

The Archaeology of Orbital Space

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Summary: More than 10 000 objects larger than 10 cm are currently in earth orbit. These objects include satellites, launch vehicle upper stages, mission-related debris and “space junk”. The amount of debris constitutes a threat for the successful development and delivery of space services. In the near future, space agencies are considering the necessity of removing material from orbital space. In the longer term, some orbital material may be both the subject of commercial salvage operations, and a destination for space tourists. Orbital objects and debris are the cultural heritage of the “Space Age” inaugurated by the launch of Sputnik I in 1957. Ever since, the formerly “empty” orbital space has become an organically evolving cultural landscape. This paper discusses the heritage value of orbital objects and space junk, and suggests avenues for managing the archaeological record of human endeavours beyond the atmosphere.

Keywords: orbital debris, cultural heritage, cultural landscape, Vanguard 1, FedSat, Syncom 3, material culture

Introduction

In the nearly 50 years since the launch of Sputnik 1 in 1957, Earth’s orbital space has become densely populated with human material culture, objects that represent a unique phase in human technological, political and social evolution. Earth orbit has accumulated more than 10 000 trackable objects, including satellites, launch vehicle upper stages, mission-related debris, human remains and “space junk”. For space industry, these objects fall into two classes: operational spacecraft, and orbital debris, which has now become a serious problem for the continued use of high density orbits.

Orbital debris constitutes a straightforward, though far from easy, management problem. Immediate solutions to control the proliferation of debris include the implementation of design and operation practices recommended by the US National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and the United Nations [1, 2, 3]. In the near future, space agencies are also considering the necessity of removing material from orbital space. Proposals include destruction using ground- and space-based lasers, and intervention missions. In the far distant future, some orbital material may be both the subject of commercial salvage operations, and a destination for space tourists.

However, the problem has another dimension that is generally overlooked. Orbital space is now an organically evolving cultural landscape formed by the interaction of human and environmental processes. Both the materials in it and their location in this landscape, or spacescape, may have significance in social, historical, scientific and aesthetic terms according to the internationally recognized guidelines of the Burra Charter [4]. Proposals for orbital clean-up need to consider how to manage cultural heritage values inherent in the orbital spacescape.

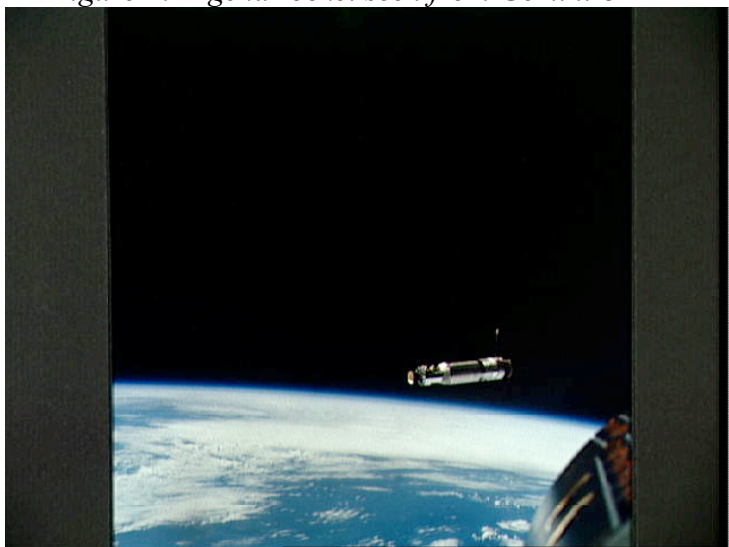
But not every object poses the same risk to space operations. By assessing the risk presented by different debris size classes, I argue that there is considerable leeway for preserving significant orbital objects such as Vanguard 1, the oldest human object in space, Australia's FedSat scientific satellite, and Syncom 3, the first true geostationary satellite. This paper discusses the heritage value of orbital material and "space junk", and suggests avenues for managing the archaeological record of human endeavours beyond the atmosphere.

Orbital debris

Orbital debris has been defined as "all man-made [sic] objects injected into orbit which do not now, nor will in the foreseeable future, serve a useful purpose" [5 p128]. The European Space Operations Centre (ESOC) calculates that after approximately 4200 launches since 1957, there are 10 000 objects larger than 10 cm left in Earth orbit. Of these, 7% are operational spacecraft, 52% are decommissioned satellites, upper stages and mission related objects, and 41% are debris from the fragmentation of orbital objects (Figure 1). This has produced an estimated 100 to 150 000 pieces of debris larger than 1 cm [6] with a cumulative mass in excess of 2 000 000 kg [7]. The primary source of orbital debris is the fragmentation of satellites and launch vehicle upper stages, both of which tend to be left in orbit after the end of their mission.

Figure 2: Agena rocket seen from Gemini 8

Operational and decommissioned spacecraft include scientific and telecommunications satellites, weather and earth observation satellites, navigation and surveillance satellites, satellite constellations, and military satellites. Many have passed their mission life but are still capable of transmitting information. Upper stages include the durable Agena, in use from the time of the Gemini programme to the mid-1980s, and those of the Ariane family of rockets, first launched in 1979 (Figure 2).



Other objects come from deployments and separations of spacecraft. These manoeuvres typically involve the release of items such as separation bolts, lens caps, flywheels, nuclear reactor cores, clamp bands, auxiliary motors, launch vehicle fairings, and adapter shrouds [8]. Solid rocket motors used to boost satellite orbits have produced various debris items, including motor casings,

aluminium oxide exhaust particles, nozzle slag, motor-liner residuals, solid-fuel fragments, and exhaust cone bits resulting from erosion during the burn. Discarded fuel is also present as debris (Figure 3).



Figure 1: Debris photographed in Low Earth Orbit

Explosions are the principal causes of spacecraft fragmentation ([5], Figure 4). They occur when residual liquid fuel components accidentally mix, or when fuel or batteries become over-pressurised [8]. Some satellites have also been deliberately detonated, either to prevent re-entry or to conceal their presence or purpose [9]. The rate of satellite breakup increases each year and more than 124 breakups have been verified so far [8]. Another major source of debris is material degradation from a range of environmental effects, resulting in the production of particulates such as flakes of paint and insulation.

As well as space hardware, there is organic material in space in the form of urine and solid waste, discarded from crewed missions. If these materials survive, snap-frozen among the orbital debris, they could conceivably one day be an important source of archaeological information.

Disposal of human remains in space is likely to become more popular in the future, with suppliers already offering this service on the Internet [10].



Figure 4: Satellite breakup

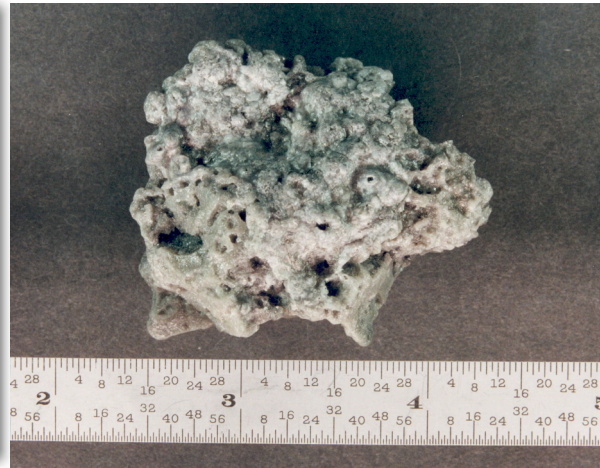


Figure 3: Slag from solid rocket fuel

The location of orbital objects

There are a number of orbits that are commonly used in the space industry. They are defined by altitude above the earth's surface, inclination and eccentricity. The orbit employed depends on the purpose of the satellite and the location of the launch site (Table 1).

Table 1: Commonly used orbital configurations

Orbit	Description	Function
Low Earth Orbit (LEO)	250 km – 1200 km, low inclination	Crewed missions, remote sensing
Medium Earth Orbit (MEO)	1200 km – 35 000 km	Global Positioning Systems
Geosynchronous	At least 35 000 km, period of 24 hours	Telecommunications, meteorology
Geostationary (GEO)	35 786 km	Telecommunications, meteorology
High Earth Orbit (HEO)	Above 35 786 km	Disposal orbit for GEO
Polar	LEO, inclination near 90°	Earth observation and mapping, reconnaissance
Molniya	Highly elliptical, inclination 63°	Used mainly by former USSR for coverage of high latitudes
Sun-synchronous	LEO or MEO	Meteorology, remote sensing, surveillance

Most objects are in the nominally circular orbits, LEO or GEO ([5], Figures 5 and 6), and most communication satellites are in GEO. Medium Earth Orbits are less widely used to avoid the Van Allen radiation belts.

Figure 5: Debris in LEO

Below 600 km, aerodynamic drag acts as a “natural cleansing mechanism”, causing objects to re-enter the atmosphere and (mostly) burn up [5]. Re-entry can take only a few months below 400 km in altitude. However, above 600 km, objects can remain in stable orbits for a few decades up to thousands of years. Higher in the Low Earth Orbit region, debris builds up near polar inclinations from sun-synchronous satellites and at altitudes near 800, 1000 and 1500 km [5, 7]. There are an estimated 70 000 pieces of debris about 2 cm in size at the 850 – 1000 km altitude [8]. Another peak is at 25 000 km, where there are objects in geosynchronous orbit, constellations of navigation satellites and objects in the Molniya orbit. The highest peak is at 42 000 km, consisting of objects at or near the geostationary ring [5]. Within the GEO region peaks of debris occur at:

- The equatorial inclination
- 28.5°, due to the latitude of the main US launch site at the Kennedy Space Centre.
- 63°, from Molniya and Glonass satellites.

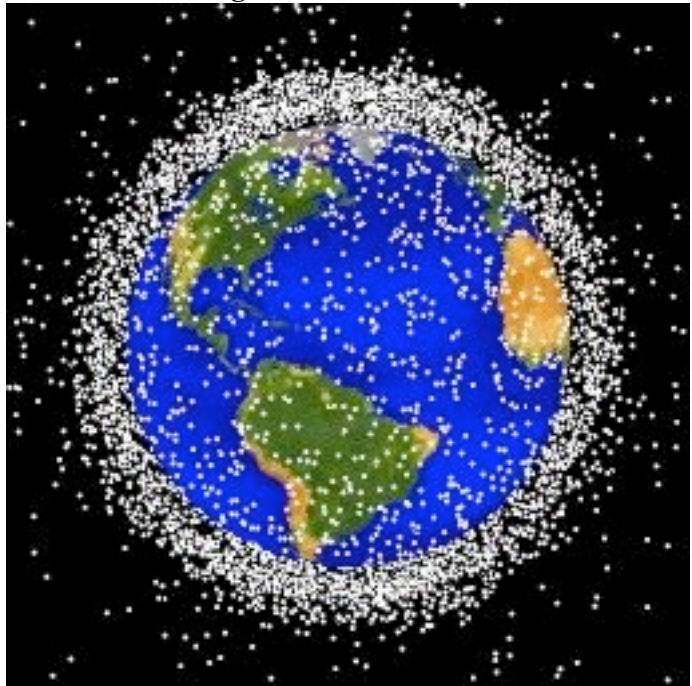
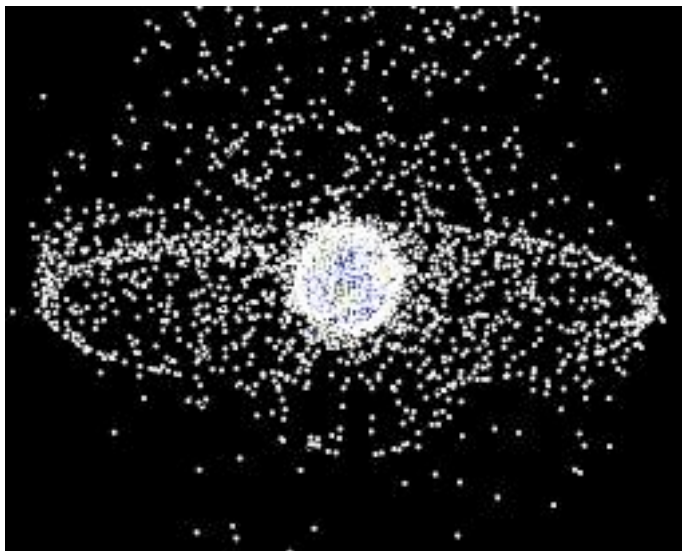


Figure 6: Debris in GEO



Assessment and modelling of the orbital debris problem is reliant on data collected from optical and radar tracking. In GEO, an object must have a diameter of 1 m to be visible; in LEO, radar can detect pieces as small as 5 mm. The population of smaller debris is estimated on the basis of returned spacecraft surfaces [7]. Debris over 10 cm is tracked by US Space Command (USSPACECOM), using 25 land-based radars and optical telescopes in the Space Surveillance Network, such as the NASA Orbital Debris Observatory (NODO). Over the former USSR's

territory, debris is tracked by the Russian Space Surveillance Centre [9]. ESA maintains the DISCOS database of space debris.

Managing orbital debris

It is now recognised that the need to control orbital debris has reached a critical point. Management strategies for orbital debris include (1) operational and design solutions, (2) Earth-based removal programmes, and (3) intervention missions.

Design and operational mitigation

This involves designing the spacecraft and the mission to minimise the amount of debris created and the potential for fragmentation. Design solutions include using tethered lens caps and bolt catchers for explosive bolts to reduce mission-related debris, shielding or augmenting components to withstand impact, and the use of operating voltages below arc thresholds. Operational measures include post-mission manoeuvres to place the spacecraft within the range of aerodynamic drag or in a graveyard orbit, and expelling remaining propellants and pressurants to prevent accidental explosion [7]. The NASA guidelines for limiting orbital debris recommend that an object should not remain in its mission orbit for more than 25 years [7, 8].

Earth-based removal programmes

Project ORION, developed at NASA's Marshall Space Flight Centre, has studied the prospect of removing debris between 1 cm and 10 cm in diameter in LEO by ground-based lasers. The laser ablates particles from the surface of the debris, creating enough thrust to edge it into re-entry [11]. A similar programme is being investigated by Electro-Optical Systems in Canberra [12]. Space-based laser removal has also been considered, for example, to move debris out of the path of the International Space Station, but is considered too costly in time and energy to be feasible at this stage.

Intervention missions

QinetiQ's ROGER study investigated scenarios where a specialised re-orbiting spacecraft could dock with a decommissioned satellite and remove it from GEO, concluding that such an intervention is plausible if not at present feasible. In LEO, a Royal Melbourne Institute of Technology (RMIT) group has proposed the use of space-based electrodynamic tethers to capture and remove debris. Others have raised the possibility that intervention missions could retrieve decommissioned surveillance satellites and transfer them to a LaGrange point for scientific data collection.

While few would disagree that orbital debris is a serious hazard for space missions and that ultimately, its removal is desirable and even necessary, I believe there is a further question to be addressed before the implementation of active debris mitigation measures. Does orbital debris have cultural heritage values, and are these worth preserving? Can cultural heritage values be managed without compromising safety or service delivery?

The archaeology of orbital objects

Spacecraft are more than utilitarian objects that further industrial, environmental or military objectives. They can also be regarded as artefacts, the material record of a particular phase in human social and technological development. On Earth, the preservation of material culture is considered important at a number of different levels: because it tells a story that is different to that presented in written documents, because it supplements written history, because material culture is the repository of people's memories, ideas, and attachments. Material culture both shapes the world and is shaped by it:

...the things which constitute our world, which direct its functions, in turn influence our most basic cultural assumptions. A society which has access to jet aeroplanes, fast cars, and an international mass media based on television, fax machines and the information super-highway views the world entirely differently from a society dependent on the bullock dray and sea mail [13].

That people see the material culture of space exploration as important is demonstrated by the popularity of museums such as the National Air and Space Museum (NASM) in Washington DC. More people visit NASM than any other Smithsonian institution. They don't go to see photographs of space, or to read interpretations of space history on storyboards. Words are not unique, and they are cheap. So why are visitors drawn in such staggering numbers to this museum?

Because the NASM has on display a Gemini capsule, a section of Skylab, and an astronaut's complete moon-walking suit ... It's the artifacts, stupid [14]

The material culture of space exploration captures something that no written word can convey, and an object that has flown in space is perceived as more charged with meaning than a model, prototype, or unflown spacecraft. Being there is important on both sides of the equation.

The material culture of space exploration is clearly seen as significant. However, its significance is often assumed to be self-evident. A well-used aphorism in the space community maintains that space exploration is the outcome of an innate human urge to explore. Thus, space objects are perceived to have a globally understood meaning that appeals to our common human nature [15]. Just as the great navigators and explorers ventured out into unknown seas to discover the New World, so we have now left the cradle of Earth to satisfy a fundamental curiosity about our universe. This curiosity is one of the most commonly cited rationales for pursuing space exploration, far more palatable than the *realpolitik* of military and commercial dominance.

Another implicit and popular model for understanding the significance of space material culture is what I have called the Space Race model [15]. In this formulation, objects and places have significance for their contribution to the Cold War confrontation between the USA and the USSR. This model focuses on these two states, ignoring the achievements of other countries like France, Britain, China, Japan and Australia in the development of space technology. It emphasises competitiveness rather than cooperation in space, and overlooks the contributions of and impacts on non-spacefaring countries, like the colonial territories where potentially dangerous space installations were located. The relationship of space exploration to inequalities between the developed and developing world is unexplored, and indeed unproblematic, in the Space Race scenario, where US hegemony in space assumed to benefit all [15].

The significance space artefacts might hold, therefore, is far from self-evident. To obtain a deeper and more inclusive understanding of heritage significance, I turn to the guidelines adopted

by the Australian National Committee of the International Council on Monuments and Sites (ICOMOS) in the Burra Charter [4], which outlines four different categories of significance:

- aesthetic: consideration of form, scale, colour, texture, material, smells and sound
- historic: association with historic figures, events, phases or activities
- scientific: importance of the data in terms of rarity, quality, representativeness, degree to which a place can contribute further substantial information.
- social: the qualities for which a place has become a focus of spiritual, political, national or other cultural sentiment to a majority or minority group

The Burra Charter also stresses that significance may be multivocal, and Article 6.3 states that the “Co-existence of cultural values should be recognised, respected and encouraged, especially in cases where they conflict”.

These kinds of significance are already the basis for museum collections of space artefacts around the world, and have been used in nominating space sites on Earth for heritage listing. They can equally be applied to objects in Earth orbit. In following sections, I look at some of these aspects in relation to three pieces of space debris: the Vanguard 1, Syncom 3 and FedSat satellites.

Vanguard 1

The Vanguard I satellite, launched successfully on March 17, 1958, is now the oldest manufactured object in orbit (Figure 7). It is no longer transmitting, but is in a highly stable LEO orbit with every prospect of remaining there for perhaps another 600 years. It is a physical testimony to the momentous period when humans first ventured beyond the atmosphere. Despite its failure to be first in the ‘Space Race’, Project Vanguard is acknowledged as ‘the progenitor of all American space exploration today’ [16]. For example, the Minitrack network, set up for Vanguard, became the backbone of the NASA Satellite Tracking and Data Acquisition Network used to track all the early generation of satellites [16].



Unlike Sputnik 1 and Explorer 1, Vanguard was designed as a scientific satellite with no military “taint”. It was launched using sounding rockets rather than missile technology, and originally was to have flown four experiments, including James Van Allen’s. In the spirit of international cooperation created by the International Geophysical Year, the Vanguard team recruited a network of volunteers across the world to carry out visual tracking in Project Moonwatch [17]. As it turned out the Moonwatch volunteers first applied their training and equipment to pick up Sputnik’s 1 orbit.

Figure 7: Vanguard satellite

Ultimately though, Vanguard represents the conflicting motivations and rationales for space exploration in the critical period of the 1950s, when the United Nations also first moved to set up

the principles of the Outer Space Treaty. Although it was designed as a peaceful scientific satellite, it was also an ideological weapon, a “visible display of technological prowess” aimed at maintaining the confidence of the free world and containing Communist expansion [16, 18]. Vanguard’s design and mission reflect the competing models of cooperation and confrontation in space, at a time when there were no rules, laws or guidelines to structure the human-orbital interaction [19]. It is now the only one of the early satellites to remain in LEO. Apart from significance at the aesthetic, historic and social levels, Vanguard 1 is also the only object that can tell us what happens to materials when exposed to the LEO environment for 50 years.

Figure 8: Syncom 3

Syncom 3

Syncom 3 was the first true geostationary communications satellite, launched in 1963, nearly two decades after Arthur C. Clarke [20] predicted the potential of GEO for telecommunications (Figure 8). Prior to the Syncom series, communication satellites were located in LEO where they required massive terrestrial infrastructure. Syncom 3 was aimed at providing live television coverage of the 1964 Olympic Games in Tokyo, as well as carrying telephone transmissions. But its uses were not confined to the civil sphere. Syncom 3 and its geosynchronous sister Syncom 2 were the primary communications link between South East Asia and the western Pacific in the Vietnam War.



Only six years after the first satellite, Syncom already shows how satellite design has moved past the early templates of the baby moon (Sputnik and Vanguard) and the rocket (Explorer 1). The Syncom series were the first spin-stabilised satellites. The basic design is still in use, for example, in the Aussat and Optus B series.

Syncom 3 is the ancestor of the satellites that provide telecommunication services today. Technologically, Syncom 3’s design and mission helped shape the world of the second millennium where nearly everyone is within reach of almost every point on the globe, and transnational entities flicker and spark into existence between hardware on Earth and in orbit. Syncom 3 was a major step in the process of globalisation that has been developing since the 1400s when navigation connected previously separate old and new worlds. For some, globalisation has meant new possibilities and opportunities; for others, it has meant the erosion of identity in contexts where colonial exploitation has already exacted a high cost.

FedSat

FedSat is the first all-Australian-designed satellite to be launched since WRESAT 1 in 1967 (Figure 9). Its mission is primarily scientific: it carried instrumentation to test aspects of communications, the Earth's electromagnetic field, remote sensing, and engineering research. FedSat's mission ends in 2005, but at an altitude of 800 km, it is expected to remain in orbit for approximately 100 years before aerodynamic drag causes re-entry. At 50kg, it is a microsatellite, part of a trend towards miniaturisation after the growth in satellite sizes to thousands of kilograms.

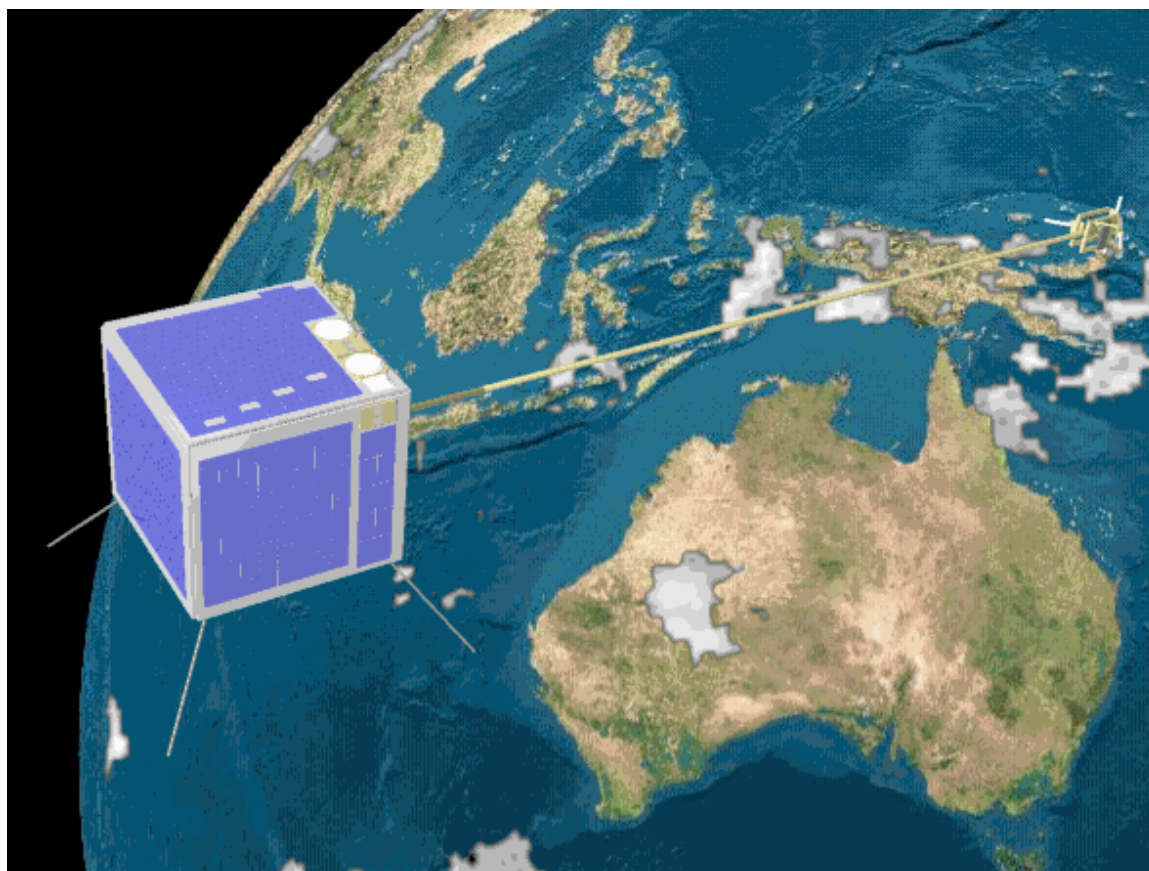


Figure 9: Artist's impression of FedSat in orbit

FedSat was launched in December 2002 from Tanegashima. Under a special arrangement between the CRCSS (Cooperative Research Centre for Satellite Systems, a joint venture of several Australian companies, universities and government agencies) and the National Space Development Agency of Japan (NASDA), the launch service was supplied in exchange for scientific data from the satellite and as a Centenary of Federation gift to Australia.

FedSat's symbolic role as an Australian presence in orbit was very much part of the project's design. FedSat's name and original scheduled launch in 2001 commemorate a significant date in Australian history: the centenary of federation. In addition to its scientific instruments it carries a CD with Australian music legend Paul Kelly singing *From little things, big things grow*. The satellite was seen by many as a hopeful renaissance of Australia's eminence in space exploration in the 1960s, when Woomera was second only to Cape Canaveral in launch activity and

Australian technology and design were at the forefront of space development. The choice of Paul Kelly's song reflected these hopes.

The CD also carried messages from "the average Aussie", recorded from March 2000 on the SpaceGram phone line. The CD project was conceived as a time capsule, a record of what Australians thought at the turn of the millennium.

This project means that any Australian can get into space, virtually speaking. The messages we will record through the SpaceGram service will circle the Earth for about a hundred years. Perhaps during that time space systems will advance so that the satellite and its time capsule can be recovered. Just to be on the safe side, we are leaving a copy of the CD—and a compact disc player—at the National Museum of Australia ... [21].

It's perhaps too early to tell how FedSat may sit in terms of aesthetic, scientific or historic significance. It's clear, however, that FedSat has high social significance not only because the mission design chose to make that a focus, but also because it symbolises a national presence in an orbital space overwhelmingly populated by hardware from the leading spacefaring nations.

All of these satellites are linked to historic events, places and people. They illustrate the unfolding of human interactions with orbital space, from their Cold War origins, to the development of modern telecommunications, and the hopes of marginalised nations to participate in the next phase of space exploration. They are also unique objects: if any one of them were to be destroyed by collision, re-entry or deliberate removal, there are no equivalent spacecraft in orbit. There are no other objects that tell the same story.

The spacescape

Many would have no argument with the outlines of significance as I have presented them here. However, a case could be made that the best means of preserving the heritage value of these satellites would be to remove them to Earth, when such an operation becomes feasible. Here, they could form part of a museum collection and be accessible to the public, while also protected from the destructive impacts of other orbital debris themselves. In essence, these satellites and other retrieved objects would become souvenirs of a faraway and inaccessible place, something to remember orbit by.

If space objects are considered as isolated artefacts, then their cultural heritage value inheres in their physical characteristics. This value may be considered to be intact if the object is intact, even though removed from its original location. However, the question alters significantly if we include the relationship of the artefact to other artefacts and to its physical location. In this case, its significance is assessed as part of a cultural landscape. This question hinges on the importance of place. Rather than regarding spacecraft and orbital debris as unrelated objects in an empty substrate, they can also be regarded as related by location, history and function. They are not separate from the space they inhabit, but part of it. They form a new kind of cultural landscape.

On Earth, a cultural landscape approach has come to replace older ideas of the division between nature and culture in the field of environmental management. This is most obvious in the reformulation of the notion of "wilderness". It is now recognised that most wilderness areas of

the world are in fact the homelands of Indigenous people, and the record of human occupation cannot be erased to return the landscape to a mythical state of nature that has not existed for the last 2 million years (eg Denevan, 1992, Jacques, 1995, Taylor, 2000). Rather, the interaction of human and natural processes has resulted in the topography, vegetation and visible features of the landscape. Together, the landscape created by both natural and human processes has been called a cultural landscape [22, 23, 24]. Cultural landscapes are

... illustrative of the evolution of human society and settlement over time, under the influence of the physical constraints and/or opportunities presented by their natural environment and of successive social, economic and cultural forces, both external and internal [25].

The World Heritage Convention recognises three processes that can create a cultural landscape:

- Design or intention, for example, in the case of gardens, parklands and urban landscapes;
- Organic evolution, resulting from human actions within the natural environment, both past and ongoing;
- Association with religious, artistic or cultural meanings rather than evidence of material culture alone.

These landscapes are deemed to be worthy of preservation because they capture the interaction of human and natural processes. I argue that orbital space is just such a cultural landscape. It is an organically evolving formation in which spacecraft and space debris contribute their physical properties to an environment also containing plasmas, cosmic rays, electromagnetic storms, meteoroid swarms, etc. Space debris is now as much part of this environment as is the debris from the creation of the solar system. There's no going back.

If space objects are seen as part of a cultural landscape, then their location is an important feature of their heritage significance. It's important that orbital objects are *up there*: once they come down, their meaning changes. But the spacescape is not simply a distant and (largely) invisible location. Space objects are linked to place, processes and people on the surface of the Earth. The spacescape is a three-tiered vertical landscape, starting from designed space landscapes on Earth (launch facilities, tracking stations, etc), organic landscapes in orbit and on the surface of celestial bodies (satellites, rocket stages, landers, debris), and beyond the solar system, the rich associative landscape of the night sky [15].

A cultural landscape approach offers a framework for studying the relationship between places, associations and material culture:

Cultural significance is embodied in the place itself, its fabric, setting, use, associations, meanings, records, related places and related objects. Places may have a range of values for different individuals or groups [4].

For each of the three satellites I have investigated, place is an integral part of their significance. Vanguard 1 was not the first satellite, or even the first US satellite; but it is the only satellite of the early generation that remains in orbit. No model or unflown satellite is interchangeable. Similarly, Syncom 3 is significant because it is in GEO. From its location, Syncom 3 hooked the world up to watch an international event, foreshadowing events such as the Live8 concert in 2005. FedSat represents Australia in space through its name, the song, and the voices on the CD. Sure, we can hear them on the CD deposited in National Museum, but what matters is that those

now-silent voices have left the Earth on a different journey. In space, their words carry a meaning they could never have on Earth.

Risk assessment

For each of these three satellites, the best management option at this stage is to leave them in orbit. This strategy also fulfils another principle of cultural heritage management: do as much as is necessary, and as little as possible. But, in doing so, are we merely contributing to the orbital debris problem? What is the risk posed by objects like Vanguard 1, Syncom 2 and 3, and FedSat, after the completion of their mission, to other functioning satellites in Earth orbit? In order to assess this, I will consider the damage caused by different size classes of debris, and the probability of collision.

Size classes

Orbital debris can be divided into three size classes:

- Large: with a diameter greater than 10 cm. Large debris can be optically tracked (Figure 10).
- Medium: diameter between 1 mm and 10 cm. Tracking depends on size and altitude.
- Small: diameter less than 1 mm. This is the largest population of orbital debris, and cannot be tracked.

Collision with space debris causes mechanical damage, material degradation or catastrophic breakup of operational spacecraft. Impacts occur at hypervelocity, that is, when the magnitude of the impact velocity is greater than the speed of sound in the impacted material [26]. In LEO, the average relative velocity of space debris at impact is 10 km/sec (36,000 km/hr) [7]. Given the high relative velocities, even small untracked objects can damage orbital objects or cause catastrophic break up [5]. Particles less than 1 mm erode sensitive surfaces such as payload optics, although they generally do not cause damage to spacecraft function. Penetration by a debris fragment 1mm to 1 cm in size, through a critical component, can result in the loss of the spacecraft. Fragments greater than 1 cm can penetrate and damage most spacecraft ([8], Figure 11).

In the geosynchronous altitude, the average relative velocity is much lower, about 200 m/sec (720 km/hr). Nevertheless, fragments at this velocity can still cause considerable damage upon impact. A 10-cm fragment in geosynchronous orbit has roughly the same damage potential as a 1-cm fragment in LEO. A 1-cm geosynchronous fragment is roughly equivalent to a 1-mm low Earth orbit fragment [8].

Impact from the medium debris class, 1 mm to 10 cm can cause significant damage and mission failure [7]. Collisions with objects in the large size class (> 10 cm) can cause fragmentation and breakup, a process which contributes to the proliferation of debris in all size classes.

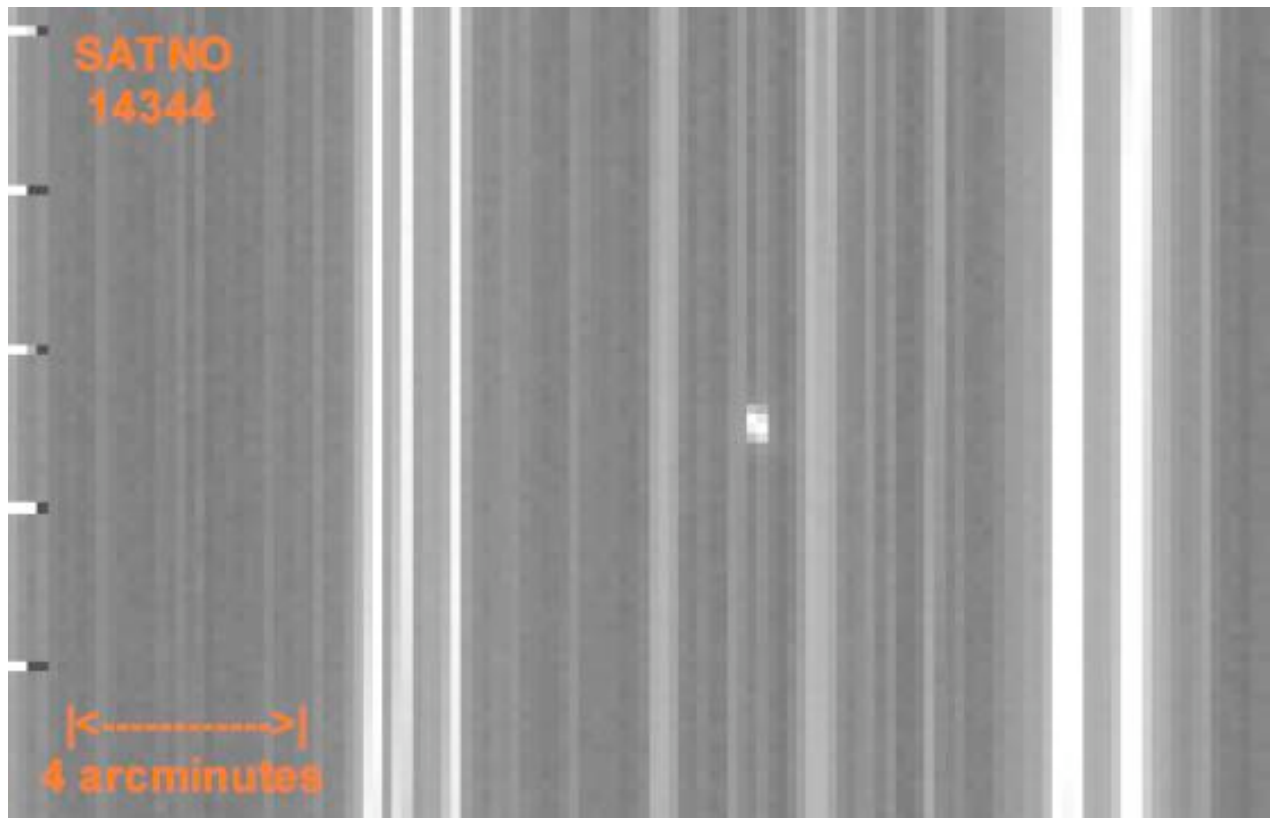
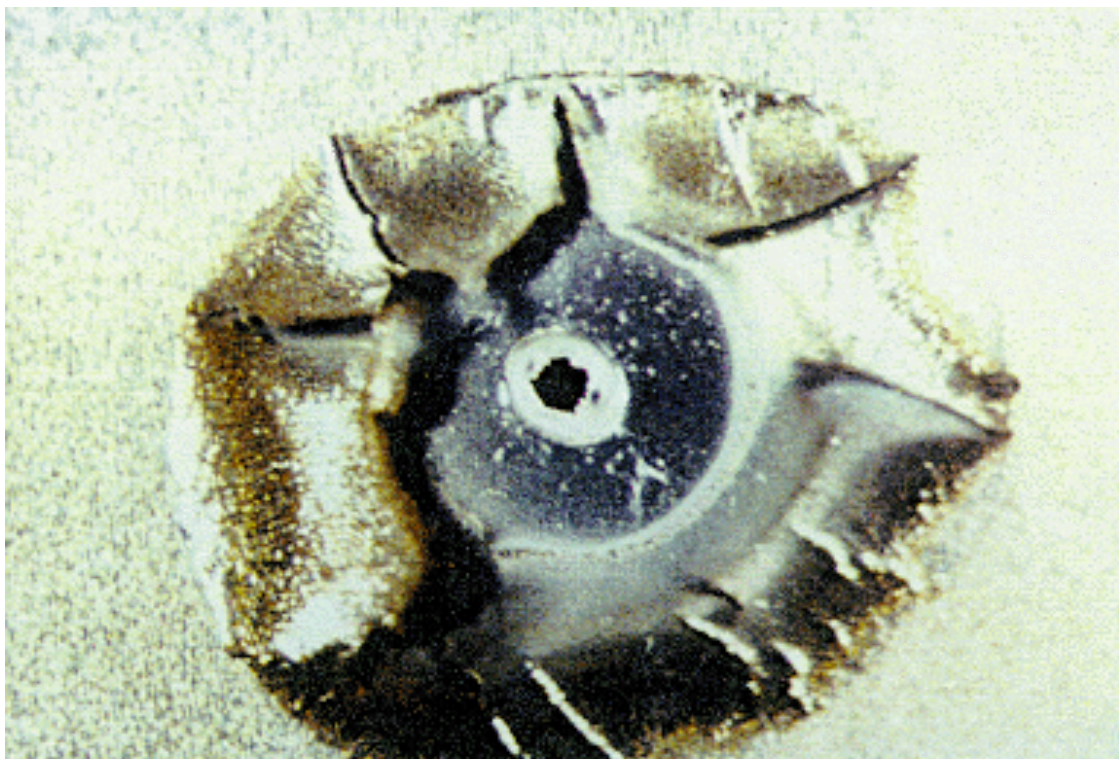


Figure 10: debris tracked by NASA's Orbital Debris Observatory



Penetration through an aluminized Mylar foil

Figure 11: Hypervelocity impact on spacecraft materials

Collision probability

There is a direct relationship between the numbers of debris in each size class and the probability of impact or collision. In LEO, spacecraft experience continuous bombardment by very small particles. Collisions with large objects over 10 cm are rare, and there are only a few recorded breakups due to catastrophic collisions [5]. The population of large debris is much lower than the medium and small classes, but the severity of impact is much greater when collision does occur [3].

In GEO, the risk of collision is significantly lower than in LEO. Satellites and upper stages are widely spaced and have lower relative velocities (500 m/s) [3]. The increasing use of disposal orbits after decommissioning means that the rate of debris accumulation is slow. Approaches between operational spacecraft and tracked objects can be predicted and evasive manoeuvres undertaken to avoid collision. Because most objects in the geosynchronous ring move along similar orbits, objects in GEO are more likely to collide with a meteoroid than debris [7]. However, untracked debris in GEO is not as well modelled as that in LEO [3].

Table 2 illustrates the mean time between collisions with objects in the three size classes in different orbits.

Table 2. Mean time between impacts on a satellite with a cross-section area of 10 square metres [3].

Height of circular orbit	Objects 0.1 – 1.0cm	Objects 1-10 cm	Objects > 10 cm
500 km	10 – 100 years	3500 – 7000 years	15 000 years
1000 km	3- 30 years	700-1400 years	20 000 years
1500 km	7-70 years	1000 – 2000 years	30 000 years

On the basis of this data, the greatest risk of impact derives from the small debris size class in LEO. The larger the piece of debris and the higher the orbit, the less likely it is that a collision will occur.

It is the medium debris class, 1 mm to 10 cm, which is the most destructive. Medium debris are far more numerous than the large class, have a higher risk of collision, and can cause significant damage and mission failure [7].

It is important to note that controlling human debris in the space environment does not automatically eliminate all hazards to materials or human life. Collisions with meteoroids, meteor swarms like the Leonids and Perseids, and high-energy particles, will still occur. There are many other elements of the space environment that cause material degradation and loss of function. One of the most significant results from the Long Duration Exposure Facility (LDEF), launched in 1984 to examine the effect of the space environment on commonly used materials, was the recognition that significant amounts of damage were caused by the synergistic effects of several environmental factors of LEO space including exposure to ultraviolet radiation and atomic oxygen erosion [5, 27]. The risks posed by debris of human origin cannot be considered in isolation from the total space environment, of which it now forms a part.

The implications of this assessment for the preservation of large objects in Earth orbit are that retaining them *in situ* will not have an adverse effect on safety and operation of crewed and uncrewed missions. If an object, such as one of the three satellites discussed here, has been identified as having heritage value, then it can be excluded from any future debris mitigation projects that involve de-orbiting. Potentially catastrophic approaches can be avoided by on-orbit manoeuvres. Debris mitigation proposals must be designed to avoid operational spacecraft in any case, so extension to include objects of heritage significance should not provide difficulties in implementation.

I have not examined the possible significance of large debris other than complete satellites, such as large fragments and mission-related objects like the astronaut glove, currently tracked by Electro-Optical Systems [12]. The contents of, and possible significance of, debris in the other size classes also needs to be examined separately. The intuitive reaction is to assume that there is little of significance; but only a systematic investigation can establish this.

Conclusions

Early science fiction accounts saw the Space Age as a technological utopia where human existence was severed from the ugly, disorganised world of the past; but we now know that continuity and connection to the past are vital elements of survival in the modern world. They're also hard to maintain. The destruction of cultural heritage has accelerated with the growth of population, development and industrialisation, and UNESCO, through the World Heritage Convention, recognises that "that deterioration or disappearance of any item of the cultural or natural heritage constitutes a harmful impoverishment of the heritage of all the nations of the world". The UN has also recognised that infringing on an individual or community's access to their own cultural heritage has adverse impacts on their human rights.

Generally, the understanding of cultural heritage has not encompassed the recent past, since World War I or II. But there is a growing interest in historical archaeology and cultural heritage management in the material culture of war, the nuclear industry and Cold War confrontation [19, 28]. Heritage authorities are now protecting landscapes shaped by these events, for the reason at the heart of the heritage management: once cultural heritage is destroyed, we can never get it back.

To date, all considerations of the space debris problem have focused on the risk posed to satellite services and crewed missions. The potential for space debris mitigation to impact on cultural heritage values has not been examined. In this discussion, I have argued that:

- (1) the material culture of space exploration does have cultural heritage significance
- (2) this significance can be demonstrated for objects classed as orbital debris
- (3) Orbital debris is part of a cultural landscape that represents a unique phase in human technological and social development, and
- (4) Preserving significant orbital objects in the large size class *in situ* does not add to the risk posed by orbital debris to space missions.

From this, it follows that the implementation of active debris mitigation strategies such as de-orbiting into the atmosphere or into graveyard orbits should consider what impact this will have on the cultural landscape of orbital space and on the object as part of that landscape.

At this time, there is a unique opportunity to incorporate a cultural heritage component into debris management. As terrestrial industries continually find, it is often extremely costly to ignore cultural heritage issues at the planning stage. After millions of dollars have been invested in a development, legal requirements or public pressure can be brought to bear, and a strategy that would have been simple and cheap in the early phases now causes large and expensive changes. Before active debris mitigation strategies are implemented, there is a window of opportunity to assess the nature of the material record in orbit, and ensure that significant objects are not unwittingly destroyed. What would future generations of space tourists think, if they found that Vanguard 1 was destroyed needlessly through lack of forethought?

However, there are no international heritage laws or conventions that apply to cultural heritage in space. While the World Heritage Convention recognises cultural landscapes, it does not include movable items or those which may become movable in the future. Application of national heritage legislation, as each space object remains the property of the launching state, is also problematic. Extending national heritage jurisdiction to orbital space could be interpreted –as the USA believes with reference to Tranquility Base – as equivalent to making a territorial claim [29].

In the absence of legal instruments, cultural heritage in orbit could be protected by agreed guidelines. In 1999, an environmental symposium at the UNISPACE conference recommended that the concept of international environmental impact assessments be developed, required for all proposed space projects ‘that might interfere with scientific research or natural, cultural and ethical values of any nation’ [30]. Cultural impacts were identified primarily as affecting the night sky as seen from Earth; the symposium’s report did not consider the cultural heritage dimension of actual objects in space. In fact the idea of space as an environment to be managed is in general very poorly developed in space industry as compared to terrestrial industry. Effective cultural heritage management in space will require a deeper understanding of environment that can only be beneficial in the long term.

Following terrestrial models such as those used in Australia, an environmental impact assessment for a space enterprise might include:

- Assessment of the extent of the cultural resource (objects of significance can be identified at a national or agency level)
- Identification and consultation with stakeholders (designers, scientists, government, industry, clients and users of the service)
- Significance assessment including aesthetic, historic, scientific, social or spiritual value for past, present or future generations [4].
- Formulation of management recommendations and procedures.

A cultural landscape approach has direct and practical implications for managing the cultural heritage of space exploration. In orbital space and on celestial bodies, it is not possible to simply remove human material to return the spacescape to its pre-1957 state. Commercial salvage, de-orbiting, or destruction of material culture in space has the capacity to damage the integrity of cultural landscapes that present or future generations may consider highly significant.

The time to consider how to manage the cultural heritage of orbital space is now. Space industry has a chance to learn from the mistakes of terrestrial industry and implement well-grounded, effective cultural heritage management strategies to protect a precious resource: the material record of the Space Age.

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