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Cultural Resources Management in Outer Space: Historic Preservation in the Graveyard Orbits

Luke A. Idziak[1]

1. NASA Ames Research Center, Mission Design Center, Moffett Field, CA, Email: luke.a.idziak@nasa.gov.

Abstract

Continuing advancements in commercial on-orbit servicing and operationally responsive space capabilities will soon allow new degrees of latitude in how satellites are interacted with and perceived. Now seen primarily as increasingly hazardous debris, non-operational artifacts in orbit can be re-envisioned as repairable or refuelable, as raw material, and also in some cases, as historic objects worthy of preserving into the future. The same robotic servicing platforms that will allow such a potential sorting of use, also make possible the relocation and clustering of certain satellites into specific orbital sequestration refuges that would be similar in function to museums. In addition to the ethical and cultural dimensions of preserving representative examples of such historical material, practical and economic rationales for doing so exist in the form of long-term material science research potential, and in supplying future space tourism and cultural resource management related fields. The advent of both fractionated and miniaturized satellite architectures, partly achieved already, will likely accelerate the already rapid rate at which the current generation of monolithic satellites will become obsolete and potential candidates for new on-orbit technology applications.

Keywords: historic preservation, outer space, satellites, orbital debris, on-orbit servicing

Introduction

In the beginning: the realized dream of remote sensing

The desire to sense and have immediate knowledge of distant events has been a pervasive theme throughout all of human history, on both an individual and an organizational level. Only recently though, through a combination of advances in rocket propulsion technology and the physical realization of what were previously solely science fiction concepts, has that ancient need been satisfied. The development and launching of Earth orbiting artifacts provides to global humanity the effective stretching of our sensory faculties into outer space. These satellites not only massively expand our collective analytical and appreciative apparati, but they expand our communicative interoperability as well in an unprecedented fashion. First envisioned by Arthur C. Clarke in 1945 (1), global positioning, communication, and remote sensing satellites allow all of modern global society to be linked together in an immediacy of massive import for all imaginable facets of human enterprise and experience.

The cultural and historical valuation of satellites as an ethical imperative

Satellites possess a truly unique style and engineered functional elegance all of their own in response to the unprecedented requirements of outer space operation, and represent the first complete departure that the earth has ever seen in terms of situational systems design, placing satellites in a rare and unique artifact class. From the first

generation of artificial orbiting bodies, the Sputnik series, to the current field of mobile multi-mission platforms and stations, they are the first objects created by humans to operate unconfined by earthly parameters and constraints. From a purely functional, much less aesthetic, standpoint they are invaluable examples of state of the art period machines that are worth preserving examples of into the future as they, and the time and minds that produced them are unique and will never again be repeated. Many older and currently operated satellites, with exceptions such as those in constellations like Iridium (2), are entirely bespoke and singular creations which, if any survive, may one day be seen in a similar light to priceless artworks or ancient computational engines.

Viewed in the purely functional light of current cultural and technical utilization, they are merely complicated conglomerations of alloy that once no longer useful, instantly become garbage, fit only for destruction. However, seen in a larger swath of time and technological evolution stretching both into the past and the future, existing satellites are representatives of not only the fulfillment of an early dream of humankind, but serve as tangible and lasting memorials to all those who allowed them to exist; from the sci-fi writers who first described them, to the designers, engineers, and technicians who created, launched, and operated them, and to the global era of technological humanity which first made use of them.

Historic preservation in outer space

The academic and scientific field of Historic Preservation has as its goal, the saving and interpreting of elements from the past and current built world in order that we may better understand from whence we have come and where we may choose yet to go (3). Indeed, if we are made blind to the past through a lack of information and extant examinable material, we become hindered in charting a course into the future and our potential agency as individuals and societies is greatly diminished. One of the best methods by which we can understand past peoples and their operating environments is through their legacy which exists into the present day in the form of the tools they used; and if we can in some ways understand those who have come before through these tools, then we will be better equipped to understand ourselves in the current time. It follows then that if we value, and have an affinity for and with, who and what we may become as a global and even interstellar civilization, it is incumbent upon us to preserve now that which still exists and has been saved from the past. In doing so, it is essential to take concrete steps to save elements of our current time in the form of tangible articles through which people of the future may come to understand our current perspectives and thus also potentially benefit as a result.

As a premier technology involved intimately with informing and shaping our current society, human-made Earth orbiting satellites are a class of material objects from which representative examples must be preserved in-situ for interpretation in the future; not only for anthropological understanding of the current time, but for research into the long term duration material science dimensions of contemporary spacecraft surfaces and components, and for the generative, wide-scale economic potential inherent to all rare and historical artifacts. In light of these reasons for preserving obsolete and current satellites, there emerges a discrete and defined way in which to "help sentient creatures" (4), ourselves and future humans in this case, in understanding our time and profiting from a preserved, irreplaceable material legacy. With newly developed technological abilities to do so, and a host of pressing economic and safety factors that threaten to supplant and or destroy orbital objects, a clearly explicated ethical imperative for contemporary humanity writ large becomes evident and actionable in the management of orbital cultural resources.

Any discussion regarding the idea of, and methods for, dealing with orbital material as historically and scientifically valuable, should be prefaced by making clear that in no way or case should the value of any orbiting artifact be weighed or compared against current or future human lives in space. The primacy of personnel and operational missions must be, of course, paramount and no debate over preserving historic orbital resources should attempt to hinder efforts to clear space lanes for decreased impact likelihood. Rather, efforts to preserve orbital material must focus on constructive and economical approaches that are, at least initially, concurrent to other missions and preferable to destructive methods.

Background

Precedents in space historic preservation and the current lack of coverage

Efforts heretofore, while describing in-situ orbital objects and debris as artifacts of a valuable cultural nature (5-9), and even broaching the concept of saving such relo-

cated artifacts within partially stable Lagrangian holding points (10), have primarily focused on calling for preventative actions while applying terrestrial legal precedents, treaties, and organizational methods to preserve lunar landing sites and artifacts (11). Using provisions within existing preservation and legal frameworks including the Antarctic Treaty System, the Moon Treaty, and the Outer Space Treaty, prior efforts and ideas have been generated in order to secure various lunar landing sites from harm; most recently by Rob Kelso, formerly of NASA and consultant to the Google Lunar X Prize who, alongside Dr. Beth O'Leary of New Mexico State University, helped to author the recently released NASA guidelines for non-impingement of the lunar landing sites and artifacts (12). This was done largely in response to the Google Lunar X Prize competition (but also in anticipation of Indian and Chinese robotic Moon landings) in which private teams and companies compete to land rovers on the Moon (13), with some teams also attempting a secondary competition of executing a mobile visit to an Apollo landing site in order to capture high resolution images of the lander surfaces for material science purposes: a bonus mission objective for which NASA will award a monetary prize (14). Russian national space agency officials have expressed desire for the Selenakhod X Prize team to carry out a similar inspection of the early Lunakhod Moon rovers (15). Both of these ancillary challenges are evidence of international interest in both the tangible historic legacy of specific national space craft and missions, and also in the scientific value of determining how the exposed artifacts have aged over the past half century, exposed to cosmic radiation, dust, micrometeorite impacts, extreme temperature cycling, and the ablation effect of nearby craft landings.

Previous examinations have called for orbital artifacts to be regarded as important elements of extant human cultural heritage, but come from a period in which the only practical intervention possible with an obsolete orbital body was through kinetic impact, and do not discuss how on-orbit preservation actions and arrangements might actually be performed. Barclay and Brooks in their paper, "In Situ Preservation of Historic Spacecraft" go farthest in this regard by mentioning the possible addition of boosters to historic spacecraft exteriors for altitude modulation and by suggesting the various Lagrangian points as potential locations for historic artifacts to be gathered into "scrapyards" and perhaps serve as tourist attraction zones (10). How or with what technology the application of external propulsion might be applied, and also specifying altitudes close to the graveyard orbits that might be suitable for clustering historic material still requires further examination. Additionally, all of the Lagrangian points of positional stability between the orbital intersections of the Earth and its moon are multiple times farther away than the 35,000 km of the geosynchronous orbit (GEO) and transportation to, and stabilization within them represents a more expensive and complex task than station keeping above the graveyard orbits in GEO and low-Earth orbit (LEO) due to distance and fuel expenditure. The mechanics of station keeping and interception at the Lagrangian, or libration, points is not fully understood yet in the way that such maneuvers in Earth orbit are, making any such location of material there more of a challenge as well. In addition, only two of the closest libration points are potentially suitable for the stable location of material, and these are also the intended jump off points for future interplanetary missions and associated fuel depots, making for a perhaps crowded mission critical real estate point in the future. Furthermore, and most crucially, if near future on-orbit historic preservation missions must rely on partnerships with concurrent and nearby commercial service missions, then transportation far beyond GEO will not be economically reasonable for the operating companies. This is not to say however that the Lagrange points are unsuitable entirely for the museum clustering of artifacts in the future, only that in the nearer term future where harsh economic and functional realities reign, museum cluster or altitude establishment closer to Earth will be a more immediately feasible option with current and developing technology, and will also be much more effective in allowing for tourism and research visitations.

The wide-spread, existing attitude towards artifacts in orbit is summed up well by PJ Capoletti in his 2010 book, *The Human Archaeology of Space:* "…and, finally, the vast archaeological space "midden" which encircles Earth. For our purposes, we will largely leave aside (this) third category…" (9). Only now beginning to take shape in any formal way a decade after the first publications by O'Leary and Gibson advocating for the application of United Nations heritage site protections and US National Trust for Historic Preservation applicability to the lunar landing sites (6), has the concept of preserving valuable cultural artifacts in space developed from a fringe idea into an intimately integrated and technically specified subject area presently found within planned Lunar exploration missions. Further in-depth works recently carried out by Castro (16), and Hearsey (17) in this vein also include new research regarding both establishing a body

to administer legal heritage site status on the Moon, and calling for the future conservation of solar system wide natural resources, landscapes, and human artifacts as an ethical duty.

To date however, there has yet to be any subsequent investigation or analysis into how, and with what specific technologies, orbital preservation efforts could take shape, or in showing a pressing need to do so based on evolving technical ability and accelerating obsolescence in the face of rapidly evolving space systems. In the same fashion that the above imminent revisiting of the Moon by private teams has spurred formal, technical recommendations regarding the protection of historic lunar artifacts from impingement, the coming revolutions in commercial on-orbit servicing and fractionated satellite architectures necessitate a new scrutiny of methods for interacting with and preserving historic orbital objects. Through an increased awareness of the dangers of collisional runaway debris, and advances in responsive satellite platforms, the operational nature of space access and utilization will soon come to be drastically altered. Alongside such transformations, the field of Historic Preservation now must grow to encompass these changes and orient them towards solving existing capability and articulation gaps in dealing with orbital concentrations of historic human space activity.

The state of the matter: current object locations and impact dangers

The next closest area, besides the Moon, in which human artifacts exist in great quantity, subject to various interactions, is in orbit around the Earth. Clustered in LEO at altitudes ranging from 100-2,000 km and in GEO at altitudes of around 35,000 km are tens of thousands of human launched objects ranging in size from radioactive particles (18) and centimeter long copper needles (19) from the early Starfish Prime and Westford experiments, to gigantic communications and sensing satellites like the recently lost Envisat (20) that can extend to school bus-like dimensions. The majority of derelict space objects are concentrated in LEO, moving at speeds of up to 10 km/s, and pose a serious risk to satellites, launch vehicles, and space stations. GEO, farther away, is harder to scan for objects and derelict craft with less being known about the state of debris concentration in this orbit. Generally, the objects in GEO travel at lower velocities and have less risk for collision. GEO, though, is a natural, limited resource which is currently under an allocation regime similar to that of the frequency spectrum and must also be kept free from harmful interferences. The monitored and tracked debris, along with largely uncounted thousands of minute to medium size projectile objects including nano satellites, paint flecks, hardware, tools, a glove, radiation degraded solar cell fragments, frozen human waste, rocket upper stage sections, propellant slag, and assorted cataclysmic impact fragments, are most often moving in unknown attitudes and pose an active risk to current missions in both GEO and LEO (21).

Within the period of a generation, the initial wondrous visage of the satellite artifact as a new heavenly body and extension of human faculties has been tarnished by the lens of time, familiarity, and frequency through which we now most often view satellites and their post-operational remainders as starkly functional units at best. In the worst, and most realistic light, we can see a worryingly harmful and potentially fatal clutter of debris which infest certain Earth orbits and present the spectre of a new dark age of reduced space access through runaway collisional cascading, the so called Kessler Syndrome (22, see below).

Current debris mitigation strategies and safety measures

This exponentially growing cloud of spacecraft debris promises to, if left unchecked, effect a valence around the planet of such a density and velocity, that lofting any new objects into orbit will become impossible due to impact strikes. Some models predict that unless immediate mitigation measures are undertaken, humanity will become trapped on Earth within the period of another generation due to this carromming and expanding shrapnel field which will not dissipate for hundreds of years (22). However, in addition to his description of this problem, Donald Kessler also provides models showing that a solution to the above potential isolation problem exists in a rather simple form: by removing just four to five large objects from an orbit per year, the growth potential for a collisional cascade is drastically reduced along with the likelihood of impacts with operational spacecraft (23). This model has led to an urgency in the debate over, and proposed solutions for dealing with, the debris problem including new guidelines being issued by organizations with space access capabilities to limit the amount and type of material allowed to separate from spacecraft during launch and while in orbit. An example of this new thinking can be seen in the US Federal Communications Commission (FCC) current requirement that satellites retain enough propellant to be sent into a 200-300 km higher altitude “graveyard” orbit

removed from active travel lanes upon cessation of mission or operational lifespan (24). However, approximately only one third of satellites, for various reasons, ever achieve this disposal orbit and remain inactive and non-responsive while still orbiting in heavily trafficked lanes, providing material for the above. In addition, governments and space agencies have joined together in such bodies as the Inter-Agency Space Debris Coordination Committee (IADC) to establish guidelines for spacecraft launch providers and operators to follow in order to limit the amount of hardware and orbital separation detritus resulting from launching spacecraft. The Committee on the Peaceful Uses of Outer Space (COPUOS) publishes orbital debris mitigation guidelines as well (25), and the US Federal Aviation Administration (FAA) also states that among other legal measures "…we require upper (booster) stages to vent their fuels and power down their batteries so as not to have any 'untoward' events." (26).

Various active methods are seen as necessary (27) to counter the threat of orbital debris and have been designed to assist in mitigation efforts that primarily utilize destructive or ablative techniques in which high altitude undesirables would be targeted with lasers (28), dragged down into a reentry and disintegration orbit by virtue of electrodynamic tether attachments (29), or through interception and grappling by robotic satellites (30). All of these methods to date rely upon merely limiting new debris generation or share in causing a destructive, atmospheric end for the interacted-with orbital object. As the debris impact problem becomes more pressing, destructive measures and actions to deorbit satellites will only increase, and along with fragments and scrap, valuable artifacts will certainly be lost which could have, in many cases, been instead saved with a different application of very similar intervention platform technology.

Towards a new altitude: orbital museum clusters

Preservation among the bodies of the graveyard orbit

There is an urgent necessity for a change in the perception of non-functional orbital material commonly considered to be "space trash" (31), and an accompanying legal, operational framework governing how orbital debris are regarded and managed by international bodies in positions of actionable authority over the access to and management of space objects. I posit that there is also an immediate need for the proposal of a strategy, through which on-orbit service technology existing and in development would be utilized to relocate derelict space objects with valuable historicity from currently used orbits and travel lanes to within stable orbital clusters specifically set aside for their preservation and stewardship in positions closely above both the LEO and GEO satellite disposal graveyards. Besides the tangible cultural value in saving certain artifacts from the ravages of time, the benefits from the instantiation of such sequestration and preservation refuges will include assisting in the prevention of the Kessler syndrome, while providing space tourists and travelers alike with historic destinations to visit. Such clusters will also be essential in allowing materials science researchers access to an expandable and unmatched long term space weather exposure laboratory. In addition, through such orbital establishments, the field of Historic Preservation will gain a new high frontier in its efforts to conserve cultural memory through material preservation in space and thus be better able to serve the collective human desire for continuity of memory.

Just as the field of Outer Space Historic Preservation is an idea yet in its infancy, the same was once true for all other established historical disciplines. By way of comparison, the early settlers on the North American coast could never have imagined that there would one day be an entire ecosystem of academic, technical, research, and interpretation institutions, with tens of thousands of associated professionals employed based largely on digging up the trash that had been discarded so offhandedly by the same colonists just a few generations ago (31). Invariably, those elements of a material culture considered trash at the end of their functional life and relegated to the scrap heaps of time by one society, find new life upon becoming deemed a valued informational and economic commodity by a later society which fervently locates such garbage in order to conserve and interpret it within cultural and scientific institutions. Indeed, Historic Preservation as a field, exists only by virtue of the detritus of the past being examined and studied in an analytical fashion, thus providing the necessary raw subject material to the many higher educational institutions, museums, historical societies, private consulting companies, public and private research organizations, materials science laboratories, and other specialized institutions and individuals whose focus is the understanding and presenting of material from past societies.

In the same way that existing terrestrial trash deposits have provided one of the most clear windows into the life of the past and have generated entire new worlds and

ways of life in the future societies which value understanding the past through the aperture of material culture, the artifacts in space that have been produced by the current generation, if allowed to exist intact into the future, will be absolutely essential in allowing the creation and development of brand new disciplines and fields specialized for the space environment. The new field of Outer Space Historic Preservation, made possible through conservation efforts directed towards orbital objects as well as those situated on the surfaces of planetary bodies, will have a vital role in generating a much richer and more nuanced future culture than ever would have been possible if much of the "trash" now cluttering space is perfunctorily destroyed.

Space tourism and historical destinations: benefits and challenges

History has shown that tourists consistently desire to visit locations and destinations which tell stories and have tangible material existing from a past period. From the ancient Greeks who reveled in conceptions of a past high technology culture in the form of Atlantean myths, to the present day where vessels ply the air and sea to deliver curious visitors to distant locations around the globe, a widespread desire and market have always existed in visiting and marveling at the technical achievements of past cultures in the form of grandiose historical sedimentia which stand in mute testimony to previous herculean engineering efforts. People have desired these personal adventures not only for the novelty and grandeur of such tangible experiences, but also for the sense of personal development and historical continuity that is to be found when gazing through time via such artifactual lenses. This narrative aspect of the visitors experience is one that will undoubtably continue into the future and one which would be especially well served by the preservation of certain space artifact concentrations in the vast emptiness of space.

Visits to space by civilian tourists are continuing and will soon become more economical and common with the fulfillment of efforts by companies such as *Space Adventures*, *Virgin Galactic*, and *Sierra Nevada Corporation* to bring paying customers to the edge of space and beyond (32). *Space Adventures*, in addition to its asteroid prospecting spin-off *Planetary Resources*, is already advertising for planned circumlunar trips for tourists (33). While such a trip may be a goodly number of years away still, an emergent space landscape becomes evident in which the old desire for new vistas continues into space with unique destinations providing a powerful draw. Humans have already visited historical space destinations numerous times in official capacities, through repairing older satellites and performing subtractive archaeology on lunar landers (34), and as the commercial market in space continues to extend to human visitation, such visits will certainly continue and could even include sight seeing and research visits to historical artifacts in orbit by paying customers. One can imagine a scenario in which a multi-millionaire space tourist, who as a child saw the launch of Vanguard 1, could now become enthralled with the possibility of tangibly visiting the same satellite in person so many years later, and might pay a few extra million for a flyby and viewing of it.

One of main points of a recent report by the Futron Corporation concerns the necessity of destinations for tourists in ensuring that the market will be economically viable: "Location, location, location – The most important thing about on-orbit destinations is options." (35)

In the near future paying space tourists will go where there are things to see and do, just as on Earth, and with the current limited number of choices, ie: the ISS, efforts to provide additional space destinations in LEO and GEO besides the space station, could make economic sense. Such location provision efforts however must be paired with a fully developed on-orbit service market that is already engaged in the location, interception, and relocation of satellites.

An essential element of such visits to historic space sites and artifacts must be the preservation of them. Tourists have a way of methodically degrading valuable sites through contact and frequency; this potential issue exists in space as well. In a substantial way, this is already being addressed through measures such as the non-impingement guidelines issued by NASA for future lunar lander teams, and through the ownership and liability provisions of the Outer Space Treaty (36). It may prove easier to provide protective measures to orbital cultural resources if they are clustered together with blanket regulations applying to all those in a specific museum grouping along with collective, transferred ownership. Liability in such a case would still reside with the launching state of each specific object, and this factor must be addressed and clarified through future laws and agreements.

In the interests of preserving long term economic and scientific value, visiting tourists and researchers may provide the funding and economic model by which on-orbit missions to relocate satellites designated as historic can be afforded and their targets conserved for the long term with regard to considerations such as station keeping and insurance costs. Additional sources of funding for establishing orbital museum clusters could potentially be seen by looking at terrestrial analogs in which public/private partnerships are used to equip projects like the restoration and redevelopment of historic buildings and structures. Often a property developer becomes eligible for grants or tax benefits if certain elements of existing historic structures are preserved and integrated within the new construction (37). Such projects usually will involve the local government in the form of an Architectural Review Board, a Historic Preservation Office, the developer, the owner, and sometimes outside philanthropists. Similar incentives and arrangements might be possible between actors in space where the disposition of historic orbital material is involved in the future. The attraction for donors in having their name attached to an object or museum cluster, that will conceivably far outlast any similar cultural establishment on Earth, should not be discounted.

Material science studies in space

I agree that it is vitally important to preserve the cultural and technological memory of humanity and secure its continuity into the future through a mechanism such as museums in space. Perhaps more importantly, orbital artifacts existing from the dawn of the space age and continuing into the present day have a unique value in that they are the only man-made objects which have recorded and preserved space weather conditions and the attendant effects upon their constituent materials for constant, long term durations.

Any conception of proposed multi-generational space travel or colonization missions will require a detailed understanding of the myriad effects upon, and behavior of, potential spacecraft and structural materials over time spans with which humankind has no experience or data. Radiation, micrometeorite impacts, ionizing gases, thermal cycling, and a wide variety of other space weather elements all act upon the materials that compose spacecraft in very different ways that are not at all entirely yet understood, especially over long periods. There are no data yet in existence that will allow us to know with certainty how materials will perform in space past approximately 65 years; the longer that objects remain in orbit, the more information humanity will accrue that is directly relevant to material science and long term mission success in the future. The surviving objects and satellites now in orbit are the sole human repository of material science exposure data over periods beginning to approximate such missions, and their ongoing study will be essential in validating and rating the performance of materials intended for potential interstellar voyages and other applications of similar duration. Known phenomena such as vacuum welding for example, still trouble current satellites and missions (38). Unforeseen behaviors and combinatory properties may well affect or inhibit familiar materials over unfamiliar periods of mission time and space weather exposure. If wholesale efforts to eliminate or harvest orbital objects are carried out with no thought towards either their cultural or scientific dimensions, humanity will be less knowledgeable and prepared for future spacecraft design and mission planning.

Just as a demonstrated market for space tourism exists, with the potential for expansion alongside access capabilities into new markets such as heritage site and object tourism, I opine that the field of materials science research will greatly benefit from having such clusters of historic satellites and objects. Such locations could well become important field research destinations and the setting of laboratory space station facilities. Such installations could likely be used for both artifact conservation and material science research, supporting two new space fields and potentially allowing productive cross disciplinary fertilization and new future research directions which, as space preservationist Alice Gorman claims, “we cannot anticipate” (39).

By allowing legacy satellites and other historic orbital objects to be saved over long periods of time, a rich nutritional medium will be created and provide many fields, organizations, and individuals with information and material with which to add to the space economy of the future. Every location established in orbit, such as the hypothetical laboratory research station focused on a museum cluster, is a potential visitation destination for paying tourists and scientists, as well as a potential point of rescue or assistance depot to other space operators. Much like in the way that even a small chunk of garbage floating in the open ocean will cause sea life to cluster around it and develop micro eco-systems (40), orbital clusterings of objects previously rejected by their builders, could become cornerstones of a larger space economy and cultural

landscape partially based on salvage, preservation, and research activities.

Game changing on-orbit technologies

New capabilities in satellite repairing, salvaging, stabilizing, recreating, sensing, communication, and on-demand rapid fabrication that effect proposed Historic Preservation space mission concepts

Far from being a new concept, on-orbit servicing has been a vital fixture of the human operational presence in space from its early days. Beginning with the first docking, assemblage, and subsequent repair of the Skylab space station in 1973 (41), and the retrieval and repair of satellites such as the Solar Maximum Mission in 1984, which was the first example of a modular satellite architecture designed for potential repair; intercepted and repaired by the space shuttle and crew (42). Following quickly after was the first precedent for a pairing of space salvage with repair mission in which the malfunctioning Palapa B2 satellite was intercepted by an astronaut floating freely with a manned maneuvering unit back pack, and returned to Earth aboard the shuttle for repair and relaunch (43). To date, the largest involvement with on-orbit servicing have been the four separate missions to modify and repair the Hubble Space Telescope by space walking astronauts (44). Besides being invaluable to continued research, development, and the maximization of investment, such demonstrated orbital service successes are of interest to many groups including insurers and underwriters of space missions as well as those who hope to prolong the life of existing satellites or resurrect ones long inactive due only to a lack of fuel or external component malfunction.

Although humans and robots working together on tasks is an optimal long term strategy in the space environment, the role of robotic platforms in servicing missions is receiving the most attention and development. Beginning with the US Defense Advanced Research Projects Agency Agency (DARPA) MiTeX satellite duo (45) which demonstrated robotic interception and manipulation in space, robotic interfacing and interception with cooperative and non-cooperative targets has been repeatedly demonstrated. Additionally, the robotic arms aboard the ISS are an on-orbit service technology which have a proven ability to modify and construct structures in space, one of the eventual end goals of on-orbit service spacecraft. The basic technology and elements already exist in terms of docking, manipulation, and modification capability and have been employed in space primarily with the space shuttle, the ISS, and the Hubble Space Telescope thus far. With the growing appreciation of both space debris dangers and of the value inherent in previously inaccessible and dead satellites, the development and integration of these existing technologies into mobile, multi-mission spacecraft by the commercial satellite industry is proceeding.

At the DARPA *Fostering Sustainable Satellite Servicing Conference*, in Arlington, VA on June 26, 2012 (46), current projects and intentions, including business models, towards fielding service platforms were presented under the rubric of the DARPA 'Phoenix' program and included presentations of hardware by MDA, Boeing, DLR, and JAXA. Showcased in the setting of the Phoenix program and its call for new integrated service abilities, were the latest robotic interface arms and techniques that could be used for refueling satellites and modifying them through the addition or subtraction of components including fuel. Installing new batteries and antennas were shown to be feasible, as well as the removal of useful hardware for repurposing on other satellites. A significant difficulty that was expected to be encountered by the conference participants and presenters was the refueling of and general interfacing with legacy spacecraft due to their lack of accessible fuel tank ports and interfaces. Cutting new fuel ports with lasers, among other means, was proposed as an option, and the general lack of standardized interfaces among satellites and manufacturers among all production and usage periods was identified as a significant hurdle to be overcome in designing the robotic arms and manipulation interfaces needed for on-orbit service missions.

With only a few uses of the European automated transfer vehicle (ATV) for resupplying the ISS remaining, new uses are being developed for the robotic docking platform which include orbital debris interception and collection. In this iteration the ATV will be called the OTV (Orbital Transfer Vehicle) and is intended to be used in fielding innovative approaches towards interception and capture of orbital resources (47). If used as intended, the OTV will likely prove to be a capable system for on-orbit service interactions of various types as well as debris mitigation efforts due to it's sophisticated laser range finding and docking technology. Its fuel capacity and prior proven interoperability with robotic arm systems like those on the ISS will doubtlessly also lessen hurdles towards it's use for future on-orbit missions. The example of the ATV/OTV dual use capacity is instructive in visualizing new uses for current on-orbit rendezvous platforms in the fu-

ture which might include commercial satellite service and historic preservation missions.

On November 2, 2012, MacDonald Dettwiler and Associates (MDA) corporation, a major Canadian space technology and satellite contractor, completed the purchase of Space Systems/Loral, a US based satellite manufacturer. A stated goal of the buyout was increased access to US Department of Defense (DoD) business, which occurred directly in the recent awarding of a $30 million contract from DARPA to MDA for space robotics work and development on the Phoenix in-orbit satellite servicing project (48).

Historic recreation of service modified satellite components

Service missions which disrupt the historic fabric of existing satellites, either to add new features or to remove components such as antennas or photovoltaic panels for use on other craft will be a feature of the new orbital landscape (49). Historic preservationists and potential space cultural resource managers should begin to consider how to address such alterations to orbital artifacts. One possible solution to the problem of element removal can be seen by looking at current museum interpretation practices; objects with missing elements are often augmented, or more accurately restored, to their original state in form if not actuality by the inclusion of fascimile replacement sections. In a similar fashion, and in a future of common on-orbit service paired with preservation missions, the use of 3D printer type deposition heads could conceivably be employed on the ends of robotic arms by service craft to faithfully reproduce and install replacement parts of historic satellites slated for re-use or salvage. In the, so far, material scarce environment of space, priority must naturally be given to the needs functional current missions, but preserving the historic appearance and shape of impacted-upon historic craft is an area that bears further study.

On-demand interface fabrication for on-orbit service missions

The challenges of obsolete and non-standardized interfaces among almost all periods and types of satellites, in terms of fuel access, electronics, and hardware present formidable challenges to on-orbit service efforts. Often new tools and equipment must be designed for specific missions at additional expense and mission delay. A stated objective of new on-orbit service projects such as the DARPA Phoenix program is the establishment of industry wide standards to make future service missions less complex. Legacy spacecraft however, with their wide variation in interface systems, must still be dealt with and require innovative solutions in terms of robotic manipulation tool heads. One possible solution to this incompatibility issue might be found in the use of rapid deposition fabrication to create new tools and interfaces as needed while on-orbit. Additive techniques such as 3D printing or selective metal sintering, if developed to work in the space environment could provide the ability for service craft to have such capabilities.

Proposed clustering and station keeping methods for orbital museums

A detailed analysis of propulsion, maneuvering technology, and couplers is beyond the scope of this address; However, here I provide a few potential types and general applications as suggestion for further research:

1. Magnetic coupling systems might be used to link the individual objects in a museum cluster. These could be stand-off mechanisms in which opposed magnets at the ends of elongated trusses are used to hold two artifacts together while not actually touching the outer skin of either. If ferrous surfaces were not extant on certain craft, induced magnetism through eddy currents might be used, or magnets might be affixed by service craft in the least intrusive fashion possible. Dry adhesion technologies may also provide a means of affixing objects in space with minimal disruption of historic fabrics (50).

2. The addition of electrodynamic tethers to objects in orbit could be used to gradually relocate them into desired locations, and could potentially be used in station keeping duties once an object was tied into a cluster with others at the same point. Fieldable examples exist, produced by Tethers Unlimited Inc., which are designed to be added to the exteriors of spacecraft before and after launch and could be installed by service craft (51).

3. Ion thrusters in various forms can also be used to gradually relocate objects to locations including future museum clusters. One promising type is the Hall effect type thruster produced by Busek Inc. (52), which has the potential to be affixed to the exterior

of existing craft and could also be used for station keeping of a cluster.

4. Recently developed by the MIT Space Propulsion Laboratory, working micro electromechanical electrospray propulsion units the size of postage stamps have been created, producing 1-2 micro newtons of thrust each (53). These revolutionary ion thrusters are only 2.5 mm in thickness and are intended as propulsion units for cube sats and other miniaturized satellites. This new ion thruster technology shows dramatic promise and if scalable or producible through rapid deposition, will potentially allow surfaces of spacecraft and objects to be covered with sheets of ion drives, permitting very minute and almost infinitely adjustable pointing and attitude adjustments in addition to station keeping functions. If 3D printing feed stock material and deposition technology develops to allow its use in outer space, it is conceivable that on-orbit service craft might literally be able to print the layered substrates of this thruster technology directly onto derelict craft which lack remaining onboard fuel. With the use of existing solar cells, these deposited ion thruster sheets could allow the object to achieve and maintain a museum cluster location. Another related option might be for servicing satellites to be equipped with "quivers" of terrestrially produced ion thruster sheets which could then be affixed to surfaces in space. Areas to be addressed in investigating such options further include provisions for power and attitude and stability control of thus retrofitted craft.

5. Besides the current intended use for cube satellites, this technology also has potential for propelling pico and mote class satellites in the future (54). The current movement towards communicative fractionated satellite architectures, seen in the DARPA F-6 program and the NASA Ames Research Center's EDSN program, has as a potential future evolution, the use of flexible "smart dust" swarms that will effect mesh networks and take over many sensing and signaling functions formerly possible only to much larger, and more costly spacecraft.

6. Electrostatic grasping technology developed by Altius Space Machines Inc., has recently been tested successfully and show promise for both intercepting and potentially coupling together space artifacts with no disruption of historic surface fabric (55).

Fractionated space architectures with distributed micro, nano, and chip satellites: a structural game changer

The lag-time between technology development and the fielding of satellite sensor payloads and hardware often results in a situation where the technology in orbit is obsolete from the beginning of it's useful life. A recent attempt to resolve this problem and also allow more flexibility and interoperability of system and payload components in the case of damage or failure is the introduction of the distributed satellite architecture concept (56).

Currently, a newly launched satellite may rely on ten year old technology by the time it begins its service life and then must be used for another 10-15 years to ensure a return on initial development and continuing operations investments. A new model of responsive satellite swarm architectures will allow each component of a satellite to be modular and replaceable when a new version comes on line or an existing unit is damaged. In much the same way as the former Soviet Union relied upon frequent launching of satellites to replace those damaged in the periodically radiation-soaked Molniya orbits, the new model of modular and miniaturized satellite systems, as seen in the DARPA F-6 program, will allow less of a focus on the shielding, robustness, and hardening of components and will instead replace them rather frequently, which will have the ancillary benefit of allowing new technology and abilities to come to bear with a new standard of rapidity. This coming revolution in satellite scale and architecture, and also that of the swarm and mote class satellite concepts also being worked towards, represent a fundamental departure in both how satellites have been traditionally seen, and in how they function. The idea of distributed satellite functioning is envisioned to eventually rely upon multiple generations of small, disposable satellites which have short lifespans in order to allow the rapid fielding of newly developed technology and the timely elimination of non-operable or obsolete units.

With the standardization and routine orbiting of the 10 cm cube satellite bus configuration now established, efforts towards even smaller functional satellites are underway. Currently, the smallest operational satellite platforms now in space are a prototype satellite-on-a-chip called Sprite which is currently being tested on the exterior of the ISS.

These Sprite board satellites mass just 10 grams and are 3.8 by 3.8 cm in size and contain, in miniature, many of the basic elements and capabilities of their monolithic macro satellite brethren. These and other even smaller models to come, are envisioned as being the fundamental units in a new model of how space sensing and data transfer might take shape (57).

A desired use of these types of "smart dust" satellites is in the creation of mesh networks of numerous and disposable units which could be deployed in space quickly and at low cost for temporary situational awareness needs. Many would be destroyed by radiation and deorbiting atmospheric drag, but in a distributed network they would have a statistical robustness that would surpass that of a traditional satellites in which one component failure frequently renders the entire craft useless. A major limitation to such ultra miniaturized satellites is their lack of propulsion and pointing ability. This limitation shows signs of potentially being overcome however by micro ion electrospray thrusters that have been built and tested by the MIT Space Propulsion Laboratory and which are able to generate micro newtons of thrust in the 2,000-3,000 second specific impulse range. The technology that is being created for use on cube, chip, and even mote satellites is one that can be conceivably reproduced in varying scales by automated deposition techniques. An attractive future concept for the use of such technology in commercial on-orbit servicing missions, envisions the application of ion thruster laminate sheeting or panels to the exterior of non-operational craft, artifacts, and irregular material. In such a way could the lifespans of satellites be extended and new maneuvering capabilities added to inert objects and those intended for museum clusters without pre-existing or functioning propulsion units.

If this technology is able to be extended into space in an economical manner, then it will likely prove useful in a wide variety of areas. The placement of ownership transmission beacons on space resources including asteroids and salvageable craft will be a necessary niche to fill and in a similar way, such ultra miniaturized 'mote' sats might also be used to locate and shadow even very small debris items while providing a locational or proximity warning, especially useful in the less mapped GEO orbit. Using such mote sats to deorbit debris could be imagined as well in the form of agglomerated chipsats acting in an exobrake drag function. The identification, tracking, and preservation of historic material would be facilitated by such a fieldable development, and the interception of objects followed by attachment and relocation to cluster nodes in other orbits might be a possible function of a collective swarm of powered mote sats. In addition, once in formation, the attached or nearby mote sats might be able to perform station keeping calculations and duties for the constituents of the cluster or formation with remaining fuel or through utilizing the surface material of the attached object as reaction mass.

Interdiction of non-cooperative space assets and preservation as diplomacy

On-orbit service technologies and platforms can be used in offensive or defensive capacities as well as in repair and modification of satellites. This is a facet of ORS space that must be acknowledged and taken into account in discussions over future servicing missions. Deliberations over the use of such technology for benign historic preservation efforts that address cultural issues in a long term global rubric may prove to be a neutral international meeting ground for lateral diplomacy. There exist world wide variations in how historicity is seen to imbue objects and structures, and more specifically in the appropriate balance between recreation and restoration is, especially in an oriental/occidental dichotomy. Such minor, non-militarized gulfs could prove to be useful in drawing together international actors in space access for conferences and meetings which would serve to increase the potential for dialogue and provide new discussion topics closely related, but differentiated, from traditional military concerns.

Service implications: illicit use of bent-pipe satellites

Some of the non-functioning satellites proposed as being candidates for relocation and preservation schemes are actually still in use as passive "bent-pipes" that are often clandestinely employed by criminal gangs and rebel organizations. Primarily used by the sophisticated criminal underworld in Brazil, these reflector dish satellites can be used to bounce coded transmissions and pirated media content for effective point to point ground communications (58). One seemingly remote, but imaginable factor that must be addressed in plans to reutilize or alter satellite orbit profiles is the potential danger to advocates and actuators of such on-orbit techniques that disrupt the communication networks of underworld groups. Hard data is lacking in this area, and further research and analysis are indicated to gauge the extent of both unofficial satellite usage and of any potential danger from this sector. Other, unknown as yet, users of such bent-pipe satellites should

be investigated to better understand the scope of illicit satellite communication and the potential ramification of on-orbit activities in affecting such users.

Recommendations

The critical need for greater space situational awareness and understanding of the state of orbital objects, along with the ability to interact with them in ever more finite ways, is evident now and is only expected to grow with increased space access and utilization in the near future. Developing areas like on-orbit servicing and salvage, space material sciences, space tourism ventures, and cultural resources management in space will affect, and in turn be affected by, near-future factors which together will create disruptive change, altering the technological, cultural, and situational status quo of orbital space:

- The imminent collision threat posed by uncontrolled and abandoned objects in orbits shared or intersecting with operational spacecraft, and the new technologies designed to mitigate or eliminate the former; the new and widely held perception that all such obsolete or defunct satellites and other related objects and materials in orbit are "space junk" or "orbital debris" with no remaining use or value.

- Recent steps towards commercial on-orbit servicing mission platforms utilizing new operationally responsive space technology capabilities and combined with novel satellite interception and manipulation capabilities.

- The launching and testing of new types of increasingly specialized and miniaturized satellites along with the evolution of a new space satellite architecture model relying on distributed "swarms" of disposable micro satellites to perform specific mission functions while situationally mesh networked.

- The very recent expansion of the heretofore terrestrially bound field of Historic Preservation into outer space; thus far largely confined to efforts in protecting the Lunar landing sites and artifacts left by astronauts from impingement during future Moon landings, whether by national or private space actors, but likely to be legally involved in matters of ownership and responsibility.

Further steps that should be taken in order to preserve existing and future satellites in orbit while also securing material science research repositories and tourism destinations include:

1. A survey of certain representative examples should be performed for identification and inclusion within a new registration regime, with attendant legal and liability issues addressed for each, and international facilitation and partnership opportunities examined.

2. The on-orbit, operationally responsive technology to interact with them must be further described, developed, and brought to bear in an economically feasible and sustainable manner concurrent with other nearby servicing missions.

3. Long term, station-kept orbital preservation cluster positions and altitudes should be designated and allocated in orbit at altitudes near both LEO and GEO.

Conclusion

Non-functional spacecraft and related objects still in orbit are potentially valuable historical resources with epoch-spanning intrinsic and extrinsic cultural value, perhaps exceeding any other known human technological artifacts. Never before in recorded human history have we been in a position to have such an accumulated and tracked deposit existing in a totally extant orbital stratigraphy. Enabled and hastened by new on-orbit service technologies and spurred by structural changes beginning to emerge in satellite architecture, a once-in-a-civilization chance to mitigate debris and also preserve the cultural resources that provide an artifactual record of our very first, and continuing steps outwards from the gravity-well is now before us and must be seized.

I put forth that preserving a tangible, material record in the form of representative examples of the spacecraft and artificial satellites which make up a large part of the history of our collective initial journey into space is both an ethical imperative, and a vital, necessary endeavor. Currently under threat of destruction from collisional cascades, deorbiting mitigation methods, and potential salvage efforts, I urge that it is incumbent to begin planning for the active preservation of historic orbital artifacts in order to allow long term scientific study, new economic activity generation, and also to secure continuity of understanding and appreciation for the dreams and efforts of

all those who imagined, designed, built, and operated the cold and dark technology now abandoned in orbit.

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Competing interests

The author declares that he has no competing interests.

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