Cubesat Fourier Transform Spectrometer (CubeSat-FTS) for Three-Dimensional Global Wind Measurements

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Global 3-D Wind Vectors are Useful for Improved Forecasts

- Global wind fields are used as initial conditions to numerical weather prediction models
  - Wind information currently comes from Atmospheric Motion Vectors (AMVs) from space-based imagers, plus ground-based assets such as radiosondes
  - Improved knowledge of wind fields can improve forecast accuracy
  - Studies of lidar wind measurements from space suggest that improved wind information would be very useful
- Improved wind information and forecast accuracies are potentially useful for:
  - Hurricane Prediction Accuracy Improvement
    - Improved forecasting of tropical cyclone environmental winds
  - Transportation cost reductions

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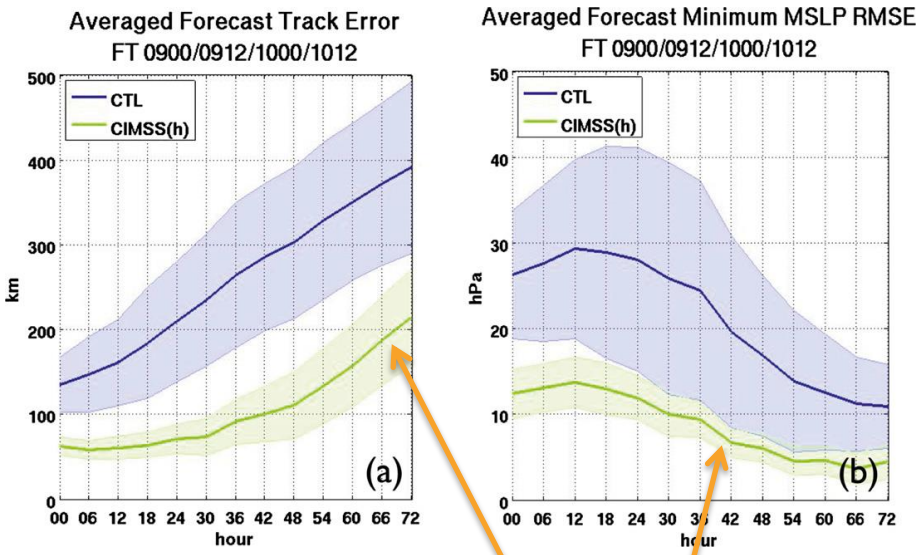
Example: Improved Hurricane Forecasts

Studies have demonstrated improvement in Tropical Cyclone forecasts using Atmospheric Motion Vectors (AMVs)

AMV uncertainty is largely due to height assignment uncertainty [#]

- Wind errors as large as 5-7m/sec can occur due to incorrect heights
- Hyperspectral imagery should help to reduce this uncertainty



Courtesy: Wu et al., *Monthly Weather Review*, Jan. 2014

MSLP = Mean Sea Level Pressure
RMSE = Root Mean Square Error
CTL = "Control" Forecast
CIMSS = Forecast With AMVs

Using current AMVs reduces forecast track and intensity errors

[#] e.g. Sears & Velden, *J. Appl. Meteorology*, Oct. 2012

Improved forecasting of tropical cyclone environmental winds

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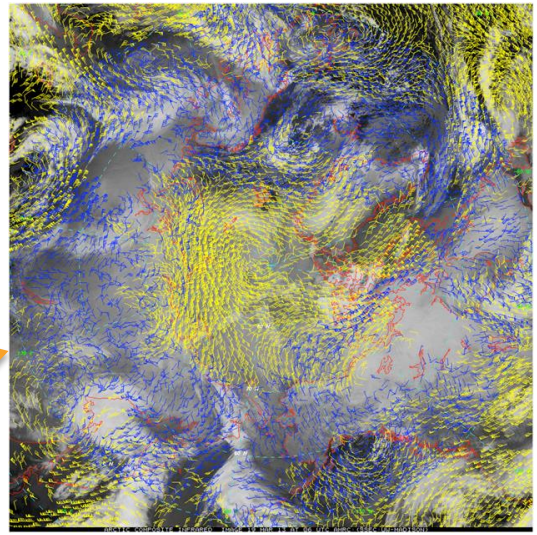
Current state of the art, and potential FTS alternative

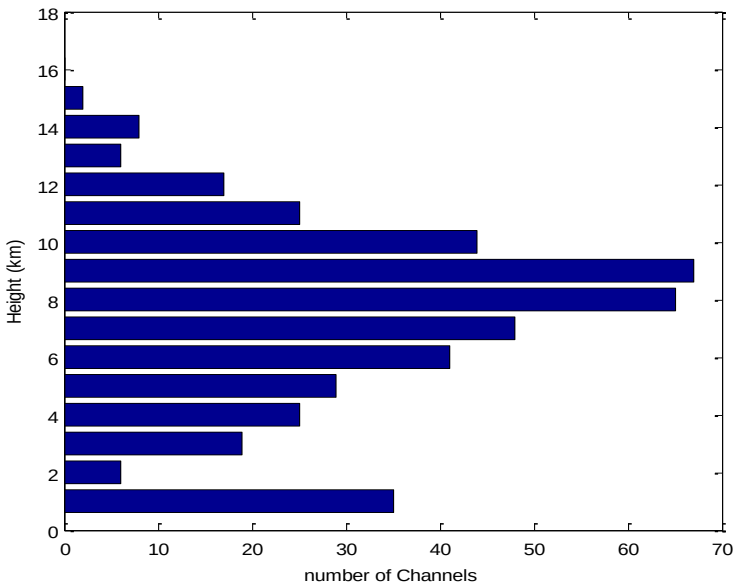
- GOES AMVs are limited to +/- 60 deg latitude
  - > Track clouds or single layer of upper trop water vapor
- Polar AMVs from MODIS/AVHRR/VIIRS provide >70 deg
- UW CIMSS provides combined Polar/Geo products to mind the gap: RAOB comparison shows 5-9 m/s RMSE
- GOES Performance Assessment using wind profilers*
  - > RMSE = 4-5 m/s, Vector RMS = 5-6 m/s



Courtesy: Lazzara et al., *J. Appl. Meteor.*, Feb. 2014

* Bedka, et al., *J. Appl. Meteor.*, Aug. 2009

Current AMV products are limited to 3 layers



- Proposed Cubesat FTS Polar orbiting constellation will provide hyperspectral imagery which has hundreds of channels that can potentially provide a more vertical layer resolution with more accurate height assignment

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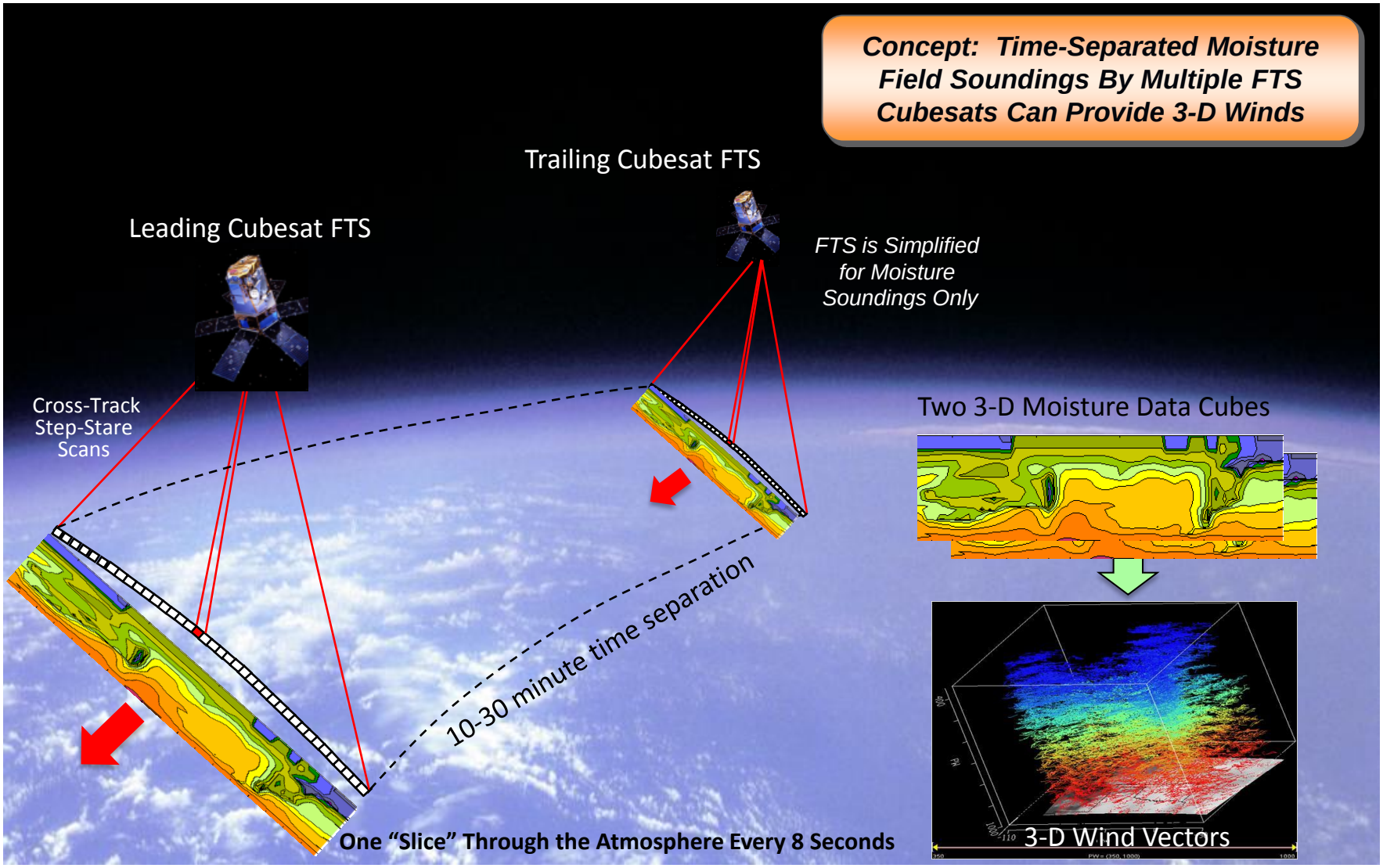
Global 3-D Wind Measurements Using FTS Cubesats



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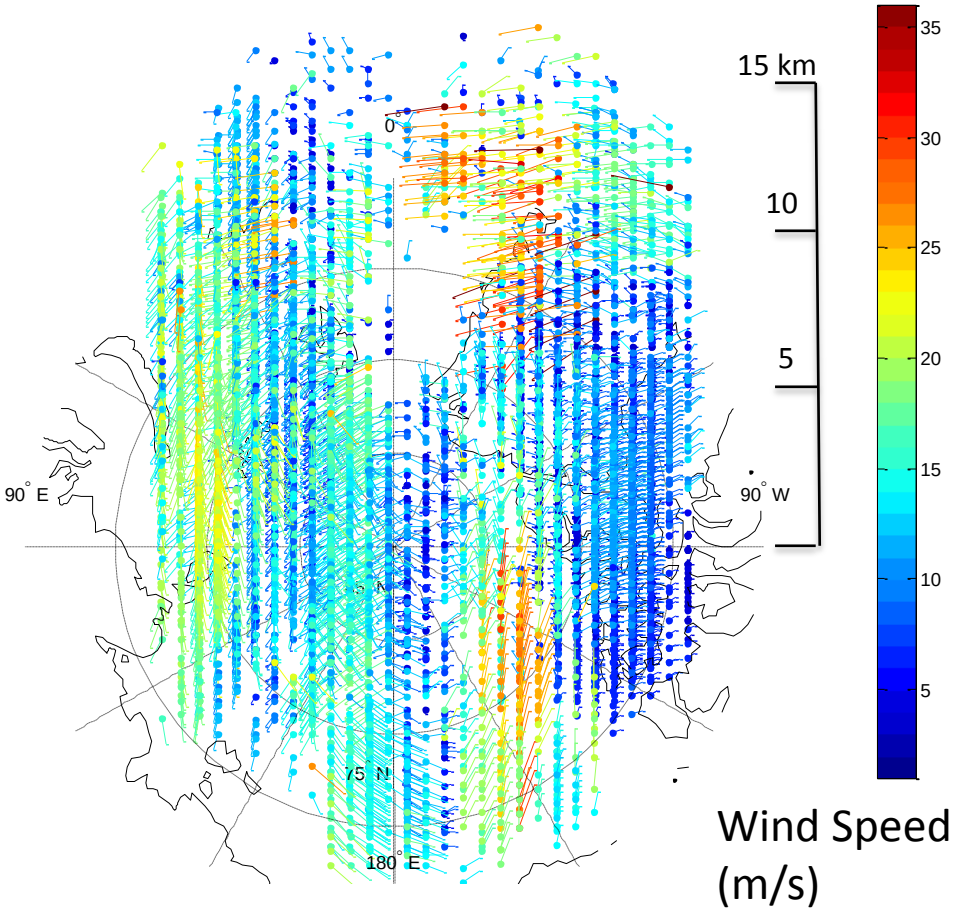
Technique Demonstrated Using On-Orbit CrIS Data

- Polar winds derived from successive passes of CrIS over the poles (right)
  - CrIS's knowledge of moisture profile provides accurate height assignment
- CrIS data shows that dense wind field measurements are possible with FTS
- Main limitation of CrIS is its relatively large ground footprint of 14km
  - Limits accuracy of wind vectors to 5-10 m/sec
  - Data is also limited to polar regions, and to situations in which CrIS and AIRS are in the correct orbital phasings

- <u>Next step</u>: Develop concept for a Cubesat-sized instrument optimized for 3D wind measurements



3-D Perspective

Proof-of-Concept Tests Using CrIS Data Near Poles Shows Concept is Feasible

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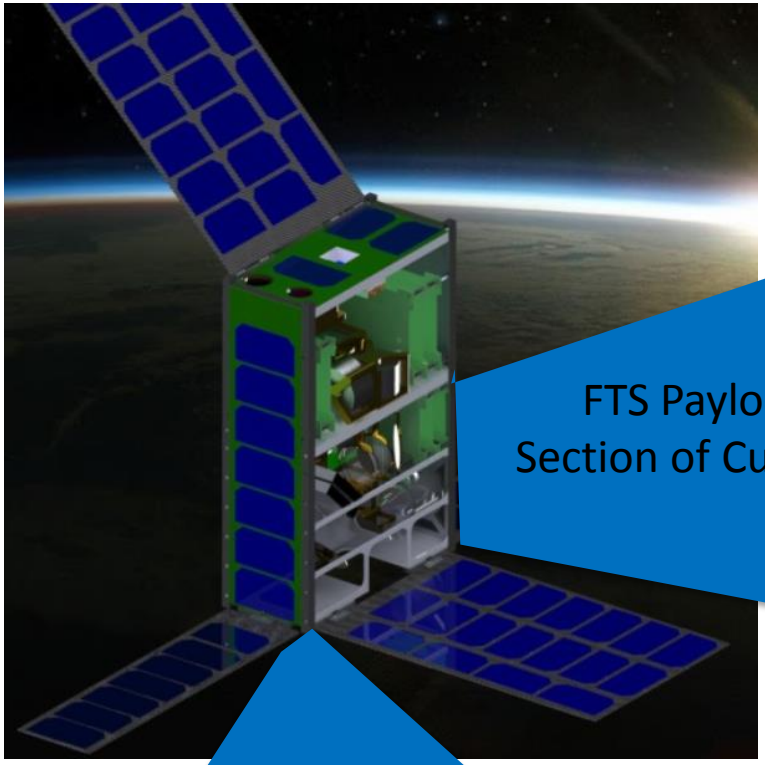
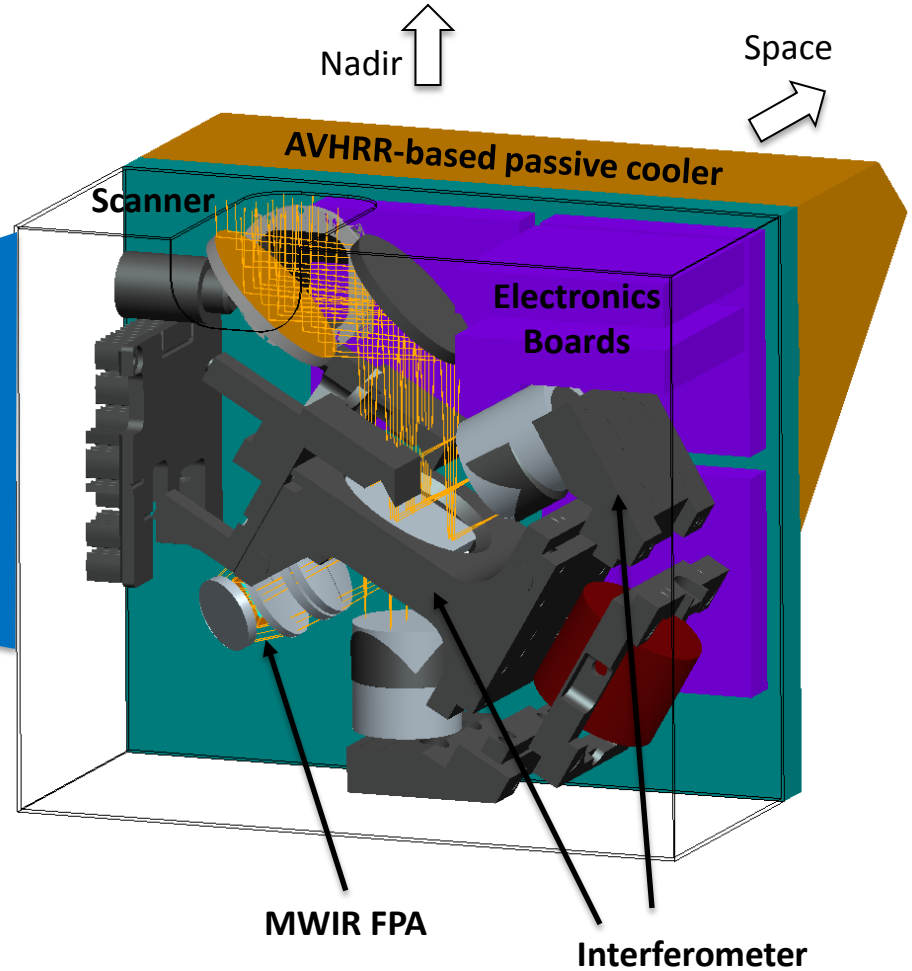
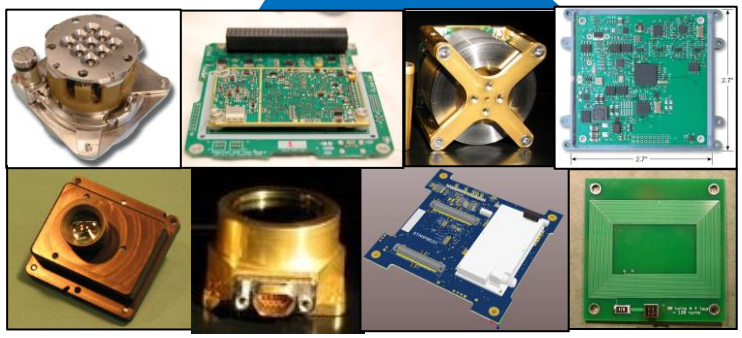
FTS and Cubesat Technologies Have Recently Matured to Levels Needed to Make a 6U FTS Cubesat a Reality



FTS Payload Section of Cubesat





Extensive Use of Recently Flight-Proven Cubesat Technologies

6U Cubesat Provides Instrument Volume of 10cm x 17cm x 22cm; Mass is 5kg

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Key FTS Instrument Parameters

- +/-26 deg crosstrack scan angle (16 CT step-stares)
- 8 seconds per swath to avoid gaps between swaths, ~3/8-sec per stare
- 4cm aperture
- 1.25 cm^{-1} spectral resolution
- MWIR band only (5.7-8.3 um)
- FPA is a 6x6 effective array with 7km square FOVs
  - Cooled to ~120K using an AVHRR-based passive cooler
  - 9um cutoff wavelength
- Onboard FFT and selection of key spectral channels to limit downlinked data rate

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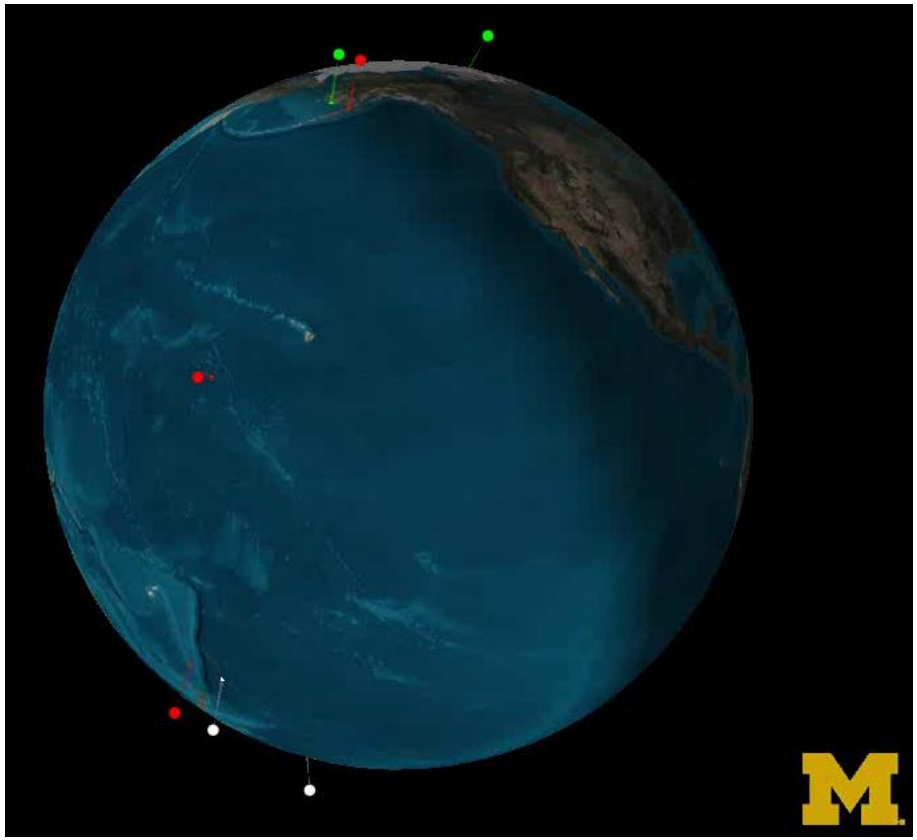
Cubesat FTS Constellation Was Optimized Via Studies at the University of Michigan

Measurement Goals

- Each data point requires three overlapping measurements separated by ~15 minutes
- Twice daily global coverage

Selected Constellation

- 830 km Sun Synchronous Orbits
- 12 Total Satellites
  - 3 Orbital Planes
    - Separated by 3.1° RAAN
  - 4 satellites per plane
    - Separated by 90° TA
- 12.7 minutes between corresponding measurements
- 44.2° phase separation between satellite pairs



Joint UM/Exelis Paper Was Presented at 2013 USU Small Satellite Conference

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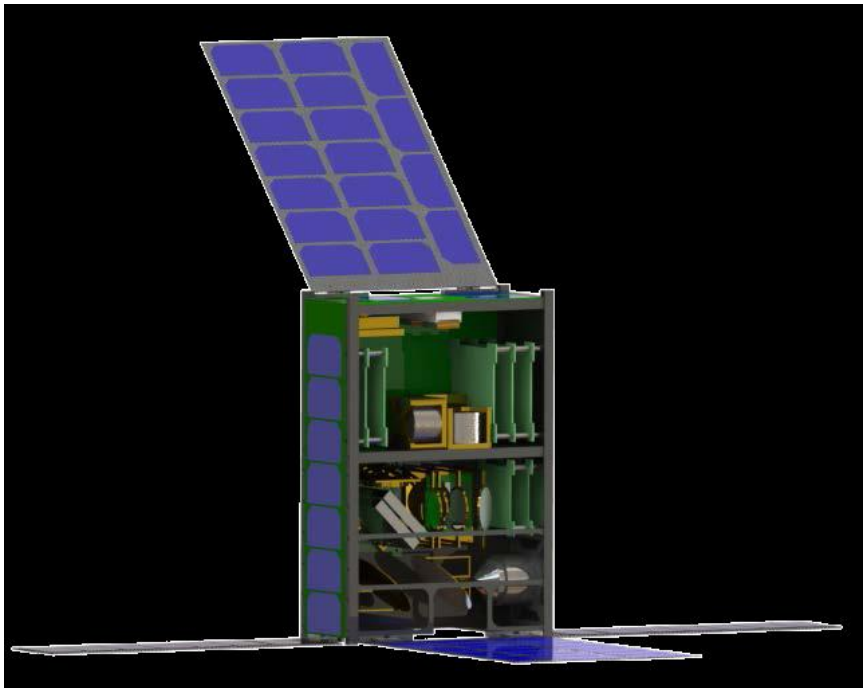
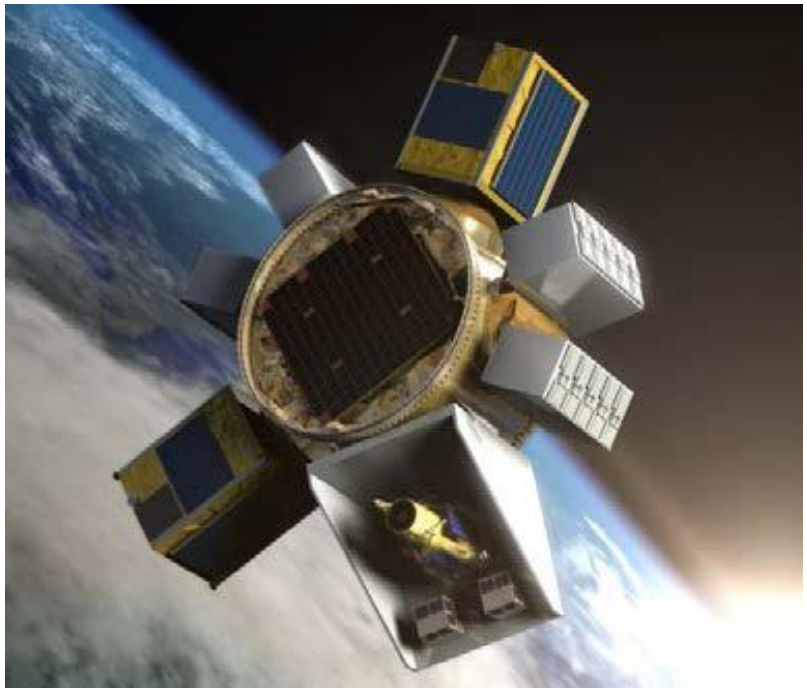
Spacecraft and Deployment Concepts





- Spacecraft section of the FTS Cubesat employs flight-proven components
  - Deployable solar array panels (30W average)
  - Reaction wheels, magnetorquers, and sun/earth sensors for attitude control
  - Electrospray thrusters for station keeping
  - Compact, low-power control electronics
  - L3 Cadet Nanosatellite Radio transmits science data to the ground (1.5 Mbps)

- Multiple Cubesat FTS units would be deployed via a "SHERPA" upper stage
  - Developed by Spaceflight Services
    - First flight planned for later this year
  - Can deploy up to sixty 6U cubesats
  - SHERPA "tug" has a total ΔV capability of ~400 m/s, which is used to individually place each Cubesat FTS into its appropriate orbit

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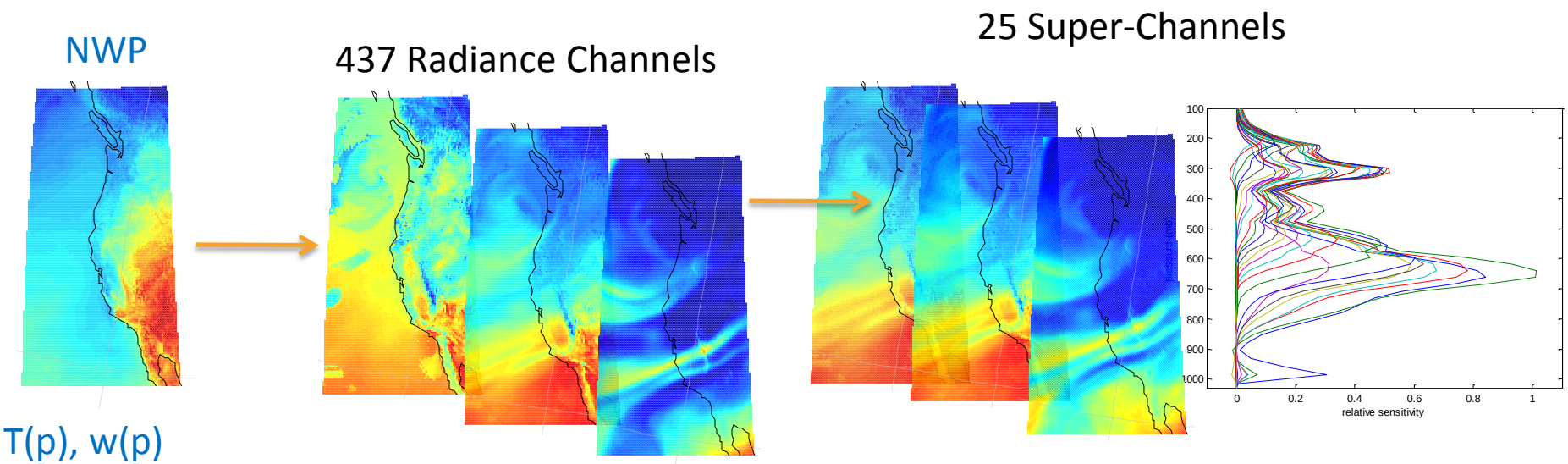
Investigation of potential Cubesat FTS performance uses simulated observations

- 5km, hourly NWP forecasts from NCEP are used as input for PCRTM* to simulate top of the atmosphere (TOA) radiances
- TOA radiances are spatially sampled and sensor noise added to produce simulated Cubesat FTS observations
- 3 successive scenes are observed by the Cubesat FTS constellation
- Spectral radiance observations are averaged based on peak values of spectral weighting functions to produce 25 super-channels



* PCRTM: Principal Component-based Radiative Transfer model, courtesy of Xu Liu, NASA LaRC

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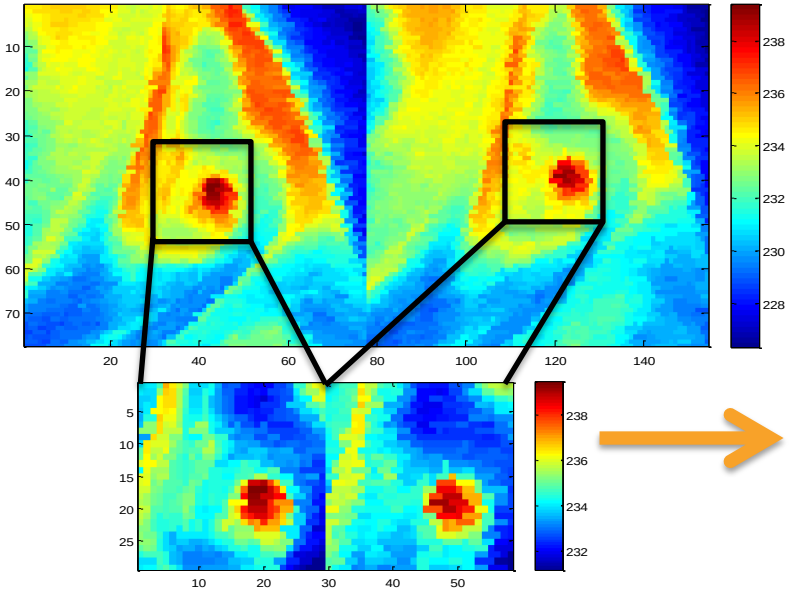
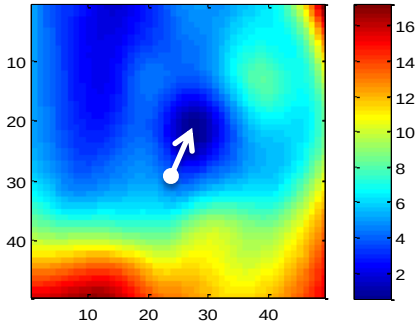
Wind Estimation Uses A Simple Correlation Algorithm

- The 25 super-channel images are formed by stitching together the observations from the Cubesat FTS constellation
- The correlation algorithm moves through each image to find the displacement of features from Scene 1 to Scene 2, and Scene 2 to Scene 3
- Wind vectors are created and compared between Scenes 1-2 and Scenes 2-3
  - > Those that have dissimilar magnitude or direction are discarded

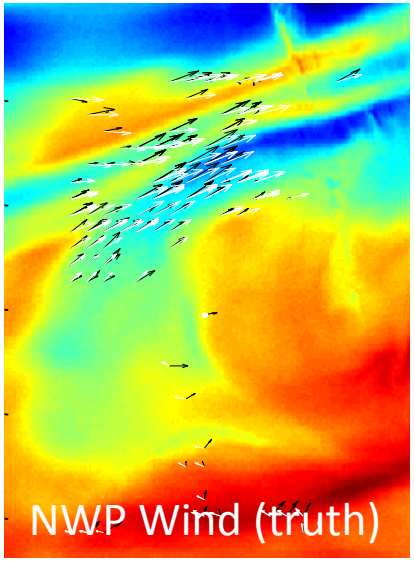


Mean Sum Square Difference and Search for Minimum

Calculate Wind Vector: Original location to Minimum



Estimated Wind



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Expected Wind Extraction Algorithm Performance

- Cubesat estimated wind vector accuracy
  - 3-4 m/sec
  - More accurate height assignments than GEO imagers
- Cubesat Wind Vector Density
  - Spatially equivalent to GEO imagers, but with more vertical layers
    - 5 or 6 vertical layers, compared to 1-3 layers for imagers
  - Better detection of winds in cloud-free areas
- Cubesat Global wind vector datasets
  - Twice per day near equator, more often at higher latitudes
- Algorithm optimization work is currently underway

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Exelis Plan for the Continued Evolution of Cubesat FTS

- Wind Extraction Algorithm Refinement
  - Now working to improve the accuracy of wind measurements using simulated Cubesat FTS data
  - Will also use algorithms to better optimize instrument and constellation configuration
- Observing System Simulation Experiments (OSSEs)
  - Providing inputs to Simpson Weather Associates for use in OSSEs
  - Goal is to determine the improvement to weather forecasts that can be realized with Cubesat FTS data
- FTS Cubesat Instrument Development
  - Instrument prototype is now in development, and is expected to be operational in Spring 2015
    - Initial testing will demonstrate key performance characteristics
  - To be followed by additional tests to advance the TRL of the instrument
- All work is being funded via Exelis IRAD
- We also plan to submit the Cubesat FTS system as a proposed Earth Venture mission

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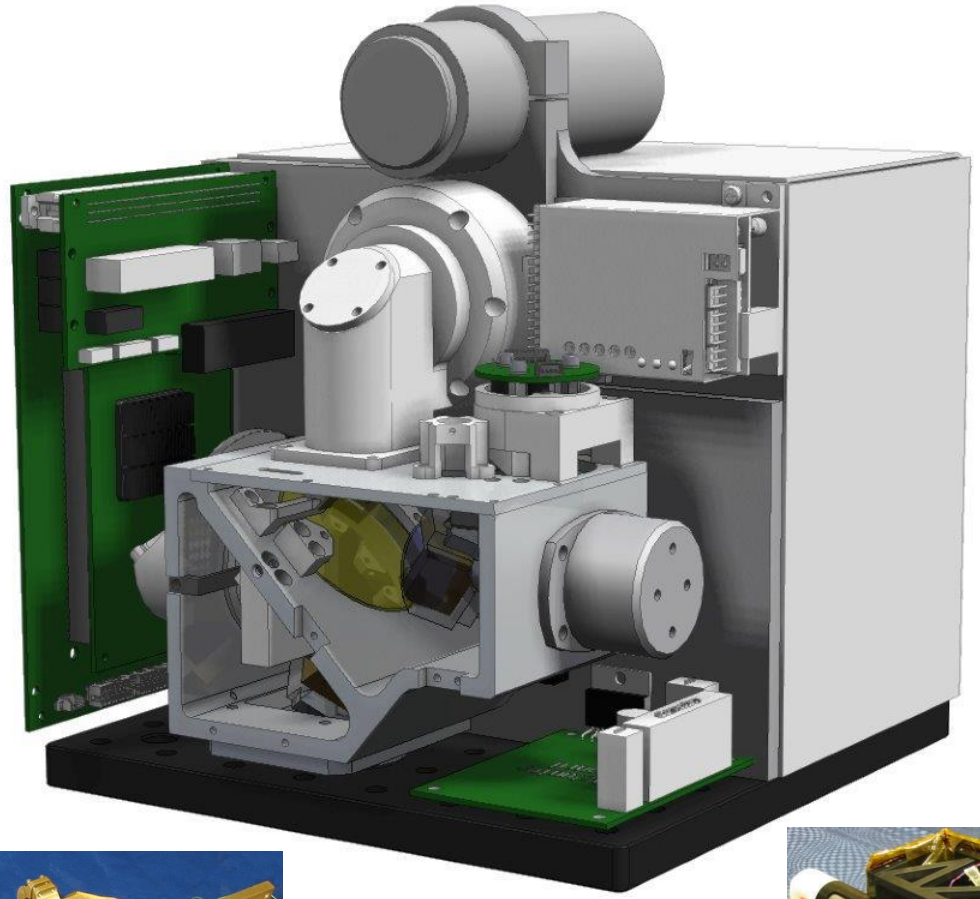
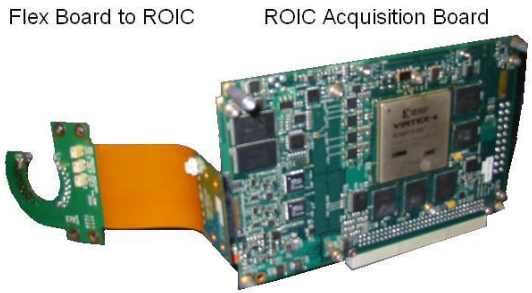
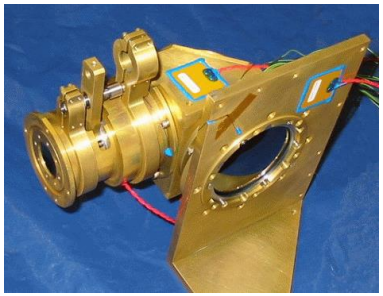
FTS Cubesat Prototype is in Development

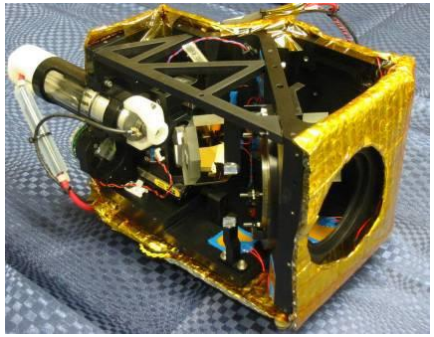


Focal Plane Assembly





Aft Optics Module



Interferometer Module

Interferometer Controller

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Summary

- Cubesat FTS is a simple near-term solution for providing global 3D Winds
- Mission benefits look very attractive, and we are working to better quantify this now
- We are currently building a prototype of the Cubesat FTS instrument , and will use test results to refine the FTS Cubesat concept

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