3-D Water Vapor Retrieval Using a Remote Sensing Network of Scanning Compact Microwave Radiometers

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Abstract

Quantitative precipitation forecasting is currently limited by the paucity of observations of thermodynamic variables in the troposphere, such as temperature, winds and water vapor. To initialize models of available water for convective initiation, measurements are needed of the 3-D water vapor distribution as a function of time at sub-meso-γ scales in pre-storm conditions. This can be achieved using a network of remote sensors to obtain water vapor with high spatial and temporal resolution. Such measurements may be used for assimilation into and validation of numerical weather prediction (NWP) models. Measurements from a ground-based network of coordinated, scanning microwave radiometers are expected to provide 0.5-1 km resolution both vertically and horizontally with better than 15-minute temporal sampling. In such a remote sensor network, radiometer measurements of the same volume from multiple perspectives, i.e. different sensor nodes, will be combined using tomographic inversion to retrieve the 3-D water vapor distribution as a function of time.

1. Introduction

Water vapor in the troposphere is highly variable, both temporally and spatially. Profiles of water vapor are typically measured using radiosondes with high vertical resolution. However, in the U.S., radiosondes are launched from National Weather Service stations separated by ~70 km on average. Radiosondes are not reusable, restricting operational launches to twice daily, 0 and 12 UTC, at most stations. Remote sensing techniques to retrieve moisture profiles include ground-based networks receiving Global Navigation Satellite Systems (GNSS) signals, including GPS, and GPS receivers aboard the COSMIC satellite constellation for atmospheric occultation [1]. These methods provide measurements with high vertical resolution but with coarse horizontal resolution (50 km for ground networks and 200 km for COSMIC satellites).

In terms of scientific requirements, improving prediction of convective initiation requires knowledge of the water vapor content on meso-γ scales (2-5 km) [2]. Currently, water vapor profiling by commercial radiometers is limited to zenith-pointing observations [3]. Measurements using a network of multi-frequency microwave radiometers scanning overlapping atmospheric volumes have the potential to provide improved horizontal and temporal resolution. Tomographic inversion and spatial interpolation techniques will be implemented to retrieve the 3-D structure of the water vapor in the troposphere with fine spatial and temporal resolution. To this end, compact microwave radiometers designed for network deployment were developed and fabricated at the Microwave Systems Laboratory at Colorado State University (CSU) [4].

2. Compact Microwave Radiometers for Humidity Profiling

To obtain high-resolution measurements of humidity in the troposphere, the Microwave Systems Laboratory at CSU has developed, fabricated, tested and deployed two Compact Microwave Radiometers for Humidity Profiling (CMR-H). The CMR-H takes advantage of the latest monolithic microwave integrated circuit (MMIC) technology and packaging developed by the communications industry to achieve small size (24 cm x 18 cm x 16 cm / 9” x 7” x 6”), low mass (6 kg / 13 lbs.) and low power consumption (25-50 W, depending on the season of the year). In addition, the low cost of CMR-H facilitates its deployment in a network. CMR-H field measurements were validated at the NCAR Mesa Laboratory during the Refractivity Experiment For H2O Research and Collaborative operational Technology Transfer (REFRACTT’06). The observational focus of REFRACTT’06 was to obtain very high resolution measurements of water vapor variability and transport in the convective boundary layer using a wide variety of instruments. The CMR-H performed collocated measurements with the commercially-available Radiometrics WVP-1500. Water vapor profiles retrieved from CMR-H and WVP-1500 brightness temperatures were compared with Vaisala RS-92 radiosonde measurements. During REFRACTT'06, Vaisala RS-92 radiosondes were launched near the CMR-H for comparison [5].

3. Retrieval of 3-D Atmospheric Water Vapor

An Observation System Simulation Experiment (OSSE) was performed to demonstrate the retrieval of the 3-D distribution of water vapor in the troposphere using measurements from a network of scanning microwave radiometers. For the OSSE, the 3-D water vapor distribution predicted by the Weather Research and Forecasting (WRF) numerical model was compared with retrievals using synthetic brightness temperatures measured by a virtual network of CMR-H's. The WRF model output simulated a cold front and deep convection over northwest Indiana (40.7˚ N, 86˚ W) from 1:00 UT to 3:00 UT with 500-m spatial resolution.

A forward radiative transfer model [6-7] uses the high-resolution WRF model output to calculate synthetic brightness temperatures at the CMR-H frequencies as a function of both azimuth and elevation angles. To determine an optimal scanning strategy, the decorrelation time of the atmosphere was estimated by finding the autocorrelation peak of a long time series (~3000 s) of zenith microwave brightness temperatures measured during REFRACTT'06. The decorrelation time of the atmospheric downwelling emission on the spatial scales of the radiometer measurement was determined to be on the order of tens of minutes for an unstable atmosphere in the presence of rapidly evolving moisture gradients. This provides an upper bound, or maximum duration during which a radiometer node must complete a scan of its coverage volume, typically the upper hemisphere centered at the node. If each radiometer node completes its hemispherical scan within this duration, measurements at these spatial scales can be considered to be simultaneous.

An optimally-packed topology for a 3-node radiometer network is shown in Figure 1, assuming 10 km between each pair of nearest-neighbor nodes. The proposed volumetric scanning of each CMR-H radiometer node is every 30º in azimuth (12 angles) and 8 angles in elevation from zenith to 30º above the horizon. The elevation angles were chosen based on an eigenvalue analysis of the ray length in each grid cell. The segments in Figure 2 represent the azimuth angles for each radiometer in the network within a triangular "unit cell" of the small test network. An extended deployment would consist of replicas of an optimal hexagonal unit cell.

To retrieve water vapor profiles between nodes as well as above each node, algebraic tomographic reconstruction was used to combine brightness temperatures observed by multiple radiometers in overlapping scanning volumes. The scanning method described above is similar to transform-based fan-beam projections used in medical imaging [8]. This is based on the simultaneous requirements to measure a large number of projections and for these projections to be uniformly distributed over 180° or 360°. However, brightness temperature measurements by a radiometer network do not satisfy both of these requirements simultaneously. As opposed to medical imaging, reconstruction problems of this type tend to be more amenable to solution by algebraic matrix inversion reconstruction techniques, such as those used in seismic tomographic retrievals.

A forward radiative transfer model uses measured water vapor (WRF model outputs for the OSSE) to calculate the brightness temperature that would be measured by a radiometer as

$$T_B(z) = T_{CMB} e^{-\tau(0,z)} + \int_0^z k_{abs}(z') T(z') e^{-\tau(z',z)} dz' \tag{1}$$

where T_B is the brightness temperature in K, z is the height above ground level in km, k_{abs} is the absorption coefficient in Np/km, τ is the optical depth and T_{CMB} is the cosmic microwave background radiation (2.73 K). If the scanned domain is divided into M grid cells, the discrete form of the forward model can be expressed as [9]

$$T_{Bi} = T_{CMB} e^{-\sum_{j=1}^{M} k_{abs\_j} \Delta r_{ij}} + \sum_{j=1}^{M} k_{abs\_j} T_j e^{-\tau_{ij}} \Delta r_{ij} \tag{2}$$

where T_{Bi} is the integrated brightness temperature measured by a radiometer pointing at the ith elevation angle; k_{abs_j} is the absorption coefficient in the jth grid cell; T_j is the thermodynamic temperature in the jth grid cell; $\triangle r_{ij}$ is the length of the segment of the ray at the ith elevation angle within the jth grid cell; and the opacity τ_{ij} is given as

$$\tau_{ij} = \sum_{l=1}^{j-1} k_{abs\_j} \Delta r_{il} \tag{3}$$

Replacing the exponential terms in (2) by truncated Taylor series, the linearized forward model becomes

$$T_{Bi} = T_{CMB}(1 - \sum_{j=1}^{M} k_{abs\_j} \Delta r_{ij}) + \sum_{j=1}^{M} k_{abs\_j} T_j \ (1 - \sum_{l=1}^{j-1} k_{abs\_j} \Delta r_{il}) \Delta r_{ij} \tag{4}$$

Next, we start with a reference profile of the pressure, temperature and water vapor density for a typical atmosphere for the general latitude, longitude and season. For example, the mid-latitude summer reference atmospheric profile is used in this study. The absorption coefficient in each grid cell is calculated at the CMR-H frequencies using the most up-to-date microwave absorption models of the atmosphere [10-11]. Variations in the absorption coefficient from the reference value can be related to variations in the calculated brightness temperature from its reference value, T_{Brefi}, also found using the forward model with the reference profile as input. The two quantities are related by a Jacobian matrix G as

$$T_{Bi} - T_{Brefi} = G \cdot (k_{abs\_j} - k_{absref\_j}) \tag{5}$$

The Jacobian matrix elements are given as

$$g_{ij} = \frac{\partial(\Delta T_{Bi})}{\partial(\Delta k_j)} \tag{6}$$

where g_{ij} is the partial derivative of the change in the brightness temperature at the i^{th} elevation angle with respect to the change in absorption coefficient in the j^{th} grid cell. The variation in the absorption coefficient for a measured variation in brightness temperature can be computed as

$$\Delta K = G^{-1} \Delta T_{Bi} \tag{7}$$

However, finding the value of G is an underdetermined problem, so there is no unique solution. Regularization techniques are needed to solve such ill-posed problems. Therefore, Bayesian optimal estimation was used to calculate the values of $\triangle K$. The Kalman filter technique [6] was implemented to take into account the sequential time evolution of water vapor densities by requiring that the retrieved values vary smoothly between successive measurements in time. The absorption coefficients retrieved in each high-resolution WRF model grid cell (0.5 km x 0.5 km typical horizontal resolution) at the four operating frequencies of CMR-H were used to compute the water vapor density in the grid cell using the Van-Vleck Weisskopf absorption line shape, which varies with altitude due to pressure broadening [12]. 3-D moisture fields were retrieved and compared with the WRF model output. Figure 2(a) shows the WRF model output of the water vapor density at 3.4 km AGL at 3:00 UT. Figure 2(b) shows the percentage error in the retrieval at 3:00 UT obtained by algebraic tomographic reconstruction, as described above. The *a-priori* used for this retrieval was the WRF model output at 2:00 UT. Water vapor densities at the unsampled locations were estimated by using the kriging spatial interpolation technique. This algorithm was based on the spatial characteristics of water vapor densities, including semi-variogram and correlation lengths, calculated using the high-resolution WRF model output [13-14]. The OSSE results show that the 3-D water vapor density field can be retrieved with an accuracy of better than 15-20% at all altitudes above ground level.

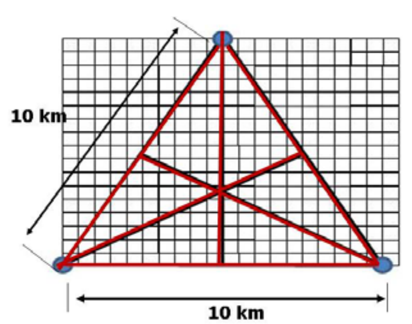

Figure 1. Locations and azimuthal scan directions for 3 CMR-H network nodes.

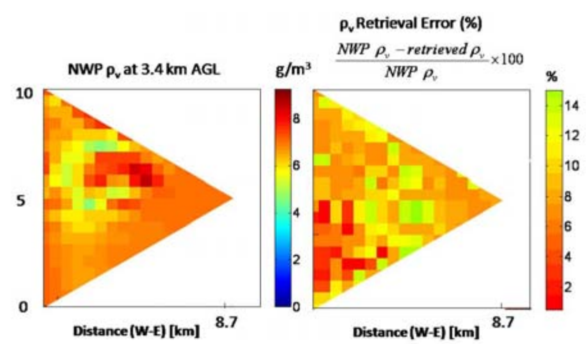

Figure 2. (a) WRF model output of the water vapor density at 3.4 km above ground level (AGL) over northwest Indiana at 3:00 UT. (b) Percentage error of the water vapor density retrieved from synthetic brightness temperature measurements also at 3.4 km AGL with WRF model output at 2:00 UT used as the *a priori*.

5. Conclusion

The Compact Microwave Radiometer for Humidity Profiling (CMR-H) is small, light-weight, inexpensive, robust and consumes little power. The low cost of CMR-H enables the deployment of a number of scanning microwave radiometers in a coordinated network. CMR-H was designed for network operation, in which each sensor performs a complete volumetric scan within a few minutes. Radiometer measurements of the same volume from multiple perspectives, i.e. different sensor nodes, will be combined using tomographic inversion to retrieve the 3-D water vapor distribution as a function of time. An OSSE was performed to demonstrate this retrieval and compared with WRF model output with a grid resolution of 0.5 km. The OSSE demonstrated a retrieval accuracy of 15-20%. Water vapor profiles retrieved from the brightness temperatures measured by two CMR-H's show good agreement with those measured by RS-92 radiosondes. Two CMR-H's have been field demonstrated and a third is being fabricated. In order to retrieve 3-D water vapor distributions with high spatial and temporal resolution to validate NWP models, we will deploy a ground-based network of three radiometers during upcoming experiments, in collaboration with radiosonde measurements and GPS networks.

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7. References

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