ASSIMILATION OF GNSS-R DELAY-DOPPLER MAPS INTO WEATHER MODELS

Feixiong Huang[1], *James L. Garrison*[1], *S. Mark Leidner*[2], *Bachir Annane*[3], *Giuseppe Grieco*[4], *Ad Stoffelen*[4], *Ross N. Hoffman*[2]

[1]Purdue University, West Lafayette, IN, USA
[2]Atmospheric and Environmental Research, Lexington, MA, USA
[3]Cooperative Institute for Marine and Atmospheric Studies, Miami, FL, USA
[4]Royal Netherlands Meteorological Institute, De Bilt, The Netherlands

ABSTRACT

Global Navigation Satellite System Reflectometry (GNSS-R) observations from the Cyclone Global Navigation Satellite System (CYGNSS) mission are expected to improve numerical weather prediction (NWP) models. Level 1 GNSS-R observables, delay-Doppler maps (DDMs), contain information that is lost in producing the Level 2 wind speed retrievals at the specular point. DDMs could, therefore, prove to be a better observable for data assimilation. In this study, assimilation of GNSS-R DDMs into both global and regional NWP models is demonstrated. In the global case, DDM assimilation shows improvements on the European Centre for Medium-Range Weather Forecasts (ECMWF) background for one month of data. In the regional case, DDM assimilation shows its impact on the hurricane structure and intensity. Results using a two-dimensional variation analysis method (VAM) are presented. A plan for an Observation System Experiment (OSE) experiment is proposed.

Index Terms— GPS, GNSS-R, DDM, ocean wind, data assimilation, NWP

1. INTRODUCTION

The Global Navigation Satellite System Reflectometry (GNSS-R) technique has been shown to be an effective technique for ocean remote sensing [1]. The Cyclone Global Navigation Satellite System (CYGNSS) constellation launched in December 2016 provides GNSS-R measurements over the Earth's surface between $\pm 35^\circ$ degree latitude with a short 4 hour mean revisit time and observations at the inner core of the tropical cyclones [2].

Level 1a data products of the CYGNSS mission are the delay-Doppler maps (DDMs). From these, a Level 2 product, the surface wind speed within a 25 km resolution cell centered at the specular point, is obtained [3, 4]. We have recently demonstrated that the lower-level DDM product can be assimilated to improve a two-dimensional gridded wind field using a forward model [5] and the Variational Analysis Method (VAM) [6]. Assimilating the DDM would incorporate more information from the reflected signal and could potentially result in improved performance.

This paper presents early results demonstrating DDM assimilation in both a global data assimilation (DA) case and a regional DA case. A description of the DA method is presented in section 2. Assimilation results for global case are shown in section 3 and those for the regional case are shown in section 4. The conclusions are stated in section 5.

2. VARIATIONAL ASSIMILATION METHOD

The DDM is produced by cross-correlating the total received scattering power with a GNSS baseband signal model. A well-established scattering model [1] relates the DDM to the surface wind field within the glistening zone under certain assumptions. This model has been implemented in code for the CYGNSS end-to-end simulator [7] and adapted to a forward model [5]. We have applied the 2D variational analysis method (VAM) [6] with this forward model to assimilate a series of DDMs to improve a background wind vector field obtained from a numerical weather model. VAM accomplishes this, producing the analysis wind vector field, by minimizing the following objective cost function J,

$$J(\boldsymbol{x}) = J_b(\boldsymbol{x}) + J_o(\boldsymbol{x}) + J_c(\boldsymbol{x}) \tag{1}$$

where J_b is the background term representing the misfit between the analysis and background,

$$J_b(\boldsymbol{x}) = \lambda_b(\boldsymbol{x} - \boldsymbol{x_b})^T \boldsymbol{B}^{-1}(\boldsymbol{x} - \boldsymbol{x_b}) \tag{2}$$

J_o is the DDM observation term representing the difference between the observed DDM and the simulated DDM,

$$J_o(\boldsymbol{x}) = \lambda_o(\boldsymbol{h}(\boldsymbol{x}) - \boldsymbol{y})^T \boldsymbol{R}^{-1}(\boldsymbol{h}(\boldsymbol{x}) - \boldsymbol{y}) \tag{3}$$

and J_c is an additional smoothness and dynamic constraint term including Laplacian, divergence and vorticity. x, x_b are

This work was funded by NASA Grant NNX15AU18G and EUMETSAT OSI SAF Visiting Scientist Program.

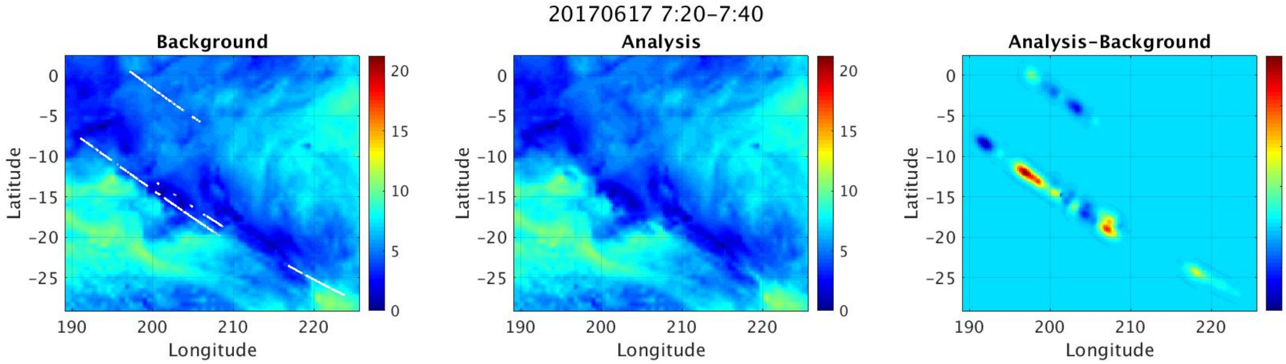

Fig. 1. An example of the global data assimilation results shown by ECMWF background, analysis after assimilating CYGNSS DDMs, and the increment for the time block of 7:20-7:40 UTC on 17-June-2017.

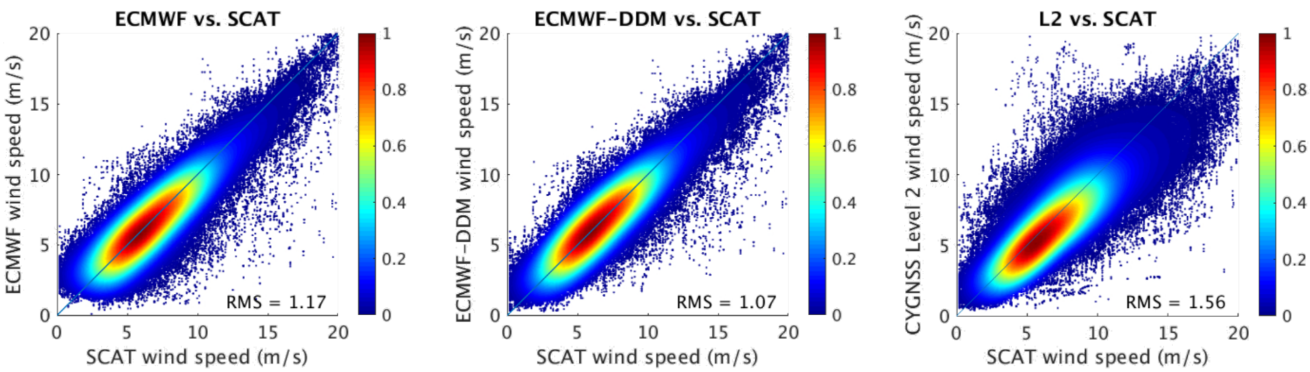

Fig. 2. Scatter plots of the comparison of ECMWF background winds (left), analysis winds after assimilating CYGNSS DDMs (middle) and CYGNSS Level 2 winds (right) with SCAT winds at the CYGNSS specular points for one month of data in June-2017.

vectors of u, v components of the analysis and background. λ_b, λ_o are ad hoc weights to control the influence of each term. $\boldsymbol{B}$ is the covariance matrix of the background. $\boldsymbol{h}(\boldsymbol{x})$ is the DDM forward model [5]. $\boldsymbol{y}$ is the observed DDM and $\boldsymbol{R}$ is the DDM observation covariance matrix.

3. GLOBAL ASSIMILATION CASE

In the global data assimilation experiment, forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) are used for the background. The observation is CYGNSS v2.1 Level 1a DDM data (calibrated to units of Watts at the receiver). Scatterometer (SCAT) winds from ASCAT and OSCAT ($<$ 1 m/s error), collocated with the CYGNSS specular points are used for comparison. Data assimilation was performed every 20 minutes with the background interpolated into the center of each time block, assuming the wind field does not change during the time. One month of data with 663909 DDMs from 1-June-2017 to 30-June-2017 was assimilated.

Observed DDMs can be biased as a result of inaccurate estimation of the transmitter power, receiver antenna pattern and representation error in the forward model. Similar to the "track-wise" bias correction on the retrieved winds [8], a bias correction was implemented in the DDM space before assimilating the DDMs. Since the background is a global NWP model, it is assumed to be unbiased. Therefore, a constant bias correction to the DDM power is computed for every CYGNSS track by matching the modeled DDMs from the background with the observed DDMs using a least square fit.

Figure 1 shows an example of the background, analysis and increment of the 20-minute data block for 7:20-7:40 UTC on 17-June-2017, in which the CYGNSS specular point tracks are shown in the left subfigure as white circles. The increment figure shows that assimilation of a track of DDMs can impact a swath of wind field with a width of 200$\sim$250 km.

Wind speeds at the CYGNSS specular points in the background and analysis are compared quantitatively with the SCAT winds. The result is shown in Figure 2 (left and middle). The left plot is the comparison between the background and SCAT and the middle one is the comparison between the analysis and SCAT. The total root-mean-square (RMS) error has de-

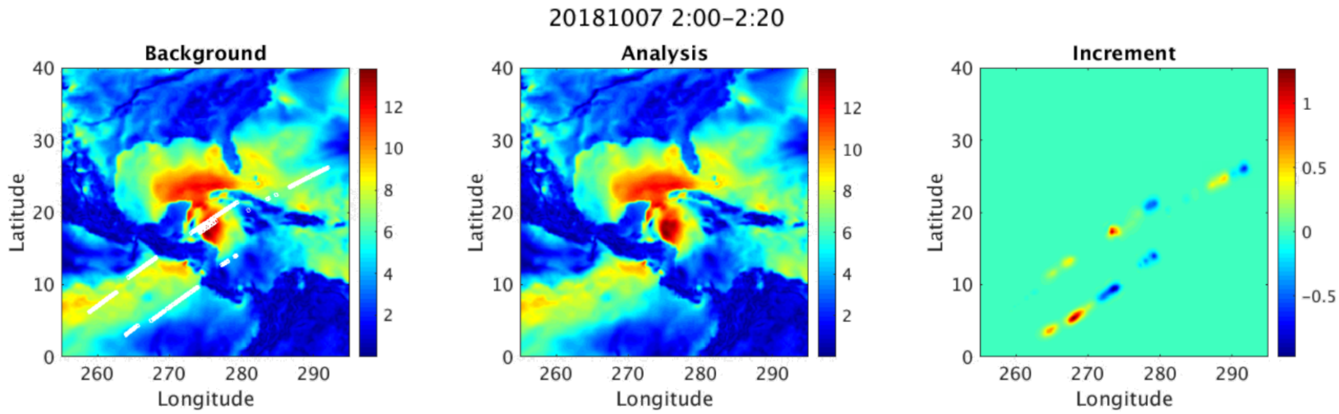

Fig. 3. An example of the regional data assimilation wind field map results shown by background, analysis and increment for Hurricane Michael for the time block of 2:00-2:20 UTC on 07-Oct-2018.

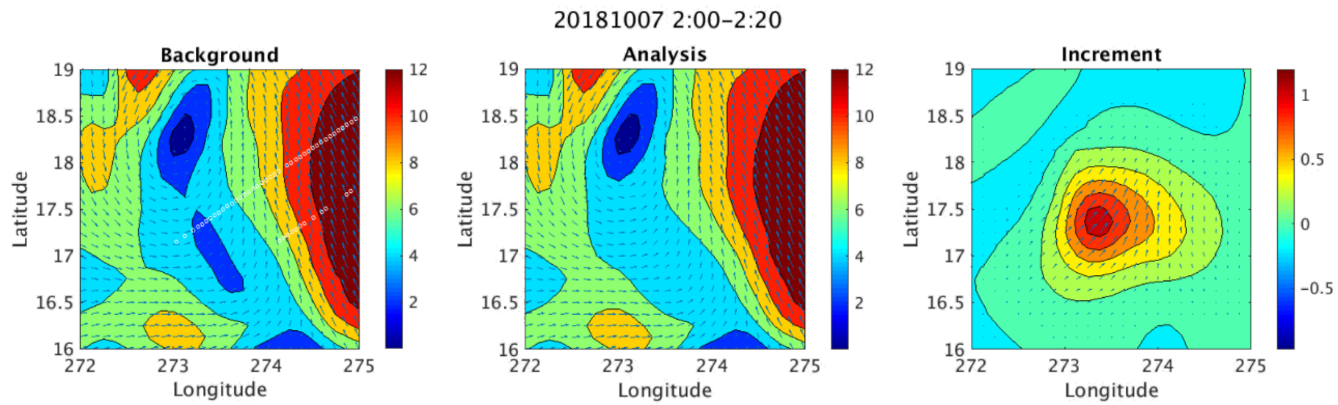

Fig. 4. An example of the regional data assimilation wind field map results shown by background, analysis and increment for Hurricane Michael shown by contour plots and wind barbs for the time block of 2:00-2:20 UTC on 7-Oct-2018.

creased from 1.17 m/s to 1.07 m/s as a result of assimilating the CYGNSS DDMs. This shows the contribution of DDM on improving model fields.

The CYGNSS level 2 wind speeds at the same specular points are also compared to the SCAT winds. The result is shown in Figure 2 (right). The CYGNSS Level 2 wind speeds have an RMS error of 1.56 m/s and present a larger variance. Comparison of the middle with the right plot in Figure 2 shows the improved precision of VAM-derived wind vectors and suggests that this data product may be a better source of input for global NWP data assimilation systems. The comparison between assimilating CYGNSS retrieved wind speed and DDM using the same background is expected in future work.

As the impact of assimilating DDMs is much larger than the scale of the specular points, the wind speed RMS error of the background and analysis are compared to the collocated SCAT wind speeds over a swath along the CYGNSS specular point tracks with different widths. The result is shown in Table 1. It shows the DDM assimilation can improve the background wind field over a swath of at least 150 km.

	80-km	120-km	150-km
Background	1.18	1.19	1.20
Analysis	1.10	1.11	1.13

Table 1. Wind speed RMS error of the ECMWF background and analysis after assimilating CYGNSS DDMs over a swath of with different width (80, 120 and 150 km). Units in m/s.

4. REGIONAL ASSIMILATION CASE

In the regional data assimilation experiment, Hurricane Michael during 6-8-October-2018 was selected, at a time before the rapid intensification stage (on 9-October). It was still classified as a tropical depression on 9-October. As a category 4 hurricane, Michael was poorly forecast by the current operational models, e.g., Hurricane Weather Research and Forecasting Model (HWRF), which makes it a perfect case to assess the impact of DDM assimilation on the hurricane forecasts.

Following a similar approach in the previous global case, the time period between 21:00 UTC on 6-October to 9:00 UTC on 8-October was divided into 20-minute blocks. Interpolated ECMWF forecasts were used for the background and bias correction was also implemented for each CYGNSS track. At each time block, CYGNSS DDMs were assimilated by the VAM, producing wind vector analysis.

Figure 3 shows an example of the background, analysis and increment of the 20-minute block from 2:00-2:20 UTC on 7-October. CYGNSS specular point tracks are shown in the left subfigure as white circles. It can be observed that several observations pass across the hurricane center and the wind maximum was increased in the analysis. Figure 4 shows the contour plots of the impact of DDM assimilation on a region near the hurricane center at the same time. Wind directions are shown on each subplot. The structure of the wind field estimate was changed by the DDM observation. DDM assimilation was also found to not only change the wind speed, but also the wind direction. The wind field remained smooth and the hurricane circulation was retained in the analysis as a result of the smoothness and dynamic constraints in the VAM cost function.

Our next step is to compare the impact of data assimilation on hurricane forecast through an HWRF Observation System Experiment (OSE). Forecasts of HWRF will be verified by the best track data.

5. CONCLUSION

We have demonstrated that data assimilation of Level 1 GNSS-R DDMs using a 2D-VAM is possible. This approach could be more effective than assimilating the Level 2 retrieved wind speeds. The DDM assimilation is assessed on both a global case and a regional case. In the global case, assimilating CYGNSS DDMs reduced the RMS error (using one month of data and comparing with scatterometer winds) from 1.17 m/s to 1.07 m/s. The analysis wind speeds at the specular points also show significant improvements as compared with CYGNSS retrieved wind speeds. In the regional case, the impact of DDM assimilation on the hurricane intensity and structure is presented. An OSE experiment is proposed to verify the impact of DDM assimilation on the hurricane forecast comparing with other types of observations.

6. REFERENCES

[1] Valery U Zavorotny and Alexander G Voronovich, “Scattering of GPS signals from the ocean with wind remote sensing application,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 38, no. 2, pp. 951–964, 2000.

[2] Christopher S Ruf, Robert Atlas, Paul S Chang, Maria Paola Clarizia, James L Garrison, Scott Gleason, Stephen J Katzberg, Zorana Jelenak, Joel T Johnson, Sharanya J Majumdar, et al., “New ocean winds satellite mission to probe hurricanes and tropical convection,” *Bulletin of the American Meteorological Society*, vol. 97, no. 3, pp. 385–395, 2016.

[3] Scott Gleason, Christopher S Ruf, Maria Paola Clarizia, and Andrew J O’Brien, “Calibration and unwrapping of the normalized scattering cross section for the cyclone global navigation satellite system,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 54, no. 5, pp. 2495–2509, 2016.

[4] Maria Paola Clarizia and Christopher S Ruf, “Wind speed retrieval algorithm for the Cyclone Global Navigation Satellite System (CYGNSS) mission,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 54, no. 8, pp. 4419–4432, 2016.

[5] Feixiong Huang, James L Garrison, Mark Leidner, Bachir Annane, and Ross Hoffman, “A GNSS-R forward model for delay-Doppler map assimilation,” in *IGARSS 2018-2018 IEEE International Geoscience and Remote Sensing Symposium*. IEEE, 2018, pp. 3323–3326.

[6] RN Hoffman, SM Leidner, JM Henderson, R Atlas, JV Ardizzone, and SC Bloom, “A two-dimensional variational analysis method for NSCAT ambiguity removal: Methodology, sensitivity, and tuning,” *Journal of Atmospheric and Oceanic Technology*, vol. 20, no. 5, pp. 585–605, 2003.

[7] Andrew O’Brien, Scott Gleason, Joel Johnson, and Chris Ruf, “The CYGNSS End-to-End Simulator (E2ES),” in *GNSS+ R 2015 Workshop*, 2015.

[8] Faozi Said, Zorana Jelenak, Jeonghwang Park, Seubson Soisuvarn, and Paul S Chang, “A ‘track-wise’wind retrieval algorithm for the CYGNSS mission,” in *IGARSS 2019-2019 IEEE International Geoscience and Remote Sensing Symposium*. IEEE, 2019, pp. 8711–8714.