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MODELING THE LA PALMA LANDSLIDE TSUNAMI

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ABSTRACT

The tsunami expected from a lateral collapse of the Cumbre Vieja Volcano on La Palma in the Canary Islands was modeled. The flank collapse for a 'worst case" landslide was modeled as a 650 meter high, 20 kilometer radius water wave after 30 kilometers of travel as predicted by physical modeling studies of Fritz at ETH in Zurich, Switzerland.

The modeling was performed using the *SWAN* code which solves the nonlinear long waver equations. The tsunami generation and propagation was modeled using a 10 minute Mercator grid of 600 by 640 cells. The small wavelength and period of the tsunami expected from the landslide source results in an intermediate wave rather than a shallow water tsunami wave. The use of a shallow water model only describes the geometric spreasing of the wave and not the significant dispersion such a short period wave would exhibit. Dispersion would reduce the wave amplitudes to less than one-third of the shallow water amplitudes.

The upper limit shallow water modeling indicates that the east coast of the U.S.A. and the Caribbean would receive tsunami waves less than 3 meters high. The European and African coasts would have waves less than 10 meters high.

Full Navier-Stokes modeling including dispersion and geometric spreading for the Fritz initial wave profile predicts that the maximim wave amplitude off the U.S. east coast would be about a meter. Even with shoaling the wave would not present a significant hazard.

INTRODUCTION

The lateral collapse of the flank of the Cumbre Vieja Volcano on La Palma in the Canary Islands represents the "worst case" La Palma submarine landslide. This La Palma slide involves 500 cubic kilometers of material runing out 60 kilometers at a mean speed of 100 meters/second. Hermann Fritz of the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland has physically modeled the landslide as one single block and determined that the landslide would generate a 650 meter high wave with a wavelength of 30 to 40 kilometers and period of 3 to 4 minutes. The wave profile he obtained is shown in Figure 1. It was measured after the wave had effectively traveled 30 kilometers or about 0.04 hours from the source.

He states that such a wave is not a shallow water tsunami wave but an intermediate wave that would undergo significant dispersion as it propagated away from the source region. The experimental apparatus created by Fritz and used to physically model the La Palma landslide is described in reference 1.

If one considers only geometric spreading in a constant depth basin then to an upper limit approximation the wave height as a function of distance from the source would be

$$H = H_o \frac{R_o}{R}$$

where R_o is the initial source radius, R is the distance the wave has traveled from the source, and H_o is the initial height of the source. For the La Palma event R_o is 20 kilometers, and H_o is 650 meters. The wave height after 1000 kilometers of travel is 13 meters, after 5000 kilometers is 2.6 meters and after 10,000 kilometers is 1.3 meters.

To obtain another estimate of the effect of geometric spreading throughout the Atlantic Ocean and of the upper limit wave amplitude, shallow water numerical modeling was performed using the actual depths throughout the Atlantic Ocean.

In addition to geometric spreading the short wavelength and short period wave would undergo significant dispersion as it traveled. To a first approximation dispersion would reduce the heights to less than one-third of the above values as shown in reference 2 and 3 and discussed in the section on dispersion modeling.

For comparision, the great Lisbon tsunami was caused by the November 1, 1755 earthquake generated a tsunami which arrived at Lisbon between 40 minutes and one hour after the earthquake as a withdrawing wave that emptied the Lisbon Oeiras Bay to more than a mile out. Then a tsunami wave with an amplitude of about 20 meters arrived followed by two more waves about an hour apart. The tsunami wave had a period of one hour and amplitude of up to 20 meters at Lisbon and along the African and south European coasts, of 4 meters along the English coast, and of 7 meters at Saba in West Indies after 7 hours of travel. To reproduce the observed tsunami wave characteristics a source source 300 kilometers in radius with a drop of 30 meters is required to be located in the region of the 1969 earthquake near the Gorringe bank as described in reference 4.

The May 23, 1960 Chile earthquake had a magnitude of 8.5 and generated a tsunami with a 25 minute period from a source about 150 kilometers wide and 800 kilometers long or 120,000 sq kilometers. The March 26, 1964 Alaskan earthquake near Prince William sound had a magnitude of 8.4 and generated a tsunami wave with a 30 minute period from a source about 300 kilometers wide and 800 kilometers long or 240,000 square kilometers.

To a first approximation the tsunami wave period is determined primarily by the width of the ocean floor displaced by the earthquake and the wave amplitude by the height of the ocean floor displacement.

SHALLOW WATER MODELING

The modeling was performed using the *SWAN* non-linear shallow water code which includes Coriolis and frictional effects. The *SWAN* code is described in Reference 5. The calculations were performed on 866 Mhz Pentium personal computers with 128 megabytes of memory.

The 10 minute Atlantic topography was generated from the 2 minute Mercator Global Marine Gravity topography of the earth of Sandwell and Smith of the Scripps Institute of Oceanography and described in Reference 6. The grid was 600 by 640 cells with the left hand corner at 20 S, 100 W. The grid extended from 20 N to 65 N and from 100 W to 0 W. The time step was 10 seconds.

The source used in the calculations was a 20 kilometer radius of 650 meter high water located near La Palma island. This source is the same height but larger in area than the Fritz wave shown in Figure 1.

The Table 1 locations are shown in Figure 2. The units of the X and Y axis are 10 kilometers. The travel time chart is shown in Figure 3.

The maximum deep water amplitudes at various locations are given in Table 1. The positive wave arrives first followed by several waves with the first wave usually having the maximum amplitude.

As shown in Reference 5 the run-up amplification may be from 2 to 3 times the deep water wave amplitude. Locations with depths less than 1000 meters have some of the run-up amplification included. Dispersion would reduce the wave amplitudes by more than the run-up amplification so the upper limit amplitudes in Table 1 are also upper limit values after run-up.

The east coast of the U.S.A. and the Caribbean receive a tsunami wave with an upper limit less than 3 meters high. The European and African coasts receive a tsunami with an upper limit less than 10 meters high.

Computer generated animations of these calculations are available at http://t14web.lanl.gov/Staff/clm/tsunami.mve/tsunami.htm.

The use of a shallow water model to describe the propagation of waves that are really intermediate water waves dispersing to deep water waves as they travel can only furnish an upper limit estimate of the amplitude and period of the waves. To obtain more realistic wave characteristics a full Navier-Stokes model is needed.

The assumption that the Fritz wave represents the initial displacement at the source is an approximation that needs to improved as the wave was actually equivalent to the wave after it had traveled 30 kilometers of 0.0376 hours. An initial displacement was determined that would approximately reproduce the Fritz wave at 30 kilometers and the calculations repeated to obtain a more realistic model.

DISPERSION MODELING

To obtain an estimation of the effect of dispersion the procedures described in reference 5 were used.

The linear gravity wave model solves the two-dimensional linear gravity wave with a Gaussian or a square wave displacement using Fourier transforms for any time of interest. The wave description is obtained for any uniform length, density, gravity and Gaussian break width or square wave half-width. The model is two-dimensional and symmetrical about the center of the initial displacement, only half of the wave profile is calculated and thus the dispersion effects are described without any geometric spreading.

To model the dispersion effects for the case modeled previously using the SWAN code, a 650 meter high, 20 kilometer square half-width, water displacement in 5000 meter deep water was studied. The initial profile and the wave at 0.5, 2.0, 5.0 and 10.0 hours (400, 1600, 4000, 8000 km) are shown in Figure 5. The wave disperses into a train of waves with a maximum amplitude of 320, 220, 180, 150 meters or from one-half to one-fourth of the initial wave amplitude.

A 650 meter high Gaussian surface water displacement in 5000 meter deep water with Gaussian break of 10km (which is equivalent to an Airy wave with a half-wavelength of 45 kilometers) is a good approximation of the Fritz wave shown in Figure 1. The initial profile and the wave at 0.5, 2.0, 5.0 and 10.0 hours (400, 1600, 4000, 8000 km) are shown in Figure 5. The wave disperses into a train of waves with a maximum amplitude of 220, 150, 110, 90 meters or from one-third to one-eighth of the initial wave amplitude.

The ZUNI code solves the two-dimensional time dependent Navier-Stokes equations for incompressible flow and is described in detail in reference 5.

To approximate the Fritz wave shown in Figure 3, a 650 meter high Airy wave surface water displacement in 5050 meter deep water with with a half-wavelength of 40 kilometers was modeled using ZUNI for 3000 kilometers of travel. The calculations for this geometry were performed with 15 cells in the Y or depth direction and 5000 cells in the R or radial direction. The cells were 500 meters high in the Y direction and 1000 meters long in the radial direction. The time step was 0.1 seconds. These calculations are an extension of those described in references 2, 3, and 5.

The calculated wave profiles are shown in Figure 6 after various times and distance of travel. The calculated wave amplitude as a function of time and distance is shown in Table 2. The wave amplitude with geometric spreading and diffusion has been reduced to 2.6 meters after 2500 kilometers of travel. The wave amplitude after 10,000 kilometers of travel would be about half a meter.

FRITZ SOURCE AT 30 KM MODEL

The Fritz wave in Figure 1 was measured by a gauge in front of the landslide that was at an equivalent location of 30 kilometers from the slide.

In the previous study the source was described as a displacement of water with the geometry of the Fritz wave and centered at the source. The wave observed by Fritz was 2-D and would not exhibit geometric spreading like a 3-D one with distance of travel. The 2-D linear gravity wave model has 320 meters amplitude after 24 km of travel for the Gaussian wave and 460 meters for the square wave. To more closely approximate the wave Fritz observed at 30 km, the initial 40 km diameter square displacement amplitude needs to be increased to 990 meters as shown in Figure 7 and the Gaussian displacement to 1400 meters as shown in Figure 8.

Using the linear gravity model to model the dispersion effects without geometric spreading, the wave profile at 0.5, 2.0, 5.0 and 10 hours are shown in Figures 9 and 10. The amplitudes are increased by a factor of about 2.0 for the Gaussian model and a factor of about 1.4 for the square displacement over those of Figures 4 and 5.

Using the square displacement with a 990 meter initial height that gave an approximately 650 meter high wave at 30 km, the SWAN calculation gave the wave heights shown in Table 3 which are about 1.52 times higher than those of Table 1. Using the Airy displacement with a 1400 meter initial height that gave an approximately 650 high wave at 30 km, the ZUNI calculation gave the wave heights shown in Table 4 which are about 2.15 times larger than those of Table 2. The wave profiles as a function of distance are shown in Figure 11. The wave amplitude off the U.S. coast would be less than one meter. Even with shoaling the wave would not present a significant hazard.

REFERENCES

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2. Charles L. Mader, Dennis W. Moore, George F. Carrier *Numerical Tsunami Propagation Study - III*, Science of Tsunami Hazards, **11**, 93-106 (1993).
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4. Charles L. Mader, *Modeling The 1755 Lisbon Tsunami* , Science of Tsunami Hazards, **19**, 93-116 (2001).
5. Charles L. Mader *Numerical Modeling of Water Waves,* University of California Press, Berkeley, California (1988).
6. W. H. F. Smith and D. T. Sandwell, *Global Seafloor Topography from Satellite Altimetry and Ship Depth Soundings,* Science, April 7, 1997.

TABLE 1
UPPER LIMIT WAVE HEIGHTS
FOR FRITZ LA PALMA TSUNAMI

No	Depth Meters	Location	Maximum Amplitude Meters	Minimum Amplitude Meters
1	953	Off Lisbon	+9.0	-10.
2	4747	East of Saba	+2.2	-2.2
3	825	East of Saba	+2.0	-1.9
4	3446	North of San Juan	+1.8	-1.6
5	783	East of Miami	+0.3	-0.2
6	2922	East of Washington	+3.0	-3.0
7	178	South West of England	+2.5	-1.9
8	4574	West of Lisbon	+5.0	-5.0
9	3868	West of Lagos	+4.0	-2.0
10	3923	West of Gibraltar	+6.0	-5.0
11	4376	West of Gibraltar	+6.0	-4.0
12	1717	West of Casablanca	+7.0	-4.0
13	3314	N-W of Source	+8.0	-6.0

DISPERSION WOULD REDUCE HEIGHTS TO

LESS THAN ONE THIRD OF ABOVE VALUES

TABLE 2
ZUNI WAVE HEIGHTS
FOR FRITZ LA PALMA TSUNAMI

No	Time Hours	Radial Distance Meters	Amplitude Meters	Amp/650. Percent
1	.03	24,000	170.	26.
2	.05	40,000	120.	18.
3	.10	80,000	71.	11.
4	.125	100,000	60.	9.2
5	.250	200,000	30.	4.6
6	.625	500,000	14.	2.1
7	1.25	1,000,000	7.0	1.1
8	1.88	1,500,000	4.6	0.71
9	2.50	2,000,000	3.4	0.52
10	3.12	2,500,000	2.6	0.4

TABLE 3
WAVE HEIGHTS
FOR FRITZ LA PALMA TSUNAMI AT 30KM

No	Depth Meters	Location	Maximum Amplitude Meters	Minimum Amplitude Meters
1	953	Off Lisbon	+14.0	-15.
2	4747	East of Saba	+3.2	-3.0
3	825	East of Saba	+2.9	-2.5
4	3446	North of San Juan	+2.2	-2.0
5	783	East of Miami	+0.7	-0.5
6	2922	East of Washington	+4.1	-4.0
7	178	South West of England	+3.5	-2.0
8	4574	West of Lisbon	+7.0	-8.0
9	3868	West of Lagos	+6.0	-3.0
10	3923	West of Gibraltar	+8.0	-7.0
11	4376	West of Gibraltar	+8.0	-6.0
12	1717	West of Casablanca	+10.0	-6.0
13	3314	N-W of Source	+12.0	-9.0

DISPERSION WOULD REDUCE HEIGHTS TO

LESS THAN ONE THIRD OF ABOVE VALUES

TABLE 4
ZUNI WAVE HEIGHTS
FOR FRITZ LA PALMA TSUNAMI AT 30 KM

No	Time Hours	Radial Distance Meters	Amplitude Meters	Amp/1400. Percent
1	.03	24,000	370.	26.
2	.05	40,000	272.	19.
3	.10	80,000	160.	11.
4	.125	100,000	133.	9.5
5	.250	200,000	70.	5.0
6	.625	500,000	30.	2.1
7	1.25	1,000,000	15.0	1.1
8	2.50	2,000,000	7.3	0.52
9	4.03	3,228,000	4.2	0.30
10	5.00	4,005,000	3.2	0.21
11	5.70	4,565,700	2.6	0.18

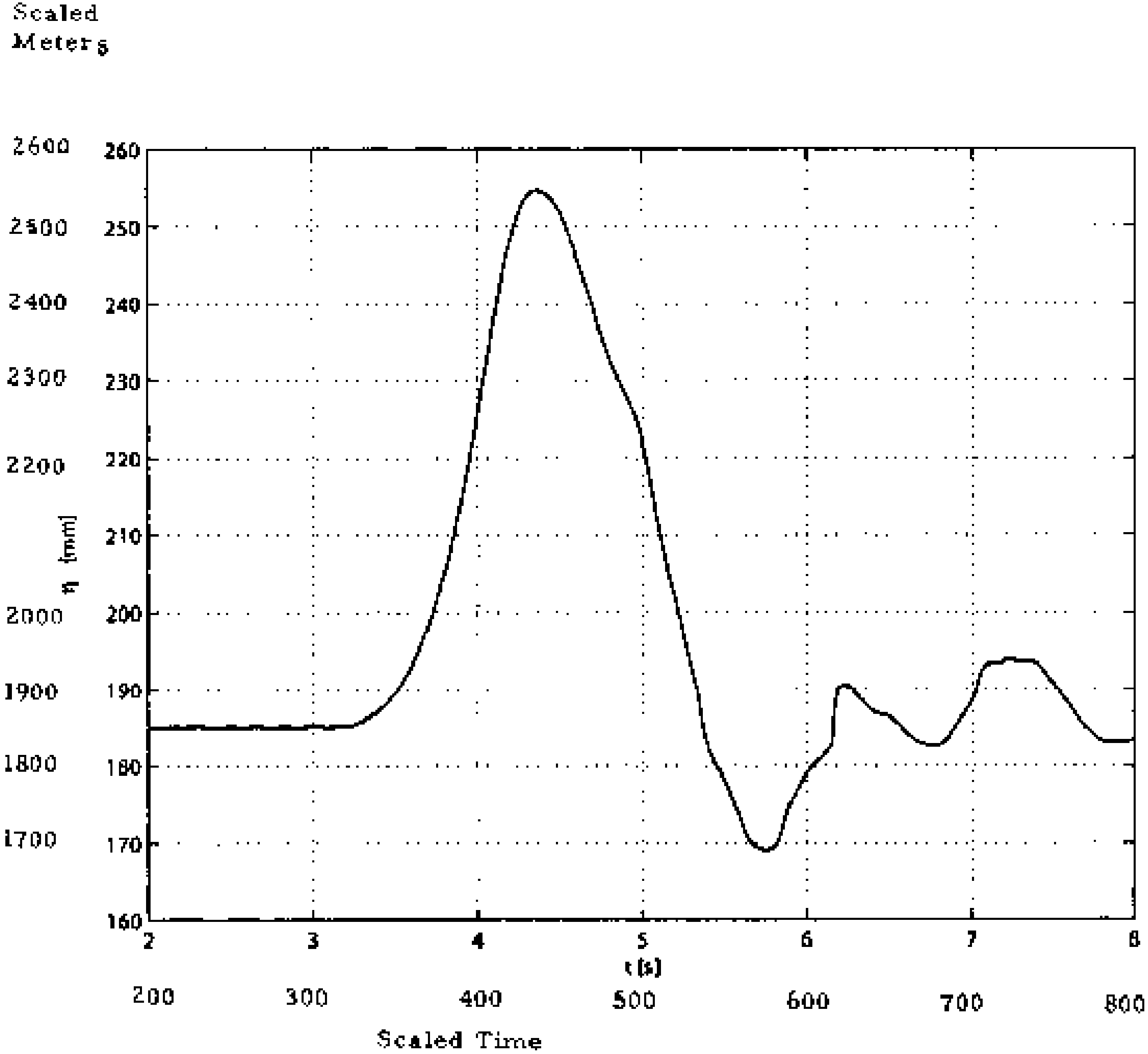


Figure 1. Fritz LaPalma Source Wave record.

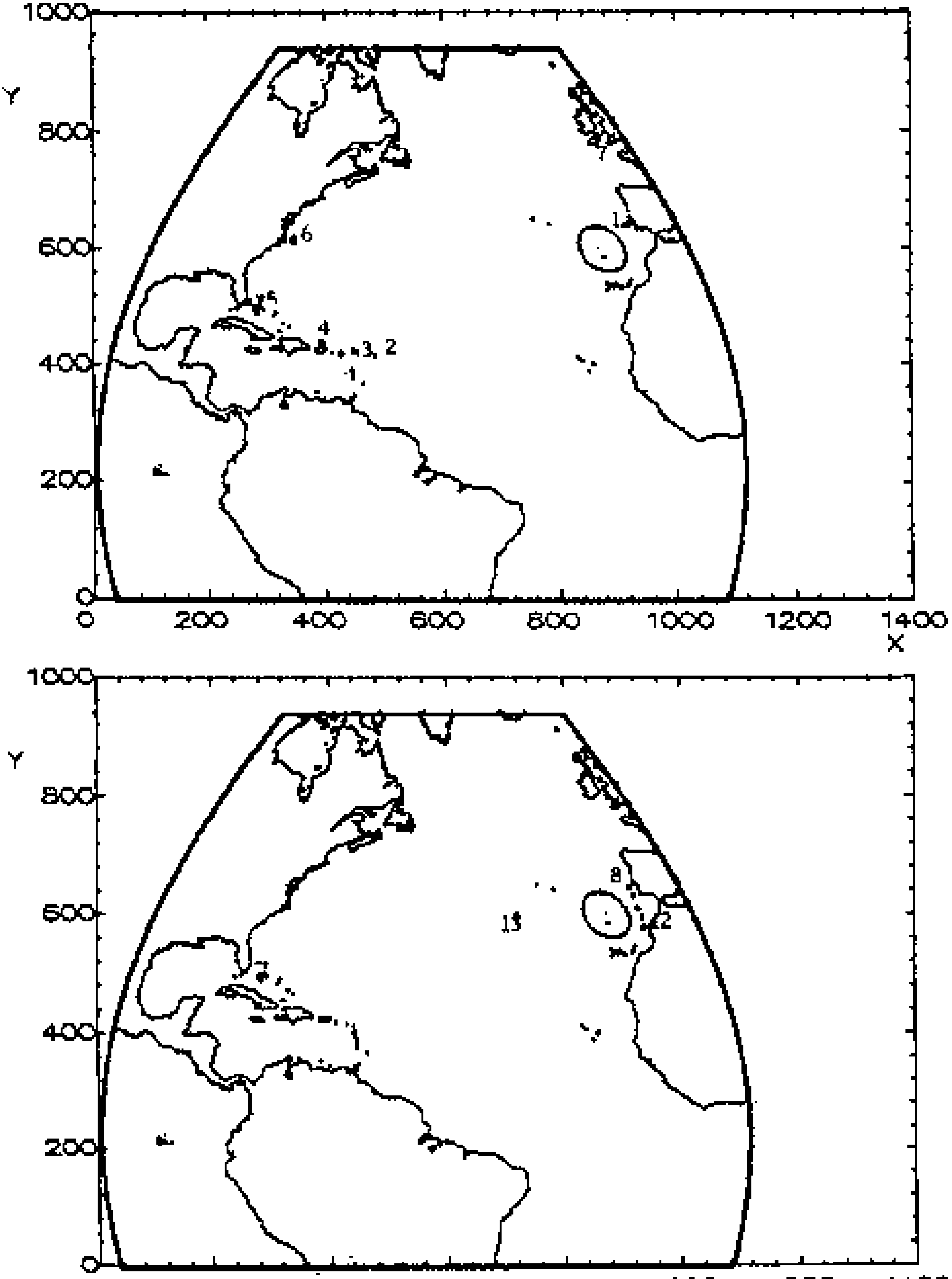


Figure 2. The source region and Table 1 locations. The X and Y axis units are 10 kilometer

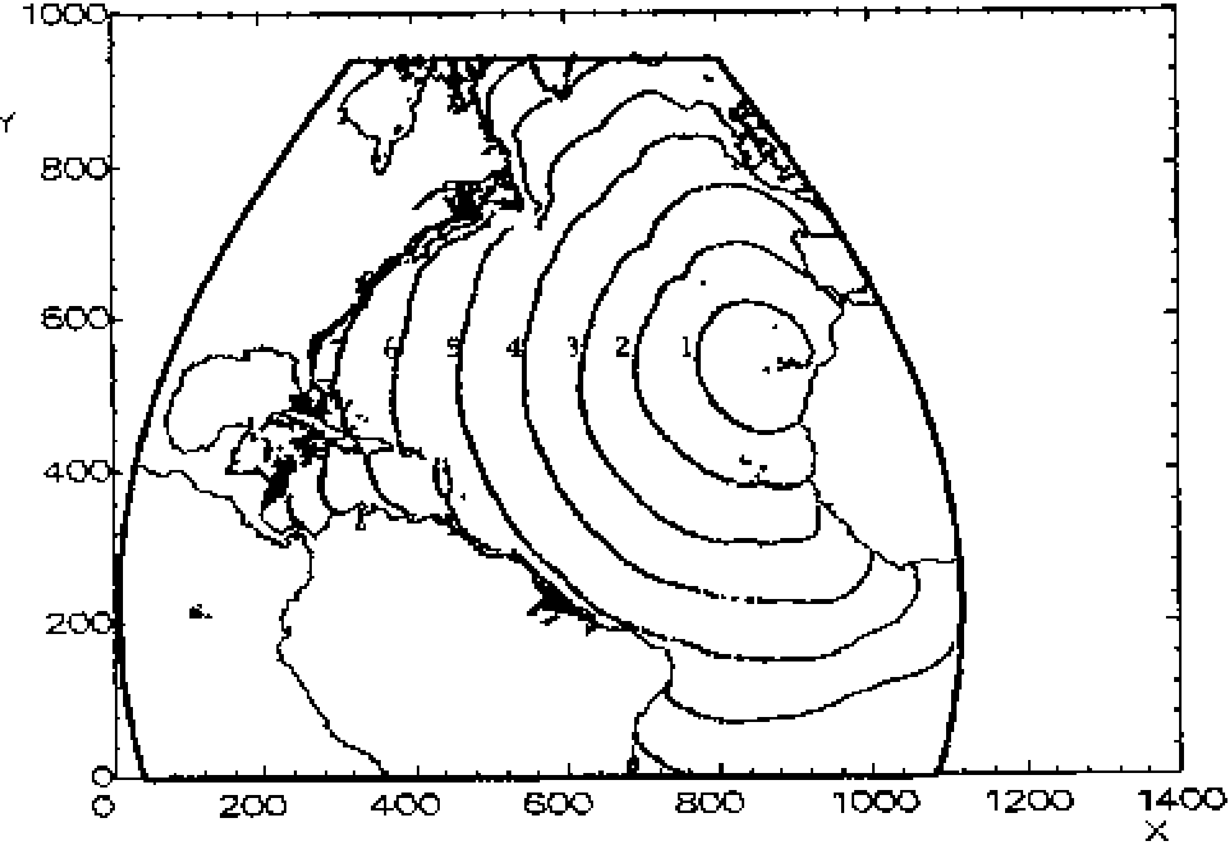


Figure 3. The travel time chart at one hour intervals.

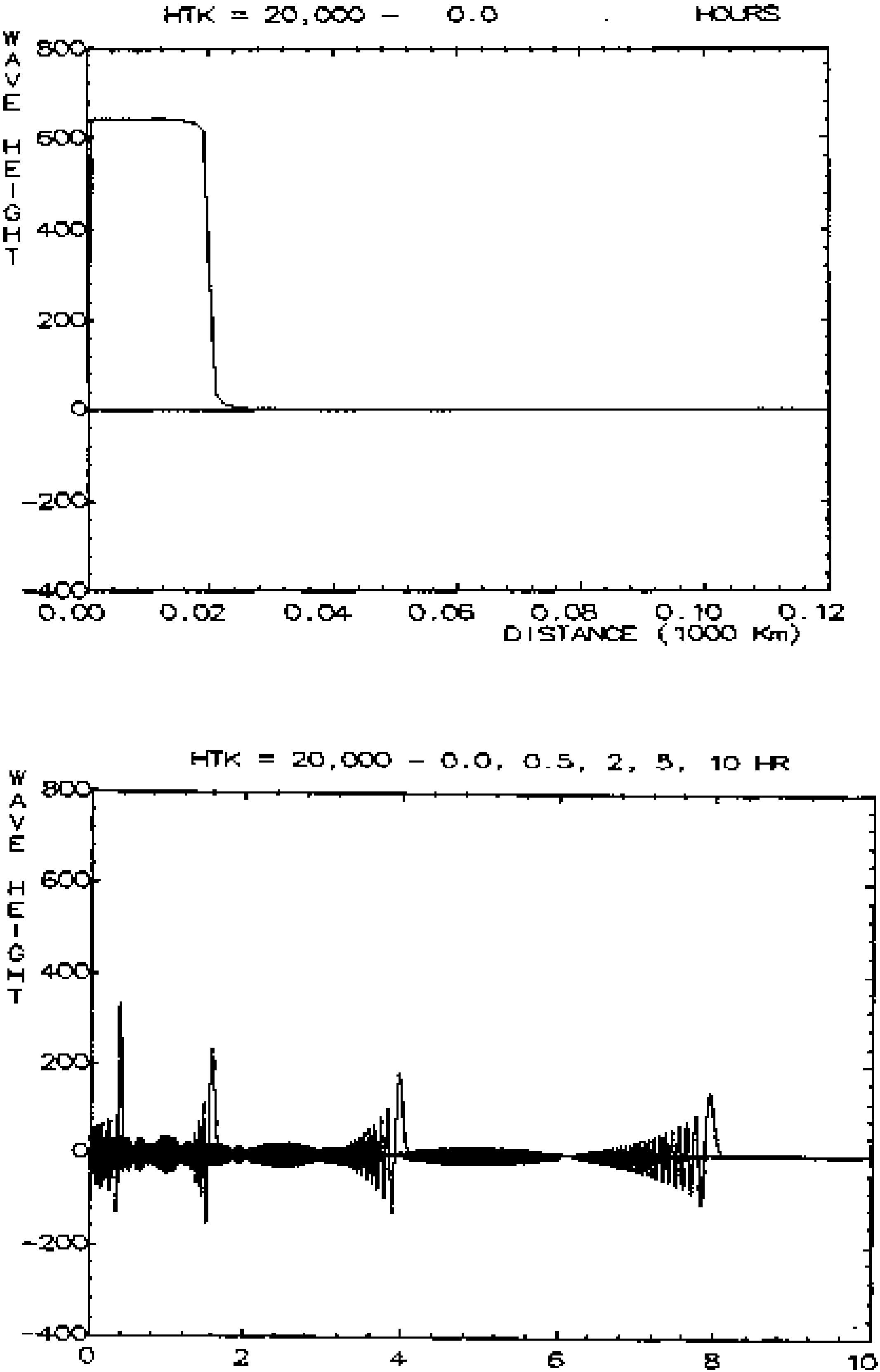


Figure 4. The wave profile in meters as a function of distance for a 650 meter high square displacement of water with a 20 kilometer half-width in 5000 meter deep water. The linear gravity model is used which models dispersion with no geometrical spreading.

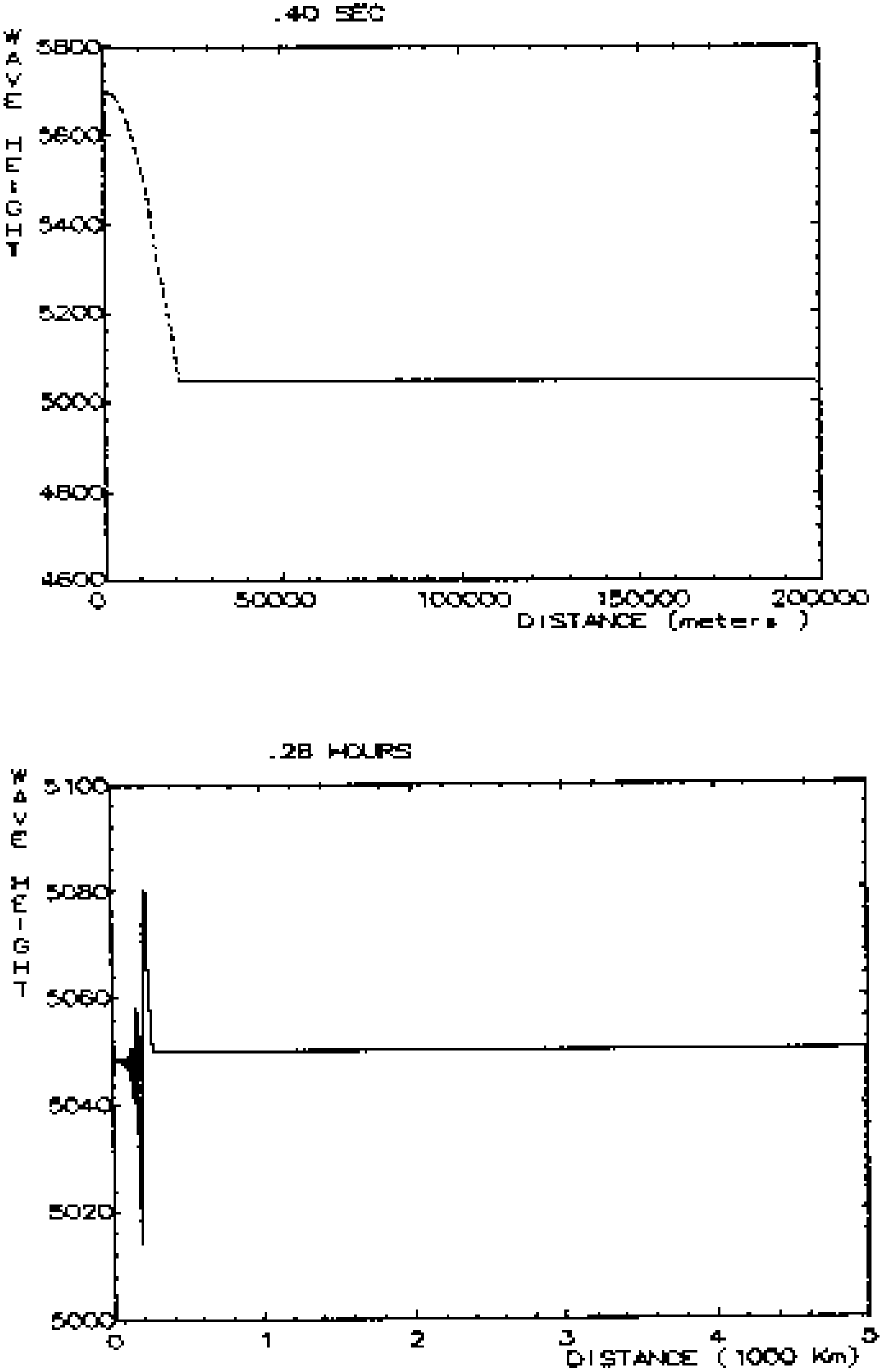
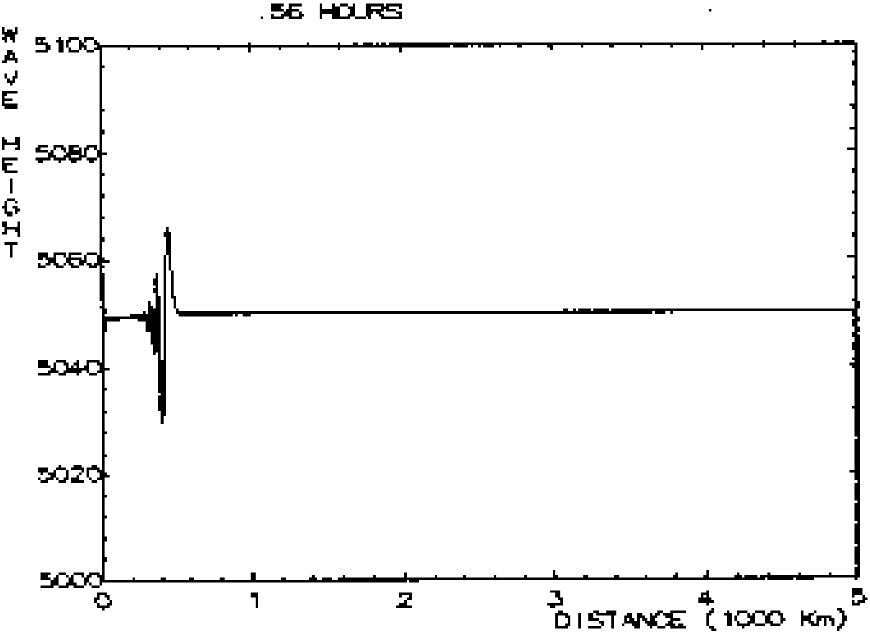
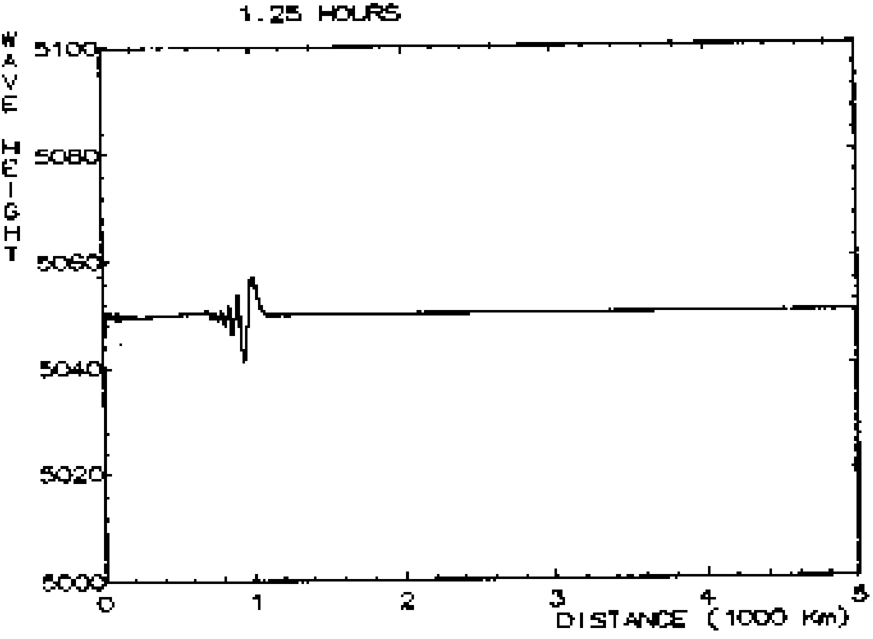
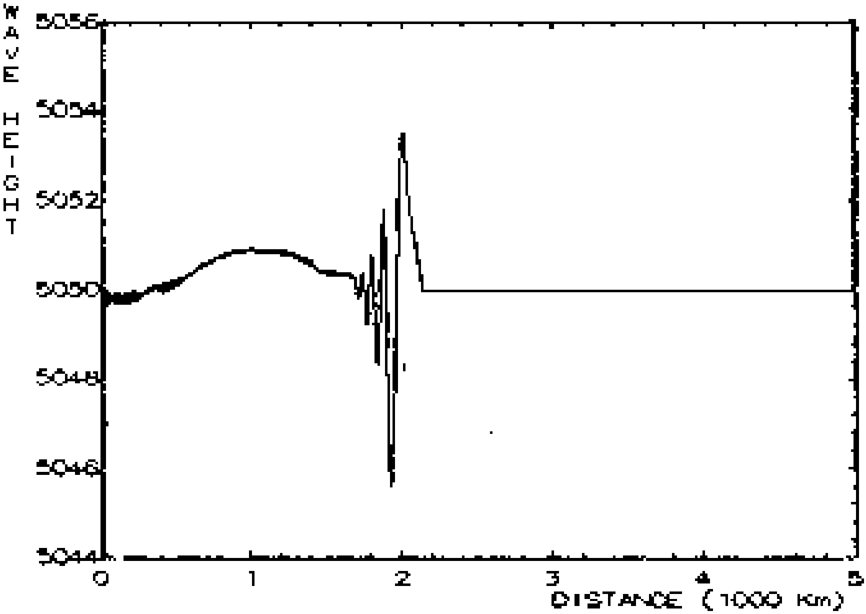


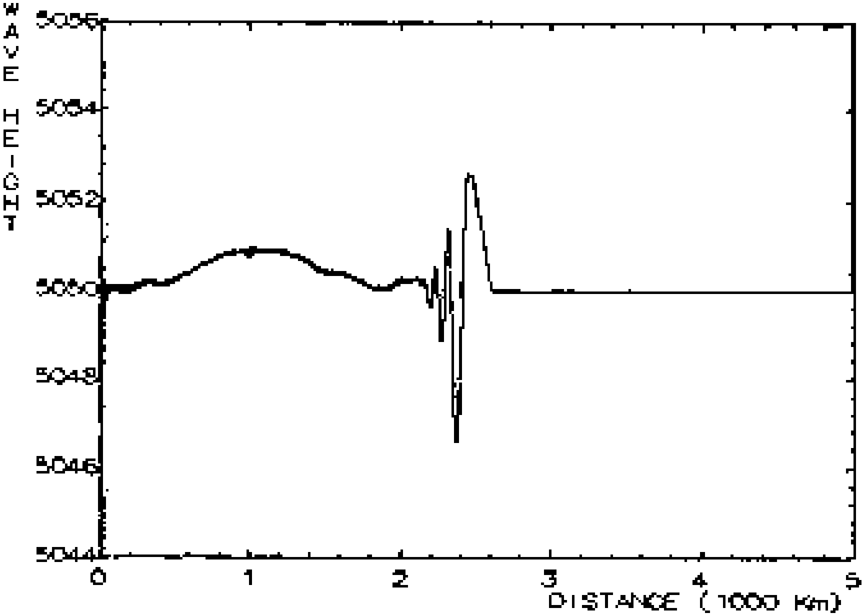
Figure 6. The wave profile in meters as a function of radius for the Fritz LaPalma displacement (first frame) in 5050 meter deep water for the full Navier Stokes Model.


.56 HOURS
WAVE HEIGHT
5100
5080
5060
5040
5020
5000
0
1
2
3
4
5
DISTANCE (1000 Km)


1.25 HOURS
WAVE HEIGHT
5100
5080
5060
5040
5020
5000
0
1
2
3
4
5
DISTANCE (1000 Km)



2.50 HOURS



3.06 HOURS

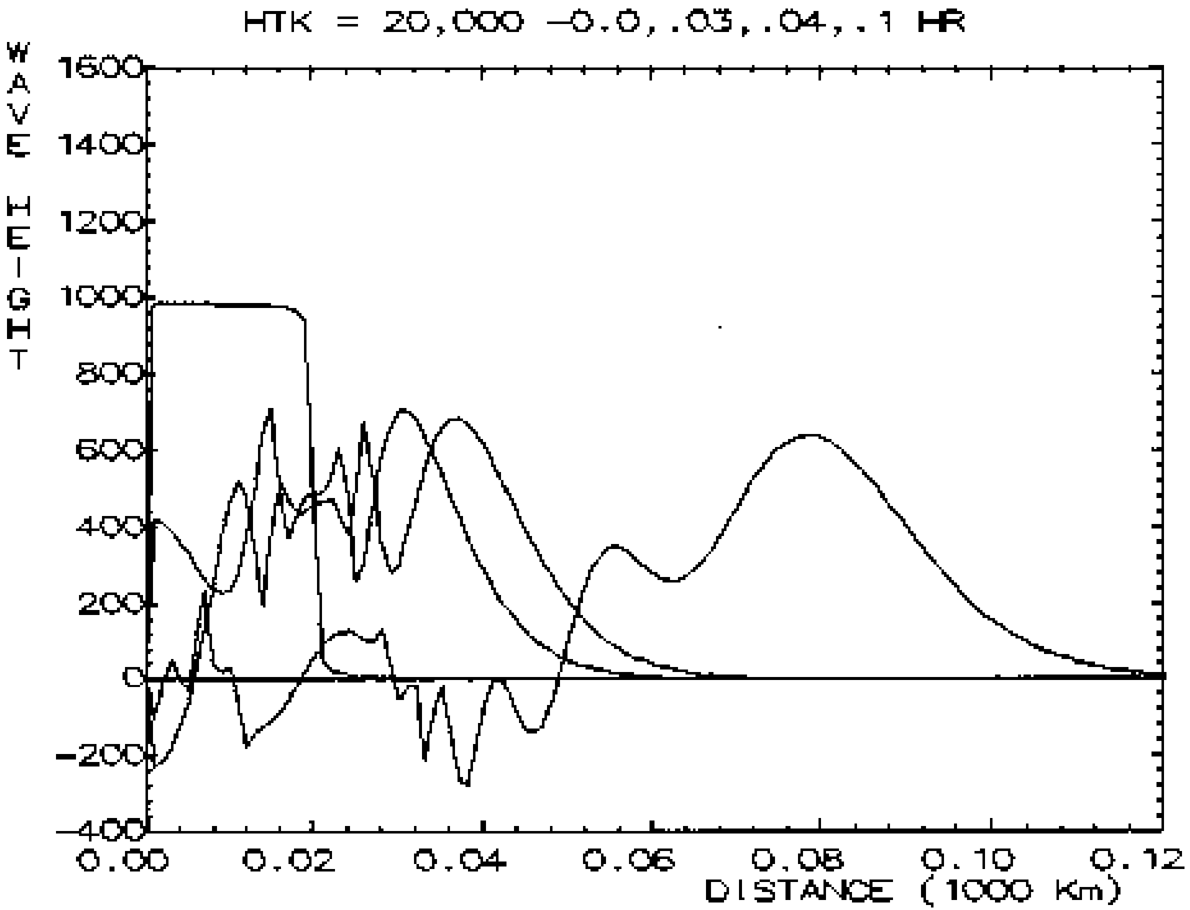


Figure 7. The wave profile in meters as a function of distance for a 990 meter high square displacement of water with a 20 kilometer half-width in 5000 meter deep water. The linear gravity model is used which models dispersion with no geometrical spreading. The wave approximates (in height and front profile) the Fritz wave shown in Figure 1 after 30 kilometers (0.038 hours) of travel.

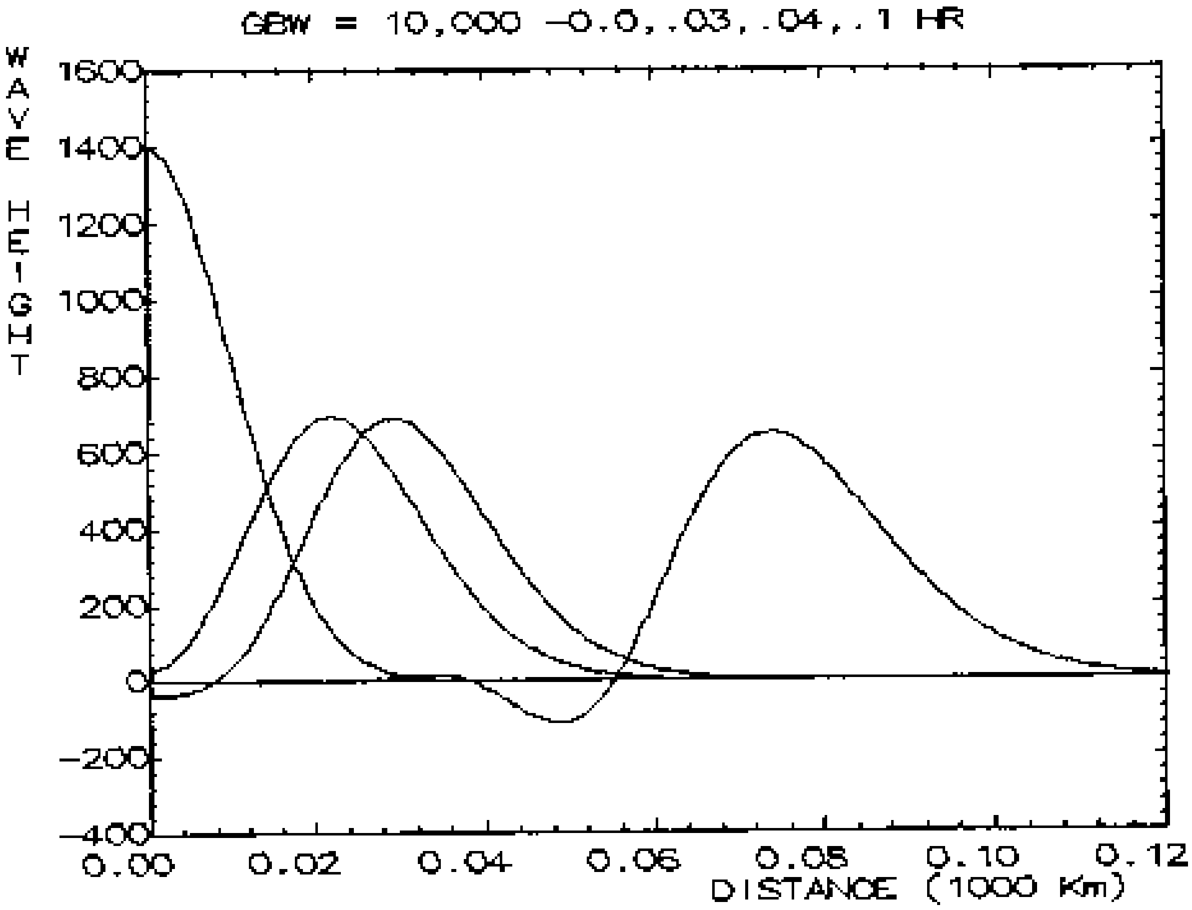


Figure 8. The wave profile in meters as a function of distance for a 1400 meter high Gaussian displacement of water with a break width of 10, in 5000 meter deep water. The linear gravity model is used which models dispersion with no geometrical spreading. The wave profile is similar to the Fritz wave shown in Figure 4 after 30 kilometers (0.038 hours) of travel.

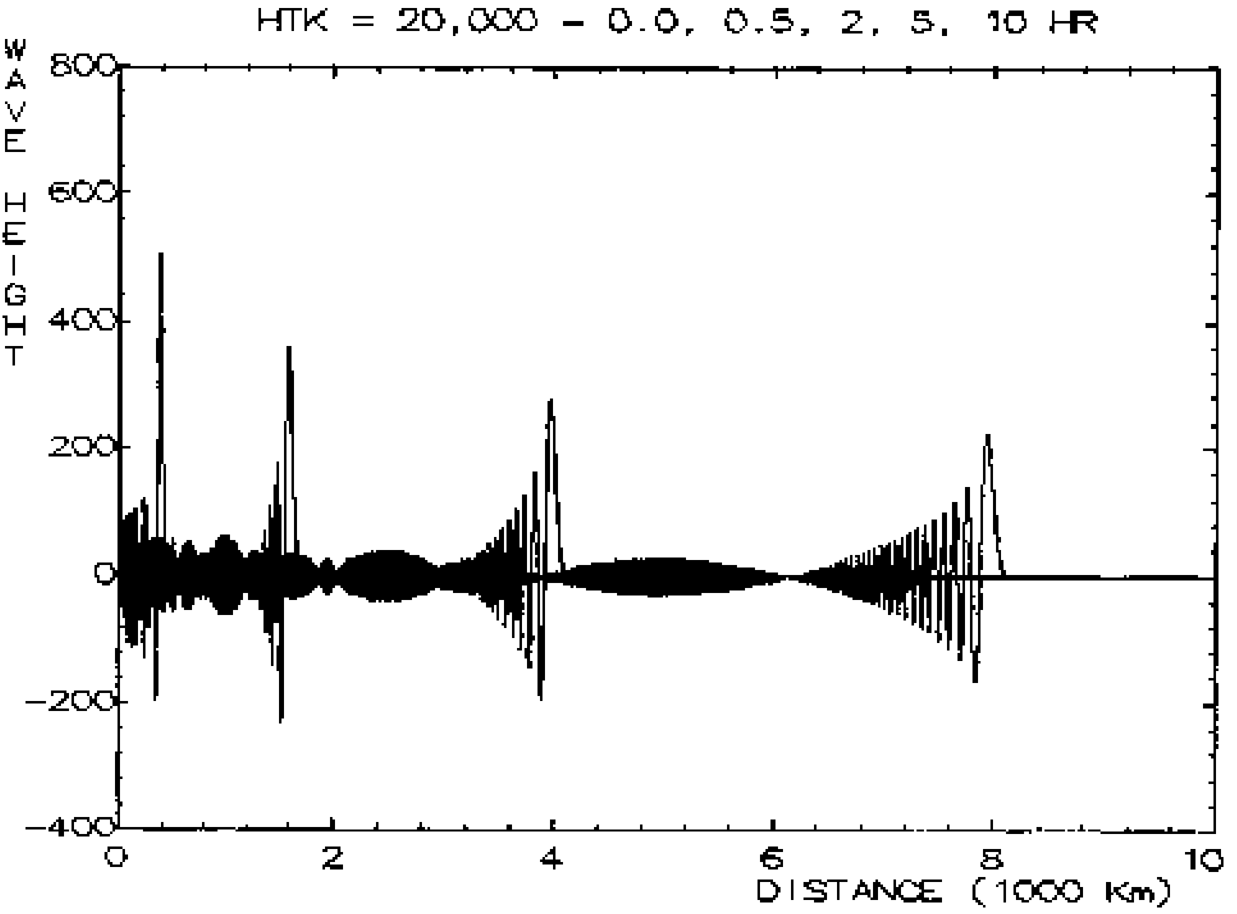


Figure 9. The wave profile in meters as a function of distance for a 990 meter high square displacement of water with a 20 kilometer half-width in 5000 meter deep water (Figure 7). The linear gravity model is used which models dispersion with no geometrical spreading. The wave amplitudes are about 1.4 times larger than those of Figure 4.

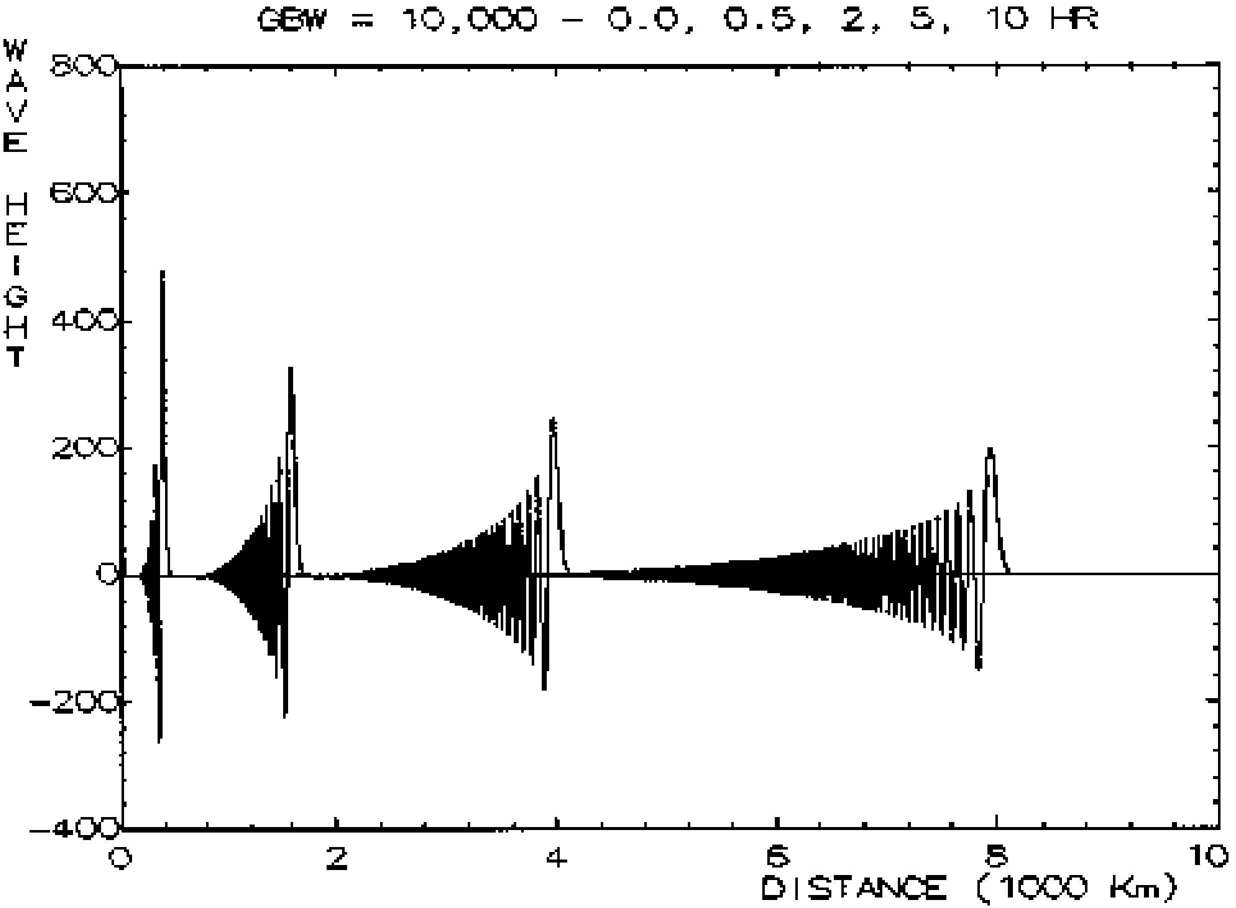


Figure 10. The wave profile in meters as a function of distance for a 1400 meter high Gaussian displacement of water with a Gaussian break length of 10 in 5000 meter deep water (Figure 8). The linear gravity model is used which models dispersion with no geometrical spreading. The wave amplitudes are about twice those of Figure 5.

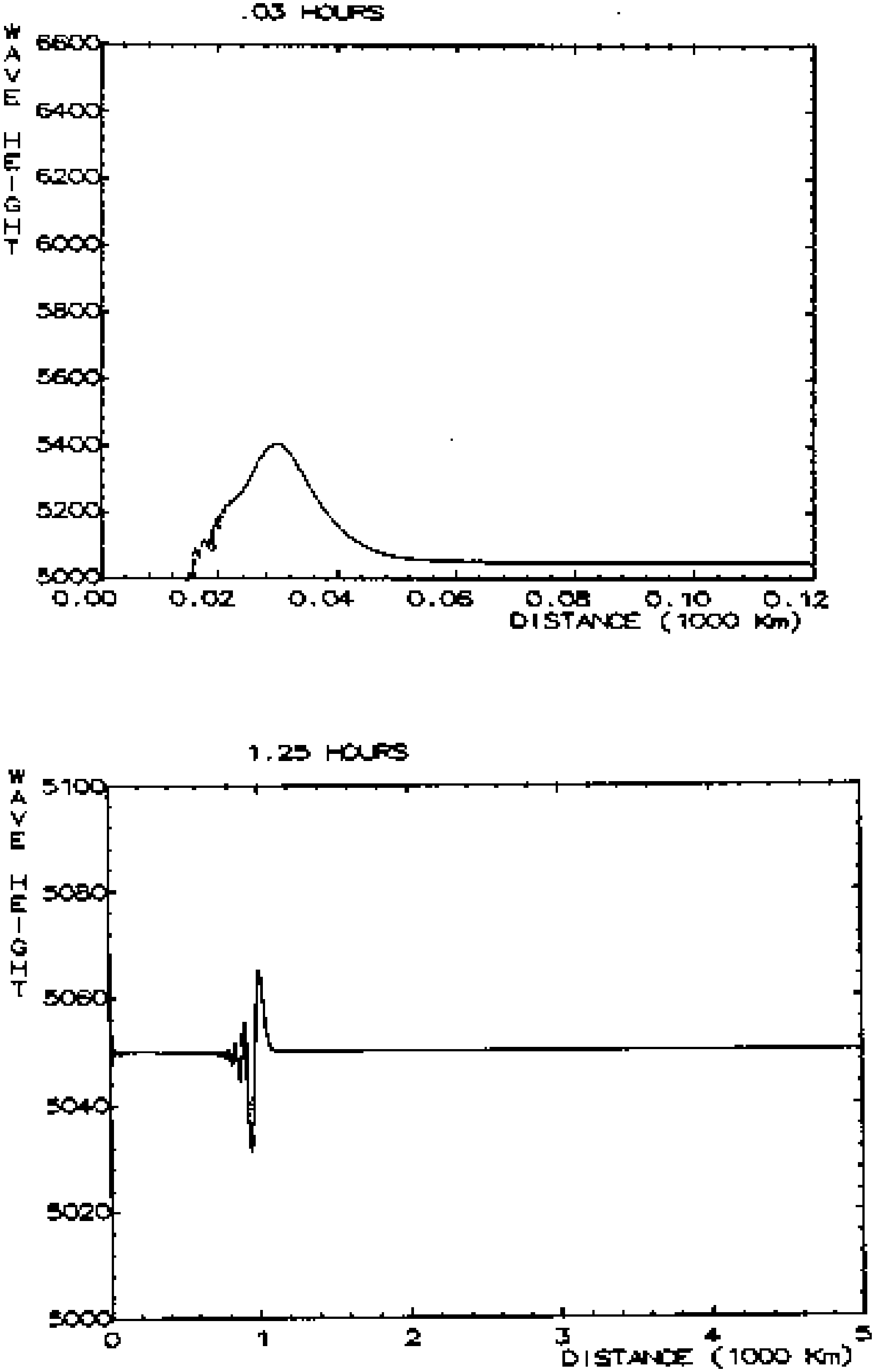
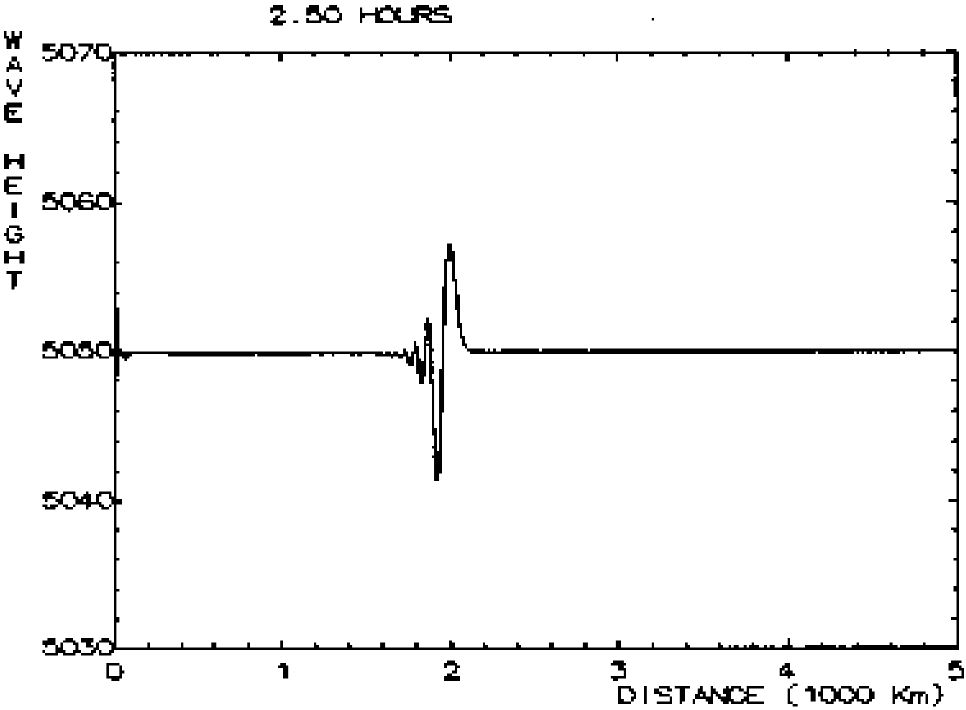
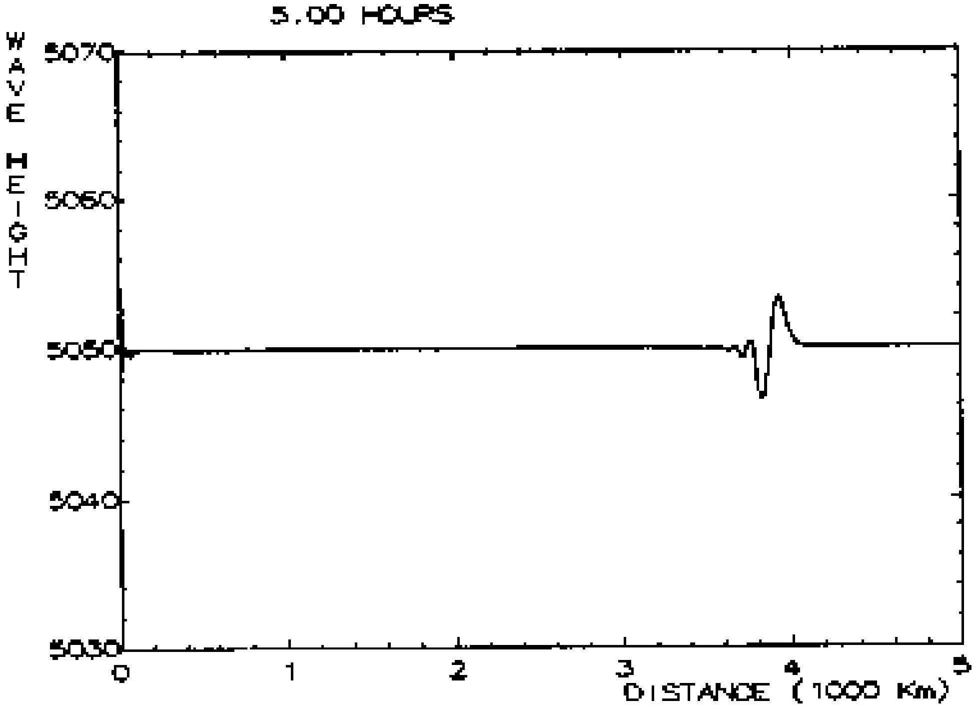


Figure 11. The wave profile in meters as a function of radius for the Fritz LaPalma wave at 30 kilometers (Figure 8) meter deep water for the full Navier Stokes Model. The wave amplitudes are about 2.15 times larger than those of Figure 6.


2.50 HOURS
WAVE HEIGHT
5070
5060
5050
5040
5030
0
1
2
3
4
5
DISTANCE (1000 Km)


5.00 HOURS
WAVE HEIGHT
5070
5060
5050
5040
5030
0
1
2
3
4
5
DISTANCE (1000 Km)