One-Hop ELF/VLF Measurements at the HAARP Conjugate Point: Buoy Feasibility Study

Noah F. Reddell
VLF Group
Stanford University

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Abstract

This report summarizes the results of an initial feasibility study conducted from August to December 2002 at Stanford University. The VLF Group at Stanford University desires to place a receiver at the magnetic conjugate point of the HAARP transmitter. The transmitter generates strong radio waves in Alaska, some of which will propagate along the magnetic field lines of the earth, and fall upon the point 56.19° S, 173.80° E. Important conclusions of this feasibility study include the ability to moor a buoy in 5400 meters ocean depth, preliminary weather and sea state expectations, deployment options, and a preliminary buoy design.

1 Introduction

The Very Low Frequency Group at Stanford University has made many important discoveries about the earth, ionosphere, magnetosphere and the interactions between them. Research has focused both on the physical nature of these regions and how to effectively propagate radio waves through them.

In continuation of this important effort, the group is uniquely positioned to conduct experiments in conjunction with the High Frequency Active Auroral Research Program (HAARP) transmitter in Alaska. This transmitter can operate as a modulated ionospheric heater causing ELF/VLF waves to develop high above the site.

Some of these waves are ducted and propagate along the magnetic field lines of the earth. They return to the earth, along with other possible triggered effects, at the magnetic conjugate point. For HAARP, the magnetic conjugate point has been carefully calculated to be 56.19° S, 173.80° E.

This location is in the southern Pacific Ocean above 5400 meters of seawater. Surface conditions range from inhospitable to severe year-round. This study began in order to determine the feasibility of recording important ELF/VLF signals at the HAARP conjugate point in spite of the difficult conditions.

1.1 Selection of an Open Ocean Buoy

The first and most obvious question asked is: How to operate an ELF/VLF receiver at a remote spot in the southern Pacific Ocean? There are a few options, but only one turns out to be practical.

A ship could be chartered to maintain station at the conjugate point with the receiver embarked. This option turns out to be prohibitively expensive as the charter cost for a capable ship and crew is over $15,000 per day. The one-hop campaign will need to operate for multiple years in order to gather complete data. Even without financial limitations, a large ship would likely produce excessive interference in the ELF/VLF experimental spectrum of interest.

A second option is to create a station-keeping buoy that would not require a mooring system. In the ocean area of interest, this would realistically have to be a large unmanned ship. As this would be even more expensive than the chartering option, it would only be considered if mooring a buoy is not possible.

Mooring systems are in fact possible in depths at or greater than 5400 meters. This survey discovered around one dozen such mooring systems. A few of those have been employed in seas similarly tempestuous. See [1] and [2].

1.2 Organization

This report highlights the major hurdles considered to assess the feasibility of the project described. Each area is described and where potential difficulties exist, a reasonable work-around has been identified.

The topics are as follows:

Section 2 Weather and Sea Conditions

Section 3 The Buoy

Section 4 The Mooring System

Section 5 Buoy Deployment

Section 6 Unique Challenges

Section 7 Contacts

Appendix A Project Capital Expenses

2 Weather and Sea Conditions

For a long duration experiment, the most significant challenge for an open ocean surface buoy and mooring system is the weather and sea conditions at the deployment site. The one-hop experiment is challenged by both an operational goal of two years and by being located in an often violent part of the Southern Pacific Ocean. For these reasons, it is important to gather as much information about the weather and sea conditions as possible. This information will be critical for design of the mooring system and the buoy's keel.

The area around the deployment location 56.19° S, 173.80° E is remote and not frequently visited by ships nor has its bathymetry or current profiles been studied in detail. For these reasons, the information summarized below was gathered from a limited number of sources.

NIMA Chart 624: New Zealand to Cape Adare This is the only nautical chart published by the National Imagery and Mapping Agency which covers the deployment location. It covers an expansive area of the ocean between New Zealand and Antarctica. The most current bathymetric data appears to be from 1957. [3]

Atlas of Pilot Charts: South Pacific Ocean This publication provides a great deal of information useful to mariners with data displayed for each month of the year. Since it covers the entire South Pacific Ocean, it does not cover the deployment area with great detail. Most data are compilations of reports from mariners which typically read like: 'For the month of March, 36% of reports have wave heights were greater than 12 feet.' [4]

Satellite Wave Height Data There are two satellites currently in orbit that measure average and significant wave height near the deployment location one or two times per day. These are the TOPEX and the ERS satellites. Their data can be accessed on the internet and is managed by the University of Colorado at Boulder.[5] Additionally, Geosat (1986-1989) data also provides significant wave height and wind speed averages by month.

Papers Provided by NIWA Dr. Lionel Carter of New Zealand's National Institute of Weather and Atmospheric Research provided several oceanographic papers presenting current data collected at six mooring locations. The closest of the six still was located many miles from the deployment location. Its relevance is questionable due to the proximity of the Campbell Rise and its associated deep sea currents. The illustration of major currents in Figure 3 was provided by NIWA.

Studying the nautical chart for the region of ocean, it becomes apparent that the HAARP conjugate point is not fortuitously located. Table 1 summarizes the challenges faced. Not only is it in a remote, deep, and often violent part of the ocean, it is almost the deepest point for 250 nautical miles. The conjugate point is on the eastern (down-current) side of a trough up to 5700 meters deep. The Campbell Rise starts about 100 nautical miles to the northwest and at 150 nautical miles from the deployment zone the depth is just 550 meters.

Summary of Weather and Sea Challenges	
Currents	Fortunately less than one knot. No concern.
Wave Height	Greater than 12 feet between 30% and 50% year round. Swells average 12 feet on top of that.
Wind	Gale conditions 10% to 30% of the time year round (Beufort 8).
Icing Concerns	Sea spray icing can occur on exposed surfaces during colder months. Antenna dome will help with this potential problem.
Ice Bergs	Yes, its a possibility. Buoy is below maximum drift of icebergs eleven months out of the year – by as far as 20 degrees latitude. Highly improbable.

Table 1: Summary of Weather and Sea Conditions affecting the buoy.

The bathymetric information contained in chart [3] does not have a high level of detail. The chart itself was last published in 1981, but it appears most of the soundings were taken in 1957. For this reason, either more detailed bathymetric information should be found, or the deploying ship should be equipped with a depth sounder and the mooring system should have an adjustable length section.

The four months in Table 2 are of particular interest. The southern summer peaks in December and January and these months see the best sea conditions at the deployment

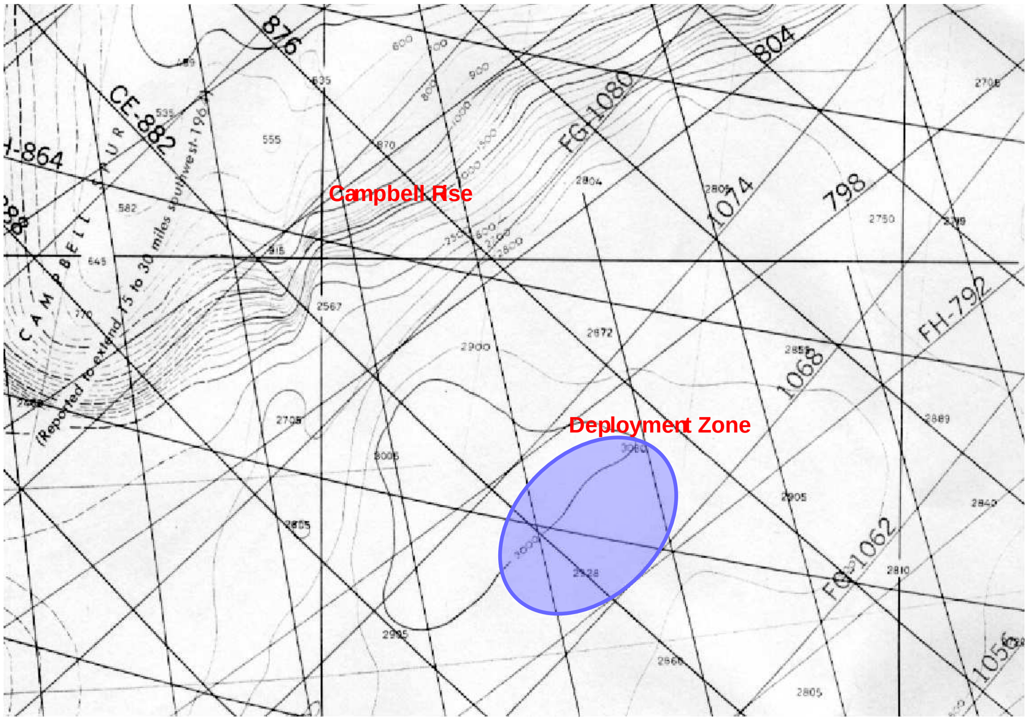

Figure 1: Buoy deployment location superimposed on a portion of the nautical chart [3]. Depths are in fathoms.

locations. March arose as an alternate possibility to deploy the experiment. Looking at the expected conditions in March, it would be risky that a vessel and crew could safely deploy the buoy and mooring system. July is among the worst months and is shown for comparison.

Beaufort 8 winds reported in Table 2 are considered a fresh gale and blow between 30 and 40 knots. At sustained durations, the winds create light foaming waves averaging 21 - 28 feet crest to trough with significant wave heights 35 - 45 feet. This is equivalent to a Sea State 7. [6]

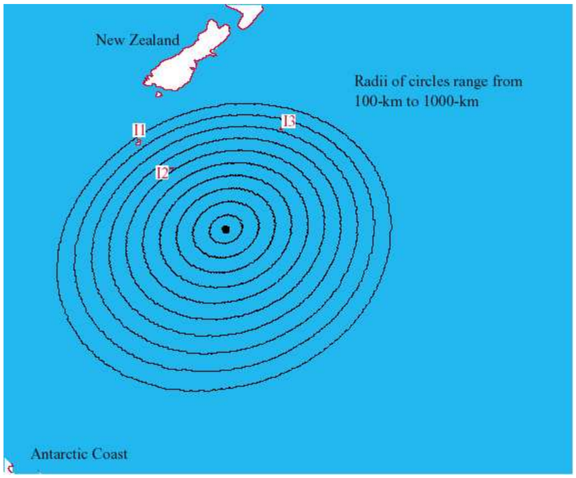

Figure 2: Range circles surrounding the HAARP conjugate point. Circles are separated by 100 km.

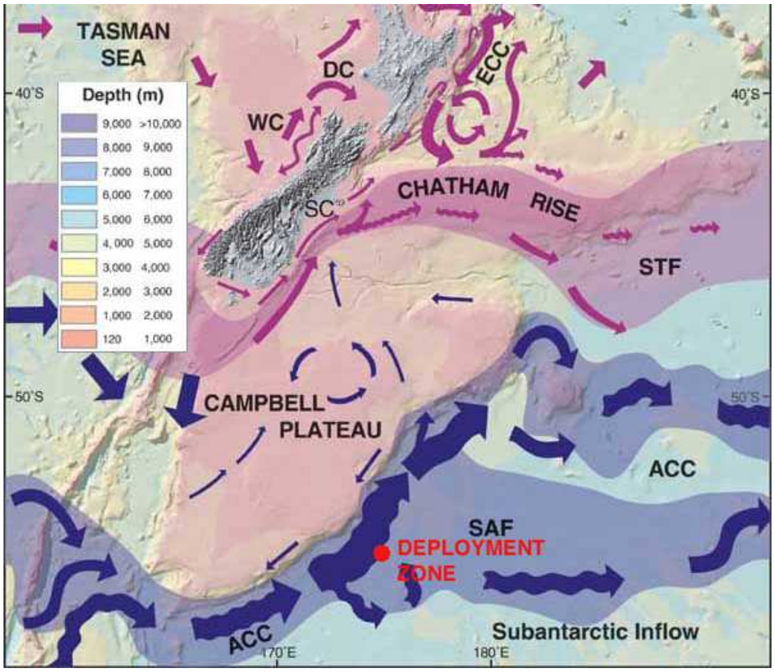

Figure 3: Persistent currents in the region of interest. Provided by NIWA.

Sea Conditions for Selected Months from *Atlas of Pilot Charts*				
	DEC	JAN	MAR	JUL
% of wave height observations $\geq$ 12 ft.	20%	30%	36%	45%
Within maximum extent of icebergs?	Yes	Yes	No	Yes
% of wind speed observations $\geq$ Beufort 8	5%	8%	13%	Not avail.
Avg. air temperature	$6°C$	$8°C$	$7°C$	$3°C$

Table 2: Weather and sea state information of interest for selected months gathered from [4].

Monthly Averages from Geosat (1986-1989)		
	Wave Height (ft.)	Wind Speed (kts.)
JAN	21.5	10.2
FEB	19.3	10.2
MAR	23.0	12.5
APR	25.8	14.4
MAY	24.2	14.8
JUN	24.8	14.1
JUL	22.5	12.8
AUG	22.3	11.8
SEP	19.9	10.5
OCT	17.0	10.8
NOV	21.5	11.0
DEC	22.5	10.5

Table 3: Wave Height and Surface Wind data from Geosat. Wave Heights are average significant wave height. Winds are scalar averages.

3 The Buoy

The buoy that will be used for this experiment is a round bottom buoy made of soft SURLYN foam. It is currently owned by the Naval Research Labs and has hosted several experiments since its construction in 1994. Using an existing buoy allows significant cost savings compared to designing and constructing a new one.

In order to determine if this buoy is suitable for this experiment, the author travelled to the NRL site near Chesapeake Beach, Maryland in November. The buoy is located there outside of a NRL warehouse. The conclusion of this trip was that the buoy is in fact appropriate to host the experiment and to be deployed at the HAARP conjugate point. It will need several modifications as expected.

Figure 4: The reusable foam section of the buoy located at the NRL site near Chesapeake Beach, MD.

Figure 5 illustrates major components of the buoy after planned modifications. The reused orange foam section is ten feet in diameter. (See figure 4.) There will be a fiberglass antenna dome on top of that, sealed water tight. This structure will support the three orthogonal air-core loop antennas, provide a mounting point on the top for the Iridium and GPS antennas, and mitigate sea ice build up.

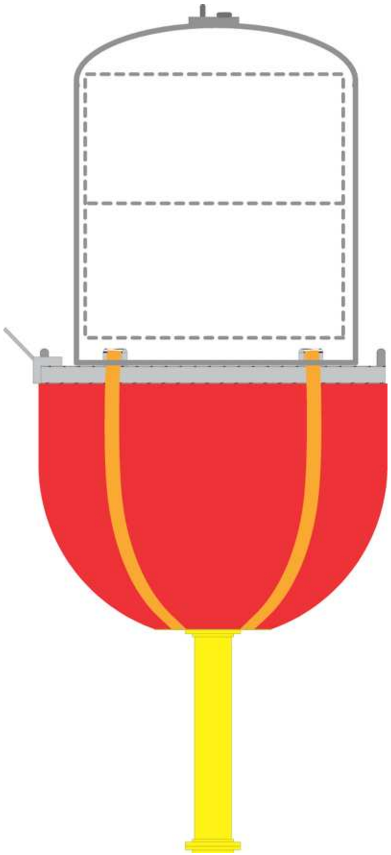

Figure 5: An illustration of the three major buoy components: the fiberglass antenna dome, the foam body, and the keel for stability.

The fiberglass dome is mounted on a new aluminum deck structure. This structure is secured by several nylon straps around the circumference of the buoy that run taut from the deck to the top of the keel.

The keel shown is only for illustration purposes as a new one must still be designed. The previous keel was designed for a larger payload, different sea state and has undergone an uncertain degree of metal fatigue. The new keel will likely be a single steel pipe about one foot in diameter. The length will be determined after considering several stability calculations. The mooring line will attach to the bottom of the keel at a U-joint fitting.

All electronics for the experiment will be housed in a well, 72 inches deep and 40 inches in diameter, in the center of the foam section. The batteries will be secured at the bottom of the well and the mu-metal enclosure will be secured above them. The well will be water tight, but difficult to access after deployment.

The buoy components will be centrally assembled prior to shipment to New Zealand at the NRL site. The antenna dome will likely be constructed nearby in Maryland. Four trips to Maryland are planned for the Stanford team for assembly and testing of the experiment components and to oversee the overall assembly of the buoy.

4 The Mooring System

Several key factors drive the design of the mooring system. They are: water depth, sea conditions, targeted duration of operation, and the significant expense of ship time at the deployment location.

4.1 Should the Mooring Line be Recoverable?

Since the cost of the mooring system is on the same order as the cost of a ship for its deployment, the possibility of an expendable mooring system has been considered and deemed appropriate for this experiment.

The mooring system components (minus an appropriate anchor) will cost $95,000 It would cost an additional $35,000 to include an acoustic release and the other hardware necessary to recover the mooring system above the anchor. This option is frequently employed in case of a mooring line break or for final recovery.

The experiment is targeted to operate for up to two years. This will push the mooring system to its design limits. If the mooring continues to hold at the two year point when a second-generation buoy is to be deployed, its remaining value will not be worth the up front cost of the acoustic release and other recovery components and the expense of additional ship time for hauling in over 6.5 km. of mooring line.

If the mooring line fails, it will not matter financially if it happens two weeks into the experiment or two weeks from the end. It will cost over $100,000 to bring a ship to the buoy or the deployment location regardless. This is assuming that a large ship could be chartered on short notice and that the failure occurs at a time of year when such operations are possible. Both are not likely to be the case.

The prudent path to take with the mooring system and buoy design is to forgo the recovery option for the mooring line and concentrate on ensuring the mooring and buoy have the best chance of surviving the full two year goal.

If the mooring does fail prematurely, the buoy and experiment still have a good chance of remaining operational. One option would be to let the buoy drift with the experiment operating until it came closer to land and salvage would be possible. Prevailing winds and currents would likely take the buoy to South America before it could be recovered.

Of course, to choose this option would be to accept the very real risk that the buoy and experiment will be destroyed. In this case, the re-usable components on the buoy would be of less value than the cost of a recovery ship. A disposable mooring system without a planned specific recovery mission is the most prudent option. The buoy itself can be recovered while deploying its second generation replacement.

4.2 The Mooring System Design

There are a limited number of shops in the country that can design and build a mooring system to meet the project requirements. Woods Hole Oceanographic Institution has agreed to design and build the mooring system. The ocean engineers there are the most experienced in the world with this sort of challenge.

The mooring will likely be an inverse catenary style originally developed by the National Data Buoy Center and perfected over many years by both NDBC and WHOI. It is characterized by a single mooring line made up primarily of two different synthetic materials. The upper half is typically Nylon which is more dense than the sea water. This provides downward tension on the buoy for stability. The lower half is usually Polypropylene which is less dense than the sea water. This provides positive tension at the anchor in order to keep the mooring line from fouling in the anchor components. The overall shape has been dubbed an inverse catenary. (See figure 6.)

The illustration shows some additional features of the mooring system. The acoustic release and glass backup recovery balls will not be implemented as discussed above. The top 200 meters of mooring line is composed of wire rope. This section of the mooring line is in the epipelagic layer. The vast majority of marine life lives in this mixed layer that receives light from the sun. Some marine life can be a fish bite hazard and several moorings have failed before adding an upper section of wire rope.

5 Buoy Deployment

Deployment refers to the phase of the experiment when the buoy and mooring system are first placed at the HAARP conjugate point. For a buoy as sizeable as this, it takes a large ship with a lifting crane to perform the deployment. The sea conditions at the HAARP conjugate point further dictate ship size. The ship must be well equipped and the whole operation should be conducted by an experienced crew.

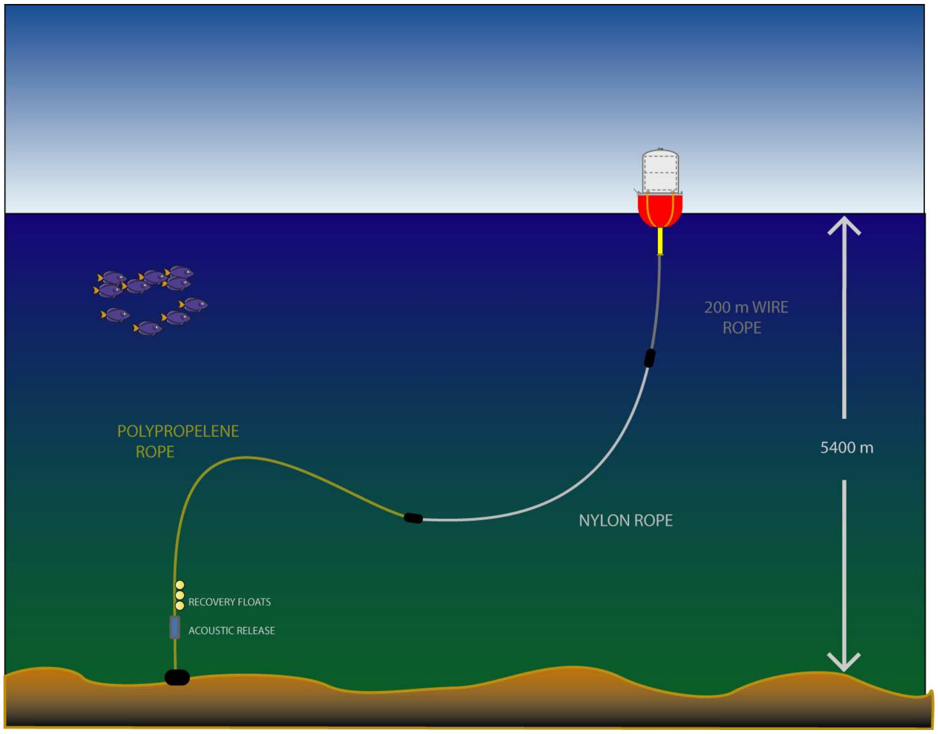

Figure 6: Mooring system illustration for inverse catenary style mooring.

5.1 Deployment Window

The targeted deployment window has been set to be mid-December 2003 through mid-January 2004. This limited range is predominately dictated by expected weather conditions. Only during these two months, the peak of the southern summer, do the seas usually calm enough for a ship to set the buoy over the side. Even then, weather delays must be anticipated.

The deployment is targeted for approximately one year from now in order to take advantage of several unique opportunities not available two years from now. Also, in many ways the first buoy can be considered a learning mission for a second generation buoy when the HAARP management complete a major upgrade of the transmitter. There is little lost between a two and one year development schedule besides the accelerated pace.

5.2 Requirements of the Deployment Vessel

Availability The ship must commit to performing the deployment during the souther summer 2003/2004. It must agree to a specific window well before deployment in order to coordinate with other personnel and the HAARP transmitter.

Experienced Crew The crew shall be well experienced in open ocean buoy and mooring line deployment. Stanford will provide only minimum personnel to oversea the experiment.

Deck Gear The ship must be equipped with an appropriate winch for the mooring line and tension carts. If not, they will have to be supplied.

Lifting Crane The ship must have a crane capable of deploying the buoy which in total will weigh approximately 5,500 pounds.

5.3 Potential Ships

Out of an extensive search to identify potential ships that would be available to perform the deployment, only two have been identified to date. Attempts to find a vessel already operating in the deployment region have failed. To deploy the buoy will require a specific mission. Figure 7 and 8 show the *Tangaroa* and *Pacific Chieftain* respectively.

Figure 7: NIWA research vessel *Tangaroa*.

Figure 8: Sea Works anchor handling tug *Pacific Chieftain*.

The *Tangaroa* is operated by New Zealand's National Institute of Weather and Atmospheric Research. They have made an initial offer to deploy the buoy in October 2003 or March 2004. They would charge on a per day basis. Expecting one to five days of weather delay gives a cost ranging from $174,000 to $242,000. NIWA cannot currently commit the *Tangaroa* for the summer deployment window.

The *Pacific Chieftain* is operated by SeaWorks of New Zealand. They have made an offer to deploy the buoy in December 2003 for $75,000 flat rate excluding fuel costs which are expected to be around $30,000. Weather delays would be at the expense of SeaWorks. The offer is subject to the availability of a suitable vessel in their fleet. This is not expected to be a problem, but gives rise to the need to enter a contractual agreement with SeaWorks early if identified to be the deployment company of choice.

5.4 Current Status

At this point, of the two potential ships identified, SeaWorks has the only ship available during our target window and is offering the best price on an attractive flat rate basis.

The author and project investigator will meet with SeaWorks in January 2003 to discuss details of the deployment and financial arrangements.

We are continuing to investigate other options but most ships are either too busy during the summer or this project is too small an opportunity for a ship that is typically chartered for six months or more at a time.

6 Unique Challenges

In many ways this experiment is like launching a satellite. It will be conducted in an extreme environment at a remote location. There are also many unique challenges caused by operating the experiment on an open ocean buoy.

6.1 A Sea that Never Calms

They buoy will always be in motion. Roll, pitch, and yaw will all be experienced simultaneously. In addition to sampling ELF/VLF fields then, the experiment must also simultaneously determine the buoy's three dimensional orientation. This is necessary in order to determine spatially where the electromagnetic waves arrive from and to compensate for the growing and fading of the signals as the antennas change their orientation to the incoming electromagnetic wave by ocean wave action.

Tilt sensors that work by gravity can give two of the three orientations, but not yaw. Two options have been considered to determine yaw. A digital magnetic compass is one, but has several problems. Since the compass will likely produce electromagnetic noise that would interfere with the experiment, it must be placed in the mu-metal enclosure described below in 6.2. Doing so, however, would likely seriously interfere with the compass' operation.

The second option is to use the existing VLF antennas and receiver equipment with some additional on board processing to reverse direction find to known high-powered Naval transmitters. NWC in Australia and NPM in Hawaii are the closest two. This appears to be the best option, as it should provide more accurate results than a compass. There is the potential for a 180 degree ambiguity in the yaw position.

6.2 Electronic Noise

Housing the experiment on the buoy offers a limited ability to spatially isolate electronic noise from the ELF/VLF measurements. The existing VLF line receivers employed in Alaska require 200 feet of separation from the antennas to the recording devices in order to eliminate interference with the received signal. On the buoy, the greatest separation that may be achieved is four feet.

To work around this, we will use a mu-metal enclosure that attenuates the magnetic field by 90-100 dB in the frequency range of interest. The enclosure is made of three or four layers of thin sheet metal formed into four concentric cylinders separated by an air gap. The metal is a special hydrogen annealed high nickel-content alloy.

The drawback of this technique is that all noise producing electronics must be contained in this relatively small enclosure. This is possible, but packaging and circuit board layouts must be designed with this in mind.

6.3 Power Supply

As discussed, the most costly part of this experiment will be the ship to travel to the deployment location. It is desirable, then, for the experiment to run for as long as possible on the power supply contained on board at deployment.

The most common methods of power generation on open ocean buoys are diesel generators and solar panels. Both methods have problems at our location. A generator would be unlikely to remain reliable for the two year deployment goal and would have difficulty operating in the rough sea conditions that will be experienced by

Figure 9: A 12V AGM battery that offers 255 AH of power for its 162 pound weight.

the buoy. These conditions, coupled with icing concerns, and the southerly latitude make solar panels undesirable as well.

Fortunately, the experiment has relatively small power demands and most of the time the electronics can be in an ultra-low-power sleep mode. For these reasons, batteries can be expected to power the buoy throughout the two year operational goal.

Around six absorbed glass mat (AGM) Marine batteries can power the buoy for two years. Large ones such as in Figure 9 weigh 162 pounds but can be secured at the bottom of the buoy's electronics well where their weight will also improve the buoy's stability.

6.4 Data Return and Telemetry

The buoy will not be visited after its deployment except for an uncertain recovery mission after two years. For this reason, the experimental data cannot be left on the buoy. Additionally, the receiver on the buoy must be coordinated with the HAARP transmitter in Alaska. These reasons alone dictate the need for communication with the buoy throughout the experiment.

Several commercial satellite communication systems were considered. The general criteria are only met by the system operated by Iridium Satellite LLC. Data modems that work with Iridium will be able to handle all experimental data and telemetry needs.

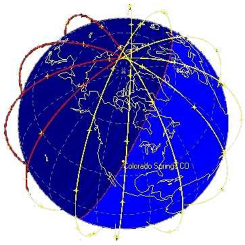

Figure 10: The Iridium 66 satellite constellation and their polar orbits.

Near-real time data availability Shortly after a VLF observation has been recorded on the buoy, it should be transmitted back to Stanford and made available for analysis. The Iridium system has continuous coverage.

Telemetry monitoring Information about the health of the buoy's subsystems should be available for monitoring. This includes digital camera images taken of the buoy from the buoy. The experiment's scheduling must also be modified by this data link.

Coverage Footprint The satellite system must offer coverage at the southerly deployment location. Many geostationary communication satellites do not. Most that do require a high-power transmitter and an antenna that physically tracks the satellite. Iridium operates a network of 66 low earth orbit satellites that provide continuous and global coverage.

Omnidirectional antenna A system that requires an antenna that tracks the satellite would draw too much power and be too mechanically unreliable for the lengthy deployment. Iridium devices use a small omnidirectional antenna.

Limited Power Budget The greatest user of power on the buoy will be the satellite communication link. Low earth orbit systems require less power for the transmitter than higher geostationary systems. Iridium modems require less than 9 Watts of power while transmitting as opposed to commercial marine communications satellites that require one-hundred Watts or more.

Reliability Not long ago, there were at least three companies struggling to offer LEO satellite communication products. All three failed financially. The original Iridium, having successfully launched and implemented its system, was saved by the U.S. Government and in its current form is a solvent company.

Data Rate The drawback of the Iridium system is its low data rate. The current service offers data rates between 2.4 and 3.0 kilobits per second. The unprocessed data rate from the three-channel receiver will be at least 355 kbps. Therefore, without any compression or onboard data processing, the communications link must operate a factor of 148 times as long as any observations. This emphasizes the need for both on board processing and compression.

7 Contacts

The author extends his gratitude to the following individuals who gave advice or provided product and design information for the purpose of this feasibility study.

Sean Kery
Oceaneering
501 Prince George's Blvd.
Upper Marlboro, MD 20774
(301) 249-3300
skery@adtech.oceaneering.com

Richard Harriss
Scripps Oceanographic Institute
San Diego, CA
(858) 534-1843
dick@mpl.ucsd.edu

Jeff Lord
Woods Hole Oceanographic Institution
360 Woods Hole Rd.
Woods Hole, MA 02543
(508) 289-3386
jlord@whoi.edu

Don Trumpy
Marine Designs and Composites
Maryland
(410) 257-0477
dtelite@aol.com

George Warner
Gilman Corporation
Box 68
Gilman, CT 06336
(800) 622-3626
mail@gilmancorp.com

Ngoc Hoang
NAL Research
8708 Studley Road
Manassas, VA 20110
(703) 392-5386

Ed Kennedy, John Perkins, and John Bashista
Naval Research Laboratory
Washington D.C.
kennedy@itd.nrl.navy.mil (202) 767-2761
perkins@ghost.nrl.navy.mil (202) 767-9037
bashista@itd.nrl.navy.mil

Fred Smits, Mike Williams and Dr. Lionel Carter
New Zealand's National Institute of Weather and Atmospheric Research
Private Bag 14 901
Wellington, New Zealand
f.smits@niwa.co.nz +64 4 386 0389
m.williams@niwa.co.nz +64 4 386 0389

Mark Randall and Steve MacIntyre
SeaWorks of New Zealand
SeaWorks House
Waterloo Quay P.O. Box 39
Wellington, New Zealand
mark.randall@seaworks.co.nz +64 21 942 469
steve.macintrye@seaworks.co.nz +64 4 499 6891

Larry Maltin, President Technical Products
Amuneal
4737 Darrah Street
Philadelphia, PA 19124
(800) 755-9843
larrym@amuneal.com

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