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A Taskable Space Vehicle

Realizing Cost Savings by Combining Orbital and Suborbital Flight

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The use of space gives the United States distinct advantages in any battlefield environment, but the high cost of space operations increasingly jeopardizes those advantages. Although the United States pioneered much of the current space technology, declining budgets for space research, development, and operations leave our legacy systems vulnerable to adversaries around the world. Other nations formerly incapable of space exploitation are quickly learning to counter US space technologies at surprisingly low costs. In order to reduce the expense of deploying and maintaining a robust space capability, the Department of Defense (DOD) must change the status quo in space operations or risk losing its dominance. The US Strategic Command, National Aeronautics and Space Administration, Defense Advanced Research Projects Agency, and Air Force recognize the problem of sustaining the United States' edge in space despite declining budgets. Tasked with bridging the gap between available resources and operational needs, the Operationally Responsive Space (ORS) Office envisions significant progress, but we should expand its vision. This article proposes a phased approach that will multiply the cost savings of the ORS program (hereafter referred to simply as ORS) and increase US space capabilities; this approach harnesses the potential of the orbital and suborbital flight of space planes and existing satellites for repeatedly maneuvering and performing multiple missions.

Established in 2007 as a joint initiative of several agencies within the DOD, the ORS Office seeks to develop low-cost access to space via missions responsive to war fighters' needs. Access to space is not cheap; vehicle development and launch comprise the largest part of space expenditures. ORS strives to drive down the costs of both those components simultaneously so that we can prepare and launch a space vehicle within weeks at a fraction of the current outlay (for as little as a penny for every dollar now spent on comparable missions).[1] At present, however, ORS focuses only on quickly preparing vehicles and launching them cheaply—it does not envision maneuverable space vehicles that could change their orbits to perform more than one mission during their service lives. According to Dr. James Wertz, an ORS proponent, "[Responsive space] cannot be achieved with already on-orbit assets. [It is] like hoping the bad guy will step into the path of a bullet which has already been shot."[2] Using the same satellite for multiple missions by employing nontraditional, orbital-change tech-

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niques can enhance responsiveness to war fighters' needs while reducing program costs even further.

Implementation of this new responsive-orbit approach should proceed in four phases. The first phase will show that some currently operational satellites can modify their orbits significantly in an efficient manner simply by changing the concept of operations (CONOPS). The hardware for this technology already exists and is well tested and understood. Such a system needs an electric propulsion system (gridded ion thruster or Hall Effect thruster) and a small satellite platform (weighing 500–1,000 kilograms).[3] The second phase will apply moderate amounts of aerodynamic drag to the satellite, such as those experienced in the outer atmosphere for altitudes ranging between 150 and 700 kilometers (km) above the earth's surface (known as the thermosphere).[4] In addition to a new CONOPS, electric propulsion, and a small platform, the third phase will demand a vehicle capable of manipulating aerodynamic forces (similar to the space shuttle and X-37). We find these three hardware components employed individually in spacecraft today. Therefore we need only a new CONOPS and the right combination of vehicle characteristics to turn an on-orbit satellite into a maneuverable space asset. The fourth and final phase will combine maneuverability with ORS concepts under development. Evolution of the first phase is under way, showing the potential of the responsive-orbit concept. Future phases will progress as follows.

Operationally Responsive Space

The United States' present use of space drives a DOD space program that typically costs billions of dollars. Traditional space missions are strategic, durable (designed for 10- to 20-year life cycles), inflexible, expensive ($100 million–$2 billion), highly capable, complicated, and hard to replace.[5] These characteristics are interrelated. Due to the considerable expense of launching spacecraft, designers make their systems extremely capable and reliable. Those traits come at a premium cost and produce long life cycles. Highly capable, reliable, and long-lasting systems must have redundancies for all components critical to their operation (almost the entire system)—and those redundancies add weight, which leads to greater launch expenditures. Clearly, this self-sustaining cycle creates ever-growing, supercapable spacecraft that cost billions of dollars and take a decade to build. This paradigm has become the defining characteristic of space culture. Today's requirements for rapid reconstitution and assets responsive to unplanned threats and disasters necessitate additional space-acquisition models.

Current space missions often fall short of meeting the needs of war fighters. The systems demand long development times to mature and integrate the necessary technologies. By the time a system is ready to deploy, many of its electronic components are no longer state of the art, so engineers must design new ones. The DOD cannot keep up with the demands of military operations.[6] Users often wait several years beyond the originally planned delivery date before they finally receive a new asset whose intended purpose may have already changed. During the planning for Operation Desert Storm in September 1990, planners realized that existing satellite communications (SATCOM) capacity would not be sufficient to support the war effort; consequently, they urgently attempted to launch an additional Defense Satellite Communications System III spacecraft. The mission finally launched on 11 February 1992, missing the war by more than a year.[7] Designers produced the follow-on to that spacecraft, the Wideband Global SATCOM, as a commercial off-the-shelf system because of advertised time savings in the acquisition schedule. When its development began in 2001, the launch was scheduled for the fourth quarter of 2003, yet the satellite did not attain operational orbit until 2008 (after launch on 7 October 2007)—five years behind schedule.[8] This delay caused critical communication shortages in the Pacific Command and Central Command theaters, resulting in up to 80 percent reliance on commercial assets at inflated costs to taxpayers.

ORS seeks a paradigm shift in space operations. In contrast to the latest methodology, ORS missions are designed to be tactical, short (intended for a one-year life cycle), flexible (adaptable to mission need, timeline, and geographic region), cheap (less than $20 million), specialized (spacecraft provide a specific function and work with other spacecraft to realize an objective, making the overall system less vulnerable to an attack), technologically simple, and immediately replaceable.[9] ORS emphasizes smaller satellites and launch vehicles; rapid, on-demand deployment; and quick availability of capabilities to users. Concepts under development will continue to rely on traditional, Keplerian orbits, meaning that each launched asset serves only a single purpose.[10] Even a cursory comparison of a traditional mission and ORS shows that the latter is everything the former is not.

The ORS approach marks a significant shift in the US space culture. Stakeholders generally agree on the desirability of reducing mission cost and elevating responsiveness to user needs, but fulfilling those goals is difficult, requiring persistence and willingness to change existing hardware, command and control, and testing norms. Hopefully, policy planners will acknowledge the benefits of transforming this culture and embrace new business rules, allowing rapid changes to give us the flexibility to meet user needs quicker and more efficiently.

ORS could offer even greater benefits if it included development of a maneuverable satellite, such as a small one in the 500-kilogram weight class, which can carry sufficient fuel on board to perform multiple maneuvers.[11] That is, the vehicle could perform an orbital change after completing one mission, thereby permitting retasking to carry out a new one. Assuming that the desired orbital changes were small, the satellite could maneuver 15 times or more.[12] One maneuver would reduce the number of launches by 50 percent—three maneuvers, 75 percent. Regardless of the cost savings in hardware and testing that ORS might realize, launches will remain expensive, especially if we must launch a new satellite for each tasking. Therefore, a maneuverable satellite that we could retask on orbit multiple times could prove far less costly than the ORS version.

Meeting User Needs with a Maneuverable Asset

ORS optimistically presents a single low-cost vehicle launched on demand and to the proper orbit within hours of tasking. This long-term vision of ORS has a target date of 2020. Assuming that such a vehicle exists and that the launch capability and ground control segment are in place, the perennial shortage of available assets to meet operational user needs would expend any on-hand capability as quickly as it could be produced, thereby precluding a truly responsive system. Responsiveness is not limited to the space segment; quick launches can also improve the timeliness of meeting a new user need. Rapidly launching augmentation or replenishment spacecraft can prove essential to maintaining a specific capability. At present, spacecraft production follows a launch-on-schedule concept, but responsive vehicles must be prepared for launch on demand. An effective shift to the latter approach would require maintaining an inventory of war-reserve materiel, spacecraft, and associated launch vehicles at the launch sites.[13]

The ORS concept relies on the ability to launch rapidly from an available inventory to respond to developing crises. It might necessitate launching one satellite and positioning it to monitor a tsunami-devastated area in the Pacific one day and launching another to gather intelligence about a peasant uprising in Central Asia the next day. This capability requires having readily available spares prepared at a moment's notice for launch and operation. However, for the foreseeable future, operational needs will continue to far outpace the rate at which we can field new assets to meet those needs. As demonstrated by the previously discussed SATCOM scenarios, military capacity quickly diminishes as a consequence of supporting newly operational terrestrial and aerial systems that demand substantial bandwidth to transmit data between forward-deployed forces and command centers. In order to build up a responsive capacity (with available inventory), we need a different approach.

Complementing the ORS design with the ability of the space vehicle to maneuver via nontraditional (or novel) orbits would reduce the pressure of a high operations tempo and lower the necessary capacity. Maneuverability would enable a single satellite launched into low Earth orbit to change its orbital plane sufficiently in a timely manner to respond to multiple world events or user requirements. In doing so, the satellite's on-orbit life span might decrease to less than the ORS program's current one-year standard, depending on how many different taskings the asset fulfills. Enabling a single vehicle to meet multiple user demands could greatly lessen the need for repeated launches and thereby reduce cost by millions of dollars per vehicle.

Specifically, these proposed novel orbits would leverage aerodynamic forces of the earth's atmosphere to change orbital parameters. Using simple technology developed during the days of Gemini, Mercury, and Apollo, we can design a space vehicle to reenter the atmosphere, using lift and drag to change orbit by altering its flight path, velocity, and altitude.[14] In essence, the orbital space vehicle becomes akin to a suborbital spacecraft, behaving like an aircraft while inside the atmosphere. Based on multiple reentry profiles simulated using the equations of motion provided by Lt Col Kerry Hicks, a vehicle designed with sufficient lift capability can perform aircraft-like maneuvers such as climbing, diving, and rolling.[15] This non-Keplerian part of the flight profile not only would enable a change in the orbit (the ground track required to fulfill a new operational objective) but also would add a degree of uncertainty for adversaries interested in tracking this vehicle. Thus, an adversary might be caught by surprise, having little or no prior warning of the vehicle coming overhead. The depth to which the satellite penetrates the atmosphere determines the control authority of the mechanisms put in place to modify orbital parameters. A deep atmospheric penetration can drastically change the orbit in ways that even high-thrust, liquid-propellant rocket engines cannot because of the prohibitive amount of fuel expended by those engines.[16]

A vehicle capable of entering and exiting the atmosphere unharmed by g-forces and heating due to atmospheric friction would certainly require some design changes. Since ORS strives to change the culture of space operations and architecture completely, it presents the perfect opportunity to take the idea further by considering novel approaches to increase flexibility and provide greater benefit to the effort with relatively simple modifications. The effects, controls, benefits, and dangers of reentry have been well known since the early days of manned space flight. By carefully selecting features of a vehicle's design, we can greatly enhance its lift capability and, therefore, the aerodynamic control authority to modify its orbit. Doing so would expand the flight envelope and increase operational flexibility.

The maneuverable vehicle concept, to a much lesser extent for altitudes above 150 km, also applies to current operational satellites not designed with ORS capabilities. Atmospheric-drag forces play a role in a satellite's orbit at or below an altitude of 700 km. The space shuttle and the International Space Station experience these forces constantly and must counter them to prevent orbital decay. The technology that allows satellites to maneuver is available and in use, but the CONOPS must change (phase one). Low-thrust electric engines enable satellites already in orbit to perform slow, precise, and highly efficient station-keeping maneuvers. The current CONOPS calls for the spacecraft to arrive at its orbital state and maintain orbit, almost exclusively, for the life of the vehicle. Because most spacecraft are designed in this manner, we don't give much thought to powered flight and its potential. When necessary, these engines can move large satellites into orbits to serve different terrestrial theaters, in the case of a geosynchronous system, or change the time a satellite arrives over a target (time over target [TOT]) for a system in low Earth orbit.[17] To harvest this potential, the CONOPS must proceed from the assumption that these spacecraft do not necessarily have to operate within the orbit into which they were first launched. Additionally, when we take into consideration the potential of the upper atmosphere to change a vehicle's orbit (even small drag forces can induce a noticeable change), a system already on orbit can maneuver significantly to change its TOT or geographical location even without modifying vehicle characteristics (phase two).

Concept Design and Results

A small orbital change can affect the terrestrial ground track of a satellite. An asset without ORS hardware that continuously thrusts with an electric engine over a seven-day period can sufficiently change its velocity within the same orbital plane to produce a 24-hour TOT change by modifying the ground track.[18] The ground-track alteration is proportional to the lead time provided to adjust the orbit. In simple terms, the more time available to implement a TOT change, the greater the magnitude of the potential change. Phases one and two of the research program can realize this result when an existing system's CONOPS is modified to allow maneuvers that change the TOT. Yet, the response time cannot compare to the potential response time claimed by ORS systems under development. Ultimately, an ORS asset will be capable of reaching any location on the earth within 45 minutes of launch and only nine hours following initial tasking.[19] However, this ORS goal has not yet become reality. A current asset that can maneuver in orbit using electric propulsion but not enter the atmosphere (i.e., remain above an altitude of 122 km) can reach any location on the earth at any specified TOT in seven days. In comparison, simulations show that a maneuverable asset designed with aerodynamic characteristics capable of leveraging atmospheric forces and out-of-plane maneuvers could reduce the time required to attain the desired orbit by about 75 percent (i.e., from seven days to approximately two), as discussed in phase three. With a little ingenuity, we can combine the atmospheric maneuvers with an ORS satellite to provide an inexpensive, highly effective system capable of quickly responding to the threats that the United States faces today.

An ORS asset is designed as a small, light satellite capable of maintaining attitude (pointing) and location (station keeping). To make it maneuverable (phase four), we could design the satellite with both a small impulsive-thrust (rocket) engine and a highly efficient electric-thrust capability (such as a Hall Effect thruster). Impulsive thrust enables rapid yet small changes in orbit, and continuous electric thrust builds up the energy to reach a stable parking orbit enabling repetition of the process. The design concept would involve launching such a satellite into a specific orbital plane to meet the needs of the initial tasking. After completing its first mission, the vehicle would impulsively modify its orbit slightly to cause its perigee (point in the orbit closest to the earth's surface) to enter or "dip" into the atmosphere where the satellite could use aerodynamic forces to change its orbital plane to meet requirements of the next tasking. Each time the vehicle performs such a maneuver, it loses energy. Simulations show that when the satellite's energy level can barely sustain orbital flight, the continuous electric-thrust system will efficiently raise that level enough to keep the vehicle in orbit. This process can be repeated until the satellite runs out of fuel for its propulsion system. A space plane equipped with the two types of engines described above (rocket and electric) could respond to multiple user taskings by using present-day technology—yet the knowledge of how to execute these maneuvers effectively remains quite limited. This design concept would strive to increase the number of taskings the system could fulfill by a factor of six compared to traditional assets in low Earth orbit equipped solely with chemical propulsion. (The efficiency [or gas mileage] of low-thrust electric engines is five to six times greater than that of high-thrust engines.) Such a space plane could fulfill 15 or more taskings, thereby completing 15 ORS missions with a single launch and reducing the advertised mission cost significantly.

Conclusion

The current space culture of fielding large, expensive, and capable satellite systems is not sustainable; it can neither satisfy the operational needs of US war fighters nor keep up with threats posed by other spacefaring nations. Just as conventional warfare must adapt to today's counterinsurgency demands, so must conventional space culture adapt to today's space environment. New initiatives such as ORS and the research discussed in this article seek to do just that.

We should take a phased approach to expanding the current ORS concept. In phase one, a new CONOPS built around a different paradigm for an existing on-orbit asset can provide a test bed for demonstrating the feasibility of attaining significant TOT change by using electric propulsion while remaining outside the atmosphere. The necessary technology is already in use, well tested, and understood. The fact that this phase does not require developing any new equipment would keep costs low. The second phase will enable greater flexibility and increased responsiveness to war fighters' needs by incorporating aerodynamic forces in orbits as low as 122 km to open opportunities previously thought impossible due to vehicle and fuel constraints. The third phase will involve a new vehicle designed to enter the atmosphere, perform the desired orbital change, and climb back into space. The technology to create vehicle characteristics best suited to take advantage of lift and drag forces also exists and has undergone much study. Yet, because the countless possibilities for changing a satellite's ground track to support multiple missions as proposed remain poorly understood, we need to conduct more research. This phase offers great potential for effecting large-scale orbital changes at very low fuel costs, increasing the life span of a satellite (when compared to inducing the same amount of change using traditional chemical propulsion), and enabling it to fulfill five to six times as many taskings as current operational satellites not designed to maneuver significantly. The final phase would expand the scope of ORS to include maneuverability. Allowing such effective, low-cost satellites to perform multiple taskings during their operational life spans would reduce the number of launches and give us sufficient capability to make ORS a truly responsive system.

The inevitable paradigm shift in the US space program has begun. Our future conventional space operations must include small, cheap, responsive, and maneuverable assets that we can develop and launch in months rather than decades. ✪

Wright-Patterson AFB, Ohio

Notes

1. James R. Wertz, *Responsive Space Mission Analysis and Design* (El Segundo, CA: Microcosm Press, 2007), 4. (This is a manual that accompanies a course on the subject taught by Dr. Wertz.) We compare the responsive mission's cost of $20 million for launch, spacecraft, payload, and one year of operations to the $2 billion spent on traditional programs (before including operation costs).

2. Ibid., 5.

3. A Hall Effect thruster is a type of ion propulsion engine in which an electric field accelerates the propellant. Hall thrusters trap electrons in a magnetic field and then use them to ionize propellant, efficiently accelerate the ions to produce thrust, and neutralize the ions in the plume. In a Hall thruster, an electron plasma at the open end of the thruster, rather than a grid in a standard ion thruster, provides the attractive negative charge. See *Wikipedia: The Free Encyclopedia*, s.v. "Hall effect thruster," http://en.wikipedia.org/wiki/Hall_effect_thruster; and "Hall Effect Thruster Systems," Busek, accessed 2 March 2011, http://www.busek.com/halleffect.html.

4. The boundary between the earth's atmosphere and outer space is not definite. Satellites are affected by atmospheric drag below an altitude of 700 km above the earth's surface. Atmospheric reentry forces become significant at an altitude of 120 km. Current satellites are not designed to withstand such forces.

5. Wertz, *Responsive Space Mission Analysis*, 7.

6. In a series of briefings and meetings during 2007–9, joint wideband working groups discussed the limited capacity of military satellite communications provided by DOD systems and ways of using them to meet military needs. Military systems such as Global Hawk, Predator, and Blue Force Tracking require high-capacity, flexible, and readily available satellite bandwidth that the then-current satellite constellation could not provide. Of growing concern was the DOD's 80 percent reliance on commercial assets. The working groups met quarterly in various locations, including California, Colorado, and Florida. See also Greg Berlocher, "Military Continues to Influence Commercial Operators," *Satellite Today*, 1 September 2008, http://www.satellitetoday.com/military/milsatcom/Military-Continues-To-Influence-Commercial-Operators_24295.html.

7. David N. Spires, *Beyond Horizons: A Half Century of Air Force Space Leadership*, rev. ed. (Peterson AFB, CO: Air Force Space Command in association with Air University Press, 1998), 268.

8. "Wideband Gapfiller System," GobalSecurity.org, 10 April 2005, http://www.globalsecurity.org/space/systems/wgs-schedule.htm. The Wideband Gapfiller System was later (about 2007) renamed the Wideband Global SATCOM.

9. Wertz, *Responsive Space Mission Analysis*, 7–9.

10. "Keplerian" refers to the orbit of a satellite around another body governed by the force of gravity and in the absence of atmospheric drag or propulsion (thrusters).

11. Robert Newberry, "Powered Spaceflight for Responsive Space Systems," *High Frontier* 1, no. 4 (2005): 48.

12. Ibid.

13. Les Doggrell, "Operationally Responsive Space: A Vision for the Future of Military Space," *Air and Space Power Journal* 20, no. 2 (Summer 2006): 49.

14. Lt Col Kerry D. Hicks, *Introduction to Astrodynamic Reentry*, AFIT/EN/TR-09-03 (Wright-Patterson AFB, OH: Graduate School of Engineering and Management, 9 September 2009), 239–41.

15. Ibid.

16. "Mars Reconnaissance Orbiter Successfully Concludes Aerobraking," National Aeronautics and Space Administration, 30 August 2006, http://www.nasa.gov/mission_pages/MRO/news/mrof-20060830.html.

17. In 2008 the WGS-1 satellite moved from its test latitude of 122.8 degrees West to 180 degrees West while it was in geosynchronous orbit. The spacecraft executed this phasing maneuver solely by using Xenon Ion Propulsion System thrusters (a type of electric propulsion). For a discussion of TOT change for satellites in low Earth orbit, see Newberry, "Powered Spaceflight," 46–49.

18. Ibid., 48.

19. Wertz, *Responsive Space Mission Analysis*, 9.