FTS CubeSat Constellation Providing 3D Winds

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ABSTRACT

A novel small satellite constellation utilizing a Fourier Transform Spectrometer (FTS) instrument onboard 6U CubeSats would allow weather forecasters to have unprecedented understanding of global tropospheric wind observations from space; enabling more accurate, reliable, and longer-term weather forecasts.

Three FTS CubeSats flying in formation and separated by a known time delay would provide cooperative measurements and overlay scenes necessary to compile vertical profiles of the wind field. A constellation of formation-flying FTS CubeSats would allow measurement of the global wind field; providing unparalleled coverage and allowing longer-term weather forecasts.

This paper will describe the recent advancements in CubeSat capabilities and future work required to meet the objectives of the FTS mission. The innovative approach the Exelis/University of Michigan team is taking to power, attitude determination and control, communications, and constellation formations will also be discussed. System and subsystem trades were optimized with emphasis on science mission requirements while balancing overall mission cost.

3D WINDS MISSION BACKGROUND

The 2007 Earth Science Decadal Survey established the need for three dimensional (3D) wind knowledge to improve weather forecasts. According to the survey, “tropospheric winds are the number-one unmet measurement objective for improving weather forecasts” and “would provide direct and measurable societal and economic effects”. The survey calls for a 3D Winds demo mission using a Doppler lidar in a sun-synchronous (SSO) low earth orbit (LEO). Anticipated launch would be in the later half of this decade at an estimated cost of $650M.\(^1\)

3D Winds from On-Orbit Instruments

To address the unmet need of 3D winds, there have been efforts to improve upon data products from existing on-orbit assets. While wind field estimation using visible/infrared imagers like GOES, AVHRR and MODIS is well documented, they are unable to resolve the vertical structure of cloud tops and upper tropospheric water vapor distributions. As a result, these products are usually provided for three layers of the troposphere, are spatially discontinuous, and cannot adequately support Numerical Weather Prediction (NWP).\(^2,5\)

Current 3D Winds Development Efforts

The two major ongoing efforts for 3D Winds mission, TWiLiTE and OAWL, have used a Doppler Lidar instrument via airborne platform as recommended by the decadal survey.\(^4,5\) The Doppler lidar profiles winds by transmitting a laser pulse through the atmosphere, a fraction of which is backscattered by molecules and aerosols in the air and then detected by a Doppler receiver in the instrument. The received signal is then analyzed to determine the frequency shift introduced by the mean velocity of the scatterers, which yields the horizontal wind velocity of the air.\(^4\)

The issue with a Doppler lidar system is that it has never been proven on a spaceborne platform, requires large volume and power, and is still in development testing.

Currently, there is no published plan to move either instrument from airborne testing to spaceborne operation. This paper speculates that a $650M+ demo mission for a spaceborne Doppler lidar mission is unlikely in the current fiscal environment for terrestrial observation platforms within NASA and NOAA. Yet the need for 3D winds data remains critical for NWP.
As such, it is warranted to approach the 3D Winds mission with focus on core science requirements, not specific instrument capability, to determine if there is overlap in existing capabilities to reduce cost and risk to the 3D Winds mission.

**3D Winds Requirements**

A science requirement traceability matrix was created to understand the flow between the recommendations discussed in the decadal survey to the core scientific measurement requirements, see Columns 1-3 of Table 15. This matrix will establish the requirements from which any proposed mission will need to adhere to meet the 3D Winds need.

**FTS INSTRUMENT**

A Fourier Transform Spectrometer (FTS) instrument, which is based off of the flight heritage Exelis Crosstrack Infrared Sounder (CrIS) instrument on Suomi NPP, would be capable of meeting the science requirements for 3D Winds.

**CrIS Instrument on Suomi NPP**

The CrIS instrument is a Michelson interferometer with dynamic alignment and automatic internal spectral calibration capabilities. CrIS has 1305 channels over three spectral bands (shortwave, midwave and long wave infrared). Launched in October 2011, the data products from the CrIS instrument have been successfully analyzed to produce 3D wind field vectors over the North Pole, where it revisits every ~100 minutes. The imagery from CrIS is used to extract features from one orbit to the next which is used to calculate the wind vector located at the center of the feature, as shown in Figure 1.

**FTS Instrument Design and Operation**

To obtain global 3D wind fields, a constellation of FTS instruments is required in SSO. To reduce the overall constellation costs for the system, the CrIS instrument was ‘miniaturized’ by retaining the same front end optical chain and reducing the backend to only a midwave infrared (MWIR) focal plane. This concept reduces new design risk while eliminating capabilities not required for the 3D Winds mission. The output of this effort was the FTS instrument with capabilities and characteristics listed in Table 1 and Figure 2.

**Table 1: FTS Instrument Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>5kg</td>
</tr>
<tr>
<td>Power</td>
<td>20 W (peak)</td>
</tr>
<tr>
<td>Volume</td>
<td>22.6 × 10 × 17cm</td>
</tr>
<tr>
<td>Scanning</td>
<td>±26° uni-directional cross track</td>
</tr>
<tr>
<td>Pointing</td>
<td>Nadir</td>
</tr>
<tr>
<td>Thermal</td>
<td>Deployable Earth Shield</td>
</tr>
</tbody>
</table>

![Figure 1: 3D Wind Field over North Pole](image1.png)

![Figure 2: FTS Instrument (non-ITAR)](image2.png)
The reduction in volume, mass and power allows the FTS instrument to fit onto a 6U or larger CubeSat, which provides a standardized form factor satellite bus. The CubeSat standardized bus dramatically reduces interface and design complexity of the satellite, allowing further reduction in system cost.

**CONSTELLATION**

The orbit and constellation design is a major driver to meet the 3D Winds requirements utilizing an FTS instrument onboard a 6U CubeSat. An appropriately arranged constellation, in both space and time, will meet the 3D Winds science requirements summarized in Table 15.

**Constellation Drivers and Definition**

The drivers for the design of the constellation primarily stem from the science requirements of the mission. To generate the 3D wind profile, each ground swath has to be sampled three separate times at a known time separation. The resulting three images are then compiled to produce the 3D wind field. For the data from the 3D Winds constellation to impact the meteorological community, it must be uploaded to the NWP which updates twice daily. As such, the mission must provide global coverage with a maximum revisit time of 12 hours. This will drive the need for multiple ‘sets of three’ satellites flying in formation in a SSO orbit.

Altitudes ranging from 500 to 830km would be compatible with the FTS instrument. An altitude of 830km was chosen as a baseline this mission because it provides the most coverage per satellite, most available solar power, and least aerodynamic drag disturbances. The time of the local ascending node was chosen to be 14:00 based on available power from simulations.

**Measurement Separation Time**

The time required between the three overlapping measurements is defined by a combination of the ground resolution and the wind speed resolution. The wind speed resolution of the 3D winds profile needs to be on the order of 1-2 m/s to generate meaningful data for the NWP. The FTS instrument’s focal plane array is capable of supporting a ground resolution of 7km or better.

In order for three spacecraft to produce overlapping measurements, it is necessary for each of their respective ground tracks to overlap. If all three satellites were positioned in the same orbital plane, but separated by the required time duration, their ground tracks would not overlap due to the rotation of the Earth. For this reason, it is necessary to place each spacecraft into a separate orbital plane with the same orbital altitude and inclination. This can be accomplished by separating the right ascension of the ascending node (RAAN, ) of each spacecraft’s orbit by the angular distance that the Earth rotates over the duration of the measurement separation.

For example, a separation of 60 minutes between measurements would require that each orbital plane be separated (in terms of RAAN) by the amount the Earth rotates in 60 minutes (15°). The required angular separation can be calculated in degrees from Equation 1,

\[
\Delta \Omega = \frac{\text{Time between Measurements} \cdot \text{Wind Speed Resolution}}{1440}
\]

where \(t\) is the separation time in minutes.

The relationship between ground resolution, wind speed resolution, time between measurements (as defined by the functionality of the payload), and the corresponding RAAN spacing is shown in Table 2 below.

<table>
<thead>
<tr>
<th>Wind Speed Resolution [m/s]</th>
<th>Time Between Measurements [min]</th>
<th>RAAN Spacing [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>116.7</td>
<td>14.5 – 29.0</td>
</tr>
<tr>
<td>6</td>
<td>100.0</td>
<td>12.5 – 25.0</td>
</tr>
<tr>
<td>5</td>
<td>83.3</td>
<td>10.4 – 20.8</td>
</tr>
<tr>
<td>4</td>
<td>66.7</td>
<td>8.3 – 16.6</td>
</tr>
<tr>
<td>3</td>
<td>50.0</td>
<td>6.3 – 12.5</td>
</tr>
<tr>
<td>2</td>
<td>33.3</td>
<td>4.2 – 8.3</td>
</tr>
<tr>
<td>1</td>
<td>16.7</td>
<td>2.1 – 4.1</td>
</tr>
</tbody>
</table>

For the baseline constellation, a ground resolution of 1km was chosen; which allows for minimal RAAN spacing between orbital planes and will significantly decrease the amount of time necessary to assemble the constellation. One downside to choosing this resolution is that data generated will be increased by a factor of seven, as compared to the 7km resolution. The impact of this on the communications system will be discussed.

After ground resolution was selected, a measurement spacing of 12.7 minutes was chosen, corresponding to a RAAN spacing of 3.1°. Choosing a value in the middle of the acceptable range will allow for some drift.
without falling out of the 1-2 m/s wind speed resolution range.

In addition to the separation of the orbital planes, each satellite must be appropriately positioned within its own orbital plane such that it trails the leading satellite by the necessary separation time. This is accomplished by offsetting the true anomaly ($\theta$) of each satellite by the angular distance that it travels over the duration of the measurement separation time. This can be calculated using Equation 2,

$$\Delta \theta = \frac{360t}{T}$$

where $t$ is the measurement separation time, and $T$ is the orbital period. For the baseline constellation, $\Delta \theta$ is equal to 45°.

It is important to note that the combination of $\Delta \Omega$ and $\Delta \theta$ are coupled for a given separation time, $t$. Any deviation from the coupled pair, whether from orbital insertion inaccuracies or constellation degradation, will result in incomplete overlap between measurements and a reduced volume of useful science data.

**Revisit Time**

In order for the generated science data to be valuable for the NWP, the constellation must be capable of twice daily global coverage which corresponds to an average twelve-hour revisit time.

The minimum number of sets necessary to meet the coverage requirement will have their ground swaths line up continuously with no gap between them. This configuration will ensure that all points on Earth are measured when they pass through the orbital plane. This configuration minimizes the number of sets such that the 12-hour global revisit is achieved; every point on Earth will pass through the orbital plane twice per day, once on the ascending side and once on the descending side. Figure 3 illustrates this concept.

![Figure 3: Ascending side of the orbit. With sets required to provide 12 hour revisit time.](image)

The number of sets required to achieve this level of coverage is dependent upon the payload swath width and orbital period. To determine how many sets are required, it is necessary to first calculate the cross-track swath width, $D$, using Equation 3,

$$D = 2A \tan(\delta + \theta) \frac{\pi}{180}$$

where $A$ is the orbital altitude, $\delta$ is the half-cone angle of the payload in degrees, $\theta$ is the half scan angle of the payload in degrees. For the FTS instrument, $\theta$ was optimized for the constellation at 26°, but $\delta$ varies with orbital altitude in order to maintain a 42 km square nadir footprint. At 830 km, $\delta$ is 1.45°; thus $D$ is equal to 862 km.

Swath width was optimized to lower the number of satellites required in the constellation, while maintaining science performance. This determined the number of sets necessary to achieve the desired coverage, $N$, can be calculated using Equation 4,

$$N = T \left[ \frac{D}{R_E \omega * 60} \right]^{180/\pi}$$

where $T$ is the orbital period in minutes, $D$ is the cross-track swath width, $R_E$ is the radius of the Earth, $\omega$ is the angular rotation rate of Earth ($\omega = 0.00416$ deg/s). The value of $N$ must be rounded up to the nearest integer in order to achieve the 12-hour revisit time. For the baseline constellation, $N$ is equal to 3.27, which is then rounded to 4 sets satellites required. Since there are 3 satellites per set, 12 satellites minimum are required to complete the constellation.

Figure 4, Figure 5, and Figure 6 illustrate the full baseline constellation.
Figure 4: 2D representation of the baseline constellation. The four different color ground tracks correspond to the four sets of satellites. Each orbital plane has one satellite from each set.

Figure 5: Constellation similar colors indicate same ground swath (perspective normal to the orbital planes)
**Constellation Summary**

Using the above parameters, the baseline constellation is defined as follows:

- 830km sun-synchronous orbits
- 12 total satellites
- 3 orbital planes separated by 3.1° RAAN
- 4 evenly spaced satellites per plane (one satellite from each set)
- 45° true anomaly offset between satellites within the same set
- 12 hour average revisit time covering 99.7% of Earth

**Constellation Assembly**

One of the most challenging aspects of a constellation mission is assembling the constellation on orbit. The FTS constellation will be especially challenging due to the very particular spacing required between satellites. Multiple options have been considered for this task; including low-thrust micro-Newton onboard propulsion only or a combination of onboard propulsion and the SHERPA in-space tug.

**RAAN Drift Maneuver**

To limit the amount of propellant necessary to assemble the constellation, FTS could utilize natural drift due to small changes in orbital altitude in order to move satellites relative to one another.

Two maneuver types will be required in order to assemble the constellation once on orbit. The first will be a maneuver to change the RAAN of the orbits relative to one another. To do this, FTS will utilize the same phenomenon that allows for a sun-synchronous orbit – the natural drift of RAAN. This drift is characterized by Equation 5.

$$
\Omega = -\frac{3}{2} J_2 R_E^2 \frac{\mu}{a^3 \cos i}
$$

where $J_2$ is a constant equal to 1.083E-03 for Earth, $R_E$ is the radius of Earth, $a$ is the semi-major axis of the orbit, $\mu$ is Earth’s standard gravitational parameter, and $i$ is the inclination of the orbit. For a Sun-synchronous orbit, $\Omega$ is equal to approximately 1° per day.

By adjusting the altitude of the satellite orbit, and thus the semi-major axis, the corresponding change in RAAN drift rate will cause the satellites orbit to drift from the initial orbit. Once the desired separation has been reached, the altitude can be adjusted back to 830km to lock in the RAAN separation. This type of maneuver can be accomplished with a continuous low-thrust burn along the satellite velocity vector. Figure 7 illustrates an example of this type of maneuver using a low-thrust propulsion system.
The red lines correspond to a satellite initially thrusting along its velocity vector to increase its orbital altitude. The green lines correspond to a satellite initially thrusting along its anti-velocity vector to decrease orbital altitude. Once half of the desired separation is reached, the thrust is oriented in the opposite direction in order to adjust the orbits back to the nominal 830km sun-synchronous orbit shown in blue.

While the maneuver in Figure 7 requires a relatively small amount of $\Delta V$ (136m/s), it can take a significant amount of time if the required plane spacing is large. The maneuver requires approximately 70 days to reach a RAAN separation of just 2.2°, approximately 70% of what is required for the baseline constellation.

**In-Plane Phasing Maneuver**

The second maneuver type necessary will be to adjust the in-plane phasing of the satellites in terms of true anomaly. This can be accomplished using the same maneuver outlined above for the RAAN drift, but with different timing. By slightly changing the orbital altitude, we create a difference in the orbital period of two satellites and cause their phase to naturally drift over time. The orbital period is characterized by Equation 6,

$$T = 2\pi \sqrt{\frac{a^3}{\mu}}$$

where $a$ is the semi-major axis and $\mu$ is Earth’s standard gravitational parameter. Figure 8 shows an example of this type of maneuver where a satellite adjusts its in-plane phase by 45°.

**Figure 7: Low thrust maneuver to change RAAN spacing. Shaded regions indicate thrust duration.**

**Figure 8: In-plane phasing maneuver to set true anomaly difference to between two satellites to 45°. The example maneuver took 6 days to complete using 10m/s $\Delta V$.**
In the above example, the satellite utilized a continuous, 12-hour low-thrust maneuver to increase its altitude, drifted for 5 days, then applied a continuous 12-hour low-thrust maneuver in the opposite direction to decrease its altitude back to the nominal value. In total, this maneuver took 6 days and required 10m/s of ΔV.

**SHERPA Insertion Maneuvers**

A second option for assembling the constellation is to utilize the Spaceflight Services SHERPA in-space tug to individually place each satellite in its respective orbit. This SHERPA space tug has a ΔV of 400 m/s or greater and capacity up to sixty 6U satellites. The space tug will first house the spacecraft within the launch vehicle (LV) fairing. Once the LV has achieved orbit, the space tug, carrying all of the FTS CubeSats, will be deployed from the LV. The space tug will then begin to use its onboard power, control, and propulsion systems to consecutively drop off each FTS CubeSat in the appropriate orbit.

The insertion accuracy for SHERPA, according to Spaceflight, is shown in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis</td>
<td>± 5 km</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>± 0.005°</td>
</tr>
<tr>
<td>Inclination</td>
<td>± 0.05°</td>
</tr>
<tr>
<td>RAAN</td>
<td>± 0.05°</td>
</tr>
</tbody>
</table>

The main threats to the FTS constellation due to these uncertainties come from the semi-major axis and inclination. These two parameters strongly affect the RAAN drift rate and orbital period. In the worst case scenario, where semi-major axis and inclination are offset by their maximum values, the constellation spacing will degrade in less than 7 days and the science requirements will not be met. Figure 9 shows the constellation degradation in terms of phase angles, an insertion correction maneuver, and a station keeping maneuver.

![In-plane phase degradation due to worst case insertion accuracy. An insertion burn of 12m/s is required to lock in phase, and a station keeping burn of 0.2m/s is shown 45 days later.](image)

The insertion correction burn is similar to the in-plane phase maneuver in that it adjusts the orbital altitude to lock in the orbital periods of two satellites. The maneuver in Figure 9 required two days of continuous thrusting and a total ΔV of 12m/s. In addition, a 0.2m/s stationkeeping maneuver was executed 45 days later. It is clear that onboard propulsion will be absolutely necessary if SHERPA is used to place the constellation.

**SPACECRAFT**

The constellation will be assembled from 12 autonomous 6U CubeSats that utilize recent developments in nanosatellite technology across multiple subsystems.

**PROPULSION**

Constellation assembly and stationkeeping of the FTS CubeSats will require propulsive maneuvers. As described in the Constellation Section, the SHERPA will place the FTS CubeSats in orbits within specific insertion accuracy. In the worst case tolerance stack up, however, this accuracy will not be sufficient to ensure the required wind speed resolution, i.e., orbital RAAN separation. On-board propulsion is thus
necessary to correct the orbit due to insertion accuracies.

The mass, volume, and power constraints of a CubeSat make it very difficult to add propulsion to the satellite. Over the past several years, however, there have been significant developments in nanosatellite propulsion systems, both chemical and electric. The FTS CubeSat mission is able to take advantage of these efforts.

Nanosatellite propulsion systems have either high specific impulse (\(I_p\)) or thrust, but not both. While high \(I_p\) is desirable to reduce fuel mass, the associated low thrust means an orbital insertion correction could take months to accomplish and delay the start of science operations for a two year mission. In Table 4, propulsion subsystem requirements were created to properly trade the best existing option.

### Table 4: Propulsion Subsystem Requirements

<table>
<thead>
<tr>
<th>Propulsion Requirements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Propulsion system mass shall be less than 1.5kg.</td>
</tr>
<tr>
<td>P2</td>
<td>Propulsion system shall consume less than 10W of power.</td>
</tr>
<tr>
<td>P3</td>
<td>Propulsion system shall fit within a 1U volume, defined as 10 x 10 x 10cm</td>
</tr>
<tr>
<td>P4</td>
<td>Propulsion system shall be able to deliver a total (\Delta V) of 4m/s per year for stationkeeping.</td>
</tr>
<tr>
<td>P5</td>
<td>Propulsion system shall be able to deliver a total (\Delta V) of 24m/s for orbital insertion correction.</td>
</tr>
<tr>
<td>P6</td>
<td>Thrusters shall be mounted through the spacecraft center of mass.</td>
</tr>
</tbody>
</table>

The conclusion of the propulsion system trade was to use the Busek CubeSat Electrospray Thruster, which has heritage on nanosatellite missions.

### ATTITUDE DETERMINATION AND CONTROL

Precise pointing knowledge and control is required to meet the science requirements of 3D Winds. The FTS CubeSat Attitude Determination and Control System (ADCS) will be comprised of both heritage and new components that collaboratively function to meet the pointing knowledge and control requirements as outlined in requirements A1 through A4 in Table 5.

### Table 5: Attitude Determination and Control Requirements

<table>
<thead>
<tr>
<th>ADCS Requirements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>FTS CubeSats shall have spatial knowledge less than 2km.</td>
</tr>
<tr>
<td>A2</td>
<td>FTS CubeSats shall have temporal knowledge less than 1 second.</td>
</tr>
<tr>
<td>A3</td>
<td>FTS CubeSats shall have attitude control within 1° from nadir.</td>
</tr>
<tr>
<td>A4</td>
<td>FTS CubeSats shall have pointing knowledge less than 0.17°.</td>
</tr>
<tr>
<td>A5</td>
<td>ADCS system shall fit within 1U volume.</td>
</tr>
</tbody>
</table>

The FTS instrument has precise spatial and temporal requirements, as outlined in requirements A1 and A2. The conventional method of two line element sets (TLE) are only provided once per day for spacecraft in LEO, and thus will not meet the requirements of the FTS mission. The alternative to TLEs are to fly a GPS receiver. The Michgan Exploration Laboratory’s (MXL) RAX-2 CubeSat was able to achieve maximum positional errors under 5 meters and temporal accuracies well under one second. The FTS mission will utilize the heritage RAX-2 system, which comprised of a NovAtel OEMV family GPS receiver, Antcom patch antenna, and the MXL PTB.

### Control Hardware

Three-axis stabilization is required to control the CubeSat within 1° from nadir. Reaction wheels sized to a minimum of 22 mN-m s to counteract all predicted disturbance torques, the dominant of which is thruster torque (calculation of these disturbance torques and the required reaction wheel sizing are well documented and thus not discussed further in this paper). A set of three, 30 mN-m s Sinclair Interplanetary reaction wheels will be utilized to control the FTS CubeSat within all three axes as they meet all of the FTS CubeSat ADCS requirements.

To reduce stored momentum in the reaction wheels, magnetorquers will be employed to transfer the angular momentum to the Earth’s magnetic field. Free air core magnetorquers are highly customizable and can be printed onto one face per axis of the CubeSat. The number of turns and printed wiring board (PWB) layers required for each axis were designed to compensate for the sum of all external torques when aligned with each respective axis, the summary of which is documented in Table 6.

### Table 6: Free Air Core Magnetorquer Characteristics

<table>
<thead>
<tr>
<th>Axis</th>
<th># of turns required</th>
<th>Turns/Layer</th>
<th>Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>121</td>
<td>79</td>
<td>2</td>
</tr>
<tr>
<td>Y</td>
<td>35</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>Z</td>
<td>207</td>
<td>79</td>
<td>3</td>
</tr>
</tbody>
</table>

As state in ADCS requirement A4, the FTS CubeSat needs pointing knowledge less than 0.17° in order to...
meet the 3D Winds science requirements. To achieve this knowledge requirement, the FTS CubeSat will employ both star trackers and sun sensors.

**Determination Hardware**

The FTS instrument has a scan mirror, as such it could be dual purposed as a star tracker or perform landmarking. The cost to integrate this architecture into the instrument would exceed that of an off the shelf solution, which will be pursued for the FTS CubeSat. The Sinclair Interplanetary S3S star tracker mounted on the anti-nadir face can provide pointing knowledge to 0.0019° cross boresight and 0.019° around boresight. Fourteen S3S star tracker flight units have been delivered with the first flight to occur in 2013. This will provide a stable baseline from which the FTS mission can be built upon.

The star tracker will be sufficient to meet the pointing requirement, but only during periods when no direct sunlight enters the tracker’s field of view. During periods of star tracker ‘blindness’, the FTS CubeSat will utilize a Sinclair Interplanetary SS-411 Two-Axis Digital Sun Sensor; which has an accuracy of ±0.1° over a ±70° field of view. Software being developed at the University of Michigan will increase sun sensor accuracy by using prior star tracker data, inertial measurement units, and control simulation methods.

**COMMAND AND DATA HANDLING**

The Command and Data Handling (CDH) subsystem controls all spacecraft operations and functions. The subsystem serves as an interface between ground stations and the FTS CubeSat; managing all data flow between satellite subsystems and ground controllers.

The requirements for the FTS CubeSat CDH subsystem are driven by mission- and system-level requirements and constraints, as outlined in Table 7.

<table>
<thead>
<tr>
<th>CDH Requirements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CD1</td>
<td>The CDH subsystem shall be able to handle at minimum 496.2 kbps, which includes all housekeeping, subsystem, and science data rates.</td>
</tr>
<tr>
<td>CD2</td>
<td>The CDH system shall fit within a 0.25U volume, defined as 10 x 10 x 2.5cm.</td>
</tr>
<tr>
<td>CD3</td>
<td>The CDH system shall have a mass less than 0.25kg.</td>
</tr>
<tr>
<td>CD4</td>
<td>The CDH system shall provide an RS-422 interface to the FTS instrument.</td>
</tr>
<tr>
<td>CD5</td>
<td>The CDH system shall be capable of recovering from single event effects, including upsets.</td>
</tr>
</tbody>
</table>

The minimum date rate in requirement CD1 accounts for the maximum potential science data rate from the FTS instrument at a resolution of 1km, though the baseline mission is for 2km.

Data compression will be used to decrease the amount of data that must be stored on the spacecraft and downlinked to the ground. Compression will help to prevent possible single-event effects that could corrupt memory sectors. Error-checking will also be performed during every transfer operation to ensure data fidelity through collection and transmission.

**Data Flow**

Three main data sources exist in the FTS mission: FTS instrument payload, GPS receiver, and the ADCS attitude sensors. The ADCS data may be collected by a secondary computer to lighten the load on the FCPU if deemed necessary at a later time; the current baseline calls for the attitude data to be collected by the FCPU directly. The GPS data will similarly be collected directly by the FCPU.

After collection, data must be synchronized, compressed, and then sent to the spacecraft memory. Eventually, the data will be fed into the S-Band radio buffer memory in preparation for downlink and then sent to ground stations around the world. Archived GPS ephemeris data will be added on the ground (to alleviate downlink file size), and then uploaded to an online archive or given directly to the field users. This process is shown in Figure 10.
CDH Hardware Design

The Argo Bus Controller (ABC) board currently in development by MXL at the University of Michigan board was selected due to its high customizability. The flexibility of the ABC board is desirable due to the relative immaturity of the FTS CubeSat mission. The fewer constraints the CDH board places upon the system, the better.

CDH Software Design

The CDH system is not required to have a real-time operating system (RTOS) due to the relatively loose timing requirements of the data delivery system. The FTS system must have some in-payload storage in order to be capable of performing averaging, and therefore it is not critical that data is delivered with strict timing. For ease of development, a custom embedded Linux environment will be used. MXL has extensive heritage with systems of this nature.

CDH software will be responsible for collection, synchronization, compression, and storage of payload and attitude/positioning data. Additionally, the CDH subsystem is responsible for management of communications channels, including interpreting ground commands and managing downlink and beaconing. Many of these processes have already been implemented in previous Michigan CubeSats and may easily be adapted as necessary for the FTS CubeSat mission.

COMMUNICATIONS

The communications subsystem is responsible for transmission of all data via radio frequencies (RF). The subsystem’s primary responsibility is the downlink of science data and spacecraft health telemetry from the FTS CubeSat to ground station operators.

Like the Command and Data Handling subsystem, requirements for the communications system are driven by mission- and system-level requirements and constraints and are show in Table 8.

Table 8: Communication Requirements

<table>
<thead>
<tr>
<th>Communication Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1 Communications shall not transmit until 30 minutes have elapsed after deployer ejection</td>
</tr>
<tr>
<td>CO2 Communications shall maintain a 3 [dB] margin minimum on all links</td>
</tr>
<tr>
<td>CO3 Communications system shall use S-Band for science data</td>
</tr>
<tr>
<td>CO4 Communications shall broadcast spacecraft housekeeping telemetry in a UHF beacon</td>
</tr>
<tr>
<td>CO5 Communications shall be capable of relaying all data to the ground with a maximum delay of two orbital periods</td>
</tr>
<tr>
<td>CO6 UHF Communications shall operate within the Amateur UHF bands</td>
</tr>
<tr>
<td>CO7 S-Band Communications shall operate within the 2.2-2.3 [GHz] S-Band</td>
</tr>
<tr>
<td>CO8 The Communication system shall fit within a 0.25U volume.</td>
</tr>
<tr>
<td>CO9 The Communication system shall have a mass less than 0.75kg.</td>
</tr>
</tbody>
</table>

The communications subsystem is driven primarily by the maximum delay requirement (COM-5) imposed by ITT Exelis. Downlink rate and ground station capabilities will be highly driven by the speed necessary to downlink the large payload data volumes in time to meet this requirement.

Figure 10: Data flow of the FTS CubeSat. The Flight Computer is responsible for data sampling, synchronization, compression, and storage.
**Downlink Calculations**

The speed necessary to transmit all required science data to the ground was calculated using a one-year simulation. Four potential ground station locations were selected at ITT Exelis facilities across the globe and access to these ground stations was calculated by Systems Tool Kit (STK). These ground stations are listed below in Table 9.

<table>
<thead>
<tr>
<th>City</th>
<th>Country</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rochester</td>
<td>USA</td>
<td>43°9' N</td>
<td>77°36' W</td>
</tr>
<tr>
<td>San Diego</td>
<td>USA</td>
<td>32°42′ N</td>
<td>117°09′ W</td>
</tr>
<tr>
<td>Melbourne</td>
<td>AUS</td>
<td>37°48′ S</td>
<td>144°57′ E</td>
</tr>
<tr>
<td>Basingstoke</td>
<td>UK</td>
<td>51°16′ N</td>
<td>1°5′ W</td>
</tr>
</tbody>
</table>

Access time to each of these ground stations, with an initialization time of 120 seconds, was calculated utilizing STK. The speed required to downlink the data generated during the longest gap over the shortest access was determined to 5Mbps. The speed imposed for this worst case scenario would impose unrealistic requirements upon the spacecraft radio and ground station receiver. Analyzing individual gaps and accesses, it was determined that a radio speed of 3 Mbps satisfies requirement CO-5 in 99.2% of cases over one year, with only 1.5Mbps is required on average (analysis is not documented in this paper in order to meet required paper length).

**Radio Hardware**

For the UHF radio, the AstroDev Lithium UHF radio was selected due to its extensive heritage within MXL.16

For the S-Band radio, the L3 Cadet radio was selected. The L3 Cadet has flight heritage on the DICE mission, where speeds of up to 3Mbps have been realized over UHF and the average transmission rate is 1.5Mbps.17

**Ground Station**

Due to the data volumes, downlink requirements, and number of satellites on orbit, the ground stations used for the FTS mission will need to have large dishes and be operationally robust.

In order to close the link with 3.0dB margin, a ground station dish of at least 7m diameter is required. Link budget analysis concluded a 9m dish results in a 6.0dB margin. The DICE mission used ground stations greater than 18m in diameter, so larger dishes may be necessary.15 Custom ground stations will be required at each of the selected sites, so sizing will be likely driven by the FTS mission requirements and future business applications.

**Operational Complexity**

The FTS mission calls for several satellites in close proximity to one another, and will encounter scenarios where two satellites are overhead simultaneously. The L3 Cadet radio has sufficient speed such that skipping passes or prioritizing downlinks is possible, but this will require advanced operations planning in order to fulfill requirement CO-5. Other strategies will be investigated in order to lessen the operational complexity of the FTS mission.

**POWER**

The power subsystem will be a major driver in determining the mission parameters and the satellites functional design. With the payload consuming 20W of power during nominal operations, the FTS CubeSat will consume more power per “U” than any other MXL heritage CubeSat.

Power requirements are driven by mission lifetime science operations. The requirements are outlined in Table 10.

<table>
<thead>
<tr>
<th>Power Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 EPS Shall provide peak power to all satellite subsystems</td>
</tr>
<tr>
<td>P2 EPS Shall provide power to the FTS payload during nominal operations</td>
</tr>
<tr>
<td>P3 EPS Shall provide a minimum of 150,000 joules per orbit during nominal operations</td>
</tr>
<tr>
<td>P4 EPS Shall provide a minimum of 101,000 joules per orbit during orbital maneuver operations</td>
</tr>
</tbody>
</table>

**Power Consumption**

A detailed analysis of the energy consumed by each component during the six spacecraft modes was completed. These energy consumption numbers, along with adequate contingency have been used to determine the power that will need to be generated in order to power the spacecraft during the mission. Table 11 provides an overview of the energy consumption for FTS CubeSat. In the nominal science mode, the FTS CubeSat will consume 42W-hrs per orbit. This means the per-orbit average power must be at least 25W.
Table 11: FTS CubeSat Energy Consumption by Mission Mode [Joules]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Safe</th>
<th>Deploy</th>
<th>De-tumble</th>
<th>Standby</th>
<th>Orbit Maneuver</th>
<th>Nominal Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>117,476</td>
</tr>
<tr>
<td>ADCS</td>
<td>0</td>
<td>0</td>
<td>15,314</td>
<td>15,983</td>
<td>24,022</td>
<td>15,983</td>
</tr>
<tr>
<td>CDH</td>
<td>1,570</td>
<td>1,570</td>
<td>1,570</td>
<td>1,570</td>
<td>1,570</td>
<td>1,570</td>
</tr>
<tr>
<td>Power</td>
<td>2,983</td>
<td>6,230</td>
<td>2,983</td>
<td>2,983</td>
<td>2,983</td>
<td>2,983</td>
</tr>
<tr>
<td>Comm</td>
<td>3,139</td>
<td>3,139</td>
<td>3,139</td>
<td>3,139</td>
<td>6,062</td>
<td>6,062</td>
</tr>
<tr>
<td>Propulsion</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>65,772</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>7,692</td>
<td>10,939</td>
<td>23,006</td>
<td>23,675</td>
<td>100,409</td>
<td>144,074</td>
</tr>
</tbody>
</table>

Power Generation
A novel approach to power generation is required to support the FTS CubeSat mission. The heavy and continuous power demands of the FTS CubeSat instrument are the first of its kind.

Basic trade studies were completed for multi-panel deployable and reticulating panel configurations, but ultimately the single panel deployable configuration was deemed to be the most desirable due to the low risk associated with using a technology with previous MXL CubeSat heritage.

In order to determine the feasibility of using single-panel deployables, several configurations were analyzed in an 830km, sun-synchronous orbit with local ascending node times of 12:00, 14:00 15:00, and 18:00 using the STK solar panel tool. The analysis baselines a configuration in the 14:00 orbit that was able to meet the power generation requirements P3 and P4.

The baseline panel configuration was then analyzed to determine power generation in the orbital maneuver orientation. Figure 11 and Table 12 show the baseline panel configuration, the energy generated per orbit based upon the STK simulations, and the orientation of the spacecraft during the critical modes (where blue is nadir, and red is the ram vector).

Figure 11: FTS CubeSat Orientations in Different Modes

Table 12: FTS CubeSat Power Margin

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Science</td>
<td>144,079</td>
<td>172,760</td>
<td>+28,681</td>
<td>16.6</td>
</tr>
<tr>
<td>Orbital Maneuver</td>
<td>100,414</td>
<td>148,350</td>
<td>+47,936</td>
<td>32.3</td>
</tr>
</tbody>
</table>

STRUCTURE
For CubeSats, the structure defines the interface to the launch vehicle adapter as well as the volume that all other subsystems must be mechanically packaged to fit within. The mechanical packaging of the FTS CubeSat is unique in that it has a precision optical payload,
propulsion, a complex attitude system as well as large solar arrays to meet the high power demand.

The requirements for the structure are derived from the CubeSat form factor for a 6U launch aboard the SHERPA can be found in Table 13.¹⁸

Table 13: Structural Requirements

<table>
<thead>
<tr>
<th>Structural Requirements</th>
<th>Total Mass [g]</th>
<th>Total Mass + Contingency [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 FTS CubeSat shall be 36.6 x 10 x 22.6 cm (6U)</td>
<td>4,500</td>
<td>4,950</td>
</tr>
<tr>
<td>S2 FTS CubeSat shall not exceed 10kg (6U) in mass</td>
<td>8,52</td>
<td>1,023</td>
</tr>
<tr>
<td>S3 FTS CubeSat shall survive a 24-G static load without any permanent deformation or failures</td>
<td>1.787</td>
<td>1.968</td>
</tr>
<tr>
<td>S4 FTS CubeSat shall have a fundamental frequency &gt;100Hz</td>
<td>1.150</td>
<td>1.495</td>
</tr>
<tr>
<td>S5 The system center of mass shall be within a 2cm sphere whose center is at the system geometric center</td>
<td>872</td>
<td>959</td>
</tr>
<tr>
<td>Reserve</td>
<td>805</td>
<td>935</td>
</tr>
<tr>
<td>Total</td>
<td>11,125</td>
<td>12,506</td>
</tr>
</tbody>
</table>

Packaging

To verify packaging, a computer aided design (CAD) model was created that houses models of all spacecraft subsystem and components would fit within a 6U spacecraft. All CAD components were put into the structure such that adequate structural support and room for harnessing are available. The CAD model, shown in Figure 12 verified the results seen from a preliminary volume budget (not discussed here).

![Figure 12: FTS CubeSat CAD Model (non-ITAR)](image)

Mass

The spacecraft mass is major system driver because the payload requires half of the mass and volume budget. This requires the spacecraft bus to be less than 5kg to meet the 10kg requirement per the 6U specification.¹⁸

Table 14 provides the FTS CubeSat mass budget. The mass budget takes contingency into account and holds a system level reserve to provide the most conservative estimate possible. Although it does not meet the 10kg requirement per 6U guidelines, the SHERPA will be able to handle payloads in access of the allocated 10kg.⁸

Table 14: FTS CubeSat Mass Allocation

<table>
<thead>
<tr>
<th>Item</th>
<th>Total Mass [g]</th>
<th>Total Mass + Contingency [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>4,500</td>
<td>4,950</td>
</tr>
<tr>
<td>Structure</td>
<td>8,52</td>
<td>1,023</td>
</tr>
<tr>
<td>Power Generation</td>
<td>1.787</td>
<td>1.968</td>
</tr>
<tr>
<td>Propulsion</td>
<td>1.150</td>
<td>1.495</td>
</tr>
<tr>
<td>Electronics</td>
<td>872</td>
<td>959</td>
</tr>
<tr>
<td>Sensors</td>
<td>158</td>
<td>173</td>
</tr>
<tr>
<td>Actuators</td>
<td>805</td>
<td>935</td>
</tr>
<tr>
<td>Reserve</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Total</td>
<td>11,125</td>
<td>12,506</td>
</tr>
</tbody>
</table>

FUTURE WORK: OPERATIONAL CONCERNS

The operations of the FTS constellation will be difficult and further complicated by the distance between ground station networks. For the system to be truly robust, it should be recoverable from two simultaneous failures on each individual satellite.

Loss of Satellite(s)

Loss of a single satellite, without the ability to recover, will critically limit the science capabilities of the FTS CubeSat constellation. The third satellite for each flying trio provides a data quality confirmation, so each trio has built in redundancy. The science objectives will need to be robust to such a loss, however, and the team will focus on identifying key reliability issues.

Should multiple satellites fail simultaneously, ground operators will need to coordinate and prioritize which failures to fix. To combat confusion if this situation occurs, the satellites should have a robust safe (hold) mode and operations should be well practiced prior to launch.

Downlink Prioritization

The number and arrangement of spacecraft in the FTS constellation will result in situations where multiple spacecraft are within range of a ground station at the same time. The FTS CubeSats will have enough bandwidth to skip passes if necessary. The transmission rates will also be fast enough that it will be possible to initiate and complete two links on a given pass, depending on spacecraft positioning. Tracking of collection time of data assets will be necessary to ensure that the two-orbit downlink delay requirement is met for all data sets, but the FTS CubeSats should be...
capable of meeting this requirement with further operations planning.

CONCLUSION

This paper described the recent advancements in CubeSat capabilities and future work required to meet the objectives of the FTS mission. Table 15 provides traceability from the 3D Winds decadal mission to FTS CubeSat Constellation capabilities. Several novel approaches to subsystem design and constellation formation were optimized with emphasis on science mission requirements while balancing overall mission cost. The small satellite community has the capabilities to provide decadal mission data.

ACKNOWLEDGEMENTS

Large thanks to the Masters of Engineering in Space Systems team at the University of Michigan for conducting the satellite and mission architecture trades. Their efforts were constrained to a semester’s work, yet they were able to determine that a nanosatellite platform was feasible for conducting a decadal mission for 3D Winds.

Table 15: Science Requirements Matrix from Decadal Survey Recommendations

<table>
<thead>
<tr>
<th>Decadal Survey Recommendations</th>
<th>Science Objectives</th>
<th>Scientific Measurement Requirements</th>
<th>Instrument/Satellite Requirements</th>
<th>Projected Instrument / Satellite Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characterize three-dimensional tropospheric winds on a global scale.</td>
<td>Measure three-dimensional wind fields on a global basis with accuracy and spatial resolution values that support the Decadal Survey mission goals</td>
<td>Wind measurement altitude range: 0-20 km</td>
<td>Spectral: Range: 1210-1750 cm-1 Resolution: &lt;1.25 cm-1 Accuracy: &lt;10 ppm</td>
<td>Spectral: Range: 1210-1750 cm-1 Resolution: 1.25 cm-1 Accuracy: 5 ppm</td>
</tr>
<tr>
<td>Because wind is ultimately related to the transport of all atmospheric constituents, its measurement is crucial for understanding sources and sinks of constituents, such as atmospheric water.</td>
<td></td>
<td>Vertical Resolution: 0.5 km (at altitude of 0-2 km) 1 km (at 2-16 km) 2 km (at 16-20 km)</td>
<td>Radiometric: NEdT: &lt;200mK Accuracy: &lt;200mK</td>
<td>Radiometric: NEdT: 200mK Accuracy: 200mK</td>
</tr>
<tr>
<td>The transport of water vapor is essential to closing regional hydrologic cycles, and its measurement should enable scientific advances in understanding El Niño, monsoons, and the flow of tropical moisture to the United States.</td>
<td></td>
<td>Horizontal resolution: 25 km.</td>
<td>Spatial: IFOV: &lt;7 km Scan Range: +26 deg LOS Pointing Accuracy: &lt;0.5deg LOS Pointing Knowledge: &lt;1 mrad LOS Jitter: &lt;100 urad Satellite Position Knowledge: &lt;100m</td>
<td>Spatial: IFOV: 1 km Scan Range: +26 deg LOS Pointing Accuracy: &lt;0.5deg LOS Pointing Knowledge: &lt;1 mrad LOS Jitter: &lt;100 urad Satellite Position Knowledge: &lt;10m</td>
</tr>
<tr>
<td>Reliable global analyses of three-dimensional tropospheric winds are needed to improve the depiction of atmospheric dynamics, the transport of air pollution, and climate processes.</td>
<td></td>
<td>Wind Velocity Measurement Accuracy: 1-2 m/sec over the full altitude range</td>
<td></td>
<td>Temporal: Global Revisit: &gt;1x per day Data Latency: &lt;2 hours Swath Repeats: 3 satellites in a train needed to re-measure ground swath within 8.3-16.7min</td>
</tr>
<tr>
<td>Finally, the value of accurate wind measurements in day-to-day weather forecasting is well-known; for example, the tracks of tropical cyclones are modulated by environmental wind fields that will be better analyzed and forecasted with the assimilation of newly available wind profiles.</td>
<td></td>
<td>Wind Vector Directional Accuracy: &lt;30 degrees</td>
<td>Other: Number of Satellites: As needed to meet global coverage requirements</td>
<td></td>
</tr>
</tbody>
</table>
REFERENCES


8. Email correspondence with Spaceflight Services, March 2013.


