National Aeronautics and Space Administration

3D Tomography of Convective Environments with a Locally Dense Constellation of CubeSats

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Program: R&TD Topic Area

Project Objective:

Study a new mission concept that can yield highly detailed structures of tropospheric water vapor under all-sky conditions, with vertical resolution of ~200 m and horizontal resolution of ~10 km, with the following objectives:

1. Demonstrate that this can be achieved using a constellation of CubeSats consisting of a dense cluster of GNSS radio occultation (RO) receivers flying in formation with one or more microwave radiometers (MW) [Fig 1];
2. Establish the relationship between the accuracy/resolution of water vapor and the number of satellites and their orbital characteristics;
3. Apply the concept in targeted atmospheric conditions simulated using mesoscale models.

FY19 Results:

Substantial progress has been made towards achieving our objectives. Key results are as follows:

- ***Forward simulations for both RO and MW have been implemented and adapted for this mission study***.

  RO: Raytracing from GNSS transmitter to receiver through 3D refractivity field computed from the WRF simulations. Observables are path-integrated water vapor density. For simplicity, the bending of the rays was ignored in this initial study.

  MW: Forward model designed and developed in a modular framework to take into account of different instrument configurations and scanning geometry. An orbital simulator has also developed to mimic CubeSat constellations of MW instruments at various altitudes and a list of orbital elements. We have also performed preliminary retrieval of water vapor profiles using TEMPEST-like microwave instruments.

- ***Initial atmospheric scenario has been identified and simulated.***

  For initial testing, we have chosen a WRF simulation that shows a strong frontal system in the Pacific. Even though it does not represent deep convection which is the primary focus, the strong horizontal inhomogeneity in the frontal system is a good scenario to test our algorithms. Fig 2a shows a longitude-height cross section of the water vapor.

- ***A baseline constellation has been chosen***.

  We considered a string-of-pearls configuration where 15 RO smallsats are spaced evenly (by 30 seconds) on the same circular orbit at an altitude of about 400 km. To maximize RO/MW collocations, it is desirable to have the nadir-pointing MW sensors located forward and behind the RO satellites by the same angular separations (Fig 1). In addition, since RO observations span a range of azimuth angles, it would be advantageous to arrange the satellites in two or three sets of orbital planes. We are developing collocation metrics which can be used to assess the merit of different constellation configurations. A paper discussing the advantage of a dense constellation of RO observations has been submitted to a peer-reviewed journal [Turk et al., 2019].

- ***Joint retrieval algorithm has been developed and tested.***

  Joint water vapor retrieval from multiple RO and MW observations is performed using a tomographic approach based on singular value decomposition with the "ATom" (Atmospheric Tomography) software package [Moeller and Landskron, 2019].

  In the test case, the RO observations were from the constellation of 15 smallsats mentioned above. The MW water vapor retrievals (at lower horizontal and vertical resolutions) were used as a priori in the tomographic inversion. The results showed that the observation geometry allowed for reconstruction of the water vapor distribution in the lower 8 km of the atmosphere with high spatial resolution (Fig. 2).

Benefits to NASA and JPL (or significance of results):

JPL has long been a leader on RO and MW technologies and has invested on the development of instruments that fit in a 6U CubeSat (Cion for GNSS-RO and mm-wave radiometer for TEMPEST-D – both are currently flying).

Results from this study will help formulate innovative Earth Science mission concepts that capitalize on JPL's instrument capabilities and are responsive to 2017–2027 Decadal Survey for Earth Science and Applications, particularly in the targeted area of Clouds, Convection, and Precipitation (CCP).

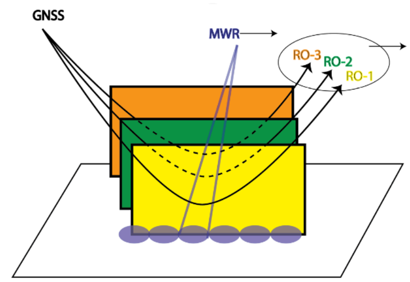

Figure 1. A constellation of CubeSats consisting of a dense cluster of RO receivers (3 shown) and MW (1 shown) flying in formation can provide 3D atmospheric water vapor information. Each RO will give vertical water vapor information in a "slice" indicated by the color planes. By flying behind the RO cluster, the MW will provide horizontal information of the water vapor along the setting RO raypaths. Similarly (not shown), a MW instrument preceding the RO cluster will provide collocated information along the rising RO raypaths.

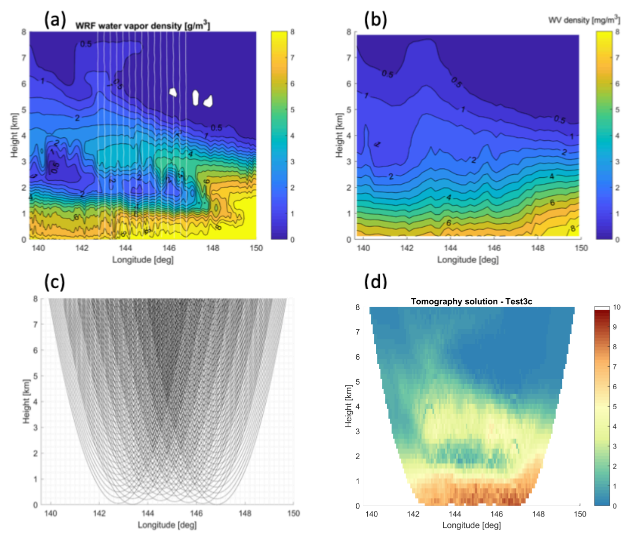

Figure 2. An example of 2-D tomographic water vapor retrieval obtained by combining multiple RO in a dense constellation with collocated MW observations. (a) water vapor density from a WRF simulation showing strong spatial variability; (b) an approximation of MW retrieval used as a priori for the inversion; (c) Ray paths from the multiple RO smallsats that cover the simulation domain; (d) the resulting tomographic solution which resolves the spatial variability of the water vapor density at high vertical (200 m) and horizontal (8 km) resolutions.

References:

G. Moeller and D. Landskron, Atmospheric bending effects in GNSS tomography, *Atmos. Meas. Tech*, 12, 23-24, doi: 10.5194/amt-12-23-2019, 2019.

Acknowledgments:

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Publications:

F. J. Turk, R. Padullés, C. O. Ao, M. de la Torre Juárez, K.-N. Wang, G. W. Franklin, S. T. Lowe, S. M. Hristova-Veleva, E. J. Fetzer, E. Cardellach, Y.-H. Kuo, and J. D. Neelin, Benefits of a closely-spaced satellite constellation of atmospheric polarimetric radio occultation measurements, *Remote Sensing*, under review, 2019.

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