A Constellation of Fourier Transform Spectrometer (FTS) CubeSats for Global Measurements of Three-Dimensional Winds

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HARRIS®

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The FTS CubeSat Mission

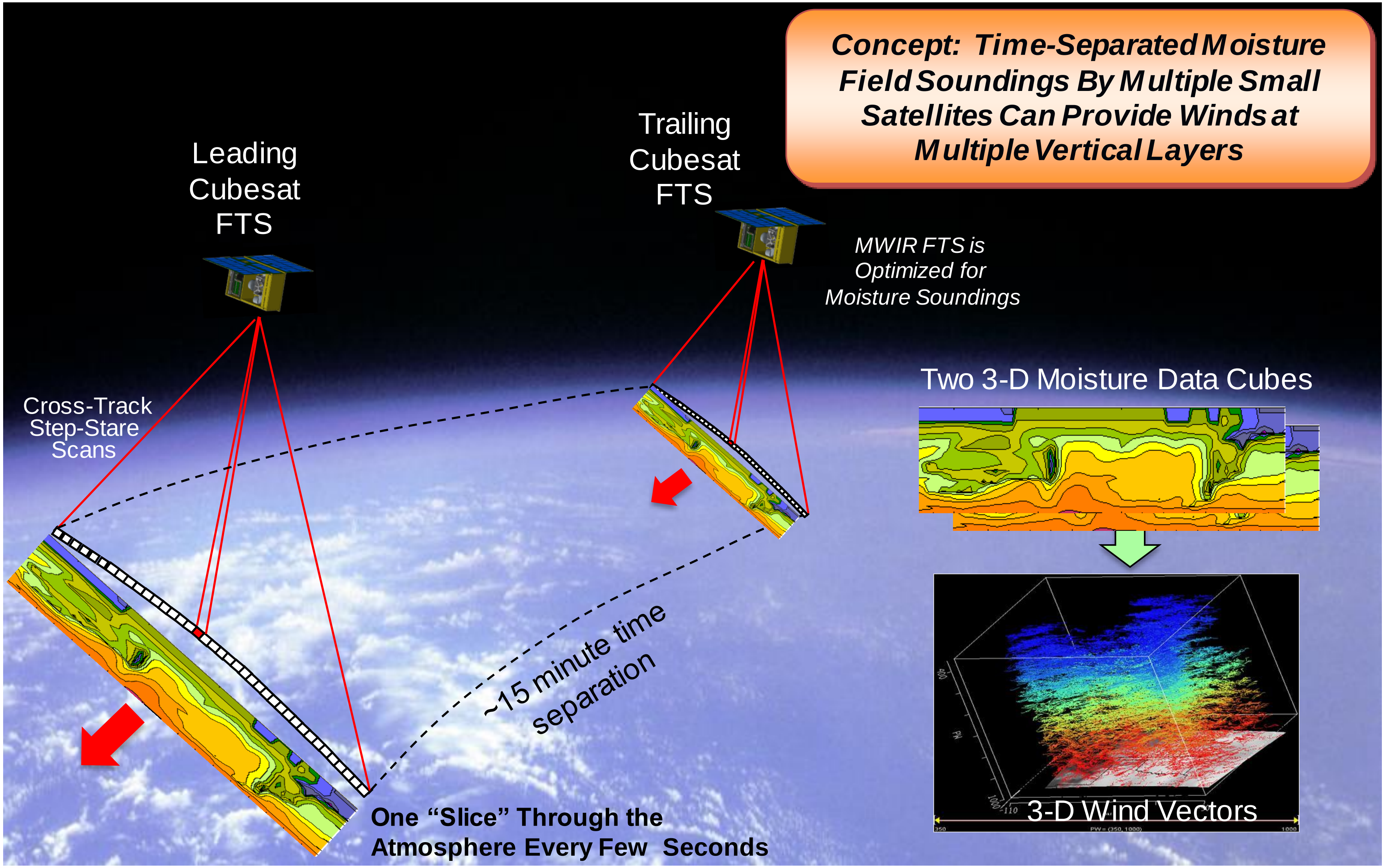
Use a small constellation of 6U CubeSats equipped with hyperspectral Fourier Transform Spectrometer (FTS) instruments to provide measurements of global tropospheric wind profiles from space

- Vertically-resolved winds as a function of altitude
- Achieved through moisture soundings by the FTS instruments

Vertically-resolved global wind data is valuable for several applications

- Improvements to weather forecasts, especially in low-latitude regions and over oceans
- Improved hurricane intensity and track predictions
- Earlier warning of severe weather (e.g., tornadoes)

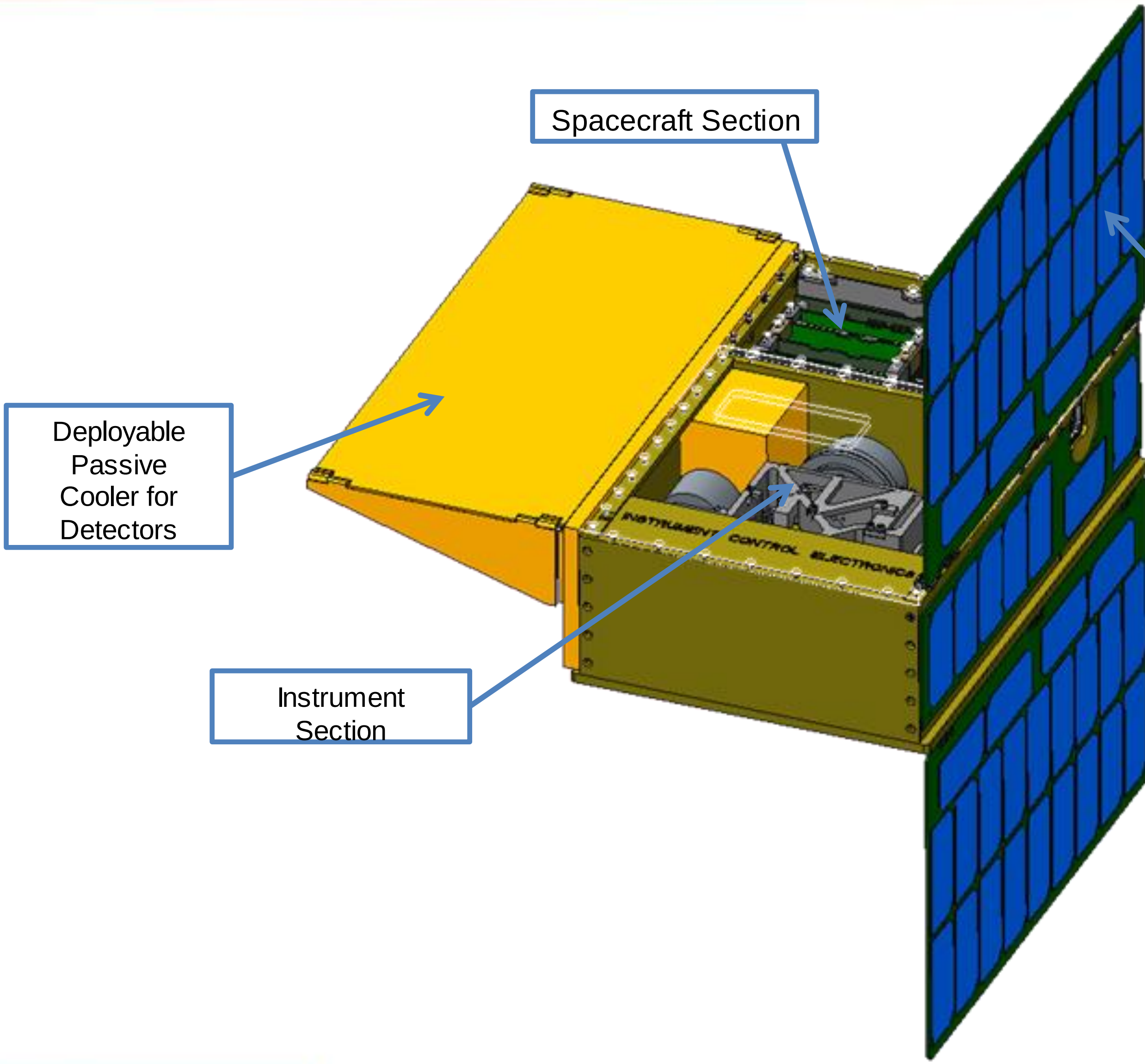
3-D Wind Measurements Using FTS CubeSats



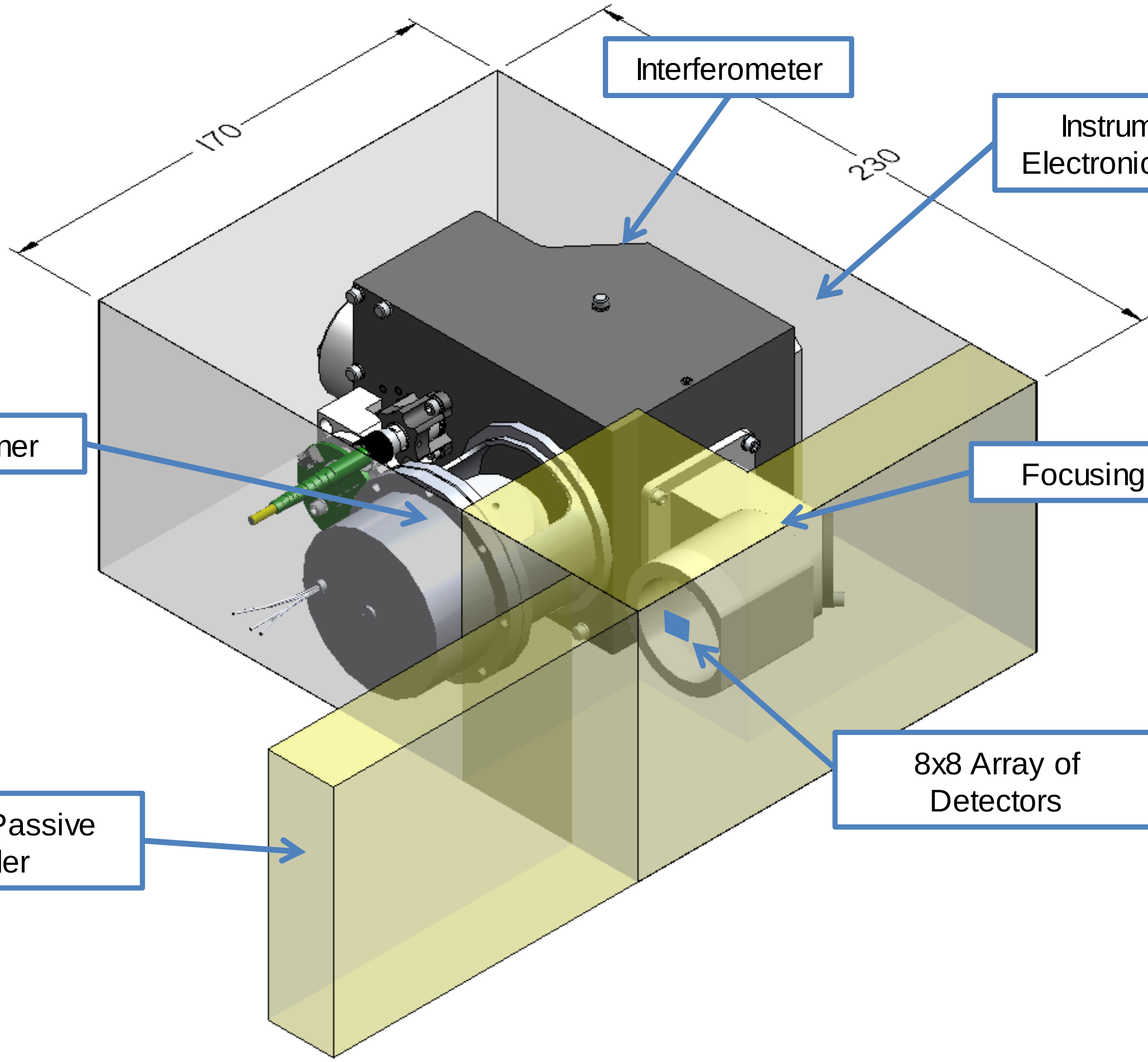
Wind Extraction Measurement Technique

- **Each FTS CubeSat is equipped with a hyperspectral Mid-Wave Infrared (MWIR) instrument which provides hundreds of spectral channels**
  - Data is used to retrieve the vertical moisture distribution at each ground location
  - In effect, each satellite will construct a 3-D moisture data cube
- **A second FTS CubeSat will fly over the same ground track roughly 15 minutes later**
  - From moisture feature movements between the two data cubes, wind vectors can be extracted at multiple vertical locations
- **12-satellite polar constellation provides twice-daily coverage at equator, more frequent at higher latitudes**

FTS CubeSat Concept (6U)



Instrument Section Details



Instrument Section Key Parameters

Parameter	Value
Spectral Range	5.7 – 8.3 microns
Spectral Resolution	1.26 cm^{-1}
NEdN	0.15 mW/(cm^{-1} m^2 sr)
Swath	730km
GSD	5.1 km; 8x8 array
Mass	5 kg
Power	20 W
FPA Cooling	Passive
Total Cycle Time	6.25 seconds
Operating Temperature	Nominal 20°C (15-25)
Orbit Altitude	650 km
Interferogram Acquisition Time	0.2 seconds
Absolute Calibration Accuracy	<0.5K

Instrument Concept Operations

The step-stare scanner performs 16 cross-track steps per scan line

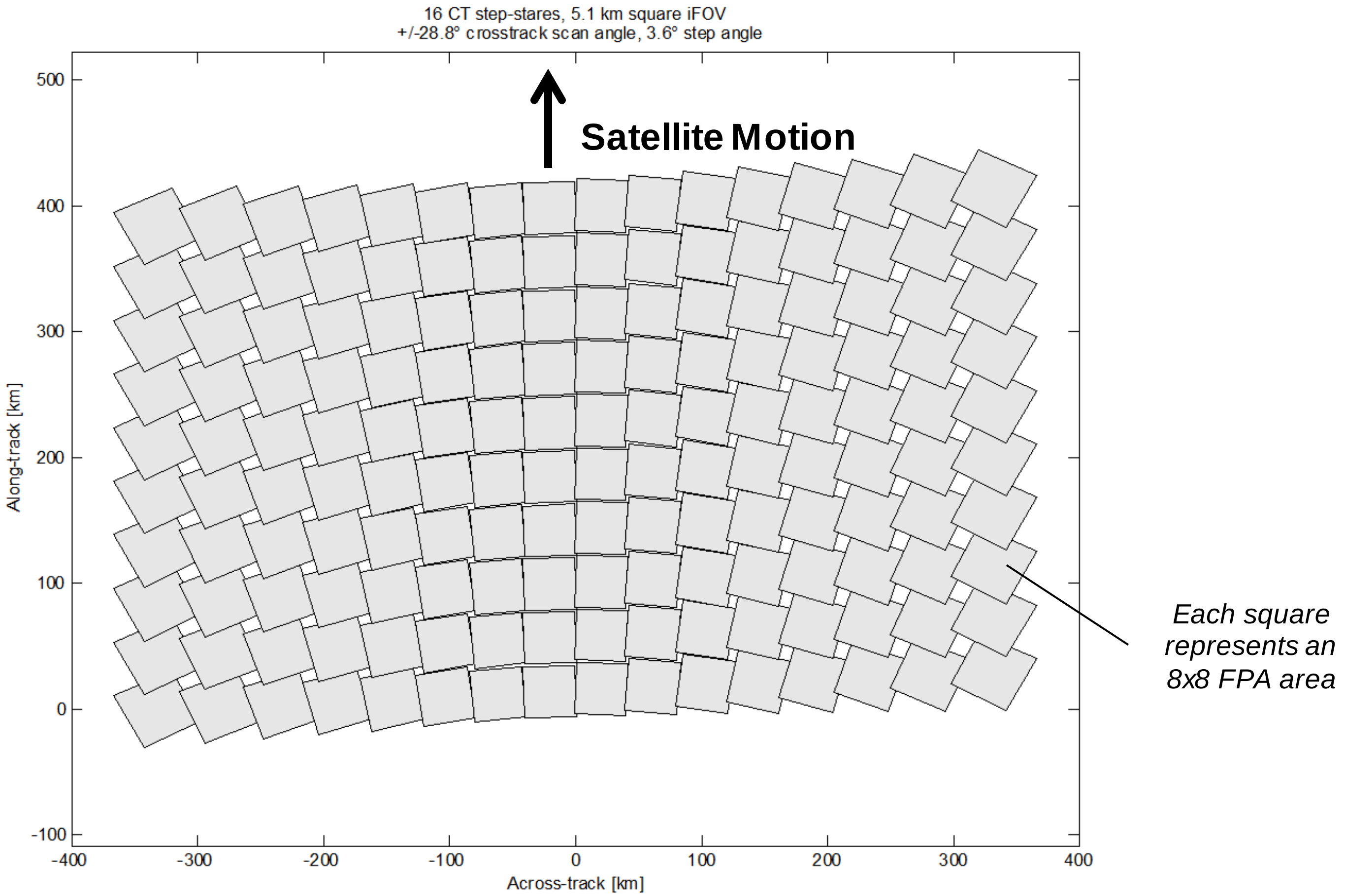
- A 3.6-degree step-stare occurs every 0.3 sec (0.1 sec step time)
- The interferometer performs a +/- 0.476cm Optical Path Difference (OPD) sweep in 0.2 seconds, and creates a double-sided interferogram in each sweep.
- Simple focusing optics behind the interferometer place the optical beam onto the 8x8 array of SLS detectors
- Electronics convert the interferograms to calibrated spectra in real time, select key spectral channels, and route this data to the Spacecraft Section

At its nominal altitude of 650km, each detector has a ground footprint at nadir of 5.1 km, and the overall array has a field of view of 41x41km at nadir

- Ground swath is about 730km wide

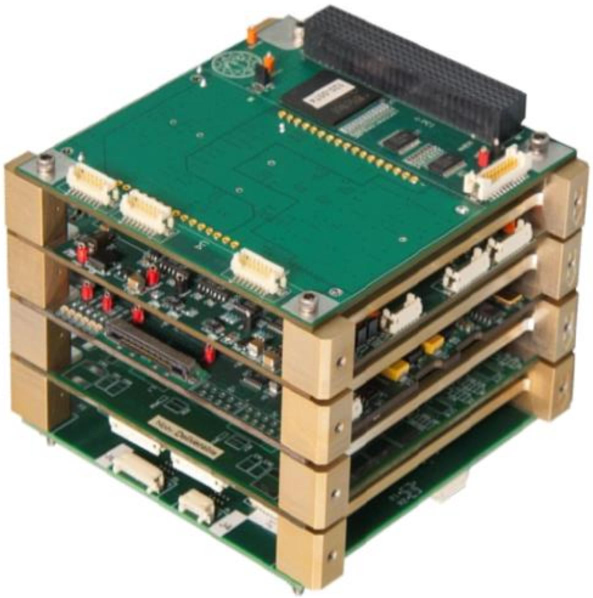
Data is downlinked to the ground every few orbits

Instrument Concept of Operations



The ground swath is shown above. The goal is to minimize gaps in the collected data

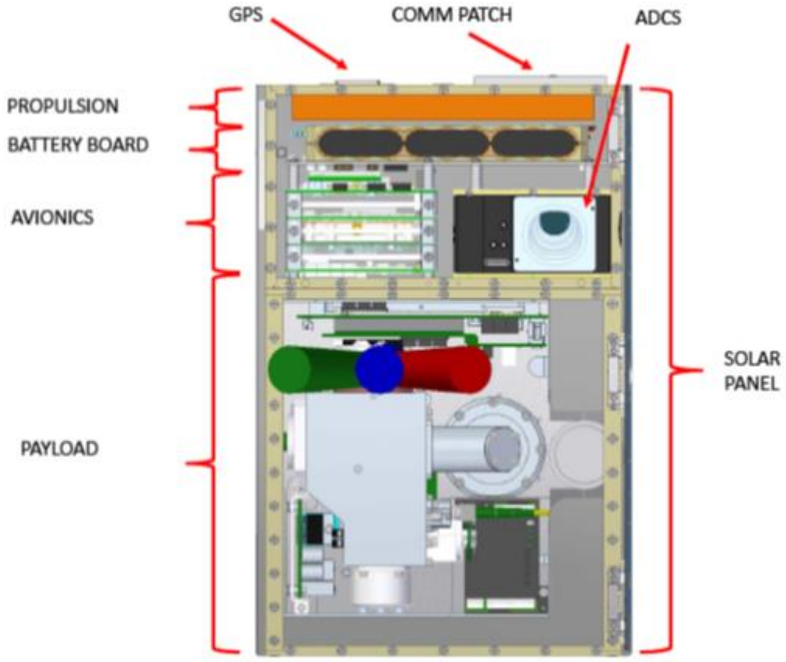
Spacecraft Section of 6U CubeSat



Provides power, attitude control, and data downlink for the instrument

- Components made by Space Dynamics Laboratory (SDL), particularly the reuse of avionics from the PEARL CubeSat electronics
- PEARL offers higher reliability than traditional CubeSats, and the avionics are radiation tolerant to ensure extended mission lifetimes of several years

Spacecraft Section of 6U CubeSat



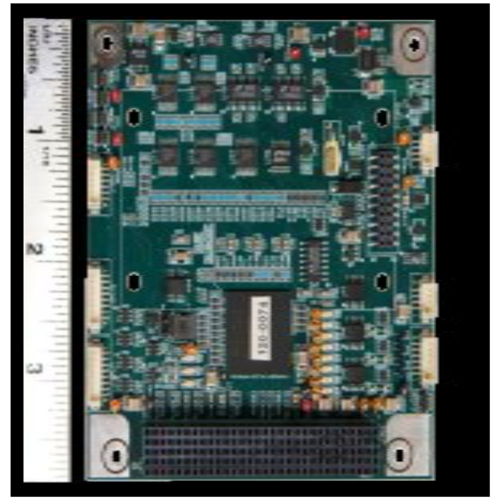
Spacecraft Section Features:

- 32-bit SPARC processor
- VxWorks Operating System
- PEARLSoft Flight Software
- 12V / 2.15A-h battery
- Power system capable of up to 40 W peak power
- S-Band radio for uplinks and downlinks at up to 2 Mbps
- Low thrust propulsion system to maintain the relative orbital spacing between the FTS CubeSats
- 3-axis Stabilized Attitude Control Unit
- GPS Receiver Unit

Spacecraft Electrical Boards

Bus Interface Controller (BIC)

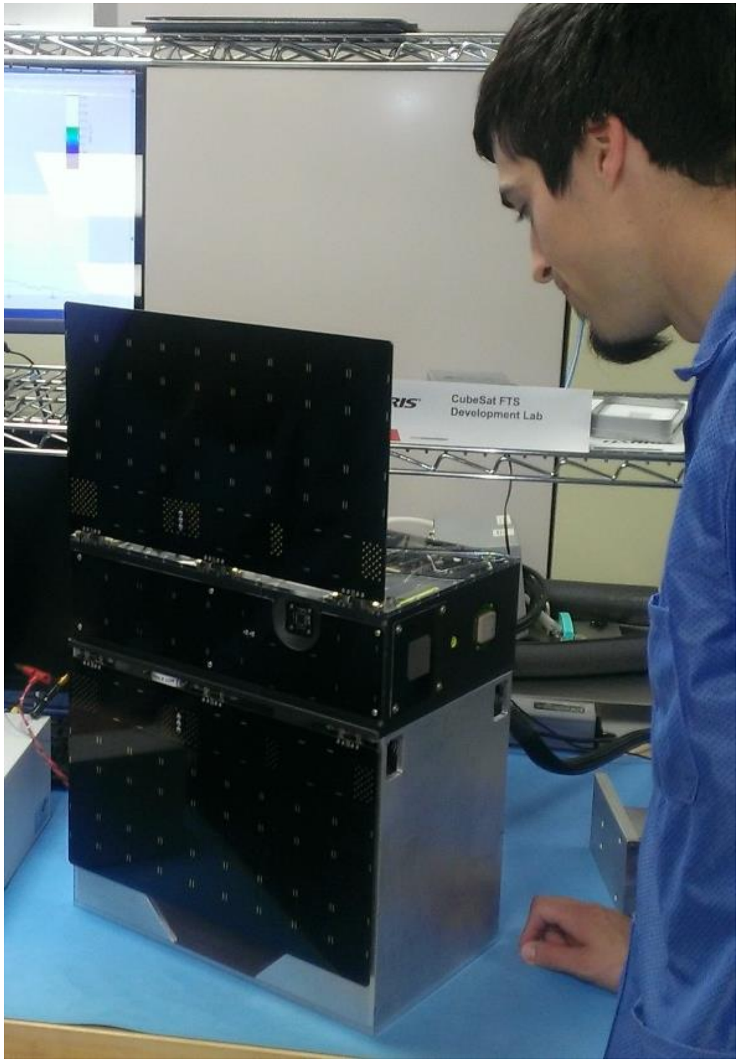
Payload/Radio Board (PRB)



PEARL Interface Board (PIB)

Maximum Peak Power Tracking Electrical Power Systems (EPS)

FTS CubeSat Prototype



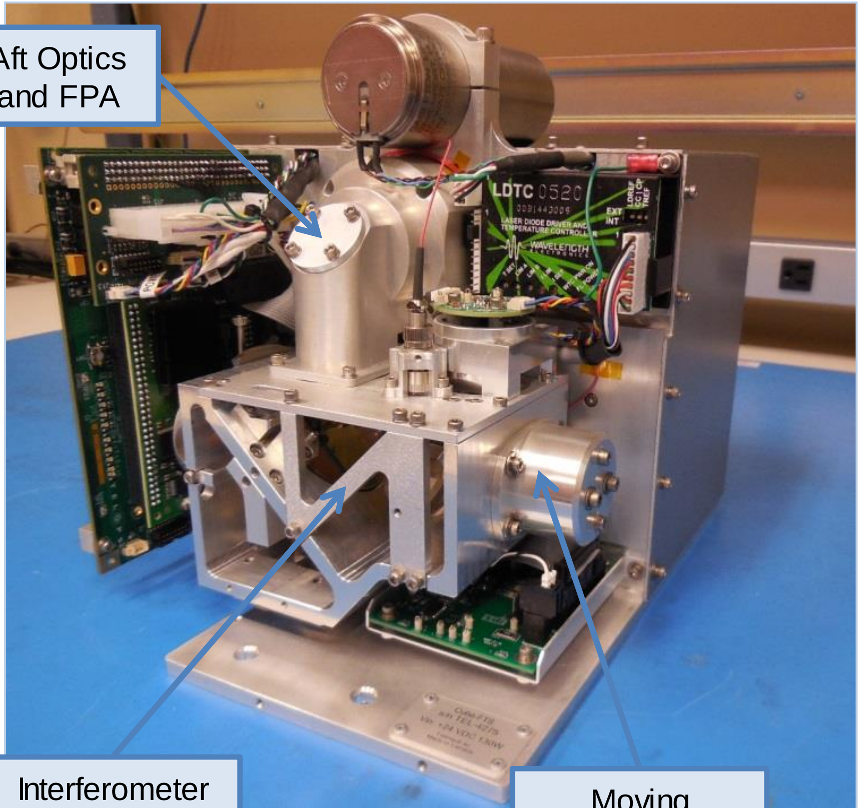
Harris and its teammates, have recently completed building a complete end-to-end laboratory prototype of the FTS CubeSat in a 6U configuration

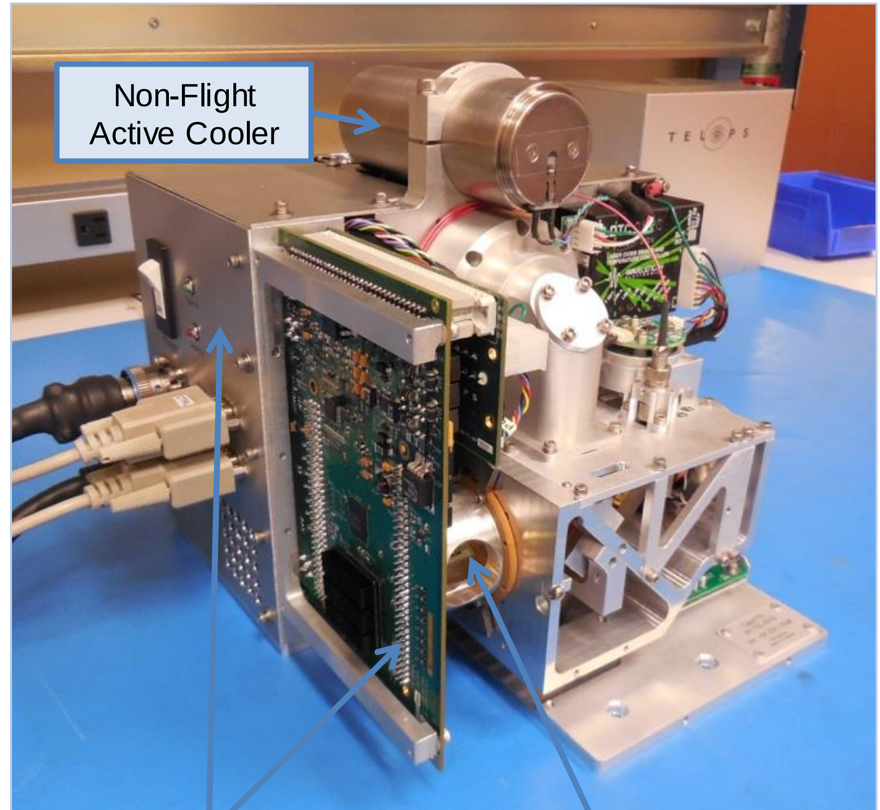
Used to verify:

- Packaging feasibility
- Overall performance
- Hardware/software interoperability between the Instrument and Spacecraft sections

FTS CubeSat Prototype Has Been On Display This Week at the Harris Booth

FTS CubeSat Prototype: Instrument Section





FTS Prototype Instrument Section

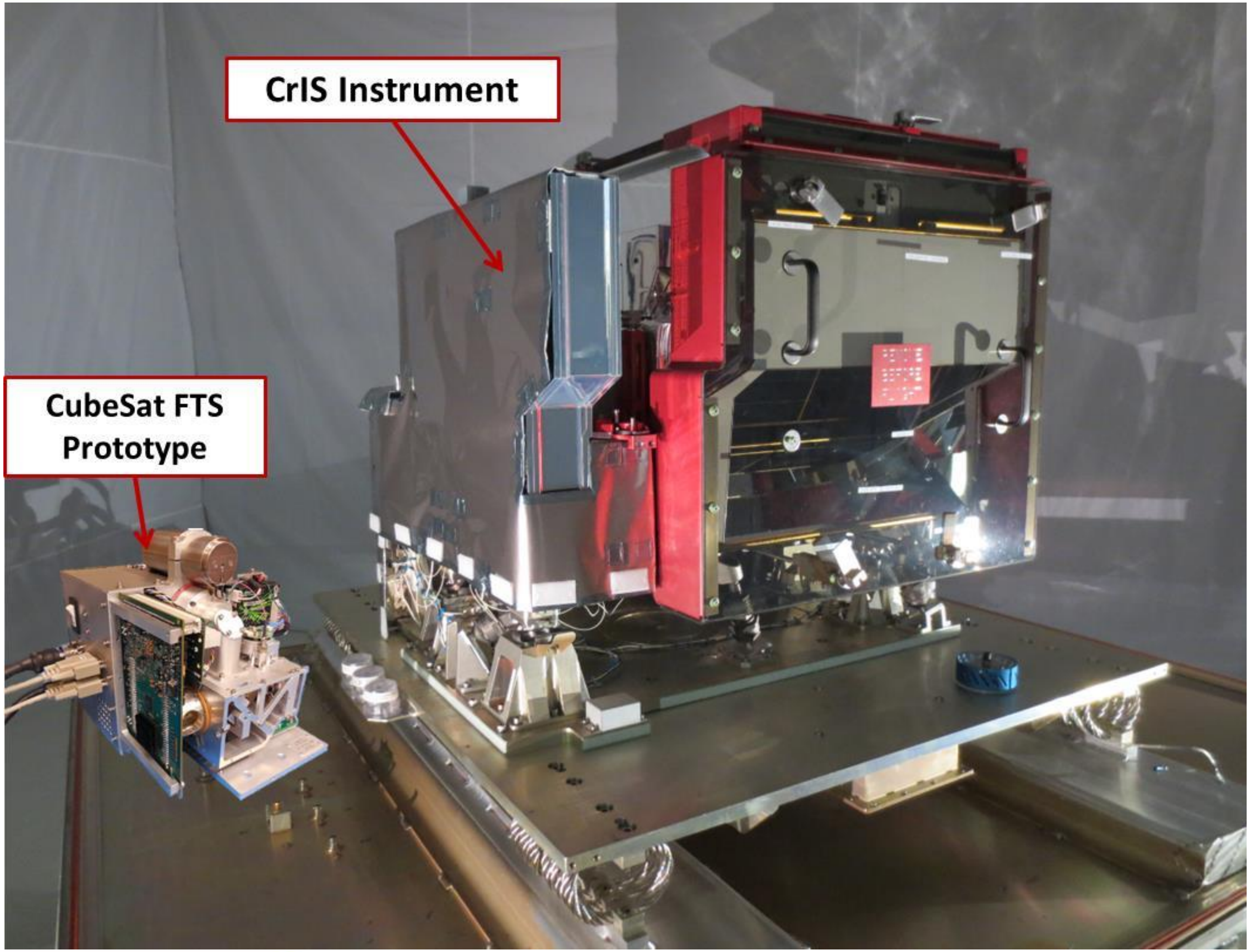
Instrument is opto-mechanically very similar to the flight design

- 1.3cm Aperture
- ±0.476 OPD Sweep Distance
- Signal processing electronics which convert the interferograms to calibrated spectra

There are a few differences, however:

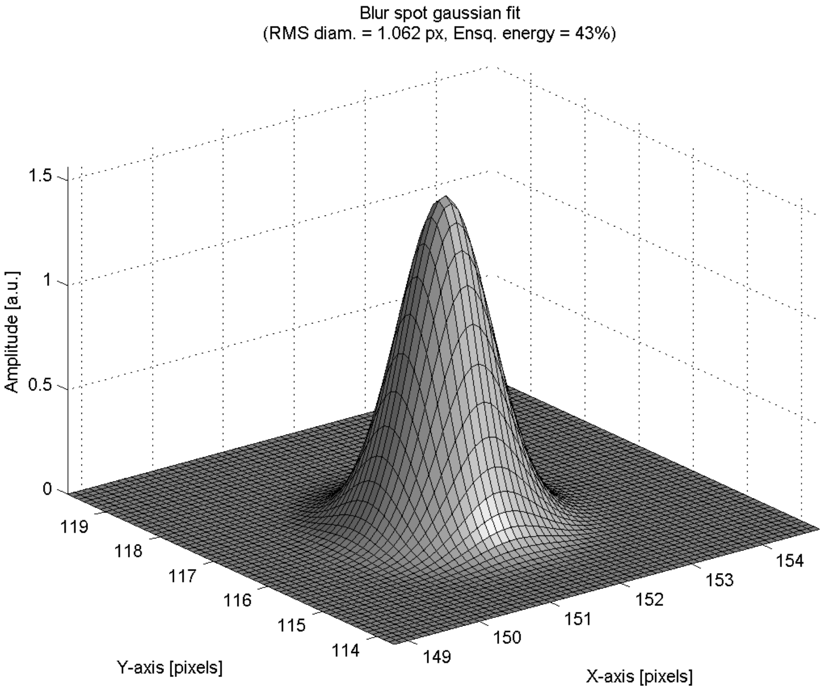
- FPA is a larger-format array with readout of 128x48 pixels that are then aggregated to a more flight-like 6x6 effective FPA
- A small ground-only active cooler has been added
- Instrument electronics are somewhat larger in board area and power than the flight boards
  - Miniaturization of electronics is now underway

CubeSat FTS Instrument is Much Smaller Than the CrIS Instrument, Also Built by Harris



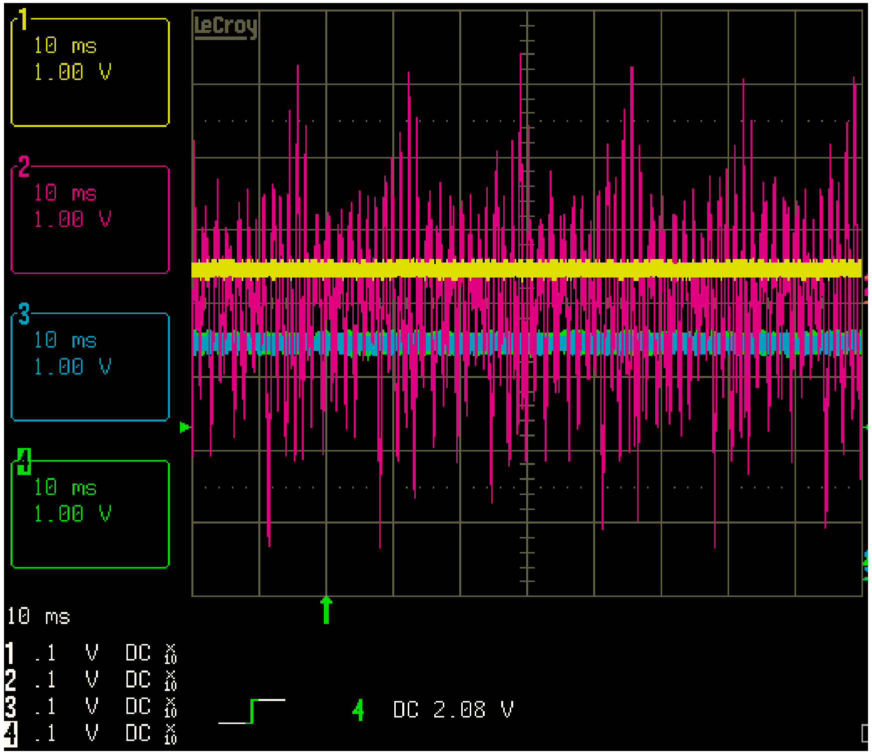
CubeSat FTS Prototype Data

Parameter	Measured Performance
Spectral Resolution	1.26cm^{-1}
Spectral Range	7.2-11.1 µm (900-1385 cm $^{-1}$)
EFL	27 mm
iFOV (aggr'd to 6x6)	8.9 mrad
FOV	53.5 mrad
Entrance Pupil Diameter	~13.7 mm
NESR (@10µm, single sweep)	0.32 mW / (m^{2}sr cm^{-1})
OPD Velocity Stability	1.3% with active cooler on 0.25% projected for flight
Radiometric Accuracy	0.5 K (over entire band)

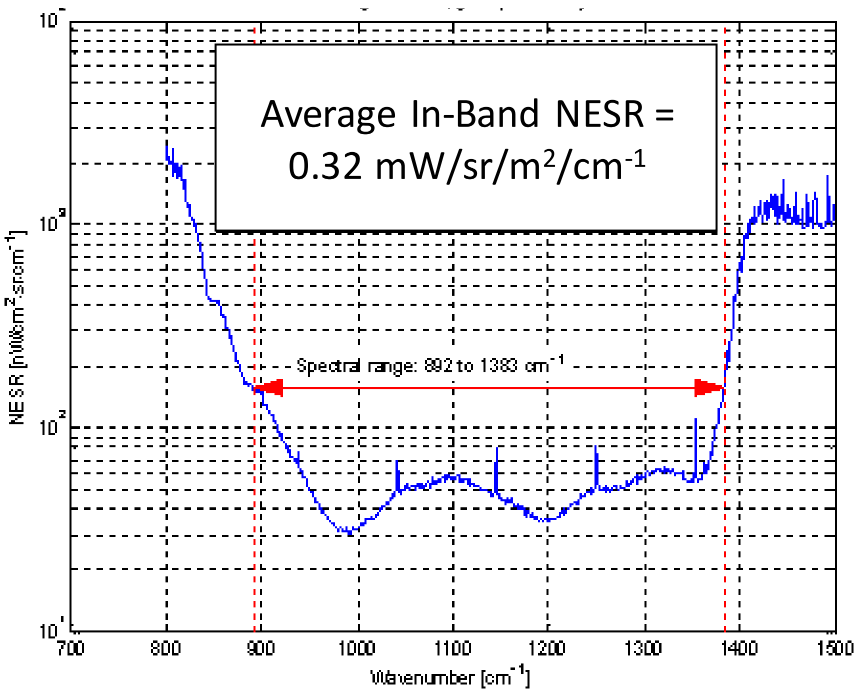


Blur Spot Size is Diffraction Limited

CubeSat FTS Prototype Data



OPD Velocity Stability = 1.3%
(With active cooler on; 0.25% expected for flight)



Noise Equivalent Spectral Radiance Data

NESR is higher than flight due to very low integration time per pixel (limited well depth for prototype FPA)

Instrument Prototype Successfully Integrated With SDL Spacecraft Prototype

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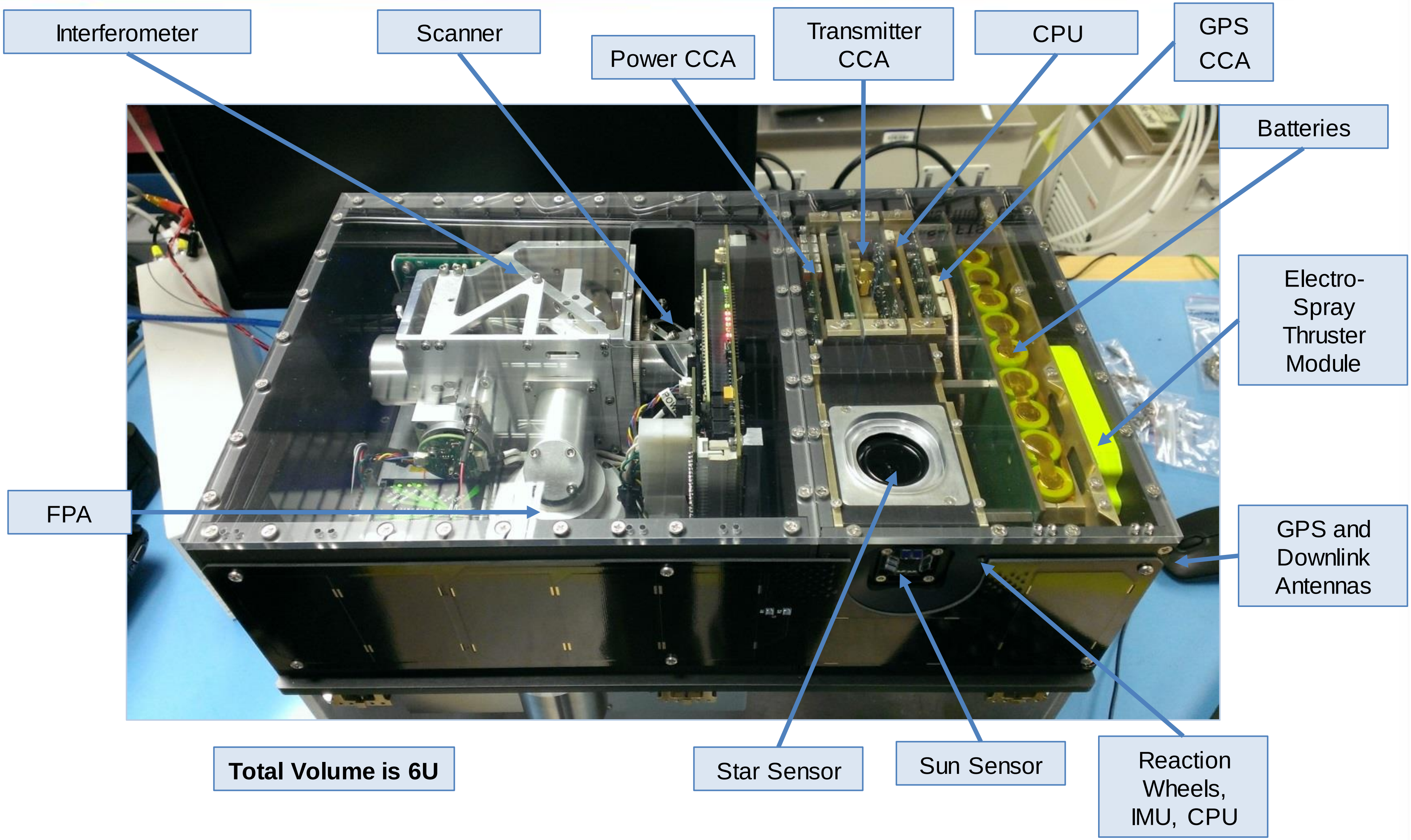
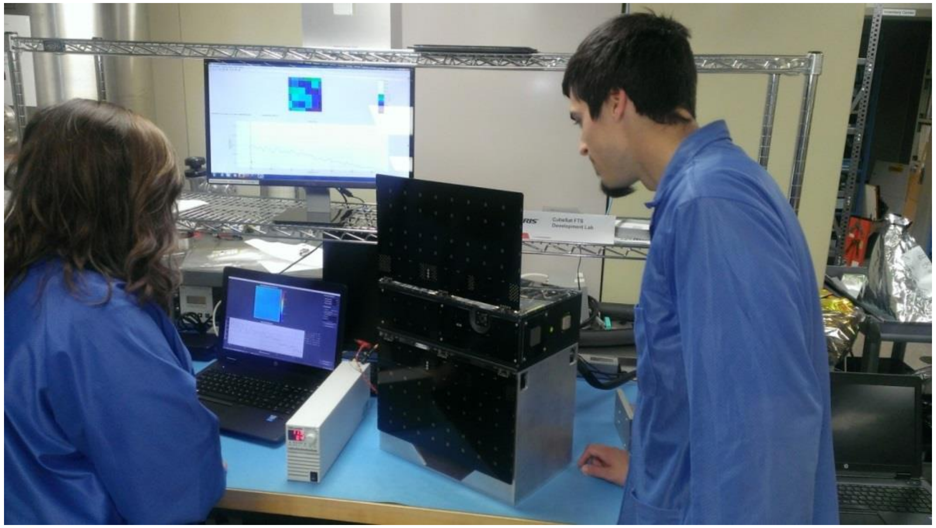


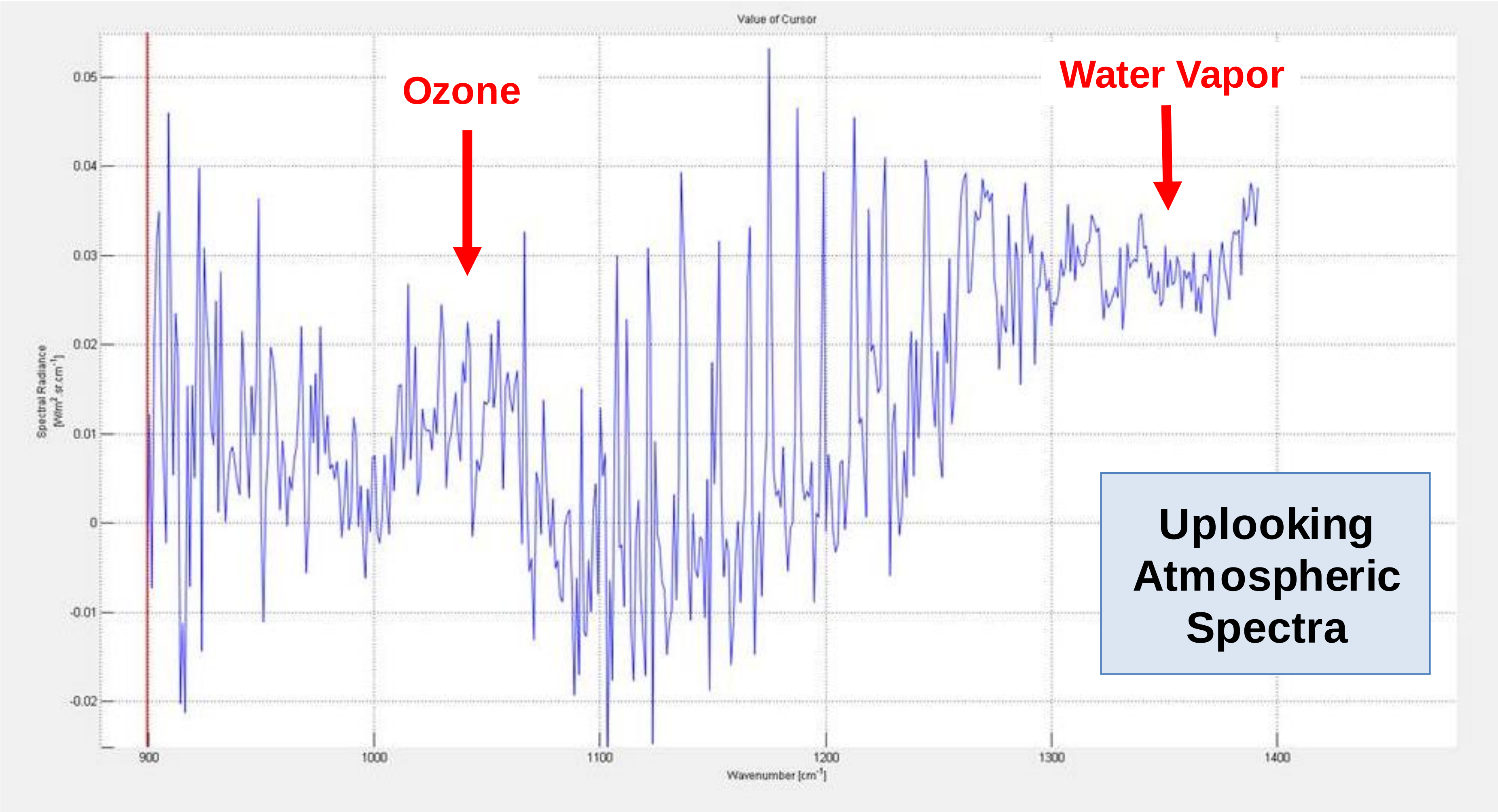
Total Volume is 6U

Instrument / Spacecraft Data Compatibility Tests Were Successful

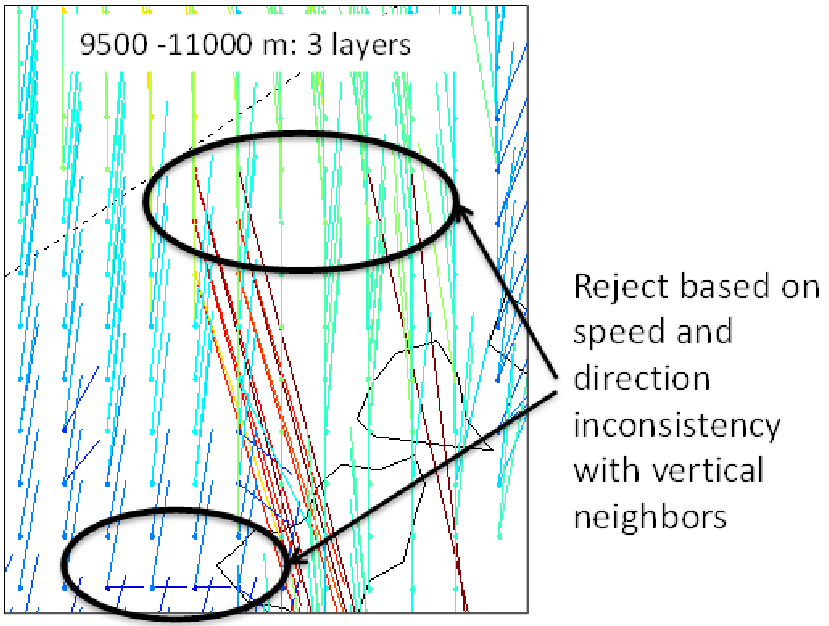
- Instrument performs conversion to spectra (FFT), calibration, pixel aggregation, and trimming of spectral channels to reduce data rate
- Data is transmitted to spacecraft avionics over a serial interface
- Spacecraft adds telemetry, and packetizes / time tags the data
- Spacecraft outputs data to GSE computer



Field Testing is Underway



Wind Extraction Algorithm Improvements



Improved quality control rejects incorrect wind vectors using comparisons between pairs of satellites

- Quality control is applied using horizontal and vertical vector comparisons, and the algorithm performs rejections based on inconsistencies in both wind speed and direction.

Algorithm modifications also minimize bias errors in the wind estimates.

- The approach uses the retrieved humidity profile rather than radiances directly.
- Initial evaluation using a simulated set of scenes over North America (next page) indicates an improvement in height assignment accuracy, and a reduction in bias errors.

Updated Wind Extraction Performance

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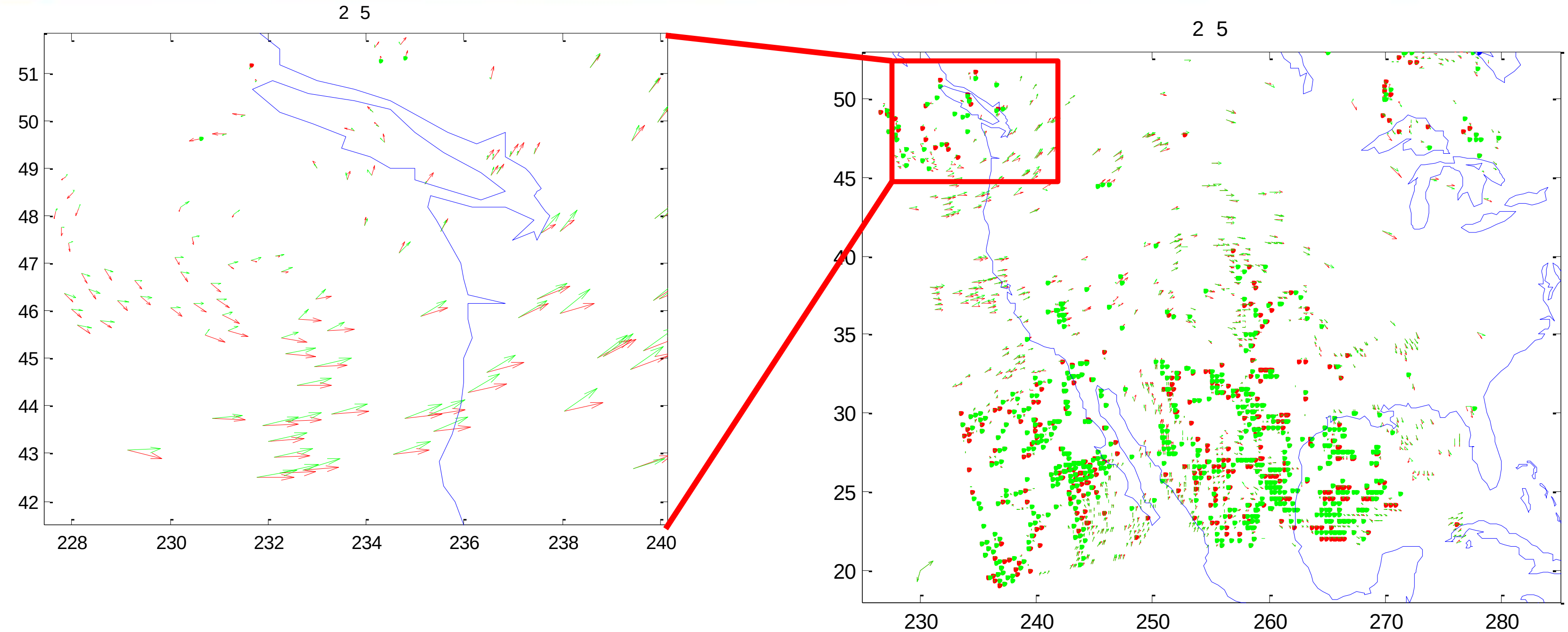

Pressure (Pa)	95000	87500	80000	72500	65000	57500	50000	42500	35000	27500	20000
U stdev (m/s)	3.04	3.30	4.03	4.08	3.80	3.51	4.39	5.18	5.38	4.78	3.79
U bias	0.11	-0.11	0.24	-0.48	-0.42	-1.01	-0.76	-1.00	-1.59	-1.41	-0.57
V stdev	4.18	3.68	3.06	2.99	2.89	3.28	3.94	4.76	4.31	3.11	2.71
V bias	-0.95	-0.80	0.18	-0.09	0.67	0.92	1.48	1.68	1.53	1.36	1.08

Current estimated accuracy levels are shown in the table above

- Further improvements are expected to yield a total accuracy of 3-4 m/sec, with at least 5 vertical layers of wind data.

Summary

The FTS CubeSat constellation:

- Can provide accurate measurements of global wind patterns at many vertical layers
- Lower mission cost than active lidar options

Prototype development at Harris and its partners, Telops and Space Dynamics Laboratory, is demonstrating the feasibility of the FTS CubeSat technology