Space Traffic Management Conference | 2014 Roadmap to the Stars

Nov 6th, 1:30 PM

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1st Annual Space Traffic Management Conference
Embry-Riddle Aeronautical University
Daytona, Beach, FL
November 5-6, 2014

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ABSTRACT

A viable space traffic management program faces a great barrier caused by the ever-increasing number and variety of orbiting objects ranging in size from a few microns to several meters. Although several international agreements to limit the growth rate of orbital debris are in place, the risk of damage and destruction to active satellites is continually rising. The urgency of this situation was highlighted by the 2007 Chinese ASAT test and the collision of Iridium and Cosmos satellites in 2009. Although many debris removal techniques have been posited none have been implemented. Unless a space debris reduction program is undertaken in the near future, continued access to space and use of space for applications and exploration may be extremely compromised. The growing collision threat will continue to complicate any future space traffic management program. Space junk is a man-made, growing threat to space-based applications such as communications, weather forecasting and Earth observation among many others. Space commerce is expanding and as this industry grows the need for an effective traffic management system will become critical to commercial growth and exploration of space. An integrated approach to resolving the debris issues through a carefully designed research program is described. Such a program could facilitate resolution of orbital debris impediments to a controlled space environment.

I. Introduction

Those familiar with air traffic management architectures understand the constraints of aircraft flying in the atmosphere, vehicle dynamics and command and control techniques. Unfortunately, compared to air traffic space traffic has many more degrees of freedom and much less control capability. Add to this the completely uncontrolled nature of space debris and the reality that most debris objects cannot be tracked and motion cannot be accurately measured or simulated.[1] In fact, orbiting debris is a product of negligence. Over the first 50 years of space flight, mission plans ended with the completion of in-space operations. Satellites were shut down and left in their orbits, subject to natural influences. Little thought was given to any collateral effects of objects "adrift" in space, because "space" was thought of as "big." An analogy might be the ocean disposal of waste items, where junk gets lost in the vastness of the seas, either by sinking to the bottom or by simply drifting with ocean currents. By contrast, a "drifting" satellite remnant in low orbit is travelling at a speed in excess of 7.3 km/sec (16,300 mph). Since orbiting objects can travel in all directions, collisions between satellites and debris can occur at speeds of over 14.6 km/sec (32,600 mph).

Of the suspected hundreds-of-thousands of debris objects, only about 22,000 are four inches or larger in size and can be tracked.[2] The majority of junk items remain beyond current tracking capabilities, but are just as dangerous in terms of causing significant damage to operating spacecraft. Just as weather affects our daily lives, so does Earth's orbiting junkyard. The detrimental effects of space junk grow worse each year, putting our daily lives and national infrastructures increasingly at risk as our communications, science and security networks rely ever more heavily on the interconnected system of satellites orbiting the skies. Yet, a space traffic management system may have to deal with possible debris interference.

While we understand weather and have learned techniques to deal with it, the impact and disposition of orbital debris are not fully understood. Unlike weather, space junk is man-made and will significantly hinder the nation's future economy and security. It is a growing threat to space-based communications, weather forecasting, banking processes, scientific exploration, Earth observation and future space tourism. Space commerce is growing, and as this industry expands the need for an effective traffic management system will become critical to commercial growth and exploitation of space.

At the moment, there are no programs in place to deal with orbital debris, even though new satellites continue to be launched at a rate of over 100 each year. Most of these launches will contribute to the already-large orbital debris population. With over 60 countries operating in space, the exponentially growing problem of orbital debris will take international collaborations and partnerships to conceive and develop innovative solutions and strategies as part of a worldwide space traffic management architecture.

II. The Debris Problem

The past excesses and neglect associated with the unabated launch of satellites that use space for both earth-bound applications and as a dumping ground for discarded upper stages, old satellites, and a large variety of miscellaneous pieces and parts from thousands of once-active high-tech space machinery now leave us with one of the most complex challenges since the beginning of the Space Age. The debris has accumulated to the point where operational satellite traffic lanes are not only getting clogged with expired satellites and space trash, but are approaching "gridlock." When referring to terrestrial traffic, gridlock means the movement of vehicles cannot continue.[2] When referring to space flight, this means space is inaccessible to all prospective users. Although space gridlock is still years or decades away, it is clearly in our future if nothing is done to "mitigate" the situation. Neglect of space has gone on so long that "mitigation" in this case means several significant measures must be taken to avoid future dumping in space.

Some steps have already been implemented that will delay gridlock.[3] Shielding has been added to some spacecraft to assist in the survival of collisions with very small pieces of debris that number in the millions. Most space-faring nations have agreed to remove satellites from high risk zones when they reach their end-of-life, and most launch vehicle upper stages now purge propellant tanks in order to prevent later explosions due to material degradation. In some cases, maneuvering to avoid a collision is appropriate. Nevertheless, these precautions only delay the onset on gridlock because there is still sufficient ongoing debris production through collisions and spacecraft breakups to sustain the continued buildup of debris. Thus, a focused debris reduction program may well be needed in the future, possibly within the next decade. The long research, planning and development cycles for space systems dictates that we begin serious debris reduction research and technology development in the near term.

III. The Spectrum of Issues

The number of organizations using the near-Earth space environment for applications ranging from exploration to exploitation and national security is impressive and continues to grow. Safety is a prime concern for both equipment and personnel. For government operators, the control of risk is mandatory. For commercial operators, operational efficiency and favorable cost/benefit considerations are paramount. In recent years several government agencies have been studying space traffic management, i.e., regulation of orbital traffic.[4] To date, there has been little control over what is placed into orbit. Each space-faring nation is able to operate independently and with little, if any, international coordination or cooperation. This is quite different from the international air traffic management system that allows the free-flow of airline traffic over a major part of the world. Every airliner uses designated airspace that is protected during its flight by air traffic controllers. Most airliners travel at comparable speeds and collisions are avoided by horizontal and vertical separation standards. This ensures that mid-air collisions are, indeed, rare.

The flight paths of low-orbiting satellites, on the other hand, are not coordinated and the selection of orbits is not centrally controlled by any international agency. This situation has evolved, at least in part, because near-Earth space is thought to be "big." In fact, it is big. But, the concept of "big" is only valid as long as the density of things in a given region is extremely low. As the number of satellites and debris objects continue to grow the concept of "big" begins to shrink. In addition, objects in low orbits are all travelling at speeds in excess of 7.3 km/sec. Unlike aircraft, satellite and object separations are not controlled. The continued increase of traffic in these orbits leads one to quickly conclude that space traffic management may soon be necessary in order to sustain the viability of many current space applications. However, the management of space traffic presents a daunting challenge. At the moment, we lack much of the required technology, there is little international cooperation or collaboration regarding space traffic planning and the political environment is not amenable to creating an all-inclusive space traffic control architecture. Consider the physical separation of air traffic into commercial and military categories with completely different flight rules. While satellites may be restricted to low-latitude flight paths, they must overfly all longitudes as they circle the earth. In fact, some of the most popular orbits are shared by civil, commercial and military satellites.

The situation is further complicated because we lack the ability to accurately track and predict the precise movement of satellites and large debris objects. As mentioned, the location and movement of most debris objects are not known. We do not even know sizes, shapes or materials of most debris objects. None of the orbiting junk is controllable, and very few active satellites can maneuver responsively to avoid possible collisions. Finally, many satellites are used for national security and their exact orbits are often classified. Yet, all classes of spacecraft fly in similar orbits. The issues of national sovereignty and sensitivity lead to some nasty legal and political arguments. It is easy to conclude that any meaningful space traffic control architecture may be decades away.

IV. Dealing with Orbiting Debris

The space community has worked hard to mitigate excessive proliferation of debris by establishing rules for spacecraft manufacturers and operators that help minimize the creation of new debris. However, there is no system or program in place to remove or clean up near-earth orbits and there are no serious programs addressing the long-term environmental control of space. Orbital debris is a threat to operating spacecraft, human spaceflight and critical communications systems and the level of this threat is building exponentially.

Satellite operators have been fortunate so far. Debris has been little more than a nuisance (except for the Iridium/Cosmos incident) and has created minimal damage. In other words, the threat has been "acceptable" and therefore, the high cost of solving any debris issues has not been justified. Since a solution has not been needed, actual cleanup costs have not been fully investigated. However, it is likely that at some point in the future the debris threat will require a solution. Many options have been proposed but none, so far, appear to be affordable and/or effective.

While many aspects of orbital debris mitigation and remediation have been addressed through concept proposals and studies, few, if any, organizations have ventured toward an integrated, multidisciplinary and international approach to all aspects of the technical and non-technical issues. This is understandable because most debris-related efforts are narrowly focused on various specific aspects of the problem. Faculty researchers at the University of Maryland realized this shortcoming in debris resolution activities. As a result, the Center for Orbital Debris Education and Research (CODER)[5] was conceived and is currently ramping-up during its first year of operation.

Indications are that CODER will quickly develop into an international collaborative center of education and research that addresses solutions to the space trash problem in an integrated and all-inclusive manner. Issues being addressed include technologies and systems, relevant space policies, economics of solutions, legal and treaty aspects and sociological issues. A long-term goal of the center is to help in the development of policies, laws and space systems that will lead to the efficient remediation and control of space environmental pollutants.

A university-based center allows a maximum level of transparency and inclusion for all those interested in studying the problems and conceiving solutions through education and research. As the center seeks international collaboration and inclusiveness it envisions multiple sources of domestic and international support. CODER may quickly become an international clearing house for research and educational programs that address the various orbital debris issues and it will be a focal point for idea interchange through conferences, meetings and outreach programs.

CODER will fulfill its mission through the development and implementation of innovative educational and research activities in support of the center goals. It is already fostering the collaboration of academic, governmental and commercial entities, both within the US and internationally. An initial core interdisciplinary team has been established to spearhead early research activities into each dimension of the orbital debris problem. CODER has begun to solicit research and development funds across multiple agencies and organizations in support of the center's mission. An initial economic plan is in place as a guide for achieving both near-term and long-term center objectives. One of the primary center objectives is to contribute to and to support the development of international policies governing the mitigation and remediation of orbital debris. One significant advantage of an academic research center is easy dissemination and distribution of knowledge and findings to the international community.

V. General Issues of Space Traffic Management

There is little doubt that the number of government, commercial and academic operations in space will continue to increase. A primary concern is always safe robotic and human operations for space systems and space-based services. While collision risks are still probabilistically low, the risk is real and growing. The level of concern for space system operators is slowly rising and the threat must be addressed on a continual basis.

A minimum requirement for effective space traffic management is timely, accurate position data on all space objects in a controlled traffic region. Traditional two-line orbital element sets and processes that were used during the Cold War are not adequate for precision conjunction analysis. If debris avoidance is to be successful, real-time precise updates on position and movement of derelict objects are essential for safe flight in low-earth orbits. Furthermore, future satellites that operate in this region will need quick-response maneuvering capabilities that most current space systems do not carry.

Even if there were no debris, the implementation of space traffic management procedures and operations may require that future satellites operating in low-earth orbits will need maneuvering capabilities not common on current systems. In addition, some form of space-born technology that complies with yet-to-be-established international protocols should ensure clear traffic lanes among the several national systems that share the space. Devices that are analogous to aircraft avoidance equipment may alert approaching space traffic and autonomously issue maneuver commands. However, closing speeds in space can be 30 times higher than possible for aircraft. Thus, close-approach warnings must be issued much earlier than for aircraft. Typically, two approaching aircraft can respond to a warning in a few seconds. Two approaching satellites may require at least 30 minutes, or more, to execute a maneuver after a warning is received. Clearly, a number of new technologies, procedures and design approaches are going to be needed to achieve space traffic management objectives.

It appears reasonable to assume a first step in developing a space traffic management system is to address the issue of managing the large number of passive derelict objects that could eventually jam the traffic lanes.

VI. Potential Technology Needs for Debris Management

It was pointed out earlier that the first requirement in managing a derelict space object is to know its exact position and motion at any time and to be able to project its movement in time and space. At the beginning of the space age, some 50 years ago, there was little need for this level of accuracy. As space systems evolved, it became important to send telemetry data to the ground and to send operational commands from the ground. During the Cold War the US and USSR built ground stations, ships and aircraft to perform telemetry, tracking, and command (TT&C) functions.

Management of the space volume continues to rely on Cold War technology heritage and civil and commercial capabilities. The USAF detects, tracks, identifies and catalogs man-made orbiting objects through use of the Space Surveillance Network (SSN). To observe the 20,000+ objects in orbit, the SSN utilizes ground-based, electro-optical and radar sensors. In recent years, the USAF has introduced space-based methods of tracking orbiting objects. One approach is the Space Based Space Surveillance (SBSS)[6] system. Originally planned to be a constellation, SBSS 1, the first of the SBSS satellites, was placed into low-earth orbit on September 25, 2010. This spacecraft has a 30.5-cm telescope on a two-axis gimbal with a 2.4-megapixel image sensor and has a projected mission duration of five-and-a-half years. Earlier this year the Air Force announced another space-based system, the Geosynchronous Space Situational Awareness Program (GSSAP). The use of GSSAP[7] satellites will lead to significant improvements in space object surveillance at geosynchronous altitudes, because they will operate in the near-geosynchronous region, providing a clear, unobstructed vantage point for viewing objects in that region. These satellites will carry electro-optical imaging sensors, while drifting around the geosynchronous belt, allowing them to locate and inspect many objects with relative ease.

From a space traffic management point of view, it is unfortunate that the population of nonfunctional orbiting objects far outnumbers operational assets. Debris is responsible for a high stress condition on the SSN in terms of number, distribution and even size. In reality, the current surveillance architecture has several shortcomings:

- Inability to monitor all objects all the time
- Insufficient timeliness and availability of orbital data
- Lack of awareness of planned maneuvers
- Orbital data errors
- Powered flight problems
- Little standardization of data types
- Operational errors or system anomalies that introduce uncertainties

The international nature of the space domain is an important factor. In the future, space vehicles will continue to be flown by a multitude of entities including civil space agencies, militaries, intelligence organizations, commercial companies, academic institutions and perhaps even private individuals.

Space-faring nations have been working together for years to develop guidelines and regulations to minimize the creation of space debris. Arguably, these efforts have been successful in reducing the rate of growth of debris. Unfortunately, these rules are not enforceable. Furthermore, the United Nations' Committee on the Peaceful Uses of Outer Space (COPUOS) is focused on promoting the use of space and increasing awareness of space issues, but is insufficiently funded to adequately perform even this limited mission.

VII. Learning from the Air Domain

Space traffic management systems will likely evolve from some simple concepts. Take, for example, the evolution of navigation aids for civil aviation in the US. This may provide some insight for the future of space traffic control. The first radio navigation aids emerged around 1930. Pilots then used these to assist in en-route navigation and landing approaches. Safe separation of aircraft depended on pilots reporting their locations relative to known landmarks. Controllers at airport control towers had to keep notes on aircraft positions and used these to clear aircraft for takeoffs and landings. Radar emerged after World War II and provided a way to maintain safe separation of aircraft. The tracking of aircraft in the National Airspace System (NAS) by radar remains the standard, some 60 years after its introduction in the 1950s.

In 1994, the Federal Aviation Administration (FAA) integrated the Global Positioning System (GPS) as part of the US air traffic system.[8] Pilots use GPS as a navigation aid, but air traffic controllers still depend on radar to manage safe aircraft spacing from the ground. In the early years of GPS usage accuracy, availability and reliability of the system were not sufficient for use as the primary navigation aid for aircraft landing. However, in 1998 the FAA initiated the development of two GPS augmentation systems: WAAS (Wide Area Augmentation System) and LAAS (Local Area Augmentation System). In 2000, military-level GPS accuracy was made broadly available, providing navigation accuracy to 15 meters. Today, WAAS is operational and provides accuracy to 3 meters over most of North America.

LAAS[9] is an all-weather aircraft landing system based on real-time differential correction of GPS signals. Reference receivers located around the airport send data to a central location at the airport. These data are used to formulate a correction message, which is then transmitted to users via a data link. A receiver on the aircraft uses this information to correct GPS signals, which then provides information for precision approaches. The first installation at Newark Liberty International Airport achieved operational approval in September 2012. A second system was installed at Houston Intercontinental Airport and received operational approval in April 2013. Operational approval of several more systems is expected shortly.

The recent introduction of ADS-B (Automatic Dependent Surveillance–Broadcast)[9] extends the application of GPS from aircraft navigation to air traffic control. Aircraft equipped with ADS-B automatically broadcast a message containing the aircraft's current location, direction and speed. This new technology introduces the possibility of an air traffic management approach that is independent of ground-based surveillance radar. ADS-B accuracy exceeds the performance of current surveillance radars, but such a system must have assured availability and reliability. The adoption of radar, and then, GPS in aviation, first for navigation and then for air traffic control may provide insights that can help to formulate approaches to space traffic management.

VIII. Fundamental Physical Limitations of Space Traffic Management

Consider the fundamental differences between air traffic management and space traffic management from a physical point of view. Airliners typically travel at speeds near 0.25 km/sec (550 mph) and are easily separated because they travel in two-dimensional planes that are defined by altitude. In-plane separation is accomplished by defined airways and air traffic controller instructions. Navigation is easily accomplished with GPS and other devices. Aircraft can easily maneuver to change course. In space, satellites travel roughly 30 times faster than airplanes. They travel in circular or elliptical paths. Most satellites cannot maneuver at will and closing speeds can be as high as 14.6 km/sec. Satellite tracking accuracies are not sufficient enough to predict collisions ahead of events. Thus, response times for avoidance maneuvers, if possible, are extremely short. Propellant expenditures for such maneuvers are prohibitively high. With today's technology the only way to ensure safe flight is to assign orbits to users of the near-earth region that are essentially free of debris.

Unfortunately, most orbits of choice are dictated by naturally induced advantages.[10] For example, sun-synchronous orbits are ideal for earth observation and surveillance missions. Such orbits all have similar altitudes and high inclinations. Furthermore, all such orbits are in planes that cross each other. The result is highly congested traffic over polar regions of the Earth. Compared to equatorial regions, collision probabilities between satellites go up dramatically near the poles. To further complicate the situation, almost every country that flies earth observation and surveillance satellites has multiple spacecraft flying in sun-synchronous orbits. None of these orbits are actively controlled or separated. The only reason there have not been more collisions in these orbits is that the number of operational and expired satellites is not yet sufficient to "jam" the space.

Early space traffic management architectures will likely ignore travel to and from orbit and focus just on in-orbit traffic. Once in-orbit traffic comes under management, it may be time to integrate air and space traffic into one system. By that time, air and space vehicles may operate interchangeably, assuming reusable space launch vehicles come of age.

IX. Mitigating the Future

The objective of an active debris reduction program must be limited to establishing an acceptable level of collision risk for active satellites.[4] This can be interpreted as selectively reducing debris in certain size categories and in specified orbital zones that correspond to increased risks to operating satellites. An acceptable level of risk must be established by international consensus of a majority of space-faring nations. This, in turn, may lead to the establishment of an international body that oversees debris collision risk levels and regulation of orbital usage. All, or most, space-faring nations would have to agree to abide by the decisions of the body. Assuming the political and treaty issues can be ironed out, the actual debris reduction process can proceed.

Over the past four decades a number of debris reduction ideas have been set forth. All of these have a few things in common. They tend to be complex and expensive. A key parameter in collecting debris seems to be the size of the debris pieces. We know that space debris sizes range from microns to several meters. Based on many studies of returned satellite parts, low earth orbits appear to contain up to millions of debris pieces in the size range from microns to one centimeter. In the size range from one to 10 cm (4 in.) there appear to be tens of thousands of objects. Since objects of 10 cm or more in size can be individually tracked, we know there are currently more than 20,000 large orbiting debris pieces.

Another key parameter in selecting orbital regions from which to extract debris seems to be altitude. This assumes that the debris of interest travels in circular orbits that have altitudes close to those of operating satellites. As it turns out, there are only a few popular orbital altitudes. Other parameters of importance are inclination and right ascension, the combination of which establishes the orbital plane of motion.[10] In cases where debris pieces are in orbits with similar altitudes to those of operational satellites, collision probabilities tend to be high.

There are a number of candidate removal technologies for which investment may be appropriate.[11] Starting with small debris collection for objects of size below 10 cm, technologies that are needed include special materials that can survive hypervelocity impacts such that debris pieces can be absorbed, or at least slowed, without creating more debris.

Large debris object removal will require the use of highly maneuverable satellites that can rendezvous with large debris objects. In each case the debris would be captured and stowed for de-orbit later, or a retro-pack would be attached to effect individual reentry. Technology studies to determine optimum mission operations must be carried out to make the best use of limited maneuverability due to propellant capacity limitations. Since there may be a large number of such spacecraft operating in close proximity, some kind of space traffic control will be essential to avoid collisions among the collection vehicles.

X. Conclusions

Clearly, space traffic management represents a totally new paradigm that will use some of the technologies and processes of air traffic management, but will require significant new and innovative approaches to operating in the space environment. Even if orbit management can be accomplished, given the complex nature of space flight, there is the persistent issue of debris interference. As yet, there is no way to manage or control individual or collections of debris objects that clutter desired "space-ways." One approach may be to ignore the debris threat and proceed without controlling debris. Another approach would be to address the debris problem and try to clean up space. A third approach option might be to avoid the high-density debris regions and reinvent how space is used. In other words, current, desired orbits would be abandoned and all new satellites would be placed in low-density debris regions of near-earth space. From an economic aspect, this last option may eventually prove the most cost-effective. While the first option may prove initially workable, as the debris builds, the threat level will become unacceptable. The second option seems attractive, but the cost of cleanup may prove too excessive. Research activities at CODER will address all of these options.

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