Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington, DC 20554

In the Matter of	)	
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Tyvak Nano-Satellite Systems LLC	)	
	)	
Application for Authority for Ground	)	
Testing, Launch, and Operation of	)	File No. ____-EX-PL-2014
Experimental Non-Geostationary	)	
Low Earth Orbit Satellites	)	

NARRATIVE EXHIBIT

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NARRATIVE EXHIBIT

Tyvak Nano-Satellite Systems LLC ("Tyvak") provides nano-satellite and CubeSat space vehicle products and services that target advanced state-of-the-art capabilities for government and commercial customers to support operationally and scientifically relevant missions. With this Application, Tyvak requests five-year authority for ground testing, launch, and operation of a pair of identical experimental non-geostationary ("NGSO") low earth orbit ("LEO") CubeSat satellites. The RF communications links for these satellites include low-power transmissions in the 2.4 GHz Industrial, Scientific, and Medical ("ISM") band for inter-satellite ranging; two-way telemetry monitoring, tracking, and command ("TT&C") transmissions and inter-satellite communications in the 400 MHz UHF range; and space-to-Earth downlink transmissions in the 2.2 GHz S-band.[1]

[1] Tyvak will also file an application for experimental authority to operate an associated UHF Earth station. Authority for additional associated UHF Earth stations may be sought by Tyvak affiliates in separate applications, as explained below.

I. NARRATIVE INFORMATION REQUIRED BY FCC FORM 442

Question 6A. Description of the Nature of the Research Project Being Conducted

Tyvak has been selected by NASA to execute the Proximity Operations Nano-Satellite Flight Demonstration ("PONSFD") project under NASA's Edison Small Satellite Flight Demonstration Missions program, government contract number NNA12AC39C. The PONSFD validates the technologies needed to support rendezvous, proximity operations, docking ("RPOD"), servicing, and formation flight by utilizing a pair of identical nano-satellites, and leveraging the inherent relative low costs of their vehicle manufacture and launch capabilities.

The proposed satellites will adhere to a design specification co-developed by Stanford University ("Stanford") and California State University, San Luis Obispo ("Cal Poly") referred to as the CubeSat Standard. Additional information regarding the CubeSat Standard can be found at the CubeSat Community website, http://www.CubeSat.org/.

The spacecraft will be fabricated, tested, launched, and operated by Tyvak using its Mission Operations Center ("MOC") in Irvine, California, and using affiliated Earth stations in other locations, the authorizations for which will be secured under a separate application.[2] TT&C for the satellites will be carried out by Tyvak via a two-way link in the UHF band between 399.9-400.05 MHz. The UHF link will also be used for communications between the two satellites at a significantly reduced power level. Additionally, there will be a payload communications capability that is separate from the TT&C communications system to report data gathered on experimental operations. The payload communications system will downlink data from the test instruments to NASA-operated Earth stations using spectrum in the S-band

[2] References to Earth stations in this application are included to provide a comprehensive system overview, but are solely advisory.

between 2,200-2,290 MHz. Finally, the satellites will conduct ranging determinations between the two satellites using low-power commercial-off-the-shelf ("COTS") ISM transmitters in the 2.4 GHz range. The 2.4 GHz system may also be used for some inter-satellite communications, as an alternative to the primary UHF inter-satellite link.

Prior to launch, Tyvak will conduct developmental testing of satellite components, including its transmitters and receivers, at its Irvine, California facilities. Post launch, the satellites are intended to be short-lived, with an expected lifespan of 9 to 12 months on-orbit, which will permit adequate time to demonstrate the inter-satellite link and rendezvous operations under investigation.

Question 6B. Showing that the Communications Facilities Requested are Necessary for the Research Project

The primary purpose of this mission is to demonstrate proximity operations, such as relative station-keeping, circumnavigation, and docking. On-orbit operation is the only effective way of collecting functional and performance data in the relevant operational environment, and cannot be adequately substituted by ground testing or computer simulation.

With the proliferation of the CubeSat Standard and the availability of low-cost space access for those adhering to that standard, the cost to test miniature components on-orbit has become relatively inexpensive compared to equivalent ground testing and simulation. This is largely due to the availability of low-cost secondary payload launch options and cost sharing among multiple CubeSat developers.

In addition, on-orbit data provides confidence to customers that future systems will operate successfully on-orbit through maneuvers. The evaluation of hardware and software in an environment similar to that found in space is not easily replicated on Earth. On-orbit component failures are often attributed to unforeseen conditions or coupling of effects that cannot be tested adequately until on-orbit. Consequently, the use of an on-orbit test bed provides significant direct and indirect financial benefits, as well as risk reduction for future satellite programs.

Question 6C. Showing that Existing Communications Facilities are Inadequate

Currently, there are no comparable communications facilities to support the operation of the CubeSat system for any of the three required operations.

For the inter-satellite ranging operation in the 2.4 GHz ISM band, no existing facilities can be used for this purpose because a primary mission objective is to test inter-satellite ranging capabilities during on-orbit proximity operations.

For the TT&C and inter-satellite communications link in the 399.9-400.05 MHz UHF band, as discussed in a later section of this Application, Tyvak is unaware of any currently authorized use of the UHF band between 399.9-400.05 MHz in the United States or other countries. Thus, there are no suitable existing facilities.

For the payload downlink in the 2,200-2,290 MHz S-band, the payload data must be downlinked directly from the satellites to pre-existing NASA Earth stations using these frequencies and thus no alternative existing facilities will be adequate.

Question 8. Justification of the Need for a Five-Year Experimental License Term

Under Section 5.71 of the Commission's rules, the regular license period for stations in the Experimental Radio Service is either 2 or 5 years.[3] An applicant desiring to apply for a five-year license must provide justification for its need for a license of that duration.

[3] 47 CFR § 5.71.

Grant of a full five year experimental license is well justified by the long timeline and significant potential for delays and schedule changes inherent in space operations. As illustrated in Table 10, below, the CubeSat System Major Milestones require that experimental authorization be secured prior to fabrication and RF testing that begins more than nineteen months before launch, and experimental authorization must extend through on-orbit experimental operations and decommission, at least nine months after launch. Indeed, frequency authorization must be secured before equipment specifications can be finalized and prior to construction or testing, let alone actually carrying out the experimental mission. Due to the importance of the PONSFD experiment and the need for continuity of operations at all times from development through decommissioning, a shorter term with the possibility of renewal mid-mission would be inappropriate and authorization should be granted for the requested five-year term.

As further explained in Section II below, grant of the requested license term will not adversely impact any other spectrum users, and is critical to provide the long-term assurance necessary to support the extended development and mission cycle inherent in cutting-edge space research.

Question 10. Transmitting Equipment to be Installed, Including Manufacturer, Model Number and Whether the Equipment is Experimental in Nature

Each of the two identical CubeSats comprise three transmitting elements for which authority is being sought from the Commission: a) an inter-satellite ranging component that transmits and receives in the ISM band at 2.4 GHz; b) a TT&C and inter-satellite communications component that transmits and receives in the UHF band between 399.9-400.05 MHz; and c) a payload component that transmits in the range of 2,200-2,290 MHz. The following graphic provides an overview of the transmitting and receiving components of each element. The specific model numbers are subject to change based on product availability and system upgrades.

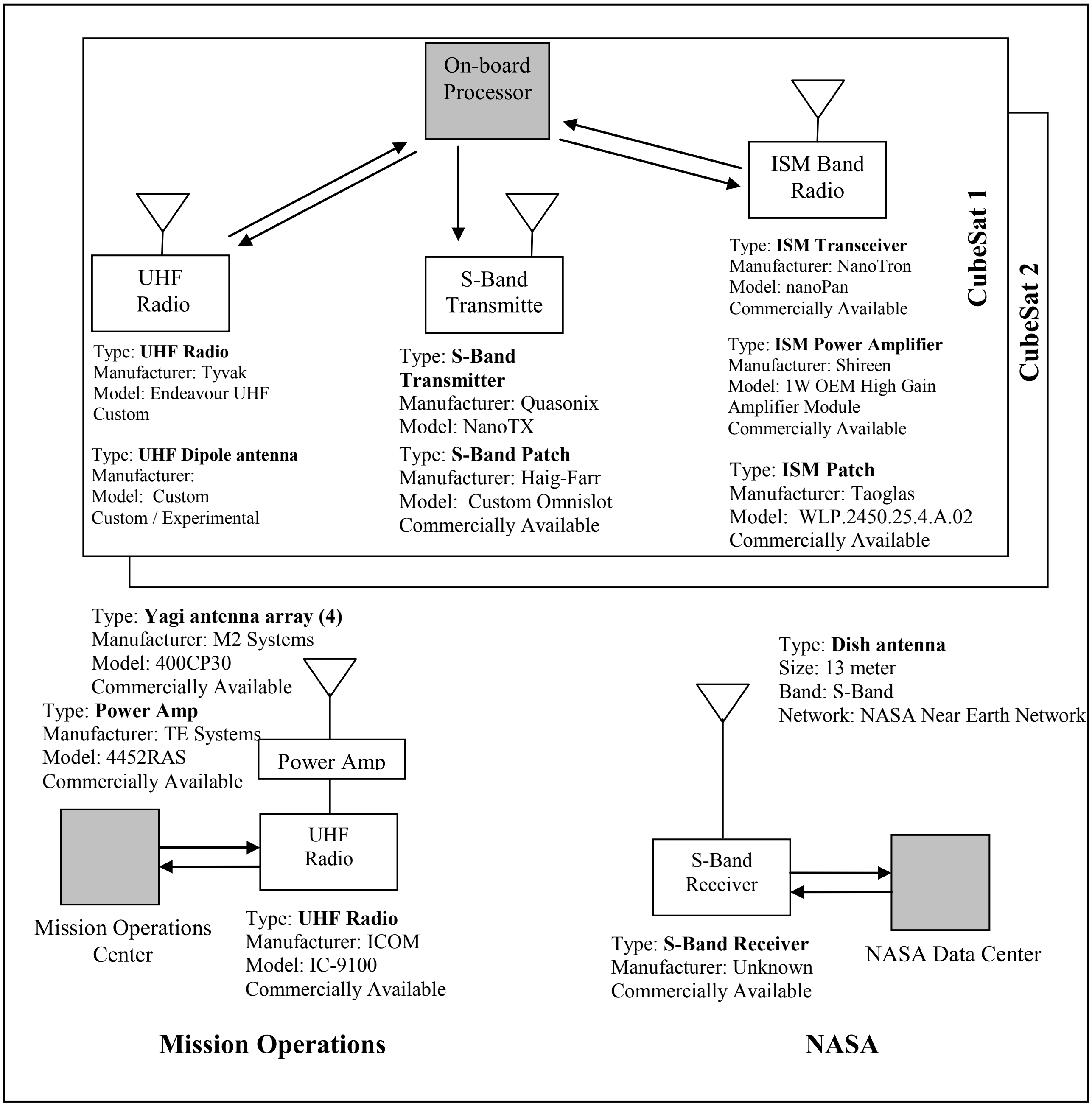

Figure 1: CubeSat System Communications Components

The transmitting components aboard the CubeSats are controlled by a dedicated on-board processor, which processes data for transmission, sends and receives data from the modem, and activates the appropriate radio systems depending on the state of operations. Each vehicle possesses a COTS ISM band system for inter-satellite ranging, a UHF system for vehicle command, telemetry retrieval, and inter-satellite communications, and an S-band system for payload data download. The two satellites will use the same spectrum.

The inter-satellite ISM system uses a ceramic surface mount patch antenna from Taoglas. This is an off-the-shelf RHCP antenna with a gain of 5dBi, and a -10dB RL bandwidth of 85 MHz.

The TT&C and inter-satellite communications UHF system uses a Tyvak-developed UHF radio derived from commercially-available UHF communications systems. The radio operates at 9,600 baud using GMSK. The UHF system will use a custom designed half-wave dipole antenna.

The TT&C ground segment can address each unit or both units through the use of different message destination addresses, authentication counts and/or encryption keys using the same frequency allocation. The transmitting component located at the Irvine Earth station is controlled by dedicated Microsoft Windows workstations. The workstations are used for antenna pointing control, Doppler frequency shift corrections, and data processing for transmission. The antenna (manufacturer/model: M2 Antenna Systems, Inc./400CP30) and radio (manufacturer/model: ICOM/IC-9100) are commercially available, off-the-shelf units, which will be modified with additional hardware to function at the requested frequencies.

The payload downlink S-Band system uses a patch antenna currently under development by Haigh-Farr. The antenna will be sold commercially once completed. The antenna is RHCP with a gain greater than 2dBic at the boresight and a bandwidth of 12 MHz with a VSWR < 2:1.

Question 11A. Is the Equipment Listed in Item 10 Capable of Station Identification Pursuant to Section 5.115

Each transmitting component of the system is capable of station identification at the end of each complete transmission. The station identification process is incorporated into the mission operations procedure. The space component will transmit in Morse code the assigned call sign at the end of each complete data transmission. The space component also transmits the call sign in every packet transmitted as part of its frame header. The frame header is not encoded or encrypted. The ground component will broadcast in clear voice the assigned call sign at the end of each data transmission by ground station operators.

Question 4: Antenna Registration Form; Operation of Directional Antenna

The CubeSats are low earth orbit ("LEO") satellites in a sun-synchronous orbital with an orbit period of approximately 1.6 hours. The satellites will pass over the Earth station roughly one to twelve times per day depending on its location with an average access time of five to seven minutes for each Earth station location. The UHF Earth station will use a computer-controlled tracking antenna to point the Earth station's antenna in the direction of the moving satellites. The antenna has a maximum gain of +20.2dBi along the bore-sight of the antenna and a half-power beam-width (*i.e.*, -3dB) of approximately 30 degrees. The antenna array uses four off-the-shelf, yagi-type antenna developed by M2 Antenna Systems, Inc.

Because the CubeSats are NGSO satellites, the range of antenna azimuth and elevation will vary based on the relative motion of the satellites with respect to the ground station. It will also differ for each satellite pass. The Earth station will only transmit above a 10 degree elevation angle. Consequently, the range of antenna elevation angles for all satellite passes will be between 10 and 170 degrees. The azimuth can vary between 0 degrees and 360 degrees.

Earth station software will be used to control the antenna azimuth and elevation rotors for antenna pointing and limit the range of permissible elevation angles. In addition, the software will be used to predict satellite contact times and antenna pointing angles to support Earth station planning and operations.

In addition to on-orbit operations, the satellite components will undergo developmental testing at Tyvak's Irvine, CA facility beginning in April 2014. Testing for the 2.4 GHz ranging transmitters, the S-band payload link, and the UHF TT&C and inter-satellite communications link will be conducted in carrier current (*i.e.*, closed-loop) configuration and will produce only unintentional emissions. Under the Commission's rules, unintentional radiators operating in the frequency range between 9 kHz to 30 MHz must comply with the radiated emission limits for intentional radiators as provided in 47 C.F.R. § 15.209.[4] As Tyvak's test program may marginally exceed these limits, Tyvak seeks experimental authority for emissions in the appropriate ranges at the Tyvak facility. These developmental tests are expected to begin in April 2014.

II. RELEVANT INFORMATION ADDRESSED IN SECTION 25.114 OF THE COMMISSION'S RULES

Section 25.114(c)(4)(i) Radio Frequency Plan

<u>UHF Communications System</u>

The CubeSats' UHF communications system will operate using half-duplex communications within the 399.9-400.05 MHz frequency band for telecommand (*i.e.*, earth-to-space), telemetry (*i.e.*, space-to-earth), and inter-satellite (*i.e.* space-to-space) communications. Although the CubeSats require only 50 kHz of spectrum bandwidth, Tyvak requests herein

[4] 47 C.F.R. § 15.109(e).

authority to operate within the entire 399.9-400.05 MHz frequency band for the mission to facilitate design flexibility.

The following diagram shows the proposed spectrum use of the CubeSats and ground stations and also shows authorized spectrum uses in adjacent bands, such as the use by the Orbcomm Little LEO MSS network of the 400.075-400.125 MHz band as a beacon frequency. As explained below, the 399.9-400.05 MHz frequency band does not appear to be used by any authorized government or non-government operator in the United States. Tyvak acknowledges that the Commission has proposed to authorize operation of a federal Mobile Satellite System in the 399.99-400.05 MHz portion of this fallow band, however, any Tyvak transmissions related to this mission will be completed well before any Federal operations in the band commence.[5] Therefore, Tyvak's proposed operation of its experimental satellites in 50 kHz of the 399.9-400.05 MHz frequency band will not cause harmful interference to any authorized spectrum user.

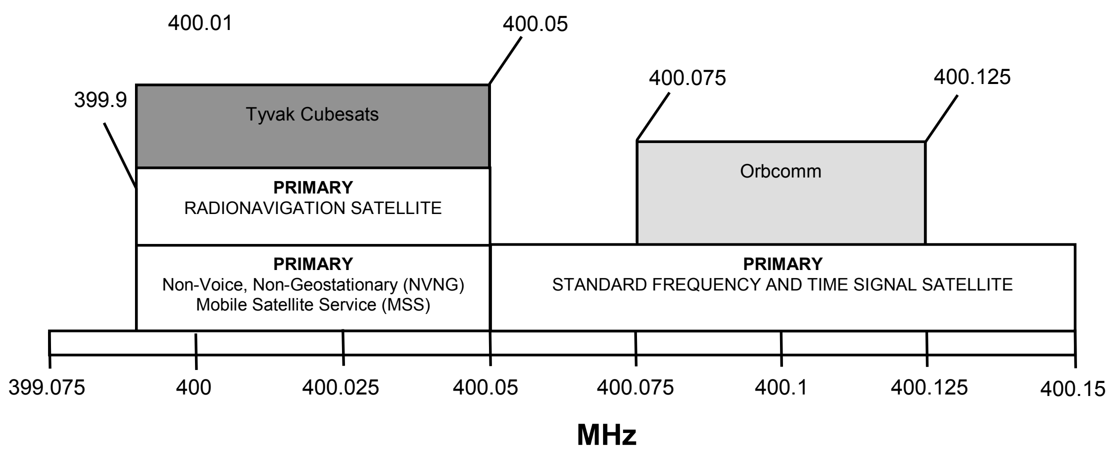

Figure 2: CubeSats Spectrum Diagram **(UHF)**

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[5] *See Federal Space Station Use of the 399.0-400.05 MHz Band*, *ET Docket No. 13-115*, Notice of Proposed Rulemaking, FCC 13-65, ¶ 63 (2013).

The 399.9-400.05 MHz frequency band is allocated internationally on a primary basis to the Mobile Satellite Service ("MSS") (earth-to-space). The 399.9-400.05 MHz frequency band is also allocated internationally on a primary basis to the Radionavigation Satellite Service ("RNSS") until January 1, 2015.[6] In the United States, the 399.9-400.05 MHz frequency band is allocated to the MSS and RNSS services for both government and non-government use.

During the 1995 World Radiocommunication Conference ("WRC-95"), the International Telecommunication Union ("ITU") allocated the 399.9-400.05 MHz band for the Little LEO MSS service. The Commission subsequently designated the 399.9-400.05 MHz band as available for use by Little LEO MSS networks.[7] None of the applicants for Little LEO MSS licenses in the United States, however, requested authority to operate in the 399.9-400.05 MHz band.[8] Therefore, the Commission refrained from adopting service rules for Little LEO MSS networks operating in the 399.9-400.05 MHz band and did not issue any licenses to Little LEO MSS networks authorizing them to operate in the band.[9] Tyvak is unaware of any Little LEO

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[6] *See* 47 C.F.R. § 2.106 n.5.224B.

[7] *See Amendment of Section 2.106 of the Commission's Rules to Allocate Spectrum to the Fixed-Satellite Service and the Mobile-Satellite Service for Low-Earth Orbit Satellites*, Report and Order, 8 FCC Rcd 1812 (1993); 47 C.F.R. §§ 2.106 n.US320 & 25.202(a)(3). Although the Commission originally included the 399.9-400.05 MHz band in footnote US320, reference to the 399.9-400.05 MHz band was inadvertently deleted from US320 during a Commission effort to consolidate footnotes. The Commission corrected the error, reincorporating the reference to the 399.9-400.05 MHz band in footnote US320. *See Amendment of Parts 2, 25, and 73 of the Commission's Rules to Implement Decisions from the World Radiocommunication Conference (Geneva, 2003) (WRC-03) Concerning Frequency Bands Between 5900 kHz and 27.5 GHz and to Otherwise Update the Rules in this Frequency Range*, Report and Order, 20 FCC Rcd 6570, 6625 (2005).

[8] *See Amendment of Part 25 of the Commission's Rules to Establish Rules and Policies Pertaining to the Second Processing Round of the Non-Voice, Non-Geostationary Mobile Satellite Service*, Report and Order, 13 FCC Rcd 9111, 9120-21 (1997).

[9] *See id.* at 9121.

MSS network operating anywhere in the world (and particularly not in the United States) that uses the 399.9-400.05 MHz band.

The 399.9-400.05 MHz frequency band is also allocated internationally on a primary basis to RNSS until January 1, 2015. The 399.9-400.05 MHz frequency band was previously used by the U.S. Department of Defense for its TRANSIT-SAT RNSS system, which was a polar orbiting satellite network that was primarily used for commercial and government maritime navigation. The TRANSIT-SAT network, however, was decommissioned in December 1996.[10]

It does not appear that the United States government or commercial operators are using the 399.9-400.05 MHz frequency band for any other RNSS service. As a consequence, the 399.9-400.05 MHz frequency band appears to be fallow of any authorized use in the United States. Therefore, the short term operation of Tyvak's experimental CubeSats will not result in harmful interference to any authorized spectrum user.

Space-to-Earth and Earth-to-Space UHF Communications

Despite the absence of any authorized spectrum users in the 399.9-400.05 MHz band, the CubeSats have been designed to include several precautions to prevent harmful interference to other services from space-to-Earth transmissions. First, as noted above, space-to-Earth satellite transmissions will be controlled from the Earth station and the spacecraft will not transmit until it receives a request from the Earth station.

Second, the satellite uplink and downlink will use the same 50 kHz bandwidth in half-duplex mode to send digital data using standard GMSK modulation with maximum data rates up to 9,600 baud. The spacecraft transceiver uses a packet-based (non-continuous) communications,

[10] *See Federal Long-Range Spectrum Plan,* Working Group 7 of the NTIA Spectrum Planning Subcommittee (Sept. 2000), available at http://www.ntia.doc.gov/osmhome/LRSP/LRSP5a.htm.

which allows command reception between transmissions of packets to provide the ability to command the satellite to cease space-to-Earth transmission operations in a timely manner, if required.

The satellite transmitter can be adjusted to provide up to two watts of power output when communicating with the Earth station. Transmission power on the Earth station transmitter can be adjusted to provide up to 200 watts of power output. The communications parameters for the UHF communications system for the space-to-Earth and Earth-to-space links are show in the following tables.

CubeSat Communications Parameters	**Value**
Emission Designator	40K9G1D
Service	Digital Data
Center Frequency	400.03 MHz
Requested Bandwidth (includes Doppler)	50 kHz
Modulation	GMSK
Data Rate	9,600 bps
Polarization	Linear
Antenna Type	Dipole
Antenna Gain	+2 dBi (Max)
RF Power Output	2W
Line/Misc Losses	-2dB
EIRP	1.0 dBW

Table 1: Tyvak CubeSat UHF Communications Space-to-Ground Parameters

Earth Station Communications Parameters	Value
Emission Designator	40K9G1D
Service	Digital Data
Center Frequency	400.03 MHz
Requested Bandwidth (includes Doppler)	50 kHz
Modulation	GMSK
Data Rate	9,600 bps
Polarization	Linear (H, V) or Circular
Antenna Type	Yagi array
Antenna Gain	+20.2 dBi (Max)
RF Power Output	200 W
Line Losses	-3dB
EIRP	40.2 dBW

Table 2: Tyvak Earth Station UHF Communications Parameters

Inter-Satellite Space-to-Space UHF Communications

The satellites will only initiate space-to-space communications upon a command from the MOC using UHF TT&C links. However, the space-to-space link can continue intermittent, low power communications throughout the orbit to pass relative position or vehicle state information between the spacecraft, including when they are not in contact with an Earth station. Thus, in the unlikely event that potential interference is reported, the Tyvak MOC would issue the command to cease transmission during the next contact period, which will occur one to twelve times per day at intervals of one to twelve hours.

The UHF transmitter will provide up to 100 mW of power output when communicating between the satellites. Based on the power levels to be used with the inter-satellite link, the maximum energy received at the surface of the Earth will not exceed -148 dBW. The table below shows a link budget for the worst case power flux density at the ground during space-to-space transmission.

Item	Value	Comments
From	LEO	620km LEO orbit
To	GND	
Transmit Power (Watts)	0.1	Transmit power for Inter Satellite Link over UHF
Frequency, GHz	0.4	400 MHz
Satellite Line Loss to Antenna, dB	-2	Coax, filtering, balun
Transmit Antenna Gain, dBic	2	Isotropic Antenna
Satellite Antenna Pointing Loss	0.0	Peak gain oriented Nadir
Transmitter EIRP, dBW	-10.0	
Slant Range, km	620	620km altitude, 90 degree angle of arrival (δ)
Path Loss, dB	-140.3	
Atmospheric Loss, dB	-0.3	
Signal power at the ground	**-150.7**	**-148dBW/m2 allowed under 5.268 of NTIA Redbook for an adjacent band (410-420 MHz)**

Table 3: Power Flux Density for Space-to-Space Transmissions

The communications parameters for the UHF communications system for the space-to-space inter-satellite link are show in the following table.

CubeSat Communications Parameters	**Value**
Emission Designator	40K9G1D
Service	Digital Data
Center Frequency	400.03 MHz
Requested Bandwidth (includes Doppler)	50 kHz
Modulation	GMSK
Data Rate	9,600 bps
Polarization	Linear
Antenna Type	Dipole
Antenna Gain	+2 dBi (Max)
RF Power Output	100 mW
Line/Misc Losses	-1dB
EIRP	2.0 dBW

Table 4: Tyvak CubeSat UHF Inter-satellite Link Parameters

S-Band Communications System

The CubeSats' S-band communications system will operate using simplex communications within the 2,200-2,290 MHz frequency band to downlink recorded payload data to NASA-operated S-band Earth stations. The Tyvak UHF Earth station at the Irvine MOC or Tyvak-affiliated UHF stations at other locations will issue commands in the UHF-band to trigger the satellite to transmit payload data in the S-band when over an S-Band NASA site. The Tyvak MOC will have no transmission or reception capabilities in the S-band. The NASA Earth stations will relay received communications frames to the Irvine MOC over a Virtual Private Network ("VPN") using the NASA Integrated Network Services ("NISN"). As noted previously, Tyvak is seeking to operate the S-band transmitter at the direction of the NASA mission coordinator.

CubeSat Communications Parameters	Value
Emission Designator	1M00G1DDN
Service	Digital Data
Band	2,200-2,290 MHz
Requested Bandwidth	1MHz
Modulation	QPSK
Data Rate	1 Mbps
Polarization	RHCP
Antenna Type	Patch
Antenna Gain	+2 dBic (Max)
RF Power Output	2W
Line Losses	-2dB
EIRP	3 dBW

Table 5: Tyvak CubeSat S-Band Communications Parameters

The CubeSats will communicate with the MOC, other UHF ground stations, and NASA ground stations only when they are within line-of-sight of the Earth stations and have received a communication from the Earth station directing the spacecraft to initiate transmissions. As a consequence, the spacecraft will utilize the 399.9-400.05 MHz and 2,200-2,290 MHz spectrum band only when in contact with specified Earth stations and potentially conflicting uses of the band in other regions of the world are not relevant to this application.

<u>Inter-Satellite Ranging System</u>

The CubeSats' inter-satellite ranging system will operate using COTS-based transceivers within the 2.4 GHz ISM frequency band. The COTS transceiver, nanoPan 5375, by Nanotron (www.nanotron.com)[11] provides ranging and communications functions.

CubeSat Communications Parameters	**Value**
Emission Designator	80M0V1D
Service	Digital Data
Frequency Band	2.4 GHz ISM band
Requested Bandwidth (includes Doppler)	80 MHz
Modulation	Chirp Spread Spectrum (CSS) - Proprietary
Data Rate	250 kbps
Polarization	RHCP
Antenna Type	Patch
Antenna Gain	+5 dBic (Max)
RF Power Output	1W
Line Losses	-1dB
EIRP	+4 dBW

Table 6: Tyvak CubeSat ISM Communications Parameters

Section 25.114(c)(5)(i) Orbital Locations

The CubeSat system comprises two space vehicles operating in NGSO. The spacecraft will be connected together when deployed from the launch vehicle. The spacecraft will separate

[11] FCC ID SIFNANOPAN5375V1, Granted Mar. 26, 2009.

and operate untethered and free-flying, but will operate in controlled proximity/formation flying throughout mission life and will share the same orbital characteristics. The spacecraft are intended to operate in LEO with the orbit parameters shown in Table 6. The satellites will have an orbit period of roughly 1.6 hours with typical ground access times of five to seven minutes per pass. The orbit parameters are presented in the following table:

Parameter	Units	Value
Orbit Period	[hrs]	1.6 hrs
Orbit Altitude	[km]	620 km (circular)
Inclination	[deg]	97.9 degrees

Table 7: CubeSat Orbit Parameters

Section 25.114(c)(10) Physical Characteristics of Satellites

The space vehicles are nano-class satellites (< 10 kg), in which each element conforms to the CubeSat Standard. CubeSats can be designed in different sizes as long as they are multiples of the basic CubeSat standard unit, which is 10×10×10 centimeters, generally referred to as a 1U CubeSat, meaning one unit in size. The space vehicles will consist of two 3U CubeSats, which means each CubeSat will have the dimensions of approximately 30×10×10 centimeters. The CubeSat dispenser limits the total vehicle mass of a 3U CubeSat to less than 6 kilograms. The CubeSat vehicles have been designed primarily as a single-string system using commercial off-the-shelf parts with a mission lifetime of less than one year on-orbit. The mass budget is identical for each of the two elements and is provided in the following table:

Component / Subsystem	Mass [g]
Payload	1400
Spacecraft (Subtotal)	4300
Structure	300
Electrical Power System	1500
Propulsion System	1400
ADCS	400

Component / Subsystem	Mass [g]
C&DH	100
Communication	500
Thermal	100
TOTAL	5700

Table 8: CubeSat Mass Budget per Element

For propulsion, each of the space vehicles is equipped with eight miniature cold gas thrusters. Each thruster is fed from a common gas storage vessel with propellant capacity of 400 grams and an initial pressurization of 83 psi (at 20degC). The thrusters are not mechanical and propulsion uses common refrigerant (R143a) involving no combustion. The thrusters are highly integrated with the sensors to provide for precision maneuvering, and will be used to demonstrate formation flying and docking.

For power generation, each space vehicle is equipped with body-mounted and deployed GaAs solar cells that generate approximately 16 watts of power during a typical orbit. Because of the short operational lifetime of the satellite (*i.e.*, less than a year), the difference between the beginning-of-life ("BOL") and end-of-life ("EOL") power generation is negligible. To permit operations during eclipse, energy is stored on-board using Li-ion batteries, with power being distributed to subsystems and components through the electrical power subsystem circuitry. The EOL power budget is provided in the following table:

Component / Subsystem	EOL Power [mW] Orbit Averaged
Payload	3500
Spacecraft (Subtotal)	10000
Propulsion System	140
ADCS	5000
C&DH	600
Communication	3500
Thermal	400
TOTAL	13500

Table 9: Power Budget per Space Vehicle

Section 25.114(c)(12) Schedule

The project timeline and major milestones for the launch and operation of the CubeSat system are provided in the following table. The dates are approximate and contingent upon the exact launch date ("Time of Launch" or "ToL"), orbit parameters, and unforeseen events during on-orbit operations.

Milestone	**Date**	**Notes**
Fabrication and RF closed loop testing	March 2014-July 2015	ToL - 19 months
Delivery for Launch Integration	July 2015	ToL - 3 months
Pre-launch testing of transmitting components	Aug 2015	ToL - 2 months
Launch	Oct 2015	ToL + 0
Release from launch adapter	Oct 2015	ToL + 0hr 30min
On-orbit check	Oct 2015	ToL + 24 hours
Start of experiments	Oct 2015	ToL + 4 weeks
Decommissioning	July 2016	ToL + 9 months
Re-entry	Oct 2016	ToL + 17 year

Table 10: CubeSat System Major Milestones

Section 25.114(d)(1) General Description of Overall System Facilities, Operations and Services

The Tyvak CubeSats provide a platform for on-orbit testing of advanced maneuvering and proximity operations technologies. The onboard systems on each space vehicle provide nominal attitude, electrical power, data storage, and command function for a set of mission payloads. The space vehicles communicate with the Earth stations through a low-rate (9.6 kbps) half-duplex communications link operating in the UHF band.

The CubeSat mission will be supported by a UHF Earth station at the Irvine MOC and several additional Earth stations operated by Tyvak affiliates at sites in North Pole, Alaska; Bozeman, Montana; and Columbia, Maryland. Tyvak affiliates will seek authorization for each of the UHF Earth stations in separate applications. The S-band Earth stations will be operated by NASA.

The primary responsibilities of the Irvine MOC will be to command the space vehicle to initiate the experiments, recover spacecraft engineering telemetry, and manage the function of the spacecraft. The Earth station equipment comprises a UHF yagi antenna array and UHF transceiver. The MOC will also have vehicle control workstations and a mission data archive server.[12] The workstations will serve as the primary interface with the ground controllers and will be used for data processing, antenna/radio control, and engineering analysis. The mission data archive server will archive command and telemetry data to support mission operations, status, troubleshooting, and post-mission assessment.

Section 25.114(d)(3) Predicted Spacecraft Antenna Gain Contours

The spacecraft UHF antenna is a half wavelength L-dipole antenna, which is essentially omni-directional when mounted on the corner of a CubeSat structure. A simulation of the antenna design is shown in Figure 3.

[12] TT&C data will be received directly from the spacecraft via UHF link; payload data will be downlinked via S-band to NASA and securely transmitted to the MOC via a VPN over the Internet.

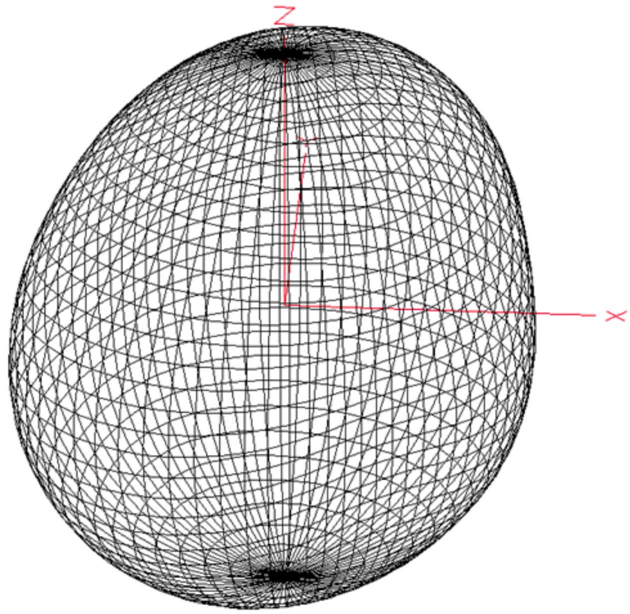

Figure 3: CubeSat L-Dipole UHF Antenna Gain Plot

The spacecraft S-band antenna is a microstrip patch antenna possessing a maximum gain perpendicular to the surface normal to the patch. A generalized antenna gain contour plot is provided below representing the S-band patch .

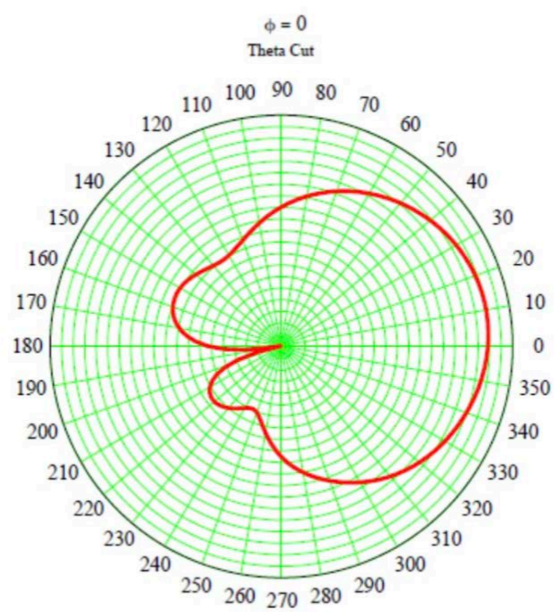

Figure 4: CubeSat S-band Antenna Gain Plot

The spacecraft 2.4 GHz antenna is a microstrip patch antenna possessing a maximum gain perpendicular to the surface normal to the patch. An antenna gain contour plot from the antenna datasheet is provided below representing the ISM-band ceramic patch

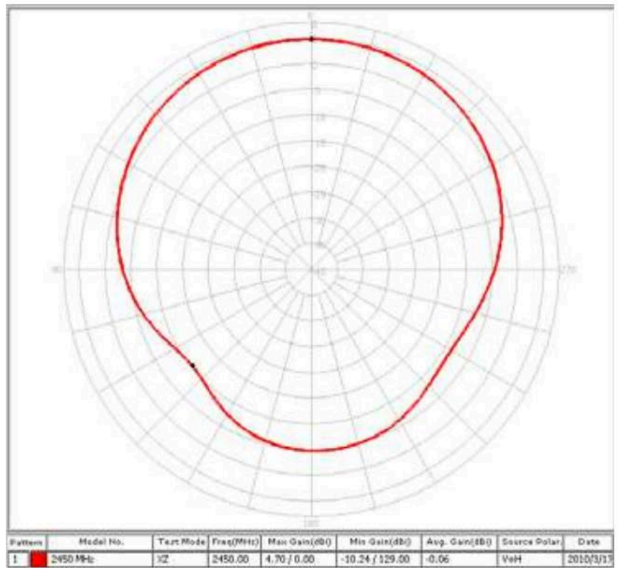

Figure 5: CubeSat 2.4 GHz Antenna Gain Plot

Section 25.114(d)(14) Orbital Debris Mitigation

The CubeSat spacecraft will mitigate orbital debris by the following means:

Section 25.114(d)(14)(i) Limiting the amount of debris released during normal operations and the probability of the satellite becoming a source of debris by collisions with small debris or meteoroids that could cause loss of control and prevent post-mission disposal

In order to limit the amount of debris generated during normal operations, the CubeSats have been designed so that all parts will remain attached to the satellite during launch, ejection, and normal operations. This requirement is intrinsic to all satellites conforming to the CubeSat Standard and compliance is required for launch using the Poly-Picosatellite Orbital Deployer ("P-POD") system.

The basic geometry of each of the two satellites is a monolithic cubic structure (*i.e.*, 30cm x 10cm x 10cm) with two pairs of 30cm x 10cm deployable panels. Based on an orbital debris model (ref. NASA DAS v2), the probability of a single particle impact with a size of 1 millimeter or larger over the mission lifetime is very low (*i.e.*, roughly 1.3×10^{-3}). This low probability of impact for the mission is a result of the small effective area of the space vehicle (*i.e.*, effective area ~ 0.15 m^2) and the relatively short mission duration (*i.e.*, mission life less than one year).

Catastrophic system failure due to orbital debris or micrometeoroid impact will not affect the vehicle's ability to de-orbit within the guidelines for vehicles operating in LEO (*i.e.*, less than 25 years). Based on the mission orbit of 620 km, the space vehicle is anticipated to re-enter the atmosphere within 17 year based on lifetime prediction simulations for the current mission epoch (*i.e.*, launch in CY2015).

Section 25.114(d)(14)(ii) Limiting the probability of accidental explosions during and after completion of the mission operations

The demonstration of technologies for formation flying and proximity operations are primary mission objectives for the CubeSats. Thus, each satellite is equipped with small cold-gas propulsion systems employing low specific impulse, low-pressure gas. The pressure vessel is made from aluminum, has a volume of 400 ml and an initial pressurization of 83 psi (at 20degC). The vessel has been designed to an ultimate safety factor of 2.5 times the operating pressure at maximum storage temperature. These vessels will be fully depressurized as a part of the deorbit maneuver process.

In addition, the vehicles possess energy storage devices (*i.e.*, Li-ion batteries), which will be left in a nearly discharged state as part of the decommissioning procedure.

Section 25.114(d)(14)(iii) Limiting the probability of the satellite becoming a source of debris by collisions with large debris or other operational space stations

Based on a simple orbital debris model (ref. NASA DAS v2), the probability of the CubeSats colliding with large debris or other space systems of sizes one centimeter or greater at the mission orbit altitude and inclination is negligible (*i.e.*, roughly $4x10^{-6}$). Although the vehicles do possess propulsive capability for proximity operations demonstration, station keeping, and deorbit, no maneuvers to avoid in-orbit collisions are planned for or anticipated.

The launch provider has instituted deployment procedures in order to place the co-manifested satellites in the launch vehicle into slightly different orbits in order to reduce the risk of collision. One of these procedures is to stagger deployment times.

Section 25.114(d)(14)(iv) Post-mission disposal plans for the space station at end of life

The post-mission disposal plan for the CubeSats includes the transition of all vehicle systems to a dormant state, which includes the cessation of all radio operations (*i.e.*, transmit and receive). Energy storage devices will be held at a minimal charge state at the end of the life of the vehicles. All propellant remaining at end of life will be expended to initiate deorbit, resulting in anticipated atmospheric re-entry of the satellites within 17 years of mission completion based on its mission orbit, vehicle mass, geometry and mission epoch (*i.e.*, launch in CY2015). Although no active de-orbit maneuvers are required to meet the 25 year re-entry guidelines, Tyvak anticipates accelerating de-orbit using the measures described above.

Re-entry debris and probability of human casualty will be negligible. The materials used on the vehicle include aluminum and PCB material, which have a relatively low melting temperature as compared to other materials such as Ti or stainless steel, and are not expected to survive reentry.

III. CONCLUSION

The Experimental Licensing Branch should grant Tyvak's application for five-year experimental authority to launch and operate two NGSO LEO satellites, which will permit Tyvak to demonstrate and evaluate advanced proximity operations for NASA customers, adding valuable on-orbit performance data for future CubeSat Standard satellites. Tyvak's experiment will not cause harmful interference to any licensed service. Tyvak will conduct its experiment using low-power transmissions in the 2.4 GHz ISM band, the vacant 399.9-400.05 MHz UHF band, and, pursuant to NASA direction and coordination, in the 2.2 GHz S-band. Further, the Tyvak operation will meet the Commission's orbital debris mitigation requirements. Therefore, Tyvak's application should be granted at the soonest practicable time.