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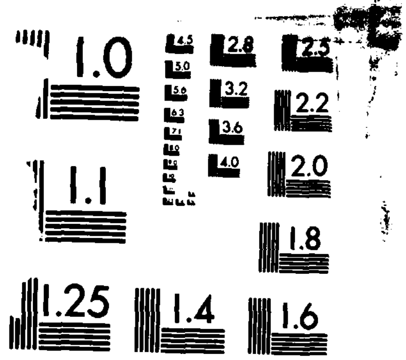
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Measurements of Internal Waves in the Strait of Gibraltar Using a Shore-Based Radar

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Foreword

This report deals with internal waves off the Strait of Gibraltar, but more importantly it shows how a sharing of information between dissimilar agencies can benefit both. Information provided by the U.S. Space Shuttle crew of Mission 41-G helped Navy ocean scientists develop a theory on how internal waves travel through the Strait. This report is an example of how this combined effort presents new approaches to studies of the ocean that would otherwise be unavailable.

R. P. Onorati, Captain, USN
Commanding Officer, NORDA

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Frontispiece. The Strait of Gibraltar and the western Alboran Sea as seen from the approximately 200 km altitude by the U.S. Space Shuttle crew of Mission 41-G at 12:21 hrs GMT on 11 October 1985. The photograph shows the noon sun reflecting off variations in roughness of the ocean surface (very little of the photograph contains clouds). In the photograph, the most prominent roughness features are those seen bowing eastward into the Mediterranean Sea. These features are the surface manifestations of a packet of ten or more internal waves. It should be emphasized that the internal waves have very small surface amplitude, and it is likely that the brighter reflections in the wave groups come from the bands of disturbed (and thus, more reflective) water that comprise the rip area. This report describes tidal-induced internal waves in the area of Gibraltar and infers that the waves may not become sorted into discrete packets until they leave the Strait. This shuttle photograph shows the surface manifestation of several wave packets advancing eastward from the Strait through the Alboran Sea.

The photograph raises the interesting supposition that the successive wave packets do not remain separate from one another, but eventually blend in overlapping patterns. It indicates that the fastest wave in the lead of one packet may in time catch up and pass the slower trailing waves in the preceeding packet. In situ data has not as yet shown this to be true, and studies to test this hypothesis have yet to be made. This, however, is a good example of how the Space Shuttle photographs can present approaches to the studies of the ocean that might not have been made without their broad and often beautiful views (NASA photograph 34-081).

Executive summary

During the period 22–24 October 1983, a feasibility study was made on the use of standard shore radars to monitor the temporal and spatial distribution of internal waves. A radar (150 m elevation) situated at Gibraltar was used to monitor the surface manifestations of internal waves in the Strait of Gibraltar during three semidiurnal tidal periods. The eastward progression of internal waves within an arc approximately 19 km from the radar was observed. These observations fill a gap in the evolution of the surface signatures of internal waves between the small-scale view of ship radars and the large-scale view afforded by satellites and the Space Shuttle.

Acknowledgments

This work would not have been possible without the assistance of the Royal Air Force and Navy. Exceptional thanks go to Desmond Hyde, principal meteorological officer of the Royal Air Force Meteorological Office, Gibraltar, for his kind assistance in arranging our stay at the Windmill Hill Radar Station and also to the Royal Navy watch standers at the Station, who were invaluable in providing experienced advice. Thanks should also go to Gregorio Parrilla, Instituto Espanol de Oceanografia, for the tide gauge data from Algeciras and Tarifa. T. H. Kinder was funded by the Office of Naval Research, Coastal Sciences Division.

Contents

Measurements of internal waves in the Strait of Gibraltar using a shore-based radar

1. Introduction

Internal waves associated with the tides in the Strait of Gibraltar long have been studied (e.g., Jacobsen and Thompsen, 1934; Cavanie, 1972; Boyce, 1975; Lacombe and Richez, 1982; and Kinder, 1984). These studies indicate that the waves usually occur in groups, or packets, and that passage of the wave packets generally follows the period of the semidiurnal tide. Indications are that the waves are generated at, or near, the bathymetric sill located at 5°45′W, slightly west of the narrowest section of the Strait (Fig. 1). In addition, the waves manifest themselves at the surface as north-south lines of roughness or tide rips. Some investigators (Frassetto, 1964; Zigenbein, 1969; and Cavanie, 1972) have observed these surface disturbances on ship radar. Numerous ship captains (e.g., *Mariner Observer*, 1926; 1938; 1948) have also reported this phenomenon, as well as reporting steering problems on encountering the edges of these disturbances.

These surface effects have also been noticeable in U.S. Space Shuttle photographs taken of the Strait of Gibraltar (frontispiece). In this example, several internal wave packets are indicated by the reflection of the sun off arcuate patterns of surface roughness. Spatial displays of the internal waves' surface manifestation are best seen at high altitudes,

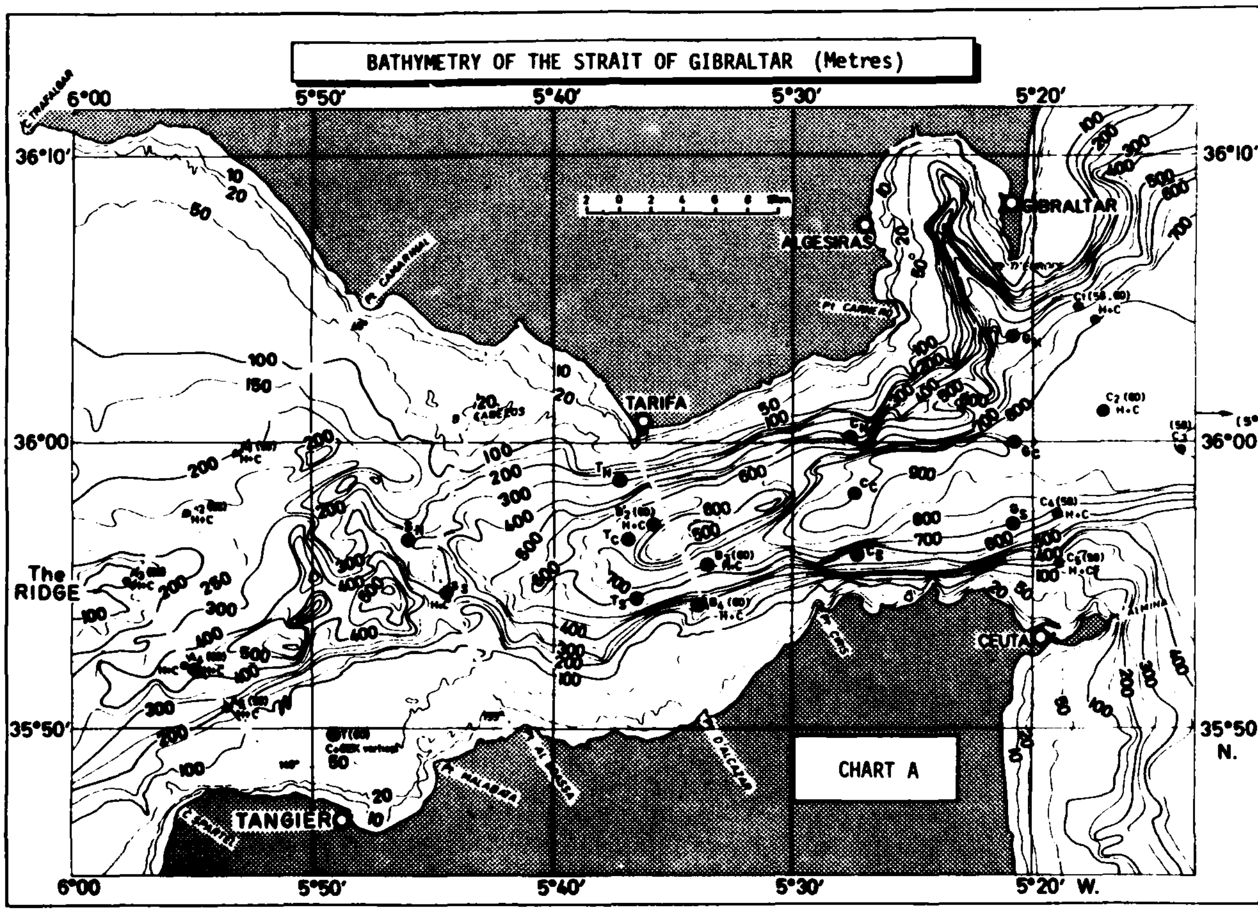

Figure 1. The bathymetry of the Strait of Gibraltar (Lacombe and Richez, 1982).

and similiar displays have been seen regularly by one of the authors during research aircraft flights over the Strait of Gibraltar during 1982–1984.

This phenomenon has been noted in other regions of the world. U.S. astronauts, taking part in the 1975 Apollo-Soyuz mission, photographed long-wave periodic phenomena in the Andaman Sea (Osborne and Burch, 1980). Analogous signatures in the Sulu Sea were observed in visible wavelength imagery obtained from satellites of the Defense Meteorological Satellite Program. Apel et al. (1985) stated that the features were probably the surface effects of large, nonlinear internal waves produced by tidal flow over bathymetric features.

Osborne and Burch (1980) gave in situ evidence that the internal waves in the Andaman Sea were actually solitons. They inferred that the shallow regions near northern Sumatra are the source of the solitons and that these solitons are generated in phase with the tides. They described the cause of the surface roughness as being related to horizontal surface convergence. Kinder (1984) suggests that the internal waves in the Strait of Gibraltar also become solitons and that the waves are probably generated at the bathymetric sill during tide reversal.

La Violette (1984) published a NOAA satellite visible-range image of the Strait of Gibraltar that showed a semicircular feature bowing eastward from the Strait into the Alboran Sea (Fig. 2). This feature resembles the arcuate structures photographed from the Space Shuttle, but is closer to the Strait and (probably because of the coarser resolution of the sensor) showed a single rather than multiple waves. If a propagation speed of 1.5 m/sec is used, the position of the feature in this satellite image correlates with the arrival of an internal wave packet at current meters concurrently deployed farther to the east (Kinder, 1984).

Much of the problem with quantitatively observing the internal waves in the Strait has been the difficulty in getting a time series of spatial measurements. Although the surface manifestations of the internal waves in the Space Shuttle photography are informative in providing a spatial

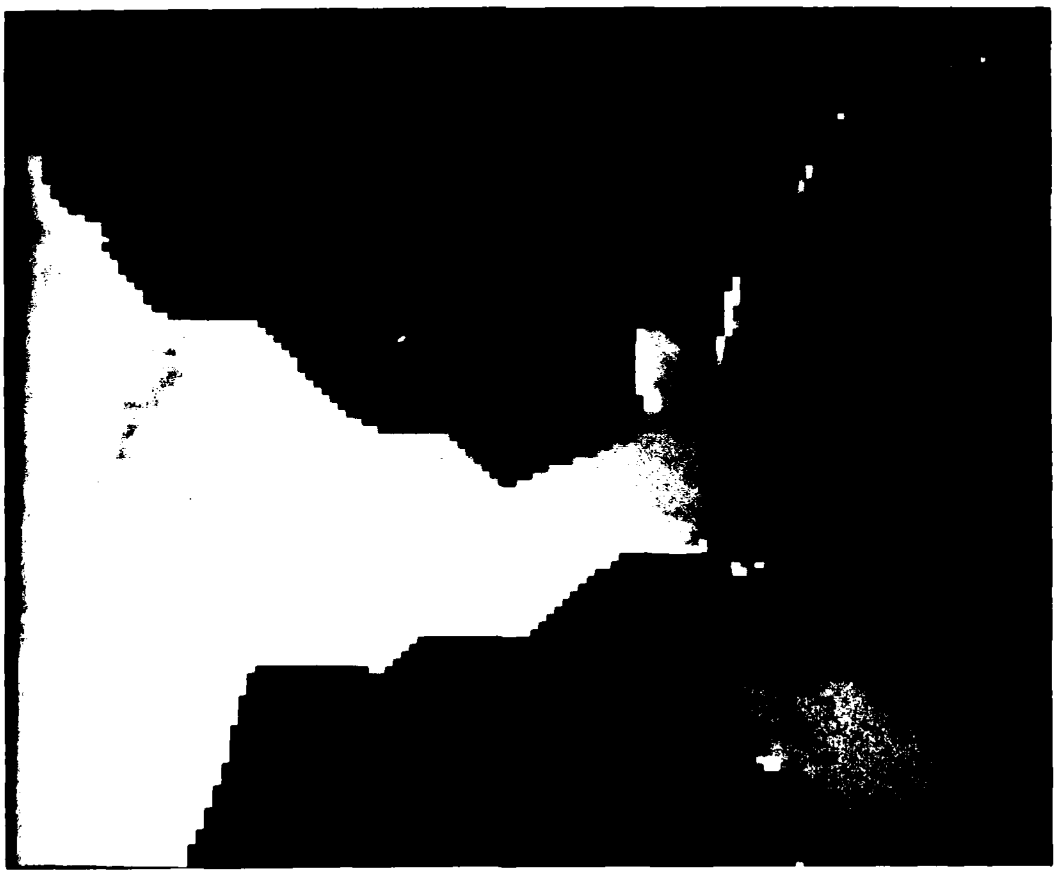

Figure 2. A computer-enhanced, visible-range NOAA image (#6284) for 14:29 GMT, 11 September 1982 (La Violette, 1984). As with the Space Shuttle photograph, the definition of the arcuate feature is a result of sunlight reflecting off varying roughnesses of water. The resolution of the satellite sensor is approximatly 1 km.

display, their isolated presentations have obvious temporal limitations. The surface features of the waves seen in shipboard radars look promising in providing repeated spatial displays. However, the ship radars are limited in that the sea clutter containing the wave information can be detected only a short distance from the ship. This limitation is caused partly by the low elevation of the average ship radar antenna above the sea surface. Removing ship motion from the temporal evolution of the surface patterns is a further complication with this technique.

For this reason, the 150 m elevation of a shore-based radar operated by the British Royal Navy at Windmill Hill, Gibraltar, seemed ideal to test the feasibility of using a radar to obtain quantitative temporal and spatial measurements of internal wave fronts. From this station, sea clutter in the radar screen, which contained the surface features of internal waves, could be detected to a range of approximately 19 km (the actual distance varied with sea and atmospheric conditions). Wave speed measurements and evidence of the wave refraction are some of the results that might be expected to come from such a study.

The following remarks present the results of measurements made at the Windmill Hill Radar Station during the period 22–24 October 1983. This short study is a prelude to a longer period study.

2. Description of measurements

Although observations of the internal wave packets began on 22 October 1983, only the measurements of two wave packets, one on the morning of 23 October and the other on the night of 23/24 October, were recorded. The method of measurement was to take those radar bearings and ranges of points along each wave front that would best describe each wave. The disadvantage of this procedure was that the waves were moving as their positions were recorded. With practice, however, a rapid recording skill was developed. An average of slightly more than four measurements were made along each wave front with an average total measurement time for a single wave of 2 min. Measurements of the entire wave packet were repeated roughly every 15 min.

A reasonable estimate for the errors in individual phase speed calculations is to assume an accuracy in time of 2 min, i.e., the time of one wave observation and a bearing error of about 1°. At 1.25 m/sec, the 2 min translated to 150 m along line x—x′ (this error would increase with faster phase speeds), and the 1° bearing error translated to about 170 m along x—x′ (assuming an average range of 10 km). Thus, the speed error for estimates at 15-min intervals is 320 m/15 min = 0.35 m/sec. This encompasses all but a few outliers, and suggests that we were not able to detect small changes in phase speed between observations. If the observation period is considered as a whole, accuracy becomes much better. For the 3 hours the wave packet was observed on the night of 23/24 October, the accuracy is 320 m/3 *h* = 0.03 m/sec.

Recordings began on the packet of waves for the morning of 23 October at 08:26 GMT and continued until 10:31 GMT. The packet was already well developed when these observations began. Indications are that the lead wave had probably been immediately south of Gibraltar 2 hours prior to the start of observations, or approximately 06:30 GMT. The wave packet associated with the next tidal period of 23 October appeared south of Gibraltar at 20:55 GMT. Since the progress of this wave packet was monitored across the entire radar field, it was the more complete of the two sets. Also, by this time the observers had become skilled at making the measurements, so the nighttime set is the better recorded of two data sets.

Hourly tide observations were obtained from the Instituto Espanol de Oceanografia for Algeciras and Tarifa (Fig. 3). The reference tide presented here will always be Tarifa. The tides for 23 October occurred three days after the full moon.

The data for the internal wave packet for the night of 23/24 October are presented in various ways in Figures 4 and 5. Figure 4 (showing the wave packet at the start, middle, and end of observations) demonstrates how the wave packet first appeared on the western portion of the radar screen, marched across the screen, and then began to disappear off the screen to the east and northeast. The bulk of the Gibraltar massif blocked radar coverage of the northeastern area, and no data is available in this shadow region.

Both refraction and spreading showed in the radar patterns. Near the European coast, the wave fronts became nearly parallel to the coastline, and as the wave packets passed Gibraltar, a nearly stationary thick line of radar return formed across the entrance to the Bay of Algeciras (this is not shown in the figures because our study concentrated on the wave's progression in midchannel). Radar ranges were inadequate to determine if a similar pattern developed along the African coast. (Curiously, Cavanie (1972) observed the waves only near the African coast.) We assume that the change in orientation in the inshore part of the wave fronts was caused by the refraction of the waves as they entered nearshore shoal waters. (Note

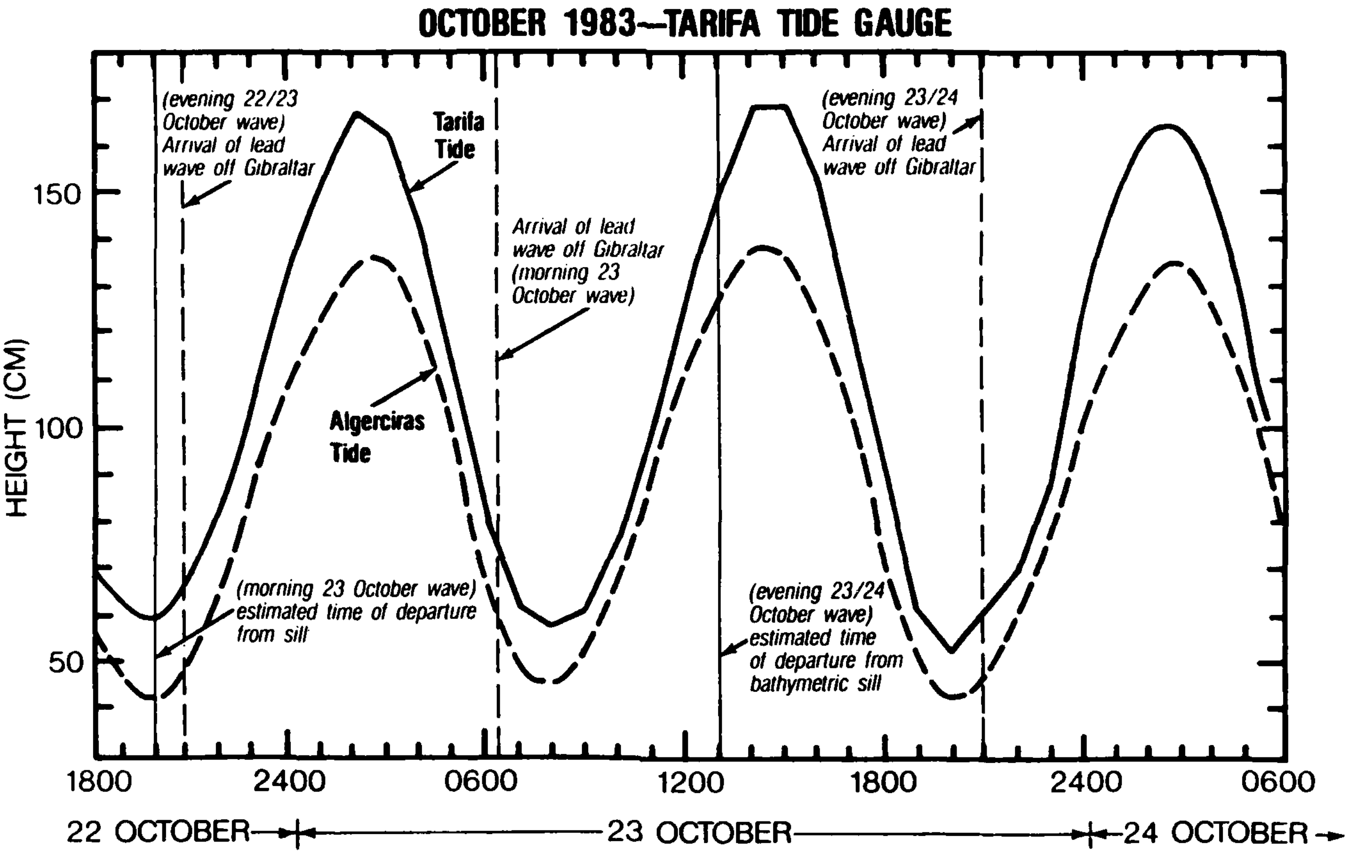

Figure 3. Hourly tide gauge data from Algeciras and Tarifa. All tidal references used in the text refer to the Tarifa tides. The Algeciras data (dashed) are presented only to show the tide conditions near the radar station.

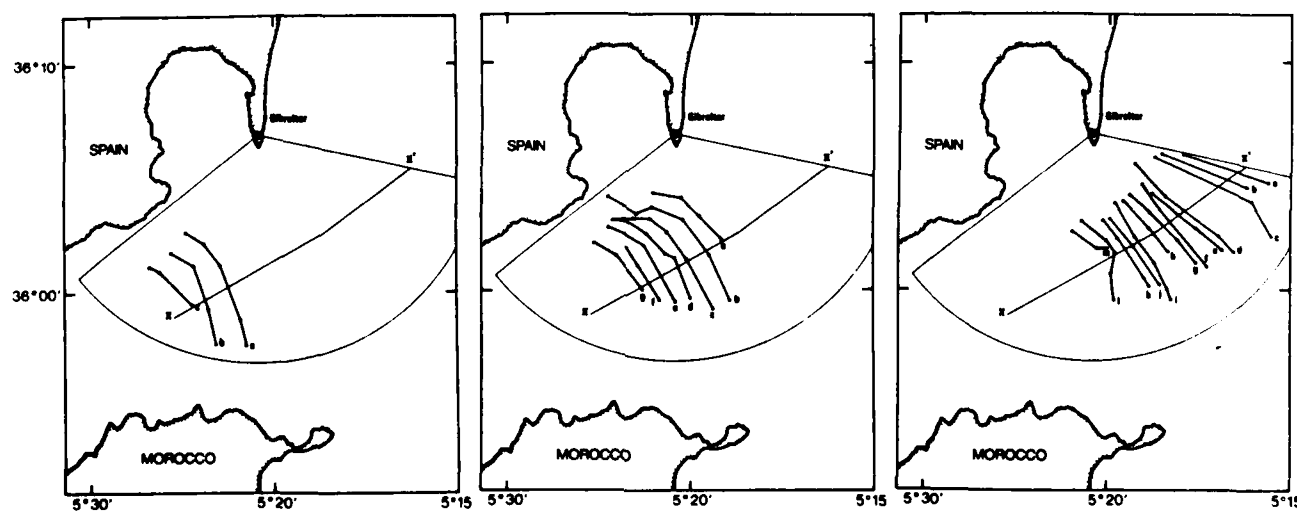

Figure 4. The positions of the internal waves in the nighttime packet of 23/24 October at (a) 20:55 GMT, (b) 22:25 GMT, and at (c) 00:40 GMT.

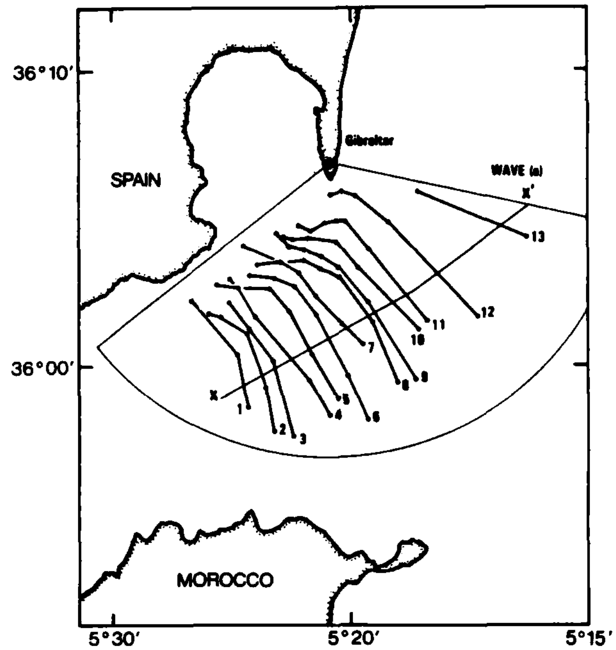

Figure 5. The successive spatial displacements of the lead wave (wave a in Fig. 4) of the internal wave packet of the night of 23/24 October 1983.

the wave fronts in the Bay of Algeciras in the Space Shuttle photograph presented in the frontispiece.)

As the waves left the eastern end of the Strait and entered the Alboran Sea, a change in orientation to a more east/west direction took place (Figs. 4 and 5). Although we could not see the entire wave front, we assumed that the portion beyond radar range was oriented in a more north/south direction to form a bow similar to those shown in the NOAA satellite image in Figure 3 and in the Space Shuttle photographs (frontispiece).

3. Estimate of wave speed

Wave speeds were calculated using the distance between each wave position along the line x—x′ and dividing these distances by the elapsed time. (The line x—x′ is in the same location in all of the figures.) The line was chosen as being the closest line to the longitudinal axis of the strait that would include sufficient data for analysis. It is nearly orthogonal to the wave fronts except for the waves close to the eastern edge of the area, which were not included in the calculations.

The average phase speed calculated by the displacement of the lead wave from the observation at 19:45 GMT, 23 October to 00:52 GMT 24 October gives an average speed of 1.1 m/sec. This speed is on the low range of earlier estimates (Table 1).

The linear phase speed for first-mode internal waves can be estimated by using hydrographic data. Although no hydrographic data is available for October 1983, data from hydrographic station 172 (occupied in October 1982 by Kinder et al. (1984) and situated just east of the Strait) is probably a reasonable approximation of the mid-channel conditions in 1983. Assuming two homogeneous layers of thickness $h = 95$ m and $h = 585$ m, and of densities $\rho_1 = 1.027$ g/cm^3 and $\rho_2 = 1.029$ g/cm^3, the phase speed is

$$C = \left(g \frac{\rho_2 - \rho_1}{\rho_1} \frac{h_1 h_2}{h_1 + h_2}\right)^{1/2} \sim 1.25 \ m/sec\ .$$

The phase speed for nonlinear internal waves would be higher by an amount proportional to the wave amplitude (e.g., about 5% increase for 10 m amplitude: Osborne and Burch (1980), Eq. 15).

4. Discussion

The wave packets arrived at Gibraltar at different phases of the semidiurnal tide (Fig. 3). Both nighttime packets arrived at Gibraltar 1 to 2 hours after low tide, while the morning packet arrived 1 to 2 hours before low tide. It is likely that the different arrival times was caused by the diurnal tidal current. This difference is strongly indicated by the match in the phase times of the two nighttime packets. Although the tidal height is predominantly

Table 1. Measurements of phase speeds of internal waves in the Strait of Gibraltar.

Frassetto (1964)	1.3 knots (0.7 m/sec) 4.0 knots (2.0 m/sec) 4.4 knots (2.2 m/sec)
Zigenbein (1970)*	1.6 m/sec 2.2 m/sec 2.6 m/sec 1.2 m/sec 1.6 m/sec
Cavanie (1972)	3.5 knots (1.8 m/sec) 4.3 knots (2.2 m/sec) 3.8 knots (1.9 m/sec) 3.8 knots (1.9 m/sec)
Lacombe and Richez (1982)	3.0 knots (1.5 m/sec)
La Violette, Kinder and Green (this report)	1.1 m/sec

*Individual waves measured between thermistor chain moorings. Speeds may be inflated if moorings were not orthogonal to waves.

semidiurnal (the form number $F = (K + O_1)/(M_2 + S_2) = 0.08$, Defant (1961)), there is a significant diurnal current in the Strait. Cavanie (1973) found strong diurnal currents in records of four days duration. He showed an internal wave front arriving off Gibraltar about 7.5 hours after high tide at Tarifa for one semidiurnal tide, and about 3.5 hours after high tide of the subsequent semidiurnal tide. H. L. Bryden (personal communication) found that the diurnal component was 20% of the semidiurnal component in his analysis of a two-week current mooring data set taken near the bathymetric sill in 1984.

Although the internal waves appear to be generated at the sill more than 35 km away, the area about Gibraltar may still be in the near-field where the waves have not yet evolved into well-ordered solitons (e.g., Maxworthy et al., 1984). The data shown by Lacombe and Richez (1982, 1984) and by Zigenbein (1969, 1970) suggest that this may, indeed, be the case. If so, then the identification of individual wave crests may not be possible. At times, it appeared as if the wave fronts crossed one another (see lines 4, 5, 7, and 8 in Fig. 5). If so, then the waves may not be discrete but still in an unsorted state. Thus, the fastest wave in a given packet might not yet have become the lead wave in the area we were observing. The sorting of the waves into well-organized solitons may occur nearby to the east. Clearly, a longer series of more accurate measurements is required to address the question of phase speed variation and wave front uniqueness.

5. Conclusion

This study demonstrates the major advantage of radar observations of internal waves in the Strait of Gibraltar: i.e., the large areal realization of internal wave front patterns and their temporal evolution. In addition, we have shown that a relationship exists between the features seen in both the U. S. Space Shuttle photographs and satellite imagery and the measurements of internal waves made from radars and current-meter mooring data.

Because the experiment was meant to be a feasibility study, the results are limited. We hope they will form the start of a longer study. Continuous recording using a clock-activated camera mounted on a radar screen will be the next step. Such a study will provide accurate phase speeds, wave separations, and more detailed observations of refraction and spreading effects. These observations should extend at least over one full spring-neap tidal cycle to derive the variations due to the strength of the tide.

To realize the full value of such data, concurrent in situ measurements are needed. These measurements would relate the density and current conditions that occur at the sill to those in the radar area. Point measurements, such as current moorings or shipboard hydrographic and velocity profiling will allow quantitative estimates of relationships between phase speed, wave width, wave separation, and wave amplitude. These measurements could then be compared to theory and relevant laboratory experiments.

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During the period 22–24 October 1983, a feasibility study was made on the use of standard shore radars to monitor the temporal and spatial distribution of internal waves. A radar (150 m elevation) situated at Gibraltar was used to monitor the surface manifestations of internal waves in the Strait of Gibraltar during three semidiurnal tidal periods. The eastward progression of internal waves within an arc approximately 19 km from the radar was observed. These observations fill a gap in the evolution of the surface signatures of internal waves between the small-scale view of ship radars and the large-scale view afforded by satellites and the Space Shuttle.

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