Advancing Atmospheric Thermodynamic Sounding From Space Using Hyperspectral Microwave Measurements: Introducing The Hyperspectral Microwave Photonic Instrument (HyMPI)

Antonia Gambacorta[1], Mark Stephen[1], Jeffrey Piepmeier[1], Joseph Santanello[1], Rachael Kroodsma[1], Fabrizio Gambini[2], Isaac Moradi[3], Alexander Kotsakis[3], John Blaisdell[4], James Mackinnon[1], Priscilla Mohammed[7], Jie Gong[1], Ian Adams[1], Paul Racette[1]

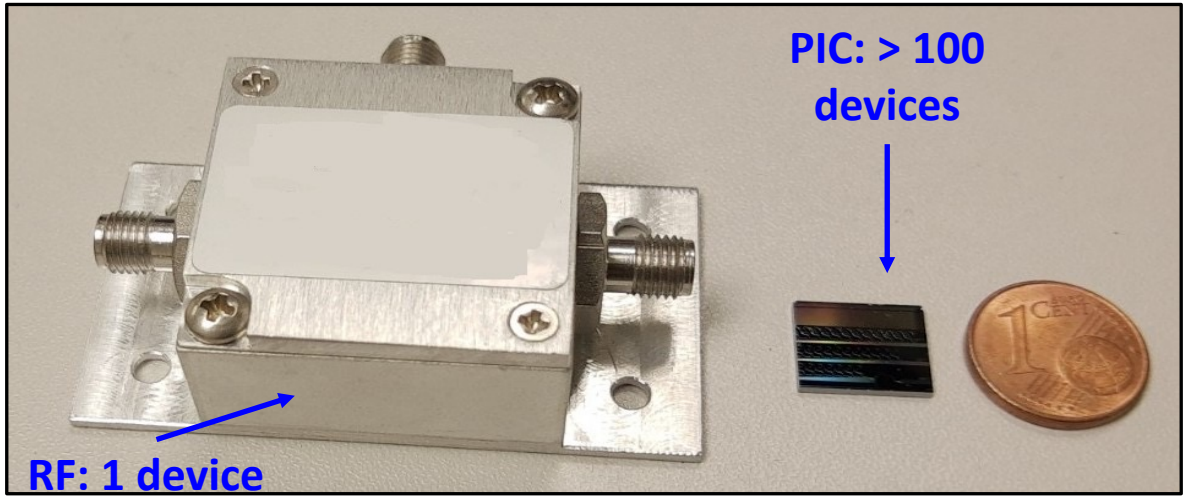
ESTF, Pasadena, June 22nd 2023

[1] NASA Goddard Space Flight Center (GSFC)
[2] University of Maryland Baltimore County (UMBC)
[3] University of Maryland (UM)
[4] Science Applications International Corporation (SAIC)
[7] Morgan State University (MSU)

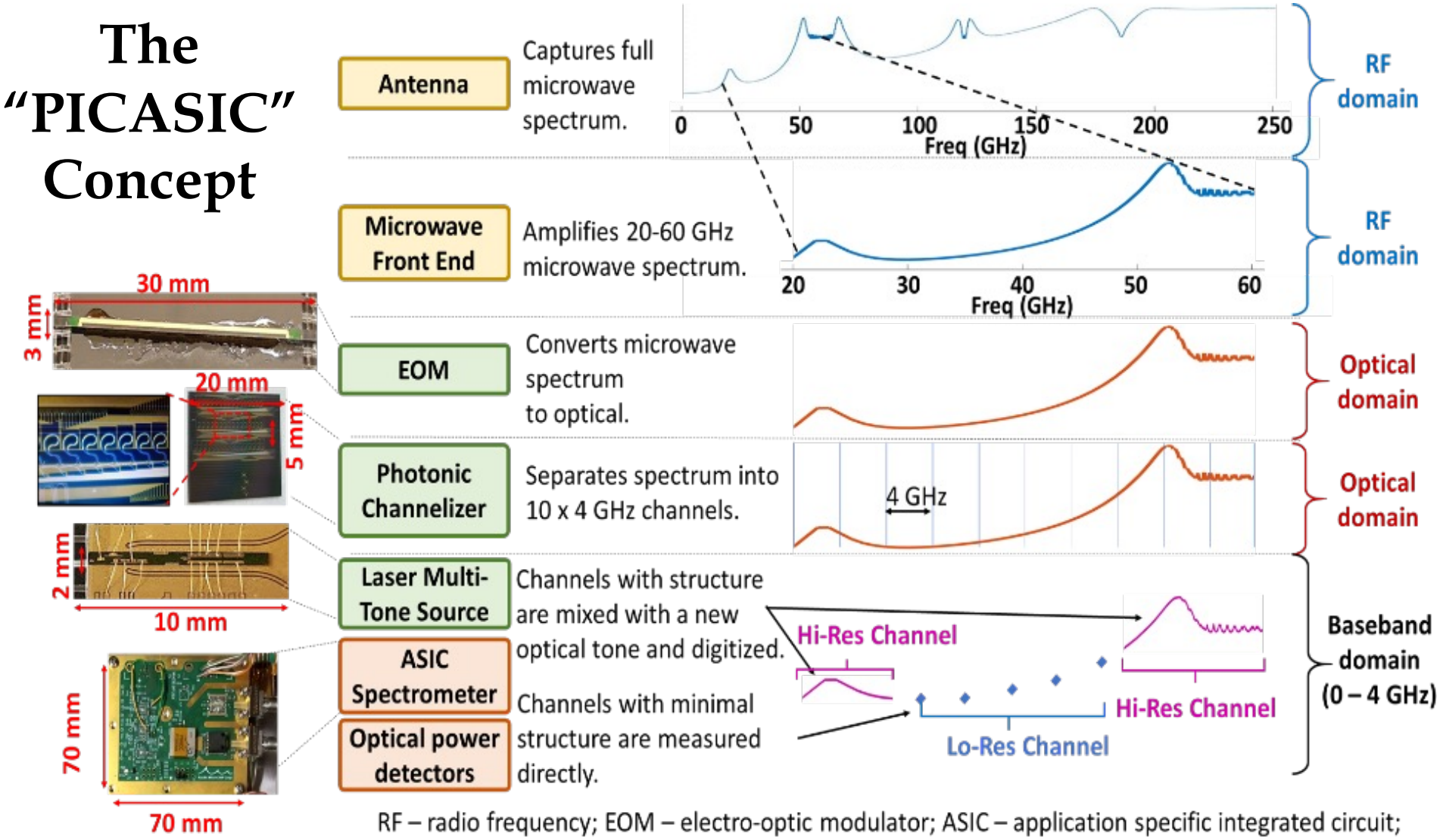
Integrated Photonics

- **<u>Integrated photonics</u>:** emerging branch of photonics in which multiple devices are fabricated as an integrated structure onto the surface of a flat substrate

- **<u>Properties of photonic integrated circuits (PIC)</u>:**
  - Ultra compact devices (low size/weight)
  - Low power consumption
  - Process ultra-high bandwidth
  - Tunable channels
  - Reduced cost with integration
  - CMOS compatible



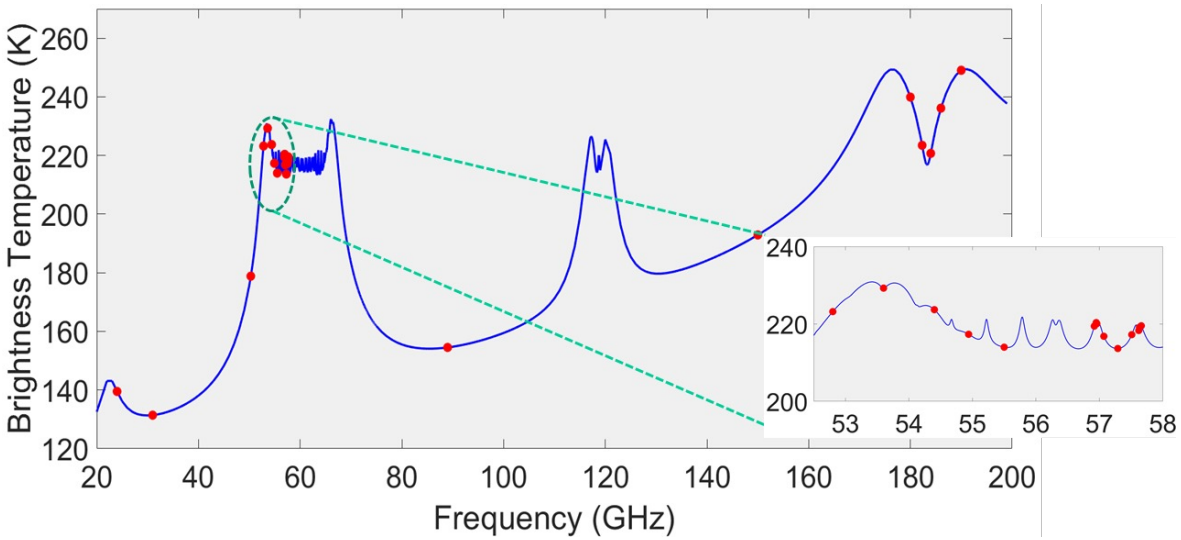
The "PICASIC" Concept

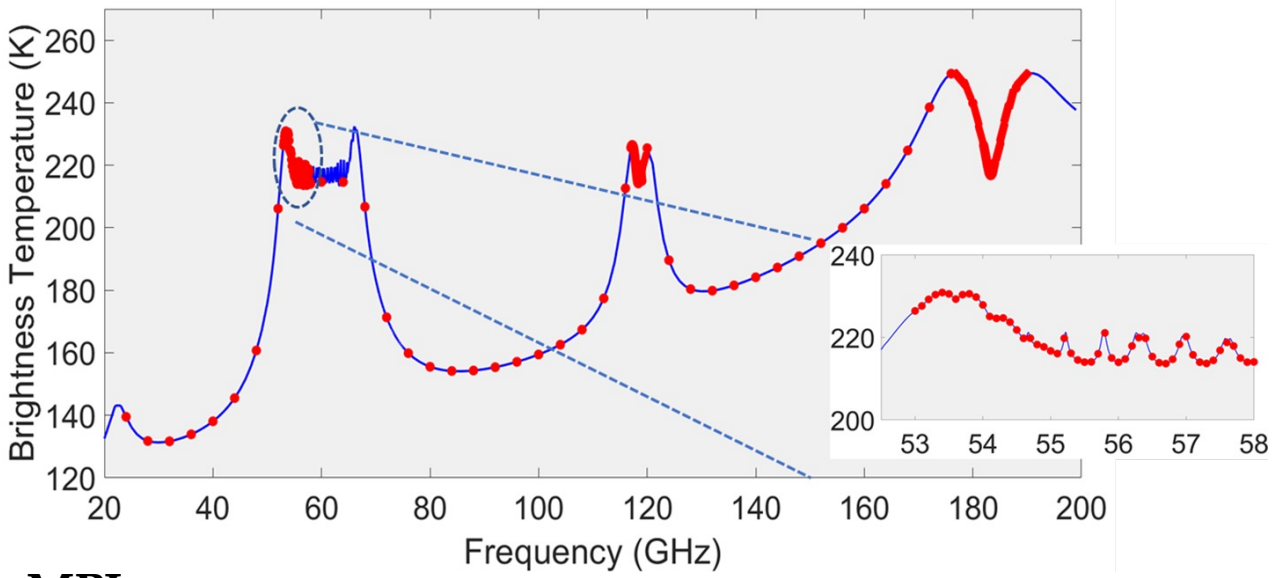


RF – radio frequency; EOM – electro-optic modulator; ASIC – application specific integrated circuit;

Gambini et al., 2021, doi: 10.1364/HISE.2021.HF4E.5; Turner et al., 2020, doi:10.23919/MWP48676.2020.9314456; Gambacorta et al., 2023, doi: 10.1109/JSTARS.2023.3269697

What Can Integrated Photonics Do for MW Remote Sensing?





ATMS:

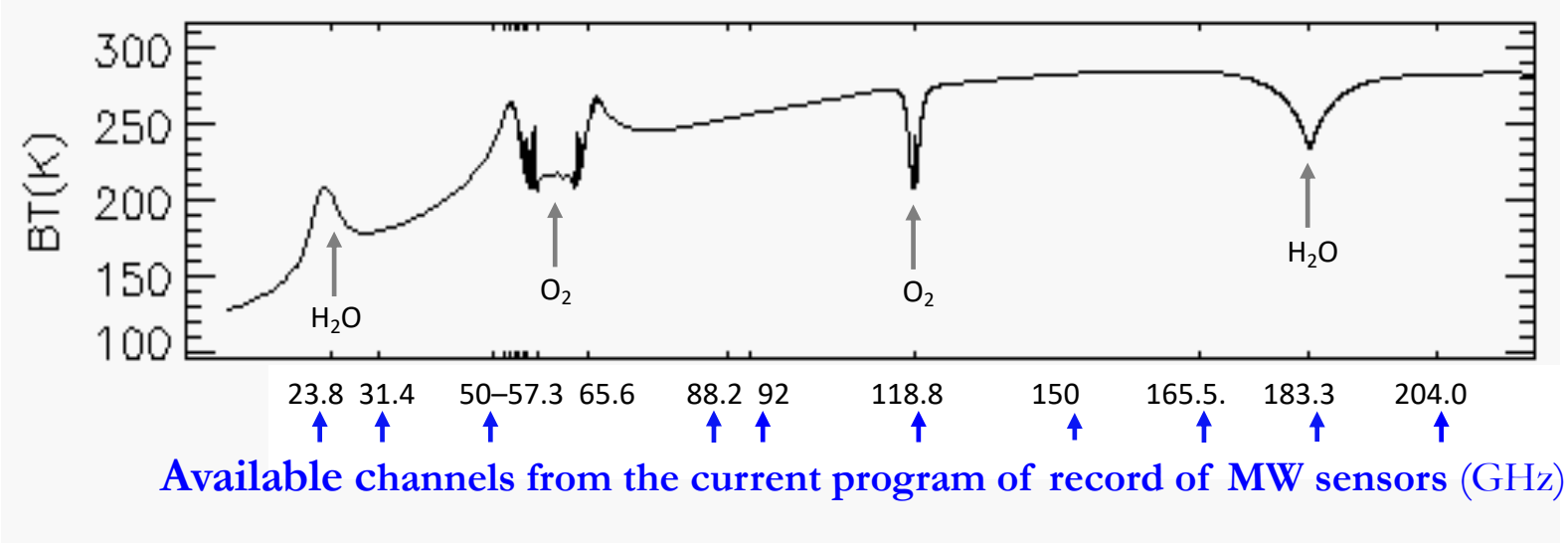
- ~20 sparse channels (not contiguous spectrum)
- Missing critical information
- >> 2-U cubesat footprint

HyMPI:

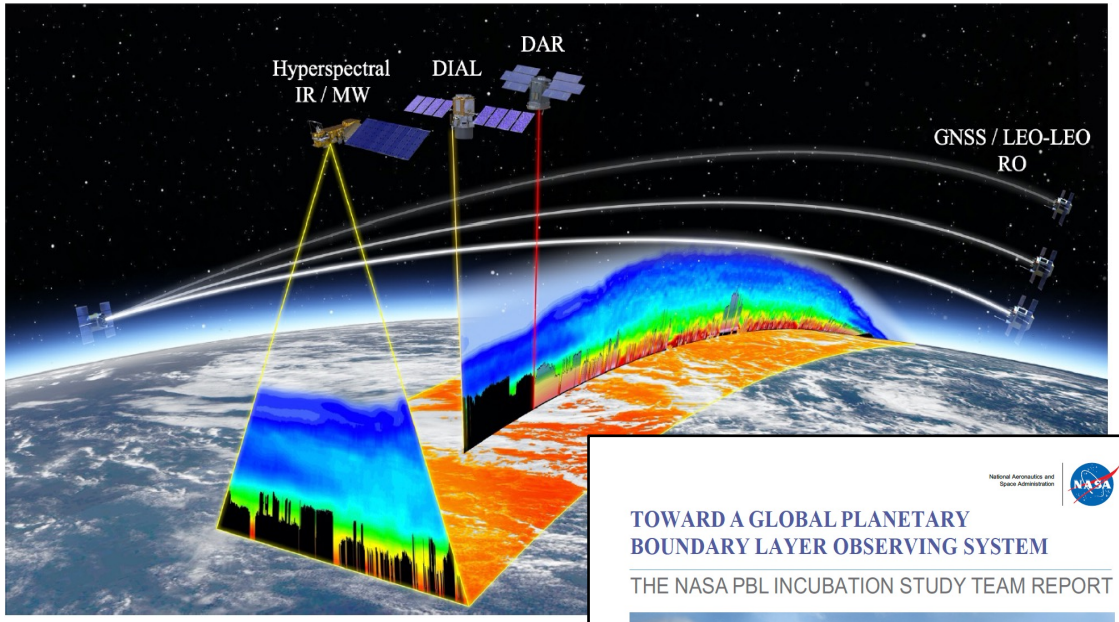
- Contiguous spectrum coverage
- Hyperspectral resolution: up to 500KHz with support of ASIC
- 1U / 2-U cubesat footprint

- **The key characteristic of the PIC is its capability to process 40 GHz of instantaneous signal bandwidth.** Combined with ASICs, this translates into a programmable spectral resolution as fine as 500 KHz, covering the full contiguous 10-250 GHz range (equivalent to 80,000 frequency sub-channels) with efficient SWaP-C.
- **This makes HyMPI a first of a kind *combined sounder* + *imager sensor*, suitable for space deployment.**

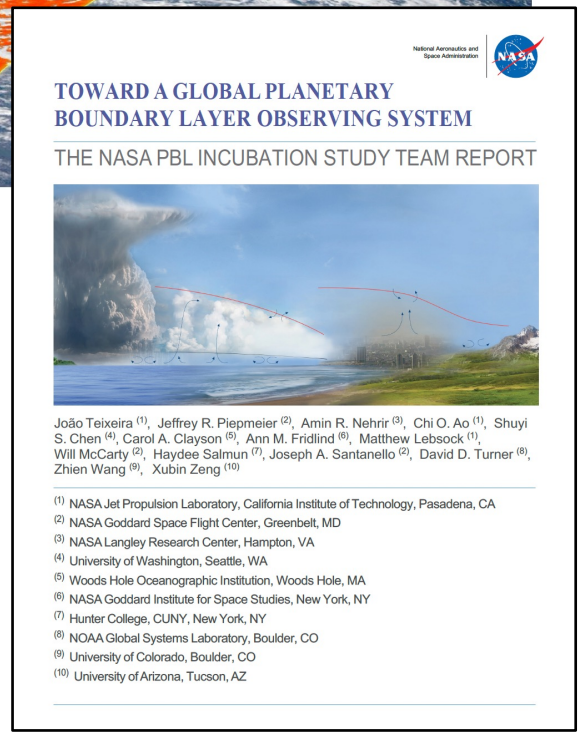
Hyperspectral Microwave Measurements of the Earth's surface and atmospheric radiation



MSU	AMSU A/B & MHS	ATMS	CoSMIR-H	HyMPI
4 chns	**20** chns	**22** chns	**1200** chns	*xx,000*
1978	1998	2011	2024	~2030s



Teixeira et al., 2021

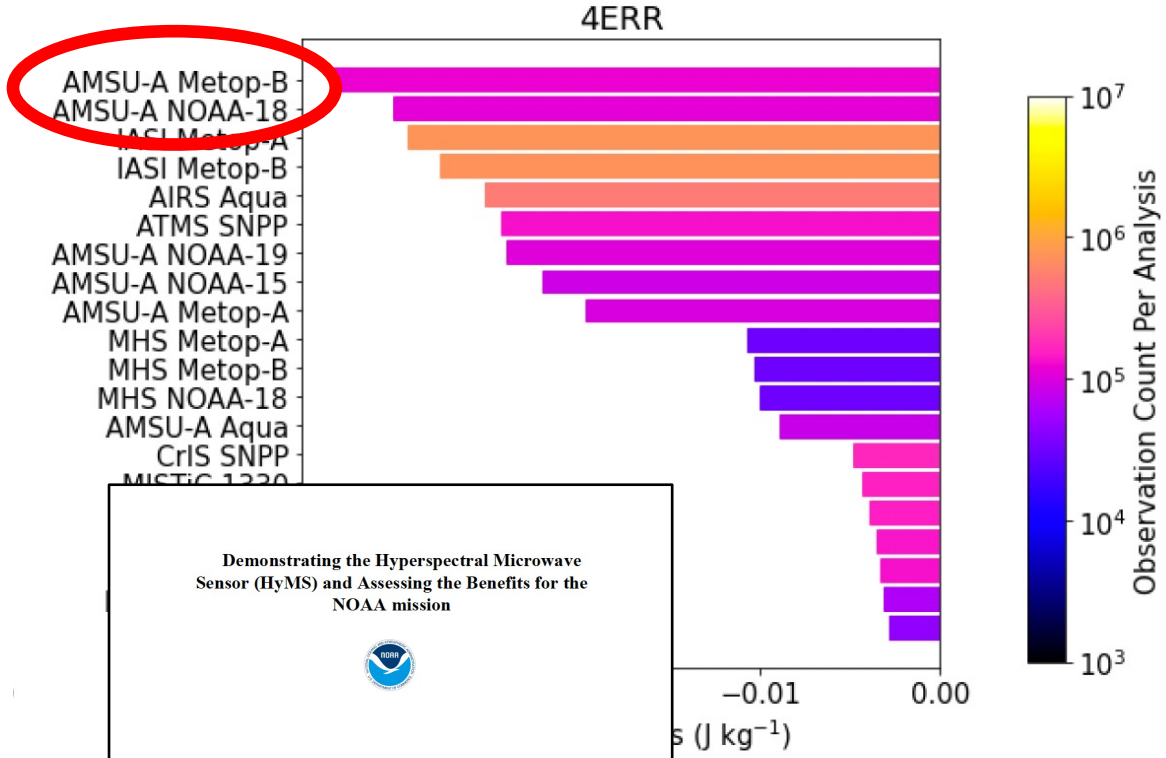


TOWARD A GLOBAL PLANETARY BOUNDARY LAYER OBSERVING SYSTEM

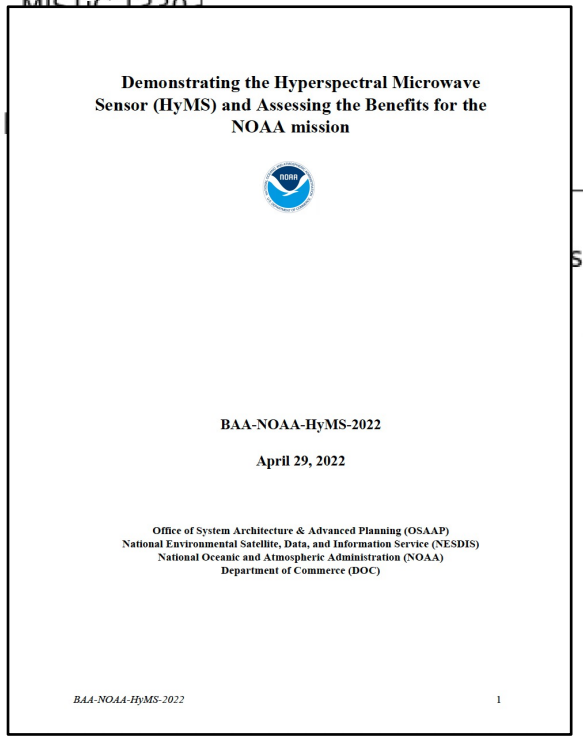
THE NASA PBL INCUBATION STUDY TEAM REPORT

João Teixeira [1], Jeffrey R. Piepmeier [2], Amin R. Nehrir [3], Chi O. Ao [1], Shuyi S. Chen [4], Carol A. Clayson [5], Ann M. Fridlind [6], Matthew Lebsock [1], Will McCarty [2], Haydee Salmun [7], Joseph A. Santanello [2], David D. Turner [8], Zhien Wang [9], Xubin Zeng [10]

[1] NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
[2] NASA Goddard Space Flight Center, Greenbelt, MD
[3] NASA Langley Research Center, Hampton, VA
[4] University of Washington, Seattle, WA
[5] Woods Hole Oceanographic Institution, Woods Hole, MA
[6] NASA Goddard Institute for Space Studies, New York, NY
[7] Hunter College, CUNY, New York, NY
[8] NOAA Global Systems Laboratory, Boulder, CO
[9] University of Colorado, Boulder, CO
[10] University of Arizona, Tucson, AZ



McCarty et al., 2020



Demonstrating the Hyperspectral Microwave Sensor (HyMS) and Assessing the Benefits for the NOAA mission

BAA-NOAA-HyMS-2022

April 29, 2022

Office of System Architecture & Advanced Planning (OSAAP)
National Environmental Satellite, Data, and Information Service (NESDIS)
National Oceanic and Atmospheric Administration (NOAA)
Department of Commerce (DOC)

BAA-NOAA-HyMS-2022 1

Goddard SPACE FLIGHT CENTER

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

- **Our team at GSFC has initiated a NASA Earth Science and Technology Office Incubation Instrument Proposal research project titled**: "*Photonic Integrated Circuits (PICs) in Space: The Hyperspectral Microwave Photonic Instrument (HyMPI*)", to develop and demonstrate the first MW photonic integrated sensor with science grade performance, https://esto.nasa.gov/project-selections-for-iip-21/#Gambacorta

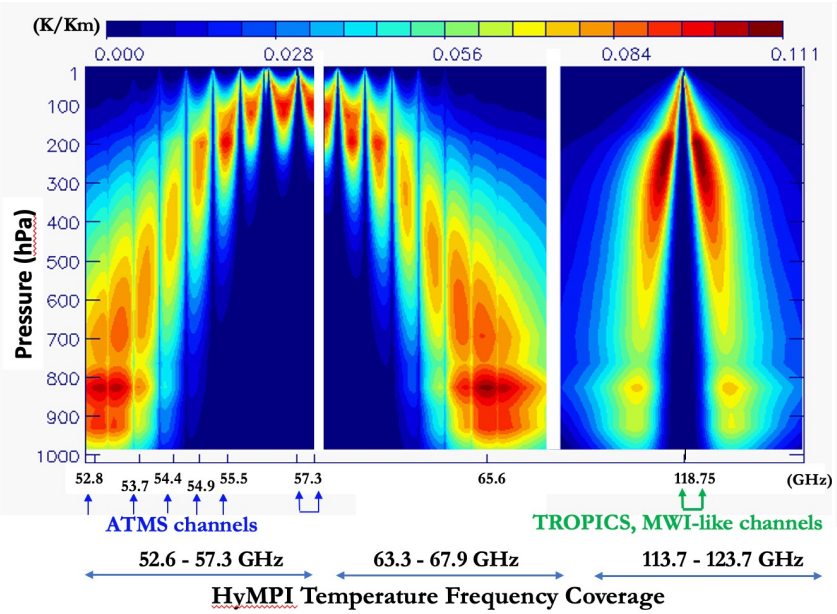
- **We are also funded through the NASA Decadal Survey Incubation Planetary Boundary Layer project to deploy an airborne campaign to demonstrate an Application Specific Integrated Circuits (ASIC) -based MW hyperspectral technology that will form the baseline for HyMPI, titled:** *"Hyperspectral Capability for the Conical Scanning Millimeter-wave Imaging Radiometer (CoSMIR): Enhancing Capability for Future PBL Suborbital Campaigns and Enabling PBL Science from Space* , https://esto.nasa.gov/project-selections-for-dsi-21/#Kroodsma

- **Our team has initiated an active-passive data fusion project, titled:** A Combined Passive-Active, Multi-Sensor Approach to Earth's Planetary Boundary Layer (PBL) Sounding to verify and quantify the enhanced 3D thermodynamic structure achieved by MW sensors (*e.g.*, ATMS, HyMPI) in combination with active sensors and perform signal/noise trade studies intended to inform future pathways (*e.g.*, enhanced passive and active sensors) to fill technology and uncertainty gaps, https://esto.nasa.gov/project-selections-for-dsi-21/#Gambacorta

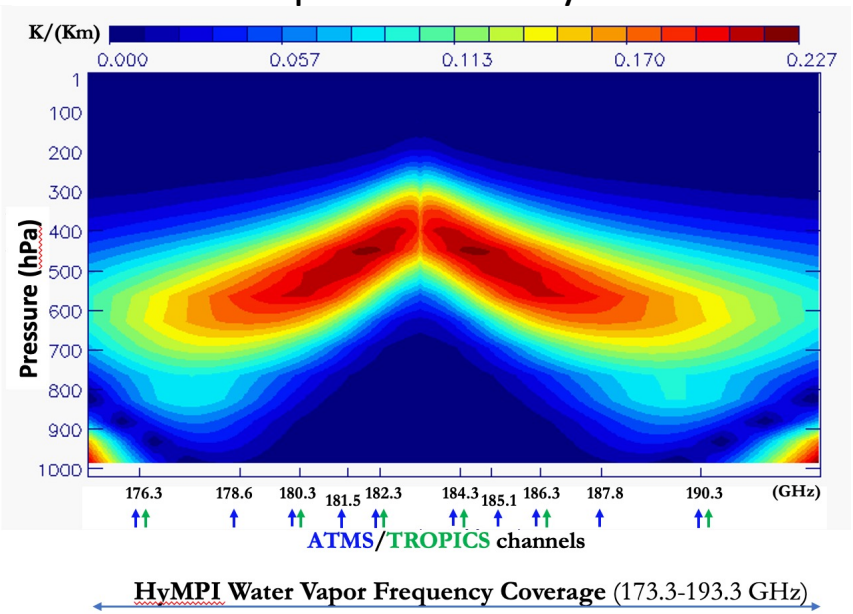
- **Our team at GSFC has initiated a NOAA Broad Agency Announcement funded project to deploy an airborne field campaign (WHyMSIE, the West-coast Hyperspectral Microwave Sensor Intensive Experiment), titled:** *"Developing the NOAA Next Generation Hyperspectral Microwave Sensor (HyMS): Instrument Concept and Demonstration of Benefits for the NOAA Mission"* , https://www.nesdis.noaa.gov/news/noaa-awards-joint-venture-program-broad-agency-announcements

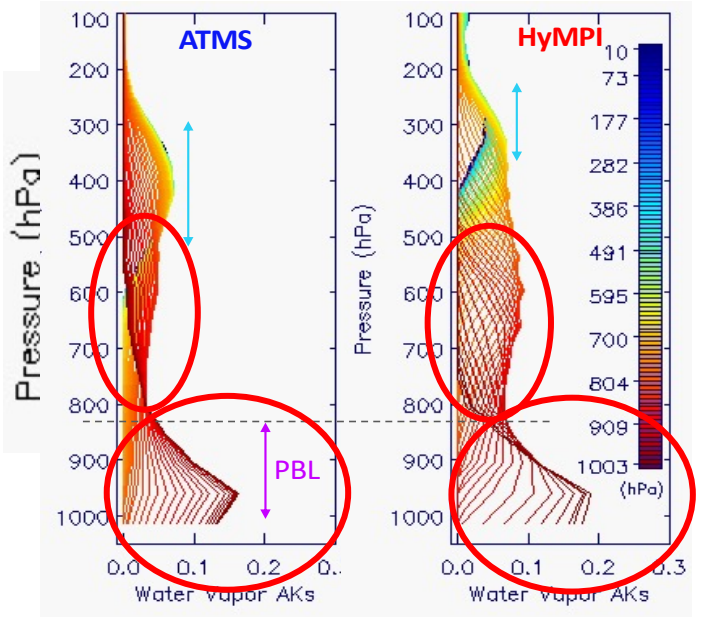
Filling The Gap in Information Content left by the POR

Temperature Sensitivity Functions



Water Vapor Sensitivity Functions

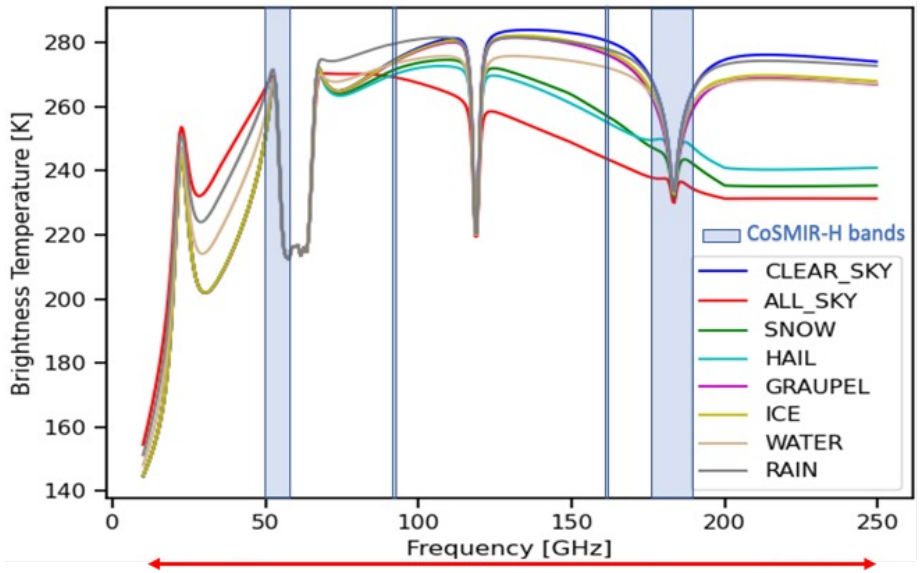




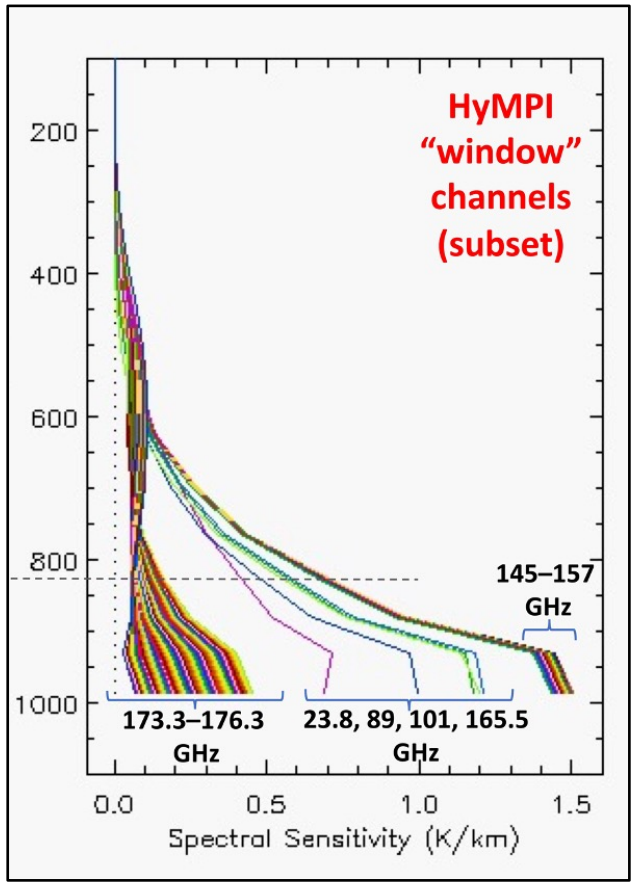
HyMPI will be configured to respond to the Science Applications and Traceability Matrix requirements outlined in the NASA Incubation PBL Study Team Report and to satisfy the broader needs of the weather and climate community.

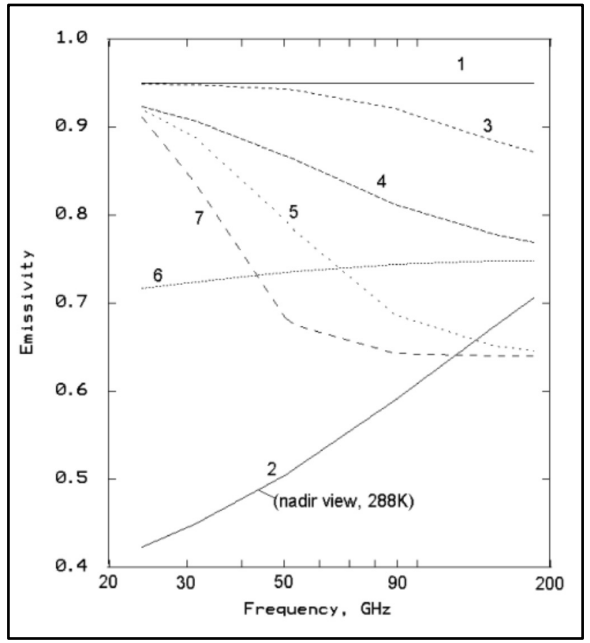
Gambacorta et al., 2023, doi: 10.1109/JSTARS.2023.3269697

Measuring unexplored information in the MW "window" regions



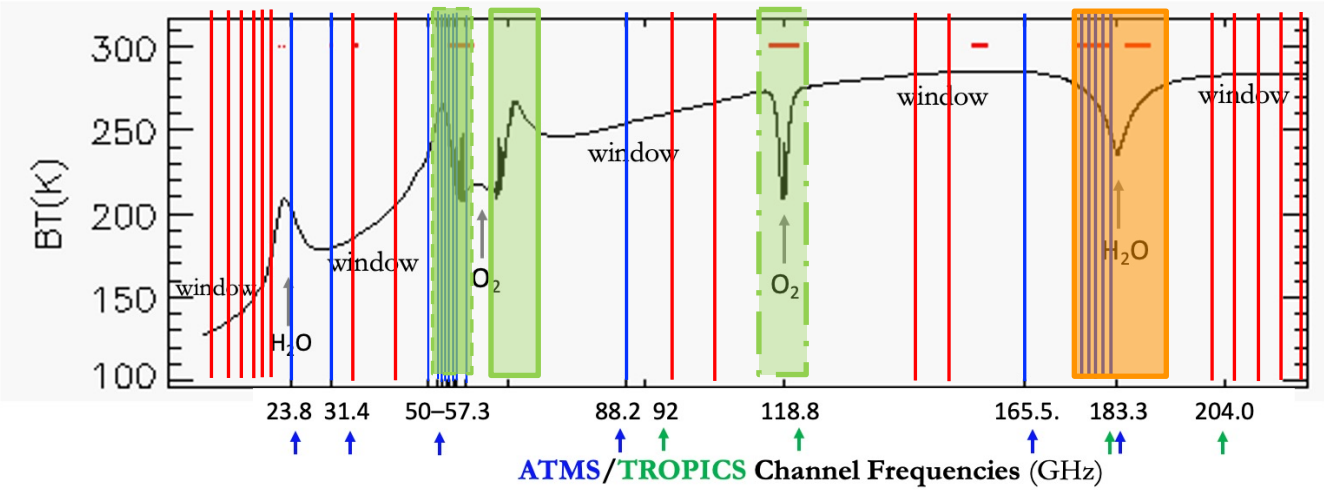
Spectral Coverage of our HyMS Space Concept (HyMPI)

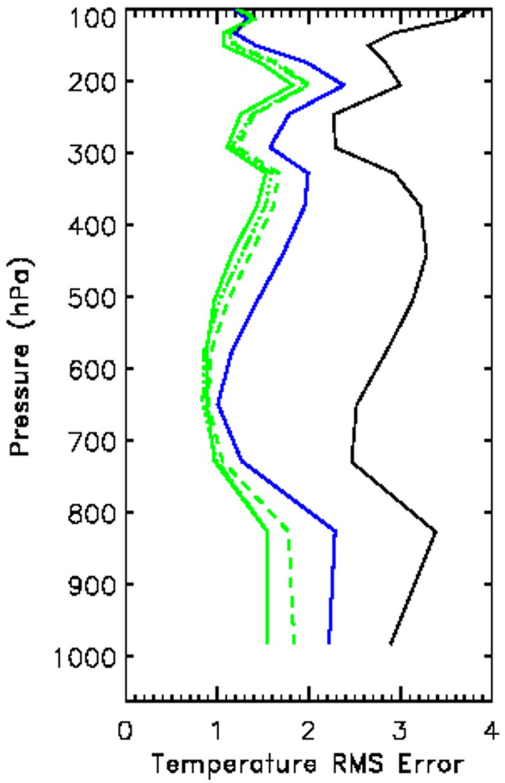


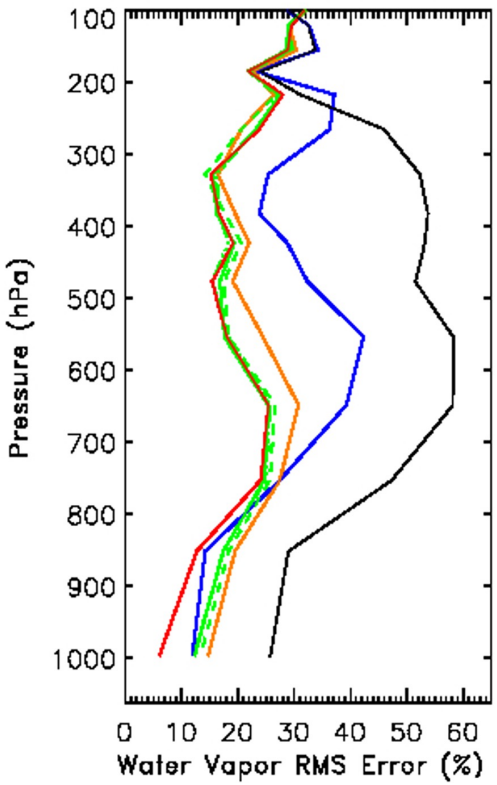


Type	Surface
0	coastline[a]
1	land
2	water[a]
3	high-emissivity sea ice
4	low-emissivity sea ice
5	snow (high-frequency scattering)
6	glacier/snow (very low frequency scattering)
7	snow (low-frequency scattering)

Temperature and water vapor trade studies







Baseline (ATMS)

Step 1: ATMS + 173.3 – 193.3 GHz

Step 2: Step 1 + 52.7 – 57.3 GHz (dash curve)

Step 3: Step 2 + 63.3 – 67.9 GHz (solid)

Step 4: Step 3 + 118 GHz (dot-dash)

Step 5: Step 4 + 16 novel window chns

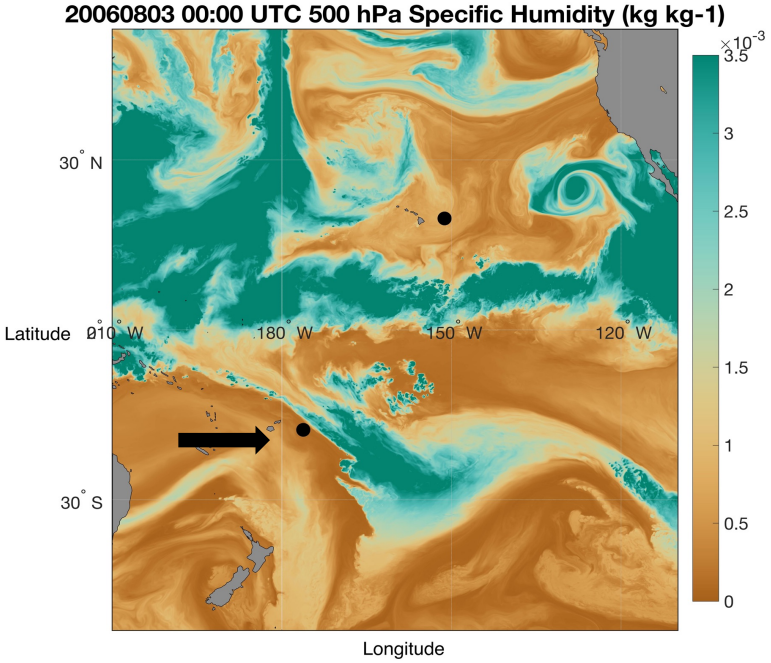
Full exploitation of the MW thermal spectrum (HyMPI's strategy) enables highest performance

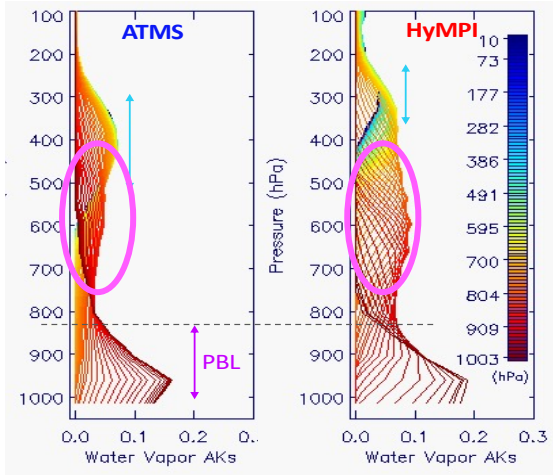
Gambacorta et al., 2023, doi: 10.1109/JSTARS.2023.3269697

CASE #1 : *HyMPI improvement in mid-to-upper troposphere*

HyMPI resolves the gap in **mid-to-upper troposphere** retrieval vertical resolution and sensitivity in existing microwave sounding technology and instruments

Extending *water vapor* sensitivity throughout full tropospheric column increases confidence in retrieving atmospheric state for entire profile and improves moisture information content within mid-to-upper layers, where MW instruments often lack skill.

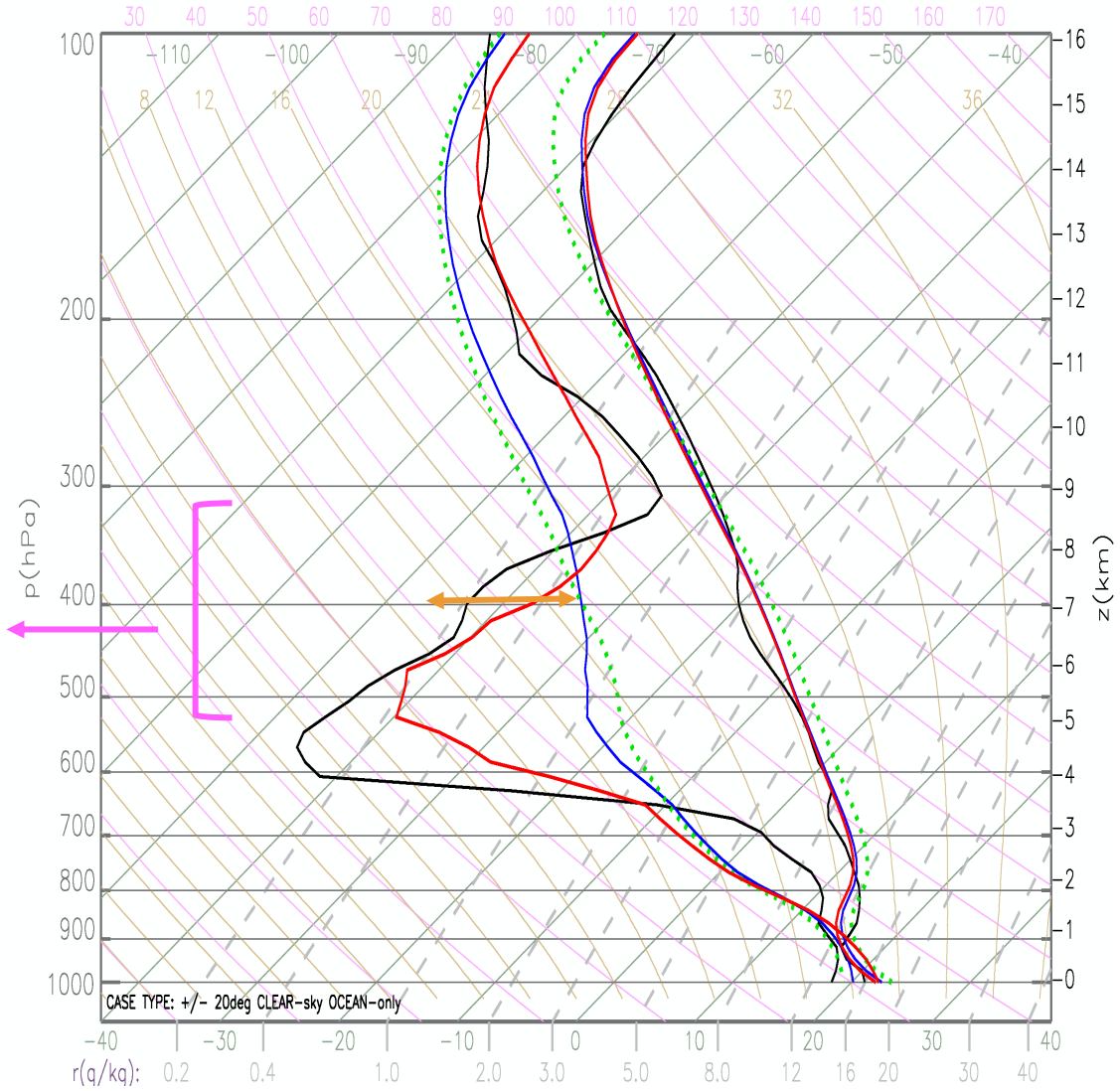




+/-20 degree HyMPI Retrieval Runs

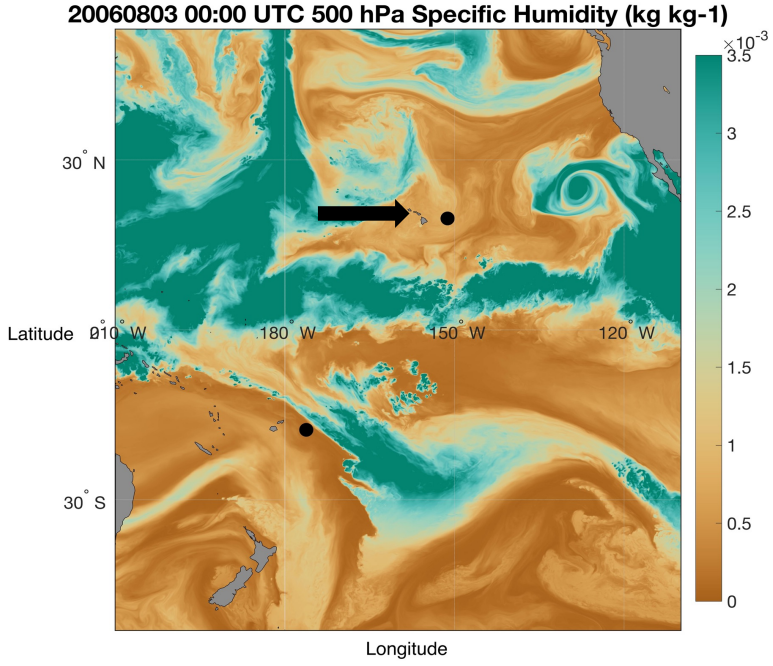
DATE: 2006080300z | **LAT**: -18° **LON**: -176.25 | **TYPE:** Clear-sky, Ocean-only

TRUTH – ATMS – HyMPI – 1st GUESS



CASE #2 : *HyMPI improvement in the Planetary Boundary Layer (PBL)*

- In the PBL, HyMPI shows a ~1K temperature improvement over ATMS.
- HyMPI's improvements, in the PBL and the free troposphere provide improved convective indexes and will enhance the identification of the PBL height



+/-20 degree HyMPI Retrieval Runs

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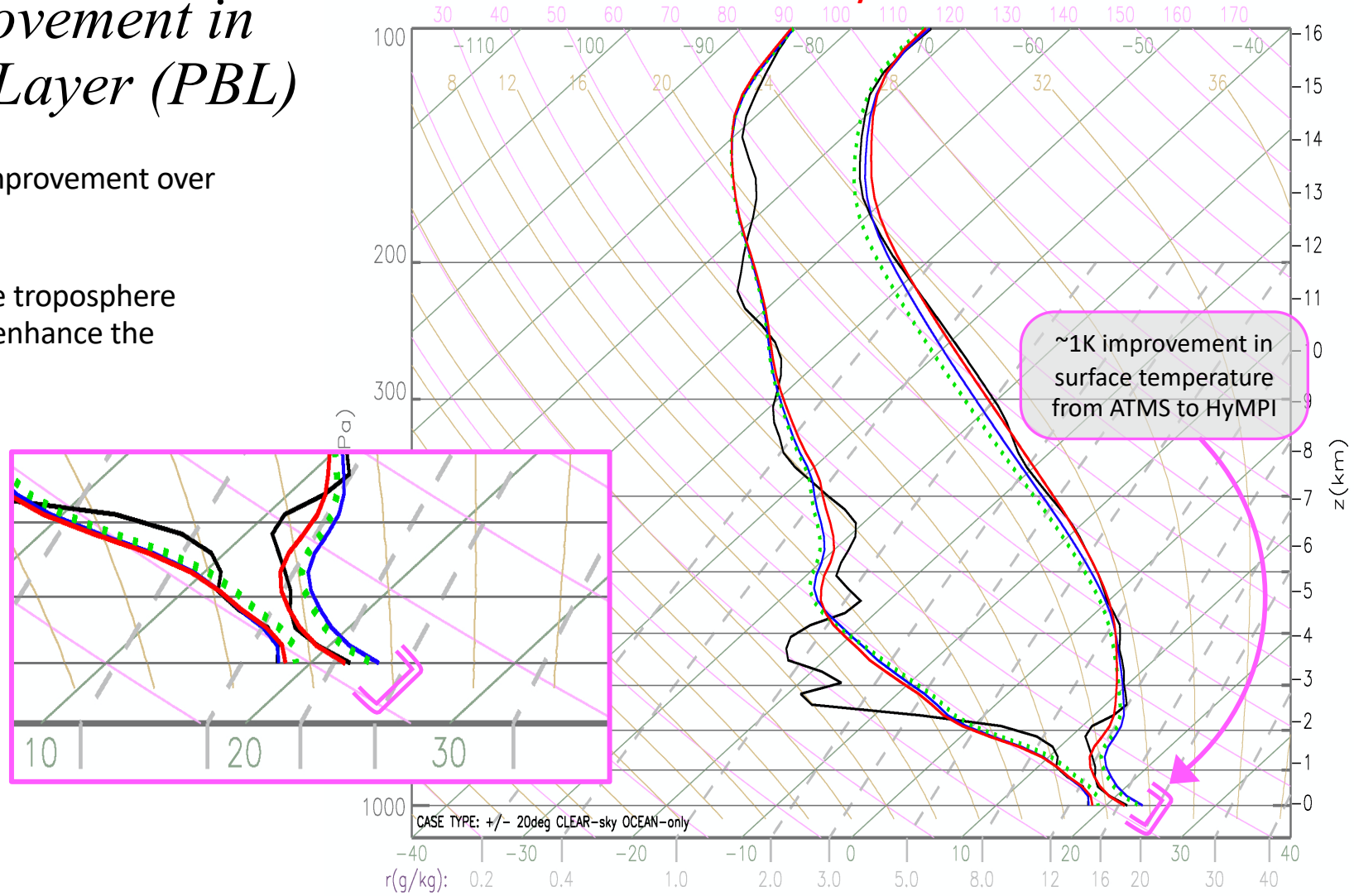
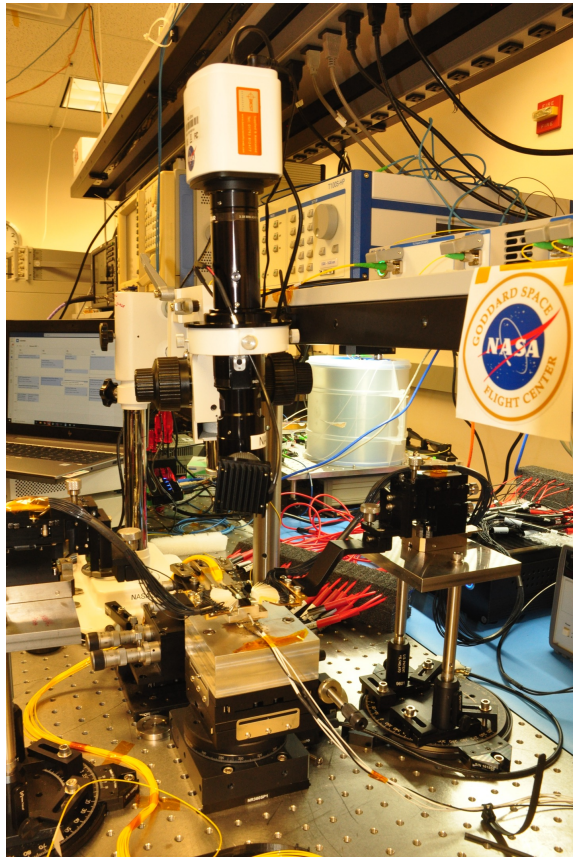
TRUTH – ATMS – HyMPI – 1st GUESS



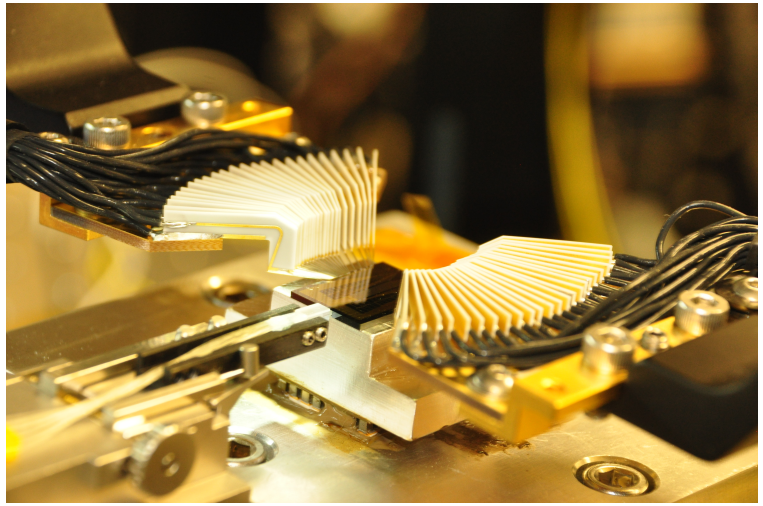
typ	scan	FOR	Prof ID	time	lat	long	CAPE	CIN	LCL	EL	LFC	Tsurf
TRUTH	11	7	L0005304	0.00	20.00	-151.25	24	-445	948	780	948	23.322
ATMS	11	7	L0005304	0.00	20.00	-151.25	0	0	930	930	0	24.671
HyMPI	11	7	L0005304	0.00	20.00	-151.25	28	-388	957	814	952	23.01
FG	11	7	L0005304	0.00	20.00	-151.25	19	-215	946	814	939	24.357

HyMPI Development Status Update

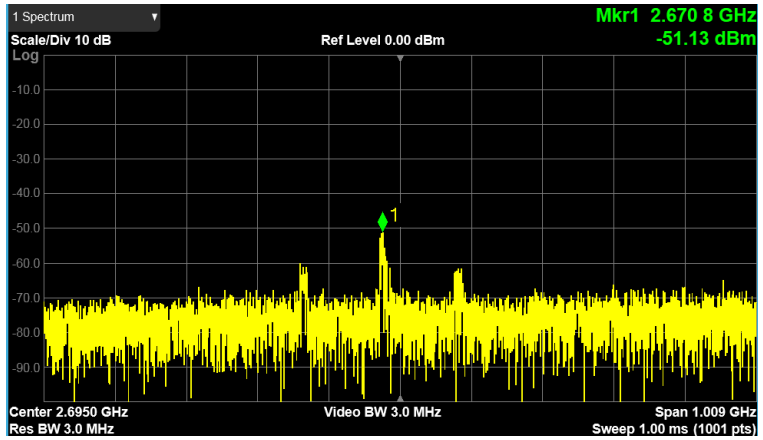
- **February 2nd, 2022**: Project Kick-off
- **August 30th, 2022**: Semi-annual review successfully completed
- **February 2nd, 2023**: Annual Review successfully completed
- **Bi-monthly reports** on schedule.



HyMPI Workbench, NASA Goddard Space Flight Center, Bldg. 33, Room F321

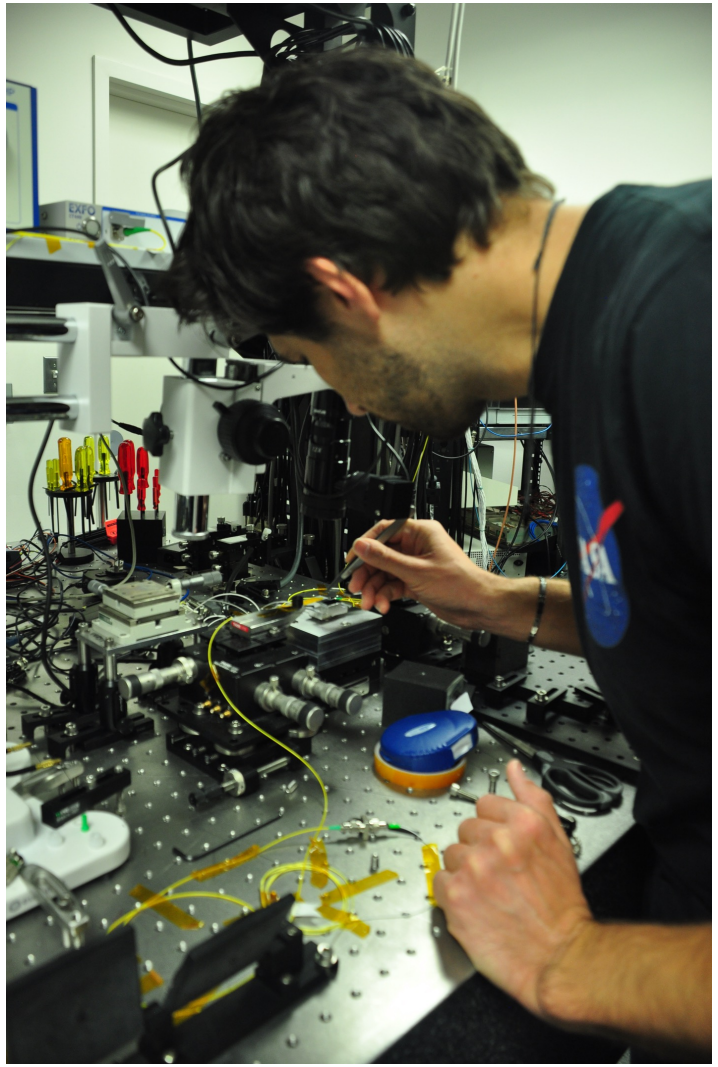


HyMPI Photonic Integrated Circuit



HyMPI First Light – October 6th, 2022

Looking forward to a Hyperspectral MW future…



References

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Thank you

NASA PBL Incubation Study Team Report

PRELIMINARY SCIENCE & APPLICATIONS TRACEABILITY MATRIX (SATM)

Overarching PBL Vision	Science Goal	Science Questions
Globally characterize the thermodynamic structure of the PBL	**G1. PBL, Convection and Extreme Weather**	**Q1.1**: What is the role of mesoscale variability (e.g., cold pools, aggregation) in the interactions between PBL and convection? **Q1.2**: How does the thermodynamic structure of the PBL and lower troposphere foster a transition to deep convection? **Q1.3**: What is the role of PBL and surface processes in the diurnal cycle of precipitation?
	G2. Cloudy PBL	**Q2.1**: How do the PBL thermodynamic structure and cloud properties covary and interact with each other, and how does it depend on cloud type? **Q2.2**: How are these PBL-cloud interactions mediated by turbulent surface fluxes and overlying free tropospheric thermodynamic conditions? **Q2.3**: What is the role of mesoscale variability in modulating the vertical structure of the cloudy PBL temperature and water vapor?
	G3. PBL and Surface Interaction	**Q3.1**: What is the impact of surface heat fluxes on the PBL thermodynamic structure (and vice-versa)? **Q3.2**: Which processes control the water vapor near (~ 100 m above) the surface? **Q3.3**: What is the impact of surface heterogeneity on the PBL thermodynamic structure and convection initiation? **Q3.4**: How does PBL thermodynamic structure and evolution modulate local and remote processes and feedbacks that govern hydrological and climatic extremes ?
	G4. PBL Modeling, Mixing and Air Quality	**Q4.1**: What are the main PBL mechanisms responsible for vertical transport of atmospheric constituents? (e.g., entrainment, turbulent diffusion, thermals/plumes) **Q4.2**: What are the optimal methods to more effectively use space-based PBL observations in order to develop and evaluate unified PBL parameterizations in weather, climate and air quality models?

HyMPI's demonstrated advancements in low-to-upper level temperature and moisture are critical for addressing the *NASA PBL Incubation Study Team Report* and SATM science goals/questions, including the following:

- ✓ *A -- identifying aerosol regimes and transport (SATM-Q4.2),*
- ✓ *B -- tracking/forecasting TC rapid intensification (SATM-Q1.2),*
- ✓ *C -- improving satellite observations (SATM-Q4.2) and overall understanding of the PBL; thermodynamics, temporal/spatial variability, interaction with "other" environments and atmospheric processes, etc. (SATM-G1,2,3,4)*

NASA PBL Incubation Study Team Report SATMs

Goal	Science Questions	Geophysical Variables and Measurement Requirements	Potential Measurement Technologies from Space
G1. PBL, Convection and Extreme Weather	**Q1.1**: What is the role of mesoscale variability (e.g., cold pools, aggregation) in the interactions between PBL and convection? **Q1.2**:How does the thermodynamic structure of the PBL and lower troposphere foster a transition to deep convection? **Q1.3**: What is the role of PBL and surface processes in the diurnal cycle of precipitation?	• Spatial distributions of **T** and **q** in clear and cloudy conditions to measure PBL mesoscale variability (0.5-1 km vertical resolution) • To estimate variability within 10-100 km requires **T** and **q** at 1 km horizontal resolution or better • PBL height Temporal sampling to characterize storm evolution: • For weather - multiple times per day in same locations • For climate - statistical sampling of diurnal cycle	**Horizontal/Vertical resolution – combination of:** • IR sounding (1 km horizontal resolution, clear sky) • MW sounding (5 km horizontal resolution, through clouds) • SW observations of related variables (~100m horizontal resolution) • DIAL/DAR measures nadir water vapor curtains with 200 m vertical resolution **Temporal sampling**: • For weather - i) GEO IR sounder, ii) CubeSat constellation or iii) LEO complementing operational CrIS, IASI, MW sounders • For climate - LEO inclined orbits

Goal	Science Questions	Geophysical Variables and Measurement Requirements	Potential Measurement Technologies from Space
G2. Cloudy PBL	**Q2.1**: How do the PBL thermodynamic structure and cloud properties covary and interact with each other, and how does it depend on cloud type? **Q2.2**: How are these PBL-cloud interactions mediated by turbulent surface fluxes and overlying free tropospheric thermodynamic conditions? **Q2.3**: What is the role of mesoscale variability in modulating the vertical structure of the cloudy PBL temperature and water vapor?	• **T** and **q** profiles (in PBL and free troposphere) with high vertical resolution (100-200 m) in clear and cloudy conditions • **T** and **q** profiles at horizontal resolutions as in G1 • PBL height • Cloud properties (synergistic measurements) • Radiative fluxes (synergistic measurements) • Surface fluxes (based on synergistic measurements)	**Horizontal resolution as in G1:** Combination of IR, MW and SW. **Vertical resolution:** • DIAL measures **q** profiles, 200 m vertical resolution from space in clear sky (2D curtain) • DAR measures **q** profiles, 200 m vertical resolution from space in cloudy sky (2D curtain) • GNSS RO measures **T** or **q** profiles with 100 m vertical resolution from space (scattered sampling)

Goal	Science Questions	Geophysical Variables and Measurement Requirements	Potential Measurement Technologies from Space
G3. PBL and Surface Interaction	**Q3.1**: What is the impact of surface heat fluxes on the PBL thermodynamic structure (and vice-versa)? **Q3.2:** Which processes control the water vapor near (~ 100 m above) the surface? **Q3.3:** What is the impact of surface heterogeneity on the PBL thermodynamic structure and convection initiation? **Q3.4:** How does PBL thermodynamic structure and evolution modulate local and remote processes and feedbacks that govern hydrological and climatic extremes?	• PBL **T** and **q** resolution: Minimum: Mixed-layer mean **T** and **q** + PBL height Enhanced: 100-200 m vertical resolution Diurnal sampling: weather and climate sampling as in G1 • **T** and **q** high vertical resolution close to surface • **Surface properties:** surface temperature, soil moisture, surface fluxes, heterogeneity, vegetation (synergistic platforms and observations) • **Near surface:** T and q (2m), winds (10m) (synergistic observations, analyses and reanalyses)	**Horizontal resolution as in G1:** Combination of IR, MW and SW. **Temporal sampling as in G1:** For weather - i) GEO IR sounder, ii) CubeSat constellation or iii) LEO complementing operational CrIS, IASI, MW sounders. For climate - LEO inclined orbits **Vertical resolution as in G2:** DIAL, DAR and/or RO.

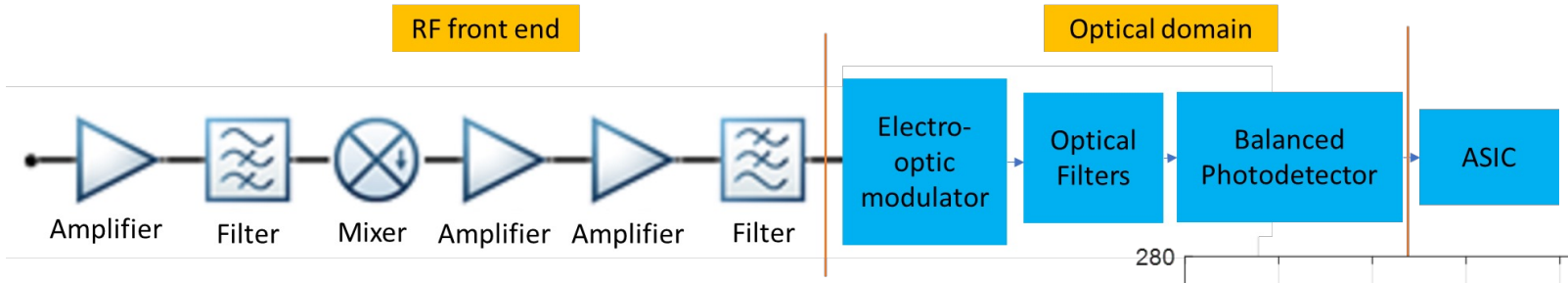
Goal	Science Questions	Geophysical Variables and Measurement Requirements	Potential Measurement Technologies from Space
G4. PBL Modeling, Mixing and Air Quality	**Q4.1**: What are the main PBL mechanisms responsible for vertical transport of atmospheric constituents? (e.g., entrainment, turbulent diffusion, thermals/plumes) **Q4.2**: What are the optimal methods to more effectively use space-based PBL observations in order to develop and evaluate unified PBL parameterizations in weather, climate and air quality models?	• Variables related to PBL transport/mixing (e.g., **T** and **q** spatial variance, PBL top entrainment) • Combinations of different instruments with high vertical (100-200 m) and horizontal (< 1 km) resolutions of **T** and **q** • PBL height measurements with high horizontal resolution (~1 km) • Cloud properties and radiative fluxes (synergistic measurements) • PBL winds (synergistic measurements or analyses)	**Horizontal resolution as in G1:** Combination of IR, MW and SW. **Temporal sampling as in G1:** For weather: i) GEO IR sounder, ii) CubeSat constellation or iii) LEO complementing operational sounders. For climate: LEO inclined orbits **Vertical resolution as in G2:** DIAL, DAR and/or RO. **PBL height**: from **T** and/or **q** profiles (see above) and/or measurements of cloud, aerosol properties

Existing components, current and future Technology Readiness Level (TRL)

- **HYMPI component TRLs are also maturing and on schedule.**
- The instrument maturity is set by the least mature component which is currently photonic integrated channelizer (**TRL-3**) and an integrated multi-tone laser source (**TRL-3**.)
- The required development processes for these components are straightforward, and we have allocated ample time and resources to their maturation under our NASA ESTO-funded research program.
- We will advance the instrument TRL to 4 by combining our PIC-based sub-system with a microwave front end by Dec 2023, including performance testing of the integrated microwave-photonic system.
- **TRL 5** will be reached by Dec 2024 after demonstrating a fully functional HyMPI PICASIC that combines the microwave (MW) front end, PIC-based sub-system, and ASIC for 40-GHz of spectral coverage. This demonstration will consist of sky observation tests, measurement analyses, and a final instrument packaging.

Level 1 Data quality and Cal-Val activities

- Developing end-to-end calibration model for HyMPI architecture



- Will apply to CoSMIR-H (remove microwave photonic components) when characterization data is available
- Used model to determine systematic calibration offsets arising from receiver non-idealities (inter-channel isolation, image rejection, ADC aliasing)

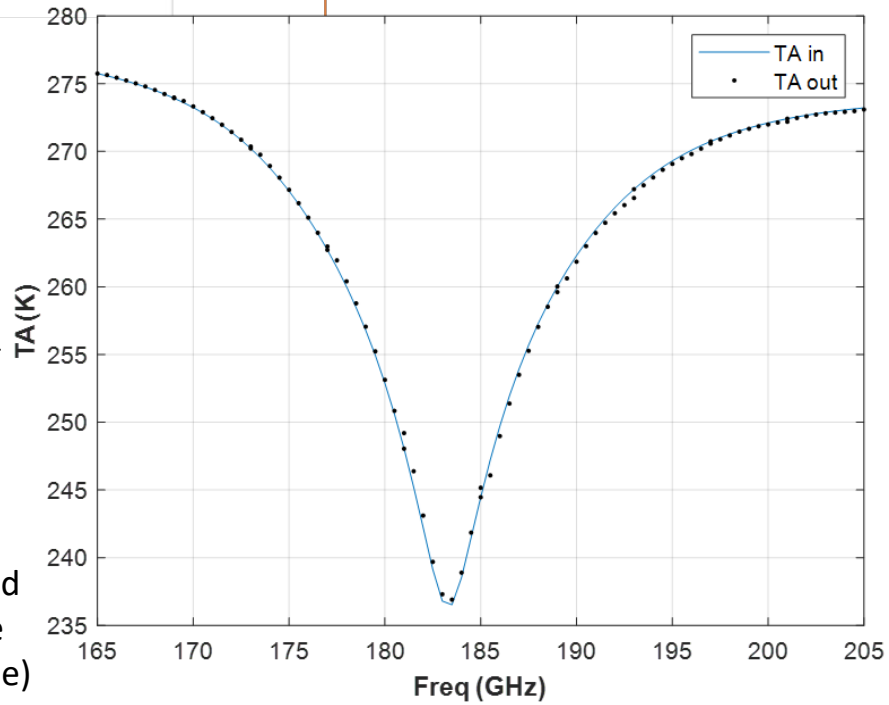
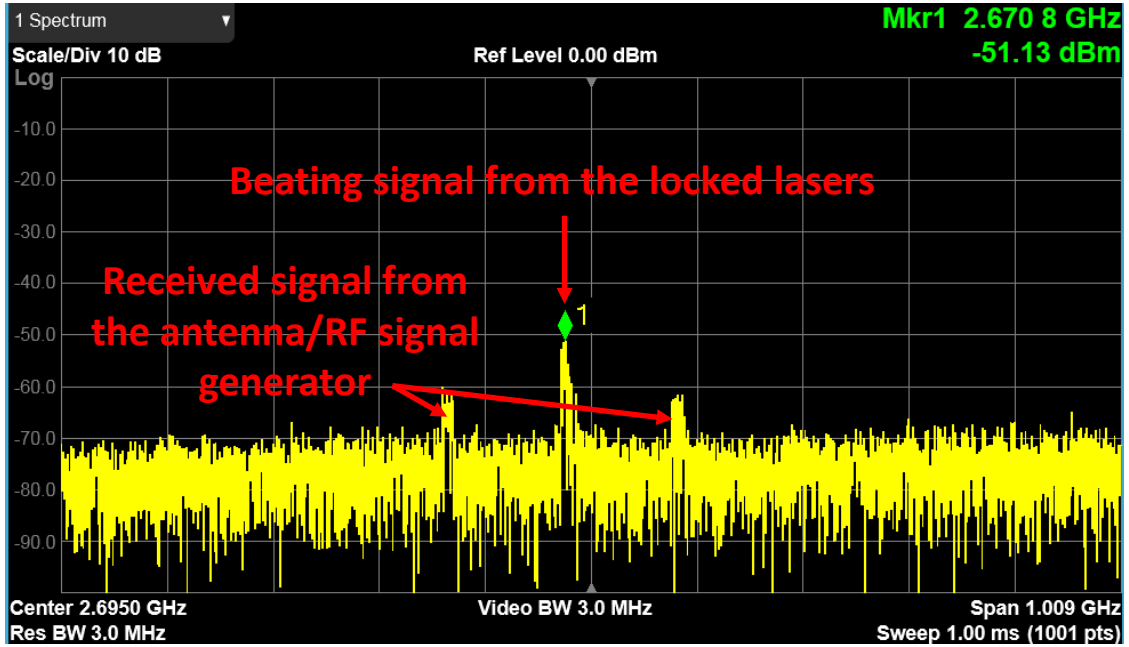


Figure shows model calibrated outputs (black dots) and the original input spectra (blue line)

(*) = **covered by NASA ESTO HyMPI funding**



The first received signal from HyMPI system. The first demonstration was performed locking two lasers and using a single ring filter as channelizer and modulating the optical carrier with 100 MHz modulation. A radio-frequency (RF) signal generator was used to simulate the received signal from the RF antenna.

The picture shows the down-converted RF spectrum at the balanced photoreceiver. The central lobe in the picture is due to the beating of the two lasers' signals (separated by 2.67 GHz), while the two lower lobes are due to the actual RF spectrum from the antenna (signal generator). This test showed, for the first time, the feasibility of the system.