Acquisition of Aircraft-Based GPS Instrumentation for Atmospheric Remote Sensing Research
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Project Summary

This proposal aims to purchase the necessary equipment to carry out the proof-of-concept of an entirely new type of high-resolution atmospheric remote sensing technique, “airborne GPS radio occultation”, which addresses a critical need in weather prediction and climate studies.

High resolution observations over data-sparse oceanic regions are critical if the trend towards higher resolution global numerical weather prediction (NWP) models is to be converted into tangible improvements in weather forecasting success. GPS radio occultation sounding of the atmosphere from airborne platforms has the potential to fill this unique niche in the global meteorological observing system. GPS radio occultation sensing of the atmosphere involves sub-horizontal line-of-sight measurements made at normal cruising altitudes as transmitting GPS satellites set or rise behind the horizon. A single 8 hour transatlantic flight could provide more than 22 vertical profiles of water vapor. The large number of humidity profiles, the frequent sampling, and the high vertical resolution in the range from the surface to 200 mbar are exactly the type of observations that are sorely needed, for example, as input for forecasting severe European storm systems that develop over the Atlantic Ocean, or for forecasting hurricanes developing over oceans off the coast of the U.S.

Information on the structure of the atmosphere is retrieved from the amplitude, refractive phase delay, and Doppler shift of the GPS radio waves. The technique requires a state of the art GPS receiver integrated with an inertial measurement unit (Applanix POS/AV 510) capable of measuring the aircraft velocity with an accuracy better than 5 mm/sec in order to remove the effect of the relative transmitter-to-receiver motion. High accuracy in-situ pressure, temperature, and humidity sensors are required to derive refractivity at the aircraft flight level for inverting the GPS data for the refractivity profile, and for data validation. High sample rate (10 Hz) humidity data are provided by an infrared gas analyzer. We propose to expand on the existing capabilities of the Purdue Airborne Laboratory for Atmospheric Research (ALAR) aircraft (Beechcraft Duchess) to enable atmospheric water vapor profile measurements by equipping it with this state of the art airborne ultra-high accuracy GPS-INS navigation system and auxiliary sensors.

The proposed instrumentation will support research for development and testing of the airborne radio occultation technique using input data from local flight campaigns. Flights for the validation of the technique will be carried out in targeted dense fields campaigns, for example, in the Southern Great Plains DOE/Atmospheric Radiation Measurements test bed for summertime heavy convection and tornado prediction. The data will contribute to the objectives of these future campaigns concerning the role water vapor plays in convection. We will carry out flights over the ocean on the Atlantic seaboard to demonstrate the data impact in the case of offshore extra-tropical cyclone development.

The facility will also be used for research training in Earth Science Remote Sensing, both using GPS as the signal source for atmospheric remote sensing, as well as using the GPS navigation system as ancillary equipment for high resolution remote sensing imagery.
Project Description

Background

The primary objective of the research activities using the requested instrumentation is to carry out a proof-of-concept experiment for the airborne radio occultation technique in order to evaluate the accuracy for its use in numerical weather prediction and climate studies.

GPS radio occultation sensing of the atmosphere involves sub-horizontal line-of-sight measurements of atmospheric refractive delays as a signal source rises or sets behind the Earth relative to the receiver. Radio occultation was first used for studying planetary atmospheres ([Fjeldbo et al., 1971]). Since the GPS/MET experiment ([Kursinski and al., 1996; Rocken et al., 1997]) and the current CHAMP ([Wickert et al., 2001]) and SAC-C missions, it has become a well known upper atmospheric profiling technique for the Earth. It is proposed to become an operational sensing system on METOP and N-POESS. The current limitations of space-borne radio occultation are that sampling in the lower atmosphere is unreliable because of signal attenuation and multipath, and that the horizontal sampling of an individual satellite is sparse. Typically, 6-8 profiles per day over a region the size of the North Atlantic are observed. Airborne radio occultation is a complementary new technique that can overcome these limitations, and make a significant contribution to operational meteorology.

Airborne radio occultation has the potential to provide humidity data from the surface to mid-troposphere that is critical for improving global and regional numerical weather prediction. Uncertainties in the vertical humidity structure over the oceanic areas limit the prediction accuracy of cyclone development and intensification. Resulting errors in forecasts can increase the societal impact of severe storm systems when they arrive at the coast, leading to increased casualties and property damage.

For climate studies, the effect of climate change measured in terms of percentage change in humidity is roughly the same at all levels in the troposphere. Therefore, a smaller absolute change could be detected in the mid-troposphere than in surface measurements. However, the mid-troposphere global data sets are sparse over the oceans.

A future operational system based on the airborne radio occultation concept, using a fleet of properly equipped commercial aircraft, could provide hundreds of humidity profiles daily over oceanic regions. These regions are greatly under-sampled with the current configuration of space-borne sounders and infrequent drop-sondes and ship-launched radiosondes. Satellite-borne radiometric sounders have poor vertical resolution especially near the surface where backscattered energy can contaminate the signals. High resolution ground-based profilers typically do not measure much higher than 3 km. Airborne radio occultation could provide moisture measurements in a range and at a resolution that is not covered by existing systems. This could be accomplished at significantly lower cost than implementing a constellation of space-borne occultation receivers.

Target areas of the research with the proposed instrumentation will include the intense convective storm region in the southern Great Plains. Here we will have access to extensive independent validation data and we will be able to test the ability of the high resolution vertical profiles to resolve structure that is important in predicting precipitation rates.
target areas are the eastern U.S. seaboard and Gulf of Mexico. Here we plan to test the impact of the measurements made over the ocean in NWP model forecasts and their application to extra-tropical cyclone development.

The GPS Radio Occultation Method

GPS radio occultation sounds the atmosphere using radio signals that traverse the atmosphere as a moving receiver sets behind the horizon relative to the transmitting GPS satellite. The radio wave is refracted and its travel time is delayed due to variations of refractivity. The refractivity in the neutral atmosphere depends on the pressure, temperature, and humidity. Information on the structure of the atmosphere can then be retrieved from accurate measurements of the amplitude and phase delay of the radio waves.

The method in its application to space-borne sounding is fully described in ([Kursinski et al., 1997; Melbourne et al., 1994; Vorobev and Krasil'nikova, 1994]). We recall the main points of the theory. The refractive index of the neutral atmosphere at L-band GPS frequencies is given by

\[ N = (n - 1) \times 10^6 = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{P_w}{T} \]  

(T1)

where \( N \) is refractivity, \( n \) is the refractive index, \( P \) is the atmospheric pressure in hPa, \( T \) is atmospheric temperature in Kelvin, \( P_w \) is water vapor partial pressure in hPa.

The integrated bending angle caused by refraction, \( \alpha \), derived from Snell’s Law, is

\[
\alpha = \int_{\zeta}^{\rho} d\alpha + \int_{\zeta}^{\rho} d\alpha
\]

\[
\alpha = \int_{\zeta}^{\rho} \frac{1}{\sqrt{n^2r^2 - a^2}} d (\ln n) dr + \int_{\zeta}^{\rho} \frac{1}{\sqrt{n^2r^2 - a^2}} d (\ln n) dr
\]  

(T2)
where $r_a$ is the distance from the center of the Earth to the GPS receiver, and $r_b$ is the distance to the GPS transmitter, $r_t$ is the distance to the tangent point, or point of closest approach to the surface, and $a$ is the impact parameter given by $a=nr$.

The bending angle is derived from the excess Doppler shift measurement of the GPS signals ([Vorobev and Krasil'nikova, 1994]). The measured bending angles are inverted to retrieve refractivity using an Abel transform inverse of eq (T2), thus providing refractivity as a function of distance from the Earth’s center, $r$, as follows:

$$
n(r) = \exp \left( \frac{1}{2\pi} \int_{a_t}^{a_b} \frac{\alpha}{\sqrt{a^2 - a_t}} \, da + \frac{1}{2\pi} \int_{a_t}^{a_b} \frac{\alpha}{\sqrt{a^2 - a_t}} \, da \right) \quad (T3)$$

It is important to note that the dependence on both $P_w$ and $T$ in equation (T1) leads to an ambiguity in the retrieval of humidity profiles from the refractivity. The water vapor profile can be retrieved from equation (T1) if we assume an a priori temperature profile from a climatological or NWP model, and assume hydrostatic equilibrium. Alternatively, bending angle or refractivity observations can be directly validated or assimilated into numerical models, thus avoiding the $P_w/T$ ambiguity.

**From GPS Phase measurements to a refractivity profile**

GPS receivers provide (ambiguous) phase measurements of the satellite-receiver range. Estimating refractivity (or other atmospheric parameters) from these raw measurements requires 3 main steps:

1) estimating the precise trajectory of the airplane, necessary to remove the effects of its motion with respect to the satellite from the raw GPS carrier phase data,

2) extracting from the GPS carrier phase data the excess phase and Doppler shift due only to refractive delay, and

3) retrieving refractivity as a function of altitude.

In addition, a fourth step involves a non-unique retrieval of humidity as a function of altitude, in the case where it is not possible to adapt the validation or assimilation objectives to use refractivity directly. There are instrument requirements associated with each of these steps that define the equipment configuration requested in this proposal. There are also modeling errors associated with each step that limit the accuracy of the technique beyond the instrumental error of the GPS receiver. These errors are addressed in the feasibility study section of this proposal.

1) Navigation processing

The position of the airplane is calculated at the reference navigation GPS antenna (=NAV antenna). Other GPS antennae on the aircraft will collect the GPS data used for radio-occultation (=RO antennae). Once the position of the NAV antenna is known, the positions of the RO antennae are calculated from their offset with the NAV antenna (precisely measured on the ground) and from the orientation of the aircraft in flight. The precise position and velocity of the RO antennae cannot be calculated directly from the GPS signals recorded by these antennae because they are oriented favorably for tracking low elevation satellites in one hemisphere, and thus do not provide a good sky view for the geometric calculation of position.
Position of the NAV antenna:
The position and velocity of the NAV antenna are calculated from observations of the range to each satellite measured by the navigation GPS receiver. This requires:

- A dual frequency navigation GPS receiver to eliminate the refractive effects of the ionosphere;
- A dual frequency ground reference station or network of ground stations to remove satellite and receiver clock errors from the range to each satellite by double differencing;
- Precise orbits of the GPS satellites provided from a separate calculation using a global receiver network. Such orbits are available from the International GPS Service for Geodynamics (IGS) with accuracies on the order of 2-3 cm ([Kouba and Mireault, 1998]). Note that satellite clock corrections with accuracies better than 0.1 ns are also provided together with the IGS orbits. They will be used in the second step, see below;
- A sampling rate of the GPS phase data of at least 10 Hz;
- An Inertial Navigation System (INS) for determining attitude and acceleration;
- A filtering software able to combine GPS and INS data in order to constrain the GPS-derived position and velocity solution at frequencies above 1 Hz.

Several software packages exist to calculate high precision kinematic positions, including the Applanix POS/AV software, the JPL GIPSY software ([Webb and Zumberge, 1997]), and the AGNS software that we have developed. The Applanix software is the only one of these that currently uses the INS aided filtering in the distributed version. The GIPSY software has the advantage that it can be run in a point positioning mode using one-way GPS phase measurements, so that ground reference stations are not needed as in double differencing techniques ([Zumberge et al., 1997]).

Calculation of the RO antenna position:
The calculation of the RO antenna position and velocity at each time sample during the occultation profile requires the following:

- Surveyed offset between navigation and RO antennae on the aircraft (using classical methods, i.e. a theodolite, on the ground)
- Aircraft attitude: This will be provided by the INS system.

2) Excess phase delay and Doppler shift

This step reduces the raw carrier phase measurements at the RO antenna to a measure of excess phase by subtracting the geometric range and correcting for other errors such as satellite and receiver clock errors, the phase wind-up from any aircraft rotation, integer wavelength ambiguities, and ionospheric delays. This processing requires the following:

- A dual frequency RO receiver to eliminate the refractive effects of the ionosphere;
- High sample rate (10 Hz) L1 and L2 carrier phase measurements from occulting satellites. The sample rate determines the vertical sampling interval during the occultation;
- A priori RO antenna position from the previous step;
- Precise orbit of the occulting satellite in order to calculate the antenna-transmitter geometric range. As above, the IGS final orbits are appropriate for this purpose.
- Satellite clock offset and drift for the occulting satellite, consistent with the GPS orbit, as are provided by IGS products for instance. Satellite clock offset and drift are then interpolated to the 10 Hz sampling rate and removed from the RO phase data;
• An estimate of the receiver clock offset and drift. This quantity is derived from single
differences of two non-occulting satellites at the NAV receiver and the satellite clocks
(or some average over several non-occulting satellites). The RO receiver clock must
be driven by the NAV receiver clock;
• The attitude and attitude history of the aircraft in order to account for phase wind-up
terms in the GPS phase measurements.
The software required to carry out this step must contain precise GPS observable models. It
must be configured to output the individual carrier phase residuals. The AGNS software,
having been developed internally, is the most straightforward to configure for this specialized
output. It also permits the use of stochastic or kinematic constraints on the RO antenna
position while estimating excess phase delays.

Of the corrections described above, the horizontal RO antenna position has the largest
uncertainty, which maps directly into the excess phase delay. The GPS orbit error also
contributes to the error budget, but is of smaller magnitude (2-3 cm using IGS precise GPS
orbits). Local multipath from reflecting aircraft surfaces also produces errors, which
unfortunately cannot be modeled. Multipath errors must be limited by choosing an optimal
place ment of the antennae on the aircraft.
An additional observable, the excess Doppler shift, is calculated by taking the filtered time
derivative of the excess phase delay. This observable has the property that it is less sensitive
to the carrier phase ambiguities, receiver clock offsets, and orbit errors.

3) Refractivity profile retrieval

Refractivity profiles can be retrieved using either the excess phase delays in a ray tracing
linearized inversion technique ([Aparicio and Rius, 2001]) or the Doppler shift measurements
in a bending angle Abel Transform inversion technique ([Melbourne et al., 1994; Zuffada et
al., 1999]).

Ray tracing linearized inversion for refractivity
For this method, an initial guess of the atmospheric profile is used for ray tracing, from which
phase residuals are calculated. Then a linearized inversion is used to recover an improved
estimate of the refractivity field. This requires:
• A priori estimates of P, T, RH, (and their derived N profile), i.e., from an NWP or
climatological model;
• In-situ measurements of P, T, and RH and the derived local refractivity N, used to
provide additional control on the a priori refractivity profile;
• Data from +10 degrees to –10 degrees from the horizon for removing the phase delay
due to the travel path through the atmospheric layers above the height of the receiver.

Bending angle Abel transform inversion for refractivity
For this method, the excess Doppler shift is used to calculate the deviation of the direction of
the line of sight from the geometric straight line distance which is related to bending angle
([Vorobev and Krasil’nikova, 1994]). The bending angle is inverted using equation (T3) and
an Abel transform. This requires:
• In-situ measurements of P, T, and RH and the derived local refractivity N for taking
into account deviations in the line of sight due to refractivity variations near the
receiver;
• Data from +10 degrees to –10 degrees from the horizon for removing the bending angle contribution from the atmosphere above the height of the receiver (Healy et al).

In both cases, errors in the a priori assumptions will affect the accuracy of the estimated refractivity. Phase delay measurements are most sensitive to the accumulated refractive delay, whereas Doppler measurements are most sensitive to the refractive bending angle. Inverting phase delay measurements has the advantage that the method is less sensitive to local receiver errors such as aircraft velocity, attitude and local refractivity, which can contaminate Doppler measurements. However, inverting Doppler shift measurements has the advantage that this observable cancels some of the terms of the observation equation, in particular the integer carrier phase ambiguities and receiver clock offsets. In both cases assumptions of spherical symmetry are made, which contributes to the error budget.

4) Humidity/Temperature profile retrieval

Since the variability of water vapor is much greater than that of temperature, water vapor profiles are recovered by solving for water vapor pressure in equation (T1) using assumed profiles of P and T from NWP models, climatological, or synoptic data. Additional constraints are provided by in-situ data:

• A priori estimates of P, T, RH, and N profiles, i.e., from an NWP or climatological model, or synoptic data;
• In-situ measurements of P, T, and RH and the derived local refractivity N, used to provide additional control on the a priori profile

Because of the strong dependence on a priori information, validation and assimilation directly of the refractivity, bending angle or Doppler data is preferred. However, in practice, the errors in model fields of T and P are significantly smaller than humidity errors. A 1% error in T in the assumed profile leads to approximately 5% error in humidity ([Melbourne et al., 1994]), still making the measurements useful compared to typical humidity field uncertainties ([Palmer et al., 2000]).

Feasibility Study

We performed the following feasibility study over the past year in the framework of a contract with the European Space Agency ([Haase and Lesne, 2001; Lesne et al., 2002]). The objective was estimate the effects of the major error sources that can come into play in the data processing presented above:

• RO antenna position errors (relevant for the case of ray tracing linearized inversion);
• RO antenna velocity errors (relevant for the case of bending angle Abel transform inversion);
• In-situ P, T, RH measurement errors;
• A priori profile errors;
• Spherical symmetry assumption error.

The remaining errors are significantly smaller than the positioning error, therefore are not limiting errors:

• Orbit errors (2-3 cm)
• Clock receiver errors (<0.1 ns)

The results of this feasibility study will define requirements for the instrumentation and the processing scheme. They also provide estimates of the expected sampling characteristics, in
order to establish requirements for the raw GPS phase data sampling, and provide a preliminary basis for the evaluation of the usefulness of the derived refractivity profiles. We carried out the simulations presented below using a three-dimensional atmospheric ray tracing algorithm ([Hoeg et al., 1995]) and the EGOPS simulation tool ([Poetzi et al., 1999]).

**Sampling characteristics of the derived products**

The United States, Canada, and Europe cooperate on exchanging aircraft based measurements of pressure and temperature during commercial flights in the AMDAR program (Airplane Meteorological Data Reporting (http://www.met.govt.uk/sec5/obs_land/ol6/)). In order to evaluate the potential sampling of an operational airborne radio occultation system, we simulated the occultation geometry for a set of AMDAR flights that occurred in a typical day-long period (Figure 2). We assumed a constellation of 26 GPS satellites and an aircraft cruising altitude of 11 km and cruising speed of 900 km/hr. We derived more than 225 occultations for 14 trans-Atlantic flights, with an average of 1 occultation every 220 kilometers of flight.

![Figure 2: AMDAR flights for one day (dark line trajectories) and the resulting occultation profiles (light line segments) above the Atlantic Ocean. The profiles are indicated by the horizontal trace of the tangent point as it descends from 10 km to the surface.](image)

Because the GPS transmitter is moving at high velocity relative to the airborne GPS receiver, the tangent point does not descend vertically through the atmosphere, but with some horizontal drift. For the airborne case, our calculations give a minimum horizontal drift of about 280 km when the aircraft and the GPS move in opposite directions. With the aircraft and the GPS moving in the same direction, the drift can reach up to 450 km.

The information is averaged over the horizontal distance corresponding to one Fresnel zone, approximately 200 km. Therefore, the observation is not a local measurement near the airplane, but a horizontally averaged value. The measurement is most sensitive to the refractivity at the tangent point, or closest point to the surface, of the ray path. The vertical resolution, based on the diameter of the first Fresnel zone, is less than 240 m.

**Error sensitivity tests**

As previously mentioned, one advantage in the airborne technique compared to the spaceborne technique is that one expects better sampling in the lower troposphere. This is because atmospheric attenuation and high dynamics carrier phase variations due to multipath limit the
ability of the space-borne receiver to acquire and track the signal. In a comparison of simulations for a space-borne receiver occultation and an airborne receiver occultation, we demonstrate that signal loss in the lowest atmosphere is only 6dB for the airborne geometry as opposed to 13 dB for the space-borne geometry (Figure 3). This illustrates that the higher signal to noise ratio for airborne receivers will eliminate many of the problems of data acquisition in the lower troposphere.

Figure 3 Excess phase delay, excess Doppler shift, atmospheric loss, and bending angle as a function of tangent point altitude (point of closest approach to the surface) of the ray path. Light lines are for the space-borne geometry and dark lines are for the airborne geometry. Signal loss in the atmosphere is only 6dB for the airborne geometry as opposed to 13 dB for the space-borne geometry.

In Figure 4 and Figure 5 we show the sensitivity of the technique determined from forward modeling tests. In these simulations we superimposed a Gaussian shaped disturbance of a given percentage in refractivity on a 1-dimensional refractivity profile and compared the difference in phase and Doppler shift to that observed in the profile without the disturbance. For example, Figure 4 (first panel) shows that an input disturbance of 1% refractivity produces a maximum phase delay of 4 meters. This is much greater than the expected errors on the phase data, primarily the 10 cm of horizontal position error. Figure 4 shows the effect on the phase delay of a disturbance imposed at each altitude level from 3 km to 10 km. The same tests are shown for the excess Doppler shift in Figure 5.

We extracted from these curves the maximum refractivity error at each height corresponding to the magnitude of each of the major error sources. Compiled on Figure 6 are lines corresponding to 1 mm/sec, 2 mm/sec, and 5 mm/sec velocity errors. Also shown are lines corresponding to the estimate of the aircraft position error (10 cm), and the a priori in-situ measurement error (1° C, approx 5% RH). We show for reference the magnitude of expected signatures in the refractivity due to sharp gradients associated with weather fronts (5° C/100 km), large scale three dimensional variations from ECMWF global model fields (1.125 deg latitude grid), and humidity variations at the horizontal scale of 30 km from higher resolution ECMWF model fields.
Figure 4: Predicted excess phase delay as a function of tangent point altitude produced by a given percent change in refractivity at a given height.

Figure 5: Predicted excess Doppler shift as a function of tangent point altitude produced by a given percent change in refractivity at a given height.
In-situ measurements of P, T, and RH reduce the error in the Abel transform due to uncertainties at heights above the aircraft. Figure 6 shows that the effects of in-situ measurement errors and upper level profile uncertainty are negligible at altitudes below 9 km.

If retrievals are performed using a spherical symmetry assumption, then the retrieved profiles will contain an error due to horizontal variations in the (P, T, RH) fields, for instance in the presence of a weather front. Two examples are shown in Figure 6: a "front error" assuming a steep temperature front and "3D error" coming from NWP model fields. These are not limiting measurement errors, but rather provide motivation for developing 3D algorithms for assimilation of the bending angle data.

For the space-borne case, which samples higher in the atmosphere, humidity is assumed to be negligible or a known climatological value, so that Temperature profiles can be retrieved. In the lower troposphere, if this assumption is made, the existing humidity produces an error in the retrieved temperature that is not negligible. The magnitude of this error (transformed into refractivity) is shown as “humidity error”. This illustrates that the measurements cannot provide useful temperature profiles. The measurements are much more useful as a source of humidity data assuming the temperature profile is approximately known. In this case, the curve “humidity errors” can be interpreted as the magnitude of the humidity signal that we desire to measure, and Figure 6 illustrates the large size of the humidity signal relative to the error sources.

![Figure 6: Summary of refractivity errors versus tangent point altitude. Red line indicates target accuracy of 0.5% refractivity.](image)

The target accuracy for the retrieved refractivity is on the order of 0.5%, which corresponds to about 1°C at 10 km. These are the requirements applied for operational sounding by the space-borne missions ([GRAS-SAG, 1998; Hoeg et al., 1995]). Figure 6 illustrates that velocity errors become negligible (i.e. translate into less than 0.5% refractivity error) below 4
km, even assuming a 5 mm/sec error. 5 mm/sec is the maximum expected velocity error, but may be reduced to 1 mm/sec or 2 mm/sec by optimal filtering techniques, at the expense of slightly reduced vertical resolution. Figure 6 also shows that a 10 cm error on the aircraft position (typical error in the configuration of our experiments) translates into lower refractivity errors than velocity errors. Figure 6 shows that the accuracy of the derived refractivity decreases as a function of increasing altitude. Any increase in velocity accuracy shifts the line to the left, effectively increasing the height range over which observations can be reliably retrieved.

In summary, the compilation of error sources shown on Figure 6 shows that the sensitivity of the airborne occultation method is sufficient to provide useful information about the refractivity and water vapor distribution, provided that the aircraft velocity is known to better than 5 mm/sec. We find that the velocity error, due to uncertainties in the true aircraft motion and attitude, is the most important "instrumental" error. **This result is the main motivation for the purchase of a state-of-the-art GPS-INS integrated navigation system.**

**Research instrumentation and needs**

**Navigation equipment**

In order to fulfill the velocity accuracy requirements described above, we have chosen the Applanix GPS POS/AV 510 system with an integrated inertial measurement unit. This system provides the highest accuracy position, velocity, and attitude that is currently available on the market, with a velocity accuracy of 5 mm/sec and roll and pitch accuracy of 0.005 degrees and heading accuracy of 0.008 degrees. As shown on Figure 6, an error of 5 mm/sec on the aircraft velocity should allow us to retrieve refractivity from 4 km and below with an expected error level of 0.5% refractivity.

**Radio occultation equipment**

The radio occultation technique requires high sample rate carrier phase measurements made by the RO GPS receivers (Figure 7). For these measurements, we will use 2 dual-frequency Ashtech Micro-Z receivers that we recently purchased for the Purdue/Earth and Atmospheric Department Geodesy Lab. These receivers were purchased with choke-ring geodetic antennae for field measurements that cannot be installed on an aircraft. We therefore need to purchase 2 additional avionics antennae that can be mounted on an airplane fuselage. We will install these antennae on each side of the airplane in order to provide additional visibility for low elevation angle satellites (Figure 9).

**Auxiliary in-situ measurements**

As explained above, in-situ temperature, pressure, and humidity are needed for the retrieval algorithms and for acquiring validation data. We have chosen two instruments for humidity: a standard chilled mirror hygrometer to provide the absolute reference at low sample rates, and a high sample rate infrared gas analyzer designed by the NOAA ATDD group ([Auble and Meyers, 1992]). We will measure pressure using a short static pressure boom and a Setra barometer. Ambient temperature will be measured by a PRT which comes as an option with the chilled mirror unit. An A/D serial interface and a datalogger/computer are required for logging the in-situ data.
## Needed Instrumentation Requirements

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<tr>
<th>Needed Instrumentation</th>
<th>Requirements</th>
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<tbody>
<tr>
<td>GPS/INS navigation system (incl antenna)</td>
<td>5 mm/sec velocity accuracy or better is necessary for the smallest possible noise in the Doppler measurements, sampling rate 50-100 Hz.</td>
</tr>
<tr>
<td>2 additional avionics L1/L2 GPS antennae</td>
<td>RO antennae must be mounted on both sides of aircraft with visibility below the horizontal, thus must be separate from GPS NAV antenna.</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>&lt; 0.5 deg C required for in-situ refractivity and validation, 10 Hz sampling rate.</td>
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<tr>
<td>Humidity sensor</td>
<td>&lt; 2% accuracy required for in situ refractivity and validation, 10 Hz sampling rate.</td>
</tr>
<tr>
<td>Barometer/altimeter</td>
<td>&lt; 0.3 mbar accuracy required for in situ refractivity and validation, 10 Hz sampling rate</td>
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## Existing Instrumentation Requirements

| Aircraft (Beechcraft Duchess)            | 7 km ceiling or higher. |
| 2 RO GPS receivers (Ashtech Micro-Z)     | L1/L2 freq, 10-20 Hz sampling, phase recording, 85 Mb memory. |
| Ground reference GPS site (Ashtech Micro-Z) | L1/L2 freq, 10-20 Hz sampling, phase recording, 85 Mb memory, equipped with choke-ring antenna. |
| Processing computers                    | Pentium 90 processor minimum, 16 MB RAM |

Figure 7 Schematic diagram of instrumentation required for radio occultation measurements.

Figure 8 Instrumentation required for in-situ measurements, and rack-installed equipment for data logging.
Figure 9 Installation diagram for radio occultation and in-situ instrumentation in the Beechcraft Duchess aircraft.

### Equipment Description

**Applanix system navigation antenna. (Nav GPS antenna)**
- 12 cm L X 8 cm W X 2.5 cm H; 230 g
- Cabling: coaxial cable to PCS
- Mounted on top exterior of fuselage along centerline mid-length of aircraft.

**Applanix system Inertial Measurement Unit:**
- 10.9 cm diameter X 8.9 cm H; 1.6 kg
- Power: supplied by PCS
- Cabling: power cable from PCS, serial cable to PCS
- Mounted in rack on rear seat rails

**Applanix system PCS (POS Computer System)**
- System accuracy: post-processed position 0.05 m; velocity 5 mm/s; roll and pitch 0.005 deg; true heading 0.008 deg.
- 33.5 cm X 48.3 cm X 11.1 cm; 7.7 kg
- Power: 28VDC 100 W (max)
- Cabling: power cables to battery, coaxial cable to Nav antenna
- Mounted in 19 inch rack on back seat rail

**Two (2) radio occultation GPS antennae**
- 12 cm L X 8 cm W X 2.5 cm H; 230 g
- Power: no power, passive antenna
- Cabling: coaxial cable to Micro-Z receivers
- Mounted on side of aircraft above storage window

**Edgetech Model 200 DewTrak Humidity Transmitter**
- Accuracy: dewpoint temperature 0.6° C
- 22 cm H X 13 cm X W 8.6 cm; 1.6 Kg watertight plastic probe is 17 cm L X 5 cm Diameter
- Power: 12-30VDC, 850 mA
<table>
<thead>
<tr>
<th>Equipment Description</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabling: power cable to battery, cable to A/D serial interface, 1/8” air supply line from pitot tube to probe</td>
<td>Mounted in fuselage after nose cone</td>
</tr>
<tr>
<td>PRT Temperature Sensor (included as option on Edgetech)</td>
<td>Accuracy: 0.5° C 3 cm L X &lt; 1 cm diameter, &lt; 100g Power: 12-30VDC supplied through Edgetech Mounted on aircraft exterior</td>
</tr>
<tr>
<td>NOAA-ATDD Infra-red Gas Analyzer (IRGA)</td>
<td>Accuracy: 10 mg/m³ H₂O Approx 12 cm diameter X 50 cm long; &lt; approx 3 kg (TBC) Power: 10.5-15 VDC, 3 amps Cabling: cable to power supply/data transmitter, to battery. Mounted in a housing on the aircraft nose with the top 30 cm (open frame) exposed vertically outside the nose cone. Power supply/data transmitter mounted in rack.</td>
</tr>
<tr>
<td>Setra Systems Model 270 Pressure sensor</td>
<td>Accuracy: 0.01% 8 cm X 8 cm X 4 cm; 250 g Power: Nominal 24 VDC, 8 milliamp (0.2 watts) 20-32 VDC Cabling: cable to datalogger, cable to power supply/battery, air supply line from static pressure probe. Mounted on plate behind nose cone</td>
</tr>
<tr>
<td>Static Pressure Boom</td>
<td>Approx 75 cm L X 3 cm Diameter; 170 g Cabling: air supply line (non-compressible) to barometer.</td>
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<tr>
<td>Rackmounted Industrial PC</td>
<td>48 cm W X 17.7 cm H X 44.6 cm D; 12 Kg without cards Power: 12V, 300W, 12V 3500 mAmph Lithium-Ion battery. Cabling: serial cable to A/D converter Mounted in 19inch rack. Or rackmounted shock resistant drawer with PC docking station and a portable PC for approximately the same weight. Includes A/D serial interface card.</td>
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<tr>
<td>Two DC to DC regulated power supplies with with sealed lead acid battery backup</td>
<td>Power: provides one 12 VDC and one 24 VDC output Size: Approx 80cm W X 30 cm D X 25 cm H, 20 kg</td>
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Existing Equipment:
Acquisition and installation plan

The outfitting of the proposed equipment in a Raytheon/Beechcraft B-76 model Duchess aircraft will involve extensive coordination between elements at Purdue University and the Federal Aviation Administration. The end result will be a fully certificated aircraft with modifications that can be converted from a scientific laboratory into a flight training laboratory and back, while retaining its standard airworthiness certificate in both uses. The only FAA required flight testing will be to determine that atmospheric probe attachment will not adversely affect the flying qualities of the aircraft. As a caution, with many of the necessary approvals through the FAA un-presented at the present time, alteration from the January 2002 planned design may result from FAA input. This alteration of the design may impact the final experimental configuration.

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<tr>
<th>PHASE</th>
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<th>YEAR 2</th>
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<tbody>
<tr>
<td>Planning and approval</td>
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<td>Plan installation</td>
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<td>FAA modifications proposal</td>
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<td>Flight test with mock-up</td>
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<td>Preliminary FAA approval</td>
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<td>Final weighing and flight tests</td>
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<td>Final FAA approval</td>
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<td>Aircraft modifications</td>
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<td>Instrument mounts, rack</td>
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<td>Aircraft housings</td>
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<td>Instrumentation</td>
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<td>Order equipment</td>
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<td>Develop A/D interface/datalogging</td>
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<td>In-situ instrument integration</td>
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<td>In-situ instrument calibration and ground tests</td>
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<td>Installation</td>
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<td>GPS antennae multipath tests</td>
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<td>Install GPS antennae</td>
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<td>Rackmount GPS receivers and power supply</td>
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<td>Install In-situ instruments</td>
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<td>Data acquisition tests</td>
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<td>Post-processing software installation and testing</td>
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<td>Archiving system development</td>
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<td>Ground data acquisition tests</td>
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<td>Flight data acquisition tests</td>
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<td>Data verification</td>
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Figure 10 Acquisition and installation plan for aircraft modifications, in-situ measurement equipment integration and equipment installation.
Management Plan

The aircraft on which the instrumentation will be deployed is jointly owned by the Chemistry/EAS and Avtech departments. Flight time is allocated both to research and flight training. The instrumentation will be deployed during all radio occultation flight time. The instrumentation will be removed during flight training. The instrumentation will be deployed during boundary layer flux experiment flight time whenever available (i.e. not being used for testing off the aircraft). Flight time for the airborne radio occultation experiments and other uses will be scheduled as follows:

- Installation down time for the aircraft is 3 months during 2002.
- Radio occultation experiments will have 4 or more 1-2 day flight tests reserved for development and testing during 2002. These will be scheduled during Summer 2002, and during the Fall and Spring semesters during low use times by Avtech, through a reservation process with a 2 week lead time.
- Radio occultation experiments will have a 3 week dedicated flight campaign reserved during Late Summer 2002 or Early Summer 2003 or Late summer 2003. The actual date will be reserved 3 months in advance, depending on the final installation date.
- Avtech will have priority for flight training during Fall and Spring semester, with intense (full time) use during the mid semester and the final weeks of the semesters.
- Boundary layer flux experiments will have 100% of the flight time reserved for summer 2003, with the exception of the 3 week radio occultation experiment.
- Aircraft maintenance down time has scheduling priority each 100 hours of flight time. Maintenance for the major instrumentation items (Applanix POS/AV 510, IRGA) will be provided by the manufacturer under the purchase agreement. Aircraft maintenance will be provided by Avtech at no cost to the project.

Planned research experiments

This proposal covers only the acquisition, integration, installation, and testing of the equipment necessary to carry out airborne radio occultation measurements. Further experiments are planned for determining the absolute sensitivity of the technique, validation of the measurements against independent observational data and NWP models, and for application of the technique to NWP modeling of convection. These experiments are not covered by this proposal but will be the primary use of the equipment and thus are described below as scientific justification to the equipment requested in this proposal.

Error analysis test flights

We will carry out 2 or more local test flights to test the data processing and retrieval software, and to determine the final noise level due to instrumental noise, processing techniques, and aircraft dynamics. Statistical studies of the signal to noise ratio of the data, especially for the lowest elevation angles will be made with the test flight data to estimate the actual coverage and sampling compared to the theoretical sampling. The signal-to-noise ratio of the phase residuals must be quantified in order to design the filtering algorithms to reduce the effects of multi-path and random errors. It also will also be used to estimate the true observation sampling capability in the presence of realistic atmospheric attenuation. The statistics will be used to plan flight requirements (for example, turn bank) for optimal flight data recording.
Local validation test flights

The second set of tests will be for validation of the meteorological retrievals. We will use data from 2 or more local flights to collect data over a range of occultation geometries in order to optimize the retrieval algorithms given the noise characteristics of the data.

At the beginning and end of the flights, in-situ humidity, temperature and pressure measurements will be made by sensors on the aircraft during the ascending and descending legs that approximate the sampling path of the RO profile. These will be used as data for validating the retrieved radio occultation humidity profiles. The flights will take place in the local region where radiosonde data will be available.

Validation and scientific campaigns

Great Plains mid-level moisture
The experiments to be carried out once the technique is tested locally are directed at increasing the availability of high vertical resolution humidity profiles in the mid-troposphere, and investigating the impact of this increased resolution in climate studies and weather prediction.

This campaign would be planned in collaboration, if possible, with other dense field campaigns in order to benefit from an increased availability of field data for validation. Though the system would not be ready before the IHOP (International H2O Project) campaign in May-June 2002 (), the same observation region would be used. A significant amount of instrumentation used in IHOP at the Cloud and Radiation Measurement (CART) Site is in permanent operation, and would be valuable as a potential source of validation data. This could include the ARM/CART radiosondes, the existing ground-based GPS tomography array, the profiling radiometer, and the Raman LIDAR, depending on the actual configuration at the ARM/CART site at the period of the campaign. In addition, we expect that the University of Oklahoma and NOAA NWP model data would be available as an additional source of validation data. The accuracy of the airborne radio occultation (ARO) data would be compared to other techniques at specific heights in the troposphere. We will focus determining the horizontal representativeness of a single profile measurement at heights where it is not possible to sample with ground-based profilers. Model validation is best done by ray tracing through the NWP fields or other independent measurement profiles to generate excess phase or excess Doppler profiles, rather than bending angle or P or T profiles. This makes the validation stage less sensitive to assumptions in the humidity retrieval process.

A second objective of this campaign is to evaluate the impact of the high vertical resolution ARO data in weather prediction models. In convective situations, the prediction of precipitation rates is linked to the vertical profile of water vapor. It is a high priority for the U.S. Weather Research Program and was one of the major arguments for the IHOP campaign (Parsons () Emanuel et al 1995; Dabberdt and Schlatter 1996). The flux of latent heat and exchange of dry air across the boundary layer is also important. ARO profiles at short time intervals would be sensitive to these fluxes, which show up in the humidity profiles. We will work with collaborators to assimilate the ARO data during active convection to assess the impact of the high resolution data in the humidity field initialization.
Oceanic profiles and the boundary layer
Water vapor information in the 300 to 700 mbar range is the most critical for providing accurate forecasts of high precipitation low pressure systems that develop over the ocean ([Cardinali, 2000]; [Gerard, 2000]). Sensitivity tests of the ECMWF global model for different observation scenarios shows that the 48 hour forecasts errors are most sensitive to humidity errors over the ocean (Figure 11).

ARO observations have a promising potential to provide this type of data. In contrast to existing commercial aircraft humidity sensor systems such those used in as AMDAR and ACARS, the aircraft used in ARO measurements do not have to fly through the region to be sensed, but can fly several kilometers above and fifty to hundreds of kilometers to the side. This has distinct advantages since commercial aircraft usually are directed to fly outside of areas of severe turbulence and convection.

Figure 11 Climatology of 2-day RMTE key analysis errors integrated over surface to 200 hPa. Contours show sensitive areas for the 48 hour forecast over southern Europe in summer (right) and in winter (left) (Figure from [Cardinali, 2000]).

We plan a campaign to evaluate the accuracy of model profiles, for example NCEP forecasts, over the ocean in the mid-troposphere range, using the RO data as a source of data for model validation. This flight would be taken over the Atlantic seaboard to provide oceanic profiles on both sides of the aircraft. Vertical profiles of humidity will be compared to model profiles in the surface to 200 hPa range. The ability of the model to reproduce the height of the marine boundary layer would also be tested through comparison with the RO observations.
Auxiliary use of the equipment: Boundary layer flux measurements

In addition to the radio occultation research, the high accuracy GPS/INS instrumentation will enable the aircraft to be used for flux measurements at the atmospheric boundary layer by Dr. Paul Shepson’s group at Purdue University. An aircraft is being purchased jointly by the Aviation Technology and Chemistry/EAS Departments for this purpose. The measurements are aimed at research on the flux of isoprene and other chemicals into the atmosphere from forest environments and its contribution to the ozone balance. Funding for the flux instruments and the aircraft is provided through an existing grant.

The flux measurements will be made by a "bat probe" ([Crawford et al., 1993]) extending from the nose of the aircraft, equipped with an air sampling chamber for later analysis of samples on the ground. The flux calculation requires knowledge of the aircraft vertical velocity to better than 1 cm/sec. Also, the time duration over which the air sample is taken depends on the aircraft velocity and requires vertical accuracy better than 0.2 m/sec in real time. The Applanix POS/AV 510 more than satisfies these requirements.

The in-situ humidity sensors, in particular the NOAA IRGA, will be a valuable source of calibration data. The bat probe will be used to carry out additional measurements on H₂O fluxes, which can be validated by the NOAA IRGA. Calibrating the techniques on water vapor using two independent methods reduces the detection threshold for chemical constituents.

**Strategy and impact**

Potential long-term benefits and impact

The long term impact of developing the airborne radio occultation technique, and bringing it to an operational state, will be on increasing the knowledge of humidity fields over oceans for both NWP and climate.

The positive feedback between water vapor and temperature makes knowledge of the distribution of atmospheric water vapor critical for predicting global warming with climate models. The current meteorological observation system under-samples these fields with the present configuration of low vertical resolution space-borne sounders, infrequent drop sondes and ship-launched radiosondes. The technique has the potential to provide humidity data from the surface to mid-troposphere that complements existing data sources. The technique relies on the GPS signal which is a very stable source, and stability is important for climate studies.

The impact in NWP would be significant, by reducing uncertainties in the vertical humidity structure over the oceanic areas that limit the prediction accuracy of cyclone development and intensification.


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