The Continuity Microwave Limb Sounder (C-MLS) –

Capitalizing on New Technology to Continue the MLS Record of Daily Global Middle Atmosphere Composition Observations

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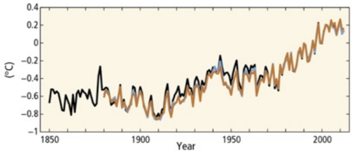
Photograph by ISS astronaut Ron Garan

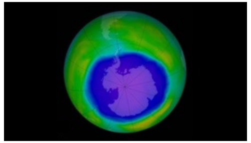
The role of the upper troposphere and stratosphere in the Earth system

- We greatly need improved understanding and predictive capability for atmospheric composition
  - both on the minutes-to-weeks timescales needed for air quality forecasting
  - and on the seasonal-to-decadal timescales needed for climate forcings and feedbacks



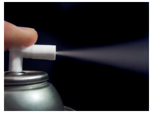
- The poor representation of key processes in the upper troposphere and stratosphere (UTLS) in models is a significant barrier to meeting this need
  - These altitudes are where impacts of water vapor (the strongest greenhouse gas) and ozone (a strong and variable greenhouse gas) are greatest
  - The region is characterized by strong gradients and large spatial and temporal variability (e.g., from convective outflow), as well as long chemical lifetimes and strong winds that promote the long-range transport of pollutants

- Further up in the atmosphere, the stratosphere will continue to undergo severe ozone destruction so long as anthropogenic halogen levels remain high
- Furthermore, considerable but poorly understood variability in stratospheric water vapor significantly affects surface temperature and the ozone layer

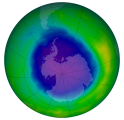


The stratosphere's history of surprising us

1974: Molina and Rowland show that long-lived chlofluorocarbons (CFCs) can survive the journey to the stratosphere, where the strong sunlight breaks them down, releasing ozone-destroying chlorine. Prior to then, the prevailing wisdom was that the main threat to the ozone layer was the slow increase in N_2O from fertilizers.



1985: Farman et al. report decreases in springtime ozone over Antarctica (the so-called "ozone hole"). Prior to that discovery, the expectation had been that CFCs would slowly deplete ozone world-wide, mainly in the upper stratosphere.



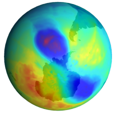
1991: Mt. Pinatubo erupts, leading to strong enhancement in stratospheric aerosol.

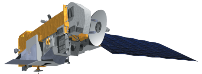
1992: UARS MLS observations show forest-fire pollution lofted to lower stratosphere following PyroCumlulonimbus convection; among the earliest evidence of such transport.

1991–2000: UARS MLS

2000: The steady climb in stratospheric humidity during the 1980s (when routine balloon-based observations began) and 1990s ended with a sudden ~10% drop. This is estimated to have reduced surface warming in the subsequent decade by ~25%.

2002: An unprecedented "major warming" event in the Antarctic winter stratosphere results in the smallest ozone hole since the 1980s.





2004–: Aura MLS

2011 (& 2020): For the first (and second) time, the prolonged cold conditions in the Arctic winter stratosphere result in degrees of ozone depletion typically associated with Antarctic ozone holes.

2015/2016: The Quasi Biennial Oscillation (QBO), an alternating pattern of downward-propagating easterly and westerly equatorial wind regimes with an average period of ~28 months departed from it's usual periodic behavior for the first time in the ~55-year observation record.

2019: An unexpected slow-down in the poleward transport of air in the northern hemisphere mid-stratosphere. A far "older" chemical signature is seen than in previous years.

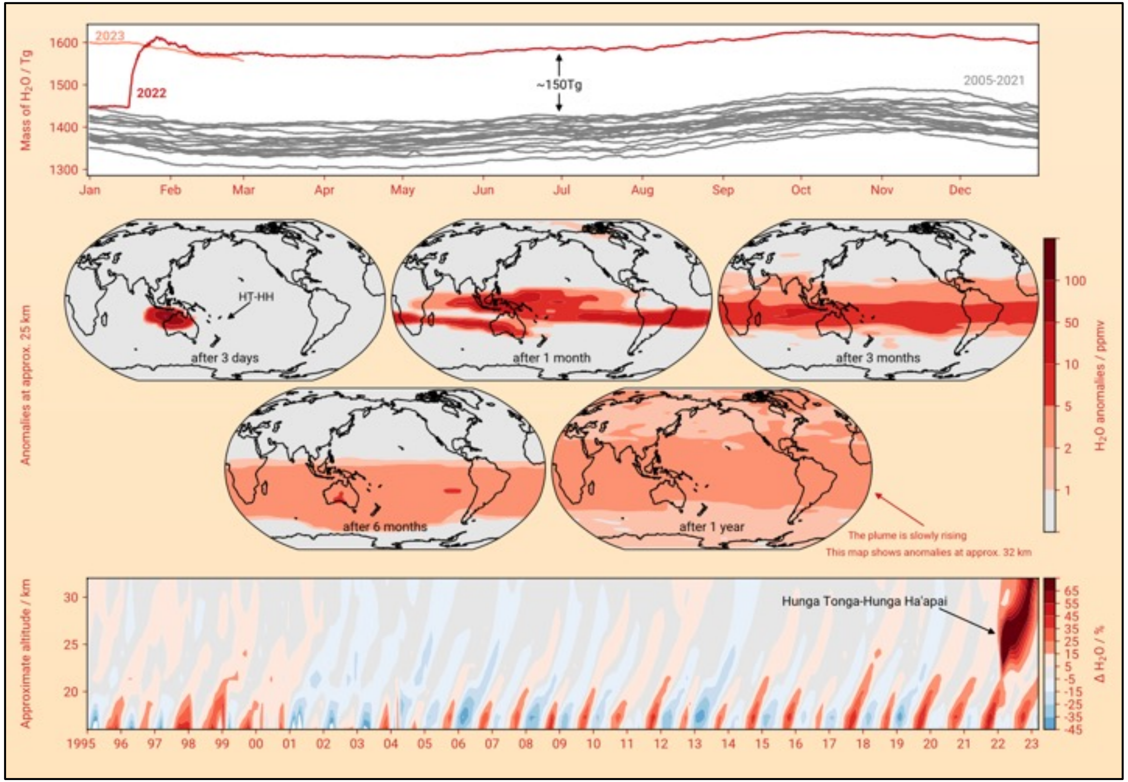
2020: An unprecedented fire in Australia lofts record levels of the pollution to the lower stratosphere where it continues to rise and circulate in a coherent plume for four months.
Stay tuned for news of the implications of this event…

1970s | 1980s | 1990s | 2000s | 2010s | 2020s

2022: The Hunga Tonga–Hunga Ha’apai eruption

- The January 15, 2022 eruption of the undersea Hunga Tonga–Hunga Ha’apai (HT-HH) volcano increased stratospheric water vapor, a strong greenhouse gas, by ~10% (~150 Tg).

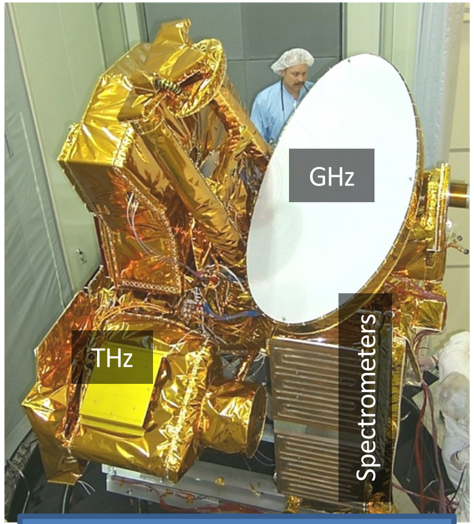
- HTHH is the first volcano in the observational record expected to warm rather than cool Earth’s surface.
- The humidity plume is impacting stratospheric dynamics and chemistry and is expected to linger for several years.
- Aura MLS is the only sensor making daily near-global measurements of stratospheric H_2O and other trace gases needed to track these impacts.



The Aura Microwave Limb Sounder (MLS)

- MLS is one of four instruments launched on Aura in July 2004
- MLS measures profiles of 16 trace gases along with Temperature, geopotential height, and cloud properties
- More than 1400 papers to date use Aura MLS observations
- Currently only MLS and OMI still operate on Aura

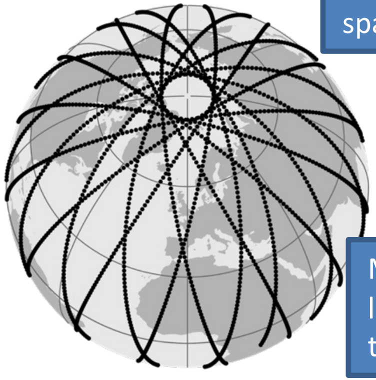
    "Should [MLS be the only Aura instrument still working], the panel finds that Aura would still be a high priority mission given the value of MLS as the most comprehensive source of stratospheric observations with high vertical resolution." – Senior review report, 2015 (similar, though less explicit statements in 2017 and 2020 reports)



Aura MLS prior to delivery for spacecraft integration.

Aura MLS spectral bands.

Receiver	Frequency	Main objectives
R1A, R1B	118 GHz	Temperature and pressure (from O_2)
R2	190 GHz	Water vapor, N_2O, and HCN
R3	240 GHz	O_3, CO, HNO_3, and cloud ice
R4	640 GHz	Stratospheric halogens and radicals
R5H, R5V	2.5 THz	Stratospheric and mesospheric OH



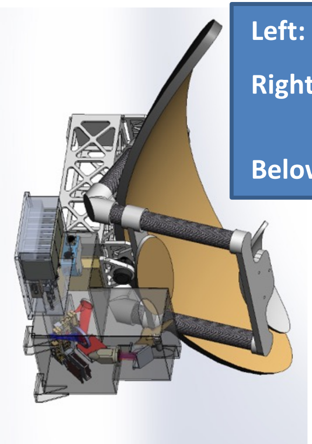
MLS observation locations for a typical day.

Aura MLS vs. Continuity MLS

- Microwave instruments have historically been bulky and power hungry
- Profound innovation in the past decade, driven by the communications industry, enables dramatic reductions in mass/power/volume for most of a future MLS-like instrument, although a fairly large (70 cm to 3 m) antenna will continue to be needed
- The ESTO IIP project "Continuity MLS" started earlier this year, with the goal being to develop an Earth-Venture Common Instrument Interface compliant instrument
- Ideal for a suitable EV-Continuity call, or for the "Ozone and Trace Gas" Explorer opportunity

	Aura MLS	**Continuity MLS**
Measurements	O_3, H_2O, CO, HNO_3, N_2O, HCl, ClO, HOCl, BrO, HO_2, OH, CH_3CN, HCN, CH_3Cl, CH_3OH, SO_2, T, GPH, IWC, IWP	O_3, H_2O, CO, HNO_3, N_2O, HCl, ClO, ~~HOCl~~, ~~BrO~~, ~~HO_2~~, ~~OH~~, CH_3CN, ~~HCN~~, CH_3Cl, CH_3OH, SO_2, T, GPH, IWC, IWP + H_2CO and others TBD
Resources	**500 kg, 500 W** 160 x 80 cm primary antenna with ~1 m^3 electronics	Estimate **60 kg / 90 W** 160 x 40 cm antenna with ~0.05 m^3 electronics
Receivers	118, 190, 240, and 640 GHz, 2.5 THz	340 and 640 GHz
Sidebands	118 GHz single sideband, all others folded sideband	Sideband separating 340 GHz, folded sideband 640 GHz
IF processing	~40 local oscillators, 60+ IF mixers, hundreds of amplifiers, attenuators and splitters	Two local oscillators, 3 IF mixers, Ten amplifier/attenuator paths
Spectrometers	542 individual channels; 4 narrow digital spectrometers	Ten 3-GHz wideband CMOS digital spectrometers

C-MLS instrument overview

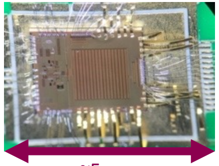


Left: Preliminary sketch of C-MLS

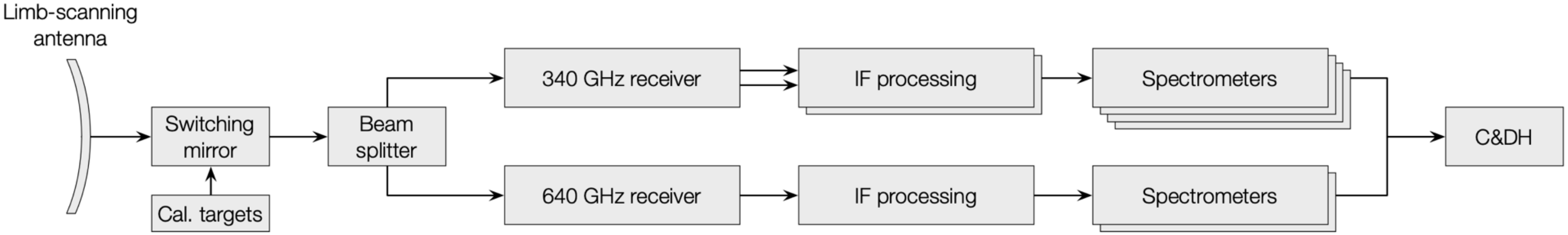
Right: Comparison of C-MLS and Aura MLS spectrometer technology

Below: High level C-MLS block diagram

C-MLS: A 4096-channel 3-GHz spectrometer on ~5 mm chip. Overall PCB is ~credit-card-sized.

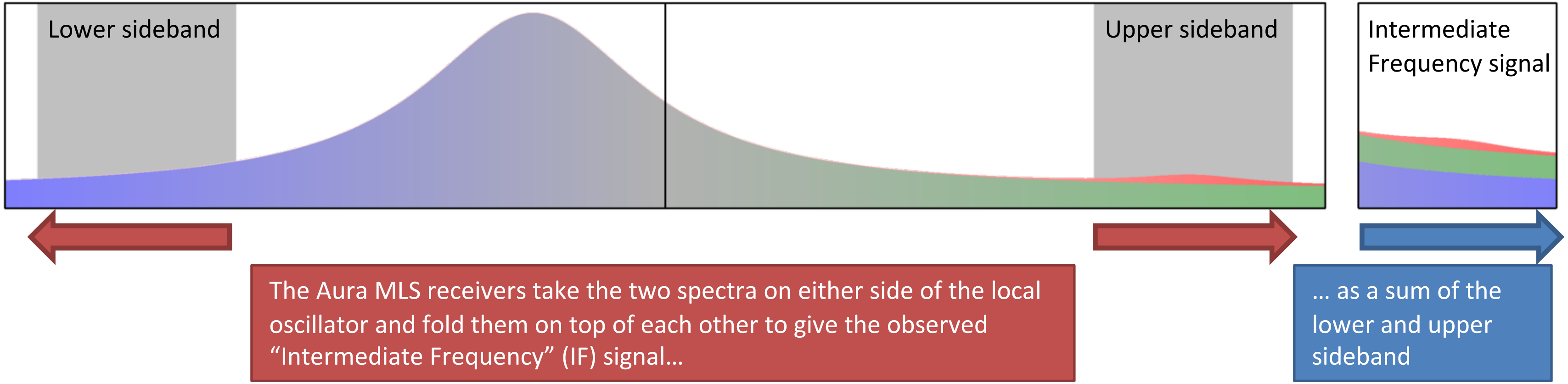


Aura MLS: A 25-channel ~1.5-GHz spectrometer from Aura MLS, ~1.5 kg, ~40 cm.



- The block diagram resembles that of many previous microwave spectrometers (including Aura MLS)
- The CMOS 3 GHz digital spectrometer offers huge reduction in back-end complexity and power consumption
- Newly developed tunable CMOS W-band tone generators also provide a low mass/power approach to generating needed “Local Oscillator” tones

Consequences of using “folded sideband” measurements

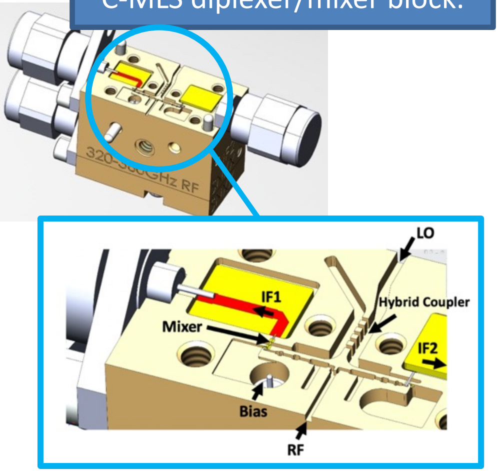


- The “folded sideband” nature of the Aura MLS signals presents a significant challenge to measurements in the upper troposphere and lower stratosphere
- The far-wing/continuum signal in the upper sideband (green) adds a “baseline” but also partially attenuates the weak spectral signal from the target molecule (red)
- The far-wing/continuum signal in the lower sideband (blue) simply adds more baseline
- Deducing the abundance of the “red” molecule from the total signal, given the two differently behaving background signals, equates to pulling three unknowns (red line and two continua) from only two measurements (“line shape” and “background”)
- **C-MLS solves this by reporting upper and lower sideband 340 GHZ signals separately**

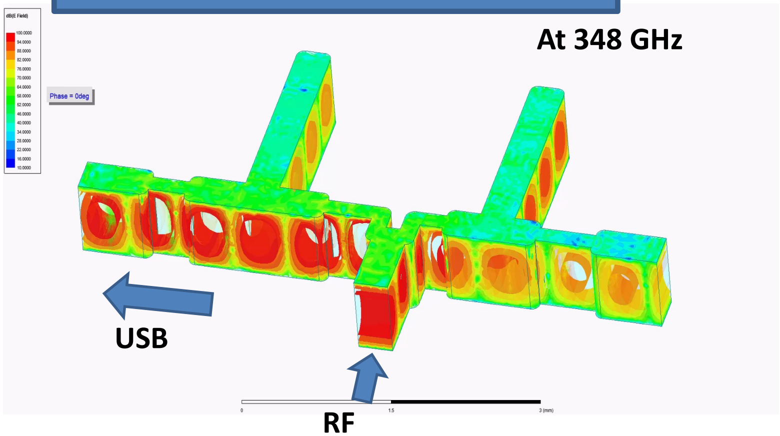
C-MLS 340 GHz diplexer block design

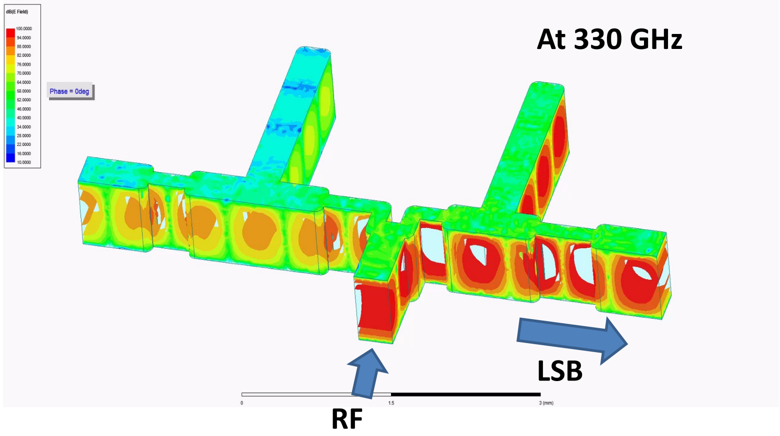
- C-MLS accomplishes the sideband separation using a “diplexer”
- One block contains two mixers (LSB, USB) and the splitter/filter waveguide structures for separating the two signals

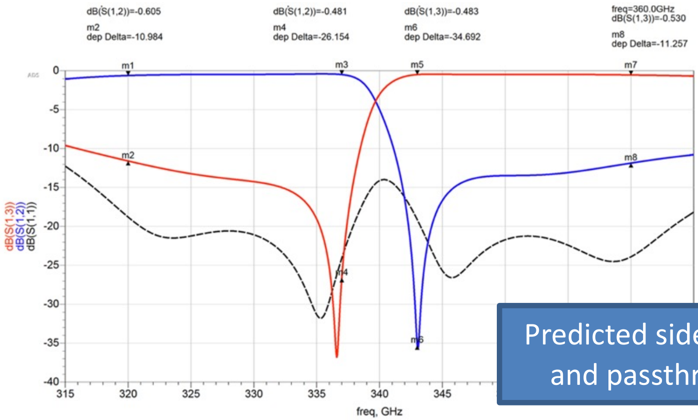
C-MLS diplexer/mixer block.



Propagation of waves above (upper) and below (lower) the center frequency.

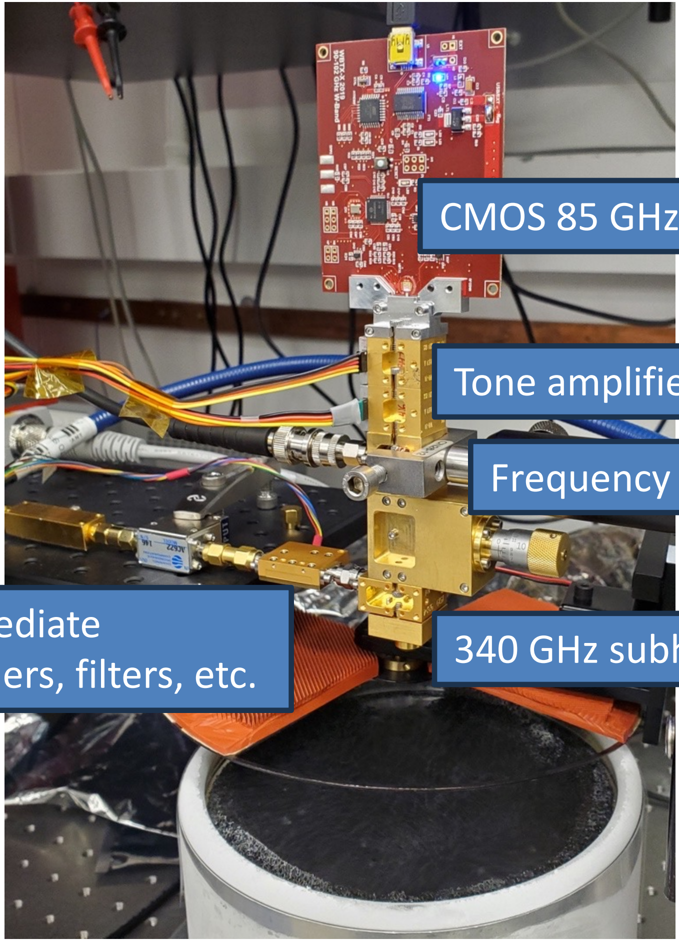






Predicted sideband rejection and passthrough factors.

C-MLS 340 GHz receiver under test (single sideband)

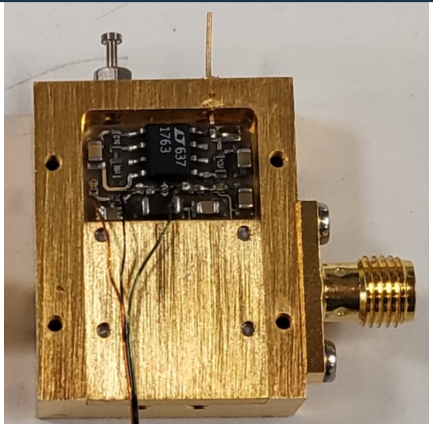


- The C-MLS 340 GHz receiver meets requirements having a 1,500 K noise temperature (requirement ~4000)

C-MLS Intermediate Frequency (IF) subsystem

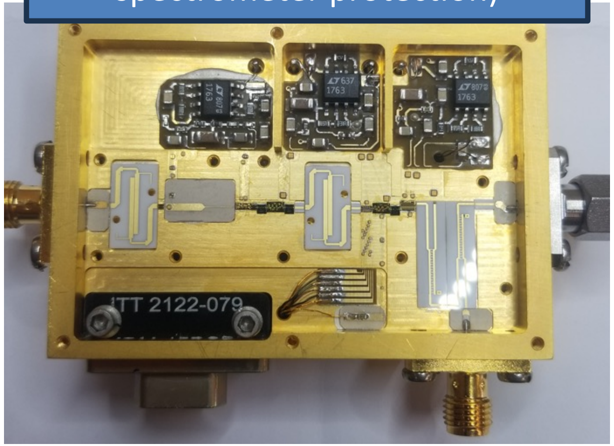
- We have worked with a local company (Cosmic Microwave) to develop compact custom modules containing the amplifiers, attenuators, mixers, filters, etc. needed for “Intermediate Frequency” (0–18 GHz) signal processing

1–18 GHz Low Noise Amplifier



2nd stage downconverter
(12–18 GHz → 3–9 GHz)

3–6 GHz ”IF processor” module
(amplifiers, filters, attenuators, spectrometer protection)



Summary

- Continuation of the Aura mission beyond 2023 is not assured as yet
- Regardless of its continuation beyond 2023, Aura is expected to cease operations sometime between mid-2025 and early-2026, owing to limited electrical power
- The “Continuity Microwave Limb Sounder” (C-MLS) instrument could deliver most of the Aura MLS measurements while requiring <20% of the Aura MLS mass/power
- NASA has funded C-MLS technology development through the Instrument Incubator Program
- Key components have been fabricated and shown to meet requirements
- Subsystem integration and testing is underway
- System level integration and testing is planned for late 2023 / early 2024
- C-MLS is ideally suited to future NASA programs including the “Earth System Explorer” and “Earth Venture Continuity”

- Many thanks to ESTO NASA for their support of Aura, C-MLS, and other programs
- Many thanks, also, to the large community of MLS data users