The Economic Value of Space Telescope Servicing

Zach Bailey[*] and Mark Baldesarra
Massachusetts Institute of Technology, Cambridge, MA, 02139

Background

The development of space telescopes has led to many advances in astronomical knowledge. Operating outside of the atmosphere, space telescopes are not subject to atmospheric attenuation of electromagnetic radiation, nor to atmospheric refraction and absorption. Relative to their ground-based counterparts, space telescopes have high lifecycle costs (over $5 Billion for HST [5]).

For a given space observatory program budget, the general goal is to maximize the science return. Traditionally this has been done by designing a single spacecraft to conduct a specific science mission. Eventually this spacecraft will meet its end of life due to component failure, depletion of consumables, or obsolescence of its instruments. If the broad science goals of a program have not been met by this spacecraft, then the spacecraft can either be replaced, be serviced, or no action can be taken.

Designing a space telescope to be serviceable is one way to extend its lifetime and science capability, thereby increasing the value derived from the initial investment in the spacecraft. Serviceability is a tool to manage the various uncertainties implicit in any space telescope program. Uncertainty in a program can arise from technology growth, unknown failure rates, and changing mission requirements, among other things.

Telescope servicing addresses all of these issues. Failures of engineering components and science instruments can be dealt with by the ability to replace failed items on-orbit. The result is a program lifetime that is robust to uncertainties in component failure rates.

Telescope servicing also increases the value of a program by allowing instruments to be upgraded with changes in technology and science goals. As new detectors are developed, or as science priorities shift to different wavelength ranges or different detector technologies (i.e. from imaging to spectroscopy), new instruments can be installed on-orbit. This strategy has been successful in many ground-based telescopes. For instance, The Palomar Observatory, which saw first light in 1949, has remained a relevant tool for astronomers over the last six decades by upgrading its instrumentation from photographic plates to advanced CCDs and spectrographs today. [6]

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[*] zbailey@mit.edu

The Hubble Space Telescope has also demonstrated the value of servicing to improve its science return, through the four missions that have been conducted to date. [1] As a result of the instrument servicing that has occurred for Hubble, its science capability has undergone continuous improvement. In Figure 1, the ten most productive NASA programs are shown, as ranked by the cumulative number of science news stories generated by them over time. [4] After each servicing mission, the HST program has seen an increase in the slope of its science impact curve. Furthermore, the HST program has not yet reached a plateau in its science impact, as many other programs have.

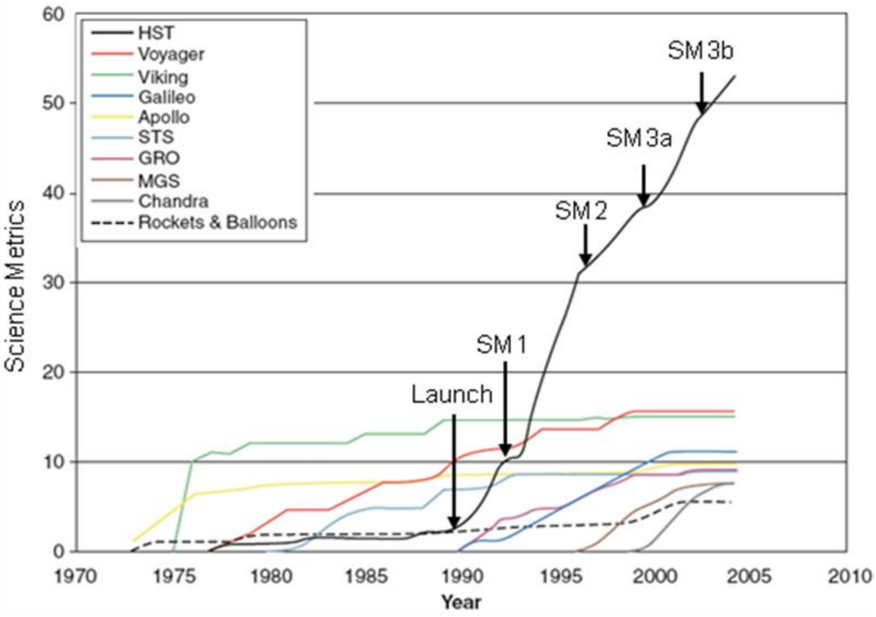

Figure 1. Cumulative science contributions of the ten most productive NASA programs over time [4]

Adding serviceability to a space telescope comes with a number of costs, many of which are realized during the development and construction stage of the program. These costs include: making the telescope sufficiently modular to allow for servicing, adding a docking interface, selecting an orbit that allows for servicing access, the potential cost incurred by damage during servicing, and the opportunity cost of the offline time during a servicing mission. It should be noted that modularity may in fact reduce costs for a program in the testing and integration phase.

Understanding the value of serviceability derived from increased program lifetime and science return is critical for future space telescopes. It is important that decision makers have the tools they need to understand this complex issue and make an informed decision in the design phase of the next generation of space telescopes. The remainder of this paper presents a method for assessing the value delivered from adding serviceability to a telescope design, and a case study to illustrate this method.

Methodology

The value of adding serviceability to a space telescope design is in the fact that it increases the flexibility of an on-orbit observatory. As has been illustrated, this benefit comes at some initial cost. It is difficult for engineers, scientists, and policy makers to understand how the value of serviceability relates to its costs because the value generated (increased science return and mission flexibility) is not readily quantified. Estimating the costs of servicing missions is also difficult due to the small number of historical data points and the fact that servicing mission costs have traditionally not been counted in the telescope program's budget. [2]

The value of serviceability can be found by comparing two similar telescope programs: one with servicing and one without. [3]

In this analysis, a program without servicing is a replacement program, where a new upgraded telescope is launched after an initial telescope fails. In the program with servicing, upon failure (or below a minimum reliability threshold), a mission is sent to repair and upgrade the telescope. In the analysis presented here, the costs of any servicing missions themselves are not included in the cost of the program with servicing. The difference between these two program costs is referred to as the "Equilibrium Cost," and is the maximum amount that the program should be willing to pay for the servicing missions. This concept is illustrated in Figure 2.

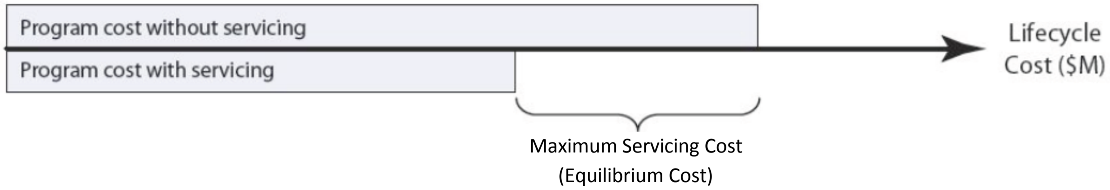

Figure 2. The Equilibrium Cost is the difference between a program without servicing and a program with servicing. This is also the maximum cost for all servicing missions. [3]

Cost Model

For the two different programs analyzed here, the costs are calculated as follows:

- Replacement Program:
    - Initial telescope, instrument, and launch costs;
    - Replacement telescope, instrument, and launch costs;
    - Costs of operating the telescope
- Servicing Program
    - Initial telescope, instrument, and launch costs
    - Additional cost of designing a telescope to be serviceable (a multiplier)
    - Costs of any instruments upgraded over the telescope lifetime;

  - Costs of any components replaced over the telescope lifetime
  - Costs of operating the telescope.

Not included in the servicing program cost are any costs related to the servicing missions themselves, including: training costs; facility costs; and the costs of a servicing mission (launch, servicing spacecraft, etc.).

Science Return Model

In this model, discovery efficiency (defined as the quantum efficiency or throughput of an instrument times its field of view) is used as a metric for instrument utility. For simplification, this model assumes that the space telescope has only a single instrument on board. The discovery efficiency of the telescope as a function of time is governed by the following three rules in the model:

1. Without servicing or replacement, discovery efficiency remains constant through time.
2. Increases in discovery efficiency can only occur if a new instrument is installed, either via a servicing or replacement mission.
3. When a new instrument is installed, the discovery efficiency of the new instrument lags the technology available on the ground.

The progression of improvements in discovery efficiency is modeled with an exponential growth curve. This progression has been observed for charge-coupled devices (CCDs), which are widely used on telescopes as image capture devices. The size of CCD chips has decreased and the number of detectors (pixels) per unit area has increased exponentially according to Moore’s Law.

Since this model investigates the marginal change in science return between the replacement and servicing cases, it is not important to express the absolute value of the discovery efficiency, but instead express the relative change of discovery efficiency from an older to a newer instrument.

The simulation tracks the telescope discovery efficiency throughout its entire lifecycle, as shown in Figure 3. The jumps in the telescope discovery efficiency represent the installation of new instruments, and the gap between the state-of-the art and technology discovery efficiency is due to instrument construction latency. The integral of the telescope discovery efficiency curve represents the total science return of the telescope.

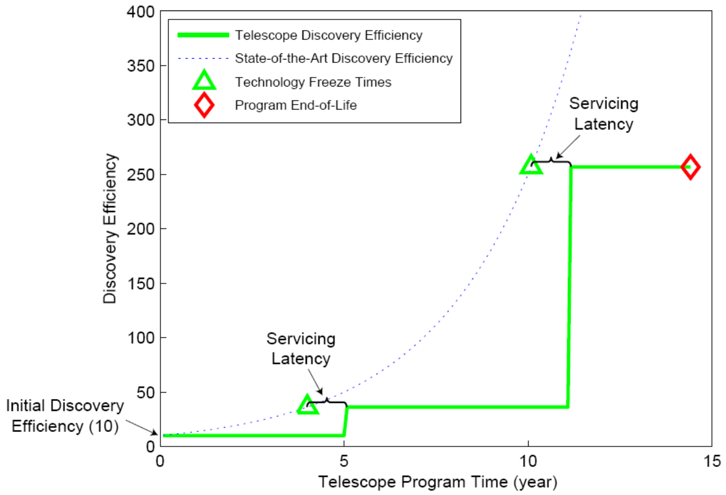

Figure 3. Discovery efficiency of state-of-the-art technology and the telescope [3]

Hubble-Class Case Study

As an example of the usefulness of this analysis for making program funding decisions, it was applied to a Hubble-like telescope. In this model, the telescope uses a single instrument and a simplified component model. A Monte Carlo simulation was developed with a stochastic telescope failure model. Two cases were considered with this model: a fixed-interval servicing program, where the telescope is serviced every 3.5 years; and a fixed-interval replacement program, where a new telescope is launched every 7.5 years. For each case the probability distributions of the final failure time of the program, the total cost of the program, and the science return of the program were calculated. The probability distributions, of the science return and total lifecycle cost for each case are plotted in Figure 4.

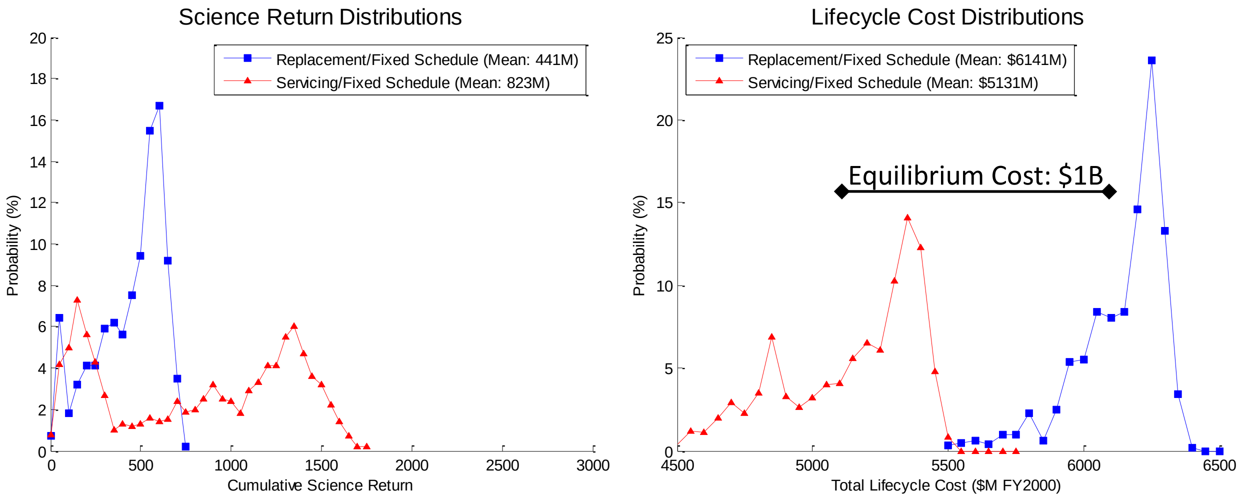

Figure 4. The science return and lifecycle cost of a Hubble-like program. The equilibrium cost between a replacement program and servicing program is $1 Billion. The mean science return of a servicing program is approximately twice the return of a replacement program.

The difference between the mean lifecycle costs of the two cases is approximately $1B. This difference is the equilibrium cost, and can be interpreted as the maximum amount the program should be willing to pay for servicing missions. The analysis of science return for these two cases indicates that a program with servicing has an expected return of twice that of the replacement case.

Program Lifetime Analysis

The initial case study presented is for a fixed number of servicing and replacement missions. For a longer program length, the number of prescribed servicing and replacement missions increases. In this section, the changes in science return and equilibrium cost as a function of program length are investigated.

The Hubble-like Monte Carlo model was used to analyze how program costs and science return vary as a function of the program lifetime. For both the servicing and replacement cases, the cost of a program increases with time, due to increased lifetime-dependent total operational cost, and the increased number of replacement telescopes, or servicing missions.

The rate at which the program cost increases with a longer lifetime is greater for a replacement program than for a servicing program. This is due to the fact that, for the replacement case, a new telescope is launched every 7.5 years. In the servicing case, only new instruments and components are being costed every 3.5 years. (Note: the cost of the servicing mission is not included in the servicing program cost.)

The science return of a program as a function of the maximum program lifetime was calculated. For the servicing case, science return increases more quickly than for the replacement case. This is because instruments are upgraded more frequently; the telescope's discovery efficiency vs. time curve therefore better approximates the actual growth rate of technology.

Program cost vs. time, and science return vs. time are presented in a combined plot in Figure 5. Here science return is plotted as a function of program cost. Isolines of constant program length are shown in black. From this plot, the equilibrium cost can be determined by finding the horizontal distance between the science return vs. costs curves for a servicing program and replacement program. In general, the equilibrium cost increases with program length, meaning that more money can be spent on servicing missions for longer duration programs (though this money must be spent over a larger number of servicing missions).

In principle there are two different equilibrium costs: the constant-time equilibrium cost, which represents the maximum cost one should be willing to spend on a servicing mission campaign for a program of a given length; and the constant-science-return equilibrium cost, which represents the maximum cost one should be willing to spend on a servicing mission campaign for a program with a fixed science return.

The constant-time equilibrium cost can be found by comparing the horizontal distance between points for a servicing program and replacement program that fall on the same constant program length isoline. This is shown as cost B in Figure 5 (for a 30 year program length).

The constant-science-return equilibrium cost can be found by found by subtracting the replacement cost from the servicing program cost along a horizontal (constant science return) line. This is shown as cost A in Figure 5. In general, the constant-science-return equilibrium cost is greater than the constant-time equilibrium cost, due to the fact that a servicing program has a quicker increase in science return than a replacement program.

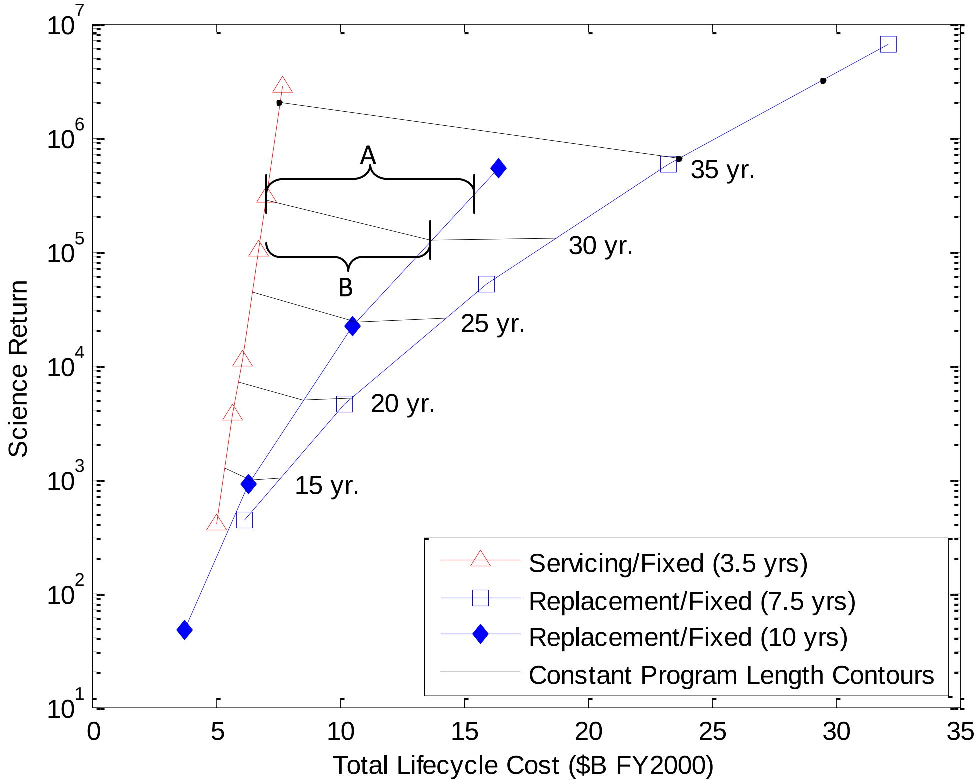

Figure 5. Science Return vs. Total Lifecycle Cost for fixed schedule servicing and fixed schedule replacement programs. Constant program length contours are shown in black. Also shown are: A) a constant-science-return equilibrium cost; B) a constant-program-length equilibrium cost.

Conclusion

When deciding whether to add serviceability to a spacecraft design, the expected cost of the program where the spacecraft is serviced should be compared to the expected cost of a program where the spacecraft is replaced. If the entire campaign of spacecraft servicing missions can be completed for a cost less than the equilibrium cost (the difference between the replacement program and servicing program), then it is economical to add serviceability to the spacecraft.

Though this paper focuses on the application of this methodology to space telescopes, this analysis framework is easily applicable to other spacecraft where adding serviceability may be of interest (such as earth observatories, or geostationary communication satellites). All that is needed is an objective figure of merit to represent the utility of the spacecraft.

As the astronomy community looks beyond Hubble to the future of space-based observatories, a metric is needed to inform the persistent argument about servicing. This method can be applied in the design phase of future space telescope programs to give engineers, managers, and policy makers an objective way to assess whether it is economical to add serviceability to their design.

Recommendations to the NRC

1. For expensive, long-lifetime spacecraft, begin conducting trade studies on the value of adding serviceability to these spacecraft early in the conceptual design phase. This includes future NASA space telescopes, NOAA earth observatories, and large DoD satellites.

2. Study the ways in which the Constellation system can leveraged for the use of on-orbit servicing of future space telescopes and other spacecraft. This includes investigating servicing mission concepts at Lagrangian points, and the development of robotic manipulator arms and other hardware to be used in servicing missions.

3. Undertake studies into the costs of future servicing missions using the Constellation infrastructure or robotic servicing spacecraft, so that this cost information can be incorporated into serviceability trade studies for future spacecraft.

4. Undertake additional non-advocate studies into the value of on-orbit spacecraft servicing.

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