AIAA SciTech Forum
January 8-12, 2024, Orlando, FL

Control ID: SATS-01, 4124559

Retrieving History: Options for Returning Vanguard 1 to Earth

Matt Bille,[1] Michael Ferguson,[2] Christopher Vanwy,[3] William Austin,[4] Catherine Russell,[5] Dakota Welch[6]
Booz Allen Hamilton, Colorado Springs, Colorado, 80915, USA

ABSTRACT. In 1958, the Naval Research Laboratory (NRL) Vanguard 1 microsatellite reached orbit. Almost 70 years later, it is still there, the oldest satellite of any nation, and one of the most precious objects in existence from the early Space Age. Vanguard 1, a 15-centimeter aluminum sphere with a 91-centimeter antenna span, occupies an elliptical orbit of 654 x 3969 kilometers at an inclination of 34.25 degrees. This paper explores the options for missions and payloads using technology that could safely inspect, and, if desirable, retrieve the satellite for study and display.

One approach is a U.S. Space Force (USSF) mission in partnership with NASA/NRL or industry. The USSF could use a prototype or pathfinder spacecraft to demonstrate maneuvering, inspection, and other capabilities on a peaceful mission. Alternatively, NASA, which took over the Vanguard program, or private industry could lead the mission with military support if needed. NRL, still the owner of the spacecraft, is currently investigating options for such a mission as well.

A rendezvousing spacecraft would require precision maneuver capabilities and onboard intelligence to provide high-resolution images while avoiding collision and plume impingement. Vanguard 1's current characteristics, most notably spin rate, will dictate the practicality of and approach to a capture. Mission stages include Part 1 (rendezvous, close imaging, and evaluation) and Part 2 (if practical, capture and return to Earth). These could be done by a robotic imager, followed by either a retrieval vehicle (which might be the same as the imager) or a crewed vehicle. The satellite could be returned directly to Earth, moved to a lower orbit for retrieval, or taken to the International Space Station (ISS) to be repackaged for its journey to Earth and then the Smithsonian National Air & Space Museum. These options vary in cost, required delta-v, and other factors, among them the extant hardware used and the capabilities any mission sponsor might wish to demonstrate or mature. Future missions (space debris removal, materials capture for on-orbit manufacturing, and even deep space exploration) could build on techniques demonstrated in the retrieval of Vanguard 1.

It is outside this paper's scope to predict, should such a mission be created, which agencies will be involved, but the possibilities are attractive for potential partners. For the USSF, the appeal would be the ability to demonstrate chosen capabilities while working with a scientific objective of great public interest. For NRL and NASA, it would be a major scientific and public engagement success. For private firms like Boeing, Sierra Space Corporation, SpaceX, or firms developing space repositioning services, it would be a demonstration of their capabilities. For materials engineers and space historians, it would be a learning opportunity like no other. Retrieving Vanguard 1 would be a challenge, but an achievable and invaluable step forward for the entire U.S. space community.

Disclaimer: This paper presents the thoughts of the authors. It is not a business proposal or offering and does not represent the views, policies, or plans of Booz Allen Hamilton or any other organization.

---

[1] Research Analyst, Booz Allen at time of publication, currently freelance, AIAA Associate Fellow
[2] Lead Engineer, Booz Allen Space Solutions, AIAA member
[3] Staff Engineer, Booz Allen Space Solutions
[4] Chief Engineer, Booz Allen Space Solutions
[5] Associate, Communications, Booz Allen Health Group
[6] Senior Lead Engineer, Booz Allen Space Solutions

I. Introduction

The Vanguard program was selected in 1955 as the first publicly declared U.S. space program. Vanguard was an evolution of the NRL Viking sounding rocket program, and NRL had won the International Geophysical Year (IGY) assignment over the Army Ballistic Missile Agency (ABMA).

It would be Vanguard's task to perform observations of the Earth from space, furthering scientific knowledge as a part of the IGY, which would run from 1 July 1957 to 31 December 1958. Project Vanguard would also potentially orbit the world's first artificial satellite. This first goal would be met and exceeded. The second would not.

Two critical events prevented Vanguard from orbiting the world's first satellite. The first was the successful orbiting of Sputnik 1 by the Soviet Union on 4 October 1957. This feat had shocked the world because many in the West had, up to that time, underestimated Soviet technological capabilities. [1] The second disruptive event was the first attempted orbital launch of the full Vanguard rocket with satellite payload on 6 December 1957. The rocket rose just a few feet off the pad, then toppled over and exploded in view of a national television audience. One response to this failure was that the ABMA was given the go-ahead to revive its program. ABMA succeeded by orbiting Explorer I on 31 January 1958, the first U.S. artificial satellite, which reentered in 1970. Despite setbacks, including another launch failure on 5 February 1958, the NRL was able to orbit Vanguard 1 on 17 March 1958 as the second U.S. satellite.

Vanguard 1 (COSPAR ID: 1958-002B) was, by 1958 standards, a technically sophisticated satellite, and the first to generate power using solar cells. Its greatest scientific contribution, however, was orbital data that made a second-order correction to the geodetic model of a perfectly spherical Earth. Vanguard 1's movement showed our planet is not round but pear shaped, with a different mass distribution between its Northern and Southern Hemispheres.

Vanguard 1 kept transmitting for six years, finally falling silent in 1964. It is still tracing its path around Earth, the oldest artificial object in space, and barring a collision, could remain in orbit for hundreds of years.

In this paper we examine the possibility of retrieving Vanguard 1 for posterity and to demonstrate the viability of the technology required to perform such a delicate feat. We briefly touch upon the importance of the decision to be made once we know more about Vanguard 1's status, specifically, whether it should be retrieved at all. But the primary focus of this paper is on the mission parameters and technologies that would be required to recover this significant piece of space history.

We developed this project with a team that included aerospace engineers, historians, and writers, with the goal of researching and documenting the available options given the technology extant or possible in 2025. Research was conducted between January and November 2024. Our approach included:

- Survey of literature
- Discussions with Vanguard program veterans and NRL experts
- Interviews with technical experts from government, industry, and the military
- Examination of existing and practical technology from all sectors of the space community
- Modeling in Ansys STK
- Development of criteria for selecting among technical options
- Recommendations for next steps in developing a mission architecture

Because there are different organizations that could potentially direct, fund, or execute this mission, we refer here to the as-yet-unidentified lead organization as the Vanguard Mission Authority (VMA).

II. Description of the Proposed Vanguard 1 Retrieval Mission

A. Phase I: Ascertain Vanguard 1's Condition

Characteristics of the Satellite

The 1.46-kilogram (kg) Vanguard 1 satellite was built of 5052S aluminum alloy, with interior surfaces plated with zinc, copper, cadmium, silver, and solder plate. Some of these elements were vacuum plated with gold to reduce radiant heat transfer. Transmitters and batteries were potted in plastic foam (Eccofoam FB).

Seven Mallory mercury-cell batteries powered one of the satellite's two Minitrack transmitters, while the other was powered by solar cells. That mercury appears to be the only hazardous material within Vanguard 1.

Its 30-centimeter (cm) antennas were fixed and are now presumed to be too fragile to use as grab or attachment points. The cylindrical adapter visible at the top of the sphere in model generations was eliminated, so the actual satellite body has no docking mechanism or easy grab point.

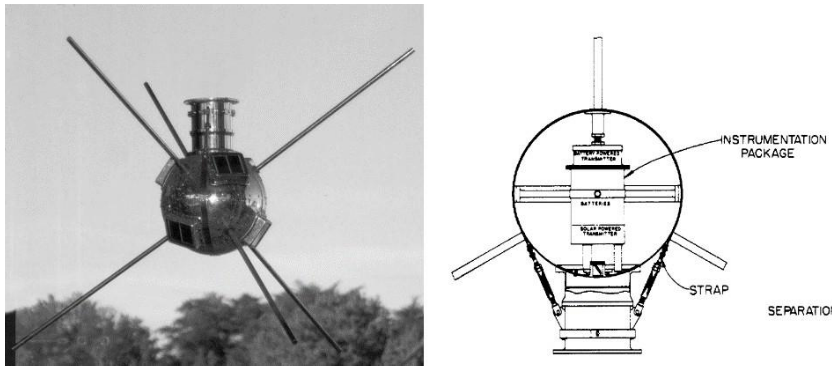

Figure 1. Vanguard model (L) and cutaway diagram (R). (NASA)

Orbital State

Vanguard 1 is in an elliptical orbit with its perigee at 660.9 km (410.66 miles) and apogee at 3823.3 km (2375.69 miles), with a 34.245 degree inclination. Before any retrieval attempt of the Vanguard 1 satellite can be made, we must first determine its condition so VMA can decide whether retrieval should be attempted. On the assumption that a retrieval decision will be required mid-mission, we can assume that the overall mission will be split into the following phases:

Phase I: Imaging to determine the condition of Vanguard 1 prior to a retrieval decision
Phase II: Retrieval of Vanguard 1

These mission phases would likely need to be independent of one another and separated by an appropriate span of time. That would minimize mission cost risk by avoiding a situation where, for example, retrieval technologies and systems are anticipated and developed, but ultimately never used.

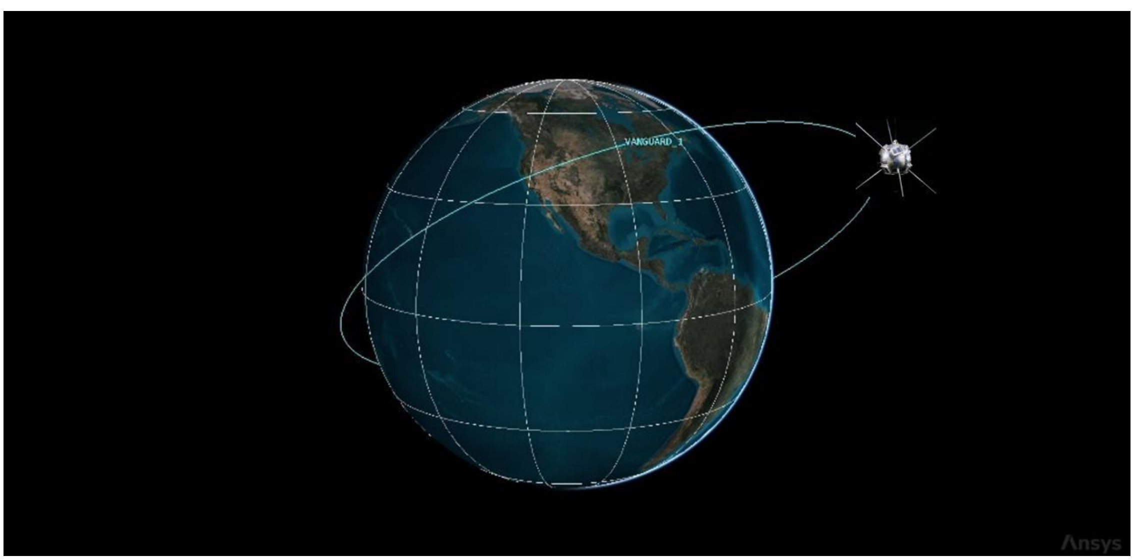

Figure 2: Current orbit at 34.245 degrees. Created by Dakota Welch in Ansys STK(TM)

The Phase I options fall into the following three categories:

Category 1:

Use existing ground-based resources to collect data, such as radar and/or imaging provided by government or commercial providers. This option would depend on whether such assets could capture enough data to determine the viability of a Vanguard 1 retrieval mission. The United States military has an array of capabilities for space situational awareness, on Earth and in orbit, some of which are classified and unavailable to the authors of this paper. Public information does not indicate whether imagery of Vanguard 1 is possible at the smallest object resolution of the National Imagery Interpretability Rating Scale (NIIRS) of 9 (corresponding to resolution of objects <0.10m in diameter).

A variety of installations around the world can image satellites, but we will need to investigate which would be suitable for this mission:

- The United States Space Surveillance Network (SSN) operates a network of ground-based telescopes and radars to track and monitor objects in space, including satellites.
- Certain optical and infrared telescope installations built primarily for astronomy are capable of satellite imaging, including:
  - The Gemini Observatory, two identical telescopes located in Hawaii and Chile
  - The Large Optical Infrared Telescope, an astronomical observatory in Arizona
  - The European Southern Observatory (ESO) telescopes in Chile, the Very Large Telescope (VLT) and the upcoming Extremely Large Telescope (ELT)
  - The W. M. Keck Observatory in Hawaii
- The Murchison Widefield Array in Western Australia has also been used to detect and track satellites using radio signals, and such radar cross-section imaging complements information from optical observations.

Category 2:

Use existing space-based resources. As with ground-based resources, space-based resources could include radar and/or imaging provided by government or commercial providers. This option could be more challenging and costly, but it would provide substantially more detail than ground-based observations alone. Trajectories for space-based resources to inspect Vanguard 1 in its current orbit could either fly by or rendezvous with Vanguard 1 by matching its orbit, though a matching orbit would require significantly more spacecraft onboard propellant. There is enough interest in performing rendezvous and proximity operations (RPO) and on-orbit servicing (OOS) that the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) was created by the Defense Advanced Research Projects Agency (DARPA) in 2017 to set voluntary technical standards for commercial vehicles. [2] Examples of recent spacecraft demonstrating relevant capabilities include:

- Astroscale's 150-kilogram Active Debris Removal by Astroscale – Japan (ADRAS-J) satellite, which was launched 18 February 2024. The satellite was built to approach a derelict rocket stage and make close observations to evaluate the practicality of potential methods for de-orbiting. The company advertises increased capability is coming, not only for inspections but for satellite life extension missions. [3]
- True Anomaly, which launched its first two 300-kg Jackal spacecraft on 4 March 2024 to perform RPO, including providing "high-resolution multi-phenomenology data of resident space objects." [4] The first mission's objectives featured the two craft practicing on each other, closing to within hundreds of meters.
- The USSF's reusable X-37B has been launched on seven orbital missions since April 2010. Its details are classified, but it has been conducting missions in widely varying orbits and releasing smaller payloads. It is not known whether it can perform close inspection of Vanguard 1, but the necessary equipment could easily be fitted, and Vanguard 1's orbit is well within its publicly known envelope. [5]

Category 3:

Use a yet-to-be-developed ground-based or space-based resource. A ground-based observatory is technically possible, albeit unaffordable unless an organization were to fund it for a range of missions. However, a space-based imager that would be optimized for satellites like Vanguard 1 could potentially be developed as an inexpensive Smallsat mission. It is logical to assume that any newly developed imaging spacecraft would be designed for a mission set that includes but is not limited to Vanguard 1. This new imaging Smallsat could be launched in conjunction with other payloads, thus fulfilling aspects of Phase II of the mission (e.g., a capture and propulsion module able to circularize the Vanguard 1 orbit at its perigee for easier recovery by a later mission).

One typical element of selecting a viable option would be parametric cost studies. Such a review is beyond the resources available for this paper, but it is work in which a government or sponsoring organization would certainly find value. However, the applicability of parametric cost studies has limits because there are no exact comparisons for such a unique mission, one that incorporates aspects of space situational awareness, re-servicing, active debris-removal, and sample return missions. There are, however, several previous rendezvous and inspection missions, such as the ADRAS-J or the smaller-scale 2007 Air Force Research Laboratory (AFRL) XSS-11, which have components that would warrant future examination.

Of these three categories, space-based resources would be the most desirable because they would capture the highest-fidelity observations of Vanguard 1 and also limit the costs of research and development (R&D). However, the costs of re-tasking an existing mission to observe Vanguard 1 must also be considered, though it is unclear whether any current assets could capture enough detail. Given the unique orbit of Vanguard 1 and the orbit(s) of currently orbiting imagers, the propellant requirements are likely to have significant mission impact on the tasked satellite. Nonetheless, they merit investigation.

Pre-Mission Preparations

As discussed earlier, imaging and tracking support needs to be established. For ground-based systems, it would be necessary to evaluate Vanguard 1's ground track to determine the opportunities for observation.

For space-based assets, the evaluation of suitability would be more complicated. It would require determining the points of closest approach (PoCA) in the relative orbits of the imaging satellite and Vanguard 1, and also determining whether the PoCAs are adequate for observations of sufficient resolution and duration. Another question to a provider of a space-based imaging spacecraft would be whether the spacecraft could be re-tasked to observe Vanguard 1 with available onboard resources and to what extent re-tasking would deplete satellite resources such as onboard propellant. A final consideration would be whether the mission parameters of the space-based imagery spacecraft could be adjusted to accommodate observations of Vanguard 1 while still fulfilling its other duties.

Another key aspect of pre-mission preparation would be to define for ground-based or space-based systems the parameters that would be necessary to support a retrieval decision. Such observation parameters are critical in order to avoid expensive collection of ambiguous data that cannot support a definitive retrieval decision. Such parameters would include, but not be limited to:

- Vanguard 1 physical condition
  - Evidence of impact damage, such as damage imparted by micrometeorites
  - Evidence of outgassing or cold welding serious enough to make the satellite more fragile
  - Any other evidence of damage (e.g., antennas no longer attached or otherwise in multiple pieces)
- Vanguard 1 attitude and orientation
  - Rate of spin (Vanguard 1 was deployed as a spin-stabilized satellite)
  - Axis of spin relative to orbital motion vector
  - Stability (Is Vanguard 1 spinning neatly along a single access, or is there wobbling/nutation?)

Launch and Early Orbit

Any new imaging spacecraft must have the ability of the imaging spacecraft to pass Vanguard 1 in its orbit close enough (without posing an unacceptable collision risk) to capture sufficient resolution imagery to support a retrieval mission. To minimize costs of access to space, an imaging Smallsat could be placed in low Earth orbit (LEO) at a minimum of the Vanguard 1 perigee of 654 km with a well-defined orbital period that is a specific fraction of the Vanguard 1 orbital period (e.g., potentially such that the observer space craft completes precisely five orbits when Vanguard 1 completes precisely three orbits). The benefit here is that the orbit is stable and well-characterized: There is no timing requirement for when a single flyby rendezvous must take place.

The new Smallsat could be launched as a rideshare on as closely matched an altitude and orbital plane as available, one which permits a spacecraft with sufficient propulsion to make small adjustments until the trajectory is correct, or to use a dedicated small launcher that is able to meet the desired launch window, spacecraft mass, and trajectory requirements.

Examples of Smallsat launch providers with operational systems include:

- Northrup Grumman (Pegasus XL, Taurus XL, Minotaur I)
- Rocket Labs (Electron)

- Firefly Aerospace (Alpha)

The new Smallsat would need to be launched with an instantaneous launch window to ensure that it is placed in an orbit with a true anomaly that periodically brings the imaging satellite into close-approach imaging opportunities with Vanguard, which could preclude use of a rideshare launch unless other rideshare customers can accommodate the launch window constraints.

Rendezvous and Proximity Operations

A common shorthand for RPO is "prox ops" because NASA includes RPO as part of the subject area rendezvous, proximity operations, and docking (RPOD). For the Vanguard 1 mission, an on-orbit imaging satellite will need to approach close enough to Vanguard 1 to ascertain its status both in terms of its structural condition and its dynamics (e.g., how fast it is spinning), which will factor into the feasibility of capture and retrieval. We envision three types of rendezvous and proximity operations for Phase I:

1. A flyby of Vanguard 1 by an imaging spacecraft in an orbit distinct from Vanguard 1, at the closest approach between the two satellites. This would involve launching a new spacecraft on a trajectory that brings it into proximity with Vanguard 1 or re-tasking an existing spacecraft to make a sufficiently close approach to capture images/video of Vanguard 1 during a single, time-critical attempt. This would likely be the most affordable option in terms of energy and propellant for a spacecraft designed to perform RPO with multiple targets.
2. A periodic flyby where the spacecraft could be placed in an orbit that matches the altitude of the Vanguard 1 perigee inclination to allow the imaging spacecraft to do periodic flybys of Vanguard 1, thus allowing multiple opportunities to capture imagery. The imager may perform a slow flyby in a slightly lower (posigrade flyby) or higher (retrograde flyby) orbit compared with Vanguard 1.
3. A matching orbit, which keeps the imager close enough to make close passes whenever desired. This would be the least affordable in terms of energy and propellant for a spacecraft designed to perform RPO with multiple targets.

Two key considerations for the imaging spacecraft will be prevention of on-orbit collisions between the imaging satellite and Vanguard 1, and prevention of thrust plume impingement on Vanguard 1 from imaging satellite propulsion systems. It would therefore be necessary to define a specified Keep-Out Sphere (KOS) that establishes a minimum safe proximity to Vanguard 1. The requirements for maintaining a KOS with Vanguard 1 would need to be balanced against the need for collection of imagery of sufficient resolution to support a retrieval decision.

Considerable work has already been done on the challenges of a close approach and contact with a spinning and/or tumbling spacecraft. The literature is too extensive to include here, but it is interesting to note this is not just a focus for American researchers. Numerous recent publications by Italian and Chinese engineers are collected in the Reference section, herein. [6] (This is a subset of an even more active area of proximity operations: a search based on that term in the archives of one major conference, the Conference on Small Satellites, returns 179 papers. [7])

Conclusion of Phase I Mission

At the conclusion of Vanguard 1 observations, the imaging satellite will either be re-tasked to perform other missions or put into a safe disposal trajectory to ensure that it does not contribute to debris in LEO or collide with Vanguard 1 during any future conjunctions.

B. Phase II: Capture and Retrieve Vanguard 1

Pre-Mission Preparations

Preparations would begin with analyzing the data from Phase I. For the purposes of this paper, we assume the VMA has issued a go decision. The next step would be selecting an existing or new space vehicle (or combination thereof) capable of safely capturing Vanguard 1, putting Vanguard 1 on a trajectory to reenter Earth's atmosphere, protecting Vanguard 1 from the heat and dynamic stresses of reentry, and enabling a safe landing.

The Phase II Vanguard 1 retrieval mission would include the following four subsystems:

1. A capture mechanism that would be capable of stabilizing Vanguard 1 without damaging it and then enveloping it in protective packaging to survive return to Earth. (This packaging could be a crewed or uncrewed vehicle or a new package resembling robotic sample return missions).
2. A sophisticated guidance and navigation system (potentially enhanced by AI) capable of precision navigation, without causing damage, to within centimeters of a small and fragile historical object.
3. A propulsion system capable of shifting the orbit of Vanguard 1 into a new desired trajectory (either to return to Earth via a deorbit burn or on a rendezvous trajectory to the ISS). For certain maneuvers (excluding a

deorbit burn), an electrical ion propulsion system may be considered, given there is no urgency associated with these maneuvers.

4. A landing and recovery system that can survive reentry into the Earth's atmosphere with an internally controlled environment (thermal and physical) that would minimize potential damage to Vanguard 1 during its return.

Also important is to determine where Vanguard 1 will return to Earth. A pre-selection of landing/splashdown locations would be needed with the identification of a primary landing/splashdown site and at least one alternate site. For all identified primary and alternate landing/splashdown sites, a formal evaluation of airspace would need to be conducted with the Department of Defense (DoD) and Federal Aviation Administration (FAA) to ensure that the returning spacecraft does not create a hazard and that the proper notifications and trajectory constraints are in place.

Launch and Early Orbit

As with Phase I, the crucial aspect of orbital timing would require the retrieval spacecraft to use an instantaneous launch window to ensure that it is placed in an orbit that closely matches that of Vanguard 1. Most likely, a dedicated launcher will be required for this. Upon launch, the retrieval spacecraft will need to maneuver into an orbit that closely matches Vanguard 1 while complying with an established KOS to avoid collision or thruster impingement.

This launch and early orbit trajectory would include, at a minimum, the following three maneuvers:

1. An initial launch trajectory into an orbit that matches the altitude, inclination, and eccentricity of the Vanguard 1 orbit, with the ability to make reasonable adjustments to the trajectory provided by the launch vehicle, especially if the retrieval spacecraft is launched on a rideshare mission
2. A phasing burn to adjust the remaining orbital parameters of the retrieval spacecraft (e.g., true anomaly) to place it on a rendezvous trajectory with Vanguard 1
3. A series of station-keeping burns to place and maintain the retrieval spacecraft just outside of the KOS from Vanguard 1

Rendezvous and Proximity Operations

The Phase II retrieval spacecraft would be placed in an orbit close enough to keep station on Vanguard 1 (potentially approaching within a meter). As with Phase I, the retrieval spacecraft will need to maintain the same KOS as defined for the Phase I imaging spacecraft. There will need to be a defined command and control structure in place to permit the retrieval spacecraft to enter the KOS and start physically affecting the orbit of Vanguard 1. A set of flight rules will need to establish clear parameters under which the retrieval spacecraft may enter the KOS, and under which conditions the retrieval spacecraft must pause or abort the mission. These flight rules will be developed based on those for crewed and cargo missions that rendezvous with the ISS. The size of the KOS would depend on the current state of technology for developing guidance and navigation systems that can station-keep to an accuracy of centimeters near a target. The systems for RPO could be derived from existing robotic sample return missions (e.g., OSIRIS-REx), satellite servicing missions, or active debris removal missions.

It is not possible to completely plan a mission without knowing the number of spacecraft or the mass, but reasonable assumptions can be made. Our suggested starting point in making such a mission as affordable as possible is to see whether a new or tailored satellite design can be fitted to ride as a secondary payload on an Evolved Secondary Payload Adapter (ESPA) ring. ESPA can be fitted to a variety of launch vehicles because of its use of the standard National Security Space Launch interface bolt pattern, which allows it to launch on United Launch Alliance (ULA) Vulcan, Blue Origin New Glenn, and SpaceX Falcon 9 medium-lift launchers. ESPA is designed to carry payloads up to 257 kg (about 566.59 pounds [lb.]), which we are assuming as an upper-bound for mass to orbit of a retrieval spacecraft. There is an optional Heavy interface with a capacity of 450 kg (about 992.08 lb.) There are limits on the dimensions of the spacecraft, and the center of gravity (CG) must not be more than 50.8 cm from the ESPA port surface. Finally, it can be replaced with the Grande version, hosting satellites up to 700 kg (about 1543.23 lb.) Previous ESPA customers have included NASA, DoD, and private industry. [8]

The SpaceX Falcon 9 currently dominates the American launch market and will likely remain the least-expensive launcher for the foreseeable future. SpaceX advertises secondary payload rates that begin at $300K for 50 kg into LEO, and then increase with additional weight and higher orbits. As an example, a 200 kg spacecraft desiring a LEO launch in January 2026 costs $1.2M as of October 2024. [9] SpaceX offers the "Cake Topper" position service, the top of the rideshare stack, for spacecraft weighing 500-2.500kg at an as-yet undisclosed price. [10]

Secondary payloads sharing a rideshare launcher with a Phase II mission would require that the launcher or primary payload accommodate a trajectory within a reasonable distance of the orbit of Vanguard 1. Depending on the orbital altitude, inclination, and other factors, the retrieval spacecraft may require extra propellant or an extra kick stage on the payload to rendezvous with Vanguard 1. SpaceX launches more than 100 missions per year, making it more likely that such a compatible mission could be found. The ability to combine the retrieval spacecraft on a launch with other missions with little or no time criticality would further increase the chances of identifying a rideshare launch. However, the chances of finding a suitable launch may be diminished if planned launches to a similar orbit do not carry an ESPA ring. If a dedicated launch is required, the lowest current price available is for the Electron launcher, at $7.5M. [11]

For any option using a crewed vehicle for part of the mission, the cost goes up significantly. The unknown state of the vehicle and its spin or tumbling motion make it impractical to presume anything as seemingly simple as grasping it in an astronaut's gloved hand. (There may be no rationale for a crewed vehicle at all, but for the purposes of this paper and to cover all the possible options, we include crewed missions.)

A crewed vehicle can either be part of the inspection phase or, in theory, part of the recovery, using the capsule to control a robot craft that does the grasping. We know from the privately funded Polaris Dawn mission that a currently available capsule can reach the perigee of Vanguard 1, but the speed of travel and altitude (both constantly changing) mean that anything more than a short encounter requires a great deal of propellant. Accordingly, if someone wants to involve a crewed vehicle, it may be more practical for the inspection phase.

A crewed or crew-supervised recovery would be more practical if Vanguard 1's orbit could first be circularized at or near its current perigee of 660.9 km (410.66 mi). Such a maneuver would require that the spacecraft first be captured robotically and redirected into a new orbit. Given this complication, it may be simpler to deliver the Vanguard 1 to a reentry vehicle or to the ISS for repackaging and reentry. Redirecting Vanguard 1 to the ISS using an attached propulsion system would require, at a minimum, a plane-change maneuver from 34.25 degrees to 51.6 degrees (most efficiently performed at apogee), followed by maneuvers to lower and circularize the Vanguard 1 orbit to the ISS altitude of 400 km, with a final phasing burn to adjust the true anomaly to place Vanguard 1 on a rendezvous trajectory with the ISS. Such a maneuver may be too costly and complicated to implement compared with a direct retrieval from its existing orbit by a new robotic retrieval spacecraft. If it is desirable to return Vanguard 1 to the ISS, NASA's extensive safety protocols for the station come into play. NASA would examine the craft's construction and materials and decide whether it can approach the ISS, followed by detailed examination to confirm that the retrieval spacecraft design meets the human spaceflight requirements associated with ISS visiting vehicles. ISS use requires satisfying layers of safety protocols and months of advance planning. [12]

Capture and Packaging

The most delicate part of the Phase II mission will be the challenge of removing Vanguard 1 from its open space environment and placing it into a protected environment capable of surviving reentry, landing/splashdown, and recovery. The delicacy of this operation requires either robotics that can be controlled (perhaps via AI) very precisely or the more complex option of human intervention. The package used to protect Vanguard 1 would need to provide a tightly controlled interior environment to protect the spacecraft from moisture or other environmental contaminants. It would resemble those used for deep space sample return missions but would have greater shock protection requirements.

A robotic spinning grappler would need to be perfectly synchronized with the motion of Vanguard 1. There are no (or not enough) ferromagnetic materials in Vanguard 1 to allow the use of electromagnetic devices. A robotics expert at NRL is working on a device that would wrap around the sphere to grip it evenly, without too much pressure on any one point, and especially ensure that the delicate Vanguard 1 antennae are not damaged. The robotics laboratory at the University of Southern California has a parallel program, and the two have cooperated. NRL is already a leader in developing robotic arms for satellite servicing; two will go to space in 2026 on SpaceLogistics' Mission Robotic Vehicle (MRV).

Another option to capture a noncooperative spacecraft is a net. There are several organizations currently researching ways to help reduce debris in space. One such effort was headed by The University of Surrey, which led a coalition to successfully launch the RemoveDEBRIS spacecraft in June 2018. RemoveDEBRIS successfully deployed a net from one vehicle, capturing a free-flying CubeSat. [13]

The RemoveDEBRIS concept, if feasible, would require major customization to adapt for a Vanguard 1 retrieval spacecraft. The net used in the RemoveDEBRIS demonstration is too massive to recover Vanguard 1 undamaged. Additionally, any net has to remain connected to a retrieval spacecraft. In general, the specific need to protect the target "debris" here from damage is where any similarity between a debris removal mission and a Vanguard 1 retrieval mission ends.

It is unknown whether a net system capable of capturing Vanguard 1 without damage could be built. Assuming that imaging and spin rate indicate that such a net system is feasible, the retrieval mission might use a clutch and winch system similar to a fishing reel. This net, as light and stretchable as possible, would be wrapped around Vanguard 1 by its spin or any other motion, with Vanguard 1's motion itself pulling the net from the retrieval spacecraft. An onboard clutch would slow the line release, eventually coming to rest relative to its previous spin/tumbling state. Once Vanguard 1 is stabilized, the winch would draw it in to be secured within or against the outer structure of the retriever.

Currently marketed spacecraft that may be relevant for this mission include:

- Rocket Lab's custom-built spacecraft for Varda Space Industries, which recently returned a capsule with space-manufactured pharmaceuticals to Earth. Rocket Lab's 3D-printed Curie propulsion system fired several times to change the Varda capsule's orbit from circular to elliptical and then initiated a precision reentry. [14]
- Sierra Space's Space Ghost system, which was tested earlier this year, provides a method for objects to be returned safely from space. Although it is not a capture system, it may be able to be part of the capture and delivery process. This is a hexagonal craft that would land using a parafoil. [15].

Deorbit and Recovery

Once Vanguard 1 is placed inside a protective package that would protect it from the uncontrolled environment upon return to Earth, it will also need to be protected from the considerable heat and dynamic forces associated with reentry through Earth's atmosphere and landing/splashdown. If this is to be accomplished through automated means, new systems would need to be developed that could be leveraged for debris-clearing missions, satellite servicing missions, and deep space sample return missions. Another automated option could be to enhance current recoverable spacecraft (e.g., DoD X-37 or Sierra Space Dream Chaser) with robotic systems capable of performing the packaging and capture activities, while leaving the problem of reentry and recovery to these existing systems. Human participation at the ISS (or, potentially, a privately operated space station) to arrange a return could utilize multiple visiting vehicles in operation and in development, including the Dragon 2 cargo vehicle and the Dream Chaser cargo spaceplane. A crewed Dragon 2 or Starliner would likely not be able to transfer a sphere 1 m across to the ISS in a custom-built package because the ISS passage for crew and small cargo transfer has a diameter of 0.8 meters (31 inches). The Vanguard 1 package would need to use the larger cargo hatch via the Common Berthing Mechanism, which means it would be grabbed by the robot arm and guided into the berthing port.

For deorbit from Vanguard's current orbit, at a minimum the following maneuvers would need to be performed:

- A maneuver to place Vanguard 1 into a circular orbit at its perigee. This could potentially be provided by an electrical ion propulsion system because it is not a time-critical maneuver; it could be performed over a period of weeks or even months.
- A deorbit maneuver to remove Vanguard 1 from LEO to a specified landing/splashdown point on the surface of the Earth. This would need to a more traditional chemical propulsion system due to the need for precise timing to ensure landing/splashdown conditions are favorable for recovery teams and to ensure that recovery teams are deployed and ready to receive Vanguard 1 when it arrives.

For rendezvous with the ISS, a phasing maneuver to adjust the true anomaly of the orbit to rendezvous with the station would be needed. At the end of this maneuver, other thrusters would need to transition to various RPO maneuvers to obey the ISS waypoints (Approach Ellipsoid and Keep Out Sphere) like any other visiting craft. For ISS Proximity Operations, the retrieval will need to be designed to obey the same protocols as ISS crew and cargo service vehicles, and to obey the same Flight Rules as ISS service vehicles.

If Vanguard 1 is retrieved via an existing ISS cargo or crewed service vehicle, a suitable container would need to first be transported up to the ISS to allow crew to package Vanguard 1 safety and then handle the packaged Vanguard 1 with other cargo that is brought back to Earth via existing systems (e.g., Dragon 2 or Dream Chaser).

Another possible consideration for a crewed Vanguard 1 retrieval mission would be to use a crewed Dragon 2 similar to the recent Polaris Dawn Mission, which would be configured to rendezvous with Vanguard 1 after an initial Phase I imaging mission combined with a partial Phase II mission to attach a propulsion module (could be an electrical ion system) to circularize Vanguard 1 at its perigee of 660.9 km. Polaris Dawn carried crew to an apogee of 1200 km, which is significantly higher than the Vanguard 1 perigee, indicating it is probably feasible for Dragon 2 to rendezvous with Vanguard 1 in a circularized perigee orbit. We did not find specific figures for the diameter of the Dragon 2 EVA hatch used for Polaris Dawn. But we estimate that it may be possible for an EVA hatch that can accommodate the shoulders of a suited astronaut could also accommodate an object roughly 1-meter wide (Vanguard 1's six antenna tips describe a sphere 91 cm across), on the assumption that a suitable container would be brought up on the crewed mission and the astronauts would package Vanguard 1 for its return to Earth. There would be a cost trade-off between purchasing a dedicated Falcon 9 and crewed Dragon 2 capsule vs. developing a new robot capable of deorbiting Vanguard 1 or redirecting it to the ISS for retrieval. It is also assumed that a Vanguard 1 retrieval mission by a dedicated, crewed mission would need to be congruent with other scientific or technology objectives.

Post-Mission

Upon return of Vanguard 1 on land or at sea, we assume that handling protocols would resemble those for deep-space sample return missions, whereby Vanguard 1 would be maintained in its sealed container until it is conveyed to a similarly controlled environment at a designated laboratory for further research. Specific handling protocols would need to be developed like those established for sample-return missions or like those for handling delicate payloads (e.g., perishable biological experiments) by crewed and cargo ISS support vehicles (e.g., Dragon 2, Dream Chaser). Also, a defined terrestrial means of transportation and destination facility would need to be designed to evaluate Vanguard 1 after its return to Earth.

III. Key Technical Challenges

A. Rendezvous and Proximity Operations

One of the biggest challenges with rendezvous and proximity operations with Vanguard 1 is the diminutive size of the satellite. Vanguard 1 is an aluminum sphere 152 mm in diameter with six antennae. This makes it a very small target for any mission designed to rendezvous in close proximity to determine its condition and to potentially retrieve the target for return to Earth. Proximity operations with Vanguard 1 would be non-cooperative. That is, the target itself would be sending no signals to the imaging or retrieval spacecraft to assist the operation.

An imaging satellite would need to pass close enough to take pictures of sufficient resolution to support a retrieval decision. A retrieval mission would require a spacecraft to closely match the Vanguard 1 orbit with a proximity close enough to potentially capture Vanguard 1 and either place it in a protective container for return to Earth, or provide the means of adjusting the orbit Vanguard 1 to match another vehicle for retrieval (e.g., the ISS). Launch trajectories and maneuvers would be similar to those performed by crewed and cargo vehicles to the ISS (which is 109 m, close to the length of an American football field), but would require approximately two orders of magnitude more precision than typical for imaging and/or radar systems designed for rendezvous and proximity operations. Rendezvous would be further complicated by the fact Vanguard 1 is an entirely passive object with no functioning onboard radio systems or visual beacons, except potentially the reflective aluminum surface of Vanguard 1 illuminated by sunlight.

RPO of the retrieval spacecraft/Vanguard 1 with the crewed ISS would require that the retrieval satellite follow rigorous protocols to protect the ISS crew. The ISS is surrounded by a controlled zone in the form of an ellipsoid extending two kilometers above and below the station and four kilometers ahead and behind (all directions are relative to the ISS itself.) There is an ISS Keep Out Sphere (KOS) of 200m in all directions: ISS Visiting Vehicles (VVs) must get permission to approach closer and do so in dedicated corridors. Exceptions can be made when needed, but any vehicle must stay at least two meters from any structure on the station unless docking with the Mobile Servicing Structure. [16] The object to be docked with or gripped must hold a position within 30 cm of the docking point. [17]

A Vanguard 1 capture vehicle would fall into the ISS VV category of "free-flyer vehicles," vehicles that operate independently and attach (dock or berth) for mission reasons. Any VV must meet certain standards for maneuvering capability, ability to determine its orientation and position. operating in darkness, and other conditions, as well as exchanging information with the ISS. Ground testing and other verification steps are required. A Vanguard 1 retrieval spacecraft, whether off the shelf or a new build, must be designed as an ISS VV. [18]

Alternatively, a Vanguard 1 retrieval spacecraft could attach to the arm, with the work needed to inspect and package it done by astronauts on EVA. EVA events are very costly, but this avoids the safety requirements for bringing an object onto the ISS. Or the satellite can be brought inside through the cargo hatch. NASA has stringent review procedures for items allowed inside the habitable or pressurized environment. [19] Vanguard 1 would not meet ISS standards for circuit protection, grounding, etc., for ISS cargo, but it should be simple to confirm that Vanguard 1's batteries and panels are dead and there is no risk of current, excess touch temperatures, etc. [20]

The normal process for developing, approving, and bringing a payload to the ISS is extensive. It is uncertain what steps might or might not apply to a completed satellite removed from another orbit.

The objective in bringing the payload to the ISS (or potentially a private space station) would be to hand-inspect it for fragility and place it in the optimal packaging for a trip to Earth. The packaging would be custom-made on Earth and sent to the ISS on a previous supply flight. The dimensions of Vanguard 1 indicate that a properly designed casing should fit through the hatches used when transferring cargo between the ISS and VVs or when astronauts are taking things in and out of the station. The cargo hatch to incoming spacecraft is approximately 1.3 meters on a side, allowing an object larger than a standard-size refrigerator to pass; the hatch used for EVAs is 0.914 meters by 1.01 meters. [21]

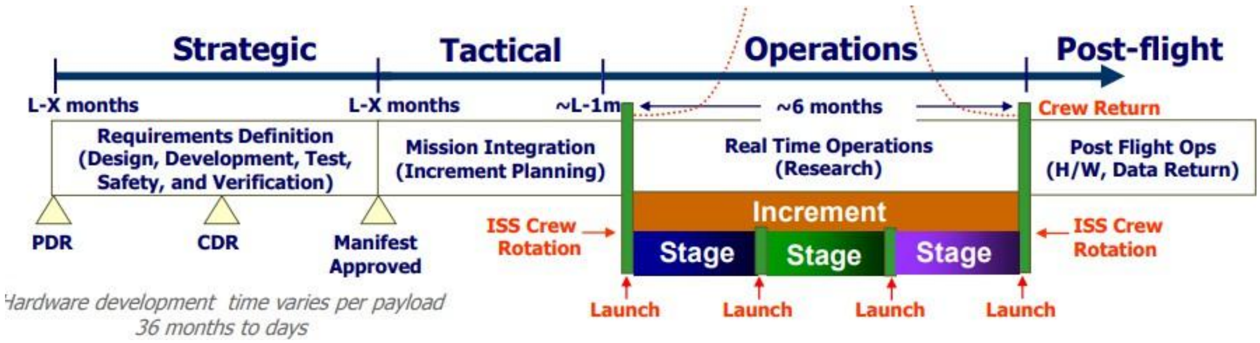

Figure 3. Normal ISS Payload Sequence (NASA)

B. Capture and Recovery

Compared with imaging to determine the condition of Vanguard 1, capture and recovery would be significantly more challenging, due to the presumed fragility of the aging satellite. Early satellites were all spin stabilized. The third stage of the Vanguard 1 launch vehicle was spin stabilized to ensure directional stability, with a spin of 200 rpm provided by small solid rocket motors firing perpendicular to the long access of the rocket stage. [22] The capture system would need to determine the residual spin of Vanguard 1, apply thrust to de-spin Vanguard 1, and then either place Vanguard 1 in a protective container for return to Earth from its original orbit, or apply propulsion to move Vanguard 1 to an orbit more conducive to recovery (e.g., the ISS).

C. Modeled Options

Using STK, we examined the parameters and costs of three simplified options with two variants: inspection only, and inspection and recovery. At submission time, the data gathered was inadequate: see the presentation.

Modeled options include the following changes to the Vanguard 1 satellite:

1. Circularization of Vanguard 1 by a propulsion module that is included with a multi-payload mission followed by later capture and retrieval by a cargo or crewed spacecraft (e.g., Sierra Space Dream Chaser or SpaceX Dragon 2)
2. Matching of current Vanguard 1 orbit by a dedicated Phase II spacecraft or a multi-payload mission that also performs Phase I imaging activities, followed by packaging into a dedicated re-entry vehicle and a deorbiting maneuver (Potentially done in two phases involving circularization at perigee first, then a deorbit burn)
3. Trajectory change from current Vanguard 1 orbit to a rendezvous trajectory with the ISS using an attached propulsion module; Vanguard 1 would be "berthed" using existing ISS systems and would then be retrieved by astronauts for return on an existing ISS cargo retrieval or crewed vehicle

Table 1 Options for Imaging and Retrieval (MODELING IN PROGRESS)

Option	# of space vehicles (SV) involved (besides Vanguard 1) dedicated to mission	Working estimate of SV mass	Total Delta-V Magnitude Required	ROM Cost Factors: Update with fuel used
Direct ascent, imager only	1	300 kg	14,312 m/sec	TBD
Direct ascent and imager detached from recovery vehicle	2	Highly option-dependent	TBD	TDB
Flyby using multipurpose SV	1	6,000 kg	14,330 m/sec	TBD

Table 2 Options for Retrieval Missions (MODELING IN PROGRESS)

Option	# of SVs involved (besides Vanguard 1) dedicated to mission	Working estimate of SV mass	Total Delta-V Magnitude Required	ROM Cost Factors: Update with fuel used
Direct ascent, retrieval, reentry	1	6,000 kg	15.490 m/sec	TBD
Mission to and from baseline orbit	1	6,000 kg	Calculate separately for each orbit considered	TBD
Routed through space station (ISS used) with transshipment	2	6,000 kg	21.349 m/sec	TBD

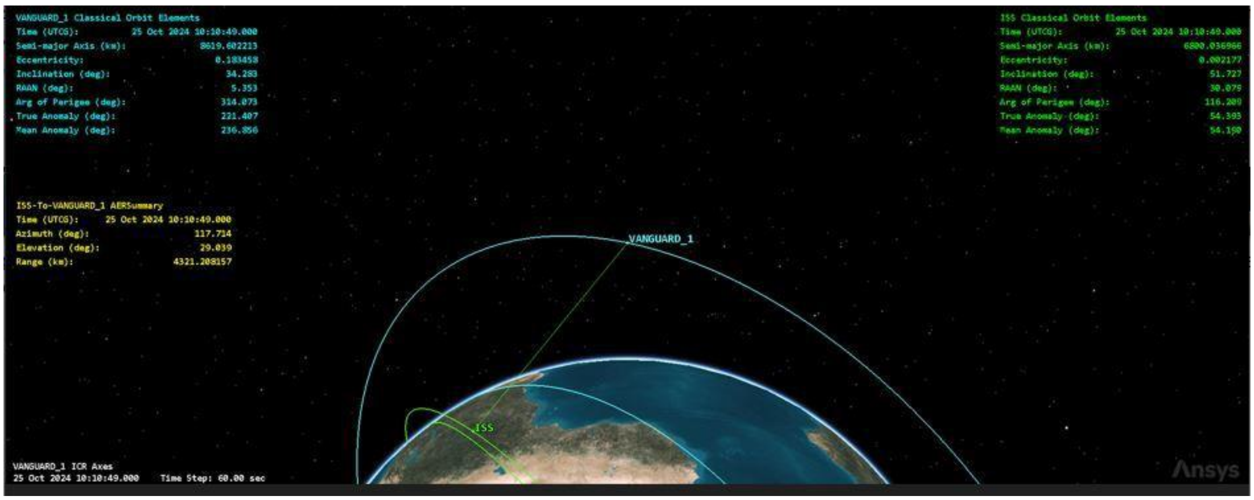

Figure 4: Snapshot of a Vanguard 1 to ISS trajectory. Created by Dakota Welch in Ansys STK(TM)

IV. Potential Mission Performers and Supporters

A. Roles of NASA and the NRL

NRL remains the owner of the satellite and the developer of its technology. Its Naval Center for Space Technology develops, deploys, and operates advanced space systems involving new, cutting-edge capabilities. Its robust spacecraft design and systems engineering capabilities are today studying a possible Vanguard 1 mission.

As the premier civil space agency and the leader in performing scientific missions, NASA is the only American organization that has acquired material in space and returned it to Earth via spacecraft.

NASA's interests in a Vanguard 1 mission are many. NASA's Johnson Space Center (JSC) has the lead for RPOD systems requirement definition, study, design, and test of spacecraft and components. Such work crosses several NASA technology areas, notably TX04, Robotic Systems; TX08, Sensors and Instruments; TX15, Flight Vehicle Systems; and TX17, Guidance, Navigation, and Control (GN&C). JSC's Flight Operations Directorate Flight Dynamics team employs the results of RPOD development, enabling execution of dynamic spacecraft operations for safe and successful human spaceflight missions. [23]

RPOD, spacecraft imaging, in-space servicing, and cargo transfer are integral to current and future space architectures. The Artemis lunar missions will require an undetermined but significant number of meetings between crewed and uncrewed vehicles, including refueling, repair or salvage missions, and transfers of people and supplies. Many smaller interactions will occur as satellites, probes, and samples are moved between the two celestial bodies and their orbiting outposts. While most multi-vehicle activities will involve craft linked by radio or laser, there will be failures of such links, and thus a need to deal with nonfunctional spacecraft. For example, a lunar position, timing, and navigation (PNT) Smallsat could go dead and need inspection (and possibly retrieval) to be repaired or avoid a collision hazard. NASA engineers from Ames Research Center and Kennedy Space Center have published a concept for small spacecraft holding 10 kg of payload to provide on-demand capability from Gateway to complement the limited number of Orion flights with samples. The spacecraft would use a Hall Effect Thruster, optimal for small spacecraft not requiring high delta-V. JSC hosts NASA's Orbital Debris Program Office, which investigates technology including interceptor/capture/deorbiting spacecraft for debris remediation. [24]

NASA explored the latest RPOD technology using two 5-kg three-unit (3U) CubeSats by the CubeSat Proximity Operations Demonstration (CPOD) mission led by Tyvak Nano-Satellite Systems. In 2023, the mission tested a navigation suite with delta GPS, radio intersatellite link with ranging capabilities, and infrared and visible imagers, using a cold gas propulsion system. The satellites had GNC problems and never docked, despite closing to within hundreds of meters, but provided data for future missions. [25]

NASA's upcoming Starling project will use four CubeSats to test technologies that let spacecraft operate autonomously in a synchronized mission. The agency's annual State of the Art of Small Spacecraft Technology report covers RPOD and other relevant technology, and in 2023 it added a section on Orbital Maneuvering Vehicles (OMV).

NASA's Moon-to-Mars (M2M) architecture is still being defined, but the reach to another world involves numerous factors that make in-space RPOD, inspection, and other activities even more vital. Robotic probes of Mars have been highly successful: Establishment of a crewed station will need to re-create the lunar architecture but at a distance requiring many months for support. Inspecting, recovering, repairing, and reusing spacecraft will be important activities. Samples, equipment, and humans will be transferred between landers, orbiters, and Mars-Earth spacecraft.

The NASA OSIRIS-REx mission recently demonstrated the ability to return delicate cargo from deep space by returning samples of the carbonaceous near-Earth asteroid *101955 Bennu* in September 2023. The capsule technology used to retrieve these samples could inform the design of a container to be used by a robotic Vanguard 1 retrieval spacecraft.

B. Potential U.S. Military and Intelligence Organization Contributions

The space enterprise within DoD is the world's largest and includes historical and scientific endeavors, such as maintaining museums, teaching space science, technology, and history, and other areas relevant to a Vanguard 1 retrieval mission. Possible reasons for DoD agency participation in a Vanguard 1 mission, aside from the obvious interest of the NRL in retrieving its historic satellite, include testing technology, demonstrating capabilities, and conducting training exercises. It is inescapable to all, including potential adversaries, that some capabilities demonstrated on a peaceful scientific mission to rendezvous, image, capture, and return an uncooperative space target could have other uses.

There are numerous organizations reporting to the Office of the Secretary of Defense with space responsibilities that include innovation and experiment. The Defense Innovation Unit (DIU) has a space portfolio. The Defense Advanced Research Projects Agency (DARPA) has developed Smallsats including the Blackjack technology demonstrators launched in 2023, performed initial development of the X-37, and led many other space innovation efforts.

The USSF's broad mission is to "Secure our Nation's interests in, from, and to space." This mission, which includes operating more than 200 satellites, has expanded to encompass an increasing interest in the ISAM (in-space servicing, assembly and manufacturing) sector. The new Proliferated Space Warfighter Architecture requires access to many different orbits and inclinations. Military space operations are carried out by the separate United States Space Command (USSPACECOM), which also provides support to NASA. The USSF includes the Satellite Control Network, which supports all military space activities, and several organizations dedicated to innovation and experiment in space, including the Space Development Agency and Space Rapid Capabilities Office, parent of the recent Tactically Responsive Space experiments orbiting Smallsats on short notice. The AFRL's Space Vehicles Branch continues to build on its legacy of small satellites and innovative spacecraft technology.

The USSF is pursuing a new concept, Dynamic Space Operations (DSO). DSO is comprised of concepts and capabilities giving space platforms persistence and maneuver characteristic analogous to those of aircraft platforms, enabling advantages like surprise unavailable using traditional large satellites in fixed orbits. The Space Systems Command in early 2024 created the Servicing, Mobility and Logistics (SML) Program Office and released a Request for Information (RFI) asking industry for "potential capabilities/technologies/services for development of Combat Space Mobility concepts." [26]

One part of a force capable of DSO related to, or demonstratable using, a Vanguard 1 mission is expendable low-cost satellites that can perform missions including close inspection of targeted space object. Another is refueling of large satellites, requiring precision approach and docking. The USSF's Space Systems Command (SSC) and AFRL Tetra-5 mission in 2025 will use three Orion Space Solutions Smallsats to test autonomous RPOD capabilities for on-orbit refueling. [27]

The National Reconnaissance Office (NRO) has shed some of its traditional secrecy in efforts such as the Broad Agency Announcement for Agile Launch Innovation and Strategic Technology Advancement. The NRO is funding solutions for in-space mobility to enable access to non-traditional orbits as well as maneuvering between orbits, and on-orbit logistics, including rendezvous and docking, refueling, and de-orbiting. In October 2024, the NRO announced funding for two of these. Impulse Space is developing vehicles to transfer payloads between orbits or trajectories. Also receiving money was Starfish Space, whose Otter spacecraft will use autonomous navigation and computer vision capabilities and a gripper for flat surfaces to provide servicing to exiting satellites. [28] The agency's increasing openness signals the possibility of participating in an unclassified demonstration of certain relevant capabilities, potentially including missions like Vanguard 1 retrieval.

Taken as a whole, the national security space community offers many capabilities and technologies that could be used in retrieving Vanguard 1, some of which reside within the government, and some contracted out.

C. International Contributions

While Vanguard 1 retrieval is a prestigious mission and would be headed by American agencies, we should not rule out any imaging or robotic technology offered by international partners. Certain countries, notably Japan with its partnership with Astroscale, have relevant technology, launch capability, or funding for retrieving objects launched by their own country. International partners could assist in Vanguard 1 or use the technology or mission plans from a Vanguard 1 retrieval for their own satellites. All the advantages in technology test, prestige, marketing, etc., for American agencies and firms apply equally to other nations.

D. Private Contributions

Private industry could fund, partially fund, or partner in the mission to demonstrate a company's technology and operational capabilities. Numerous companies are building spacecraft that can rendezvous with objects in orbit and inspect them and/or grapple them, while other firms are offering orbit-to-Earth return craft that could be demonstrated. Private firms may also participate for the benefit of marketing, prestige, promoting business with other entities involved in the mission, and the recruiting of aerospace-related candidates.

A private funder with historical or philanthropic interests is another possibility. Jared Isaacman, an internet entrepreneur, funded the Polaris Dawn mission using a SpaceX capsule to perform the first civilian EVA. He has proposed a mission to the Hubble telescope. Jeff Bezos of Blue Origin funded retrieval of Apollo-program Saturn V engines from the Atlantic for museum displays.

We have already mentioned many potential corporate participants, but others exist, some of which are notable for having gained funding from potential government participants to fund their technology, increasing the possibility of partnerships.

V. Mission Option Downselect Criteria

A. Cost

We are assuming for the sake of discussion that adequate funding can be found for the mission, but in an era where spending on space is restricted in government budgets and requires return on investment for corporations, the cost of a mission will be a significant determinant in selection.

Costing methods for space missions are well-established, and mostly applicable here. The first step is to determine whether commercial firms might donate launch services or other support in return for being part of a prestigious national heritage mission and possible ancillary benefits such as television rights. Financial sponsorship from space firms, documentary networks, etc., should also be explored.

If adequate sponsorship is not forthcoming, then existing contracts or a Request for Proposal (RFP) for launch opportunities and stages can be used in accordance with the normal processes of the organization selected to direct the mission. Bids will be evaluated based on established factors including price, reliability, and suitability.

The imaging system or spacecraft may be bought or adapted for the mission. The costs of ground support are well characterized. Hardware procurement is intertwined with the technical options: a preferred option may be unaffordable, or a budget limit may narrow the options.

The unique part of a recovery mission is the robotic arm and gripper. The likely spin of the spacecraft rules out capture by a human hand but does not rule out arm/gripper deployment by a crewed spacecraft, should a reason (such as sponsorship) dictates using one. This hardware may come from a government source, be adapted from commercial equipment, or be a new development for an academic institution or private firm. Other items, such as custom packaging and a reentry system, may also require R&D if commercial items are not suitable. The VMA should emphasize how aspects of a system customized for Vanguard 1 retrieval can benefit other servicing missions or efforts for clearing orbital debris.

B. Technical

As with cost, technical options for launch and orbital maneuvering are relatively simple to evaluate for each possible mission profile. For example, use of a separate imager vs. use of a single spacecraft with adequate imaging and capture arm will have different technical risks and choices. Any proposal for use of crewed vehicles and/or the ISS would dictate another set of evaluations.

Factors will include (not an exhaustive list):

- Launch options
- Availability of existing hardware
- Technology Readiness Level (TRL) and schedule of hardware in development
- Policy conditions and licensing
- Input of historians and museum experts in recovery and preservation

Also as with cost, the final stages of the mission (capture and return), hold the most technical risk.

NASA trade study methodology is well established, as is the DoD equivalent, the Analysis of Alternatives. This mission is unique but not so unique that existing approaches will need modification.

Some NASA technical work is worth mentioning here. Goddard Space Flight Center (GSFC) has a Space Servicing Capabilities Project (SSCP) at developing systems for servicing space assets. NASA has patented an Active Debris Removal Vehicle (ADRV) to remove large orbital debris in LEO, whose principles to some degree would also apply to small objects. Engineers at Goddard developed a LIDAR-based system to help spacecraft identify, pursue, and attach to a target satellite, as well as a robotic gripper to grasp a disabled satellite. [29]

Capturing a small uncooperative target, especially a potentially fragile one without its own docking or grappling features, will require countless minute adjustments as the capturing spacecraft performs rendezvous, station-keeping, close approach, and contact. Moving the command ability to the intercepting or capturing spacecraft using AI would eliminate the latency involved commands from the ground. The first successful deployment and operation of a generative AI large language model (LLM) in space, which used a Hewlett Packard Spaceborne Computer-2 on the ISS, was accomplished in 2024. [30] The process for a mission like Vanguard 1 capture would use a satellite-based LLM that fuses the ability to use a more basic ML algorithm (such as finding an uncooperative target), then using the LLM and computer vision to identify and execute the optimal steps to rendezvous and capture. A capability proven on the very challenging Vanguard 1 mission could dramatically improve the ability of spacecraft to maneuver autonomously in orbit to avoid collisions with space debris or to assist dock-and-refuel and repair missions. Those capabilities will support future missions including those forecast for NASA's complex M2M architecture.

An example of a relevant AI approach is Stanford University's Autonomous Rendezvous Transformer(s) (ART) as a means for spacecraft approach. Their team reports ARTs are "…able to generate near-optimal trajectories efficiently…" that would enable autonomous rendezvous and docking operations. [31]

The recovery vehicle will need to establish a minimum standoff from Vanguard 1 and maintain its position within extreme tolerance. AI will enable us to conduct station-keeping maneuvers while simultaneously attempting the docking activity. The need for constant evaluation of the activity requires reliance on AI and other flight safety systems to make real-time decisions regarding the interaction. For ART or any similar technology, there are reasons the creators would be interested in helping recover Vanguard 1. The successful demonstration of this technology with a small object establishes the utility of this capability for other space operations (wherein significantly larger objects are involved). Next, depending on the mission parameters (one vehicle vs. two), there may be an opportunity to test the AI system with a pair of cooperative vehicles prior to engaging with a non-cooperative RSO. Finally, if the initial retrieval is successful, there may be a follow-on opportunity to demonstrate the technology while actually docking with the ISS or another station.

The technology and techniques involved in recovering Vanguard 1 could also be used in capturing other museum objects. One potential target, if the spacecraft owner desires its return, is Asterix, France's first satellite, launched 26 November 1965. The 42-kg satellite, which made France the third nation to launch a satellite on its own rocket, is in a safe and accessible orbit of 527 km × 1697 km at 34.3°. The Holy Grail of potentially retrievable American artifacts in inner Solar System space (in a heliocentric orbit) is the Lunar Module ascent stage from Apollo 10, fondly dubbed "Snoopy." In 2037, it will pass within 6.437 million km of Earth. [32] Recovering Snoopy would be challenging and costly, but it is possible. A different form of archaeology, a flyby with an observation spacecraft, would be more practical. A close inspection would rely heavily on onboard AI given the 43-second roundtrip delay in communications with Earth.

One option we feel is worth considering is launching a space platform that is capable of hosting and deploying multiple small satellites. This could further prove this technology and enable an imaging and retrieval vehicle to be manifested with a single launch vehicle. On such a space platform, satellites for both surveillance and capture/retrieval could be simultaneously hosted, potentially reducing the number of launches required to achieve the overall mission.

VI. Key Technology Opportunities

During our evaluation of a potential mission to ascertain the condition of Vanguard 1 and potentially retrieve this venerable satellite for further study, we identified the following technologies that could be leveraged. This is only a preliminary list; some of these may prove less applicable, and some we did not even envision could be relevant.

1. Small satellite launchers customized with the proper upper stages to perform precision placement of spacecraft in the proximity of Vanguard 1
2. Ground-based and space-based optical (e.g., LIDAR) and radar systems that could be used to ascertain the precise ephemeris of Vanguard 1 in its current orbit or a modified orbit
3. Space-based imagery (still and motion) of sufficient resolution to evaluate the condition of Vanguard 1 and provide images to the broader scientific community and public
4. Automated systems (potentially controlled by AI) to perform precise station-keeping with Vanguard 1
5. Mechanical systems that could be used to gently capture Vanguard 1 and influence its trajectory, which could be based on existing or in-development debris-clearing and/or satellite servicing systems
6. Small, portable environments that could be used to protect Vanguard 1 from terrestrial conditions until it can safely be conveyed to a controlled environment in a laboratory
7. Small, lightweight propulsion systems, such as ion propulsion systems, which could gently impart high specific impulses to coax Vanguard 1 from its current orbit into a new orbit conducive to retrieval
8. Automated AI decision-making algorithms that could help perform delicate activities on Vanguard 1 without the need for direct human intervention
9. Overall innovation of Smallsat systems, including potentially multi-Smallsat platforms, which could demonstrate improved capability and reduced costs over traditional systems
10. Flexible mission-planning strategies to adjust mission parameters upon the receipt of new information during the course of the mission

VII. Conclusion

A Vanguard 1 retrieval mission would excite the imagination of the space community and the interested public at large, providing unique challenges that could demonstrate the technological capabilities of private companies and government organizations. Even though the technical challenges of a retrieval mission are great, the potential of showcasing the capabilities of Smallsat missions could well be worth it. This mission provides the opportunity to potentially showcase improved capabilities of precision rendezvous and proximity operations, small-scale propulsion systems, and artificially intelligent spacecraft. The retrieval mission also provides an opportunity to study an integral piece of space history from an archeological perspective to determine how well materials and technical instruments can survive more than 66 years in the hostile environment of space.

Determining the right approach awaits trade studies, further research, and input from government and industry experts. The modeling done in this paper supports that the first step is imaging with an existing spacecraft or a low-cost Smallsat adapted from an existing bus to establish the satellite's condition. The best course from there, if the satellite is retrievable will depend heavily on the availability of funds and technology as well as the desire for minimal risk. An emerging truth is that every handoff or docking increases risk, but every handoff or docking eliminated may raise costs by requiring increased customization of vehicles. Further exploration of the optimal path is beyond what we can accomplish here. We can only outline the starting conditions for a trade study.

Funding and mission-launching bodies will have their own criteria and quite possibly a different result from a trade study done purely on technical merit. It is possible that there is no practical approach within existing funds for the retrieval portion. Even if it turns out not to be feasible to retrieve Vanguard 1, though, Phase I of the mission to determine the condition of Vanguard 1 would still provide significant opportunity to showcase in-space observation technology focused on a very small target and would provide the scientific and technical community with valuable information regarding the condition of the oldest human-made object still in space.

Acknowledgments

The authors wish to acknowledge the help of indispensable colleagues at Booz Allen Hamilton, including Senior Vice President Chris Bogdan, Executive Advisor James Reilly, Principal Matt McGuire, Vice President Karen Fields, Senior Associate Trae York, and Media Relations Coordinator Benjamin Stanton. Contributors from other organizations include David Barnhart, University of Southern California; Blake Davis, Lockheed Martin (retired);

Roger Easton; Dennis Wingo, SpaceBilt; Pete Wilhem, NRL (retired); Alan Holt, NRL; Robyn Kane, independent cost analyst..

Disclaimer

This paper presents the thoughts of the authors. It is not a business proposal or offering and does not represent the views, policies, or plans of Booz Allen Hamilton or any government or private organization.

Authors

Matt Bille is a Booz Allen Hamilton Research Analyst with over 30 years' space experience. A former Air Force missile officer, he authored the NASA-published "The First Space Race: Launching the World's First Satellites" and more than 30 shorter works. He holds a master's in space systems management from Webster University. An AIAA Associate Fellow, he belongs to the AIAA History Committee and National Association of Science Writers.

Mike Ferguson is a lead engineer with Booz Allen with over 25 years of experience in civil space operations and systems engineering, including space communications and human space flight programs such as Constellation, Commercial Crew, and Artemis. Mike holds a master's in physics from the University of Colorado, Colorado Springs. His interests include space history, music, travel, foreign languages, and numismatics.

William Austin is a senior associate at Booz Allen with over 25 years of experience in space and intelligence. His Air Force, DoD, and Intelligence career in space acquisition, operations, surveillance, and space control included work on the Space-based Space Surveillance System, and Space Tracking and Surveillance System and service at the Deputy Assistant Secretary of Defense level. He holds a master's in engineering management from Mercer University.

Chris VanWy is an Associate on Booz Allen's Joint Combatant Command Organization, working in the USPACECOM Joint Integrated Space Team (JIST) supporting USEUCOM. He retired from the U.S. Air Force after 20 years of service and is finishing his degree in Astronomical and Planetary Science with Arizona State University.

Catherine Russell is a staff writer and editor with Booz Allen Hamilton. She joined Booz Allen in 2022 and has supported communications and project development for multiple clients. Her editorial experience prior to consulting included projects in the disciplines of law, academia, media, technology, and journalism.

Dakota Welch is a Booz Allen systems engineer with over 15 years of experience in developing innovative solutions for complex technical challenges. He authored the AIAA paper "Finding a Safe Way to Land and Live on Mars" and provided this paper's STK analysis. He holds a master's in aerospace engineering from Webster University.

References

[1] Bille, Matt and Erika Lishock, *The First Space Race: Launching the World's First Satellites*, NASA Centennial Series Books, Texas A&M University Press, College Station, TX, 2004, Chapters 5 and 9: McLaughlin Green, Constance, and Milton Lomask, *Vanguard: A History*, NASA, 1970.
[2] CONFERS web page. URL: https://satelliteconfers.org/ [retrieved 18 September 2024]
[3] Rocket Lab, "Rocket Lab Sets Launch Window for Astroscale Orbital Debris Inspection Demonstration Mission," press release, February 2024. URL: https://www.rocketlabusa.com/updates/rocket-lab-sets-launch-window-for-astroscale-orbital-debris-inspection-demonstration-mission [retrieved 18 May 2024].
[4] Unnamed True Anomaly spokesperson quoted by Sandra Ervin, "Space tech startup True Anomaly set to launch its first satellites," *Space News*, 10 February 2024. URL: https://spacenews.com/space-tech-startup-true-anomaly-set-to-launch-its-first-satellites [retrieved 15 May 2024]
[5] Secure World Foundation, *Global Counterspace Capabilities: An Open Source Assessment*, April 2024, p. 1-04. URL: https://swfound.org/counterspace.
[6] Pesce. Vincent, *et. al.,* "Stereovision-based pose and inertia estimation of unknown and uncooperative space objects," *Advances in Space Research*, Volume 59, Issue 1, 1 January 2017, Pages 236-251: Peng, Jianqing. *et. al*.,"Dual-arm coordinated capturing of an unknown tumbling target based on efficient parameters estimation," *Acta Astronautica*, Volume 162, September 2019, Pages 589-607: Xin, Min, and Heija Pan, "Nonlinear optimal control of spacecraft approaching a tumbling target," *Aerospace Science and Technology,* Volume 15, Issue 2, March 2011, Pages 79-89: Zhang, Lijun, et. al., "Relative attitude and position estimation for a tumbling spacecraft," Aerospace Science and Technology, Volume 42, April–May 2015, Pages 97-105
[7] "Conference Proceedings," https://digitalcommons.usu.edu/Smallsat/
[8] "ESPA User's Guide, Moog, September 2024," https://www.moog.com/products/spacecraft-payload-interfaces/espa.html
[9] SpaceX, "Smallsat Rideshare Program," current as of 22 October 2024, https://www.spacex.com/rideshare
[10] SpaceX, "Cake Topper Payload User's Guide," January 2023
[11] Next Spaceflight, https://nextspaceflight.com/launches/details/7303#, 2024.

[12] Reesman, Rebecca, "Getting in Your Space: Learning from Past Rendezvous and Proximity Operation," Aerospace Corporation. May 2018.
[13] UKSpace, "RemoveDEBRIS net successfully snares space debris," 19 September 2018, https://www.ukspace.org/removedebris-net-successfully-snares-space-debris/
[14] Rocket Lab, "Rocket Lab Successfully Returns Spacecraft Capsule to Earth, Brings Back Pharmaceuticals Made in Space," press release, 21 February 2024, https://www.rocketlabusa.com/updates/rocket-lab-successfully-returns-spacecraft-capsule-to-earth-brings-back-pharmaceuticals-made-in-space/.
[15] *Aviation Week and Space Technology*, "Sierra Space's Ghost Emerges From Stealthy Development Strategy," 18 April 2024: https://www.sierraspace.com/press-releases/sierra-space-ghost-enters-flight-test-enabling-global-payload-delivery-in-90-minutes/
[16] Interface Definition Document (IDD) for International Space Station (ISS) Visiting Vehicles (VVs), International Space Station Program Office, SSP 50235, 10 February 2000
[17] Interface Definition Document (IDD) for International Space Station (ISS) Visiting Vehicles (VVs), International Space Station Program Office, SSP 50235, 10 February 2000
[18] *Ibid.*, Section 4.1, 2
[19] SSP 51721, Baseline ISS Safety Requirements Document, ISS Baseline, September 2019
[20] International Space Station Capabilities and Payload Accommodations
[21] Oberg, James, "Space station benefits from a wide opening," https://www.nbcnews.com/id/wbna137558577 July 2006
[22] NASA Technical Note D-498, "Balancing Vanguard Satellites," April 1961
[23] NASA, "Rendezvous, Proximity Operations & Docking Subsystems," 12 February 2024, https://www.nasa.gov/reference/jsc-rendezvous-prox-ops-docking-subsystems/
[24] Cassell, Alan, *et. al*., "Small Spacecraft Sample Return Mission Concept to Support Gateway and Lunar Science SSC22-III-04, 2022, https://smd-cms.nasa.gov/wp-content/uploads/2023/11/ssc22-iii-04.pdf
[25] NASA, "CubeSat Proximity Operations Demonstration (CPOD)," 23 June 2023, https://www.nasa.gov/smallspacecraft/cpod-project/
[26] Space Systems Command, "SML Mobility Cross-Cutting Operational Enabler: Refueling and Mobility for Dynamic Space Operations, RFI2_MobCOE_LOE4, 11 December 2023
[27] Orion Space Solutions, "Orion Space Solutions Completes Critical Design Review (CDR) for U.S. Warfighter Support," press release, 2 January 2024
[28] Starfish Space, "The Otter," https://www.starfishspace.com/the-otter/, retrieved 25 November 2024.
[29] U.S. Patent numbers for this paragraph are in, sequence, 9,187,189; 9555905; 7,240,879; 7,438,264
[30] Wald, Dan, and Karen Fields, "Generative AI Is Now in Space," https://www.boozallen.com/markets/space/generative-ai-is-now-in-space.html
[31] Guffanti, T., Gammelli, D., D'Amico, S., & Pavone, M. (2024). "Transformers for trajectory optimization with application to spacecraft rendezvous," 2024 IEEE Aerospace Conference, 34, 1–13. https://doi.org/10.1109/aero58975.2024.10521334
[32] Dickinson, David, "Astronomers Might Have Found Apollo 10's 'Snoopy' Module," *Sky & Telescope*, 14 June 2019. https://skyandtelescope.org/astronomy-news/astronomers-might-have-found-apollo-10-snoopy-module