The Feasibility of Radar-Based Remote Sensing of Barometric Pressure

Final Report

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ABSTRACT

This study assesses the feasibility of radar-based remote sensing of barometric pressure of the air at the sea surface. Currently, sea surface barometric pressure measurements can only be obtained from in situ observations including buoy and dropsonde measurements, which are sparse in spatial coverage and expensive to implement. There are no operational remote sensing methods available even in experimental stages. The proposed technology is to use differential absorption radar working at the 50-56 GHz O_2 bands to fill the observational gap. The numerical simulation results for homogeneous sea surface backgrounds show that with an airborne radar working at these O_2 absorption bands, the rms errors of the instantaneous radar surface pressure estimates with 15 dB signal-to-noise ratios can be as low as 4–7 mb. With multiple measurements over an area about 10 km the uncertainty in radar sea surface pressure estimates would drop to about 1 mb which is similar to conventional in situ buoy measurements. A radar system that covers the O_2 absorption wavelengths over the ocean will have great potential for weather observations and other meteorological applications, especially for forecasts of hurricanes. Case studies show that with the capability of remotely sensed sea surface barometric pressure data, the errors of hurricane center pressure, the most important indicator of hurricane intensity, in weather prediction models would reduce from about 48 mb to about 1.5 mb. The increased accuracy is about 1/3 of whole range of possible variations of hurricane center pressure. The uncertainties in the weather model predicted landfall positions or tracks of hurricanes also shrink greatly from ~350 km to within 100 km. Based on conventional radar system design and radar engineering models, our assessment clearly illustrates that it is realistic to develop our proposed airborne radar system with existing technology. That is, all major subsystems of the proposed instrument could be built using available Commercial Off The Shelve (COTS) components. An investment would be required to integrate and test the whole instrument as well as to install it onto the aircraft or UAV. The Technology Readiness Level (TRL) assessment before this feasibility analysis was based upon the basic principle and technology concept and resulted in TRL 2. The current analysis and assessment, especially the analytical results of the O_2-band radar, applications, sea surface air pressure retrievals, and airborne radar system designs, advances the O_2-band radar technology to TRL 3. Finally, a roadmap for further studies on the radar system to advance the TRL to higher levels, such as 6 and higher, is shown in this report.

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1. Introduction

Surface air pressure is one of the most important atmospheric parameters that are regularly measured at ground based surface meteorological stations. Over oceans, sea surface air barometric pressures are usually measured by limited numbers of in-situ observations conducted by buoy stations and oil platforms. The spatial coverage of the observations of this dynamically critical parameter for use by weather forecasters is very poor. For example, along the east coast of the United States and Gulf of Mexico, only about 40 buoys are available under the NOAA Ocean Observing System (NOOS) of the NOAA National Data Buoy Center (NDBC; http://www.ndbc.noaa.gov/). The tropical atmosphere ocean (TAO) program only has 10 sites from which the barometric pressure is measured. For severe weather conditions, such as tropical storms and hurricanes, these NOOS and TAO buoy systems usually cannot provide spatially desirable in-situ measurements due to either the lack of buoy stations on the track of storms or malfunctions of buoys caused by the severe weather itself.

Under tropical cyclone conditions, including tropical depression, tropical storm, hurricane, and super-typhoon cases, the surface barometric pressure is one of the most important meteorological parameters in the prediction and forecast of the intensity and track of tropical storms and hurricanes. The central air pressure at sea level of tropical cyclones is the most commonly used indicator for hurricane intensity. The classification of tropical storms and hurricanes on the Saffir-Simpson Hurricane Scale (SSHS) is based on the maximum sustained surface wind speed that is a direct result of the interaction between the central air pressure and the pressure fields surrounding tropical storms. Because intensity predictions and landfall forecasts heavily rely upon them, measurements of the central pressure of tropical storms are extremely important. The only method currently available for use is a manned aircraft dropsonde technique. The problem with the dropsonde technique is that each dropsonde supplies only one spatial point measurement at one instant of interest during the passage of the storm. This limits data to the number of dropsondes used and their spatial distribution and thereby leaves most of the storm area unmeasured. Furthermore, dropsondes are difficult to precisely position and cannot be reused. Figure 1 shows the current capability for sea surface barometric measurements; all of them are in situ observations.

Figure 1. Drift Buoy (left), Moored Buoy (middle), and Dropsonde (right).

To improve predictions and forecasts of the intensity and track of tropical storms, large spatial coverage and frequent sampling of sea surface barometry are critically needed for use in numerical weather models. These needed measurements of sea surface barometric pressure cannot be realized by in-situ buoy and aircraft dropsonde techniques. The only hope of barometry in large spatial and temporal scales over oceans is from remote sensing techniques including those on board manned aircraft, unmanned aerial vehicles (UAVs), and satellite platforms.

During the last two decades, the development of remote sensing methods, especially airborne and satellite techniques, for large and global scale sea surface pressure measurements significantly lagged methods for other important meteorological parameters, such as temperature and humidity. There have been suggestions for using satellite oxygen A-band methods, both passive and active, to measure pressure (*Barton and Scott* 1986, *Korb and Weng* 1982, *Singer* 1968, *Wu* 1985, and references therein). The active instruments rely on the operation of complicated, highly-stable laser systems on a space platform and are thus technically difficult. Passive methods are restricted to daytime measurements and areas of low cloud cover (*Barton and Scott* 1986). Thus, after about 2 decades of discussion, there are still no realizations of remote sensing measurements for atmospheric surface pressure, even with experimental systems.

This project assesses the feasibility of an active microwave radar working at moderate to strong O_2 absorption bands in the frequency range of 50~56 GHz for surface barometric pressure remote sensing, especially over oceans. At these radar wavelengths, the reflection of radar echoes from water surfaces is strongly attenuated by atmospheric column O_2 amounts. Because of the uniform mixture of O_2 gases within the atmosphere, the atmospheric column O_2 amounts are proportional to atmospheric path lengths and atmospheric column air amounts, thus, to surface barometric pressures. Historically, *Flower and Peckham* (1978) studied the possibility of a microwave pressure sounder using active microwave techniques. A total of six channels covering frequencies from ~25GHz to ~75GHz were considered. A major problem in the wide spectral region is significant additional dependence of radar signals on microwave absorption from liquid water (LW) clouds and atmospheric water vapor (WV). Atmospheric and cloud water temperatures also have different effects on the absorptions at different wavelengths (*Lin et al*. 1998a, 1998b, & 2001). The complexity in matching footprints and obtaining accurate surface reflectivities of the six different wavelength channels makes their system problematic (*Barton and Scott* 1986). Recently, *Lin and Hu* (2005) have considered a different technique that uses a dual-frequency, O_2-band radar to overcome the technical obstacles. They have outlined the characteristics of the novel radar system, and simulated the system performance. The technique uses dual wavelength channels with similar water vapor and liquid water absorption characteristics, as well as similar footprints and sea surface reflectivities, because of the closely-spaced spectra. The microwave absorption effects due to LW and WV and the influences of sea surface reflection should be effectively removed by use of the ratio of reflected radar signals of the two channels. Simulated results (*Lin and Hu* 2005) suggest that the accuracy of instantaneous surface air pressure estimations from the echo ratio could reach 4 – 7 millibars (mb). With multiple pressure measurements over less than ~1km^2 sea surface spots from the radar echoes, the pressure estimates could be significantly reduced to a few millibars, which is close to the accuracy of in situ measurements and very useful for tropical storm and large scale operational weather modeling and forecasting over oceans.

Since the suggestion of *Lin and Hu* (2005) is based on a brand new concept for barometric pressure measurement, investigation of the suggested technique is needed in order to advance the technique from concept and theoretical simulations to realistic instrumentation and a complete system for remote sensing measurements. For simplicity, hereafter, we call our technique the RAdar Oxygen Barometric Sensor (RAOBS). Our assessment of the novel RAOBS technique includes two stages: initial evaluations and final feasibility studies. Each stage will have a corresponding report. We have finished the initial evaluation and reported the results to the NASA ESTO office. In this final report, we have included all findings of this project including those included in the initial report. We are trying to answer two primary questions: A) *What Earth-Science Research or Operational improvements – such as reduced measurement costs, increased coverage or repeat rates – could be realized by development of a new instrument that uses RADAR to remotely sense barometric pressure?* B) *If desirable improvements could be realized by deployment of this new capability, how could we best approach its development?* To answer these primary questions, the following secondary questions also will be addressed:

With respect to primary question A:

1) Within NASA's Earth-Science framework of the six Science Focus Areas, what potential Research and Applications users exist for radar based (i.e. remotely sensed) barometric measurement datasets?
    a) What degree of performance (theoretical and practical) can be obtained (vs. state-of-the-art measurements) with the proposed measurement concept? In other words, could sufficient performance be obtained to replace existing instrumentation?
    b) What measurement improvements would this approach yield for its users?
    c) Could one instrument be capable of meeting the user needs, or would different instrument implementations be needed?

With respect to primary question B:

2) What are the technical specifications, system-level performance requirements, and system-level trades for a radar-based barometric instrument prototype that would meet the needs of users identified for (1)?
    a) What would be the performance capabilities (e.g. accuracy, resolution) and technical parameters (e.g. size, power) of instrument(s) identified for (2) if built with existing radar components?
    b) Describe the proposed "observing scenario" concept(s) for (2a) in detail and explain how the instrument design overcomes challenges posed by the environment (i.e. provide a rationale for why the retrieval is possible in the presence of adverse conditions).
    c) For instrument options identified for (2), are there specific performance improvement(s) that could be realized by focused development of relevant technologies?

3) Given the answers to (1) and (2), does it make sense to start building a prototype of this instrument with existing technologies, or would it be better

to engage in focused technology developments leading to a future (near-term) build

a) Which of the prototype option(s) identified by (2) would it make sense to build first?
b) Given (3 and 3a), how would the prototype implementation roadmap(s) look like?

This report separates into two parts: the applications of remote sensing barometric pressure and the assessment of the instrumentation development. Each part of this report is designed to answer each of the two primary questions.

The first half of this report, referred to as Part I, describes the applications and benefits from the development of the RAOBS concept. Much of this part of the report was described in the initial report for this project but is retained for completeness. Part I contains 3 sections. The first of these three sections (i.e., Section 2 of this report), discusses the application of RAOBS for hurricane intensity and tracking estimation based upon the critical influence of barometric pressure on hurricane dynamics. Research and experimental uses of RAOBS is addressed in the next section (Section 3). The first primary question and its associated secondary questions listed above are also answered in Section 3. We summarize Part I of this study in Section 4.

The second primary question and its associated secondary questions that are more directly related to the details of the RAOBS instrument and measurement conditions are discussed in the Part II of this report. Part II of this report begins with Section 5 and has a total of four sections. Section 5 of this report discusses the theoretical and technical basis and model simulated retrievals of barometric remote sensing. The system design of a baseline RAOBS system is considered in the Section 6. Our findings to the second primary question and its associated secondary questions can also be found in the section. Section 7 provides implementation recommendations for operational RAOBS developments**.** Based on conventional radar system design and radar engineering models, our assessment clearly illustrates that it is realistic to develop a prototype airborne radar system with existing technology. For a satellite orbital system, major potential technical issues are discussed. The solutions to the potential issues and a roadmap to realize airborne/satellite RAOBS measurements are addressed. The 8th section provides answers of the second primary question and its associated secondary questions and summarizes all major results of this project, especially on those related to RAOBS instrumentation. Thus, Part II of this final report adds the RAOBS assessment to the findings described in the initial report. These analyses and there results are the core of our project, and will lead to future development of RAOBS for barometric remote sensing in meteorological, especially hurricane forecast, applications.

Part I:
Applications of Remote Sensing of Barometric Pressure

2. Forecasts of Hurricane Intensity and Track

To address the usefulness of barometric measurements for weather forecasts and predictions, especially for hurricanes, we use weather prediction models to simulate predicted hurricane intensities and tracks. Predicted results with sea surface air pressure data incorporated are compared with those without the pressure measurements. These surface pressures were obtained from later analysis of in-situ measurements and the assimilated data of the actual hurricane events. During these actual hurricane events, these sea surface pressure data were not available a priori for modeling and prediction. Quantitative potential improvements in the forecasts and predictions of studied hurricane cases are evaluated.

As mentioned before, near surface wind speeds are one of the major indicators of hurricane intensity. Basically, wind speeds in weather systems are determined by the balance of all forces applied to the atmosphere. Pressure fields and its gradients introduced mainly by air mass and gravity, along with apparent forces produced by the earth's rotation, are the key forces of atmospheric dynamics and wind fields. The general force balance for atmospheric dynamics has been studied for decades and can be found in classic textbooks (e.g., *Holton* 1979). These basic meteorological dynamics are not discussed here. In hurricane cases, the sea surface air pressure of the hurricane vortex, P, can be expressed as:

$$P(r) = P_C + \Delta P\,(1 - (1+0.5(r/R)^2)^{-1/2}) \qquad (1),$$

$$V(r) = (r/\rho\; \partial P/\partial r + f^2 r^2/4)^{1/2} - r|f|/2 \qquad (2),$$

where P_C, ΔP and V are the hurricane center pressure, the pressure (P) gradient parameter, and the wind field, respectively (*Xiao et al*. 2000). The r and R values are the radius from the cyclone center and the radial distance of maximum P gradient. Clearly, given pressure measurements, hurricane wind fields can be calculated from Eqs. 1 and 2. Thus, the general dynamic meteorology and equations 1 and 2 provide a solid theoretical foundation for the application of pressure measurements for weather, especially hurricane, forecasts and predictions.

2.1 Hurricane Center Pressure for Forecasting

2.1.1. Weather forecast model description

The numerical weather forecast model used in this section is the Advanced Regional Prediction System (ARPS) developed by the Center for Analysis and Prediction of Storms (CAPS) of the University of Oklahoma and adopted by NASA Langley Research Center (*Wang et al*. 2001; *Xue et al*. 2003; *Wang and Minnis* 2003). The forward prediction component of the ARPS is a three-dimensional, non-hydrostatic compressible model in a terrain-following coordinate system. The model includes a set of equations for momentum, continuity, potential temperature, water vapor, and turbulence kinetic energy (TKE). It also includes five conservation equations for hydrometeor species: cloud water (small cloud liquid droplets), cloud ice (small ice crystals), rain, snow, and graupel/hail (*Tao and Simpson* 1993). The cloud water and cloud ice move with the air, whereas the rain, snow, and graupel/hail fall with their terminal velocity. It has multiple-nested capability to cover the cloud-scale domain and mesoscale domain at the same time. The model employs advanced numerical techniques (e.g., a flux-corrected transport advection scheme, a positive definite advection scheme, and the split-time step). The most unique physical processes included in the model system are a scheme of Kessler-type warm-rain formation and 3-type ice (ice, snow, and hail/graupel) microphysics; a soil-vegetation land-surface model; a 1.5-order TKE-based non-local planetary boundary layer (PBL) parameterization scheme; a cloud-radiation interaction atmospheric radiative transfer scheme; and some cumulus parameterization schemes used for coarse grid-size. Furthermore, a sophisticated long- and short-wave cloud-radiation interaction package (*Chou* 1990; 1992; *Chou and Suarez*, 1994) has been applied to the ARPS model. The ARPS can provide more physically realistic 4D cloud information in very-high-resolution of spatial (cloud processes) and temporal (minutes) scales (Fig. 2).

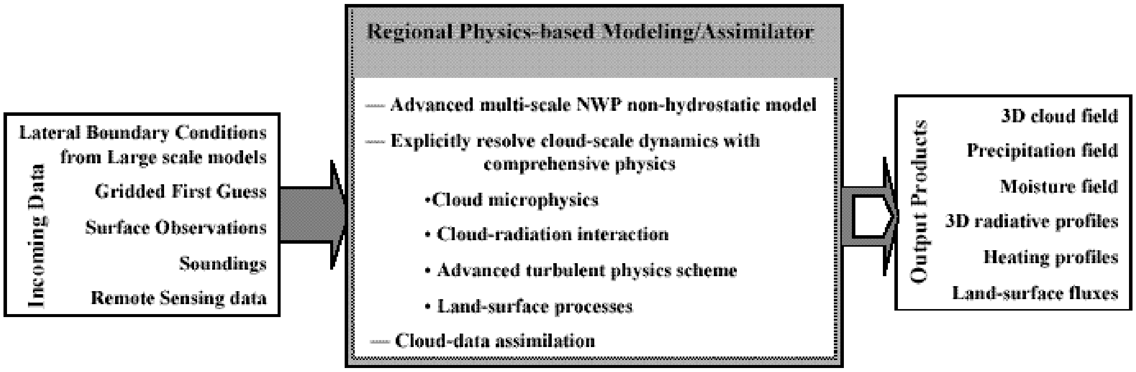

Figure 2. ARPS: a regional cloud-scale modeling/assimilation system.

The ARPS model was run in a horizontal domain of 4800 km, east-west and 4000 km, south-north, and a vertical domain of 25 km. The horizontal grid spacing is 25 km, and the vertical grid space varies from 20 m at the surface to 980 m at the model top. These spatial resolutions are used because they are comparable to those of the models used in the Global Modeling and Assimilation Office, NASA Goddard Space Flight Center. The options for ice microphysics and atmospheric cloud-radiation interactive transfer parameterization were both used in the model. Because of the use of the relatively coarser grid-size of 25 km, the new Kain & Fritsch cumulus parameterization scheme was used together with explicit ice microphysics.

2.1.2 Forecasts with the measurements of hurricane center pressure

The analyzed case here is hurricane Ivan (2004). Ivan was a classical, long-lived Cape Verde hurricane that reached Category 5 strength (SSHS) three times and caused considerable damage and loss of life as it passed through the Caribbean Sea (Fig. 3). Ivan developed from a large tropical wave accompanied by a surface low-pressure system that moved off the west coast of Africa on 31 August 2004. The development of the system continued and became tropical storm Ivan at 0600 UTC 3 September and a hurricane at 0600 UTC 5 September. After passing Grenada and moving into the southeastern Caribbean Sea, the hurricane's intensity leveled off until 1800 UTC on 8 September when a brief period of rapid intensification ensued. Reconnaissance aircraft data indicated Ivan reached its second peak intensity -- 140 kt (~158mph) and category 5 strength (SSHS) -- just 12 hours later. This was the first of three occasions that Ivan reached the category 5 level. Figure 3 depicts the "best track" of the tropical cyclone's path.

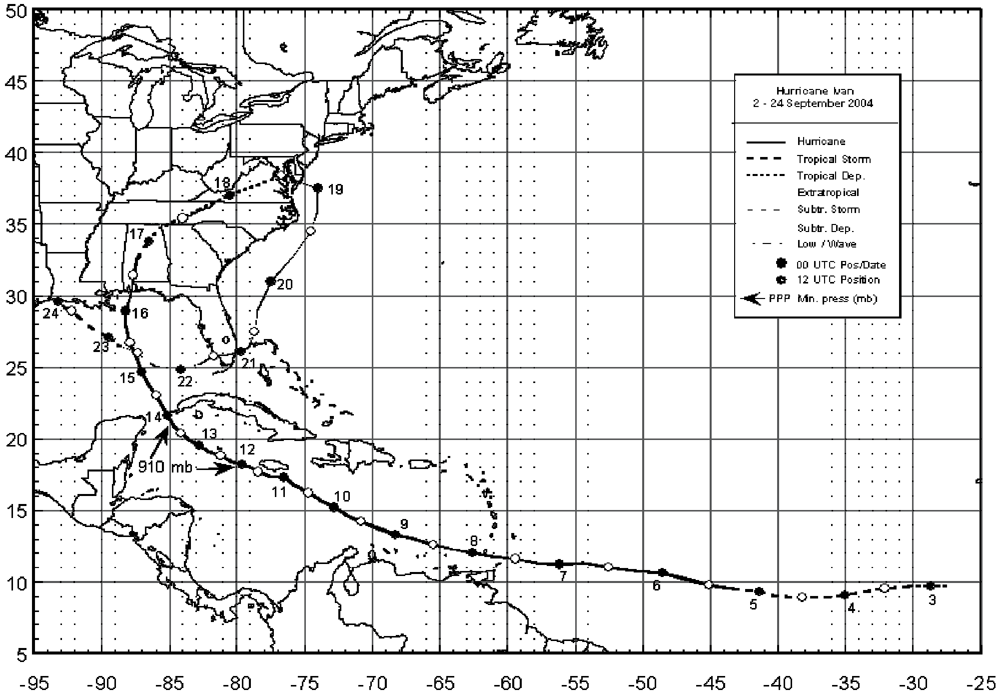

Figure 3. Observed track of Hurricane Ivan during the period of from 0000 UTC 2 Sep 2004 to 0000 UTC 24 Sep 2005. This best track is determined by the NOAA National Hurricane Center.

We choose the forecast period from 0000 UTC 8 Sept. to 0000 UTC 11 Sept. 2004 to examine effects of the central sea surface air pressure on predicting the hurricane track. For the control run (referred as CTL), the model started at 0000 UTC 8 Sep 2004 with the NOAA NCEP Global Forecast System (GFS) analysis fields as the model initial condition. For the central sea level air pressure experiment run (referred as SLP), only the observed central pressure was added to the initialization, using the GFS analysis as the first guess. The lateral boundary conditions for both simulations came from the GFS 6-hour forecasts. The same model physics options were used for the two experiments.

As shown in Fig. 4, from run CTL, the hurricane central pressure at the initial time of 0000 UTC 8 Sept 2004 is about 998.7 hPa (obtained from the NOAA/NCEP GFS global large-scale analysis), which is and at least ~15 hPa lower than normal conditions. Although this simulated pressure drop is much smaller than the real hurricane center air pressure depression (see below) and relatively weak for a hurricane, it still could be well captured with our proposed O_2-band radar systems. At 0000 UTC 8 Sept 2004, based on the report of the National Hurricane Center, hurricane Ivan was located at 12.0° N and 62.6° W, and the value of central sea level pressure of the hurricane is actually 950 hPa. This observation-based central pressure estimate was assimilated into the model analysis system. The assimilated initialization field shown in Fig. 5 is used as the initial condition in run SLP. The value of the central pressure of the hurricane now is about 951.5 hPa, much closer to the observed 950 hPa and within the error bar of observations. Compared to Fig. 4, the change in the initial hurricane center sea level pressure is about 47mb, which significantly improves the predicted hurricane intensity. Since sea surface pressure variations for hurricanes are about from 1020bm to 880mb (882 mb for Wilma 2005), this 47mb improvement covers ~1/3 of entire range of sea surface pressure variations.

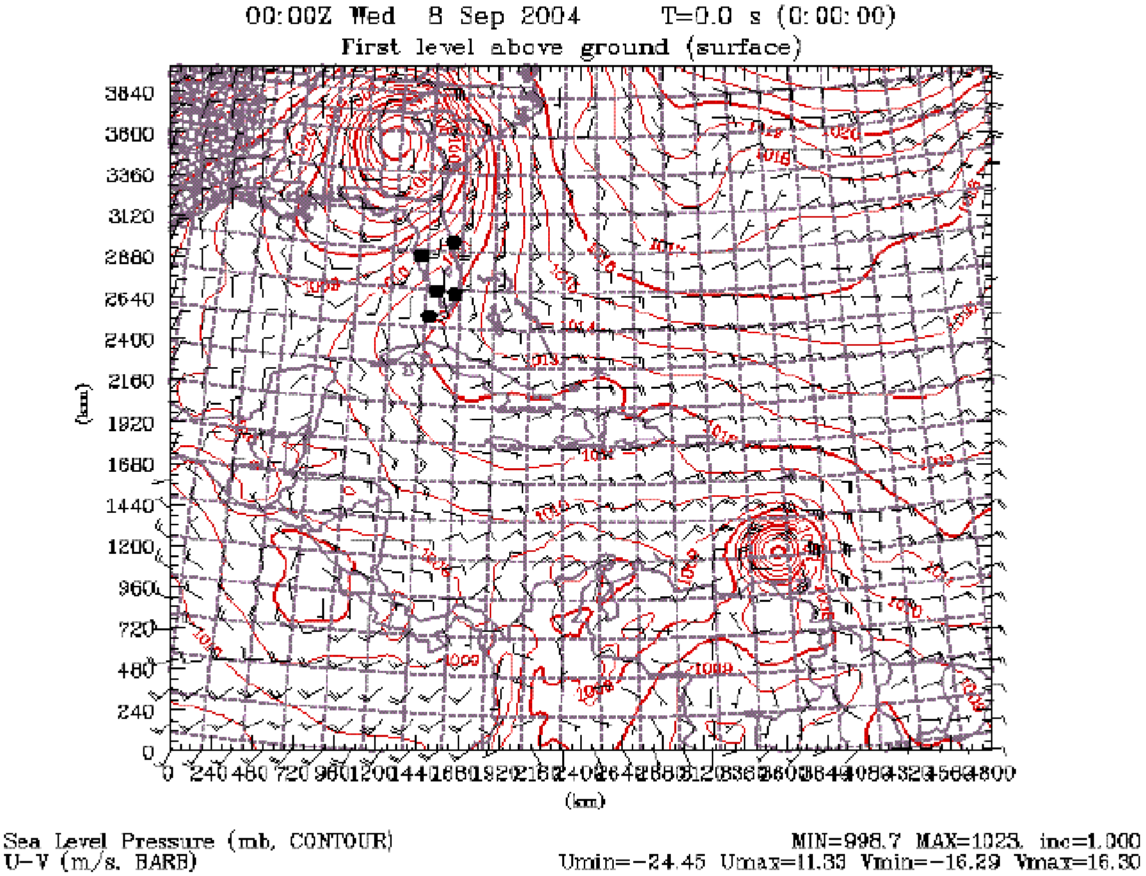

Figure 4. The sea level air pressure at the initial time of 0000 UTC 8 Sep 2004 for the control run CTL. It is directly interpolated from GFS analysis.

The model was integrated for 72 hours at a time step of 15-seconds. It is not surprising that both of the experiments capture the hurricane track much better than the operational GFS global forecasting (Fig. 6). This is mainly because the regional numerical model is non-hydrostatic with explicit cloud/ice-physics parameterizations, cloud-radiation interaction, as well as advanced turbulence schemes, and land-surface interaction. This kind of advanced regional model can better resolve multi-scale atmospheric processes, especially for organized convective cloud systems. A significant improvement in the predicted hurricane track resulted from the use of the observations of the central surface pressure in the initialization of SLP, as shown in Fig. 6. The SLP experiment generated a more realistic hurricane track, especially for the first two forecasts. The results of our sensitivity tests suggest that it is possible to make better predictions of hurricane track by using surface pressure observations/measurements within the targeted tropical cyclone region.

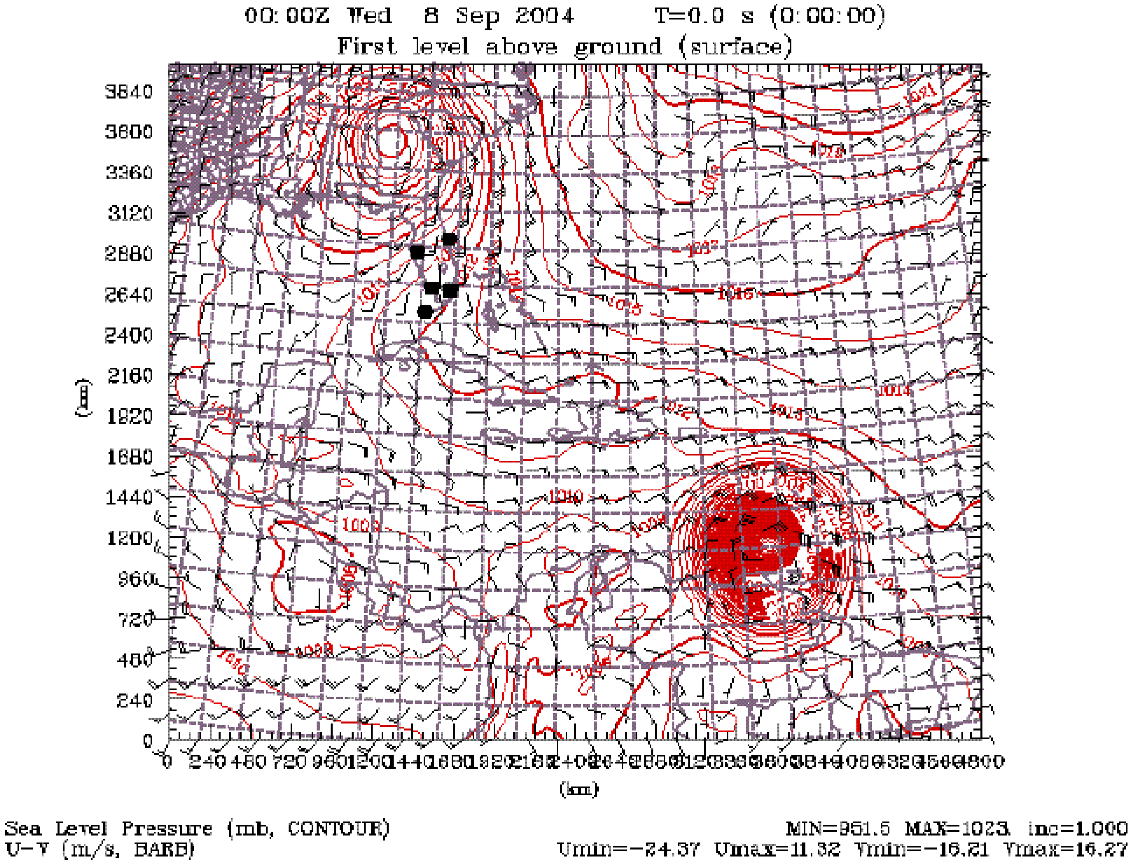

Fig. 5. The sea level pressure at the initial time of 0000 UTC 8 Sep 2004 for the experimental run SLP. The observed central pressure was used for the initialization with GFS analysis as the background.

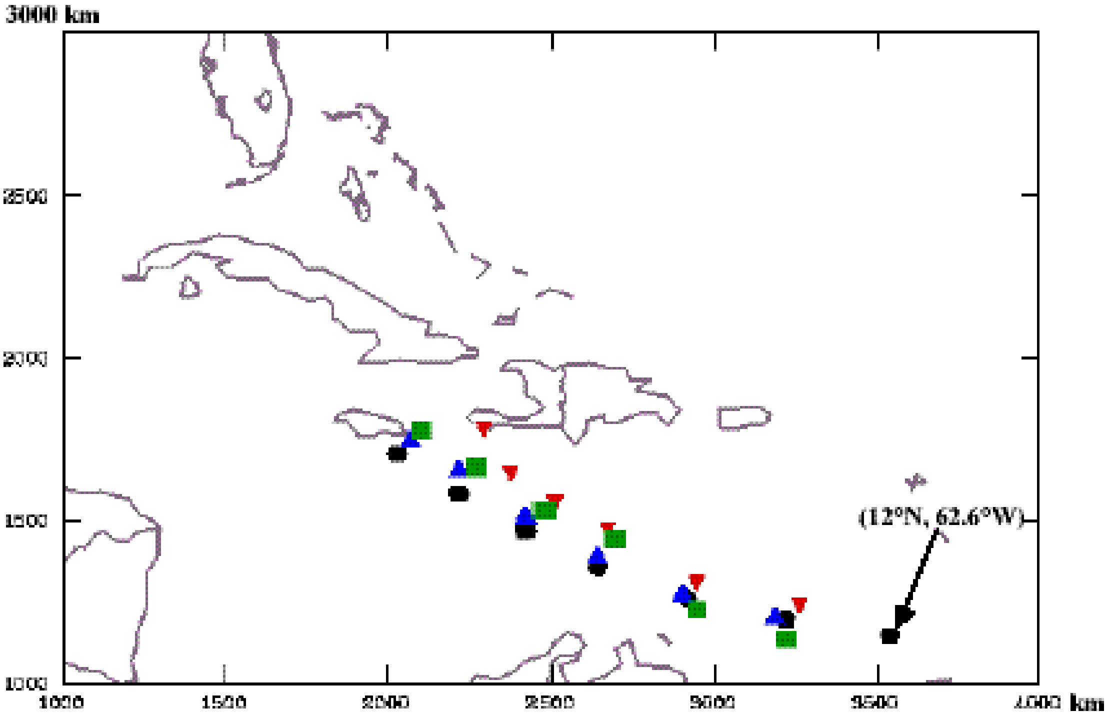

Figure 6. The predicted hurricane tracks from 0000 UTC 8 Sep 2004 to 0000 UTC 11 Sep 2004 for run CTL (green square), run SLP (blue up-triangle), and NOAA/NCEP GFS operational forecast (red down-triangle). The observed best track (black filled-circle) is also shown. The track positions are shown at 12-hour intervals.

2.2 Pressure Fields for Hurricane Forecasts

The results of typical weather predictions for a tropical cyclone, using not only center sea surface air pressures but also large area pressure fields, is shown in Fig. 7 for 1996 hurricane Fran, which occurred from 0000UTC September 3 to 0060 UTC September 6, 1996 (Xiao et al. 2000). Our research team still remembers the pouring rain, windy weather, and floods caused by the hurricane in Hampton Roads. Due to the lack of data, the model standard run (control run; CTL curve) started with a location error of about 100km, and gradually deviated from the observed hurricane track (OBS curve) up to about 350km for the predicted landfall site. With pressure data and calculated wind fields as inputs, the assimilations with 54km (A80 curve) and 18km (B80 curve) spatial resolution significantly reduced the errors in predicted storm tracks. Comparing the 3 day forecasts, the high-resolution model (18 km, B80) had a small starting location error of about 10 km that increased to about 100 km at the predicted landfall site, and the low-resolution model (54 km, A80) had a starting error of about 35 km and predicted landfall with a 170 km error. Such greatly improved predictions could make hurricane preparation and evacuation much easier, especially for the high resolution forecast (B80) case.

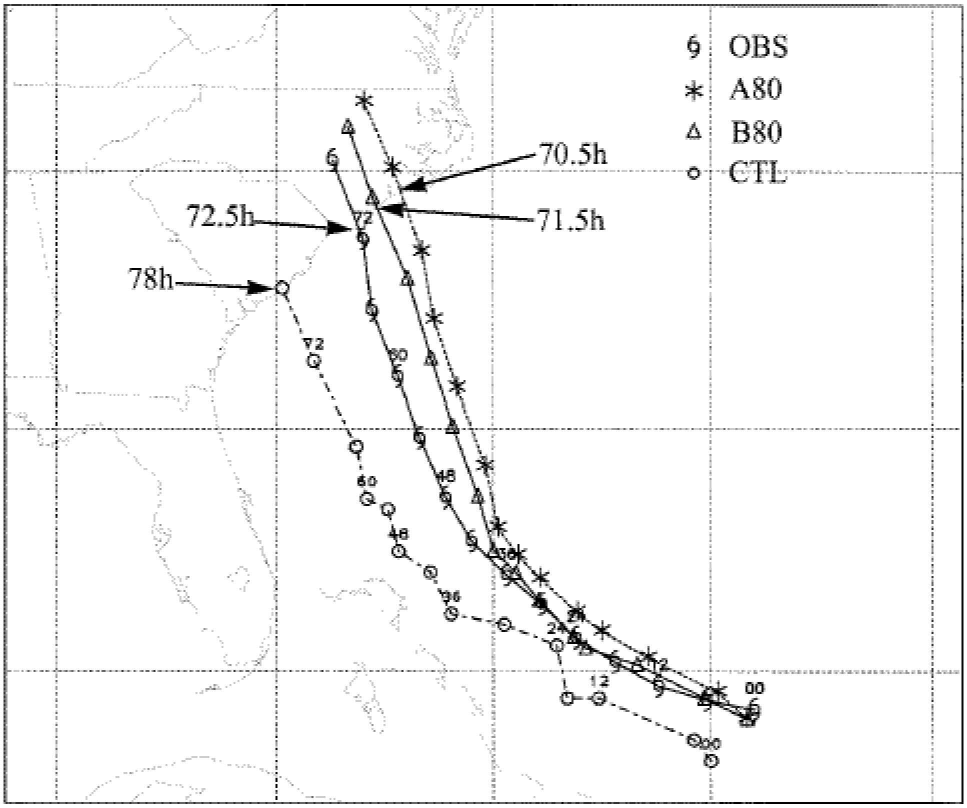

Figure 7 Predicted tracks of 1996 hurricane Fran by CTL, B80, and A80, along with observations, from 0000 UTC 3 Sep to 0600 UTC 6 Sep. Predicted landing times are also indicated in the figure.

Storm intensity predictions can also be improved with knowledge about the storm center pressure, pressure gradients, and derived wind fields. As expected, the intensity of the B80 prediction is very close to observations at the landfall site (*Xiao et al.* 2000). The hurricane eye, rain band, and precipitation intensity determined from radar reflectivity simulations (a) and radar observations (b) are very similar (Fig. 8). The similarity between these predicted hurricane intensity fields, using pressure fields as one of critical initial conditions, and fields based on observations is remarkable and is the result that operational weather forecasters dream of. Unfortunately, there have been no operational, or even experimental, surface air pressure measurements over open oceans from both in-situ and remote sensing instruments, and thus it remains difficult to predict the tracks and intensities of tropical storms with high accuracies (within 100km landfall site for 3-day forecasts).

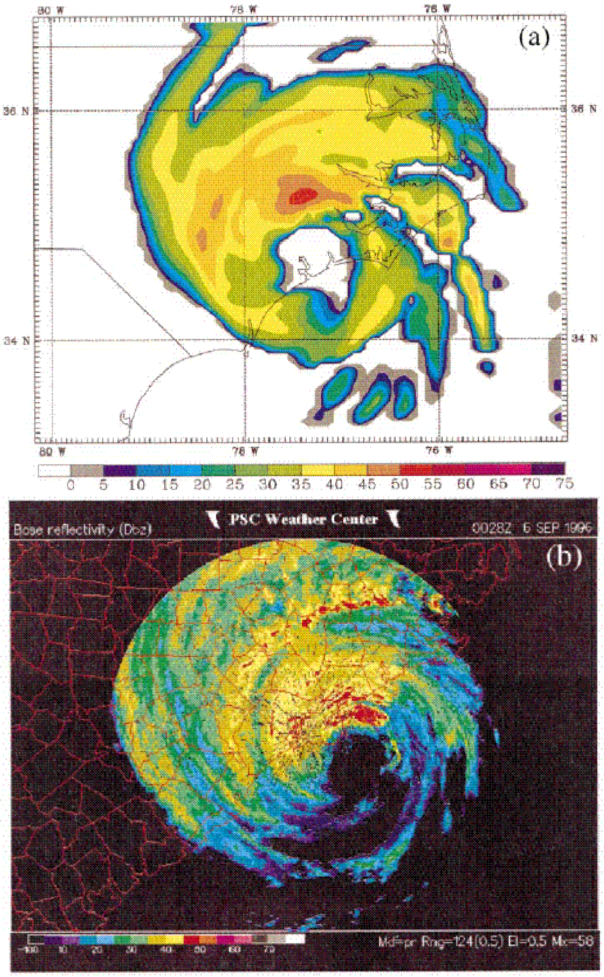

Figure 8. Radar reflectivity (dBZ) (a) predicted by B80 at 0000 UTC 6 Sept 1996 and (b) captured at Wilmington, NC, at 0028 UTC 6 Sept 1996.

3. Assessment of the Improvements for Earth Science

Now we rephrase the first primary RAOBS question: *what Earth-Science Research or Operational improvements – such as reduced measurement costs, increased coverage or repeat rates – could be realized by development of a new instrument that uses RADAR to remotely sense barometric pressure?*

Based on the discussions in the previous sections, the answer to the question is: RAOBS radar systems will fill a gap in remote sensing of sea surface air pressure, and improve weather forecasts, especially for predictions of tropical cyclone intensities and tracks because of the direct relationship between air pressure fields and atmospheric dynamics. The RAOBS technique will dramatically improve the availability of data from the current, sparsely-distributed in situ barometric measurements from buoys and dropsondes to regional and/or large scale observations when airborne and/or space borne, respectively, systems are used. With the maturation of the RAOBS technique, regular regional monitoring of sea surface air pressure, especially over existing and potential tropical cyclone areas, will be realized, providing unprecedented barometric sampling in terms of spatial coverage and repeat rates. For normal airborne systems and regional barometric reconnaissance, the observational coverage and repeat rates will only be dependent on the existing funded flight times that could be shared with the current NOAA weather reconnaissance flights. For the same amount of flight hours, the radar system will cost less than dropsondes, due to expendable nature of the sondes, and it will return many times the data at the same pressure resolution but much higher spatial density. If a UAV is used, the cost of flying RAOBS for the barometric measurements will be significantly lower than that of current operations using in-situ techniques with the accompanying increase in personnel safety. For space borne systems, a repeat rate of twice a day for a single campaign of local measurements is possible. The costs would be minimal compared to any current operational barometric technique applied on the same spatio-temporal scales. Furthermore, simply comparing the costs associated with operational improvements ignores the enormous economic effect of greatly improved weather forecasts for catastrophic events. Using RAOBS to provide barometric measurements to support the forecasting of severe weather can significantly reduce human loss and property damage.

Within NASA's Earth-Science framework of the six Science Focus Areas, potential research and applications users for the radar based barometric measurement datasets are the Weather, Climate Variability and Global Change, and Water and Energy Cycle Focus Areas. The users in the Weather Focus Area are obvious due to direct dynamic influences of barometric measurements. Long-term, large-scale, and improved observations of atmospheric dynamics can also increase the understanding of the variations in large-scale climate phenomena of atmospheric oscillations and teleconnections such as EL Nino, North Atlantic Oscillation and Northern Pacific Oscillation. Furthermore, the knowledge of water vapor and energy transport processes of the atmospheric system will be improved with the observations of the atmospheric dynamics. These improvements will benefit the studies in the Focus Areas of Climate Variability and Global Change and Water and Energy Cycle.

As discussed before, there are three secondary questions associated with the above primary question. We will discuss these secondary questions in the following sub-sections.

3.1 Replacement of Existing Techniques

The 1st secondary question: (a) *What degree of performance (theoretical and practical) can be obtained (vs. state-of-the-art measurements) with the proposed measurement concept? In other words, could sufficient performance be obtained to replace existing instrumentation?*

A simple answer to this question is that currently there are no any operational remote sensing techniques that can be used to measure sea surface air pressure. Even in experimental stage, there is no existing remote sensing method for sea surface barometry. As mentioned previously, simulation studies show that with a reasonable system design, a multiple frequency radar working at the O_2 band (50 ~ 56 GHz) will have a high enough signal-to-noise ratio (SNR) to estimate sea surface air pressure at acceptable spatial resolution. This technique will significantly increase the spatial coverage and temporal repeat rates of pressure measurements compared to current in situ measurement capabilities and instrumentations. The accuracy of the RAOBS measurements will meet requirements of meteorological applications. Thus, the radar pressure estimates can be used for weather forecasts and tropical cyclone predictions. The RAOBS system can fill the current gap in remote sensing of sea surface air pressure and may even result in replacement of currently–existing, sparse-point, in-situ instrumentations. Table 1 lists detailed comparisons between current existing techniques and proposed RAOBS technique.

Table 1 Comparison of existing instruments with RAOBS

	area coverage	repeat rate	resolution	cost	error bar
buoy	sparse	high	~10 m	very high	~ 1 mb
dropsonde	point	flight depend	~ 100 m	high	~ 1 mb
airborne-RAOBS	regional	flight depend	~200m/1km	moderate	~ 4 mb/1mb
satellite-RAOBS	global	2 time/day	~4km/ 1° grid	low	~ 4 mb/1mb

3.2 Improvements

The 2nd secondary question: (b) *What measurement improvements would this approach yield for its users?*

The RAOBS remote sensing technique is a novel concept for sea surface air pressure measurements. The approach of applying remote barometry of center pressure and whole pressure fields of tropical cyclones to improve predictions and forecasts of hurricane intensity and track is also new. Compared to in-situ barometric techniques, such as buoy and dropsonde, the RAOBS will dramatically extend their limited point measurements to regional and/or large scale observations when airborne and/or space borne, respectively, systems are used. Using the RAOBS technique can considerably increase the performance of the measurements not only for spatial coverage but also for temporal repeat rates. In addition to higher repeat rates, the data returned from a satellite would be more valuable because of the concurrence of the data. This would also be true of an airborne system to some extent, because from a high altitude, a large swath of the storm area could be covered in a single flight leg, and full coverage of the storm would take a fraction of the time that it would take to sample it with dropsondes. For normal airborne systems and regional barometric reconnaissance, the observational coverage and repeat rates are generally only dependent on the funded flight times.

3.3 One or More RAOBS Instruments

The 3rd secondary question: (c) *Could one instrument be capable of meeting the user needs, or would different instrument implementations be needed?*

According to our studies (c.f., previous discussions, *Lin and Hu* 2005, and Sections 5 and 6 of this report), a single RAOBS instrument will be able to meet the applications of weather forecasts and hurricane predictions for sea surface air barometry. No other instrumentations will be needed to reach the goal of the air pressure measurements and monitoring. As a practical matter, the value of this system would require that there was some redundancy to the capability, so that in the event of a system failure, there would be a back up. For example, a single satellite-based system might be backed up by an airborne system, and the airborne system could be used to supplement the satellite measurements in special circumstances.

4. Summary of the Part I

This part of the final report assesses a novel concept, namely differential Oxygen absorption radar working at 50~56GHz frequencies, to remotely sense sea surface air pressure. Simulated results (*Lin and Hu* 2005) suggest that the accuracy of surface air pressure estimations from each ratio of reflected radar signals of two different frequency channels (i.e., different O_2 absorptions) could reach ~4 mb over oceans. With multiple measurements in ~10km sea surface spots from the radar echoes, the pressure estimates could be significantly reduced to a few mbs, which is similar to the accuracy of in situ measurements and very useful for operational weather modeling and forecasting.

With the pressure measurements of the center and whole field of tropical storms, our simulations using regional weather forecast models show that the prediction of hurricane tracks and intensities can be significantly improved. For the hurricane Fran case, model prediction reduces the landfall site errors from ~350km in the standard prediction to ~100km for 3 day forecasts, which could make hurricane preparation and evacuation much easier.

In terms of research and/or operational improvements such as reduced measurement costs, increased coverage or repeat rates, the proposed radar system will fill a gap in remote sensing of sea surface air pressure, and improve weather forecasts, especially for predictions of tropical cyclone intensities and tracks because of the direct relationship between air pressure fields and atmospheric dynamics. The radar technique will dramatically extend the current, limited-point (in situ) barometric measurements from buoys and dropsondes to regional and/or large scale observations when airborne and/or space borne, respectively, systems are used. This technique will provide unprecedented barometric measurements in terms of both spatial coverage and repeat rates. The radar costs will be also minimized compared to any current operational barometric techniques for the spatial and temporal scales commonly used in meteorological studies. Furthermore, resulting improvement of weather forecasts using the radar barometric measurements can significantly reduce human and property losses, especially for hurricane cases.

Finally, any techniques, such as RAOBS, used in weather forecast operation have to be validated by field experiments. This is exact the reason why developments of experimental systems are needed. Developments are needed for both aircraft measurements to prove concepts and to validate the actual collection and analysis of the data of sea surface barometric pressure. Once the capability of remotely sensing of barometric pressure is proven to be practical by in-situ measurements and field campaigns, the next validating step is to apply the pressure measurements into weather models to prove model prediction improvements using real-time data, analysis, and forecasts. After these steps, the operational application, then, can be achieved. This may be a long way to go, and is beyond the scope of current study. We will pursue future studies for the RAOBS technique in this direction after the conclusion of this project.

Part II:
Assessments of the Instrumentation Development

5. Theoretical Basis and Model Simulated Retrievals

5.1 Theoretical Basis of Sea Surface Barometry

This study serves as an initial investigation into surface pressure remote sensing. We are going to use a simplified radar signal propagation model to show the basic relationship between O_2-band radar reflected signals and surface pressure measurements in this current section. The actual simulations of radar reflected signals, which utilize complicated microwave radiative transfer (MWRT) calculations accounting for full physical processes of the radar signal propagation, will be discussed in the next section. This simplified model considers atmospheric gas and cloud water absorptions and transmissions of radar signals. This avoids the extreme complexity of analysis of the radar signal propagation for atmospheric and surface scattering conditions. The temperature dependences of microwave absorptions and transmissions for cloud water and atmospheric gases are not included in the current discussion, but will be accounted for in the full MWRT simulations of the next section. Although it is a simple analysis of the radar signal propagation process, analysis will show the fundamental characteristics of the signals with surface pressure. The retrieval method, then, will be developed based upon these characteristics.

Table 2. Spectral characteristics of considered radar systems.

Ch. No.	Pass-band center freq. (GHz)	bandwidth (MHz)	No. bands
1	50.300	161.14	1
2	52.800	380.520	1
3	53.596±0.115	168.20	2
4	54.400	380.54	1
5	54.940	380.56	1
6	55.500	310.34	1

For the initial theoretical consideration of airborne radar remote sensing technology for surface air pressure measurements, we assumed that the radar will operate at the same wavelengths (frequencies: 50–56 GHz) as those of existing passive O_2 band temperature sounders, such as the Advanced Microwave Sounding Unit (AMSU). Investigation showed that the highest frequency AMSU O_2 absorption channels would not be needed. We will show later that the wavelengths around 50–55 GHz are the best choices for O_2 band radars in surface air pressure measurements. The O_2 bands have been used in passive microwave remote sensing for more than two decades, and theoretical uncertainties of radiative transfer processes at the bands are generally small because of dominant line-by-line absorption characteristics and reasonably predictable line-broadening features of the O_2 microwave absorptions at the spectra (Goldberg 1999; Smith et al. 1979; Spencer and Christy 1993). This selection of frequencies also provides strong contrasts for the reflected radar signals from different radar channels to differentiate atmospheric O_2 path lengths (or microwave optical depths of the atmospheric O_2 absorptions) from similar LW and WV absorption characteristics and spatial resolutions to then remove these effects from the reflected radar signals. Since the optical depths at these wavelengths are proportional to atmospheric column O_2 amounts, surface pressure may be estimated from the O_2 amounts, especially when multiple channels are used. Table 2 lists the spectral information of considered sea surface barometric pressure radar systems.

Considering a radar with a transmitted power P_T at wavelength λ and antenna gain G, we obtain the power ΔPs reaching a small surface area Δa at the range R in the viewing angle θ as:

$$\Delta Ps = P_T\, G\, T(\lambda, \theta)\, \Delta a / (4\pi\, R^2(\theta)), \tag{3}$$

where T is the atmospheric transmittance at the radar wavelength. The power ΔPr received by the radar receiver is:

$$\begin{aligned} \Delta P_r &= \Delta Ps\sigma^0(\lambda, \theta)T(\lambda, \theta)A_e/(4\pi\, R^2(\theta)) \\ &= P_T G A_e T^2(\lambda, \theta)\sigma^0(\lambda, \theta)\Delta a/(4\pi R^2(\theta))^2, \end{aligned} \tag{4}$$

where A_e is the effective aperture of the antenna and equal to $\lambda^2 G/(4\pi)$, and σ^0 is the backscattering coefficient of the surface. The total power received by the receiver from all areas covered by radar illuminating angles Θ and Φ can be expressed as:

$$\begin{aligned} P_r(\lambda) &= \frac{P_T G^2 \lambda^2 \sum T^2(\lambda,\theta,\varphi)\sigma^0(\lambda,\theta)\Delta a}{(4\pi)^3 R^4(\theta)} \\ &= \frac{P_T G^2 \lambda^2 \sum T^2(\lambda,\theta)\sigma^0(\lambda,\theta,\varphi)\Delta\phi\Delta\varphi}{(4\pi)^3 R^2(\theta)}, \end{aligned} \tag{5}$$

where the summation (∑) of Δϕ and Δφ integrates over antenna illuminating angles Θ and Φ or over the radar angular beam widths. Note that the product of the angular beam widths, Θ and Φ, is decided by antenna gain (i.e., ΘΦ = 4π/G). When the radar angular beam widths, Θ and Φ, are small enough, the viewing angle, θ, and range, R, can be considered as constants for the integration over radar-illuminated areas. Thus,

$$Pr\ (\lambda) = P_T G^2 \lambda^2\ (4\pi)^{-3}\ T^2(\lambda, \theta)\sigma^0(\lambda, \theta, \varphi)\Theta\Phi/R^2(\theta) \tag{6}$$

or,

$$Pr\ (\lambda) = P_T A_e T^2(\lambda, \theta)\sigma^0(\lambda, \theta, \varphi)/(4\pi R^2(\theta)). \tag{6'}$$

Eqs. 5 and 6 are generalized radar equations of area-extensive targets with simplified atmospheric radiative transfer processes. Since only parameters T, σ^0 and R in the equation 4 are related to environmental conditions, and the rests are associated with radar system designs, the Eq. 6 can be further simplified as:

$$P_r\ (\lambda) = C(\lambda)\ T^2(\lambda, \theta)\sigma^0(\lambda, \theta, \varphi)/R^2(\theta), \tag{7}$$

where $C(\lambda) = P_T A_e/4\pi$ is the radar system parameter varying with the radar wavelength. At nadir (θ = 0), the radar equation can be further simplified as:

$$P_r\ (\lambda) = C(\lambda)\ T^2(\lambda)\sigma^0(\lambda)/R^2. \tag{8}$$

Since under non-precipitation conditions, atmospheric scattering effects on the radar signal propagation are negligible, the major atmospheric agents attenuating the radar signals are O_2, cloud liquid water, and water vapor. Thus,

$$T(\lambda) = \exp\ (-\tau_O-\tau_L-\tau_V) = \exp\ (-\alpha_O O-\alpha_L L-\alpha_V V), \tag{9}$$

where wavelength dependent numbers τ_i and α_i are the atmospheric optical depth and effective absorption coefficient for the atmospheric agent i (i = O, L, or, V) at the radar wavelength, respectively, and O, L, and V are the atmospheric column O_2 amount, cloud liquid water path, and column water vapor, respectively. Note that α_O values are weakly dependent on atmospheric pressure and temperature. We assume these values are only functions of wavelengths to simplify current discussion, and will consider this effect (actually and other radar signal propagation effects) in our next section's simulations.

In the atmosphere, O_2 is generally uniformly mixed with other gases. The column O_2 amount is proportion to column air mass, i.e., $O = M_O A$ where M_O is the mixing ratio of O_2 to total air, and A is the column air mass. Since $A = P_0/g$, where P_0 and g are the surface air pressure and the acceleration of the earth's gravity, respectively, the equation 8 can be expressed as:

$$P_r(\lambda) = \frac{C(\lambda)\sigma^0(\lambda)}{R^2}\exp\left(-\frac{2\alpha_o M_o P_0}{g} - 2\alpha_L L - 2\alpha_v V\right). \qquad (10)$$

When two radar channels with close enough wavelengths λ_1 and λ_2 such as those listed in Table 2 are used, the surface radar backscattering coefficient, liquid water absorption coefficients, and water vapor absorption coefficients are very similar. The ratio of the radar received powers from these two channels, then, is:

$$\frac{P_r(\lambda_1)}{P_r(\lambda_2)} = \frac{C(\lambda_1)}{C(\lambda_2)}\exp\left[-\frac{2(\alpha_o(\lambda_1)-\alpha_o(\lambda_2))M_o P_0}{g}\right]. \qquad (11)$$

This ratio is dominantly decided by the surface air pressure. The temperature and pressure dependences of the effective O_2 absorption coefficients have secondary influences on the spectrum power ratio. Rearranging Eq. 11, we have the surface air pressure as a function of the radar spectrum power ratio:

$$P_0 = \frac{0.5g}{[\alpha_o(\lambda_2) - \alpha_o(\lambda_1)]M_o}\ln\left[\frac{C(\lambda_2)P_r(\lambda_1)}{C(\lambda_1)P_r(\lambda_2)}\right] \qquad (12)$$

or simply written as:

$$\begin{aligned} P_0 &= C_0(\lambda_1, \lambda_2) + C_1(\lambda_1, \lambda_2)\log_e(P_r(\lambda_1)P_r^{-1}(\lambda_2)) \\ &= C_0(\lambda_1, \lambda_2) + C_1(\lambda_1, \lambda_2)\,Ri(\lambda_1, \lambda_2), \qquad (13) \end{aligned}$$

where C_0 and C_1 are the wavelength dependent coefficients of the relationship between the radar spectrum power ratio and surface air pressure, and can be estimated from the radar measurements or theoretical calculations of the radar system design. The $Ri(\lambda_1, \lambda_2)$ value is the logarithm of the radar spectrum ratio at wavelengths λ_1 and λ_2, , i.e.,

$$Ri(\lambda_1, \lambda_2) = \log_e(P_r(\lambda_1)P_r^{-1}(\lambda_2)), \qquad (14).$$

Thus, hereafter, it is called the differential absorption index. In radar engineering, this term usually is written as a subtraction of two logarithmic values that are measured in dB.

From Eq. 13, it can be seen that a simple near-linear relationship between surface air pressure and the differential absorption index is expected from the O_2 band radar data. A linear regression retrieval method for surface pressure estimation is a straightforward result of current analysis. Equation 13 provides the fundamental characteristics of the considered O_2 band radar for surface pressure remote sensing. The simplified analysis here highlights the basic physics of O_2 band surface air pressure remote sensing. Details of the radar system simulation, baseline design, and retrieval accuracy will be discussed in following sections using a full microwave radiative transfer model.

5.2 Model Simulated Results

The technique used to simulate the propagation of radar signals within the atmosphere is based on a plane-parallel, multiple layered atmospheric microwave radiative transfer (MWRT) model that has been used to determine cloud liquid/ice water path, column water vapor, precipitation, land surface emissivity and other parameters over land and oceans (*Lin and Rossow* 1994, 1996, 1997; *Lin et al*. 1998 a & b; *Lin and Minnis* 2000; *Ho et al*. 2003, *Huang et al*. 2005). To avoid complexities of microwave scattering by precipitating hydrometeors and surface backscattering, this study deals only with non-rain weather conditions and homogeneous backgrounds (such as sea surface). Thus, transmission and absorption of radar signals within each atmospheric layer are the major radiative transfer processes considered in the model calculations. For the absorption process, this MWRT model carefully accounts for the temperature and pressure dependences of cloud water and atmospheric gas absorptions (*Lin et al*. 2001). At microwave wavelengths, temperature dependences of gas and water absorptions are significant, and produce some difficulties for MWRT modeling. The several models available to account for gas absorption differ mainly in their treatment of water vapor continuum absorption. The *Liebe* model (1989, i.e., MPM89) was used here. It yields results that differ negligibly from those of the *Rosenkranz* (1998) model at the O_2 bands. Liquid water absorption coefficients were calculated from the empirical water refractive index formulae of *Ray* (1972), which agree well (relative differences < 5%) with those from *Liebe et al.* (1991) for $T > -15°$ C. For colder clouds, the uncertainties in the absorption coefficients could be larger by more than 15% (*Lin et al*. 2001) because of a lack of direct measurements of the refractive index.

Current MWRT model is consistent of 200 constant-thickness layers from surface to 40km. There is virtually no gas absorption above the modeled top-of-atmosphere (TOA) at our considered spectra. The atmospheric profiles of temperature, pressure, humidity and gas amount are obtained from NOAA 1988 (NOAA'88) global radiosonde measurements. This NOAA'88 data set is widely used in radiation simulations and satellite remote sensing (e.g., *Seemann et al*. 2003) and covers both land and oceans. The data set has more than 5000 profiles, and about 1/3 of them are for cloudy skies. In cloudy cases, the NOAA'88 profiles can have up to two layers of clouds. Thus, the simulated results represent both clear and cloudy conditions. Since the model TOA (40km) height is much higher than that of radiosonde measurements, whenever there are no radiosonde upper atmospheric observations, interpolated climatological values of the upper atmosphere (*McClatchey et al.* 1972) are used. The weighting functions for the interpolation are decided from the surface air temperatures and pressures to meet the radiosonde measured weather conditions. In order to have large variations in surface air pressure, for each NOAA'88 measured profile, the surface pressure is randomly shifted by a Gaussian number with standard deviation 12mb, and the ratio of the shifted surface air pressure to the measured surface pressure is calculated. The atmospheric pressures in the measured profile above the surface are, then, adjusted to the values using the same ratio as that of the surface pressure.

For the analysis in this section, the radar system is assumed to fly on an aircraft at

15 km altitude with velocity 200 m/s, downward-looking and having a beamwidth of 3°, which produces a footprint of 785 m, and narrowband channels as shown in Table 2. The NOAA hurricane reconnaissance aircraft generally fly above 10 km height through and/or over hurricanes. Since this study is the first step in the model simulations for the radar system to show feasibility of the radar remote sensing for sea surface barometry, the 15 km altitude simulations provide us sufficient theoretical and technical insights for the radar sea surface pressure measurements. For other altitudes, the radar retrievals should have similar accuracy to those simulated here. During our simulation, since all wavelengths used in the radar system are very close to each other, we assume the surface reflection (or σ^0) to be the same (11 dB) for all frequency channels (*Callahan et al*. 1994). As we have showed in the previous section, the absolute magnitude of the surface reflectivity is not very important for surface pressure estimation as long as the spectrum dependence of σ^0 within the O_2 bands is negligible or even the ratios of the reflectivity in different spectra vary by very small amounts (c.f., Eqs. 10~13).

Simulated signals are analyzed in the form of relative received power (RRP), i.e., the ratio of the received and transmitted powers of the considered radar system. Since the system works at the O_2 absorption bands, the relative received powers are generally weak. Certain signal coding techniques for carrier frequencies, correlators for signal receiving and long-time (0.2s) averages of received powers are useful components for consideration for the radar system. Preliminary studies have disclosed advantages from a number of commonly employed radar techniques. A common binary, biphase pseudo-random noise coding with ~1μs code chip may provide reasonable signal strengths for a bit of radar transmission at the potential cost of a larger ground spot size. More detailed discussions on the system design and measurement scenario under certain orbiting and sub-orbiting conditions can be found in the following sections of this report. We focus on the RAOBS retrievals from radar signals to geophysical parameters (i.e., sea surface pressure).

The radar-received signals reflected from sea surfaces, i.e. RRP values, used in this section are simulated through the complicated MWRT calculations discussed previously. With the RRP values, we calculate the radar differential absorption index discussed in the previous section (Section 5.1). As shown in the Section 5.1, the index and sea surface air pressure have a near-linear relationship, which points out the basic directions and sensitivities for surface air pressure remote sensing.

Atmospheric extinctions (or attenuations) vary dramatically at the O_2 band radar frequencies listed in Table 2. The higher the frequency, the stronger the O_2 absorptions are at these wavelengths. At the lowest frequency (50.3GHz), the atmospheric extinction optical depth is about 0.5, and at the highest frequency (55.5GHz), the optical depth goes sharply up to about 9. These two frequency cases represent the two extreme ends of weak and strong, respectively, atmospheric O_2 absorptions for our considered active microwave remote sensing of sea surface barometric pressure. With a weak O_2 absorption (i.e., small optical depth) radar signals would have significant influence from environments, such as atmospheric water vapor, cloud water amount and atmospheric temperature profile but transmitted powers used might be lower. While the atmospheric O_2 absorption is too strong, most of radar-transmitted powers would be close to attenuation, and small changes in surface air pressure (or column O_2 amount) would not produce significant differences in the received powers. This might be offset somewhat by using higher transmitted power. Thus at constant transmitter power levels, wavelengths with moderate to reasonably strong O_2 absorptions in the atmosphere are expected to serve our purpose best by giving a reasonable compromise between transmission and visibility.

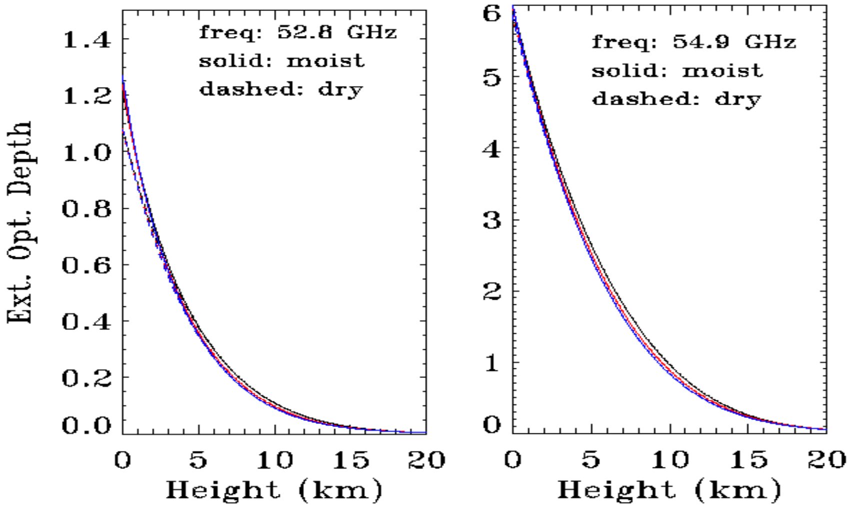

Figure 9 Atmospheric extinction optical depths for various atmospheric temperatures and moisture levels at 52.8 and 54.9 GHz.

Figure 9 shows examples of atmospheric extinction optical depths counted from TOA under clear conditions using the standard profiles (*McClatchey et al.* 1972). The three different color curves represent atmospheric surface temperatures of 280, 290 and 300K, respectively. It can be seen that these curves are very close each other, indicating atmospheric temperature effects are minimal. For channel 2 (i.e. 52.8GHz, left panel) cases, the optical depths for moist atmospheres (solid curves) with 40mm column water vapor are about 1.25 and only 0.1 higher than those of dry atmospheres. At 54.9GHz (right panel), the optical depths are increased considerably to about 6, and different temperature and moisture conditions have little effect on the total extinctions. For this frequency, the atmospheric extinctions of radar received signals due to double atmospheric path lengths reach about 50dB. This may require enhancements to the radar signals to control end to end noise, as mentioned before. For tropical meteorological cases, such as hurricane cases, the changes in temperature and moisture profiles are even much smaller than those shown in the figure due to limited temperature and humidity conditions for the tropical storm development. Generally, the atmospheric O_2 absorptions for channels 2 to 5 are at reasonable level for surface pressure remote sensing. To test accuracies of surface pressure measurements, a 15 dB SNR (signal-to-noise ratio) for radar-received signals is assumed for this primary study.

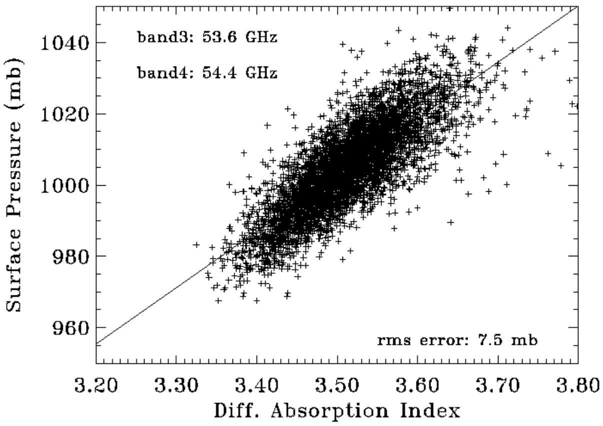

Figure 10. Simulated relationship between the differential absorption index, the logarithm of the radar spectrum ratio at wavelengths 53.6 and 54.4 GHz (or channels 3 and 4), and surface air pressure.

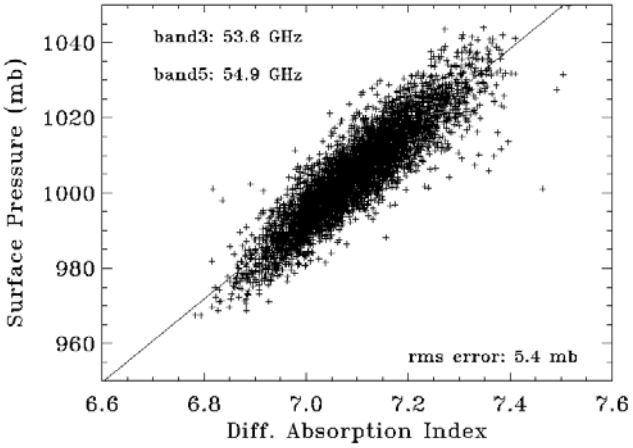

Figure 11. Similar to Fig. 10, except frequencies are changed to 53.6 and 54.9 GHz, or Channels 3 and 5.

Figure 10 shows the simulated relationship between the differential absorption index (the logarithm of the radar return ratio of relative received powers at wavelengths 53.6 and 54.4 GHz (or channels 3 and 4); c.f. Eqs. 13 and 14) and sea surface air pressure. Each point in the figure represents one adjusted NOAA'88 profile. As discussed in the Section 5.1, good linear correlations of the two variables are further established by these simulations. A linear regression gives the root mean square (rms) error in sea surface air pressure estimates about 7.5 mb, which may be suitable for normal meteorological uses. For channels 3 and 5 (Fig. 11), simulated results (5.4 mb) are close to current theoretical O_2 A-band results. The best results (in Fig. 12) we found are those from the differential absorption index of channels 2 and 5. The rms error in this case is about 4.1 mb, which may be better than most other proposed leading remote sensing techniques for sea surface air measurements. The tight linear relation between the sea surface air pressure and differential absorption index provides a great potential of remote sensing surface air pressure from airborne radar systems. Note that in Figs. 10~12, the dynamic range of sea surface barometric pressure is only from ~ 960mb to ~1050mb.

The low end of the dynamic range of the sea surface pressure is significantly higher than some sea surface air pressures of hurricane centers. NOAA 1988 profiles were measured in generally average weather and meteorological environments, and were not taken from tropical storm cases. Thus, there were no extreme low sea surface air pressures in the NOAA data set. Actually, for tropical storm cases, the signal strength and SNR of the radar measurements at all O_2 band channels would be higher than those in normal conditions due to low atmospheric radar attenuation caused by low O_2 amounts (or the low hurricane center pressures). Also, the hurricane centers are generally clear skies. So, the accuracy of radar retrievals of the sea surface barometric pressure for hurricane center cases would be higher than those shown in the figures. The key to reach high accuracies of sea surface barometric pressure measurements is to have a high SNR of radar received powers reflected from sea surfaces.

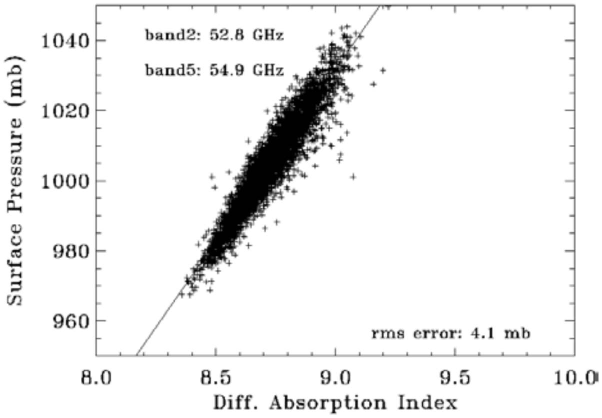

Figure 12. Same as Fig. 10, except for 52.8 and 54.9GHz or Channels 2 and 5.

This theoretical and modeling study establishes a remote sensing method for sea surface air pressure. Simulated results show that with an airborne radar working at about 53~55GHz O_2 absorption bands, the rms errors of the radar surface pressure estimations can be as small as 4~7mb. The considered radar systems should at least have 2 frequency channels to obtain the relative received power ratios of the two wavelengths. For the best simulated combination of 52.8 and 54.9 GHz channels, the power loss of radar received signals due to dual atmospheric path length absorptions could be as high as about 50 dB. High signal-to-noise ratios for radar reflected powers after these atmospheric absorptions can be achieved by using modern radar technologies as shown in the following sections. As indicated in the Part I of this report, radar systems have great potential for weather observations and numerical weather forecasts, especially for prediction of hurricane tracks and intensities. Initial studies on detailed radar system parameters will be presented in following sections.

6. RAOBS System Development

6.1. Objectives and Requirements

6.1.1. Operational scenario

The operational flight environment for a RAOBS instrument will be similar to those of current operational hurricane monitoring systems. The NOAA hurricane reconnaissance aircraft generally fly above 10km height through and over hurricanes. Therefore, the expected environment for RAOBS measurements is a high altitude (>10km) tropical or mid-latitude-summer atmosphere. At the extreme, an airborne RAOBS system will fly at 22km altitude, and the radar signal will experience almost the entire tropospheric O_2 absorption. Thus, our system design is for a 22 km flight altitude, and it will also work for lower altitudes where the high O_2 microwave absorption will be less of a problem. Due to progress in applying unmanned aerial vehicles (UAV) for tropical storm monitoring (such as the Hurricane Tracker), this report considers both manned and UAV airborne platforms. Compared to normal aircraft, the main disadvantages of a UAV are limitations in the weight, size and power for payloads.

Table 3. Airborne platforms for the proposed RAOBS

	Regular Airborne	**UAV**
Coverage	regional	regional
Repeat Rate	flight dependent	flight dependent
Altitude	15 – 22 km	~22 km
Potential Platform	Hurricane Hunter, ER-2	Hurricane Tracker
Velocity	150 – 300 m/s	~100 m/s
Resolution	200m - 1km	200m - 1km
Weight	moderate	very light - moderate
Error Bar	~4mb / 1mb	~4mb / 1mb
Environment	troposphere	troposphere

6.1.2. Signal-to-Noise

A key operational characteristic and a determining factor in most design tradeoffs for the RAOBS system is the signal-to-noise ratio or SNR. SNR is a function of a number of factors, and sufficient SNR is required to make an accurate retrieval of surface pressure. The principle of operation for this instrument is transmission of frequencies on the O_2 absorption band from 50 ~ 56 GHz. Six frequency channels have been defined, and the calculation of surface pressure requires the use of at least two separate channels. Atmospheric path loss increases dramatically with frequency, so that the highest channels are most likely to experience low SNR. The differential absorption between adjacent channels also increases with frequency, making the higher channels more desirable for use in the calculation of pressure. As a result, the RAOBS system seeks to obtain a good SNR in the highest channel possible.

The primary interference to the RAOBS signal is noise. Assuming there are no incursions into the signal path by objects such as aircraft, the sea surface will be the only reflector in the beam. Interference from the sidelobes will be negligible in general, with the exception that a highly-reflective target, such as an aircraft, in a sidelobe could result in significant interference. Theses events will be transient and rare, and they are not considered a problem. Energy transmitted in the sidelobes will be subject to the lower antenna gain in the sidelobes and arrive at the sea surface at a large angle, such that only a small part of the reflected energy will return in the direction of the antenna. Therefore sidelobe energy will be well below the noise.

The signal-to-noise objective for RAOBS is established by performing the pressure calculation with data subject to particular SNR values (Section 5.2, Figures 10 - 12). In these simulations, the higher channel of the pressure retrieval channel pairs is assumed to be at a particular SNR, and the SNRs of the lower channels are higher due to the difference in path loss. Results show that an SNR of 15 dB (in the higher channel of frequency pairs used for the pressure calculation) is more than sufficient to support the accurate (~1 mb) calculation of pressure in 1°×1° gridbox. While an exhaustive study of the tradeoffs between SNR and other factors like differential loss has not been conducted, calculations have been made with lower SNRs to understand the tradeoffs.

The following three figures (Figs. 13 - 15) show simulated results for sea surface pressure retrievals in a tropical environment (sea surface temperature > 298K) from top-of-the-atmosphere RAOBS measurements. These results are obtained for an SNR at channel 4 of 5 dB. Other channels (1 – 3) have higher SNRs due to decreasing O_2 absorption of the signal. The 5 dB assumption is significantly different from what was discussed in Section 5.2 and what has been presented in previous writings; however, it is not unrealistic in terms of engineering a baseline system.

It can be seen in Fig. 13, that due to noisier signals (SNR = 5 dB) at channel 4 the pressure estimates have large errors. Weak signals at higher channel (Ch. 4) cause very small values of the power ratios of the two different channels, generate very large absolute differential absorption indexes, and, thus, produce large errors in the pressure retrievals. In this low SNR case, channels with clean signals provide better results (Figs. 14 and 15), although these channels have weaker O_2 absorption and there is less differential absorption between adjacent channels. With cleaner signals (higher SNRs) the stronger O_2 absorption frequencies give the best retrievals (channel 2 & 3 combination), and the errors are about 5.5 mb. For hurricane cases with ~10 km hurricane eyes, 1 km spatial resolution (see Section 6.1.3 next) and using retrievals of both pairs, channels 1 & 3 and 2 & 3, the errors are reduced to about 5.7 mb/sqrt(20) = ~1.3 mb for single flight track. This is a very accurate measurement for hurricane forecasts when the variability in the pressure can be greater than 120 mb (from ~1020 to ~900 mb) and even close to in situ measurements.

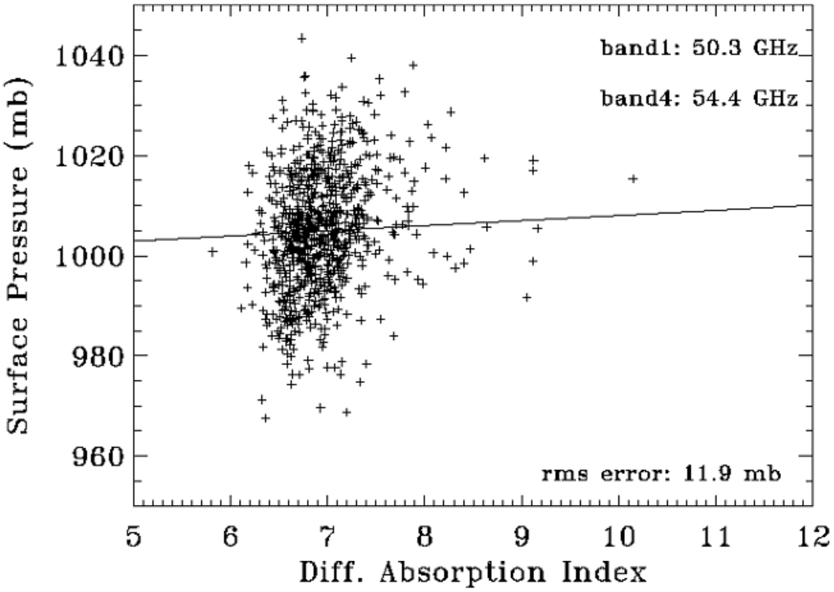

Figure 13. Surface air pressure calculated using channels 1 and 4 where the SNRs are 46 dB and 5 dB, respectively.

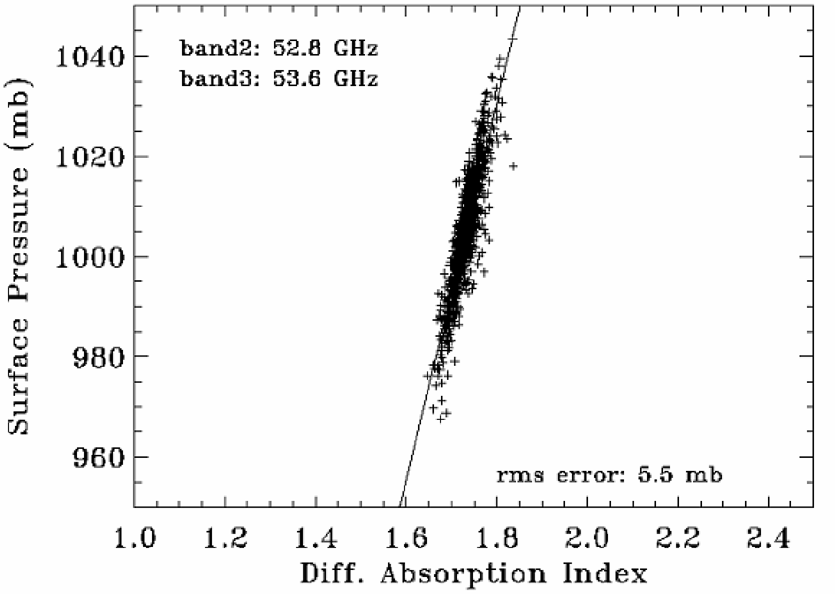

Figure 14. Surface air pressure calculated using channels 2 and 3 where the SNRs are 39 dB and 31 dB, respectively.

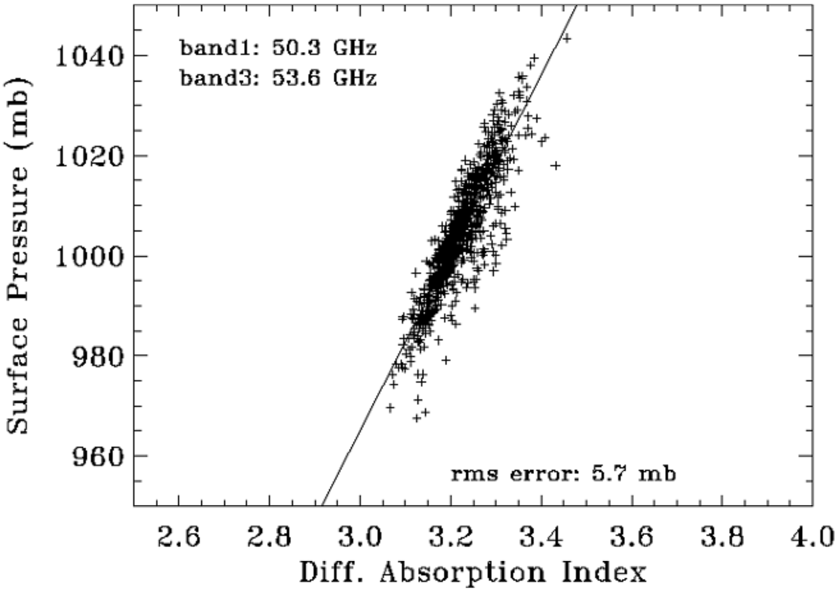

Figure 15. Surface air pressure calculated using channels 1 and 3 where the SNRs are 46 dB and 31 dB, respectively.

It has been shown that a 15 dB SNR provides an excellent estimate of surface pressure and that a calculation using adjacent channels with more differential path loss provides better estimates. Furthermore, the differential in loss increases with frequency. Thus we would like to use the higher channels for the measurement due to high loss differential, but we require a minimum SNR of 5 dB for usefulness and a 15 dB SNR for a robust measurement. The problem remains to determine what the design goal should be with respect to SNR. Based on radar system studies, a 15 dB SNR is achievable for channel 4 with some compromise in other design factors. The instrument will have useful performance with a SNR of only 5 dB in channel 4, so setting the design objective to be a 15 dB SNR in channel 4 promises excellent instrument performance with a 10 dB margin. This design objective is a compromise in that channels 5 and 6 are expected to be unusable, although channel 5 might have a small positive SNR. Channels 5 and 6 are not necessary for our performance goal.

6.1.3. Spatial resolution and pointing

In order for the RAOBS measurement resolution to be commensurate with those of other instruments, the desired spatial resolution is 1 km or less. Some satellite-based instruments have spatial resolutions in the neighborhood of 4 km (e.g. CloudSat CPR and TRMM PR), so 1 km resolution is not a firm requirement but is considered an obtainable objective commensurate with an airborne platform. Using larger antennas with higher gain improves resolution and the theoretical SNR; however, as the beam gets narrower and the reflecting spot on the ground becomes smaller, the measurement system will become highly sensitive to antenna pointing and to the stability of the platform. In addition, the nature of the sea surface as a reflector is based on the assumption that sea state is statistically stable, i.e., no changes in the sea surface reflection within the time of measurements for all channels. This assumption relies on the spot being significantly larger than the surface features. To avoid these issues, it is desirable to consider 200 m as the lower limit on spot diameter and to realize that as the spot size diminishes pointing issues can arise.

Resolution is not solely a function of spot size and antenna beamwidth. To improve SNR, multiple pulses will be integrated. Because the platform is moving, the beam moves during and between pulses so that the integration process averages the measurement over some along-track distance. In this design, the along-track resolution is taken as the resolution figure of merit, and it will equal the spot diameter plus the along-track movement (Fig. 16).

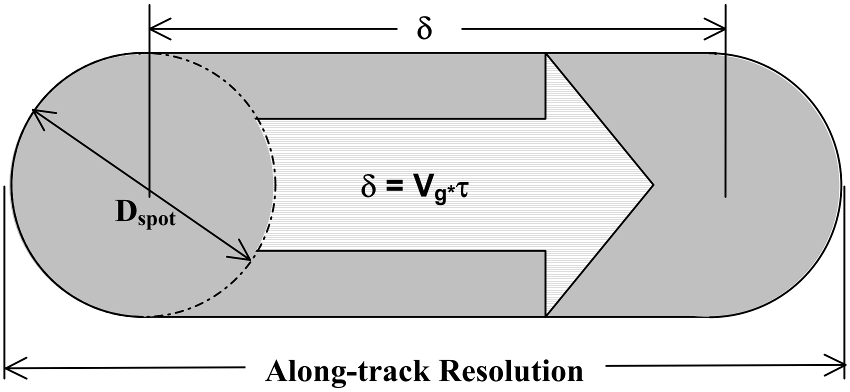

Figure 16. Along-track resolution is the sum of the spot diameter and the distance traveled by the platform during the pulse, or if pulse integration is used, during the integration time.

6.1.4. Platform factors

A normal, piloted aircraft, such as the Hurricane Hunter, has been chosen for this design. In general, the RAOBS instrument will not be unusual in its physical requirements, and weight, volume and power are not expected to be a problem. The design presented here is based on some assumptions about the platform, but fixed physical limits were not imposed. There is flexibility in the design and it can be adapted or optimized for a specific platform when one is chosen. The choice of a UAV platform would likely impose some physical constraints, because UAVs vary greatly in terms of size and capacity, but it is expected that a large UAV could accommodate the RAOBS instrument with proper adaptation.

There are factors associated with the platform that affect the instrument design, including packaging and layout. Space will be required to accommodate a control/data-recording computer, a control interface, and radio frequency (RF) electronics. A typical equipment rack could be used. The waveguide runs between the transmitter/receiver and the antenna will have to be minimized to control loss, so the system might be split in order to locate RF electronics near the antenna. Such physical details would be determined based on the platform selected.

The antenna required by RAOBS, about a half meter diameter, is not overly large, but it is significant. It will either be mounted externally or require a penetration to look downward. In the simplest case, it will be mounted statically, and no active pointing will be used. In this case, platform stability will be important, and aircraft pitch and roll stabilization will be necessary during data collection. Without active pointing, periods of maneuvering will not be useful for data collection, and data flights would have to be planned accordingly.

Platform velocity is an interesting factor in the instrument design. Due to platform motion, the resolution objective of 1 km applies a constraint on integration time. In addition, platform movement affects the target so that it is less stationary over time and the coherency of the integration process is reduced. The integration process may become less efficient, reducing the available improvement in SNR. Since the resolution equals the sum of spot diameter and movement during integration (Fig. 16), a smaller spot allows longer integration and implies a higher antenna gain, both factors that can increase SNR. At the same time, using a small spot and longer integration decreases the integration efficiency and increases pointing sensitivity. Furthermore, the spot diameter that results good resolution and pointing sensitivity when flying at 22 km will be proportionally reduced at lower flight altitudes, which may become a problem. Since there is flexibility in the design, tradeoffs such as these can be made for a specific platform when it is chosen.

6.2. RAOBS Baseline Design

6.2.1. Background

This section of the report describes the methods and results of the instrument performance modeling performed to date. The conceptual RAOBS system requires the measurement of the reflected signal strength from two frequencies between 50-55 GHz including the propagation and attenuation through the atmosphere. This instrument concept does not specify whether these frequencies are transmitted serially or simultaneously, so for the purposes of these analyses we treat them as separate events since that will stress the performance requirements the most. Additionally, although a wide variety of platform and sensor design scenarios were investigated, this report focuses on the high altitude airborne application and an instrument point design that is commensurate with Commercial off the Shelve (COTS) equipment.

While the ultimate performance metric for the RAOBS instrument is measured against atmospheric surface pressure, the fundamental measurement performed by the instrument is the detection and quantification (i.e., measurement) of the reflected power received for each frequency transmitted. The standard metric for the detection of a transmitted/reflected signal is Signal-to-Noise Ratio (SNR). Therefore the underlying performance metric for the RAOBS concept is the SNR for the radar-portion of the instrument.

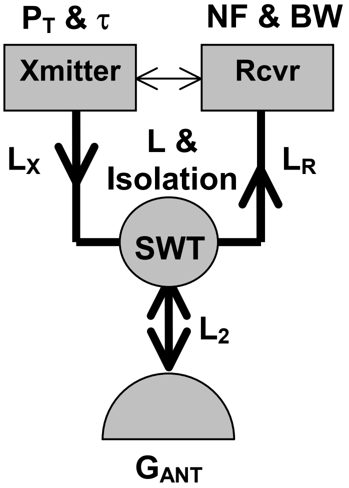

Figure 17. Basic Radar Components

Any radar system can be conceived as a transmitter and a receiver linked and synchronized with timing signals; antenna(s) to direct the electromagnetic energy; and waveguide/wires, switches/isolators, and other discrete components required to control, transfer, and route the electromagnetic signals during the system's operation. A simple block diagram of these components is shown in Figure 17 (the symbols are defined below in section 6.2.2). In addition to the radar itself there are signal and/or data processing units that are often embedded within the radar; however, for the purposes of these analyses the radar system only consists of the electronics required to transmit, receive, and measure the signal strength of the reflected signal(s). Additional possessing is required to compute atmospheric surface pressure based upon the RAOBS algorithms described previously in this report (Section 5). This additional processing and the hardware required to perform it will not affect the SNR of this system, so it is not considered a limiting factor for the overall RAOBS performance and therefore is not discussed further in this report.

Additionally, it is useful to know that two different radar design engineers at NASA Langley Research Center (LaRC) took independent paths, developed independent models, and produced their own RAOBS instrument designs that were then briefed to the RAOBS team. Interestingly, there were almost no substantial differences between the designs and the results of their analyses. What minor differences did exist, were discussed and reconciled. The following is the discussion of the findings from the system design.

6.2.2. Basic equations

For pulsed radar the fundamental parameters that define the system's performance (i.e. SNR) as shown in Figure 17 are: peak power (P_T), pulse width (τ), noise figure (NF), band width (BW), antenna gain (G_{ANT}), and the individual path losses (L_X, L_R, & L_2). The radar equation describes how the power received (P_R) is calculated from these fundamental parameters. In simplified form the radar equation is,

$$P_R = \frac{P_T G_{ANT}^2 \lambda^2 L_{sys}}{(4\pi)^3 R^4}\sigma$$

where P_R is the power received, G_{ANT} is the gain of the antenna, λ is the wavelength of the signal, R is the one-way range from the radar to the scatterer, σ is the effective radar cross section of the scatterer, and L_{sys} is the loss in the system. This equation has been presented by numerous authors (e.g. *Skolnik*, 1970). The system loss term includes all losses including attenuation by the atmosphere; it can be expressed as,

$$L_{sys} = (L_X + L_2)*(L_R + L_2)*(L_{ant})^2*(L_{radome})^2*(L_{atm})^2$$

where L_X is the loss in the transmission path to the isolator/switch, L_R is the path from the isolator/switch to the receiver, L_2 is the loss from the isolator/switch to the antenna, L_{ant} is the loss in the antenna subsystem, L_{radome} is the one-way loss through the radome, and L_{atm} is the loss associated with absorption of the signal as it propagates through the atmosphere. This last term is what RAOBS exploits to measure atmospheric pressure. This expanded radar equation is used to calculate the strength of the reflected signal in the SNR calculation.

All electronics exhibit some electrical noise which competes with the signal during detection. The quality metric for receivers is noise temperature since the basic equation for the noise level in the electronics is given by (*Skolnik*, 1970),

$$P_N = k\ B_N T_N$$

where k is Boltzmann's constant (1.38×10^{-23} J/K), B_N is the noise bandwidth, and T_N is the noise temperature of the system. It is useful to note that T_N is not the actual temperature of the electronics; instead, it is an effective temperature based upon the actual amount of electrical noise measured. The term noise figure (NF) is often used to avoid confusion, where NF = T_N/T_0 and T_0 = 290K. Noise figures are generally expressed in decibels, i.e. $10*LOG_{10}(T_N/T_0)$.

Receivers use a matched filter prior to detection in order to maximize the signal strength. This filter is matched to the expected returns characteristics; specifically, to the bandwidth of modulation signal. For radar's with a square pulse this has been shown (*Skolnik*, 1970) to occur for 1.4/τ. Using these expressions in the noise power equation results in,

$$P_N = \frac{1.4\, k\, (NF)\, T_0}{\tau}$$

This equation is used to compute the noise power used in the SNR calculation. The ratio of the power received divided by the noise power produces the SNR and is given by,

$$SNR = \frac{P_T \tau\sigma}{R^4} \frac{G_{ANT}^2 \lambda^2}{(4\pi)^3} \frac{L_{sys}}{1.4k\, T_0 (NF)}$$

This is the equation that was used to estimate the SNR for all scenarios and the trade-offs between all the design parameters. Naturally most SNR values are quoted and discussed as decibels which is obtained by $10*LOG_{10}(SNR)$.

6.2.3. RAOBS baseline design

In order to calculate SNR, values for all the radar parameters must be estimated (i.e. define the waveform and hardware characteristics). While this path is straightforward, there are numerous avenues and side-streets that can and needed to be explored in order to produce a baseline design that both meets the current requirements and offers growth and/or additional capabilities.

The initial designs used classical waveforms and hardware characteristics to establish a baseline design and system performance. The baseline design used specifications from existing COTS hardware. This baseline design was used to perform a design trade-off study and performance assessment. Only small deviations from this baseline system were considered, primarily because major changes did not appear to be warranted based upon SNR calculations. Additionally, the performance estimates for all the system's characteristics were conservative, suggesting additional margin maybe expected. The following table summarizes the RAOBS baseline design which meets the SNR and resolution requirements for an aircraft flying at 22km altitude and a ground speed of 600kts (~ 300m/s or less).

Table 4 RAOBS Baseline Pulse Radar Parameters

TRANSMITTER		ANTENNA		RECEIVER	
P_T (dBm)	20	D_{ANT} (m)	0.5	NF (dB)	4
τ (μs)	140	G_{ANT} (dBi)	45^+	CPI (pulses)	1024
PRI (μs)	282	D_{spot} (m)	300	L_{sys}	2.5
No. of channels	4	σ^0	-10	No. of channels	4

6.2.4. RAOBS baseline design trade-off

A quick inspection of the SNR equation reveals that most of the terms in the equation increase/decrease SNR linearly; that is, doubling/halving any of these terms will double/halve the resulting SNR. All SNR comparisons are made for a common altitude and at the same wavelength; thus, the only exception to the linearity rule is antenna gain. So the natural response is to increase antenna gain, which is accomplished by increasing the antenna diameter. But increasing the antenna diameter also decreases the beam width which reduces the spot diameter and therefore the signal strength. So these two factors drive the antenna diameter in opposite directions and that suggest that an optimum diameter may exist. However, a quick calculation of G_{ANT} and σ shows these two terms change at exactly the same rate with antenna diameter. Since G_{ANT} is squared in the SNR equation, this term produces twice the affect on SNR and thus drives the designer to ever larger antenna diameters, limited only by platform constraints.

All of the RAOBS SNR calculations are performed using -10 dB for NRCS. There are few to no actual measurements of the sea surface reflectivity at 50-60 GHz; however, the conductivity of sea water should not be substantially different than the conductivity of sea water at 35 or 90 GHz where data does exists (*Currie, Hayes, and Trebits*, 1992; *Ulaby Moore, and Fung*, 1981). So an interpolated NRCS was determined from measurements made at 35 and 94 GHz. While this technique can produce a reasonable result, it must be emphasized that the NRCS used is an estimate and represents the weakest part of these analyses. If wrong, it will directly and linearly impact the SNR results, decibel for decibel of improvement or degradation. An analysis for the surface reflection based on rough sea surface statistical model (*Lin et al.* 1999) shows that this NRCS is consistent with current understanding of ocean surface microwave reflectivity. Furthermore, passive microwave measurements at these O_2 bands using MSU and AMSU show that the sea surface emission (i.e., 1 – reflection) at these bands is within the range of those of 37 and 85 GHz channels. Thus, the interpolation of the sea surface reflection at these wavelengths from the values at 35 and 94 GHz should be a reasonable solution for the NRCS value. Validation/determination of this value will be one of the primary scientific results of the proposed flight tests of a proof-of-concept RAOBS in 2007.

In addition to these parameters, estimates for transmitter power and receiver noise were also needed to calculate SNR. The RAOBS team decided to begin the design process by using the specifications from a laboratory-grade RAOBS instrument currently being developed under Creativity and Innovation program at NASA Langley. This system is being developed using an Agilent E8362B Vector Network Analyzer as the transmitter/receiver. The manufacturer claims 20 dBm transmit power and a noise figure of 7 dB. Subsequently we have found COTS hardware that claims as much as 35 dBm and noise figures below 4 dB; however, the RAOBS team decided to use 20 dBm for transmitted power and 4 dB as the noise figure for the SNR analyses to produce conservative results.

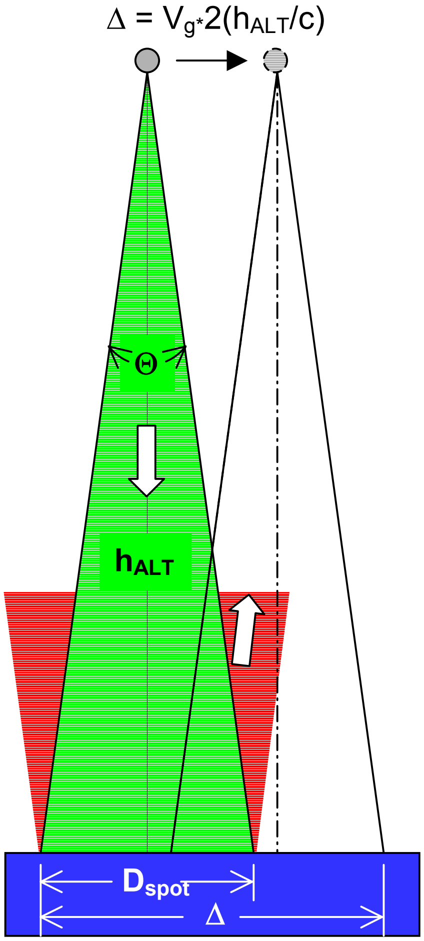

Figure 18. Use of Pulsed Radar for RAOBS Measurement

The last design parameter is pulse width. In most radar applications, the designer needs to reduce the pulse width to improve the spatial resolution; however, the RAOBS application does not require range resolution so using a longer pulse width increases SNR without degrading other properties of the system. The maximum pulse width is only slightly less than twice the platform's altitude; graphically this is shown in Figure 18. For the RAOBS baseline SNR calculations a pulse width was used equal to twice the light travel time for the platform altitude minus a few micro-seconds (to allow for settling of the transmitter and receiver). Compared to typical pulse lengths of 1-10 ms, the baseline RAOBS design produces nearly an additional 20 dB of signal strength while reducing the bandwidth requirement on the receiver.

While this “long pulse” design provides a substantial benefit to SNR, it does produce a larger resolution area on the sea surface. As previously described in Section 6.1.3, the platform moves during the transmission and reception of these “long pulses”. However even for aircraft ground speeds of 600 kts (~300 m/s) the platform only moves a few centimeters. It may be useful to note that Mach 1 is approximately 333 m/s.

SNR was calculated for the RAOBS baseline design using a single “long-pulse” for each of the 6 millimeter-wave channels. Channels 1 through 4 produced SNR levels greater than 0 dB (a rudimentary benchmark). However, the objective was to produce 15 dB SNR in all the useable channels (Chs. 1 ~ 4). This would be achieved by integrating multiple pulse measurements.

Use of pulse integration is a common technique, especially in radar signal processing. There are different models for the amount of gain that can be achieved through pulse integration. These models differ based upon the amount of coherency observed in the measured signal. The most basic, and most conservative, model assumes little to no coherency and only adds to the SNR at the rate of $\sqrt{N}$, where N is the number of pulses being integrated. This produces an additional 1.5 dB each time the number of pulses is doubled. In practice, integration gains far in excess of this are achieved; however, for this analysis, integration gain has been restricted to this lower gain rate. In order to achieve 15 dB SNR in Channel 4, 1024 pulses must be transmitted, received, and integrated. The table below summarizes the SNR estimates for the baseline RAOBS instrument.

Table 5 SNR (dB) estimates for baseline RAOBS design without and with integration gain from 1024 pulses.

Channel	1	2	3	4	5	6
Single Pulse	25.3	19.6	13.2	0.6	-12.6	-31.0
Including Integration Gain	40.3	34.7	28.3	15.7	2.5	-15.9

By integrating numerous pulses the SNR requirements are met; however, this further elongates the resolution area. If 1024 pulses are transmitted and received for each frequency and only 4 frequencies are used, then the Coherent Processing Interval (CPI) expands to greater than 1 second (1155 ms). This produces a swath along the surface approximately 300 meters wide and 600 meters in length, but this resolution is better than the objectives (1 km spatial resolution) described in Section 6.1.3. It should be noted that only Channel 4 (or higher) requires an appreciable number of pulses to achieve the 15 dB SNR requirement. So, other waveforms could be used to optimize data collection. Some of these waveforms allow measurements using Channel 5 but not at 15 dB SNR.

The baseline design was produced to assess the feasibility of the RAOBS concept. This design used specifications from only COTS hardware, much of which is neither space nor airworthiness qualified. As such it does not represent an optimized design. Still, it may be of some value to discuss the baseline waveform as it relates to existing COTS equipment and/or future RAOBS designs.

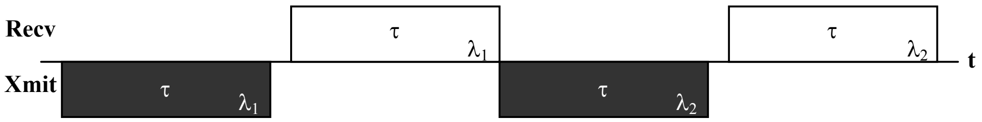

Figure 19 Pulse Timing

The baseline design transmits a pulse of electromagnetic energy at a single frequency (e.g., f_1), then a very short time later (i.e., a few microseconds) the receiver is activated and it measures the reflected energy, see Figure 19. After the single pulse integration period, a second pulse at a second frequency (e.g., f_2) is transmitted and received, and measured. It may be useful to note that the baseline RAOBS instrument only requires a transmitter capable of 140 microsecond pulses and 3550 pulses per second. Additionally, it is important to note that the baseline design does not have excessive time, or time gaps, so it runs at approximately 50% duty factor, which may be in excesses of current hardware specifications.

6.2.5. RAOBS implementation discussion

The radar analysis and system trade study of Section 6.1 were used to identify critical subsystem or component level performance required to meet the RAOBS objectives. A brief discussion of requirements with respect to available Commercial off the Shelve (COTS) hardware was used to estimate the level of technology risk for the identified critical subsystems. Figures 20 and 21 below illustrate a notional example of an implementation of the RAOBS instrument for an aircraft platform. Figure 20 illustrates the millimeter wave electronics that make up the front end of the radar system. This is the part of the instrument that contains the components most likely to require special components or optimization. The particular frequency band in this application is not utilized to the extent that neighboring bands are, because of the high losses due to O_2 absorption although passive microwave instruments, such as MSU and AMSU, have used this wavelength band extensively for decades. For that reason, millimeter wave components are not in general available off the shelf; however, the technology is mature, and components for neighboring bands can be adapted or optimized for RAOBS, as for passive instruments. The penalty is some extra cost for non-recurring engineering.

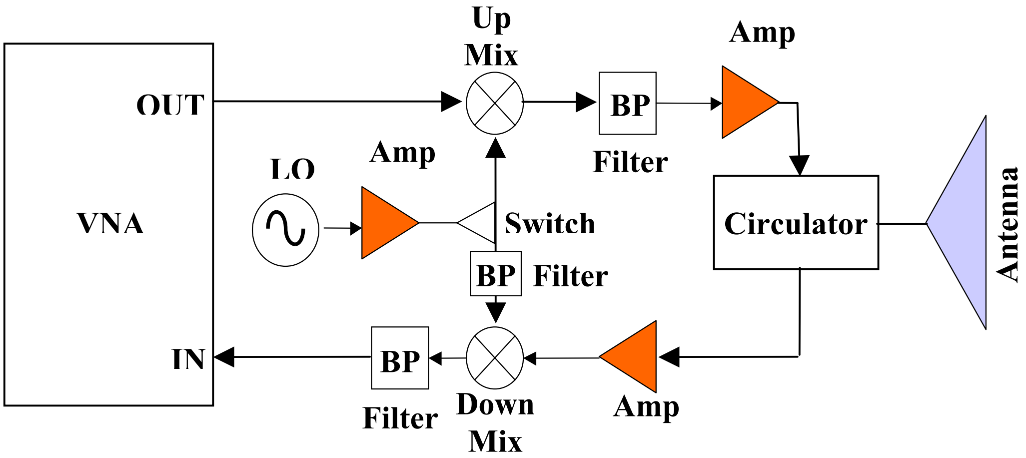

Figure 20. Diagram of the front end of the baseline radar system.

The items listed in Table 6 are considered critical to meeting the system performance used in the radar analysis. The assumed transmit power for the baseline RAOBS instrument is 20 dBm, so an output power amplifier that can provide linear operation at 20 dBm output power is required. We have found some COTS components for the Low Noise Amplifier (LNA), Transmitter/Receiver (T/R) switch and waveguide that provide loss budget consistent with assumed receiver noise figure (NF) of 7 dB in the analysis (c.f. previous sections). A T/R switch with isolation of 30 dB is required to limit receiver saturation during the transmit cycle. The optimization of the T/R characteristics, including switch loss, isolation, and switch speed could result in improvement of the RAOBS SNR by 1 to 2 dB. While useful this was not considered an area for technology investment. We viewed the switch and isolator optimization to be COTS with some modest engineering improvements rather than an area for technology improvement. The millimeter wave T/R switch and circulators were considered to be at a Technology Readiness Level (TRL) of 9.

Subsystem/component	Est. Performance		Notes
Power Amplifier	Max output	10 dBm	Published COTS through 30 dBm
LNA	Noise Figure	3.5 dB	Published COTS
MMW T/R switch	Loss	1 - 2 dB	Published COTS
	Ioslation	20 dB	
Antenna	Gain		Requires 0.5 m aperture (COTS)

Table 6: Available performance of subsystem/components

An example, practical implementation of the RAOBS instrument is illustrated in Figure 21. Here the electronics are packaged as three units. The first unit, the Status and Remote Control (SRC), is a small control head that displays status and can be used in the cockpit to start and stop the RAOBS, and potentially, to exert other control functions.

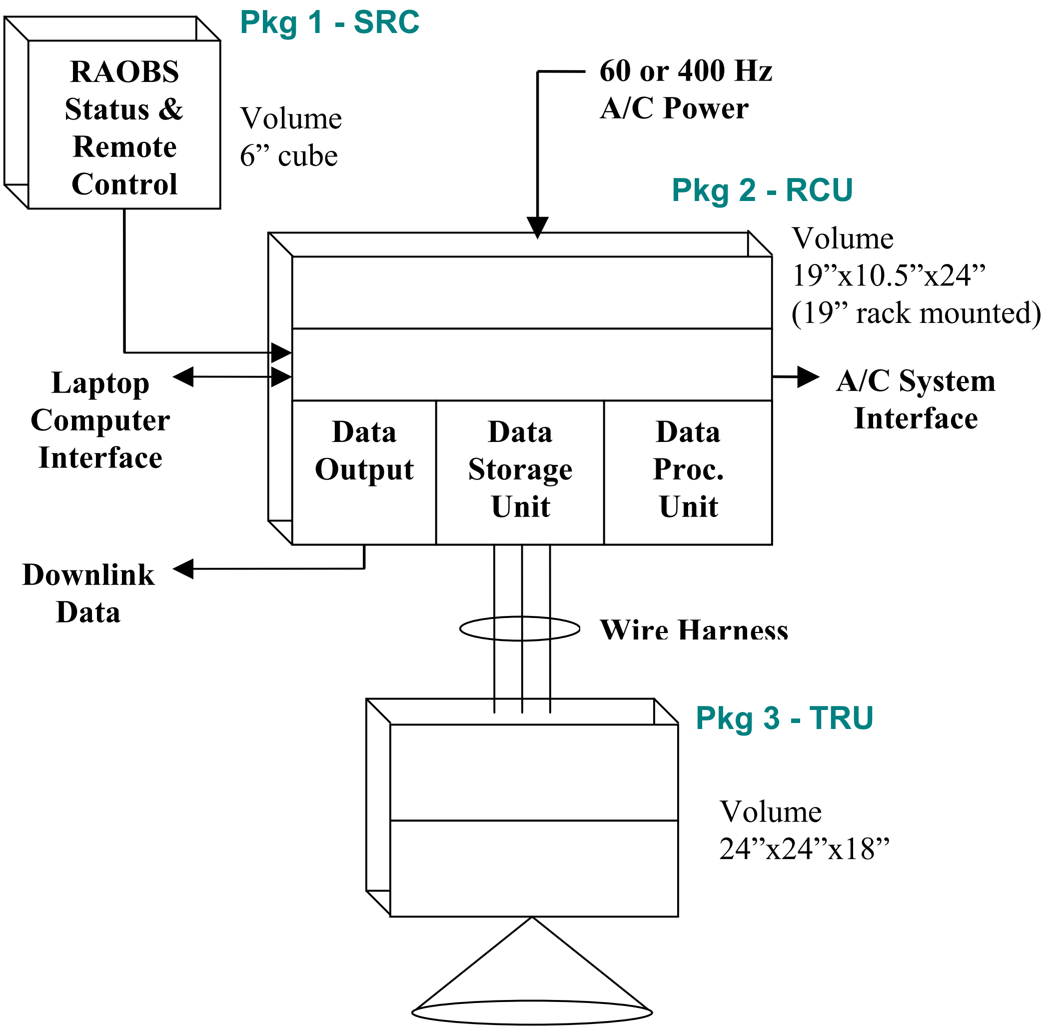

Figure 21. Notional implementation of the RAOBS system for an aircraft. The system has three main units: the SRC, RCU, and TRU.

The second unit, the Radar Control Unit (RCU) contains the major part of the electronics, including the power conditioning, control functions, and data processing and handling. It has a port for the connection of a laptop or other computer for programming, diagnostics, data retrieval, and set up. A wire harness connects the RCU to the Transmitter-Receiver Unit (TRU), which is collocated with the antenna to minimize waveguide loss and improve the receiver noise figure.

In the system depicted in Figure 21, packaging was assumed to be typical for airborne experimental systems. Physical requirements for the system and packaging information are summarized in Table 7. The control head, or SRC, is a small enclosure located in the cockpit. The RCU is housed in a typical 19 inch (~48 cm) instrument rack. As depicted, the RCU has 3 rack units, and the combined space requirements are given in the Table. The TRU is a separate enclosure, depicted as a unit with the antenna. In a practical application there might have to be some distance between these components, but in any case, it would be minimized. In this instance, they are combined and the space requirements are estimated together. Weight and power requirements are estimated based on experience and discussions with vendors, and these are believed to be conservative.

In summary, a review of available COTS hardware and relevant component indicates that the hardware required to provide the performance shown in Tables 4~7 is available. Although some engineering development may be needed in some cases, the critical components are considered to be at TRL 9, and no further investment is required. For the analysis in Section 6.2, COTS values for loss and isolation were used and found to be acceptable for the RAOBS baseline.

Pkg	Name	Vol. (ft^3)	Wt. (lbs)	Pwr. (W)
1	SRC	0.2	< 5	< 1
2	RCU	3.2	< 30	< 150
3	TRU	6.0	< 30	< 100
	Cabling/WG		< 20	
Total	RAOBS	~ 10	< 85	< 250

Table 7. Physical requirements for the notional RAOBS system.

6.3 Design Summary

The radar concept developed in Section 6.2 provides the required performance to measure surface barometric pressure from 10 ~ 22 km altitudes. The discussion of Sections 6.1 and 6.2 indicates that the major system performance parameters were the SNR of the system and the required antenna beam width. The SNR of the radar for the highest frequency used is a major factor in the system performance of the RAOBS instrument (see Section 6.1.2). The beam width of the antenna is also important, since an excessively narrow beam may require platform stability that is inconsistent with aircraft operating in the vicinity of hurricanes. Further, big enough antenna beams will produce RAOBS observations on statistically stable sea surfaces during different channel measurements.

The baseline radar concept summarized in Figures 17, 20, and 21 is intended to depict a potential approach that would provide an instrument to meet the RAOBS objectives from 22 km. This is not intended to be considered the optimum radar system, but rather to provide a straightforward approach that demonstrates the measurement concept can be implemented with minimum technology development. The detail discussion in Section 6.2 described the many trade offs between various subsystems for this long pulse radar concept. The next section will provide a description of a technology development program that will rapidly eliminate the modest risk and enable an operational RAOBS instrument.

7. RAOBS Implementation Recommendations

The description of baseline radar concept in Section 6.2 includes an estimate of existing subsystem performance (see Tables 5 and 6). While the aircraft RAOBS instrument appears to be within the present state-of-the-practice, that is no new technology appears necessary, there are several assumptions to be verified and some uncertainty as to the final optimization of the radar system for RAOBS. In this section we will suggest a possible technology investment strategy, or Roadmap, to develop the RAOBS remote sensing barometer concept to enable the new Earth Science capability discussed above in Part I of this report.

7.1. Technology Areas Impacting RAOBS Performance

The radar instrument concept developed above can be implemented with out the development of new technologies. Further, the analysis in Section 6 provides insight into the relationship between subsystem performance and the uncertainty of surface pressure estimates for the RAOBS instrument. The fundamental system level parameter of interest is the SNR of the highest frequency used to measure O_2 absorption. While a complete discussion was presented in Section 6.2, a few general comments regarding the SNR for the aircraft RAOBS instrument are repeated here for convenience.

1) Higher transmit power will generally improve SNR. The baseline transmit power is limited by available technology and the isolation that can be achieved between the transmitter and the receiver LNA (low noise amplifier).
2) Lower receiver Noise Figure will improve the SNR. This will be limited by available technology and, depending on implementation, the time required for the LNA to recover from saturation. Also it should be noted that losses between the antenna and the LNA will minimize the improvement available from improved LNA noise (c.f., Transmit/Receive (T/R) switch and isolator losses in Section 6.2)
3) Higher antenna Gain will improve the SNR. Increased antenna Gain will require larger antenna aperture. This will be limited by vehicle accommodations. The limitation in increasing the size of antenna is the spatial resolution. In order to keep sea state statistically stable, a low limit ~200 m as the antenna spot size on the sea surface is considered.

7.2. Technology Readiness Level Assessment

In this section the Technology Readiness Level (TRL) estimate for the measurement approach will be discussed. Often a TRL is assigned to basic component technologies, subsystems, or instruments. Since our goal is to identify the risks associated with developing a new measurement concept, we will discuss both component technology needs and the TRL of the differential radar absorption measurement approach itself. That is, we must identify required improvements in microwave components needed to implement the RAOBS radar, as well as, system level uncertainties and assumptions.

The microwave hardware required to build an aircraft instrument meeting the performance requirements defined in Section 6.2 can be accomplished with existing technology. The microwave components with the performance listed in Figures 17, 20, and 21 are available commercially. In fact, the subsystem performance goals used in these figures are all published and available as Commercial-off-the-shelf (COTS) hardware. Optimization of the components for the specific RAOBS application would likely improve the component performance. Improved T/R switch loss, isolation, Noise Figure, etc. would likely result in improvements in the RAOBS SNR less than 3 or 4 dB. While useful, optimization of the COTS hardware was viewed as modest engineering improvements rather than an area for technology investment. While no specific vehicle has been identified the 0.5 m antenna is not atypical of research instruments and could be accommodated on several aircraft, including the high altitude Proteus shown in Figure 22. The microwave components for aircraft applications were considered to be at a TRL of 9. The baseline system describes an approach with minor technology risk and can be implemented without the need for fundamental technology development. Originally, only a theoretical concept was proposed for the RAOBS system, and the entry TRL was level 2. This assessment project advances the TRL to level 3.

Figure 22 A UAV platform, Proteus, that has the potential to carry a RAOBS system.

7.3. Space-specific Antenna Technology Assessment

While not within the scope of this task some discussion of the TRL required for spacecraft instrument would be of interest. A quick assessment of the system modifications for a Low Earth Orbit (LEO) RAOBS instrument indicated that the major required modification was the need to increase the antenna aperture to 2 to 3 meters. The assumed requirements for the reflector are a surface accuracy on the order of 100 μm rms, an approximate primary aperture of 2 m. Further, the technology should provide near zero Coefficient of Thermal Expansion (CTE), good thermal conductivity, high stiffness and low weight. There are several spaceflight antennas with proven performance that would meet the requirements of the baseline concept. The Special Sensor Microwave Imager (SSM/I), TRMM Microwave Imager (TMI), and Advance Microwave Scanning Radiometer (AMSR) have antenna reflectors with surface roughness on the order of 25 μm and reflector diameters of 0.6, 0.6, and 1.6 meters. Spaceflight antenna concepts based on this proven technology have been developed, including a 2.2 m deployable antenna concept developed for the NPOESS Conical Microwave Imager/Sounder (CMI/S). The required 2 m reflector is already at TRL 9 (e.g., the antennae used by Cloud Profile Radar in CloudSat and by Precipitation Radar in TRMM) and does not represent appreciable technology risk for a RAOBS LEO instrument.

The major issue regarding further increases in the reflector size of the composite reflector panel is the scaling of state-of-the-practice fabrication techniques. These technologies include the development of precision mold or tool manufacturing, mold-release techniques to minimize surface roughness of the finished part and appropriate material selection to ensure sufficient stiffness, thermal conductivity and low CTE. The baseline reflector panel would likely utilize a precision molded reflector surface, reinforced composite front and back face sheets and extremely stiff low mass core structure. The existing materials technology, thin sheet design, and manufacturing techniques can provide near zero CTE and extremely high structural efficiency (i.e. lightweight stiff structures). The allowable surface roughness of the tool is on order of one-half the rms roughness of the final part. For surface roughness of the final reflector on the order of 100 μm no significant technology issues are expected in the development of a 3 to 4 m.

The atmospheric absorption modeling and radar system calculations discussed above suggest that the measurement approach is very feasible with little technology development. It is important to discuss several assumptions and approximations used in these models, since reducing the uncertainty associated these assumptions is likely to be the short-term focus of a risk reduction effort. An important parameter in the radar model is the scattering from the ocean surface. This term will vary with sea state and the wavelength of the radar. The radar modeling in Section 6.2.3 was based on reported analysis of the reflection of microwave radar from the ocean (*Currie et al.* 1992; *Ulaby et al.* 1981; *Lin et al.* 1999) and assumes a fixed value for the surface backscatter which represents most cases of sea surfaces. There are two aspects of this assumption that should be noted. Besides the reflectivity change due to modeled changes in sea surface refractive indexes over different frequencies, any change in surface reflection from channel to channel (unpredicted change over the frequency difference between channels) was not included in the predicted surface pressure errors. This was addressed in Section 6.2.3 and the variation with frequency was considered to represent a very minor error term. While not considered a major issue for RAOBS, there is some uncertainty as to the variability in the radar backscatter over widely varying sea states. Of greater interest, there is uncertainty in the nominal backscatter coefficient due to the lack of analysis and experimental data. Although current estimation is conservative, this directly impacts the estimated system SNR and may become a greater concern.

7.4. Potential Investment to Enable the RAOBS Concept

7.4.1 Investment to enable the RAOBS concept

As discussed above, the TRL of the component technology is very high (TRL 9) for aircraft and perhaps a bit lower for the spacecraft version, with space qualification being the major issue. The TRL of the differential atmospheric absorption measurement approach is 3, since the concept has been "studied and detailed analysis does support the assumption". Passive measurement techniques relying on O_2 band absorption, for applications other than surface pressure, have been used for decades (for example, AMSU, e.g., Goldberg, 1999). Furthermore, analytical results of the O_2-band radar, applications, sea surface air pressure retrievals, and airborne radar system designs, especially analytical results for the critical function and components of the proposed airborne RAOBS system, are clearly presented in this report. Validation of the atmospheric absorption predictions, pressure retrieval, and the surface reflection at 50 to 55 GHz would advance the TRL to 4.

The next step to advance the TRL of the RAOBS concepts is to experimentally verify the results of our simulation and analytical results, advancing the TRL to 4. Although some simulation using laboratory equipment is possible to verify radar performance, a minimum short duration flight test providing sufficient propagation path to directly measure the differential absorption predicted by the atmospheric propagation models and validate the measurement approach is needed. This minimum system test would provide validation of the O_2 absorption for each channel, evaluate radar performance and pressure estimation, and provide some additional assessment of the suitability of our assumed surface reflectivity. The development of such an instrument is presently supported by the Creativity & Innovation (C&I) program of NASA Langley Research Center. This task will complete a laboratory instrument and complete essential performance testing in the laboratory environment. The instrument was design to be later "hardened" to fly a short duration mission to provide differential O_2 measurements to validate the RAOBS concept.

Once the model predictions are experimentally verified, through minimum flight testing, an aircraft RAOBS instrument should be developed for science missions. This instrument would be developed to be compatible with existing hurricane aircraft resources and perhaps other experiment aircraft. The instrument would not only provide barometric pressure data in support of science missions, but would also provide additional information of atmospheric variations and sea surface reflectivity in a wide range of conditions. The expectation would be that this instrument would be modified and become a resource for aircraft science missions.

At this point a system study to define a spacecraft instrument and a RAOBS mission should be developed. This system study would determine modifications (such as channel selection, frequency agility, or changes to the approach) that may improve the performance of the spacecraft instrument. The results of this study and the history of successful flight campaigns would position the O_2-band radar concept in developments of a space flight instrument, providing the first barometric pressure measurements from space.

The above technology investment approach is illustrated in Figure 23. There are two-steps toward realizing operational capability of the RAOBS sensor: developing a laboratory proof-of-concept instrument and a high altitude scientific experiment sensor. Much of the early research to validate the basic measurement approach is presently underway, as part of NASA LaRC's "Proof of Concept" (POC) development efforts. Modest technology developments could provide a flight test of the RAOBS instrument. Once this was accomplished, the actual aircraft RAOBS instrument could be developed with very little technical risk. The aircraft RAOBS instrument would enable the validation of the measurement technique and the development of algorithms to provided barometric pressure in a variety of atmospheric and sea state conditions. The availability of flight data would allow the assumptions used in the above analysis to be evaluated, and the precision and accuracy of the final surface pressure science measurements to be more realistically assessed. This would advance the TRL to 6, "System/subsystem model or prototype demonstration in a relevant environment (ground or space)".

The analysis presented suggests that a new measurement concept to provide surface pressure from space may be possible with minimum technology development. Validation of the overall O_2 measurement through short-range aircraft flights would rapidly increase the TRL of the measurement concept.

7.4.2 Assessment of the approach of the RAOBS concept

With all knowledge discussed above, we try to answer the second primary question of this project: *If desirable improvements could be realized by deployment of this new radar barometry capability, how could we best approach its development?* We propose a two-step approach to realize the application capability: laboratory proof-of-concept instrument and high altitude scientific experiment sensor. These aircraft instruments will enable the validation of the measurement concept and technique and the development of algorithms to provided barometric pressure in a variety of atmospheric and sea state conditions. The availability of flight data will also allow the assumptions used in the above analysis to be evaluated, and the precision and accuracy of the final surface pressure science measurements to be more realistically assessed.

With respect to this second primary question, we further answer its secondary questions below:

1) What are the technical specifications, system-level performance requirements, and system-level trades for a radar-based barometric instrument prototype that would meet the needs of users identified for the first primary question?

Answer: The detailed answer to this question is shown in the second part of this report. The key for system development and RAOBS performance is the SNR of the radar system and the required antenna beam width (or, spatial resolution). With 15dB SNR for high frequency channels, an airborne RAOBS will produce accurate sea surface pressure measurements for hurricane predictions. The beam width of the antenna is also important, since an excessively narrow beam may require high platform stability. Further, big enough antenna beams will provide RAOBS observations on statistically stable sea surfaces during different channel measurements.

a) What would be the performance capabilities (e.g. accuracy, resolution) and technical parameters (e.g. size, power) of instrument(s) identified for the second primary question if built with existing radar components?

Answer: With existing radar components, the instantaneous spatial resolution and retrieval accuracy would be within 1km and ~5.7mb, respectively. The size and power should be similar to normal airborne weather radars. Averaging multiple measurement samples, the accuracy of hurricane center pressure measurements would be as high as ~1.3mb for single flight track, which is very accurate for hurricane forecasts, and close to in situ observations.

b) Describe the proposed "observing scenario" concept(s) for (a) in detail and explain how the instrument design overcomes challenges posed by the environment (i.e. provide a rationale for why the retrieval is possible in the presence of adverse conditions).

Answer: The proposed scenario is for tropical environments for hurricane observations. The retrieval accuracy can be achieved due to favorable conditions for RAOBS observations of clear sky and low radar-power loss of hurricane centers. The detailed discussion can be found in Sections 5 and 6.

c) For instrument options identified for this second primary question, are there specific performance improvement(s) that could be realized by focused development of relevant technologies?

Answer: There is no fundamental need of focused development of relevant technology for prototype airborne RAOBS systems. Existing radar technologies are mature enough in development of a prototype airborne RAOBS. Only minimal technology advance is needed for the RAOBS instrumentation, as discussed in Section 6.

And, 2) Given the answers to the two primary questions, does it make sense to start building a prototype of this instrument with existing technologies, or would it be better to engage in focused technology developments leading to a future (near-term) build.

Answer: Yes, it does make sense to start developing a prototype airborne instrument with existing technology because of the feasibility of existing technology for the instrumentation and the importance of barometric pressure data in improving hurricane forecasts to significantly reduce the loss of life and property damage.

a) Which of the prototype option(s) identified by (1b) would it make sense to build first?

Answer: A high altitude airborne prototype RAOBS should be built first.

b) Given (2 and 2a), how would the prototype implementation roadmap(s) look like?

Answer: The proposed roadmap is a two-step approach: laboratory proof-of-concept instrument and high altitude scientific experiment sensor.

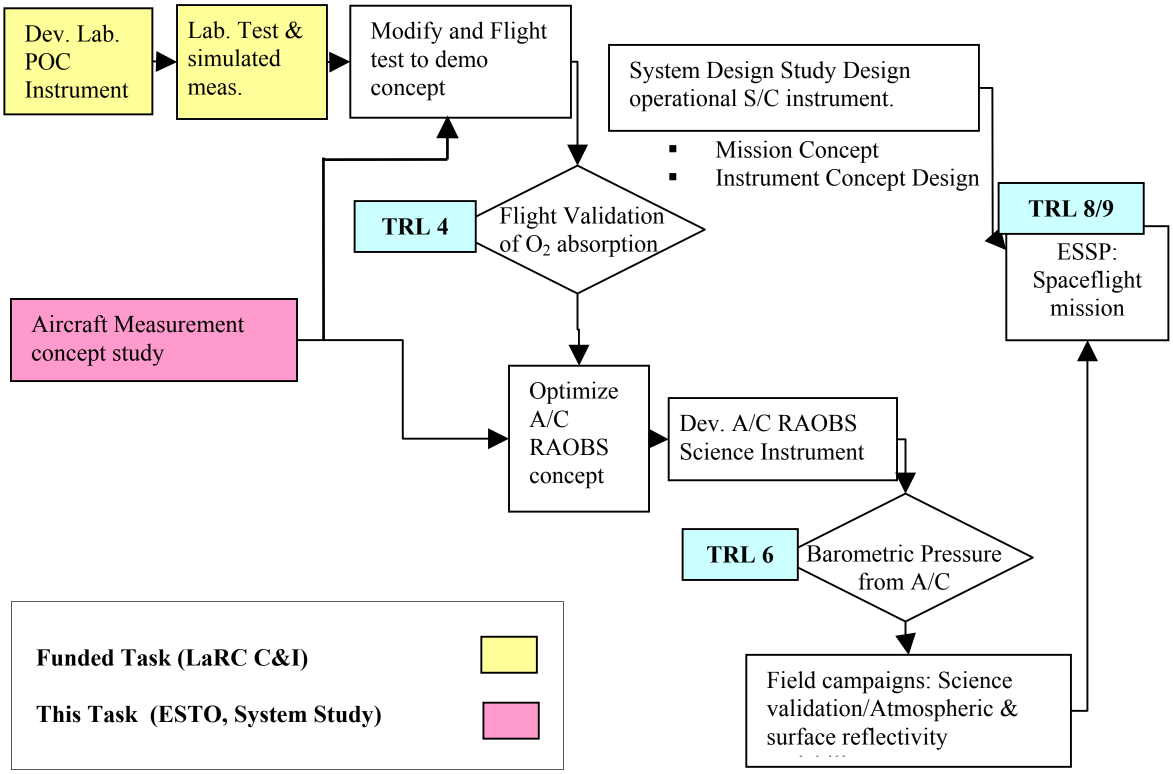

Figure 23: Technology development Road map

8. Summary

The overall objective of the task was to investigate two primary questions: 1) *What Earth-Science Research or Operational improvements could be realized by the development of a new instrument that uses RADAR to remotely sense barometric pressure, i.e., the RAOBS instrument? And, 2) If desirable improvements could be realized by deployment of this new capability, how could we best approach its development?*

The first primary question and its associated secondary questions were discussed in the Part I of this report and summarized in Section 4. The differential O_2 absorption approach could provide unprecedented barometric pressure data over the ocean, greatly extending both spatial coverage and temporal sampling. These data would substantially improve weather forecasts, especially for predictions of tropical cyclone intensities and tracks. The RAOBS data could significantly reduce the loss of life and property damage due to tropical cyclones. In addition, this newly developed capability would provide new perspectives in the NASA's Weather, Climate Variability and Global Change, and Water and Energy Cycle Focus Areas (see Section 3).

The second primary question addresses the feasibility of the RAOBS instrument and the technology roadmap to develop the concept. The analysis of radar systems shown in Figures 17, 20, and 21 and atmospheric absorption processes indicated that a baseline radar concept can meet the measurement objective with little technology development. The operational scenario and radar technical specifications discussed in section 5 and 6 will provide the required performance. This radar concept, utilizing Commercial-off-the-Shelve components provides the performance objectives described in Table 1.

Section 7 provides a proposed approach to advance the TRL of the RAOBS measurement concept and future approaches for RAOBS development, i.e., the Roadmap. Based on our previous analysis, especially those in Sections 5-7, for the second primary question, our assessment is that it is realistic to develop a prototype airborne radar system with existing technology to meet science requirements. *Further, only minimum technology development would appear necessary to develop this aircraft RAOBS sensor and provide flight data to validate this new measurement concept and take the first steps toward a new capability for NASA's Earth Science Program.*

Acknowledgement

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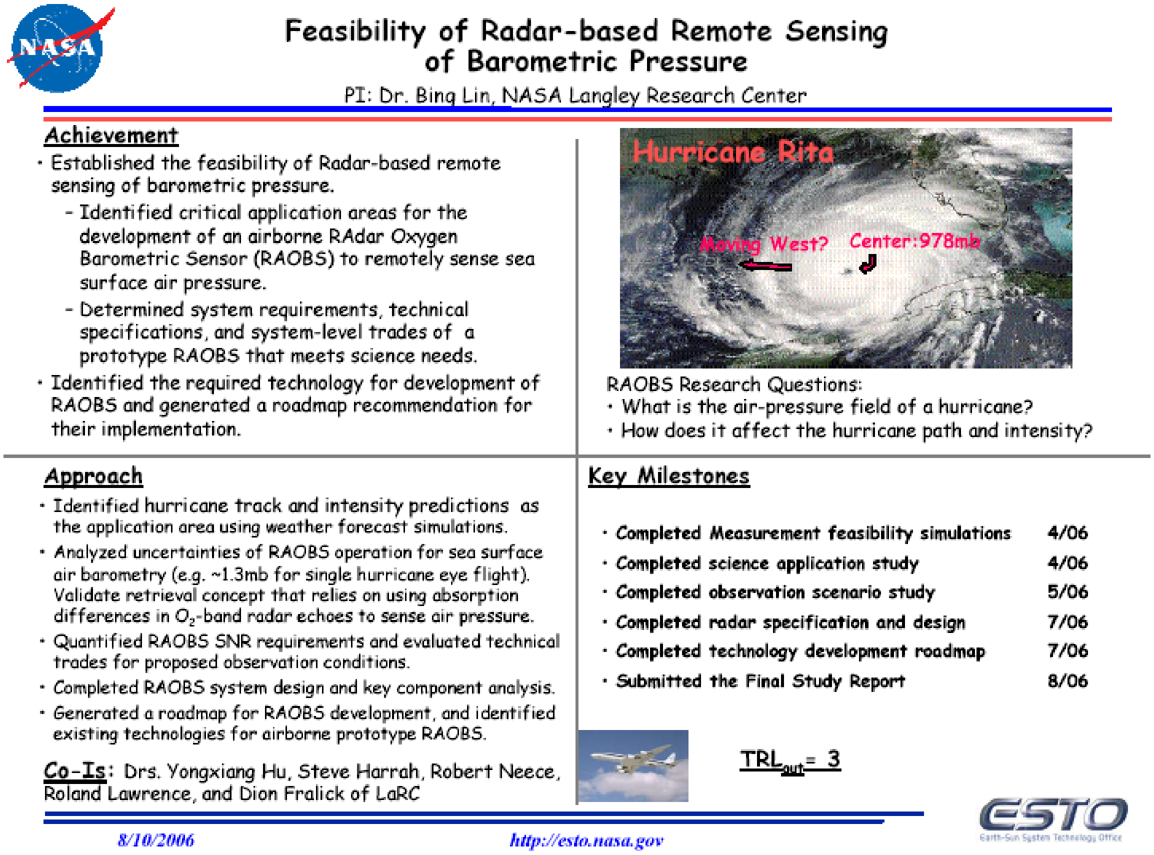
Update of Quad Chart



Feasibility of Radar-based Remote Sensing of Barometric Pressure

PI: Dr. Bing Lin, NASA Langley Research Center

Achievement

- Established the feasibility of Radar-based remote sensing of barometric pressure.
  - Identified critical application areas for the development of an airborne RAdar Oxygen Barometric Sensor (RAOBS) to remotely sense sea surface air pressure.
  - Determined system requirements, technical specifications, and system-level trades of a prototype RAOBS that meets science needs.
- Identified the required technology for development of RAOBS and generated a roadmap recommendation for their implementation.

RAOBS Research Questions:

- What is the air-pressure field of a hurricane?
- How does it affect the hurricane path and intensity?

Approach

- Identified hurricane track and intensity predictions as the application area using weather forecast simulations.
- Analyzed uncertainties of RAOBS operation for sea surface air barometry (e.g. ~1.3mb for single hurricane eye flight). Validate retrieval concept that relies on using absorption differences in O_2-band radar echoes to sense air pressure.
- Quantified RAOBS SNR requirements and evaluated technical trades for proposed observation conditions.
- Completed RAOBS system design and key component analysis.
- Generated a roadmap for RAOBS development, and identified existing technologies for airborne prototype RAOBS.

Co-Is: Drs. Yongxiang Hu, Steve Harrah, Robert Neece, Roland Lawrence, and Dion Fralick of LaRC

Key Milestones

• Completed Measurement feasibility simulations	4/06
• Completed science application study	4/06
• Completed observation scenario study	5/06
• Completed radar specification and design	7/06
• Completed technology development roadmap	7/06
• Submitted the Final Study Report	8/06

$TRL_{out} = 3$

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Roadmap for RAOBS Technology Development