The Need for a Global Space-Traffic-Control Service

An Opportunity for US Leadership

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Losing a satellite to an accidental on-orbit collision is no longer hypothetical but real and increasingly likely. As a result, the spacefaring nations of the world, especially the United States, need to address a global space-traffic-control service. The fiscal and national security ramifications are too significant to ignore. The replacement cost of a satellite, perhaps hundreds of millions of dollars, is the most obvious impact. But this may be the most trivial consideration. The greatest concern is the potential catastrophic loss of vital communications, navigation, weather, and other services we depend on for daily global commerce and defense. This paper explains the problem, examines some possible paths to address the problem, and recommends actions.

In February 2009, a spectacular collision grabbed headlines around the world. In low Earth orbit (LEO) 400 miles above Siberia, an American commercial communications satellite, *Iridium 33*, collided with the defunct Russian satellite, *Cosmos 2251*.[1] The probability of this first known satellite-to-satellite collision was estimated to be one in 100,000.[2] With a closing velocity of 22,000 mph, the satellites were instantly pulverized into debris clouds, creating more than 870 objects observed by the US Air Force Space Surveillance Network (SSN).[3]

The specter of collisions is not new, despite the "big sky" theory.[4] Although *Iridium-Cosmos* is the first known collision between two satellites, this was the fourth documented accidental collision in space (intentional destruction is described later). In 1991, coincidently, a defunct Russian satellite, *Cosmos 1934*, collided with a fragment from another Cosmos launch.[5] Five years later, the French reconnaissance satellite *Cerise* was damaged by colliding with a fragment from an Arianne rocket body, another French object. In this collision, the fragment struck *Cerise* with a closing velocity of 32,400 mph, cleaving its 20-foot boom in half. Experts estimate the probability of this collision was one in a million—so much for the big sky theory.[6]

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Luckily, the satellite remained operational.[7] In 2005 the third confirmed collision occurred. The final stage of a US *Thor Burner 2A* rocket, in orbit more than 31 years, struck a fragment from the upper stage of a Chinese *Long March 4* rocket.[8]

Beyond collisions, other events also present dangers to satellite traffic. Lt Gen Larry D. James, commander of the Joint Functional Component for Space, reported that the Chinese antisatellite test that destroyed *Fengyun-1C* in January 2007 was the worst fragmentation event in the history of spaceflight. This event added "2,400 pieces of potentially destructive debris," increasing the number of objects that Air Force Space Command (AFSPC) tracked by over 10 percent.[9] A month later, a Russian upper stage from a Proton rocket, loaded with fuel leftover from a failed boost, exploded and created another 1,100 pieces of debris.[10] As of April 2009, the Air Force was tracking approximately 19,000 objects larger than 10 centimeters. If it could track objects down to one centimeter, the Air Force estimates that number would increase to about 300,000.[11]

As space becomes more crowded with debris, it may be reaching a precarious tipping point. In 2006 National Aeronautics and Space Administration (NASA) scientists warned that unless space debris is removed, the likelihood of collisions will increase. They predict that beyond 2055 "the creation of new collision fragments [will exceed] the number of decaying debris," while the "current debris population in the LEO region has reached the point where the environment is unstable and collisions will become the dominant debris-generation mechanism in the future." In other words, as collisions create more debris, the collisions themselves become the primary source for debris.[12] As a result, NASA is concerned about the risk debris poses to its manned systems.

During 2008, with the aid of the Department of Defense's (DOD) Joint Space Operations Center (JSpOC), NASA made five collision-avoidance maneuvers to protect its human spaceflight missions and maneuverable robotic assets.[13] In March 2009 alone, the International Space Station had three near misses, which required the crew to prepare for emergency evacuation in one case and change orbit in another.[14] GeoEye, a commercial imaging company, reported it has maneuvered its Ikonos satellite seven times and *GeoEye-1* satellite four times to avoid space junk in the LEO region.[15] In addition, the Massachusetts Institute of Technology's Lincoln Laboratory has recommended 65 avoidance strategies in the geosynchronous Earth orbit (GEO) belt since 1997.[16] Although these efforts are encouraging, they are insufficient.

Today, most of the world's satellites fly in the blind, operating under the safety assumptions inherent in the big sky theory. However, Gen Kevin P. Chilton, commander of US Strategic Command (USSTRATCOM), stated that big sky has now "[come] to a close."[17] Of the 19,000 objects that AFSPC and the JSpOC were tracking in April 2009, 1,300 were active payloads.[18] In the next decade, an additional 200 payloads are expected.[19] This growth in satellite numbers and the world's dependence on these systems points to the need for global space-traffic control. As the *Iridium-Cosmos* collision illustrates, the ad hoc efforts of NASA and others are not enough. Without a robust service to mitigate potential collisions, operators of military, civil, and commercial satellites are without the means to avoid catastrophe.

This paper advocates that the United States establish a global service with the cooperation of the international community and private sectors. To support this recommendation, we will examine existing global services that could serve as a model for a space-traffic-control service. But first, we will review the functional components of a service, the current space environment, the state of fielded space situational awareness (SSA) systems, gaps in these systems, and liability implications.

The Current Landscape

Before discussing the current space environment and the systems which monitor space, let's first describe what would make up a worldwide 24/7 space-traffic-control service. From a functional view, this service must be able to accurately search, detect, track, identify, and catalog space objects in Earth's orbit. The service would then need to predict the future positions of these objects, analyze the traffic for possible collisions (referred to as conjunctions), issue timely warnings to affected parties, and direct avoidance maneuvers, if required. If damage is sustained, per international treaties, the service would then need to assist to the greatest extent feasible in identifying the space objects and nations involved to help determine liability.[20] Logically, these functions can be organized into three categories: acquire, analyze, and act (see fig. 1), which parallel how data can be transformed into information and knowledge.

Monitoring and understanding the space environment comprise the essential first steps towards building a space-traffic-control service.[21] This is traditionally referred to as SSA. SSA by itself is necessary but insufficient. A space-traffic-control service goes beyond this by also actively mitigating potential collisions (acting with knowledge, see fig. 1). Currently, a service which actively controls the global space

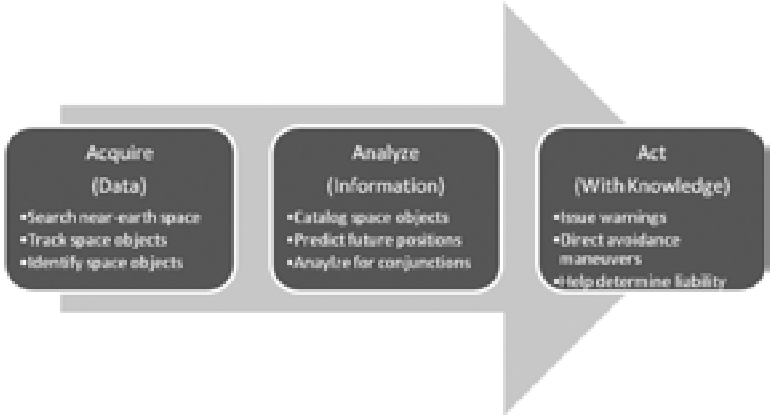

Figure 1. Functional view of a global space-traffic-control service

traffic does not exist.[22] To begin this discussion, let's first examine the near-Earth space environment.

The number of man-made objects in Earth's orbit tracked by the Air Force has quadrupled to 19,000 over the past 29 years.[23] By 2015 the Air Force plans to upgrade its space surveillance network. With its increased sensitivity, the Air Force expects the catalog to grow fivefold to 100,000 objects.[24] The vast majority of these space objects and debris are in the LEO region.[25] This is the orbital region of most manned space flights and also where all the collisions described earlier occurred. However, objects in LEO are not the only ones susceptible to collision. The GEO belt is another region of concern.[26] Almost one-third (380) of the total 1,300 active payloads is in the GEO belt. Most of these are the high-value, high-bandwidth communication satellites used for television and communications. To complicate matters, another 750 dead satellites dangerously drift uncontrolled in the GEO belt.[27] In all, the Air Force tracks between 2,000 and 2,500 objects in GEO.[28]

Beyond satellite-to-satellite collisions, as discussed earlier, satellite collisions with debris are another concern. Historically, 94 percent of all tracked objects is debris. Debris includes nonfunctional spacecraft, spent rocket bodies, breakup fragments, deterioration and exhaust products, objects released during spacecraft deployments and operations, and refuse from human missions.[29] In the last 20 years, fragmentation debris has comprised roughly 40–45 percent of all objects tracked. Large debris, such as dead satellites and old rocket bodies, comprises another 35–40 percent.[30]

Recent events in the LEO region have made the debris environment even messier. The 2007 Chinese antisatellite test added another 2,400 pieces of potentially destructive orbital debris, a 2.7-fold increase in debris centered at 850 kilometers (km) in altitude. The *Iridium-Cosmos* collision added another 870 objects, a 33 percent increase at 780 km.[31] As discussed earlier, unless debris can be removed, the problem will only get worse. Scientists predict that by 2055 new debris generated by collisions will outpace debris naturally removed through orbital decay.[32]

Currently, only two nations have the necessary network of ground-based sensors and computational capabilities to attain the minimum degree of SSA to bootstrap a global space-traffic-control service. These are the American SSN and Russian Space Surveillance System (SSS).[33] Other government agencies with limited or nascent capabilities include the Chinese, French, and German militaries and the European Space Agency (ESA). Nongovernmental agencies such as the International Scientific Optical Network, operated by the Russian Academy of Sciences, and amateur astronomers also produce orbital data.[34] However, to achieve a truly global system, none of these are adequate; they all require upgrades and/or cooperation.[35]

The US SSN is by far the most comprehensive system in the world. It is a global network of 29 ground-based sensors. In general, it uses radars to track LEO objects and optical telescopes to track GEO objects. Combined, these sensors provide the JSpOC with roughly 300,000 to 400,000 measurements (observations) per day. The JSpOC then has the enormous computational task of merging these observations into tracks, correlating the tracks with a priori information on known objects, and updating the 19,000 objects in the unclassified space catalog.[36] For high-priority US military and NASA analyses, the JSpOC also generates high-accuracy analyst sets available only to military personnel at JSpOC.[37]

In comparison the Russian SSS has 22 sensors, which include military and civilian radars and telescopes. These systems collect approximately 50,000 observations per day. To make up for fewer observations (as compared to the Americans), the Russians depend on superior mathematical and predictive abilities to maintain their catalog. However, the SSS is not a global network; it is geographically confined to the longitudes of Russia and former Soviet republics. This geometry hinders their ability to track low-inclination LEO and GEO satellites in the Western Hemisphere. Further, unlike the Americans, the Russians do not publish a publically available catalog.[38]

For self-stated reasons of sovereignty and independence, the Europeans are proposing an SSN of their own. The European Union realizes that its economy depends on space technologies and that protection of space systems is vital to its security. Some of its member states, such as Germany and France, already have some space-surveillance assets, but these are limited and not integrated into a holistic system. The ESA's director general said that "Europe is blind to what happens in space and wholly dependent on US supplied data."[39] To remedy this situation, the ESA plans to invest $66 million over the next three years to develop its own capability.[40]

A new US government initiative is also emerging. In 2003 Congress directed the secretary of defense to conduct SSA for all US government space systems and, as appropriate, for commercial and foreign entities (CFE). In response, AFSPC made available conjunction analyses via the Space-track.org Web site to nongovernmental entities as a pilot program. As of September 2009, 18 commercial companies, which operate 66 satellites, have signed quid pro quo agreements with the US government for conjunction analyses and launch support. In October 2009, AFSPC transitioned CFEs to USSTRATCOM as an operational program. However, the high-precision conjunction analyses needed for effective collision avoidance are not universally available. This is limited to high-value satellites (as prioritized by the US military) because it is labor intensive and not automated.[41]

Along with Space-track.org (as part of CFEs), several other public-domain services, such as HeavensAbove.com and Celestrack.com, also publish the space catalog on the Internet. Although they provide a valuable service, they are not necessarily providing new data. Essentially, they republish the unclassified space catalog provided by the Air Force, the so-called two-line element (TLE) sets. Although available to the world, these TLE sets do not have the requisite accuracy needed for precision conjunction analysis. In fact, the Air Force warns Space-track users to use the data at their own risk.[42] Additionally, at least 6,000 objects do not appear in the Space-track catalog because the launching nation could not be identified.[43] With these restrictions and limitations, the underlying message is that users need more accurate data.

In an apparent response to these deficiencies, three of the world's largest commercial satellite operators—Intelsat, SES, and Inmarsat—in a cooperative private venture, created the Space Data Association in November 2009. They expect eight companies to participate in collision avoidance and another 14 companies to be involved in reducing satellite radio-frequency interference. Although they acknowledge that the US CFE program has some benefit, they feel compelled to invest their own capital because the "information is not always as precise or up to date—nor is it disseminated as quickly—as it needs to be to protect against close encounters between satellites."[44]

Two other organizations also provide conjunction analyses and warnings of possible satellite collisions. Lincoln Laboratory, as part of a cooperative research and development agreement, fielded the Geosynchronous Monitoring and Warning System (GMWS) for its four member partners. The automated GMWS, via high-precision orbits derived from three Lincoln Laboratory–operated radars merged with SSN data, produces 60-day watch lists and two-week warning lists of close encounters for 60 commercial satellites. Lincoln Laboratory typically reports 250 conjunctions per year and has recommended 65 avoidance strategies to its partners since 1997.[45] A second service, the Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES), is hosted on Celestrack.com and available to anyone interested. It provides twice-a-day analyses for all orbital regions based on the Air Force's unclassified TLE sets. Although it's not very accurate—the positional uncertainties are hundreds or thousands of meters due to the limitations of the TLE sets—the SOCRATES reports can be used as tip-offs by satellite operators for further investigation.[46]

Despite these efforts, there is a significant gap between current space surveillance capabilities and what is needed for comprehensive, global space-traffic control. For example, as good as the US system is, General James says it still lacks the ability to acquire all on-orbit objects. He stated that the SSN has a significant coverage gap in the Southern Hemisphere and often loses some GEO satellites.[47] To plug this hardware gap, the Air Force is investing $45 million to field a new ground surveillance system—an expansion of the "Space Fence"—with initial deployment by 2015.[48] In addition, the Space-Based Space Surveillance System, slated to launch in 2010, will provide the ability to scan the entire GEO belt from space and maintain "track custody" of GEO objects every 24 hours.[49] However, these efforts mainly address data acquisition (see fig. 1), not holistic solutions for space-traffic control.

Beyond hardware, the US software system is also imperfect and antiquated. In some cases, the Americans are behind Russian mathematical practices to process and predict high-quality space tracks.[50] For example, the US military is still using decades-old astrodynamic techniques to create element sets, mainly because the costs to redesign and recertify its operational systems would be enormous.[51] To make up some of this deficit, the Air Force uses the brute-force method of oversampling (lots of observations) versus elegant mathematics. Until recently JSpOC was performing conjunction analyses only for priority US satellites, such as manned flights and US defense satellites. After the *Iridium-Cosmos* collision and renewed interest by DOD senior leaders, the JSpOC recently upgraded its computational systems to give it the ability to run conjunction analyses for all active satellites within the catalog.[52] However, precision analysis needed for positive collision avoidance is still only on a case-by-case basis because it is labor intensive and not automated.[53]

Another challenge is data sharing. Only the United States currently shares its unclassified space TLE catalog with the world (with some restrictions). But its information sharing is criticized for being untimely and insufficient for conjunction assessment and warning.[54] Russia and China currently do not share.[55] And the ESA does not plan to publicly share data either. An ESA official stated, "We will send our data only to those who really need it."[56] Further complications arise from security. For example, the Americans do not share orbital information on their national-security satellites. The French were frustrated that the United States publishes data on French classified satellites and asked that the Americans withhold this information.[57] Dr. William Ailor, Aerospace's director for the Center for Orbital and Reentry Debris Studies, states that an effective space-traffic-control system would need to incorporate data from all sources, government and private, and would need to protect proprietary and sensitive data.[58]

Beyond the inadequacies of data policies, no international treaties or guidelines "mandate a legal set of approaches towards space traffic management."[59] Only liability resulting from collisions is presently addressed by international law. The Outer Space Treaty of 1967, the Liability Convention of 1972, and the Registration Convention of 1976 make it clear that both intergovernmental organizations and state parties are liable for damages caused by their space objects (including their components) whether on the ground or in the air or outer space. Unfortunately, the treaties are silent on the issues of debris management or removal. If debris happens to be involved in a collision, the Registration Convention obligates nations with space surveillance systems to assist to the greatest extent feasible in identifying the origin of the space object.[60] To address this problem, the State Department's deputy director of space policy is looking "at ways to protect critical government and commercial space infrastructure against orbital debris" and improve SSA at the 2010 United Nations (UN) Conference on Disarmament.[61]

If a global service is required to avoid satellite collisions, is there precedence for such a service? We next look at three global services operating today, some of which have been in use for more than a century.

Precedents for Global Services

Three existing services could be models for a global service.[62] These include a free US-operated service and international services that would help to manage the global commons on behalf of their members.

The Global Positioning System (GPS) demonstrates the first type of global service, one provided free by the United States. Today, GPS is used by virtually the entire world for positioning, navigation, and timing. According to senior US State Department officials, although its genesis was military uses, GPS evolved into a global utility and a centerpiece of US diplomacy. In 1983 President Reagan offered free civilian access to GPS to help enhance aviation safety around the world. President Clinton in 1996 expanded the policy to ensure the worldwide availability of the service for peaceful civil, commercial, and scientific purposes, free of user fees. In 2004 President Bush furthered the policy to ensure that the GPS meet the increasing and varied domestic and global requirements. These successive policies "helped unleash the power of free markets and private enterprise for the good of all users worldwide."[63] Clearly, this type of service is a likely candidate. With the largest, most comprehensive space surveillance system in the world, the United States is uniquely poised to offer another free service to the world.

A second precedent for a global utility is the International Telecommunication Union (ITU), a specialized UN agency based in Geneva, Switzerland. The ITU manages the worldwide radio spectrum usage and slot allocation for GEO satellites on behalf of its members. The ITU currently consists of 191 member states (nations), 574 sector members (commercial companies), and 150 associates (commercial companies). The members underwrite operations and participate in its decision making.[64] The ITU ensures the rational, equitable, efficient, and economical use of radio frequencies and orbital slots—both of which are finite resources—and creates the conditions that harmonize development of systems, taking into account all parties involved. According to the director of its Radiocommunication Bureau, the ITU "plays a vital role in the global management of the radio-frequency spectrum and satellite orbits."[65]

The third example of a global service is the International Civil Aviation Organization (ICAO). Founded in 1947, it governs the international civil aviation system. With the rise in aircraft use during World War II, the United States and others saw the need for a global aviation system. According to the ICAO, "A vast network of passenger and freight carriage was set up, but in order for air transport to support and benefit the world at peace there were many political and technical obstacles to overcome. In those early days of 1944, the Government of the United States conducted exploratory discussions with other allied nations to develop an effective strategy."[66] The ICAO is now a specialized UN agency with 190 member states that have voluntarily entered into its conventions. These conventions established the rules, procedures, requirements, and techniques to govern the movement of international civil aviation. Although each nation governs air traffic within its own sovereign territory, the ICAO successfully established protocols and procedures for the operations of international traffic, the transition of aircraft from one nation to the next, and the operation of aircraft over global commons, such as the high seas.

Photograph courtesy of the ICAO

In November 1944, under the leadership of the United States, 54 nations met in Chicago, resulting in a Convention on International Civil Aviation. In 1947 the ICAO became permanent.

Possible Solutions

Which model is most appropriate for the management of a global space-traffic-control service? One USAF general advocates a unilateral solution for protecting global utilities. "Having the Air Force assume responsibility for global satellite protection as an extension of its existing space-control responsibilities seems the most feasible option. Since the Air Force is tasked with controlling space, placing global utilities under the protective umbrella of space control would be a matter of policy—not an expansion of technology or costs."[67] On the other hand, the State Department's International Security Advisory Board proposes a multilateral solution and recommends that the

United States "seek to enlist allies and friendly nations in cooperative efforts to improve situational awareness."[68] The following examines four possible constructs and their pros and cons.

The first conceptual model is a US-owned-and-operated service akin to GPS. There are many compelling reasons why the US government could do this. First, it is probably the most expedient avenue to establish a global service because it could quickly leverage the existing SSN infrastructure and nascent CFE program. Second, the United States, as the leading spacefaring nation and the only nation with the necessary resources, has treaty obligations to ensure safety of space operations in the global commons. Lastly, as matter of national interest, the United States has the most at stake and most to gain. As the world's superpower benefiting from globalization, maintaining international institutions and their associated systems that contribute to the current world order is paramount to its economic security. Moreover, a global space-traffic-control service would enhance military space security as a defensive system.

Many believe there is a significant drawback to this type of service; that is, a utility provided by a single nation with the power to turn it off. For example, despite US public law, presidential policy, and diplomatic engagement, many nations are still wary of US intentions with the GPS and are pursuing their own navigational systems. The Europeans, Russians, and Chinese all have satellite programs that aim to implement organic capabilities. With respect to SSA, it's much the same. ESA's director-general articulated Europe's worry of being "blind" and wholly dependent on US-supplied data.[69] Despite these reservations, the United States could leverage this opportunity and promote US leadership and diplomacy just as it has done with space-based navigation applications.[70]

A second model could involve a multinational cooperative service, as "it takes a village to build a (good) catalog."[71] This could be a bilateral or multilateral arrangement among the United States, Russia, China, and/or the European Union. Significant diplomatic negotiations would be required to establish such an alliance, but the benefits could be significant. Doug Messier suggests that "the key benefit to international participation in SSA is greater capability for relatively low cost, by combining existing sensor and data sources."[72] This model would also align with President Obama's anticipated space policy focusing on international cooperation.[73] Another benefit of cooperation is that each nation would have access to the same space operating picture, thus lowering mutual suspicion and increasing international security.

This construct does have several flaws. Data sharing could be sticky—especially information about defense satellites that each nation would want to protect.[74] As stated earlier, Russia and China currently do not share their catalogs, and the Europeans have already expressed reluctance to share theirs. Equitable cost sharing associated with the operations, maintenance, and upgrades of this service would also need to be negotiated, probably not an easy matter. The service could disintegrate if one or more of the cooperating nations decided to withdraw from the arrangement.

The third model could be a commercial utility with clients—nations or private sector—that would pay for the service. A fledgling operation similar to this, the Space Data Association, is already in planning stages. The association plans to compile satellite positional data from its members' satellite telemetry feeds. A benefit to this kind of service is the built-in perception that it is independent from any one state or member. The association also aspires to be more nimble, timely, and responsive compared to the current US CFE paradigm.[75] However, without a robust, organic space surveillance system, its situational awareness will be limited to the collective knowledge of its members, and it would not be able to globally track nonmember satellites or debris unless a government augments the data.

The last model examined is an international global utility similar to ICAO. Advocates for this model include Dr. Ailor and the Secure World Foundation, a space-policy think tank. They propose a nonprofit space-operations clearinghouse with a board of governors and members drawn from governments of spacefaring nations and major nongovernmental satellite owners "to establish common standards and practices."[76] This service would have the benefit of being recognized as legitimate and unbiased by nations and private-sector interests alike. The purpose and aims of such an organization could be orchestrated to parallel existing international laws and customs, such as the Outer Space Treaty and US space policy. This organization would also provide a forum for substantive discussions on debris control and unimpeded, safe access to the global commons. One drawback to such an arrangement would be that its members would be subject to rulings from an international body. However, this is no different than what already happens today with the ITU and ICAO.

Because an ICAO-like service has the most advantages and is more likely to enjoy international support, it is most likely to succeed. Pursuing this model would constructively leverage existing SSA infrastructures and capabilities as well as international cooperation while also suppressing mutual suspicions. The United States, as the leading spacefaring nation in the world, would additionally benefit indirectly in terms of diplomatic leadership and international prestige. It would also benefit directly, as would the world, from improved military and economic security via improved space control and a safer environment for commerce.

Findings and Recommendations

Based on this research, this paper identifies five critical findings. First, the big sky theory for safe operations is no longer valid. Space is becoming congested and prone to collisions. It will only get worse with time. Second, the global economy and international security are in part dependent upon space systems. Consequently, safe operation of satellites is essential. Third, no governmental, international, or nongovernmental organization is ultimately responsible for global space-traffic control. Some governments, namely the United States, and several nongovernmental organizations have taken nascent steps to address this problem. However, these efforts are not synchronized or comprehensive. Fourth, an international consensus is building for improved SSA and space-traffic control.[77] Finally, the United States is the world's premier source for SSA. However, even with its future planned hardware upgrades, the United States is not configured to meet the needs of global space-traffic control, especially in terms of timely high-precision data analysis, data sharing, and policy.[78]

These findings coalesce into a need for a global space-traffic-control service. This paper recommends first, as in 1944, that the US Department of State, in concert with applicable US agencies and departments, convene an international conference with the purpose of establishing a global space-traffic-control service. Within the next two years, the United States should engage spacefaring nations and interested private-sector companies in exploratory discussions to develop an effective strategy for such a service. Second, AFSPC, in concert with USSTRATCOM, should upgrade its antiquated software and databases utilized to track and catalog space objects. Although the planned Space Fence and Space Based Surveillance System will greatly expand data available, these hardware upgrades by themselves do not fundamentally bridge the processing gap required for timely, accurate collision mitigation.

As revealed by the fourth documented collision in space and the increasing orbital congestion, the need for global space-traffic-control service is clear. Ignoring the issue will not ease the problem. Within the US government, the USAF, NASA, STRATCOM, the State Department, and Congress all have stated the need to improve SSA and mitigate orbital collisions. Outside the US government, the ESA, the Secure World Foundation, and private industry have also advocated the need. What is missing is a comprehensive, synchronized plan to addresses the problem in its entirety. As a matter of national prestige, leadership, and security, the US government should endeavor to establish an international institution to govern global space traffic.

Notes

1. Secure World Foundation, "Iridium 33-Cosmos 2251 Collision," fact sheet, 13 February 2009, http://www.secureworldfoundation.org/siteadmin/images/files/file_273.pdf; and Liz DeCastro, "Update on Iridium Satellite Constellation," 11 February 2009, http://iridium.mediaroom.com/index.php?s=43&item=885.

2. William Ailor, director, Center for Orbital and Reentry Debris Studies, The Aerospace Corporation, briefing, subject: Space Traffic Control and Space Debris, 8 May 2009, slide 5, https://www.mcgill.ca/files/iasl/Session_5_William_Ailor.pdf.

3. Statement of Lt Gen Larry James, commander, Joint Functional Component Command for Space, before the Subcommittee on Space and Aeronautics of the House Committee on Science and Technology, "Keeping the Space Environment Safe for Civil and Commercial Users," 28 April 2009, http://gop.science.house.gov/Media/hearings/Space09/april28/james.pdf (accessed 16 September 2009).

4. "Big sky" theory, borrowed from the aviation community, proposes that space is so large the probability of a collision is infinitesimally small. Some also use the term "big space."

5. Tony Reichhardt, "Satellite Smashers: Space-faring nations: Cleanup low Earth orbit or you're grounded," *Air and Space Magazine*, 1 March 2008; and Ailor, briefing, slide 5.

6. Ailor, briefing, slide 5.

7. Reichhardt, "Satellite Smashers."

8. Ibid.; and Ailor, briefing, slide 5.

9. James, "Keeping the Space Environment Safe," 3.

10. House, Committee on Science and Technology, Subcommittee on Space and Aeronautics, Hearing Charter, *Keeping the Space Environment Safe for Civil and Commercial Users*, 28 April 2009, http://democrats.science.house.gov/Media/file/Commdocs/hearings/2009/Space/28apr/Hearing_Charter.pdf (accessed 16 September 2009).

11. NASA, briefing, subject: The Threat of Orbital Debris and Protecting NASA Space Assets from Satellite Collisions, 28 April 2009, www.secureworldfoundation.org/siteadmin/images/files/file_308.pdf. Although space debris mitigation, by physical means, policy, or international agreement, is an important topic unto itself, it has been extensively discussed by others and is not addressed in this paper.

12. Nicholas Johnson and Jer-Chyi Liou, "Risks in Space from Orbiting Debris," *Science Magazine* 311, no. 5759 (January 2006): 340; and Reichhardt, "Satellite Smashers."

13. NASA, briefing.

14. Doug Messier, "Secure World Foundation Proposes Global Space Debris Tracking System," *Parabolic Arc*, 29 April 2009, http://www.parabolicarc.com/2009/04/29/secure-world-foundation-proposes-global-space-debris-tracking-system (accessed 17 September 2009).

15. Warren Ferster, "GeoEye Dodging Space Junk with Increasing Frequency," *Space News*, 4 November 2009, http://www.spacenews.com/earth_observations/091104-geoeye-dodging-space-junk.html.

16. Richard Abbot and Timothy Wallace, "Decision Support in Space Situational Awareness," *Lincoln Laboratory Journal* 16, no. 2 (2007): 313.

17. Gen Kevin P. Chilton (address, Strategic Space and Defense Conference, Offutt AFB, NE, 4 November 2009). In this speech, General Chilton refers to "big sky" as "big space."

18. James, "Keeping the Space Environment Safe," 3. The number of active payloads cited in literature varies from 900 to 1,300. For consistency, this paper uses 1,300 payloads cited by General James during his 2009 congressional testimony. The math for the number of objects reported in public forums by the USAF does not add up in a straightforward manner either. For example, 6,000 objects are tracked but not cataloged because the launching country cannot be determined.

19. Ibid.

20. US Congress, Office of Technology Assessment, *Orbiting Debris: A Space Environmental Problem—Background Paper*, OTA-BP-ISC-72 (Washington, DC: US Government Printing Office, September 1990).

21. For this paper, *space environment* is narrowly defined to be just the man-made space objects and associated debris orbiting the earth. It does not include space weather commonly included in the definition of space environment.

22. The United States, in a nonroutine, limited fashion, maneuvers some of its high-priority satellites to avoid collisions. But the United States does this only for its own satellites. A global service that could direct space traffic for all satellites irrespective of their origin (governmental or nongovernmental) does not exist. The CFE program (discussed later in this paper) does provide some collision avoidance warnings for non–US government entities, but these warnings lack sufficient accuracy for collision avoidance maneuvers. The Air Force only passively warns and makes suggestions; it does not recommend maneuvers or enforce maneuvers for collision avoidance. In fact, the Air Force cautions the users to use the information at their own risk. See Space-track.org, "User Agreement," www.space-track.org/perl/new_account.pl.

23. James, "Keeping the Space Environment Safe," 3.

24. Jim Hodges, "Space Fence Reinvented," *C4ISR Journal*, October 2008, 37.

25. *LEO* is defined as an orbit less than 2,000 kilometers (km) in altitude.

26. *GEO* is defined as an orbit 36,000 km above the earth. The medium Earth orbit (MEO) region, although containing some important constellations such as the Global Positioning System, currently is at low risk for collisions and is not discussed at length in this paper.

27. Abbot and Wallace, "Decision Support in Space Situational Awareness," 306.

28. USSTRATCOM, "Space Control and Space Surveillance," fact sheet, 19 February 2008, http://www.stratcom.mil/files/STRATCOM_Space_and%20Control_Fact_Sheet-25_Feb_08.doc (accessed 18 September 2009).

29. Committee on Space Debris, *Orbital Debris: A Technical Assessment* (Washington, DC: National Academy Press, 1995), 12.

30. US Congress, *Orbiting Debris*, 2; and Committee on Space Debris, *Orbital Debris*, 22.

31. James, "Keeping the Space Environment Safe," 3; and NASA, briefing, slide 5.

32. Johnson and Liou, "Risks in Space from Orbiting Debris," 340; and Reichhardt, "Satellite Smashers."

33. Committee on Space Debris, *Orbital Debris*, 32.

34. Brian Weeden, "The Numbers Game: What's in Earth Orbit and How Do We Know?" *Space Review*, 13 July 2009, http://www.the spacereview.com/article/1417/1 (accessed 16 September 2009).

35. Committee on Space Debris, *Orbital Debris*, 32.

36. USSTRATCOM, "Space Control and Space Surveillance."

37. The US military uses two different mathematical models to describe orbits and conduct its analyses. The first is general perturbations; it describes orbits with two-

line element (TLE) sets compatible with the Simplified General Perturbation computer model; these are made public. The second method—far more accurate and complex—is special perturbation, which uses state vectors with double-precision positions and velocity vectors. It is only used for high-priority mission support on a case-by-case basis. State vectors are available only to the US government and are not shared with the public like TLE sets. See US Space Command Instruction 10-5, *DOD, Commercial, Civil and Foreign Space Support*, 1 April 2002, 2, 9.

38. Committee on Space Debris, *Orbital Debris*, 32.

39. Quoted in Peter B. De Selding, "Despite SSA Collaboration, Europe Leery of U.S. Intentions," *Space News*, 19 January 2009, 6.

40. Ibid.

41. Lt Col Charles Spillar, interview by the author, 24 September 2009, Peterson AFB, CO; Lt Col Charles Spillar, USAF Space Command/A3CN, briefing, subject: Commercial and Foreign Entities (CFE) & U.S. Government (USG) SSA Sharing, 24 September 2009.

42. Space-track.org, "User Agreement," www.space-track.org/perl/new_account.pl (accessed 17 November 2009).

43. Weeden, "Numbers Game?"

44. Peter B. De Selding, "Satellite Firms Moving Ahead on Orbital Database," *Space News*, 18 November 2009, http://spacenews.com/satellite_telecom/091118-satellite-firms-moving-ahead-orbital-database.htm (accessed 22 November 2009).

45. Abbot and Wallace, "Decision Support in Space Situational Awareness," 307–13.

46. Lt Gen John Campbell, USAF, retired, et al., *Examining Codes and Rules for Space*, Forum on National Security Space (Washington, DC: George Marshall Institute, 27 June 2007), http://www.marshall.org/pdf/materials/554.pdf, 17; and T. S. Kelso and S. Alfano, "Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES)" (address, 2005 American Astronautical Society/American Institute of Aeronautics and Astronautics Space Flight Mechanics Conference, 23–27 January 2005), http://celestrack.com/publications/AAS/05-124.

47. James, "Keeping the Space Environment Safe," 8.

48. Jeremy Singer, "Air Force Seeks to Triple Funding for Space Surveillance," *Space News*, 7 April 2008, 50.

49. James, "Keeping the Space Environment Safe," 8.

50. Author's personal experience and knowledge.

51. Weeden, "Numbers Game?"

52. Spillar, interview.

53. In addition to its antiquated data processing and orbit prediction software, the associated Air Force databases are also archaic. Currently, the database is hard coded to handle only a limited number of objects, so it will also need to be upgraded. "Out of the 69,999 entries allocated for cataloged objects, about half are already used and growth is accelerating every year. Compounding this situation are the plans to add new sensors to the SSN in the near future that will greatly expand the number of objects tracked." Refer to Weeden's article, "Numbers Game?"

54. Iridium Satellite LLC, "Iridium Provides Update on Satellite Constellation," 9 March 2009, http://www.iridium.com; and De Selding, "Satellite Firms Moving Ahead on Orbital Database."

55. Edward O'Hara, *Space Situational Awareness*, Technological and Aerospace Committee, European Security and Defense Assembly, Assembly of Western European Union, Document C/2035, 6 May 2009, 6.

56. Quoted in "ESA Approves Space Situational Awareness Program," *C4ISR Journal*, 7–8 July 2008, 8.

57. Campbell et al., *Examining Codes and Rules for Space*, 17.

58. Ailor, briefing, slide 7.

59. House, Hearing Charter, *Keeping the Space Environment Safe*, 28 April 2009, 20.

60. US Congress, *Orbiting Debris*, 28–31.

61. Amy Klamper, “Obama Space Policy to Focus on International Cooperation,” *Defense News*, 7 December 2009, 44.

62. This paper does not attempt to analyze these services in detail in terms of structure, cost, or degree to which they provide totally comprehensive solutions—only as appropriate examples to consider.

63. Alice A. Wong and Raye E. Clore, “Promoting International Civil GNSS Cooperation through Diplomacy,” *High Frontier* 4, no. 3 (May 2008): 25–27.

64. ITU membership overview, http://www.itu.int/members/index.html (accessed 21 November 2009).

65. Valerie Timofeev, “Welcome to ITU-R,” International Telecommunication Union Web site, http://www.itu.int/ITU-R/index.asp?category=information&rlink=itur-welcome&lang=en.

66. International Civil Aviation Organization, “Memorandum on ICAO,” http://www.icao.int/icao/en/pub/memo.pdf.

67. Gen Bruce Carlson, “Protecting Global Utilities: Safeguarding the Next Millennium’s Space-Based Public Service,” *Air and Space Power Journal* 14, no. 2 (Summer 2000): 37–41.

68. US Department of State, International Security Advisory Board, “Report on U.S. Space Policy,” Washington, DC, 25 April 2007, http://www.state.gov/documents/organization/85263.pdf (accessed 16 September 2009).

69. De Selding, “Despite SSA Collaboration, Europe Leery of U.S. Intentions,” 6.

70. Wong and Clore, “Promoting International Civil GNSS Cooperation,” 25–27.

71. Weeden, “Numbers Game?”

72. Messier, “Secure World Foundation.”

73. Klamper, “Obama Space Policy,” 44.

74. Edward O’Hara, *Space Situational Awareness*, Technological and Aerospace Committee, European Security and Defense Assembly, Assembly of Western European Union, Document C/2035, 6 May 2009, 10.

75. De Selding, “Satellite Firms Moving Ahead on Orbital Database.”

76. Peter N. Spotts, “Does Space Need Air Traffic Control? As More Countries Race to Launch Satellites and Manned Craft, Some Warn of a Space Jam,” *Christian Science Monitor*, 14 March 2008, http://www.csmonitor.com/2008/0314/p01s02-usgn.html. See also Ailor, briefing; and Doug Messier, “Space Traffic Control Conference to be Held Next Week in DC,” *Parabolic Arc*, 20 March 2009, http://www.parabolicarc.com/2009/03/20/space-traffic-control-conferences-held-week-dc.

77. Ailor, briefing; Spotts, “Does Space Need Air Traffic Control?”; Messier, “Space Traffic Control Conference”; De Selding, “Satellite Firms Moving Ahead on Orbital Database”; Messier, “Secure World Foundation”; and Space.com staff, “Out There: Space Traffic Control System Needed,” *Space.com*, 9 November 2008, http://www.space.com/new/081109-space-traffic.html.

78. Albert Glassman, “The Growing Threat of Space Debris,” *IEEE-USA Today’s Engineer online*, July 2009, http://www.todaysengineer.org/2009/jul/space_debris.asp.

Abbreviations

AFSPC	Air Force Space Command
CFE	commercial and foreign entity
DOD	Department of Defense
ESA	European Space Agency
GEO	geosynchronous Earth orbit
GMWS	Geosynchronous Monitoring and Warning System
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
ITU	International Telecommunication Union
JSpOC	Joint Space Operations Center
km	kilometer
LEO	low Earth orbit
MEO	medium Earth orbit
NASA	National Aeronautics and Space Administration
SOCRATES	Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space
SSA	space situational awareness
SSN	space surveillance network
SSS	space surveillance system
TLE	two-line element
UN	United Nations
USSTRATCOM	United States Strategic Command