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ADVANCING EARTH'S PLANETARY BOUNDARY LAYER SOUNDING FROM SPACE USING HYPERSPECTRAL MICROWAVE MEASUREMENTS

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ABSTRACT

We present a comprehensive Earth Planetary Boundary Layer temperature and water vapor retrieval improvement demonstration by the use of hyperspectral microwave measurements. Our results indicate that the use of a hyperspectral sampling in the oxygen and water vapor sounding lines alone provides significant improvements in the lower and free tropospheric thermodynamic fields (up to 40%), when compared against the program of record (*i.e.*, the Advanced Technology Microwave Sounder, ATMS). Our experiments also demonstrate the essential role played by extending the coverage in the so called spectral window regions, leading to an overall PBL temperature and water vapor improvement of up to 50%.

1. Introduction

The National Academies of Sciences, Engineering and Medicine (NASEM) 2017-2027 decadal survey for Earth Science and Applications from Space has identified the Earth's Planetary Boundary Layer as an Incubation Targeted Observable [1]. The survey recognizes the need for improved observations of the Earth's Planetary Boundary Layer (PBL) temperature and water vapor profiles, and of PBL height as a priority to address fundamental PBL science questions and societal applications related to weather, climate and air quality. In response to the ESAS 2017, NASA established the decadal survey incubation program and established a NASA PBL Study

Team with the scope of identifying the PBL science advancement and technology development priorities for the next decade [2]. One of the outcomes of this study was the identification of the observational gaps from the current program of record (PoR) along with the critical technology components needed to achieve a global PBL observing system from space. In this framework, the study lists hyperspectral microwave sensors as an “*Essential Component*” of the future global PBL observing system, to provide “*accurate PBL and free tropospheric 3D temperature and water vapor structure context to active measurements (e.g., lidars and radars)*” and in combination with other passive sensors (e.g., infrared and radio occultation).

Our team at the NASA Goddard Space Flight Center initiated two NASA funded projects aiming to develop core innovative technology that will enable hyperspectral microwave measurements to augment thermodynamic sounding capability of the Earth's PBL. The first is an Instrument Incubator Program (IIP) project funded through the Earth Science Technology Office (ESTO) and titled, “*Photonic Integrated Circuits (PICs) in Space: The Hyperspectral Microwave Photonic Instrument (HyMPI)*”. The second is a Decadal Survey Incubator PBL project titled: “*Hyperspectral Capability for CoSMIR:*

Enhancing Capability for Future PBL Suborbital Campaigns and Enabling PBL Science from Space”. Augmented microwave sounding capability is also central to the NOAA mission for improved weather prediction, under all-sky and all-surfaces scenarios. To that end, our team has

partnered with NOAA in pursuing an inter-agency project titled: “Developing the NOAA Next Generation Hyperspectral Microwave Sensor (HyMS): Instrument Concept and Demonstration of Benefits for the NOAA Mission”.

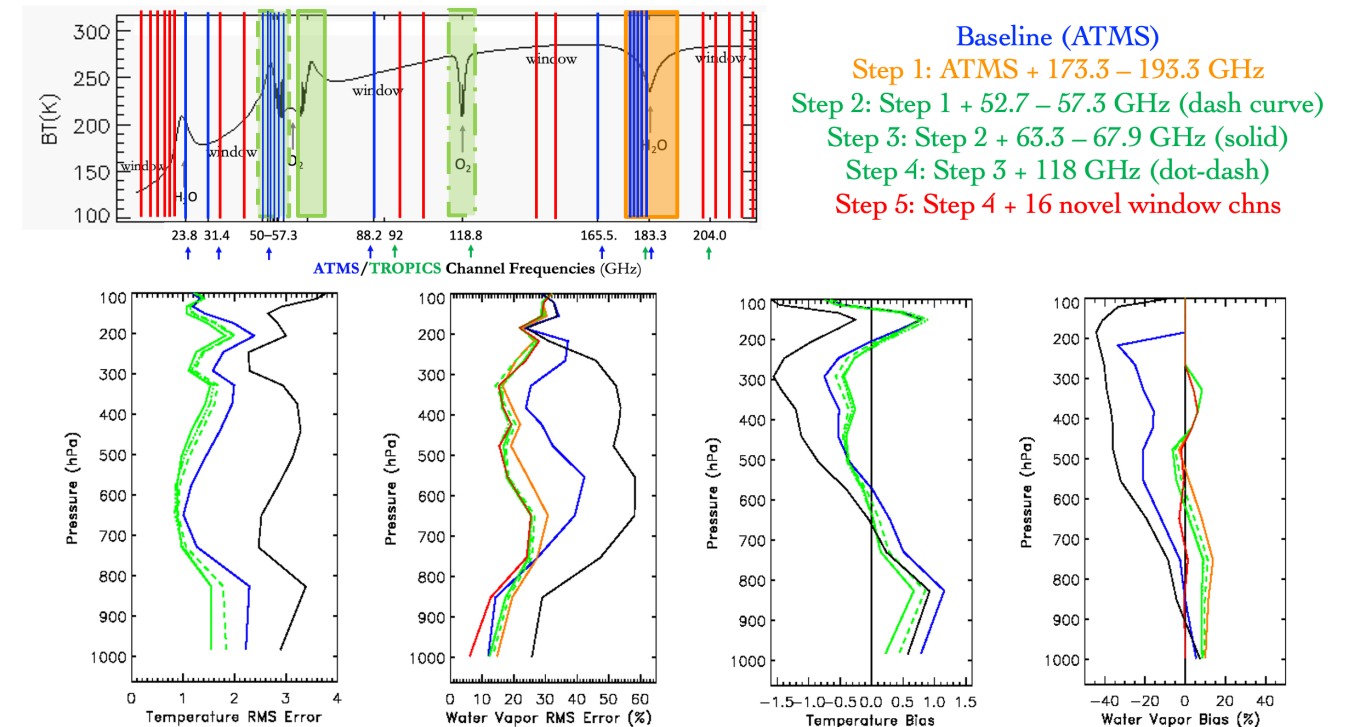


Figure 1. Figure 6 from Gambacorta et al. 2023 [3]. See text for details.

2. Preliminary Hyperspectral microwave PBL thermodynamic retrieval results

The hyperspectral microwave configuration used in this study is described in Table 1 of the study published by Gambacorta et al., 2023 [3] and previous experiments published in [4] and [5]. The baseline for retrieval comparisons is provided by the Advanced Technology Microwave Sounder (ATMS).

A particular focus of this study is devoted to quantifying and comparing the impact on PBL retrieval performance resulting from specific bands and channels, by means of data addition and denial trade studies. In doing so, we assess

different spectral configurations, each reflecting specific technology solutions intended to maximize PBL geophysical product performance within feasible size, weight, power and cost constraints. This experiment is carried on in incremental steps, as described below and illustrated in Figure 1 (Figure 6 in Gambacorta et al. 2023, [3]). Hyperspectral retrievals statistics are compared against equivalent results from ATMS (blue curves) and from the retrieval first guess (black curves). The data set used for this retrieval demonstration spans an ensemble of global, ocean, clear-sky scenes from August 15th, 2003 of the GMAO GEOS-5 Nature Run.

Step 1: Replacement of five ATMS 183 GHz water vapor channels with 500 hyperspectral water vapor channels from the 173.3 - 193.3 GHz region (orange box in upper left figure). Statistical results are represented by orange curves in the bottom figures of the water vapor RMS and bias statistics.

Step 2: Replacement of eleven ATMS 52.8 - 57 GHz temperature sounding channels with the hyperspectral 52.6 - 57.3 GHz temperature sounding channels (dash-contoured green box in upper left figure). Statistical results are represented by dash green curves in the bottom figures of the temperature and water vapor RMS and bias statistics.

Step 3: Addition of the hyperspectral 63.3 - 67.9 GHz temperature sounding channels (solid-contoured green box in upper left figure). Statistical results are represented by solid green curves in the bottom figures of the temperature and water vapor RMS and bias statistics.

Step 4: Addition of the hyperspectral 118 GHz temperature sounding channels (dash-dot-contoured green box in upper left figure). Statistical results are represented by dash-dot green curves in the bottom figures of the temperature and water vapor RMS and bias statistics.

Step 5: Addition of novel window channels (rows 4 - 25 except channels marked by one asterisk, which are already in the ATMS channel set. Those are marked as red bars in upper left figure). Statistical results are represented by red curves in the bottom figures of the water vapor RMS and bias statistics.

Our results indicate that the use of hyperspectral sampling in the oxygen and water vapor sounding lines provides significant improvements along the PBL and free tropospheric thermodynamic fields (up to 50%), when compared against the program of record (i.e., the Advanced Technology Microwave Sounder, ATMS). An up to 40%

improvement with respect to the baseline (blue curve), is observed in the middle and upper troposphere water vapor statistics. The slight degradation observed in the lower troposphere may be the result of an imbalance introduced by the use of hundreds of similar channels. We performed a separate test (not shown for brevity) where some lower tropospheric sensitive channels were removed from the hyperspectral list and obtained an improved result in the lower troposphere, compared to ATMS.

The use of the 52.6 - 57.3 GHz hyperspectral line alone provides a noticeable improvement along the full atmospheric column, in both RMS and bias temperature statistics (dash green versus blue). The incremental addition of the remaining 63.3 - 67.9 GHz channels is observed to further improve the temperature statistical performance, particularly in the PBL. This is an important aspect in that it provides an indication of the improved signal to noise that can be derived from the full exploitation of the primary oxygen line. As expected from the sensitivity analysis, the addition of the 118 GHz line provides an improvement in the upper reaches of the atmosphere. Finally, it must be noted, that improvements are observed not only in the temperature but also in the water vapor statistics. This aspect originates from the sequential order of the two retrieval steps, where the temperature retrieval acts as a background for the water vapor retrieval. As such, any improvement in temperature is often consistently reflected in an improvement in water vapor performance.

These novel window channels are observed to provide an additional ~10% improvement in the water vapor RMS and bias performance (now ~50% better than the baseline), particularly in the PBL (red versus orange and blue curves). This result confirms the value of extending the coverage in the microwave window bands towards improved sensitivity to water vapor, particularly in the boundary layer. Future studies will examine land scenarios for which the role of extended window coverage is key to improved retrieval of

surface properties (classification, surface temperature).

3. Summary

Using an extended, high-resolution coverage in the thermal microwave domain shows significant advances in PBL thermodynamic sounding. An overall RMS and bias improvement of up to 50% and 25% in the PBL and free tropospheric temperature respectively, compared to the performance offered by the program of record. The water vapor field is observed to undergo a significant improvement as well. The water vapor RMS error is observed to improve by about 50% in the PBL and along the full extent of the free troposphere with respect to the baseline (solid red versus blue curves). It must be said, that the GMAO GEOS-5 Nature Run first guess presents already a relatively good performance in the PBL water vapor field (black curve). However, the hyperspectral configuration is capable of correcting the shape of its bias statistics, bringing it to a nearly flat zero value, throughout the entire extent of the PBL. This feature is indicative of high retrieval skill in this region. Both

improvements, in the PBL and free troposphere temperature and water vapor, are expected to benefit the identification of PBL height.

The observed improvements in atmospheric thermodynamic sounding obtained from these hyperspectral microwave measurements will be critical to enhance numerous driving applications that are important to climate science [2] and numerical weather prediction [6]. Of particular interest will be the utilization of hyperspectral microwave measurements in combination with other passive (*e.g.*, hyperspectral infrared, global navigation satellite system radio occultation) and active measurements (*e.g.*, lidar and radar), as envisioned by the NASA PBL Incubation Study Team report [2]. To that end, hyperspectral microwave soundings of the quality demonstrated in Figure 1 (Figure 6 from [3]), are expected to help improve depiction of the thermodynamic structure of the PBL, so as to address each of the critical PBL science questions outlined in the PBL Study Team Report Science and Application Traceability Matrix (SATM) [2].

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