A Continuity Microwave Limb Sounder (MLS) instrument to extend the 15+ year record from Aura MLS.

NASA Earth Science Technology Forum 2020

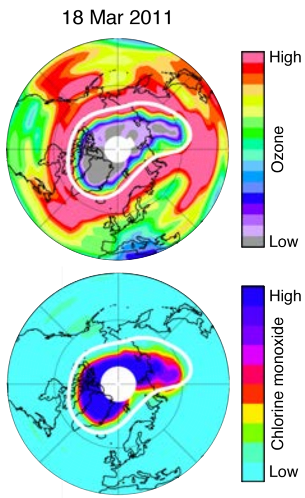
Nathaniel Livesey, Goutam Chattopadhyay, Adrian Tang, Robert Stachnik, Robert Jarnot, Luis Millan, Michelle Santee, and others from the MLS team.
Jet Propulsion Laboratory, California Institute of Technology

Mau-Chung (Frank) Chang and Rulin Huang
University of California, Los Angeles

© California Institute of Technology, Government Sponsorship Acknowledged

Photograph by ISS astronaut Ron Garan

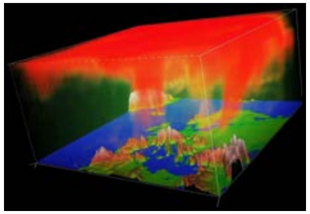
Introduction – Science areas targeted by MLS-class instruments



Ozone layer stability

- The atmospheric ozone (O_3) layer in the lower and middle stratosphere (20–30 km altitude) shields life on earth from harmful solar ultraviolet
- However, chlorine and bromine from long-lived anthropogenically emitted ozone depleting substances (e.g., CFCs) continue to destroy ozone
- Full “recovery” is not expected until the 2050s or later
- Climate change complicates ozone layer recovery through decreases in stratospheric temperature and through potential changes in the large-scale circulation of the stratosphere

Role of the stratosphere in climate



- The humidity of the stratosphere is a key climate variable, for example, a 10% drop in stratospheric water vapor around 2000 resulted in a 25% reduction in surface warming over the subsequent decades [*Solomon et al., Science,* 2010]
- Stratospheric humidity is controlled by multiple incompletely understood processes including tropopause temperature, stratospheric circulation, and tropospheric convection, the future evolution of which in a changing climate is uncertain
- Tropospheric ozone is also a strong greenhouse gas whose long-term evolution in response to changing precursor emissions, and any changes in influx of ozone-rich stratospheric air, is poorly understood
- Radiative forcing from both water vapor and ozone is typically strongest in the upper troposphere and lower stratosphere (~10–15 km altitude)

Air quality

- Influx of ozone-rich air from the stratosphere is a significant contributor to ozone in the troposphere (where ozone is a pollutant), accounting for 50% of the interannual variability [*Neu et al., Nature Geosci.,* 2013]

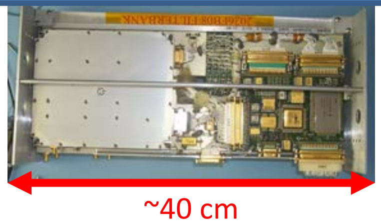
Limb sounding of the atmosphere

- Looking at the atmosphere edge on and scanning an instrumental field of view across the limb (~1°) yields information with good vertical resolution
  - Resolution of 1–5 km can be achieved
- The long path length associated with limb viewing provides stronger signals for the more tenuous trace gases
- However, this same path length results in coarser horizontal resolution (at least in the line-of-sight direction) than can be achieved with nadir sounders
  - “Tomographic” approaches to observation and data analysis can help redress this
- Also, atmospheric opacity limits the measurements to the region of Earth’s atmosphere above ~5–10 km (lower limit varies somewhat with wavelength)
- Microwave limb sounding instruments are able to make measurements in the presence of aerosol and all but the thickest clouds
- A related technique is solar (or lunar/stellar) occultation, where profiles are measured during each spacecraft sunrise/sunset
  - Gives better signal to noise than limb viewing, but much sparser coverage (e.g., 30 profiles per day, compared to several thousands with limb emission/scatter sounding)

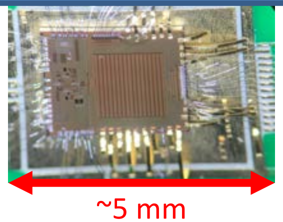
Beyond MLS – Development of a Continuity MLS instrument

- 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

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



A 4096 channel 3 GHz spectrometer on a single ~5 mm chip.



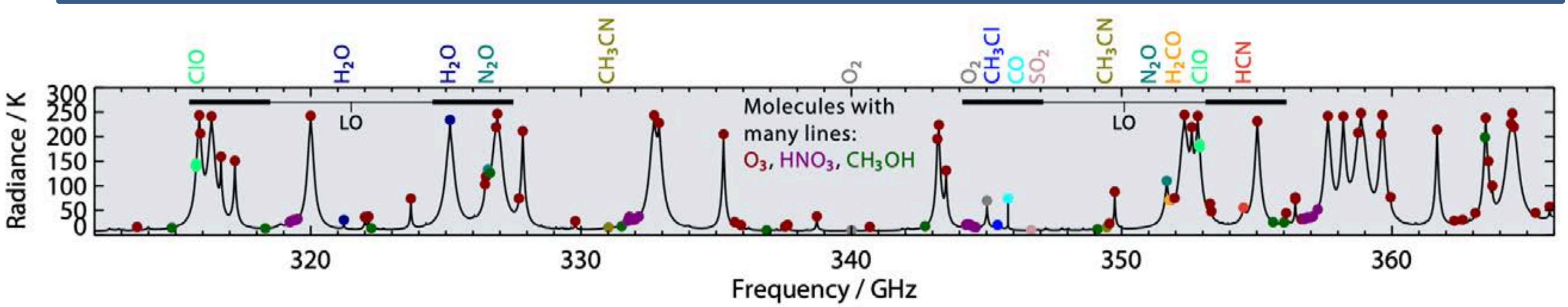
- The ESTO IIP project "Continuity MLS" started earlier this year, with the goal being to develop an Earth-Venture Common Instrument Interface compliant instrument
- Ideal for a suitable EV-Continuity call, or for the "Ozone and Trace Gas" Explorer opportunity

	Aura MLS	CAMLS
Species observed	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** 1.6m primary antenna with ~1 m^3 electronics	Targeting **20 kg, 40–60 W,** 70 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, double sideband 640 GHz
IF processing	~40 local oscillators, 60+ IF mixers, hundreds of amplifiers, attenuators and splitters	1 local oscillator, 2 IF mixers, 10 amplifier/attenuator paths
Spectrometers	542 individual bandpass filter channels (discrete capacitors, inductors etc.) plus 4 narrow-band Digital Autocorrelator Spectrometers	Ten 3 GHz wideband CMOS digital spectrometers

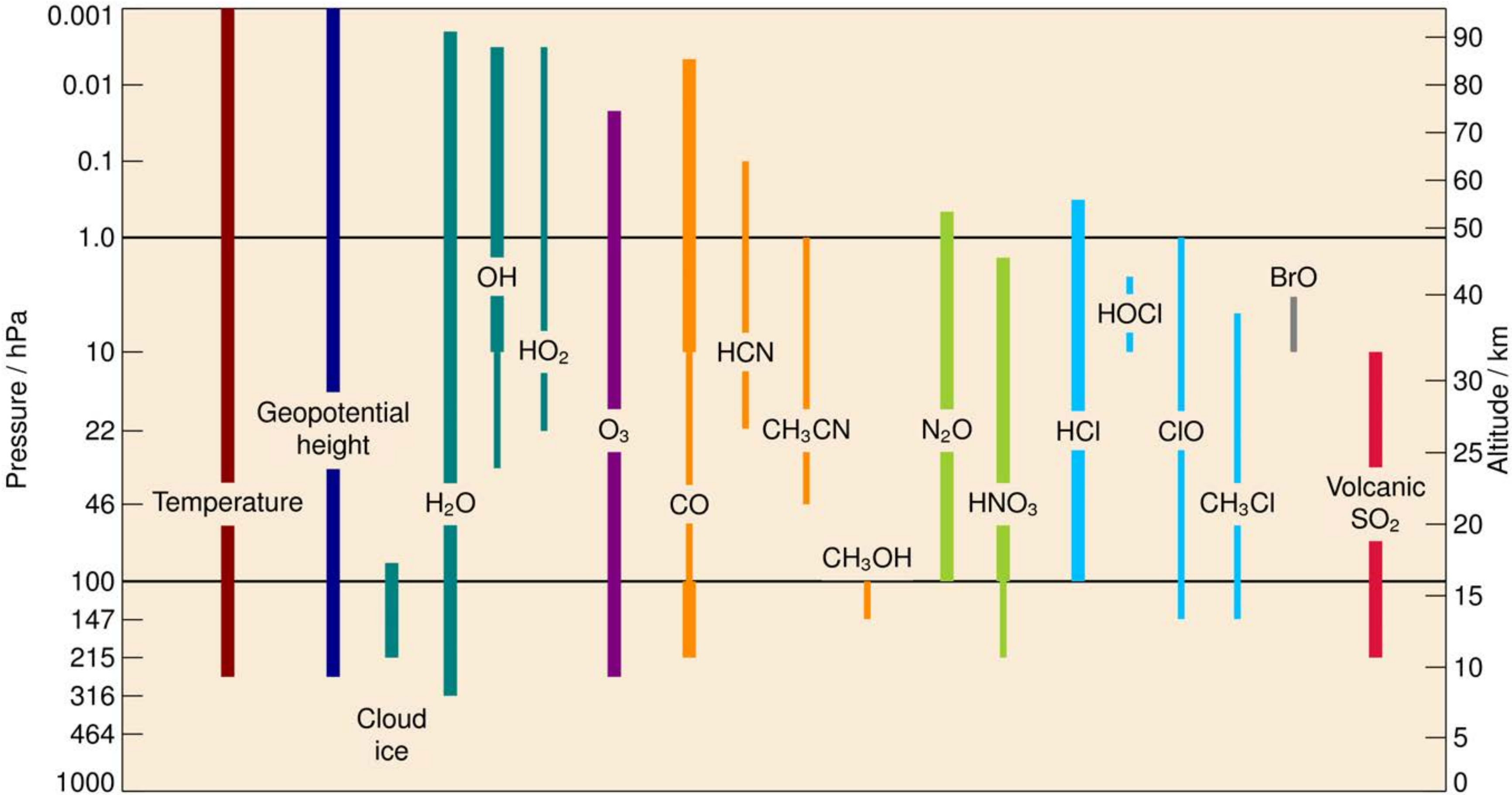
Spectral region targeted by C-MLS

- Aura MLS measured in seven spectral regions from 118 GHz to 2.5 THz
- The C-MLS instrument focusses on the 340 GHz spectral region, chosen because:
  1. it contains useful spectral lines for both H_2O and CO, key molecules whose lines occur sparingly in the microwave spectrum, while…
  2. Broadband atmospheric absorption is small enough that measurements can be made down to ~10 km altitude
- This region, however, does not include lines for HCl (the first of which is at 625 GHz), to cover this we add a second ~640 GHz receiver
  - Note, opacity limits observations to altitudes above ~15 km in this band
  - HCl is the main reservoir of ozone-destroying chlorine in the stratosphere, and also an important marker of stratospheric air transport

Sample 340 GHz radiances from a limb view at ~20 km tangent altitude. Selected spectral lines are annotated. Black horizontal lines indicate candidate spectrometer locations.

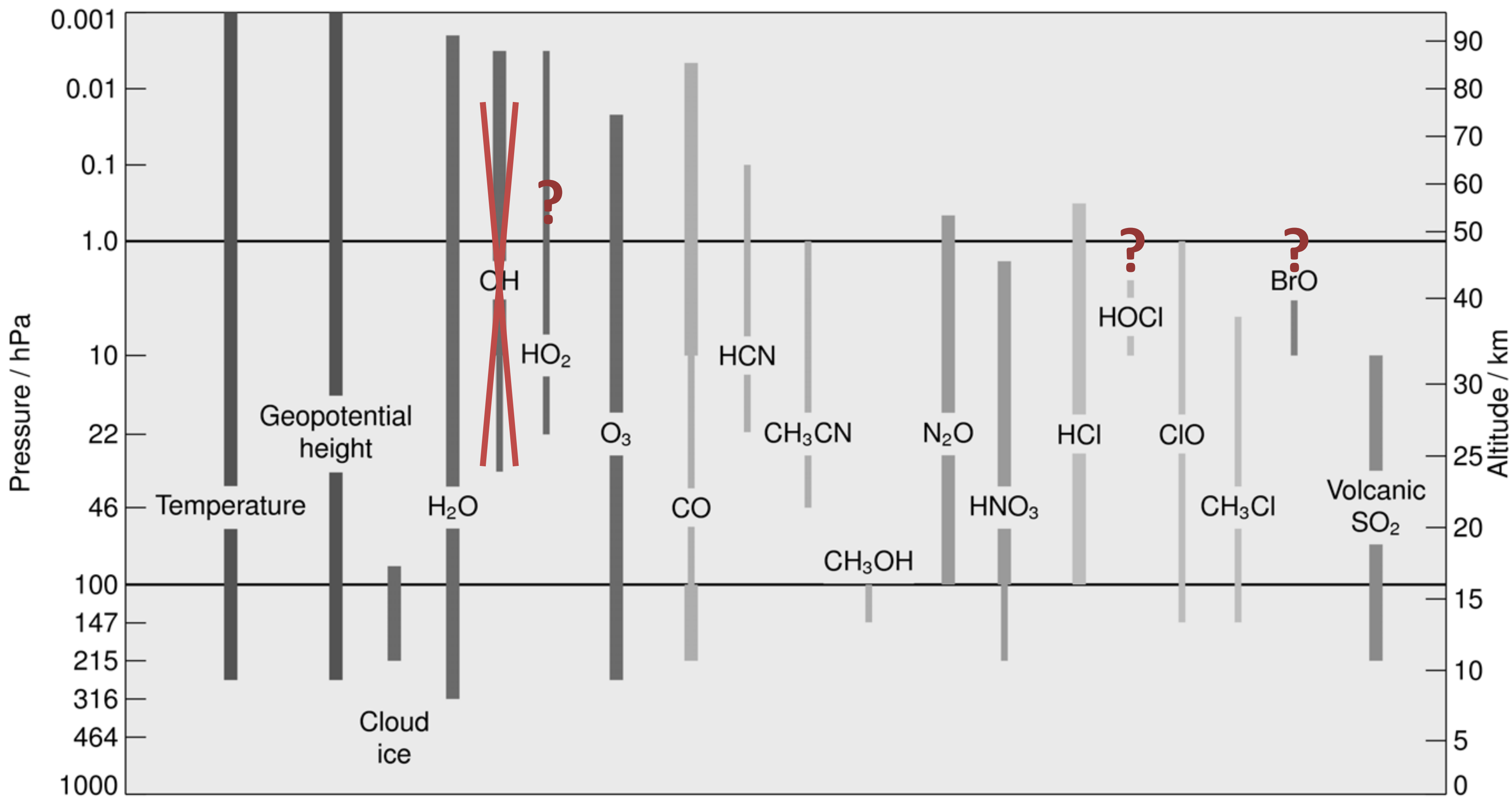


MLS data products



- Thinner lines show where the signal to noise is such that averaging (e.g., weekly map, monthly zonal mean, etc.) is typically needed

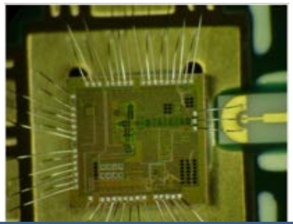
C-MLS data products



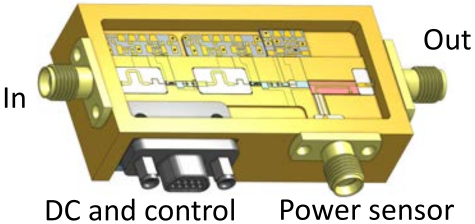
- C-MLS measures nearly all the MLS species except OH
- Timesharing of measurements will reduce useful temporal resolution of noiser species (HOCl, BrO, HO_2)

Key C-MLS technologies

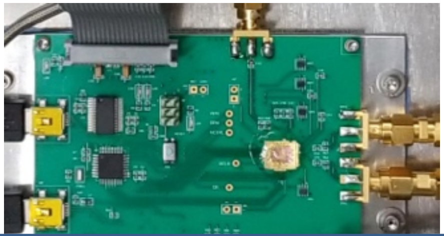
- CMOS System on Chip (SoC) W-band oscillators
  - These devices produce a phase- and frequency-tunable tone in the 107–116 GHz range, which is then tripled to produce the Local Oscillators needed for the 340 GHz and 640 GHz mixers
  - Two of these will be driven with a 30° phase difference
  - The resulting 90° phase difference in the LO's will provide "I" and "Q" signals needed for sideband separation
- State-of-the art Schottky diode mixers at 340 and 640 GHz
  - Previously developed components are already available, based on flight proven designs (e.g., in Aura MLS)
- Modular microstrip-based Intermediate Frequency processor units
  - Figure to right shows a previously developed example, these will amplify, filter and, in some cases, further downconvert, the IF signals
- CMOS SoC spectrometers
  - Our current instrument design focuses on a proven 3 GHz bandwidth, 4096 channel, 1.5 W device
  - A 6 GHz device is under development that would enable a simpler instrument design (though the unit cost is higher).



Earlier 90–100 GHz SoC. 107–116 C-MLS device include phase tuning.



3–6 GHz IF processor unit. Includes amplifiers, filters, and a step attenuator



3 GHz spectrometer integrated on a board in the A-SMLS instrument

Summary and future plans

- C-MLS is a new project to develop an engineering model of a future “Continuity Microwave Limb Sounder” instrument
- We are targeting an Earth Venture-Instrument Common Instrument Interface compliant instrument form factor
- The instrument will include
  - Microwave receivers at 340 GHz (sideband separating) and 640 GHz
  - State-of-the-art 3 GHz CMOS spectrometers (6 GHz if available)
- …and interface to various potential antenna systems (all 70 cm nominal aperture)
  - A conventional vertically-scanned antenna system as in Aura MLS
  - An alternative antenna design that accomplishes the vertical scan with a moving-lens tertiary element
  - A static antenna that could be rigidly mounted to a single-instrument spacecraft that nods up and down to accomplish the limb scan
- We plan to complete integration and test in early 2022, and then perform environmental testing and instrument characterization, calibration etc.
- At this early design stage, the work is thankfully largely unaffected by COVID-19-related work restrictions

Many thanks to ESTO for support of this and other projects