THE HYPERSPECTRAL MICROWAVE PHOTONIC INSTRUMENT (HYMPI) - ADVANCING OUR UNDERSTANDING OF THE EARTH'S PLANETARY BOUNDARY LAYER FROM SPACE

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ABSTRACT

This paper presents an overview of the Hyperspectral Microwave Photonic Instrument (HyMPI), a 2021 NASA Instrument Incubation Proposal funded project aimed at developing the very first hyperspectral microwave sensor to augment thermodynamic sounding capability from space, with a focus on the Earth's Planetary Boundary Layer. This research responds to the recommendation expressed in the 2018 National Academies of Sciences decadal survey to accelerate the readiness of high-priority PBL observables not feasible for cost-effective spaceflight in 2017-2027. This paper provides an overview on HyMPI's design, configured as the objective instrument concept needed to fly in the future PBL mission and presents preliminary trade studies aim at demonstrating HyMPI's enhanced thermodynamic sounding skill in the Earth's Planetary Boundary Layer over conventional microwave sounders from the current Program of Record.

Index Terms— Hyperspectral Microwave, Photonic Integrated Circuits, Planetary Boundary Layer.

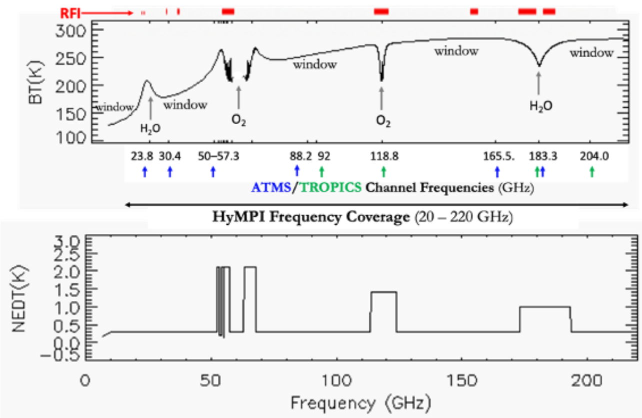
1. INTRODUCTION

The NASA Planetary Boundary Layer (PBL) Incubation Study Team Report 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 sensors (*e.g.,* lidars, radars) and in conjunction with other passive sensors (*e.g.,* infrared, radio-occultation sensors) [1]. The call for this Incubation Study reflected the consensus reached during the NASA Planetary Boundary Layer Incubation Community Forum, hosted during the 2019 American Geophysics Union Meeting and lead by Dr Gail Skofronick-Jackson [2]. Its primary goal was to respond to the National Academies of Sciences decadal survey, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (2017), recommendation to accelerate the readiness of high-priority PBL observables not feasible for cost-effective spaceflight in 2017-2027 [3]. To that end, our team at the NASA Goddard Space Flight Center was awarded an Instrument Incubator Program (IIP) project funded through the Earth Science Technology Office. This IIP project titled, "Photonic Integrated Circuits (PICs) in Space: The Hyperspectral Microwave Photonic Instrument (HyMPI)" aims to develop core innovative technology that will enable the very first hyperspectral microwave sensor in space to augment thermodynamic sounding capability of the Earth's PBL.

This paper presents an overview of HyMPI's core technology, along with its preliminary spectral and noise baseline specifications (section 2). We provide an overview of its preliminary temperature and water vapor sensitivity features, assess its improved information content and the overall resulting impact on PBL retrieval vertical resolution and accuracy. We conclude with a few summary notes on the expected benefits to numerous scientific applications using HyMPI future's data that are relevant to climate monitoring, air quality and numerical weather prediction.

2. THE HYPERSPECTRAL MICROWAVE PHOTONIC INSTRUMENT (HYMPI)

Liquid droplets and ice particles make most clouds completely opaque in the infrared region, but in the microwave domain, they are partially transparent, enabling retrieval of the full column vertical temperature and water



vapor profiles, under all sky conditions. Operational passive microwave spaceborne sensors from the current Program of Record (POR) and even planned sensors, however, continue to be constrained by only a couple dozen channels, sparsely sampled across the thermal microwave spectral domain. This aspect constrains the information content in the measurement to only a few degrees of freedom, limiting vertical resolution and accuracy in the retrieved thermodynamic fields. The Earth's PBL is the most affected region, due to the opacity introduced by the overlaying absorbing gas layers.

The reason for stalled progress in hyperspectral microwave technology rests in the numerous technological challenges associated with simultaneously processing an ultra-wide bandwidth (20-200 GHz) at hyperspectral resolution (< 1 GHz), while maintaining a feasible instrument size, weight and power consumption, and cost (SWaP-C). Traditional microwave radiometers are based on radiofrequency (RF) technology, whose constraints limit the capabilities of current microwave spectrometers.

Recent advances in Photonic Integrated Circuits (PICs) have opened a new era of hyperspectral microwave instrument development. SWaP-C can be improved by means of photonic signal processing techniques, enabled by up-conversion of a microwave signal to an optical carrier [4]. Our team at GSFC has been awarded the development of a Hyperspectral Microwave Photonic Instrument (HyMPI), which aims to solve the SWaP-C challenge of current RF technology by combining Photonic Integrated Circuits (PICs) and Application Specific Integrated Circuits (ASICs) into a "PICASIC" module [4, 5]. The results will yield a low mass, low power, high spectral resolution, and wide band instrument.

2.1 HyMPI's spectral and noise configuration

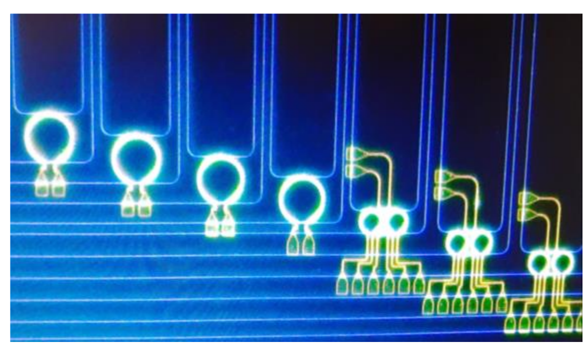
The PICASIC modular approach enables full-spectrum and contiguous spectral coverage with a tunable capability to measure the spectrum with higher resolution where higher structure in the signal is exhibited. The PICASIC forms the heart of HyMPI, configured to provide extended, high spectral resolution coverage in the microwave domain of the Earth's thermal radiation.

HyMPI's baseline design leverages the results of a series of hyperspectral microwave trade studies presented in [6] and [7], with some augmentation tailored to further improving PBL sounding skills. This baseline design (Figure 2) is characterized by continuous spectral coverage over the 20 - 200 GHz spectrum with a variable spectral resolution. The oxygen absorption lines in the 52.6-57.3 GHz, 63.3-67.9 GHz are sampled with a spectral resolution of 10 MHz. The oxygen line at 113.7-123.7 GHz is sampled with a spectral resolution of 20 MHz. Both are used to retrieve the vertical temperature profile. The water vapor absorption line centered in the 173.3-193.3 GHz band is

Figure 1. Photonic Integrated Circuits are like electronic circuits, but in this case the signal carrier is optical (photons). Optical waveguides (blue lines) carry the propagation of the optical signal. Metal conductors (yellow lines) are used to induce electro-optic effects on the waveguides to tune the filter response. Photonic integrated technology carries the unique advantage of reducing instrument size, weight and power and coast (SWaP-C). Photonic integrated technology also offers high compatibility with existing electronic technology.

Figure 2. Top: An illustrative example of a HyMPI spectral coverage (black curve). Bottom part illustrates HyMPI's noise characteristics. To ensure continuity to the Program Of Record (POR), HyMPI includes all ATMS (blue arrows) and TROPICS channels (green arrows) at their native spectral resolution, a feature made possible by the PICASIC's unique modular design. This technology also enables to increase spectral resolution up to 500 KHz to detect and remove Radio Frequency Interference (RFI), whose spectral allocations are indicated by the red bars in the top figure.

sampled with a spectral resolution of 40 MHz. In addition to



the conventional "window" regions used in conventional microwave sensors from the POR (*e.g.*, the Advanced Technology Microwave Sounder), we studied the full interstitial window regions using contiguous sampling with a spectral resolution of 0.5 GHz. Window channels are used to retrieve key information about the surface (*e.g.*, emissivity, temperature, classification) but are also

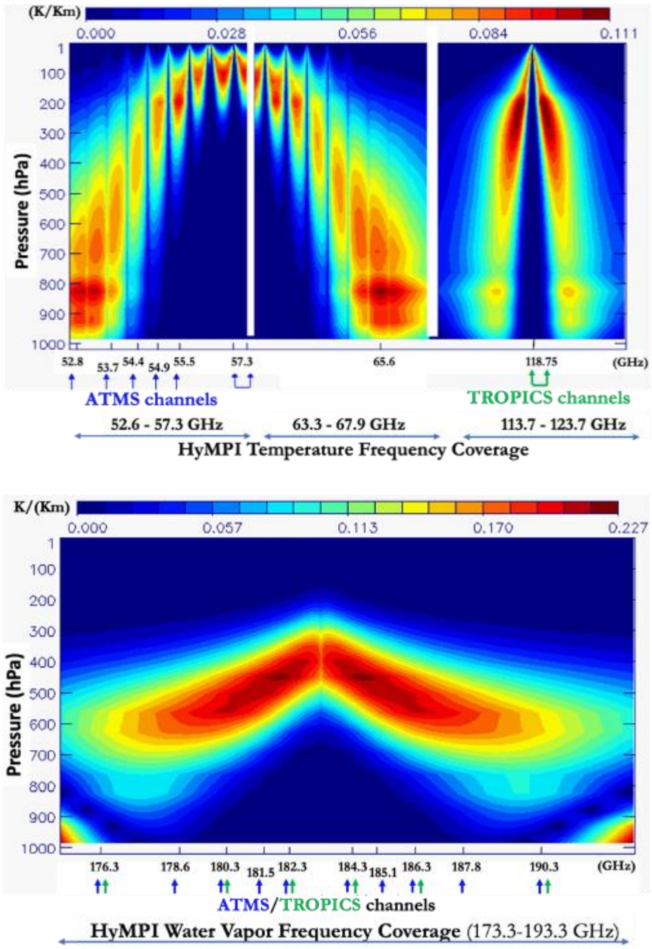


Figure 3. HyMPI's brightness temperature sensitivity to variations of temperature (top) and water vapor (bottom). 1K temperature (5% water vapor) perturbations in each 1 km-pressure layer of the atmospheric profile have been applied to measure the response in brightness temperature at each frequency of HyMPI's oxygen (water vapor) bands. For comparison purposes, ATMS and TROPICS spectral channel frequencies are highlighted by blue and green arrows, respectively.

important for their extended sensitivity to temperature and water vapor in the PBL. As highlighted in [8], hyperspectral coverage in the window region should not be underestimated, given their high sensitivity to different types of atmospheric hydrometeors (e.g., cloud ice/liquid water, all forms of precipitation).

3. SENSITIVITY ANALYSIS

We illustrate HyMPI's brightness temperature sensitivity to variations of temperature (Figure 3, top) and water vapor (bottom). While in the infrared domain, trace gas interference often requires a large amount of subsetting in the temperature and water vapor bands, the microwave domain is spectrally purer [9]. This feature makes the high

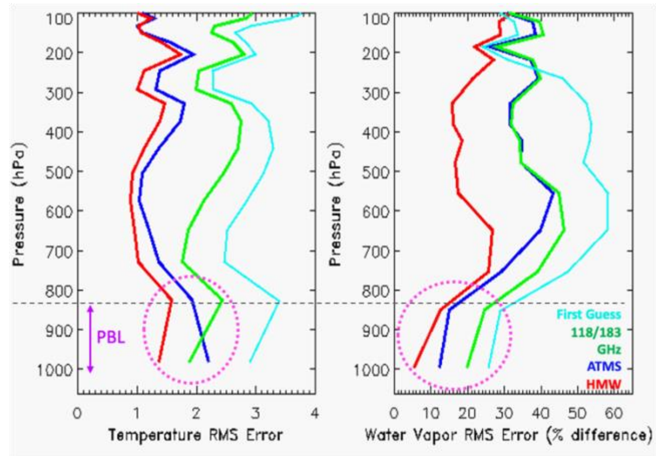


Figure 4. Impact of HyMPI's enhanced spectral coverage and resolution on the retrieval performance. See text for details.

redundancy in HyMPI's measurements fully exploitable and is expected to provide high signal-to-noise to the retrieval process and to significantly improve retrieval performance over the POR.

4. RETRIEVAL PERFORMANCE

Figure 4 illustrates the impact of HyMPI's enhanced spectral coverage and resolution on retrieval performance. This analysis was derived from a preliminary global ocean, clear sky ensemble of atmospheric profiles. HyMPI reduces the POR temperature Root Mean Square (RMS) error (left) by 50% in the PBL and 20% (versus ATMS) and ~55% (versus a 118GHz only configuration similar to TROPICS)) in the mid/upper troposphere. Water vapor RMS error (right) improves by ~50% in the PBL and along the full extent of the mid/upper troposphere. Both improvements, in the PBL and the free troposphere above, will potentially enhance the identification of the PBL height.

4. CONCLUDING REMARKS

The improvements demonstrated by HyMPI are key to provide accurate thermodynamic soundings to numerous science applications that are relevant to the NASA and NOAA missions. HyMPI addresses each of the critical PBL science questions and themes outlined in the PBL Study Team Report Science Applications Traceability Matrix (SATM). Furthermore, meteorological and space agencies worldwide (GMAO, NOAA, European Centre for Medium-Range Weather Forecasts (ECMWF), and Meteo France) strongly advocate hyperspectral microwave sensors to enhance numerous driving applications that are important to climate prediction and weather forecasting, such as tropical cyclone intensification forecasting, convective initiation, land surface-atmosphere coupling, atmospheric winds, RFI detection, to only cite a few [6, 7, 8, 10, 11, 12, 13]. Thanks to the reduced SWaP-C enabled by the PICASIC technology, HyMPI can meet the 5km spatial resolution requested by the PBL Study Team Report. HyMPI can be realized as a single instrument or a disaggregated constellation of smaller instruments each covering a portion of the spectrum. Alternately, a dedicated NASA HyMPI, covering for example 90-210 GHz, could be flown in formation with the NOAA next sounders generation. The PICASIC technology is even flexible enough that it could be incorporated into the NOAA sounders of the next decade. In the near term - this decade - several realistic paths exist for the proposed PICASIC technology: airborne technology transition, in-space demonstration, and Earth Venture or Explorer. Following this research effort, the PICASIC can be the first rigorous in-space demonstration of an integrated hyperspectral microwave photonic system with PBL science-grade performance.

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