Analysis of Alternatives: Atmospheric Measurements Supporting Naval Operations

Prepared for
SPAWARSYSCEN CHARLESTON

by

Prof. C. Russell Philbrick
Professor of Electrical Engineering
Applied Research Laboratory Senior Scientist
Penn State University

Prof. Richard Clark
Professor of Meteorology
Chair, Department of Earth Sciences
Millersville University

and
Adam Willitsford
PhD Candidate
Penn State University
Electrical Engineering

Principal Investigator
Dr. C. R. Philbrick
Penn State University
315 Electrical Engineering East
University Park, PA 16802
814-865-2975
crp3@psu.edu

List of Acronyms Used

ADM - Advanced Development Model
ALAPS - Advanced Lidar Atmospheric Profile Sensor
ANSI - American National Standards Institute
AoA - Analysis of Alternatives
AREPS - Advanced Refractive Effects Prediction System
COAMPS - Coupled Ocean Atmospheric Mesoscale Prediction System
DOD - Department of Defense
EDM - Engineering Development Model
EM - Electromagnetic
EO - Electro-optic
FNMOC - Fleet Numerical Meteorology and Operational Center
GOES - Geostationary
GPS - Global Positioning System
HMMWV - High Mobility Multipurpose Wheeled Vehicle
IR - Infrared
ISCCP - International Satellite Cloud Climatology Project
LAPS - Lidar Atmospheric Profile Sensor
LASER - Light Amplification by the Stimulated Emission of Radiation
LIDAR - Light Detecting and Ranging
METOC - Meteorology and Oceanography
MIDDS-Next - METOC Integrated Data Display System-Next
MOE - Measures Of Effectiveness
MOP - Measures Of Performance
MPE - Maximum Permissible Exposure
MRS - Mini Rawin Sonde
MRS AN/UMQ-12A
MWRP - Microwave Radiometric Profiler
ND:YAG - Neodymium Yttrium Aluminum Garnet
NITES - Navy Integrated Tactical Environmental Subsystem
NOGAPS - Navy Operational Global Atmospheric Prediction System
NPMOC - Navy Pacific Meteorology and Oceanography Command
NPOESS - National Polar Orbiting Environmental Satellite System
QA/QC - Quality Assurance/Quality Control
RADAR - Radio Detecting and Ranging
RAWS - Remote Automated Weather System
RDT&E - Research Develop Test and Evaluation
RF - Radio Frequency
S/N - Signal to Noise ratio
SCOS97 - Southern California Ozone Study - 1997
SAASM - Selective Availability Anti-Spoofing Module
SODAR - Sound Detecting and Ranging
SPAWAR - Space and Naval Warfare Systems Command
SIPRNET - Secure Internet Protocol Routing Network
T-AGS - Aerographer Surveying Ship
UV - Ultraviolet

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PREFACE

As combinations of factors bring about the necessity to make changes and take advantage of the next generation of technology, we arrive at the point where major improvements can be made in our ability to monitor atmospheric variables to better understand the influence of the environment when performing complex missions, as well as the day-to-day tasks in the operational Navy (see the description in http://www.nwdc.navy.mil/Concepts/Sea_Strike/SeaStrikeM.aspx). The traditional use of balloon sonde expendable instrument packages has served well as the source for atmospheric data profiles, but cannot provide the time resolution of atmospheric changes to meet the needs of the present and future naval systems. However, major improvements in remote sensing technologies now make possible several opportunities for extending our ability to measure and define the atmospheric conditions. Instead of two per day sonde releases with data products two hours later, the atmosphere can be continuously profiled using Raman lidar techniques, which provide real time data products of the primary data on temperature, density, and water vapor profiles. In addition to these, new data products available from lidar include profiles of optical extinction, range resolved visibility, cloud height – and most important for the forecaster or the operations planner, the profiles are updated every few minutes to resolve rapid changes in the parameters. Water vapor and temperature profiles are used in real-time calculations of the RF-refraction that is needed for radar interpretation. The profiles of the meteorological properties, the electro-optical (EO) environment and the electromagnetic (EM) environment can be obtained simultaneously using a single instrument. Other remote sensing techniques can add further important information. For example, microwave radiometers can be used to receive the path integrated brightness temperature from the microwave emission of molecules. The microwave brightness temperature can be used to select the most appropriate atmospheric model to represent the current conditions. By entering the microwave data into a model such as COAMPS, an appropriate model representation for the atmospheric conditions can be selected. Another technique that can add information on the low altitude wind velocity is an SODAR, or sound detection and ranging. The Doppler shift in the frequency of an acoustical wave is used to measure the range resolved radial wind component. Current SODAR systems use phased-array transmitters to point the sound wave and determine the total wind vector from the surface to above 1 km.

While preparing this document, we have considered three additional points which are important regarding the development of the Navy's capabilities for conducting future operations. The first has to do with the importance of distributive data processing and data/model availability for local support/forecasting during deployment, the second is the recognition of the value in a multisensor capability to support naval operations, and third is the potential contribution of the T-AGS ships.

(1) The COAMPS model was developed to provide a high resolution mesoscale model for local prediction of atmospheric conditions within an operating region, and it uses the regional boundary from the global NOGAPS model. The importance of distributive processing has been demonstrated in many ways, but the current plan appears to be to depend on a center, such as FNMOC, receiving data products from the local area, processing it and preparing a model to distribute back to the deployed unit. A better approach appears to be installing a dedicated microprocessor cluster computer (ballpark cost $50k) on one of the ships in a battle group so that the local data can be assimilated, and the COAMPS model

can be locally run for battlespace forecasts. This approach would avoid problems in distant communications and provide the best support for the commander.

(2) The atmosphere is a complex fluid medium and no single instrument or system can measure all of the key properties. In particular, no single sensor is able to provide measurements of its particular parameters at all times. For these reasons, the most logical approach is to develop an operational plan that would allow the selection of data from several different sensors. It should be possible to develop an operational approach that could obtain measurements using Raman Lidar, microwave radiometer, MRS balloons and SODAR. All have added value at different times in support of different missions.

(3) The T-AGS ships provide valuable mission support in defining the oceanography and the undersea stratigraphy (https://www.navo.navy.mil/pao/other/about_us.htm). The mission for these ships could be expanded to include the function of providing: (1) a suite of atmospheric sensor measurements (lidar, radiometer, balloon sondes, SODAR), (2) assume a role gathering the data from other ships and assets deployed in the area, (3) facilitate the assimilation of the data into forecasting models by communicating it back to FNMOC, and (4) running the regional COAMPS model for local forecasting. A cluster computer could be dedicated to ingest the local data, gather the NOGAPS regional boundary model updates, and provide the local model for operational forecasting.

EXECUTIVE SUMMARY

A study has been carried out to investigate the current and alternative technologies for obtaining atmospheric profiles of properties that describe the EM (Electromagnetic), EO (Electro Optical) and meteorological conditions of the lower atmosphere. The purpose of this effort has been to provide an Analysis of Alternatives (AoA) that can assist in developing the best approach for future operational support for Navy systems. [Analysis Handbook, 2004] The current technology is based upon the use of instrumented balloon sondes that have provided the primary atmospheric profile data over the past 50 years. Through the years, several modifications have been included to improve and modernize the sonde performance, however the balloon sonde system suffers from several problems, such as providing only a single profile for each launch, timeliness of the data, non-covert operation, drifts in location, ability to provide surface layer data, requirements for storage and handling of the helium, and cost considerations. The very limited temporal resolution of balloon sondes does not match current and future requirements for support of Navy systems and missions. The balloon sonde has been proven to be a most valuable tool over the years and it will continue to be needed for support of specialized missions, such as high altitude winds, or in certain types of weather conditions during which other sensors, such as lidar and microwave, are not operable.

Advances in sensitivity of DOD systems and their mission applications require improved atmospheric data to fully utilize the capabilities of several systems. Additionally, the meteorological conditions affect short- and long-range planning, and real time decisions for many DOD mission situations. In the future, the primary data on atmospheric properties should be provided by remote sensing techniques. Technology advances have permitted a steady growth in sensor techniques which now provide capabilities for continuous profiles of the atmospheric properties. The description of the regional scale features in the meteorological properties will be markedly improved by the next generation of satellite remote sensing instruments, which are in preparation by the NPOESS program. The description of the atmospheric properties in the littoral area must be obtained locally by sensors deployed by various assets in that region. The current and future generation operational systems require real-time data products for the EM, EO and meteorological properties. The EM propagation conditions for communications and radar applications depend upon the distribution of electromagnetic wave scatterers, i.e., the molecules, aerosols, and particularly water vapor. The strong vertical gradients and the large electric dipole moment of water vapor cause its distribution the most important factor influencing radar propagation and ducting. The EO conditions that affect flight operations and surveillance opportunities depend on the optical extinction profiles of the aerosols. Meteorological forecasts for mission planning require data profiles for adequate assimilation into models such as NOGAPS and COAMPS, which are the primary tools for regional scale and local forecasting, respectively.

This analysis has been carried out using the methods for Analysis of Alternatives (AoA) reviews that are outlined in the AoA Handbook [USAF, 2004]. The process has been carried out by first addressing three tasks. A list of ten operational activities or tasks that would require atmospheric analysis and support were formulated. Set of statements for Measures of Performance (MOP) and Measures of Effectiveness (MOE) were developed as evaluation tools. The analysis was then carried out by critically evaluating each of the sensors and scoring the MOP and MOE against each of the ten operational tasks proposed as typical of the support required for a strike force.

The techniques that have been evaluated in this study include the MRS Balloon Sonde, Raman Lidar, Microwave Radiometer, and SODAR. Many other types of sensors were considered but only these sensors could justify the detailed evaluation. In summary, our recommendations are:

(1) Raman Lidar is the best choice to provide the data required to operate in and forecast the EM, EO and meteorological conditions.
(2) A COAMPS numerical modeling system for high resolution mesoscale forecasts of the littoral region should be deployed with each strike group (a carrier or expeditionary strike group).
(3) Co-location of a SODAR on ship is the best current choice for boundary layer winds.
(4) Operation of a microwave radiometer with each strike group will provide very useful temperature and moisture constraints on the COAMPS and NOGAPS models.
(5) A long range plan should include maintaining a balloon sonde capability deployed on T-AGS ships that continues after the operation of MRS on capital ships is curtailed in favor of remote sensing instruments.

Evaluations of the technical and weighing the cost factors result in our recommendation that the Raman Lidar is best choice (even considering that the lidar approach is more expensive) to provide the data required to operate in and forecast the EM, EO and meteorological conditions. In addition to being the only technique that can provide the continuous realtime direct measurements of range resolved parameters including meteorological profiles of temperature, water vapor, and density, the Raman Lidar is also the only technique that can measure the vertical and horizontal profiles of visibility, the cloud ceiling, distance to fog banks, as well as determine the rates of change in these parameters, and can detect and discriminate chemical agent clouds. The time to commence or to suspend air operations or conduct other missions can be accurately determined by the lidar which provides better measurements of the cloud ceiling and the visibility than current shipboard sensors. The Raman lidar measures the vertical profiles of two key parameters, water vapor and temperature, that are used to calculate the profiles of refraction in the AREPS model to determine the propagation characteristics of radar and radio signals. Lidar is the only practical approach that is able to provide the high resolution required for monitoring and describing the effects of RF-refraction causing elevated radar ducts and surface-based evaporation ducts.

The primary recommendations are to install Raman Lidar sensors on the 27 capital ships and prepare approximately 33 sensors that can be deployed as complete self-sufficient instruments (including environmental and power generation when required). The 33 sensors would be divided among the tasks of supporting METOC teams deploying on additional ships, assignment to Navy shore locations for operational support, and units to be installed on HMMWV for use as rapidly deployed units to accompany Marine Corps operations. The operational advantages in having the COAMPS model locally available to use for planning and forecasting should justify locating dedicated cluster computers on each capital ship. SODAR provides a useful solution for obtaining boundary layer winds to support aircraft and helicopter operations. Installation of a microwave radiometer on Navy capital ships will provide valuable information on temperature and moisture fields to constrain the COAMPS model and provide useful input for the NOGAPS model. Adding a suite of atmospheric sensors to the T-AGS ships would provide a very useful resource for Navy operations in litoral areas.

INTRODUCTION

This report is intended to show the best path forward for meeting the future Navy needs for sensors to measure the atmospheric parameters that are required for direct support of systems and operations, and for the data required for models that support mission planning. This effort is primarily driven by the need to modernize and replace the current instrumented balloon sonde technique as the primary source for measuring the profiles of atmospheric properties. The GPS-rawinsonde system is costly, requires substantial manpower and shipboard storage volumes, provides only a couple of profiles per day during normal operation, reliability issues exist for the GPS signal used for wind data (this problem is being corrected), and operations are not covert. Unsecured civilian GPS signals that have been used during recent years are subject to jamming and are difficult to lock-on, resulting in the loss of wind vector information in nearly 50% of the rawinsonde releases during the past few years. This review concludes that the developments in remote sensing technologies can provide more useful techniques with wider capabilities that eliminate most of the concerns regarding past approaches for obtaining atmospheric measurements.

Weather remains one of the most critical factors in battle theater planning and operation. The knowledge of the atmospheric condition is in no small way crucial to operational success and for protecting the lives of crews and soldiers. The environmental conditions are a major factor in determining the successful outcome, or the failure, of many missions. A study by Yokosuka (NPMOC) found that "nearly two-thirds of all weather-related mishaps were judged to be preventable with perfect weather forecasts ***believed*** by the aircrew."[Cantu et.al., 2003] Not only must numerical models provide better forecasts, but accurate forecasts are paramount to convincing a crew of the reliability and the utility of the models.

While rawinsondes present many operational problems for the Navy, they have for years provided essential upper atmospheric data needed to constrain numerical models, initialize high resolution mesoscale models of the battlespace, provide critical information on electromagnetic (EM) and electro-optical (EO) effects, and have directly supported analysis for advanced system interpretation. Because of the intrinsic benefits attending the characterization of the lower atmosphere, the decision by the Department of the Navy to terminate shipboard rawinsonde operations can only be justified if it is prepared to replace this system with a modern system that is capable of providing in-situ profiling of the lower atmosphere. Numerical models with the standard measurements and profiles from the civilian community ***cannot provide*** an adequate description for the ship environment or the critical description of the littoral area, including the all-important characterization of the evaporation duct and other RF effects. [Frederickson and Davidson, 2004] Algorithms used to empirically predict the existence of evaporation ducts affecting radar can only be verified and refined with observations. Furthermore, while it may be easy to initialize a model with a coarser grid model output, the only way to constrain the model is to include a useful minimum set of in-situ observations. The value of the model result for prediction relies upon timely input of measured profile data.

In recent years remote sensing capabilities have advanced to the degree where they have evolved from "proof-of-concept" to a viable means of documenting profiles of lower atmosphere properties. These systems are now sufficiently robust and reliable to be considered as a replacement for the GPS-rawinsonde system. ***The goals of this analysis are to assess the current state of operations, provide a detailed evaluation of the alternative techniques, and produce a plan for the deployment of the next generation of shipboard instrument/sensors that will replace the GPS-sonde balloon data with in-situ remotely-sensed, high resolution atmospheric observations of the battlespace. The roadmap will serve as a guide for the strategic replacement of the GPS-sonde with: 1) a small volume Advance Lidar Atmospheric Profile Sensor (ALAPS) to obtain high resolution measurements of temperature and moisture profiles for RF-refraction, optical extinction coefficient for visibility, and backscatter for ceiling height out to a ship-relative radius of 10 kilometers; 2) a co-located wind profiler (either Doppler radar, SODAR, or direct detection Doppler lidar) for continuous observations of the low altitude 3-D wind field.***

<u>Current Situation</u>

The decision to find a new solution for the GPS-sonde operation is understandable given the problems and costs associated with this system. However, not to replace the atmospheric measurements with a modern instrument or suite of instruments would be misguided. Numerical models such as NOGAPS and COAMPS are critical for battlespace forecasting efforts and the successful model requires at least limited regional data for initialization and for constraint. However, these models are incapable of simulating the detailed structure of the lower troposphere where RF ducting effects create significant hazards for deciphering the speed and location of approaching enemy aircraft and missile attacks, or accurately describing a radar target. [Collier, 2004] In order to characterize this structure in real-time, a detailed knowledge of meteorological variables, especially in the vicinity of sharp gradients in moisture and temperature, is needed from the sea surface to the middle troposphere. [Davidson et.al.,2002] Rawinsondes have been used for more than 50 years to delineate these gradients and profile the full troposphere, but they have the following significant limitations:

(1) Rawinsonde balloons are launched too infrequently and require more than one hour to retrieve a full data profile. Two soundings per day are insufficient to resolve rapid changes that are known to occur in the lower troposphere and marine boundary layer, where gradients are often most pronounced.

(2) Spatial resolution is too coarse and results in poor characterization of the representative area.

(3) The procedures used by the Navy to transmit the rawinsonde data for ingestion into a model data assimilation system have been archaic, resulting in significant latencies in the retrieval of data at modeling centers. Only a few percent of the total number of rawinsonde soundings are ever used to constrain or initialize models. [Goroch, et al., 2004]

(4) The cost/sounding to maintain the rawinsonde system, the manpower necessary to sustain operations (3, 2-person crews), and the storage of the sensor packages and helium tanks are disadvantageous, and not commensurate with the scope of activities in a modern Navy.

(5) The transmission of the radiosonde signal to a shipboard receiver reveals the approximate location of the ship from distances of many hundreds of miles (greater than 500 NM). This non-covert activity can jeopardize a mission and place the well-being of the ship and crew in harms way.

The Tactical Environmental Processor (TEP) has been prepared as an additional tool that uses the data products generated from the Navy’s SPY-1 radar system to determine wind speed from Doppler velocity of signals scattered from refractive gradients, and to describe the distribution of water droplets/flakes and precipitation from those regions. The cloud distribution and precipitation maps obtained, and the wind field measurements (when sufficient large aerosols and droplets are present), provide an important data products from those ships with these radars available. It is expected that these data will become part of the standard data available from several ships.

Plan for the Future

Remote sensing measurements of atmospheric properties will provide continuous data products for the critical input to decisions on operations, and the data that are necessary for proper interpretation of many systems. In particular, the shipboard radar and self-defense systems are affected by the gradients in RF-refraction which can be continuously monitored in real time with lidar. The meteorological, electromagnetic and electro-optical properties are traditionally measured using point sensors on ships and at shore sites and the upper air measurements are normally obtained by point sensors on balloon-borne payloads (radiosondes). The traditional techniques for profiling atmospheric properties have many limitations and problems, including limited time resolution (about two profiles per day), non-covert data (radio signals can be observed over ranges of 600 to 1000 km), time delayed data processing (ascent time and profile calculation), cost per profile measurement (~$300), manpower support requirements (6+ man teams), storage space for consumables, and others. Future Navy operations in littoral areas require improved atmospheric data with higher data rates, real time data products and covert operations. Several of the next-generation systems, such as advanced radar and self-defense systems, will require real time data for local atmospheric parameters. Recent developments in remote sensing technology provide the opportunity to obtain the needed profiles of atmospheric data. The following sections provide a description of the criteria that have been used to evaluate the alternative approaches. The analysis using those criteria and the recommendations for meeting the future needs of the Navy are presented in the following sections.

1. Goals, Mission Needs, and Deficiencies

The primary goal of this study is to determine the best path forward for defining and mitigating the atmospheric effects upon military systems and operations. The major effects of the atmosphere upon systems and operations are due to variations in the profiles of key parameters; temperature, water vapor, aerosol size/concentration and wind velocity. ***The goal is to develop a sensor program that will obtain the required data products, and is capable of providing continuous, covert, real-time, accurate, high resolution and economical data products.***

Military operations are dependent upon an accurate and detailed description of the environmental conditions present during the period of an operational mission for successful conclusion. The environmental conditions can be used to benefit and support operations when conditions are properly characterized and predicted, but can lead to failure in attaining mission goals when unexpected conditions are encountered.

Statements of Requirements

Shipboard in-situ observations of the atmospheric moisture and temperature fields are critical for air-operation safety, numerical model initialization, interpretation of radar-screen holes, mission planning, battlespace decision-making, and risk assessment. We can begin with the premise that knowledge of the real-time in-situ atmospheric conditions, and the forecasting of those conditions, is vital to Naval operations. NOGAPS can provide reasonable forecasts out to several days for the large-scale atmospheric condition when sufficient regional data are available for assimilation. COAMPS has the ability to provide short-term forecasts for the littoral region [COAMPS Version 3, 2003]. These models are especially useful for providing the forecasts for the spatial extent and timing of weather systems, mean sea surface roughness, and wave heights, but they fail to capture the detailed horizontal and vertical structure, local gradients, and rapid developments in the immediate battlespace. Satellites can supplement the model output, as well as be assimilated into the model initialization. But satellite data, just as with model output, are too coarse to resolve the fine-scale spatial structure and high frequency temporal variability of the lower atmosphere where a description of the RF field is known to be largely dependent on such information. The minimum requirements for data are summarized in Table 1. These requirements are based on a critical analysis of several sources but particularly upon the investigations of Goroch et al. [2003 and 2004].

Statements of Deficiencies

Upper air profiles using rawinsondes combined with shipboard measurements have been the long-standing source for initializing numerical weather models, performing single station and battlespace Nowcast in remote locations, and for characterizing electromagnetic (EM) refractive effects. For nearly as long, the deficiencies in the current atmospheric measurements related to the use of radiosondes as the primary retrieval platforms have been recognized. Rawinsondes systems have the following limitations:

(1) too infrequent measurements to provide meaningful assessment of rapidly changing weather and RF ducting conditions,

(2) substantial manpower (three, 2-person shifts) requirement to sustain operations,

(3) significant ship storage volume for equipment (e.g., helium tanks),

(4) spatial resolution too coarse for adequate representation of the littoral area,

(5) exhibit unreliable GPS-derived winds,
(6) non-covert because of their data transmitter,
(7) expensive balloon package expended for every profile.

Table 1. Summary of the minimum data requirements to support Navy systems and operations.

Parameter – Region Accuracy Space Resolution Time Resolution	Surface to 20 m	Surface to 2 km	2 to 10 km	Greater than 10 km
Temperature	±0.2ºC Surface&Elev Pt 1 min	±0.5ºC 50 m 15 min	±1.0ºC 200 m 60 min	±2.0ºC 500 m Infrequent
Water Vapor	±0.05g/kg (~0.5%) Elevated Point 1 min	±0.1 g/kg (1-2%) 50 m 15 min	±0.2g/kg(1-10%) 200 m 60 min	No req No req No req
Aerosol Extinction	+/- 0.01 km^{-1} Elevated Point 1 min	+/- 0.02 km 50 m 15 min	+/- 0.05 km 200 m 60 min	No req No req No req
Wind Velocity	+/- 0.2 m/s Elevated Point 1 min	+/- 0.5 m/s 50 m 15 m	+/- 1.0 m/s 200 m 60 min	No req No req No req

2. Operational Environments and Alternatives

Naval operations affected by the environment occur primarily in the region of the atmosphere between the ocean surface and about 5 km altitudes. Within this region, most of the effects on electromagnetic (EM) and electro-optic (EO) propagation occurs and most operations are carried out. The environmental factors determine operational limits, such as radar screen performance, self defense protection, ability to conduct flight operations, and success of surveillance activities. The lower troposphere altitude region encompasses the weather influences controlling sea state, visibility, and the operational limits for various systems. Data products describing the properties of the region are critical for successful predictions to support planning and carrying out various missions. The developments in remote sensing technology are now ready for implementation to provide the required measurements for the future. It must be pointed out that no single system will provide all of the measurement parameters under all conditions, however, major improvements are possible using the technologies that are now available. To accurately describe the regional characteristics, several sensors should be deployed within a littoral area. Data from three or four sensors deployed over an area of several hundred kilometers should ideally provide a data set that would permit the models to accurately predict the environmental conditions.

In recent years, the tropical ocean region's environment has presented the most challenges for naval systems, including extremes in moisture concentration and gradients, airborne dust clouds, smoke, and concerns about toxic vapors. However, the atmospheric concern for Navy operations includes the entire globe from equatorial to arctic regions, and between the ocean surface and about 5 km altitude. The special factors to consider in naval operations frequently occur in locations, and under battlespace atmospheric conditions, that cannot be described with climatology or with the data products available from the civilian sources. The local measurements that are supplied by the deployed assets provide the most important input for system analysis and for model calculations that support operations in a littoral area.

One important factor that must be considered in selection for future sensors is the requirements of the Marine Corps, as well as compatibility with the Air Force and Army, so that the maximum degree of interoperability can be attained. Several small packages are available that provide the point sensor data. Sensors can be easily selected to obtain a common data base for point sensors between the DOD elements. The requirement for a transportable instrument for lower atmospheric profiling that replaces the balloon sonde can also be met with a remote sensing package which can be carried in a HMMWV, or a small towed trailer.

<u>Operating Conditions</u>

The sensors supporting missions and major systems need to be able to provide that support under all conditions. However, there are no sensors for measuring the atmospheric environment that can perform continuously under all conditions. For example, sonde release is limited by high wind, lidar is limited by heavy clouds and fog, and a microwave radiometer is limited by rain. Because clouds are probably the most significant limitation for the lidar techniques, a description of the global mean cloud distribution follows. Even when clouds are present, the lidar is capable of measuring through thin clouds and during periods of rain, it also measures properties below heavy clouds on horizontal paths and measures cloud ceiling height.

Cloud Cover - The cloud cover throughout the world is shown in Figure 1 (a), (b), (c), and (d) for January and July from data supplied by the International Satellite Cloud Climatology Project (ISCCP). These data are available for cloud cover during each month, but here we have selected the January and July figures to represent the seasonal extremes in the two hemispheres. The most general conclusion that can be drawn from these plots is that cloud cover is heavier on the west coast of each continent. The optical depth of the clouds varies according to the season with less dense clouds during the winter months and more dense clouds in the summer months, with the most optically thick clouds residing near arctic and antarctic regions. One should notice that although there are times with heavy cloud cover, they are rarely more than 50% of the time, which would allow instruments affected by cloud cover to be used.
[http://isccp.giss.nasa.gov/products/onlineData.html]

Cloud cover fraction (or amount %) -This parameter represents the fractional area covered by clouds as observed from above by satellites. It is estimated by counting the number of satellite fields-of-view (pixels, about 5 km across for ISCCP) that are determined to be cloudy and dividing by the total number of pixels in a region about 280 km across. Cloud amount for lower-level clouds are only that fraction of the area actually observed to be covered by clouds at that level. This way of determining cloud amount assumes that each cloudy pixel is covered completely by clouds.

Cloud optical thickness and its mesoscale variability - This parameter represents the optical thickness of clouds at visible wavelengths (approximately 0.6 microns). It is determined from the satellite-measured visible solar reflectivity of cloudy scenes, assuming that the pixel is uniformly covered by clouds. The retrieval depends on an assumed particle size and shape. The standard ISCCP products assume that clouds warmer than 260 K are liquid clouds composed of spherical droplets with an effective radius of 10 microns and that colder clouds are ice clouds composed of crystals with a fractal shape (aspect ratio unity) that have an effective radius of 30 microns. The albedo of a cloud covering a larger area, about 280 km across, is reduced by the mesoscale variations of optical thickness; however, the ISCCP optical thickness values are averaged so as to give the correct albedo.

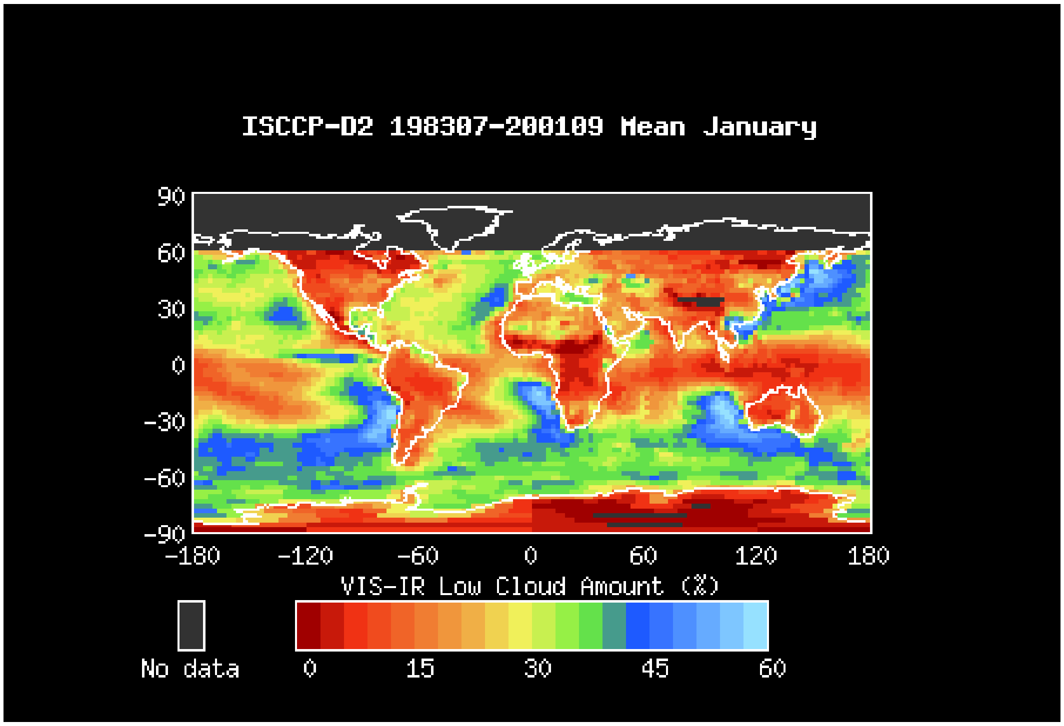

Figure 1(a). Mean Monthly cloud cover during January.

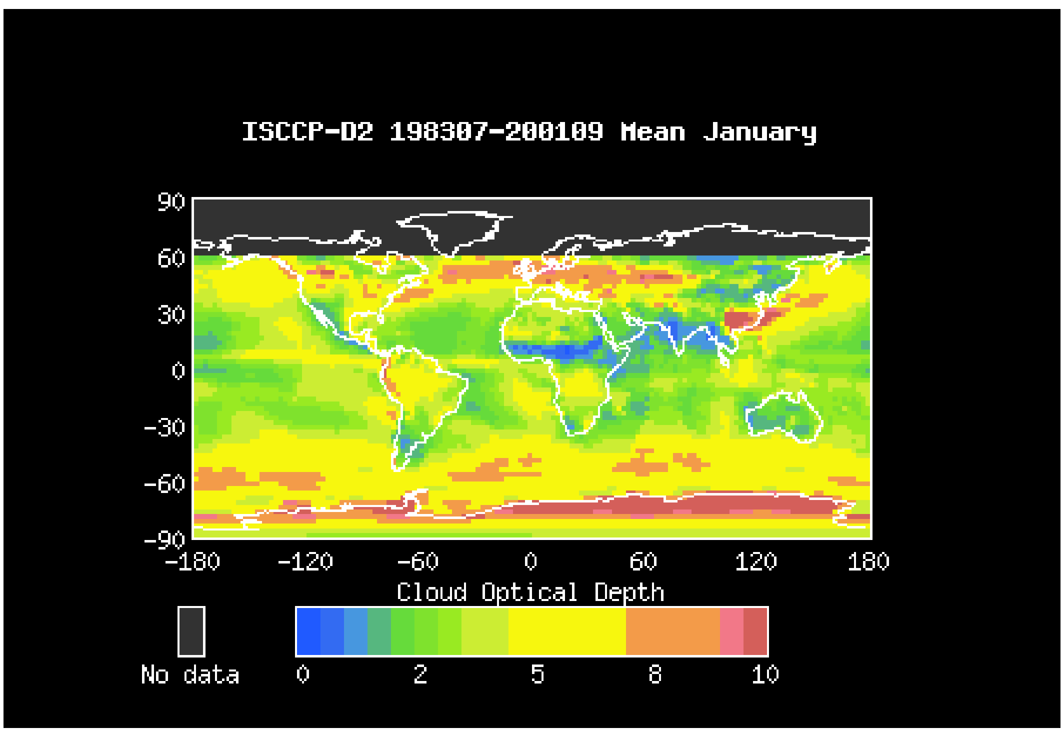

Figure 1(b). Mean Cloud Optical Depth during January.

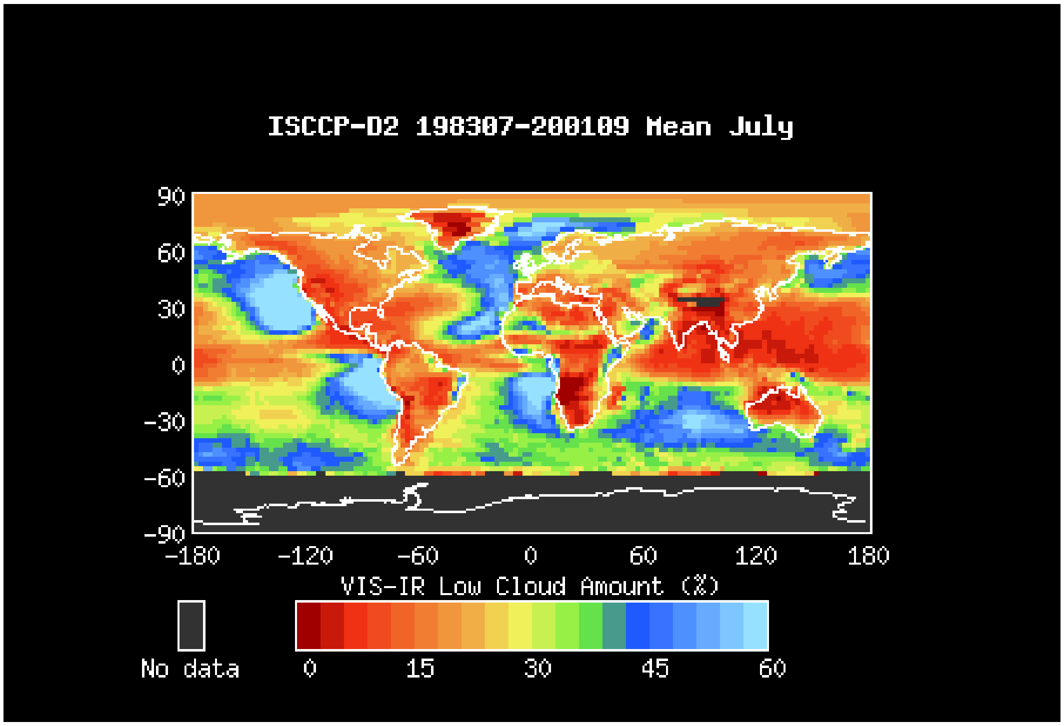

Figure 1(c). Mean Monthly Cloud Cover during July

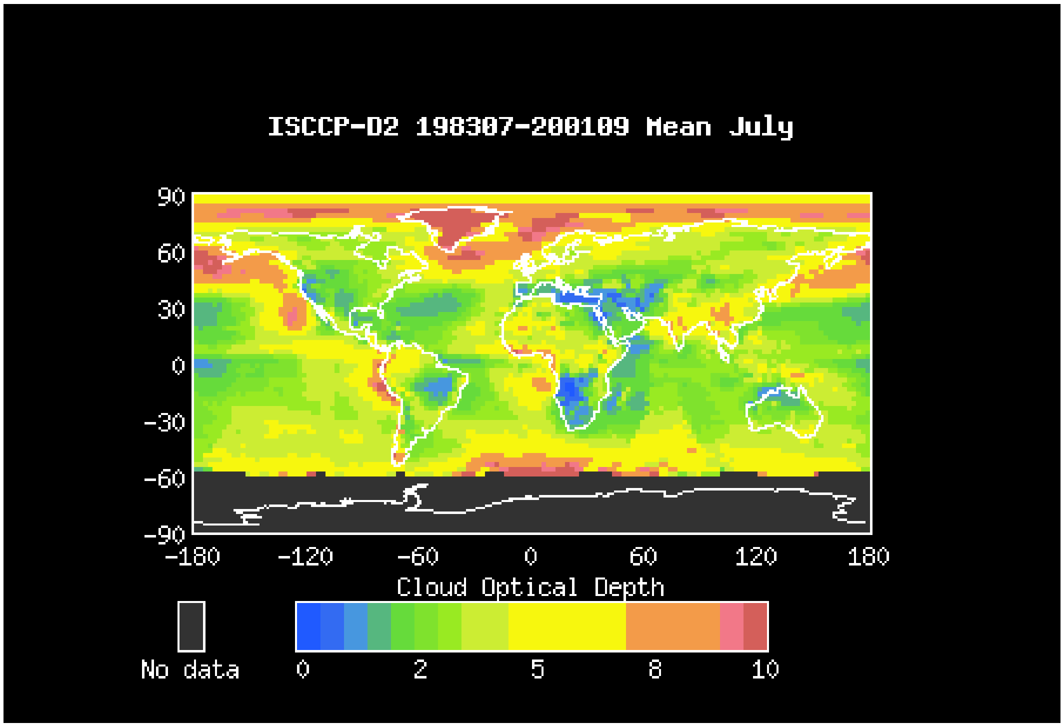

Figure 1(d). Mean Cloud Optical Depth during July

3. Operational Concepts and Tasks

As a strike force of US Navy ships transits the world's oceans and/or deploys for a mission in a littoral region, it is necessary that the environment conditions be considered and used for added advantage in planning every operational mission. The optimum performance of every high-tech system in the modern fleet requires that the atmospheric environment be considered. Radar, communications, and surveillance systems require knowledge of RF-refraction conditions, aerosol optical extinction, and propagation conditions over much of the electromagnetic spectrum. The only practical way to describe and forecast the atmospheric condition is to measure a time sequence of key properties at a few locations within a regional volume and use a physics-based model to fill-in the volume description. The information available on large scale forcing at the boundaries, together with information on the trend of the local measurements is then used in models to forecast the conditions for hours and days ahead. The following list of tasks provides several cases – not intended to be an exhaustive list – to use in considering and evaluating the capability of various atmospheric sensors. The tasks considered are:

(1) RF Refraction Data for Radar Defense Screen

The RF-refraction profile, which is directly calculated from empirical formulas using the profiles of water vapor and temperature, defines the propagation ducts and refractive conditions affecting radar defense screens around a deployed strike force.

(2) Using Radar Ducts for Strike Enhancement

Vertical profiles of RF-refraction define surface and elevated zones for penetration of shore and shipboard radar defenses in support of covert and offensive missions.

(3) Communications Link Analysis and Jamming (RF/EM)

Refraction profiles describe propagation characteristics that can be used to optimize communications paths, or to jam enemy communications links.

(4) Visibility Limits on Aircraft and Missile Operations

Optical extinction at visible and IR wavelengths limit flight operations of carrier, ship, and shore-based strike aircraft, helicopters, and cruise missiles.

(5) VIS/IR Surveillance

Infrared and visible sensors provide an increasing important part of the automatic detection and alarm systems for force protection, as well as the role these sensors play in detection and surveillance of friendly and unfriendly activities in the region.

(6) EO Support for Covert Operations

Description and forecasting of the illumination conditions and optical propagation at visible and IR wavelengths are critically important in carrying out covert military operations, which can be vitally important to littoral area operations.

(7) NOGAPS Model Parameters (72 hrs)

Shipboard data products must be formatted and transferred automatically to NOGAPS model processing centers so that the local measurements are used to help formulate the large scale grid data (~0.5 degree resolution) for forecasting. The NOGAPS model provides the initialization for the COAMPS local scale model that supports the Strike Force or the Littoral Area Command.

(8) COAMPS Local Model Parameters (4-24 hrs)

The working model for mission planning and forecasting is the COAMPS model. It uses the large scale grid products from the NOGAPS model to provide boundary conditions on a grid of several hundred kilometers and forecasts the changes expected at those boundaries based upon the motions of large scale atmospheric low pressure and high pressure cells, as well as other features. The COAMPS model describes the influence of those boundaries and uses all of the data products available from local and nearby regional sources to provide an accurate forecast of the local conditions over the next 24-hour period. [COAMPS Version 3 Model Description, 2003]

(9) Regional Data Network with NITES (Navy Integrated Tactical Environmental Subsystem)

NITES IV is the portable tactical environmental support system used aboard unit-level ships and at undeveloped shore sites by Navy and Marine Corps weather service personnel. The main purpose of NITES IV is to enhance the automated capabilities of these teams/units to provide meteorology and oceanography (METOC) data product support at remote locations, which are often in harsh environments. The system is portable, lightweight, rugged, flexible and independent and allows deployment of the minimal hardware and software configuration needed to support each mission. By sharing data on a regional scale, the holes in defensive shields of one location can be filled using data from other elements deployed in the area. The data collected over the regional scale can be used in the COAMPS model to generate accurate predictions.

(10) Weather Related Hazards for OPS and Flight

Weather hazards include a wide range of types of events that occur when unusual atmospheric conditions are present. Factors such as extreme temperature, heavy precipitation, icing, high wind, high wave-heights, and fog, can impact operations. These conditions should be forecast sufficiently ahead of time to permit planning.

4. Sensors Alternatives

The broad categories for atmospheric instruments are divided into two groups 'point measurement' and 'remote sensing' instruments. The point sensors provide high-quality measurements of many parameters, but the measurements are limited to the immediate vicinity of the sensor. The Mini-Rawin System (MRS) uses point sensors for measuring the temperature, dew point (to determine water vapor), and wind velocity. Also, the balloon sonde instruments measure the pressure, which is used to assign a pressure height altitude to the other data. The remote sensing instruments include Lidar, Radar, SODAR, Microwave radiance, and several types of satellite remote sensing instruments. Each of these techniques is examined using the following outline, and that discussion is included in the analysis of alternatives:

- Description of Sensor
  - Hardware
  - Technique
- Relation to MOP and MOE
  - Advantages
  - Limitations
  - Readiness Level for Use
  - Risk Analysis of the Sensor to Perform and Achieve Expected Results

5. Measures of Performance (MOP)

Several Measures of Performance (MOP) have been identified in evaluating how well the data will meet the needs for the Navy's use. The factors against which each of the systems will be measured are:

(1) Latency: Minimizing latency improves performance. Sensor alternatives are chosen to optimize rapid data retrieval, reduction, processing, and analysis to provide the observer with near real-time information that can be interpreted and used in battlespace decision-making in times that are short in order to realize a timely and effective response.

(2) Accuracy of Data Product: Observers must have confidence that the data products derived from sensor measurements represent the actual conditions of the near-ship environment, or otherwise understand the limitations of a given derived product. No single sensor/instrument will ever fully characterize the atmospheric condition. It is imperative that the observer understands the accuracy of the data and is able to integrate different sensor products to gain a full perspective of the atmospheric condition.

(3) Time Resolution: The next generation of upper air sensors must provide better time resolution than the twice-per-day soundings that are currently available. Sensor alternatives are chosen that will provide nearly continuous measurements, or measurements at selected time intervals that will capture the variability and trends of the atmospheric medium. For numerical models, a sampling frequency of one mean measurement per hour should be sufficient. However, it is absolutely critical that this data is transmitted to modeling centers (via SIPRNET) at appropriate times to be assimilated into the NOGAPS model initialization

fields. This is most important for short-term (COAMPS) model calculations for forecasting the littoral battlespace region.

(4) Spatial Resolution: Horizontal and vertical resolution are key to resolving the characteristic structures of the atmosphere needed as useful input to empirical models for EM/EO analysis, and numerical models for short and longer term prediction. For comprehensive characterization of the littoral battlespace, remote sensors must be located on ships with a proximity that allows collection of a set of measurements that will resolve the lower troposphere gradients for mapping of the refractive ducts and other EM/EO effects. The shipboard sensors should be capable of surveying the entire battlespace, and be made available to the deployed elements via NITES. For numerical models, the spatial resolution should be such as to constrain the model within the particular battlespace region. The vertical resolution of sensor alternatives is critical for identifying the sharp gradients in the marine boundary layer. Detailed profiles of water vapor and temperature are required to calculate the strength and location of evaporation ducts, elevated ducts, and other RF refraction and EM/EO effects relative to active radars.

(5) Real Time Data: Model simulations are not capable of providing the detail that is needed in order to resolve the variability and gradients in the marine boundary layer. Even COAMPS running with a horizontal grid-spacing of 9 kilometers (with future plans for 3 km grids) will not fully resolve the vertical gradients in moisture, temperature, aerosol concentration, visibility and index of refraction. Real-time data in the hands of experienced observers is essential for resolution of the ducting, and other EM/EO effects. Real-time data is essential for Nowcast in the littoral area, safety of the aircrew, and assessing the current atmospheric condition surrounding the battlespace. Real-time data exhibits the detailed structure characterizing the marine boundary layer where models fall short of describing the present conditions.

(6) Validity of Inferred Data Parameter: The shipboard observer must have confidence in the validity of the data parameter used to create products for interpretation and decision-making. Sensor alternatives must be tested in areas that are representative of the deployment environment. The sensors must be ruggedly designed and capable of self-calibration to insure against spurious data records and instrument drift.

(7) Nowcast Capabilities: Perhaps the most important justification for a new generation of sensor alternatives is the ability to assess, in near real-time, rapidly changing environmental conditions (Nowcast) that may affect the safety and success of battlespace operations. Access to shipboard sea surface, upper air, and satellite measurements will provide decision-makers with a real-time, reliable, accurate, and valid assessment of the near-ship atmospheric conditions. From these data products, an observer can reasonably and effectively extrapolate, or interpolate between model outputs to reduce errors in judgment and misinterpretation, which has been often due to the paucity of relevant data. In-situ, high frequency measurements, and decisions based upon current information about conditions in the near-ship environment can significantly elevate the confidence level of shipboard personnel and reduce the time and uncertainty associated with decision making.

6. Measures of Effectiveness (MOE)

The Measures of Effectiveness (MOE) are related to the Measures of Performance but have a different context. While the MOP's represent the hardware capability, the MOE's are representative of the actual utility of the final delivered data product. The MOE factors that are considered in evaluating the several alternatives include:

(1) Timeliness: Data products used in making critical decisions in the battlespace are of no use if they arrive late. A key element of the Analysis of Alternatives is the time interval from measurement to the end user. This time period varies considerably depending on the instrument platform, sampling frequency, method of acquisition, locations of data acquisition, delays due to data collection, processing, performing QA/QC analysis, time for dissemination, integration with other data sources, interpretation, and communication of decisions based upon the information. Estimates of optimal timeliness will be given for each sensor alternative. In the case of direct measurements onboard the ships, the data products can be immediately available. However, the transmittal of measured parameters and profiles to FNMOC (U.S. Navy's Fleet Numerical Meteorology and Oceanography Center) for use in the next NOGAPS (Navy Operational Global Atmospheric Prediction System) model run will be dependant upon the communications links available.

(2) Consequences of Uncertainty in Conditions: The accuracy and validity of the data products used in decision making are critical to the evaluation and quantification of uncertainties in conditions that these data products represent. Ideally, a decision maker has the data products or parameters available in engineering units, and also has a measure of its uncertainty, together with a description of the consequences of this uncertainty. For example, numerical models should provide ensemble products based on dynamic stochastic forecasting, not just a single forecast. Ensembles provide an estimate of the uncertainties in model output that an end user can use to assess risk. Similarly, the location of an evaporation duct can be presented with errors representing the uncertainties in measurement due to sensor accuracy, algorithm bias, and resolution.

(3) Representativeness of Data: Data must represent typical or characteristic measures of the atmospheric condition. Statistics based upon frequently sampled conditions is considerably more representative (and reliable) than data sampled infrequently. In rapidly changing or highly variable environments, the numerical models (NOGAPS and COAMPS) based on twice-per-day soundings obtained from the MRS AN/UMQ-12A system will not be representative, and may deviate significantly from the condition at-hand. Next generation sensor alternatives such as those considered in this AoA have, for the most part, high sampling rates, such that their data should be much more representative of the near-ship environment. Shipboard sensors are likely to be more representative of the spatial regime as well, and can be used to constrain the data products from models and less frequent sampling methods.

(4) Ease of Use of Sensor: The emphasis on sensors considered in this AoA is on turnkey operations with minimal person-hours required for calibration, alignment, maintenance, and support. The current MRS AN/UMQ-12A upper air system is cumbersome and person-intensive. The next generation of sensors will significantly diminish the number of individuals and person-hours needed to support the system. In order for this to be effective across the spectrum of operations, the Navy should commit to upgrading and automating its communication systems, especially the transfer of data from the sensor system to the message center, followed by the use of SIPRNET for transmission of shipboard data to modeling centers.

(5) Resources Expended: The sensor alternatives proposed in this AoA are chosen to minimize recurring expenses while offering a suite of next generation instruments appropriate to the modern battle theater. They are primarily intended to reduce personnel costs through automation of remote sensing devices, and provide a secondary benefit of freeing these individuals for other tasks and reducing the number of trained personnel required to obtain the METOC data products. There will be a need to train end-users (weather observers) in the operation of instruments and the interpretation of data and data products. The cost/benefit ratio is expected to improve significantly compared to existing technology. When measured on a cost/sample basis, the next generation of sensors will provide considerably more samples for each unit cost expended.

(6) Continuity of Data: No sensor is capable of providing continuous data products under all environmental conditions. This evaluation considers the capability of a sensor to provide a mostly continuous data record with sufficient information to perform its primary goal of supporting the mission and planned operations.

7. AoA Analysis

AoA: Balloon Sonde
Mini Rawin System (MRS) AN/UMQ-12 A

Identification of Sensor: **MRS AN/UMQ-12A**
Hardware: The Mini Rawin System (MRS) AN/UMQ-12A has been in service since 1987. The present MRS system is based upon the advances in sonde instruments that have been made over the past 50 years, and it has served as the primary atmospheric profile instrument during these many years. The MRS AN/UMQ-12A is a meteorological system that measures air pressure, air temperature, humidity, wind speed, and wind direction received from ascending instrumented weather balloons.

Technique: Balloon-borne meteorological sensors measure temperature, humidity, pressure, and wind velocity. Measurements are based on the use of a free-flying expendable meteorological sondes, which transmit pressure, temperature, and humidity measurements to the AN/UMQ-12A over a radio link. The expendable meteorological sonde includes a navigation network receiver to obtain the sonde location, which is relayed via the radio link to the AN/UMQ-12A. The AN/UMQ-12A uses the sonde location data to process and compute the wind profile. Tables 2 and 3 below give the parameters and the performance characteristics for the balloon system. Figure 2 shows a profile of water vapor measured by the MRS compared with a Raman lidar. The differences exhibit the profile variations during a 30 minute period, while the sonde ascends making point measurements as the lidar signal is integrated, and the spatial separation caused by the balloon drift in the background wind. The local small scale variations of the atmospheric structure have been found to be approximately ± 4%. [Philbrick, et al. 1978]

Table 2. Upper Air Pressure, Temperature and Humidity Parameters

Parameter	Performance
Temperature Range	-90 to +60 °C
Temperature Resolution	0.1 °
Temperature Accuracy	±0.2 °C
Temperature Lag	≈ 2.5 seconds at 6 meters per second ascent rate
Humidity Range	0 to 100%
Humidity Resolution	1.0%
Humidity Accuracy	±3.0%
Humidity Lag	≈ 1 second at 6 meters per second ascent rate
Pressure Range	3 to 1060 hPa
Pressure Resolution	0.1 hPa
Pressure Accuracy	±0.5 hPa
Sampling Rate	7 samples per 10 seconds for each parameter

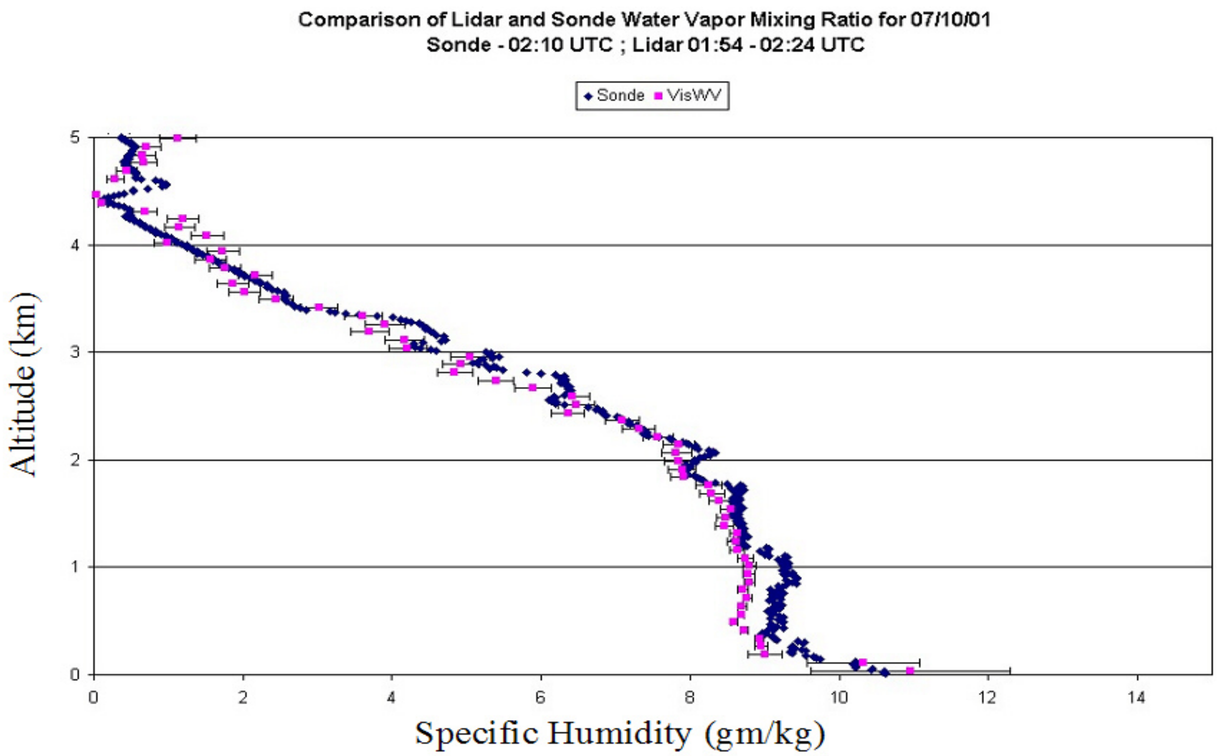

Figure 2. Example plot comparing water vapor measured by a sonde with the LAPS Raman lidar.

The local variations are due to the difference between instantaneous point measurements as the balloon ascends and travels downwind compared with the 30 minute averages of the vertical profile.

Table 3. Upper Air Wind Profile Parameters

Parameter	Performance
Wind Speed Range	0 to 180 meters per second
Wind Speed Accuracy	0.1 meters per second
Wind Direction Range	0 to 359 ˚
Wind Direction Accuracy	±1 ˚
Wind Vector Accuracy	0.5 meters per second
Wind Update Rate-Raw	2 samples per second
Wind Update Rate-Filtered	every 2 seconds

Relation to Tasks: The MRS AN/UMQ-12A can be directly or indirectly relate to Tasks 1-3 and 7-10. Tasks 1-3 are dependent upon obtaining RF-refraction profiles that can be calculated from the sonde profiles of water vapor and temperature. The sonde profiles support the Tasks 7-10 with the local meteorological analysis using data input to COAMPS and the regional forecast using NOGAPS. It is expected that the next generation of satellite instruments in the NPOESS (National Polar Orbiting Environmental Satellite System) program will provide improvements in the global coverage of regional scale meteorological information, but it is not realistic to expect that the data required for carrying out operations within a littoral area will be significantly improved. The retrieval techniques for measurements from satellites do not provide the spatial and temporal resolution that is needed.

Relation to MOP and MOE:

Advantages: The AN/UMQ-12A MRS uses conventional off-the-shelf meteorological sensors, balloons, data acquisition system, and signal transmission downlink protocols. It is capable of profiling the atmosphere from the ship deck to the upper troposphere/lower stratosphere. The AN/UMQ-12A uses the public access GPS system to derive wind velocity. The system has been upgraded and used extensively over the past 50 years with several commercial versions of the sonde available during the period.

Limitations: Dependence on the AN/UMQ-12A MRS suffers from not being capable of providing continuous, covert, real-time, representative, high resolution and economical data products. The operation of the GPS-sonde requires significant ship storage volume (e.g., helium tanks) and necessitates substantial manpower (three, 2-person shifts) to sustain operations. Sondes are launched too infrequently (poor temporal resolution) to provide meaningful assessment of rapidly changing weather and RF ducting conditions. During operations the sondes are not usually released from two or three locations in the region and thus exhibit a spatial resolution too coarse for adequate representation of the littoral area. Use of sondes is non-covert because of the radio data link which is easily detected at ranges greater than 500 nautical miles. The GPS wind system has recently suffered from a very high rate of failure in obtaining wind profiles, because of interfering signals or improper lockup on the GPS signal prior to balloon release, however solutions to this problem are being implemented. Even though the sonde package is designed to be biodegradable, complaints have arisen about the litter caused, particularly in arctic areas where the rate of decay is extremely slow and the batteries are an environmental hazards. In addition to the many factors described, the balloon sonde system has several other limitations that restrict the availability of data at times:

(1) the balloon sonde cannot be prepared and released during periods of high surface winds;

(2) when the sensor passes through regions of freezing rain, the data on water vapor can be lost for a significant period before the sensor recovers;

(3) the extent of the profile can be limited by premature balloon burst.

Readiness Level for Use: The technique has been used during the past 50 years and the current sensor model has been upgraded to use the GPS signals for wind analysis.

Risk Analysis of the Sensor to Perform and Achieve Expected Results: The principal performance limitations related to the MRS AN/UMQ-12A are the limited frequency of profiles, concern for covert operations because of the sonde radio transmitter, and the unreliable performance of the GPS wind velocity sensor (over half of the soundings are missing wind velocity data).

Measures of Performance (MOP)

Latency:

The MRS AN/UMQ-12A operation has several sources contributing to the latency of data. It can routinely take 1-1.5 hours from the time of launch to complete a vertical profile. Once the data is retrieved, under current procedures it must be hand-carried to the message center where it is encrypted and transmitted to the modeling centers. This latency is cited as one of the limitations to incorporating in-situ atmospheric profiles into the numerical model data assimilation system. Only about two percent of the shipboard soundings make it to the destination in time to be of use in numerical model preparation.

Accuracy of Data Product:

The MRS AN/UMQ-12A sensors have accuracies that are quite adequate for their intended purpose. However, these accuracies are local to the sensor and may not represent the aloft atmospheric condition above the ship due to the drift range of the balloon, especially under high wind conditions.

Time Resolution:

Twice-per-day soundings at 00 and 12 UTC are not sufficient to resolve rapidly evolving atmospheric conditions in the littoral area. Nor are they adequate to be used as input to the COAMPS model when it is initialized at intermediate times. The twice-per-day soundings are useful for NOGAPS initialization fields, but poor latency limits the number of soundings that are actually used in this manner.

Spatial Resolution:

The MRS AN/UMQ-12A system has poor horizontal spatial resolution, with a single profile often being used to represent an area much larger than the battlespace. This is especially problematic in the vicinity of coastlines where the vertical profile is affected by land-sea discontinuities, but is used to represent atmospheric conditions in the near-ship environment. The vertical resolution of the MRS is a function of the pressure sensor resolution (0.1 hPa), the ascent rate (6 meters per second), and the sampling rate (~ every 10 seconds), or approximately every 60 meters with an accuracy of ± 5 meters.

Real Time Data:

The MRS AN/UMQ-12A has the capability of producing a vertical profile in near real-time (1-1.5 hours after the launch). Analysis of the vertical atmospheric structure can occur by 0200 and 1400 UTC, for launches respectively at 0000 and 1200 UTC. There is an absence of real-time data during the intervening times between soundings when operations would have to rely on either extrapolating the sounding results to the current condition, or using COAMPS to forecast the times between soundings. Neither method is adequate.

Validity of Inferred Data Parameter:

The MRS data retrieved by the AN/UMQ-12A is valid only for the local position and time that the sensor recorded the data. Under high wind conditions, the validity of the data as representative of the near-ship environment may be questioned.

Nowcast Capabilities:

Because the data from the MRS is retrieved in near real-time, it can be used onboard the ship for extrapolation, and integrated with other data, to infer a Nowcast (short-term forecast) for shipboard weather observers.

Measures of Effectiveness (MOE)

Timeliness:

For reasons cited in the MOP, the timeliness of the data is a principal problem for the MRS AN/UMQ-12A system. The full sounding is only available approximately two hours after a launch, and the procedure used to distribute this data to be used in model data assimilation systems is inefficient, especially in a modern theater of operation where decisions rely on the timeliness and accuracy of information.

Consequences of Uncertainty in Conditions:

The twice-per-day soundings are insufficient to resolve rapid changes in the atmospheric conditions during the 12-hour period between balloon launches, and will lead to uncertainties that grow larger in times of active weather systems, high wind speeds, and a rapidly developing boundary layer. The consequences are uncertainties in the location and depth of the evaporation duct, interpretation of RF refraction, Nowcast of weather-related hazards, and poor representation of the meteorological conditions in the littoral area.

Representativeness of Data:

Providing that the wind does not carry the sonde over land, large islands, or other topographic features, the data retrieved from the MRS should be representative of the aloft conditions in the near-ship region, except as frontal boundaries approach.

Ease of Use of Sensor:

The MRS AN/UMQ-12A requires a significant number of dedicated person-hours to operate. Conversely, the operational maintenance is inconsequential due to the disposable/replaceable nature of the sonde sensor package and balloons. Nevertheless, there are several procedural steps involved in the deployment of the GPS-sonde, and the lock-on to a GPS signal remains a serious limitation that impedes ease of use. The procedures that limit the ease of use includes battery activation, balloon inflation and launch, especially under high wind conditions, calibrations prior to launch, signal lock-in, and handling and storage of helium tanks used for balloon inflation.

Resources Expended:

The GPS-sonde system typically requires three, two-person shifts to maintain the data capability. The cost of expendables (sensor package, balloon, battery, incidentals) for a single launch is approximately $300/sounding. A substantial ship volume is needed in handling and storage of helium tanks. Two per day soundings are estimated to cost approximately $54K, plus $6K for personnel, so the total cost per station for operation of one year is more than $60K.

Continuity of the Data:

The MRS AN/UMQ-12A data product is discrete, with each balloon-borne instrument providing one data point measurement at each height as the balloon ascends. In a typical operation, two sondes per day are released. For special operations it is possible to release four or more sondes in a 24-hour period, however this approach may still not provide adequate resolution. Sondes are not always available as a data source because high wind conditions can make the release difficult to impossible. At the times of covert operations the radio beacon provided by a sonde release is not advisable.

AoA: LIDAR
Advanced Lidar Atmospheric Profile Sensor (ALAPS) Raman Lidar

Identification of Sensor: **ALAPS**
Hardware: The ALAPS (Advanced Lidar Atmospheric Profile Sensor) sensor is a Raman lidar that has been developed to the stage of an advanced development prototype (ADM) with the goal of meeting the Navy's primary needs for atmospheric measurements. A lidar is best described as a radar at optical wavelengths. The advantage of using optical wavelengths is that the properties of the molecules of the atmosphere are determined from the scattered signals, whereas at longer wavelengths radars provide a measure of the properties of the larger droplets in clouds. The Raman lidar technology was demonstrated for the Navy in 1996 using a prototype (LAPS) that was deployed onboard the USNS Sumner. It is a self-contained instrument mounted in a weatherproof cabinet. The operational instrument will be a self-contained unit, designated as ALAPS, which is estimated to be a meter cube weighing approximately 500lbs. The instrument has interfaces with the ship that include electrical power (approximately 4 kW), and a data port connection to a computer that controls the instrument and receives/displays the data products. The instrument consists of four principal subsystems; transmitter, receiver, detector, and data/control systems. The ALAPS lidar transmitter will use a flash-lamp pumped Nd:YAG laser transmitter operated at the 3rd harmonic (355 nm) ultraviolet wavelength (other wavelengths will be trapped within the transmitter). The transmitted beam at this wavelength is eye-safe. This spectral range is not transmitted by the eye and thus cannot be focused onto the retina by the eye-lens. The ANSI Standard for the Maximum Permitted Exposure (MPE) at 355 nm is approximately four orders of magnitude less restrictive than the 532 nm wavelength and thus the expanded beam will be eye-safe at all distances outside of the instrument. [ANSI Z136.1 -2000] For example, expansion of a 355 nm beam with 300 mj pulses to a diameter of approximately 10 cm will make the beam eye-safe at all ranges. The flash-lamp pump approach can eventually be replaced with diode pump lasers, however the present cost and lifetime performance for diode pumping high power lasers does not support this approach. It is reasonable to expect that the instrument can be operated continuously for a period of approximately 3-4 months between planned maintenance activity. Planned shipboard maintenance service would include replacement of flash lamps, cleaning and inspection of optical elements can be performed by a trained technician. A biannual maintenance activity would involve a depot level disassembly of the instrument, inspection, and replacement of any degraded optical coatings, followed by a one day performance test of the instrument. If the instrument is operated at a lower duty cycle, then the time between planned maintenance activities could be lengthened. The only other service requirements include infrequent washing of the exit window. Since most of the measurements depend upon ratios of the Raman scatter signals, then the results are independent of any changes in the transmitter and receiver optical performance as long as useful signal levels are still obtained. Degraded signals will primarily lead to increases in the magnitude of the calculated error applied to and displayed with the result, not to an erroneous result.

Technique: Applications of Raman lidar at optical wavelengths provide unique signatures for each molecular species, and information on the temperature of the gas. The ratio of the Raman scatter signals of water vapor and nitrogen directly measure the water vapor concentration. [Balsiger et.al., 1996] The ratios of rotational Raman scatter signals provide a direct measure of the temperature, because the rotational state distributions are established by the velocity of the molecular collisions. [Haris, 1995] A major advantage of the Raman lidar technique is due to the fact that most of the potential measurement errors are canceled by taking the ratio. The Advanced Lidar Atmospheric Profile Sensor (ALAPS) will provide profiles of the following atmospheric properties:

(a) water vapor (specific humidity) - The water vapor time sequence is the most valuable parameter for determining RF refractivity, optical propagation, cloud formation, and weather forecasts.

(b) temperature - The gradients in the temperature profile determine heat transfer, stability, and inversion conditions through the atmospheric layers. The temperature profile provides a direct measure of the density profile of the molecules when combined with a surface pressure measurement and the hydrostatic equation. Temperature profiles combined with the water vapor (specific humidity) profiles are used to provide the relative humidity profiles.

(c) optical extinction - The extinction profile of the atmosphere is directly determined from the slope of the molecular profiles of the lower atmosphere. Measurements of extinction at two different wavelengths can be used to infer changes in size of aerosol particles and estimate optical transmission at other wavelengths.

(d) optical backscatter - The direct backscatter measurements provide profiles of aerosol distribution, cloud ceiling height, and ranging to a distant target.

(e) RF refraction - The refraction effects at radar and radio wavelengths depend mostly upon the moisture gradients because of the large electric dipole moment of the water molecule, and the fact that water vapor phase state changes lead to strong density gradients in the lower atmosphere. The refractivity profile is directly calculated from the profiles of water vapor and temperature. The refraction data can be used to analyze the radar propagation characteristics and radio communications links in realtime. [Philbrick et.al. 1995]

(f) electro-optical conditions - The measurements are used to determine visibility on horizontal and vertical paths from extinction coefficients, ceiling from backscatter measurements, development of clouds from sub-visual aerosol scattering and relative humidity, optical mirage conditions from temperature gradients, rate of change in the environment conditions to forecast near term conditions, and transmission characteristics for the full optical spectrum based on extinction measurements at multiple wavelengths.

(g) evaporative duct measurements - Using a 15-meter range-gated profile at an angle of 1-2 degrees below and above horizontal yields a height resolution of 25 to 50 cm for water vapor and temperature above the ocean surface, thereby defining the evaporative duct properties.

(h) wind profile measurements - The direct detection Doppler wind technique has been recently demonstrated by NASA researchers. This technique could be used together with the Raman lidar measurements to simultaneously obtain a wind profile.

(i) detection of Chem-Bio clouds - The scattering properties, distribution of scatterers and the fluorescence of Chem-Bio materials can be used to detect, and then discriminate agent clouds. Recently conducted fluorescence studies use the same 355 nm wavelength that is planned for the ALAPS measurements. The addition of a detector for the fluorescence measurement would be a straightforward addition to implement.

The measurements planned for the ALAPS sensor are listed in Table 4 and the parameters determined are described above. The detector channels will be photon counting photomultipliers with 1 GHz count rate capability. The operating range gate resolution can be selected, however it is expected that a 100-nsec gate providing 15 meter range resolution will be preferred. A single channel high-speed detector unit has been fabricated and tested to demonstrate current component technology that can be used to obtain 3 meter range resolution. Investigations of the significant features of the atmosphere do not appear to justify such high spatial resolution. The useful time resolution for most data products is one minute or longer, but the data will probably be processed with one-second resolution with a data tag for angle of the local nadir. One or more channels could be used for target ranging with an analogue detector having a range resolution better than 1 meter. Most of the data collection will be done with the instrument pointed in the vertical direction, but the horizontal data will be most important for defining the evaporation duct and describing approaching conditions. By using a scanning mirror with a tilt of 45 ± 5^{o} relative to horizontal (see Figure 2), the operator can make measurements of the evaporative duct and horizontal conditions for atmospheric parameters, such as horizontal visibility.

Table 4. Measurements made by the ALAPS lidar instrument

Property	**Measurement**	**Altitude**	**Time Resolution**
Water Vapor	407/387 H_2O/N_2 Raman	Surface to 10 km	1 min. with 5 min filter
Temperature	351/354 Rot. Raman	Surface to 10 km	5 min with 30 min filter
Optical Extinction at 354 nm	354 nm Rot. Raman	Surface to 10 km	1 min with 5 min filter
Optical Extinction at 387 nm	387 nm N_2 - 1st Stokes	Surface to 10 km	1 min with 5 min filter
Backscatter at 355 nm	355 nm Rayleigh/Mie	Surface to 10 km	1 min with 5 min filter
Fluorescence at 360 nm	Bio-fluorescence	Surface to 5 km	1 min with 5 min filter

<u>Expected ALAPS Performance</u> - The ALAPS instrument is expected to be operated by a desktop or laptop computer at the ship's weather office where the data products can be distributed automatically as needed. The operation of the sensor can be programmed to provide data profiles according to a selected program of continuous measurements or at a less frequent rate. The data will be processed automatically as final results and provided to the operator display in realtime, and can be distributed to any other locations on the ship, as well as to other elements of the deployed strike force. The primary data interface will be used for setting the operating protocol for display/storage of the data. The program for preprocessing the data signals into data packets will reside in the sensor and the data processing/display software programs will reside on the operator's computer. The sensor is planned to operate in a fully automatic mode selected by the operator. A self-calibration mode for the instrument should be selected by the operator every few days to permit a verification of the instrument performance. The self-calibration mode is expected to be a sequence of automated switching of filters and detectors in the several channels to verify the measured signal ratios, and it should take no longer than 5 minutes to complete. In addition to obtaining vertical profiles, the ALAPS instrument will have a mode with the capability of horizontal pointing with very high vertical resolution, based on using a mirror pointing 1-2 degrees below and above horizontal (with each measurement referenced to and angle relative to the local gravity nadir). The vertical resolution of the water vapor and temperature profiles between the surface and 500 meters will be about 20 cm. Figure 3(a) shows a concept diagram for the ALAPS sensor, which is approximately one-third of the size of the LAPS instrument. Figure 3(b) is a picture of the LAPS prototype operating of the USNS Sumner in the Gulf of Mexico in 1996.

An example of the water vapor measurements obtained with the PSU LAMP lidar, which was a research instrument that was used to demonstrate the measurements planned for the LAPS prototype, are shown on Figure 4. The profiles shown were obtained at Point Mugu in 1993. A simultaneously released MRS balloon sonde is compared with the lidar data, and with the 100% RH profile based upon the measured temperature profile. Figure 5(a) shows an example of more than eight hours of one-minute updated profiles of LAPS lidar measurements of the water vapor distribution measurements during the SCOS97 ozone study in Hisperia CA. On the day of the measurements shown in Figure 5(a), an instrumented aircraft ascended and descended while circling the location of the lidar beam at a distance of only a few hundred meters, and the comparison of the measurements from the aircraft sensors made by Prof. John Carroll of University of California - Davis with the LAPS data is plotted. A balloon sonde was also released from the site and ascends through an interesting feature in the atmosphere that was detected by the lidar. An inserted plot shows the balloon profile compared with lidar data taken a half-hour earlier. The result serves to show the kind of variations that occur in the lower atmosphere, and emphasizes the importance of continuous measurements compared with infrequent daily profiles. The results in Figure 5(b) were obtained during the Navy tests of the LAPS instrument on the USNS Sumner in 1996. The time sequence of the water vapor and temperature data of the LAPS lidar are combined to calculate the relative humidity and the RF-refractivity during a six-hour period on 11 October 1996 in the Gulf of Mexico.

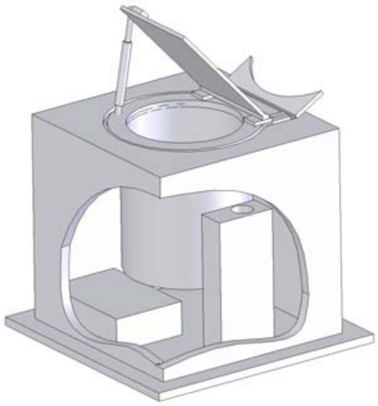

Figure 3(a). Sketch shows the planned one cubic meter ALAPS sensor with scan table and tilt mirror shown in position for measurements near the local horizon.

Figure 3(b). The LAPS prototype instrument deployed on the USNS Sumner during tests in August - October 1996.

Examples: The Raman lidar examples include a profile from the LAMP lidar at Point Mugu in 1993 and a time sequence of the LAPS measurements on the USNS Sumner in 1996.

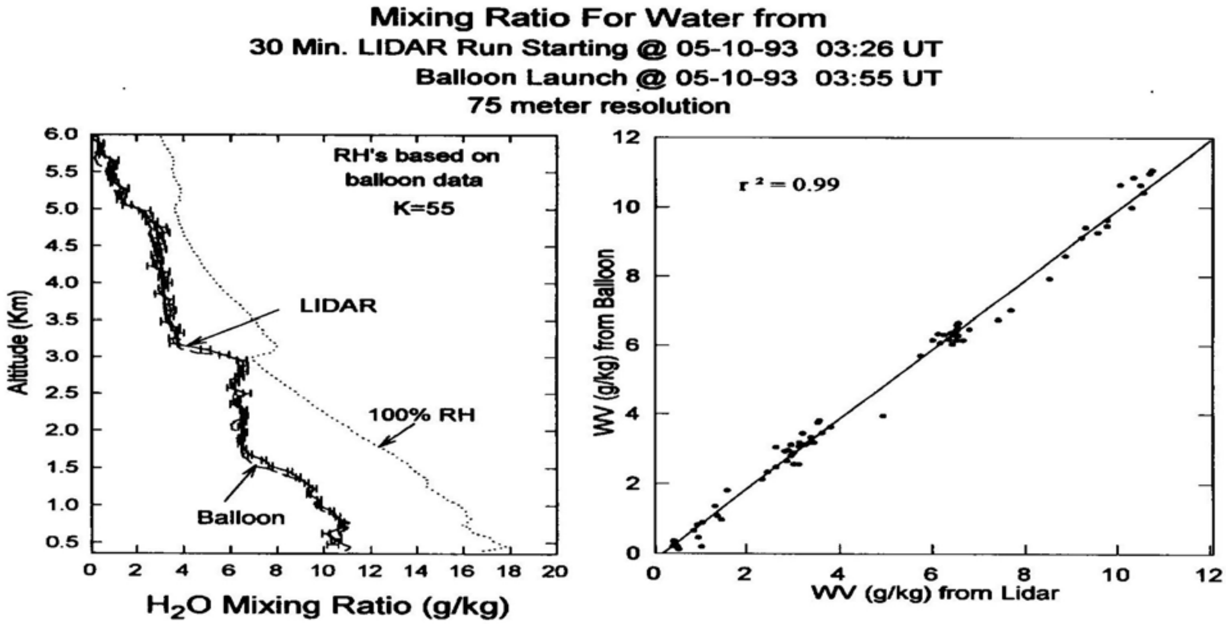

Figure 4. An example from the LAMP lidar (predecessor of the LAPS instrument) shows the comparison of a Raman lidar water vapor profile compared with a balloon sonde during tests conducted at Point Mugu in 1993. [Rajan et al., 1994]

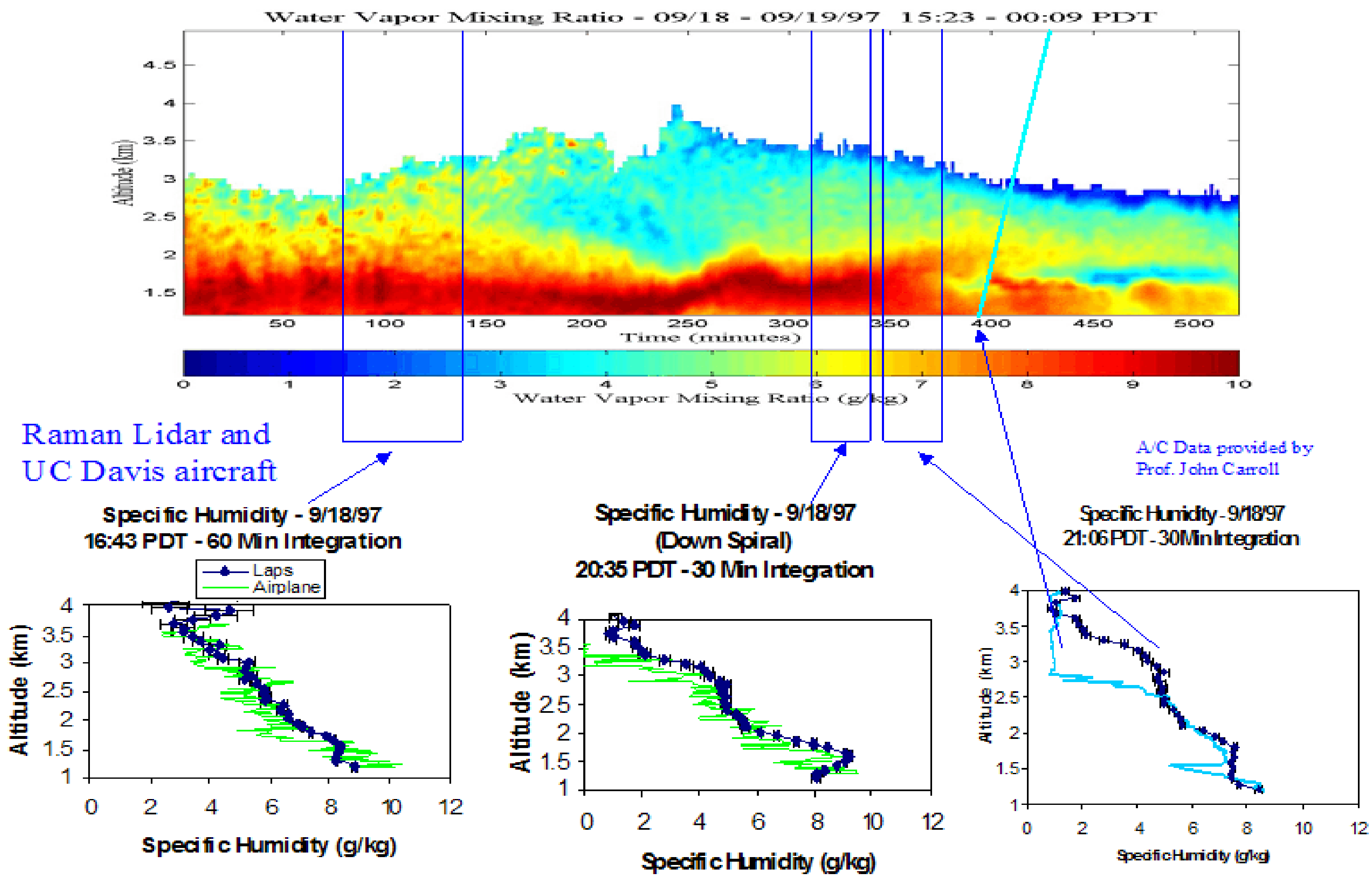

Figure 5(a). An eight-hour sequence of one minute updated profiles of the LAPS Raman lidar from the SCOS97 program show water vapor data compared with an instrumented aircraft that circled the beam and a MRS balloon sonde. Examination shows the advantage in continuously updated time sequences of profiles to understand the atmospheric variations, note the differences between the sonde and the lidar at 30 minute separation.

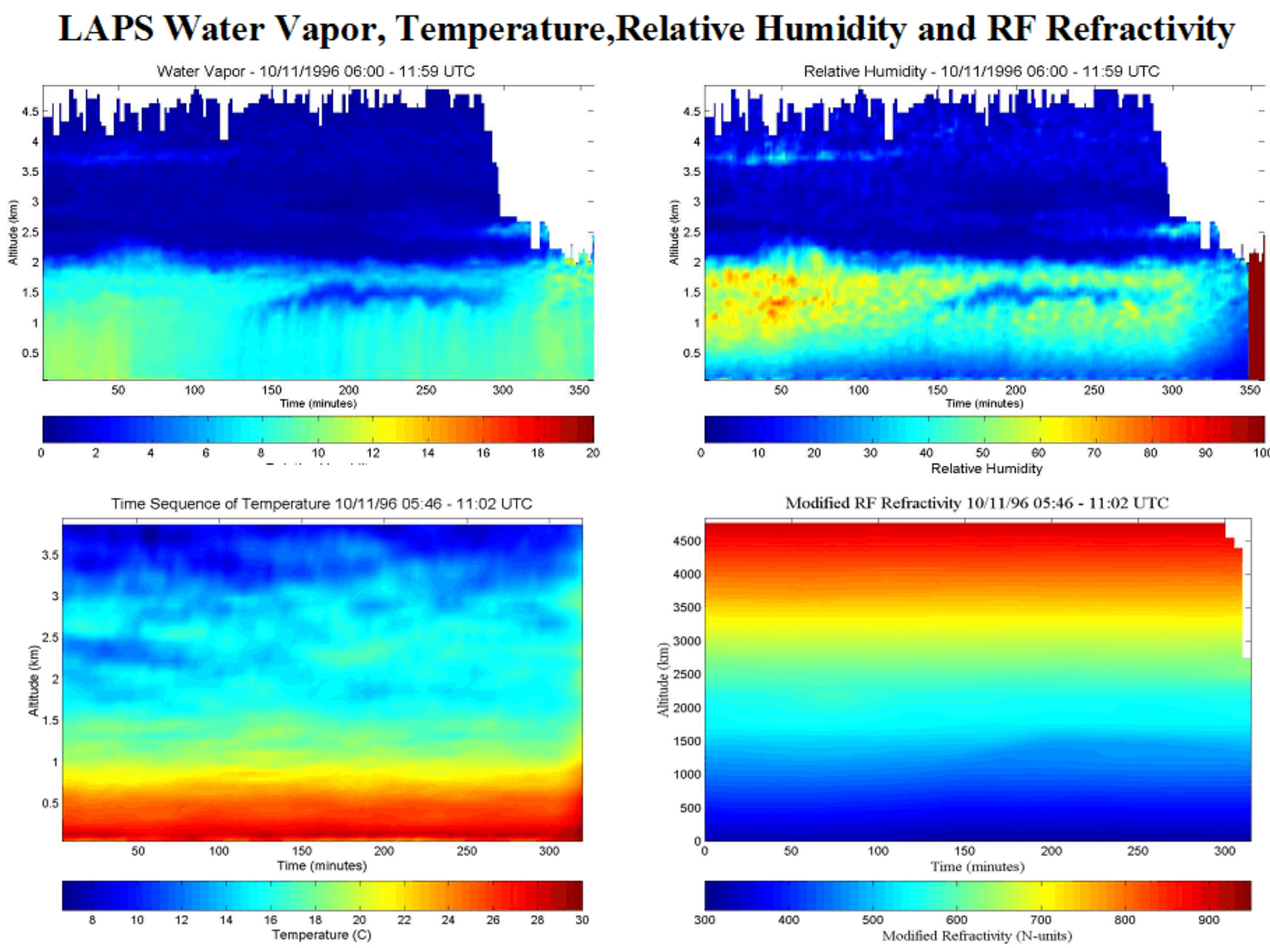

Figure 5(b). An example 6-hour plot of a LAPS lidar data set obtained onboard the USNS Sumner 11 October 1996 in the Gulf of Mexico. The measurements of water vapor and temperature were used to directly calculate the relative humidity and the modified RF-refractivity. [Philbrick, 2002]

<u>Lidar Capability for Defining the Evaporation Duct</u>

One of the special additional measurements that is possible with the ALAPS instrument is the direct measurement of the characteristics of the evaporation duct. Currently, the description of the radar refraction in the evaporation duct is obtained by using point sensors and IR-emission measurement of sea surface temperature. A better measurement can be routinely obtained by using the lidar at a small angle relative to horizontal to obtain measurements of water vapor and temperature with vertical resolution of about 20 cm from the surface to 200 m. These data could result in major improvements in our ability to describe the low angle radar refraction in the evaporation duct. Figure 3(a) indicates the configuration for the use of the ALAPS instrument in the horizontal measuring mode. The mirror shown on the top of the instrument would be in the configuration as shown for horizontal measurements or will be stowed into the cabinet for vertical profiling. The mode of operation will be selected by the weather officer or controlled by an automatic operation sequence selected for that period.

The evaporation duct has proven to be a difficult problem for radar propagation in both littoral and open ocean environments. To describe the radar beam propagation the evaporation duct must be located and quantified. The two key elements defining an evaporation duct are the temperature and relative humidity, and their respective gradients. Today these measurements are made at the surface of the water and then at another height on the deck of a ship, these two points are then used in a curve fitting technique based on the Monin-Obukhov similarity theorem. This technique is used to infer the gradients in both moisture content and temperature; however, a more accurate representation would be obtained with continuous vertical profiles of the parameters.

To accurately describe the evaporation duct it is necessary to have high spatial resolution measurements of water vapor and temperature as well as high temporal resolution. By maintaining these measurements continuously it is possible to see and track changes in the marine surface layer, thereby describing the development and evolution of the evaporation duct. [Mabey, 2002] Until recently it has not been possible to measure water vapor and temperature profiles with high enough accuracy and resolution above the ocean surface. The Raman lidar is able to make these measurements with high accuracy, high resolution and on a mostly continuous time scale. This is a significant step forward compared with inference from point measurements as well as balloon sondes. Sondes that are launched from the deck of a ship are also non-covert, giving away the position of a ship as it floats upward. By using lidar, the ship's position is no longer compromised while measuring the surrounding atmosphere. A major advantage in using lidar to covertly measure the temperature and water vapor profiles is that the refractive profile can be calculated continuously and provided for radar system analysis. Furthermore by continuously monitoring the lower atmosphere, the effect of any intermittent turbulent cells can be observed and averaged to avoid any large error due to a single measurement that could be obtained with an individual balloon profile. Direct measurements in lieu of utilizing models will also remove errors due to modeling assumptions and will show variations of the required parameters.

Relation to Tasks: The ALAPS instrument will do an excellent job of providing data that answers all 10 of the tasks outlined in Section 3. The only parameter that the lidar is not presently capable of providing is the wind velocity. Direct detection of the Doppler velocity of the atmospheric molecules could be considered in a next generation system that combines the Raman measurements described previously and simultaneous wind measurements. Another lidar approach for the wind measurements is an infrared coherent Doppler detection lidar as an independent system. The coherent detection lidar technology is well advanced, however, because of its expense and technical sophistication that technology was not considered in this study. The SODAR technique is discussed later as the best current option for meeting the current Navy requirements for wind measurements.

Relation to MOP and MOE:

Advantages: The Raman lidar provides the best approach for direct measurements of the profiles of molecular species. The Raman lidar techniques for water vapor and temperature profile measurements use the ratio of signals at two wavelengths and thereby eliminate most of the potential errors in the measurement. The Raman lidar is now regarded as the standard technique for profiling water vapor in the lower atmosphere. The Raman lidar technique has been pioneered in the US by groups at NASA Goddard and Penn State University (AF Cambridge Research Labs prior to 1987). In addition to the water vapor and temperature profiles, there are many atmospheric properties that are simultaneously measured. Recent advances in fast electronics have been used to demonstrate a range resolution of 3-meters is possible using photon counting technique. Advances in filter and detector technologies provide an opportunity to measure profiles of the atmosphere every minute. Time sequences of the profiles, such as those shown in Figure 5, provide the best opportunity to observe changes in the atmosphere. No special requirements exist for support of the instrument which will be controlled according to the operating mode selection by the weather officer. The expected costs for the lidar instruments would be quickly amortized by the costs of expendables and manpower.

Limitations: There will be a small fraction of time that heavy overcast conditions will limit the ability of lidar to obtain a full data profile, only up to the cloud or on a horizontal path below the heavy overcast. Only small breaks in the clouds are necessary to obtain a profile. Profiles were available approximately 95% of the time during the LAPS tests on the USNS Sumner, and measurements are always possible below the ceiling. A summary of the global cloudiness that shows some locations and seasons are much poorer is given in Section 2 of this report.

The laser beam will be eye-safe outside of the instrument, however if the instrument cover is removed, high-power laser beams that are not eye-safe and hazardous high voltages can be accessed. Safety interlocks will be included to interrupt laser operation when the cover is removed. One concern for the instrument operation is the case in which the telescope optical axis would point within a few degrees of the sun-line. This condition could be a problem when operating at equatorial latitudes near local noon, or accidently pointing at the sun on the horizon near sunrise or sunset. An automated interrupt mode will be included to avoid the possibility of damage by focusing the sun on a surface or into the detector by the primary telescope. It is expected that the permanent installation on Capital ships will use the chilled water line to provide the instrument heat removal, and that the transportable units will carry an additional 20-inch cube unit containing a chiller and pump for instrument environment control. In addition, the remote deployment by the Marine Corps will include an auxiliary power generator.

One of the cautions with regard to service and lifetime for systems employing high power optical beams is that the inner surfaces, prior to beam expansion, must be kept very clean. Small dust particles on optical coatings will cause anomalous surface heating and damage the optical coatings used for anti-reflection and reflection in the beam path. As a precaution, the deployed unit will be designed to be hermetically sealed and will use filters to remove dust particles from the internal environment.

The flash-lamp pumped laser is recommended for the first generation instruments because of the expense of laser diodes and their poor reliability in high power laser operations. The operation of a flash-lamp laser does require some care in the service and maintenance. The flash-lamp lifetime can be extended by operation slightly below the nominal lamp power rating and lifetimes of $> 2\text{x}10^8$ shots (~4 months of operation at 20 Hz) have been obtained. A shipboard technician should change the flash-lamps after two months of continuous operation (about 3 hours of work and $500 in parts).

Readiness Level for Use: The LAPS instrument was built and tested in 1996 and some progress has been made toward an operational instrument since that time – in particular, new high speed electronics components were used to demonstrate 3 m range resolution and the concept was developed for self calibrations of the detectors. Approximately 18 months would be necessary to complete the design, fabrication, and testing of the engineering prototype ALAPS instrument. Probably the earliest date that multiple instruments (8 to12) could be ready to install is about 30 months after program commitment. R&D activities that would support the program development during the near term could include:

(1) demonstration of the self calibration mode using modifications to the LAPS instrument.
(2) demonstration of evaporation duct measurements using modifications to the LAPS instrument – testing could be carried out in conjunction with the Navy's radar test facility at Wallops Island VA.
(3) R&D activity to develop the direct detection Doppler wind lidar.

Risk Analysis of the Sensor to Perform and Achieve Expected Results: The technologies that are used in the ALAPS instrument do not encumber any significant risk. The most difficult problems are associated with the careful engineering design that will be needed. All of the measuring techniques have been demonstrated, and the recent advances in detectors, electronics, optical filters and lasers have been followed closely so these will be used to full advantage in the instrument design.

Measures of Performance (MOP):

Latency:

The ALAPS Raman Lidar will measure continuous profiles of water vapor concentration, temperature, optical extinction, and optical backscatter. The measurements will be used to directly calculate profiles of RF-refraction, relative humidity, visibility, and cloud ceiling. The profiles will be calculated each minute and time sequences can be filtered and displayed as selected by the weather officer. The data products in final engineering units, and with calculated error bars, will be continuously available in real-time for local display, for use by local systems and models, and available for transmission to other assets deployed in the area, as well as to the Navy centers for assimilation into the NOGAPS model predictions.

Accuracy of Data Product:

The measurements of the Raman lidar are quite accurate because the scattering cross-sections are known to about 0.5% based upon laboratory studies. The error is primarily due to the signal strength at the time of measurement and it is described using Poisson statistics, which are associated with photon counting. All of the data products include an associated error, which can be reduced in proportion to the square-root of the integration time interval and the selected range resolution.

Time Resolution:

The ALAPS lidar will be capable of continuous measurements, and the profile calculations can be carried out with a time resolution selected by the weather officer. Most likely, the time resolution for profiles will be set to an interval between 1 and 5 minutes. Time resolutions of a few minutes appear to provide an opportunity to observe all of the significant variations in the lower atmosphere. The profiles obtained over the period of an hour would probably be combined to provide an update for assimilation by the modeling activities, however the shipboard analysis of radar performance or visibility analysis may require data products updated as often as once per minute. The data products will be processed in real time and can be disseminated to several different activities simultaneously.

Spatial Resolution:

Considering the scenario of the littoral area leads to the idea that if three or four instruments could be deployed within a region of a few hundred kilometers, then information on the changing conditions of the region could be ideally represented. The key to have communications for transferring the required data products within the strike force and relay data to the NOGAPS forecast center. Better data products supplied to the centers running the models will result in great improvements in the boundary conditions used to generate the local models. The ALAPS instrument will have the capability to examine the atmosphere horizontally to ranges beyond 10 km. The instrument should be able to examine the local spatial structure over a range of azimuths greater than 180 degrees (depending upon shipboard location).

Vertical Resolution:

The range resolution can be selected by the operator. The LAPS instrument was limited to 500 ns range bins (75 m) because of the electronics available in 1994 when that instrument was designed. Since that time, advanced components have been used to demonstrate 1 GHz photon counting with range bins of 3 meters. It is expected that the minimum useful resolution is about 15 meters (100 ns) to capture information for high resolution applications. The ability to profile 1-2^{o} below and above horizontal will result in vertical resolution of 10 to 50 cm from the ocean surface to 200 meters. The high vertical resolution data in this region will permit direct measurement of the characteristics of the evaporation duct and will greatly improve the description of this important feature.

Real Time Data:

The data products and their error assignments are available in real-time.

Validity of Inferred Data Parameter:

The measurements of the Raman lidar provide robust data products on the profiles of the atmospheric properties.

Nowcast Capabilities:

The data products of the ALAPS Raman lidar are ideally suited for Nowcast of the atmospheric conditions.

Measures of Effectiveness (MOE):

Timeliness:

The profile update rate can be selected, but realtime profiles at a selected interval of 1 to 5 minutes should be sufficient for most applications.

Consequences of Uncertainty in Conditions:

The uncertainty in the ALAPS measurements is primarily due to the statistical error in the measured signal.

Representativeness of Data:

Each of the data points in the profile of each of the measured parameters are unique for that defined altitude and time. The range location or altitude of the measured point is known precisely (within about a meter) from the circuit stability and the speed of light. The display of the time sequence of the data shows the weather officer immediate changes in the meteorological, EM and EO parameters.

Ease of Use of Sensor:

The ALAPS instrument should be available continuously with updated measurements of atmospheric properties. The operator controls the operation cycle, data display type, and data distribution with a set of commands from a display panel. The only requirement for user intervention would be an occasional wipe (perhaps daily) of the exit window.

Resources Expended:

The fabrication of multiple instruments in quantities of 10 or more should be possible for less that $500K each. The annual maintenance for an instrument is estimated at $15K. Development and testing for an engineering prototype are expected to cost about $5M. The installation onboard a Navy ship was estimated at $20K on Force Level ships and $60K on other ships if any relocation of hardware is necessary [report prepared in 2000 by URS Corporation].

Continuity of the Data:

Data from the instrument can be obtained continuously during a ship deployment. A down time of about 3 hours on about two month intervals should be planned to inspect the optical path and replace laser flash-lamps. The measurements will be limited by heavy clouds and fog. In Section 2 of this report, a description of the global/seasonal distribution of clouds is presented.

AoA: Ground-based Microwave Radiometric Profiler (MWRP)

Identification of Sensor: **MWRP**

Hardware: The Radiometrics MP3000 is a good candidate for a microwave radiometer designed to retrieve temperature, humidity and cloud profiles in the lower troposphere, see Figure 6. The system includes sensors for atmospheric pressure, temperature and humidity, a rain sensor, as well as an infrared radiometer (Heimann KT19.85) to measure the cloud base temperature.

Figure 6. The Radiometrics MP3000 microwave radiometer is shown. [www.radiometrics.com]

Technique: The radiometric profiler observes radiation intensity at 12 frequencies in a region of the microwave spectrum that is dominated by atmospheric water vapor, cloud liquid water, and molecular oxygen emissions. Microwave observation channels centered at 22.035, 22.235, 23.835, 26.235, 30.0, 51.25, 52.28, 53.85, 54.94, 56.66, 57.29, and 58.8 GHz were chosen by eigenvalue analysis to optimize profile retrieval accuracy. The bandwidth for each channel is 300 MHz. The radiometer observes with a 2 to 3 degree beamwidth at 51-59 GHz and with a 5 to 6 degree beamwidth at 22-30 GHz. Errors resulting from beamwidth differences are insignificant for temperature and humidity retrievals but may slightly degrade the accuracy of liquid water retrievals in the presence of variable low clouds. No attempt has been made to correct this error. The radiometric profiler includes a zenith infrared sensor with 5 degree beamwidth, surface temperature, humidity and pressure sensors, and a liquid water detector (rain flag) on top of the radiometer housing. The infrared sensor provides cloud base temperature measurements that are combined in the radiometer software with retrieved temperature profiles to obtain estimates of cloud base height. The infrared and surface meteorological measurements are used in the neural network retrieval algorithm. The radiometer is portable, with 50 x 28 x 76 cm dimensions and 32 kg weight. The radiometric profiler observation cycle interval can be as short as 10 seconds. The 22-30 GHz channels are calibrated by automated tipping procedures. The accuracy of a 22.8 and 31.4 GHz radiometer with similar design to the radiometric profiler and calibrated by tipping was demonstrated as 0.3 K RMS for the microwave radiometric brightness temperature by comparison with forward modeled radiosonde observations. The 51-59 GHz radiometric profiler channels are calibrated to 0.5 K RMS using a liquid nitrogen target. Neural network methods based on historical radiosondes from co-located or regional sites are used for profile retrieval; neural network training is effective if it is based on radiosonde records from sites located in the same climatological region as the observation site. Forward radiative transfer modeling for clear skies and for cloudy conditions of several years or more of 2 or 4 per day radiosonde soundings are used in a standard back propagation neural network training algorithm. The surface pressure input allows the neural network algorithm to adjust for differences in radiosonde and observation site altitudes. Cloud top height was determined from an algorithm using a threshold option based on the retrieved relative humidity profile. The algorithm also set the retrieved liquid water density equal to zero below cloud base and above cloud top.

Example: An example of temperature, humidity and liquid water profiles retrieved by neural network from radiometer observations is shown in Figure 7.

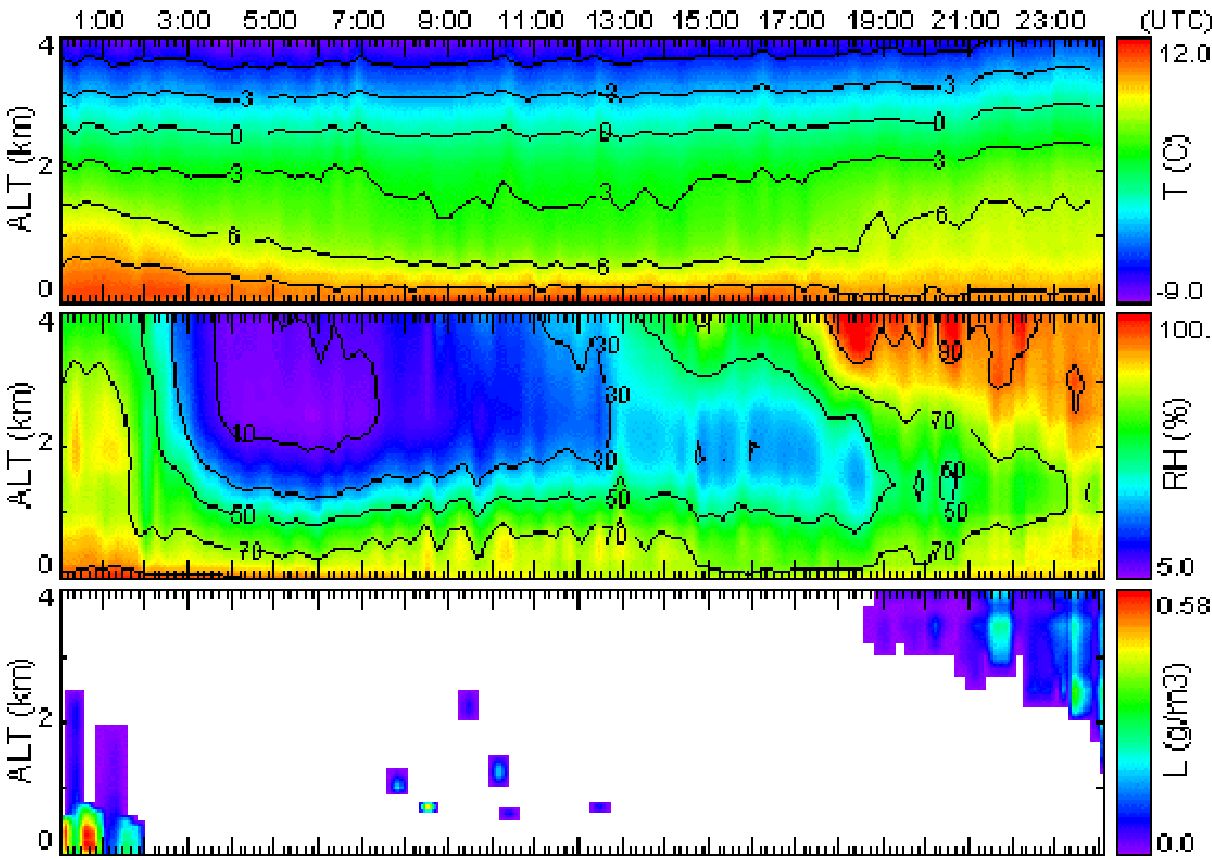

Figure 7. Data from Camborne 25/4/02 between passage of Cold Front (00:00) and Warm Front (02:00 following day) are shown from a Radiometrics MP3000 microwave radiometer.

Relation to Tasks: The MWRP can be used to provide vertical profiles for assimilation into NOGAPS (Task 7) and COAMPS (Task 8), and to provide information on weather-related hazards (Task 10).

Relation to MOP and MOE:

<u>Advantages</u>: The MWRP has several capabilities that make it worthy of consideration as a sensor alternative. The main advantages of the MWRP are:

(1) No transmitting signal to reveal the ship location (covert operation).

(2) A high sampling rate will yield vertical profilers as frequent as 1/20 second (0.05 sampling frequency)

(3) MWRP can adequately resolve dynamic weather conditions such as approaching fronts, squalls, density currents, and moist or dry intrusions.

(4) Radiometric profiler errors are in line with assimilated radiosonde profiler errors.
(5) Relatively inexpensive ($250K)
(6) Ready for deployment

Limitations: The MWRP can be a very useful instrument for resolutions on the order of those in models such as COAMPS. However, the instrument is limited because of its inability to resolve detailed structure in the marine boundary layer and through the troposphere. In summary, the limitations of the MWRP are:

(1) Uncertainties and biases are on the order of model errors and will not resolve detailed structure.

(2) Requires the use of the standard atmosphere reference (climatology) for its retrievals, this is a major concern for this sensor's viability on shipboard platforms deployed worldwide.

(3) Vertical spatial resolution (100 m < 1 km; 250 m > 1 km) will not sufficiently resolve the evaporation ducts and other RF/EM/EO effects, or the detailed marine boundary layer structure, especially under stably stratified conditions. This system will not provide the detail between the surface and 1 km where most of the boundary layer structure and RF ducting problems are confined. The radiometer measures an integrated brightness and will not yield a unique profile of the atmosphere, but it does an important job in constraining model solutions.

(4) Retrieval errors are based on stationary testing over land with in-situ co-temporal radiosondes. No data is available comparing radiosondes and the radiometric profiler on a platform moving long distances over water. Neural network methods based on historical radiosondes from collocated or regional sites were used for profile retrieval for the examples presented. In general, neural network training is effective if it is based on radiosonde records from sites located in the same climatological region as the observation site. If the radiometer and radiosonde sites are co-located or if data are available from regional radiosondes from sites with altitudes spanning the observation site altitude, then a neural network training can be utilized. This approach allows accurate retrievals for radiometer site altitudes within the radiosonde site altitude interval. Even when detailed climatology data are available, the dependance upon climatology for analysis within an actual battlespace environment is likely to result in serious errors.

(5) It is uncertain whether data from a network of radiometric profilers deployed on ships, when used as input to a high resolution numerical model (COAMPS), will result in any demonstrated improvement in forecasts. Caution should be exercised in "buying into" a system that can only do as good as the "assimilated" radiosonde profiles used for model initializations. It would be valuable to run COAMPS initialized with only the buoy data and the NOGAPS initialization fields to quantify the value added by assimilated radiometric profiles. This would provide an assessment of what could be anticipated from a network of radiometric profilers that exhibit errors similar to the assimilated data.

(6) Timeliness of the retrieved data is also a concern, as it is necessary to assimilate the retrieved brightness temperatures directly into the COAMPS model (W. McKeown, 18 May 2005). This would require transmitting the data back to the Navy computational center where analysis would take place and then have the results

sent back to the ship. This communications requirement could be even more restrictive for the Marine Corps deployments.
(7) "Radiometers are mainly used in non-precipitating conditions because the radiometer measurements become less accurate in the presence of a water film on the outer housing (radome). Recently there is some progress in applying rain-effect mitigation methods to the radiometer, such as a hydrophobic radome and forced airflow over the radome surface. As a result, reasonably accurate thermodynamic profiles are obtained in a rainfall rate up to 15mm/hour. However, this rainfall rate is still much lower than that observed in typical heavy rain episodes in the subtropical areas, which normally reaches at least 30mm/hour." [Chan et. al.]
(8) Some redesign issues exist because of concerns about salt water corrosion of the instrument (private communications, W. McKeown 18 May 2005)

Readiness Level for Use: Microwave radiometers are commercially available from vendors in the US and Europe, and could be ready for deployment with minimal expense and effort. The commercially available MWRP will have to undergo significant R&D before it can be deployed as an operational system. This R&D effort must consider two important issues 1) the MWRP requires a suitable data base of upper air measurements in order to derive robust and reliable algorithms before vertical profiles are realized; 2) the MWRP may require a gimbaled mounting platform to maintain the angle of the local horizon, however the manufacturer now indicates that the instrument can be operated by using the ship's roll and pitch information; 3) Ruggedization and finding a suitable surface treatment must also occur in order for the MWRP to be ready for use in the corrosive ocean environment.

Risk Analysis of the Sensor to Perform and Achieve Expected Results: The sensor is expected to be quite effective in constraining the COAMPS model and providing useful input for model updates. The microwave radiometer is able to provide a long term continuous monitoring of the integrated microwave emission. However, the MWRP does not have the capability to resolve detailed atmospheric structure of the lower troposphere, and therefore is not an instrument that is capable of locating and characterizing evaporation ducts and elevated ducts, or measuring EM/EO properties. It provides no information of the optical properties of the lower atmosphere.

Measures of Performance (MOP):

Latency:

The Radiometrics Inc. ground-based microwave radiometric profiler is capable of 1) retrieving temperature and relative humidity profiles to an altitude of 10 km, 2) one-layer cloud liquid sampling, 3) cloud base temperature and approximate height, 4) integrated water vapor, and 5) integrated liquid water, with an observation cycle interval as short as 10 seconds. However, as noted above the measurements obtained are the integrated microwave emissions at several wavelengths and elevation angles. The integrated brightness temperatures retrieved from the radiometer must be assimilated into the models in order to retrieve a profile of a property that matches the measured microwave emission. This requires the time to send the data to the COAMPS computational center and return the representative profile.

Accuracy of Data Product:

Radiometric profiler retrieval accuracy can be estimated by comparison with radiosonde soundings. However, the comparison is approximate due to spatial and temporal sampling differences, as well as atmospheric variability. Spatial differences occur because a radiosonde launched at a radiometer site often ascends outside of the radiometer field of view. In addition, sampling differences between radiosonde point measurements and radiometer volumetric measurements can be significant. When comparing the data retrieved from a radiometric microwave profiler to assimilated radiosonde data (i.e., radiosonde point measurements with "representativeness" errors added by NOAA prior to assimilation into models), the radiometric statistical errors in temperature and humidity are less than the assimilated radiosonde errors in the boundary layer. Above the boundary layer, the radiosonde error is about 50% smaller for temperature than the radiometric error, but humidity error from assimilated radiosonde data remains larger than the radiometric error throughout the atmospheric column. Thus, the retrievals from the ground radiometric microwave profiler are smaller than the assimilated radiosonde profiles, except for temperature above the boundary layer, where the errors are on the order of 0.5-0.8^{o}K for the neural network retrievals and 0.3-0.5^{o}K for the radiometric regression with historical radiosonde profiles. Continuous radiometric retrievals can provide a major improvement in the time resolution of the lower atmosphere air measurements compared to radiosonde soundings with 12 hr resolution. Improvements in atmospheric models are gradually improving neural network retrieval accuracy. Many recent studies and evaluations show the accuracy and the limitations of the microwave technique, but several studies have been conducted by the British Meteorological Office.

Time Resolution:

Twice-per-day balloon soundings at 00 and 12 UTC are not sufficient to resolve rapidly evolving atmospheric conditions in the littoral area. The MWRP cycles through an observation in approximately 10 seconds, and provides a profile of the atmosphere to about 10 km as frequently as every 10 seconds.

Spatial Resolution:

The retrieval algorithms used in the MWRP system are based on climatology of the locality which has been developed by prior studies using rawinsondes. As such, the derived profiles lack structural detail making a single profile representative of the approximate climatology conditions (not actual detailed conditions) in the littoral battlespace. While this is a disadvantage for resolving boundary layer and lower tropospheric structure, it has the advantage that a single instrument can provide a reasonable estimate of the bulk characteristics of an atmospheric column over a large spatial area (assuming that no weather activity or changes caused by smoke or munitions within the battle space have contaminated the assumed climatology profile characteristics). It is likely that a single instrument can provide a crude profile that is representative of the entire littoral area under many conditions. The vertical resolution of radiometric profiler microwave measurements can be characterized by weighting functions. The instrument uses algorithms that are designed to yield profiles that have a resolution that closely resembles assimilated radiosonde profiles and vertical layers in high resolution models such as COAMPS. Thus, the instrument is suitable for providing data sets that can be easily incorporated into COAMPS data assimilation systems. The vertical resolution is not sufficient to resolve the vertical gradients, inversions, and variability that can be important for locating evaporation ducts and isolating other EM/EO effects. The vertical resolution in retrieved temperature decreases in a roughly linear fashion from ~0.1 km at the surface to ~6 km at 8 km height and then remains at ~6 km to 10 km height. The vertical resolution of the retrieved water vapor density decreases in a roughly linear fashion from 300 m at the surface to 1.5 km at 6 km height and then to 3.5 km at 10 km height. Vertical resolution of ground-based radiometric retrievals can be substantially improved using satellite soundings. For example, when temperature and water vapor profiles from the GOES-8 satellite sounder were combined with radiometric retrievals using inverse covariance weighting, the vertical temperature resolution improved substantially to 1.6 km at 6 km height and 1.9 km at 10 km height, and vapor density vertical resolution improved marginally above 4 km height.

Real Time Data:

The MWRP can cycle through soundings once every 10 seconds to yield a vertical profile of temperature and relative humidity, single layer cloud liquid water content, cloud base height and temperature, integrated water vapor and integrated liquid water. This data is available in real time to shipboard observers and decision makers. Although the vertical resolution is poor (100 m < 1 km; 250 m > 1 km), the data can be used effectively in real time to determine the passage of fronts and other atmospheric discontinuities. The realtime data product is integrated microwave brightness temperature as a function of the angle. These data will be transmitted to the nearest location running the COAMPS model for processing, and the best fit vertical profiles will be returned to the ship in engineering units.

Validity of Inferred Data Parameter:

The key question related to the MWRP is that its ability to retrieve valid data parameters depends on the neural network algorithms obtained from a comparison with hundreds of soundings using the traditional rawinsonde system. Without this comparison, the schema developed by the neural network would have no statistical base, and confidence in the validity of the data would diminish. However, even if the profile information were totally discounted because of its strong dependence on climatology, the measurements of microwave brightness temperature still provide a useful test for the validity of the COAMPS and the NOGAPS models in that region.

Nowcast Capabilities:

Although the data is retrieved in realtime, it does not allow for any Nowcast capabilities. This is because the integrated brightness temperatures must be assimilated into a model in order to retrieve the regression algorithms best guess at the current atmospheric profile.

Measures of Effectiveness (MOE):

Timeliness:

The MWRP is an instrument with a high sampling frequency. A new data set can be retrieved every 20 seconds and distributed to the METOC crew for analysis and interpretation. The major time-consuming activity will be the transfer of the microwave brightness values to the center running COAMPS, processing the data and returning the result to the ship. Given an upgrade to the communication and messaging to modeling centers, this data can be distributed to and ingested into numerical weather models rapidly. Moreover, because the MWRP produces soundings with a resolution close to that of mesoscale models (COAMPS), and the data is not as noisy as rawinsondes, it can be ingested and assimilated more quickly into models.

Consequences of Uncertainty in Conditions:

The MWRP is a very useful instrument for producing model-compatible vertical profiles of the atmospheric conditions in real-time, similar to rawinsonde data <u>after</u> it has been assimilated for modeling purposes. Because it relies on neural networks that compare to climatology, the individual profile will only be as good as the neural network retrieval technique, and this relies on comparison with many rawinsonde sounding in proximity to the atmospheric condition being sampled. Thus, each sounding retrieved from the MWRP will have an inherent uncertainty that will limit its ability to provide details that are currently readily available using the MRS AN/UMQ-12A. In addition, the location and structure of the evaporation duct, and other EM/EO effects, will go largely unresolved by the MWRP, which will introduce large uncertainties in the RF field within the marine boundary layer. Moreover, the presence of sharp gradients within and above the marine boundary layer will go largely unresolved. Nevertheless, the MWRP can resolve in-situ trends, variability, and rapid changes due to propagating weather systems.

Representativeness of Data:

The MWRP will provide temperature profiles, relative humidity profiles, the approximate height of cloud base, and measurements of the integrated water vapor and liquid water that are representative of the bulk characteristics of the atmospheric column. The data will not be representative of the actual complex structures that are observed in marine boundary layers.

Ease of Use of Sensor:

The MWRP is a turnkey operation requiring virtually no assistance from the crew. It is self-calibrating and capable of extended usage in a wide range of weather conditions. Its data products should be readily available to METOC observers for analysis and interpretation.

Resources Expended:

A single MWRP can be procured from Radiometrics Inc for approximately $250K. It should be noted that this cost does not include installation, which has been estimated at $100k, for proper gimbal stabilization. A single MWRP should be sufficient to provide the bulk characteristics of the atmosphere for an entire littoral area, because the profile is based upon the course resolution of the climatology. Shipboard operation requires a small stabilization platform to mount the microwave sounder so that the instrument's measurement angle relative to the local horizon is preserved.

Continuity of the Data:

The data from the microwave radiometer should be available most of the time. The major loss of data is during periods when heavy rain on the surface of the instrument distorts the received signal.

<u>AoA: Phased-array Doppler SODAR</u>

Identification of Sensor: **SODAR**

Hardware: The antenna recommended in this proposal for Navy deployment is the REMTECH PA1 with a 0.65x0.65 meter footprint and a maximum altitude of 2000 meters (average altitude = 1300 meters). Larger versions are available with a larger footprint and increased maximum altitude, such as the model PA5 (1.8x1.8 meters) because its altitude range extends from 15 to 5000 meters AGL (average altitude = 3500 meters). The three dimensional monostatic Doppler SODAR system consists of one phased array, 52 element antenna and an electronic case. In the electronic case are the computer, transceiver, and power amplifier. Also, included are interconnecting cables and a small mount for the antenna. Specifications for the PA1 and PA5 are given in Table 5 and a picture is shown in Figure 8.

Figure 8. SODAR model PA5 (1.8x1.8 meter footprint) has a range 15 – 5000 meter (average altitude under typical conditions 3500 m); frequency 800 Hz, and model PA1 (0.65x0.65 meter footprint) has a range 15 – 2000 meters. (average altitude under typical conditions 1300 m); frequency

Phasing of the system transmit arrays permits full control of the antenna beams. Four of the electronically steered beams are tilted (30˚ or 15˚) from vertical and rotated 90˚ to measure the horizontal component of wind velocity. The last beam is pointed vertically and measures the vertical component of the wind. The system software controls the sequence and rate of operation for each beam. System parameters can be changed through operator input, along with averaging and sampling times, transmitting power, antenna orientation, range gates, and maximum range.

The SODAR employs a signal to noise detection and comparison technique that has been developed through many years of research. The system produces reliable data in a noisy environment with comparatively short data averaging times because of the discrete rejection of all spurious signals. Data which are, in fact, considered suspect, due to adverse ambient-noise, are deleted to prevent users from being misled by erroneous data. No additional data processing is required in order to achieve the system's full accuracy. Archived data can be directly processed to provide complete statistical data summaries and climatological analyses. System performance and maintenance are facilitated by special software diagnostic routines. If required, repair is accomplished by swapping the complete electronic case to reduce downtime.

Table 5. Specifications for PA 1 and PA5 REMTECH SODARs

Receiver gain	100 dB
Number of range gates*	Up to 300 (selectable)
Thickness of each gate*	10 to 200 meters, in 1 meter layer increments
Averaging period*	2 min (1min optional) to 1 hour
Receiver filter type	Sixth order Cauer
Initial processing	1024 frequency point FFT
Background noise correction	S/N ratio continuously measured and used for validation of data vs. background noise
Horizontal wind speed range	0 to 50 m/s for PA1 and PA5
Horizontal speed accuracy	0.2 m/sec or 3 % for wind speed > 6 m/s
Vertical speed range	- 4 to + 4 m/sec (± 12 m/s optional)
Vertical speed accuracy	5 cm/sec or better
Horizontal direction accuracy	3˚ or better for winds > 2 m/s.
Operating conditions	
Antenna: Temperature/ Humidity	-40˚ C to + 60˚ C /10-100%
Electronic case: Temp/ Humidity	5˚ C to 40˚ C / 20 to 80% non-condensing
Power consumption	
PA1	25 W w/o heat; 250 W w/heat
PA5	190 W w/o heat; 1150 W w/heat

* Parameters easily changed by key-in command.

Technique: Phased array Doppler SODAR can continuously and reliably measure wind speed and direction, vertical motions, turbulence, thermal structure, and mixing depth at heights ranging from 15 m up to 5,000 meters depending on the type of antenna. The nominal central operating frequency of 2250 Hz (PA1) and 800 Hz (PA5) provides high time resolution Doppler wind data throughout and above the boundary layer. The wind measurement is accomplished by emitting a strong acoustic pulse in the audio band and detecting the Doppler frequency shift of the received backscattered echo. The Doppler shift yields the radial velocity component and the time delay is integrated to find the range and altitude. This backscattered echo signal is due to thermal turbulence in the atmosphere. The signal frequency shift (Doppler shift) and its relative strength is processed in various ways to produce more information than was previously available through more conventional methods, such as instrumented towers, tethersondes, etc. An example of SODAR data products is shown below in Figure 9. For the mobile SODAR applications, the PA1 instrument would usually provide the required wind data, and the capital ships may consider the benefits from the installation of the PA5 instrument. A GPS position sensor or input from the ship instruments will provide the coordinate transformation information for converting the measurements of a moving ship to local wind velocity.

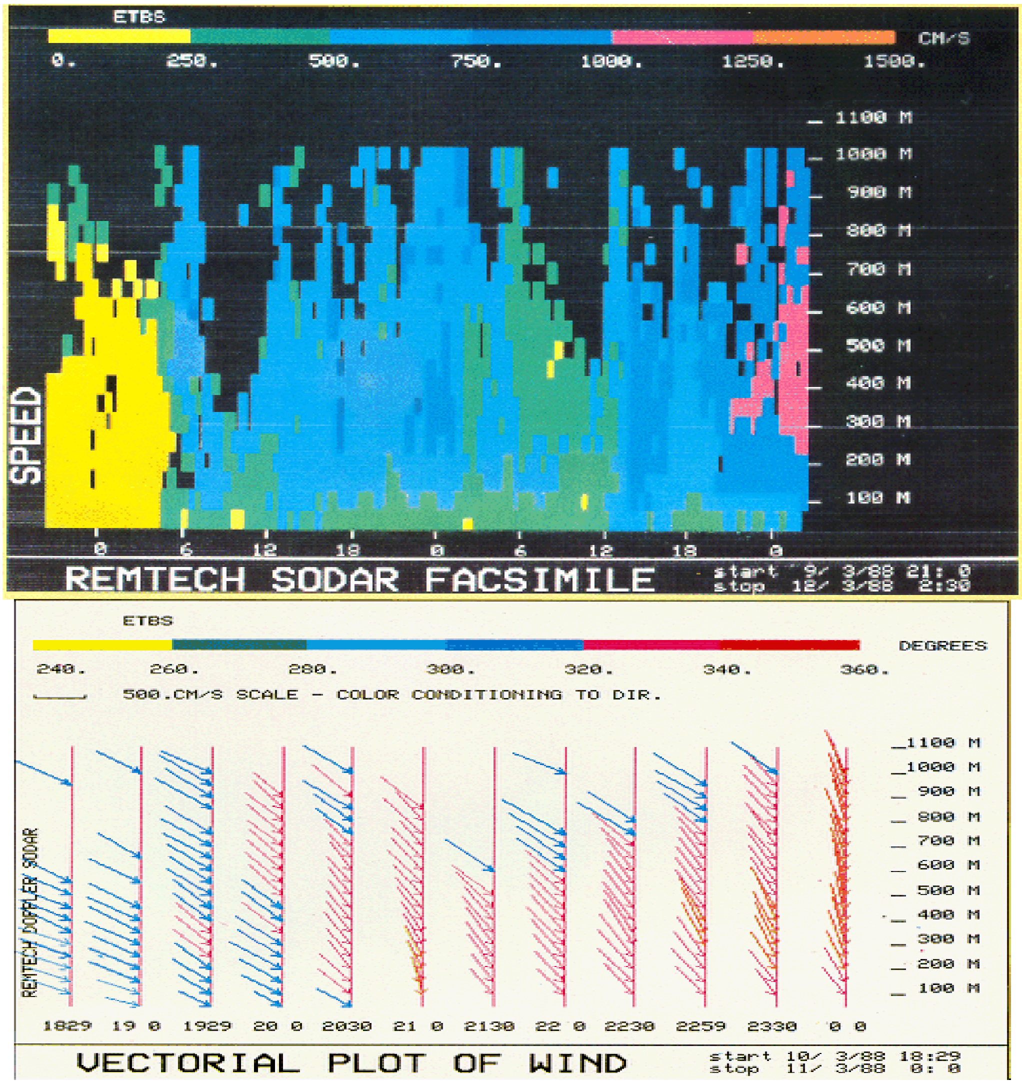

Figure 9. An example data product from the REMTECH SODAR acoustic sounder shows the wind speed and direction for a small PA1 sensor.

Relation to Tasks: The SODAR can be used to provide high resolution vertical profiles for real-time analysis of the winds from the surface to 5 km (depending on model selection) in the littoral region. The wind data is important in providing information on weather related hazards for aircraft and helicopter OPS and flights (Task 10), assimilation into NOGAPS (Task 7) and COAMPS (Task 8), and for quantifying the effects of atmospheric turbulence on the propagation of light and radio waves (part of Task 6).

The SODAR system is included in this AoA as a supplement to the next generation remote sensing Raman Lidar system (ALAPS) in order to gather wind data until the ALAPS has undergone R&D as part of the EDM, at which time the ALAPS will be able to assume the task of providing wind data in addition to the array of variables for which it is already capable. Currently, conventional meteorological variables and horizontal winds are obtained twice per day using the MRS. With the implementation of next-generation lidar systems, and until *sufficient R&D has taken place to derived winds from the lidar, there will be a period (~ 4 years) when shipboard wind profilers are needed to insure safe flight operations, and this can only be obtained with a separate and distinct wind profiling sensor system. Several systems were considered based upon their feasibility, utility, and appropriateness for shipboard operations. The SODAR appears to provide the greatest utility, smallest footprint, and best cost/benefit ratio for shipboard operations. Of the two SODARs described above, it is recommended that the NAVY consider the PA1 for the transportable systems because of its smaller footprint and lower cost, the PA5 may be considered on the Capital ships to provide higher altitude in-situ wind measurements.*

Relation to MOP and MOE:

Advantages: The PA1 SODAR has several advantages when used in tandem with other observing systems. As a stand-alone system, the SODAR's main functionality is providing 3-D wind data at high temporal resolution sufficient to resolve the detailed kinematic structures that include: 1) the characterization of elevated stable layers, 2) vertical wind shear and turbulence parameters, 3) rapid changes in vector wind associated with approaching fronts, squalls, density currents, and turbulent eddies. The winds obtained from the SODAR have a better accuracy, much higher frequency (2 minute turnkey system), and requires significantly fewer person-hours to maintain than the Mini-Rawinsonde System currently in use. When used in conjunction with another platform such as ALAPS to gain a full array of atmospheric data, shipboard METOC capability is considerably greater than that achieved by the MRS. Other advantages are 1) Continuous operation and measurement; no intrusion into the space being sampled; low labor costs for measurements.

Limitations: The PA1 SODAR is proposed as an ancillary system for deployment with the ALAPS. By itself, the PA1 SODAR, as with all SODAR, can only provide kinematic information on the wind field directly above the ship. This is a limitation if only used in a stand-alone operation. The antenna should be heated, thereby increasing the power requirement to the antenna from 190 to 1150 W. The SODAR has practical limitations for shipboard operations, among them:

(1) Range - sound is attenuated in the atmosphere, with higher frequency sound attenuated much more than lower frequencies. With increasing temperatures, and/or lower relative humidity, the attenuation of sound increases. The height performance of a SODAR in a hot, dry, environment may only be 60% of the same instrument in a cool, damp, location.

(2) Audible sound - the generation of sound can limit its use in high traffic areas;

(3) Background noise - the background noise where a SODAR is operating can also limit a SODAR's performance. In general SODARs should not be operated in areas where the noise level (at the frequency of operation of the SODAR) is high;

(4) Local structures- SODAR should not be installed near structures (or vegetation) which can produce fixed echoes;

(5) SODARs must be mounted horizontally, thus a platform which will keep the system level (local gravity leveling) may be needed for the shipboard installation.

Readiness Level for Use: SODARs are commercially available and are easy to install. A gravity leveling system or alternate system may be required to maintain the SODAR in a horizontal position, however, the errors that would be encountered from normal roll and pitch angles should be simulated to determine if the leveling system is required.

Risk Analysis of the Sensor to Perform and Achieve Expected Results: The SODAR can only provide winds. It is an easy to install turnkey system with minimal maintenance. However, is must be suitability leveled and affixed to the ship. With proper installation, a SODAR should operate with minimal risk, and should be able to perform continuous measurements and achieve accurate, high frequency samples of winds and turbulence.

Measure of Performance (MOPS):

Latency:

The REMTECH PA1 SODAR is capable of providing 3-D wind measurements to a maximum altitude of 2 kilometers with an observation cycle as short as 2 minutes, with options to reduce that further to one minute.

Accuracy of Data Product:

Wind measurements can be obtained from the PA1 with a horizontal accuracy of 0.2 m/s and a vertical wind accuracy of 0.05 m/s, significantly better than the accuracies inherent in MRS measurements. The error that would be encountered with normal ship motion should be evaluated.

Time Resolution:

The PA1 SODAR requires 2 minutes to cycle through an observation sequence. This time resolution is adequate to be used in conjunction with the Raman lidar and is far better than conventional MRS techniques.

Spatial Resolution:

The PA1 SODAR has selectable range gates to provide a vertical resolution between 10 and 200 meters. The higher resolution is sufficient to resolve detailed boundary layer kinematic structure, elevated stable layers, rapid changes in wind fields associated with weather hazards.

Real-Time Data:

The SODAR system can yield a vertical wind profile every 2 minutes that can be made available continuously to shipboard observers in near real time. This level of availability will allow this data to be assimilated into NOGAPS and COAMPS in sufficient time to be incorporated in the model initialization fields.

Validity of Inferred Data Parameter:

The PA1 is capable of self-adjusting S/N ratio and self calibration. The accuracy is at least as good as that specified in the Table above.

Nowcast Capabilities:

Because the wind data from the SODAR is retrieved in near real-time, it can be used onboard the ship for extrapolation, and integrated with other data to prepare a Nowcast for shipboard weather observers.

Measures of Effectiveness (MOE):

Timeliness:

SODAR data is timely with minimal latency. A new 3-D wind profile can be retrieved every 2 minutes with the commercially available model, 1 minute with manufacturer modifications. The wind data can be used immediately with other meteorological data to identify weather hazards that can affect aircraft and helicopter OPS and flights. In addition, with necessary upgrades to the shipboard communication and messaging systems, this data can be transferred to modeling centers where it can be assimilated and ingested for model initialization.

Consequences of Uncertainty in Conditions:

The SODAR is intended to provide vector wind profiles in support of the Raman lidar, which will supply a wealth of meteorological information to assess conditions. Standing alone, the SODAR is not an appropriate sensing technology for the next generation of shipboard meteorological platforms.

Representativeness of Data:

The PA1 SODAR is capable of providing in-situ observations of the vector wind field that are highly representative of the near ship environment. There is no attempt to consider this system as representative of anything more than the wind field, but it can be a valuable asset if it is used in conjunction with the Raman Lidar (ALAPS).

Ease of Use of Sensor:

The PA1 SODAR is a turnkey operation requiring virtually no assistance from the crew once installed. It is self-calibrating and self-adjusting of the S/N ratio, and autocorrects or auto-eliminates bogus data. Installation will require the addition of a self-leveling platform, and a heated antenna is recommended.

Resources Expended:

The PA1 can be acquired for $100K. The self-leveling platform will add $50K to the cost of each unit. Once installed, virtually no person-hours and associated expenses would be required, and maintenance would be part of the routine operation. System maintenance is greatly facilitated by special software diagnostic routines. If ever required, repair is accomplished by swapping the complete electronic case, vastly reducing down time.

Continuity of the Data:

The data from the SODAR should be available most of the time. The major loss of data is during periods of noise, and when heavy wind and rain on the surface of the instrument distorts the received signal. It is likely that the selected operating mode will be to turn on for the first five minutes of each hour, because this would probably provide sufficient data and it would then be less annoying to individuals working nearby.

Relationship of sensor to MOP and MOE for Operational Concepts and Tasks

In order to perform an evaluation of the sensors, each of the sensors are rated against the MOP and MOE for several of Operational Concepts. Tables 6, 7 and 8 rate the Mini Rawin System (MRS), the Advanced Lidar Atmospheric Profile Sensor (ALAPS), and the Microwave Radiometric Profiler (MWRP) against the Measures of Performance (MOP) and Measures of Effectiveness for each of the ten Operational Concepts and Tasks described in Section 3. The rating is accomplished by using the following scale:

0 - Not useful
1 - Low Utility
2 - Some Usefulness
3 - Adequate
4 - Good Result
5 - Major Improvement

The rating attempts to weight the strength and weakness of each of the techniques. When the rating is considered, the MOP #2 and MOE #3 should be weighted most heavily, because it really does not matter too much about the other factors if the result is not sufficiently accurate or representative of the conditions.

Because the lidar (in its present design), nor the radiometer, are able to provide the vertical profile of the wind, the planned approach is to obtain the low altitude wind data with a SODAR instrument. The SODAR instrument can provide a vertical profile of the wind from the surface to about 3.5 km (Model PA5) or 1.3 km (Model PA1), depending on the array size, transmitted power and frequency.

Table 6. MOP and MOE rating for the Mini Rawin System (MRS)

MRS	1 Radar Defense	2 Strike Enhance	3 Comm	4 Visibility Air OPS	5 Visibility Surveil	6 EO Covert OPS	7 NOGAPS Model	8 COAMPS Model	9 NITES Data Comm	10 Weather Hazards
1. Latency	2	2	3	1	0	0	3	2	3	2
2. Accuracy	4	4	3	1	0	0	4	4	3	3
3. Time Resolution	1	1	2	1	0	0	3	1	3	2
4. Space Resolution	1	1	1	0	0	0	2	1	1	1
5. Real Time	2	2	2	1	0	0	2	1	1	1
6. Inferred	4	4	2	1	0	0	4	3	1	1
7. Nowcast	1	1	1	0	0	0	2	1	2	1
1. Timeliness	2	2	2	1	0	0	3	2	3	2
2. Uncertainty	4	4	3	1	0	0	4	4	3	3
3.Representative	3	3	2	1	0	0	3	2	3	3
4. Ease of Use	1	1	1	0	0	0	1	1	1	1
5. Resources	4	4	4	0	0	0	4	4	4	4
6. Continuity	2	2	2	0	0	0	4	4	3	2
Score	31	31	28	8	0	0	39	30	31	26

0 - Not useful 3 - Adequate
1 - Low Utility 4 - Good Result
2 - Some Usefulness 5 - Major Improvement

Average 20.4 (35%)

Table 7. MOP and MOE rating for the Advanced Lidar Atmospheric Profile Sensor (ALAPS)

ALAPS	1 Radar Defense	2 Strike Enhance	3 Comm	4 Visibility Air OPS	5 Visibility Surveil	6 EO Covert OPS	7 NOGAPS Model	8 COAMPS Model	9 NITES Data Comm	10 Weather Hazards
1. Latency	5	5	5	5	5	5	5	5	5	5
2. Accuracy	5	5	5	4	4	4	5	5	5	5
3. Time Resolution	5	5	5	4	4	4	5	5	5	5
4. Space Resolution	3	3	3	3	3	3	3	3	3	3
5. Real Time	5	5	5	4	4	4	5	5	5	5
6. Inferred	5	5	5	5	5	5	5	5	5	5
7. Nowcast	5	5	5	5	5	5	5	5	5	5
1. Timeliness	5	5	5	5	5	5	5	5	5	5
2. Uncertainty	5	5	5	4	4	4	4	4	5	5
3.Representative	5	5	5	5	5	5	5	5	5	5
4. Ease of Use	5	5	5	5	5	5	5	5	5	5
5. Resources	2	2	2	2	2	2	2	2	2	2
6. Continuity	4	4	4	4	4	4	5	5	5	3
Score	59	59	59	55	55	55	59	59	60	58

0 - Not useful 3 - Adequate
1 - Low Utility 4 - Good
2 - Some Usefulness 5 - Major Improvement

Average 57.8 (89%)

Table 8. MOP and MOE rating for the Microwave Radiometric Profiler (MWRP)

MWRP	1 Radar Defense	2 Strike Enhance	3 Comm	4 Visibility Air OPS	5 Visibility Surveil	6 EO Covert OPS	7 NOGAPS Model	8 COAMPS Model	9 NITES Data Comm	10 Weather Hazards
1. Latency	1	1	1	1	1	2	5	5	2	1
2. Accuracy	2	2	2	1	1	1	4	4	3	3
3. Time Resolution	5	5	5	5	5	5	5	5	5	5
4. Space Resolution	3	2	2	2	2	2	4	3	4	3
5. Real Time *	5	5	5	5	5	5	5	5	5	5
6. Inferred	2	1	1	2	2	2	3	2	2	2
7. Nowcast	0	0	0	0	0	0	0	0	0	0
1. Timeliness	2	2	2	2	2	2	4	4	2	2
2. Uncertainty	2	2	2	1	1	1	3	2	2	2
3.Representative	2	2	2	2	1	1	2	2	2	2
4. Ease of Use	5	5	5	5	5	5	5	5	5	5
5. Resources	3	3	3	3	3	3	3	3	3	3
6. Continuity	3	3	3	2	2	2	5	5	3	4
Score	35	33	33	31	30	31	48	45	38	37

0 - Not useful 3 - Adequate * Microwave brightness temperature
1 - Low Utility 4 - Good Result Average 36.1 (56%)
2 - Some Usefulness 5 - Major Improvement

8. Life Cycle Costs of Alternatives

One of the more difficult tasks is to provide an assessment of the costs for each of the alternative sensors. The expected costs for fabrication, testing, training, and maintenance can be reasonably estimated for the several sensors. In fact, some of the sensors examined are available as commercial products. However, the more difficult cost factors to assess are those associated with installation and life cycle costs. Guidelines for the cost comparison were defined in a coordination meeting held on 18 May 2005 at the Naval Observatory in Washington DC. The guideline includes the following factors:

(1) The cost to be assigned for launching two balloon sondes per day is equivalent to 3 hours per day for one person, and no extra manpower allocation is made for the Raman lidar or the radiometer

(2) Ship operation is to be estimated at 90 days of operation per year

(3) The life-cycle costing is to be based on 6 years

(4) Number of units supported is taken to be 60 units, which includes 27 capital ships, and 33 other locations that include other ships, shore sites, and HMMWV mobile units for the Marine Corps.

An analysis that estimates the life cycle costs associated with supporting the Navy's operations with a total of 60 sets of sensors during the next 6 years has been prepared.

A cost comparison was performed in order to analyze the differences between the current MRS system and two possible replacement systems, the alternatives include a Raman Lidar and a Microwave Radiometer. A SODAR capable of continuous low altitude wind profiling is also planned to support future meteorological remote sensing. The cost analysis was broken into five main categories; Capital Expense, Operational Cost, Personnel Cost, Maintenance Cost, and finally a 5th category will be addressed "Non-valued Costs." A brief description of each category of expense is described at the beginning of each section.

The Research Development Test and Evaluation (RDT&E) costs have been included in the Capital Expense associated with the preparation of the first operational unit. The RDT&E costs include those activities necessary to prepare an operational instrument for rugged, weather sealed, all-weather operations. Each of the sensors will require some amount of RDT&E efforts. The largest effort in this category will be that required to transform the Raman Lidar (LAPS) prototype into a commercial instrument (ALAPS). The microwave radiometer is already available as a commercial product, however, it will require development of a stabilization platform and a significant amount of development of the analysis algorithm for ocean operations. The software for use of the commercially available SODAR instrument will require development to use the shipboard position information to transform the data to remove the ship motion and establish the local wind field. The SODAR performance for typical roll and pitch motions to assess the possible need for a stabilization platform. Even the continued use of the MRS AN/UMQ-12A balloon sonde system will require testing with the military system for position information to analyze the wind vector.

Capital Expense

The capital expense is envisioned as the money necessary to put the system into place on the NAVAL capital ships, support ships, shore sites, and mobile Marine Corps deployment units. There are two main costs considered in the Capital Expense. First is the cost of fabrication, testing and calibration of the sensor with its supporting equipment and software, second are the costs associated with installation of the instrument for operation.

MRS AN/UMQ-12A

The capital expense for the current Mini-Rawinsonde AN/UMQ-12A system comes primarily from the cost necessary to upgrade the current MRS system equipment from the RS-80 sonde so that it will be compatible with the RS-92 series of sondes. This cost is approximately $10K per receiver and there are 122 to be upgraded. However, this system upgrade will still not make the AN/UMQ-12A SAASM compliant. The upgrade that will be needed to be put into place, approximately 2 years from August of 2005, will require a new set of ground equipment that is estimated to cost $20M. August 2005 will be the last time to order the RS80 sondes, which have a shelf life of 2 years, before they are replaced by the RS92 sondes.

Total = $1.2M

SAASM Compliant System = $10M

ALAPS

The capital expense for the Lidar system is the largest. One reason is because the Lidar needs commercial development in order to prepare the Engineering Development Model (EDM) for shipboard operation, however, the technical support payout heavily weighs the decision in its favor. The LAPS system developed as an Advanced Development Model (ADM) at Penn State University and has been shown to be robust and performed well during shipboard tests in 1996. However, a major step remains to prepare the final instrument in compact size for commercial manufacturing, and this will require additional engineering development. This development will cost approximately $5M and will be completed over a time span of about 18 months. The EDM will be fabricated and installed for testing as the manufacture of 60 units begins. These units will meet the needs of the 27 capital ships, 33 supporting ships, Marine Corps units, and shore sites. The installation cost is estimated to be approximately $100K.

Purchase first unit = $5.1M

Purchase Each additional unit = $450K

Installation Cost/unit = $50K Total $35M

Radiometer

The capital expense for the Radiometer is approximately one-half of the lidar. The radiometer costs approximately $250k, and will then require an interface to obtain the ship's data on roll and pitch. The manufacturer of one candidate radiometer first stated a requirement for a gimbal mount, but now expects to achieve a software solution by using the ship's data. If a gimbal mount should be required, the instrument cost per unit is expected to increase $100k to $150k, based upon preliminary discussions with engineering contractors for such systems. Finally in order to operate the radiometer and have confidence in its profile; balloon sondes would be used to prepare an operational set of reference models for deployment in new environment regions. The radiometer measurement of integrated brightness temperatures is only accurate in selecting the best model to represent the meteorological properties when an adequate set of model profiles is available. The balloon sonde calibrations will be required to help establish a data base in a littoral area that has not been previously documented. This calibration is necessary in order to have confidence in the profiles retrieved by the radiometer since the profiles depend strongly on the profile structure in the climatology. The cost for ruggedization and corrosion resistant treatment for a radiometer is estimated at $600K for the first unit.

Purchase first unit = $850K
Purchase each additional unit = $250K
Installation cost/unit = $35K Total $17.7M

SODAR

The capital expense for the SODAR includes the development, purchase and installation costs. The cost for the SODAR is $250K for the PA5 which includes $200K for purchase and $50K for installation. However the first SODAR instrument will cost approximately double to develop software as well as test the unit for ruggedization in the ocean environment. The cost of the PA1 is $180K with $155K for purchase and $25K for installation, again the first unit will cost approximately double in order to further develop the ocean functionality of the SODAR. Due to space constraints it is envisioned that the PA1 would be deployed on all capital ships, support ships, shore sites, and mobile Marine Corps deployment units (60 total units). The costs estimated above include the instrument, the housing for the electronics, as well as, all of the software packages available. The PA5 is cost value is included for reference.

Purchase first unit PA5 = $500K
Purchase each additional PA5 = $250K
Purchase first unit PA1 = $400K
Purchase each additional PA1 = $180K
Installation cost/unit = $25K Total $12.5M

<u>Operational Cost</u>

The operational cost includes any disposables that would be used during testing, this would include electricity, batteries, sensors (balloon package) any non-recoverable pieces.

MRS AN/UMQ-12A

The MRS system has a high operational cost, because of cost of the disposable balloons and sensor packages, and in addition the expense of helium tanks used to fill the balloons for launch. The operational cost was calculated based on two-launch's per day for 90 days out of the year. The sensor package currently costs approximately $195 but the SAASM compliant advanced sonde is expected to be more expensive, and the cost of the balloon and helium must be added. The total cost per launch for materials is then estimated to be $300 per release. The operation is considered to include two launches per day to provide a minimum data product.

Total = $54K/year/ship Total $19.44M (over 6 years)

ALAPS Lidar

The operational expense for the ALAPS unit is primarily that of the cost of electricity. Electricity was determined to be of negligible cost.

Microwave Radiometer

The operational expense for the Radiometer is also primarily that of the cost of electricity. Electricity was determined to be of negligible cost.

SODAR

The operational expense for the SODAR is again primarily that of the cost of electricity. Electricity was determined to be of negligible cost.

Personnel Cost

The personnel cost was broken into two main categories; first is the personnel training category and second is the actual man power the team that is utilized to perform the operation and analysis of the atmospheric data.

MRS AN/UMQ-12A

The MRS system currently has very little training involved with its operation and most of the personnel cost is due to manpower. The manpower assignment for the current system on 27 capital ships includes 11-12 personnel, however, the manpower devoted to the MRS was assigned an equivalent of 3 man-hours per day.

Training = $10,000/year independent of number of units Total $60K

Manpower = $5,500/year/unit Total $2M

ALAPS

The personnel cost for the ALAPS Lidar was broken into the training necessary to operate the unit and the manpower necessary for operation. The manpower was found be negligible for the ALAPS, radiometer and SODAR because of the minimal amount of time needed to operate.

Training = $50K/year independent of number of units Total $300K

Manpower = $0

Radiometer

The man power was found be negligible for the ALAPS, radiometer and SODAR because of the minimal amount of time needed to operate.

Training = $30K/year independent of number of units Total $180K

SODAR

The personnel cost for the SODAR was found to be negligible. This is because the personnel that are assigned to either the radiometer or the ALAPS system would be performing the work for the SODAR system. As either the Lidar or the Radiometer would be deployed concurrently with the SODAR system. However, a training cost is incurred in order to familiarize the crew with the operation of the SODAR.

Training = $30K/year independent of number of units Total $180K

Maintenance Cost

Maintenance Cost includes total calibration and inspection as well as the day-to-day housekeeping costs. This accounts for manpower to fix any system that is not operating properly as well as funding for replacement parts.

MRS AN/UMQ-12A

The maintenance costs for the MRS system include Helium tank removal and restocking as well as costs for pressure regulators and housekeeping costs.

Total = $10,000/year/unit Total $3.6M

ALAPS

The Lidar maintenance cost during the 6 year period includes 2 main features. It first includes $10K/year/unit for a biannual maintenance team to board during port and perform housekeeping and calibration, as well as any major repairs. A separate $5K/year/unit is allowed for onboard parts and repairs during at sea operations.

Total = $15,000/year/unit Total $5.4M

Radiometer

The radiometer maintenance costs are also for repair and housekeeping.

Total = $10,000/year/unit Total $3.6M

SODAR

The SODAR maintenance costs are also for repair and housekeeping.

Total = $10,000/year/unit Total $3.6M

Non-valued Costs

The following section describes costs that are do not have a direct conversion to a monetary value. These include environmental costs as well as space consumption on the naval vessel.

MRS AN/UMQ-12A

The current MRS system is not environmentally friendly. With each launch a balloon carrying a sensor package, batteries and Styrofoam will eventually land in the ocean or the land. The cost to the environment and its inhabits cannot be measured.

ALAPS

The ALAPS Lidar system incurs no environmental costs. ALAPS system is also estimated to take up approximately 1/10 the space (utilizes 1/10 of the footprint) of that of the current MRS system.

Radiometer

The Radiometer also incurs no environmental costs as its method of data collection is purely passive. Secondly, this system is also estimated to take up approximately 1/15 of the space (utilizes 1/15 of the footprint) of that of the current MRS system.

SODAR

The SODAR also incurs no environmental cost. The SODAR system is also estimated to take up approximately 1/15 the space (utilizes 1/15 of the footprint) of that of the current MRS system.

TOTAL COSTS

Table 9. Summary of system costs.

	Capital Expense	Recurring Cost/year/unit	Training Cost /year	Total Cost (6Y)
MRS AN/UMQ-12A	$11.2M	$69,500	$10,000	$34.5M
ALAPS	$35M	$15,000	$50,000	$37.2M
Radiometer	$17.7M	$10,000	$30,000	$20.6M
SODAR	$12.5M	$10,000	$30,000	$15.4M

After the initial investment for the Lidar or Radiometer there is a significant savings per year in the recurring costs compared with the MRS. This becomes most noticeable when the number of units in operation multiplies the recurring costs.

Shown in Figure 10 is a 6-year outlook of the total costs for the Lidar, Radiometer, and MRS system as 60 units are deployed. As stated above within the personnel cost section the MRS system assumed 27 Capital Ships, 33 support ships, Marine Corps mobile units, and shore sites. The smaller ships and shore sites were assumed to have a weather officer and an aerographer deployed as a team with the instrument for mission support. The Lidar and Radiometer recurring costs were multiplied to 60 units with the training cost remaining constant and independent of the number of units as we move into full deployment.

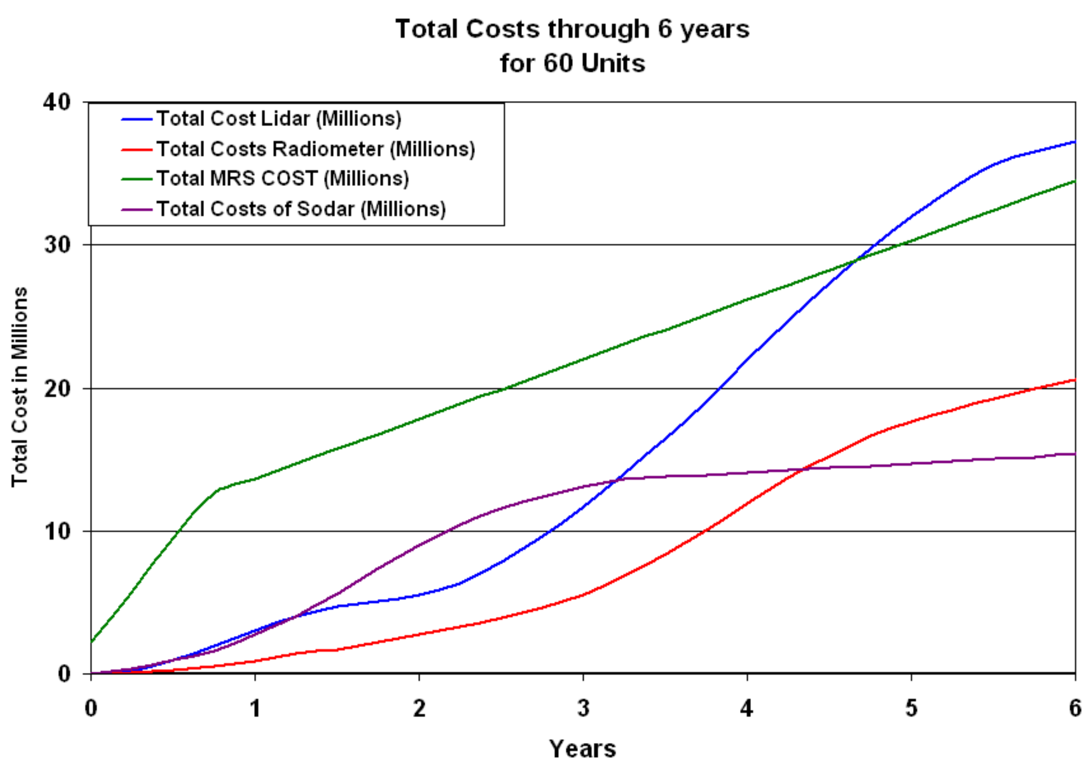

Figure 10. Cost Analysis for 60 Units of Lidar, Radiometer, MRS and SODAR over the next 6 years.

Figures 11 and 12 show the cost comparisons for the lidar, radiometer and MRS system. This chart shows the change in costs as the lidar or radiometer is fully deployed and the current MRS system is replaced. The plot is displayed in costs per quarter. The cost to operate the MRS with 2 soundings per day for 90 days out of the year on 27 capital ship units and 33 other units totals to approximately $1.1M per quarter. Looking at the chart one notices that the initial cost of lidar and radiometer is due to the cost of each unit and its installation. The initial cost of the MRS system is due to the necessary replacement and upgrade to become SAASM compliant. As time progresses the lidar and radiometer cost falls to a near constant value due to their low recurring costs. This cost is approximately $250K per quarter for 60 units in operation for the lidar and is $150K per quarter for 60 units in operation for the radiometer. These costs are primarily associated with the maintenance costs for each.

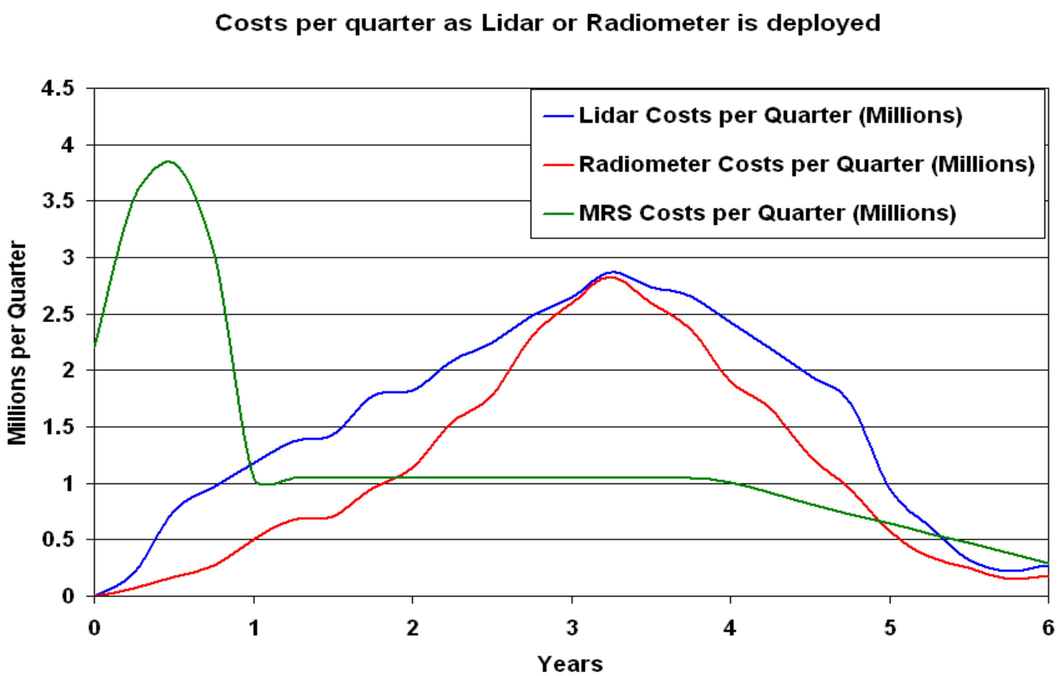

Figure 11. Cost summary as Lidar or Radiometer become fully deployed with SODAR and the MRS is retired.

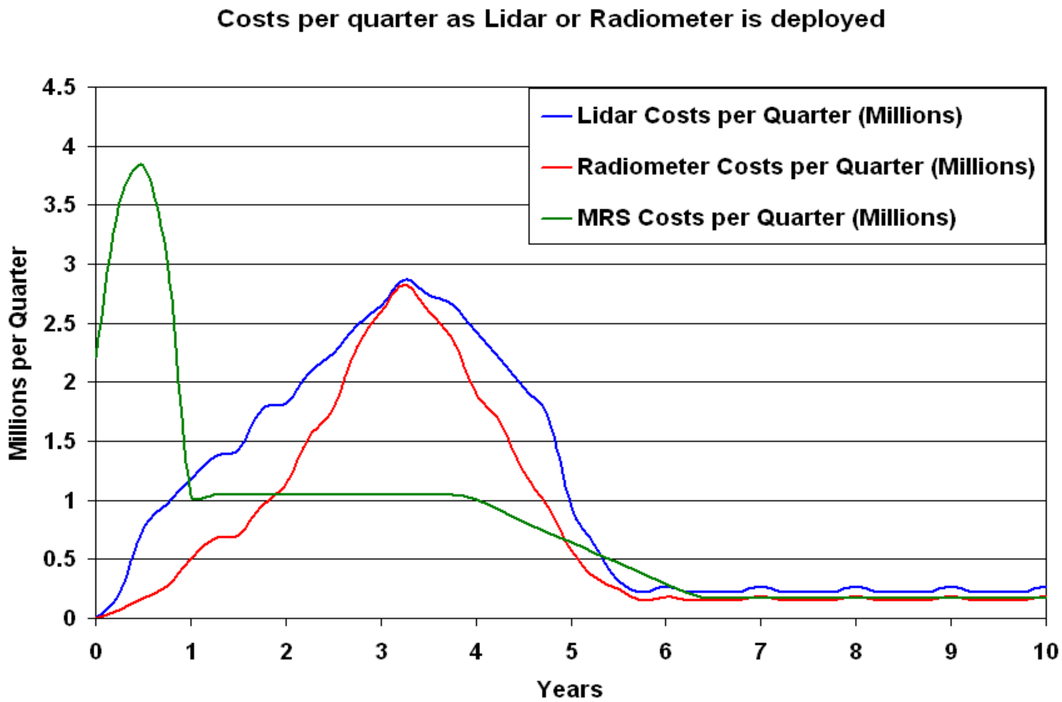

Figure 12. Cost summary as Raman Lidar or Microwave Radiometer become fully deployed with Sodar and the MRS is phased down to a lower supporting level over a 10-year cycle.

9. Implementation and Approach

Many sensors have been developed and are available for the primary use as point sensors, however the several agencies, and even different commands within the Navy, have adopted different sensor packages for use. A study of the sensor performance and trade-off should be carried out with the goal of trying to standardize on a point sensor system package that will provide the best solution for DoD and Navy needs. The systems that are being examined are: Remote Automated Weather System (RAWS); and METOC Integrated Data Display System-Next (MIDDS-Next). An additional set of remote sensing data will become available from several sensors aboard the NPOESS satellites in 2008. The TEP capability is being implemented on platforms with SPY-1 class radars and this capability will become an important tool of the METOC community. Also, the point sensor data available from buoys provide an important set of data for developing the global meteorology. The idea is to consider the whole range of measurement possibilities in an attempt to see if a optimum strategy can be developed. The most valuable component for support of Navy operations will undoubtedly be the profiles obtained with lidar in the littoral area.

As a path forward, the roadmap plan shown in Figure 13 provides a suggested approach from this point forward. The choice for the sensor to support the Navy's mission is the Raman lidar because it far exceeds any other approach for defining the EM, EO, and meteorological environment in a timely way, with high spatial and temporal resolution. The easiest step to quickly reduce the Navy's dependance on balloon sondes and to immediately add important capability for the global meteorology forecasting is to deploy the commercially available microwave radiometer (realizing its limitations) together with a small SODAR instrument. The radiometer will not have the spatial resolution required for the EM requirements because the instrument measures the integrated brightness and interprets the vertical profile based upon training algorithms that are built-up from climatology. Also, the radiometer may require mounting on a stabilization platform to properly perform onboard ships. Data from a microwave sounder and a SODAR will greatly improve the timeliness and availability of lower atmosphere data for local forecasting and for model assimilation. However, where the profiles of RF-refraction are required, it will be necessary to maintain the balloon sonde availability. The preferred option is to deploy the Raman lidar, such as the ALAPS, together with a SODAR for wind profiles. A plan to carry out the preparation of a commercialization of the Raman lidar for shipboard deployment should be undertaken as soon as possible. The recommended plan is:
(a) order sufficient sondes to provide required support using the AN/UMQ-12A system for the next 2 years,
(b) proceed with the commercialization of the Raman Lidar technology to prepare the ALAPS instrument with initial instrument installation within two years,
(c) develop the plan for integration of the Lidar and SODAR on capital ships, and prepare a plan for deploying the environmental control and power units needed for operations on smaller ships, shore sites, marine deployments, and use by other DoD elements,
(d) perform an engineering review to determine how to assure the SODAR will be seaworthy and to use the data on ship motion to transform relative wind measurements to true wind,
(e) evaluate the data exchange/transmission within a regional deployment, and to model processing locations, to assure that the data products are used most effectively for force

protection and operational support within the littoral area, and for forecasting regional and local conditions.

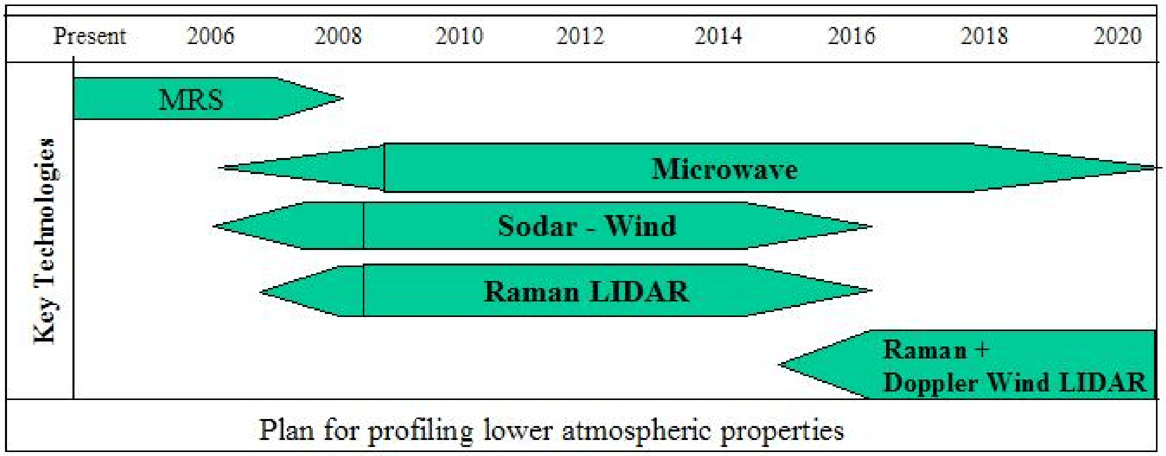

Figure 13. The plan for providing the profiles of atmospheric properties during the phase down of the dependence on balloon sondes will be met by use of microwave radiometers and acoustic sounders or by Raman Lidar and SODAR.

In order to provide the most complete solution for DoD atmospheric measurements, the idea of using a HMMWV has been considered to provide mobile meteorology support for the Marine Corps and the Army. It should be possible for the ALAPS instrument to be mounted in a HMMWV (High-Mobility Multipurpose Wheeled Vehicle), together with a small portable environmental unit and a power generator to provide ground support. Figure 14 shows a HMMWV that could be prepared as a mobile met station that would be capable of providing point sensors, Lidar, and SODAR for atmospheric measurement support. Issues that must be addressed include the thermal conditions for all-weather operations and the shock mounting for off-road deployment.

Figure 14. The HMMWV would be capable of transporting a mobile meteorological station that could accompany ground troops.

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Appendix A

Focus Group Meeting
17-18 May 2005
Naval Observatory, Washington DC

<u>List of Attendees</u>
Richard Clark, Millersville University
Ryan Collier, SSC Charleston
Chris Hall, CNMOC
CAPT Jay Haley, USMC (N7C/ASL-37)
Tim Kimbrell, SSC Charleston
Walt McKeown, MLMOC Senior Scientist
Ed Mozley, SPAWAR, San Diego (Phone link)
Russell Philbrick, Penn State University
CDR Steven Rutherford, CNO N7C
LCDR Keith Williams, NPMOC, San Diego
CDR Stephen Woll, SGOT, Norfolk
Adam Willitsford, Penn State University

A Focus Group Meeting was held on 18 May 2005 at the Naval Observatory in Washington DC to attempt to arrive at better answers on several topics involved in this study. Particular attention was given to appropriate ways to analyze several of the cost issues. The cost analysis was revised significantly as a result of the discussions. An attempt was make to better answer several questions that were asked by the participants. The suggestions and contributions of ideas by the members of the Focus Group are greatly appreciated.