The Hyperspectral Microwave Instrument (HyMPI)

Advancing Atmospheric Thermodynamic Sounding From Space

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Motivation

- **Hyperspectral Microwave Measurements** have been long advocated by meteorological and space agencies worldwide to improve temperature, water vapor and hydrometeors retrievals from space (Lipton, 2003; Bauer, 2007; Lambrigsten, 2010; Blackwell, 2010; Boukabara, 2011; Mahfouf, 2015; Aires, 2015; Aires, 2019).

- **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 imrpved PBL and free tropospheric 3D temperature and water vapor structure context to active measurements (*e.g.*, lidar, radar) and in conjunction with passive sensors (*e.g.*, infrared, RO).

- **Our team at GSFC has initiated an Incubation Instrument Proposal research project titled**:
  "*Photonic Integrated Circuits (PICs) in Space: The Hyperspectral Microwave Photonic Instrument (HyMPI)*".
  - Gambacorta A., Stephen M., Gambini F., et al., "*The Hyperspectral Microwave Photonic Instrument (HyMPI): Advancing Atmospheric Thermodynamic Sounding from Space*" in IEEE Special Issue "Advancements in the Next Generation of LEO and GEO Microwave and Infrared Sounders", under review, 2022.
  - https://esto.nasa.gov/project-selections-for-iip-21/#Gambacorta

- **HyMPI will be configured to respond to the Science Applications and Traceability Matrix requirements outlined in the PBL Study Team Report and to satisfy the broader needs of the weather and climate community.**

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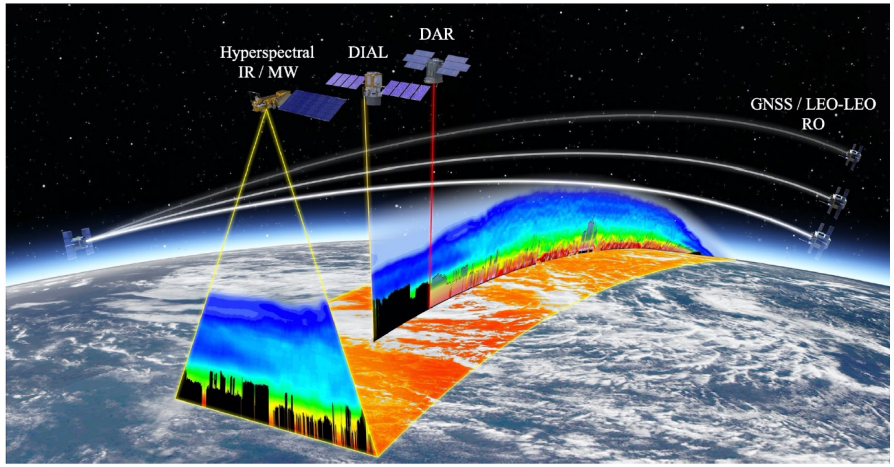
The Earth's Planetary Boundary Layer: "Target Observable" of the 2017 Decadal Survey



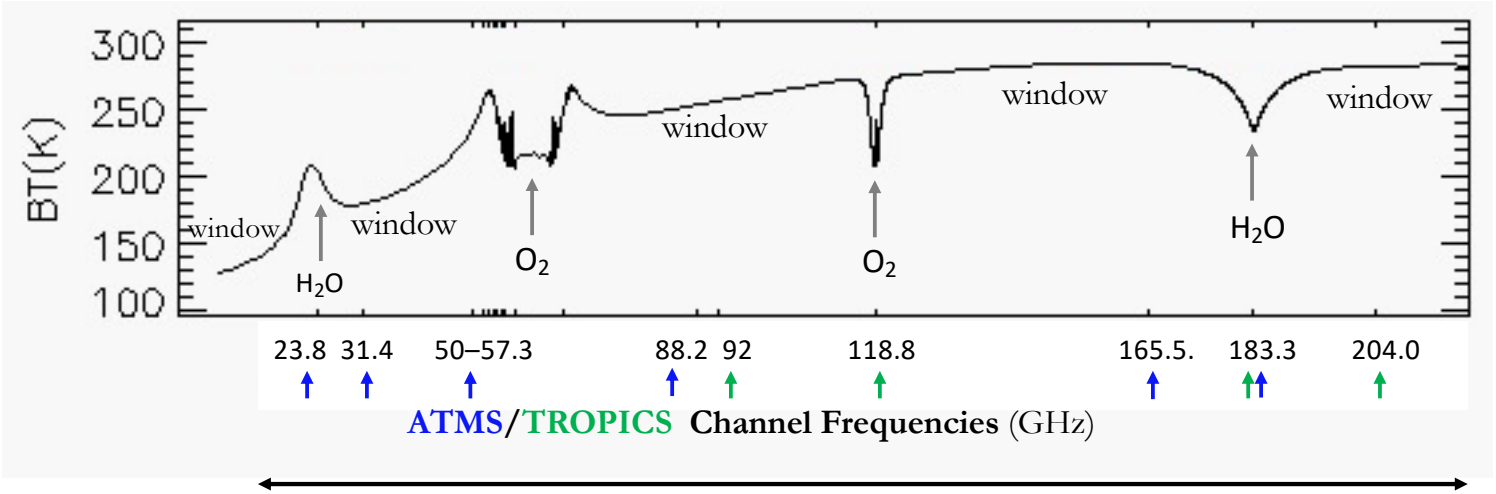
Hyperspectral Microwave sensors are listed as an *Essential Component* of the potential future global PBL observing system, to provide improved PBL and free tropospheric 3D temperature and water vapor structure context to active sensors (*e.g.*, lidars, radars) and in conjunction with other passive sensors (*e.g.*, infrared, radio-occultation).

J. Teixeira, **J. R. Piepmeier**, A. R. Nehrir, C. O. Ao, S. S. Chen, C. A. Clayson, A. M. Fridlind, M. Lebsock, **W. McCarty**, H. Salmun, **J. A. Santanello**, D. D. Turner, Z. Wang, and X. Zeng, "Toward a Global Planetary Boundary Layer Observing System: The NASA PBL Incubation Study Team Report.", NASA PBL Incubation Study Team. 134 pp., 2021.

G. Skofronick-Jackson, A.E. Emory, P. Millar, J.Teixeira, **J.R. Piepmeier**, A.R. Nehrir, B.L. Lefer, T.J. Lee, "NASA Planetary Boundary Layer Incubation Community Forum," American Geophysical Union, Fall Meeting, abstract TH45D, December, 2019.

National Academies of Sciences, Engineering and Medicine (NASEM) 2017-2027 decadal survey for Earth Science and Applications from Space (ESAS 2017) Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space. The National Academies Press. Washington, DC, 2017.

Why Hyperspectral Microwave Sounding?



HyMPI promises to be the first rigorous in-space demonstration of an integrated hyperspectral microwave photonic system with science-grade performance.

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Photonic Integrated Circuits (PICs) in Space: The Hyperspectral Microwave Photonic Instrument (HyMPI)

- **Traditional microwave radiometers** are based on radio-frequency (RF) technology whose instrument size, weight and power consumption, and cost (SWaP-C) constraints limit the capabilities of current spectrometers.
- **Recent advances in Photonic Integrated Circuits (PICs) technology** have opened a potential new era of hyperspectral microwave instrument development.
- **Our proposal aims to combine Photonic Integrated Circuits (PICs) and Application Specific Integrated Circuits (ASICs) into a "PICASIC" module,** the heart of the hyperspectral microwave spectrometer. The results will yield a low mass, low power, high spectral resolution and wide band instrument.
- **The PICASIC modular approach enables full-spectrum (10 – 200 GHz) and contiguous spectral coverage with a tunable capability** to measure the spectrum with higher resolution where higher structure in the signal is exhibited.
- **Thanks to the reduced SWaP-C, HyMPI can meet the 5km spatial resolution requested by the PBL Study Team Report** and achieve a Smallsat/Cubesat deployable capability, key to provide high temporal refresh for weather applications.

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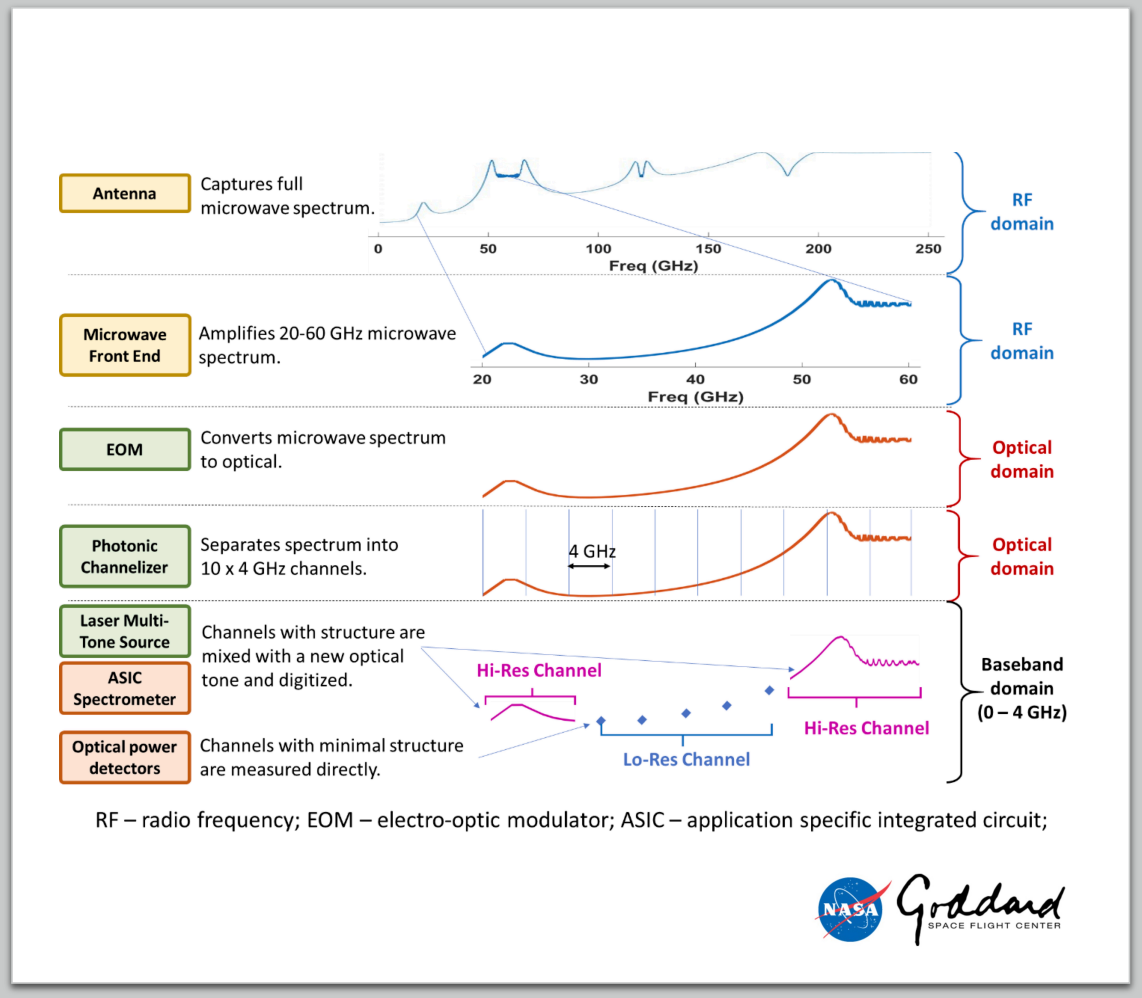
The PICASIC Concept

Gambacorta A., Stephen M., Gambini F., *et al.*, *"The Hyperspectral Microwave Photonic Instrument (HyMPI): Advancing Atmospheric Thermodynamic Sounding from Space"* in IEEE Special Issue "Advancements in the Next Generation of LEO and GEO Microwave and Infrared Sounders", under review, 2022.

C. Turner, M. Stephen, F. Gambini, G. Chin, P. Racette and T. Murphy, "*Ultra-Wideband Photonic Radiometer for Submillimeter Wavelength Remote Sensing*," \textit{International Topical Meeting on Microwave Photonics}, vol. 124-127, doi:10.23919/MWP48676.2020.9314456, 2020.

F. Gambini, R. Moreira, A. Gambacorta, J. Klamkin, M. Stephen, *"An Innovative Photonic Integrated Channelizer Design for Hyperspectral Microwave Sounding"*, \textit{Optical Sensor and Sensing, OSA Technical Digest (Optical Society of America)}, paper HF4E.5, July 2021.



Preliminary results, future applications

- **This presentation provides preliminary results** showing significant enhancements in the thermodynamic retrieval vertical structure with respect to the current and future program of record products that can be key to numerous climate and weather forecasting applications, particularly in the PBL.
- **One of the primary goals of our research is to finalize instrument design trade studies** and derive a final optimal configuration ready for follow-on airborne flight demonstrations.
- **Our goal is to actively engage the science community** during this critical trade study phase and seek feedback on product requirements that can help consolidating instrument specifications and its science and applications traceability.

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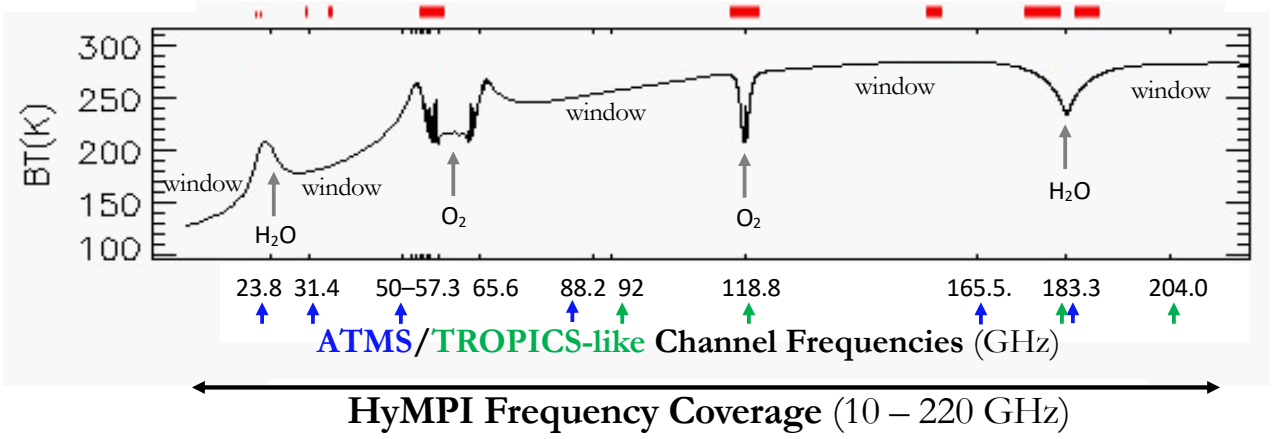
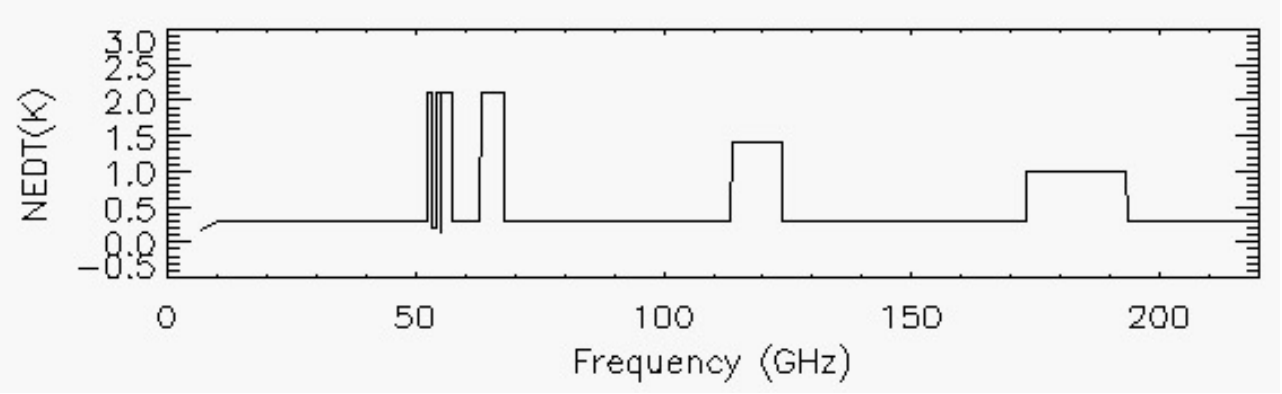
HyMPI's Baseline Configuration





- **HyMPI's baseline configurations** is based on the design presented in [Aires *et al.,* 2015; Aires *et al.,* 2017] with some augmentation.
- HyMPI baseline design is characterized by continuous spectral coverage along the oxygen absorption lines in the 52.6-57.3 GHz, 63.3-67.9 GHz (spectral resolution 10 MHz), and 113.7-123.7 GHz spectral bands (spectral resolution 20 MHz. It has full-spectrum coverage in the water vapor absorption line centered in the 173.3-193.3 GHz band (spectral resolution of 40 MHz),. In addition to selected "window" channels from the POR, we have studied the full interstitial window regions.
- Red bars indicate regions shared with compatible active services (Radio Frequency Interference, RFI).

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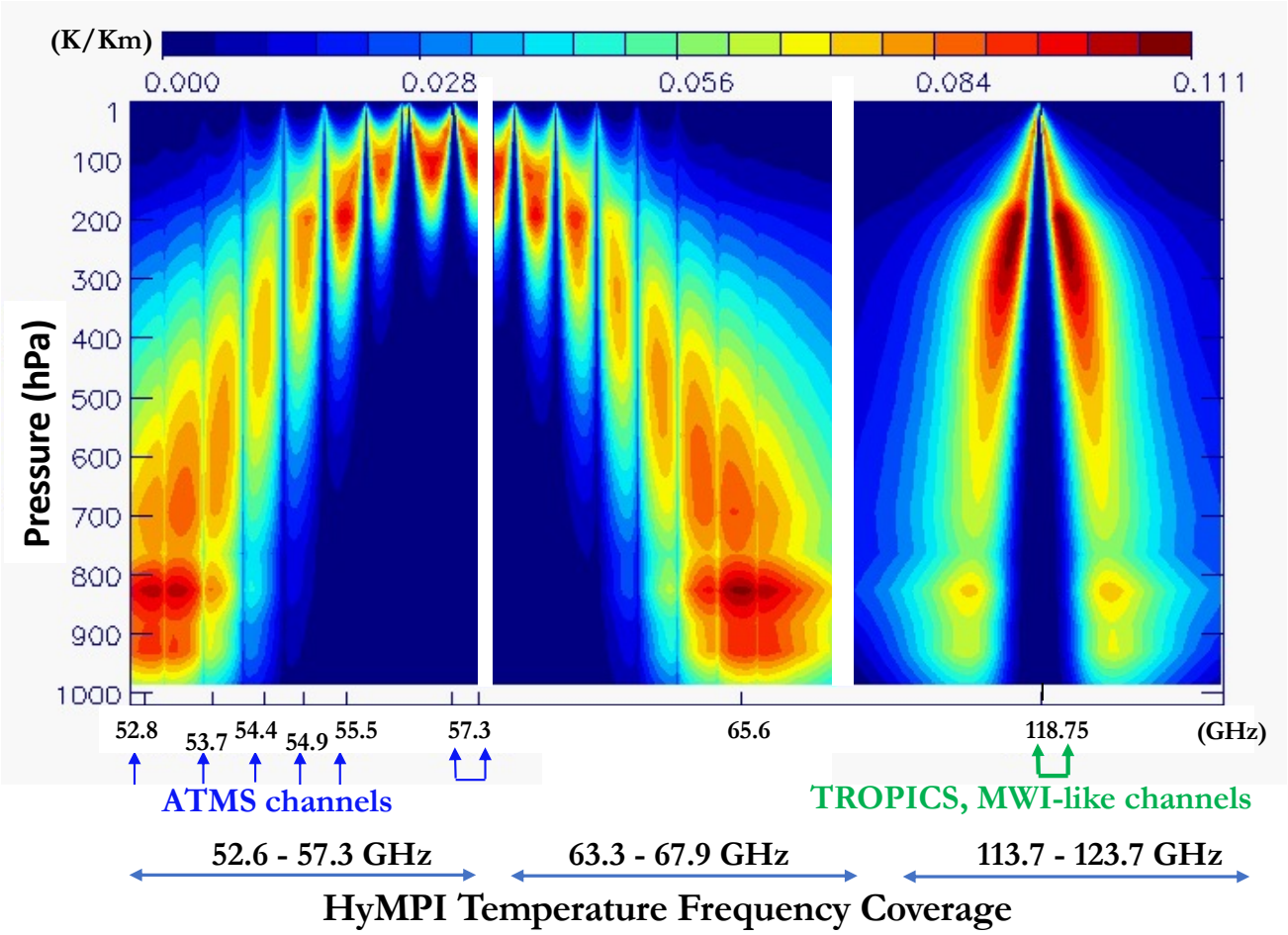

Brightness Temperature Sensitivity Analysis to Temperature

- 1-K temperature perturbations in each 1 km-pressure layer of the atmospheric profile have been applied to measure the response in brightness temperature in the oxygen bands (10 – 20 MHz resolution).
- For comparison purposes, ATMS and TROPICS spectral channel frequencies are highlighted by blue and green arrows, respectively.
- **Higher spectral resolution** narrows the sensitivity functions, improving retrieval vertical resolution
- **Higher spectral coverage** improves information content along the vertical column.

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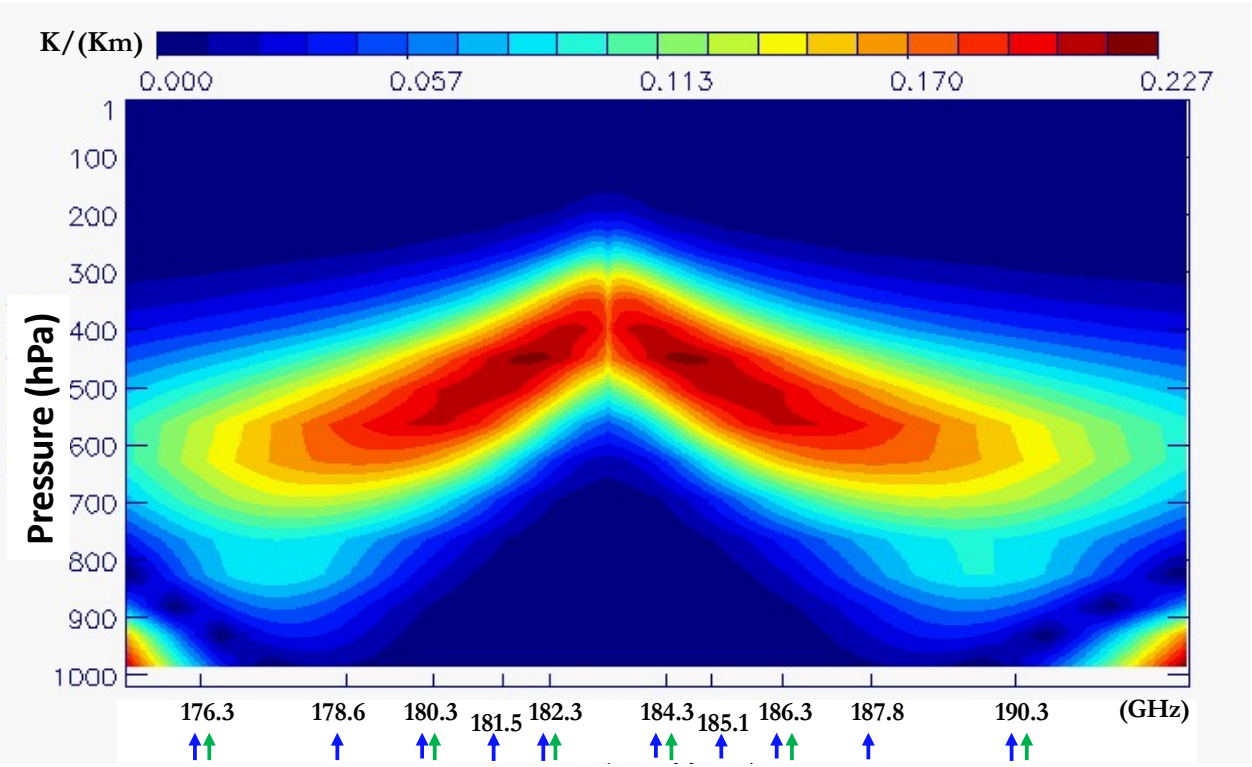

Brightness Temperature Sensitivity Analysis to Water Vapor

- 5% water vapor perturbations in each 1 km-pressure layer of the atmospheric profile have been applied to measure the response in brightness temperature in the water vapor band (40MHz spectral resolution).
- For comparison purposes, ATMS and TROPICS spectral channel frequencies are highlighted by blue and green arrows, respectively.
- **Higher spectral resolution** narrows the sensitivity functions, improving retrieval vertical resolution.
- **Higher spectral coverage** improves information content along the vertical column.

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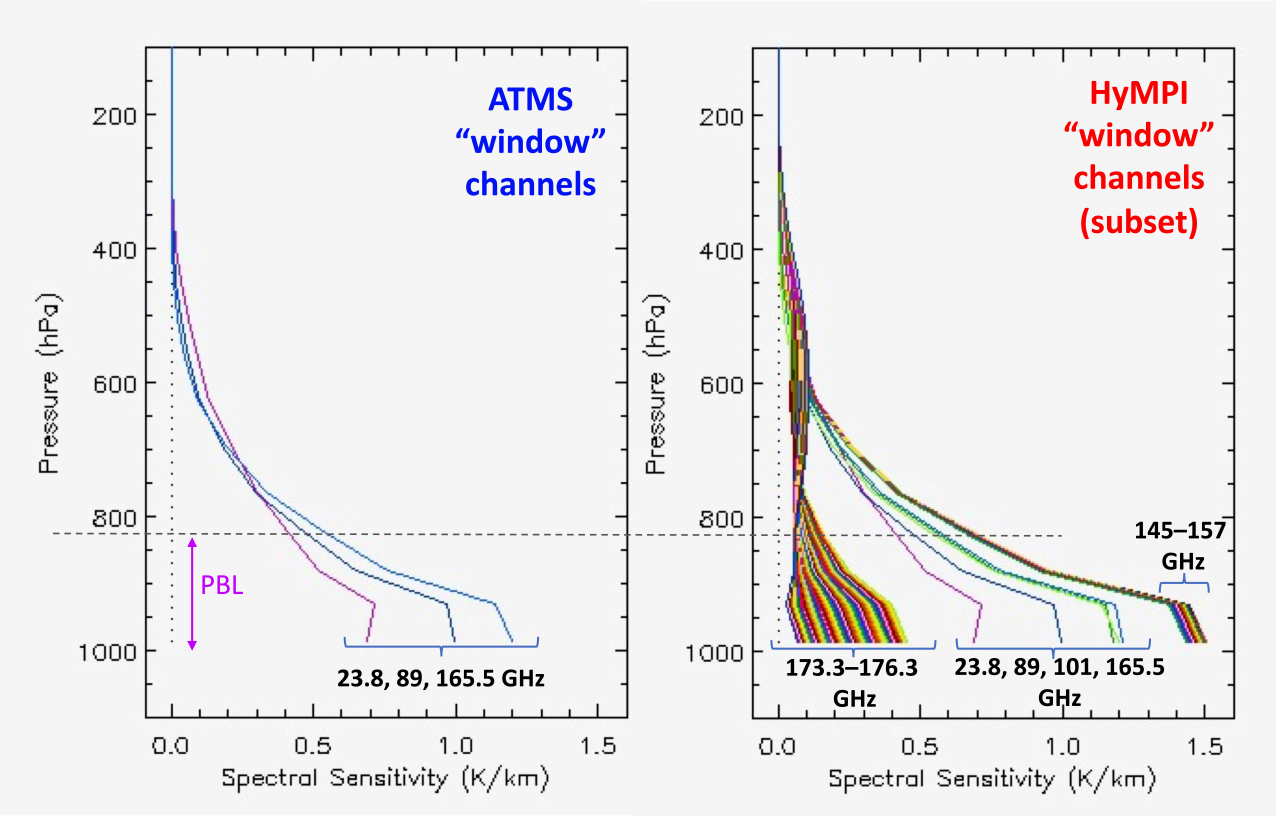

Brightness Temperature Sensitivity Analysis to Water Vapor in the "window" regions

- 5% water vapor perturbations in each 1 km-pressure layer of the atmospheric profile have been applied to measure the response in brightness temperature in the selected channels of the window region.

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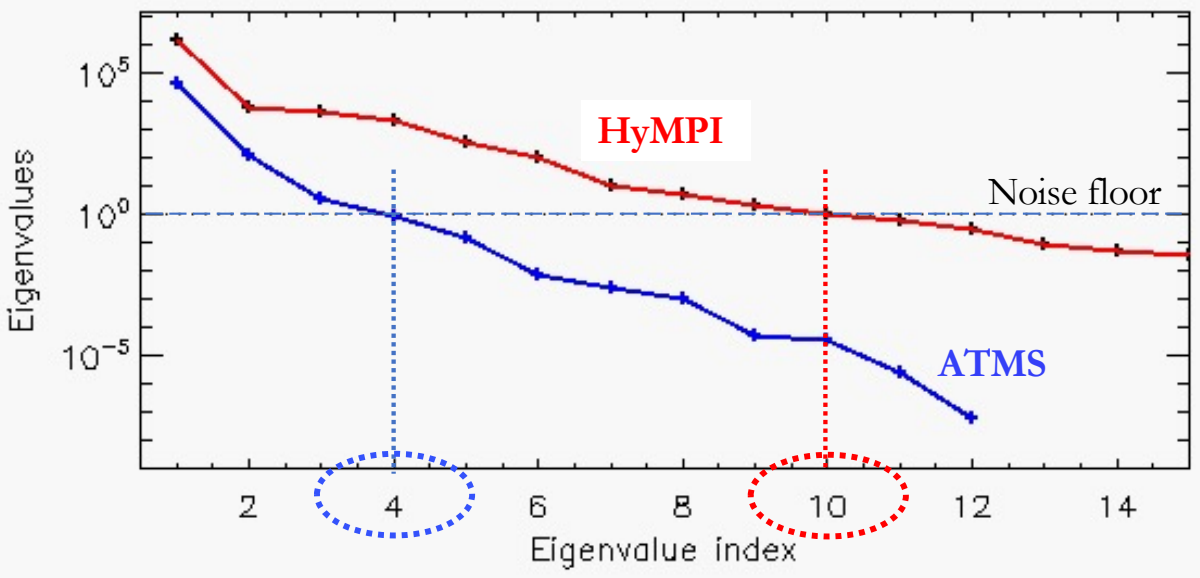
Information Content Analysis – Water Vapor



- We performed a singular value decomposition from preliminary ~3000 simulated spectra (land, ocean, clear sky and cloudy scenes), using HyMPI's (red curve) and ATMS (blue curve) water vapor and window channels.
- HyMPI has the potential to increase the retrieval water vapor vertical resolution from a few coarse layers to an effective vertical *profile* of at least ten layers.

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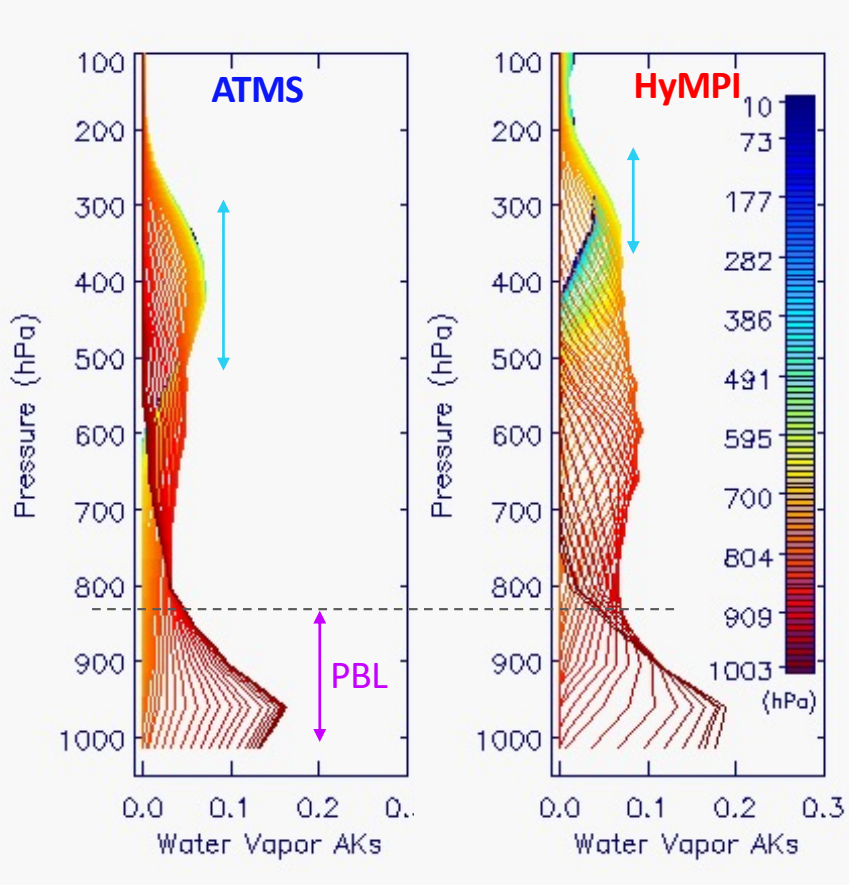
Vertical Resolution Study – Water Vapor Averaging Kernels



- HyMPI fills the mid-troposphere - 800 hPa gap in the ATMS retrieval vertical resolution and sensitivity.
- Nearly doubles the retrieval vertical resolution along the full extent of the mid/upper tropospheric column, and
- Significantly increases both vertical resolution and sensitivity in the PBL.

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Retrieval Impact Study

- **We have built an end-to-end processing system** to test instrument and algorithm capabilities, compare with the literature and perform rigorous independent demonstrations.
- **The retrieval processing system is an updated software version of the combined Atmospheric InfraRed Sounder (AIRS)/Advanced Microwave Sounder Unit (AMSU) version 7 retrieval package** [Susskind *et al*., 2011], expanded to run the Community Radiative Transfer Model (CRTM) [Liu *et al*., 2008] to process hyperspectral microwave data.
- We have also developed a fully functional **Observing System Simulation Experiment (OSSE) [Errico *et al.,* 2017] capability using the Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System, version 5 (GEOS-5)** [Rienecker *et al.,* 2008] to test assimilation of HyMPI data and assess its impact from the Numerical Weather Prediction (NWP) perspective.

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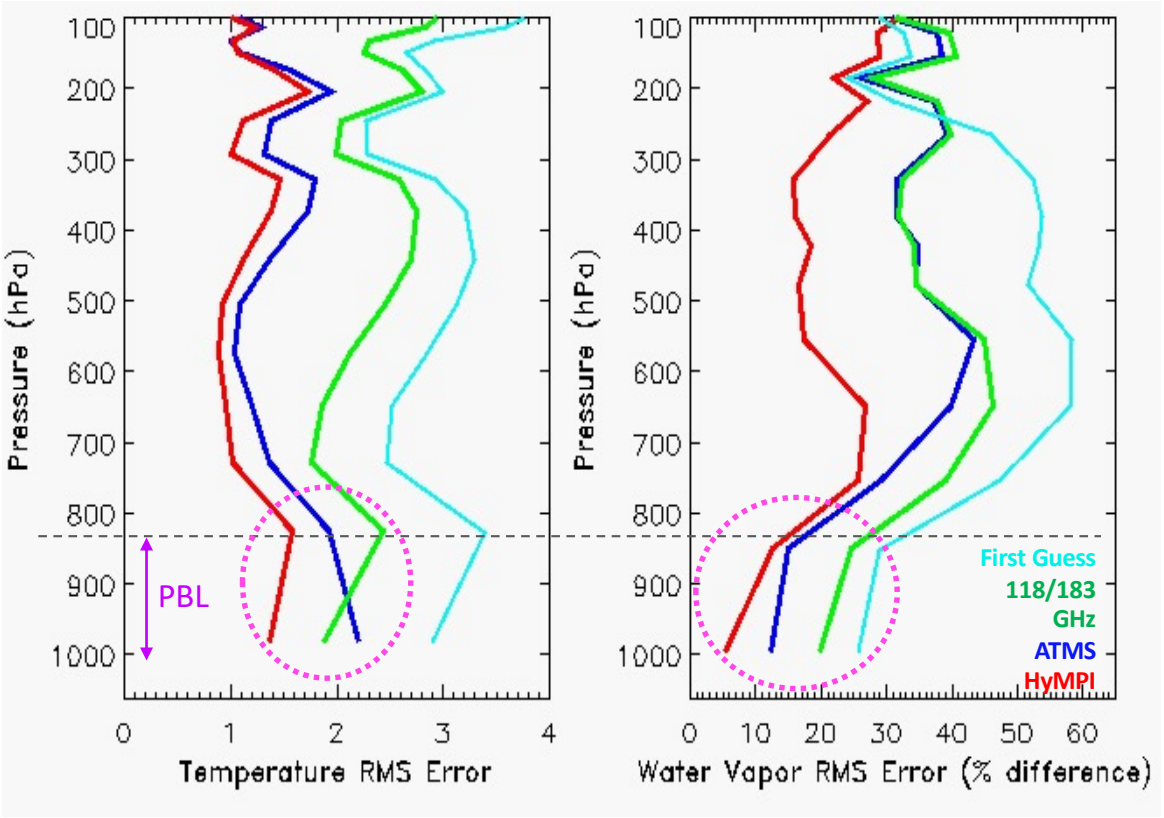
Retrieval Impact Study – RMS Error Performance (Ocean, clear, global sample)



- HyMPI reduces the POR temperature Root Mean Square (RMS) error (left) by 50% in the PBL and 20% 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, will potentially enhance the identification of the PBL height.

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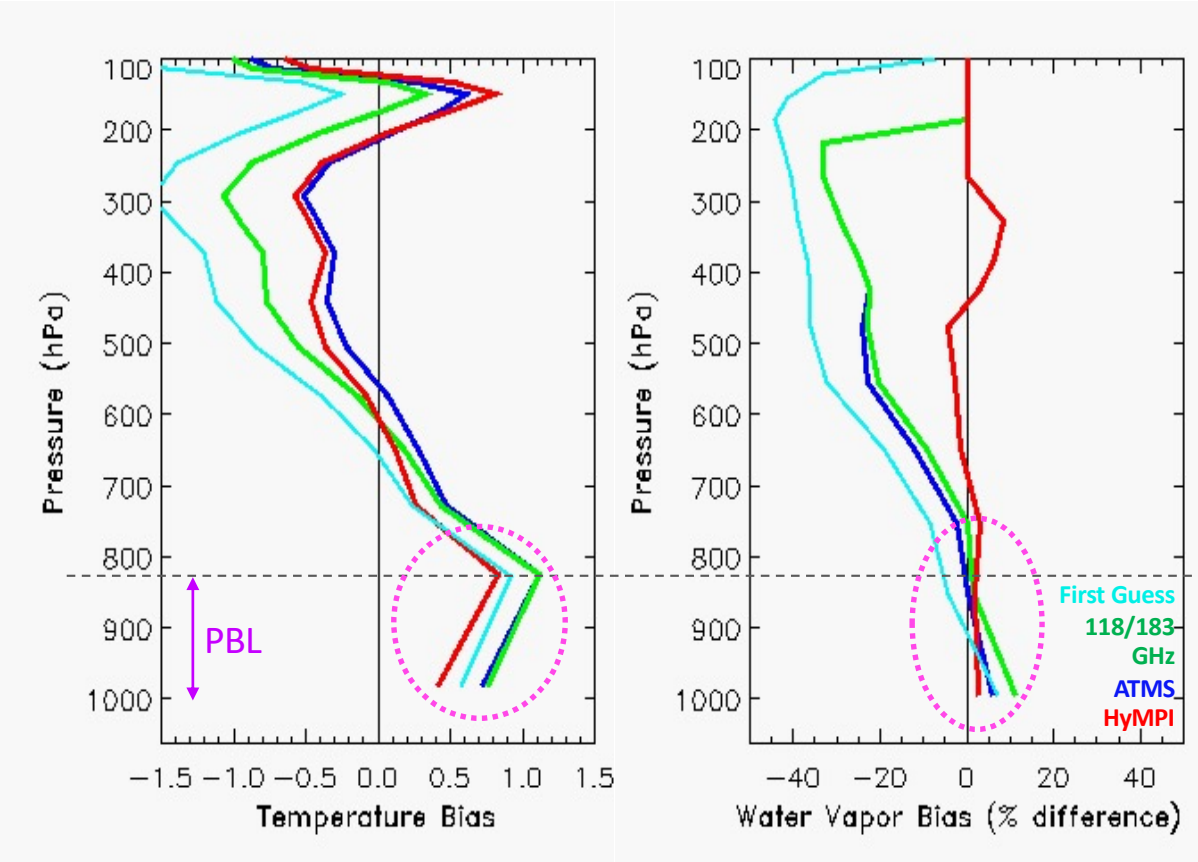
Retrieval Impact Study – Bias Error Performance (Ocean, clear, global sample)



- HyMPI reduces the POR temperature BIAS error (left) by 50% in the PBL.
- The water vapor BIAS error (right) almost reaches zero in the PBL domain and all along the free troposphere.
- The improvements shown, both in the PBL and the free troposphere, will lead to significant enhancement in the identification of PBL height.

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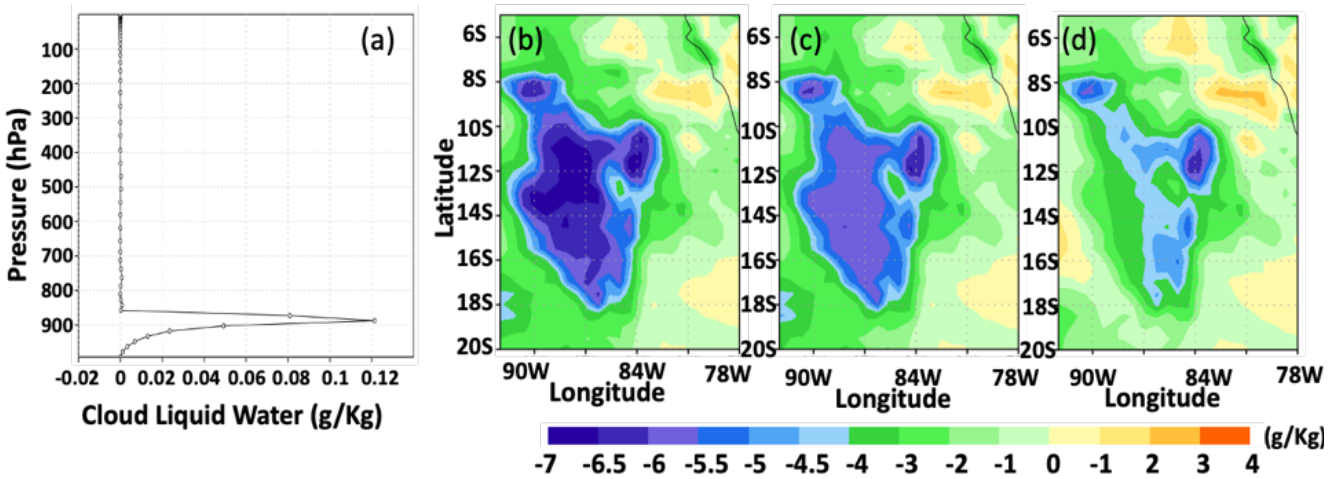
Stratocumulus PBL Cloudy Scenario



- South America West Coast Example. Figure a) is a cloud liquid water profile from the area. Figure b), c), and d) show the first guess, ATMS and ATMS + HyMPI water vapor departure from the truth at 875 hPa (results from the GMAO GEOS 5 [Rienecker *et al*. 2008] OSSE Framework [Errico *et al.,* 2017], using the GMAO Nature Run [Gelaro *et al*., 2015]).
- **HyMPI provides significant enhancement in the water vapor at the top of the PBL.** Improved water vapor fields in stratocumulus cloudy scenes are critical for cloud-climate feedbacks and numerical weather prediction .

Concluding Remarks and Outlook

- **We provided preliminary results** showing significant enhancements in the thermodynamic retrieval vertical structure with respect to POR products that can be key to numerous climate and weather forecasting applications, particularly in the PBL, that are relevant to NASA and NOAA.
- **What driving applications (improved and new) can we develop?**
  - HyMPI addresses each of the critical PBL science questions and themes outlined in the PBL Study Team Report SATM
  - Tropical Cyclone (TC) Intensity Forecasts
  - Convective Initiation
  - Cold Pools
  - Atmospheric Winds
  - RFI Detection Algorithms
  - *… and a lot more!*
- **What is needed to get there?**
  - Major sources of uncertainties: surface emissivity model, water vapor continuum, spectral absorption line shapes and positions
  - HyMPI will provide fine resolution, high precision hyperspectral MW measurements to help validate forward models, detect and filter out RFI signal, make new physics discoveries.
- **Our goal is to actively engage the science community** during this critical instrument trade study phase and seek feedback on product requirements that can help consolidating instrument specifications and its science and applications' traceability. *Contact us!*

Backup slides

Brightness Temperature Sensitivity Analysis – summary remarks

- MW domain spectrally purer than the infrared: the high redundancy is fully exploitable to increase signal to noise, with significant benefits on retrieval performance.
- HyMPI will enable an unprecedented fine resolution observations of extended window regions where the water vapor continuum is important.
- Those measurements will be critical to improve spectroscopy and forward modeling, which in turn will benefit retrieval performance, numerical weather and climate prediction models, and enable new physics discoveries.

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