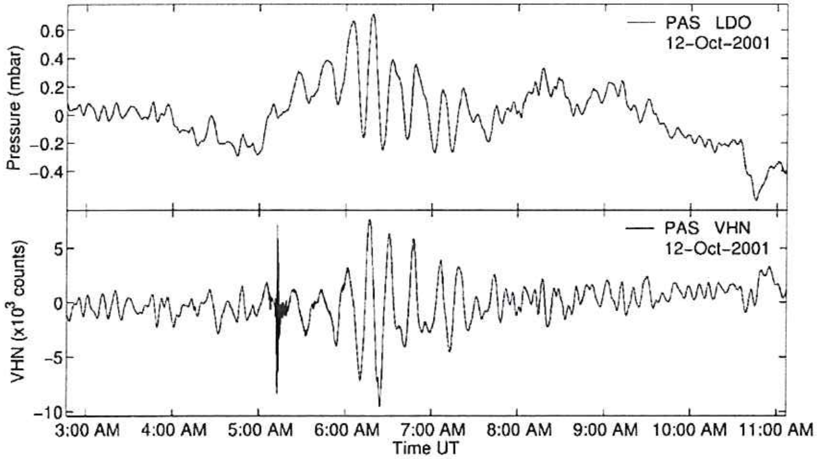
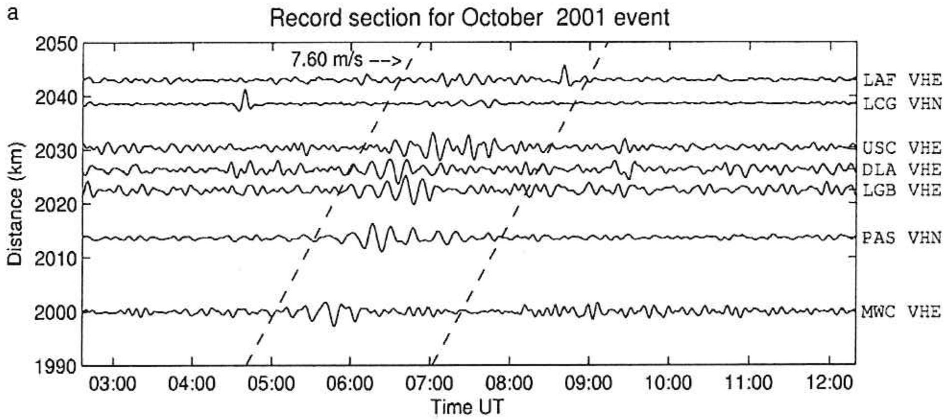


Figure 1. (top) Barograph record and (bottom) seismogram (very broadband channel) from station Pasadena for the 12 October 2001 event. The signals are correlated well in the ~1000 s period range. As a further note, there is an earthquake in Figure 1 (bottom) at around 0510 LT. For further information, refer to section 4.2.

J. Geophys. Res. **109,** *(B2),* B02307, 11 pp., 2004.



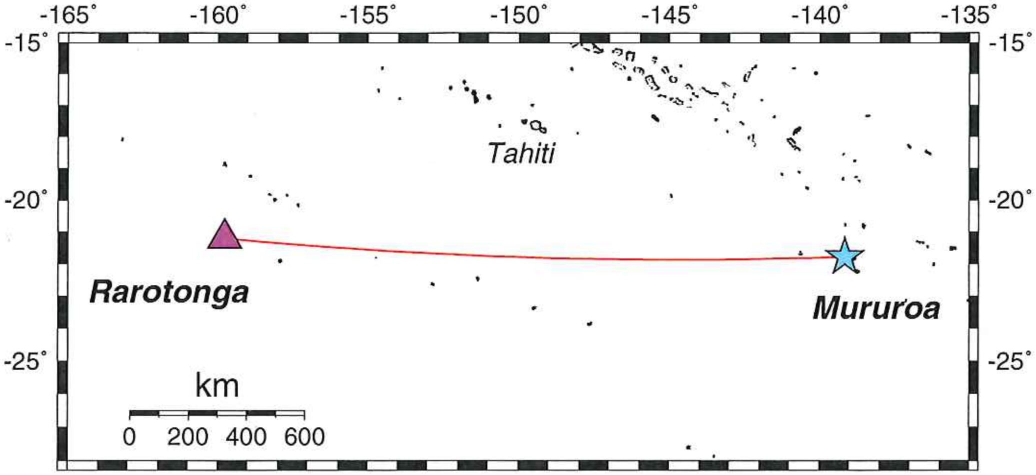
- This phenomenon was observed in Northern Australia, where it was called the **"Morning Glory"** and studied by *Christie et al.* [1978 and *Clarke et al.* [1981].

FROM AIR TO WATER TO GROUND

More Bombs at Sea

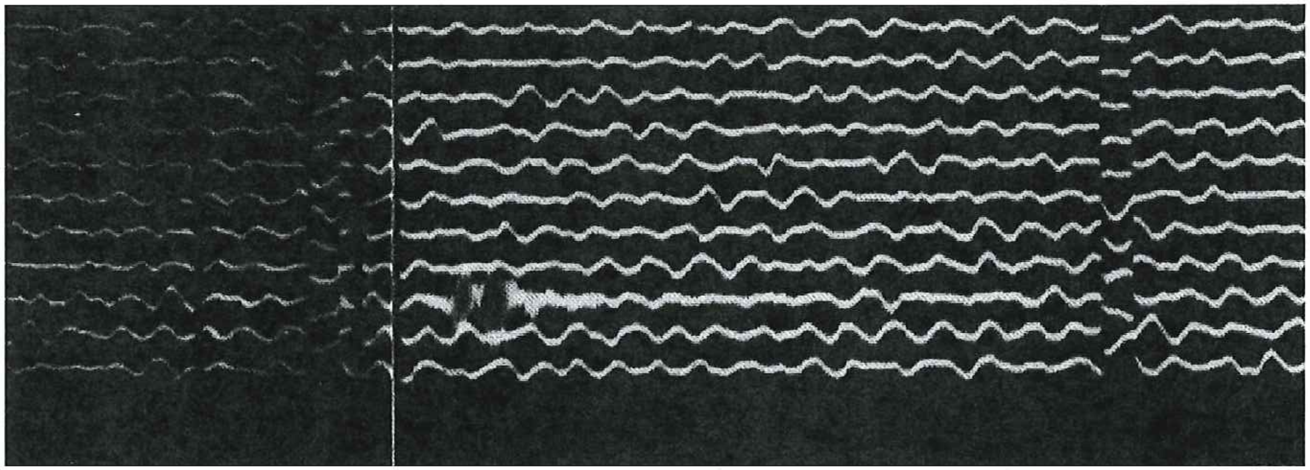
SEISMOMETERS DETECT *T* PHASES FROM ATMOSPHERIC NUCLEAR EXPLOSIONS

"PROCYON", *Mururoa Atoll, 08 SEPTEMBER 1968*



1.28 Megatons

Rarotonga, Cook Islands, WWSSN SPZ, Original magnification × 6250



Note large amplitude (26 μm/s) but very short duration (2.7 s).

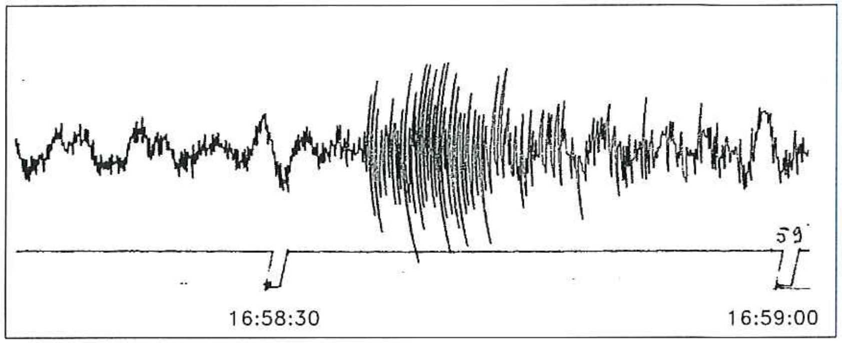
SEISMOMETERS DETECT *T* PHASES FROM ATMOSPHERIC NUCLEAR EXPLOSIONS (ctd.)

"SUNSET" *(Operation DOMINIC)*

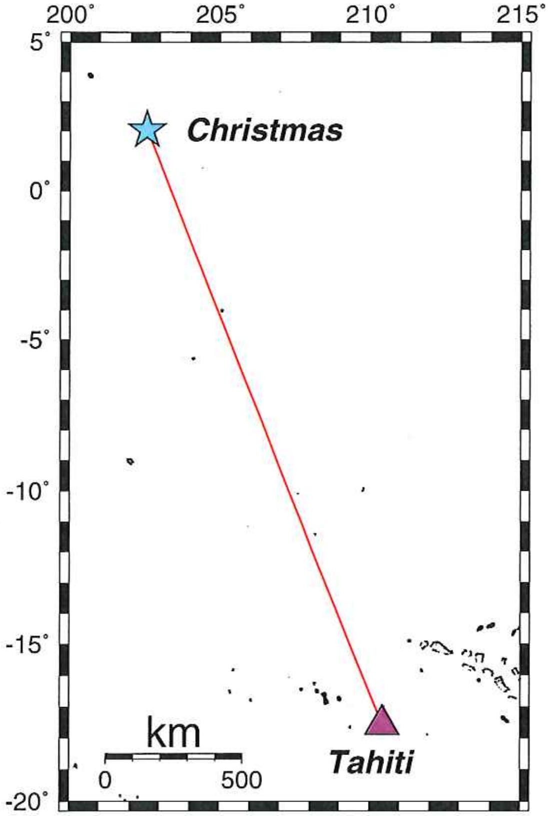
10 JULY 1962

Christmas Island

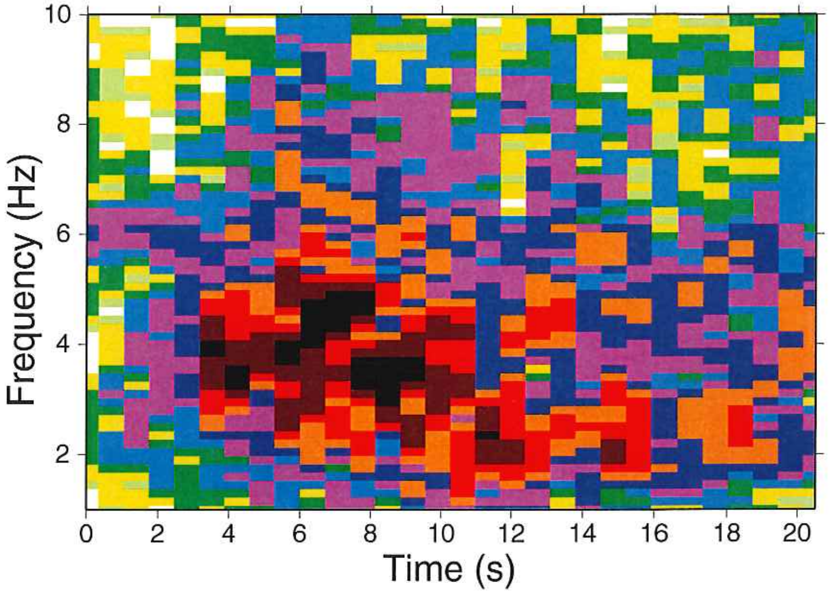
(N) ATMOS. NUCLEAR TEST, 10 JUL 1962 PPT



Recorded at PPT, Tahiti



1 Megaton

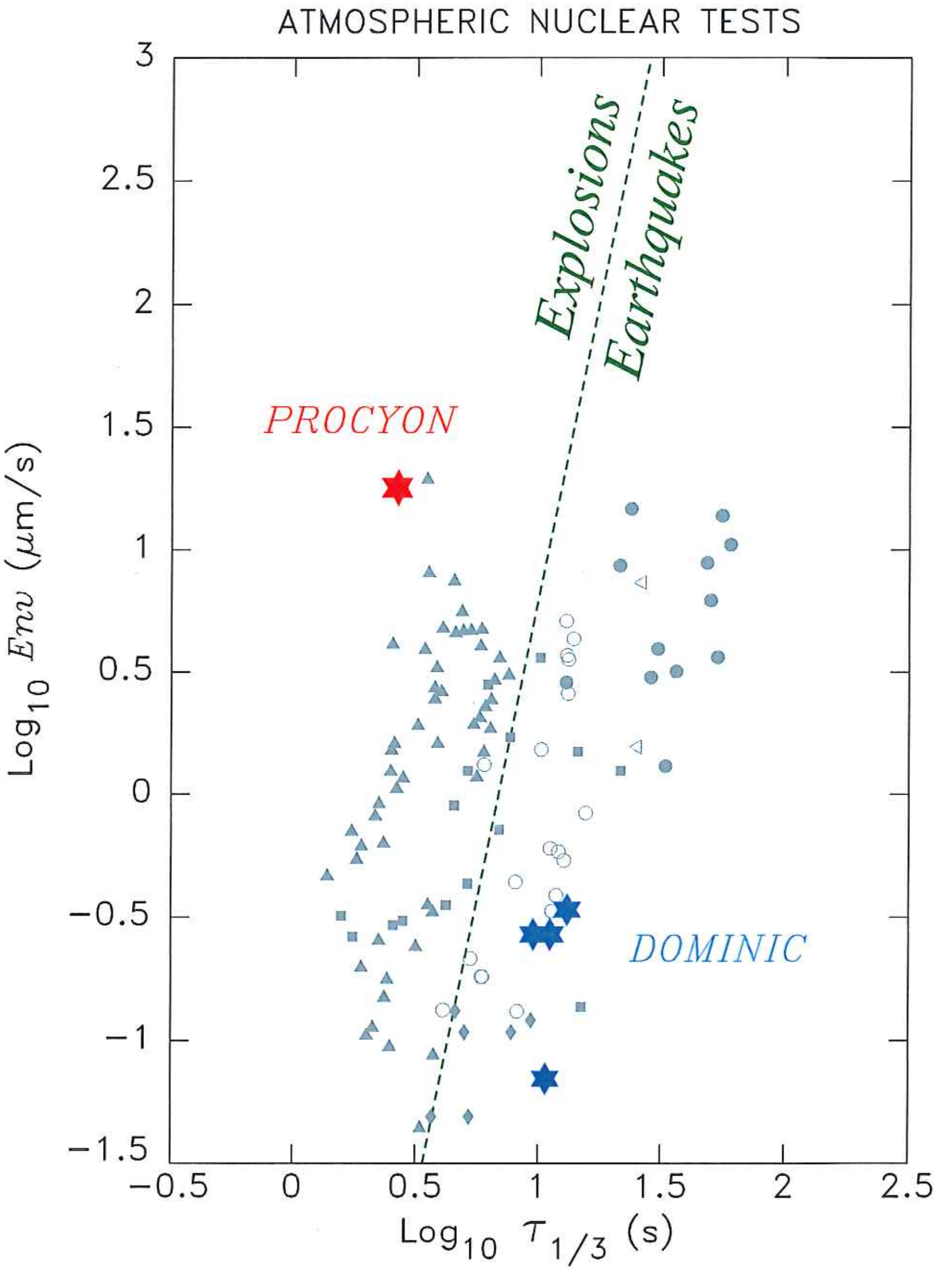


Note much smaller amplitude (0.27 μm/s) and longer duration (11.2 s).

- This difference in behavior would result in a *mis–identification* of the DOMINIC blasts as "earthquakes" using the amplitude-duration discriminant for *T* waves introduced by *Talandier and Okal* [2001].

→ As the *T* phase is probably generated by the shaking of the island structure inside the water column, itself due to the coupling of the air blast with the solid structure, the characterisitcs of the *T* wave are expected to be controled by the geometry of the atoll, in relation to the source.

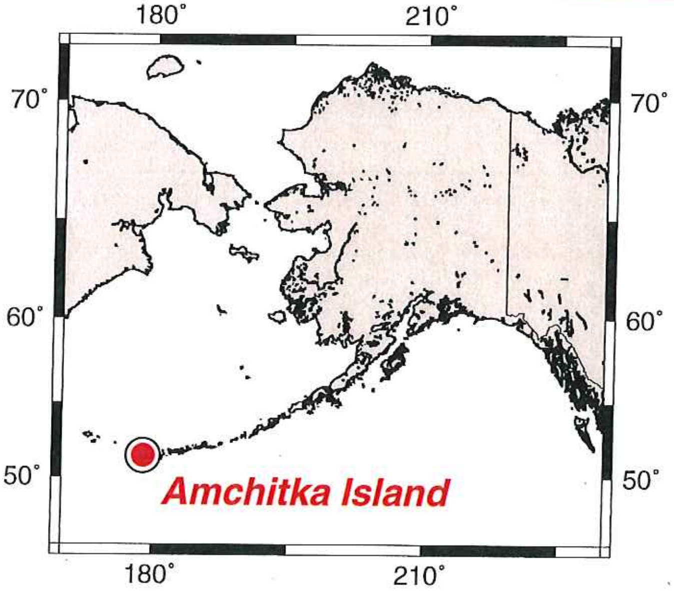
- In this respect, we note differences in the [available] characteristics of the **PROCYON** and **DOMINIC** tests: altitude (**700 m** *vs.* **1.7 km**), location (**over the atoll** *vs.* **off shore**), and to a lesser extent in the size of the atolls themselves (**154** *vs.* **322** km^2).



FROM GROUND TO WATER

Tsunami from Big Bomb !

Operation "MILROW"



Amchitka Island

02 OCT 1969

1 Megaton

VISIONARY RESEARCH PROGRAMS (1969)

- Attempt to **Detect Tsunami on the High Seas**

A " **Concept–DART** "?

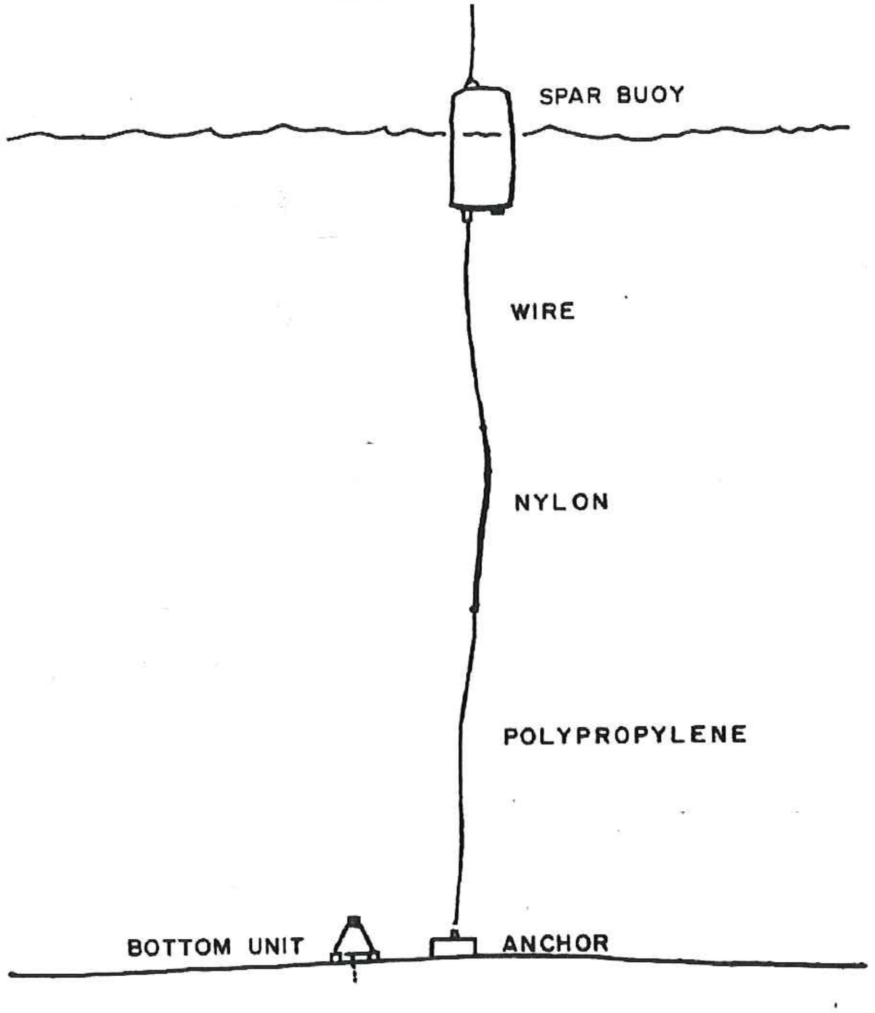
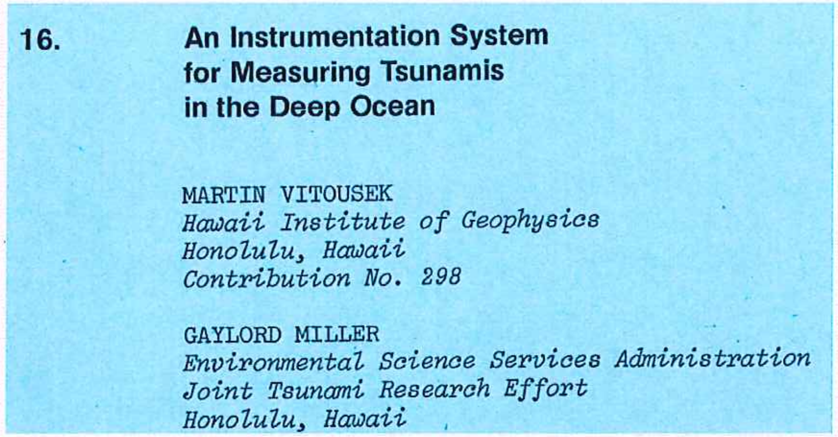


Fig. 5: Buoy system.



16. **An Instrumentation System for Measuring Tsunamis in the Deep Ocean**

MARTIN VITOUSEK
Hawaii Institute of Geophysics
Honolulu, Hawaii
Contribution No. 298

GAYLORD MILLER
Environmental Science Services Administration
Joint Tsunami Research Effort
Honolulu, Hawaii

Tsunami Signal from the Milrow Nuclear Test (1 Megaton; 02 OCT 1969) !

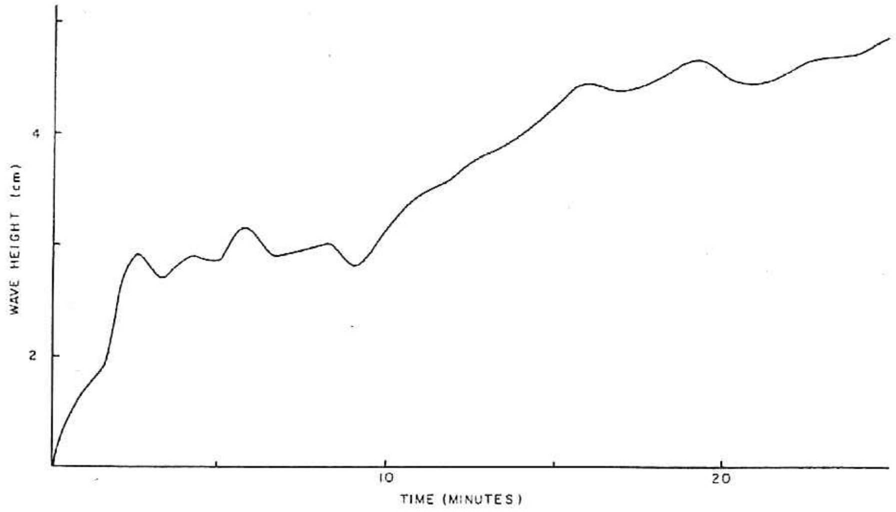
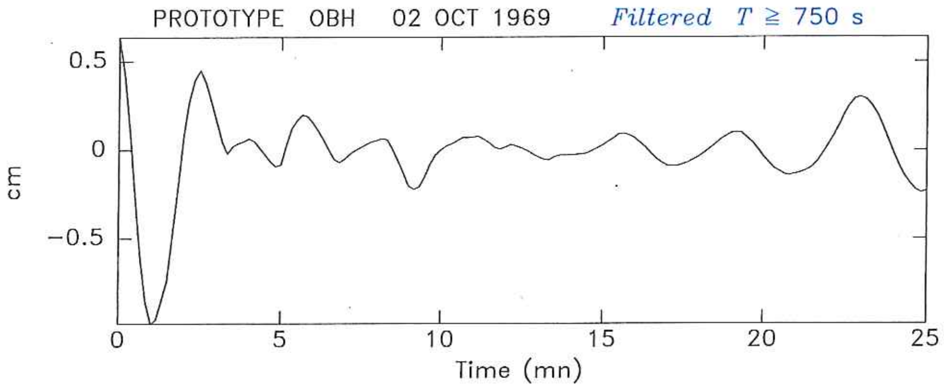


Fig. 8: Waves generated by Amchitka tests.

Tsunami Signal from the Milrow Nuclear Test (1 Megaton; 02 OCT 1969)!

CAN IT BE QUANTIFIED ?

- Once filtered this signal suggest a peak-to-peak amplitude of 1.2 cm



- Use the [outrageously simplistic] model of an explosive source 1.2 km below an ocean of depth 1800 m [as per *Vitousek and Miller,* 1970];

- Use normal mode formalism [*Ward*, 1980] to compute a synthetic maregram at distance of 0.5°; infer an isotropic moment for Milrow: $M_0 \approx 5 \times 10^{24}$ dyn*cm;

- Use *Haskell* [1967] to derive a static *reduced displacement potential*

$$\psi(\infty) = \frac{M_0}{4\pi\,\rho\,\alpha^2} = 400,000 \text{ m}^3$$

which in turn scales to a yield

W = 800 kt

which is only 20% smaller than the estimated yield of 1 Mt.

Given the approximations used, the agreement of the order of magnitude is

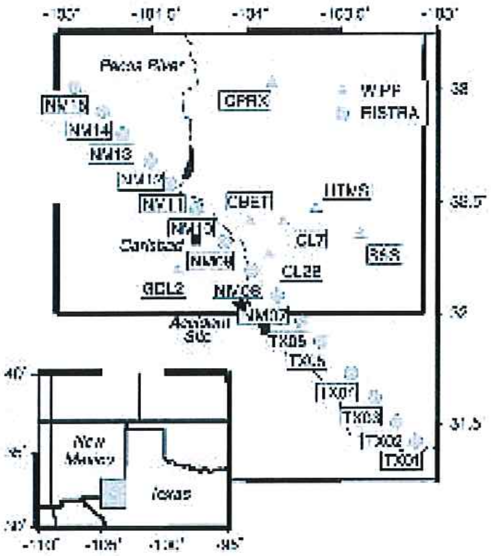
nothing short of staggering!

A ROARING TORCH

Forensic Seismology

NATURAL GAS PIPELINE EXPLOSION, *Carlsbad, N.M.*, 19 AUG 2000

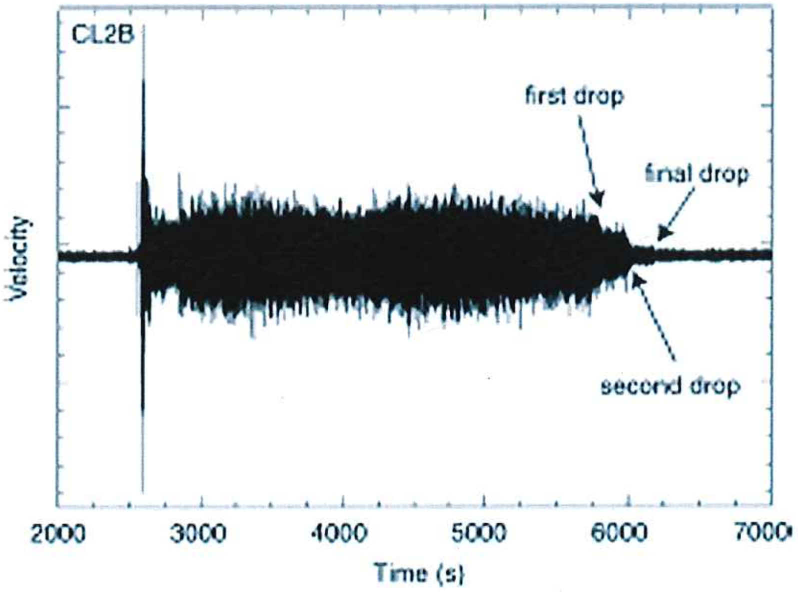
12 Campers killed



The long high-frequency signal on a nearby seismometer represents roaring of a post-explosion fire fueled by continued flow of gas in the broken pipe.

→ **It mainly represents Rayleigh waves coupled into the crust by turbulent flow during combustion at the pipe break.**

→ *It is evidence of negligence on the part of the utility for failure to operate an automatic shutdown safety system.*



[*Koper et al.*, 2003]

TSUNAMI

by

NEXT-DAY AIR ?

ups®

NEXT
DAY
AIR

TSUNAMI GENERATION by *Volcanic Explosions at Sea*

Krakatoa [Sunda Straits], 27 August 1883

A catastrophic tsunami killed 35,000 people in Batavia (Jakarta). *Nomambhoy and Satake* [1995] showed that it can be well modeled by an underwater explosion.

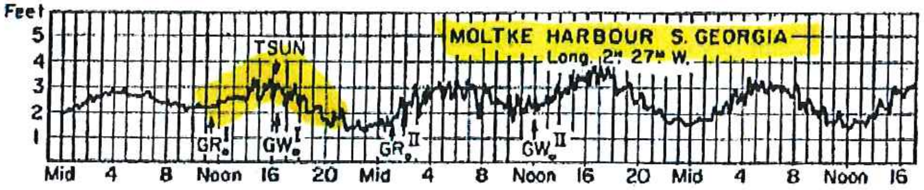
The tsunami was reported recorded world-wide (on tidal gauges), which would seem to contradict the dispersive nature of the short wavelengths associated with sources of small dimensions...

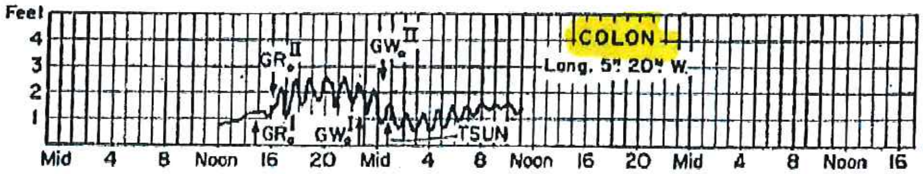
HOWEVER ...

Press and Harkrider [1962, 1964] had shown that the tsunami is actually triggered by an **air wave** generated by an atmospheric explosion, and re-exciting the ocean as it propagates.

This explains

- the propagation of the *"tsunami"* along great circle paths occasionally crossing... a continent!
- the occasional early arrival of the tsunami at distant tidal stations
- and allows an estimate of the power of the explosion (100 to 150 Mt).





DIRECT "VISUAL" DETECTION of TSUNAMI on HIGH SEAS ??

- *In principle, should be impossible*

(Amplitudes too small; wavelengths too large)

YET · · · ?

TSUNAMI SHADOWS — *Can we "SEE" Tsunamis, after all ?*

There exist a number of somewhat anecdotal reports of tsunamis accompanied by a *"shadow"* on the ocean surface.

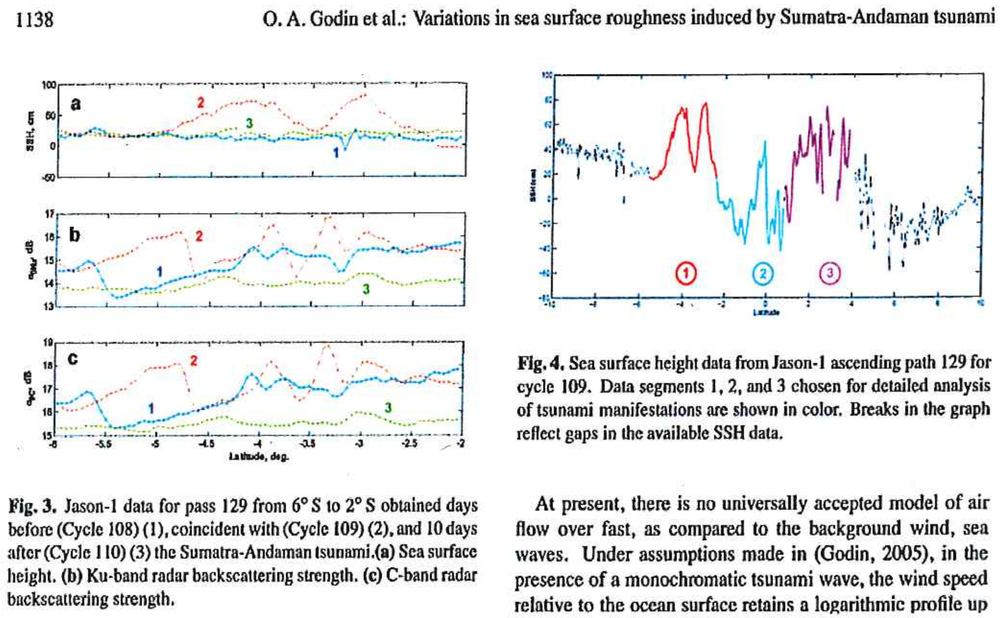
- *Walker* [1996] has published a shot from a video lending support to this idea.

11

Figure 1. The tsunami "shadow" can be seen just below the horizon and extends across the entire field of view of the camera. Approximately 12 minutes has to be added to the time indicated based on simultaneously recorded audio of a local radio station. The video was taken at an elevation of about 50 meters above sea-level.

Godin [2003] explains this phenomenon theoretically as follows:

- Tsunami wave creates steep *gradient* in sea surface.
- This gradient affects boundary condition of lower atmosphere **wind** near surface, making it ***turbulent***.
- In turn, this turbulence creates *roughness* in Sea Surface, perceived as *Tsunami Shadow*.



1138 O. A. Godin et al.: Variations in sea surface roughness induced by Sumatra-Andaman tsunami

Fig. 3. Jason-1 data for pass 129 from 6° S to 2° S obtained days before (Cycle 108) (1), coincident with (Cycle 109) (2), and 10 days after (Cycle 110) (3) the Sumatra-Andaman tsunami. **(a)** Sea surface height. **(b)** Ku-band radar backscattering strength. **(c)** C-band radar backscattering strength.

Fig. 4. Sea surface height data from Jason-1 ascending path 129 for cycle 109. Data segments 1, 2, and 3 chosen for detailed analysis of tsunami manifestations are shown in color. Breaks in the graph reflect gaps in the available SSH data.

At present, there is no universally accepted model of air flow over fast, as compared to the background wind, sea waves. Under assumptions made in (Godin, 2005), in the presence of a monochromatic tsunami wave, the wind speed relative to the ocean surface retains a logarithmic profile up

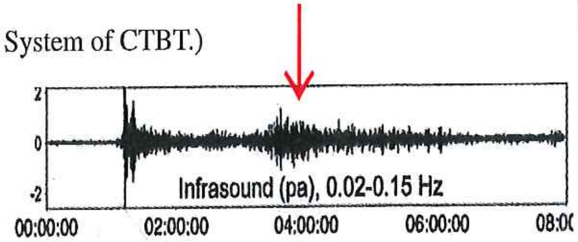
Godin et al. [2009] detect roughness in JASON altimeter records of 2004 Sumatra tsunami.

LOUD TSUNAMI ??

TSUNAMI DETECTED by INFRA SOUND ARRAYS (CTBT)

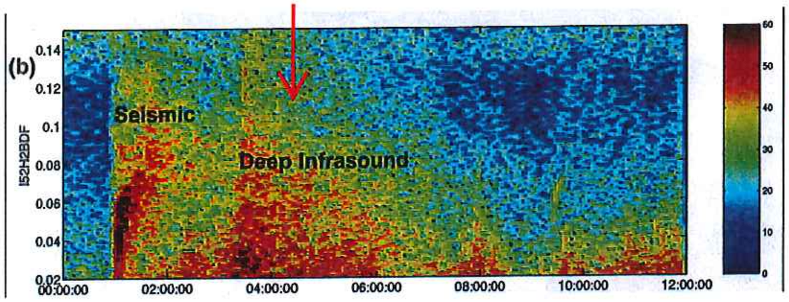
Arrays of barographs monitoring pressure disturbances carried by atmosphere.

(Deployed as part of International Monitoring System of CTBT.)



Diego Garcia, BIOT, 26 Dec. 2004

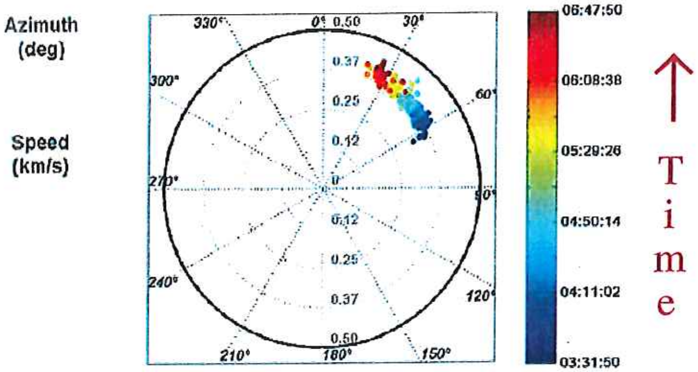
[*Le Pichon et al.*, 2005]

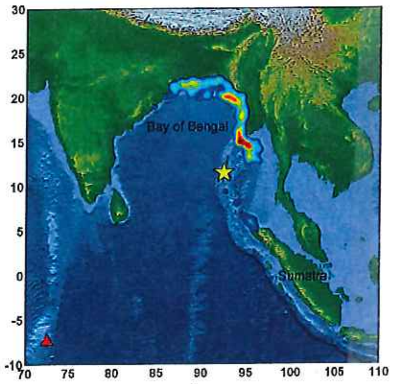


Detects signal in DEEP INFRASOUND about 3 hours after source time

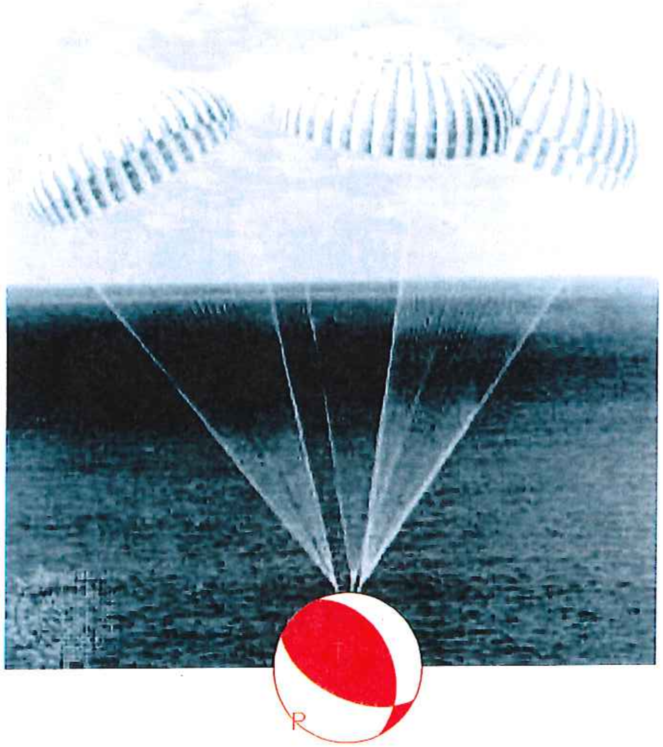
BEAM ARRAY to determine azimuth of arrival and velocity of air wave.

USE TIMING of arrival to infer source of disturbance as *TSUNAMI HITTING CONTINENT* then continent shaking atmosphere.





GRACE — *FUL*



CMT from SPACE !

A large earthquake displaces masses in the Earth, and thus perturbs its gravity field, which should affect the motion of satellites.

→ These effects are perfectly described in the normal mode formalism

Remember Saito's [1967] y_5 component of the eigenvector?

(V in *Gilbert, Dahlen, Dziewonski*... notation)

It simply characterizes the change in potential inside the Earth ($r \leq a$) during its deformation.
From there up, the potential decreases like $r^{-(l+1)}$.

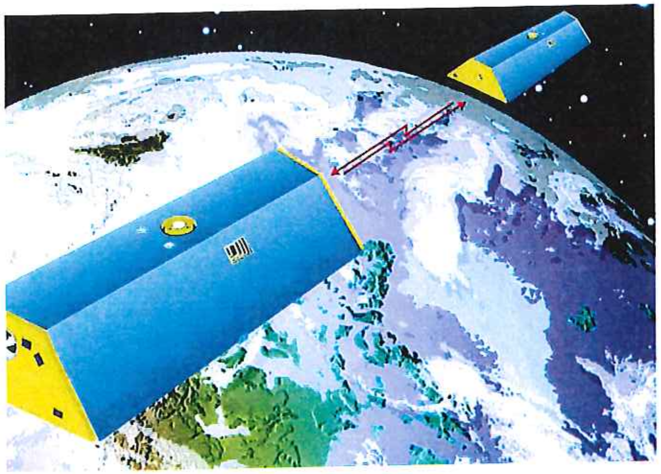
- A major earthquake will have, *a priori*, two effects

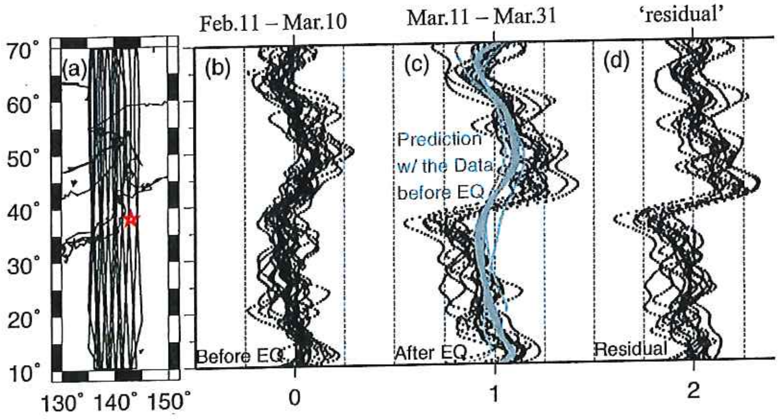
→ A **static** one, resulting from the static term **1** in the excitation $(1 - \cos \omega t \cdot e^{-\omega t/2Q})$ of the Earth's modes;

→ A *dynamic* one resulting from the damped cosine, and describing the free oscillation of the Earth.

WE WILL FOCUS (for now) ON THE STATIC TERM...

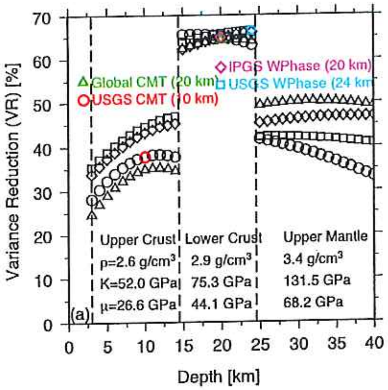
- Track disturbance of relative position of co–orbiting satellites





↑

Difference between pre– and post– Tohoku



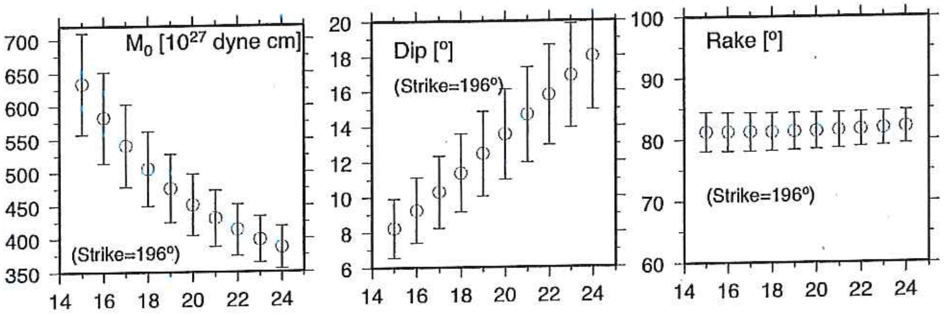
Grid search shows best depth

in **Lower Crust,**

around **20 km.**

→ M_0 trades off with dip angle, but $W-$ phase geometry yields

$$4 \times 10^{29} \leq M_0 \leq 5 \times 10^{29} \quad \text{dyn*cm}$$



IMPORTANT RESULT

- GRACE–derived moment is equivalent to CMT or W–phase moments

→ *NO PERCEPTIBLE POST-SEISMIC AFTERSLIP*

[*Han et al.*, 2011]

TSUNAMI DETECTED IN GEOMAGNETIC FIELD

A SENSIBLE IDEA...

- Tsunami moves water, a conducting fluid, inside the magnetic field of the Earth.
- Should create a current, which in turn, perturbs the Earth's magnetic field **B**.
- Indeed, tidal signals have been detected in daily fluctuations of **B** [*e.g., McKnight,* 1995].

→ *Tyler* [2005] showed that the perturbation b_z of the vertical component of **B** should be linked to the tsunami's amplitude η through

$$\frac{b_z}{\eta} = \frac{F_z\, c}{h\, c_s} \cdot e^{-\kappa z}$$

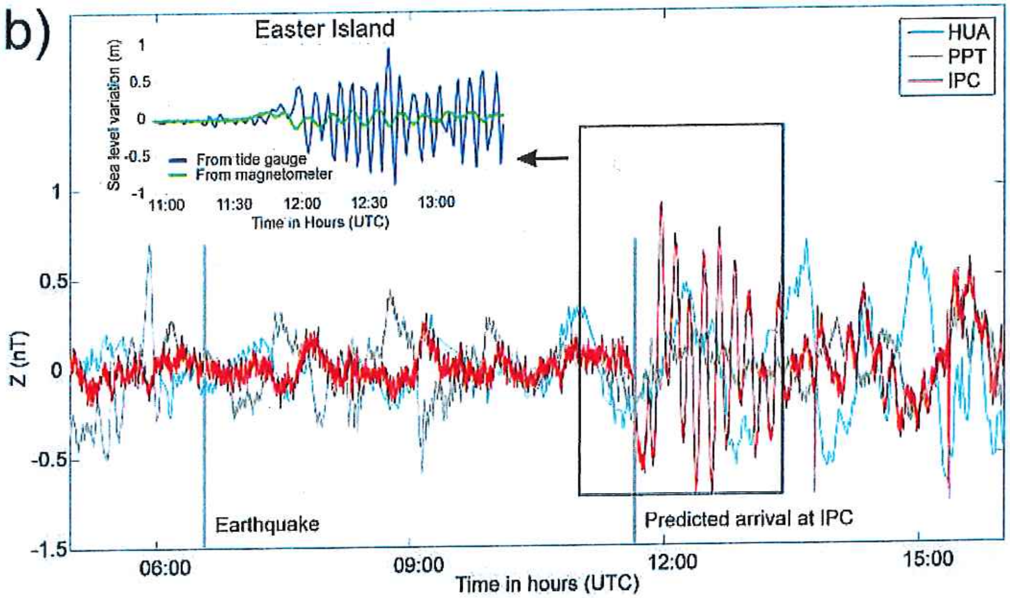
where F_z is the unperturbed vertical field, $c = \sqrt{g\,h}$ the tsunami's phase velocity, $c_s = c + i\, c_d$ with $c_d = 2\,K\,/\,h$ and K the magnetic diffusivity ($K = 1/\mu\sigma$).

- Unfortunately, in the case of the 2004 Sumatra tsunami, the areas with maximum η are at the magnetic Equator, and no signal was detected...

→ Otherwise, one would expect about **10 to 20 nT per meter** of vertical sea surface displacement...

DETECTION DURING THE 2010 CHILEAN TSUNAMI

- *Manoj et al.* [2011] detected this effect during the 2010 Chilean tsunami using the geomagnetic station at Easter Island (IPC -- below, **red**)



→ *The amplitude detected, ≈ 1 nT, is in good agreement with that of the tsunami on the high seas (15 to 20 cm),* **as recorded on DART buoys.**

- They should **NOT** be comparing to a tide gauge record, which is strongly affected by harbor response.

CONCLUSIONS

- The exceptional size of the 2004 tsunami emphasizes the detailed structure of its tsunami.

→ The tsunami includes significant high-frequency components (3–10 mHz), propagating outside the SWA and which are relevant to harbor response.

→ The tsunami does not stop at water interfaces, but is prolonged into both the solid Earth and the atmosphere.

It fully samples the "Earth's complex system"

→ This remark enables the interpetation of the tsunami as a particular case of the Earth's free oscillations; this approach allows the quantification of many secondary properties of the tsunami, as excited by a dislocation source.

→ Because of the complex nature of the tsunami eigenfunction (consisting not only of a displacement field, but also of pressure, changes in gravity, tilt, etc.), many technologies can be used to detect the tsunami, using equipment already deployed.

→ More work would be warranted to understand the generation of deep infrasound signals, as detected in Diego Garcia.