21 April 2017

Orbital Debris Assessment for TBEx on the STP-2 Mission per NASA-STD 8719.14A

The following ODAR document has been completed to the best of our abilities with the most accurate information we have available.

4/26/17

(Signature) (Date)

REFERENCES:

[A] NASA Procedural Requirements for Limiting Orbital Debris Generation, NPR 8715.6A, 5 February 2008

[B] Process for Limiting Orbital Debris, NASA-STD-8719.14A, 25 May 2012

[C] McKissock, Barbara, Patricia Loyselle, and Elisa Vogel. Guidelines on Lithium-ion Battery Use in Space Applications. Tech. no. RP-08-75. NASA Glenn Research Center Cleveland, Ohio

[D] UL Standard for Safety for Lithium Batteries, UL 1642. UL Standard. 4th ed. Northbrook, IL, Underwriters Laboratories, 2007

[E] Kwas, Robert. Thermal Analysis of ELaNa-4 CubeSat Batteries, ELVL-2012-0043254; Nov 2012

[F] Range Safety User Requirements Manual Volume 3- Launch Vehicles, Payloads, and Ground Support Systems Requirements, AFSCM 91-710 V3.

[G] HQ OSMA Policy Memo/Email to 8719.14: CubeSat Battery Non-Passivation, Suzanne Aleman to Justin Treptow, 10, March 2014

The intent of this report is to satisfy the orbital debris requirements listed in ref. [A] for the TBEx CubeSats on the STP-2 mission. It serves as the final submittal in support of the spacecraft Safety and Mission Success Review (SMSR). Sections 1 through 8 of ref. (b) are addressed in this document; sections 9 through 14 fall under the requirements levied on the primary spacecraft and are not presented here.

The following table summarizes the compliance status of the TBEx CubeSats as part of the STP-2 mission. The TBEx CubeSats are fully compliant with all applicable requirements.

Table 1: Orbital Debris Requirement Compliance Matrix

Requirement	Compliance Assessment	Comments
4.3-1a	Not applicable	No planned debris release
4.3-1b	Not applicable	No planned debris release
4.3-2	Not applicable	No planned debris release
4.4-1	Compliant	Minimal risk to orbital environment, mitigated by orbital lifetime
4.4-2	Compliant	Minimal risk to orbital environment, mitigated by orbital lifetime
4.4-3	Not applicable	No planned breakups
4.4-4	Not applicable	No planned breakups
4.5-1	Compliant	
4.5-2	Compliant	
4.6-1(a)	Compliant	Worst case lifetime 3.97 yrs
4.6-1(b)	Not applicable	
4.6-1(c)	Not applicable	
4.6-2	Not applicable	
4.6-3	Not applicable	
4.6-4	Not applicable	Passive disposal
4.6-5	Not applicable	
4.7-1	Compliant	No credible risk of human casualty
4.8-1	Not applicable	No planned tether release for the TBEx mission

Section 1: Program Management and Mission overview

The TBEx CubeSat mission is sponsored by the National Aeronautics and Space Administration (NASA). The Program Officer in NASA's Heliophysics Division is Dr. Jeffrey Newmark. Responsible program/project manager and senior scientific and management personnel are as follows:

TBEx Mission & Payload Development: Roland Tsunoda, Principle Investigator; Rick Doe, Project Manager.

TBEx Spacecraft Development: James Cutler, Principle Investigator.

The primary payload was developed and built by the Principle Investigator's team at SRI International. There are no secondary payloads. The satellite bus was built and will be operated by the University of Michigan.

Program Milestone Schedule	
Task	**Date**
Preliminary Design Review	11/04/14
Critical Design Review	01/27/16
SV Integration Complete	07/30/16
Integrated S/V Environmental Tests Complete	09/01/16
Mission Readiness Review	11/01/16
SV Arrives at Launch Site	01/15/17
Launch Site Processing Complete	02/01/17
Initial Launch Capability (ILC) (Date/Time)	03/01/17

Figure 1: Program Milestone Schedule

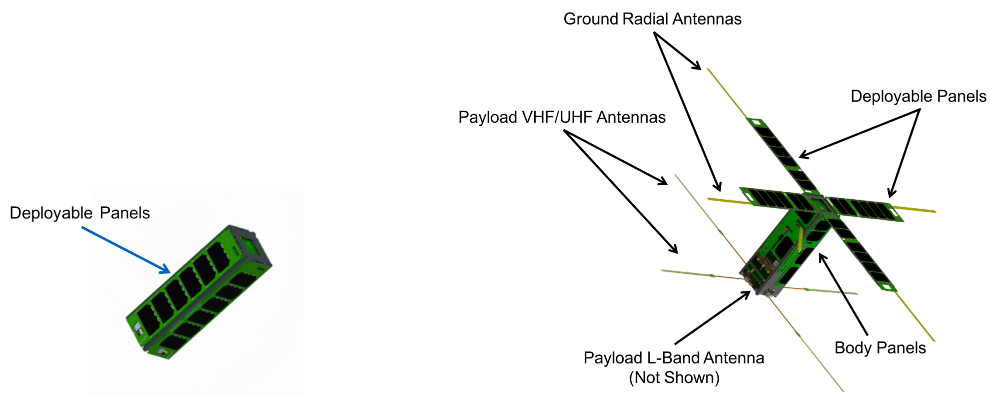
TBEx will be inserted into the nominal STP-2 CubeSat orbit with apogee at 860 km, perigee at 300 km, and an inclination of 28.4. Subsequent to insertion, one of the TBEx spacecraft will intentionally lower its ballistic coefficient (BC) to separate the two vehicles. At the conclusion of this week-long drag separation maneuver, both satellites will be commanded for the same operational BC. This maneuver will not significantly alter the nominal orbit characteristics. TBEx is manifested to be launched in March 2017 on a Falcon Heavy rocket with the STP-2 mission.

Section 2: Spacecraft Description

TBEx is a pair of 3U CubeSats developed by the University of Michigans Michigan eXploration Laboratory and SRI International manifested to be launched in March 2017 on a Falcon Heavy rocket with the STP-2 mission. Each TBEx unit houses a tri-frequency radio beacon system developed by SRI, which is designed to study equatorial ionospheric bubble formation.

Table 2: TBEx Properties

CubeSat Quantity	CubeSat Size	CubeSat Names	CubeSat Masses(kg)
2	3U($10cm \times 10cm \times 30cm$)	TBEx-A & B	4



(a) TBEx - Stowed Configuration **(b)** TBEx - Deployed Configuration

Figure 3: TBEx Configuration

The TBEx science mission will consist of a tandem pair of 3U CubeSats, each carrying tri-frequency radio beacons, in near-identical, low-inclination orbits, and a cluster of diagnostic sensors on five islands in the Central Pacific sector, all with the objective of discovering how the dynamics and processes in the troposphere can act to cause variability in the behavior of the upper atmosphere and ionosphere and to understand the plasma-neutral coupling processes that give rise to local, regional, and global-scale structures and dynamics in the atmosphere-ionosphere-magnetosphere system.

The TBEx mission will continue the C/NOFS-type measurements (Communications / Navigation Outage Forecasting System) of plasma perturbations through L-band, UHF, and VHF scintillations, but with expanded capabilities, and do so during a different portion of the solar cycle. These measurements require two points of measurement, so two CubeSats will be utilized.

The TBEx spacecraft will be launched as part of the Space Test Program (STP-2). Both CubeSats will be deployed within minutes of each other. Each CubeSat will deploy its solar panels and power on. Sometime later, the CubeSats will begin UHF beaconing, ground contact will be established, subsystem checkouts will be made, and post-ejection high data rate telemetry will be downlinked. In the next phase of the mission, one of the CubeSats will alter its attitude inducing additional air drag and causing the two CubeSats to drift into unique orbits. When the second spacecraft drifts far enough apart from the first one, such that the apparent ground period separating the two CubeSats orbits reaches 15 minutes, both CubeSats will point to nadir, and commence science measurements. As experiments are run, TBEx data will be downlinked.

The tri-band payload will only transmit at ground-commanded times. The transmission schedules will be uploaded and transmissions will occur over equatorial science receiver stations.

The CubeSat structure (Figure 2) is made of Aluminum 6061-T6. It contains mostly standard commercial off the shelf (COTS) materials, electrical components, PCBs and solar cells. There are no pressure vessels, hazardous or exotic materials or materials likely to be a re-entry concern. The electrical power storage system consists of two Panasonic lithium-ion batteries (18650B) with over-charge/current protection circuitry.

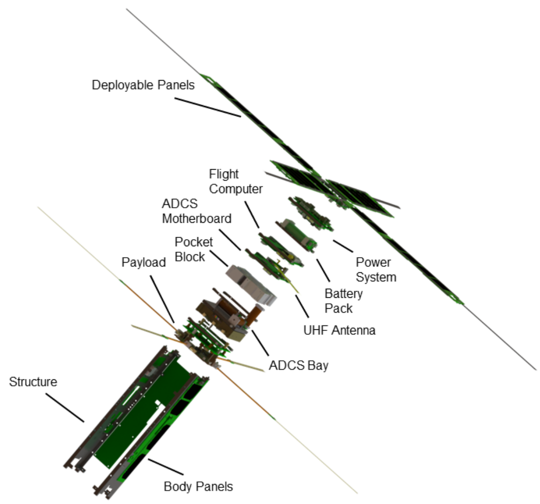


Figure 4: TBEx expanded view

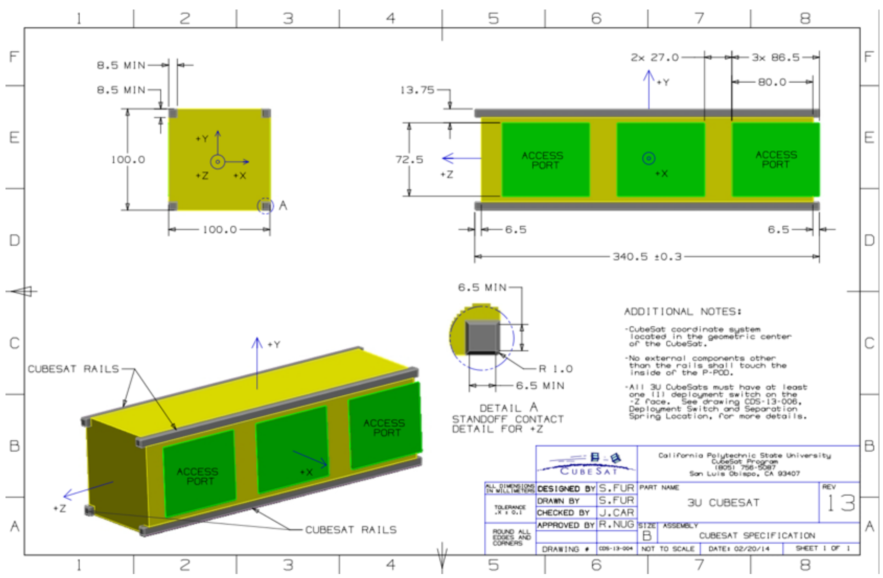


Figure 5: 3U Cubesat Specification

Section 3: Assessment of Spacecraft Debris Released during Normal Operations

The assessment of spacecraft debris requires the identification of any object (>1 mm) expected to be released from the spacecraft any time after launch, including object dimensions, mass, and material.

Section 3 requires rationale/necessity for release of each object, time of release of each object, relative to launch time, release velocity of each object with respect to spacecraft, expected orbital parameters (apogee, perigee, and inclination) of each object after release, calculated orbital lifetime of each object, including time spent in Low Earth Orbit (LEO), and an assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2.

No releases are planned on the TBEx CubeSat mission therefore this section is not applicable.

Section 4: Assessment of Spacecraft Intentional Breakups and Potential for Explosions

There are NO plans for designed spacecraft breakups, explosions, or intentional collisions on the TBEx CubeSat mission. No passivation of components is planned at the End of Mission for the TBEx CubeSats.

The probability of battery explosion is very low, and, due to the very small mass of the satellites and their short orbital lifetimes the effect of an explosion on the far-term LEO environment is negligible (ref [G]).

TBExs batteries still meet Req. 56450 (4.4-2) by virtue of the HQ OSMA policy statement regarding CubeSat battery disconnect, stating;

> CubeSats as a satellite class need not disconnect their batteries if flown in LEO with orbital lifetimes less than 25 years. (ref. [G])

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4 shows that with a lifetime of 2.0 years maximum the TBEx CubeSats are compliant.

Section 5: Assessment of Spacecraft Potential for On-Orbit Collisions

Calculation of spacecraft probability of collision with space objects larger than 10 cm in diameter during the orbital lifetime of the spacecraft takes into account both the mean cross sectional area and orbital lifetime.

$$\textbf{Mean CSA} = \frac{\sum \textbf{Surface Area}}{\textbf{4}} = \frac{[\mathbf{2} * (\boldsymbol{w} * \boldsymbol{l}) + \mathbf{4} * (\boldsymbol{w} * \boldsymbol{h})]}{\mathbf{4}}$$

Equation 1: Mean Cross Sectional Area for Convex Objects

$$\textbf{Mean CSA} = \frac{(\boldsymbol{A_{max}} + \boldsymbol{A_1} + \boldsymbol{A_2})}{\mathbf{2}}$$

Equation 2: Mean Cross Sectional Area for Complex Objects

The TBEx CubeSats are stowed in a convex configuration, indicating there are no elements of the CubeSats obscuring another element of the same CubeSat from view. Thus the mean CSA for TBEx in stowed configuration was calculated using Equation 1. This configuration renders the longest orbital lifetimes for TBEx.

Once TBEx has been ejected from the P-POD and deployables have been extended Equation 2 is utilized to determine the mean CSA. $\boldsymbol{A_{max}}$ is identified as the view that yields the maximum cross-sectional area. $\boldsymbol{A_1}$ and $\boldsymbol{A_2}$ are the two cross-sectional areas orthogonal to $\boldsymbol{A_{max}}$. Refer to Appendix A for dimensions used in these calculations.

The TBEx orbit at deployment is 860 km apogee altitude by 300 km perigee altitude with an inclination of 28.4 degrees. With an area to mass(4 kg) ratio of 0.00975 m^2/kg, DAS yields 3.97 years for their orbit lifetimes in the stowed state, which in-turn is used to obtain the collision probability. The probability of collision for both TBEx-A and TBEx-B is $10^{-6.1}$ in the stowed configuration and $10^{-6.2}$ in the deployed configuration. **Table 3** below provides complete results.

CubeSat	TBEx-A	TBEx-B
Mass(kg)	4	4

Stowed	**Mean C/S Area(m^2)**	0.039	0.039
	Area-to-Mass(m^2/kg)	0.00975	0.00975
	Orbital Lifetime(yrs)	3.97	3.97
	Probability of Collision(10^X)	-6.1	-6.1

Deployed	**Mean C/S Area(m^2)**	0.08753	0.08753
	Area-to-Mass(m^2/kg)	0.0219	0.0219
	Orbital Lifetime(yrs)	1.478	1.478
	Probability of Collision(10^X)	-6.2	-6.2

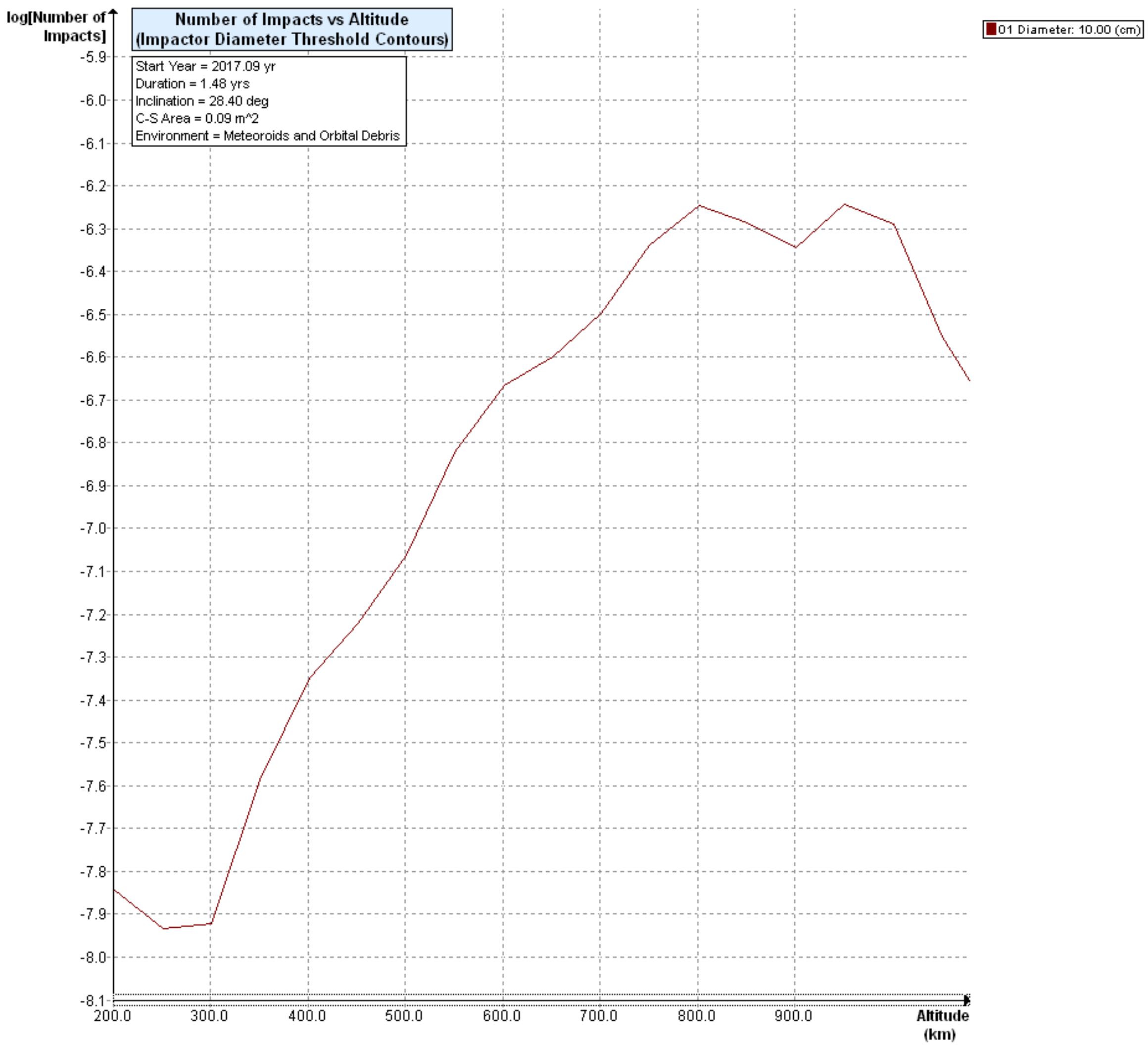


Figure 6: Orbit Collision (<10cm) vs Altitude (TBEx-A & B deployed configuration)

There will be no post-mission disposal operation. As such the identification of all systems and components required to accomplish post-mission disposal operation, including passivation and maneuvering, is not applicable.

The probability of collision for each TBEx spacecraft with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-6.1}$, for any configuration. This satisfies the 0.001 maximum probability requirement 4.5-1.

TBEx has no capability or plan for end-of-mission disposal and the probability of collision and the probability of collision with debris and meteoroids is less than 0.01. This satisfies the requirement 4.5-2.

Assessment of spacecraft compliance with Requirements 4.5-1 and 4.5-2 shows TBEx to be compliant.

Note, we follow JSPOC guidelines for CubeSat operations. In particular, we coordinate with them pre- and post- launch to provided updated estimates of initial orbit information.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

The TBEx CubeSats will naturally decay from orbit within 25 years after end of the mission, satisfying requirement 4.6-1a detailing the spacecraft disposal option.

Planning for spacecraft maneuvers to accomplish post-mission disposal is not applicable. Disposal is achieved via passive atmospheric reentry.

Calculating the area-to-mass ratio for the worst-case (smallest Area-to-Mass) postmission disposal finds TBEx in its stowed configuration as the worst case. The area-to-mass is calculated for TBEx as follows:

$$\frac{\textbf{Mean CSA}(\boldsymbol{m^2})}{\textbf{Mass}(\boldsymbol{kg})} = \textbf{Area-to-Mass}\left(\frac{\boldsymbol{m^2}}{\boldsymbol{kg}}\right)$$

Equation 3: Area to Mass

$$\frac{0.08753m^2}{4kg} = 0.02188\frac{m^2}{kg}$$

The assessment of TBEx CubeSats illustrates they are compliant with Requirements 4.6-1 through 4.6-5.

<u>DAS 2.0.2 Orbital Lifetime Calculations</u>:

DAS inputs are: 300 km minimum perigee X 860 km apogee altitudes with an inclination of 28.4 degrees at deployment in February of 2017. An area to mass ratio of 0.00975 m^2/kg for the TBEx CubeSat was input. DAS 2.0.2 yields a 3.97 years orbit lifetime for both TBEx satellites in its stowed state.

This meets requirement 4.6-1. For the complete list of CubeSat orbital lifetimes reference Table 3: CubeSat Orbital Lifetime & Collision Probability

The DAS assessment shows compliance.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on STP-2 was performed. The assessment used DAS 2.0.2, a conservative tool used by the NASA Orbital Debris Office. The analysis is intended to provide a bounding analysis for characterizing the survivability of a CubeSats components during re-entry. For example, when DAS shows a component surviving re-entry, it is not taking into account the material ablating away or charring due to oxidative heating. Both physical effects are experienced upon reentry and will decrease the mass and size of the real-life components as they re-enter the atmosphere, reducing the risk they pose still further.

The following steps are used to identify and evaluate a components potential re-entry risk relative to the requirement of less than a 1:10,000 probability of a human casualty in the event that a component survives re-entry.

1. Low melting temperature (less than 1000 C) components are identified as materials that would never survive re-entry and pose no risk of human casualty. This is confirmed through DAS analysis that showed materials with melting temperatures equal to or below that of copper (1080 C) will always demise upon re-entry for any size component up the dimensions of a 1U CubeSat.

2. The remaining high temperature materials are shown to pose negligible risk to human casualty through a bounding DAS analysis of the highest temperature components, stainless steel (1500 C). If a component is of similar dimensions and has a melting temperature between 1000 C and 1500 C, it can be expected to possess the same negligible risk as stainless steel components.

Table 3: TBEx High Temperature Component DAS Analysis

CubeSat	**High Temp Component**	**Material**	**Mass (g)**	**Length /Diameter (m)**	**Width (m)**	**Height (m)**	**Demise (Alt)**	KE(J)
TBEx-A	UHF Whip Antenna	Steel 410	10	0.1	0.013	0.164	0	1
TBEx-A	Mounting Screw	316 Stainless Steel	100	0.004	0.007	-	77.7	0
TBEx-B	UHF Whip Antenna	Steel 410	10	0.1	0.013	0.164	0	1
TBEx-B	Mounting Screw	316 Stainless Steel	100	0.004	0.007	-	77.7	0

The majority of stainless steel components demise upon re-entry. The components that DAS conservatively identifies as reaching the ground have 1 or less Joules of kinetic energy. No stainless steel component will pose a risk to human casualty as defined by the Range Commanders Council. In fact, any injury incurred or inflicted by an object with such low energy would be negligible and would not require the individual to seek medical attention.

Through the method described above, Table 4: TBEx Stainless Steel DAS Analysis, and the full component lists in the Appendix TBEx is conservatively shown to be in compliance with Requirement 4.7-1 of NASA-STD-8719.14A.

See the Appendix for a complete accounting of the survivability of TBEx components.

Section 8: Assessment for Tether Missions

The TBEx CubeSats will not be deploying any tethers.

The TBEx CubeSats satisfy Section 8's requirement 4.8-1.

Section 9-14

ODAR sections 9 through 14 for the launch vehicle are addressed in ref.[F], and are not covered here.

Appendix A: TBEx Component List

Component Name	Category	Quantity	Material	Shape	Unit Mass (g)	Length (mm)	Diam. / Width (mm)	Height / Thickness (mm)	Total Mass (g)
ADCS Board	ADCS	1	FR4 PCB	Square	115	98.25	98.25	1.59	115
Reaction Wheel	ADCS	3	Aluminum 6061	Box	100	25	25	10	300
Solid-core Magnetorquer Core	ADCS	2	Steel	Cylinder	5	70	5	N/A	10
Solid-core Magnetorquer Coil	ADCS	2	Copper	Wire	5	70	N/A	N/A	10
Air-core Magnetorquer Base	ADCS	1	Delrin Acetal Copolymer	Box	20	80	80	3	20
Air-core Magnetorquer Coil	ADCS	1	Copper	Wire	5	70	N/A	N/A	5
Torquer Control Board	ADCS	1	FR4 PCB	Square	100	98.25	98.25	1.59	100
Wheel Controller Board	ADCS	1	FR4 PCB	Square	100	98.25	98.25	1.59	100
Sensor Board	ADCS	5	FR4 PCB	Rectangle	3	25	21	1.58	15
Photodiode	ADCS	20	Glass	Box	0.25	4.2	4	1.28	5
Flight Computer Board	ADCS	1	FR4 PCB	Square	115	98.25	98.25	1.59	115
AstroDev UHF Lithium Radio PCB	COMM	1	FR4 PCB	Rectangle	10	60.4	30.4	1.59	10
AstroDev UHF Lithium Radio Housing	COMM	1	Aluminum 6061	Box	40	60.4	30.4	7.3	40
SMA Coax Cable	COMM	1	RG316	Wire	5	120	2.5	N/A	5
TT&C Antenna	COMM	1	Steel	Rectangle	5	173	10.2	N/A	5
Li-ion Battery	EPS	2	Lithium Ion	Cylinder	45	65.5	18.25	N/A	90
Battery Mount	EPS	2	Delrin Acetal Copolymer	Box	9	52.25	23	10	18
Battery Protection Board	EPS	1	FR4 PCB	Rectangle	10	52.25	22.75	1.59	10
EPS Board	EPS	1	FR4 PCB	Square	100	98.25	98.25	1.59	100
-Z Interface Board	EPS	1	FR4 PCB	Square	100	96.5	96.5	1.59	100
Wiring and Harnesses	MISC	1	PTFE, Copper, Silver	Wire	200	N/A	N/A	N/A	200
Payload Electronics Box	PAYLOAD	1		Box	226.3				226.3
Payload Electronics Box Housing	PAYLOAD	1	Aluminum 6061	Box		97	97	20.57	0
Payload Electronics Box Boards	PAYLOAD	1	FR4 PCB	Box		97	97	20.57	0
Antenna Assembly	PAYLOAD	1		Square, Plate	359				359
Phase Shift Board	PAYLOAD	1	FR4 PCB	Square		95.5	95.5	1.59	0
Combiner Board	PAYLOAD	1	FR4 PCB	Square		95.5	95.5	1.59	0
+Z Antenna Plate	PAYLOAD	1	Aluminum 6061	Plate		100	100	2.5	0
L-Band Patch Antenna	PAYLOAD	1	Copper	Square		25	25	3.96	0
VHF Monopole	PAYLOAD	4	Brass	Rod		168	4	N/A	0
UHF Monopole	PAYLOAD	4	Steel	Rectangle		252	10.2	N/A	0
LC Trap	PAYLOAD	4	FR4 PCB	Rectangle		19	12.6	1.6	0
Antenna Pocket Block	PAYLOAD	1	ABS Plastic	Box	150	97	97	25.4	150
Solar Cell	SOLAR	40	Gallium Arsenide	Rectangle	0.5	69.15	39.7	0.15	20
Solar Cell Coverglass	SOLAR	40	Glass	Rectangle	0.25	69.15	39.7	0.15	10
Solar Cell Kapton Tape	MISC	40	Kapton	Rectangle	0.25	69.15	39.7	0.13	10
Body Panel	SOLAR	3	FR4 PCB	Plate	100	286.5	82.5	1.59	300
Body Panel SMB	SOLAR	1	FR4 PCB	Plate	100	237.5	82.5	1.59	100
Deployable Panel	SOLAR	4	FR4 PCB	Plate	120	336.2	82.5	1.59	480
Carbon Fiber Strips	SOLAR	34	Carbon Fiber	Rectangle	5	75	4.5	1.45	170
Wall	STR	2	Aluminum 6061	Plate	127	340.5	100	1.5	254
-Z Plate	STR	1	Aluminum 6061	Plate	26	100	100	1.5	26
Hinge	STR	4	Aluminum 6061	Beam	3.5	54	8.14	5	14
Hinge Dowel Pin	STR	4	Steel 410	Rod	2	68.5	1.19	N/A	8
Deployment, TT&C Antenna Spring	STR	8	Steel 1085	Spring	0.5	7.2	4.75	N/A	4

Figure 7: Orbit Collision (<10cm) vs Altitude (TBEx-A & B)

Separation Switch	STR	2	Phenolic	Box	0.5	19.8	9	7.85	1
Separation Switch Plunger	STR	2	Delrin Acetal Copolymer	Rod	0.05	14.5	3.175	N/A	0.1
Beam Boardmounts	STR	10	Aluminum 6061	Beam	5.6	97	17	5	56
Beam Battery Mounts	STR	6	Aluminum 6061	Beam	7.2	97	17	5	43.2
Reaction Wheel Plate	STR	1	Aluminum 6061	Plate	160	100	97	6.35	160
Antenna Mount	STR	1	Aluminum 6061	Box	7.5	41	20	6.35	7.5
Antenna Mount Stop	STR	1	Aluminum 6061	Box	3	18.4	16	9	3
Mounting Hardware	MISC	200	Stainless Steel 316	Rod	0.2	5	1.5	N/A	40
Scotchweld 2216 Adhesive	MISC	1	Epoxy	Droplet	10	N/A	N/A	N/A	10
Arathane 5753 Adhesive	MISC	1	Epoxy	Droplet	50	N/A	N/A	N/A	50
Spectra Line	MISC	1	Thread	Wire	1	400	0.1	N/A	1
Loctite	MISC	1	Threadlocker	Droplet	5	N/A	N/A	N/A	5

Figure 8: Orbit Collision (<10cm) vs Altitude (TBEx-A & B)