A General Purpose Astronomy Small Satellite: An approach to low-cost space telescope design using space-qualified ground telescopes

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

Citation
Natasha Bosanac, Sydney Do, Hui Ying Wen and Anthony Wicht, "A general purpose astronomy small satellite: an approach to low-cost space telescope design using space-qualified ground telescopes", Proc. SPIE 7731, 77311P [2010]; doi:10.1117/12.858018 © 2010 SPIE

As Published
http://dx.doi.org/10.1117/12.858018

Publisher
SPIE

Version
Final published version

Citable link
http://hdl.handle.net/1721.1/61370

Terms of Use
Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.
A General Purpose Astronomy Small Satellite: an approach to low-cost space telescope design using space-qualified ground telescopes

Natasha Bosanac\textsuperscript{a}, Sydney Do\textsuperscript{a}, Hui Ying Wen\textsuperscript{a}, Anthony Wicht\textsuperscript{a}
\textsuperscript{a} Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, USA 02139

ABSTRACT

The General Purpose Astronomy - Small Satellite (GPA-SS) project studied the feasibility of developing a useful space telescope with a cost to launch below $100 million. An optical telescope assembly (OTA) designed for ground use is proposed for use in a space mission in order to take advantage of the economies of scale in existing mirror fabrication processes. This paper details the additional design, manufacture and test tasks required to flight-qualify the ground telescope. A near-infrared imaging space telescope was costed as a potential mission. Key subsystems were designed at a conceptual level. This design was used both to estimate subsystem costs and to inform the science achievable from a given telescope design. Subsystem costs were estimated from the design through a combination of previously published cost estimating relationships and vendor quotes. This paper concludes that the space-qualification of an existing ground telescope is a potential approach for making significant cost savings when designing a low cost space telescope. Additional work on design and cost estimation around the framework presented in this paper could be undertaken to add certainty to the cost estimate.

Keywords: space telescope costing, ground-based telescope, flight qualification, near-infrared imaging

1. INTRODUCTION

Space telescopes have traditionally cost from several hundreds of millions to billions of dollars. The space telescopes that are currently in operation are so oversubscribed that only a small number of proposed astronomy projects receive observation time [1]. In such conditions, there is great interest in General Purpose Astronomy type missions - space telescope missions that cost less than $100 million and increase the number of astronomy projects receiving observation time. Another advantage of a small, low-cost mission is that it can serve as a precursor to a more advanced space telescope mission concept that may be difficult to propose, design, and launch in one implementation. Finally, a low-cost space telescope would presumably be more accessible and available to education and outreach audiences than an expensive flag-ship mission.

One unique approach to drastically reducing the cost of space telescope development is to space-qualify existing Commercial-Off-The-Shelf (COTS) ground telescope systems. Being a new and alternative technique to space-telescope system development, no standard method currently exists to cost systems of this class. This paper attempts to fill this gap by introducing a problem-solution approach to the cost estimation of space qualification, and by combining this method with a mixture of the conventional techniques of Cost Estimating Relationships (CERs) and Detailed Bottom-Up Costing. These methods are then used to estimate the cost of development, integration, and testing for a near-infrared telescope mission called the General Purpose Astronomy - Small Satellite (GPA-SS).

2. COSTING METHODOLOGY

This section presents a novel costing methodology for space-based telescopes. An outline of this methodology is shown in Figure 1 below.
Figure 1 shows that the process of cost estimation developed in this paper relies on three primary sources:

- Manufacturer quotes (COTS subsystems, ground telescope, testing facility hire)
- Cost estimating relationships (non-COTS subsystems, integration costs, project wraps)
- A problem, solution, cost-to-fix framework (space qualifying the ground telescope)

The majority of this paper focuses on the third category of cost estimation, because manufacturer quotes are straightforward and CERs are extensively discussed in space mission cost estimation references such as [2].

Three primary assumptions are used as the starting point for the design of the low cost space telescope detailed in this paper. Firstly, the optical telescope assembly is assumed to be a ground-based telescope that has been flight-qualified in-house. The published CERs on space telescope costs showed that a telescope size of approximately one meter diameter was not achievable within the defined low-cost range of approximately $100 million, using the conventional philosophy of completely customizing the design of the Optical Telescope Assembly (OTA) [2]. The second assumption is that all other satellite subsystems would be bought off the shelf where possible. Requiring the use of COTS equipment in these subsystems significantly reduces development risk, while allowing vendor quotes to be obtained for cost estimates.
Thirdly, it is assumed that the risk inherent in reduced levels of testing is not justified by the cost savings [2] [3]. Consequently, the test program outlined in this paper complies with the level of rigor usually expected of a medium-cost space telescope.

### 2.1 Space qualification

In estimating the costs of space qualifying an existing ground telescope to produce a low-cost Optical Telescope Assembly (OTA), a problem, solution, cost-to-fix approach is adopted. This is described in more detail below.

First, this process begins with the identification of all possible causes of failure for a ground telescope subjected to the space and launch environments. Then, for each cause of failure, a series of engineering steps are developed to prevent the failure from occurring. The next step is to estimate the time and labor required to fix the problem, allowing for a cost estimate based on assumed labor rates for technicians and engineers. In general, component costs are disregarded, with the exception of the HAWAII radiation-tolerant detectors which are estimated at $500,000 each.

The cost estimation of the space qualification starts with the assumption that the ground telescope cannot be customized at customer request in any way before it leaves the manufacturer. In practice, one of our potential manufacturers, Optical Guidance Systems, states that all telescopes with mirror diameters 0.8m and greater are made to order [4]. Therefore, it should be possible to eliminate many of the material qualification steps by specifying non-outgassing, thermally compatible materials for large components like the telescope barrel. However, we do not rely on the vendor’s capability to satisfy these customer requests because there is not enough detail available about the sort of customization that can be undertaken. In summary, the OTA space qualification analysis factors in time to replace all telescope components, except the mirrors, with space-qualified materials.

Table 1 shows the problem–solution matrix developed specifically for flight qualification of a ground OTA. Note that the “likelihood” column does not affect the calculation of cost, since the analysis does not weight costs based on the probability of occurrence. Instead, the comments in that column are intended to describe the problem in more detail and give a guide to the degree of conservatism in the cost estimate.

| Problem | Solution | Likelihood | Cost (FY09$millions) |
|---------|----------|------------|----------------------|
| OTA component fails to perform at the low temperatures predicted by the thermal model | Replace component* | Likely; most of the OTA components will fail in at least one of the modes that require them to be replaced. If it does prove possible to negotiate with the manufacturer on materials beforehand this will help reduce the space qualification costs. The disadvantage is that the manufacturer is likely to charge more for the OTA itself, offsetting the benefit. | 2.4 assumes all major OTA components fail |
| OTA component fails due to stresses induced by thermal cycling | Replace component* | Included above |
| OTA component fails due to incompatible coefficients of thermal contraction between adjacent components | Replace component* | Included above |
| Detector or OTA structural materials fail due to ionizing radiation exposure | Purchase radiation hardened detector; | Likely; earth-based detectors exist in a benign radiation environment. | 0.53 |
| | Replace telescope materials* | Unlikely; most structural materials will not suffer radiation degradation. | Included above |
| | Add mass to partially protect detector | Likely; this is a key step in radiation protecting the detector. | 0.29 |
| Outgassing to vacuum: deposition on optics causes performance | Replace component* | Likely; the OTA materials are close to the cold mirror and if they do outgas will deposit material on the mirror. | Included above |
| Problem                                                                 | Solution                        | Likelihood                                                                 | Cost (FY09$millions) |
|------------------------------------------------------------------------|---------------------------------|----------------------------------------------------------------------------|---------------------|
| Outgassing to vacuum: causes structural failure                        | Replace component*              | Unlikely; we can choose the material for many of the structural components from the manufacturer. One choice for telescope barrel material is the non-outgassing aluminum. | Included above      |
| Zero gravity failure of optics components (for example due to loose balls of solder inside the detector) | Manual inspection and replacement if necessary. | Unlikely; the radiation hard HAWAII detectors have flown on several space missions and are unlikely to suffer from this problem. Therefore if the detectors are replaced, the chance of this occurring is small. | 0.080               |
| General failure of other parts in the telescope (bolts, wires etc) due to manufacturing processes which are not MILSPEC | Perform extensive preliminary vibration tests and replace parts if necessary. | Likely; the telescope is unlikely to have been designed for the launch vibration environment. On the other hand, most ground structural engineering has sufficient overdesign that the difference between MILSPEC and not is unlikely to be material. | 0.44                |
| Performance degradation due to an unanticipated thermal contraction producing an incorrect focal length. | Change barrel*                 | Unlikely; after knowing the barrel material it should be possible to accurately predict the thermal contraction. This will be confirmed in the thermal vacuum test. | Included above      |
| Performance degradation due to an unanticipated thermal contraction producing an incorrect mirror alignment. | Change supports for primary and / or secondary materials. * | Unlikely; after knowing the mirror support materials it should be possible to accurately predict the thermal contraction. This will be confirmed in the thermal vacuum test. | Included above      |
| Adverse electromagnetic interference                                   | Add shielding between bus and optics components | Likely; in ground operation the detector is kept distant from the electronics processing the signal. | 0.44                |
| Guidance failure because the alignment between finder telescope and main telescope is difficult to preserve through launch vibration. | Use the main telescope for guidance by placing a beam splitter in the optical train. Alternatively, change the image rate of the detector during operations to alternately perform guidance and image capture. | Unlikely; some additional form of fine guidance will be required, but changing the image rate of the detector is a much cheaper option. Likely; additional fine guidance will be required. | 0.67                |
| Active cooling components are not space qualified and the detector is too warm with active cooling components removed. | Place the detector on a heat sink. | Very likely. Existing detectors all use active cooling systems which are inappropriate for low cost space missions. | 0.81                |
| Optics not designed to interface with spacecraft                        | Integrate optics with spacecraft bus | Certain. The amount of custom design which can be done on the telescope prior to space qualification is small. | 0.21                |
Problem | Solution | Likelihood | Cost (FY09$millions)
---|---|---|---
bus | to manufacture will determine the extent of this task. | |
Induced vibration from bus too great; | Introduce vibration isolators into the structure. | Likely. The reaction control wheels and thrusters will produce vibrations. | 0.51

Total for worst case process in space qualifying the optical assembly | $6.4 million

*Note: Each component would be replaced only once, even if the original component would have failed several tests. Whenever a new component is introduced, it would be designed to withstand all listed failure modes in this table. In the cost model there is no double counting between these categories.*

The labor costs used in these calculations are shown in Table 2, with a multiplier to account for overhead expenses such as office space, equipment and facilities. This overhead does not include administrative and managerial staff, which are included later as “Program Wraps”.

Table 2. Labor rates used in cost estimate.

| Paid Salary | Multiplier | Effective cost | Rate per month |
|---|---|---|---|
| Technician | $80,000 | 2 | $160,000 | $ 13,333 |
| Engineer | $125,000 | 2 | $250,000 | $ 20,833 |

As an example of how each of the problem-solution costs were computed, Tables 3 and 4 below show a detailed example for two sample problem-solution sets: “replace detector” and “increase radiation protection for detector”.

Table 3. Cost estimation for replacement of the detector in the OTA.

| Task | Replace detector | Duration (months) | No of engineers | No of technicians | Total cost (FY09$) |
|---|---|---|---|---|---|
| Remove existing detector | 0.25 | 2 | 2 | 17,083 |
| Purchase additional detector | 0.25 | 2 | | 10,416 |
| Detector fixed cost | | | | 500,000 |
| Lead time on detector | 3 | 0.5 | | 31,250 |
| Detector initial testing and evaluation | 1 | 2 | 2 | 68,333 |
| Integrate detector into OTA | 0.5 | 2 | 2 | 34,166 |
| TOTAL | | | | 661,250 |

Table 4. Cost estimation for increasing the radiation protection for the OTA detector.

| Task | Increase the radiation protection for the detector | Duration (months) | No of engineers | No of technicians | Total cost (FY09$) |
|---|---|---|---|---|---|
| Redesign of heat sink focus plate | 2 | 2 | 0 | 83,333 |
| Manufacture of heat sink focus plate | 3 | 1 | 2 | 142,500 |
| Update thermal modeling | 1 | 1.5 | | 31,250 |
| Update structural modeling | 1 | 1.5 | | 31,250 |
| TOTAL | | | | 288,333 |
3. APPLICATION TO A LOW COST SPACE TELESCOPE

The analysis in Table 1 shows that a space-capable optical telescope payload with a 0.8 m diameter could be constructed for approximately FY09 $6.5 million. However, this estimate is exclusive of integration, test and other essential satellite systems. The remainder of this paper presents the design and costing of an example mission based around this optical telescope payload to better quantify the total cost of developing an operational space telescope from a ground-based telescope.

3.1 Mission Overview

The example mission costed here is that of a single-aperture near-infrared design based on a lower-capability version of the Spitzer space telescope, designed, manufactured and tested to a budget of approximately $100 million. Cost and scientific value are the main (and sometimes competing) design drivers. With these two factors in mind, some logical design assumptions were used as guiding thoughts while exploring the design trade space. For instance, limiting the design of the thermal system to utilize passive cooling is a sure way to keep costs down. Also, locating the telescope in a heliocentric orbit, such as Earth-Sun L₂ or Earth-trailing, is likely to ensure a level of observation capability that is desirable to a large segment of the scientific community [5]. The final design was arrived at through both modeling of individual subsystems and scaling of subsystems designed for analogous space telescope missions.

One CER estimates that the cost of an optical telescope assembly is proportional to telescope aperture to the power of 1.32 [6]. Fitting this relationship to historical cost values, a 0.8 m aperture optical assembly – not the whole telescope – is expected to cost approximately $500 million. This relationship is derived from historical missions whose payloads are usually custom designed and built, which inflates cost greatly. It is hoped that the alternative proposed here - purchasing a commercial ground telescope assembly and taking steps to qualify and customize it for spaceflight – will reduce cost by orders of magnitude.

3.2 System Overview

Table 5 summarizes the key design and hardware choices, explained in Section 4, for the example satellite system used in this costing example. In addition, Table 6 presents a full breakdown of the cost estimates for the satellite – including both hardware and testing costs. The details of these estimates are discussed in Section 4.

Table 5. Overview of system technical specifications.

| Subsystem    | Parameter                  | Spitzer Near IR Mission | Subsystem                       | Parameter                  | Spitzer Near IR Mission |
|--------------|----------------------------|-------------------------|---------------------------------|-----------------------------|-------------------------|
| Payload      | Instrument description     | Optical telescope       | Attitude Determination          | Attitude Determination      | Sun Sensor and IMU      |
|              | Spectral range             | 3.6-8microns            | Control                         | Stabilization instruments   | Reaction wheels         |
|              | Aperture                   | 0.8                     | Acquisition accuracy            | 0.01 deg                   |                         |
|              | Pixel size                 | 18 microns              | Propulsion                      |                             |                         |
|              | Design life                | 5 years                 | Propellant                      |                             |                         |
|              |                            |                         | Number of Thrusters             | 12 x 1N thrusters           |                         |
| Power        | Total power produced       | 500 watts               | Thermal control system          |                             |                         |
|              |                            |                         | Coatings                        |                             |                         |
|              |                            |                         | Z93 and aluminized teflon       |                             |                         |
| Avionics and Software | Hardware; Software coded in C |                         | solar reflectors                |                             |                         |
| Total mass (estimated) | 1500kg                     |                         | Communications                  | Maximum data transfer rate  | 2Mbps HGA, 2kbps LGA    |
| Configuration | See Figure 2                |                         | Ground network                  | DSN, HETE                  |                         |
| Deployed structures | 2 radiators                |                         | Transmission bands              | Ka (HGA), S (LGA)          |                         |
| Launch dimensions | 1.5m x 3.5m x 4m           |                         | Orbit                          | L₂                         |                         |
| On-orbit dimensions | 1.5m x 4.5 x 5m            |                         | Possible launch vehicles        | Ariane V                   |                         |

Downloaded from SPIE Digital Library on 09 Feb 2011 to 18.51.1.125. Terms of Use: http://spiedl.org/terms
Table 6. Satellite system and testing cost estimates.

| Program element                          | Cost (FY09$millions) | Program element                          | Cost (FY09$millions) |
|-----------------------------------------|-----------------------|-----------------------------------------|-----------------------|
| Concept design                          | $2.75                 | Attitude Determination and Control System | $6.3                  |
| Spacecraft systems                      |                       | Functional testing                       | $0.69                 |
| Power                                   | $7.1                  | Burn – in                               | $0.31                 |
| Communications                          | $4.2 (excluding ground station costs) | Vibration                               | $3.1 (quoted)         |
| Propulsion                              | $1.1                  | Separation shock test                   | Included in quote     |
| Structure                               |                       | Acoustic                                 | Included in quote     |
| Thermal                                 |                       | Thermal cycling tests                   | $0.092 million        |
| Avionics hardware                       | $3.0                  | Thermal vacuum tests                    | Included in quote     |
| Avionics and payload software           | $18.18                | Vibration due to bus components         | $0.11                 |
| Optics (without space qualification)    | $0.4                  | Radiation testing                       | $0.11                 |
| Space qualification of optics           | $6.4                  | Launch vehicle separation testing       | $0.089                |
|                                          |                       | Optical testing                         | $1.78                 |
|                                          |                       | EMC testing                             | $0.26                 |
| Integration                             | $0.41                 |                                        |                       |
| Maintaining team between launch and on-orbit operations | $2.8                 |                                        |                       |
| Program wraps                           | $24                   |                                        |                       |
| TOTAL                                   | $95                   |                                        |                       |

4. SUBSYSTEM COMPONENT DESIGN

4.1 Optics

The GPA-SS OTA is in the form of a single-aperture, Cassegrain mirror configuration with a 0.8 m aperture and F# of 12. Ground telescopes in this aperture range are available commercially, with the weight of a 0.8 m aperture ground telescope expected to be roughly 160 kg [7]. An estimate from one vendor costs a 0.8 m optical assembly at roughly $200,000 [4]. The purchase cost of a ground telescope is expected to be minimal compared to the cost of flight-qualifying and adapting it as a space payload, as shown in Table 6.

For this study, the "HAWAII" detector array series from Teledyne Scientific & Imaging, LLC [8] is also chosen, requiring operating temperatures between 40 K and 140 K. According to the concept-level thermal analysis undertaken

1 Note: some optics space qualification steps require the thermal model to be updated. These updates are not included in the thermal modeling cost here, but are included in the optics cost.

2 Thermal hardware cost included in structure since all components are passive.
for this study, an operating temperature of 140 K can be easily supported in a Sun-Earth L2 orbit, while 40 K is only achievable at the design limit of the thermal system.

4.2 Thermal

The thermal system is a major cost contributor to telescopes operating in the IR band: the longer the IR wavelength of observations, the more critical low operating temperatures are in minimizing noise. For GPA-SS, the thermal system must keep the bus temperature at approximately $283 \pm 10$ K, and the temperature of the optical components below the maximum detector operating temperature.

In order to achieve these low temperatures without the increased expense and complexity of active cooling, honeycomb panel radiators with a total area of 8.6 m$^2$ were used for passive cooling. Additionally, the thermal design includes aluminized Teflon reflectors to improve the solar panel reflectivity and Z93 paint to increase the degree of bus cooling. An MLI barrier is used to shield the telescope from solar radiation.

As no active thermal components were used on cooling the telescope, the cost estimate for the thermal system is included within the CER for the structural components of the telescope.

4.3 Structures

An initial analysis of structural cost showed that the total cost should be relatively insensitive to the structural configuration, provided the structure yielded an acceptable thermal regime. Therefore most of the structural design was based on a simplified version of the Spitzer Space Telescope.

The mass of key structural components is estimated as follows:

- **OTA:** The estimated maximum mass is 260 kg, based on manufacturer specifications, assuming that the space qualification process does not add significant weight to the telescope.

- **Bus:** The estimated mass is 1250 kg, while the mass of the structure was assumed to be 50% of the bus weight for the purposes of implementing a CER for structure cost. No structural analysis was undertaken to verify this figure, however the total mass of the Spitzer Space Telescope was approximately 950 kg at launch.

- **Thermal Components:** The masses of the major thermal components are derived from their total required area and material density. The total radiator area was found to be 8.6 m$^2$, giving a total radiator mass of 28.38 kg. Similarly, the total mass of the MLI was calculated to be 2.92 kg. Summing these masses, the total structural cost is found using the following CER:

$$Cost \ (FY00\$K) = 13.1 \times Structural \ weight. \quad (1)$$

The total cost in FY09$ is $10.3 million [2].

4.4 Communications

The configuration of the GPA-SS communications system is assumed to include a single high-gain antenna (HGA) on the base of the structure for image data transfer, and two geometrically separated low gain antennas (LGA) for command and telemetry communications.

High data rate communications will take place over the Ka band using the Deep Space Network 34 m antenna, while low data rate telemetry and commands will be transmitted and received over the S band. In order to reduce costing and availability constraints, S band communication will use the HETE 1.8 m antenna located in the Kwajalein Atoll, Marshall Islands. A downlink data rate of 2 Mbps is assumed while the command and telemetry data rate is assumed to be 2 kbps [9].
Initial link margin analyses have resulted in antenna diameters of 1.3 m for the HGA and the 0.45 m for the LGA. Using these figures, the total mass of the antennae is then estimated using parabolic mass fits to give a combined mass estimate of 11.7 kg. The cost of this combined configuration is estimated with the following relationship [2]:

\[
\text{Cost (FY00)} = 140 \times (\text{Communications Mass}).
\]

This cost is then converted to FY09 to obtain an estimate for the cost of the communications system. For GPA-SS, this cost is $2.06 million.

### 4.5 Attitude Determination and Control

The primary drivers in attitude determination sensor selection are the required pointing acquisition accuracy and angular range over which this accuracy must be met. For GPA-SS, these requirements are, respectively, 0.01° and a ±30° cone about the local vertical reference vector. In order to meet the defined angular range requirements an Adcole sun sensor is baselined as the direct attitude measurement unit [10]. For inertial measurement, a Northrop Grumman Scalable Inertial Reference Unit is used [11].

In order to control GPA-SS, three-axis control techniques will be employed. Given the torque requirements, reaction wheels are used for momentum storage and are desaturated using thrusters [25]. For this analysis, GPA-SS is assumed to have the capability to slew 15° in 150 seconds – a driving factor for the angular momentum storage capability. A survey of existing hardware capable of providing the conservatively estimated momentum storage requirement of 17 Nms showed that each of the four, tetrahedrally arranged reaction wheels would have a mass of 7 kg [12]. In order to desaturate the reaction wheels, a configuration of 12 thrusters will be used to dump momentum every 1-2 weeks.

The total mass of the ADCS components is a combination of the mass of the reaction wheels and the sensors – with an approximate total of 39kg. Based on the estimated mass for the ADCS hardware, the relationship used to calculate subsystem cost is:

\[
\text{Cost (FY00K)} = 293 \times (\text{ADCS Mass})^{0.777}.
\]

Upon conversion to FY09 dollars, the cost estimate of the attitude determination and control subsystem is $6.3 million [2]. This figure does not include the cost of the thrusters, which will be included in the propulsion subsystem design.
4.6 Propulsion

In the design of the propulsion system, GPA-SS is conservatively assumed to have an operational lifetime of 5 years, adequately satisfying all potential mission architectures and their required propulsion performance margins. Trade studies performed show that the use of cold gas as propellant provides the lowest subsystem cost. Although ΔV requirements for station-keeping at Earth-Sun \( L_2 \) depend on the orbital amplitude, a feasible estimate used in the GPA-SS design is 3.5 m/s/yr. In addition, given the frequency of desaturation detailed in Section 4.5, a cold gas system would require 1.4135 kg/yr for ACS momentum dumping. Based on parameters specified for commercial-off-the-shelf thrusters, the effective specific impulse for the cold gas system is 70 s.

With respect to costing, a conservative estimate of the spacecraft mass is used to develop preliminary propulsion system architectures for both types of propellants. Quotes from RTG Aero-Hydraulic Inc., a spacecraft propulsion company based in Bremen, Germany, price the propulsion system at $572,000.

4.7 Orbits

Spacecraft can be launched into a wide variety of orbital locations. However, considering the nature of a space telescope, this list of feasible orbits can be significantly reduced to include only those that are heliocentric – particularly, libration point and earth-trailing orbits.

Both \( L_2 \) and earth-trailing orbits were considered in an initial trade study of the combined cost for the propulsion, attitude determination and control, and communication subsystems. The result of this initial study indicated that an \( L_2 \) orbit would be the least expensive option. A reference \( L_2 \) orbit is created with an approximate C3 energy of \(-0.5\) km\(^2\)/s\(^2\) and a period on the order of 6 months [13]. In addition, this orbit benefits from the Earth shadowing the Sun for most of the orbit, providing a stable thermal environment for GPA-SS. Despite requiring station-keeping maneuvers every 3-6 weeks, the communication distance remains relatively constant and the sky coverage is quite large [14].

4.8 Software and Avionics

To approximate a rough cost for software development, it is assumed that the generic onboard software functions for the spacecraft bus include code for communications, attitude sensor processing, attitude determination and control, autonomy, fault detection, operating system software and various other functions in the control of subsystems. Standard guidelines for the memory requirements of each software function were used, yielding a total estimate of 72 Kwords of memory (1 word = 16 bits, 1 Kword = 1024 words), or about 10,000 lines of code [2].

Costing of this system yields an estimate of $9 million for the development cost of onboard spacecraft bus functions. Although the design of GPA-SS is not detailed enough to provide a development cost for onboard spacecraft payload functions, an extra $9 million can serve as a rough estimate. The cost of hardware for both onboard avionics and for development and testing is estimated to be about $2-3 million [15]. In total, the cost of software development and avionics is estimated to be $21 million.

4.9 Power

The GPA-SS power system is assumed to use solar power due to its proven reliability on other telescopes. In addition, solar cells can be bought directly from a third party manufacturer due to their widespread use. The power generating capacity required at the beginning of the satellite life is assumed to be approximately 500 W, based on the Spitzer telescope power requirements.

Although GPA-SS is in a heliocentric orbit, the CERs used for power estimation are based on typical earth-orbiting satellite configurations. Given that the operating environment is more favorable in a heliocentric orbit, this CER provides a conservative estimate. Using the estimated beginning of life power, the cost of the system can be calculated from the following CER:

\[
\text{Cost (SFY00K)} = -5850 + 4629 P_{bol}^{0.15}
\]  

(5)

where \( P_{bol} \) is the beginning of life power in Watts. This figure includes an allowance for research, development, testing and evaluation, which may not be applicable if GPA-SS purchases from a commercial vendor where the RDT&E costs are amortized across a large product line, increasing the conservative margin on this estimate. The value of FY00S5.9 million is used in the model for power, which is equivalent to an FY09 value of $7.1 million [2], using an inflation factor of 1.199.
5. SYSTEM INTEGRATION AND TESTING

System integration and testing constitutes a significant fraction of the satellite cost. In the cost model used for this paper, all COTS subsystems have a contingency added to them, priced as of a team of four engineers working for one month to test the as-delivered system prior to integration. Then, the cost estimate for system integration is based on a team of four engineers employed full time for six months. A one month allowance is made for a team of 11 engineers (one for each subsystem, plus one systems engineer and one test engineer) to conduct full-time functional testing after integration.

For the detailed whole-of-satellite tests, cost estimates use a combination of quotes from test facility operators and time-labor rate estimation, where facility prices were unavailable. Each system test included an allowance of 2 to 3 engineer months for test preparation and test evaluation, in addition to the actual test time. The estimated time varied between subsystems. The higher level costs are shown in Table 6.

6. DESIGN COSTS, TEAM MAINTENANCE AND SYSTEM WRAPS

Despite the use of COTS flight hardware, the costing analysis must include the time required to design the overall satellite and individual subsystems. The analysis used for this sample costing exercise allows six months for this concept and preliminary design process, budgeting for the equivalent of 22 engineers working full time. This figure of 22 engineers is found by allocating two engineers for each of the nine satellite systems, and adding two engineers each for testing and systems engineering. These costs are not attributed to individual satellite systems, and are a separate line item of $2.75 million in the cost summary.

Detailed design costs are, however, attributed to individual systems. These are accounted for by allowing the two allocated engineers three months to complete detailed design for each subsystem, costing approximately $125,000 per subsystem. These costs are included in the subsystem costs. All management time and cost is captured in the program wrap percentage, with a value of 34% adopted as suggested in the literature [2].

The final component of the budget allows for the entire 22 member design team to remain active for an additional six month period. This period covers launch, flight time to station and initial check-out activities. The team may be required to diagnose and / or rectify anomalies along the way. The total cost of maintaining this team for the six month period is $2.75 million. No allowance has been made for operations after the telescope begins nominal on-station operations, since the per-day operating cost of the telescope is assumed to be unaffected by the design and will therefore be comparable to other space telescopes currently operating.

7. LAUNCH COSTS

Launch costs are not included, nor examined in detail in the costing methodology. However, they must be considered to ensure that the cost savings of space qualification are not insignificant when compared with the launch costs. One possible launch option which is commensurate with a $100 million mission is to launch as a secondary payload on an Ariane V mission to L2. Reference [2] suggests that an Ariane V can launch a payload mass to L2 of approximately 6,600 kg. Based on a survey of previous missions, typical values for the secondary payload mass fraction are found to be between 30% and 50%. The estimated GPASS mass of 1,500 kg would comprise about 23% of the mass fraction, making it likely to be a suitable candidate for launch as a secondary payload, assuming an appropriate primary payload destined for L2 can be found.

8. CONCLUSION AND DISCUSSION

A costing framework for a low-cost space telescope based on the two key approaches of 1) the purchase of commercial spacecraft bus components and 2) the flight-qualification of a commercially purchased telescope payload was presented.
An example design for a near-infrared imaging mission was costed at approximately $100 million using this framework. The costs of standard spacecraft testing and integration tasks were included, but not those of launch, ground support, and operations.

This costing methodology applies only to single-aperture space telescopes, and would need to be extended for more complex configurations such as multi-aperture interferometry missions. Also, the cost estimates obtained for the example mission here is simply that – an example, whose accuracy could be greatly improved with more detailed design, further communication with manufacturers and contractors, and comparison of subsystem costs with those of similar missions. Nevertheless, the framework that was applied here can also be put to use on actual missions for which accurate component and testing costs can be obtained.

ACKNOWLEDGEMENTS

The authors wish to thank David Miller and Jeffrey Hoffman in the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology, Howard MacEwen of ManTech International Corporation, Webster Cash in the Department of Astrophysical and Planetary Sciences at Colorado University, and Daniel Lester in the Department of Astronomy at the University of Texas at Austin for their valuable guidance and advice.

REFERENCES

[1] Vu, L., "Spitzer's Legacy: The Big Picture." Spitzer Space Telescope, 11 Aug 2005, Accessed 19 Oct 2009, <http://www.spitzer.caltech.edu/features/articles/20050811.shtml>
[2] Wertz, J. R. and Larson, W. J., [Space Mission Analysis and Design], Microcosm Press, Hawthorne, (2008).
[3] Wertz, J. R. and Larson, W. J., [Reducing Space Mission Cost], Microcosm / Kluwer Academic Publishers, Torrance & Boston, (1996).
[4] Email communication with John E. Stiles, Optical Guidance Systems, Nov. 3 2009
[5] MacEwen, H., "Introductory Presentation.ppt," 11 Sep 2009.
[6] Stahl, H. P., Prince, F. A. and Smart, C. et al., "Preliminary Cost Model for Space Telescopes," Proc. SPIE 7436, 9, (2009).
[7] Optical Guidance Systems, "OGS Telescopes," http://opticalguidesystems.com/ogstele.htm (2003)
[8] Teledyne Technologies Incorporated, "Standard FPA Products," http://www.teledyne-si.com/imaging/standard_products.html (2009)
[9] Gehrz, R. D., et al, “The NASA Spitzer Space Telescope,” Rev. Sci. Instrum., 78, 011302, 2007.
[10] Adcole Corporation, 2 Axis FSS Datasheet, http://66.151.177.33/en/~redirector6/aerospace-products/page-2/ (last accessed November 5th 2009)
[11] Northrop Grumman Navigation Systems, Scalable SIRU, http://www.es.northropgrumman.com/solutions/siru/assets/scalable_SIRU_space.pdf (last accessed November 6th, 2009)
[12] Honeywell, “Constellation Series Reaction Wheels Product Brochure”, http://www51.honeywell.com/aero/common/documents/Constellation_Series_Reaction_Wheels.pdf (last accessed December 10, 2009)
[13] Cash, W., “Astrophysics Strategic Mission Concept Study: The New Worlds Observer,” Appendix J, (2009)
[14] Gomez, G., Llibre, J., Martinez, R., and Simo, C., [Dynamics and Mission Design Near Libration Points: Vol 1], World Scientific Publishing Company, Singapore, 1-5, (2001).
[15] Conversation with Dr. Alvar Saenz-Otero, Massachusetts Institute of Technology, Cambridge, MA, (December 1, 2009).
[16] Stahl, P., Sumrall, P. and Hopkins, R., “Ares V Launch Vehicle: An Enabling Capability for Future Space Science Missions”, Acta Astronaut., 64, 1032-1040 (2009).