Conf-950244--1

UCRL-JC-119080
PREPRINT

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This paper was prepared for submission to the
IEEE Fifth Working Conference on Current Measurement
St. Petersburg, Florida - February 7-9, 1995

November 3, 1994

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Near-surface Current Meter Array Measurements of Internal Gravity Waves

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Abstract—A measurement capability using a horizontal array of 10 S4 current meters mounted on a stiff floating structure with 35m aperture has been developed to support interpretation of radar imaging of surface effects associated with internal gravity waves. This system has been fielded three times and most recently, has collected data alongside the sea-surface footprint of a land-fixed radar imaging ship-generated internal waves.

The underlying need for this measurement capability is described. The specifications resulting from this need are presented and the engineering design and deployment procedures of the platform and systems that resulted are described. The current meter data are multiplexed along with meteorological and system status data onboard the floating platform and are telemetered to a shore station and on to a data acquisition system. The raw data are recorded, and are then processed to form space-time images of current and strain rate (a spatial derivative of the current field). Examples of raw and processed data associated with ship-generated internal waves are presented.

I. Introduction

Surface manifestations of oceanic internal waves have been observed by various types of imaging remote sensors for many years. Radar images of ambient internal waves have been observed for almost 20 years [1]. Images of internal waves generated by bodies such as ships are the subject of ongoing investigations within the Joint UK/US Radar Ocean Imaging Program which provides support for this research.

Such phenomena appear as coherent patterns of light and dark contrast over an underlying background, corresponding to relatively rougher and smoother water surfaces, respectively, as shown in the X-band, real aperture radar intensity image of surface ship-generated internal waves in Fig. 1. The ship is the bright object at 2300 m range, 500 s time, and the internal waves it has generated are the V-shaped lines to its right. (Details

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This work was performed under the auspices of the Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-Eng-48. This work is supported by the Joint UK/US Radar Ocean Imaging Program whose US sponsor is Donna Kulla of the Office of the Assistant Secretary of Defense, C3I. Technical direction for the Joint UK/US Program is provided by Lawrence Livermore National Laboratory, Imaging and Detection Program, Rick Twogood, Program Leader.

about the radar, ship, environmental conditions, etc. for this particular image are discussed later.) The working hypothesis within the remote sensing community for what causes this contrast is that patterns of surface currents modulate the naturally existing sea surface causing similarly shaped geometric patterns of reduced or enhanced roughness, which in turn show up as patterns of dark and light in the radar images. Similar patterns have been observed in radar images of tidal flows over shallow bottom topography which also cause patterns of surface currents [1].

A mathematical relationship between the radar modulations and the hydrodynamic currents believed to cause them is referred to as the "modulation transfer function," or "MTF." For special cases, MTF can be represented as the ratio of the normalized radar intensity modulation to the hydrodynamic strain rate, defined as the spatial derivative of the velocity component in the radar look direction. In general, MTF can be a complicated function of environmental, radar, hydrodynamic, and geometric parameters.

Although many radar images exist that contain phenomena related to surface current-induced modulations, quantitative representations of the current fields for the purposes of interpreting the modulations in the radar returns are not usually measured directly but rather are computed using some hydrodynamic model or code. This is because the measurement requirements for these currents are very difficult. The currents desired to be measured are small (a few cm/s or less), it is necessary to measure spatial patterns of the currents over tens of meters (spatial derivatives of the currents influence the MTF), sensor motion is a problem for any velocity measurement (a much smaller problem for scalars such as temperature), environmental currents such as tidal currents or ambient internal waves are present, and surface wave motions may contaminate the measurements. One other attempt to characterize surface currents and strain rates extrapolated point current measurements at depth to the surface, requiring assumptions of monochromatic waves, mode 1, and used internal wave (IW) dispersion relations derived from density profiles of the water column [2].

Fig. 1. Radar intensity image of ship-generated internal waves.

All of these difficulties aside, a direct measurement of MTF would clearly provide a major step forward in our understanding of the radar imaging of internal waves problem. We at Lawrence Livermore National Laboratory (LLNL) have developed a new measurement approach for surface current and strain rate and have completed the first steps to evaluate it.

The goals of this current meter array measurement project are:

1. Develop the capability to measure at-sea surface currents and strain rates having magnitudes and spatial scales meaningful to internal waves of interest; 2. Provide full-scale hydrodynamic data to support interpretation of radar imagery; and 3. In conjunction with nearby radar imagery of the ocean surface, provide a direct measurement of MTF.

II. Measurement Concept and Requirements

A horizontal array of n near-surface current meters is required to measure horizontal water velocity $\bar{v}_i(x, y, z_o, t)$, $i = 1, 2, \dots, n$ all at the same (shallow) water depth z_o . We would like n to be as large as possible.

The array should have one long dimension that is oriented in the approximate direction of internal wave propagation (and radar look direction). Multiple sensors in the direction of internal wave propagation are required to spatially differentiate the current measurements to derive strain rate. A carefully devised algorithm is needed to estimate the current and strain rate fields because the measurements are sparse and are corrupted with environmental currents and system noise.

It is desirable to make the current meter array as long as possible. Ideally, the array should have as much aperture as the radar images it is designed to interpret, hundreds of meters or more. Such a length is not possible with all of the other constraints. Internal wave wavelengths of interest are fairly short, 10 - 30 meters or so. The current meter array length should be at least that long.

Expected current and strain rate magnitudes of the internal waves of interest are in the ranges 0.3 - 10 cm/s and $5 \cdot 10^{-4}$ and $5 \cdot 10^{-2} \text{ s}^{-1}$, respectively. These ranges help specify the required sensitivity and accuracy of the current meters.

The choice of sensor depth is influenced by the orbital velocities of surface gravity waves that extend beneath the surface. These orbital velocities decay exponentially with depth and their magnitudes depend on the surface wave amplitude and wavelength. Furthermore, most current meters need to be submerged to work properly and some means is needed to interpret measurements made at some shallow depth in terms of conditions at the surface.

This concept is straightforward in principle, but is challenging from engineering, sensor accuracy, and logistics points of view. Some very difficult requirements emerge:

1. The structure must be very rigid. The current meters cannot be measuring structural vibrations or other motions relative to one another in the (low) frequency bands of interest. The sensor spacing must be maintained to within a few percent.

2. The measurement platform must be stable to surface wave motions.

3. The structure must be shipped to, and be deployable at, sites of interest and must have sufficient maneuverability for deployment and repositioning once in the water.

4. The structure must be rugged enough to survive the dynamic loads of surface waves and towing by surface craft. All components must withstand the corrosive sea water environment.

These requirements all point to a large, heavy, very stiff structure which imposes difficult, but not insurmountable transportation, deployment, and recovery problems.

Sensor requirements are as follows:

5. The current meters must have sub-cm/s accuracy and resolution. Because the internal wave currents of interest are low frequency (hundredths of Hz or lower), sensor accuracy can be improved by increasing measurement integration time.

6. The current meters must have ocean-going durability.

7. A short-range (a few miles) telemetry link is desired to monitor the data in real time and remotely download the current meter measurements.

8. Environmental current levels are expected to be comparable to the internal wave currents of interest. We think some noise rejection through signal processing of the array data will be possible, particularly if directional and/or time-of-arrival information is known.

9. The water column must be measured separately with a vertically profiling conductivity-temperature-depth (CTD) package and a vertically profiling current meter to determine internal wave dispersion relations and modal eigenfunctions to help interpret the data.

10. When used as a complement to radar data, meteorological data should be collected on the current meter array measurement platform. Wind speed and direction 10 meters above the water surface should be measured, along with air and water temperature.

III. Current Meter Array Description

LLNL CMA Structure

The LLNL Current Meter Array (CMA) refers to the array of 10 two-component (both horizontal) current meters, their floating measurement platform structure, their data conditioning and telemetry system, and all other subsystems that reside on the floating platform.

A photograph of the CMA taken during its first deployment at AUTECH, Andros Island, Bahamas, in spring 1993 is shown in Fig. 2. Structurally, it consists of an upper frame made out of 5-meter long sections of 10-inch and 5-inch diameter aluminum pipe, mostly filled with foam to provide buoyancy for flotation, and a flooded lower frame made out of 5-meter long sections of 4-inch diameter fiberglass pipe, to which the current meters are attached by means of fiberglass struts. The bottom frame is connected to the top frame by means of nylon rope. In the configuration shown in Fig. 2, the bottom frame is strapped to the upper frame with cargo straps, and the ropes connecting the two frames are slack. This is the configuration for assembly, lifting in and out of the water, and towing. When deployed in open water, the bottom frame is unstrapped, lowered by winches to an extended position, and is suspended from the top frame by the nylon ropes. The sensor struts are rotated 90 degrees to their vertical (data collection) configuration.

The CMA is a large structure, 36 meters long, 5 meters wide, and when its bottom frame is fully extended, the current meters are at a depth of 5 meters. Its dry weight is approximately 10,000 lbs. Two cranes, operated in a coordinated fashion are required to lift it in and out of the water.

A second deployment was made successfully at AUTECH in November 1993. The CMA configuration for that deployment was very similar to that shown in Fig. 2.

The LLNL current meter array, as configured for its third deployment, in Loch Linnhe, Scotland in September 1994, is shown in Fig. 3 on its assembly stands. Its Scotland configuration added the following features:

- New probe struts that attach directly to the main aluminum frame, eliminating the need for the lower fiberglass frame fielded during the two prior deployments at AUTECH.
- Two met stations, one on a tower 10 m above water level, and the other at 1 m above water. Wind speed and direction, air temperature, and sea surface temperature were added.

The current meter array secured to its mooring in Scotland and in a measurement configuration is shown in Fig. 4.

Fig. 2. LLNL Current Meter Array during deployment at AUTECH, Bahamas, Spring, 1993.

The current meter array transmitted its data via telemetry link to a shore station, located inside LLNL's cargo transportainer (which served a dual function as an analysis lab after the cargo was emptied).

For the AUTECH deployments, the CMA was in a free-floating mode (not moored) and thus aligned itself naturally with the direction of the sea, which generally changes slowly in time. We used two pingers (one on each end of the CMA) to track CMA position and orientation during data collection periods by AUTECH's underwater range. This approach worked very well. A DGPS receiver was attached to all ships and measurement platforms in the subsequent Scotland experiment. A precision compass measured CMA orientation in Scotland.

Current Meters

The velocity sensors are S4 current meters made by InterOcean Systems, Inc., San Diego, CA. The S4's measure two orthogonal horizontal components of velocity and can transform them internally to absolute north and east components using an internal compass. The S4's have tilt sensors that compensate for sensor motions off the vertical caused by platform motions.

Fig. 3. LLNL Current Meter Array prior to deployment in Scotland, September 1994.

Each S4 is connected to the telemetry box by its individual electrical cable.

The manufacturer's specifications for the S4 are given in Table 1. The maximum sampling rate is 1 sample per 1/2 second; we programmed the S4's to internally average for 10 seconds and report once every 10 seconds.

Table 1. Manufacturer's specifications for S4 current meter

Range	0 - 50 cm/s
Resolution	0.03 cm/s
Accuracy	2% reading $\pm$ 1 cm/s
Noise	0.05 cm/s (10 s average)
Weight	11 kg (air), 4 kg (water)
Diameter	25 cm

Telemetry System

The telemetry system is housed inside a watertight box atop the CMA. Inside the box are the wet-side electronics that consists of 10 interface units, multiplexers, and a telemetry transmit unit. External to the box are electrical connectors for the S4 sensor cables. The wet-side unit transmits a data stream consisting of S4 data, meteorological data, and system status data via an encoded RF link. During each CMA deployment, S4 data that were internally averaged over 20 samples were transmitted every 10 seconds and met/system status data were transmitted every minute. The shore unit is a receive station which we interface to our data acquisition system.

IV. Example Results

The results chosen for presentation in this paper were obtained during a recently completed field experiment conducted in Loch Linnhe, Scotland (Fig. 5), in September 1994, hereafter referred to as LL94. It involved imaging ship-generated and ambient internal waves with a land-based, dual-frequency, dual-polarization real aperture radar operated by the UK. Two wake generating ships were used; the ship corresponding to the data presented in this paper is the R/V Colonel Templer, a converted UK deep-sea trawler 56 meters in length and 1300 tons displacement. Considerable in-water data were collected by both US and UK investigators, notably including the LLNL current meter array (CMA), and also UK shear spars, water column profiling sensors, and meteorological instruments. A diagram of Loch Linnhe showing locations of radar, current meter array mooring, R/V Calanus mooring (where environmental profile measurements were collected) and the nominal ship track is presented in Fig. 6.

Fig. 4. LLNL Current Meter Array at its mooring in Scotland, September, 1994.

Current Meter Configuration

A diagram showing the sensor configuration on the CMA for LL94 is shown in Fig. 7. The current meters are uniformly spaced at 3.75 m and are staggered from port side to starboard side. The current meters are numbered beginning at the bow, and sequentially increasing toward the stern.

The S4 current meters were set up to transmit data in XY format (as opposed to NE format used at AUTECH where each S4 combines its velocity measurement with its internal compass measurement). The S4's were mounted very carefully so that they were all oriented the same way (estimated precision: $\pm$ a few degrees).

Examples

A CMA image of ship-generated internal waves was obtained on September 4, Run 2. During this run, Colonel Templer was traveling uploch at 2 m/s in a strong near-surface stratification having a peak Brunt-Vaisala (BV) frequency of 0.11 rad/s at a depth of 2 m.

Fig. 5. Map of Scotland showing Loch Linnhe experiment site.

The raw single sensor time series data are shown in Fig. 8. During the ship runs, we observed visually displays such as this for evidence of a wave like signal propagating through our array. Ten channels of the cross-track component of current are shown, with sensor 1 (nearest CMA bow, nearest ship track) on the bottom and sensors 2,3,...10 proceeding up the plot with each sensor offset from the previous by 10 cm/s. (Note that for this particular case, sensor 9, top trace in Fig. 8, was giving erroneous results but came back to normal shortly after this run). Time = 0 corresponds to the time of closest-point-of-approach (CPA) of the wake-generating ship to the CMA. The ship-generated IW appears as a sequence of about three wave forms beginning on Sensor 1 at about 800 s after CPA, and appearing sequentially on Sensors 2 through 8 and on Sensor 10, persisting until about 1200 s.

Space-time grey-scale images corresponding to the time series presented in Fig. 8 are shown in Fig. 9. The time series data were processed into current and strain rate images using the following procedure: 7-point median filter followed by 0.02 Hz lowpass filter in time, sensor by sensor, then a 4th order polynomial fit in space, at each time step. The strain rates are obtained by analytically differentiating the polynomials.

As expected, the three wave forms in the time series show up as three coherent inclined contours in the image. The filtering and smoothing operations in the processing have eliminated some of the noise seen in the raw data. The wavelength of these features appears to be about the length of the array, 30 - 35 m, and their period is approximately 150 - 200 s. (The peak BV period is about 60 s.) The phase speed of these features was estimated to be 24 ± 2 cm/s. This phase speed is consistent with time-of-arrival after ship's passage of the leading edge of

Fig. 6. Map of Loch Linnhe, Scotland, showing measurement locations and ship tracks

Fig. 7. CMA sensor configuration for Scotland experiment.

the array and the nominal distance off-track of the current meter array (125 meters). The feature at about 2000-2300 s may be a reflection of these waves from the shore.

Quantitative estimates of the details of the current and strain rates such as magnitudes and wave forms are obtained by a shift-and-add method, where each time series is shifted by its separation distance from Sensor 1 divided by the 24 cm/s estimated phase speed. The idea is to reinforce coherent wave forms and beat down any noise that is incoherent. The results, 1D average time series, are shown in Fig. 10. Here, it is seen that representative values for current and strain rate are $3-5$ cm/s and $7 \cdot 10^{-3}$ to $1 \cdot 10^{-2} \text{ s}^{-1}$, respectively. The strain rate having higher signal-to-noise than the current is evident in this figure.

These CMA data correspond to the radar image shown in Fig. 1. The particular range-time radar image (much like the current and strain rate images presented above) is for an X-band, VV-polarization, 6 degree grazing angle radar, with an average wind speed of 5.5 m/s nearly into the radar look direction. The CMA position is 125 meters off-track in the far range half of this radar image. The radar image shows the wake to be stronger in the near-range half of the image than in the far-range half. In fact, a three-wave feature is not seen in the far-range half of the radar image. We do not have a good explanation of why not yet. For this case, the CMA was approximately 1200 m uploach of the radar footprint.

We believe that these space-time images of surface current and strain rate are first-of-a-kind, and will be a valuable tool in future experiments for interpreting radar imagery.

V. Future Analysis

Future analysis of the current meter array data will include a closer examination of ship-generated internal waves from other ship passes as a function of ship type and speed. Further comparisons with radar images will be made, and estimates of MTF will be attempted. (Preliminary MTF estimates have been made and we are not optimistic that any parametric MTF characterization is possible with this data set.)

Fig. 8. Current meter time series, cross-track component, entire run of ship-generated internal wave.

Fig. 9. Cross-track current and strain rate images, entire run of ship-generated internal wave.

We will try some type of directional filtering, including an approach where along-track velocity component data will be used to suppress internal waves generated from directions other than the target ship.

In addition, some strong ambient internal wave features were seen in the current meter array data, propagating through the array in directions very different than ship-generated internal waves. If corresponding features are present in radar images, these can be used in MTF analysis in addition to the ship-generated internal waves.

Acknowledgments

A number of individuals contributed significantly to this work. Jim Davin of LLNL led the mechanical design of the current meter array platform. Doug Ravizza led the fabrication work. Eric Davis contributed to data acquisition and telemetry in early phases of the project.

Fig. 10. 1D estimates of cross-track current and strain rate waveform and magnitude.

LLNL test participants in LL94 were Dave Mantrom (experiment leader), Gary Berry (computer systems, radar data transcription), Dave Chambers (hydrodynamics and CMA analysis, MTF analysis), Ron Greenwood (CMA mechanical support), Holger Jones (CMA data acquisition and analysis), Sean Lehman (radar analysis and transcription), Carmen Mullenhoff (radar analysis), Mike Newman (current meter, meteorological, and telemetry system specialist, test logistics), Doug Ravizza (CMA mechanical specialist, profiling S4/CTD data collection), Harry Robey (profiling S4/CTD data collection and analysis), and Tom Story (current meter, meteorological, and telemetry system specialist).

The management and staff of Underwater Centre, Ltd., Fort William, Scotland, are recognized for their outstanding and skillful support services provided at the test site. We greatly appreciated the assistance of the officers and crews of R/V Colonel Templer and R/V Calanus during this experiment. We acknowledge the cooperation and assistance of our UK collaborators, particularly Giles Gibson, DRA Farnborough, who was Trials Officer for Loch Linnhe '94, and the Thorn-EMI team responsible for the radar data collection.

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