Mission Plan for the Rough Evaporation Duct (RED) Experiment

K. Anderson*, S. Doss-Hammel, C. Friehe, D. Hegg, T. Hristov, R. Janaswamy, H. Jonsson, and J. Reid

*Space and Naval Warfare Systems Center San Diego, D858
49170 Propagation Path
San Diego, CA 92152
Voice: 619 553 1420, Fax: 619 553 1417
kenn@spawar.navy.mil

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Abstract

Prediction of electromagnetic (EM) signal propagation over a wind-roughened sea relies on a thorough knowledge of its interaction with the sea surface, the mean profiles of pressure, *P*, humidity, *Q*, temperature, *T*, wind, *U*, their turbulent fluctuations (*p'*, *q'*, *t'*, *u'*) and aerosol concentration, c_n. Yet, within the marine surface layer, these mechanisms are not sufficiently understood nor has satisfactory data been taken to validate empirical models. The RED experiment will provide first data for validation of both meteorological and EM propagation models in the marine surface layer for rough surface conditions.

Over the ocean, similarity theory is often applied to construct mean profiles of *Q*, *T*, *U*, and c_n in the surface layer. For smooth seas, there is good agreement between theory and measurements, both meteorological and EM. However, recent evidence indicates that even small waves perturb *P*, *Q*, *T*, and *U* profiles throughout the surface layer. Additional, although indirect, evidence of surface induced distortion has been derived from analyses of microwave signal propagation close to the sea surface. Effects of wave interaction with the turbulent fluctuations of *q'*, *t'*, and *u'* have never been studied even though *q'*, *t'*, and *u'* are crucial for modeling optical propagation.

The RED experiment will be conducted offshore of Oahu, HI, from mid-August to mid-September 2001. The Hawaiian Islands in late summer are ideal for RED because climatology shows this area and timeframe to have the highest joint probability of high winds and intense evaporation ducts (about 20 percent of the time winds are greater than 10 m s^{-1} with duct heights exceeding 15 m). *R/P FLIP* is crucial to the success of RED. Moored about 10 km off of the NE coast of Oahu, *R/P FLIP* will host the primary meteorological sensor suites and serve as one terminus for the electromagnetic propagation links. The CIRPAS Twin Otter aircraft will be used to measure mean and turbulent temperature, humidity, and aerosol concentration in the marine boundary layer (MBL) at various ranges from *R/P FLIP*.

Introduction

Radar detection and tracking of low-altitude, low-cross-section targets over the sea are functions of the radar system parameters (power transmitted, frequency, etc.), target characteristics (radar cross-section, speed, etc.) and the environment (sea state, refractive conditions, etc.). Radar parameters and target characteristics may change a few dB from nominal as amplifiers age but changes in environmental conditions may be responsible for many (tens) of dB changes in detection and tracking capabilities. For example, Fig. 1 (from *Anderson*, 1995) shows the propagation loss between an X-Band radar (9.415 GHz) located 24 m above the ocean surface and a calibrated cross-section target 4.5 m above the ocean surface with respect to range. The solid curve is the propagation loss expected in a normal, or standard, refractive environment (*Bean and Dutton* 1968), whereas the light crosses indicate the propagation loss measured in a refractive condition of a moderate evaporation duct (*Katzin, et al.* 1947). At a range of 10km, which is a crucial range for weapons engagement, the radar signal is approximately 3 dB *below* the signal level expected in a standard atmosphere. If this radar's detection and tracking capabilities were designed for standard atmospheric conditions, as most older generation radars were, these measurements show that a change in environmental refractive conditions would cause this radar to miss detection of an incoming target with potentially disastrous consequences.

In an analogous manner, electro-optic (EO) detection and tracking of low-flying, low-altitude targets over the sea is also keenly affected by the environment. Significant refractive effects at EO wavelengths include mirages created by non standard variations in the near-surface mean temperature profile, *T*, and scintillation is created by turbulent fluctuations of temperature, *t'*. Both effects confuse tracking algorithms; mirages present two or more targets where only one is real and scintillation can cause targets to momentarily blink out of existence. Both molecular absorption as well as aerosol species and concentrations also affect EO systems. Atmospheric CO_2 is a strong absorber in the 3 to 5 μm band (midwave), as is water vapor in the 8 to 12 μm band (longwave). Over the ocean, aerosol particles consist of water drops containing dissolved salts with organics in suspension along with secondary particles such as sulfate. In littoral regions, additional aerosols are found. Typically these are anthropogenic carbon compounds from fossil fuel burning and increased density of water droplets from surf generation. Optical extinction, analogous to propagation loss for radar, is proportional to the product of the Mie efficiency factor (which is a function of wavelength, particle radius and the complex optical refractive index of the particle) and the particle size distribution.

Both radar and EO system performance in detecting and tracking low-altitude targets over the ocean are strongly affected by atmospheric refractive conditions. For radar, refractivity is dependent on the vertical distribution of mean water vapor, *Q*, whereas for EO systems, refractivity is dependent on the vertical distribution of mean temperature, *T*. To model EM (covering both radar and EO) system performance with any precision requires a thorough knowledge of the vertical refractivity profile, which implies a thorough knowledge of both the temperature and humidity profiles. Over the ocean, measurements of *T* and *Q* are difficult especially as one nears the ocean surface where large water droplets with dissolved salts and suspended organics easily collect on the sensors thereby contaminating the readings.

Aerodynamic Boundary Layer (ABL) similarity theory (*Obukhov* 1946) has been extensively used to approximate near surface *T* and *Q* profiles with considerable success in most cases. ABL similarity theory parameterizes the thermodynamics of the near-surface layer by incorporating the vertical wind speed profile, drag effects on the surface, buoyancy and inertial forces, and relating these effects to the vertical profiles through empirical "universal" functions that are stability, *i.e.*, Richardson number, dependent. Although Obukhov's ABL parameterizations have been hugely successful for flat, uniform, over-land surfaces (see *Businger et al.* 1971, and *Dyer and Bradley* 1982), the parameterizations do not account for the mechanical coupling and mixing generated by ocean *waves*. Arguably, for a perfectly flat sea, ABL theory must be correct. Extending the limit to small waves, where small may be defined as including gravity waves up to 1 m or so in amplitude, ABL theory should provide a reasonable estimate. However, there is fairly substantial evidence that ABL theory, over the ocean, begins to break down for wind speeds in excess of some 15 m s^{-1} (*Edson, et al*. 1999).

Additional indirect evidence that Obukhov's ABL theory breaks down under certain over-ocean wind speed and stability limits has been uncovered from examination of radar frequency propagation experiments. Figure 2 shows the propagation factor, defined as the ratio of signal level to the signal level expected in free space, for a set of measurements involving 16 frequencies, spanning from 2 to 18 GHz. The transmitter was located 1.3 m above the ocean and the receiver was located 4.6 m above the ocean. The red diamonds indicate the observations. The hashed (purple) line is what is expected in a standard, or normal, refractive atmosphere. The dashed line (green) represents the "best" calculations of propagation factor using a benchmark waveguide propagation prediction code assuming a smooth surface. The solid line (blue) represents the "best" calculations of propagation factor using the same propagation prediction code but assuming a wind ruffled surface (see *Baumgartner* 1983 and *Hitney et al.* 1985 for a description of the "MLAYER" full waveguide propagation assessment computer code). Surface wind speed was 8 m s^{-1} and the range separation was 35.4 km (18.7 nmi). There is good agreement between observations and predictions for the lower frequencies but, for the higher frequencies, errors approach some 15 dB. It is strongly suspected that the cause for these discrepancies is due to an improper understanding of the vertical refractivity profile.

The RED experiment is designed to assess the effects of ocean surface roughness on both meteorological quantities and EM propagation characteristics in the marine wave, surface, and boundary layers. The Space and Naval Warfare Systems Center San Diego (SSC San Diego), under Office of Naval Research (ONR) sponsorship, is hosting a one-month field experiment in Hawaii from mid-August through mid-September 2001. The principal tasks of this experiment are:

1. Determine the extent to which ocean surface roughness modifies both extinction and the distribution of EM refractivity in the marine wave, surface, and boundary layers.

2. Evaluate and validate new parameterizations, accounting for surface roughness, of meteorological quantities and aerosol distributions in the marine wave, surface, and boundary layers.

The first task involves frequent and high quality in situ observations of the mean and turbulent vertical profiles of the basic meteorological quantities pressure, temperature, moisture, and wind speed, solar radiance, vertical distributions of aerosols, multi-wavelength observations of EM propagation, sea surface elevation and wave direction. More than three weeks of intensive observations are scheduled. The second task will be accomplished by analyzing this rich data set to determine regimes where current ABL theory is and is not applicable and to develop new parameterizations where theory is lacking. Proposed platforms, geometries, methodologies and instruments are reviewed in the following sections.

Overview of the RED experiment

The heart of the RED experiment is the Research Platform Floating Instrument Platform (*R/P FLIP*) that is operated for ONR by the Marine Physical Laboratory of the Scripps Institution of Oceanography (MPL/SIO). *R/P FLIP* is a stable oceanographic research platform 110 m (355 feet) in length consisting of a long slender tubular hull terminating in a normal ship's bow section, which is some 17 m (55 feet) in length. *R/P FLIP*, in a configuration similar to what will be used for RED, is shown in Fig. 3. The port side boom, about 17 m in length, will have a similar vertical mast at its extreme but this mast will extend downwards into and below the ocean surface. Mean and turbulent profiles of the basic meteorological quantities as well as ocean surface elevation statistics will be made from this mast. Aerosols and solar radiance will be measured by instruments close to and on the bow section, which will also provide space for mounting EM transmitters.

The selection of Hawaii for the RED experiment came about from the need to have high evaporation ducts with high winds. An analysis of a world-wide evaporation duct climatology (see *Patterson* 1987 and *Anderson* 1987 for a description) included yearly joint statistics of evaporation duct height and wind speed. From these data, Hawaii has the highest probability of evaporation duct heights greater than 15 m with wind speeds greater than 10 m s^{-1}. The joint probability of such occurrences for selected locations is listed in Table 1.

Table 1. The percent of time where evaporation duct heights greater than 15 m occurs with a wind speed greater than 10 m s^{-1} (annual).

Southern California	3.3%
Greece	10.2%
Puerto Rico	11.1%
Hawaii	17.7%

For radar frequency propagation, the ideal path geometry is a low-sited receiver with low-sited transmitters on a path of approximately 30 km. For EO propagation, again, both the transmitter (source) and receiver should be low to the water but with a path length of approximately 10 km. Fig. 4 shows the planned location of *R/P FLIP* and both of the EM paths. *R/P FLIP* will be three-point moored in the location shown where the water has a depth of about 370 m (1200 feet). The three-point mooring will provide some rotational stability but it is expected to have azimuthal rotations, caused by wind loading on the structure, of up to +/- ten degrees.

Fig. 5 is a schematic representation of the instrumentation planned for *R/P FLIP*. Sonic anemometers, Lyman-Alpha hygrometers, and pressure sensors will be mounted at multiple levels on the vertical mast to measure p', q', t', and u'. A traveler, capable of roving from the top of the mast to the surface, will be equipped to measure mean profiles and provide calibrations for the turbulent measurements. Precise 3D position data will be obtained from a combination of inertial sensors and a GPS receiver array. Sea elevation statistics and wave direction will be measured using a 3D current meter with a pressure sensor mounted about 5 m below the sea surface. Additional surface statistics will be obtained from standard wave wires and from an array of wave wires

Aerosols will be measured at several locations onboard *R/P FLIP*. Larger particles (radii from 1 to ~100 μm) will be profiled using a Forward Scattering Spectrometer Probe (FSSP) and an Optical Array Probe (OAP). These units will be complimented with a sonic anemometer and a fast response hygrometer. Smaller particles will be measured using a Passive Cavity Aerosol Spectrometer Probe (PCASP) and a Differential Mobility Analyzer (DMA). A spectral radiometer will sense solar heating.

For EO propagation measurements, a wide field-of-view infrared (IR, 3 to 12 µm) blackbody source will be mounted approximately 8 m above mean sea level (msl). A receiver consisting of a telescope, IR detectors, and data acquisition circuits will be located onshore Oahu, approximately 10 km from *R/P FLIP*. Sampling rates at the receiver will vary between a few Hertz and several hundred Hertz to obtain measurements of mean and turbulent optical transmission.

Radar frequency transmitters, nominally at 3-, 10-, and 17-GHz (S-, X-, and Ku-Band), will be located at two altitudes; approximately 4 and 12 m msl. Each transmitter will radiate 2 W (33 dBm) using separate, horizontally polarized, standard gain horns with gains of about 16 dB (20-degree beamwidth). The radar frequency receiver, located at the Marine Corps Base Hawaii (MCBH), consists of a 1.2 m diameter parabolic antenna with a broadband logarithmic feed. A broadband, low-noise amplifier directs the signals to a Hewlett-Packard 8566B spectrum analyzer. With this configuration, each of the six transmitted frequencies can be sampled at rates from 0.1 to 10 Hz.

Upper-air meteorological observations (radiosondes) will be taken from *R/P FLIP* to further aid in surface-based duct detection. In addition, these radiosondes will aid in characterizing the surface layer up through the mixed layer. To minimize logistic requirements, the radiosondes will be flown on a kite, negating the normal requirement for a supply of helium to fill balloons. Flying radiosondes on a kite also provides for atmospheric profiling.

The Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) Twin Otter aircraft will be used to augment the data taken on-board *R/P FLIP*. Its capabilities were demonstrated for marine boundary layer turbulence work during the ONR Japan/East Sea project. A similar instrumentation set is ideally suited for RED measurements. The scientific goal is to measure the mean and turbulent temperature, humidity, and aerosol concentration in the lower boundary layer and relate these to the point measurements on *R/P FLIP*, the propagation effects, and models.

Principal investigators are listed in Table 2 and a schedule of *R/P FLIP* operations is listed in Table 3.

Table 2. RED PIs and responsibilities

ONR	Dr. Scott Sandgathe	Program Manager
SSC-San Diego	Mr. K. Anderson	Mission Coordinator
SSC-San Diego	Dr. S. Doss-Hammel	EM propagation
UC Irvine	Prof. C. Friehe	Surface meteorology
UC Irvine	Dr. T. Hristov	Wave boundary layer
NPS	Dr. R. Janaswamy	EM modeling
SSC-San Diego	Dr. J. Reid	Aerosols, Chemistry, Radiative Transfer

Table 3. *R/P FLIP* Schedule for Spring/Summer/Fall 2001

02 April to 16 May	WHOI S. Pac. Air-Sea Exchange Exp. with R/V Ron Brown (drift)
28 May to 08 June	Dry dock in ARCO (these dates must be confirmed with the Navy).
20 to 29 June	Sea trial and equipment test period (drift).
09-20 July	ARL sponsored cruise (Moored). *
02 to 14 August	Tow San Diego to Pearl Harbor Hawaii.
15-19 August	Inport Pearl Harbor R&R.
20 August to 18 Sept	SPAWAR RED cruise (Moored).*
19 to 30 Sept	Inport PH, offload, load and R&R.
01 Oct to 30 Oct	HOME cruise (moored).*
31 Oct to 04 Nov	Inport PH, offload.
05 to 16 Nov	Tow PH to San Diego, MC .

RED Mission Goals and Methodology

This effort will employ surface-based, airborne, and modeling components to accomplish its tasks. Keeping the mission plan simple and consistent is crucial for its success. *R/P FLIP* is the centerpiece of the RED experiment. It will be moored some 10 km offshore of Oahu and instrumented to characterize the wave-, surface-, and marine boundary layers in terms of both meteorology and EM propagation.

The following sections provide details of the mission goals, methods and personnel. There are two project areas, which are based on the mission objectives. First, a surface layer effects on EM propagation project will address the issues related to Task 1, that is, how does ocean surface roughness affect the vertical distribution of refractivity. A second project area, addressing issues related to Task 2, will encompass both meteorological and EM propagation modeling to develop new parameterizations and improved models.

Surface Layer Effects on EM Propagation.

Mission Coordinator: K. Anderson
Members: S. Doss-Hammel, C. Friehe, D. Hegg, T. Hristov, H. Jonsson, and J. Reid

The mission's primary objective is to determine how wave layer roughness modifies the vertical distribution of refractivity. To this end, quality measurements are needed of EM signal level propagation, marine boundary layer (MBL) dynamics, and both wave and surface layer characteristics. This project is subdivided into three work areas, which are loosely named EM Propagation, Marine Boundary Layer Meteorology and Aerosols, and Surface and Wave Boundary Layer Meteorology. The respective team leaders are Dr. Stephen Doss-Hammel, Dr. Jeff Reid, and Prof. Carl Friehe. These three work areas are discussed in the following sections.

<u>EM Propagation</u> (Team leader: Stephen Doss-Hammel)

The EM Propagation work area is divided into two tasks. One task is assessing sea surface layer effects on radar frequency propagation and the second task is assessing these effects on electrooptical signal propagation, especially in the infrared. Each of these two tasks is discussed in the following sections.

Radar Frequency Propagation

Recent examination of data from radio frequency propagation experiments clearly indicates that our best propagation models underestimate propagation loss by some three to twelve dB. This underestimation occurs for frequencies higher than 10 GHz, low-sited antennas (typical shipboard radar height and a low-flying target), rough ocean surface (winds > 10 m/s), and moderate to strong evaporative ducts (*Hitney*, 1999, *Hitney et al.*, 1999). There are two plausible hypotheses to explain the differences between the modeled and observed data:

- The Miller-Brown [1984] surface roughness formulation is not appropriate, or
- Obukhov's [1946] aerodynamic (surface) boundary layer model is deficient

The Miller-Brown model modifies the Kirchoff surface reflection coefficient utilizing a statistical representation of surface characteristics based on the incidence angle of the ray (wavefront normal) to the local mean surface and is generally accepted for ranges within the radar horizon. Its applicability for ranges well beyond the radar horizon is not known. Obukhov's ABL similarity theory has had success relating mean vertical profiles of temperature (T), humidity (Q), and wind speed (U) over flat, relatively smooth surfaces. However, for non-smooth surfaces such as the sea, recent studies by *Fairall et al.* [1996], *Edson et al.* [1998], and *Hristov et al.* [1998] indicate that Obukhov's similarity theory is valid for near smooth conditions but fails as the sea becomes rough. Although it can be argued that Obukhov's ABL similarity theory is applicable for heights exceeding some minimum height above the mean surface, this is not satisfactory for radar frequency propagation modeling. Therefore, the objective of the radar frequency propagation task is to collect multispectral radar frequency data over temporal periods commensurate with sea surface dynamics (i.e., time periods from sub seconds to tens of seconds). These data, in conjunction with sea surface and surface layer meteorological measurements, will generate either a validation of the Miller-Brown and Obukhov models or new parameterizations.

Both simplicity and flexibility drive the methodology of implementing this task. Simplicity arises by examining amplitude-only continuous wave (CW) signals within each of the three major radar frequency bands. S-band (2 to 4 GHz) is used for shipboard target search; X-band (9 to 12.4 GHz) is used for shipboard weapons illumination and tracking; Ku-band (12.4 to 18 GHz) is used for tracking. Atmospheric dispersion in the 2 to 18 GHz regime is well understood (*Liebe* 1981), so amplitude, which is dependent upon the propagation conditions, is essentially the critical observable. However, as one of the critical dependencies is height, the transmitters will be positioned at two heights; nominally 3.8 and 11.2 meters above mean sea level (msl), which provides height diversity. See Fig. 5 for approximate locations of the radar frequency transmitters on *R/P FLIP*.

Flexibility arises from the selection of a Hewlett-Packard model 8566/8593 Spectrum Analyzer as the signal receiver. This affords opportunities for computing self- and cross-correlation statistics of both frequency- and height-specific signal levels. Sample rates (for two terms) are estimated to be as high as 10 Hz. For very low signal levels, around diffraction, the resolution bandwidth of the spectrum analyzer can be collapsed to as low as 100 Hz, which provides the highest signal level detectability (maximizes the signal-to-noise ratio). Of course, for these very low signals sample rates decrease to approximately 0.1 Hz.

Table 4 lists the pertinent radar frequency power-budget parameters. All six transmitters are mounted on *R/P FLIP* radiating towards the single, 4 ft. diameter parabolic antenna located at

MCBH, Kaneohe, about 30 km away. Signal levels are expected to vary from diffraction levels, *i.e.*, standard atmosphere refractive conditions, to about 6 dB higher than the free space level in strong ducting situations. Therefore, signal levels are expected from about -100 dBm to about -45 dBm. The HP spectrum analyzers are capable of monitoring signal levels from about +7 dBm to about -120 dBm. The dynamic range and minimum detectable signal level of the HP spectrum analyzer is more than adequate for monitoring the RED radar frequency signals.

Table 4. RED radar frequency power budget parameters.

Freq. (MHz)	*Xmit Ht. (m, msl)*	*EIRP (dBm)*	*Rx Ant Gain (dBi)*	*Free Space (dB, dBm)*		*Diffraction (dB, dBm)*	
				Loss	*Rx_{fs}*	*Loss*	*Rx_{Diff}*
2967.40	3.8	49.5	26.0	131.6	-56.1	171.3	-95.8
3007.50	11.2	49.5	26.0	131.6	-56.1	161.7	-86.2
9624.10	3.8	53.0	37.0	141.9	-51.9	185.3	-95.3
9824.40	11.2	53.0	37.0	141.9	-51.9	173.5	-83.5
17550.00	3.8	53.0	42.0	146.8	-51.8	194.9	-99.9
17795.00	11.2	53.0	42.0	146.8	-51.8	181.2	-86.2

Electrooptical Signal Propagation

The nature of the refractivity field has a strong affect on the propagation of infrared and optical signals in the marine atmospheric surface layer. Scintillation and mirages are two important optical effects induced by variations in the refractivity field. Here we use the word *mirage* in the broadest sense to cover optical and infrared image distortions induced by refractive effects during propagation through the marine atmospheric surface layer.

These two effects are differentiated by time and length scale: scintillation is generally observed at frequencies greater than 1 Hz, and refractive effects, such as mirages, occur at frequencies well below 1 Hz. We have generated accurate predictions for transmission characteristics during previous transmission studies over the ocean in coastal regions (*e.g.*, Zuniga Shoals outside of San Diego Bay—see *Zeisse et al.*, 2000). The proposed field experiment will test the predictive capabilities of the model effort for substantially different environmental conditions.

The optical and infrared portion of the RED experiment will be conducted on a transmission path approximately 12 km long connecting endpoints at *R/P FLIP* and a receiver station on the northeast coast of Oahu. The source end of the path will be installed on *R/P FLIP*, and it consists of a broad beam chopped source mounted at the second deck level.

There are three separate optical/infrared sensor systems planned for the transmission experiment. All three will be located at the shore receiver site and they will share essentially the same path looking at the beam source on *R/P FLIP*.

Dual band transmissometer

The first element is a transmissometer installation to measure the source radiometrically. This system comprises two detectors for mid-wave and long-wave infrared radiation, and a telescope. The chopped source enables the use of a lock-in amplifier for a transmissometer receiver at the shore site. The data collection protocol consists of an alternation between scintillation and transmission measurements. Transmission measurements are recorded as one-minute average transmission intensities with one measurement for the mid-wave intensity, and one measurement for the long-wave intensity. Every twenty minutes, scintillation effects are measured at a higher rate, and both mid-wave and long-wave infrared transmission values are recorded at a 300 Hz rate for 110 seconds. This routine is sustained around the clock for the duration of the field test.

Infrared imagery
A second element of the transmission work is a high speed imaging infrared camera coupled with a telescope. With this system, we will be able to make precise measurements of the spatial perturbations induced in the propagating beam. In particular, this system will make it possible to detect and measure mirages and other imaging effects. The data collection protocol for this instrument will be synchronized with the transmissometer schedule, with 60 Hz data recorded while the transmissometer is making high-rate scintillation measurements. These data will be used for two purposes: to examine the spatial effects of scintillation on beam propagation, and the measurement of mirages and related refractive effects.

Optical imagery
The third component of the transmission installation is a visible CCD camera coupled to a Questar telescope. The imagery generated by this camera is recorded on time-lapse video recorder with a regimen that follows the scintillation measurements. The data generated from this system are the least quantitative of the three transmission elements.

Meteorological measurements and analysis.
The dominant features of this refractivity field can be deduced from careful meteorological measurements. It is critical for the analysis and application of the optical and infrared transmission data that high-accuracy and continuous meteorological data be simultaneously measured at *R/P FLIP*. The post-field data analysis is dependent on timely and high-quality meteorological data.

A cornerstone of the field effort at RED is to test the capability of models that utilize local meteorological measurements as input for a prediction of the intensity, variance, and dominant period of the propagated signal. The EO/IR data collected will be tested against model predictions initialized by the meteorological data.

MBL Meteorology and Aerosols (Team leader: J. Reid)

Measurement of the atmospheric surface layer must be made in the context of the entire marine boundary layer (MBL); both are inseparably linked. Ultimately, we will shed light on two closely linked questions: What do near surface measurements imply about the state of the MBL, and conversely, what influence does the MBL have on the surface layer? Dynamically, much is already known. However, the impact of turbulence and dynamics on marine aerosol particle size, chemistry, and vertical distribution is largely unknown. This uncertainty most likely causes huge biases in the community data set leading to misinterpretation of salt particle sizes, chemistries, and fluxes.

White-cap generated sea-salt particles have been studied for several decades. However, published results of these studies vary considerably. All that can be concluded is that the size, flux, composition, and concentration of sea-salt in the atmosphere is highly variable, and that many of the parameterizations used in geophysical models are zeroth order (or 1st order at best). Under similar environmental conditions, investigators reported median sizes varying by a factor of 5. Further, *Hoppel et al* [1989] showed that in the 1-9 μm range the correlation coefficient between salt concentration and wind speed varied between 0.4-0.8. Hence, the regression coefficient (r^2) varied by 0.16-0.64 and thus only 16 to 64% of the variance in particle concentration can be explained by wind speed alone.

Just as reports of particle size distributions vary considerably in the literature, sea-salt flux measurements are highly uncertain. *Andreas* [1998] showed that under similar conditions, salt fluxes reported in the literature vary by several orders of magnitude. Furthermore, there is considerable scientific interest in the composition of these aerosols, in particular the role of primary organic species. Collectively, the uncertainties in salt particle size and flux parameterizations may be unacceptably high for use in modeling studies. It is troubling that such variations exists, especially when one considers the importance whitecap-generated particles may play in cloud microphysics [*Johnson*, 1982; *Bower and Choularton*, 1994; *Hegg*, 1999; *Feingold et al.*, 2000].

Even particle chemistry is in doubt. Recent studies on the origin and chemical nature of aerosol particles in the MBL have suggested an important role for organics, both as contributors to aerosol mass and as cloud condensation nuclei (CCN). Not only do such studies suggest a substantial organic component (*Novakov and Penner*, 1993; *Rivera-Caprio et al.*, 1996) but also that this component is well correlated with sea salt (*Middlebrook et al.*, 1998). While this is scarcely surprising given the composition of the oceanic surface layer (*Marty et al.*, 1979), the proximate source for sea salt, it has some important implications.

Other recent work on the source strength of sea salt particles in the MBL (*e.g.*, *O'Dowd and Smith*, 1993) has suggested that such particles can, on occasion at least, dominate the number as well as mass concentration of aerosol in the MBL, even dominating the light-scattering and hence aerosol optical depth (*Quinn et al.*, 1998). If in fact the "sea salt" component of the aerosol has a substantial organic component, then similar claims could be made for these organics. On the other hand, much hinges on the chemical nature of this organic component.

Studies of the chemical nature of the organics in the sea surface layer (*Marty et al.*, 1979; *Gershy et al.*, 1983) suggest a speciation dominated by insoluble or only sparingly soluble compounds such as lipids and phospho-lipids. Indeed, this has recently led *Ellison et al.* [1999] to propose a novel chemical model for sea salt aerosol particles. Such particles are proposed to be "inverted micelles," essentially salt solution drops covered with a hygrophobic organic monolayer. Given this structure, both the CCN activity and the ability of the salt particles to deliquesce and grow sufficiently large to scatter appreciable light will hinge on the extent and rate at which the organic coating is oxidized to a more hygrophilic form by the oxidants in the MBL. *Ellison et al.* [1999], for example, estimate a pseudo first-order rate for organic oxidation by ambient OH radicals as > 1x 10^{-12} cm^3 s^{-1}. With a conservative estimate of OH at $1x10^6$ cm^{-3}, Ellison et al. calculate a time scale for oxidation of the monolayer of 10 m hrs or less. For higher OH concentrations, the time scale will be proportionately less. Hence, for mid-day conditions during the summer season, a time scale of a few hours might be expected. This is comparable to commonly occurring vertical mixing times for the MBL and suggest those vertical gradients in aerosol hygroscopicity and CCN activity might be observable in the MBL.

Given the importance of understanding the CCN activity and aerosol hygroscopicity in the MBL, the above discussion suggests that a chemical speciation of the organic component of aerosol as a function of altitude would be very enlightening and of considerable utility.

In summary, the current state-of-the-art casts doubt on frequently used parameterization for fluxes, size, vertical distribution, and even chemistry. Much of this uncertainty can be explained by "piecemeal" measurements published without the benefit of information on the MBL. As part of RED, we will avoid many of these pitfalls and we propose an integrated aerosol/turbulence study to explore how atmospheric state and aerosol properties covary. To this end, we will deploy two sets of instrumentation:

- SSC-San Diego will deploy a suite of instrumentation on the *R/P FLIP* to study the composition and flux of sea-salt particles generated by white caps. This suite of instrumentation will be used in conjunction with the complete set of turbulence measurements to characterize the surface layer (See Surface and Wave Boundary Layer Meteorology below), and

- A fully outfitted CIRPAS Twin Otter will be used to characterize the remaining boundary layer aerosol and turbulence profiles.

<u>MBL Meteorology and Aerosols Project Goals</u>

For this portion of RED, we have five principal tasks that define our mission:

1) Characterize aerosol size in support of concurrent EM experiments and marine aerosol model development.

2) Inter-compare particle sizing and radiametric probes in a marine environment. This information will be used to help understand the extent measurement artifact is responsible for the divergence in salt particle properties reported in the literature.

3) Perform aerosol compositional analysis. Study the generation of primary organic particles by whitecaps.

4) Attempt direct eddy correlation measurements of sea-salt aerosol production. From this we will attempt to directly measure aerosol particle production and flux.

5) Link surface layer and MBL properties though aerosol and turbulence measurements made on the CIRPAS Twin Otter.

<u>MBL Meteorology and Aerosols Methodology</u>

This task consists of three fundamental parts: Surface layer measurements on *R/P FLIP*, airborne measurements on the CIRPAS Twin Otter, and chemistry analysis of the aerosols. We discuss each aspect below.

Surface Layer Measurements.

SSC-San Diego will deploy a suite of particle probes, analyzers, samplers and meteorology equipment onboard *R/P FLIP* for the entirety of the RED project. A core set of particle-sizing probes will be placed on a boom 5 meters off the side of *R/P FLIP* at an elevation of 6 meters above the surface of the water. These instruments may be placed on a pulley system that allows sampling down to 2 meters above the surface. These instruments will include a PCASP (d_p=0.1-3.0 μm), FSSP-100 (d_p=1-32 μm), and an OAP-100 (d_p=30-80 μm) all operating at a 1 Hz sampling rate. These instruments will determine the basis set of particle size distributions to be used for EO propagation analysis and modeling.

Mounted along side will be a rapid response sonic anemometer and IR humidity probe. By combining the data into a uniform data set, we will be able to construct aerosol covariance (*e.g.*, $\langle c_n' w' \rangle$), and determine the extent to which small perturbations in the humidity field affect aerosol size. Further, we will compare the size distribution of sweep versus ejections and attempt to relate salt particle properties to changing ocean conditions. By unifying this data set with the complete turbulence data set on the main boom, we will attempt to determine the order of the production and dry deposition of whitecap generated aerosols.

In addition to the aerosol boom instrumentation, a set of instruments and samplers will be placed top center on *R/P FLIP*. These will include the APS3320 to measure particle aerodynamic size (d_p=0.8-20 μm), a CSASP to measure particle size between 0.5 and 40 μm, and a 3-μm nephelometer to measure light scattering. Dr. Mike Smith, University of Leeds, may also deploy a thermal DMPS and CCN system to perform particle thermal evolution analysis. At one point in the study, these instruments will be co-located with boom instruments to perform an intercomparison study.

Bulk impactors will also be placed top center on *R/P FLIP*. These impactors will collect particle samples for subsequent high performance liquid chromatography (HPLC) analysis. By collecting large quantities of salt particles, it is hoped that there will be enough organic material to determine a large fraction of the organic materials present in the white-cap generated particles.

CIRPAS Twin Otter

It is extremely useful to obtain data along and above the paths as well as on-board *R/P FLIP*. An instrumented aircraft is suited to this. The capability of the CIRPAS Twin Otter aircraft was demonstrated for marine boundary layer turbulence work during the ONR Japan/East Sea project. A similar instrumentation set is ideally suited for RED measurements. The scientific goal is to measure the mean and turbulent temperature, humidity, and aerosol concentration in the lower boundary layer and relate these to the point measurements on *R/P FLIP*, the propagation effects, and models. Specifically, the CIRPAS Twin Otter has the following instrumentation:

- Temperature: Rosemount resistance wire; UCI thermistors
- Reference Humidity: Edge Tech chilled mirror dew point
- Fast Humidity: Krypton; IRGA; Lyman-alpha
- Sea Surface Temperature: KT18
- Altitude: radar and pressure
- Winds: Radome and Rosemount 858 system
- Aerosols: PCASP, CAPS, Impactor, nephelometer/humidigraph, CCN counter
- OH: CIMS spectrometer (?)
- Aircraft Navigation and Motion: Boeing C-Migits and Trimble TANS Vector
- Data System: National Instruments

The Twin Otter will be based nearby on Oahu, which provides an excellent ratio of experiment flight time to ferry flight time. The Twin Otter aircraft will be utilized together with ship based sampling to both determine MBL aerosol composition and to gather sea surface water samples for source characterization. The Otter will perform successive ~30 minute sampling legs at altitudes ranging from its minimum altitude to the top of the MBL, all relatively close but downwind of the ship to which the sampling profile would be anchored. Vertical profiles of turbulence will be made in conjunction with aerosol size, CCN activity, and hygroscopicity. Chemical composition will be obtained and analyzed for correlations between the organic speciation and the other aerosol properties. Profiles will be obtained under several different MBL stability conditions.

Chemistry

A key facet of the study will be the chemical analysis of both the sea water and aerosol particles to determine the organic speciation. *Ellison et al.* [1999] suggest that the fatty acids and lipids of the sea surface layer will be oxidized successively to alcohols, alkenes, aldehydes, ketones and carboxylic acids. Essentially, OH attack will functionalize the initial hygrophobic organic layer and render it hydrophilic. To detect the classes of organic compounds, each aerosol and sea water sample will undergo a set of three analyses (in the case of the aerosol samples after serial extraction into ~ 10% methanol solution followed by benzene to obtain some indication of both soluble and insoluble components). The first aliquot would be analyzed by traditional ion chromatography to determine both the inorganic ions present and any polar organics such as a number of the carboxylic acids. A second aliquot would undergo liquid chromatography using a pulsed amperometric detector to look for carbohydrates and various fatty alcohols (e.g., glycerol) which might be expected from the lipids (and perhaps fatty acids) found in the sea surface layer. The final aliquot would be analyzed by HPLC after derivatization to detect various aldehydes and ketones. Taken together, these analyses should permit a reasonable assessment of the organic species of interest. Nevertheless, an additional aliquot will be reserved for LC/mass spectrometer analysis to provide additional information on high molecular weight organics that prove recalcitrant towards the other LC techniques.

<u>Surface & Wave Boundary Layer Meteorology</u> (Team Leader: C. Friehe)

Proper interpretation of EM signals is essential for Navy operations. The propagation of electromagnetic waves in the Marine Atmospheric Boundary Layer (MABL), however, is substantially affected by the atmospheric conditions and the sea state, leading to variations of signal's intensity, mirages, etc. The problem of strong intensity fluctuations (scintillation) was first explored in the 1960s and is still central to the field of wave propagation in random media. Below we will outline some of the fundamental physical processes determining the propagation pattern, important for both planing and data interpretation stages of the RED Experiment.

<u>Surface Boundary Layer Meteorology</u>

The main purpose of this portion of the RED experiment will be to measure the mean temperature and humidity gradients in the lower 20m over the ocean. The fluctuations of temperature and humidity will also be measured. Both vertical mean gradients and statistics and spectra of fluctuations are important factors in propagation of radar and optical signals in the marine atmosphere.

Issues

The temperature and humidity gradients are predicted to be small. For example, the adiabatic temperature gradient is only 1C per 100m, which amounts to 0.2C over 20m. To resolve this, individual temperature measurements at each level must be accurate to about 0.02C. This is a very stringent requirement. Therefore, we are planning a mast with a "roving" sensor carriage, so that the difference temperature from one sensor at different levels can be used rather than the difference of the absolute temperature from many levels. We may also deploy a set of fixed differential thermocouple probes. Measurement of the humidity gradient will be attempted in the same manner, *i.e.*, a fast-response sensor on the roving carriage. It will stop and "park" at boom level for in-situ comparison to chilled mirror dew point reference instrument.

Instrumentation

Humidity fluctuations will be obtained from Lyman-alpha, krypton and infrared hygrometers. They will be calibrated in-situ against chilled mirror dew point instruments. Temperature fluctuations are more problematical. We will record the quasi-virtual temperature from sonic anemometers, and also deploy small thermistor and thermocouple probes. If the salt aerosol loading is low, they may remain uncontaminated for a long enough time to obtain some good temperature statistics and spectra. Sonic anemometers will be deployed at different levels, one as close to the sea surface as possible and the others vertically to measure the stress divergence. The lowest level sonic is splash proof, so an occasional wetting from a rogue wave should not damage it. Data will be recorded on a National Instrument data system with 16-bit resolution for analog signals. Motion of the carriage package and sonics will be measured with two Boeing C-Migits inertial/GPS units, which will provide angles and velocities.

Wave Boundary Layer Meteorology

This task provides data for the statistics of the atmospheric fields in MABL as well as the surface waves. The data will facilitate the interpretation of the observed propagation patterns and help us evaluate the contribution of each of the processes listed above in the formation of these patterns. As currently planned, RED will include directional surface wave measurements, as well as measurements of the wind velocities and pressure fluctuations in the air. The instruments are to be deployed from the stable platform *R/P FLIP*.

Issues

The Marine Boundary Layers Experiment (*Hristov et al*. 1998) expanded our knowledge of the MABL structure with the following nontrivial findings:

- The surface waves induce sizeable fluctuations in the airflow, which we can now estimate by using an optimal filtering technique, based on the Hilbert transform (*Hristov et al*. 1998).

- The structure of the wave-induced flow became apparent. In particular, the data manifested the presence and the dynamic significance of the critical layer over the waves (*Hristov et al*. 1999), which has been eluding the experimentalists. Such information elucidated what deviations from the ABL similarity theory are due to the waves—information more valuable than just the clue that similarity theory no longer applies above some threshold wind speed.

From the discussion above it can be expected that the role of waves in forming the propagation pattern is threefold: **(a)** the waves cause rough surface scattering from the ocean, and **(b)** the wave-induced fluctuations in the atmosphere contribute to random refraction along with the turbulence. **(c)** The waves modify the profiles and fluxes in the MABL thus introducing deviations from the similarity ABL theory. The latter means that "wave corrections" may be needed in models that predict ducting conditions.

EM signals propagating in the MABL encounter inhomogeneities of refractivity stemming from the turbulent and wave-induced fluctuations of humidity, pressure, and temperature. The random refraction from such inhomogeneities redistributes the signal's energy, so the observed intensity increases if the rays converge and decreases when they diverge. The converging rays cause random caustics and foci, responsible for strong fluctuations in the observed intensity of pulsed signals. Figure 6 illustrates the phenomenon by showing modeling results, obtained through the parabolic equation technique (*Martin and Flatte,* 1988).

Surface ocean waves satisfy the Rayleigh criterion (*Beckman and Spizzichino*, 1963) for roughness. The surface features cause diffusive scattering, thus degrading the energy of the beam. *Miller et al.* [1984] proposed "rough surface reflection coefficient reduction factor" to model the intensity loss from such scattering. That model is supported by experimental data for paths within the horizon, but is not tested for ducting conditions (*Hitney,* 1999).

The layered structure of the troposphere is known to cause ducting. However, EM waves propagating in a refractivity stratified media are subjected to the combined influence of the layered structure and the fluctuations of the refractivity (*Wait*, 1970). As a result, different rays in a beam can be reflected from different layers, which generally deforms the wave fronts and contracts the coherence radius. A non-stratified atmosphere cannot confine EM waves, but guiding has been observed in conditions when the refractivity gradient is too small to provide ducting. It is believed that the guiding in such cases is due to a stack of relatively thin layers, termed stochastic wave-guides (*Freylikher and Gredeskul*, 1990), shown in Figure 7. The horizontal scales are expected to exceed the vertical ones by factors of tens or hundreds. There exists only indirect evidence for the existence of stochastic wave-guides. No experiments for detecting and examining stochastic wave-guides have been carried out.

EM waves in the atmosphere often propagate through droplets of rain or mist. The presence of suspended particles essentially causes the same effects on EM signals propagation as pure turbulent medium. These effects include loss of coherence and beam spreading although the typical spatial and temporal scales of the processes in both media may differ by orders of magnitude. One particular process due to suspended particles in turbulent flow is enhanced backscattering (*Ishimaru*, 1978). The enhanced backscattering confines the radiation in the medium, so by analogy with a similar solid state phenomenon it is also known as weak localization.

One important problem in radar data interpretation is the observed drop in signal intensity. For the purposes of modeling and prediction, a parameterization of this phenomenon would be very useful. A *complex refractive index* can be conveniently employed to describe both refraction and absorption of EM waves in the atmosphere (*Liebe et al*., 1992; *Liebe et al*., 1993; and *Liebe,* 1996). Although the observed intensity reduction may be a result of an intricate interplay of the physical processes outlined above and not molecular absorption, a phenomenological description of effective absorption in terms of the *complex refractive index* could serve as an appropriate parameterization.

Instrumentation
Due to the lack of a commercially available instrument for static pressure fluctuations, we propose substantial customization of a pressure sensor offered by a vendor. Currently the instrument that approaches the requirements of RED is the model Met3A from Paroscientific, Inc. However, the instrument measures the pressure fluctuations on the background of the ambient atmospheric pressure, which exceeds 10^5 times the typical fluctuations induced by the waves. Detecting such fluctuations puts the instrument at the limits of its sensitivity and also requires a 24-bit digitalization. To eliminate the sensitivity problem, we are discussing with Paroscientific an instrument built around their new differential pressure sensor model 202BG. The very small number of pressure sensors designed and built by singular scientists makes borrowing of such instruments an unlikely option. To improve reliability of the pressure measurements and to obtain good information about the vertical profile of the pressure fluctuations, at least 4 pressure sensors should be deployed along the instrument mast.

We consider complementary surface wave measurements involving a wave wire and directional wave spectra instrument. Possible candidates are Interocean System's S4, Nortek’s Vector, and Nobska’s MAVS-2. Each of the instruments exploits different physical processes to obtain directional wave spectra. We are currently determining which instrument is best suited for RED.

Although the platform *R/P FLIP* is designed to be stable and non-responsive to the waves' forcing, even small amplitude motion of *R/P FLIP* caused by the waves can distort subtle effects as wave-induced fluctuations in the wind and critical layer dynamics. Thus another major focus in our preparation for the experiment is providing an inertial navigation unit to measure the motion of the platform.

Summary

The Rough Evaporation Duct experiment is an intensive field study to assess the effects of ocean surface roughness on both meteorological quantities and EM propagation characteristics in the marine wave, surface, and boundary layers. The Space and Naval Warfare Systems Center San Diego, under Office of Naval Research sponsorship, is hosting a one-month field experiment in Hawaii from mid-August through mid-September 2001.

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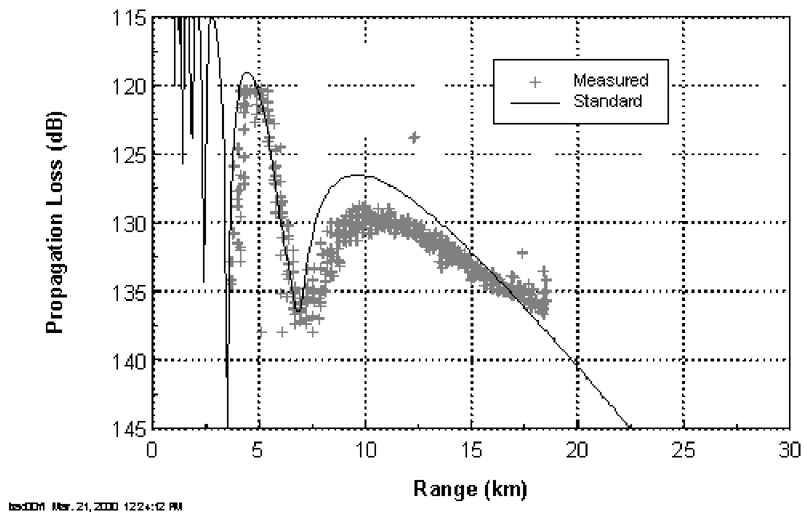

Figure 1. Measured X-Band propagation loss (gray crosses) compared to predictions for a standard atmosphere. An evaporation duct is responsible for the decrease in signal (increased propagation loss) for ranges from 7 to 15 km.

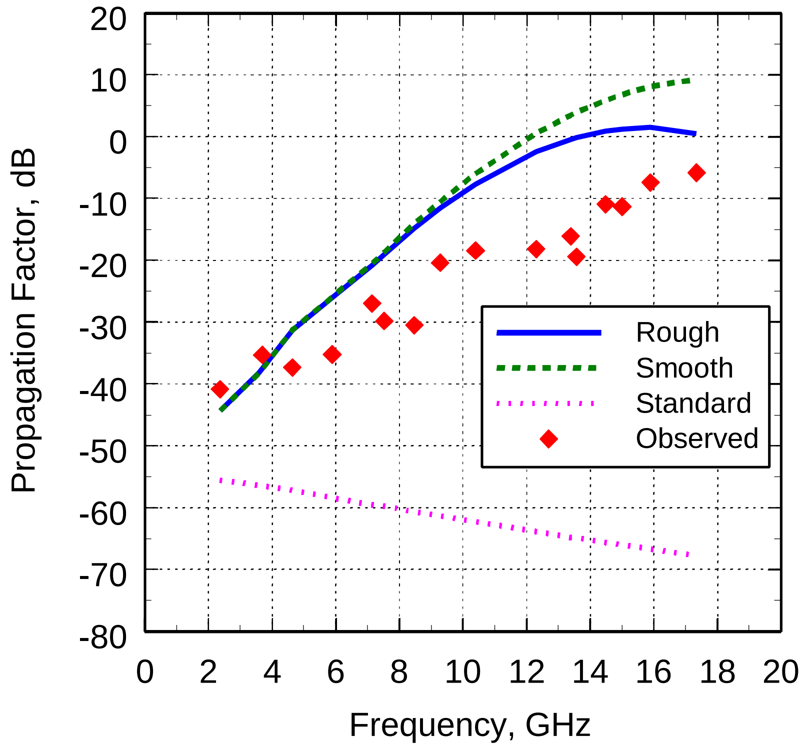

Figure 2. Multi-frequency measurements of propagation factor taken during conditions of a moderate evaporation duct with 8 m s^{-1} winds. The rough and smooth curves are modeled propagation factors assuming a rough surface (8 m s^{-1} winds) and a smooth sea surface respectively.

Figure 3. *R/P FLIP* at sea in a configuration similar to what will be used for the RED experiment.

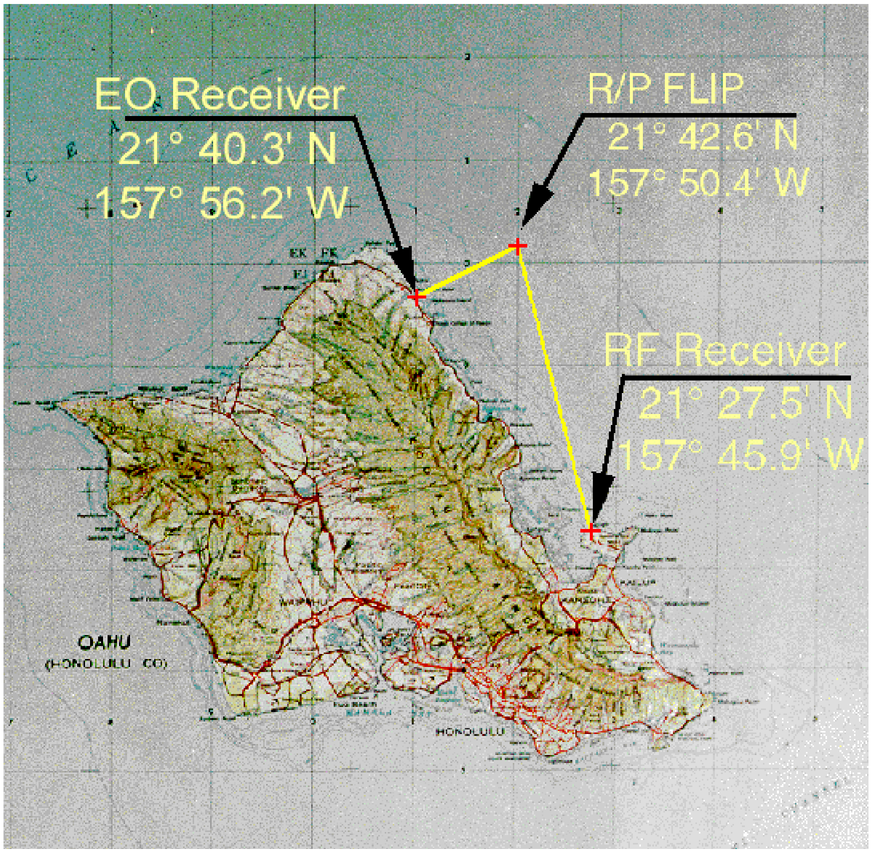

Figure 4. The approximate locations of *R/P FLIP* and the EM propagation paths.

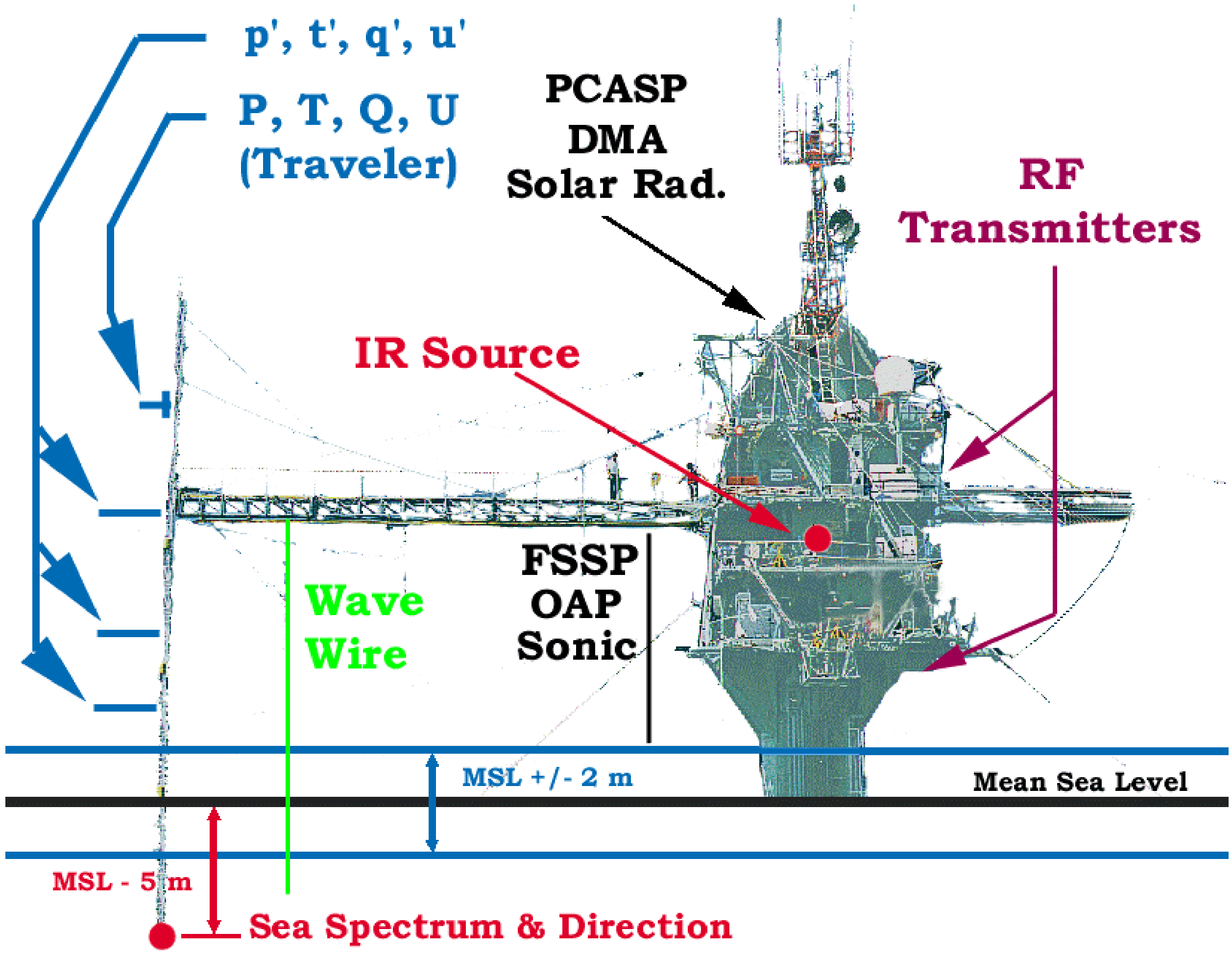

Figure 5. A schematic representation of the instrumentation planned for RED.

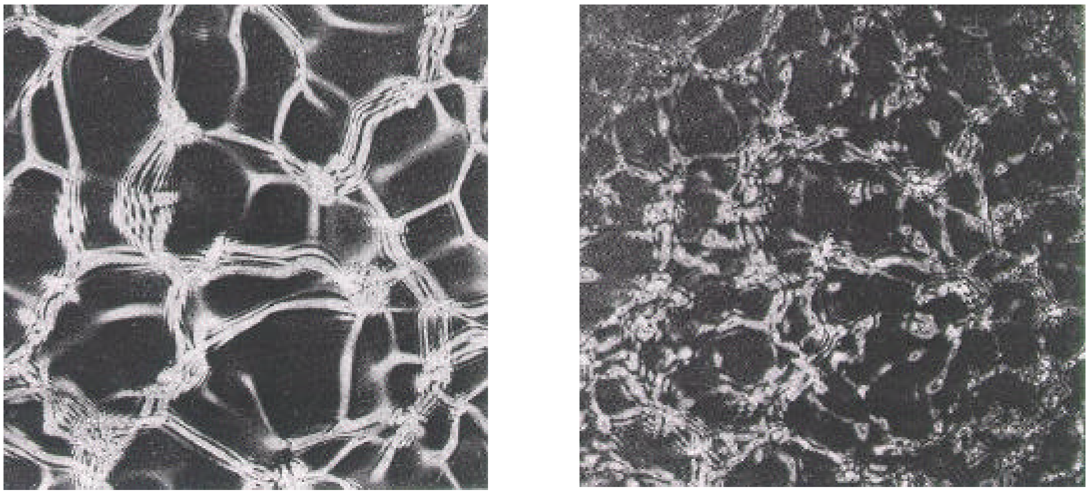

Figure 6. Intensity maps of a simulated light beam (left), in case of strong fluctuations, (right) in case of saturated fluctuations (Martin and Flatte (1988)).

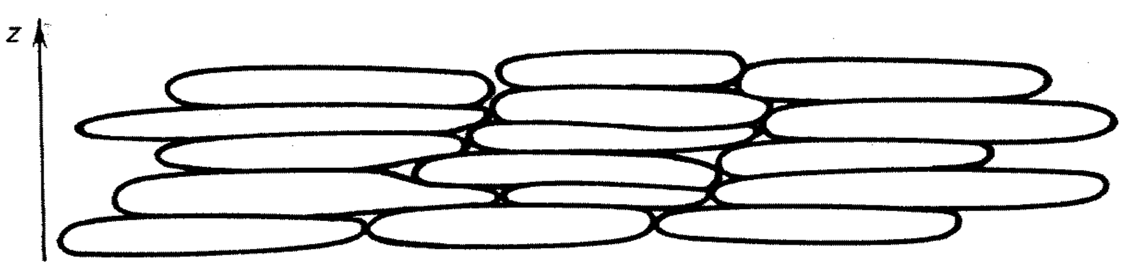

Figure 7. A structure of large-scale inhomogeneities in a layered atmosphere.

Appendix A: Personnel Directory

Kenneth D. Anderson
Space and Naval Warfare Systems Center San Diego, D858
49170 Propagation Path
San Diego, CA 92152
Voice: 619 553 1420, Fax: 619 553 1417
kenn@spawar.navy.mil

Stephen M. Doss-Hammel
Space and Naval Warfare Systems Center San Diego, D858
49170 Propagation Path
San Diego, CA 92152
Voice: 619 553 4578, Fax: 619 553 1417
hammel@spawar.navy.mil

Carl A. Friehe
Dept. of Mechanical Engineering
University of California
Irvine, CA 92697
Voice: 949 824 6159, Fax: 949 824 2249
cfriehe@uci.edu

Dean Hegg
Dept. of Atmospheric Science
Box: 354235
University oif washington
Seattle, WA 98195-4235
Voice: 206-685-1984 Fax: (206)685-7160
deanhegg@atmos.washington.edu

Tihomir S. Hristov
Dept. of Mechanical Engineering
University of California
Irvine, CA 92697
Voice: 949 824 6159, Fax: 949 824 2249
cfriehe@uci.edu

Ramakrishna Janaswamy
Code EC/Js, Dept. of ECE
Naval Postgraduate School
Monterey, CA 93943
Voice: 831 656 3217, Fax: 831 656 2760
Janaswam@ece.nps.navy.mil

Haflidi Jonsson
CIRPAS
3240 Imjin Rd., Hanger #510
Marina, CA 93933
Voice: 831-384-2776, Fax: 831-384-2777
hjonsson@nps.navy.mil

Jeffrey S. Reid
Space and Naval Warfare Systems Center San Diego, D858
49170 Propagation Path
San Diego, CA 92152
Voice: 619 553 1419, Fax: 619 553 1417
jreid@spawar.navy.mil