Model-based Cost Engineering Space Missions Estimating

Chris Price (Unison), Shawn Hayes and Mark Jacobs (Space Systems Analysts, LLC)

Abstract: NASA continually strives to improve cost estimation for the highly advanced technology flown on planetary as well as earth orbiting space missions. Over the years it has been proven that parametric cost models are a desired way to obtain accurate estimates. Still there is room for improvement. This paper will discuss two of the latest and best methods for obtaining accurate cost estimates using best-of-breed model-based cost engineering techniques.

This paper / presentation will address two relatively new methods to improve the accuracy of space missions cost estimates: TruePlanning Hardware Equipment Types and a relatively new Space Missions Catalog, with emphasis on the later. Both methods include a variety (up to 119) space specific equipment types, and the Space Missions catalog also includes novel specific models for electric propulsion, ion thrusters, lasers, parachutes, radar altimeters, and thermal protection. This paper / presentation will include two case studies (one earth orbiting and one planetary mission) featuring many of the above equipment types and unique cost models. A validation study of the results of these case studies will also be included.

Case Study Descriptions (Two Case Studies):

Two hypothetical robotic space missions were developed to demonstrate the capabilities of the TruePlanning suite of estimating tools. A space-based telescope case study was developed to highlight the process of applying TruePlanning to near Earth missions and an autonomous Mars helicopter case study was developed to highlight planetary missions with multiple flight elements.

The first case study, referred to as LUVOT (LEO UV Optical Telescope) is a 500kg Explorer class ultraviolet space-based telescope with a development schedule of 4.5 years. The flight system consists of a 100kg payload that contains a cluster of four telescopes (aperture <25cm) with CCD detectors tuned to cover different ranges in the electromagnetic spectrum and a 400kg commercial low-cost spacecraft bus. The telescope payload includes significant structural elements constructed of composite materials, several light-weighted mirrors using advanced materials, an electronics assembly and a filter wheel. The spacecraft bus utilizes standard aluminum honeycomb structural elements, has passive thermal control, is solar powered with articulated arrays and has no propulsion system. In addition, the bus is 3-axis controlled, has a Rad750 based processing unit with onboard storage and communicates with the ground using a X-band SSPA. Figure 1 provides a high-level Master Equipment List (MEL) for LUVOT and an artist's rendering of the LUVOT flight system. The complete MEL used to estimate the LUVOT system is provided in Appendix A.

		# OF UNITS			FLIGHT HARDWARE MASSES	OTHER COMPONENT INFORMATION	
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, CBE	Description (Vendor, Part #, Heritage Basis)	Other characteristics/issues (volume, power, other component-specific items)
LUVOT Spacecraft	**Flight Element #1**				**389.4**		
Structure					**130.0**		
Primary Structure	90.0	1	0	0	90.0	Standard design	Aluminum
Heaters, Thermistors	2.0	1	0	0	2.0	Standard materials, new design	
Star Tracker	5.0	2	0	1	10.0	Modified COTS part	
Spacecraft Component n.....							
UVOT Telescope Optical Assembly	**Payload Element #1**				**96.10**		
Primary mirror	0.01	10	0	1	0.12	Lightweighted design, Adv Mat'l	25cm diameter
Detectors, CCDs	9.00	4	0	1	36.00	CCDMart Part # 2021	
Filter wheel mechanism	40.00	1	1	1	40.00	Minor mod from past design	
Payload Component n.....							

Figure 1: Sample MEL for LUVOT (Complete MEL Provided in Appendix A)

The planetary case study (Marscopter) is a medium sized helicopter designed to fly autonomously across the Martian landscape. Marscopter is a New Frontiers or flagship class space mission that has a mass of 1,700kg and a development schedule of 6 years. The Marscopter flight system consists of three distinct flight elements; the entry system, the cruise stage and the helicopter. The 1,000kg entry system provides protection during Mars entry and consists of a mini "Sky Crane" to lower the payload to the surface and a thermal protection system that shields the payload during descent into the Martian atmosphere. This system utilizes a Rad750 based control computer and aluminum structural elements. The cruise stage for this space mission is a typical interplanetary support spacecraft that has a mass of 200kg. It has a biprop propulsion system, passive thermal control and standard aluminum- honeycomb structural materials. The helicopter payload is 600kg and is powered by batteries during flight but uses solar arrays to recharge between excursions on the surface. Multiple excursions can be conducted within the lifetime of the helicopter which is driven by battery charge/discharge cycles. The helicopter is mostly constructed of composite materials, has a Rad750 based electronics system and relies on X-band communications equipment. The helicopter carries a science payload made up of individual instruments consisting of a mapping spectrometer, meteorological suite and a visible camera. Figure 2 shows an artist's rendering of the three flight elements that make up the Marscopter flight system along with a summary level MEL. A more detailed MEL for this case study can be found in Appendix A.

Entry System (EDL)

Cruise Stage

Helicopter

		# OF UNITS			FLIGHT HARDWARE MASSES	OTHER COMPONENT INFORMATION	
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, CBE	Description (Vendor, Part #, Heritage Basis)	Other characteristics/issues (volume, power, other component-specific items)
Helicopter	**Flight Element #1**				**515.20**		
Multi-Layer Insulation, Coatings, etc	10.00	1	0	0	10.0	Custom design, standard materials/processes	
Battery	200.00	1	1	1	200.0	Standard cells w/ new configuration	400 Amp-hr Li-ion
RAD750 Single Board Computer	0.50	1	0	1	0.5	COTS part w/ application-specific software	Rad750-based
Helicopter Component n…..							
EDL	**Flight Element #2**				**940.00**		
Mini Sky Crane Primary Structure	150.00	1	0	0	150.0	Scaled-down heritage design	Aluminum
Heatshield TPS	300.00	1	0	0	300.0	Scaled-down heritage design	
Backshell Structure	50.00	1	0	0	50.0	Scaled-down heritage design	Aluminum
EDL Component n…..							
Cruise Stage	**Flight Element #3**				**170.60**		
Mechansims	15.00	1	0	0	15.0	COTS devices	
Fuel Tank	8.00	4	0	0	32.0	Mono-prop fuel tank	Titanium
Cruise Stage Component n …...							
Mapping Spectrometer	**Payload Element #1**				**70.50**		
Primary Mirror	4.00	1	0	1	4.00	Modified past design	
Power Supplies	2.00	1	0	1	2.00	Modified past design	
Spectrometer Component n….							
Visible Camera	**Payload Element #2**				**7.90**		
Primary Optic	2.00	1	0	1	2.00	Modified past design	
Detector, CCD	0.40	1	0	1	0.40	CCDMart Part # 1963	
Visible Camera Component n….							
Meteorological Suite	**Payload Element #3**				**9.50**		
Wind Sensor	0.50	2	0	1	1.00	Modified past design	
Harnessing	1.00	1	0	1	1.00	Custom harness, new design	
Meterorological Suite Component n….							

Figure 2: Sample MEL for the Marscopter case study (Complete MEL Provided in Appendix A)

The TruePlanning Space Hardware Equipment Types and Resulting Cost Models

Equipment Types

As an extension of a study that PRICE (now known as Unison) accomplished several years ago for NASA, we developed a significant set of 'unmanned hardware equipment types' to specifically support the estimation of unmanned space missions of all types and applications.

The derivation of these equipment types was based on two extensive sets of data:

1. Spacecraft data from the US Air Force Unmanned Spacecraft Cost Model (USCM), supplemented with some newer data from the Air Force
2. Payload / Instrument data from a set of 13 NASA historical earth-orbiting and planetary missions.

The original study was published in 2016. This included 119 hardware equipment types, as shown in Figure 3.

Structures & Mechanisms

- Actuator/Drive Ass'y
- Hinges
- Latch
- Mechanisms
- Pyrotechnics
- Pyrotechnics Ass'y
- Solar Array Yokes/Booms
- Structure, Panel
- Structure, Payload
- Structure, Primary
- Structure, Solar Sail
- Structure, Wheel

Altitude Control / GNC

- Accelerometer
- ACS Control Electronics
- Earth Horizon Sensor
- GPS Receiver
- IMU/IRU
- Magnetic Torquer
- Magnetometer
- Momentum/Reaction Wheel
- Nutation Damper/Despin Ass'y
- Rate Gyro
- Star Tracker
- Sun Sensor
- Torque Coils

Propulsion

- Filter
- Lines/Fittings,Latch/Isolation Valves
- Manifold
- Motor, Apogee Kick
- Motor, Solid Rocket
- Plumbing
- Plumbing, XIPS
- Power Processor
- Regulator
- Squib Valve, Fill/Drain Valve
- Tank, Auxilliary
- Tank, Chemical
- Tank, Flight System
- Tank, Helium
- Tank, Launch System
- Tank, Liquid
- Tank, Manned Space Mission
- Tank, MUPS
- Tank, Oxidizer/PMD
- Tank, Pressurant
- Tank, Propellant/Propulsion
- Tank, XIPS
- Thruster Module, Dual
- Thruster, ARCJET
- Thruster, Cold Gas
- Thruster, High Level
- Thruster, LAE
- Thruster, Liquid
- Thruster, Low Level Spin Control
- Thruster, REA
- Thruster, XIPS
- Thruster:.1 LB. - 110 LB.
- Transducer

Thermal Control

- Heat Pipes
- Heater/Thermistor/Thermostat
- Mirror
- Miscellaneous Passive Thermal
- MLI Blanket/Insulation/Paint/Shroud
- Optical Solar Reflector
- Radiators/Louvers

Figure 3a. Spacecraft / Bus Equipment Types

TT&C / C&DH / Communications

- Antenna
- Antenna, Hi-Gain
- Antenna, Horn
- Antenna, Low-Gain/Medium Gain
- Antenna, Omni
- Antenna, S-Band
- Antenna, VHF
- Command Receiver
- Command Telemetry Unit
- Communication Security
- Data Handling
- Data Interface
- Data Recorder
- Demodulator
- Diplexer
- Filter/Coupler
- Frequency Downconverter
- Harness/Cabling/Waveguide
- Memory
- Modulator
- Oscillator/Clock
- Power Amplifier
- Premodulator Processor
- RF Distribution
- RF Ferrite Device
- RF Plumbing
- Signal Conditioner
- Signal Switch
- Spacecraft Control Processor
- Thruster Firing Electronics
- Transmitter
- Transponder
- Transponder Telemetry Unit
- TWTA
- Valve Driver

Electrical Power

- Battery
- Battery Voltage Limiter
- Battery Voltage Pressure Monitor
- Battery,NiH
- Cabling/Wiring Harness
- Ordnance/Charge Power Controller
- Power Conditioner/Controller
- Power Control Electronics
- Power Converter
- Power Dissipators/Shunts
- Power Distribution Unit
- Power Regulator
- Power Supply Electronics
- Solar Array
- Solar Array Drive
- Solar Array -GaAs
- Solar Array -Si
- Squib Driver
- Switching Unit

Payload / Instruments

- Optics (Average Complexity)
- Digital/Analog Electronics
- Power Supply Electronics
- Power Connectors/Harnesses
- Optics (Simple)
- Optics (Complex Assy.)
- Digital/Analog Electronics (Simple Circuit)
- Digital/Analog Electronics (Complex Circuit)
- Sensor, Electronic, General

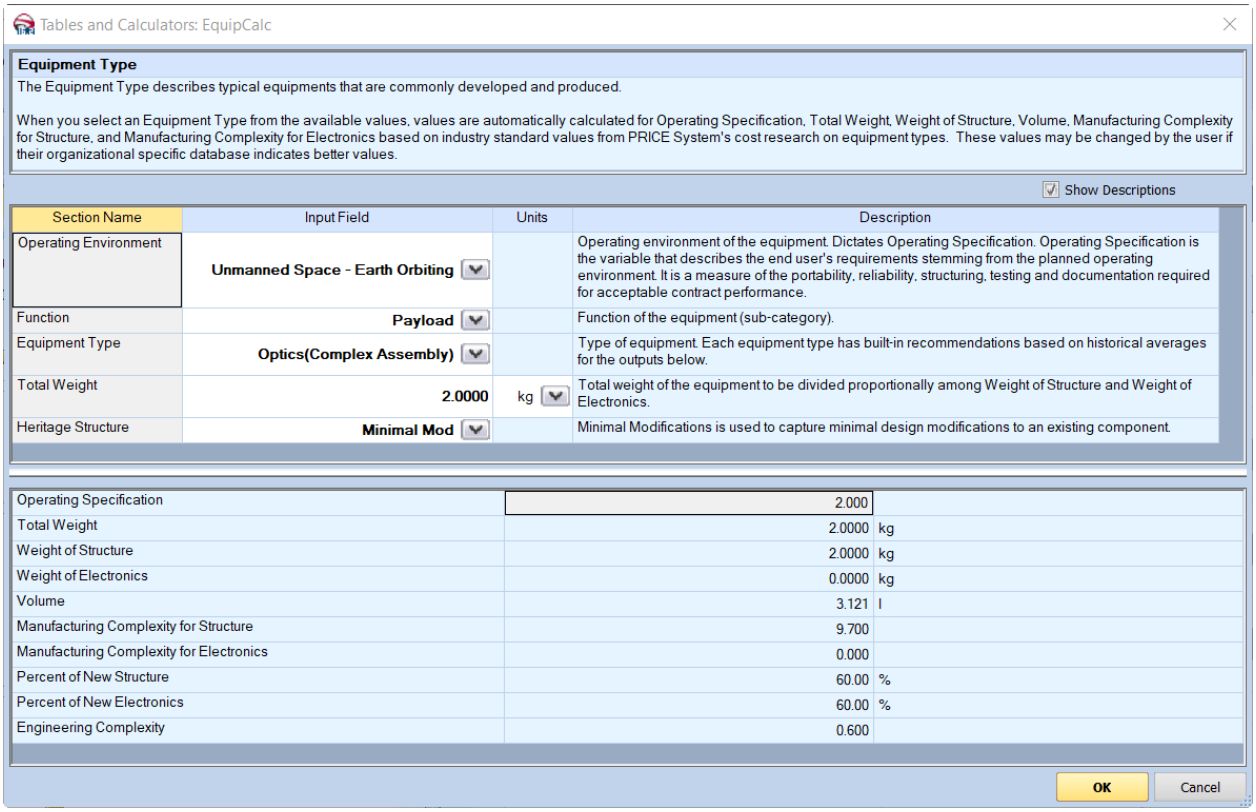
Payload and Bus

- Electronic Chassis/Housing
- Electronic Chassis/Housing (Simple / Mechanical part)
- Electronic Chassis/Housing (Sophisticated / Complex)

Figure 3b. Payload / Instrument Equipment Types

One of the advantages of estimating unmanned space missions using the hardware equipment type method is that this is merely an extension of the legacy hardware / system estimating method in TruePlanning software application. If one is already a user of the Unison TruePlanning hardware /system models, estimating unmanned space missions is merely an extension of the hardware estimating method you are already familiar with. This method is also extensible to missions other than NASA missions, and to a lesser extent, manned missions as well. It also lends itself the ability to include, and integrate software into the hardware estimate.

An example of the Hardware Equipment Type Calculator is shown below in Figure 4 depicting an example of a Payload / Instrument / Optics assembly for an Earth-Orbiting Mission. As can be seen at the bottom of the figure, the equipment type calculator derives all of the necessary inputs for TruePlanning based on a few inputs provided by the estimator at the top of the figure / calculator.



Tables and Calculators: EquipCalc

Equipment Type

The Equipment Type describes typical equipments that are commonly developed and produced.

When you select an Equipment Type from the available values, values are automatically calculated for Operating Specification, Total Weight, Weight of Structure, Volume, Manufacturing Complexity for Structure, and Manufacturing Complexity for Electronics based on industry standard values from PRICE System's cost research on equipment types. These values may be changed by the user if their organizational specific database indicates better values.

Show Descriptions

Section Name	Input Field	Units	Description
Operating Environment	**Unmanned Space - Earth Orbiting**		Operating environment of the equipment. Dictates Operating Specification. Operating Specification is the variable that describes the end user's requirements stemming from the planned operating environment. It is a measure of the portability, reliability, structuring, testing and documentation required for acceptable contract performance.
Function	**Payload**		Function of the equipment (sub-category).
Equipment Type	**Optics(Complex Assembly)**		Type of equipment. Each equipment type has built-in recommendations based on historical averages for the outputs below.
Total Weight	**2.0000**	kg	Total weight of the equipment to be divided proportionally among Weight of Structure and Weight of Electronics.
Heritage Structure	**Minimal Mod**		Minimal Modifications is used to capture minimal design modifications to an existing component.

Operating Specification	2.000	
Total Weight	2.0000	kg
Weight of Structure	2.0000	kg
Weight of Electronics	0.0000	kg
Volume	3.121	l
Manufacturing Complexity for Structure	9.700	
Manufacturing Complexity for Electronics	0.000	
Percent of New Structure	60.00	%
Percent of New Electronics	60.00	%
Engineering Complexity	0.600	

OK Cancel

Figure 4. The TruePlanning Hardware Equipment Type Calculator depicting an Earth Orbiting Optics Assembly

Cost Models / Results

As described in Section I, two notional case studies were modeled for this paper using both the Hardware Equipment Types as well as the Space Missions Catalog. The results of the Hardware Equipment Types will be presented in this section, and the results of the Space Missions Catalog will be presented in the following Section III.

Figure 5 is a snapshot of the Product Breakdown Structure (PBS) for the (LUVOT) mission. Figure 5a shows a portion of the Payload / Instrument PBS, while Figure 5b shows a portion of the Spacecraft / Bus. Note that System / Assembly Cost Objects are included to estimate NASA WBS Elements 1-3 and 10, as well as WBS 5 and 6.

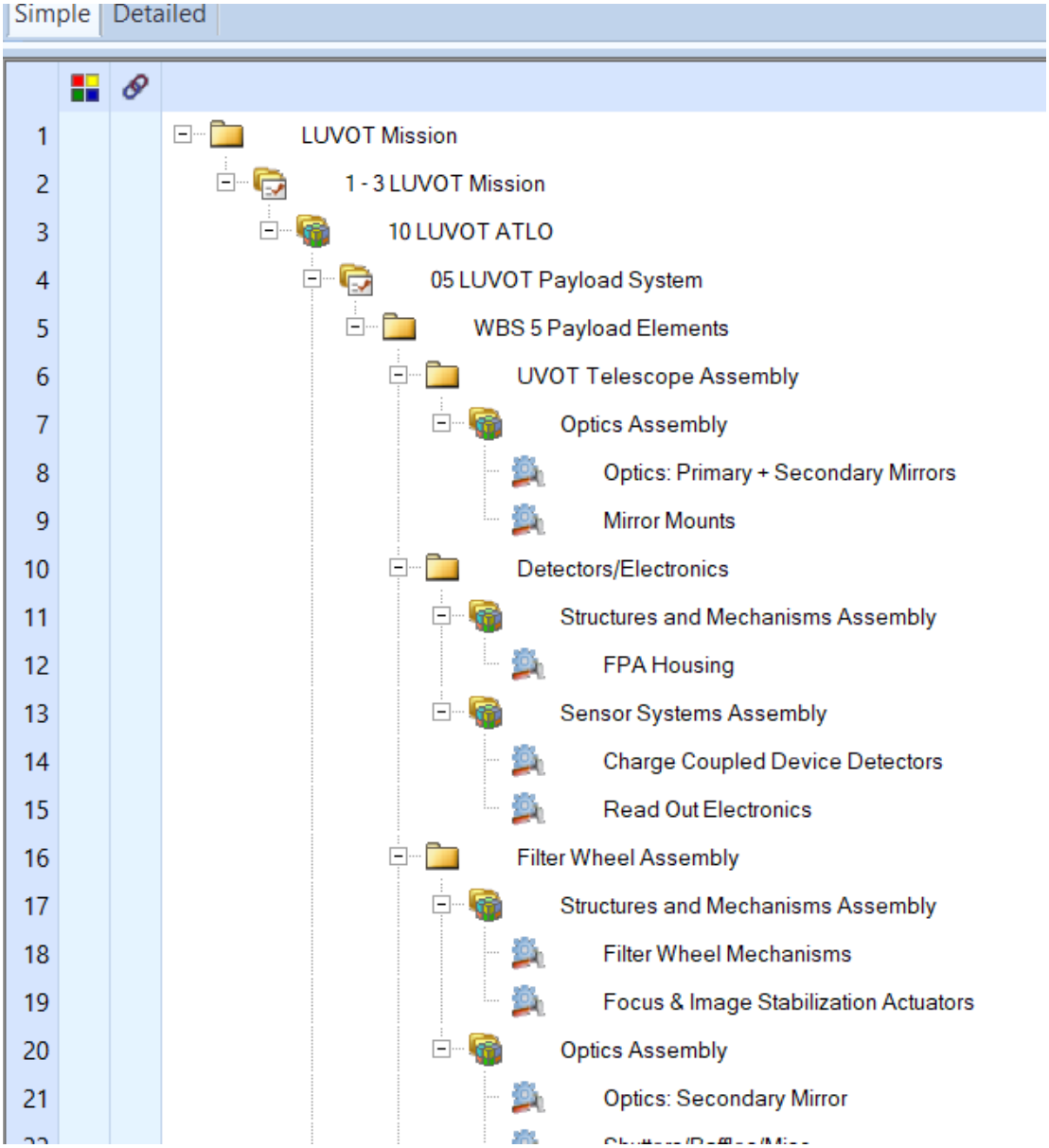


Figure 5a. Snapshot of a portion of the LUVOT Payload / Instrument PBS

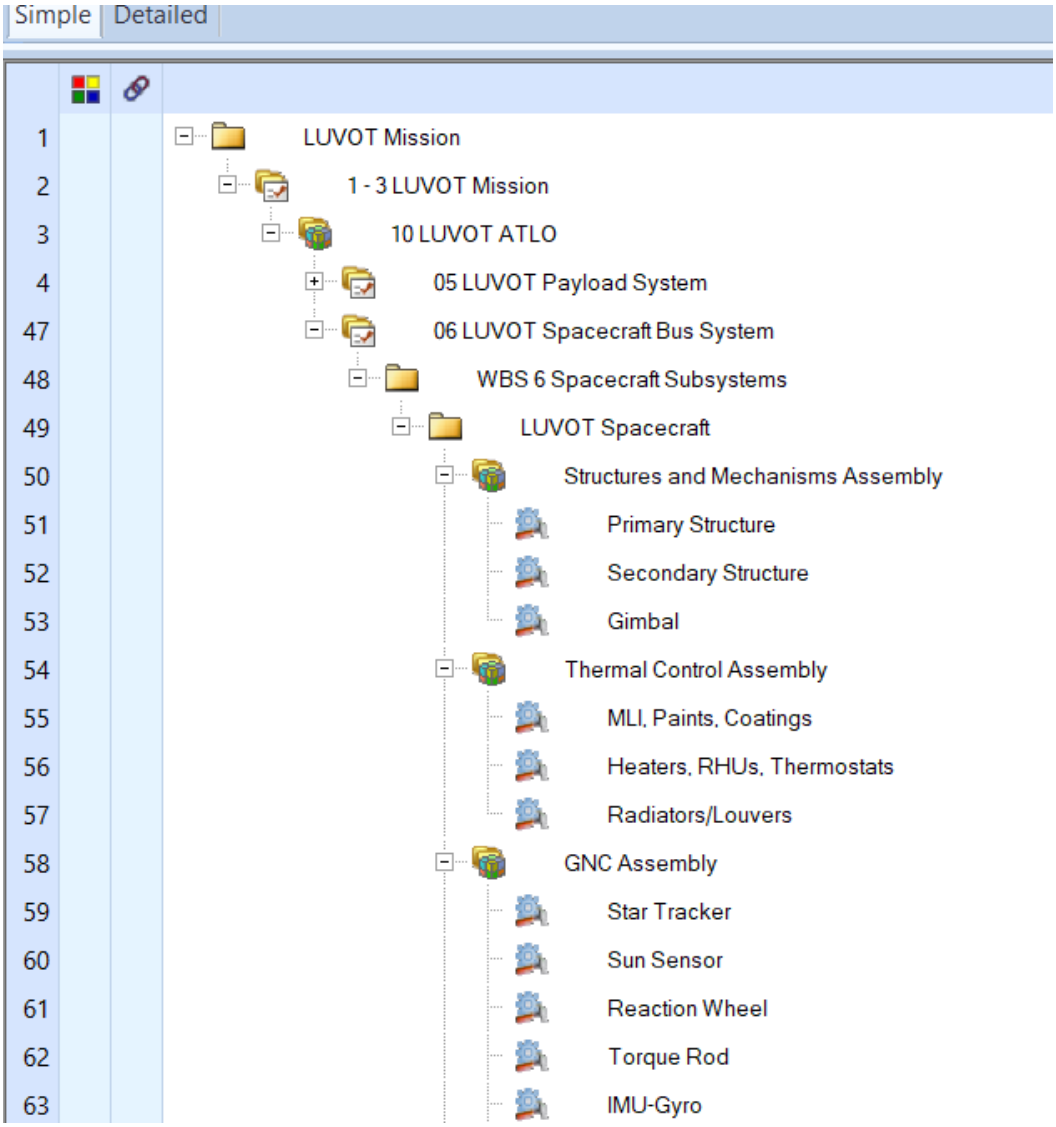


Figure 5b. Snapshot of a portion of the LUVOT Spacecraft / Bus PBS

A snapshot of the TruePlanning Hardware Equipment Type Results by NASA WBS is shown in Figure 6. As shown in the figure, the total design and development is approximately $110 million, and the total flight unit cost is approximately $71M, for a total project cost of approximately $182M. This includes approximately $114.5M for the Spacecraft bus, and $49.5M for the Payload / Instruments.

LUVOT Mission <custom>

Cost:	$181,784,997	100.00%	Labor Requirement:	989,222.37	hours
Project Cost:	$181,784,997		Project Labor Requirement:	989,222.37	hours

Phase Set: A Worksheet Set: Space v4 w Launch Opns

	Costs : LUVOT Mission - [System Folder] Currency in USD ($) (as spent)	Total	Development	Production
1	NASA Std WBS	**181,784,997**		
2	1 Project Management	**3,278,356**	2,528,510	749,846
3	2 Systems Engineering	**3,541,348**	2,432,228	1,109,119
4	3 Safety & Mission Assurance	**730,989**	509,240	221,749
5	5 Payload(s)	**49,509,281**	23,846,671	25,662,610
6	6 Spacecraft	**114,592,444**	11,833,079	4,335,281
7	6.1 Structures & Mechanisms	**10,072,484**	7,325,461	2,747,022
8	6.2 Thermal Control / Temperature Control	**2,208,725**	1,689,179	519,546
9	6.7 Guidance, Navigation & Control (GNC)	**13,099,498**	6,248,675	6,850,824
10	6.9 Communications / TeleCommunications	**16,960,457**	8,912,420	8,048,036
11	6.10 Command and Data Handling (C&DH)	**19,299,751**	13,625,662	5,674,089
12	6.11 Solar Electric Power (SEP) / Power & Distribution	**36,783,169**	21,800,688	14,982,481
13	10 Systems Integration & Testing	**10,132,579**	9,887,113	245,466
14	**Total Applied**	**181,784,997**	**110,638,929**	**71,146,069**
15	**Total**	**181,784,997**	**110,638,929**	**71,146,069**

Figure 6. LUVOT Mission Space Equipment Type Results by NASA WBS

TruePlanning was also used to estimate the cost of the Marscopter Mission as discussed in Section I. Figure 7a represent a snapshot of the Hardware Equipment Type PBS for the Marscopter Spacecraft, and Figure 7b represents the PBS for a portion of the Marscopter Payloads / Mapping Spectrometer Instrument.

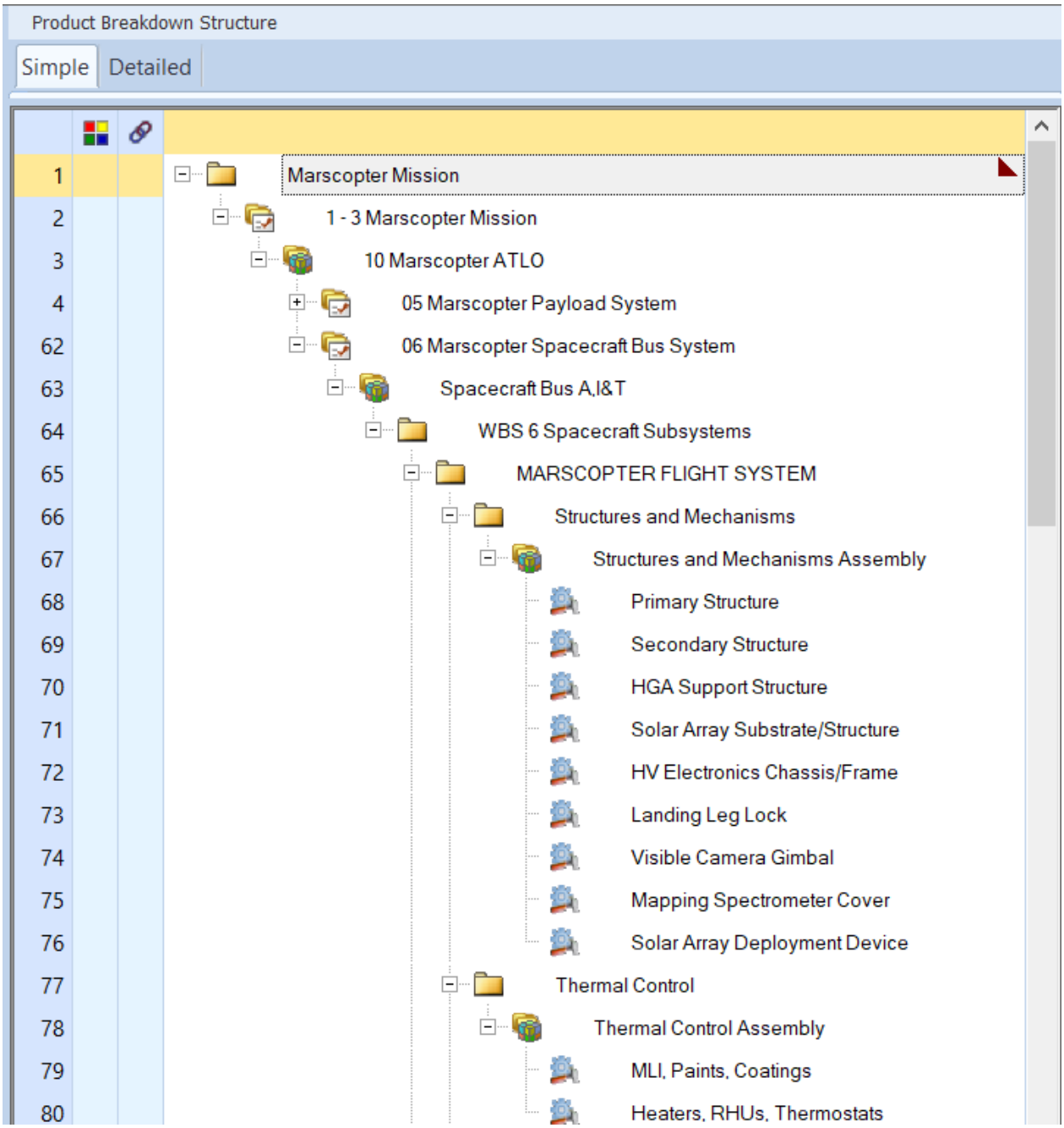


Figure 7a. Marscopter Spacecraft / bus Product Breakdown Structure in TruePlanning

The results of the Hardware Equipment Type Marscopter Mission cost estimate are shown in Figure 8, by NASA standard WBS. Note that the Marscopter Mission is much more complex than the LUVOT mission, incorporating EDL as well as a Cruise Stage, and multiple instruments, so both the Payload / Instrument costs, as well as the Spacecraft costs are significantly higher than the earth-orbiting LUVOT. As shown in the figure, the total design and development for the Marscopter Mission is approximately $739 million, and the total flight unit cost is approximately $285M, for a total project cost of

approximately $1.023B. This includes approximately $714M for the Spacecrafts, and $157M for the Payload / Instruments.

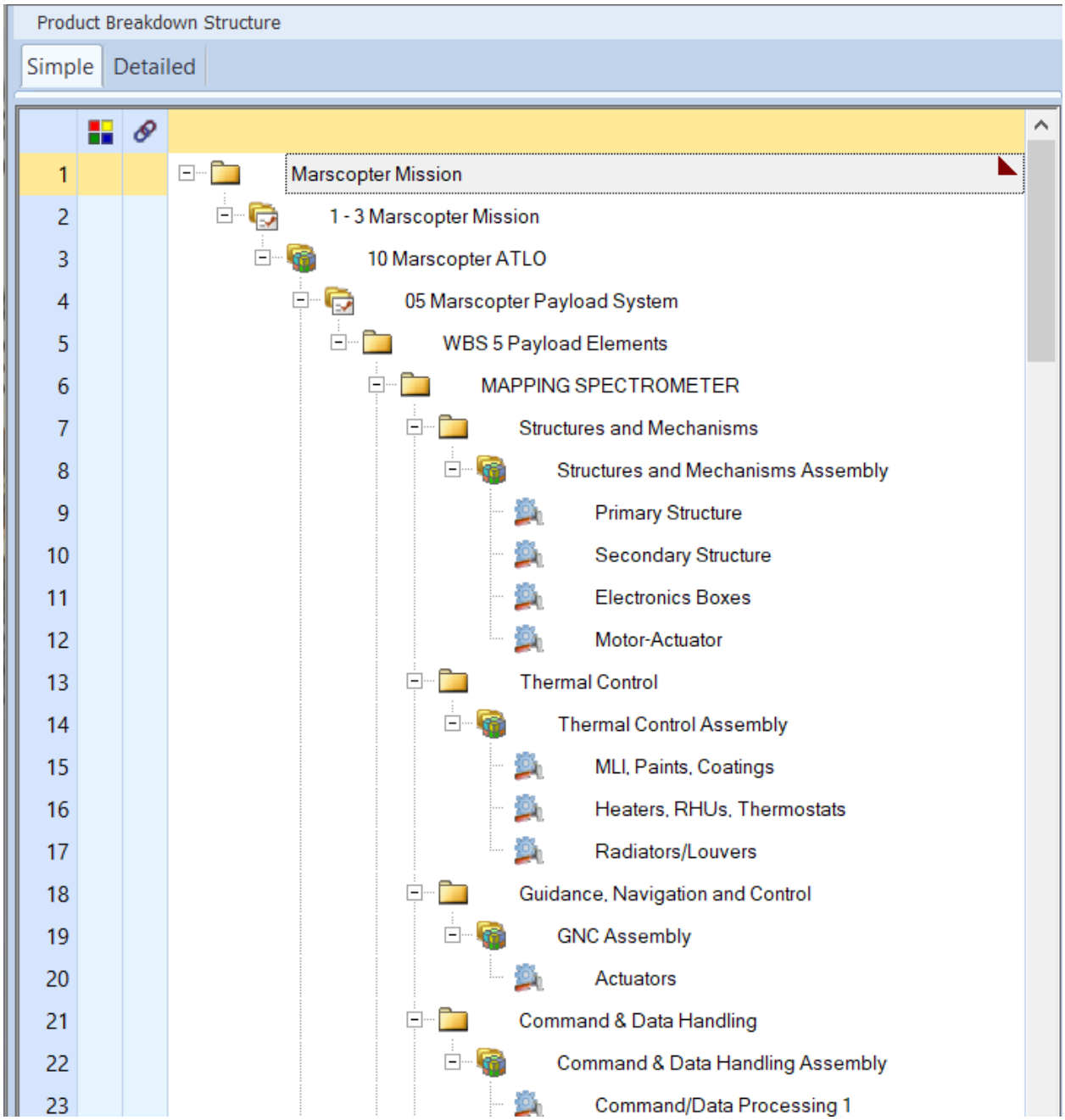


Figure 7b. Marscopter Product Breakdown Structure for the Payload Mapping Spectrometer Instrument in TruePlanning

Marscopter Mission <custom>

Cost:	$1,023,394,149	100.00%	Labor Requirement:	5,590,899.34	hours
Project Cost:	$1,023,394,149		Project Labor Requirement:	5,590,899.34	hours

Phase Set: A Worksheet Set: Space v4 w Launch Opns

	Costs : Marscopter Mission - [System Folder] Currency in USD ($) (as spent)	Total	Development	Production
1	NASA Std WBS	**1,023,394,149**		
2	1 Project Management	**19,805,099**	16,723,940	3,081,160
3	2 Systems Engineering	**35,133,715**	30,545,106	4,588,610
4	3 Safety & Mission Assurance	**4,630,652**	3,566,100	1,064,551
5	5 Payload(s)	**156,919,061**	115,419,363	41,499,698
6	6 Spacecraft	**713,865,692**	102,592,551	27,674,786
7	6.1 Structures & Mechanisms	**280,851,228**	172,434,610	108,416,617
8	6.2 Thermal Control / Temperature Control	**8,516,586**	7,202,154	1,314,433
9	6.6 Propulsion / Electric Propulsion (EPS)	**49,291,083**	28,198,942	21,092,141
10	6.7 Guidance, Navigation & Control (GNC)	**58,572,339**	36,110,545	22,461,794
11	6.9 Communications / TeleCommunications	**47,867,195**	28,099,998	19,767,197
12	6.10 Command and Data Handling (C&DH)	**27,202,016**	21,081,468	6,120,548
13	6.11 Solar Electric Power (SEP) / Power & Distribution	**111,297,908**	84,769,587	26,528,320
14	10 Systems Integration & Testing	**93,039,930**	92,075,722	964,208
15	**Total Applied**	**1,023,394,149**	**738,820,086**	**284,574,062**
16	**Total**	**1,023,394,149**	**738,820,086**	**284,574,062**

Figure 8. Marscopter Mission Space Equipment Type Results by NASA WBS

Note that individual Subsystem / Component cost (and labor) reports (not shown here) are also available in TruePlanning.

The Space Missions Catalog and Resulting Cost Models

The Space Missions Catalog

Nearly 35 years ago, a new approach for estimating NASA planetary spacecraft was developed in support of the upcoming Discovery Program. This new approach leveraged an extensive amount of historical planetary data going back to the early 1970's and utilized the framework of the PRICE H Estimating Suite. This NASA tailored cost model was later expanded to include Earth science missions and additional refinements were made to capture science instruments and approaches used by more recent missions. The overall approach of the model was to focus on perceived cost drivers versus non-

causal options. In the early 2010's, the model was migrated from PRICE H to the TruePlanning framework where it became known as the TruePlanning Space Missions (TPSM) Catalog. Over its history, the TPSM model has been used to support numerous instrument and mission evaluations and Standing Review Boards (SRBs), demonstrating its accuracy and applicability throughout all mission development phases and across the NASA portfolio.

TPSM produces an estimate that covers the development phases of a project (Phases B-D) and maps it to the NASA standard WBS structure. The payload and spacecraft flight hardware estimates are built up from component level estimates that rely on inputs such as; schedule durations, heritage, technology levels, quantities (flight, spares, prototypes, models, etc.), parts class (S, B, etc.) and mass. TPSM also estimates the cost of Instrument Assembly & Test (I&T), launch operations, and project support functions (management, systems engineering, etc.).

In addition to running TPSM within the TruePlanning environment, a recently developed Excel interface tool known as TPXL offers users the ability to run TPSM using a more streamlined approach directly from a customizable Excel interface. The process outlined here for each of the case studies will highlight the TPSM estimating procedure utilizing TPXL.

The first step in developing an estimate requires that all payload and spacecraft components are assigned a subsystem and component type as shown in Figure 9.

Subsystem / *Component*	*Subsystem* / *Component*	*Subsystem* / *Component*
STRUCTURE & MECHANISMS	**GUIDANCE, NAVIGATION, & CONTROL**	**ENTRY & DESCENT**
Primary Structure	Star Tracker	Themal Protection System *
Secondary Structure	Sun Sensor	Parachute *
Shielding	Reaction Wheel	
Solar Array Substrate/Structure	Torque Rod	**OPTICS**
HGA Structure	Gimbals	Optical Bench
Electronics Boxes	IMU-Gyro	Optics
Mechanisms	Actuators	Gratings
Motor/Actuator	Radar Altimeter *	Filter Wheel
Booms		Optics Filters/Misc
	COMMUNICATIONS	
ROBOTIC ARM	Transponder	**SENSOR SYSTEMS**
Robotic Arm - Limb	Transmitter	Laser *
Robotic Arm - Joint/Actuator	Amplifier	Sensors-Detectors
	Misc RF Electronics	CCD Detectors
THERMAL CONTROL	HGA	Magnetometer
MLI, Paints, Coatings	MGA/LGA	TOF Spectrometer
Heaters, RHUs, Thermostats	Waveguide/Comm Cabling	ESA sensor
Radiators/Louvers		Photodiode
Heat Pipes	**COMMAND & DATA HANDLING**	Bolometer
Cryocooler	Command/Data Processing	Ion Source
	Solid State Memory	Gamma Sensor
PROPULSION		Neutron Sensor
Propulsion Lines/Valves/Fittings	**POWER**	Dust Detector
Pressure Regulator	Power Management and Distribution	Readout Electronics
Tanks	Solar Cells/Electrical	
Thrusters	Pyrotechnics	
	Batteries	
ELECTRIC PROPULSION	Harness	
Ion Thruster *		
Power Processing Unit *		** Modeled using custom TPSM relationships*

Figure 9: TPSM Subsystem and Component Types

Once all of the components have been categorized, the technical and programmatic details are assigned as appropriate. Five milestone dates are used for each flight element to define the four project phases;

design, fabrication, I&T and launch operations. Technical details such as; quantities, heritage, mass and technology levels are also assigned. Figure 10 provides a high-level look at how these parameters were assigned for the LUVOT case study in the TPXL environment. The complete set of parameters used to estimate both case studies are provided in Appendix B.

Technical Details from MEL		# OF UNITS			FLIGHT HARDWARE MASSES	Heritage, Technology and Component Classifications TPSM COST MODEL INPUTS				
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, CBE	Heritage	New or Advanced Tech	Subsystem Type	Component Type	Other Type
LUVOT Spacecraft					**389.4**					
Structure					**130.0**					
Primary Structure	90.0	1	0	0	90.0	Minor Mod		Structure and Mechanisms	Primary Structure	1
Heaters, Thermistors	2.0	1	0	0	2.0	New		Thermal Control	Heaters, RHUs, Thermostats	3
Star Tracker	5.0	2	0	1	10.0	Minor Mod		Guidance, Navigation and Control	Star Tracker	2
Spacecraft Component n.....										
UVOT Telescope Optical Assembly					**96.10**					
Primary mirror	0.01	10	0	1	0.12	Major Mod		Optics	Optics	3
Detectors, CCDs	9.00	4	0	1	36.00	Copy		Sensor Systems	Charge Coupled Device Detectors	2
Filter wheel mechanism	40.00	1	1	1	40.00	Minor Mod		Structure and Mechanisms	Mechanisms	2
Payload Component n.....										

Project Schedule Milestones	Phase B start	PDR [1]	CDR	Deliver to System I&T	Ship to Launch Site	Launch	On-Orbit Chect-Out (L+30d)
LUVOT Spacecraft	1/2/2022	11/17/2022	10/2/2023	10/1/2024	4/2/2026	8/1/2026	8/31/2026
UVOT Telescope Optical Assembly	1/2/2022	11/17/2022	10/2/2023	10/1/2024	4/2/2026	8/1/2026	8/31/2026

Other Technical and Programmatic Inputs	Platform ("EO" or "P")	Parts Class (S,S1,B,B1,B2,D)	International ("Y" or "N")	Contracting Fee	Contract Monitor Burden	# of Flight Units	Notes	Mission Class
LUVOT Spacecraft	P	B	N			1		Class C/D
UVOT Telescope Optical Assembly	P	S1	N			1		Class C/D

Figure 10: Sample Technical and Programmatic Inputs for the LUVOT Case Study (Complete Input Set in Appendix B for Both Case Studies)

TPSM Cost Model Results Using TPXL solution

The TPXL solution automatically provides estimate results neatly in the NASA WBS standard format and provides a breakdown of the estimate into each of the four phases of the project lifecycle; design, fabrication, integration, test and assembly and launch operations and on-orbit checkout. The estimate results produced by TPXL can easily be imported to other software packages so that additional analyses can be performed (e.g. JCL, etc.). Figure 11 gives the TPXL output table for the LUVOT case study. In addition to this output table, TPXL also generates a TP file that contains the details used to build the estimate as shown in Figure 12. This is useful for documenting results and can be used to perform additional analyses withing the TP environment. Figure 13 and Figure 14 provide the estimate results for the Marscopter case study.

Case Study 1: LUVOT						
RY$K		DES	FAB	I&T	LOCO	TOTAL
1	PM	2,303	11,131	1,210	266	**14,910**
2	SE	2,861	3,277	998	321	**7,458**
3	MA	1,960	3,517	2,084	442	**8,003**
4	SciTm	389	2,454	1,957	476	**5,277**
5	Pyld	14,814	19,357	6,179	1,151	**41,501**
	UVOT Telescope Assembly	1,374	1,509	407	108	**3,398**
	Detectors/Electronics	4,019	9,472	2,847	570	**16,908**
	Filter Wheel Assembly	1,968	4,329	757	114	**7,168**
	Structure, Mechanical, & Thermal	2,625	2,064	666	149	**5,503**
	UVOT Electronics Box	4,250	1,939	1,332	186	**7,708**
	Harness	579	45	170	23	**817**
	Instr PM/SE/MA					**0**
	Instr I&T/GSE					**0**
6	S/C	35,761	23,647	11,766	2,051	**73,225**
	LUVOT S/C	35,761	23,647	11,766	2,051	**73,225**
	S/C PM/SE/MA					**0**
	S/C I&T/GSE					**0**
7/9	MOS/GDS	490	2,959	3,080	631	**7,160**
10	I&T	3,566	7,008	7,936	674	**19,184**
	TOTAL	**62,145**	**73,350**	**35,211**	**6,012**	**176,718**

Figure 11: TPXL Output Table (RY$k) for the LUVOT Case Study (In NASA Standard WBS Format by Phase)

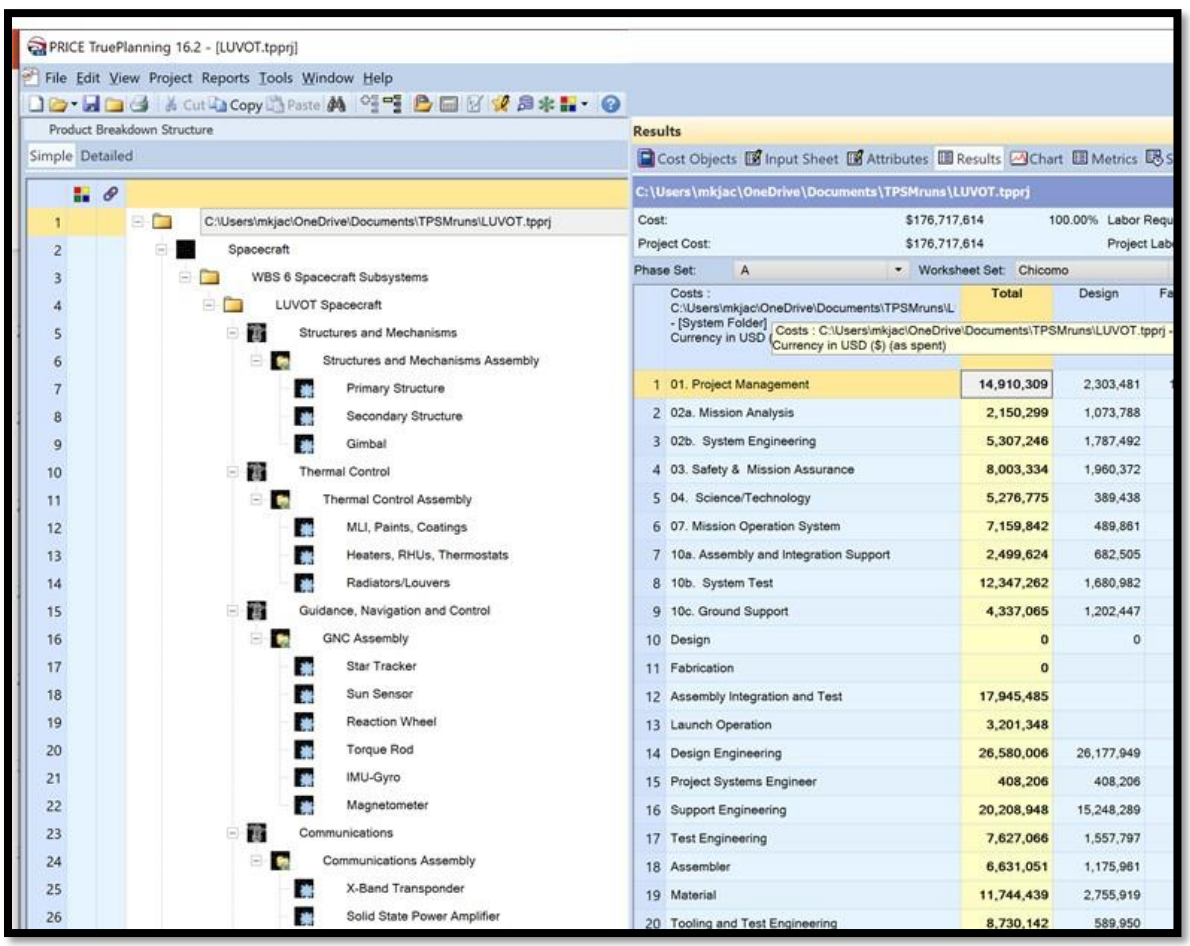


Figure 12: TruePlanning File Automatically Generated by TPXL for the LUVOT Case Study

Case Study 2: Marscopter						
RY$K		DES	FAB	I&T	LOCO	TOTAL
1	PM	26,759	79,069	9,171	1,827	**116,826**
2	SE	29,081	21,849	6,842	1,781	**59,553**
3	MA	22,773	24,982	15,793	3,045	**66,593**
4	SciTm	1,562	3,687	4,751	1,148	**11,148**
5	Pyld	49,627	23,362	15,000	2,776	**90,765**
	Mapping Spectrometer	26,208	13,226	7,625	1,380	**48,439**
	Visible Camera	5,609	2,702	1,617	333	**10,261**
	Meteorological Suite	17,810	7,434	5,759	1,063	**32,066**
	Instr PM/SE/MA					**0**
	Instr I&T/GSE					**0**
6	S/C	293,749	174,586	75,679	11,914	**555,929**
	Marscopter	134,510	76,193	44,849	8,037	**263,589**
	EDL	147,475	94,286	28,555	3,515	**273,830**
	Cruise Stage	11,764	4,107	2,276	363	**18,510**
	S/C PM/SE/MA					**0**
	S/C I&T/GSE					**0**
7/9	MOS/GDS	3,794	14,011	15,564	2,896	**36,265**
10	I&T	34,126	41,749	56,785	4,118	**136,777**
	TOTAL	**461,470**	**383,295**	**199,586**	**29,506**	**1,073,857**

Figure 13: TPXL Output Table (RY$k) for the Marscopter Case Study (In NASA Standard WBS Format by Phase)

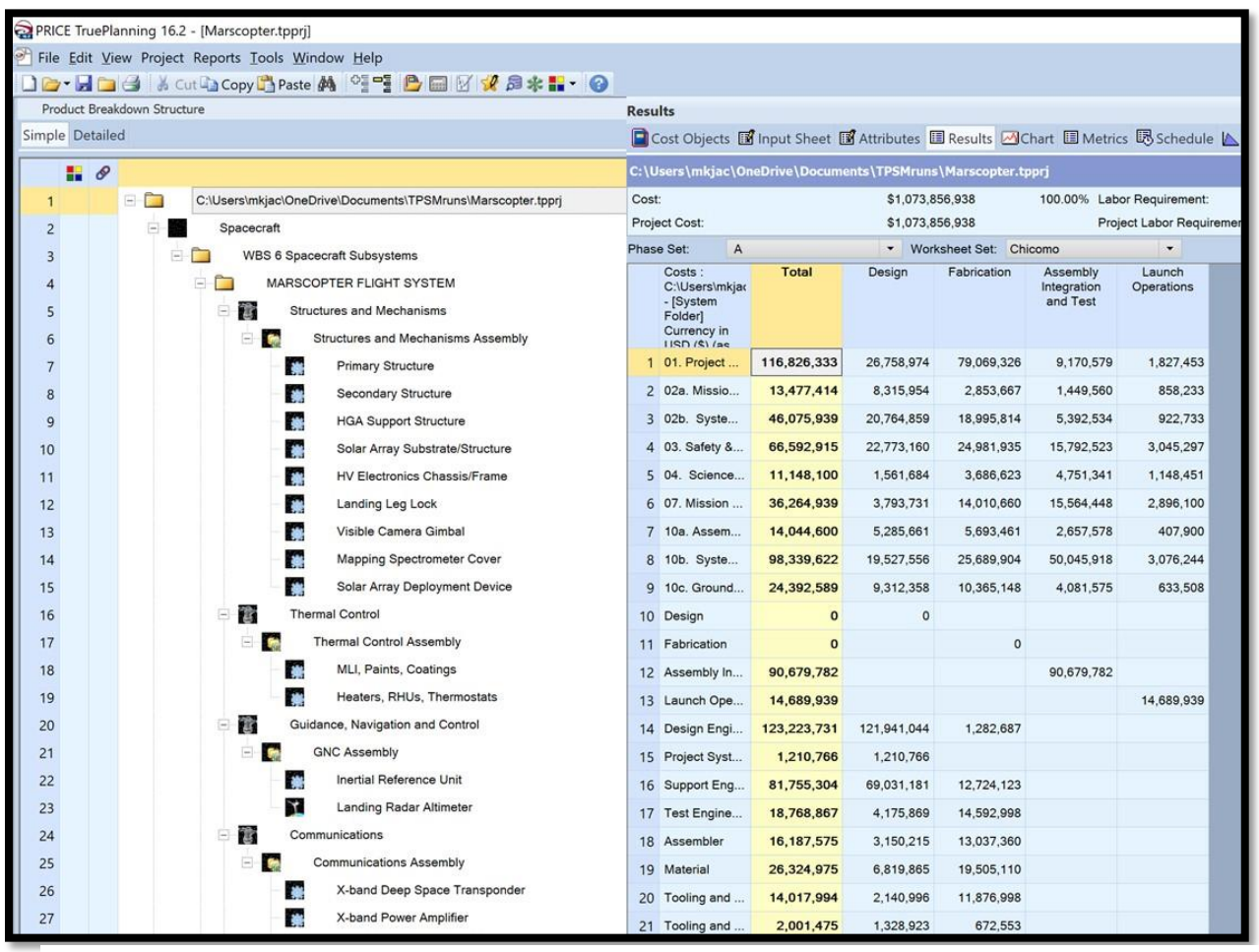


Figure 14: TruePlanning File Automatically Generated by TPXL for the Marscopter Case Study

Validation Study Results

Comparison of the Hardware Equipment Type and Space Missions Approaches / Results

To support validation, both Hardware Space Equipment Type and Space Missions Catalog were built by different people using the same mission system descriptions and MELs. The results of the different models were then compared. Figure 15 shows a comparison of the Space Equipment Type and Space Missions models for both missions. As seen on Figure 15, the results of both estimating methods compared favorably, with less than a 30% difference for the Spacecraft in the worst case LUVOT mission, and less than a 32% difference for the Payload in the worst case Marscopter mission, with an overall worst-case difference of less than 5% for the Marscopter mission. It should be noted that the Space Mission model had an advantage for the Marscopter Mission, due to the inclusion of a Parachute and Landing Radar Altimeter for which the Space Missions Catalog has devoted cost objects, whereas there is no current space equipment type for those components in the Space Equipment Type Calculator.

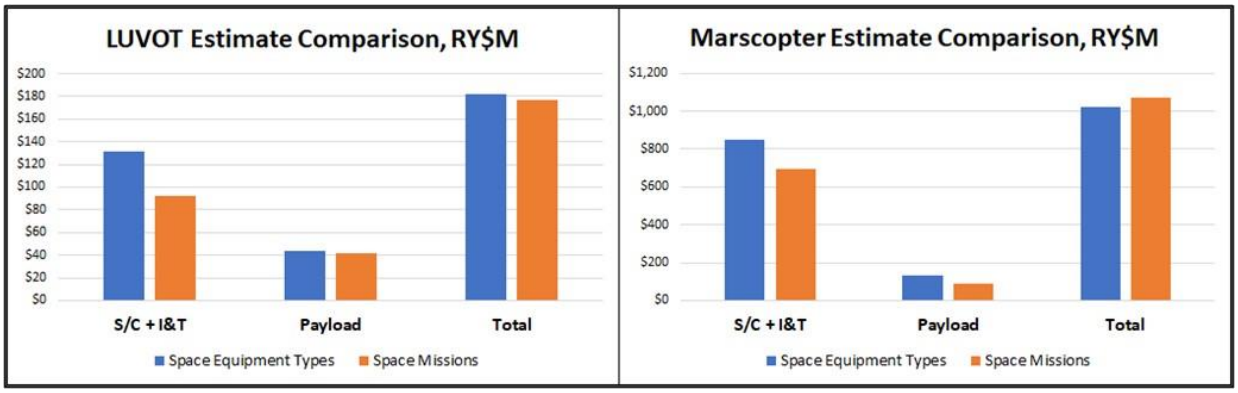


Figure 15. Comparison of Space Equipment Types and Space Missions models for the Spacecraft and Payload costs for both missions

Application Considerations

It can be noted that of the two possible approaches for estimating space missions presented in this paper, that if one is doing an estimate for NASA, or supporting a NASA project, especially for a planetary mission, that of the two approaches, the Space Mission catalog is probably the best choice, both because it does better job of estimating to the NASA Std. WBS, as well as NASA Mission Classes and includes planetary specific cost objects. Whereas, if one is estimating Earth Orbiting missions for Customers such as the Department of Defense, services / agencies, that the Space Equipment Type method may prove more useful and flexible, based on its ability to map to any WBS, including MIL-STD-881, for which mappings already exist, or any other Customer or Project WBS, in addition to the strong historical DoD Spacecraft Bus calibrations and validation behind this estimating method, and the ability to include and integrate software into any estimate. Nonetheless, both methods are generally capable of estimating any space mission as evidenced by the case studies presented in this paper, and can certainly be used as cross-checks for the other, or any other estimating method.

Validation Study Results (forthcoming)

As of this writing, additional validation studies of both estimating approaches presented in this paper are planned for later this year, as Unison is currently in the process of regaining the required NASA CADRe database access necessary to complete a though validation for NASA missions, as was done previously.

Appendix A: Case Study MELs

LUVOT:

Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, CBE	Description (Vendor, Part #, Heritage Basis)	Other characteristics/issues (volume, power, other component-specific items)
TOTAL					**485.5**		
UVOT Spacecraft					**389.4**		
Structure							
Primary Structure	90.0	1	0	0	90.0	Standard design	Aluminum
Secondary Structure	25.0	1	0	0	25.0	Standard design	Aluminum
Gimbal	15.0	1	0	0	15.0	Modified from past program	
Thermal				0			
Multi-Layer Insulation, Coatings	5.0	1	0	0	5.0	Standard materials, new design	
Heaters, Thermistors	2.0	1	0	0	2.0	Standard materials, new design	
Radiator	3.0	1	0	0	3.0	Minor mod of past design	Composite
ACS							
Coarse Sun Sensor	0.0	10	0	1	0.1		
Inertial Reference Unit	2.0	3	0	1	6.0	COTS part	
Magnetometer	0.5	2	0	1	1.0	COTS part	
Magnetic Torque Rod	1.5	3	0	1	4.5	COTS part	
Star Tracker	5.0	2	0	1	10.0	Modified COTS part	
Reaction wheels	9.0	4	0	1	36.0	Modified standard design	
Power							
Solar Array, Cells/Electrical	7.0	2	0	0	14.0	COTS cells, custom wiring	High efficiency, Multi-junction
Solar Array, Substrate/Structure	15.0	2	0	0	30.0	Modified past design	Composite
Solar Array Drives	5.0	2	0	0	10.0	Modified past design	
Battery	40.0	1	1	1	40.0	Standard cells w/ new configuration	Li-Ion, 80 Amp-hrs
Power Distribution Unit	20.0	1	0	1	20.0	Modified past design	
CDH							
Backplane	1.0	1	0	1	1.0	COTS part	
Single Board Computer	0.8	1	0	1	0.8	COTS part w/ custom software	Rad750-based
UL/DL Board	0.5	1	0	1	0.5	Modified past design	
Bus Control I/F Board	0.8	1	0	1	0.8	Modified past design	
ACS Electronics Board	0.8	1	0	1	0.8	Modified past design	
Gimbal Drive Board	0.5	1	0	1	0.5	Modified past design	
General Purpose Board	0.5	1	0	1	0.5	Modified past design	
Power Control Unit	1.0	1	0	1	1.0	Modified past design	
Solid State Recorder	5.0	1	0	1	5.0	COTS part	
Chassis	8.0	1	0	0	8.0	Modified past design	
Communications							
X-band Transponder	3.0	2	0	1	6.0	COTS part	
Solid State Power Amplifier	3.0	4	0	1	12.0	COTS part	
Antennas	1.0	4	0	1	4.0	Modified past design	
Misc RF Electronics	2.0	1	0	1	2.0	Standard design, modified COTS	
Waveguides/misc	5.0	1	0	1	5.0	Standard design, modified COTS	
Harness	30.0	1	0	0	30.0	Custom harness, modified design	

Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, CBE	Description (Vendor, Part #, Heritage Basis)	Other characteristics/issues (volume, power, other component-specific items)
UV Optical Telescope					**96.1**		
Telescope Optical Assembly							
Primary mirror	1.3	4	0	1	5.0	Lightweighted design, Adv Mat'l	25cm diameter
Primary mirror mounts	0.5	4	0	1	2.0	Modified past design	Titanium
Secondary mirror	0.8	4	0	1	3.0	Lightweighted design, Adv Mat'l	12cm diameter
Secondary mirror mounts	0.3	4	0	1	1.0	Modified past design	Titanium
Detectors & Electronics							
Detectors, CCDs	1.0	4	4	4	4.0	CCDMart Part # 2021	
Readout Electronics	1.0	4	1	1	4.0	Modified Past Design	
Focal Plane Asembly Housing	1.5	4	1	1	6.0		Aluminum
Filter Wheel Assembly							
Entrance filters assembly	0.5	4	1	1	2.0	Minor mod from past design	
Filter wheel mechanism	0.8	4	1	1	3.0	Minor mod from past design	
shutter	0.5	4	1	1	2.0	Minor mod from past design	
baffles	0.5	4	1	1	2.0	Minor mod from past design	
secondary mirror	0.5	4	1	1	2.0	Minor mod from past design	
focus mechanism	0.3	4	1	1	1.0	Minor mod from past design	
image motion compensation actuators	2.0	4	1	1	8.0	Minor mod from past design	
Structure, Mechanical, Thermal							
door Assembly	0.8	4	1	1	3.0	Minor mod from past design	
door hinge assembly	0.5	4	1	1	2.0	Minor mod from past design	
aperture selector	0.5	1	1	1	0.5	COTS part	
Telescope Tube	4.0	4	1	1	16.0	New design	Composite
spider structure	0.8	4	1	1	3.0	Standard parts/processes, custom design	
heaters	0.4	4	1	1	1.6	Standard parts/processes, custom design	
telescope harnessing	0.5	4	1	1	2.0	Standard parts/processes, custom design	
kinematic mounts	0.8	12	3	3	9.0	Minor mod from past design	Aluminum
Electronics Box							
Control Electronics	0.5	1	0	1	0.5	COTS part w/ custom software	Rad750-based
Power Management	1.0	1	0	1	1.0	Modified past design	
power switching card	1.0	1	0	1	1.0	Modified past design	
PCI backplane	0.5	1	0	1	0.5	COTS part	
housing	7.0	1	0	1	7.0		Aluminum
Harnessing	4.0	1	0	1	4.0	Custom harness, new design	

Marscopter:

Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, CBE	Contingency %	Total Mass w/ Contingency	Description (Vendor, Part #, Heritage Basis)	Other characteristics/issues (volume, power, other component-specific items)
TOTAL					**2,228.9**				
FLIGHT SYSTEM					**1,625.8**				
Mars Helicopter/Lander					**515.2**				
Structure/Mechanical									
Primary Structure	35.0								
Top Deck	4.0	1	0	0	4.0			Custom design, standard materials/processes	Composite
Bottom Deck	4.0	1	0	0	4.0			Custom design, standard materials/processes	Composite
Struts	3.0	6	0	0	18.0			Custom design, standard materials/processes	Composite
Landing Legs	3.0	3	0	0	9.0			Custom design, standard materials/processes	Composite
Secondary Structures	24.0								
Brackets/Mounts	18.0	1	0	0	18.0			Custom design, standard materials/processes	Composite
Fasteners	6.0	1	0	0	6.0			Custom design, standard materials/processes	Titanium
Mechanisms	30.0								
Landing Leg Lock	4.0	3	0	0	12.0			Custom design, standard materials/processes	Aluminum
Visible Camera Gimbal	6.0	1	0	0	6.0			Custom design, standard materials/processes	Aluminum
Mapping Spectrometer Cover	6.0	1	0	0	6.0			Custom design, standard materials/processes	Aluminum
Solar Array Deployment Device	3.0	2	0	0	6.0			Custom design, standard materials/processes	Aluminum
Thermal Control									
Multi-Layer Insulation, Coatings, etc	10.0	1	0	0	10.0			Custom design, standard materials/processes	
Heaters	3.0	1	0	0	3.0			Custom design, standard materials/processes	
Power									
Solar Arrays	62.5								
SA Cells/Electrical	20.8	2	0	0	41.7			COTS cells, custom wiring	High efficiency, Multi-junction
SA Substrate/Mechanical	10.4	2	0	0	20.8			Modified past design	Composite
Battery	200.0	1	1	1	200.0			Standard cells w/ new configuration	400 Amp-hr Li-ion
Power Supplies	8.0	1	0	1	8.0			Custom design, changes for HV operation	
Power Management & Distribution	8.0	1	0	1	8.0			Custom design, changes for HV operation	
High Voltage Box	16.0								
HV Power Conversion System	9.0	1	0	1	9.0			Custom design, changes for HV operation	
HV Chassis/Frame	7.0	1	0	1	7.0			Custom design, standard materials/processes	Aluminum
Harnesses	30.0	1	0	0	30.0			Custom harness, modified design	
Guidance, Navigation, & Control									
Inertial Measurement Unit	5.0	2	0	1	10.0			Modified COTS part	
Landing Altimeter	10.0	2	1	1	20.0			Custom design, changes for unique application	
Command & Data Handling									
RAD750 Single Board Computer	0.5	1	0	1	0.5			COTS part w/ application-specific software	Rad750-based
Payload Interface Card	0.5	1	0	1	0.5			Modified past design	
Other Cards	0.5	4	0	4	2.0			Modified past designs	
Communications									
X-band Deep Space Transponder	4.0	2	0	1	8.0			COTS part	
Solid State Power Amplifier	3.0	2	0	1	6.0			COTS part	
High Gain Antenna	12.0								
HGA Dish	8.0	1	0	1	8.0			Modified past design	
HGA Support Structure	4.0	1	0	1	4.0			Modified past design	Composite
Low Gain Antennas	0.4	3	0	1	1.2			COTS part	
Misc RF Electronics	1.0	1	0	1	1.0			Modified design, standard materials/processes	
Waveguides	2.5	1	0	1	2.5			Modified design, standard materials/processes	
Helicopter									
Rotors	1.0	4	0	1	4.0			Custom lightweight design	Advanced composite
Rotors Support Structure	0.5	4	0	1	2.0			Custom housings	Titanium
Motor	4.0	4	1	1	16.0			Custom motor, New design	New technology
Motor Controller	3.0								
Motor Controller Electronics	2.0	1	0	1	2.0			Custom cards with heritage/modified devices	Rad750-based
Motor Controller Chassis/Box	1.0	1	0	1	1.0				Aluminum

Subsystem/Component	Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, CBE	Contingency %	Total Mass w/ Contingency	Description (Vendor, Part #, Heritage Basis)	characteristics/issues (volume, power, other component-specific items)
EDL Assembly					**940.0**				
Structures & Mechanisms									
Mini Sky Crane Primary Structure	150.0	1	0	0	150.0			Scaled-down heritage design	Aluminum
Mini Sky Crane Secondary Structure	50.0	1	0	0	50.0			Scaled-down heritage design	Aluminum
Heatshield Structure	75.0	1	0	0	75.0			Scaled-down heritage design	Aluminum
Heatshield TPS	300.0	1	0	0	300.0			Scaled-down heritage design	
Backshell Structure	50.0	1	0	0	50.0			Scaled-down heritage design	Aluminum
Backshell TPS	150.0	1	0	0	150.0			Scaled-down heritage design	
Parachute (w/ mortar)	75.0	1	1	1	75.0			Scaled-down heritage design	
Propulsion									
Thrusters	2.0	12	0	0	24.0			Multiple landing thruster clusters, COTS	
Propellant Tanks	25.0	2	0	0	50.0			Multiple custom tanks (for balance)	Titanium
Propulsion Lines/Valves/Filters	10.0	1	0	0	10.0			Modified design, standard materials/processes	
Avionics									
Inertial Measurement Unit	5.0	1	0	1	5.0			Modified COTS device	
Single Board Computer	1.0	1	0	1	1.0			COTS part w/ custom software	Rad750-based
Cruise Stage					**170.6**				
Structures & Mechanisms									
Primary Structure	75.0	1	0	0	75.0			Scaled heritage design	Aluminum-honeycomb panels
Secondary Structure	10.0	1	0	0	10.0			Scaled heritage design	
Mechansims	15.0	1	0	0	15.0			COTS devices	
Balance Mass	5.0	1	0	0	5.0				Aluminum
Thermal Control									
MLI, Coatings	8.00	1	0	0	8.0			Modified design, standard materials/processes	
Temperature Sensors	0.20	10	0	0	2.0			Modified design, standard materials/processes	
Propulsion									
Fuel Tank	8.00	4	0	0	32.0			Mono-prop fuel tank	Titanium
TCM Thrusters	0.60	4	0	0	2.4			COTS items	
ACS Thrusters	0.40	8	0	0	3.2			COTS items	
Valves/Filters	3.00	1	0	0	3.0			Modified design, standard materials/processes	
Pressure Transducer	0.25	2	0	0	0.5			Modified design, standard materials/processes	
TCM Thruster Brackets	0.13	4	0	0	0.5			Modified design, standard materials/processes	
ACS Thruster Brackets	0.25	8	0	0	2.0			Modified design, standard materials/processes	
Brackets, Tubes, Fittings, etc	12.00	1	0	0	12.0			Modified design, standard materials/processes	

Subsystem/Component	Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, CBE	Contingency %	Total Mass w/ Contingency	Description (Vendor, Part #, Heritage Basis)	characteristics/issues (volume, power, other component-specific items)
PAYLOAD					**87.9**				
Mapping Spectrometer					**70.5**				
Spectrometer Assembly									
Optical elements	5.0	1	0	1	5.0			Optics use advanced materials/coatings w/ heritage	
Grating	2.0	1	0	1	2.0			Modified past design	
Filters	2.0	1	0	1	2.0			Modified past design	
Sensor, CCD	0.5	4	0	1	2.0			CCDMart Part # 1969	
Telescope Assembly									
Main Body	10.0	1	0	1	10.0			Custom design, heritage processes/materials	Composite
Baffles	5.0	1	0	1	5.0			Modified past design	
Primary Mirror	4.0	1	0	1	4.0			Modified past design	
Scan Mirror									
Scan Mirror Optics	2.0	1	0	1	2.0			Modified past design	Standard optics
Scan Mirror Actuator	1.0	1	0	1	1.0			Modified past design	
Telescope Secondary Structure	5.0	1	0	1	5.0			Custom designs, heritage processes/materials	Composite
Scan Platform									
Scan Platform Structure	5.0	1	0	1	5.0			Custom design, heritage processes/materials	Composite
Scan Platform Motor	5.0	1	0	1	5.0			Modified past design	
Scan Platform electronics	2.5	1	0	1	2.5			Modified past design	Standard microprocessor
Scan Platform cabling	1.0	1	0	1	1.0			Modified past design	
Thermal Control									
Multi-Layer Insulation/Coatings	4.0	1	0	1	4.0			Standard materials, new design	
Radiator	2.0	1	0	1	2.0			Custom design, heritage processes/materials	Composite
Temperature Sensors	1.0	1	0	1	1.0			Standard materials, new design	
Command & Data Handling									
Read-Out Electronics	1.0	1	0	1	1.0			Modified COTS item with custom software	
Solid-state Memory	1.0	1	0	1	1.0			COTS item	
CDH Chassis	2.0	1	0	1	2.0			Modified past design	Aluminum
Power									
Power Supplies	2.0	1	0	1	2.0			Modified past design	
Power Management & Distribution	2.0	1	0	1	2.0			Modified past design	
Harnessing	4.0	1	0	1	4.0			Custom harness, new design	
Visible Camera					**7.9**				
Housing	4.0	1	0	1	4.0			Custom design, heritage processes/materials	Composite
Primary Optic	2.0	1	0	1	2.0			Modified past design	
Secondary Optics	0.5	1	0	1	0.5			Modified past design	
Detector, CCD	0.4	1	0	1	0.4			CCDMart Part # 1963	
Readout electronics	0.5	1	0	1	0.5			COTS item with custom programming	
Visible Camera Internal Harnessing	0.5	1	0	1	0.5			Modified past design	
Meteorological Suite					**9.5**				
Sensors									
Temperature Sensor	0.5	2	0	1	1.0			Modified past design	
Wind Sensor	0.5	2	0	1	1.0			Modified past design	
Pressure Sensor	0.5	2	0	1	1.0			Modified past design	
Seismometer	0.5	2	0	1	1.0			Custom design with new technology	
Electronics									
Readout Electronics	1.0	1	0	1	1.0			Modified past design	
Power Conditioning	1.5	1	0	1	1.5			Modified past design	
Power									
Power Conditioning	2.0	1	0	1	2.0			Modified past design	
Harnessing	1.0	1	0	1	1.0			Custom harness, new design	

Appendix B: Case Study TPXL Inputs

LUVOT:

PAYLOAD TOTAL					**96.1**					
SPACECRAFT TOTAL					**389.4**					
FLIGHT SYSTEM TOTAL					**485.5**					
		# OF UNITS			HARDWAR	TPSM COST MODEL INPUTS				
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, CBE	Heritage	New or Advanced Tech	Subsys	Comp	Type
LUVOT Spacecraft					**389.4**					
Structure					**130.0**					
Primary Structure	90.0	1	0	0	90.0	Minor Mod		Structure and Mechanisms	Primary Structure	1
Secondary Structure	25.0	1	0	0	25.0	Minor Mod		Structure and Mechanisms	Secondary Structure	1
Gimbal	15.0	1	0	0	15.0	Minor Mod		Structure and Mechanisms	Gimbals	1
Thermal					**10.0**					
Multi-Layer Insulation, Coatings	5.0	1	0	0	5.0	New		Thermal Control	MLI, Paints, Coatings	1
Heaters, Thermistors	2.0	1	0	0	2.0	New		Thermal Control	Heaters, RHUs, Thermostats	3
Radiator	3.0	1	0	0	3.0	Minor Mod		Thermal Control	Radiators/Louvers	4
ACS					**57.6**					
Coarse Sun Sensor	0.0	10	0	1	0.1	Copy		Guidance, Navigation and Cont	Sun Sensor	2
Inertial Reference Unit	2.0	3	0	1	6.0	Copy		Guidance, Navigation and Cont	IMU-Gyro	1
Magnetometer	0.5	2	0	1	1.0	Copy		Sensor Systems	Magnetometer	1
Magnetic Torque Rod	1.5	3	0	1	4.5	Copy		Guidance, Navigation and Cont	Torque Rod	1
Star Tracker	5.0	2	0	1	10.0	Minor Mod		Guidance, Navigation and Cont	Star Tracker	2
Reaction wheels	9.0	4	0	1	36.0	Minor Mod		Guidance, Navigation and Cont	Reaction Wheel	1
Power					**114.0**					
Solar Array, Cells/Electrical	7.0	2	0	0	14.0	Minor Mod		Power	Solar Cells/Electrical	3
Solar Array, Substrate/Structure	15.0	2	0	0	30.0	Minor Mod		Structure and Mechanisms	Solar Array Substrate/Structure	4
Solar Array Drives	5.0	2	0	0	10.0	Minor Mod		Guidance, Navigation and Cont	Actuators	1
Battery	40.0	1	1	1	40.0	Minor Mod		Power	Batteries 1	3
Power Distribution Unit	20.0	1	0	1	20.0	Minor Mod		Power	Power Management and Distribution	2
CDH					**18.8**					
Backplane	1.0	1	0	1	1.0	Copy		Command and Data Handling	Command/Data Processing 8	1
Single Board Computer	0.8	1	0	1	0.8	Minor Mod		Command and Data Handling	Command/Data Processing 1	3
UL/DL Board	0.5	1	0	1	0.5	Minor Mod		Command and Data Handling	Command/Data Processing 2	2
Bus Control I/F Board	0.8	1	0	1	0.8	Minor Mod		Command and Data Handling	Command/Data Processing 3	2
ACS Electronics Board	0.8	1	0	1	0.8	Minor Mod		Command and Data Handling	Command/Data Processing 4	2
Gimbal Drive Board	0.5	1	0	1	0.5	Minor Mod		Command and Data Handling	Command/Data Processing 5	2
General Purpose Board	0.5	1	0	1	0.5	Minor Mod		Command and Data Handling	Command/Data Processing 6	2
Power Control Unit	1.0	1	0	1	1.0	Minor Mod		Command and Data Handling	Command/Data Processing 7	2
Solid State Recorder	5.0	1	0	1	5.0	Copy		Command and Data Handling	Solid State Memory 1	3
Chassis	8.0	1	0	0	8.0	Minor Mod		Structure and Mechanisms	Electronics Boxes	1
Communications					**29.0**					
X-band Transponder	3.0	2	0	1	6.0	Copy		Communications	Transponder 1	3
Solid State Power Amplifier	3.0	4	0	1	12.0	Copy		Communications	Amplifier 1	3
Antennas	1.0	4	0	1	4.0	Minor Mod		Communications	edium Gain Antenna/Low Gain Anten	3
Misc RF Electronics	2.0	1	0	1	2.0	Minor Mod		Communications	Miscellaneous RF Electronics	3
Waveguides/misc	5.0	1	0	1	5.0	Minor Mod		Communications	Waveguides - Comm Cabling	3
Harness	**30.0**	**1**	**0**	**0**	**30.0**	Major Mod		Power	Power Harness/Cabling	1

	Phase B start	PDR [1]	CDR	Deliver to System I&T	Ship to Launch Site	Launch	On-Orbit Chect-Out (L+30d)
Project	1/2/2022	11/17/2022	10/2/2023	10/1/2024	4/2/2026	8/1/2026	8/31/2026
LUVOT Spacecraft	1/2/2022	11/17/2022	10/2/2023	10/1/2024	4/2/2026	8/1/2026	8/31/2026
UVOT Telescope Optical	1/2/2022	11/17/2022	10/2/2023	10/1/2024	4/2/2026	8/1/2026	8/31/2026
Detectors/Electronics	1/2/2022	11/17/2022	10/2/2023	10/1/2024	4/2/2026	8/1/2026	8/31/2026
Filter Wheel Assembly	1/2/2022	11/17/2022	10/2/2023	10/1/2024	4/2/2026	8/1/2026	8/31/2026
Structure, Mechanical, &	1/2/2022	11/17/2022	10/2/2023	10/1/2024	4/2/2026	8/1/2026	8/31/2026
UVOT Electronics Box	1/2/2022	11/17/2022	10/2/2023	10/1/2024	4/2/2026	8/1/2026	8/31/2026
Harness	1/2/2022	11/17/2022	10/2/2023	10/1/2024	4/2/2026	8/1/2026	8/31/2026

Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	# OF UNITS Flight Units	Flight Spares	EMs & Proto-types	HARDWAR Total Mass, CBE	TPSM COST MODEL INPUTS Heritage	New or Advanced Tech	Subsys	Comp	Type
UVOT Telescope Optical Assembly					**11.00**					
Primary mirror	1.25	4	0	1	5.00	Major Mod		Optics	Optics	3
Primary mirror mounts	0.50	4	0	1	2.00	Minor Mod		Optics	Optical Bench	3
Secondary mirror	0.75	4	0	1	3.00	Major Mod		Optics	Optics	3
Secondary mirror mounts	0.25	4	0	1	1.00	Minor Mod		Optics	Optical Bench	3
Detectors/Electronics					**14.00**					
Detectors, CCDs	1.00	4	4	4	4.00	Copy		Sensor Systems	arge Coupled Device Detect	2
Readout Electronics	1.00	4	1	1	4.00	Minor Mod		Sensor Systems	Read Out Electronics	2
Focal Plane Asembly Housing	1.50	4	1	1	6.00	New		Structure and Mechar	Electronics Boxes	1
Filter Wheel Assembly					**20.00**					
Entrance filters assembly	0.50	4	1	1	2.00	Minor Mod		Optics	Optic Filters/Miscellaneous	2
Filter wheel mechanism	0.75	4	1	1	3.00	Minor Mod		Structure and Mechar	Mechanisms	2
shutter	0.50	4	1	1	2.00	Minor Mod		Optics	Optic Filters/Miscellaneous	2
baffles	0.50	4	1	1	2.00	Minor Mod		Optics	Optic Filters/Miscellaneous	2
secondary mirror	0.50	4	1	1	2.00	Minor Mod		Optics	Optics	2
focus mechanism	0.25	4	1	1	1.00	Minor Mod		Guidance, Navigation and	Actuators	1
image motion compensation actuators	2.00	4	1	1	8.00	Minor Mod		Guidance, Navigation and	Actuators	1
Structure, Mechanical, & Thermal					**37.10**					
door Assembly	0.75	4	1	1	3.00	Minor Mod		Structure and Mechar	Mechanisms	2
door hinge assembly	0.50	4	1	1	2.00	Minor Mod		Structure and Mechar	Mechanisms	2
aperture selector	0.50	1	1	1	0.50	Copy		Optics	Optic Filters/Miscellaneous	2
Telescope Tube	4.00	4	1	1	16.00	New		Optics	Optical Bench	4
spider structure	0.75	4	1	1	3.00	Major Mod		Structure and Mechar	Mechanisms	2
heaters	0.40	4	1	1	1.60	Major Mod		Thermal Control	Heaters, RHUs, Thermostats	3
telescope harnessing	0.50	4	1	1	2.00	Major Mod		Power	Power Harness/Cabling	1
kinematic mounts	0.75	12	3	3	9.00	Minor Mod		Structure and Mechar	Secondary Structure	1
UVOT Electronics Box					**10.00**					
Control Electronics	0.50	1	0	1	0.50	Minor Mod		Command and Data H	Command/Data Processing	3
Power Management	1.00	1	0	1	1.00	Minor Mod		Power	er Management and Distribu	2
power switching card	1.00	1	0	1	1.00	Minor Mod		Command and Data H	Command/Data Processing	2
PCI backplane	0.50	1	0	1	0.50	Copy		Command and Data H	Command/Data Processing	1
housing	7.00	1	0	1	7.00	Minor Mod		Structure and Mechar	Electronics Boxes	1
Harness					**4.00**					
Harnessing	4.00	1	0	1	4.00	New		Power	Power Harness/Cabling	1

	Platform ("EO" or "P")	Parts Class (S,S1,B,B1, B2,D)	International ("Y" or "N")	Contracting Fee	Contract Monitor Burden	# of Flight Units	Notes	Mission Class
LUVOT Spacecraft	P	B	N			1		Class C/D
UVOT Telescope Optical Assemb	P	S1	N			1		Class C/D
Detectors/Electronics	P	S1	N			1		
Filter Wheel Assembly	P	S1	N			1		
Structure, Mechanical, & Therm	P	S1	N			1		
UVOT Electronics Box	P	S1	N			1		
Harness	P	S1	N			1		

Marscopter:

PAYLOAD TOTAL					**87.90**					
SPACECRAFT TOTAL					**######**					
FLIGHT SYSTEM TOTAL					**######**					
		# OF UNITS			HARDWARE	TPSM COST MODEL INPUTS				
Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	Flight Units	Flight Spares	EMs & Proto-types	Total Mass, CBE	Heritage	New or Advanced Tech	Subsys	Comp	Type
Marscopter					**515.20**					
Structure/Mechanical										
Primary Structure										
Top Deck	4.00	1	0	0	4.0	New		Structure and Mechanisms	Primary Structure	4
Bottom Deck	4.00	1	0	0	4.0	New		Structure and Mechanisms	Primary Structure	4
Struts	3.00	6	0	0	18.0	New		Structure and Mechanisms	Primary Structure	4
Landing Legs	3.00	3	0	0	9.0	New		Structure and Mechanisms	Primary Structure	4
Secondary Structures										
Brackets/Mounts	18.00	1	0	0	18.0	New		Structure and Mechanisms	Secondary Structure	4
Fasteners	6.00	1	0	0	6.0	New		Structure and Mechanisms	Secondary Structure	4
Mechanisms										
Landing Leg Lock	4.00	3	0	0	12.0	New		Structure and Mechanisms	Mechanisms	1
Visible Camera Gimbal	6.00	1	0	0	6.0	New		Structure and Mechanisms	Mechanisms	2
Mapping Spectrometer Cover	6.00	1	0	0	6.0	New		Structure and Mechanisms	Mechanisms	1
Solar Array Deployment Device	3.00	2	0	0	6.0	New		Structure and Mechanisms	Mechanisms	2
Thermal Control										
Multi-Layer Insulation, Coatings, etc	10.00	1	0	0	10.0	Minor Mod		Thermal Control	MLI, Paints, Coatings	1
Heaters	3.00	1	0	0	3.0	Minor Mod		Thermal Control	Heaters, RHUs, Thermostats	3
Power										
Solar Arrays										
SA Cells/Electrical	20.83	2	0	0	41.7	Minor Mod		Power	Solar Cells/Electrical	3
SA Substrate/Mechanical	10.42	2	0	0	20.8	Minor Mod		Structure and Mechanisms	Solar Array Substrate/Structure	4
Battery	200.00	1	1	1	200.0	Major Mod		Power	Batteries 1	3
Power Supplies	8.00	1	0	1	8.0	Major Mod	New	Power	Power Management and Distribution	3
Power Management & Distribution	8.00	1	0	1	8.0	Major Mod	New	Power	Power Management and Distribution	3
High Voltage Box										
HV Power Conversion System	9.00	1	0	1	9.0	New	New	Power	Power Management and Distribution	3
HV Chassis/Frame	7.00	1	0	1	7.0	Minor Mod		Structure and Mechanisms	Electronics Boxes	1
Harnesses	30.00	1	0	0	30.0	Major Mod		Power	Power Harness/Cabling	1
Guidance, Navigation, & Control										
Inertial Measurement Unit	5.00	2	0	1	10.0	Minor Mod		Guidance, Navigation and Cont	IMU-Gyro	1
Landing Altimeter	10.00	2	1	1	20.0	New		Guidance, Navigation and Cont	Space Radar Altimeter	1
Command & Data Handling										
RAD750 Single Board Computer	0.50	1	0	1	0.5	Minor Mod	New	Command and Data Handling	Command/Data Processing 1	3
Payload Interface Card	0.50	1	0	1	0.5	Minor Mod		Command and Data Handling	Command/Data Processing 2	2
Other Cards	0.50	4	0	4	2.0	Minor Mod		Command and Data Handling	Command/Data Processing 3	2
Communications										
X-band Deep Space Transponder	4.00	2	0	1	8.0	Minor Mod		Communications	Transponder 1	3
Solid State Power Amplifier	3.00	2	0	1	6.0	Minor Mod		Communications	Amplifier 1	3
High Gain Antenna										
HGA Dish	8.00	1	0	1	8.0	Minor Mod		Communications	High Gain Antenna	3
HGA Support Structure	4.00	1	0	1	4.0	Minor Mod		Structure and Mechanisms	High Gain Antenna Structure	4
Low Gain Antennas	0.40	3	0	1	1.2	Minor Mod		Communications	edium Gain Antenna/Low Gain Anten	3
Misc RF Electronics	1.00	1	0	1	1.0	Minor Mod		Communications	Miscellaneous RF Electronics	3
Waveguides	2.50	1	0	1	2.5	Minor Mod		Communications	Waveguides - Comm Cabling	3
Helicopter										
Rotors	1.00	4	0	1	4.0	New	New	Structure and Mechanisms	Primary Structure	4
Rotors Support Structure	0.50	4	0	1	2.0	New		Structure and Mechanisms	Secondary Structure	3
Motor	4.00	4	1	1	16.0	New	New	Structure and Mechanisms	Motor-Actuator	3
Motor Controller										
Motor Controller Electronics	2.00	1	0	1	2.0	Major Mod		Command and Data Handling	Command/Data Processing 1	3
Motor Controller Chassis/Box	1.00	1	0	1	1.0	Minor Mod		Structure and Mechanisms	Electronics Boxes	1

EDL					**940.00**					
Structures & Mechanisms										
Mini Sky Crane Primary Structure	150.00	1	0	0	150.0	Major Mod		Structure and Mechanisms	Secondary Structure	1
Mini Sky Crane Secondary Structure	50.00	1	0	0	50.0	Major Mod		Structure and Mechanisms	Secondary Structure	1
Heatshield Structure	75.00	1	0	0	75.0	Major Mod		Structure and Mechanisms	Secondary Structure	1
Heatshield TPS	300.00	1	0	0	300.0	Minor Mod		Structure and Mechanisms	TPS	1
Backshell Structure	50.00	1	0	0	50.0	Major Mod		Structure and Mechanisms	Secondary Structure	1
Backshell TPS	150.00	1	0	0	150.0	Minor Mod		Structure and Mechanisms	TPS	1
Parachute (w/ mortar)	75.00	1	1	1	75.0	Major Mod		Structure and Mechanisms	Parachute	1
Propulsion										
Thrusters	2.00	12	0	0	24.0	Copy		Propulsion	Thrusters 1	3
Propellant Tanks	25.00	2	0	0	50.0	New		Propulsion	Tanks 1	3
Propulsion Lines/Valves/Filters	10.00	1	0	0	10.0	Major Mod		Propulsion	Propulsion - Lines/Valves/Fittings	3
Avionics										
Inertial Measurement Unit	5.00	1	0	1	5.0	Minor Mod		Guidance, Navigation and Cont	IMU-Gyro	1
Single Board Computer	1.00	1	0	1	1.0	Minor Mod		Command and Data Handling	Command/Data Processing 1	3

Cruise Stage					**170.60**					
Structures & Mechanisms										
Primary Structure	75.00	1	0	0	75.0	Minor Mod		Structure and Mechanisms	Primary Structure	1
Secondary Structure	10.00	1	0	0	10.0	Minor Mod		Structure and Mechanisms	Secondary Structure	1
Mechansims	15.00	1	0	0	15.0	Copy		Structure and Mechanisms	Mechanisms	1
Balance Mass	5.00	1	0	0	5.0	Minor Mod		Structure and Mechanisms	Secondary Structure	1
Thermal Control										
MLI, Coatings	8.00	1	0	0	8.0	Major Mod		Thermal Control	MLI, Paints, Coatings	1
Temperature Sensors	0.20	10	0	0	2.0	Major Mod		Thermal Control	Heaters, RHUs, Thermostats	3
Propulsion										
Fuel Tank	8.00	4	0	0	32.0	Copy		Propulsion	Tanks 1	3
Trajectory Correction Maneuver thrusters	0.60	4	0	0	2.4	Copy		Propulsion	Thrusters 1	3
Attitude Control System thrusters	0.40	8	0	0	3.2	Copy		Propulsion	Thrusters 2	3
Valves/Filters	3.00	1	0	0	3.0	Major Mod		Propulsion	Propulsion - Lines/Valves/Fittings	3
Pressure Transducer	0.25	2	0	0	0.5	Major Mod		Propulsion	Pressure Regulator - Transducer	3
TCM Thruster Brackets	0.13	4	0	0	0.5	Major Mod		Structure and Mechanisms	Secondary Structure	1
ACS Thruster Brackets	0.25	8	0	0	2.0	Major Mod		Structure and Mechanisms	Secondary Structure	1
Brackets, Tubes, Fittings, etc	12.00	1	0	0	12.0	Major Mod		Propulsion	Propulsion - Lines/Valves/Fittings	3

	Phase B start	PDR [1]	CDR	Deliver to System I&T	Ship to Launch Site	Launch	On-Orbit Chect-Out (L+30d)
Project	1/2/2022	4/3/2023	7/2/2024	1/1/2026	10/1/2027	1/31/2028	3/1/2028
Marscopter	1/2/2022	4/3/2023	5/17/2024	12/16/2025	10/1/2027	1/31/2028	3/1/2028
EDL	1/2/2022	4/3/2023	6/2/2024	12/16/2025	10/1/2027	1/31/2028	3/1/2028
Cruise Stage	1/2/2022	4/3/2023	5/2/2024	12/16/2025	10/1/2027	1/31/2028	3/1/2028
Mapping Spectrometer	1/2/2022	4/3/2023	4/2/2024	12/1/2025	10/1/2027	1/31/2028	3/1/2028
Visible Camera	1/2/2022	4/3/2023	4/2/2024	12/1/2025	10/1/2027	1/31/2028	3/1/2028
Meteorological Suite	1/2/2022	4/3/2023	4/2/2024	12/1/2025	10/1/2027	1/31/2028	3/1/2028

	Platform ("EO" or "P")	Parts Class (S,S1,B,B1, B2,D)	International ("Y" or "N")	Contracting Fee	Contract Monitor Burden	# of Flight Units	Notes	Mission Class
Marscopter	P	S1	N			1		Class A/B
EDL	P	S1	N			1		
Cruise Stage	P	S1	N			1		
Mapping Spectrometer	P	S1	N			1		Class A/B
Visible Camera	P	S1	N			1		
Meteorological Suite	P	S1	N			1		

Subsystem/Component	Unit Mass, Current Best Estimate (CBE)	# OF UNITS Flight Units	Flight Spares	EMs & Proto-types	HARDWAR Total Mass, CBE	TPSM COST MODEL INPUTS Heritage	New or Advanced Tech	Subsys	Comp	Type
Mapping Spectrometer					**70.50**					
Spectrometer Assembly										
Optical elements	5.00	1	0	1	5.00	Major Mod		Optics	Optics	3
Grating	2.00	1	0	1	2.00	Minor Mod		Optics	Optic Filters/Miscellaneous	2
Filters	2.00	1	0	1	2.00	Minor Mod		Optics	Optic Filters/Miscellaneous	2
Sensor, CCD	0.50	4	0	1	2.00	Copy		Sensor Systems	arge Coupled Device Detect	3
Telescope Assembly										
Main Body	10.00	1	0	1	10.00	New		Optics	Optical Bench	4
Baffles	5.00	1	0	1	5.00	Minor Mod		Optics	Optic Filters/Miscellaneous	2
Primary Mirror	4.00	1	0	1	4.00	Minor Mod		Optics	Optics	3
Scan Mirror										
Scan Mirror Optics	2.00	1	0	1	2.00	Minor Mod		Optics	Optics	2
Scan Mirror Actuator	1.00	1	0	1	1.00	Minor Mod	Guidance, Navigation an		Actuators	1
Telescope Secondary Structure	5.00	1	0	1	5.00	New	Structure and Mechar		Secondary Structure	4
Scan Platform										
Scan Platform Structure	5.00	1	0	1	5.00	New	Structure and Mechar		Primary Structure	4
Scan Platform Motor	5.00	1	0	1	5.00	Minor Mod	Structure and Mechar		Motor-Actuator	2
Scan Platform electronics	2.50	1	0	1	2.50	Minor Mod	Command and Data H		ommand/Data Processing	2
Scan Platform cabling	1.00	1	0	1	1.00	Minor Mod		Power	Power Harness/Cabling	1
Thermal Control										
Multi-Layer Insulation/Coatings	4.00	1	0	1	4.00	New		Thermal Control	MLI, Paints, Coatings	1
Radiator	2.00	1	0	1	2.00	New		Thermal Control	Radiators/Louvers	4
Temperature Sensors	1.00	1	0	1	1.00	New		Thermal Control	Heaters, RHUs, Thermostats	3
Command & Data Handling										
Read-Out Electronics	1.00	1	0	1	1.00	Major Mod		Sensor Systems	Read Out Electronics	3
Solid-state Memory	1.00	1	0	1	1.00	Copy	Command and Data Ha		Solid State Memory 1	3
CDH Chassis	2.00	1	0	1	2.00	Minor Mod	Structure and Mechar		Electronics Boxes	1
Power										
Power Supplies	2.00	1	0	1	2.00	Major Mod		Power	er Management and Distribu	2
Power Management & Distribution	2.00	1	0	1	2.00	Major Mod		Power	er Management and Distribu	2
Harnessing	4.00	1	0	1	4.00	New		Power	Power Harness/Cabling	1
Visible Camera					**7.90**					
Housing	4.00	1	0	1	4.00	New		Optics	Optical Bench	4
Primary Optic	2.00	1	0	1	2.00	Minor Mod		Optics	Optics	2
Secondary Optics	0.50	1	0	1	0.50	Minor Mod		Optics	Optics	2
Detector, CCD	0.40	1	0	1	0.40	Copy		Sensor Systems	arge Coupled Device Detect	2
Readout electronics	0.50	1	0	1	0.50	Minor Mod		Sensor Systems	Read Out Electronics	2
Visible Camera Internal Harnessing	0.50	1	0	1	0.50	Minor Mod		Power	Power Harness/Cabling	1
Meteorological Suite					**9.50**					
Sensors										
Temperature Sensor	0.50	2	0	1	1.00	Minor Mod		Sensor Systems	Sensors/Detectors	1
Wind Sensor	0.50	2	0	1	1.00	Minor Mod		Sensor Systems	Sensors/Detectors	1
Pressure Sensor	0.50	2	0	1	1.00	Minor Mod		Sensor Systems	Sensors/Detectors	1
Seismometer	0.50	2	0	1	1.00	New	New	Sensor Systems	Sensors/Detectors	2
Electronics										
Readout Electronics	1.00	1	0	1	1.00	Minor Mod		Sensor Systems	Read Out Electronics	2
Power Conditioning	1.50	1	0	1	1.50	Minor Mod		Power	er Management and Distribu	2
Power										
Power Conditioning	2.00	1	0	1	2.00	Minor Mod		Power	er Management and Distribu	2
Harnessing	1.00	1	0	1	1.00	New		Power	Power Harness/Cabling	1