The Compact, Adaptable Microwave Limb Sounder (CAMLS)

Developing the core system for next-generation
Microwave Limb Sounders

Nathaniel J. Livesey, Jacob Kooi, Goutam Chattopadhyay, Robert F. Jarnot, Robert A. Stachnik, Jonathon Kocz and Paul Stek
Jet Propulsion Laboratory, California Institute of Technology

William Deal and colleagues
Northrop Grumman Aerospace Systems

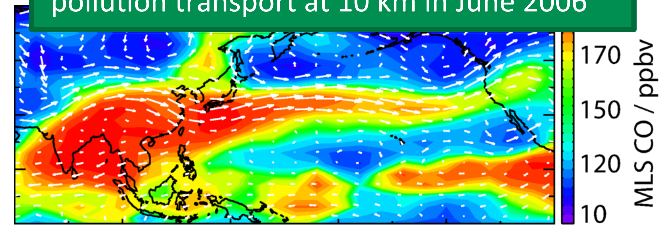
Dan Werthimer, Borivoje Nikolić and colleagues
U.C. Berkeley

CAMLS science motivation – the "UTLS"

Compact Adaptable Microwave Limb Sounder

- 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" (UTLS hereafter)
  - The ~10 km to ~20 km altitude region
- It is in this region where:
  - Radiative forcing from water vapor (the strongest greenhouse gas) and ozone are at their greatest
  - 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)

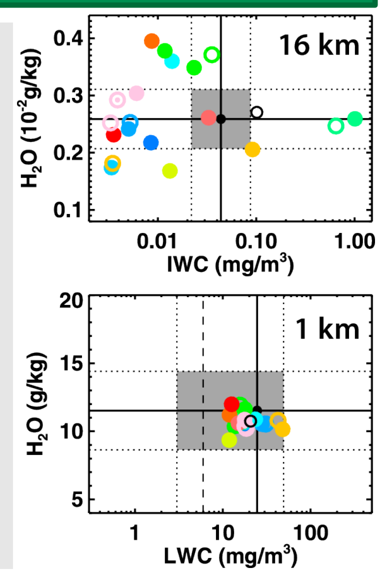
Aura MLS observations of long range CO pollution transport at 10 km in June 2006



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

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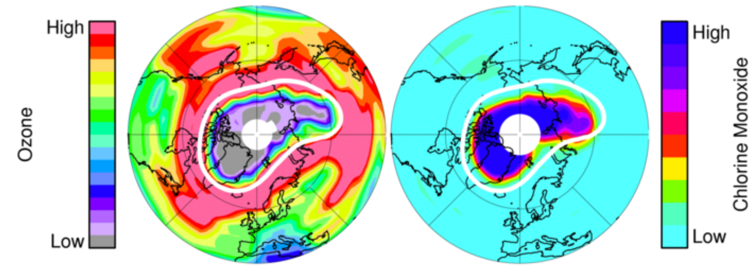
CAMLS science – issues in the stratosphere

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

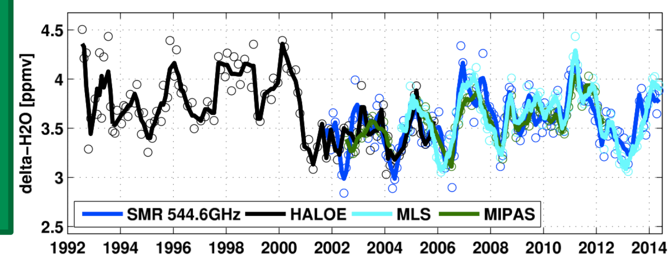
Aura MLS observations ozone (left) and chlorine monoxide (right) – the primary agent of ozone destruction – at ~20 km in March 2011, a period of unprecedented ozone loss in the northern hemisphere



Manney et al., 2011, Nature

- Unexpected and incompletely explained changes in stratospheric humidity in the past decade may have contributed to the “hiatus” in global warming

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

- 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

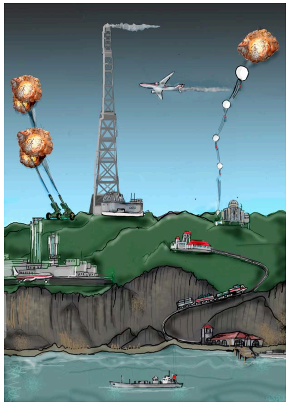


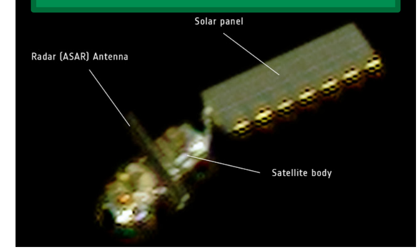
Illustration of various possible approaches to injecting sulfate aerosol into the stratosphere, in order to reduce surface heating

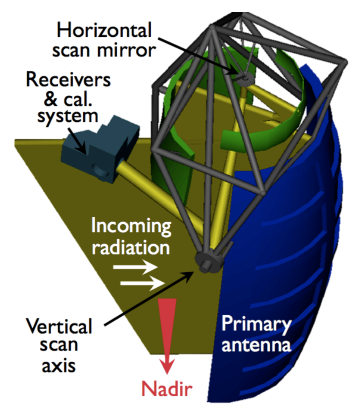
Robock, 2009, GRL

Current state of UTLS observations

- All the instruments making UTLS observations are well into extended mission
  - NASA's Aura mission launched 10 years ago, **includes the Aura Microwave Limb Sounder (MLS), whose measurements CAMLS extends and significantly augments**
  - Envisat (launched in 2002 with three UT/LS capable instruments) failed in April 2012
  - The Canadian ACE and Swedish/Canadian Odin missions are many years beyond their design life
- There are currently no plans, <u>from any agency</u>, to address the upcoming chasm in critical observations
  - SAGE III on the ISS has limited coverage and measures only a few species
  - The Suomi NPP / JPSS-2/3 OMPS limb instruments measure only ozone & aerosol
- Next-generation sensors are being developed
- However, programmatically, they may not be realized for some time

Visible image of Envisat, taken shortly after the April 2012 failure





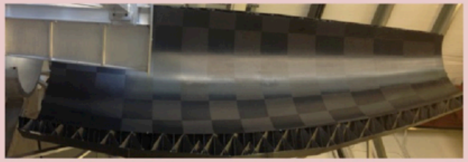
The Scanning MLS instrument concept developed under past IIPs. CAMLS will further advance SMLS technology

CAMLS context, goals and objectives

- New opportunities (hosted payloads, small satellites, the ISS) and the imminent decadal survey dictate a more nimble approach to developing:
  - A compact low-cost sounder to continue and augment critical observation records
  - A more cost-effective approach to the ambitious sounders essential for quantifying rapid/small-scale processes in the UTLS
- The CAMLS project advances technologies common to both of these needs
- We are developing a receiver/spectrometer "core system" making limb sounding observations at 340 GHz. Specifically:
  - We are developing a new MMIC LNA-based receiver subsystem, including sideband separation, that can observe all the needed species with a single receiver, and can run both cooled (e.g., for 2D limb scanning) and at ambient (for "continuity" measurements)
  - We are also developing a compact low mass/power digital spectrometer back end, enabled by dramatic innovations driven by the communications industry
  - We will integrate these into a receiver/spectrometer system and demonstrate performance over the needed temperature range
  - We will incorporate this, with coolers, into the A-SMLS airborne instrument, establishing TRL-6

CAMLS heritage and contributions

2D Scanning Antenna [IIP 2010]



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

HEMT MMIC LNA [ACT 2011]

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

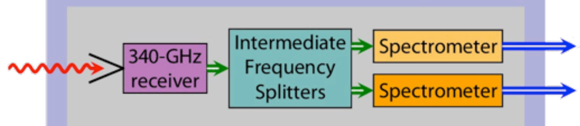
Digital polyphase spectrometer development [SBIR, PIDDP]

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

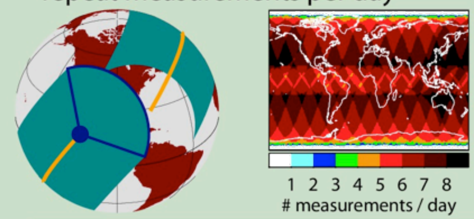
The Compact Adaptable Microwave Limb Sounder [IIP 2013]



- 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 spectrometer ASICs

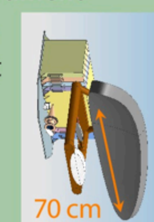
The Scanning Microwave Limb Sounder (SMLS)

- 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

Compact Adaptable Microwave Limb Sounder

	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, 80 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.

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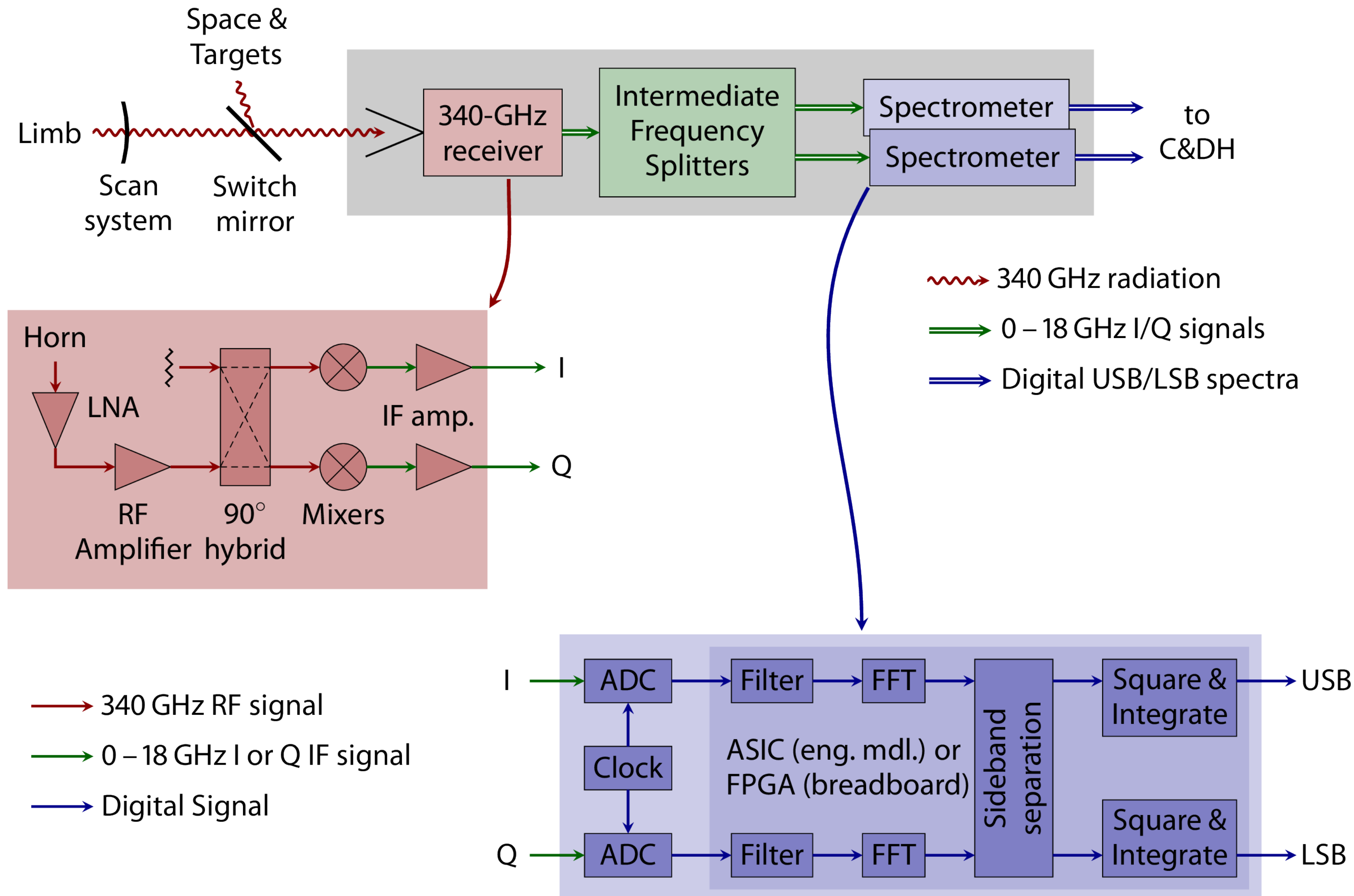
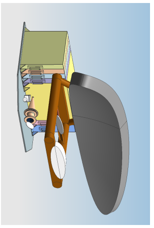
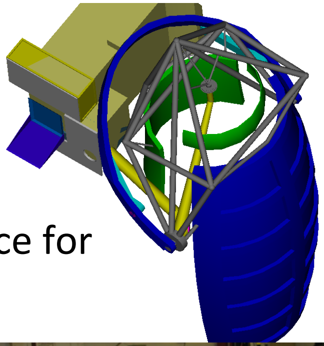
CAMLS high level block diagram



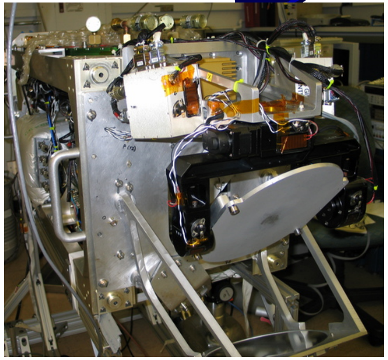
- Cooling the receiver subsystem gives improved signal to noise, enabling reduced integration time and thus addition of azimuth scanning



- The "continuity-focused" CAMLS instrument
  - does not require cooling to extend the Aura MLS record, and
  - CII power constraints restrict cooling to only modest amounts, of marginal benefit



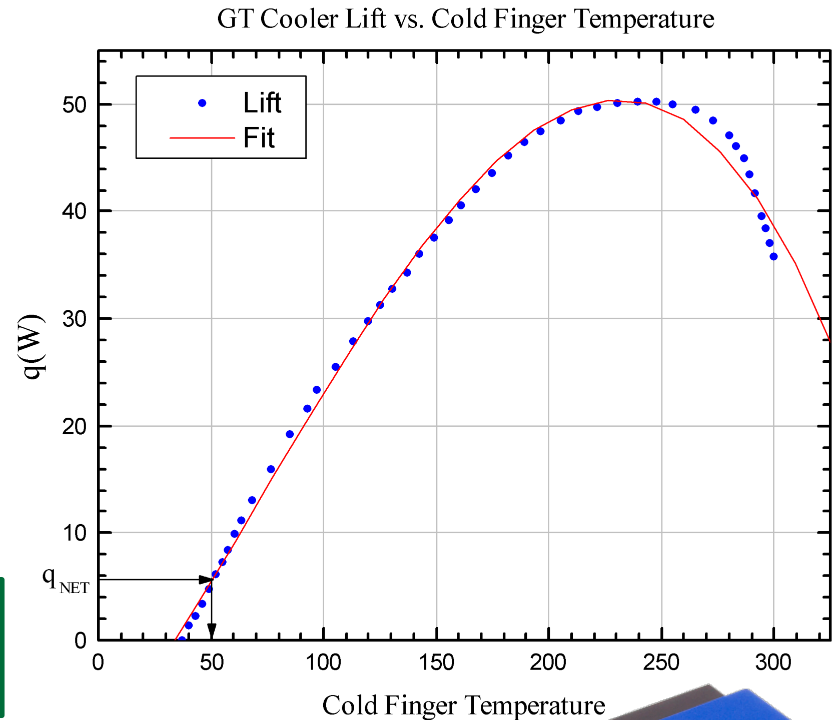
- The more ambitious "Scanning Microwave Limb Sounder" point design
  - performs best when cooled to ~20 K
  - SMLS exceeds the CII mass/volume budget and power with 20 K cooling
  - Development of a flight-qualified 20 K cooler having the needed performance for SMLS is beyond the scope of this IIP



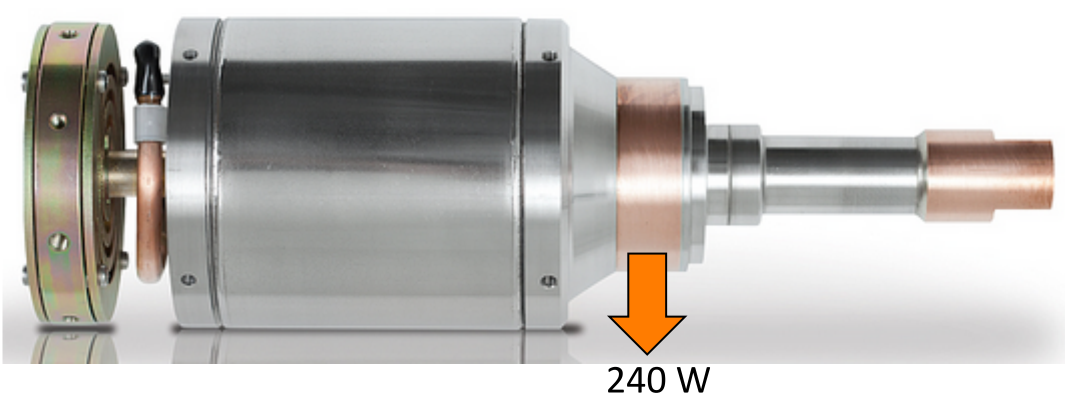
- The Airborne Scanning Microwave Limb Sounder instrument
  - Currently uses 4-K liquid helium-cooled SIS receivers (190 & 240 GHz)
  - We will replace these with the CAMLS core system
  - Cooling to ~50 K provides a very useful signal to noise for science studies
  - An integrated (e.g., "SunPower") cooler greatly simplifies deployment

CAMLS cryogenic approach

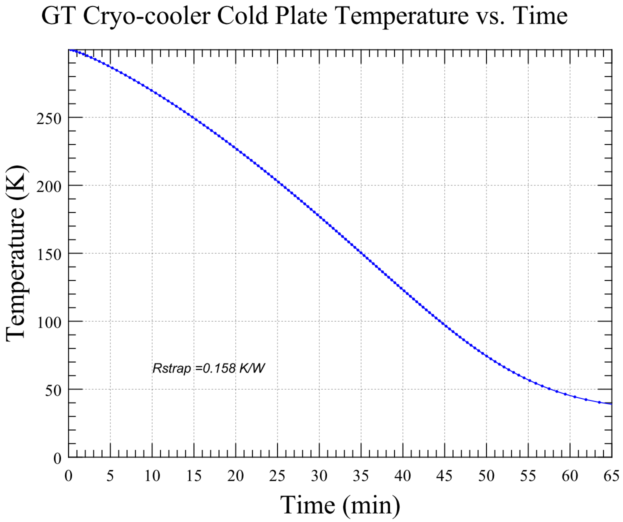
- For the A-SMLS demonstration of CAMLS our design goals include
  - Minimize power consumption for ultimate space applications
  - Minimize complexity
  - Minimize mass
  - Ability to cool in ~45 min
  - High reliability

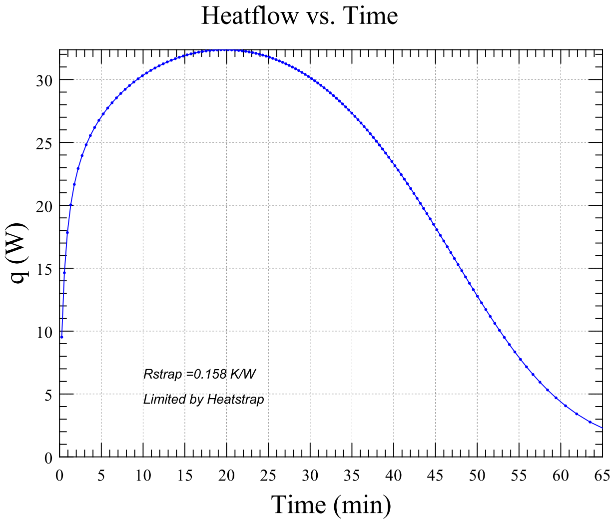


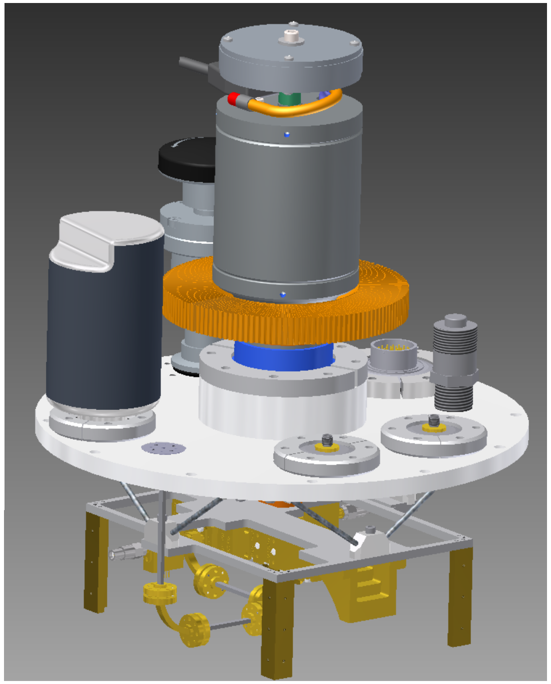
Commercial single stage "Sunpower GT" cryo-cooler (4.3 kg)



CAMLS modeled heat flow



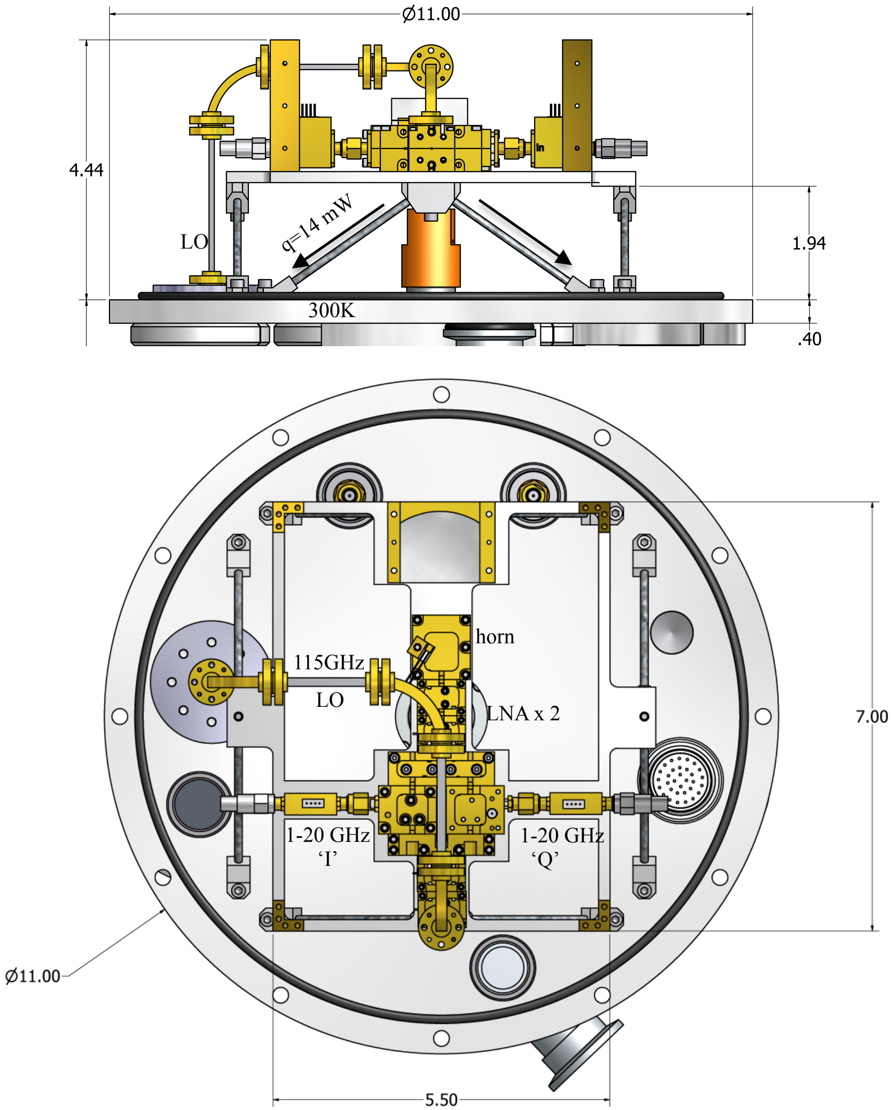


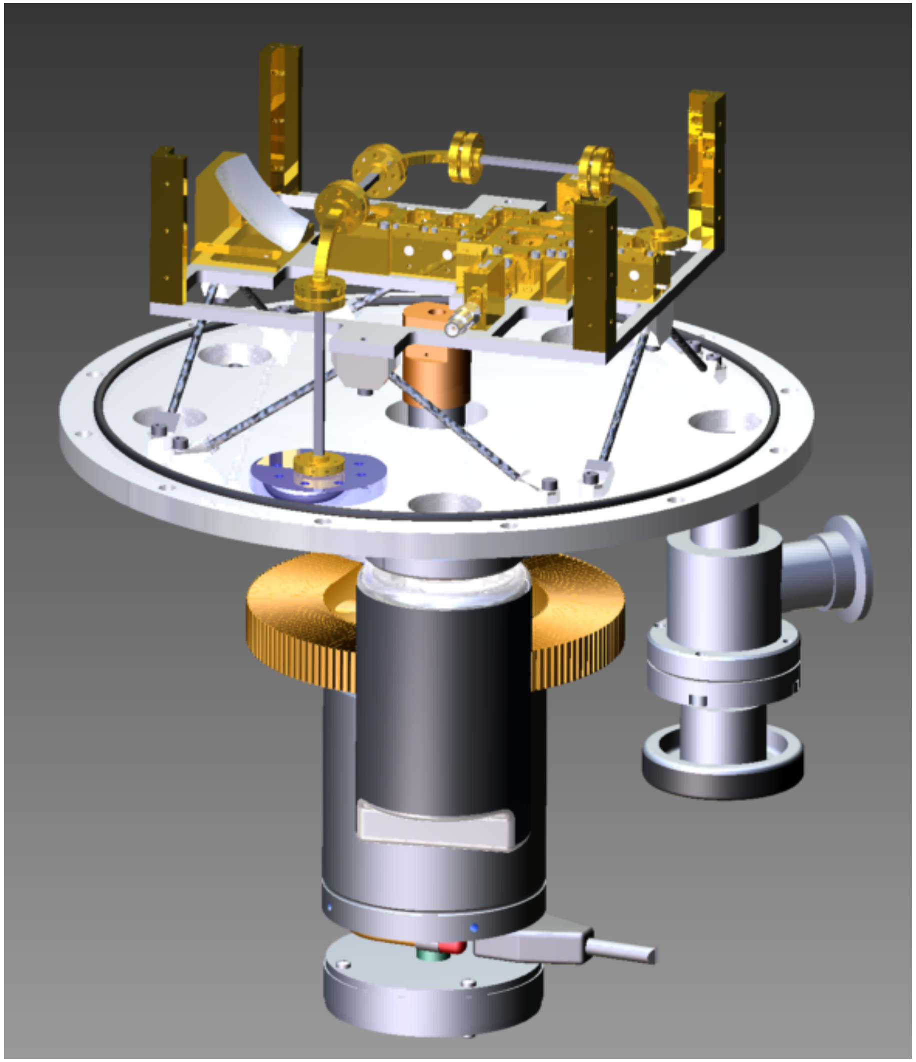


- Thermal mass: 172 g aluminum, 414 g copper
- NIST based cryogenic material properties
- Radiative heat load based on MLS shielding
- Cryotel provided cooler lift, q (T)
- This model assumes a uniform temperature distribution

CAMLS cryostat layout

Compact Adaptable Microwave Limb Sounder





20 kg for these and additional cryostat components

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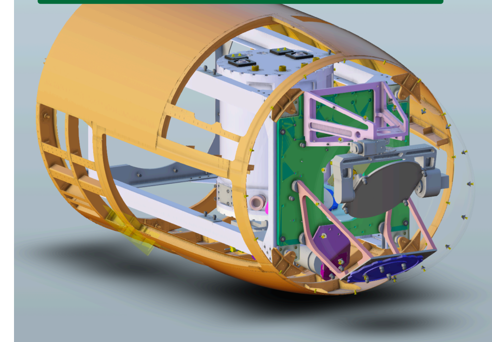
Airborne Scanning Microwave Limb Sounder (A-SMLS)

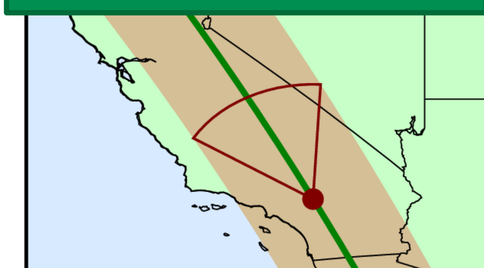
- The Airborne Scanning Microwave Limb Sounder (A-SMLS) was initially developed under IIP-2007
  - It was proposed to serve as both risk reduction for SIS-based SMLS technologies and as a "free-standing" aircraft instrument
  - A-SMLS currently uses a 4 K-cooled 240-GHz SIS receiver, with an option to add others
  - It has successfully flown on the WB-57 and is being flown on the ER-2 in July 2015
- A-SMLS makes 2D scanning microwave limb observations of UTLS composition from a high-altitude aircraft
  - A-SMLS has a ~300 km swath width in the UTLS when observing from cruise altitude
  - The A-SMLS measurements can be used to quantify critical small-scale processes affecting atmospheric composition (pollution plumes, convective outflow etc.)

A-SMLS CAD drawing

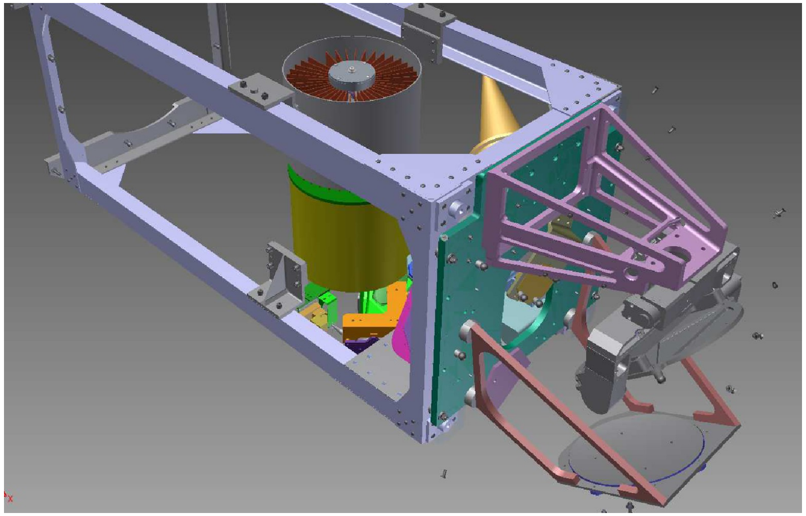


A-SMLS on the WB-57

Sample A-SMLS coverage of California

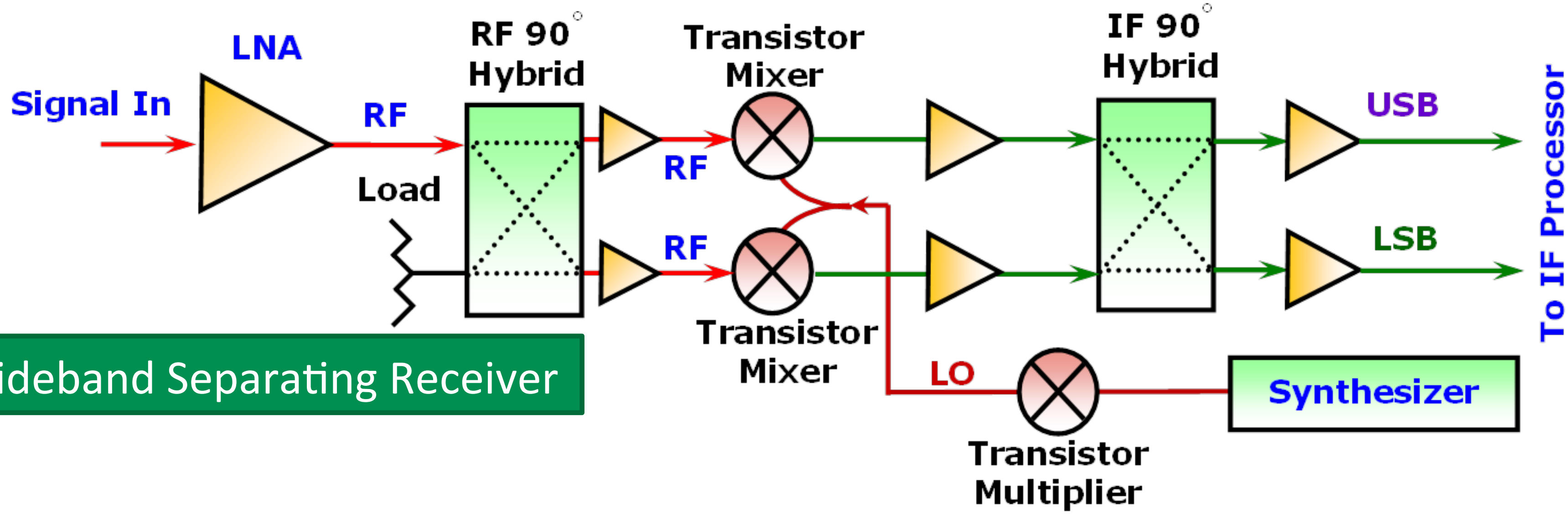


CAMLS A-SMLS integration



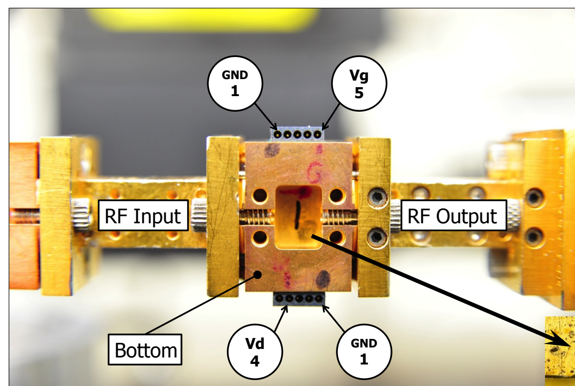
- The A-SMLS instrument can be readily modified to replace the existing receivers and spectrometers with the CAMLS core system
- This will advance the CAMLS receivers and spectrometers to TRL 6
- This also represents a significant upgrade to A-SMLS, as
  - Observing at 340 GHz will enable A-SMLS to measure a number of species, including water vapor and carbon monoxide, using a single receiver
  - Switching from SIS to MMIC LNA technology removes the need for cooling to 4 K (which mandates flying cryogen)
- A-SMLS with CAMLS technology would be ideally suited to a long-duration high-altitude flight (e.g., from UAV) in future atmospheric composition campaigns
  - Such “field survey” observations would be a great complement to more detailed in situ observations from lower-altitude aircraft
  - In particular, A-SMLS observations could be used in real time to direct other aircraft towards features of interest such as pollution plumes and convective outflow

CAMLS receiver subsystem



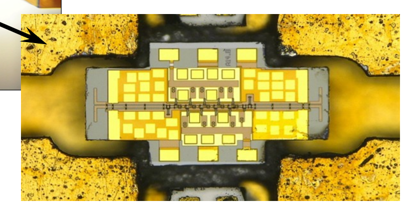
Sideband Separating Receiver

- The radio frequency (RF) signal is first amplified by a low noise amplifier
  - This can be cooled (e.g., to 20 K) for improved signal to noise
- The RF hybrid circuit along with mixers separate the two sidebands
- These are split in the back-end IF processing and spectrometer subsystems



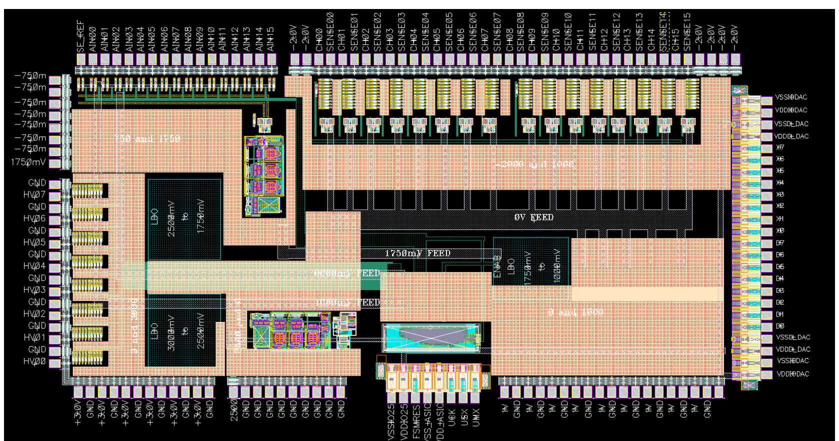
Amplifier block

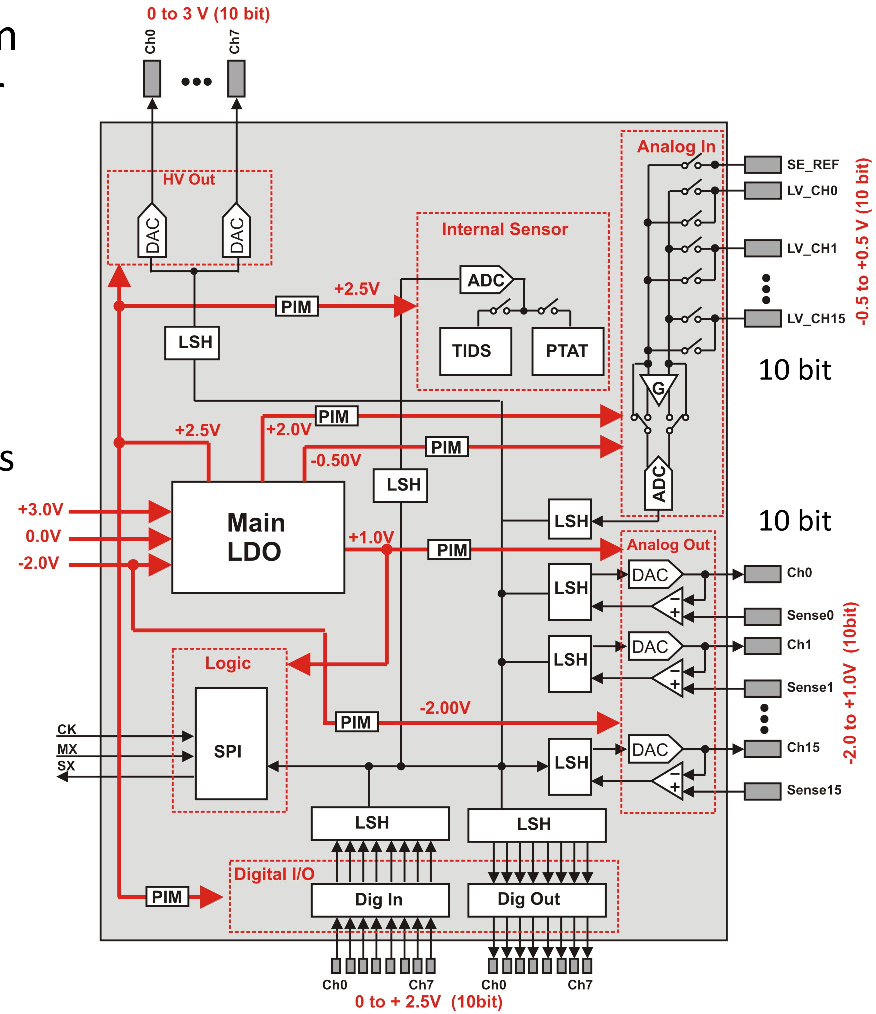
HEMT-based amplifier in split waveguide block



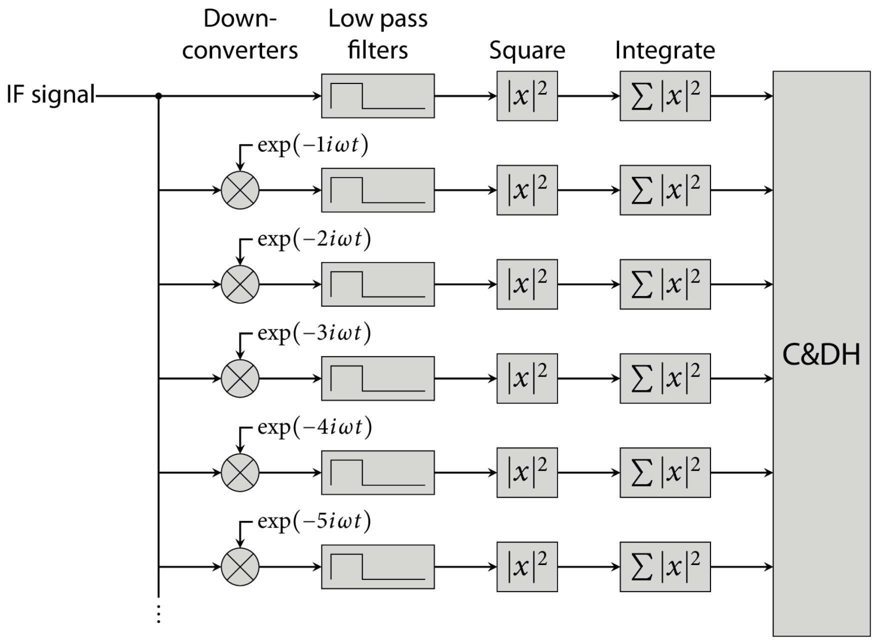
CAMLS bias voltage, control and telemetry

- The CAMLS receiver and IF processing system both need a range of bias voltages and other housekeeping
- In conjunction with other projects we are developing a custom rad-hard (>50 Mrad) CMOS Chip (tape out ~September 2015)
  - 16 Bipolar (–2 to 1 V) 10 bit DAC outputs
  - 16 Differential (–0.5 to 0.5 V) 10 bit ADC inputs
  - 8 single ended 10 bit DACs
  - 8 bit I/O
  - +3, –2 V supply, SPI interface

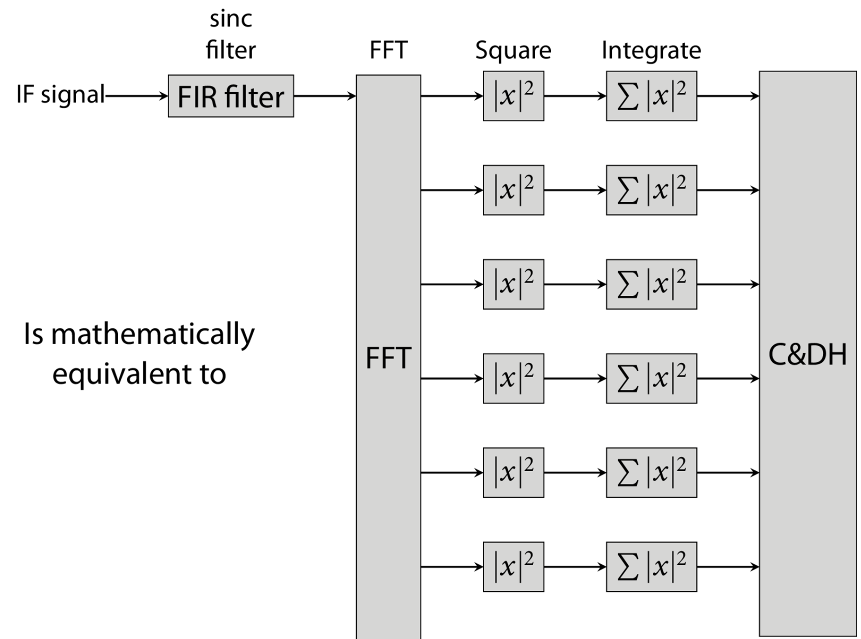




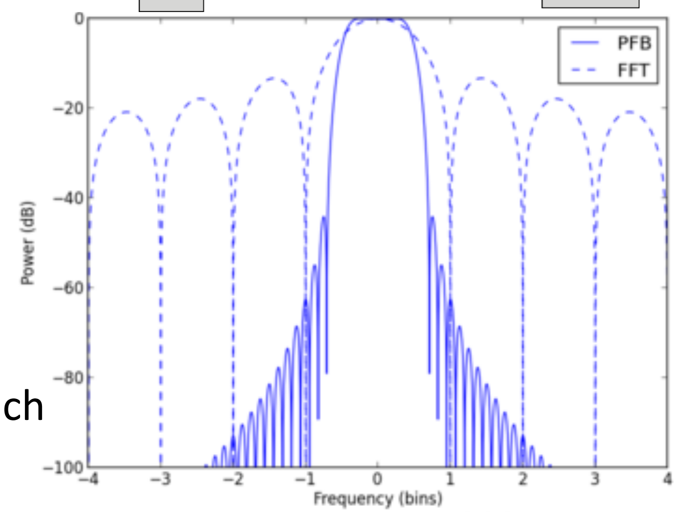
Polyphase spectrometer fundamentals



Is mathematically equivalent to

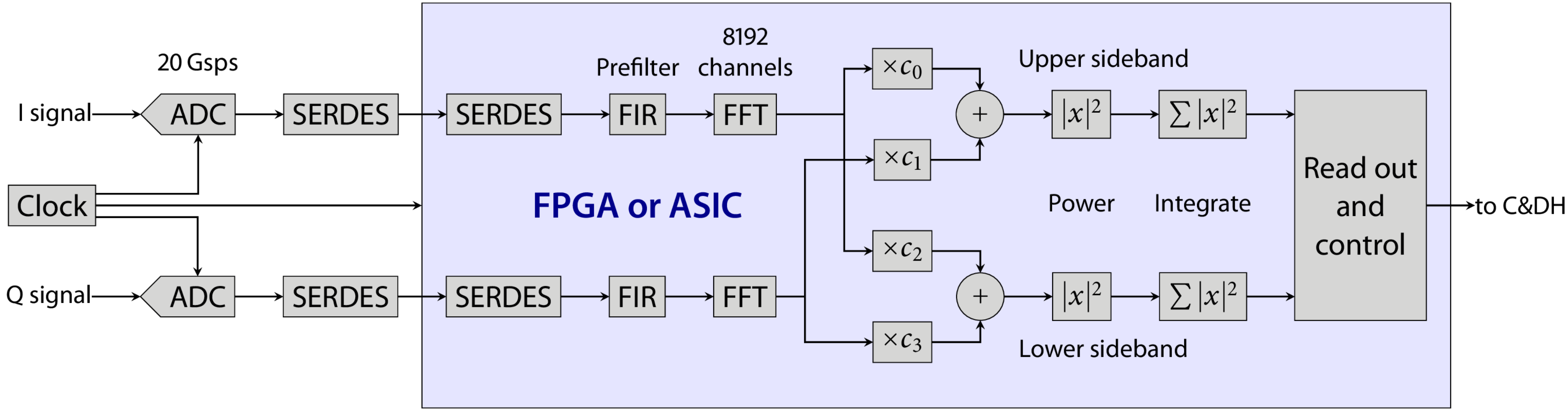


- Digital spectrometers (particularly ASIC implementations) offer dramatic reductions in mass and power over conventional analog systems
- "Polyphase" spectrometers offer much sharper channels than the sinc channel shapes obtained from FFT and autocorrelator spectrometers
  - This is important for calibration accuracy and issues such as RFI mitigation



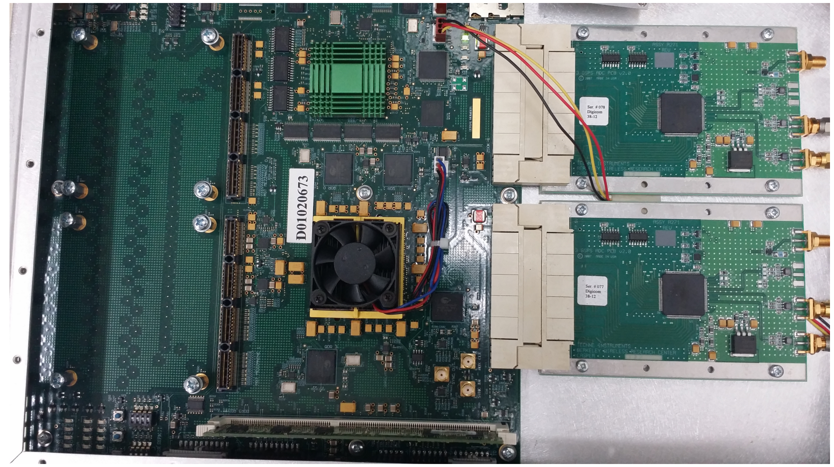
CAMLS spectrometer overview

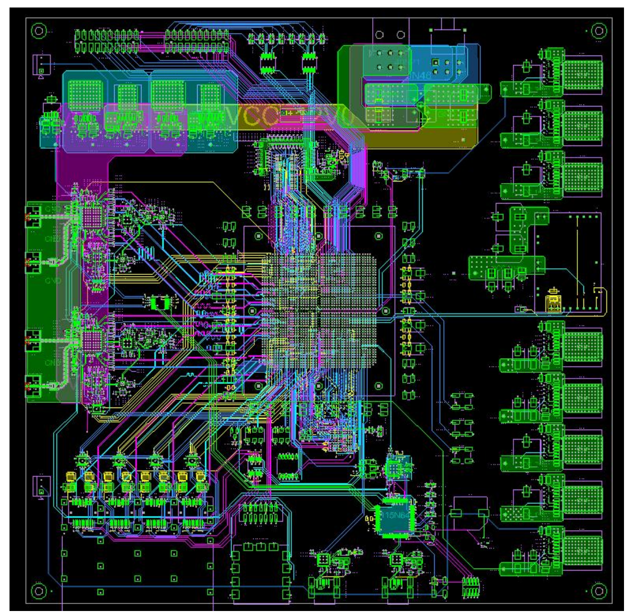
- The project includes two parallel spectrometer implementations
- A FPGA-based rapid prototype will be used for early system testing
- An ASIC-based implementation will enable meeting mass/power constraints
- Both designs will employ external ADCs (20 Gsps), requiring a SERDES interface to the FPGA or ASIC DSP chip
- Two spectrometers will each cover 10 GHz IF bandwidth in the upper and lower sidebands, giving 18 GHz total IF bandwidth (including overlaps)

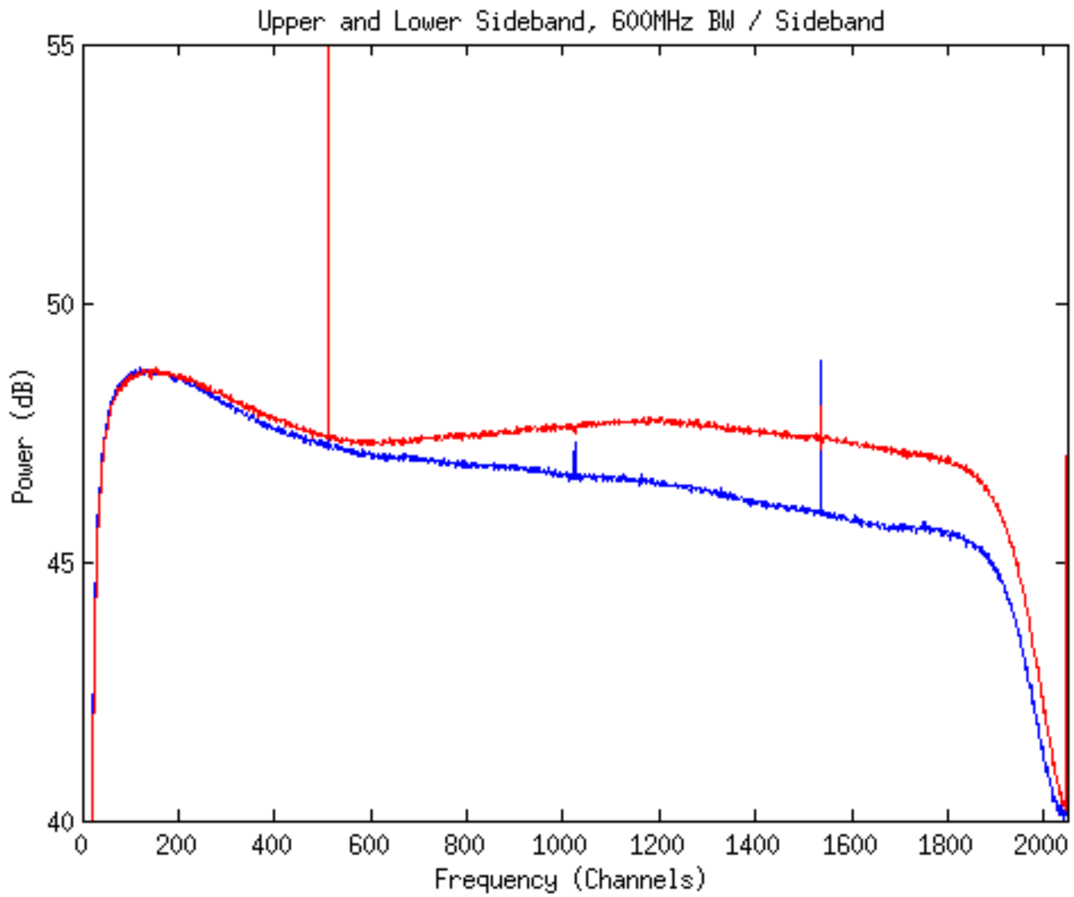


CAMLS spectrometer overview

- For prototyping and experimentation, a lower bandwidth FPGA based spectrometer is under development
  - Using the “ROACH-2” development platform for initial development
  - Enabling verification of the design and sideband separation techniques
- This will be followed by development of the full bandwidth spectrometer on a custom Virtex 7 board
- Development of the ASIC will enable us to meet the CII power requirements
- FGPA and ASIC implementations will both use the same 26 Gsps ADCs from Hittite (running at 20 Gsps)







- First light from the FPGA simple sideband separating spectrometer has been achieved. We are in the process of improving this separation
- Differences in phase and amplitude are measured on chip and corrected

CAMLS ASIC spectrometer status

- A preliminary small "interface test" (non sideband separating) ASIC has been laid out, with the device run to be undertaken soon
- In addition to spectrometer implementation verification, this will allow testing of the "SERDES" communication between the ADCs and ASIC
- The full sideband separating ASIC design and fabrication will follow
- ASIC development has been rapid due in large part to the use of "CHISEL" a new high level logic design language under development at UC Berkeley.

https://chisel.eecs.berkeley.edu/

```
/** A n-bit adder with carry in and carry out
  */
class Adder(val n:Int) extends Module {
  val io = new Bundle {
    val A    = UInt(INPUT, n)
    val B    = UInt(INPUT, n)
    val Cin  = UInt(INPUT, 1)
    val Sum  = UInt(OUTPUT, n)
    val Cout = UInt(OUTPUT, 1)
  }
  //create a vector of FullAdders
  val FAs   = Vec.fill(n){ Module(new FullAdder()).io }
  val carry = Vec.fill(n+1){ UInt(width = 1) }
  val sum   = Vec.fill(n){ Bool() }

  //first carry is the top level carry in
  carry(0) := io.Cin

  //wire up the ports of the full adders
  for (i <- 0 until n) {
    FAs(i).a := io.A(i)
    FAs(i).b := io.B(i)
    FAs(i).cin := carry(i)
    carry(i+1) := FAs(i).cout
    sum(i) := FAs(i).sum.toBool()
  }
  io.Sum := sum.toBits().toUInt()
  io.Cout := carry(n)
}
```

Summary and next steps

- Current status
  - The CAMLS project is largely on course
  - The 340 GHz MMIC device development is on track
  - We have identified a robust path forward for the spectrometers
  - System-level and cryogenics design work is proceeding well

- Planned milestones (most unchanged from last year's ESTF)

  October 2015: Complete prototype spectrometer implementation and testing

  March 2016: Complete 340 GHz receiver fabrication and testing

  October 2016: Complete system I&T using FPGA spectrometers

  December 2016: Complete ASIC spectrometer fabrication and testing

  March 2017: Redo system I&T with ASIC spectrometers

  March 2017: CAMLS test flights (probably using FPGA-based spectrometers)

- Thanks, as ever, to ESTO for their continued support