The Compact, Adaptable Microwave Limb Sounder (CAMLS)

Developing the core system for next-generation
Microwave Limb Sounders

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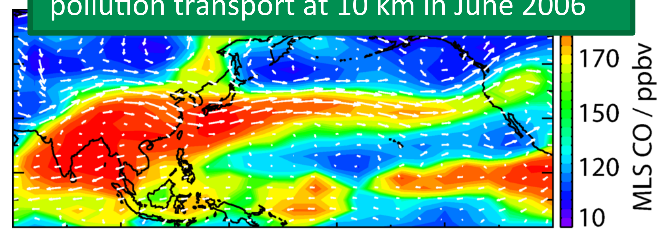
Outline of presentation

- Background
  - Importance of the upper troposphere and stratosphere in the climate system
  - Review of relevant observation techniques and past, current, and future sensors
  - Specifics on the Microwave Limb Sounder (MLS) technique
- Work to develop future MLS-class instruments
  - Goals of the CAMLS project
  - "Point designs" for future microwave limb sounding sensors
  - Comparing CAMLS-class and prior-generation MLS instruments
- CAMLS accomplishments to date
  - Receiver development
  - Spectrometer development
  - System development and integration with the Airborne Scanning MLS
- CAMLS plans for the coming year
  - System I&T
  - Airborne testing

CAMLS science motivation – the "UT/LS"

- The CAMLS-family of instruments makes measurements needed to address key outstanding issues associated with the composition and structure of Earth's "upper troposphere and lower stratosphere" (UT/LS hereafter)
  - The ~10 km to ~20 km altitude region
- It is in this region where:
  - Water vapor (the strongest greenhouse gas) and ozone have sharp gradients, and where changes in their abundance strongly influence climate
  - Winds are fast and chemical lifetimes are long, promoting global transport of greenhouse gases and pollutants (see upper figure)
  - Climate (and chemistry-climate) models continue to poorly represent key processes and their impacts on water vapor, composition and clouds (see lower figure)

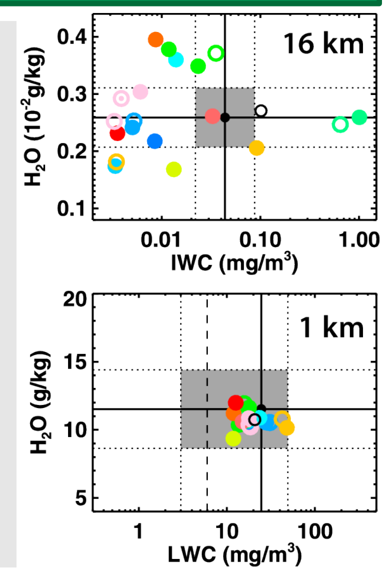
Aura MLS observations of long range CO pollution transport at 10 km in June 2006



Jiang et al., 2006, GRL

A-Train observations show climate models perform poorly in the upper troposphere (e.g., ~16 km, top panel) compared to the lower troposphere (e.g., ~1 km, bottom panel)

x-axes are cloud ice
y-axes are water vapor
Black points are observations
Grey shading denotes measurement uncertainty
Colored points are climate models
Top panel shows 16 km altitude observations from Aura MLS
Bottom panel shows 1 km altitude observations from AIRS & CloudSat



Jiang et al., 2012 JGR

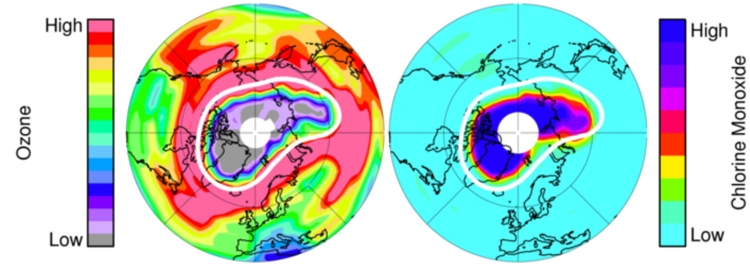
CAMLS science – issues in the stratosphere

- In the stratosphere itself (~15 – 50 km), high levels of atmospheric chlorine continue to destroy ozone

- Unexpected and incompletely explained changes in stratospheric humidity in the past decade have significantly affected surface temperature (e.g., masking 25% of expected warming during 2001–2010)

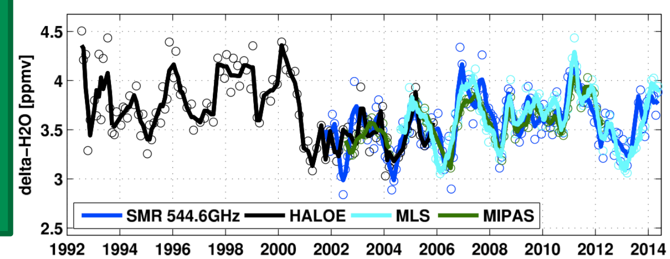
- Interest is growing in “geoengineering” approaches to tackling climate change, including injecting sulfate aerosols into the stratosphere, any study of which must be informed by observations

Aura MLS observations ozone (left) and chlorine monoxide (right) – the primary agent of ozone destruction – at ~20 km in March 2011, a period of unprecedented ozone loss in the northern hemisphere



Manney et al., 2011, Nature

Tropical water vapor at ~16 km from Aura MLS and other sensors, showing unexpected sudden declines in 2000 and 2012



Urban et al., 2014, EOS

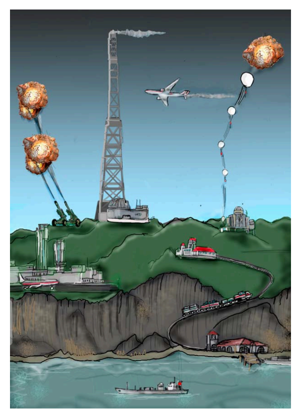


Illustration of various possible approaches to injecting sulfate aerosol into the stratosphere, in order to reduce surface heating

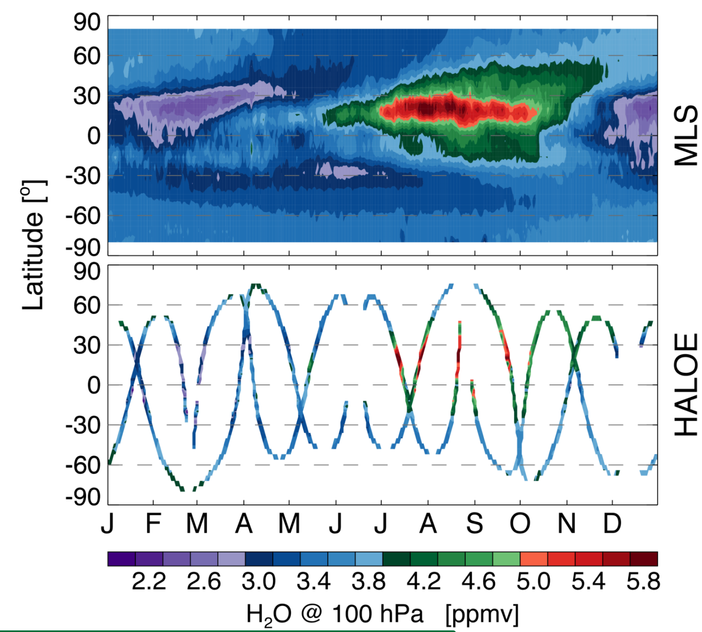
Robock, 2009, GRL

Relevant composition measurement approaches

- Nadir sounding instruments (at any wavelength) have poor (~6 km at best) vertical resolution in the upper troposphere and stratosphere (UT/S)
- GPS radio occultation measures stratospheric temperature profiles, but GPS water vapor measurements do not extend above the mid-troposphere
- Spaceborne Lidar approaches are hindered by insufficient laser power
- Accordingly, spaceborne UT/S composition sounders are either:

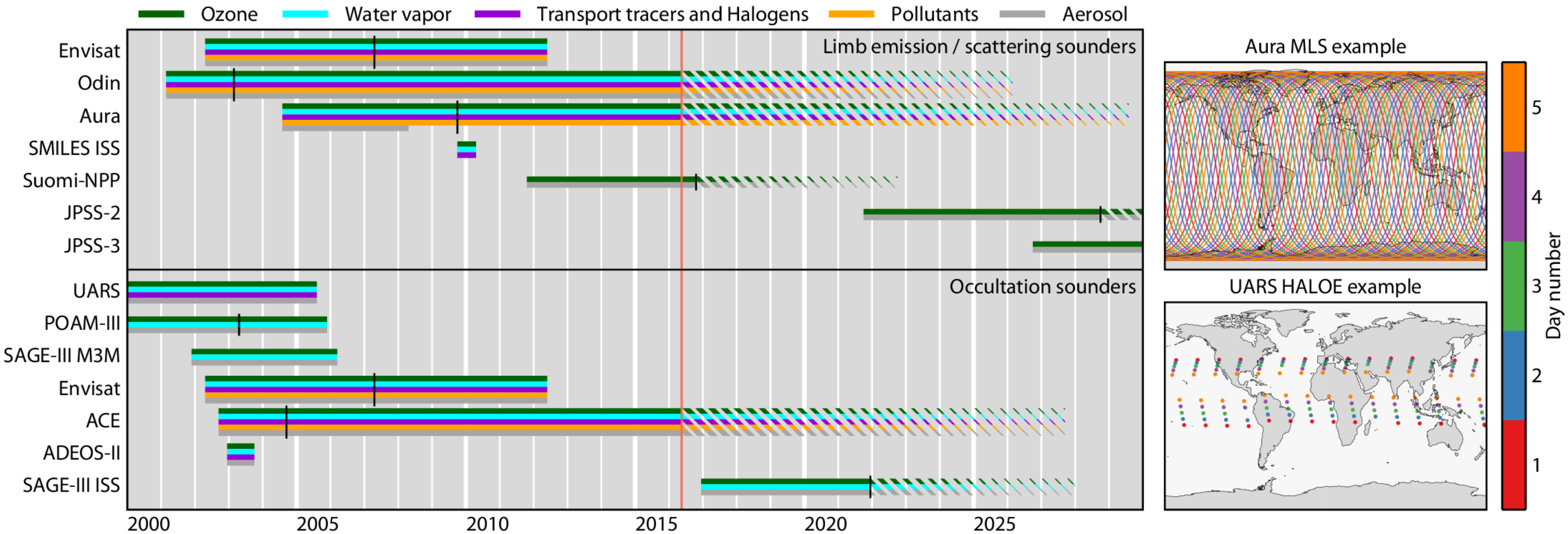
  Passive limb sounders measuring thermal emission (IR/µWave) or solar scatter (UV/Vis.), scanning the limb vertically to give daily near-global coverage (daytime only for UV/Vis)

  Solar (or lunar/stellar) occultation sounders measuring atmospheric absorption each orbital sunrise/sunset (or moon/star rise/set). They have good vertical resolution (~1 km) and excellent precision, but only makes a small number of measurements per day, at slowly drifting latitudes



Zonal (longitude) mean ~16 km H_2O vs. time as measured using limb emission (upper) and solar occultation (lower) sounders

Past, current, and future UT/S measurements



- Timeline shows past, current, and future missions making UT/S measurements of
  Ozone (green): UV shield, greenhouse gas, and lower atmosphere pollutant
  Water vapor (cyan): Greenhouse gas
  Stratospheric tracers and halogens (purple): Essential to separating impacts of (and changes in) stratospheric chemistry from those of stratospheric dynamics
  Pollution tracers (orange): Tack world-wide transport of pollutants and greenhouse gases, and diagnose change in stratosphere / troposphere exchange
- Note the paucity of many such measurements in the coming decade

The Microwave Limb Sounding approach

- Microwave limb sounders observe rotational lines from any molecule having a dipole moment (includes O_3, H_2O, many others, but excludes CO_2, CH_4)
- Instruments measure individual lines to arbitrarily good spectral resolution
- Pressure induced (collisional) line broadening gives an excellent measure of atmospheric pressure, dramatically reducing sensitivity to spacecraft pointing
- To date, NASA has flown two Microwave Limb Sounder (MLS) instruments:

UARS MLS (1991–2000)

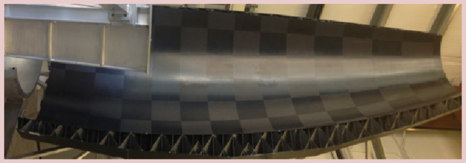
- was designed to measure stratospheric and mesospheric O_3, ClO, and H_2O
- It also measured stratospheric HNO_3, Temperature, SO_2, CH_3CN, upper tropospheric H_2O and cloud ice, and gravity waves

Aura MLS (2004–)

- Used planar diode and MMIC amplifier receiver technologies, notably enabling improved bandwidth, and thus observations to lower altitudes
- Measures 16 trace gases plus temperature, geopotential height and cloud information

CAMLS project heritage and contributions

2D Scanning Antenna **[IIP 2010]**



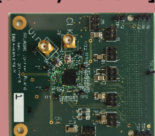
4 m × 1.8 m parabolic/cylindrical composite antenna. 79 kg

HEMT MMIC LNA **[ACT 2010]**

HEMT LNA enables both cooled (low noise) and ambient implementations

Digital polyphase spectrometer development **[SBIR, PIDDP]**

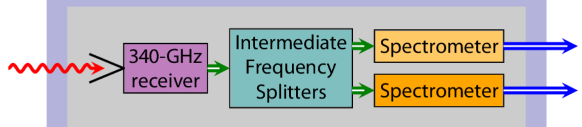
Sharp channel shapes with consistent calibration across ~10 GHz bandwidth



Airborne SMLS **[IIP 2007]**

2D scanning from ~65,000 ft, 300 km-wide swath at 10 km

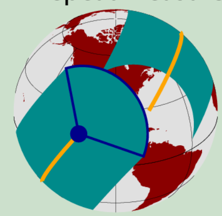
The Compact Adaptable Microwave Limb Sounder **[IIP 2013]**

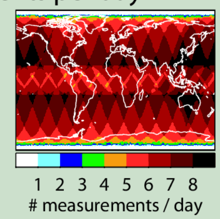


- A core receiver / spectrometer system central to multiple instrument “point designs” (see right)
- A single 340 GHz receiver can measure all key molecules
- Sideband separation for needed accuracy in upper troposphere
- HEMT MMIC LNA-based 340 GHz receiver subsystem
- 20 GHz sideband-separated IF
- Two 10 GHz bandwidth digital polyphase spectrometers

The Scanning Microwave Limb Sounder (SMLS)

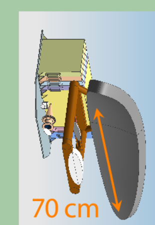
- Cool CAMLS receiver enabling reduced integration time
- Integrate with 2D scanning antenna
- 8000 km swath, 50×50 km sampling
- Swath overlaps enable multiple repeat measurements per day





A “continuity” MLS instrument

- Integrate CAMLS with similar antenna to that for Aura MLS
- Fly as instrument of opportunity or on small mission



The Airborne Scanning Microwave Limb Sounder (A-SMLS)

- Upgrade A-SMLS to use CAMLS receivers / spectrometers
- Replace SIS receivers with MMIC LNAs, no need for liquid helium

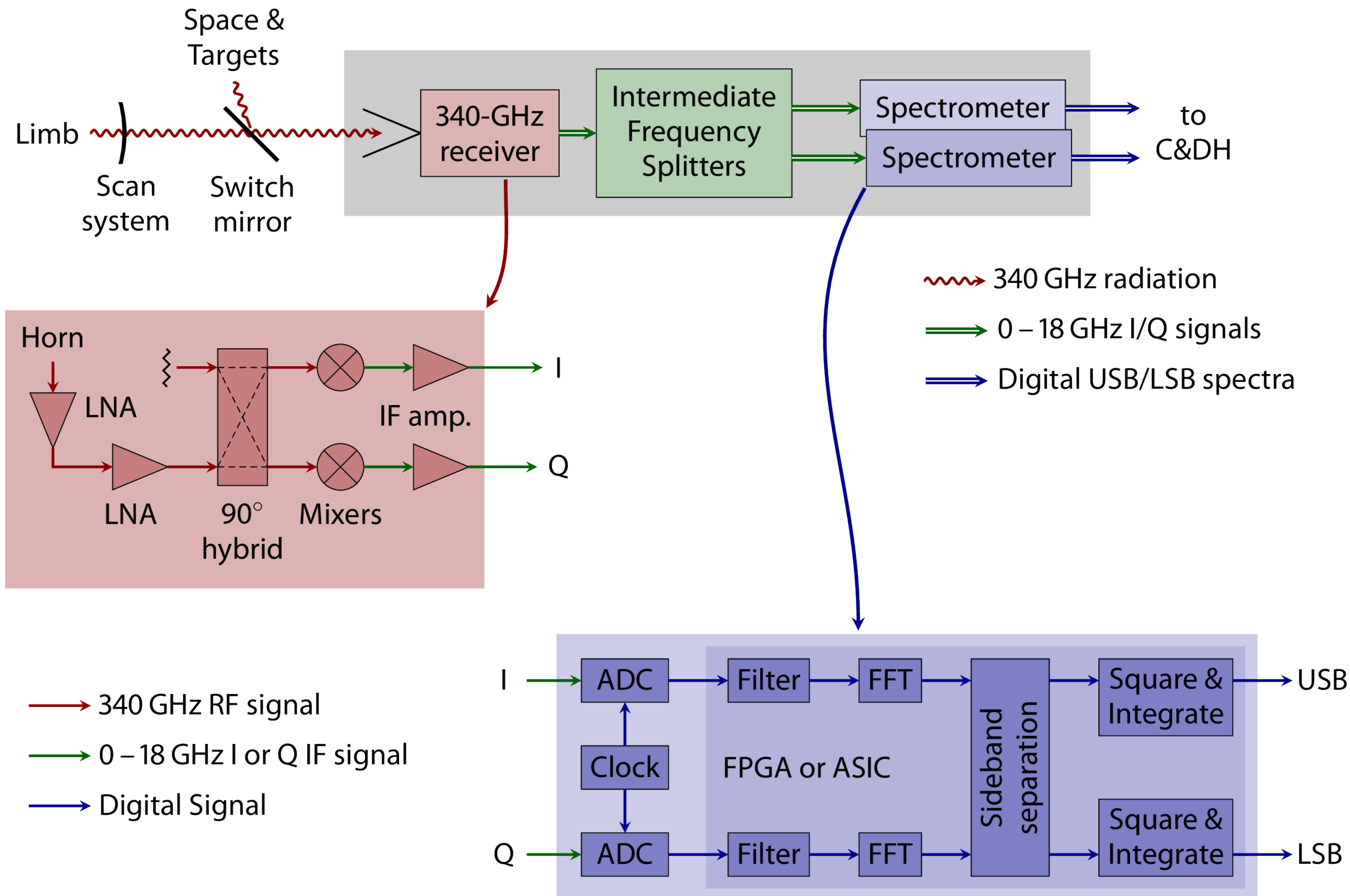
Main CAMLS advances compared to Aura MLS

	Aura MLS	CAMLS
Species observed[a]	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**
Receivers	118, 190, 240, and 640 GHz, 2.5 THz	340 GHz
Sidebands	118 GHz single sideband, all others folded sideband	Sideband separating (I/Q frontend, digital backend)
IF processing	~40 local oscillators, 60+ IF mixers, hundreds of amplifiers, attenuators and splitters	2 splitters, 4 bandpass filter / attenuator / amplifier chains
Spectrometers	542 individual channels (discrete capacitors, inductors etc.) plus 4 narrow-band Digital Autocorrelator Spectrometers	2 wideband ~8000 channel digital polyphase spectrometers including sideband separation in the digital domain
Signal to noise	~2000 – 3000 K system temperature (single sideband) for 190/240 GHz UT/LS measurements	2900 K per sideband or better system temperature requirement at ambient. 330 K when cooled to 20 K
Resolution	165 km "single pixel" along track	50 km along track for "continuity" 50 × 50 km 2D scan for SMLS
Resources[b]	270 kg, 370 W, ~1 m^3	10 kg, 100 W, ~0.01 m^3

[a] Aura MLS OH measurements (lacking in CAMLS) are focused on the upper stratosphere and above. Aura MLS HCl measurements (also not in CAMLS) do not extend deep into the upper troposphere

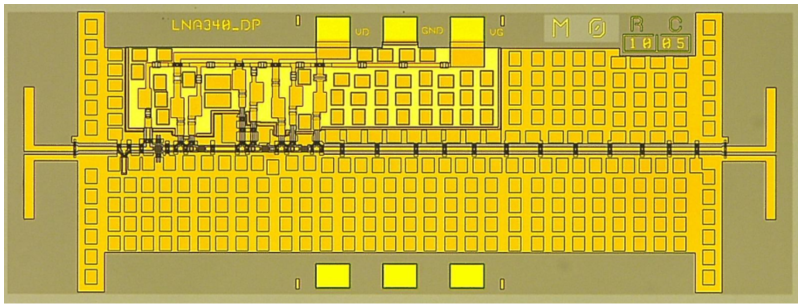
[b] Receiver, IF processing, spectrometer subsystems only. Neglects C&DH, scan and calibration systems etc.

CAMLS system and subsystem block diagrams

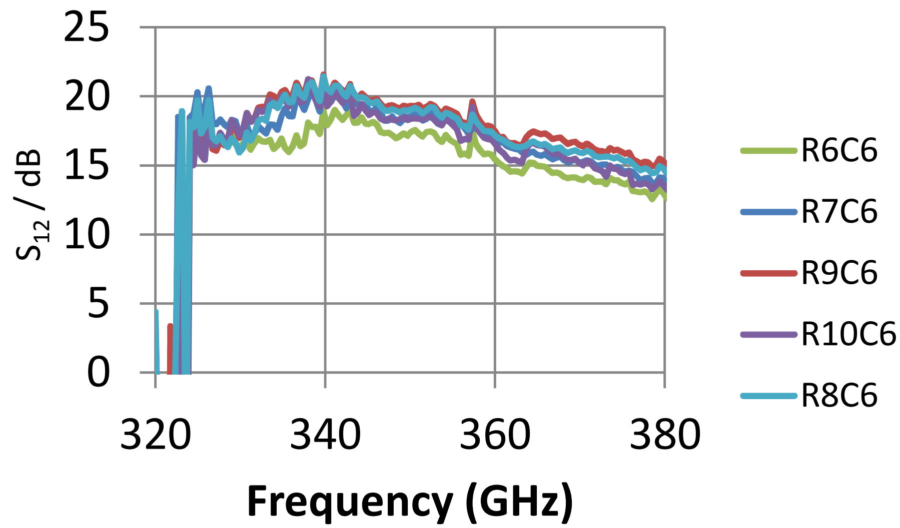


CAMLS 309 – 369 GHz LNA from NGAS

One of the CAMLS 340 GHz LNA devices, will be first element of signal chain



Gain for some of the devices produced



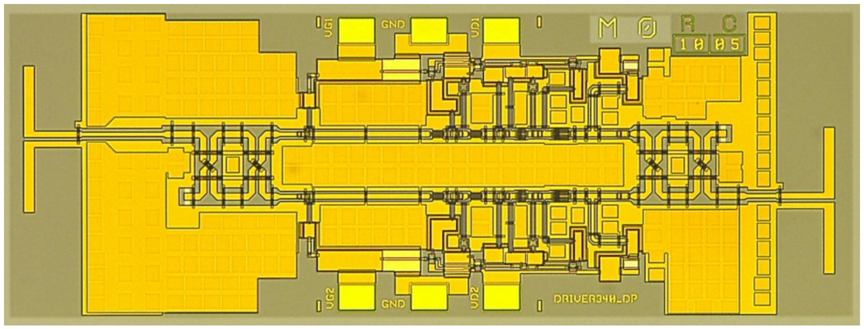
- 25-nm InP HEMT process on 1 mil thick substrate
- Single-ended common-source 4 stages
- 2-finger 20-µm devices for all 4 stages
- Biased at 450 mA/mm (9 mA each stage)
- Dimensions: 1200 µm x 450 µm

- On wafer measurement using WR2.2 extender
- Gain between 16 and 20 dB up to 370 GHz
- Due to larger parasitics from gate capacitance, gain slope shown after 350 GHz

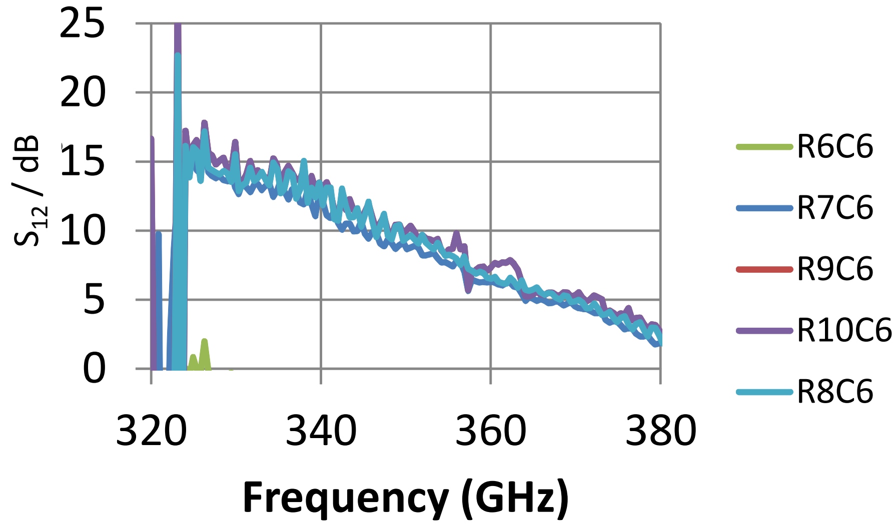
CAMLS 309 – 369 GHz LO driver amp. from NGAS

Compact Adaptable Microwave Limb Sounder

One of the CAMLS 340 GHz amplifiers to be used for Local Oscillator amplification



Gain for some of the devices produced

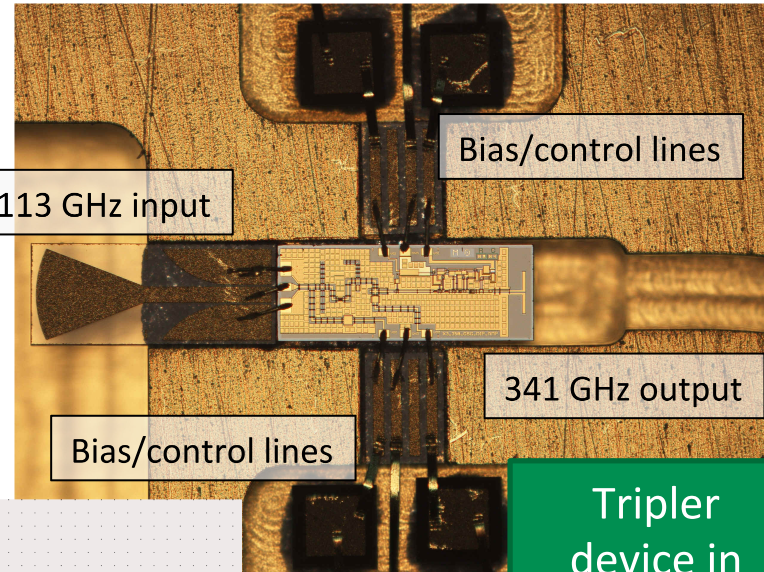


- 25-nm InP HEMT process on 1 mil thick substrate
- Balanced common-source 4 stages
- 2f30µm, 2f30µm, 4f40µm, and 4f80µm devices for 4 stages
- Biased at 450 mA/mm
- Dimensions: 1200 µm x 450 µm

- On wafer measurement using WR2.2 extender
- Gain is ~15 dB at 325 GHz
- There is gain slope due to larger parasitics from gate capacitances
- Output power may be slightly below requirements at 341 GHz
- Cascading should mitigate any shortfall

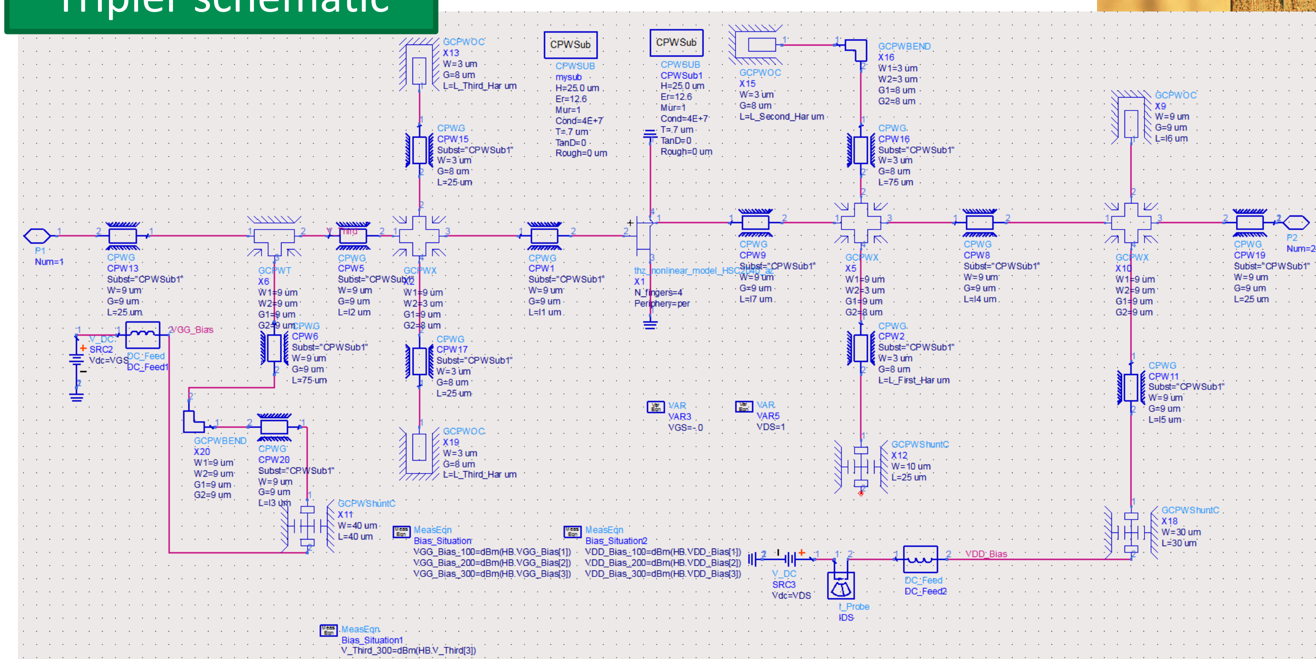
CAMLS 113 to 341 GHz LO tripler

- The CAMLS LO tripler was fabricated in the same wafer run as the amplifiers, using a JPL design



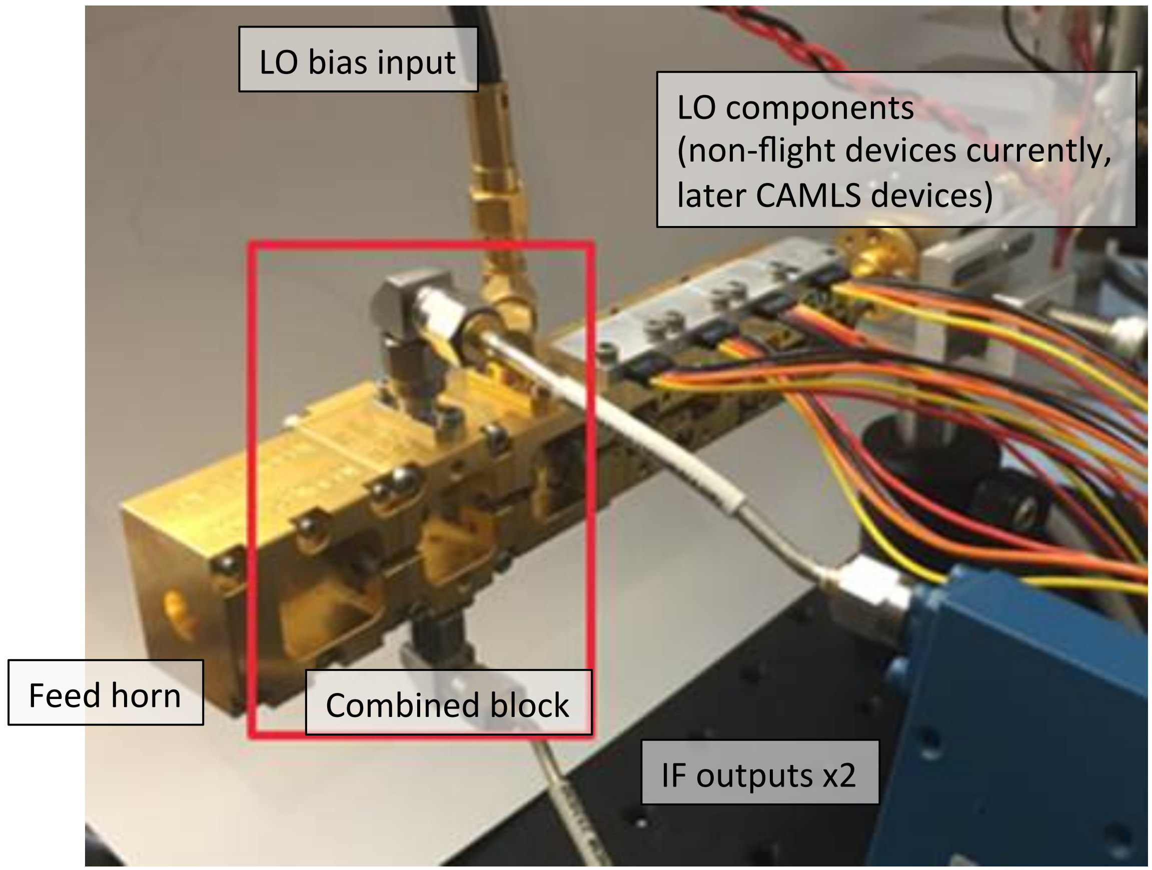
Tripler device in block

Tripler schematic



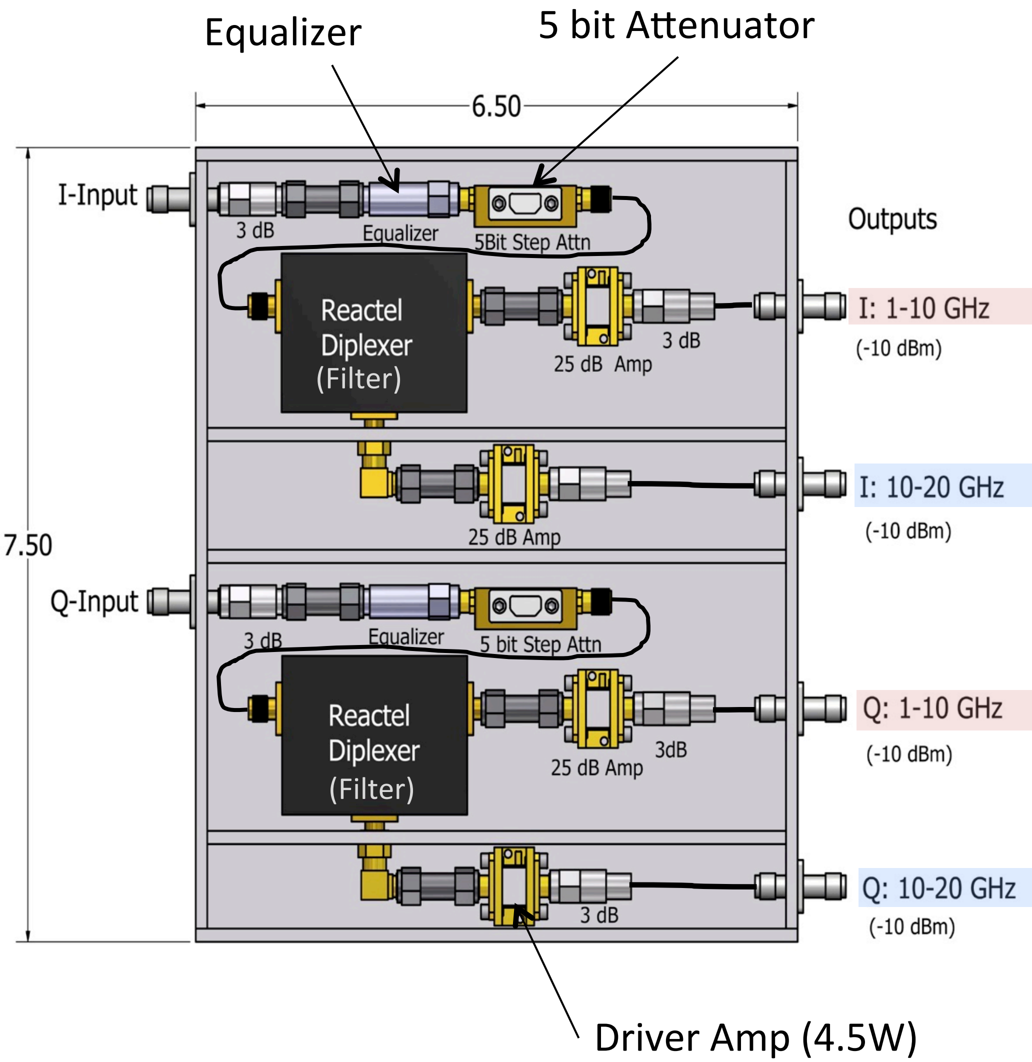
CAMLS combined splitter/mixer block

- We have developed a single block that incorporates the 90° hybrid, the LO splitter and a pair of Schottky mixers
- This provides for a more compact and lower-noise implementation
- Verification and testing is underway

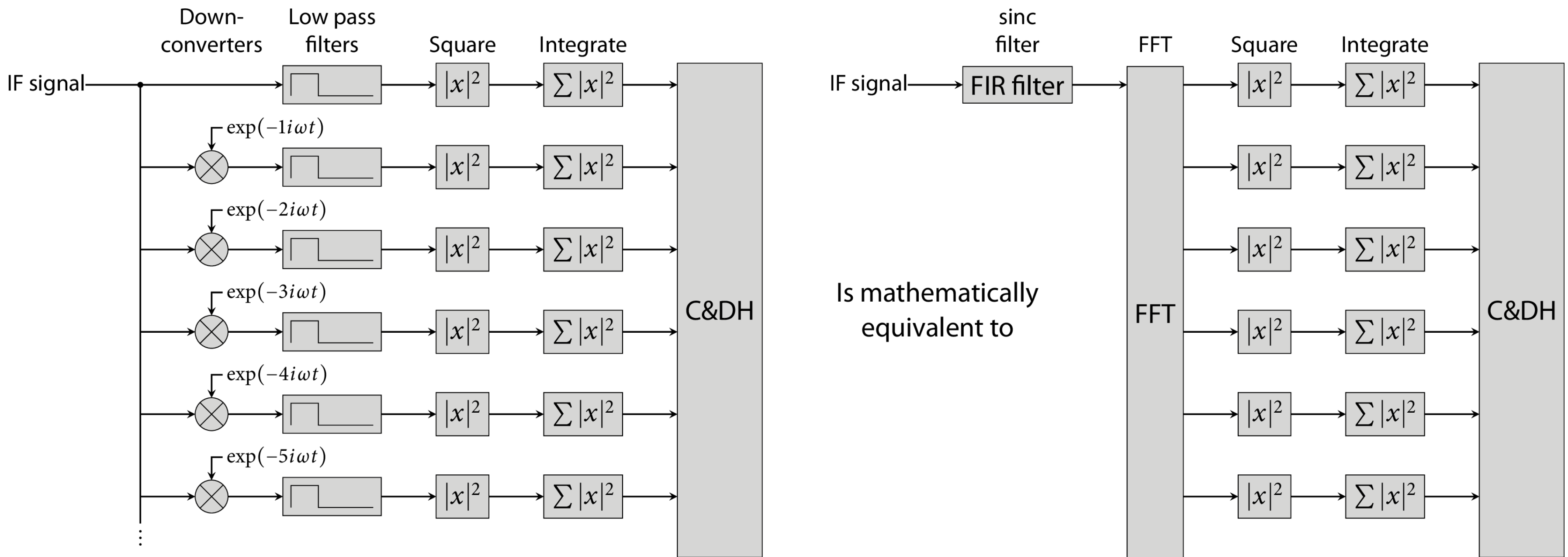


CAMLS IF processor design

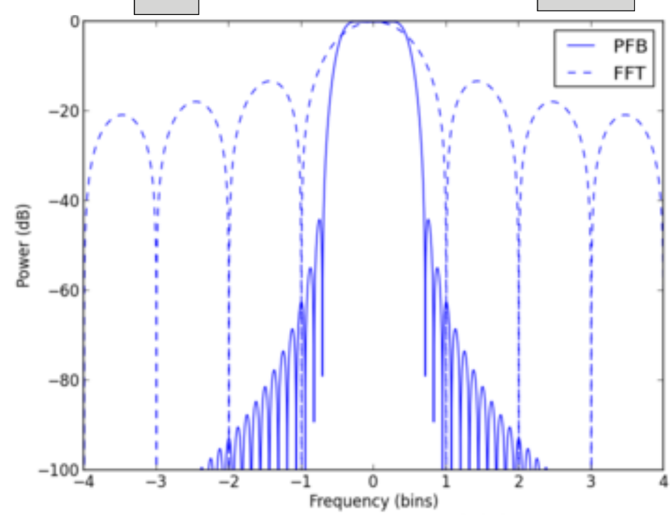
- The CAMLS IF bandwidth is 20 GHz, with separate “I” and “Q” IF signal paths
- The spectrometers digitize at 20 Gsps, giving sample bandwidth of 10 GHz
- However, the spectrometer inputs have 20 GHz bandwidth, enabling us to Nyquist-alias the 10–20 GHz down to the 0–10 GHz region
- The CAMLS IF processors split and high/low-pass filter the I and Q signals prior to digitization
- Given the high TRL of such subsystems (in both discrete and microstrip implementations), we have implemented a simple discrete design here



Reminder: Polyphase spectrometer fundamentals

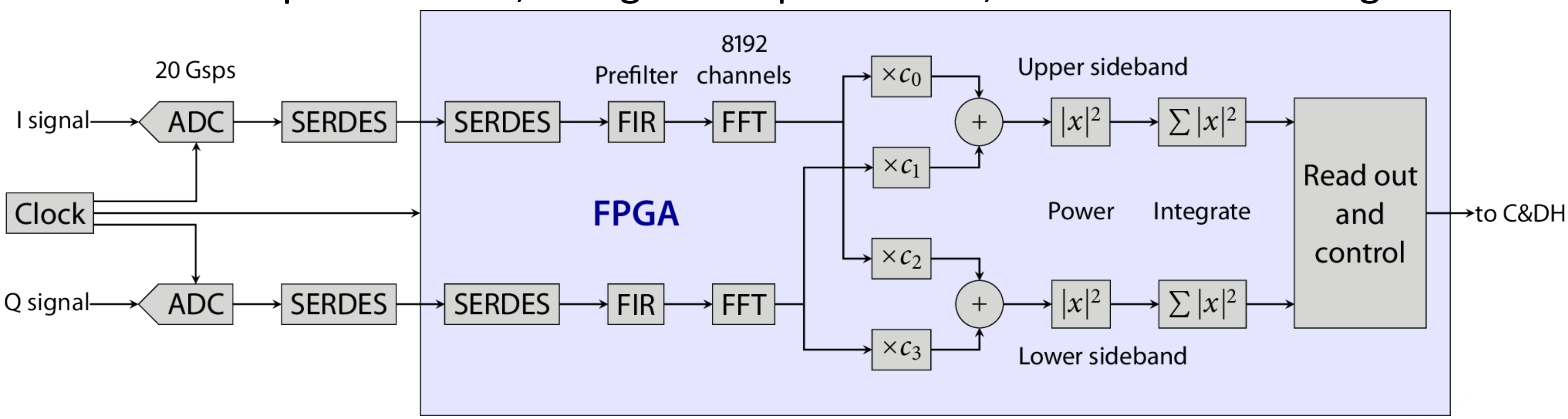


- Digital spectrometers offer dramatic reductions in mass and power over conventional analog systems
  - While ASICs need lower mass/power than FPGAs, either is a significant improvement over Aura MLS
- "Polyphase" spectrometers offer much sharper channels than the sinc channel shapes obtained from FFT and autocorrelator spectrometers
  - This is important for calibration accuracy and issues such as RFI mitigation



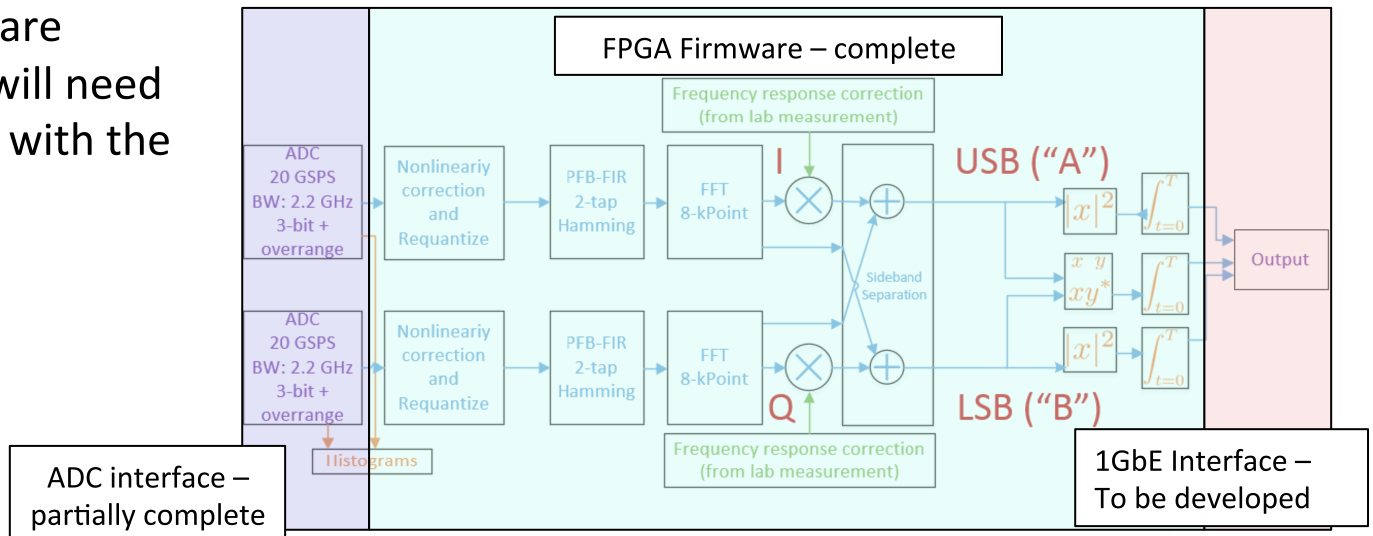
CAMLS spectrometer overview

- The project includes both FPGA and ASIC development threads
- Originally intended FPGA to be for testing, with ASIC for spaceflight
- However, newer FPGAs are LEO-radiation tolerant, and consume low enough power to be potentially compatible with (e.g.,) "Earth Venture" requirements
- Both designs employ an external ADCs (20 Gsps), requiring a "SERDES" interface to the FPGA or ASIC DSP chip
- Two 8192-channel FPGA spectrometers each cover 10 GHz IF bandwidth in the upper and lower sidebands, giving 18+ GHz total IF bandwidth
- The ASIC spectrometer, being developed at UCB, covers narrower regions



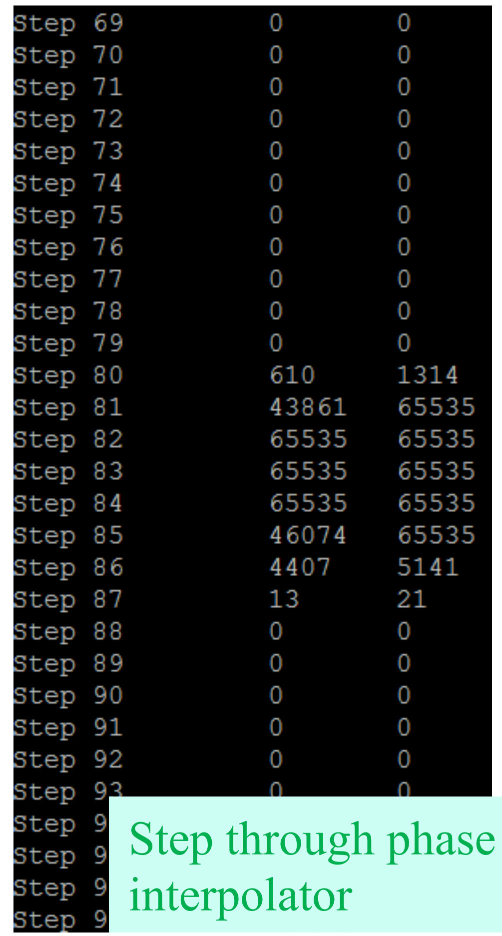
FPGA Spectrometers – Status Summary

- Primary FPGA spectrometer design is complete, but needs to be integrated into the hardware (ADC interface and 1GbE interface)
  - Timing has been achieved for placement of the spectrometer logic, with resource usage high, but in line with predictions
  - For the XC7VX690TFFG1930-2, the highest usage is BRAM (memory) at 44%, and DSP48 slices (dedicated multiply-add logic) at 77%.
  - ADC interfaces and 1GbE will not make use of the DSP48 logic, leaving abundant resources for remaining logic implementation (most significant resource estimated to be 4% BRAM).
  - Once interfaces are complete, they will need to be integrated with the FPGA firmware.

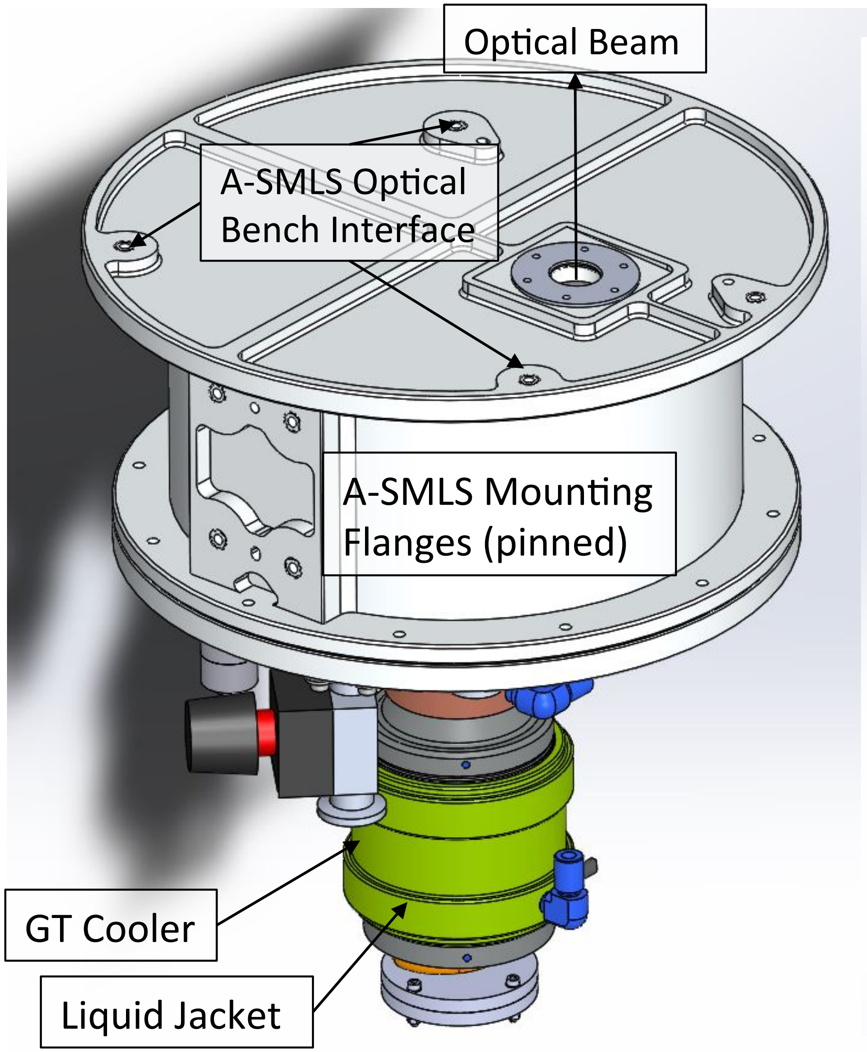


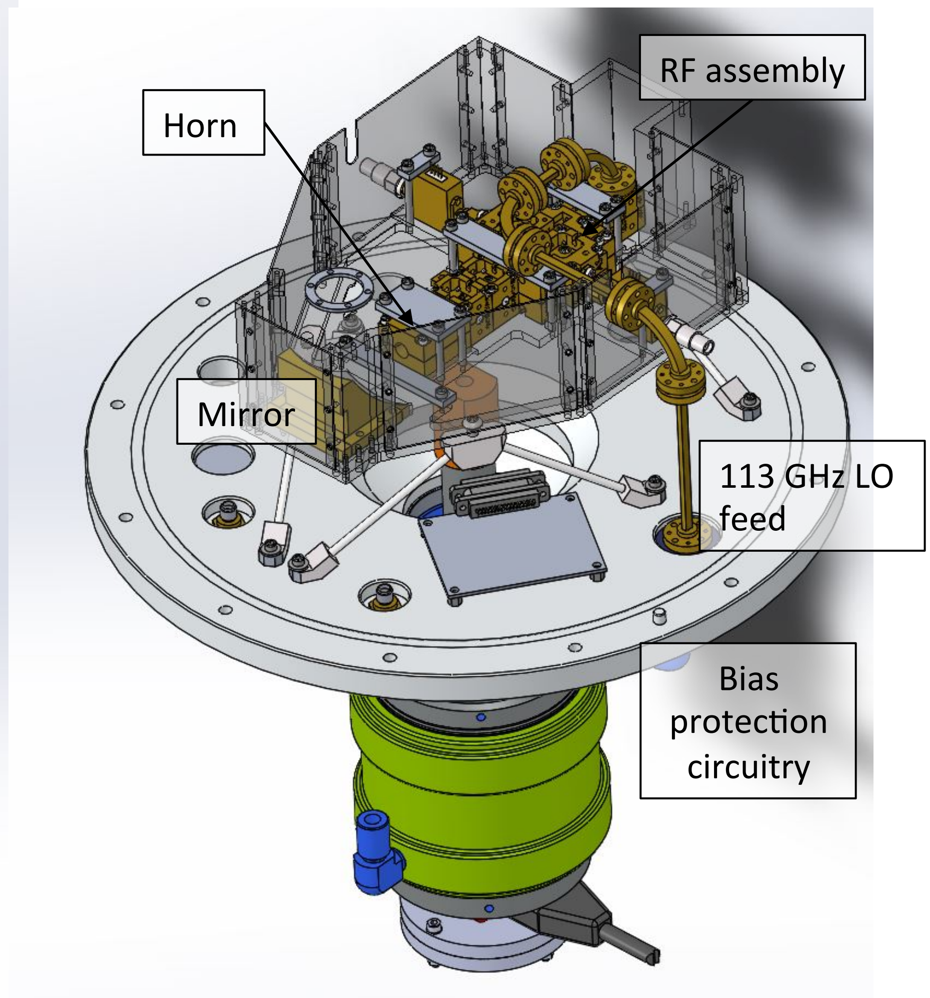
FPGA Spectrometers – ADC data

- The SERDES-based ADC interface is almost complete
- The calibration for the ADC consists of several steps (based on code from an earlier development board by Rick Raffanti for Harvard-Smithsonian CfA):
  - Set the ADC to output 0
  - Generate a pseudo-random bit sequence (PRBS)
  - Step the phase interpolator
  - Send a modulation sequence to the modulation port
  - Align transceivers using the modulation sequence
  - Turn ADC output back on
- These steps can all be completed for the new board
- The next two design steps involve:
  - On chip analysis of a known (e.g., sine) input to the ADC
  - Transmission of this data over 1GbE
- Once these steps are complete we will be ready to integrate the existing spectrometer code

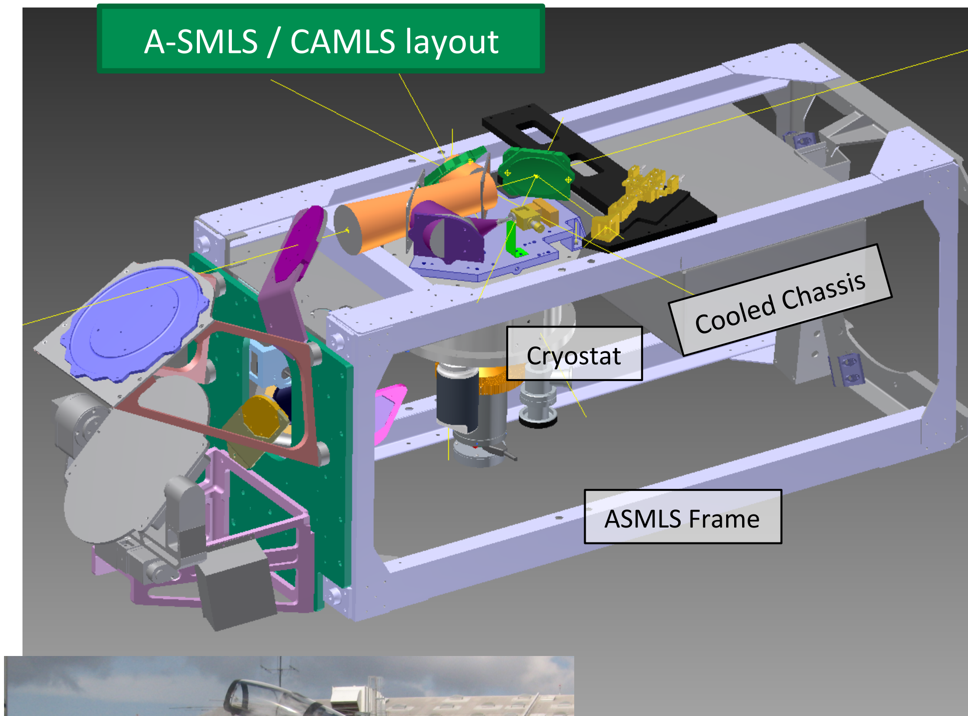


CAMLS cryostat – fabrication underway

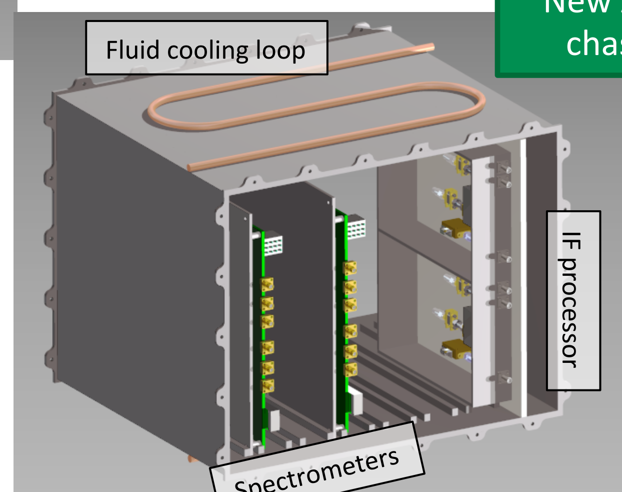




Integrating CAMLS into the Airborne-SMLS



- We will integrate CAMLS into the previously developed Airborne Scanning Microwave Limb Sounder (A-SMLS) for testing on the ER-2
- The CAMLS 340-GHz LNA receiver will replace 4K-cooled SIS devices
- A fluid loop will be used to shed heat from the cooler output and from the FPGA spectrometers
- The spectrometers, C&DH etc., will be integrated into a fluid cooled chassis



Summary of current CAMLS status

- Receivers:
  - All devices fabricated and undergoing component level testing
  - Receiver subsystem integration and test is underway
- IF processor:
  - All devices procured
  - Layout to be finalized once the "cold box" chassis is complete
- Spectrometers:
  - FPGA spectrometer development is progressing
  - Fabrication of the UCB ASIC spectrometer (lower bandwidth, non IQ separating) is completed
- System / A-SMLS integration:
  - Cryostat / receiver / optical bench etc. design complete
  - The CAMLS cryostat is being fabricated
  - We are finalizing the design of the "cold box" that will carry the spectrometers, IF processor, C&DH etc.

Plans for the coming year

- Subsystem integration and test:
  - Complete receiver integration and test
  - Complete FPGA spectrometer firmware, and test spectrometers
  - Complete ASIC spectrometer integration and test
    - Plan to use both ASIC and FPGA spectrometers concurrently, with ASIC overlapping part of the spectrum covered by the FPGA
  - Complete cryostat, chassis, A-SMLS interfaces, etc. hardware
- System integration and test:
  - Perform radiometric and spectral calibration
  - Integrate with A-SMLS
  - Perform end-to-end A-SMLS/CAMLS testing
- Test flights:
  - Plan A-SMLS/CAMLS test flights on the ER-2 in summer 2017
  - Likely co-manifested with Canadian colleagues developing a UV-limb spectrometer