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

Ronald Glumb, Christopher Lietzke, Scott Luce, Peter Mantica, Anna Glumb
Harris Corporation, Geospatial Systems Division
1919 W Cook Rd, Fort Wayne, Indiana, USA; 1-260-451-6882
Ronald.Glumb@exelisinc.com

Martin Chamberland, Jean-Philippe Déry
Telops Inc.
100-2600 Ave Saint-Jean-Baptiste, Quebec QC 62E 6J5; 1-418-864-7808 ext. 406
martin.chamberland@telops.com

Deron Scott, Jed Hancock
Utah State University Space Dynamics Laboratory
1695 North Research Park Way, North Logan, Utah 84341, USA; 1-435-713-3544
deron.scott@sdl.usu.edu

ABSTRACT

Global measurements of vertically-resolved atmospheric wind profiles offer the potential for improved weather forecasts, including superior predictions of atmospheric wind patterns. A small-satellite constellation utilizing Fourier Transform Spectrometer (FTS) instruments onboard 6U CubeSats can provide measurements of global tropospheric wind profiles from space at very low cost. These small satellites are called FTS CubeSats. The constellation consists of groups of three FTS CubeSats flying in formation and separated by a specified time delay. This geometry enables moisture-field measurements which can be combined to provide vertically-resolved profiles of the wind field on a global basis. This paper will focus on recent advances in the maturity of the FTS CubeSat concept which includes an update of the flight concept, test results from a prototype of the FTS CubeSat, and development of more effective wind extraction algorithms.

INTRODUCTION

Harris has developed an FTS CubeSat system which is capable of measuring three-dimensional winds on a global basis. As was described in Reference 1, the nominal FTS CubeSat constellation consists of 12 polar-orbiting 6U CubeSats in sun-synchronous orbits. Each FTS CubeSat is equipped with a hyperspectral Mid-Wave Infrared (MWIR) instrument which operates in a cross-track scanning mode. The multiple MWIR spectral channels are used to perform retrievals of the vertical moisture distribution at each ground location. In effect, each satellite constructs a 3-D moisture data cube. When a second FTS CubeSat flies over the same ground track about 15 minutes later, changes in the two 3-D moisture fields can be used to extract wind vectors at a variety of vertical locations (Figure 1).

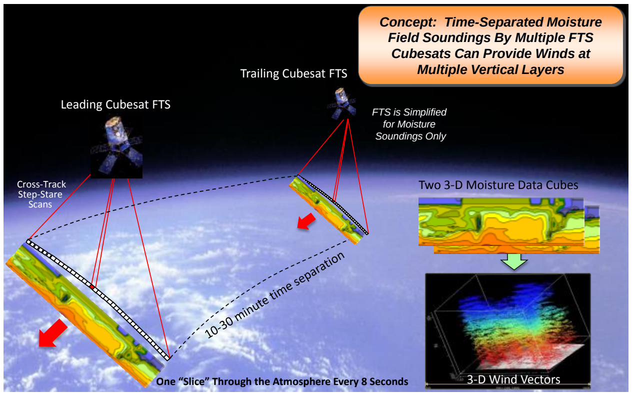


Figure 1: Global 3-D Wind Measurements Using FTS CubeSat Constellation

The Harris concept for the FTS CubeSat satellite has been refined and matured, as shown in Figure 2. A key objective has been to make the design easier to build by using existing hardware elements wherever possible. The 6U satellite consists of an Instrument Section and a Spacecraft Section.

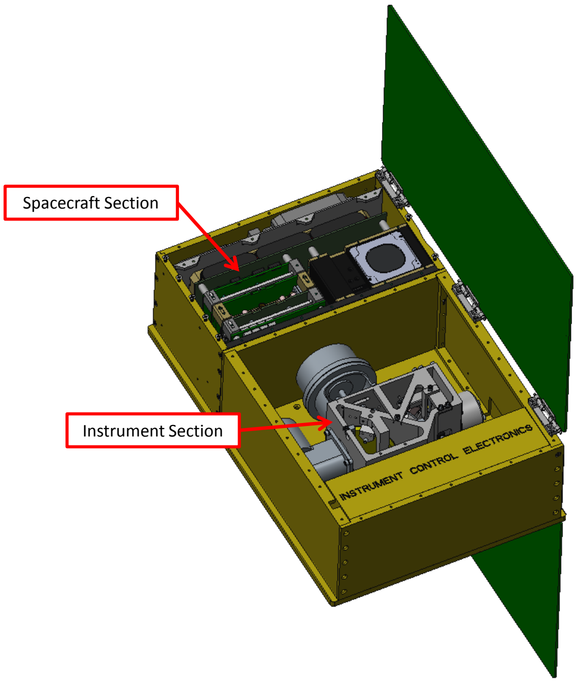


Figure 2: Updated FTS CubeSat Concept (Top Cover and Passive Cooler Not Shown)

The Instrument Section contains an FTS-based hyperspectral sounder as shown in Figure 3. Its design utilizes heritage components from prior Harris and Telops hyperspectral instruments. It uses a step-stare scanner which performs 16 cross-track steps; a step-stare occurs every 0.3 sec. Earth radiance passes through the scanner and feeds a corner-cube Michelson interferometer with a 1.3cm aperture.

The interferometer performs a +/- 0.397cm 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 an 8x8 array of Strained Layer Super Lattice (SLS) detectors.

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, and a ground swath that is about 750km wide. The array is cooled to 120K using a 2-stage passive cooler, similar in design to the cooler used by the Harris HIRS infrared sounding instrument. Electronics within the instrument convert the interferograms to calibrated spectra in real time, and route this data to the Spacecraft Section. Key parameters for the Instrument Section are shown in Table 1. The ground swath is shown in Figure 4, illustrating how the instrument produces a continuous image of the earth without gaps.

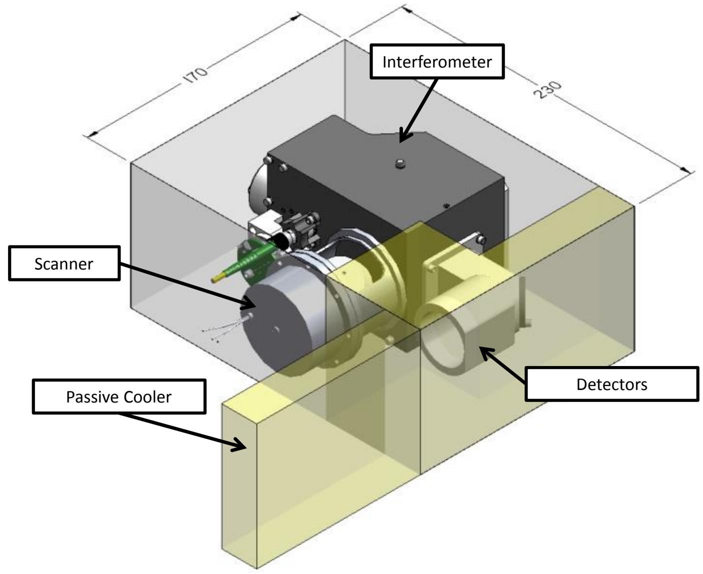


Figure 3: Instrument Section of the Prototype

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	650 km
GSD	5.1 km; 8x8 array
Mass	5 kg
Power	20 W

Table 1: Instrument Section Key Parameters

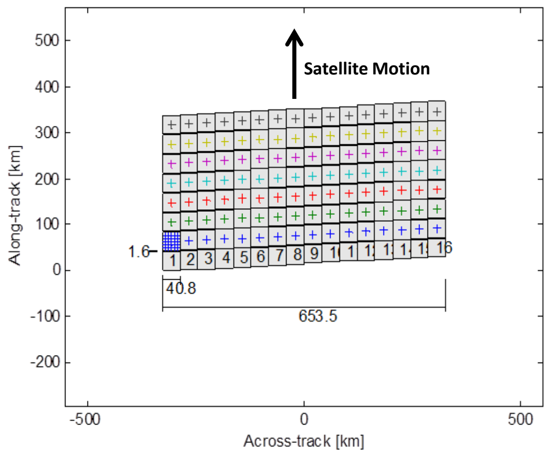


Figure 4: Spatial Coverage of 8x8 Array at 650km Altitude (A Fast Return is Performed after Each Scan Line)

The Spacecraft Section of the 6U CubeSat provides power, attitude control, and data downlink for the instrument. The Spacecraft Section utilizes a number of heritage components from Space Dynamics Laboratory (SDL). In particular, the CubeSat FTS avionics largely reuse the avionics from the PEARL Cubesat program [Reference 2], shown in Figure 5. PEARL offers much higher reliability than traditional CubeSats, and the avionics are radiation tolerant to ensure extended mission lifetimes of several years.

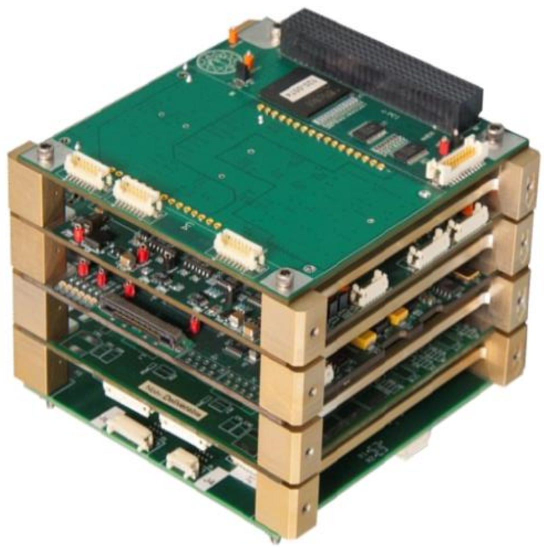


Figure 5: Avionics in SDL's Spacecraft Section are Based on PEARL Electronics

The PEARL avionics include a 32-bit SPARC processor, a VxWorks operating system, PEARLSoft Flight Software, a 12V / 2.15A-h battery, and a power system capable of up to 40 W peak power. It also has an S-Band radio for uplinks and downlinks at up to 2 Mbps. For CubeSat FTS, these avionics are augmented by a low thrust propulsion system to maintain the relative orbital spacing between the FTS CubeSats, a 3-axis stabilized attitude control unit, and a GPS receiver unit. Figure 6 shows the Spacecraft Section of the FTS CubeSat in more detail.

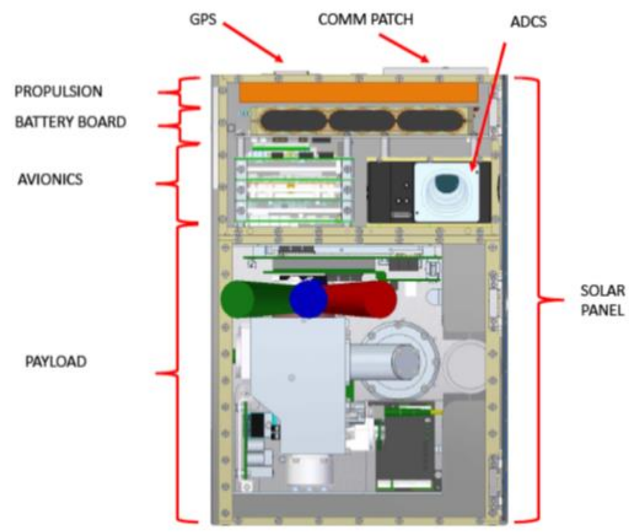


Figure 6: Further Detail in Spacecraft Section of the FTS CubeSat

FTS CUBESAT PROTOTYPE

In order to advance the maturity of the FTS CubeSat concept, Harris and its teammates have recently completed building a complete end-to-end laboratory prototype of the FTS CubeSat in a 6U configuration. The overall layout is illustrated in Figure 7. The prototype is being used to verify the performance of the overall unit, and to confirm hardware/software interoperability between the Instrument and Spacecraft sections.

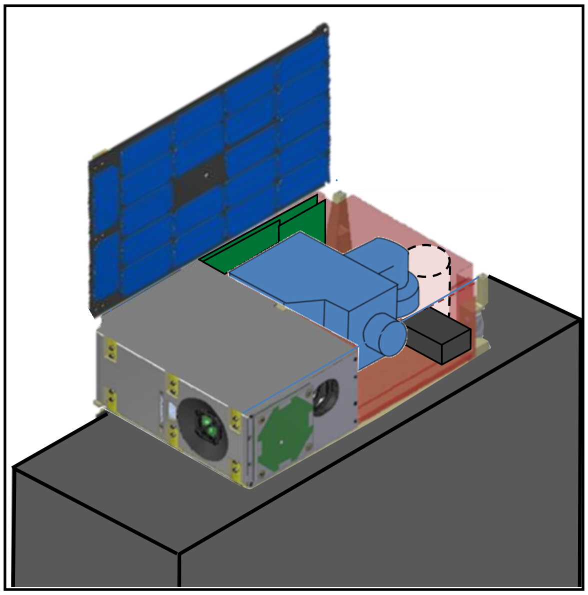


Figure 7: FTS CubeSat Prototype is Very Similar to Flight

The Instrument Section has been built by Telops, and is shown in Figures 8 and 9. The instrument is opto-mechanically very similar to the flight design, with a 1.3-cm aperture, +/- 0.397 OPD sweep distance, an onboard calibration target, and signal processing electronics which convert the interferograms to calibrated spectra. There are a few differences, however, from the flight design, which were necessary in order to support the rapid schedule for prototype development.

First, the FPA is a larger-format SLS array with readout of 48x48 pixels that are then aggregated to a more flight-like 6x6 effective FPA. Processing the increased number of raw pixels slows the readout rate and therefore requires a slower interferometer sweep rate. Second, because the prototype is designed for a laboratory test environment, a small ground-only active cooler has been added.

Finally, the instrument electronics are somewhat larger in board area and power than the flight boards; the miniaturization of these electronics is being addressed via a separate prototyping effort.

The instrument prototype has recently completed its test program. All measured performance parameters are within expected values. Optical image quality is excellent, as shown in Figure 10. Blur patterns indicate diffraction-limited performance.

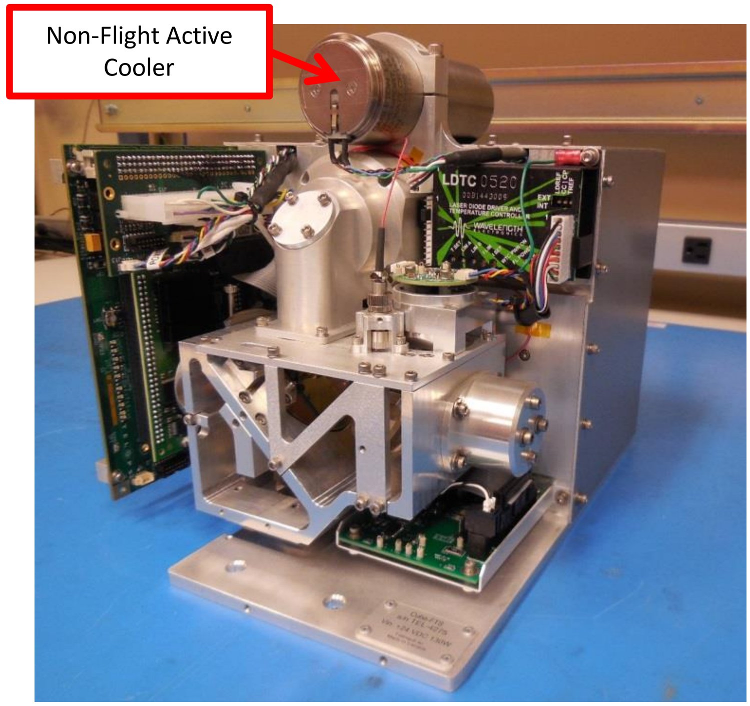


Figure 8: FTS Prototype Right View with Non-Flight Active Cooler for Ground Test

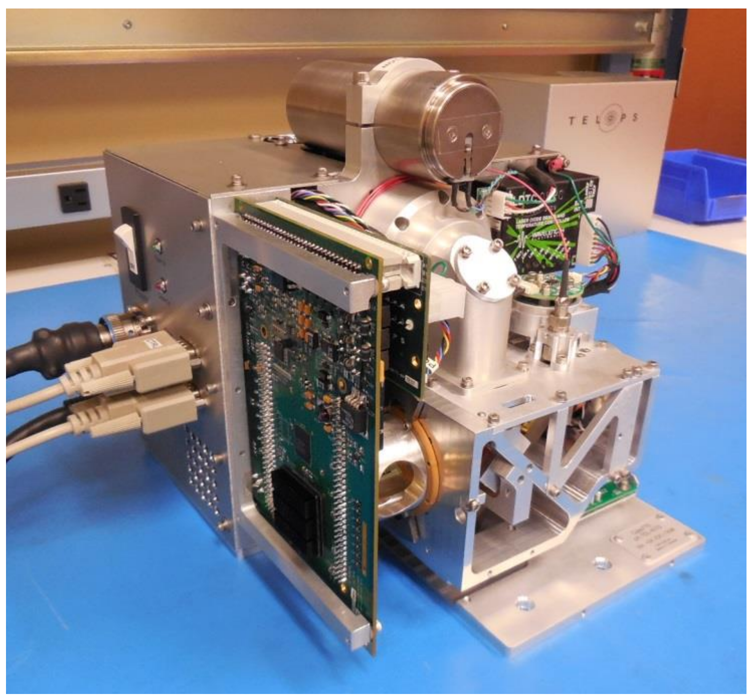


Figure 9: FTS Prototype Left View

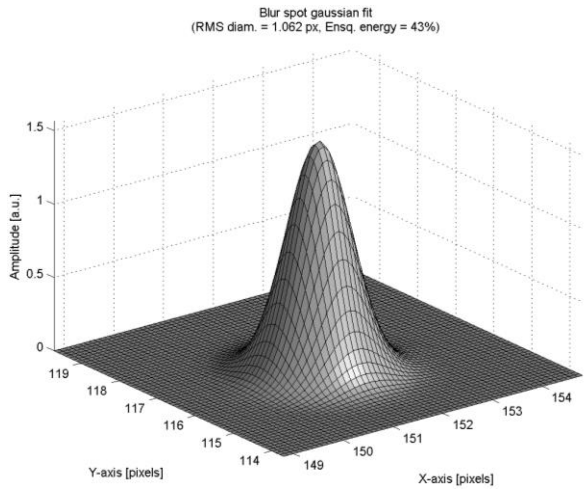


Figure 10: Blur Spot Size is Diffraction Limited

Noise Equivalent Spectral Radiance (NESR or NEdN) performance matches expectations. As shown in Figure 11, the band-average NESR of the prototype is approximately 0.32 mW / (m^2 sr cm^{-1}). This is about a factor of two higher than the flight requirement due to the different operating parameters used in the prototype, but is easily scalable to the flight performance levels when using flight operating parameters. Radiometric accuracy is quite good, and is expected to be even better for flight. OPD velocity stability is also quite good at 1.3%, even with the ground-only active cooler operating (Figure 12). When used with the flight passive cooler, OPD velocity stability should be better than 0.25%. A listing of key measured performance parameters are provided in Table 2.

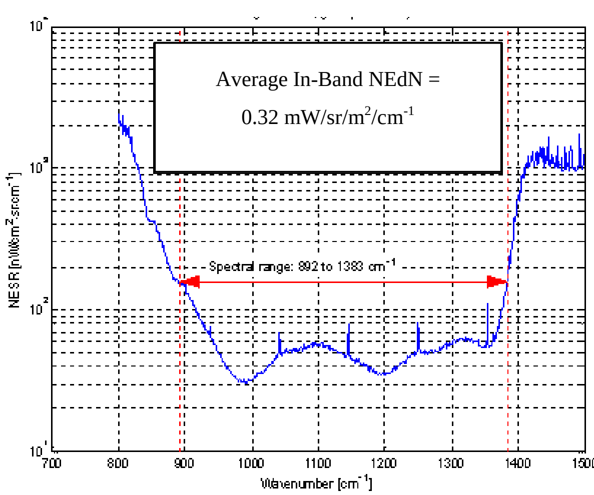


Figure 11: Noise Equivalent Spectral Radiance Data

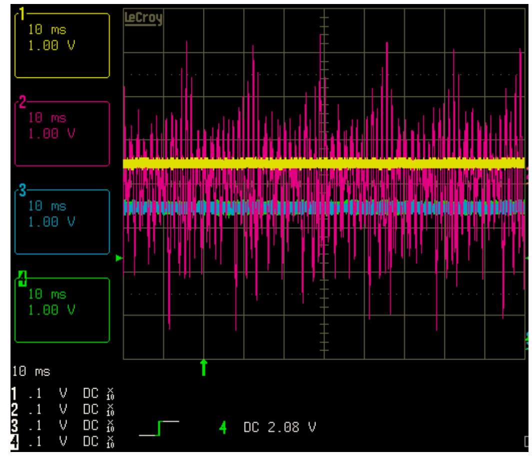


Figure 12: OPD Velocity Stability = 1.3%
(with active cooler on. 0.25% expected for flight)

Parameter	Measured Performance
Spectral Resolution	1.26 cm^{-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)

Table 2: Measured Performance Parameters

An interesting comparison photograph is shown in Figure 13, which compares the relative sizes of the FTS CubeSat Instrument Section with the Cross-track Infrared Sounder (CrIS), which is Harris' operational infrared sounding instrument flying on Suomi NPP, and a key instrument on JPSS. The much smaller size of the FTS CubeSat instrument is immediately obvious. CrIS does have a significantly larger aperture (about 40X larger in area) and additional spectral bands, yet because of its highly optimized optical design, the FTS CubeSat NEdN performance in the flight configuration is only about a factor of three higher than that of CrIS. In addition, the FTS Cubesat's other performance features are similar, and it actually has more detector pixels per band than CrIS.

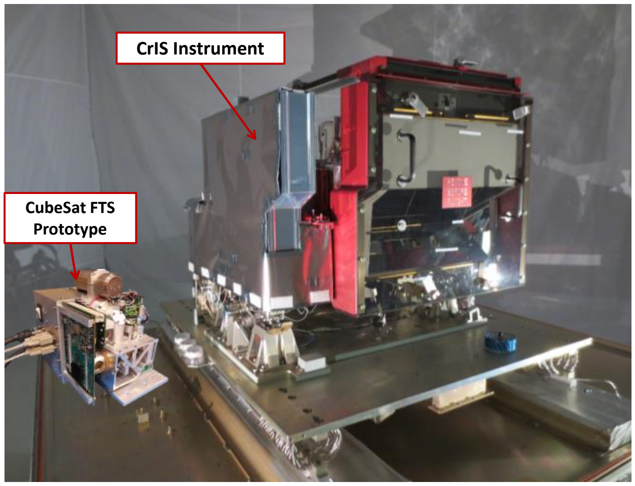


Figure 13: To-Scale Size Comparison Between the CubeSat FTS Prototype (Left) and CrIS (Right)

The avionics to be used in the Spacecraft Section are shown in more detail in Figure 14. The avionics are based on SDL's PEARL program, and are high-reliability radiation-hardened components to ensure at least a 2-year on-orbit mission lifetime The Spacecraft Section also includes a lightweight aluminum structure, a complete set of flight avionics, and a transmitter with antenna, solar array simulators, and an onboard station-keeping propulsion unit.

Figure 14: Spacecraft Electrical Boards

Top Row: Bus Interface Controller (BIC), PEARL Interface Board (PIB)
Bottom Row: Payload/Radio Board (PRB), Maximum Peak Power Tracking Electrical Power Systems (EPS)

WIND EXTRACTION ALGORITHM IMPROVEMENTS

Recent algorithm activities have focused on two areas: improved quality control (rejection of incorrect wind vectors using comparisons between pairs of satellites) and removal of retrieved wind vector biases. This work has utilized realistic simulated scenes.

The approach used for quality control is illustrated in Figure 15. A comparison is made between wind vectors extracted for the same region from Satellites #1 and #2, and the wind vector extracted from Satellites #2 and #3. Quality control is applied using horizontal and vertical vector comparisons, and the algorithm performs rejections based on inconsistencies in both wind speed and direction.

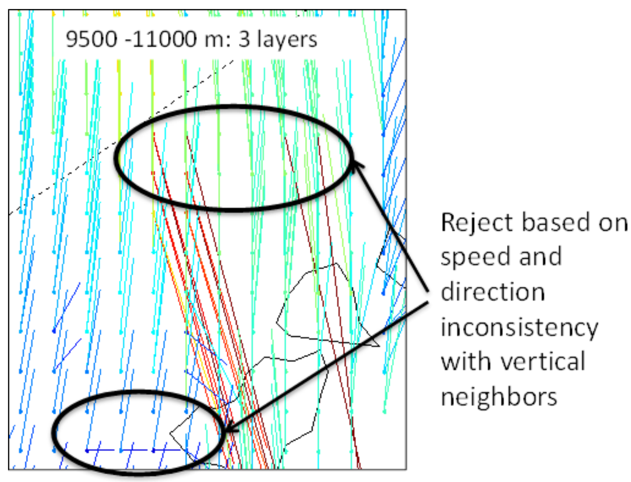
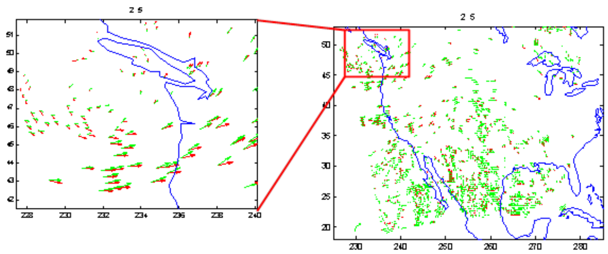


Figure 15: Quality Control Algorithm

The wind extraction algorithm has also been modified in order to 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 (Figure 16) indicates an improvement in height assignment accuracy, and a reduction in bias errors. Current estimated accuracy levels are shown in the table of Figure 16, and further improvements are expected to yield a total accuracy of 3-4 m/sec, with at least 5 vertical layers of wind data.



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

Figure 16: Results of Improved Wind Extraction Algorithm

SUMMARY

The FTS CubeSat constellation will be able to provide accurate measurements of global wind patterns from space. The FTS CubeSats can determine wind patterns in areas of low to no cloud coverage. By using CubeSat technology and miniaturized instrument approach, the cost of the mission will be significantly lower than the larger operational satellites used today. Prototype development at Harris and its partners, Telops and Space Dynamics Laboratory, is demonstrating the feasibility of the FTS CubeSat technology.

REFERENCES

1. Glumb, R., et. al., *Cubesat Fourier Transform Spectrometer (CubeSat-FTS) for Three-Dimensional Global Wind Measurements*, American Meteorological Society Annual Meeting, January 2015.
2. *PEARL: Pico-Satellite Exo-Atmospheric Research Laboratory*, Space Dynamics Laboratory Document Number SDL/10-136D.