The Compact, Adaptable Microwave Limb Sounder (CAMLS)

Developing the core system for next-generation
Microwave Limb Sounders

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

William Deal and colleagues
Northrop Grummon Aerospace Systems

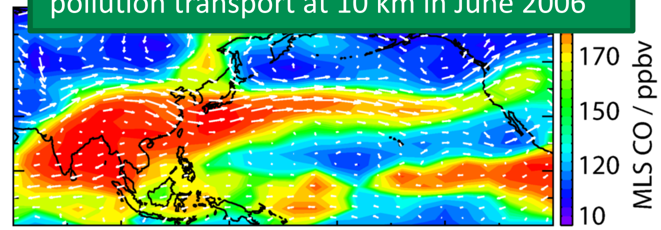
Dan Werthimer, Borivoje Nikolić and colleagues
U.C. Berkeley

CAMLS science motivation – the "UT/LS"

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" (UT/LS 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 strongest
  - 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)

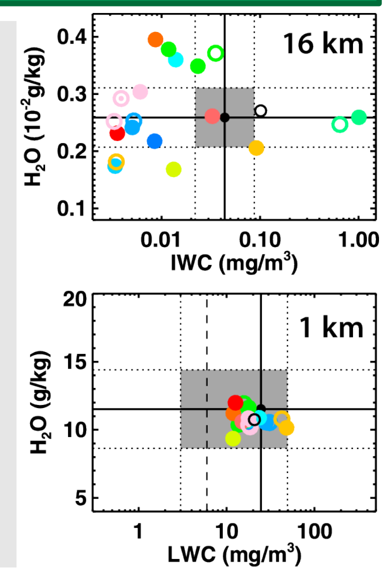
Aura MLS observations of long range CO pollution transport at 10 km in June 2006



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



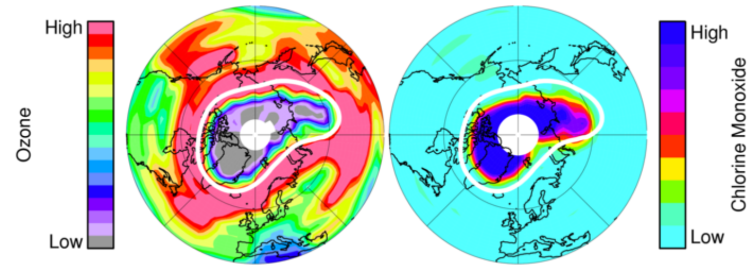
Jiang et al., 2012 JGR

CAMLS science – issues in the stratosphere

Compact Adaptable Microwave Limb Sounder

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

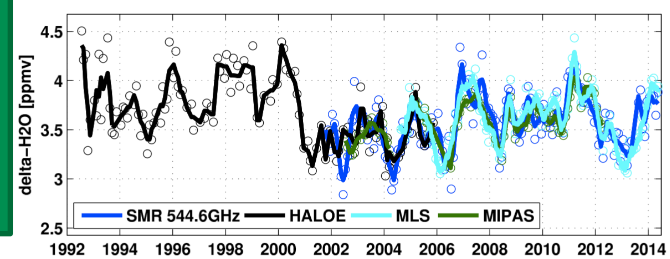
Aura MLS observations ozone (left) and chlorine monoxide (right) – the primary agent of ozone destruction – at ~20 km in March 2011, a period of unprecedented ozone loss in the northern hemisphere



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

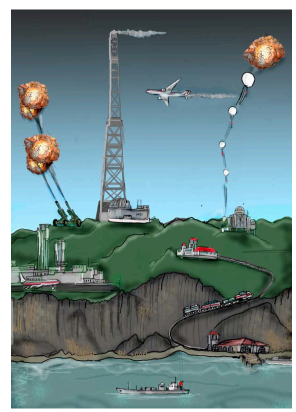


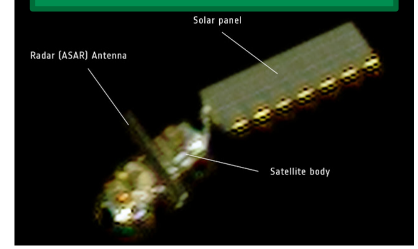
Illustration of various possible approaches to injecting sulfate aerosol into the stratosphere, in order to reduce surface heating

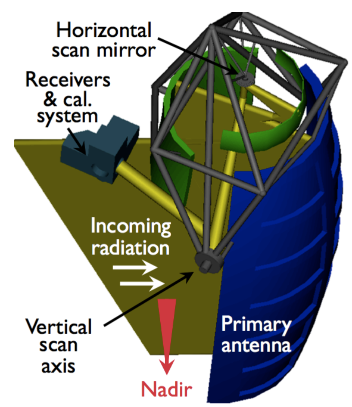
Robock, 2009, GRL

Current state of UT/LS 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, from any agency, 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 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





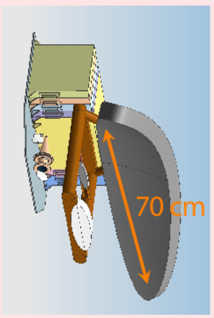
The Scanning MLS instrument concept developed under past IIPs. CAMLS will further advance SMLS technology

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 UT/LS
- The CAMLS project advances technologies common to both of these needs
- We will develop a receiver/spectrometer "core system" making limb sounding observations at 340 GHz. Specifically, we will:
  - Develop 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 SMLS) and at ambient (for "continuity" measurements)
  - Develop a compact low mass/power digital spectrometer back end, enabled by dramatic innovations driven by the communications industry
  - Integrate these into a receiver/spectrometer system and demonstrate performance over the needed temperature range
  - Incorporate this, with coolers, into the A-SMLS airborne instrument, establishing TRL-6

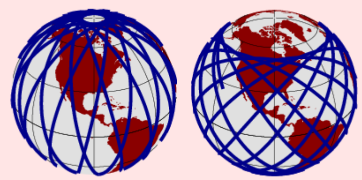
CAMLS "Point design" instrument concepts

CONtinuity STRatosphere and Upper-troposphere Experiment (CONSTRUE): Integrate with heritage antenna and fly as instrument of opportunity (e.g., for Earth Venture or "Climate Continuity")



Science:
- Continue long-term upper troposphere and stratosphere observation record
- Quantify impacts of key processes, their evolution, and feedbacks on climate, air quality and ozone layer stability
- Precessing orbit would enable coverage of full diurnal cycle

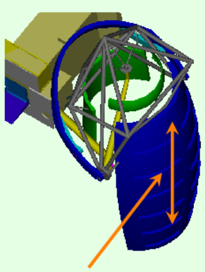
Coverage: "single pixel" ~50 km along track sampling (coverage in sun-synchronous and inclined orbits shown below)



Requirements: (as above for CAMLS plus…)
- 2900 K receiver noise temperature or better (2400 K goal)
- ~50 ms integration time

Technology / Opportunities:
- Integrate with simple antenna, as proven with MLS on UARS and Aura
- Meets Earth Venture "Common Instrument Interface" standard
- Ideal instrument of opportunity or component of small atmospheric composition mission (e.g., to ISS)
- **~20 kg, ~80 W, 0.7 m antenna size, ~0.01 m^3 electronics**
- Aura MLS was 350 kg, 370 W, 1.6 m antenna, ~1 m^3 electronics

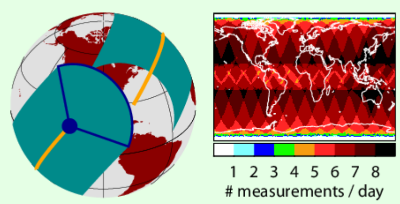
Scanning MLS: Cool LNA, integrate with scanning antenna and fly as component of comprehensive atmospheric composition mission



4 m currently. 2.8 m with CAMLS.

Science:
- As above for CONSTRUE plus…
- Multiple observations per day with ~50 × 50 km horizontal resolution
- Enables quantification of impacts of "fast processes" such as deep convection
- Resolution matches that needed to validate and improve climate models

Coverage: ~8000-km swath covering ~40% of the globe each orbit (varies with orbit altitude, 1500-km Mid-Earth Orbit assumed herein)



Requirements: (as above for CAMLS plus…)
- 330 K receiver noise temperature or better (270 K goal)
- ~3-ms integration time

Technology / Opportunities:
- Cooling receivers to 20 K enables ~80-fold decrease in integration time
- Integrate with "scanning" antenna developed under the 2010 IIP program
- Azimuth scanning accomplished by fast-moving ~20-cm mirror (4-m antenna only scans every ~10 s)
- Ideal for dedicated comprehensive atmospheric composition mission (e.g., in Decadal Survey)

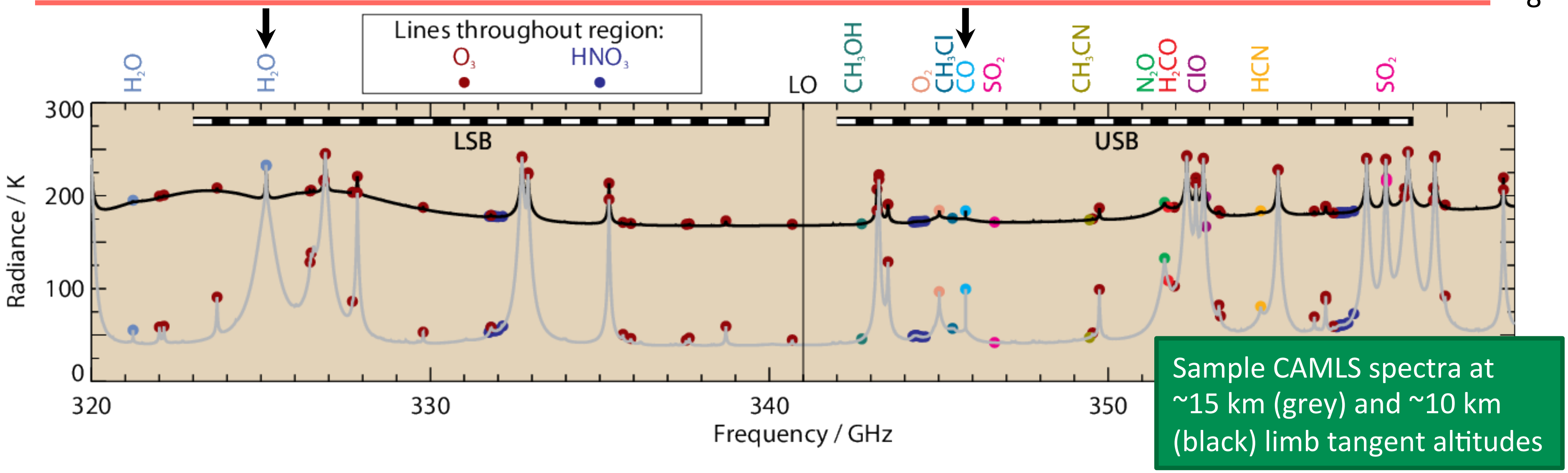
CAMLS measurements

The CAMLS-class instruments make global vertical profile observations of multiple species directly affecting climate, air quality and ozone layer stability twice daily (or more frequently for SMLS). Profile measurements include:

- **H_2O:** Strongest greenhouse gas, greatest impact in UT/LS
- **O_3:** Greenhouse gas and pollutant in troposphere, solar ultraviolet shield in stratosphere
- **CO, CH_2O, HCN, CH_3CN, CH_3OH, SO_2:** Tracers and markers of emissions from different sources
- **HNO_3:** Important player in air pollution formation and in stratospheric ozone chemistry
- **ClO, CH_3Cl, N_2O, BrO, HO_2:** Critical players in stratospheric ozone chemistry and related processes
- **Cloud ice:** Marker of convection and key climate variable

All measurements are made both day and night, and in the presence of aerosol and all but the thickest clouds.

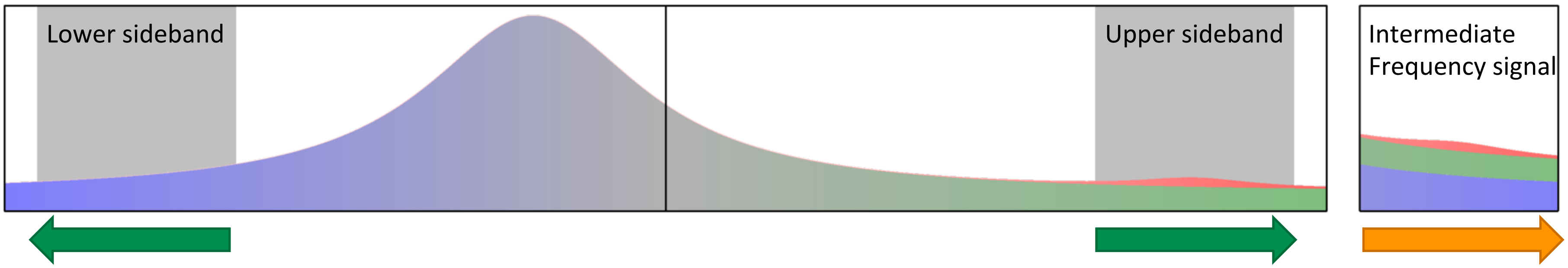
CAMLS radiance measurements



- **All the CAMLS measurements are made with a single 340 GHz receiver**
- This region includes lines for both H_2O and CO (black arrows above), key molecules whose lines are somewhat rare in the spectrum
- Aura MLS used separate 190 and 240 GHz receivers to target these species
- The CAMLS higher frequency enables a 30 – 50% reduction in antenna size for the same limb field of view width (equates to vertical resolution)
- The 340 GHz region can still penetrate to useful depths in the upper troposphere, unlike higher frequencies (e.g., 640 GHz)

The importance of sideband separation

Aura MLS “folded sideband” configuration



The Aura MLS receivers take the two spectra on either side of the local oscillator and fold them on top of each other to give the observed “Intermediate Frequency” (IF) signal…

… as a sum of the lower and upper sideband

- The “folded sideband” nature of the Aura MLS signals presents a significant challenge to measurements in the UT/LS
- The far-wing/continuum signal in the upper sideband (green) adds a “baseline” but also partially attenuate 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”)
- **CAMLS solves this by reporting upper and lower sideband separately**

Relationship to prior ESTO-supported efforts

IIP-2007: (Paul Stek, PI) developed system-level technologies for a 4 K-cooled SIS-based SMLS prototype airborne instrument at 190, 240 and 640 GHz (including receivers developed under previous ACTs). The end product was the "Airborne-SMLS" instrument

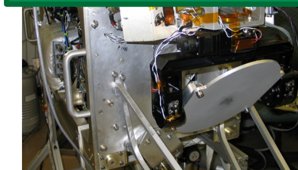
IIP-2010: (Rick Cofield, PI) developed the 4 m tall SMLS antenna and is advancing its TRL through demonstrating needed field of view responses and thermal stability

ACT-2011: (Goutam Chattopadhyay, PI) is developing MMIC-LNA versions of the 240 and 640 GHz receivers for SMLS

Other programs: (SBIR, PIDDP) have supported the development of the digital spectrometers to be further advanced by this project

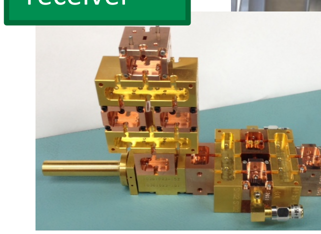
IIP-2013: (Nathaniel Livesey, PI, this project) is developing the single-receiver sideband separating 340 GHz MMIC LNA, wide-bandwidth spectrometer next generation "Compact Adaptable Microwave Limb Sounder" (CAMLS) that can serve as the core of both SMLS and a more compact "continuity" instrument

IIP-2007: The SIS-based A-SMLS instrument

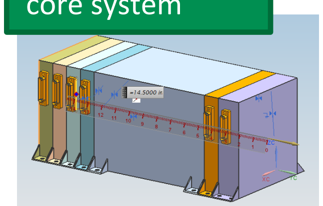


IIP-2010: SMLS 4-m antenna

ACT-2011: 240 GHz HEMT receiver



IIP-2013: CAMLS core system



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, 8[b] bandpass filter / attenuator / amplifier chains
Spectrometers	542 individual channels (discrete capacitors, inductors etc.) plus 4 narrow-band Digital Autocorrelator Spectrometers	4[c] 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[d]	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

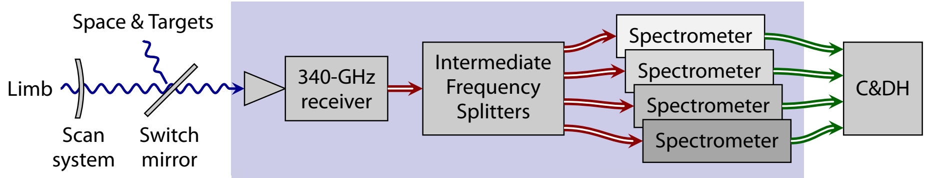
[b] Potential simplification to 4 filter / attenuator / amplifier chains, see later

[c] Potential simplification to 2, see later

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

CAMLS high level block diagram vs. Aura MLS

CAMLS, blue shading shows "core system"



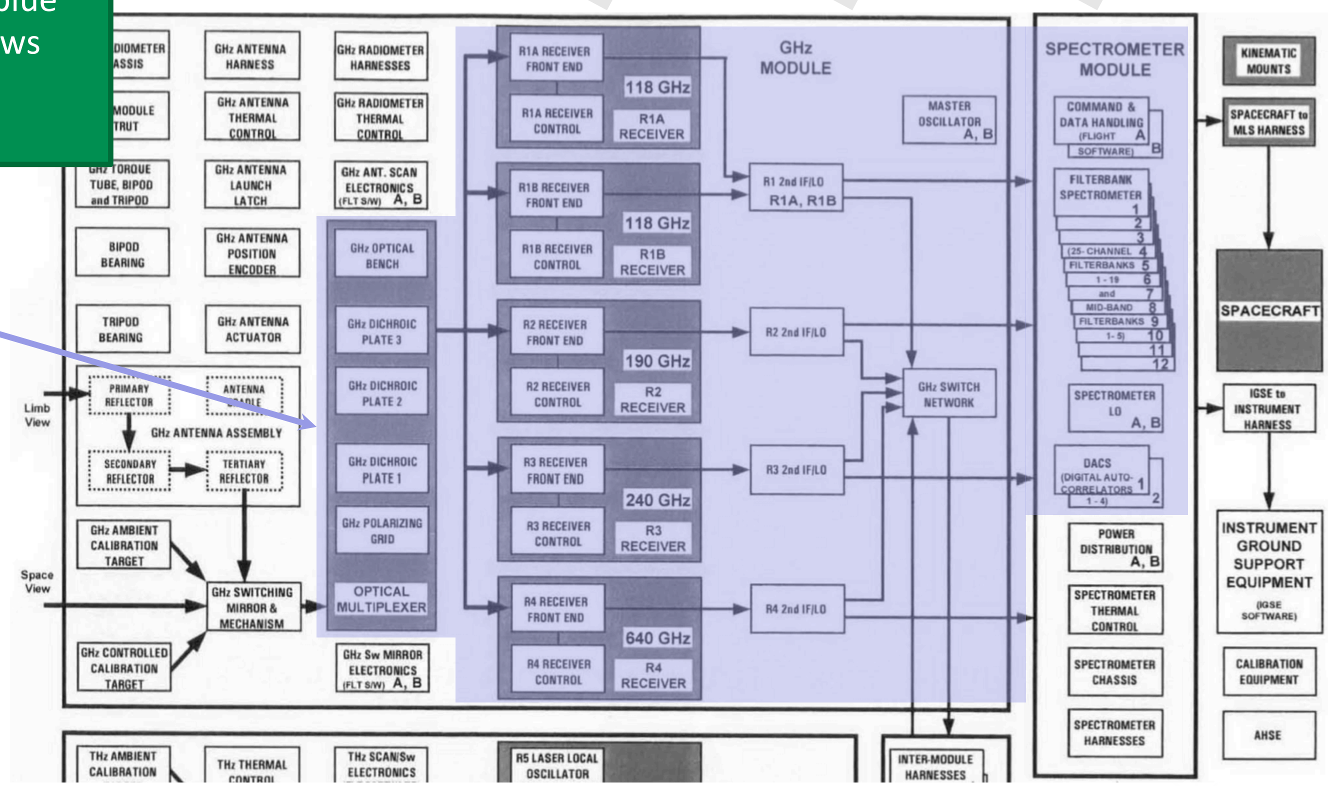
Receivers

IF processing

Spectrometers

Aura MLS, blue shading shows comparable subsystems

Optical multiplexer (CAMLS dispenses with this)



CAMLS design philosophy and choices

Our approach to this project is centered on advancing the TRL of the components, subsystems and system that we anticipate proposing for future flight opportunities

- The inclusion of CAMLS in the airborne A-SMLS instrument does represent an attractive upgrade to that instrument, but it is not the driver for this project

This philosophy drives our technology, design and implementation choices

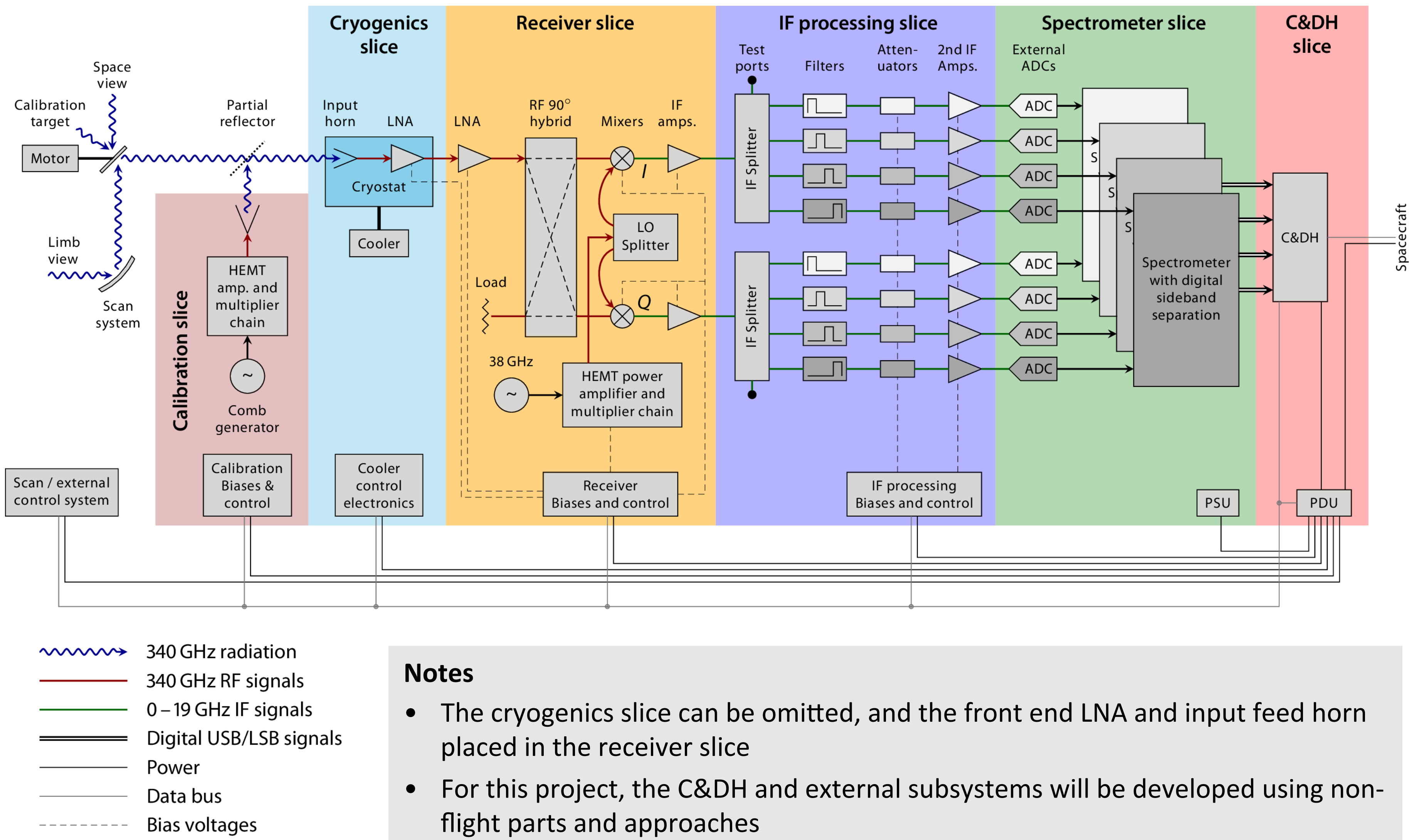
Receivers: The MMIC LNA is the only receiver technology that combines performance needed for SMLS when cooled (e.g., to 20K) while still working well at ambient (for "continuity" measurements)

- Schottkey diodes don't show as dramatic improvements in S/N with cooling
- SIS only work at 4 K or colder temperatures

Spectrometers: Broadband digital spectrometers offer dramatic reductions in mass/power/volume and have excellent spectral resolution and broadband accuracy. In addition, the "polyphase" approach offers very sharp channels with insignificant overlap, increasing resiliency to RFI, and making the "Level 2" algorithms much more straightforward.

CAMLS detailed block diagram

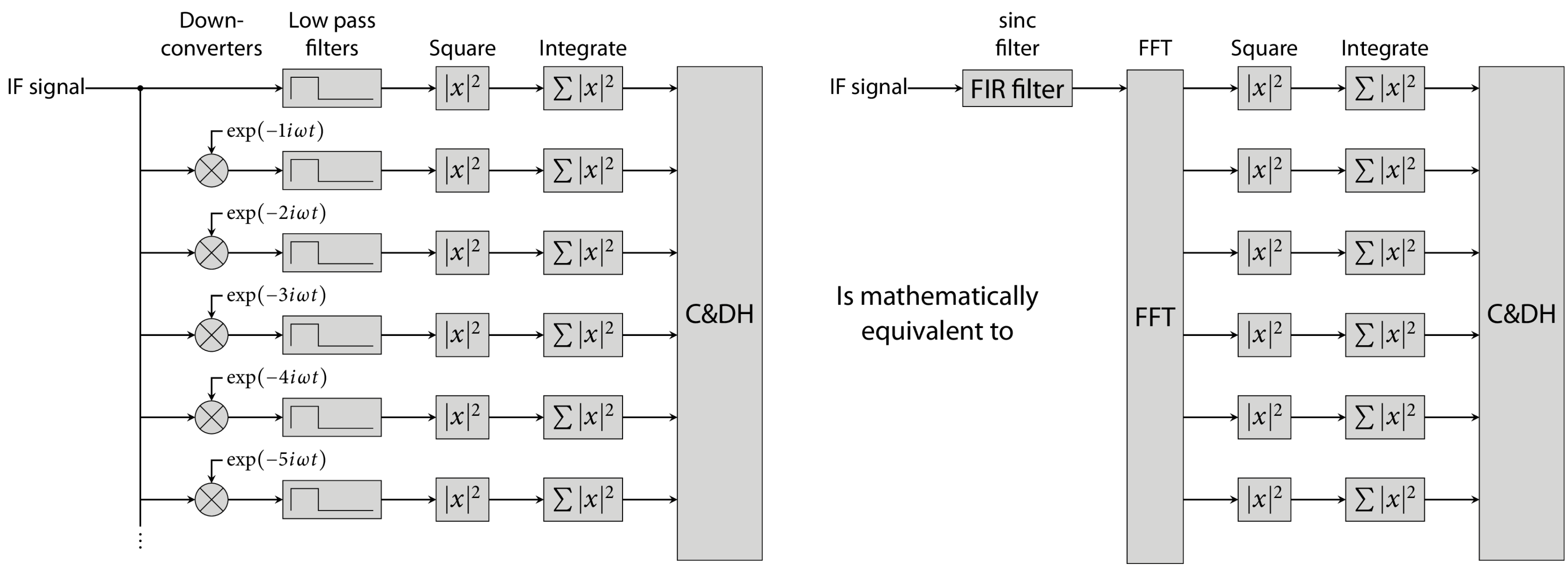
Compact Adaptable Microwave Limb Sounder



Notes

- The cryogenics slice can be omitted, and the front end LNA and input feed horn placed in the receiver slice
- For this project, the C&DH and external subsystems will be developed using non-flight parts and approaches

Polyphase spectrometer approach

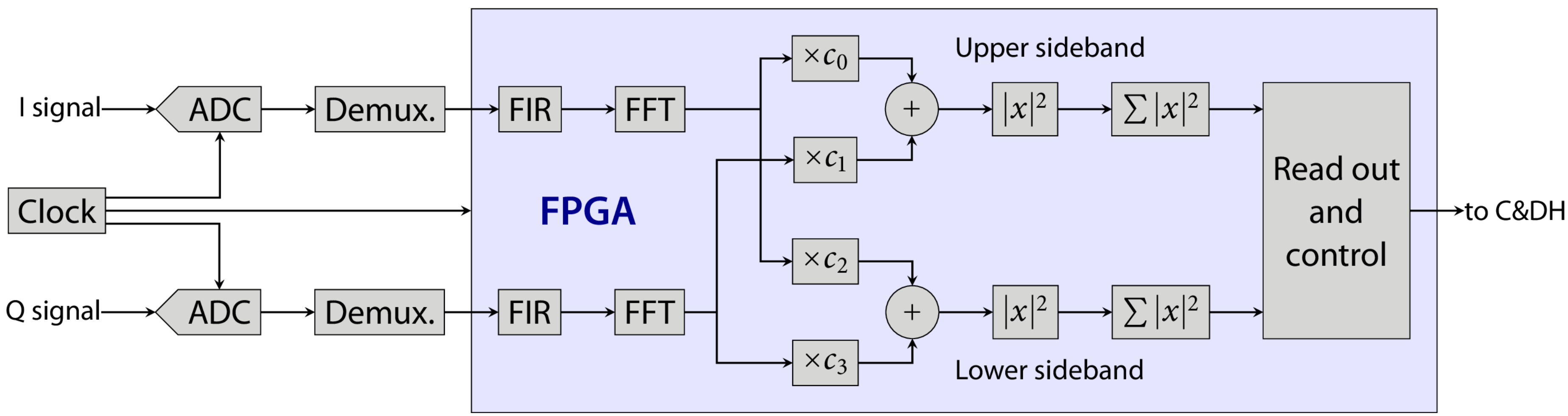


- Digital spectrometers (particularly ASIC implementations) offer dramatic reductions in mass and power over conventional analog systems
- "Polyphase" spectrometers offer much sharper channels than the sinc channel shapes obtained from FFT and autocorrelator spectrometers
  - This is important for calibration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

CAMLS spectrometer FPGA implementation

Compact Adaptable Microwave Limb Sounder

- The project includes two parallel spectrometer implementations
- A FPGA-based rapid prototype will be used for early system testing
- Four spectrometers will each cover 5 GHz IF bandwidth in the upper and lower sidebands, giving 18 GHz total IF bandwidth (including overlaps)
- We will employ external ADCs (10 Gsps), requiring a "Demux." stage to interface to the FPGA
  - The first run of these (supported under the SBIR program) exhibit problems running at 10 Gsps (6–8 Gsps is OK). We will start with these, but rework (funded by other programs) is planned



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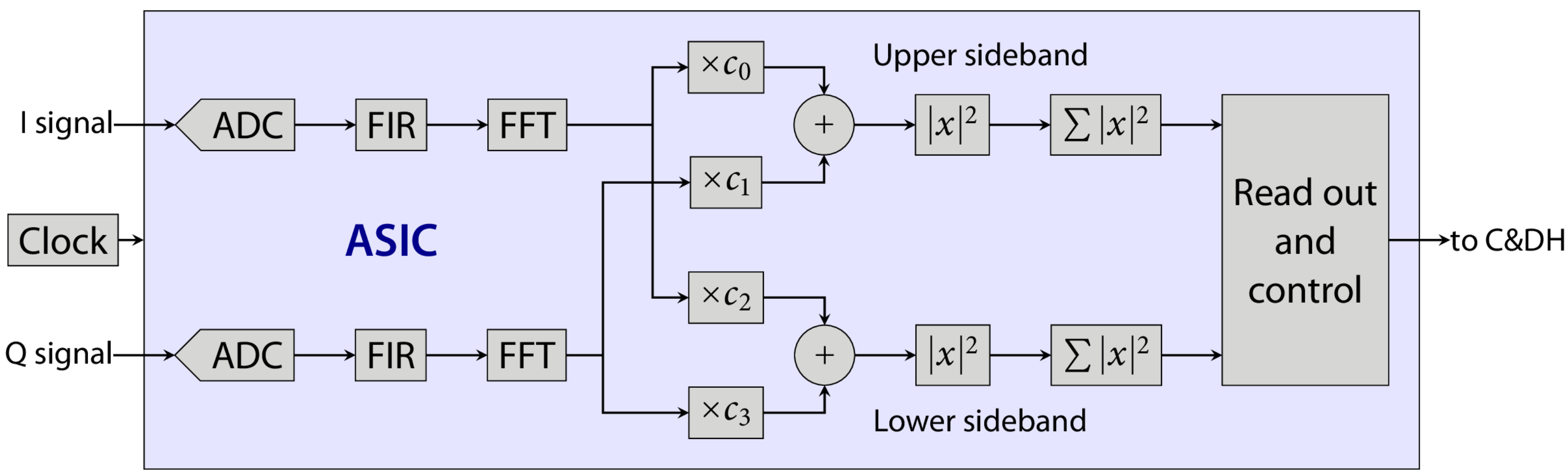
CAMLS spectrometer FPGA implementation

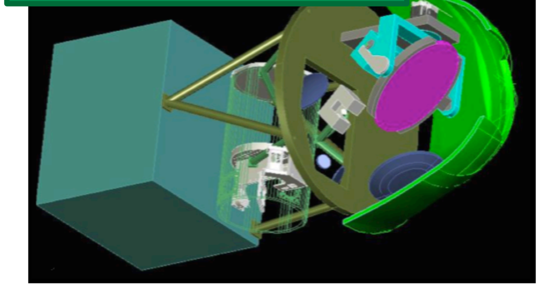
- The FPGA implementation demands too much resources to be used in flight (200 W for the complete ±18 GHz IF)
- An ASIC implementation uses only ~2 – 4 W
- Again, we will have four 5 GHz spectrometers covering 18 GHz IF bandwidth
- Our U.C. Berkeley colleagues are developing the ASIC version
- In a change from the proposed route, this will including an onboard ADC
  - Note that the integrated ADCs will be designed to be capable of 20 Gsps (10 GHz IF bandwidth per spectrometer, to advance the technology further)



Integration with A-SMLS

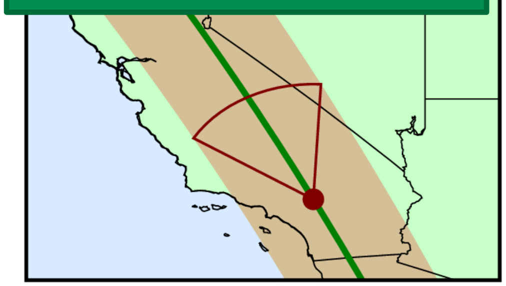
- The Airborne Scanning Microwave Limb Sounder (A-SMLS) was initially developed under IIP-2007
  - It was proposed to serve as both risk reduction for SIS-based SMLS technologies and as a “free-standing” aircraft instrument
  - A-SMLS currently uses a 4 K-cooled 240-GHz SIS receiver, with an option to add others
  - It has successfully flown on the WB-57
- A-SMLS makes 2-D scanning microwave limb observations of UT/LS composition from a high-altitude aircraft
  - A-SMLS has a ~300 km swath width in the UT/LS 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



A-SMLS integration (cont.)

- 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
  - Measuring 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 mandated flying cryogen)
  - Cooling to 60 K provides sufficient signal to noise for useful science, and airworthy coolers are readily available, extending flight duration
- A-SMLS with CAMLS technology would be ideally suited to a long duration high altitude UAV flight in future atmospheric composition campaigns
  - Such "field survey" observations would be a great complement to more detailed in situ observations from lower altitude aircraft
  - A-SMLS observations could be used in real time to direct other aircraft towards features of interest

CAMLS schedule summary

- Planned milestones

  March 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 to ESTO for the much-appreciated support