"Astronaut and Robotic Maintenance and Upgrades of Major Space Assets"

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Maintenance, repair and periodic upgrades of valuable assets are standard operating procedure for most complex systems built on the Earth. Businesses typically depreciate fixed assets at ~5-10% per year and invest the resources in maintaining and upgrading the assets for as long as it makes economic sense and then replacing them. Astronomers have done this for more than a century with ground-based telescopes, continually replacing the focal plane instrumentation to increase telescope performance while maintaining the same basic optical system. As in industry, a balance is necessary between devoting resources to upgrading instrumentation and eventually building new facilities. In space, by contrast, with the exception of the Hubble Space Telescope and the Solar Maximum Mission, all scientific assets are operated for their entire lifetime in the configuration they had at launch, with no possibility of upgrades to incorporate new technology or of repair in case of failures.

Inability to service satellites has numerous consequences:

- Because of their long design and development cycle, satellites are launched with out-of-date technology. This is especially true of sensors and computers, where space observatories cannot take advantage of Moore's law of doubling capability every ~2 years.
- Satellites may exhaust their propellant, ending their useful lives while all components are perfectly functional.
- Detector systems may run out of cryogenic coolant, rending them inoperative.
- Satellites may experience problems with initial deployment of antennas and other mechanical equipment, limiting or destroying their operational utility. A memorable example is the Galileo planetary mission, where the high-gain antenna failed to deploy, limiting the amount of data that could be transmitted to Earth.
- Having to provide robustness against component failure requires redundancy, adding weight and cost.

The Hubble Space Telescope, the first of NASA's Great Observatories, is the "poster child" for the advantages of in-space maintenance and upgrades. Not only did the initial servicing mission (STS 61; Dec. 1993) rescue the telescope from its spherical aberration-induced inability to focus, which would have seriously compromised the mission – and called into question the competence of NASA and the judgment of the US scientific community – but repeated upgrades have continually increased the sensitivity and broadened the spectral range of the telescope, with consequent increases in scientific output (Figures 1, 2). Moreover, the effective cost of servicing has decreased over time (Figure 3). The Compton Gamma Ray Telescope, another Great Observatory, had a deployment failure of its high-gain antenna, which was fixed by astronaut intervention during its April, 1991 Space Shuttle deployment. The other two Great Observatories, Chandra (X-ray) and Spitzer (infrared) were neither designed for servicing nor placed in orbits accessible to the Shuttle. However, both of these observatories could benefit

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from servicing if it were available. Chandra, launched in 1999 on STS 99, has experienced a more rapid than anticipated degradation of its thermal blankets and a degraded performance of its radiation monitoring device (EPHIN) due to warmer than planned operation[1]. By way of comparison, a similar deterioration of Hubble's thermal blankets was discovered on the second servicing mission (STS-82; Feb. 1997). The blankets were partially repaired on that mission and have been more fully repaired on subsequent servicing missions. Spitzer, launched in August, 2003, is due to run out of cryogenic coolant within the near future. This will put the mission into a "warm mode" of operation, with two of its detector systems entirely out of operation and one operating in a significantly reduced capacity[2]. Both astronaut and robotic demonstrations of in-space fluid transfer have demonstrated that Spitzer's cryogen could be replenished had the system been designed for servicing and if servicing equipment could reach Spitzer's Earth-trailing orbit. The 2002 servicing mission to Hubble installed a new cooling system for NICMOS, due to the premature loss of its expendable cryogenic cooling, extending its useful life by more than 5 years. In addition, infrared detectors are now available with far larger size and greater resolution than the detectors on Spitzer, so servicing could in principle increase Spitzer's performance, just as has been the case with Hubble.

Whether future astronomy missions would be candidates for maintenance and upgrades depends to a large degree on what servicing capabilities are developed over the next decade. It seems reasonable that astronaut-based servicing missions would, as today, be reserved for the highest-priority (and most expensive) "flagship" missions, comparable to HST. Candidate astrophysics missions that fall in this category include the International X-ray Observatory (IXO), the various alternatives for the Advanced Technology Large-Aperture Space Telescope (ATLAST), the Single-Aperture Far-IR (SAFIR) observatory, some of the large planet-seeking missions, and, further into the future, perhaps the Generation-X observatory. Detailed decisions and any significant design work depend very much on the Astro2010 recommendations and NASA's implementation. For that reason, we are not advocating requirements to service future large observatory-class missions, but rather that the potential value of maintenance and upgrades be assessed for all such missions and that future observatory designs should not <u>preclude</u> servicing until such assessments are carried out.

In addition to Shuttle-based maintenance and upgrades performed by astronauts, several demonstrations of robotic satellite servicing have been flown, the most recent and most successful being Orbital Express (OE) in spring and summer of 2007. OE demonstrated automated rendezvous and capture/docking, module replacement, and fluid transfer. No less impressive has been the European Automated Transfer Vehicle (ATV), which autonomously rendezvoused and docked with the International Space Station (ISS) and, in addition to bringing supplies to ISS, transferred more than 1000 kg of fuel. The Dexterous End Effector (DEXTRE) on the robotic arm of the ISS can be operated either by astronauts inside the station or by controllers on the ground to replace components on the ISS truss structure. The demonstrated capabilities of both astronaut and robotic in-space maintenance and upgrading suggests that new, large-scale space missions should consider the operational and economic advantages that designing for serviceability may provide.

For purely robotic systems, the choice of whether to provide in-space maintenance and upgrade capability for astronomical satellites is somewhat different than for astronaut servicing. The robotic capabilities demonstrated by other space agencies, discussed in the previous paragraph, suggest that some level of robotic maintenance and upgrading may be cost effective even for modest-cost astronomy missions. For example, simple "inspector-bots'" may be valuable to incorporate within missions costing only a few hundred million dollars. Inspection of system failures, for example, could be both inexpensive and very beneficial: NASA HQ requested some years ago that JWST incorporate small cameras strategically placed around the observatory to observe the deployment and operations. On a more ambitious scale, an evolved version of, for example, DARPA's Orbital Express (OE) appears to be able to be developed and launched for (very) approximately \$300 M, which may make it cost effective to inspect, upgrade, repair, and refuel a satellite whose original cost was in the neighborhood of \$1 B. Decisions on servicing require a detailed assessment to determine, among other things, the 'break even' point in satellite repair and upgrade, where it makes economic sense to repair or upgrade a space mission as opposed to disposing of it.

Congress has recognized the potential value of servicing with the following language in the Omnibus FY09 Appropriations Bill recently passed by Congress:

<u>*Servicing Opportunities for Science Missions*</u>. *Recognizing the historic successes NASA has achieved through the servicing of the Hubble Space Telescope, the National Research Council's recent report Launching Science: Science Opportunities Provided by NASA's Constellation System recommends that ``NASA should study the benefits of designing spacecraft intended to operate around Earth or the Moon, or at the libration points for human and robotic servicing.'' This recommendation parallels the guidance provided by section 502 of the NASA Authorization Act of 2008 (P.L. 110-422), which recommends that provision be made for servicing of future scientific spacecraft to the extent practicable. Therefore, it will be critical that the Constellation program demonstrate unique capabilities to maintain synergies between free-flying scientific spacecraft and human spaceflight endeavors. Accordingly, the bill provides \$20,000,000 for NASA to undertake an assessment of the feasibility of using the Constellation architecture to service existing and future observatory-class scientific spacecraft…*

The economics of servicing depend greatly on the cost of maintaining a cadre of people to plan servicing missions and develop an infrastructure of servicing tools and techniques[3]. The Hubble Space Telescope servicing organization at NASA's Goddard Space Flight Center devotes almost all its energy to Hubble, and its cost is charged to the Hubble project. If a servicing organization instead supported many missions, especially missions for more than one agency, costs would be amortized with reduced impact on each individual mission and agency. This white paper suggests that NASA consider the impact of serviceability, not only for future large astronomy missions, but for Earth observation missions as well, in partnership with NOAA and other national agencies conducting operational missions. Unlike astronomical satellites, where upgrading detectors is a key goal of servicing, continuity of observations with calibrated instruments over long periods of time is critical for the ability of Earth observation satellites to analyze climate changes. It appears that AURA, TERRA and AQUA, for example, are all performing very well, but are running out of station-keeping fuel. Therefore, refueling is probably the most important technology for Earth observation satellites, together with the possibility of replacing failed components.

Many military space assets derive much of their utility by being able to adjust their orbits to pass over specific locations at specific times, which requires the expenditure of propellant. Military space assets are often sufficiently costly that being able to extend their lifetimes by refueling might be economically justified, even if no other servicing, such as repairs and upgrades, were provided. Commercial geostationary telecommunication satellites are also potential targets for servicing. The more satellites and organizations that use in-space maintenance and upgrades, the more efficient and cost-effective such servicing will become.

Another benefit from refueling and/or maintenance that has only recently risen to prominence is the disposal of space assets. These assets at end of life could be targeted for reentry by a servicing vehicle, or refueled for longer life, and eventual disposal, rather than becoming “space junk” with the concomitant risk of collision. The potential advantage of this was unfortunately demonstrated by the recent collision of an active Iridium satellite with a non-functional Russian Cosmos satellite.

Any changes made to the design of space hardware after the initial design reviews are complete inevitably carry hefty price tags. Therefore, the potential impact of serviceability and its implementation should be evaluated as early as possible in the design process of future missions. In addition, several project managers over the years have made the argument that building in serviceability from the start, even if never used, has led to a significant risk reduction during late development and integration and test (I&T) phases. Modularity, ease of replacement, commonality among electrical connectors, easy removal of thermal blankets, accessible fasteners, among much else, makes the inevitable I&T fixes and corrections far easier and less costly.

In-space human maintenance and repair capability has been amply demonstrated during Hubble servicing missions and in the construction of the International Space Station. From the beginning, humans have shown the ability to service components of Hubble that were never planned to be replaced or repaired. With the success of each mission, increasingly more challenging tasks have been attempted. The final planned Hubble servicing mission (STS 125) continues this trend with the actual replacement of individual electronics boards, something never dreamed of during the initial planning for Hubble. On the ISS, astronauts have dealt with many unplanned difficulties, including cleaning and lubricating the huge solar array rotary joints, addressing a problem not originally anticipated by ISS designers. Human space flight in the United States is about to make a transition from the Space Shuttle, due to be retired in the next few years, to the Orion crew exploration vehicle and the Constellation system. The Space Shuttle has provided an extraordinary base for EVA operations in low Earth orbit. This capability will be lost with the Shuttle's retirement, and the initial planned configuration of Orion is not designed to support sophisticated EVA operations. However, Orion's planned goal is eventually to carry humans beyond low Earth orbit, to the Moon and beyond. At present, there are no plans for NASA to assess the value (or cost) of capabilities for Orion other than transfer of astronauts from Earth to ISS and, later, from Earth to lunar orbit. However, the farther from Earth humans venture, the more critical is the ability to maintain and repair their equipment, some of which will have to be serviced externally by EVA. In planning EVA systems for the lunar mission phase of Orion (essentially a "Block 2" capability following the initial use of Orion for ISS access), it will be important to consider not only lunar surface EVA capabilities, but also in-space EVA repair and maintenance capabilities, which can be applied to assets in Earth orbit as well as to lunar mission assets.

As already mentioned, astronaut intervention is not the only way to maintain and upgrade space assets. Some initial successes of robotic systems were listed above, and progress in robotics technology will continually increase the capabilities of robotic space systems. Robotic systems can operate autonomously or by teleoperation, and while roboticists enjoy developing autonomous capabilities in their robots, we should also take full advantage of teleoperation capabilities, which can be used efficiently, even with time delays of several seconds for assets on or near the Moon or at Earth-Sun Lagrange points. The medical profession has accepted "robotic" surgery, where doctors teleoperate surgical tools with greater precision than they could achieve with their own hands. Plans for robotic servicing of Hubble, following the cancellation of the final Shuttle servicing mission (since reinstated), envisaged ground operators teleoperating a robotic arm to change out instruments and modules. Combining teleoperation capability with increasingly sophisticated end effectors and sensors will markedly increase the utility of future robotic servicing. Transferring the great variety of manual dexterity systems being developed in robotics laboratories worldwide to space will revolutionize space servicing capability. While robotic servicing, at least with current and near-future technology, will take much more time than human servicing, time is usually far less constrained with robotic missions than with human missions, so this should not be an impediment to robotic servicing.

It may not be necessary to choose between human and robotic servicing in the initial design of serviceability for a satellite. Experience with Hubble has shown that the best designs for human servicing use standard interfaces with simple, easily accessed fasteners, just the kind of design that makes robotic servicing possible. In fact, a good design principle for servicing would be to design as many components and subsystems as possible for robotic servicing. This can actually be more challenging than designing for human servicing, because of the limitations of current robotic technology, but the existence of robot-compatible hardware will ease the task of astronauts if they are called on to deal with unanticipated failures beyond the capability of robotic servicing.

Even during current shuttle-based servicing missions with astronauts, human-robotic synergy is a critical requirement for mission success. Both Hubble servicing and ISS construction and maintenance make extensive use of astronauts attached to the robotic manipulator arms. The teleoperated manipulators are able to maneuver massive objects, while humans provide the final precise positioning and the ability to make and break connectors. As stated above, developing robot-compatible connectors and fine positioning capability would not only make purely robotic servicing available in more situations but would ease the task of astronauts working on these systems. Future development of tools usable both by humans and robots is very much in line with the philosophy described above of designing servicing tasks to be robot-compatible, to simplify potential intervention by astronauts, if required. We further propose that the International Space Station has the potential to be an excellent testbed for servicing technology.

The assembly and servicing of future large space structures, such as observatories, will require the use of robotics technology that is more sophisticated than what is currently available. While such observatories may be designed to be fully or partially deployable, as the size and complexity of such structures increases, the need for assistance, either by design or as needed for repair, will clearly grow. Since the pursuit of new science will drive the need for larger apertures, larger and more complex structures are inevitable. However, the larger and more complex the structures become, the more unstable they will be to any disturbance, which will make relying on conventional deployment mechanisms increasingly risky. Direct involvement in assembly and servicing by astronauts will be difficult, since many of these observatories will be at locations far from Earth (Lagrange points, earth-trailing orbit, lunar poles, etc.) making human access very difficult and expensive. Additionally, the presence of astronauts may pose contamination issues for observatories with cold surfaces.

In order to enable robotic servicing of these complex, expensive missions launched in the 2020s and beyond, the advanced robotic technology needed for such missions must be developed in the 2010s. In addition to the obvious need for better human/robotic tools and autonomous or semi-autonomous robots with self-contained power/thermal control/data command control capabilities, examples of more specialized robotic technologies include "vision" and other sensor systems with precise geospatial knowledge, and specialized end-effector tools capable of exact positioning and fastening. Such tools will need to operate with precision in the temperature extremes of full sun or deep shade, and without damaging or contaminating the observatories. As it is possible that such robotic assembly/servicing will be done telerobotically and/or with multiple robotic devices, in order to improve speed and safety some means of situational awareness of the position of each robotic element and part of the observatory will be needed in order to avoid collisions. This suggests the development of small "observer" mini-satellites. Additionally, system dynamic models must be utilized to determine how the observatories and robots will behave in zero or partial-g environments. This is important for both actual operations as well as ground testing and simulation. For repair/servicing missions, specialized sensors to evaluate problems may well be needed to help determine a corrective course of action. In addition to equipment replacement and repair, we emphasize that the capability to use simple inspection mini-satellites will be important to analyze unanticipated problems that might occur during the operation of increasingly complex satellite systems. The Webb Space Telescope requires deployment both of its primary mirror and its huge sunshade. JWST is not being specifically designed for servicing, but should a problem occur, an inspection capability would be crucial in deciding whether a servicing mission could be mounted and in designing such a mission. Inspection satellites would be critical in providing situational awareness to ground controllers during robotic servicing missions. Again, the ISS could be an excellent testbed for such inspector satellites.

Finally, we make the following recommendations to the NRC for actions that will determine the utility of in-space maintenance and upgrades for future missions and will enable such servicing if deemed economically and operationally advantageous. Congress has requested NASA to assess this, and we propose that the NRC do the same.

Recommendations to the NRC

1. Begin early in the concept study of complex, expensive "Flagship" missions to evaluate the value of robot and/or astronaut maintenance and upgrades, including design impacts of "serviceability": modular sub-systems, blind-mate connectors, accessible fasteners, etc.

2. Undertake further non-advocate assessments of cost-benefit of in-space servicing with robots and/or astronauts.

3. Consider instituting a "Constellation Applications Program" at NASA, similar to the 1960's Apollo Applications Program, where use of the human spaceflight architecture can be considered for additional uses: for example, heavy lift vehicles, multi-use technologies, astronaut-based in-space servicing, etc. One aspect of such an “applications program” would be to establish ground rules for human spaceflight systems that, while not requiring the capability for astronaut-based in-space operations to support major science facilities, would at a minimum not preclude this possibility.

4. Examine a variety of alternative concepts for servicing, for example: very small inspection robots, multiple operations at Lagrange point servicing stations, innovative integration of astronauts and robots, etc.

5. Identify key technologies, capabilities, and activities over the coming decade that would sustain NASA's current capabilities for servicing and to prepare for the flagship missions of 2020+.

6. Evaluate the value to astronomy of a space-servicing capability developed to achieve other NASA and national goals: for example, adapting robot systems developed by other government agencies (e.g., DARPA’s Orbital Express and FREND) for use by NASA and the astronomy community.

7. Conduct tests of servicing technology on the International Space Station or elsewhere, as appropriate. Without viability demonstrations, designers will be reluctant to incorporate servicing capability into new missions.

8. Conduct inter-agency studies of servicing, to determine what servicing capabilities are most useful to different agencies and how servicing costs might best be amortized among various users.

References

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FIGURES

Figure 1

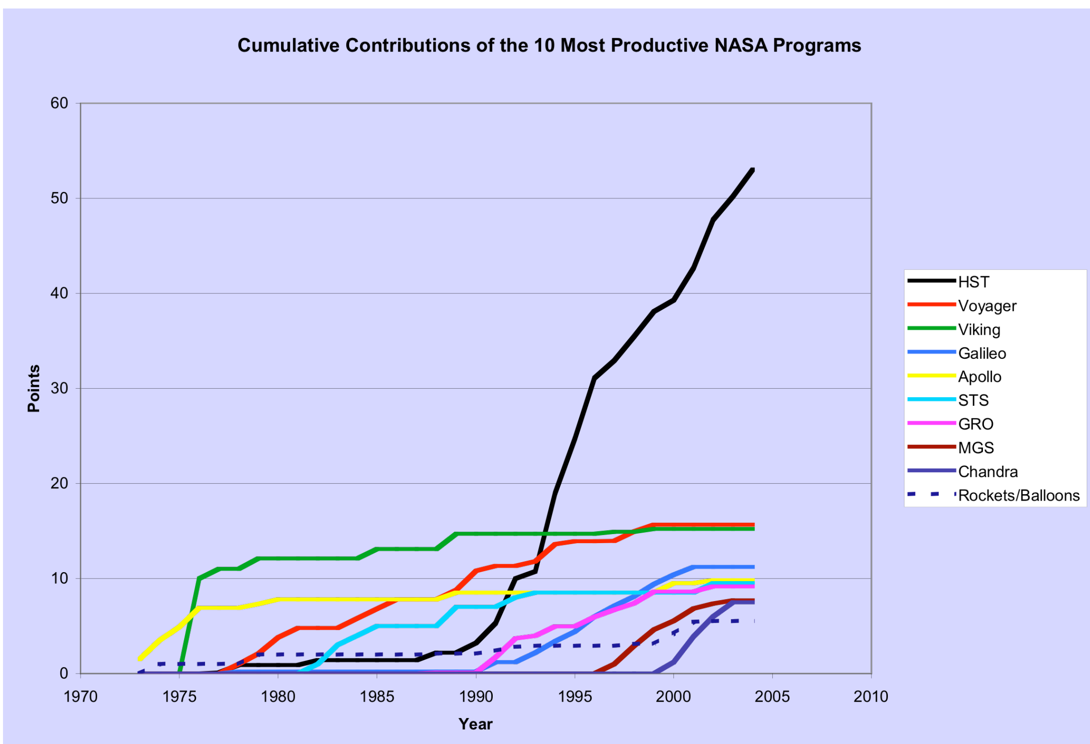

Figure 2

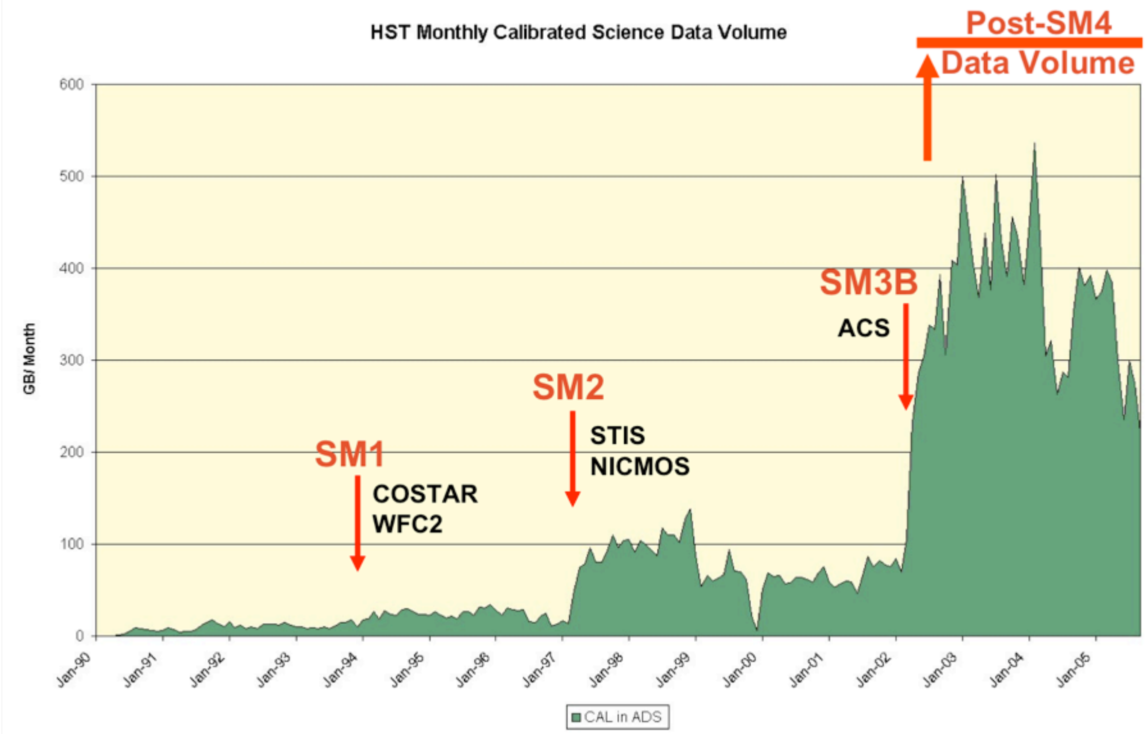

Figure 3