Assimilation of GNSS-R Delay-Doppler Maps into Hurricane Models

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1 Scientific/Technical/Management

1.1 Objectives and Expected Significance

The broad objective of this proposed research is to optimize the utilization of spaceborne GNSS Reflectometry measurements to improve hurricane track and intensity forecasts, making use of the first data available following the Cyclone GNSS (CYGNSS) launch in October 2016. We will pursue this objective on two fronts. First, through a study to determine the optimal approach for assimilating reflectometry data into hurricane models. Second, through an improved understanding of the model functions relating the ocean surface slope distribution to the surface wind vector, using new experimental data to be collected with an improved GNSS-R receiver on forthcoming NOAA P-3 “Hurricane Hunter” flights.

Experience with in-storm flights and highly detailed numerical models (see figure 1) show that winds in a hurricane vary enormously in speed and direction on short horizontal scales. CYGNSS Baseline wind retrieval algorithms however assume the wind is spatially homogeneous over a 25 km resolution cell. The goal of the proposed work is to improve this situation. We will improve forward-scatter model functions from airborne GNSS-R measurements. We will implement these new model function in a nonlinear 2d variational surface wind analysis system to extract wind fields from the full information content of the CYGNSS observations. To test and tune our data assimilation method, we will quantify and optimize the impact of the CYGNSS wind fields for predictions of hurricane track and intensity. Forecast impact experiments will be conducted in simulation and through assimilating real data in forecast systems that parallel NCEP’s operational systems.

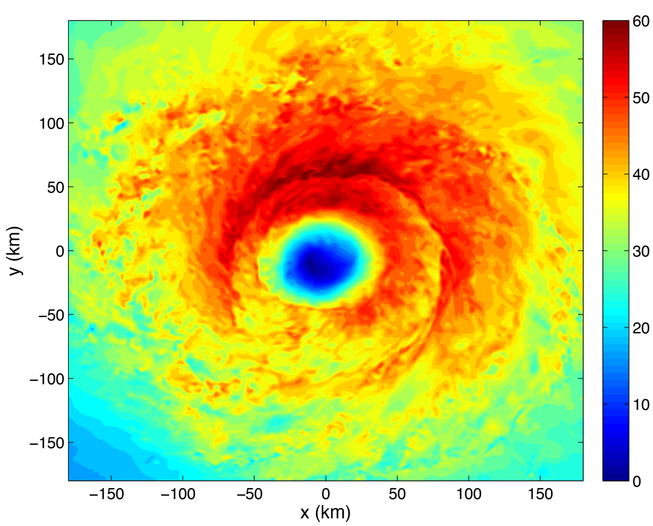


Figure 1: **High resolution simulated hurricane wind field. The simulation is from the HNR1 described by [1], which has been used by the CYGNSS project to produce simulated data. Colors represent wind speed (m/s) at 1124 UTC 04 Aug 2005 at 2.9 km above the surface. (Figure 10b from [1].)**

A primary goal of CYGNSS is to improve extreme weather forecasting, particularly in the prediction of hurricane genesis and intensification, making use of the dense spatial sampling available through a constellation of 8 GNSS reflectometry satellites and the penetration of L-band (1-2 GHz) signals through the intense precipitation in the inner core. Science requirements for CYGNSS set a surface resolution of 25 km for wind retrieval. This limits the extent of the delay-Doppler map (DDM) available for wind retrieval, essentially discarding a significant amount of data falling outside of the resolution-limited area. Furthermore, the DDM is indirectly sensitive to ocean surface winds by way of, the wave slope distribution. Extracting a wind measurement from the DDM therefore requires knowledge of a relationship between winds and surface roughness. Much of present work with CYGNSS relies upon an empirical model for this relationship, derived from over 10 years of airborne measurements. That model assumes an isotropic distribution of surface roughness, limiting its ability to incorporate the sensitivity to wind direction into the retrievals. The combination of a data assimilation approach, whereby prior constraints from a numerical weather prediction model would aid in resolving wind direction, and an improved parameterization of the bi-directional slope distribution on forward scattering at L-band, is expected to significantly improve the quality of reflectometry data products from CYGNSS and future missions.

1.2 Technical Approach

Our technical approach will build upon ongoing work on the CYGNSS science team. A forward model will be derived from the fundamental geometric-optics scattering model and discretized to express the transformation from gridded mean square slope to the delay-Doppler maps. The corresponding adjoint for this forward model will also be derived. Development of this model is described in section 1.2.1 below. Our approach to the model assimilation of DDM measurements is given in section 1.2.2 and our proposed application to the first CYGNSS data products is described in 1.2.4. In addition to a demonstration with actual CYGNSS data, we will perform a sensitivity analysis to show the impact of GNSS-R measurements on forecast model skill, as described in section 1.2.3. Finally, section 1.2.5 describes our plan for airborne measurements to improve the slope PDF model.

1.2.1 Forward Model Development

The fundamental observation produced from a GNSS-R receiver is the DDM, a real function of two coordinates, delay and Doppler, $(\tau,\ f)$. Well established models (Kirchoff approximation to geometric optics) express this as a surface integral [2] having a general form of

$$R(\tau, f) = C \iint \frac{|G(\vec{\rho})|^2}{4\pi R_I^2 R_S^2} \sigma_0(\vec{\rho}) \left|\chi\left(\tau, f, \vec{\rho}\right)\right|^2 d\vec{\rho}^2 \tag{1}$$

in which $\sigma_0(\vec{\rho})$ is a map of the bistatic scattering cross section in coordinates on the ocean surface, $\vec{\rho}$, and $\chi\left(\tau, f, \vec{\rho}\right)$ is the ambiguity function which "masks" the surface in coordinates of delay and Doppler. Observation of surface winds enters through the cross-section, $\sigma_0(\vec{\rho})$, which can be shown to be proportional to the probability density function (PDF) of surface slopes, often parameterized by the 10-m wind vector. Equation (1) represents a non-invertible transformation from a variable in surface coordinates, $\sigma_0(\vec{\rho})$, to a variable in delay and Doppler coordinates, $R(\tau, f)$. $G(\rho)$ is the antenna pattern. This also "masks" the surface, but is typically much wider than $\chi\left(\tau, f, \vec{\rho}\right)$. R_I and R_S are the ranges from the transmitter to the surface and from the surface to the receiver, respectively. C is the product of several constants that are combined for simplification, since they are not relevant to the essential understanding of the measurement.

Most approaches to airborne GNSS-R wind retrieval assume that the entire ocean surface contributing to the integral in (1) (e.g. the "glistening zone") is homogenous, represented by a single wind speed. For satellite observations of tropical cyclones, these assumptions are no longer valid. The glistening zone from space can extend for hundreds of km, whereas useful observation of tropical cyclones require a resolution of 25 km (the CYGNSS requirement) or better. Thus, only regions of the DDM in which the delay-Doppler "mask" falls within a 25 km resolution cell around the specular point can be contribute to this measurement. Consequently, much of the available information in the DDM is discarded due to this resolution requirement.

We are proposing an alternate approach, data assimilation (DA) of samples of the full DDM,

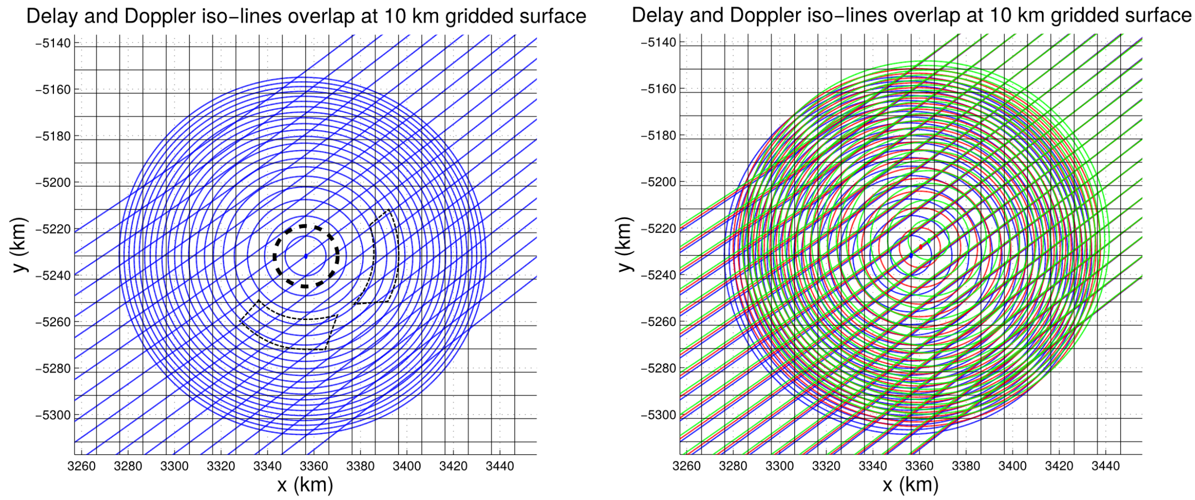


Figure 2: **Left: Iso-range and iso-Doppler curves, corresponding to the DDM overlaid on a 10 km surface grid. The dashed ellipse is the 25 km resolution cell, showing the small portion of the DDM actually used to generate CYGNSS retrievals. The two regions indicated by black lines are the contributions to $R()$ at a specific delay and Doppler, showing that this comes from two regions on the surface and thus the mapping from surface coordinates to delay-Doppler is not invertible. Right: The motion of the DDM over the ocean surface in 3 sec. Each color represents the full DDM generated once per second. Example geometry from CYGNSS mission.**

covering a heterogenous glistening zone. This approach is expected to extract more information about the ocean wind field from the DDM. Representativeness errors are thus expected to be lower than for the baseline CYGNSS retrievals which assigning a single wind speed at the specular point.

We will use the DDM model (1) to derive an observation operator (or "forward model"). Observations would be samples of the DDM in discrete steps in delay and Doppler (τ_i, f_j) at discrete time steps, t_k , as the satellite orbits over the area of interest. With a DDM consisting of N_τ delays and N_f Dopplers, an observation vector of $N_\tau N_f$ measurements will be available at each time step, t_k (1 sec, for CYGNSS).

$$\mathbf{y}_k = \left[R(\tau_1, f_1, t_k), R(\tau_1, f_2, t_k), \ldots, R(\tau_2, f_1, t_k), \ldots, R(\tau_{N_\tau}, f_{N_f}, t_k)\right]^T \tag{2}$$

The integral in (1) will be discretized using a coordinate system fixed to the ocean surface. Careful consideration to determine which factors in the integrand can be assumed constant over the entire glistening zone, which are constant within each surface grid pixel, and which must be integrated separately within each grid pixel pixel, allows us to simplify a potentially complex, time-varying model. A typical surface grid size is 9 km, as commonly used in the Hurricane Weather Research and Forecasting (HWRF) model framework [3]. Geometric effects (e.g. path-loss) for a satellite in a 500 km orbit are not expected to vary significantly over a 9 km pixel, and will be represented by the function $B()$, evaluated at the center of each grid. A similar argument can be made for the bistatic cross-section, $\sigma_0(\vec{\rho})$, which will also be evaluated at the midpoint of each grid pixel. Under these assumptions, discretization of (1) takes the form

$$R(\tau_i, f_j, t_k) = C \sum_p \sum_q B_{p,q}(t_k)\sigma_0(\vec{\rho}_{p,q})\bar{\chi}_{p,q}(\tau_i, f_j, \vec{\rho}_{p,q}) \tag{3}$$

The ambiguity function can vary significantly over a 9 km pixel, particularly at long delays from the specular point, as figure 2 shows. Fortunately, this can integrated in advance using only knowledge of the satellite geometry, giving the coefficient $\bar{\chi}_{p,q}(\tau_i, f_j, \vec{\rho}_{p,q})$ in (3), which represents the averaged effect over grid pixel centered at $\vec{\rho}_{p,q}$.

Note that the observation operator (3) is linear in the cross section σ_0. σ_0 has a nonlinear relationship to wind speed, however, and this needs to be incorporated into the forward model at some stage of the processing. We will begin our studies using existing models for this relationship used by CYGNSS [4], [5], [6]. Next, will explore an experimental study to refine them, in section 1.2.5.

1.2.2 Model Assimilation

The promise of model assimilation becomes apparent when viewing figure 2. Loci of constant delay (iso-range) and Doppler are shown on the ocean surface. Each DDM sample represents a smoothed measurement of the scattered power within the small region bounded by pairs of these two curves, as illustrated. A 10 × 10 km surface grid is overlaid on this figure. To illustrate the limitations of the CYGNSS Level 2 wind retrievals, a 25 km resolution circle is drawn at the specular point. To meet this resolution requirement, only DDM samples corresponding to the iso-range and Doppler curves within this circle are included in the baseline CYGNSS Level 2 wind retrievals. Utilization of measurements from the DDM extent beyond this area is possible when the satellite motion is considered and subsequent DDM's offer independent "looks" at the same points on the surface. This is illustrated on this figure by the different colors for different observations made at intervals of 1 sec.

The present approach to wind retrievals for CYGNSS is limited by the 25 km surface resolution requirement. This limits the retrieval to only delay-Doppler bins near the secular point (± 1 kHz and ± 0.25 chip), as shown by the dashed ellipse in the center of 2(Left). The SGR-ReSI receiver on CYGNSS can generates DDM's with 128 delays and a Doppler range of ± 6 KHz [7].

Another feature is that the area enclosed by each subsequent iso-delay ellipse decreases with increasing delay (following a square root dependence), so that the region of the surface influencing the observed signal in the first range bins, is much larger than that influencing the observed signal in longer delays. In essence, the limitation to a 25 km resolution will require that most of the samples of the DDM collected will be discarded and not included in the retrieval.

The geometry illustrated in figure 2 is similar to that of a side-looking SAR, with the exception that the mapping from delay-Doppler coordinates to surface coordinates is not invertible. This is shown on the figure, where two surface areas correspond to the same delay and Doppler. A similar problem would exist in SAR, except for the masking by a fixed antenna beam, which is not possible to do under the time-varying bistatic geometry presented by signals-of-opprotunity missions such as GNSS-R.

An Extended Kalman filter (EKF), in which the 10 km gridded wind field is the state, and each DDM is processed as a observation vector, $\mathbf{y}_k$, has been applied to perform this inversion. Using the baseline receiver design for CYGNSS, results of the EKF processing of synthetic observations generated by applying the CYGNSS end-to-end simulator (E2ES) to wind fields from TC "Danielle" are shown in figure 3. Figure 4 shows the error for the EKF retrievals, averaged over 25 km cells. As can be seen in that figure, the use of the EKF shows a significant improvement over the individual single-observable retrievals. Results are still above the CYGNSS requirements, however. This is due to the lack of editing with elevation angle or range-corrected gain (RCG) in comparing the results in this figure. Present work is studying the application of a RGC weighting to the data covariance matrix. The other important consideration here is that there are no model dynamics in this problem, the EKF retrieves the samples of the 10 km wind field independently of all others.

To guide our development of improved empirical models of the DDM in terms of ocean surface

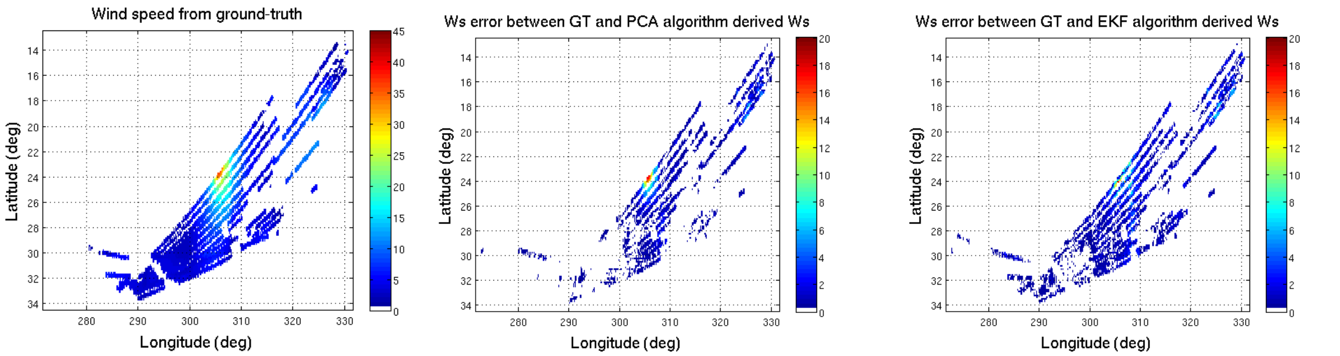


Figure 3: **Application of the EKF to wind field retrievals. (a) surface truth, from TC Danielle, used to generate synthetic DDM's (b) wind field retrieval error using PCA applied within the 25 km resolution cell near(c) wind field retrieval error using EKF applied to full DDM. Observe the higher error near the center of the storm for the PCA results.**

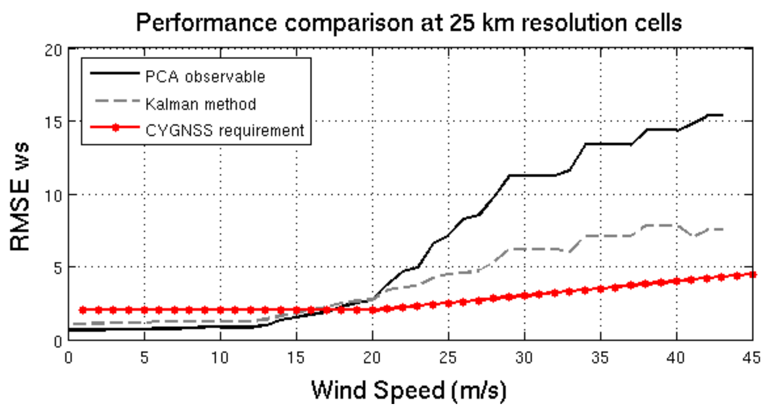


Figure 4: **RMS wind speed error (m/s) as a function of true wind speed (m/s) for the standard and (PCA) and Kalman Fillter methods. 25 km averaged along the specular point.**

roughness or wind, we will use a multi-stage data assimilation and forecast strategy that will be both efficient and cutting edge. Our approach is efficient in limiting the required level of effort by making use of existing software infrastructure. This existing software infrastructure includes the variational analysis method (VAM), a highly customizable, fully nonlinear, 2d-Var ocean surface wind data analysis system and NCEPs operational HWFR [8] Model data assimilation (DA) system which presently uses the GSI 3d-Var analysis and is transitioning to the hybrid GSI/EnKF analysis. The VAM will be extended in this work to make use of DDM observations. Then the VAM analyzed wind fields will be sampled to provide buoy-like observations to the GSI and (later) to the hybrid analysis. This strategy uses the VAM to treat the nonlinearity of the DDM observation operator (aka forward model) and eliminates the necessity to make extensive modifications to the GSI. Because the HWRF/GSI DA system that we use is an operations to research (O2R) system, it is regularly updated to match the operational system. As a result our approach is cutting edge in providing insights into and quantification of impacts of the use of CYGNSS data in the U.S. operational hurricane forecast system. The variational analysis method (VAM) of Hoffman et al. (2003) [9] minimizes a cost function of the form

$$J(\mathbf{x}) = \frac{1}{2}\left(\mathbf{y} - h(\mathbf{x})\right)^T \left(\mathbf{P}_O + \mathbf{P}_h\right)^{-1} \left(\mathbf{y} - h(\mathbf{x})\right) + \frac{1}{2}\left(\mathbf{x} - \hat{\mathbf{x}}(-)\right)^T \mathbf{P}_{\hat{\mathbf{x}}}^{-1} \left(\mathbf{x} - \hat{\mathbf{x}}(-)\right) + J_c(\mathbf{x}) \qquad (4)$$

using standard notation [10].

VAM, originally developed for data from the SeaSat-A Satellite Scatterometer (SASS) by Hoffman [11], [12], is a fully nonlinear 2d-Var approach based on smoothing splines, and includes a number of observation operators for ocean surface winds. The VAM is a very efficient research tool for CYGNSS trade studies of different observation operators, data resolution, prior information, and observation error specifications, as well as a suitable software platform for quasioperational data processing. The VAM will be configured to produce ocean surface wind analyses from CYGNSS data over regional domains at resolutions of at least 3 hours and 25 km, to use the HWRF short-term forecasts as background wind fields, and to optionally include other satellite surface winds and additional special aircraft observations, such as those collected by the SFMR. The VAM can assimilate wind speeds and other CYGNSS data produced, potentially including wind direction, ambiguous wind vectors, (unambiguous) wind vectors, surface roughness variables related to the wind field and DDMs. The wind speed observation operator exists for the VAM and has been used extensively in creating the Cross-Calibrated MultiPlatform (CCMP) data archive. Atlas, et al. [13], [14] showed a substantial increase in the accuracies of wind direction and wind speed of our CCMP product over the ECMWF wind fields that were used as the background for the variational analysis. Henderson et al. [15] used the ambiguous wind vectors observation operator developed by Hoffman [11] to remove the ambiguity of NASA Scatterometer (NSCAT) winds.

Two considerations for model assimilation will be studied. The first is the optimal level of the data extracted from the CYGNSS observations. Theoretically, this could range from the raw, Nyquist-sampled reflected signals, to the Level 2 wind speeds. Although raw signal samples will be collected occasionally for algorithm development and debugging purposes, the lowest level data product which would normally be considered is the Level 1b DDM samples, calibrated to scattering cross-section. We will focus our evaluation on three different levels of CYGNSS data.

1. DDMs (CYGNSS Level 1b) - forward models, $h(\mathbf{x})$ and adjoint $H(\mathbf{x})$ will be derived from the discrete model (3) above.

2. Bistatic scattering cross section field within the instrument footprint, extracted from the Extended Kalman Filter (EKF) processing described above.

3. The standard CYGNSS Level 2 wind product, extracted from the minimum variance or PCA retrieval.

Using DDM information in a DA system is challenging and our approach to meeting this challenge will be patterned on methods developed for handling scatterometer σ^0 data. Thépaut et al. [16] used this type of observation operator in the ECMWF 4d-Var to improve weather forecasts. 4D-Var is now used operationally by many NWP centres for assimilation of several observation types with complex observation operators, most notably GNSS-RO data and MW and IR radiances. In addition, Atlas et al. [17] illustrated substantial positive forecast impact in analyzing the ERS-1 σ^0 values in the VAM and using the results in the Goddard assimilation system (cf. their Fig. 11). The use of the DDM data in the VAM will be analogous to the treatment of scatterometer σ^0 data in the following way: An observation operator relates the observed quantities (DDM amplitudes or σ^0 values) to the surface wind at the observation location and the misfit between simulated and observed values is minimized. For use in variational data assimilation the DDM observation errors must be appropriately characterized and an adjoint of the observation operator must be implemented. Using the DDM observations directly in the VAM is also the first step towards implementing a resolution enhancement technique to analyze ultra-high-resolution CYGNSS winds (see Section 1.2.4).

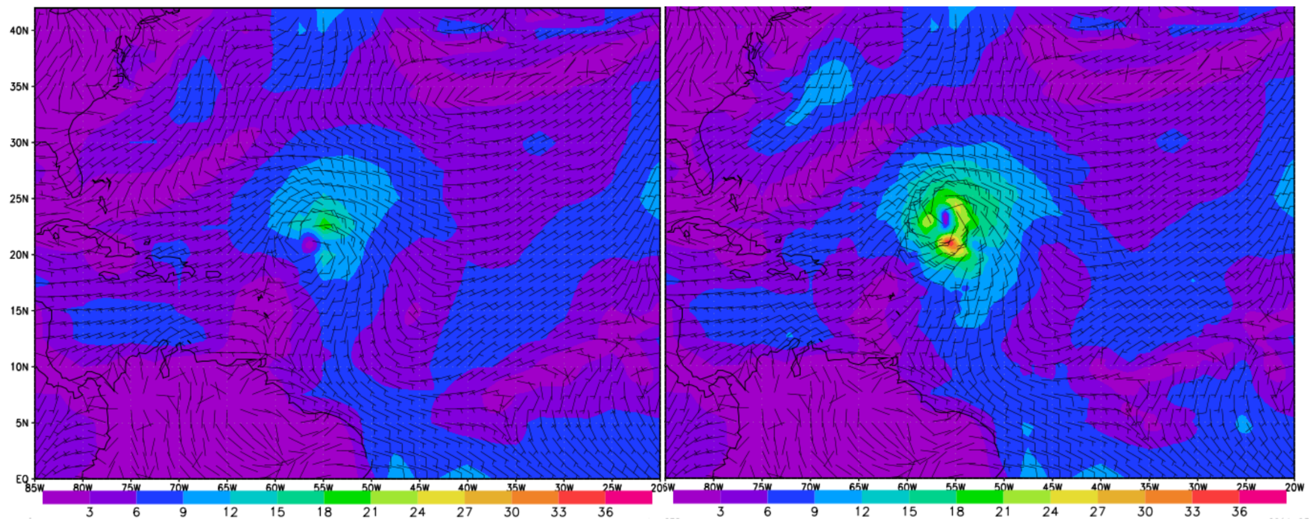


Figure 5: **VAM background (Left) and analysis (Right) of simulated CYGNSS wind speeds valid 00 UTC 08 Aug 2005. Filled colors are wind speeds in m/s given by the color bar at the bottom. Wind barbs indicate direction and speed.**

It is also advantageous to review past experience in assimilating GNSS radio-occultation (GNSS-RO) data as this measurement shares many similarities with reflectometry. A basic observable in GNSS-RO is the bending angle, α, as a function of impact parameter (a, essentially the altitude of the ray tangent). Under assumptions of a spherically symmetric atmosphere, this function has an invertible relationship to the refractive index profile, $n(x)$, through the Abel transform [18].

$$\alpha(a) = 2a \int_a^\infty \frac{dn}{ndx} \frac{dx}{\sqrt{x^2 - a^2}} \tag{5}$$

Refractivity ($n(x) \times 10^6$) depends on temperature, pressure, and relative humidity. These conventional meteorological variables can be assimilated in a straightforward manner. Horizontal gradients in the atmosphere, however, will lead to representativeness errors and a degradation in accuracy when the Abel transform is inverted to generate $n(x)$ profiles. Assimilation of bending angles directly was found to offer an improvement and allow horizontal variation in a forward model [19], [20].

Comparing the transform (5) between an observable function, $\alpha(a)$, and a profile, $n(x)$, that is closely related to standard meteorological variables, one can see similarities with the problem faced in assimilating GNSS-R observations. The bivariate DDM is also related to $\sigma_0(\vec{\rho})$, the map of bistatic scattering cross section over the ocean surface, through the integral transform in (1). $\sigma_0(\vec{\rho})$ is closely related to the surface wind speed, but the DDM is much closer to the raw observation from the GNSS-R receiver. In remote sensing, it is generally better to assimilate data at a level close to the actual measurement, rather than at the level of a retrieved product, and incorporate as much as is known about assumptions in the measurement (e.g. spherically symmetric atmosphere or homageneous wind field) into the forward model. Such an approach has been found to be beneficial in the two decades of experience with radio occultation. Similarities between RO and GNSS-R strongly suggests that it would be advantageous to begin assimilation of GNSS-R data at the level of the DDM.

1.2.3 Sensitivity Analysis

Observation System Simulation Experiments (OSSEs) will be conducted for high and low resolution VAM analysis grids to quantify the impact of the CYGNSS wind information retrieved at different scales. For example, CYGNSS winds can be produced at different horizontal scales: higher resolution generally degrades accuracy by reducing signal-to-noise, but may increase accuracy in some applications because of reduced representativeness errors. CYGNSS processing and wind retrieval algorithms will evolve during the project and we will repeat our OSSE sensitivity studies to provide feedback to the CYGNSS project. We will also extend our OSSE sensitivity studies to new OSSE runs as they become available. As a baseline, we expect to process up to three OSSE runs, with at least one of them corresponding a land falling hurricane such as Irene (2011) or Superstorm Sandy (2012). As a check on the OSSE calibration, the tuned version of the VAM will be applied to the GRIP ocean surface wind data sets and the results verified meteorologically.

1.2.4 Model Demonstration on CYGNSS Data

CYGNSS should launch October 2016 with data available by late 2016 or early 2017. We will begin our work during the pre-flight period, using CYGNSS team-provided data simulated from a detailed nature run. In OSSE mode, VAM sensitivity studies will establish performance for wind analysis and associated momentum fluxes and allow for tuning to optimize performance for circulation features ranging over hurricanes, ENSO events, MJO features, topography-induced wind fields, such as from islands, and calms. Accurate high-resolution vector wind fields are crucial to understanding the dynamics of these features. During this first period of the proposal, before CYGNSS data is released, we will be restricted to simulated observations. We will make a best effort to prepare for assimilating real data by using documental CYGNSS data formats, anticipating their limitations and optimizing analysis methodologies.

1.2.5 Experimental Improvement of Slope PDF Model

GPS reflectometry data has been collected on the NOAA P-3 Hurricane Hunter aircraft since 2000 using the NASA Langley Research Center delay-mapping receiver (DMR) [4], [5], [6]. An empirical model function relating the mean square slope (MSS) of the ocean surface to the 10-m wind speed was derived from these measurements through comparison with dropsondes and the U.S. Navy Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). This model function, which corrects a classical model [21], [22] in three wind speed regimes, forms the essential basis for CYGNSS Level 2 retrievals. Accuracy of this model improves substantially when measurements within the eye wall, near land, and from elevations below 60 deg. were eliminated [6]. When compared to dropsondes, the total RMS error is 4.1 m/s.

Two limitations of the DMR instrument are that it is only capable of observing one GNSS satellite at a time (typically the highest elevation one) and that it generates a 1-D mapping in delay only. In order to further refine theses models, particularly to identify an anisotropy effects, the observation of multiple satellites over a distribution of elevations and azimuths is required. Sensitivity to wind direction may be stronger in the Doppler direction and require a full DDM to resolve [23]. For this reason, we are proposing to fly an improved receiver, which records the full GNSS signal spectrum for later post-processing with a software defined radio (SDR) to synthesize a complete DDM. Presently, in addition to the Langley DMR, Purdue university has flown a wideband recorder for the S-band transmissions from a satellite digital radio service (SDRS). We are upgrading this system to add an L-band front-end to record GNSS signals.

Figure 6 shows a picture of the current S-band recorder, the antenna, and the bench testing of the GNSS-R upgrade to be added for the 2015 hurricane season. This figure also shows results of initial bench testing with the sky-view GNSS signals demonstrating detection of GNSS satellites and extraction of DDM's. Software is presently able to process signals from the US GPS system, along with the geostationary WAAS satellites. We are working to upgrade our software to process European Galileo and Chinese Beidou/COMPASS signals, allowing a total of 10 or more satellites to be observed at any time to better resolve the sensitivity to wind direction.

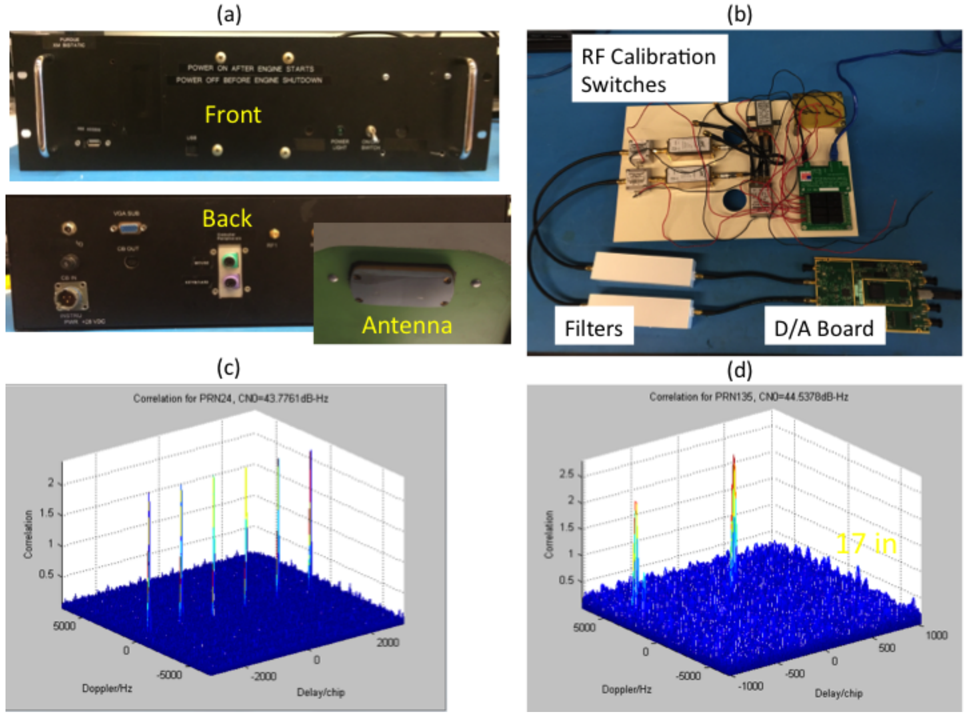


Figure 6: **NOAA P-3 GNSS and S-band Reflectometry Instrument. (a) Current S-band system (b) Lab bench test of GNSS (L-band) upgrade board (c) Test of GNSS recorder and SDR on acquisition of GPS PRN24 (d) Test of GNSS recorder and SDR on acquisition of geostationary WAAS signal. Multiple peaks are visible in these plots due to the periodicity of the transmitted signals (1KHz in the case of GPS).**

After post-processing to synthesize DDM's, we will apply our nonlinear least squares approach [24], [25] to estimate the parameters of the slope PDF from each visible satellite. These will be matched to dropsonde and other independent data sources collected during the flight and an empirical model will be derived which best fits this relationship. Bistatic scattering cross-section can be computed using well-established principles of geometric optics [26]. An important part of this model function development would be deriving a realistic error bound for it, which would enter the forward model through the covariance matrix $\mathbf{P}_h$ in (4).

1.3 Impact of Proposed Work on the State of Knowledge

The concepts and methods proposed to be developed and tested will be applicable, after some tuning and refinement, to data assimilation of real CYGNSS observations. VAM analyses of CYGNSS data will be valuable for all ocean modeling and air-sea flux studies of currently under-sampled events associated with precipitation. In particular, VAM analyses will provide accurate high-resolution surface wind fields to improve parameterizations of air-sea fluxes in extreme conditions and to act as a benchmark for weather and climate models. In the past, using the VAM as a pre-processor has improved weather forecasts [17]. VAM analyses will provide enhanced wind direction information for CYGNSS wind speed retrievals.

1.4 Relevance of Work to NASA Programs

This research is directly relevant to the Science focus area of Weather in the NASA Science Plan. Development of data assimilation methods for GNSS-R has the potential to improve weather forecast and reliability. In particular, the case of severe weather and natural hazards, through advancing our understanding of hurricane genesis and intensification and improving methods for the assimilation of the new reflectometry data types into models.

Specific contribution to NASA programs include:

- Improve CYGNSS-derived wind fields. Wind directions are critical for dynamical processes over a wide range of scales from the ENSO to the Madden-Julian Oscillation (MJO) to tropical cyclones (TCs) to ocean momentum fluxes.
- Guide validation studies and under flights and the design of follow-on GNSS-R missions. The proposed impact experiments will document the required quantity, quality, and type of data.
- Quantify and optimize the impact of CYGNSS data for TC analysis and prediction.

1.4.1 Relevance to Past and Present Work

This research builds upon some of the accomplishments of a prior GNSS Remote Sensing Science Team award to Prof. Garrison (Grant NNX12AP92G, "Application of Multi-Constellation GNSS Reflectometry Measurements to the Next Generation Salinity Mission: A Feasibility Study,") although the research topic is different. Software defined radio code has been developed under that grant to enable the synthesizing of DDMs in post process from Nyquist-sampled GNSS signals. Least squares methods for estimating the mean square slope (MSS) have also been developed on that grant as well as previous funding [24]. Prof. Garrison is on the science team for CYGNSS and the work described in this proposal directly follows on his accomplishments on that grant, namely the development of the single-point observable (PCA) [27] and the Extended Kalman filter [28] retrievals.

The first model functions for L-band bistatic scattering cross section at high wind speeds, derived from experiments on the NOAA P-3 [4], [5], [6] form a critical part of the first version forward model to be developed in this research. We expect to improve these model functions and their error bounds accounting for, at least, the effects of anisotropy. This will be an important contribution to the fundamental understanding of ocean remote sensing using the bistatic geometry.

A goal of this research is to develop the first data assimilation approach optimized for the unique features of reflectometry, and to assess the comparable performance of assimilating the DDMs vs. a more standard variable. The findings of this study will have a significant impact on the utilization of CYGNSS data.

Finally, GNSS-RO bending angle profiles have a mathematically similar structure, broadly speaking, as GNSS-R DDMs and past studies of bending angle assimilation provide excellent examples to follow in approaching the problem of DDM assimilation.

1.4.2 Relevance to Future Work

CYGNSS has two key limitations on the data products. First, the limited communication bandwidth restricted the total DDM generated onboard. Second, the 25 km resolution requirement limited the utility of this DDM further, to only 15 delay-Doppler samples near the specular point. The potential for more sophisticated methods of assimilating the full DDM may provide the motivation for reconsidering these limitations on a future CYGNSS follow-on mission. Specifically, if we show that information in the extended DDM can be used beneficially, within the resolution requirement, then a more extensive DDM, and consequently a higher bandwidth requirement, could be justified in future missions.

Parameterization of any slope PDF models using surface winds limits the applicability inside the eye, where waves are not principally driven by the local wind. Airborne measurements collected in this study may be applied to work proposed in the future for improving a physically-based wave model to better represent the wave structure inside the eye.

1.4.3 Relevance to the GNSS Remote Sensing Science Team NRA

The GNSS Remote Sensing Science Team seeks innovative approaches to the advance NASA's Earth Sciences program and the proposed research directly supports this goal. Specifically in the area of improving the capability to predict weather and extreme events, as identified in the NASA Science Plan. A secondary contribution of this work may be to further our fundamental knowledge of the air-sea interaction, which supports the Climate Variability and Change focus area.

1.5 Plan of Work

The plan of work will include 7 principal tasks, jointly conducted by Purdue University and the University of Miami over the four year period of performance. The schedule is

1.5.1 Task 1: Collection of GNSS-R Data on NOAA P-3 (Purdue)

The GNSS digitizer card and front end (section 1.2.5) will be installed into the wideband recorder box and delivered to NOAA for flight on the P-3 in time for checkout during the 2015 hurricane season (before the start of the proposed work). Resarch data collection will begin in the 2016 season. A graduate student, under supervise of Prof. Garrison, will be responsible for the assembly, checkout and installation of this system, and the extraction and processing of the data.

1.5.2 Task 2: Improved Bi-Directional Slope PDF Model (Purdue)

A parameterized model for the slope PDF will be fit to delay-Doppler maps generated from the data collected in Task 1. Software defined radio tools, developed by Prof. Garrison's research group will be used to generate delay-Doppler maps for all visible satellites. Least squares, or other parameter estimation methods, will be applied to determine the optimal fit of a parameterized PDF model. An error analysis will also be conducted to determine the uncertainty in these parameters for use in setting the model covariance matrix in the variational analysis. Details of these methods are covered in section 1.2.5. Prof. Garrison will lead this activity and supervise a graduate student.

1.5.3 Task 3: Derivation of GNSS-R DDM Forward Model and Adjoint, Version 1 (Purdue/Miami)

Building upon the preliminary work done on EKF inversion, described in section 1.2.2, Prof. Garrison will collaborate with Bachir Annane and Dr. Hoffman to derive a forward model (and adjoint) for the DDM in terms of a wind field. The input to this forward model is a horizontal grid of 10-m neutral stability u- and v-wind components, the VAM control variables. Then, in turn, the forward model calculates the corresponding wind speed and wind direction, the ocean surface roughness, expressed as a forward scattering coefficient, and then, finally a descretized DDM on grid matches that of the CYGNSS observation. The wind speed and direction to surface roughness transformation will the Cox-Munk type formulation presently used for CYGNSS Level 2 winds. The preliminary transformations in the forward model will be reused to also provide model functions for retrieved wind speed and for retrieved surface roughness. This task will overlap Task 4, to allow for iterative improvement in the model based upon preliminary results for the assimilation studies of simulated data and for improvements in the empirical roughness to DDM formulation afforded by the results of Task 2.

1.5.4 Task 4: Integration of GNSS-R DDM Forward Model into Data Assimilation Code (Miami)

The forward model derived in Task 3 will be integrated into the VAM software framework. Modifications to the VAM required to operate with the CYGNSS data and metadata formats will be made. Various configurations, using the three levels of data defined in section 1.2.2 will be assembled, tested, tuned, and validated in simulation. The best methodologies will then be used in

OSSEs (Task 6) and for the processing of CYGNSS data when it becomes available in Task 7. This task will overlap the portions of Tasks 5, 6, and 7, to allow for revision of the code, based upon experience with the OSSE results and with actual CYGNSS data.

1.5.5 Task 5: Derivation of GNSS-R DDM Forward Model and Adjoint, Version 2 (Purdue/Miami)

This task will revise the forward model, as necessary, based upon the revised bistatic scattering cross-section model, from Task 2. It is scheduled to start in the last quarter of work on that problem.

1.5.6 Task 6: Sensitivity Study/OSSE (Miami)

The VAM solutions will be sampled to provide buoy-like observations to the HWRF/GSI data assimilation system in use at the University of Miami. First tests of this setup have been done with existing synthetic wind speed data sets provided by the CYGNSS science team, thereby validating the mechanics of our approach. OSSEs will be conducted to quantify the impact of the three levels of CYGNSS observations on hurricane track and intensity forecasts.

1.5.7 Task 7: CYGNSS Data Processing (Miami/Purdue)

CYGNSS is scheduled for launch in October 2016, with the first data available a few months later. Progress on earlier tasks will enable validating the quality and testing the impact of CYGNSS retrieved winds immediately and other data products as our work progresses. The first part of this task will be to compare the CYGNSS data to the data assimilation background fields. The data are assimilated passively for this purpose. That is they go through the VAM but do not contribute to the solution. All QC decisions and analysis statistics are captured and analyzed. With the VAM background wind field taken to be an operational analysis from NCEP or ECMWF, this povides a comparison between the CYGNSS data and all other available data from a multitude of sources that has been combined under the constraint of the NWP model.

Second, it is expected that some amount of CYGNSS debug data, raw Nyquist sampled signal from the receiver front end will be available from one or two satellites during storm overpasses. We will make use of this data to synthesize alternative DDMs to study the sensitivity of the assimilation to parameters such as the delay and Doppler range, separation and the coherent integration time. Finally, impact experiments like the OSSEs of Task 5, but with real data will be conducted, in parallel to the quasi-operational HEDAS data assimilation and HWRF forecasts regularly conducted by AOML. Experiments with added CYGNSS data will be conducted during periods between active hurricanes, when the quasi-operational system is not using its computer allocation. This task will run from the first data release until the end of the project and will be led by Bachir Annane, with Prof. Garrison and his student providing support for the processing of CYGSS data.

1.5.8 Task 8: Evaluate Results and Summarize Recommendations (Purdue/Miami)

A summary evaluation will be made of the effectiveness of GNSS-R observables to tropical storm forecast. The best combination of measurements to be used in data assimilation will be identified and recommendations will be made for the next generation of GNSS-R missions.

1.6 Management Structure

This will be a collaborative activity between Purdue University and The University of Miami. Prof. Garrison at Purdue will serve as the PI and will broadly supervise the research. He will have responsibility for modeling of the GNSS-R measurement and processing of the airborne data. A graduate student, expected to begin this work in the first or second year of their doctoral research, will assist Prof. Garrison and will use this work as the basis for their dissertation. Bachir Annane at The University of Miami will serve as a Co-I and be responsible for the incorporating the new models into data assimilation codes, running the simulations, data processing and interpreting the results. Dr. Ross Hoffmann will be a Co-Investigator, proving his expertise to the project.

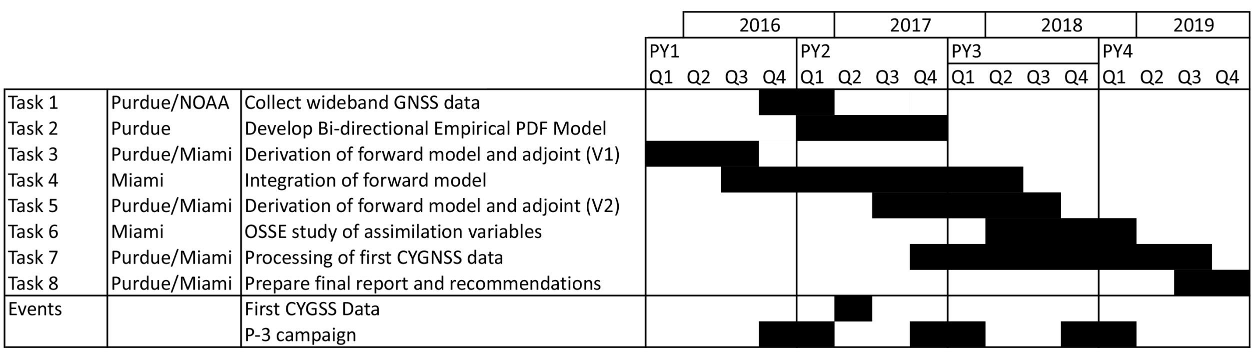
This project is fortunate to have two foreign collaborators, both well regarded experts in weather model data assimilation, Dr. John Eyre from the UK Meteorological Office and Dr. Ad Stoffelen of KNMI in the Netherlands.

1.7 Expected Contribution

Each named individual will contribute their relevant expertise, data, hardware, and/or software as listed below:

- Prof. James L. Garrison (PI) is an expert in GNSS reflectometry, field campaigns, hardware and software design. Prof. Garrison will contribute his S-band radio receiver as the basis for the L-band device to be built and flown by this project.
- Bachir Annane (Co-I, University of Miami PI) is an expert on data assimilation and numerical weather prediction. Bachir has experience running impact experiments in simulation and with real data (OSSEs and OSEs) in the specific configuration planned for this project. Bachir provides the project with access to the HWRF, GSI, EnKF, hybrid, and HEDAS software systems.
- Dr. Ross Hoffman (Co-I) is an expert on data assimilation and numerical weather prediction, as well as satellite ocean surface wind data. Dr. Hoffman provides the project with access to and expertise in the VAM.
- Dr. Ad Stofellen (Collaborator) is an expert on satellite ocean surface winds and data assimilation. Dr. Stofellen has many years of experience in the real time processing of scatterometer data and will advise the project on satellite data processing.
- Dr. John Eyre (Collaborator) is an expert on IR and MW radiance data, and GNSS/RO data. Dr. Eyre has many years of experience in research to improve the use of these data and in the operational monitoring and use of these data, and will advise the project on satellite data monitoring and diagnostics.

1.7.1 Schedule



1.8 Data Sharing Plan

All finalized data and analysis products will be documented and shared with interested parties in the broader science community. Depending on the particular type and appeal of different end-product datasets, these will be made available with related metadata and documentation at JPLs Physical Oceanography data archive and with the CYGNSS project repository. Announcement of available data will also be included in conference presentations and journal publication of findings. An Algorithm Theoretical Basis Document (ATBD) may be prepared to support the broader application of the data assimilation algorithms by the CYGNSS and future reflectometry mission communities.

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