LOCH LINNHE '94

**Test Operations Description and On-Site Analysis
US Activities**

David D. Mantrom

November 21, 1994

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LOCH LINNHE '94

TEST OPERATIONS DESCRIPTION

AND

ON-SITE ANALYSIS

US ACTIVITIES

David D. Mantrom

**Imaging and Detection Program
Lawrence Livermore National Laboratory**

November 1994

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED 35

ABSTRACT

A field experiment named Loch Linnhe '94 (LL94) is described. This experiment was conducted in upper Loch Linnhe, Scotland, in September 1994, as an exercise involving UK and US investigators, under the Joint UK/US Radar Ocean Imaging Program. This experiment involved a dual-frequency, dual-polarization hillside real aperture radar operated by the UK, Lawrence Livermore National Laboratory's (LLNL) current meter array (CMA), in-water hydrodynamic sensors, and meteorological measurements. The primary measurements involved imaging ship-generated and ambient internal waves by the radar and the CMA.

This report documents test operations from a US perspective and presents on-site analysis results derived by US investigators.

The rationale underlying complementary radar and CMA measurements is described. Descriptions of the test site, platforms, and major US instrument systems are given. A summary of test operations and examples of radar, CMA, water column profile, and meteorological data are provided.

A description of the rather extensive analysis of these data performed at the LL94 test site is presented. The products of this analysis are presented and some implications for further analysis and future experiments are discussed.

All experimental objectives were either fully or partially met. Powerful on-site analysis capabilities generated many useful products and helped improve subsequent data collection. Significant further data analysis is planned.

TABLE OF CONTENTS

ABSTRACT	i
TABLE OF CONTENTS	ii
ACKNOWLEDGMENTS.....	iii
1. INTRODUCTION	1
1.1 Background.....	1
1.1.1 Direct Measurement of Modulation Transfer Function	1
1.1.2 Two-scatterer Hypothesis.....	2
1.1.3 Airborne Radars.....	2
1.1.4 Familiarity with Test Site and Equipment.....	3
1.2 Experimental Objectives	3
1.3 Outline of Remainder of Report	4
2. DESCRIPTION OF SITE, PLATFORMS, AND EQUIPMENT.....	5
2.1 Loch Linnhe.....	5
2.2 Platforms and Targets.....	5
2.3 Equipment Description.....	6
2.3.1 Current Meter Array and Remote Meteorological Measurements	6
2.3.2 Profiling S4/CTD	6
2.3.3 MCR Radar.....	7
3. OPERATIONS SUMMARY.....	16
3.1 Day-by-day Chronology.....	16
3.2 Tabular Summary	17
4. DATA DESCRIPTIONS.....	18
4.1 Current Meter Array Data.....	18
4.2 Meteorological Data	18
4.4 Tracking Data	19
5. ON-SITE ENVIRONMENTAL ANALYSIS	21
5.1 Vertically Profiling S4/CTD Data.....	21
5.2 Met Data	23
6. ON-SITE RADAR IMAGE ANALYSIS.....	32
6.1 Analysis of Intensity Images.....	32
6.2 Analysis of (I,Q) Data	34
7. ON-SITE CURRENT METER ARRAY DATA ANALYSIS	46
7.1 Descriptions of On-Site Analysis.....	46
7.2 Examples	46
8. ON-SITE MTF ANALYSIS.....	60
9. SUMMARY.....	62
10. REFERENCES	64

ACKNOWLEDGMENTS

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.

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, Tim Lamont-Smith, DRA Malvern, who collaborated on-site on radar data analysis, and the Thorn-EMI team responsible for the radar data collection.

This work was performed under the auspices of the Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

1. INTRODUCTION

This report documents Loch Linnhe '94 (LL94) test operations and some of the on-site analysis of experimental data collected during this exercise. Emphasis is placed on work performed by US investigators associated with the Lawrence Livermore National Laboratory (LLNL).

This experiment was conducted in Loch Linnhe, Scotland, in September 1994 under the Joint UK/US Radar Ocean Imaging (ROI) Program. It involved imaging ship-generated and ambient internal waves (IW's) with a land-based, dual-frequency, dual-polarization real aperture radar operated by the UK. Considerable in-water data was collected by both US and UK investigators, including the LLNL current meter array (CMA), UK shear spars, water column profiling sensors, and meteorological instruments. Significant analysis of radar and in-water data was performed at the test site by LLNL personnel.

This introduction first presents some background leading up to why this experiment was conducted. This is followed by a statement of specific US test objectives. The introduction concludes with an outline for the rest of the document.

1.1 Background

There are a number of reasons why this particular experiment was conducted. Specifically, four classes of factors influenced the work we at LLNL performed at Loch Linnhe: modulation transfer function (MTF), two-scatterer hypothesis, no airborne radars, and familiarity with test site and equipment. A brief background discussion is provided for each factor.

1.1.1 Direct Measurement of Modulation Transfer Function

Surface manifestations of oceanic internal waves have been observed by various types of imaging remote sensors such as radars for many years. Radar images of ambient internal waves have been observed for 20 years or more (e. g., Fu and Holt, 1982). 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.

Such internal wave phenomena appear in radar images of sea surfaces as long narrow coherent patterns of light and dark contrast, corresponding to relatively rougher and smoother water surfaces, respectively. 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 in radar images have been observed for tidal flows over shallow bottom topography which also cause patterns of surface currents.

The 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 cross-track spatial derivative of the cross-track velocity component. 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 have not been usually measured directly but rather have been 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/sec), 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.

The demonstrated ability of both the UK Marine Cliffside Radar (MCR) and the LLNL current meter array make it now possible (in principle) to measure MTF directly for the first time. Furthermore, UK investigators have considerable experience and instrumentation to make in-water measurements with shear spars using S4 current meters and CTD chains, which will be useful when interpreting the CMA data.

1.1.2 Two-scatterer Hypothesis

Analysis of X-band real aperture radar images from prior Loch Linnhe experiments has revealed enhanced radar cross-section (rcs) modulations at HH polarization as compared to VV polarization at about 6 degrees grazing angle. Analysis of Doppler spectra shows that the HH spectrum peaks at a different frequency than the VV spectrum. The peak of the VV spectrum is consistent with resonant scattering from small wavelength wind waves with low phase speeds. The doppler peak of the HH return is consistent with scatterers moving with the long waves. These effects were observed with the radar looking into and with the wind; they were not present when the wind direction was cross-look. (Brace et al, 1994).

The scattering picture that emerges from these results shows at least two scattering processes that give rise to the results observed by the X-band RAR at LGA. One is the conventional resonance scattering responsible for most of the VV return and poorly modulated by the surface currents. The other "fast scatterer" mechanism is responsible for most of the HH return. Other scattering processes could also be contributing.

A broader data base is needed to better understand this hypothesis. LL94 offers an opportunity to collect additional modulation data over a wider variation in wind conditions, radar frequency, and IW strength.

1.1.3 Airborne Radars

A major long-term field experiment goal of the Joint UK/US Radar Ocean Imaging Program is to conduct an internal wave (IW) detection experiment, using high-frequency (X-band and/or higher) dual-polarization coherent real aperture radars (RARs) that image the ocean surface at low grazing angle. As discussed above, we believe that recent data analysis has begun to reveal some of the mysteries associated with radar scattering and the imaging of current-induced modulations at low grazing angle at both horizontal and vertical polarization.

In such an experiment, we would like to field radars in a realistic ocean environment from both moving and stationary airborne platforms to obtain both two-dimensional spatial images and time-evolving images of a single radar footprint on the ocean surface (range vs. time image). Such experiments would require radars having sufficient power to image the ocean (adequate clutter-to-noise) at LGA and adequate resolution to image IW's in the 10-100m wavelength range. These radars would be operated from very stable airborne platforms whose tracks are both accurately known and are precisely coordinated in space and time with that of a target.

An experimental capability meeting all of the requirements outlined above does not presently exist within the resources of the Joint UK/US Program. We are in the process of developing new systems and must overcome the engineering issues associated with such measurements.

Nonetheless, we made good use of existing capability this year to learn more about the scientific complexities of imaging the sea surface and modulations associated with internal waves at low grazing angle and to more intelligently design the data collection strategy for the future detection experiments, which realistically can only cover a narrow range of controllable parameters. The planning of those experiments will benefit significantly from a better knowledge of the scattering processes at work at LGA, and the surface current and strain rate fields associated with internal waves and the dependence of radar modulation and modulation transfer function (ratio of radar modulation to hydrodynamic disturbance level) on parameters such as radar frequency and polarization, grazing angle, wind speed, look direction re: wind, etc.

1.1.4 Familiarity with Test Site and Equipment

We have just completed conducting an experiment using an existing UK radar mounted on a hillside overlooking Loch Linnhe as in previous experiments, and deployed LLNL's current meter array (for the first time with an adjacently positioned radar) to measure the internal wave near-surface current field generated by surface ships near the footprint of the hillside radar.

Field experiments, including several conducted at Scotland sites, in the Joint UK/US program during 1989 to 1993 played an important role in the advances made in this program.

In August 1989, a major UK/US experiment was conducted at Loch Linnhe, using surface ships to generate internal wave wake signatures in both the upper and lower lochs. Four aircraft with synthetic aperture radars (SARs) participated, and internal wave wakes were imaged at six frequencies ranging from P-band to Ka band. A LGA hillside RAR was also deployed here, and for the first time revealed features that could not be explained by conventional models. A narrower scope experiment was conducted in 1990 to reproduce the hillside RAR results.

Another major experiment was conducted jointly by the UK and US off the West Coast of Scotland in 1991 (hence the name WCSEX-91). The first part involved imaging ship wakes in Loch Linnhe using two LGA hillside RARs and four aircraft SAR systems. The second part was conducted in Sound of Sleat, more representative of open-ocean-like conditions than Loch Linnhe. Much analysis of these data has been performed, particularly the hillside MCR RAR data. A number of advanced signal processing techniques have been developed and applied to these data. Additional data were collected in Sound of Sleat in another experiment in 1992, again using MCR, among others.

In 1993, LLNL's current meter array was deployed twice at AUTEC to demonstrate engineering feasibility of such a measurement, and to demonstrate an ability to collect data of sufficient scientific quality to complement radar measurements. Both CMA deployments successfully met their primary objectives.

1.2 Experimental Objectives

The general objective of the experiment as stated in the UK Trials Plan (Gibson, 1994) is to examine the phase relationship between the modulations seen in radar images and ship-generated internal waves.

The US objectives, as stated in the LLNL test requirements document (Mantrom, 1994) submitted as an input to the trials plan are stated as follows:

- Collect the signature and ambient data with the 10-sensor LLNL current meter array (CMA) required to characterize hydrodynamic currents and modulation transfer function (MTF) as a function of wind speed, radar look direction re: wind direction, radar polarization, and signal strength (current and strain rate).
- Collect and process on-site the environmental data (meteorological and water column profile data) required to support interpretation of the CMA data and MTF analysis.
- Perform on-site modulation analysis of the UK hillside radar and CMA data to provide a quick-look characterization of MTF.
- Perform on-site advanced signal processing analysis of the radar imagery (e.g., doppler analysis).

1.3 Outline of Remainder of Report

The remainder of this report proceeds as follows. Section 2 contains a description of the test site, the platforms used, and the major instrument systems fielded by US investigators. A summary of test operations is provided in tabular form in Section 3. Descriptions of the data collected by the major measurement systems are presented in Section 4. Sections 5 to 8 discuss analysis of experimental data performed at the test site, and major results for environmental data, radar data, current meter array data, and MTF analysis, respectively. The report concludes with a summary in Section 9.

Figures referred to in the text appear at the end of each section.

2. DESCRIPTION OF SITE, PLATFORMS, AND EQUIPMENT

This section provides a description of the Loch Linnhe test site, descriptions of the primary ships used in the experiment as targets and as measurement platforms, and describes the major instrumentation systems.

2.1 Loch Linnhe

The experiment was conducted in upper Loch Linnhe, a narrow salt water estuary on the west coast of Scotland as shown in Figure 2.1. This site is well known to the Joint UK/US ROI Program because it has been the site of several previous experiments as discussed in the introduction. Loch Linnhe is a good site to do an experiment of this type because its summer subsurface environmental conditions are favorable for the generation and propagation of internal waves, and the hills surrounding it are convenient to mount a land-based coherent real aperture radar imaging a footprint on the loch's surface at low grazing angle within the range of grazing angles of interest to the Joint UK/US Program.

The approximate locations of the radar, the radar footprint, the nominal ship tracks, and the moorings to which the current meter array and R/V Calanus were tied up are shown in Figure 2.2. The measurement site is about 5 miles downloch from Fort William. The current meter array mooring is about 600 meters uploch of the radar footprint, and the Calanus mooring is 100 meters uploch of the CMA. Note that prior to 6 September, these moorings were erroneously positioned twice this far from the radar footprint and were moved to the positions indicated. The radar's elevation and range correspond to a grazing angle of approximately 6 degrees. Also, the water depth on the ship track adjacent to the radar footprint and in-water instrumentation is about 80 meters; the depth at the mooring positions of the CMA and Calanus moorings is about 45 meters.

2.2 Platforms and Targets

The primary ships used in this experiment were the R/V Colonel Templer, the Dog-class tug Collie, the R/V Calanus, and the work boat R/V Loch Shiel.

R/V Colonel Templer and Collie were the wake generating vessels for this experiment. Colonel Templer, shown in Figure 2.3, is a converted deep sea trawler operated by DRA whose displacement is 1300 tons. The "CT" is 56.5 m long, has a beam of about 11 m, a draft of 5.6 m, and a speed range about 2-10 kt. Colonel Templer also was the UK command center. Collie (not shown) is a Dog-class tug of 150 tons displacement, operated by Royal Marine Auxiliary Service (RMAS). Collie's length is 29 m, her beam and draft are 8 m and 4 m, and her speed range is 4-12 kt.

R/V Calanus, shown in Figure 2.4, is an oceanographic research vessel operated by Dunstaffnage Marine Laboratory (DML), and supported DML's in-water measurements along with LLNL's vertically profiling S4/CTD current meter with fast response conductivity and temperature sensors. Every day during serials, Calanus would tie up to her mooring next to the CMA mooring, and DML personnel would deploy S4's on the shear spars, deploy their CTD chain, and perform CTD profiles at a rate of one every ten minutes. LLNL personnel would profile our S4/CTD once per hour. Meteorological data was also collected onboard Calanus.

R/V Loch Shiel is a small work boat operated by The Underwater Centre, Ltd. that was used to tow the University of Southampton laser slope gauge across the ship wakes during the serials (Figure 2.5). Loch Shiel also towed the CMA to and from its launch and recovery site (in the Caledonian Canal, Corpach) and its mooring about 5 miles downloch at the measurement site.

2.3 Equipment Description

The equipment used by LLNL for data collection and analysis is described here.

2.3.1 Current Meter Array and Remote Meteorological Measurements

The LLNL current meter array, as configured for LL94, is shown in Figure 2.6 on its assembly stands just prior to deployment alongside Caledonian Canal, Corpach. It consisted of the following components:

- 10 standard S4 current meters, uniformly spaced with a 3.75 m longitudinal separation (approximately 34 m aperture), and positioned at a depth of 2 meters. The S4's internally averaged data and were sampled once every 10 seconds (as in previous CMA experiments). They were set up in "XY mode", to measure currents along and across the primary axis of the CMA. A precision external compass was used to measure the CMA orientation.
- New probe struts that attach directly to the main aluminum frame, eliminating the need for the lower fiberglass frame fielded during prior deployments at AUTECH.
- Two met stations, one on a tower 10m above water level, and the other at 1m above water. Wind speed and direction, air temperature, sea surface temperature, and relative humidity data were recorded.
- A new telemetry system, whereby the met data and system status data would be integrated into the main CMA data stream.
- A power management system, designed so that battery voltages could be monitored and remotely switched between two banks of batteries.
- A differential GPS receive station (provided by DRA contractor RACAL) so that CMA position could be recorded (for later combining with DGPS data from targets to precisely determine closest point of approach (CPA) times and distances).

The current meter array secured to its mooring and in a measurement configuration is shown in Figure 2.7. It was oriented so that its long axis was perpendicular to the nominal ship track. Because of large tidal excursions in the Loch (upwards of 4-5 m in the water level), the horizontal position of the CMA could vary somewhat, hence the need for the DGPS receiver on the CMA.

The current meter array transmitted its data via telemetry link to a shore station near Underwater Centre's headquarters building in Fort William. The shore station was located inside LLNL's cargo transportainer (which served a dual function as an analysis lab after the cargo was emptied). A third met station was deployed next to the transportainer on a 10 m high tower (in case the remote met stations did not provide usable data). A high gain directional antenna was used to receive the telemetered data. These are shown in Figure 2.8.

2.3.2 Profiling S4/CTD

A new measurement capability was tested during LL94, namely vertically profiling an S4 current meter equipped with fast response (60 m/sec) CTD sensors. This was performed off the Calanus using a high quality winch capable of uniform profiling at approximately 1/4 m/sec. A photograph of this operation off the stern of Calanus is shown in Figure 2.9.

2.3.3 MCR Radar

The Marine Cliffside Radar (MCR) used in LL94 is an existing radar built and operated by Thorn-EMI, a DRA contractor. The particular radar fielded in this experiment is a dual-frequency (X- and S-band), dual-polarization (vertical and horizontal) real aperture radar. Some of its characteristics and operating parameters are summarized below:

	X-band (UK calls I-band)	S-band (UK calls F-band)
PRF (I only)	500 Hz	
PRF (I,F)	250 Hz	250 Hz
PRF (I, bistatic)	250 Hz	
Beamwidth	1.2°	3.6°
Range resolution	1.5 m	1.5 m
# of range cells	1024	1024
Range extent	1536 m	1536 m
Range to center of footprint	2.2 km	2.2 km
Azimuthal extent at center of footprint	46 m	138 m
Grazing angle at center of footprint	6.2°	6.2°

A photograph of the MCR antennas is shown in Figure 2.10. A view of the loch from the radar site is shown in Figure 2.11.

Figure 2.1 Map of Scotland, showing general Loch Linnhe area

Figure 2.2 Chart of Loch Linnhe showing radar hillside and footprint, nominal ship track, and nominal mooring locations of current meter array and R/V Calanus.

Figure 2.3 R/V Colonel Temppler

Figure 2.4 R/V Calanus

Figure 2.5 R/V Loch Shiel

Figure 2.6 Current Meter Array on assembly stands at Caledonian Canal, Corpach prior to deployment

Figure 2.7 Current Meter Array at mooring

Figure 2.8 Transportainer and receiver antennas at Ft. William

Figure 2.9 Vertically profiling S4/CTD off stern of R/V Calanus

Figure 2.10 MCR radar antenna

Figure 2.11 View of Loch Linnhe from MCR radar

3. OPERATIONS SUMMARY

This section summarizes test operations associated with Loch Linnhe '94 with emphasis on operations that impacted directly on LLNL activities. A day-by-day chronology appears first, followed by a tabular summary of serials and ship runs.

3.1 Day-by-day Chronology

26 August	First LLNL person arrives on site (M. Newman); finalizing logistics arrangements.
28 August	Begin equipment assembly at Corpach, Underwater Centre, and Nevis Bank Cottage.
30 August	CMA lifted into water at Corpach, towed to Ft. William pier for dockside checkouts.
2 September	CMA towed to test site, tied up at mooring. Colonel Templer (CT) conducts practice runs. Calanus collects in-water data. "Best day" for Calanus data; ship-generated IW's visible by eye.
3 September	Radar equipment being put together, no ship runs.
4 September	Begin data collection with all measurement systems up. Serial 1, 3 slow runs (CT). Best CMA data for ship-generated IW's. Realized moorings were too far from radar footprint, decision made to move moorings on 6 September.
5 September	Serial 2, 3 slow runs (CT).
6 September	No ship runs, moorings being moved.
7 September	Mooring relocation completed; Serial 3, 3 fast runs (CT).
8 September	Serial 4, 6 fast runs (CT).
9 September	Serial 5, 4 fast runs (2 CT, 2 Collie).
10 September	Serial 6, 6 fast runs (4 CT, 2 Collie). No CMA (telemetry/battery problems).
11 September	Serial 7, 5 fast runs (4 CT, 1 Collie). ERS-1 over flight during Run 1 (imaged CT in test area and Collie in lower loch).
12 September	Serial 8, 6 slow runs (2 CT, 4 Collie).
13 September	Serial 9, 4 fast runs (2 CT, 2 Collie).
14 September	Serial 10, 4 slow runs (2 CT, 2 Collie).
15 September	Serial 11, 4 fast runs (2 CT, 2 Collie); very windy day; no in-water data or LLNL profile data taken from Calanus.
16 September	Serial 12, 4 slow runs (2 CT, 2 Collie); nice radar images.
17 September	Serial 13, 4 slow runs (2 CT, 2 Collie); nice radar images; completed data collection.
18 September	CMA removed from mooring, towed to Corpach, lifted onto pier, and disassembly of equipment begun.
19 September	Disassembly of equipment completed, equipment pack-up.
20 September	Equipment pack-up complete; LLNL personnel depart Fort William.

3.2 Tabular Summary

A summary of run conditions, environmental conditions, and general appearance of signals in the radar and CMA images is presented in Table 3.1.

Date	Serial/Run No.	Ship	Ship Speed (m/sec)	Ship Dir. (up/down loch)	Radar Configuration*	Avg. Wind Speed (m/sec)	Avg. Wind Dir. (deg. from)	Max BV Freq. (rad/sec)	X-band Image Signal Strength	S-band Image Signal Strength	Radar Analysis Priority	CMA Image Signal Strength	Added Comments
9/4/94	S1R1	CT	1	Down	BAGPAG, X	5.0	269	0.16	None			None	
	S1R2	CT	2	Up	BAGPAG, XS	5.5	275	0.11	Strong	Weak		Strong	
	S1R3	CT	1	Down				0.15			3	None	
9/5/94	S2R1	CT	2	Up	BAGPAG, XS	7.0	255	0.13	None	None		None	
	S2R2	CT	1	Down	BAGPAG, X	8.7	238	0.11	None			None	
	S2R3	CT	2	Up	BAGPAG, X	5.0	263	0.09	None			None	
9/7/94	S3R1	CT	3	Up	BAGPAG, XS	4.0	228	0.08	Weak	Weak		Weak	
	S3R2	CT	4	Down	BAGPAG, X	3.0	283	0.09	Uncertain			None	
	S3R3	CT	3	Up	BAGPAG, X	3.0	319	0.09	Uncertain			None	
9/8/94	S4R1	CT	4	Down	Bistatic(5m)	8.5	69	0.05	None			None	
	S4R2	CT	3	Up	Bistatic(11m)	8.4	62	0.05	Uncertain			None	
	S4R3	CT	4	Down	Bistatic(22m)	8.7	60	0.04	Uncertain			None	
	S4R4	CT	3	Up	Bistatic(44m)	8.9	57	0.06	None			None	
	S4R5	CT	4	Down	Bistatic(90m)	6.8	58	0.06	None			None	
	S4R6	CT	3	Up	BAGPAG, XS	5.8	74	0.05	Uncertain			None	
9/9/94	S5R1	CT	4	Down	BAGPAG, X	4.2	242	0.05	Weak			None	
	S5R2	Collie	4	Down	BAGPAG, X	3.7	247	0.05	Moderate			Weak	
	S5R3	CT	3	Up	BAGPAG, XS	4.1	243	0.06	Moderate	Weak		None	
	S5R4	Collie	3	Up	BAGPAG, XS	3.7	249	0.05	Moderate	Weak	6	None	
9/10/94	S6R1	CT	4	Down	Bistatic(5m)			0.06	None				No CMA, Met
	S6R2	Collie	4	Down	Bistatic(11m)			0.15	None				
	S6R3	CT	3	Up	Bistatic(22m)			0.07	None				
	S6R4	Collie	3	Up	Bistatic(44m)			0.08	None				
	S6R5	CT	4	Down	Bistatic(90m)			0.08	None				
	S6R6	CT	3	Up	Bistatic(145m)			0.09	Uncertain				
9/11/94	S7R1	CT	4	Down	BAGPAG, XS	3.4	261	0.14	Moderate	Weak		Moderate	ERS-1 Pass
	S7R2	CT	3	Up	BAGPAG, X	3.0	286	0.08	Weak			Weak	
	S7R3	CT	4	Down	BAGPAG, X	4.1	220	0.08	Moderate		4	Strong	
	S7R4	CT	3	Up	BAGPAG, XS	4.1	226	0.11	Weak	Weak		Moderate	
	S7R5	Collie	3	Up	BAGPAG, XS	2.1	209	0.10	Weak	Weak		None	
9/12/94	S8R1	CT	2	Down	Bistatic(145m)	6.0	60	0.09	None			None	
	S8R2	Collie	2	Down	Bistatic(90m)	5.9	57	0.10	None			None	
	S8R3	CT	1	Up	Bistatic(44m)	5.2	60	0.09	Uncertain			None	
	S8R4	Collie	2	Up	Bistatic(22m)	5.5	59	0.10	None			None	
	S8R5	Collie	2	Down	Bistatic(11m)	7.3	64	0.08	None			None	
	S8R6	Collie	2	Up	Bistatic(5m)	7.5	61	0.08	None			None	
9/13/94	S9R1	CT	4	Down	BAGPAG, X	7.4	59	0.10	Uncertain			None	
	S9R2	Collie	4	Down	BAGPAG, XS	7.3	58	0.11	Uncertain	Weak		None	
	S9R3	CT	3	Up	BAGPAG, XS	6.8	58	0.11	Uncertain	Moderate	8	None	
	S9R4	Collie	3	Up	BAGPAG, X	6.8	57	0.10	None			None	
9/14/94	S10R1	CT	2	Down	BAGPAG, XS	6.2	54	0.16	Strong	Strong	1	Moderate	
	S10R2	Collie	2	Down	BAGPAG, XS	6.4	54	0.16	None	None		None	
	S10R3	CT	1	Up	BAGPAG, X	6.2	56	0.17	Moderate		5	None	
	S10R4	Collie	2	Up	BAGPAG, X	4.6	78	0.14	Weak			None	
9/15/94	S11R1	CT	4	Down	BAGPAG, XS	10.9	52		Uncertain	Uncertain		None	No Profiles
	S11R2	Collie	4	Down	BAGPAG, XS	9.6	57		Uncertain	Uncertain		None	
	S11R3	CT	3	Up	BAGPAG, X	12.1	42		Weak			None	
	S11R4	Collie	3	Up	BAGPAG, X	12.6	41		None			None	
9/16/94	S12R1	CT	2	Down	BAGPAG, X	5.8	2	0.09	Strong		2	None	
	S12R2	Collie	2	Down	BAGPAG, X	4.9	4	0.08	Weak			Weak	
	S12R3	CT	1	Up	BAGPAG, XS	4.7	15	0.13	Moderate	Weak	7	None	
	S12R4	Collie	2	Up	BAGPAG, XS	4.2	9	0.10	None	None		None	Strong CMA Amb.
9/17/94	S13R1	CT	2	Down	BAGPAG, XS	3.3	25	.07	Moderate	Weak		Weak	
	S13R2	Collie	2	Down	BAGPAG, X	3.9	354	.18	Weak			None	
	S13R3	CT	1	Up	BAGPAG, XS	3.8	346	.13	Moderate	Weak		None	
	S13R4	Collie	2	Up	BAGPAG, X	3.3	347	.09	Uncertain			None	

Table 3.1 LL94 Run Summary

* BAG = Band Agile

PAG = Polarization Agile

Bistatic = Bistatic receiver, X-band (receiver separation distance)

4. DATA DESCRIPTIONS

This section contains descriptions of the data collected by LLNL during LL94. Data collection and recording procedures and data formats are discussed. Data descriptions for the following systems are presented in order: CMA data, met data, profiling S4/CTD data and DGPS tracking data.

4.1 Current Meter Array Data

A diagram showing the sensor configuration on the CMA for LL94 is shown in Figure 4.1. The figure indicates that the current meters are uniformly spaced at 3.75 m in the direction along the main axis of the CMA and are staggered from port side to starboard side. The current meters are numbered beginning at the bow, sequentially increasing toward the stern. Sensor #1 is 1.75 m aft of the bow. Note that this is different than sensor numbering in prior experiments by LLNL with the CMA.

The S4 current meters were set up to transmit data in XY + compass format (as opposed to NE format where the S4 internally combines the velocity measurement with the compass measurement). We transform the XY current data to cross-track and along-track components, using an accurate external compass. The external compass was mounted in a watertight box next to the telemetry box on the forward kingpost. The S4's were mounted very carefully so that they were all oriented the same way (estimated mounting precision: +/- a few degrees).

We did a "calibration run" whereby the CMA was towed both in straight line and circular courses around the harbor to verify that the X and Y channels were properly set up and had the correct sign. We also verified that NE modes were set up in case we chose to switch to it (which we did not).

All current meter data were internally averaged and sampled at the rate of one sample every 10 seconds, as in previous experiments.

4.2 Meteorological Data

Three met stations were fielded during LL94. They are summarized in the table below. All data were internally averaged and sampled at the rate of one sample per minute.

Met Station	Location	Sensors
CMA 10m	Atop tower 10 m above water level on CMA	Wind speed Wind direction
CMA 1m	On CMA from 0-1 m above water level	Wind speed Wind direction Water temperature Air temperature
Local	Atop 10m tower at land-based transportainer, approx. 5 mi from CMA mooring	Wind speed Wind direction Air temperature Relative humidity

All of the wind direction and compass data have been corrected for local magnetic anomaly (difference between magnetic north and true north) by adding 9 degrees to the observed value.

4.3 Profiling S4/CTD

Density and horizontal current shear profile data were measured hourly off of R/V Calanus while moored at the test site. The data were collected using an S4 current meter equipped with InterOcean's fast response temperature (platinum thermometer) and conductivity (inductive-type) sensors and a 0-1000 dbar depth sensor (semiconductor strain gauge). The S4/CTD was vertically profiled using a high-quality, low-speed winch purchased specifically for this purpose. The winch line passed over a pulley on the stern A-frame of Calanus. Two heavy steel shackles were attached to a line approximately 2 m below the S4 to keep the line vertical during profiling.

The data were internally logged and downloaded after each cast. A profiling speed of 0.26 m/sec was used after some experimental casts made at different speeds. Data on upcasts only were used to derive profile information. Data were sampled at the maximum rate of the S4's (one sample every half-second). Current data were recorded in NE mode (using the internal compass) since the S4 sometimes rotated slowly as it was raised or lowered in the water column.

4.4 Tracking Data

Differential GPS (DGPS) receivers were attached to both ship targets and each of the major measurement platforms for LL94. This service was supplied by RACAL, a contractor to DRA.

DGPS position data of interest to LLNL were the positions of the CMA and the two targets, since we have to determine the absolute GMT time and separation distance at closest-point-of-approach (CPA) between the CMA and the target. Note that we do not need this information for the radar since the time and range gate(s) of the ship (a hard target with very large radar cross-section) as it passes through the radar footprint are very obvious.

The CMA's DGPS receiver was atop the aft kingpost which is 21 m aft of the bow.

The data are sampled every minute. The data are in the form of "British coordinates" whose least significant digit is 1m.

We do not have this DGPS position data at the time of this writing. RACAL estimates the absolute accuracy of these measurements as "a few meters."

Figure 4.1 LL94 Current Meter Array Sensor Configuration

5. ON-SITE ENVIRONMENTAL ANALYSIS

In this section, a summary of the water column data obtained with the vertically profiling S4/CTD is presented, followed by a summary of the meteorological data. These environmental data analysis results are presented prior to summaries of the radar and CMA data because we feel that what was observed (and what was not observed) in those data is likely related to favorable or unfavorable environmental conditions.

Complete data books are available in companion reports by Robey and Ravizza (1994) for the water column profile data and in Jones and Chambers (1994) for the met data.

5.1 Vertically Profiling S4/CTD Data

A total of 76 casts were made off R/V Calanus during LL94 with our vertically profiling S4/CTD. The full water column (approximately 45 m depth) was profiled in each cast. These casts were conducted during the period from 2 September to 17 September 1994. No data was collected on 15 September (Serial 11) because high winds precluded Calanus from tying up to her mooring.

On most days, if there were n ship runs in a given day's serial, we would perform $n+1$ casts. We would do one shortly prior to the day's first ship run, one in between runs, and one after the last run. Nominally, these casts would be conducted at one hour intervals.

The S4 data were sampled every 1/2 second and the winch speed was 0.26 m/sec. Data on upcasts only was processed.

An example of our standard data product generated in the field is presented in Figure 5.1. On one sheet of paper are six profile plots:

- Temperature vs. depth
- Salinity vs. depth
- Sigma-t (density) vs. depth
- Brunt-Vaisala (BV) frequency vs. depth
- Cross-track current vs. depth
- Along-track current vs. depth

BV frequency was obtained by differentiating the density profile after a seven-point moving average (approximately 1m in depth). An additional 5-point moving average was used for the BV and current profiles shown. The individual profiles are contained in the companion data book by Robey and Ravizza (1994). Internal wave dispersion relations and low mode eigenfunctions derived from these BV profiles, without shear, are also contained in that report.

Some key features of the profile data are summarized in Table 5.1. Characteristic values of the BV and cross-track current profiles included in the table will be reflected in the strength and shape of the internal wave field generated by the ships.

Date	Time (GMT)	Peak BV Freq. (sec ⁻¹)	Depth of Peak BV (m)	Peak Cross Track Current (cm/s) (+) Away (-) Into	Depth of Peak Cross Track Current (m)
9/4/94	14:42	0.16	2	-13	3
	15:45	0.12	1	15	9
	16:42	0.08	1	-32	1
	17:43	0.15	3	13	6
9/5/94	13:14	0.10	4	-26	1
	14:21	0.13	0.5	-24	3
	15:35	0.11	5	20	2
	16:28	0.09	2	14	19
	17:17	0.05	4	20	20
9/7/94	15:59	0.08	1	-8	0.5
	16:58	0.09	4	8	0.5
	17:58	0.085	3	8	18
	19:19	0.06	2	-18	1
9/8/94	10:17	0.05	3	-50	0.5
	11:16	0.045	5	-38	0.5
	12:16	0.04	8	-27	0.5
	14:16	0.06	0.5	-30	0.5
	15:16	0.06	4	13	0.5
	16:00	0.05	5	-30	0.5
9/9/94	09:30	0.045	6	-15	0.5
	10:30	0.05	0.5	-10	0.5
	11:30	0.06	0.5	-9	3
	12:30	0.05	1	-8	18
	13:30	0.07	0.5	-5	2
9/10/94	09:59	0.055	0.5	-22	0.5
	11:00	0.15	0.5	-30	1
	11:59	0.07	1	-19	2
	13:00	0.08	0.5	24	23
	14:00	0.08	1	18	0.5
	15:00	0.09	2	22	1
	16:00	0.065	0.5	-16	3
9/11/94	11:01	0.14	1	11	34
	11:55	0.075	0.5	12	34
	12:55	0.08	0.5	-8	0.5
	13:55	0.09	0.5	10	12
	14:55	0.11	0.5	9	3
	15:55	0.095	0.5	7	15
9/12/94	10:30	0.085	4	-17	1
	11:30	0.095	5	-36	4
	12:30	0.085	5	-14	0.5
	13:30	0.075	6	30	0.5
	14:31	0.095	1	-22	1
	16:30	0.075	4	-20	0.5
9/13/94	12:30	0.09	6	-17	2
	13:31	0.10	8	11	4
	14:30	0.105	8	-10	0.5
	15:30	0.105	8	-4	3
	16:29	0.10	8	6	6
9/14/94	14:00	0.16	3	-7	18
	15:00	0.16	3	-7	14
	16:00	0.17	3	-7	0.5
	17:00	0.14	2	-8	0.5
9/16/94	10:30	0.075	2	-16	0.5
	13:30	0.11	0.5	-12	4
	14:30	0.09	3	16	0.5
	15:30	0.08	2	12	24
	16:30	0.13	0.5	15	0.5
	17:30	0.095	2	12	0.5
9/17/94	10:57	0.09	1	24	1
	13:30	0.10	0.5	26	0.5
	14:30	0.07	0.5	10	2
	15:30	0.18	0.5	12	0.5
	16:30	0.13	0.5	-7	5
	17:30	0.09	0.5	-7	4

Table 5.1 LL94 Water Column Profile Summary

Additionally, a histogram has been made for the peak BV frequency in the table above. It is shown in Figure 5.2. It shows that most of the time, the peak BV frequency was ≤ 0.1 rad/sec. It will be shown later that visible IW wakes in both radar imagery and CMA data usually are present when there is a large value of maximum BV frequency (e.g., ≥ 0.1 rad/sec.) and when this maximum is near the surface. We are in the process of investigating coincidences of visible wakes with the shear data.

5.2 Met Data

There were three met stations fielded during LL94 as described in the previous section. The data processed on-site were the wind speed and direction atop the 10m tower on the CMA and the air and surface water temperature at the CMA. These data were recorded continuously during the experiment, except for the period of time the CMA telemetry unit was down on 10-11 September due to a battery failure.

The standard met data product at the test site was a time series plot of the wind speed and direction relative to CMA CPA time as shown in Figure 5.3. These data were subsequently re-referenced to the radar CPA time and replotted (as shown in Figure 5.4 for the same serial and run as Figure 5.3). Plots of wind data such as this are in the companion data reports for CMA (Jones and Chambers, 1994) and radar (Lehman and Mullenhoff, et al, 1994).

Time series plots of wind speed and direction for the entire experiment are given in Figure 5.5. All of the met data were recorded as 1-minute averages and no further averaging has been done to this point. The wind directions have been compass-corrected for magnetic offset (9 degrees was added to the measured values). Note that there is a wide variation in wind speed, mostly between 0-10 m/sec although on one day (9/15) sustained winds got as high as 15 m/sec (30 knots). Note also that the wind direction has two preferred directions, which turn out to be the approximate geographical orientation of the loch and its surrounding hills (wind directions predominantly up-loch or down-loch).

Histograms of wind speed (Figure 5.6) and direction (5.7) for the entire experiment underscore the observation that we got a broad distribution of wind speeds, but wind directions were mostly up-loch or down-loch.

The wind direction distribution result is good and bad. We have found previously from a limited data set that IW's seem to be imaged best when the radar is looking into the wind. We had only a handful of images under those conditions. On the other hand, we do not have many images in our data base of imaged IW's with the wind blowing cross-look, and this data expands that significantly.

A summary of the met data, run-by-run, is shown in Table 5.2 below. Mean values of wind speed and direction and mean air and water temperatures are shown. Mean values are computed over an interval starting 10 minutes prior to radar CPA and extending to the end of the run. Water temperature entries with a (U) denote an unstable air-sea interface (cold air over warm water).

Date	Serial/Run	Average Wind Speed (m/sec)	Average Wind Direction (deg. from)	Average Air Temp. (deg. C)	Avg. Surface Water Temp. (deg. C)
9/4/94	S1R1	5.0	269	14.2	12.5
	S1R2	5.5	275	14.0	12.4
	S1R3				
9/5/94	S2R1	7.0	255	13.4	12.5
	S2R2	8.7	238	13.8	12.4
	S2R3	5.0	263	13.3	12.3
9/7/94	S3R1	4.0	228	14.5	12.6
	S3R2	3.0	283	13.2	12.5
	S3R3	3.0	319	11.4	12.4 (U)
9/8/94	S4R1	8.5	69	12.7	12.2
	S4R2	8.4	62	12.4	12.2
	S4R3	8.7	60	12.3	12.2
	S4R4	8.9	57	12.5	12.2
	S4R5	6.8	58	12.8	12.2
	S4R6	5.8	74	12.4	12.2
9/9/94	S5R1	4.2	242	10.6	11.7 (U)
	S5R2	3.7	247	11.4	11.7 (U)
	S5R3	4.1	243	11.9	11.9
	S5R4	3.7	249	12.2	12.1
9/11/94	S7R1	3.4	261	13.9	12.2
	S7R2	3.0	286	13.4	12.2
	S7R3	4.1	220	13.7	12.3
	S7R4	4.1	226	13.6	12.4
	S7R5	2.1	209	13.8	12.3
9/12/94	S8R1	6.0	60	12.3	12.2
	S8R2	5.9	57	12.8	12.2
	S8R3	5.2	60	12.8	12.2
	S8R4	5.5	59	13.1	12.2
	S8R5	7.3	64	13.4	12.2
	S8R6	7.5	61	12.9	12.3
9/13/94	S9R1	7.4	59	11.8	12.0 (U)
	S9R2	7.3	58	11.7	12.1 (U)
	S9R3	6.8	58	11.7	12.1 (U)
	S9R4	6.8	57	11.4	12.0 (U)
9/14/94	S10R1	6.2	54	12.1	12.0
	S10R2	6.4	54	12.1	12.1
	S10R3	6.2	56	12.0	12.0
	S10R4	4.6	78	11.9	11.9
9/15/94	S11R1	10.9	52	12.8	11.8
	S11R2	9.6	57	12.5	11.8
	S11R3	12.1	42	12.9	11.9
	S11R4	12.6	41	12.8	11.9
9/16/94	S12R1	5.8	2	11.7	11.7
	S12R2	4.9	4	11.8	11.7
	S12R3	4.7	15	11.6	11.7 (U)
	S12R4	4.2	9	11.1	11.7 (U)
9/17/94	S13R1	3.3	25	12.8	12.4
	S13R2	3.9	354	12.8	12.3
	S13R3	3.8	346	12.7	12.1
	S13R4	3.3	347	12.0	11.9

Table 5.2 LL94 Met Data Summary

Figure 5.1 Standard vertically profiling S4/CTD data plot (one sheet per cast)

Figure 5.2 Histogram of maximum BV frequency for entire LL94 experiment

Figure 5.3 Standard on-site wind time series plots (one sheet per run)

Figure 5.4 Wind data plot with time referenced to radar CPA

Figure 5.5 Wind time series plots for entire LL94 experiment

Figure 5.6 Wind speed histogram, entire LL94 experiment

Figure 5.7 Wind direction polar histogram, entire LL94 experiment

6. ON-SITE RADAR IMAGE ANALYSIS

6.1 Analysis of Intensity Images

Most of the on-site analysis of the radar data involved averaged intensity images. Such intensity images were generated for each recorded channel of each scene; 168 images in all. These images tell much about data quality, how well the radar was imaging the water surface, the strength and the morphology of the ship-generated and ambient internal waves captured in the images, and qualitative differences between frequency bands, polarizations, and receive antenna separation in the bistatic cases.

For selected intensity images, further analysis was performed. For some cases where clearly visible, ship-generated internal wave signal features were seen, so-called "modulation cuts" were made. Modulation cuts involve selecting a subset of the image containing a leg or legs of one side of an internal wave signal pattern and averaging for some length down the leg so that a good quantitative estimate of the modulation can be obtained.

A handful of examples of radar images obtained during LL94 containing strong and moderate strength signals are presented here. The ones selected are presented in the chronological order in which they were collected. A complete book of images is available in a companion report by Lehman and Mullenhoff, et al (1994).

The first image is shown in Figure 6.1 and is from September 4, (Serial 1), Run 2. This image corresponds to what is considered the best current meter array image presented in Section 7. The figure shows two X-band images, HH on the left and VV on the right. The horizontal coordinate is range, increasing from left to right, and the vertical coordinate is time, increasing from top to bottom. The wake generating ship (here, Colonel Templar at 2 m/sec moving uploch) is the very bright hard target feature in the scene near the top. The average wind speed was about 5.5 m/sec from 275 degrees, which is a quartering wind into the radar look direction (which was always looking toward 308 degrees). The wind data for this run was used as an example in Figure 5.4. A shallow pycnocline was present with maximum BV frequency of about 0.1 rad/sec at a depth of 1 m. The signal is fairly symmetric (persists longer in time on the near-range side of the wake), and the contrast in the VV image appears to be a little better than in the HH image.

The yellow rectangles on the near-range side of the signals in the images indicate the subset of the images used for modulation cuts. These data were averaged downtrack and the results are shown in Figure 6.2. Here it is seen that modulations are about 30 percent for HH and 10-15 percent for VV. Doppler spectra (computed from a few seconds worth of (I,Q) data) are also shown in Figure 6.2. Note the difference in both amplitude and frequency of Doppler peak between VV and HH.

The next image shown in Figure 6.3 is from September 7, Run 3, with Colonel Templar traveling at 3 m/sec uploch. The wind was 3.0 m/sec from 319 degrees, nearly into the radar. A maximum BV of 0.08 rad/sec at 3 m depth was present. This X-band data is categorized as a strong signal, but is not quite as good overall as the image discussed above. Modulation cuts (Figure 6.4) show 5 percent modulation in HH, 30-40 percent in VV, opposite to the trend observed in the September 4 image.

The next image is from September 9, Run 4, and is shown in Figure 6.5. This wake was generated by Collie at 3 m/sec going uploch. The wind was 3.7 m/sec from 249 degrees (quartering, more cross-look than into-look). The maximum BV frequency was 0.07 rad/sec at 1 m depth. Modulations (Figure 6.6) were 2-5 percent in HH and 10-15 percent in VV.

Figure 6.7 shows the September 11 Run 3 image, with Colonel Templar going downloach at 4 m/sec. The wind was 4.1 m/sec from 220 degrees (cross-look), and the BV max was 0.08 rad/sec at 1 m depth. This image is fairly symmetric, though the near-range half looks somewhat stronger. The VV has better contrast than HH.

Perhaps our best-looking radar image from LL94 is from September 14, Run 1, where Colonel Templar was moving downloach at 2 m/sec, the wind was 6.2 m/sec from 54 degrees (cross-look), and a very strong pycnocline of 0.16 rad/sec maximum BV at a depth of 3 m. X-band images are shown in Figure 6.8 and S-band images in Figure 6.9. Many (10 or more) dispersive waveforms are seen on both sides of the X-band images (but curiously, only on the far-range side in the S-band images), and appear comparable in the two polarizations. Modulations in the X-band images are about 10 percent for HH and about 7 percent for VV.

Two more good image scenes are shown in Figures 6.10 and 6.11, corresponding to September 16, Run 1, and September 17, Run 1. Both had Colonel Templar moving downloach at 2 m/sec. The Sept. 16 scene had a wind of 5.8 m/sec from 2 degrees (quartering into radar) and a maximum BV of 0.09 rad/sec at 3 m depth. The Sept. 17 scene had a wind of 3.3 m/sec blowing from 25 degrees (cross-look) and a maximum BV of 0.07 rad/sec at 0.5 m depth.

Based on analysis of these (and the rest of the) intensity images, we have drawn the following conclusions:

- 3 "strong" IW wakes observed in X-band intensity image scenes
9 "moderate"
9 "weak"
13 "uncertain"
21 "no wake visible"
- 1 "strong" IW wake observed in S-band intensity image scenes
1 "moderate"
11 "weak"
2 "uncertain"
3 "no wake visible"
- Wakes appear to have higher contrast in X-band vs. S-band
- Signals seen more often on days where near-surface stratification was favorable
- No consistent trend in contrast, VV vs. HH
- No trend in contrast, near-wake vs. far wake (sometimes one better than the other or vice versa, sometimes both comparable)
- Modulation cuts performed for selected images
 - Typical values ranged from 5 - 40 percent
 - No consistent trends observed (yet) with VV vs. HH, wind speed, or wind direction re: radar look

We plan on performing more interpretive analysis involving internal wave kinematics on these intensity images once the subsurface environmental data get further analyzed, especially the shear profile data. We will then be in a much stronger position to conclude whether we would expect signals to be present or not, scene by scene, based on environmental conditions.

6.2 Analysis of (I,Q) Data

All of the full data rate pulse-to-pulse complex radar return data, also referred to as the (I,Q) data, were transcribed in Scotland, but only a limited amount of analysis could be done on site. Doppler spectra were generated for a few runs (examples shown above with "modulation cuts"), and two sets of Doppler-filtered images of small subscenes were generated.

There were a number of problems observed in the radar imagery that are indelibly in the data. In no particular order, some of these were as follows:

- Large, rib-like saturated structures were observed in S-band images. These are believed to be associated with the ship passing through S-band beam sidelobes.
- Vertical striping (over several adjacent range bins for long periods of time) was observed in low return regions of some images. This problem is believed to be associated with quantization noise in the A/D converter.
- The VV channel sometimes saturated. This was likely caused by adjustment of attenuator settings in another channel by a radar operator during the experiment.

Considerable further analysis of the (I,Q) data is planned.

Filenames: S4_2wave_IHHavdt, S4_2wave_IVVavdt (From Integrated Data)
 Comment: I Band, HH and VV Time Averaged Images, 70x1 Local Mean Normalized
 Date: September 4, 1994 Run Number: 2
 Start Time: 16:41:51 GMT
 Range Sample Interval: 3.00 meters/pixel, Time Sample Interval: 5.01 seconds/pixel

Figure 6.1 X-band radar intensity images, 9/4/94, Serial 1 Run 2

Filenames: S4_2wave_IHH_D_proj, S4_2wave_IVV_D_proj, S4_2wave_IHH_mod, S4_2wave_IVV_mod
 Comment: 1 Band Averaged Doppler Spectra (Top), Modulation Cuts (Bottom)
 Date: September 4, 1994 Run Number: 2
 CNR (HH): 8.8 dB CNR (VV): 12.6 dB

Figure 6.2 Intensity modulation for LL94 Serial 1, Run 2

Filenames: S7_3Pt_IHHavdt, S7_3Pt_IVVavdt (From Integrated Data)

Comment: I Band, HH and VV Time Averaged Intensity Images, 70x1 Local Mean Normalized

Date: September 7, 1994 Run Number: 3

Start Time: 18:21:31 GMT

Range Sample Interval: 4.50 meters/pixel. Time Sample Interval: 6.00 seconds/pixel

Figure 6.3 X-band radar intensity images, 9/7/94, Serial 3 Run 3

Filenames: S7_3Pt_IHH_D_proj, S7_3Pt_IVV_D_proj, S7_3Pt_IHH_mod, S7_3Pt_IVV_mod
 Comment: 1 Band Averaged Doppler Spectra (Top), Modulation Cuts (Bottom)
 Date: September 7, 1994 Run Number: 3
 CNR (HH): -4.6 dB CNR (VV): 11.4 dB

Figure 6.4 Intensity modulation for LL94 Serial 3, Run 3

Filenames: S9_4_IHHavdt, S9_4_IVVavdt (From Integrated Data)

Comment: I Band, HH and VV Time Averaged Images, 70x1 Local Mean Normalized

Date: September 9, 1994 Run Number: 4

Start Time: 13:27:06 GMT

Range Sample Interval: 4.50 meters/pixel, Time Sample Interval: 5.00 seconds/pixel

Figure 6.5 X-band radar intensity images, 9/9/94, Serial 5 Run 4

Filenames: S9_4_IHH_D_proj, S9_4_IVV_D_proj, S9_4_IHH_mod, S9_4_IVV_mod
 Comment: 1 Band Averaged Doppler Spectra (Top), Modulation Cuts (Bottom)
 Date: September 9, 1994 Run Number: 4
 CNR (HH): 7.4 dB CNR (VV): 12.0 dB

Figure 6.6 Intensity modulation for LL94 Serial 5, Run 4

Filenames: S11_3_IHHavdt, S11_3_IVVavdt (From Integrated Data)
 Comment: I Band, HH and VV Time Averaged Images, 70x1 Local Mean Normalized
 Date: September 11, 1994 Run Number: 3
 Start Time: 13:00:47 GMT
 Range Sample Interval: 4.50 meters/pixel, Time Sample Interval: 8.00 seconds/pixel

Figure 6.7 X-band radar intensity images, 9/11/94, Serial 7 Run 3

Filenames: S14_1wake_IHHavdt2, S14_1wake_IVVavdt2 (From Integrated Data)
 Comment: I Band, HH and VV Time Averaged Images, 1x40 Local Mean Normalized
 Date: September 14, 1994 Run Number: 1
 Start Time: 13:56:52 GMT
 Range Sample Interval: 3.00 meters/pixel, Time Sample Interval: 5.01 seconds/pixel

Figure 6.8 X-band radar intensity images, 9/14/94, Serial 10 Run 1

Filenames: S14_1_FHHavdt2, S14_1_FVWavdt (From Integrated Data)

Comment: F Band, HH and VV Time Averaged Images, 1x70(HH) and 70x1(VV) Local Mean Normalized

Date: September 14, 1994 Run Number: 1

Start Time: 13:36:52 GMT

Range Sample Interval: 4.50 meters/pixel. Time Sample Interval: 8.00 seconds/pixel

Figure 6.9 S-band radar intensity images, 9/14/94, Serial 10 Run 1

Filenames: S16_1_IHHavdt, S16_1_IVVavdt (From Integrated Data)
 Comment: I Band, HH and VV Time Averaged Images, 70x1 Local Mean Normalized
 Date: September 16, 1994 Run Number: 1
 Start Time: 14:25:04 GMT
 Range Sample Interval: 4.50 meters/pixel, Time Sample Interval: 6.50 seconds/pixel

Figure 6.10 X-band radar intensity images, 9/16/94, Serial 12 Run 1

FileNames: S17_1_IHHavdt, S17_1_IWVavdt (From Integrated Data)
 Comment: I Band, HH and VV Time Averaged Images, 70x1 Local Mean Normalized

Date: September 17, 1994 Run Number: 1

Start Time: 14:07:33 GMT

Range Sample Interval: 3.00 meters/pixel, Time Sample Interval: 8.00 seconds/pixel

Figure 6.11 X-band radar intensity images, 9/17/94, Serial 13 Run 1

7. ON-SITE CURRENT METER ARRAY DATA ANALYSIS

A significant amount of analysis of the CMA data was performed on-site. Some examples of processed data for the runs where internal waves were observed are presented in this section.

7.1 Descriptions of On-Site Analysis

Our primary real-time analysis capability for the CMA data consisted of scrolling time series for both X (cross-track) and Y (along-track) channels of all ten sensors, laid out on the scrolling plot in sequential order from the sensor nearest the bow to the sensor nearest the stern of the CMA. During the runs, we could observe visually these displays for evidence of a wavelike signal propagating through our array. The expected pattern for ship-generated internal waves are a series of waveforms in the cross-track component that arrive at the current meters in sequential order as the internal wave propagates through the array. For each of the 50 ship runs recorded by the CMA (we missed one day of ship wake data collection due to telemetry system battery problems), we carefully observed these displays visually in real time.

After a run, we processed the time series data to space-time grey-scale images of current and strain rate as described in the previous section, starting at CMA closest point-of-approach (CPA) time and having a record length of approximately 45-60 minutes after CPA. Expected patterns for ship-generated internal waves would be coherent contours that are inclined in the space-time display, whose slope is their propagation speed. For those images with an apparent signal, phase speeds were estimated and checked for consistency with an apparent propagation speed determined from a nominal offset from the ship track to the CMA (125 m) and the time of arrival at the first sensor after CPA.

7.2 Examples

The best CMA image of ship-generated internal waves was obtained on September 4, Run 2. During this run, Colonel Templar was traveling uploach at 2 m/sec in a strong near-surface stratification having a BV peak of about 0.10 rad/sec at a depth of about 1 m.

The raw single sensor time series data are shown in Figure 7.1. This figure looks very similar to how the data appeared in the real time scrolling display on the monitor. Ten channels of 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/sec. (Note that for this singular case, sensor 9 was giving erroneous results but came back to normal shortly after this run). The ship-generated IW appears as a sequence of about three waveforms beginning on Sensor 1 at about 800 sec after CPA, and appearing sequentially on Sensors 2 through 8 and on Sensor 10, persisting until about 1200 sec. A plot of these time series on an expanded scale is shown in Figure 7.2 where the time delays from sensor to sensor are accentuated.

These time series data were processed into current and strain rate images using the following procedure: 7-point median filter in time, 0.02 Hz lowpass filter in time, 4th order polynomial fit in space. These images are shown in Figure 7.3 for the full record, and in Figure 7.4 for the expanded record. As expected, the three waveforms in the time series appear 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 sec. (The peak BV period is about 60 sec.) Interestingly, the strain rate field (derived by analytically differentiating the polynomials fit to the current field) seems to have better SNR than the

current field. The phase speed of these features was estimated to be 24 ± 2 cm/sec and is consistent with time-of-arrival of the signal after passage of the boat.

Quantitative estimates of the details of the current and strain rates such as magnitudes and waveforms that are more accurate than those obtained by scaling off these images are derived by a shift-and-add method, where each time series is shifted by its separation distance from Sensor 1 divided by the 24 cm/sec estimated phase speed. The idea is to reinforce coherent waveforms and cancel noise that is incoherent. The results, 1D average time series, are shown in Figure 7.5. Here, it is seen that representative values for current and strain rate are 3-5 cm/sec and $7 \cdot 10^{-3}$ to $1 \cdot 10^{-2}$ sec⁻¹, respectively. The higher SNR for strain rate than for current is also evident in this figure.

This CMA image corresponds to the radar image shown in Figure 6.1. From the chart shown in Figure 2.2, the moored CMA's position corresponds to the far range half of the radar image. The radar image shows this 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. A possible explanation of why not, may be that for this case, the CMA was approximately 1200m uploach of the radar footprint due to the misplacing of the moorings, after which the CMA was moved closer to the radar footprint after Serial 2 was completed on September 5. Some coherence between the IW field at the CMA and within the radar footprint may be lost due to the separation distance.

The next-best CMA image containing a propagating feature is from Serial 7, Run 1 on September 11. Conditions were Colonel Templar moving downloch at 4 m/sec, with a peak BV of 0.14 rad/sec at a 1 m depth. The corresponding radar images are shown in Figure 6.7. Fortunately, this is also the case when the ERS-1 satellite with its C-band SAR overflew Loch Linnhe. An expanded view of the raw current meter time series is presented in Figure 7.6, the processed current and strain rate images in Figure 7.7, and the 1D current and strain rate waveforms after shifting and adding by 25 cm/sec, the estimated phase speed, are shown in Figure 7.8. This case shows one characteristic feature passing through the array. The magnitude of the current and strain rate of this feature is a few cm/sec and about $5 \cdot 10^{-3}$ sec⁻¹, respectively. The phase speed is consistent with time-of-arrival at the first sensor after CPA. Again, from the 1D plots, the strain rate appears to have a higher SNR than the current.

The three other CMA images that we consider to be unambiguous ship-generated features are shown in Figures 7.9, 7.10, and 7.11. These also show single features that coincide with the passage of the ship and are propagating at a consistent speed and direction. They were all generated by Colonel Templar. Figure 7.11 corresponds to the first run on September 14, whose radar image was shown in Figure 6.8 and is judged to be our best overall radar image because of the symmetry and large number of dispersive waveforms observed on either side of the wake in X-band and on the far-range side (same side as the CMA) in the S-band image. A train of dispersive waveforms is not seen in the CMA data and we do not as yet have an explanation for why not.

We can summarize the CMA on-site analysis results as follows:

- Five definitive, unambiguous ship-generated internal waves were seen in CMA data processed at the test site. These cases are (with target ship in parenthesis):

4 Sept. S1R2 (CT)	11 Sept. S7R1 (CT)	14 Sept. S10R1 (CT)
	S7R3 (CT)	
	S7R4 (CT)	

- All of the above CMA observations of unambiguous ship-generated IW's were on days having favorable near-surface stratification as measured by our profiling S4/CTD (0.14 rad/sec or higher max BV).
- Five additional features have been identified as "possible" ship-generated IW's. These are:
 7 Sept. S3R1 (CT) 9 Sept. S5R2 (Collie) 11 Sept. S7R2 (CT)
 16 Sept. S12R2 (Collie) 17 Sept. S13R1 (CT)
- Measured peak-to-peak ship wake currents were 3-8 cm/sec; measured peak-to-peak ship wake strain rates were $3 \cdot 10^{-3}$ to $2 \cdot 10^{-2} \text{ sec}^{-1}$.
- Rms noise levels were computed from those records outside the signals and ranged from 0.5 to 1.5 cm/sec to $4 \cdot 10^{-4}$ and $9 \cdot 10^{-4} \text{ sec}^{-1}$, respectively.

Future analysis will include quantifying and characterizing environmental noise and sensor performance, and some type of directional filtering, including types that will use the along-track velocity component data to suppress IW's from directions other than that of the target, etc.

In addition, some strong ambient IW features were seen in the CMA data, propagating through the CMA from directions very different than ship-generated IW's. If corresponding features are present in radar images, these can be used for MTF analysis (along the lines of that discussed in the next section for ship-generated IW's) in addition to the ship-generated IW's.

Figure 7.1 Current meter time series, 9/4/94, Serial 1 Run 2, entire run

Figure 7.2 Current meter time series, 9/4/94, Serial 1 Run 2, expanded time scale

Serial 1, Run 2 9/4/94

Figure 7.3 Cross-track current and strain rate images, 9/4/94, Serial 1
Run 2, entire run

Serial 1 Run 2 9/4/94

Figure 7.4 Cross-track current and strain rate images, 9/4/94, Serial 1 Run 2, expanded time scale

Serial 1, run2 1D estimates of waves (9/4/94)

Figure 7.5 1D estimate of cross-track current and strain rate waveform, 9/4/94, Serial 1 Run 2

Figure 7.6 Current meter time series, 9/11/94, Serial 7 Run 1, entire run

Serial 7, Run 1, 9/11/94

Phase speed of waves is 25 cm/s

Figure 7.7 Cross-track current and strain rate images, 9/11/94, Serial 7 Run 1, entire run

Serial 7, Run 1, 9/10/94

Figure 7.8 1D estimate of cross-track current and strain rate waveform, 9/11/94, Serial 7 Run 1

Serial 7, Run 4, 9/11/94

Figure 7.9 Cross-track current and strain rate images, 9/11/94, Serial 7 Run 3, entire run

Serial 7, Run 3, 9/11/94

Figure 7.10 Cross-track current and strain rate images, 9/11/94, Serial 7
Run 4, entire run

Serial 10, Run 1, 9/14/94

Figure 7.11 Cross-track current and strain rate images, 9/14/94, Serial 10
Run 1, entire run

8. ON-SITE MTF ANALYSIS

As stated in the test objectives (Section 1.2), we had hoped to combine the LL94 CMA and radar data to empirically characterize the modulation transfer function (MTF), the relation between the IW-induced surface hydrodynamics and the radar modulations as a function of wind speed and direction, radar frequency and polarization, and ship size and speed, and the stratification.

The approach we took here is to model the MTF by:

$$\frac{\Delta\sigma}{\sigma} = \gamma u + \xi \frac{du}{dx}$$

and estimate the coefficients γ and ξ by incoherently combining a spatially registered subset of the radar image data with the CMA image data. The details of the method are somewhat complicated and are described in the companion report by Jones and Chambers (1994).

Because of the limited number of visible IW signals observed in both the CMA data and the radar data, we have only been able to make a limited number of MTF estimates. Furthermore, the details of the features in the CMA images do not correspond very well to the detailed features in the radar images.

The results are tabulated below. Units are mks. $\lambda\gamma$ and $\lambda\xi$ are measures of the error in the estimates of γ and ξ , respectively, and their units are the same as γ and ξ . Values of u and $\frac{du}{dx}$

and $\frac{\Delta\sigma}{\sigma}$ in the table are peak-to-trough.

$$\text{The ratio } R = \frac{\left| \xi \frac{du}{dx} \right|}{\left| \gamma u \right|} = \frac{\xi / \gamma}{\left(\frac{\Delta\sigma / \sigma}{u} \right) / \left(\frac{\Delta\sigma / \sigma}{du/dx} \right)}$$

is indicative of whether the observed radar modulation is current-dominated ($R \ll 1$) or strain rate-dominated ($R \gg 1$).

Date	Ser.& Run	Freq. & Pol.	Wind Speed (m/sec)	Wind* Dir. (deg from)	$\frac{\Delta\sigma / \sigma}{u}$	$\frac{\Delta\sigma / \sigma}{du / dx}$	γ	$\lambda\gamma$	ξ	$\lambda\xi$	R
9/4	S1R2	XHH	5.5	275	4.9	22	2.5	3.9	-10	39	0.89
		XVV			2.1	9.5	2.5	0.48	-10	4.2	0.88
9/11	S7R1	XHH	3.4	261	1.4	9	2.5	1.9	-5	34	0.31
		XVV			6.4	40	7	4.7	-20	100	0.46
		SHH			2.1	13	1	1.7	21	24	3.4
		SVV			2.9	18	4.5	4.9	60	98	2.1
	S7R3	XVV	4.1	220	6.4	50	7.5	5.5	20	140	0.34
9/14	S10R1	XHH	6.2	54	10	55	5.3	14	-45	88	1.5
		XVV			6.2	33	0.4	6.2	-24	38	11.3
		SVV			6.3	34	0.8	5.4	24	26	5.6

*Radar look direction is 308°

A few general conclusions can be drawn from these estimates.

- Estimates of the coefficients γ and ξ are order-of-magnitude consistent with the gross ratios $\frac{\Delta\sigma / \sigma}{u}$ and $\frac{\Delta\sigma / \sigma}{du / dx}$.
- The values of R seem to suggest that for these cases, contributions from current and strain rate are generally comparable for X-band. For S-band, it seems that strain rate is the more dominant contributor to the radar modulation (intuitively plausible).
- The values of the MTF coefficients, particularly ξ , seem to be lower than expected. Strain rate coefficients $\frac{\Delta\sigma / \sigma}{du / dx}$ estimated previously for X-band at LGA with the radar looking into the wind were of order 1000 (Brase, 1993).

We will look into MTF's more thoroughly post-test. It does not look like we will be able to do a broad parametric characterization that we had originally hoped to do, however.

9. SUMMARY

A field experiment involving imaging ship-generated internal waves by a land-based real aperture radar at low grazing angle with in-water and meteorological supporting measurements was successfully conducted by participants in the Joint UK/US Radar Ocean Imaging Program at Loch Linnhe, Scotland during the period 4-17 September 1994. Several previous experiments had been conducted by the Joint UK/US Program at this site. The general goal of the experiment was to collect radar imagery with sufficient in-water instrumentation to be able to compare the radar modulations with the hydrodynamic measurements. LLNL was a major participant in this experiment; we collected data with our current meter array and meteorological measurements, collected water column data with our vertically profiling current meter/CTD package, transcribed radar data collected by the UK and performed substantial analysis of the radar and in-water data on-site.

All of LLNL's specific experimental objectives were either fully or partially met.

The LLNL Current Meter Array (CMA) platform was successfully assembled, deployed, moored, operated, and recovered at the Loch Linnhe site for the first time. For data collection, the CMA was moored in water 45 m deep with its long axis oriented in the cross-track direction with its bow positioned 125 m from the nominal ship track. Ten S4 current meters measuring two horizontal velocity components were fielded, with a uniform cross-track spacing of 3.75 m (total aperture approximately 34 m), all at a depth of 2 m. Ship-generated internal wave wake data were collected for 50 of the 56 ship runs in which the equipment performed well and the data quality appears excellent. Including ambient, about 240 hours total of CMA data were recorded. Analysis of CMA data was performed on-site; space-time images of surface currents and surface strain rates were generated for the 50 ship runs. These are first-of-a-kind analysis products. Only 5 unambiguous ship-generated internal waves have been seen (so far) in the CMA data; 5 additional weak features have been identified as "possibilities." The observed ship-generated internal waves have phase speeds of 15-25 cm/sec, currents of a few cm/sec, strain rates of $5 \cdot 10^{-3}$ to $1 \cdot 10^{-2} \text{ sec}^{-1}$, and wavelengths of about 30 m or so.

Intensity images were generated for all radar data, VV and HH polarization, X-band (and S-band when it was activated) and bistatic receive mode (when this mode was employed). A visual analysis of the X-band radar images shows 3 strong, 9 moderate, and 9 weak ship-generated IW features in the 55 scenes with ship wakes. 1 strong, 1 moderate, and 11 weak ship-generated features were found in the 18 S-band images. Visible IW's were imaged by the radar for all of the CMA cases where there were unambiguous ship-generated features present in the data. "Modulation cuts" were performed on selected images; IW-induced intensity modulations ranged from 5 to 40 percent.

All of the full data rate, pulse-to-pulse complex (I,Q) radar return data were calibrated and transcribed at the test site. A limited amount of analysis of these data was performed. Doppler spectra were generated for VV and HH from a few seconds worth of data. Doppler filtered images were generated for VV and HH for small subsets of two scenes.

Subsurface water column profile, meteorological environmental data, and differential GPS position data for platforms and ships were successfully collected to support interpretation of the radar and CMA data. Density profile (BV frequency profile) and shear profile data were collected with a vertically profiling S4 current meter equipped with fast response temperature and conductivity sensors. These are first-of-a-kind measurements within the Joint UK/US Program, and (we think) the first time continuous profiling has been successfully performed with an S4 current meter. Subsurface stratification was less favorable for IW-related surface effects than expected. Wind speed and direction were measured atop a ten meter high tower on the current meter array platform. Air temperature, surface water temperature, and relative humidity were also measured. Data quality appears excellent in all cases. We have concluded that the presence of visible IW features in both the CMA and the radar data correlates with

favorable stratification conditions. A good distribution of wind speed was obtained (range 2 - 15 m/sec) but wind direction was usually aligned with the longitudinal axis of the loch (cross-look for the radar).

Only very limited Modulation Transfer Function (MTF) analysis could be performed on-site because of the small number of coincident ship-generated features in the CMA and radar data.

Overall, this experiment was highly successful and significant further data analysis is planned.

10. References

- Brase, J.M. (1993) Personal communication.
- Brase, J.M., S.K. Lehman, and C.J. Mullenhoff (1994) "Low Grazing Angle Doppler Resolved Imagery at the WCSEX 91-92 Experiments," LLNL Report (in preparation)
- Fu, L.L. and B. Holt (1982) "Seasat Views Ocean and Sea Ice with Synthetic-Aperture Radar," JPL Publication 81-120.
- Gibson, G.E. (1994) "Loch Linnhe Experiment 1994: Trial Plan," Final Version 3.0, DRA/Farnborough Document No. DRA/CIS(CSC2)/4/36/4/TP1/3.0
- Jones, H. and D. Chambers (1994) "Current Meter Array Data and Modulation Transfer Function Analysis at Loch Linnhe 1994," LLNL Report (in preparation)
- Lehman, S.K., C.J. Mullenhoff, et al. (1994) "Radar Imagery From the Loch Linnhe 1994 Trials," LLNL Report (in preparation)
- Mantrom, D.D. (1994) "Radar Ocean Imaging Field Experiment. US Objectives, Requirements, and Proposed Operations, LOCH LINNHE 94," LLNL Report No. UCRL-ID-117806
- Newman, M.J. (1994) "CMA and Met Hardware Description and Operations," LLNL Report (in preparation)
- Robey, H.F. and D.L. Ravizza (1994) "Loch Linnhe Experiment 1994, Background Stratification and Shear Measurements, Part 1: Profile Summary and Dispersion Relations, LLNL Report (in preparation)