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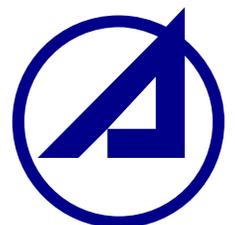APRIL 2018

GPS TRANSPONDERS FOR SPACE TRAFFIC MANAGEMENT

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Abstract

The space community relies on a decades-old system for tracking satellites—one that was optimized for military use rather than the purposes of safety and commerce. This paper proposes a radically new way of thinking about space traffic management, founded on the use of onboard GPS transponders. This approach could correct various market inefficiencies while providing valuable benefits to the host spacecraft. GPS transponders can report a spacecraft's position far more accurately, and with much less latency, than the current system. They can positively identify a spacecraft and allow operators to maintain a lock on it, even when it is thrusting or dead. As a result, military tracking resources can be liberated for other tasks. But how would such a system work, and what trade spaces need to be considered?

Introduction

Space is no longer the exclusive domain of a few select superpowers. Today, dozens of international organizations, national governments, commercial companies, universities, and even high schools have constructed, launched, and operated satellites in Earth orbit. Since the launch of Sputnik in 1957, more than 43,000 objects have been launched into space.[1] Nearly half of those objects are still in orbit today—yet only a few thousand still serve a useful purpose. All others are considered debris, an unfortunate by-product of decades of human activity in space.

This assortment of uncontrolled space flotsam proved fatal on Feb. 10, 2009, when an active communications satellite (Iridium-33) collided with a defunct Soviet military satellite (Cosmos-2251). The impact destroyed both satellites, reducing them to thousands (if not hundreds of thousands) of equally lethal debris objects that will persist in Earth's orbit for several decades.[2] This was a wakeup call to many in the space operations community. Suddenly, the sky grew a bit smaller and the need for space traffic management became a bit more urgent. Still, no such space traffic management system exists today. How might one build such a system, and how would it improve flight safety? Would the benefits of the system outweigh the costs? Who would bear these costs? What are the technical, political, and economic challenges, and how might they be overcome?

Congested Space

The first several decades of the Space Age relied upon the "big sky" approach to collision avoidance. The assumption was that the volume of space is too large compared with the volume occupied by manmade objects to permit more than an exceptionally remote chance of collision. This assumption, however, begins to break down if those objects significantly increase in number and congregate into specific orbital slots rather than evenly distributing themselves throughout the entire volume of near-Earth space.

Presently, there are nearly 20,000 tracked objects in Earth orbit. This number is expected to grow substantially due to three major factors: commercial launch prices are decreasing while the annual number of launches is increasing; the number of small satellites has ballooned in recent years and the growth is projected to increase; several "mega-constellations" (thousands of satellites) are being proposed by a number of companies. The result of this increased activity is a space environment that is far more congested than it previously has been. Some estimate that the number of operational satellites will increase by an order of magnitude and stretch the current space traffic management system beyond its limits.[3]

From a traffic management perspective, one can expect an increased number of conjunctions, collision warning messages, and collision avoidance maneuvers. Some estimates put the number of conjunction warning messages from just one of these mega-constellations at 2,000–3,000 per day, with a handful of them on the order of 50–100 meter miss distances. This implies a multiple order-of-magnitude increase in the number of conjunction warnings that operators must respond to—clearly an unmanageable situation if one wishes to safely operate in space. The cost of responding to each conjunction warning can be calculated by considering the number of staff-hours (often several dozen or more) needed to evaluate the credibility of the warning and then plan an appropriate response. If a collision avoidance maneuver is needed, the fuel used in its execution is given up only begrudgingly since it is a highly cherished commodity. Propellant reserves are usually the primary limitation of a spacecraft's total mission life, and lost life equals lost revenue.

The Cost of Orbital Debris

Normally, debris in the air or at sea is a transient problem and, at most, a modest hazard. In contrast, debris in orbit is highly threatening to other space objects and can remain so for hundreds or even thousands of years. Orbital debris can be lethal, as evidenced by Table 1. Even an object as small as 1 cm can cause catastrophic damage to a spacecraft. Furthermore, Table 2 illustrates the fact that these objects are not only small and

Table 1: Debris Size vs. Energy				
Debris Size	Mass (g): Aluminum Sphere	Kinetic Energy (J)	Equivalent TNT (kg)	Energy Similar to…
1 mm	0.001	71	0.0003	Baseball
3 mm	0.038	1,910	0.008	Bullets
1 cm	1.41	70,700	0.3	Falling anvil
5 cm	176.7	8,840,000	37	Hit by bus
10 cm	1,413.7	70,700,000	300	Large bomb
At 10 km/sec: Typical LEO impact speed				

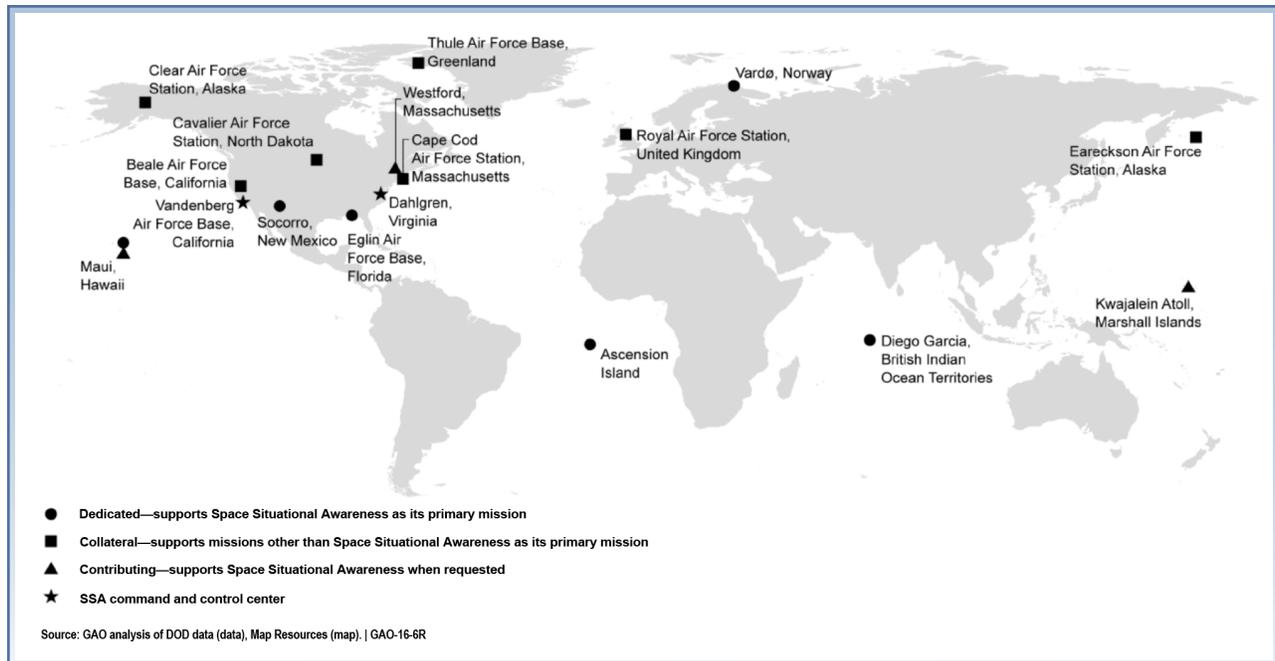| Table 2: The Trackability of Space Debris by Size		
Size Class	Quantity	Impact and Damage
1–3 mm	Tens of millions	Can't be tracked Localized damage
0.3–1 cm	Millions	Can't be tracked Localized damage Upper limit of debris shielding
1–5 cm	Hundreds of thousands	Most can't be tracked Major damage
5–10 cm	Tens of thousands	Lower limit of tracking Catastrophic damage
10+ cm	Thousands	Tracked and cataloged by Space Surveillance Network Causes catastrophic damage

Figure 1: The DoD Space Surveillance Network.

deadly but also untrackable—and therefore impossible to avoid. Clearly, the longevity and lethality of orbital debris presents the classic "Tragedy of the Commons" problem by imposing a cost to all spacecraft operators. This type of cost, known as a negative externality, is borne by operators unassociated with the mission that created the debris in the first place. While sometimes difficult to quantify, these costs must be accounted for if a truly efficient and healthy market is desired. Even the mere existence of the spacecraft imposes a non-zero cost to other satellite operators (collision avoidance and the potential to create debris) and should be accounted for.

Present Day Satellite Tracking

The value of GPS transponders lies with their ability to significantly improve space situational awareness and enhance flight safety. It is helpful to review the current method of generating space situational awareness before comparing it to the GPS transponder.

Non-Cooperative Tracking Network

For the past several decades, the DoD's Space Surveillance Network was the primary means of tracking space objects larger than a softball (smaller objects cannot be tracked). The Network consists of several sensors (telescopes and radars) spread across the globe (see Figure 1) to track non-cooperative space objects (i.e., an object that does not assist with tracking efforts).[4] The system was originally constructed during the Cold War to act as an early missile warning network as well as to track activity in space. The U.S. Air Force's Joint Force Space Component Command and the 18th Space Control Squadron work hand-in-hand to task this network to observe space objects and aggregate this data in the Joint Space Operations Center (JSpOC). Together, they are responsible for detecting, tracking, and identifying all objects in Earth orbit.[5] Several other non-cooperating tracking networks are operated by defense agencies of other countries as well as a growing cadre of commercial companies capable of independently generating proprietary data of varying quantity and quality.

Regardless of the organization, measurements taken from a generic non-cooperative tracking network are used to form predictions of where an object will be in the future. This is accomplished by using radar and optical assets to measure the object's position and velocity at a given moment in time. Of course, the prediction is never perfect, and errors in the estimate of a space object's position grow significantly over time. If left unchecked for several weeks, this error can become so large that the space object becomes lost. To prevent this from happening, the non-cooperative tracking network tasks one or more of its sensors to look for a space

object before it is lost. Since the approximate position of the object is known as a function of time (due to the laws of orbital motion), the network can determine which sensor it should task and what time it should go looking. At the indicated time, the sensor will point its boresight at the expected position of the space object. As long as the object shows up somewhere in the sensor's field of view, a measurement of that object's position can be taken and sent to the network's orbit determination center. This cycle then repeats in a track-and-predict cadence that continues until the space object is no longer in Earth orbit.

Figure 2: An example conjunction.

Thrusting Objects

This track-and-predict system works because the fundamental physics of orbital mechanics are very well understood and permit accurate orbital predictions, with errors that remain modest for a couple weeks. Of course, the predictions break down when an object is under thrust. The non-cooperative tracking network has no way of mathematically predicting the thrust profile of a space object that it does not control— so if the operator fails to notify the network of an intended maneuver, the spacecraft may not show up when and where the sensors expect to find it. The non-cooperative tracking network then needs to reacquire the spacecraft as though it had come from a brand-new launch. Furthermore, a spacecraft that performs frequent low-thrust maneuvers may never be adequately tracked, since its thrust profile is unknown to the non-cooperative tracking network, and it continuously breaks the mathematical assumptions contained within the orbit determination process. Such objects are continuously being lost and occasionally reacquired in a painful loop that only ends when the object stops thrusting.

This problem is growing, because low-thrust spirals to and from destination orbits are becoming increasingly popular for satellite operators due to a significant increase in fuel efficiency over conventional propellant.

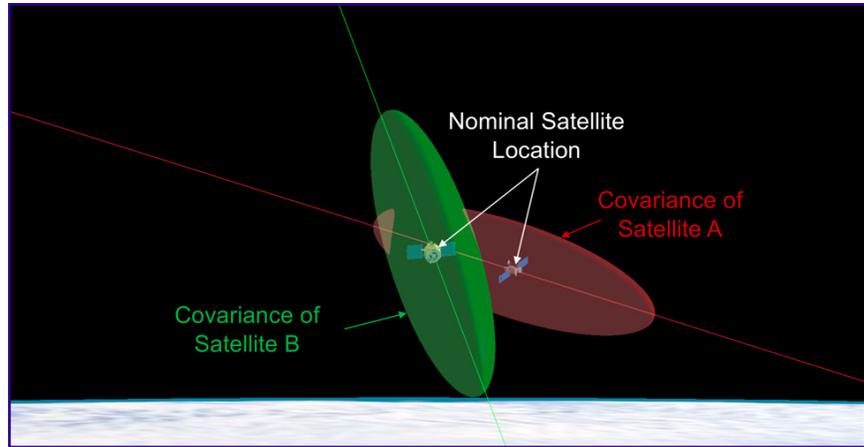Clearly, a different concept of operations is called for. This is where GPS transponders can solve a particularly formidable challenge. If the transponder can transmit the spacecraft's position at regular intervals, and with modest latency, then the low-thrust tracking problem is entirely solved.

Collision Probability

When spacecraft operators receive a conjunction warning, they must respond on strict timelines to ensure that a collision never occurs. The better known the two object's positions are, the more accurately an operator can assess if they will collide. The uncertainty associated with an object's position (and sometimes velocity) is called "covariance." Figure 2 illustrates a conjunction between two orbital objects. The uncertainty in each object's position is illustrated by drawing an ellipsoid that is centered upon the most likely location of the object. While it is expected that the spacecraft resides in the middle of the covariance ellipsoid, the reality is that it could be located anywhere inside it. If two objects find themselves with overlapping covariance ellipsoids, then they could end up in the same place at the same time—the definition of a collision. A collision is not guaranteed (especially when the covariance is very large), but it is possible to calculate the probability of collision by integrating the amount of overlap between the two ellipsoids.

To better understand covariance, it is helpful to identify the factors that govern its size, shape, and growth rate. The first factor is the uncertainty associated with position and velocity measurements acquired by the non-cooperative tracking network or a similar service. Any measurement of a physical quantity will always have a degree of uncertainty, due to the limitations of

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the measurement device itself. Sensors that measure the position, velocity, and timing of a space object are no exception. Some sensors can be highly precise (such as GPS), while others can have large uncertainties (e.g., ground-based telescopes and radars).

Of course, the precise location of a space object at the present time is not helpful unless its precise location at some future time can also be determined. If the exact forces that act on a space object can be perfectly modeled, then it is mathematically possible to predict the position of that object at any future point with no more uncertainty than the initial measurement itself. In the real world, however, such perfect modeling can never be achieved. The modeling of some space objects is better than others. Several perturbative forces are independent of the spacecraft's physical characteristics and are very well known. Other perturbative forces are coupled to the spacecraft's physical attributes and can be difficult to ascertain. Atmospheric drag is a prime example: Several models of upper atmospheric density exist, but they can deviate from the truth by an order of magnitude or more. To further complicate matters, the spacecraft's mass, orientation, and the position of appendages such as solar panels or large antennas make significant contributions to the actual drag force it experiences. Furthermore, a tumbling spacecraft—especially one with a variable tumble rate—can prove especially challenging.

Given the importance of measurement uncertainty to orbit determination, covariance size, and collision probability calculations, it is necessary to compare the approximate performance of a non-cooperative tracking network to that of a GPS transponder. The best non-cooperative tracking networks can create a satellite catalog with covariance, for a typical space object, on the order of a hundred meters or so. In contrast, GPS transponders can create a covariance on the order of 10 meters and
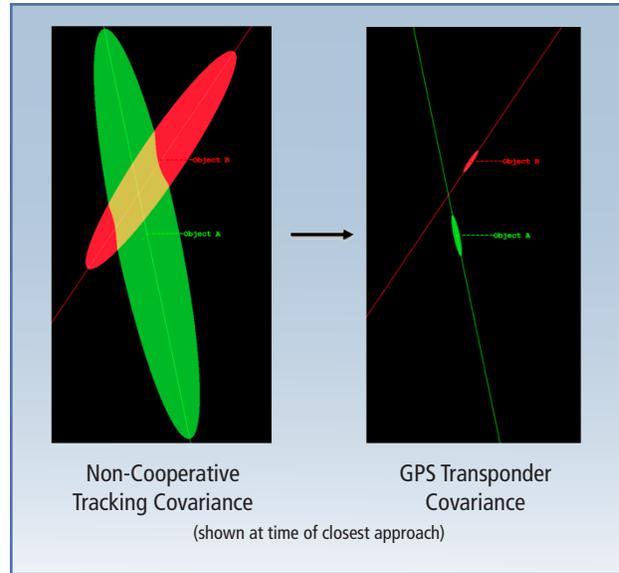

Figure 3: Identical conjunctions with differing covariance.

produce more frequent updates while expending no resources on non-cooperative tracking efforts. The effect on collision probability is stark, as can be seen in Figures 3 and 4. Figure 3 illustrates two identical conjunctions with the only difference being the source of covariance. The left of the figure shows covariance from the non-cooperative tracking network, which indicates a conjunction with non-zero collision probability; the right of the figure shows exactly the same scenario but uses a GPS transponder covariance instead—which indicates
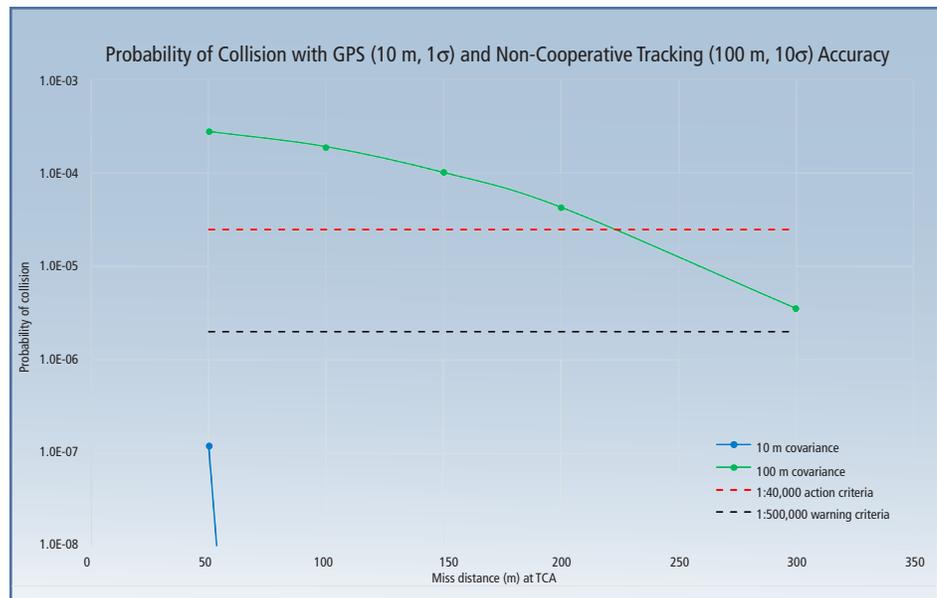

Figure 4: Effect of transitioning from passive tracking covariance to transponder covariance on collision probability.

no conjunction (essentially zero collision probability) even though the objects are in exactly the same location. Figure 4 demonstrates this concept graphically. The miss distance of a hypothetical conjunction is shown on the horizontal axis, while collision probability is shown on the vertical axis. The dashed lines represent the collision warning and action thresholds that are commonly used by U.S. government missions. The green curve shows collision probability for "high-accuracy" non-cooperative covariance, while the blue curve shows the same for objects with a GPS transponder. The green curve remains above the action criteria to a miss distance of 200 meters and always above the warning criteria. In contrast, the GPS transponder never triggers a conjunction warning—even with 50-meter misses.

Satellite Identification

The final challenge to satellite tracking lies in the ability to quickly and unambiguously identify space objects. Traditionally, a launch provider would deploy a small number of satellites (often just one). The non-cooperative tracking network would then search for new space objects in the vicinity of the launch vehicle. These objects show up as unidentified blobs on a sensor image. To associate a blob with a particular satellite, a process of elimination is used based on the origin of the launch vehicle and several other mission-specific factors. This method breaks down, however, when multiple objects are released from the same launch vehicle. For example, on Feb. 15, 2017, the Indian space agency launched 104 CubeSats in rapid succession, with a deployment rate close to one every second.[6] This could easily overwhelm the identification abilities of some non-cooperative tracking networks. Worse yet, the situation would not be remedied until a CubeSat operator, with in-house orbit determination capabilities, self-reported their orbits. Several similar launches have prompted the JSpOC to create recommendations for voluntary tracking enhancements to CubeSat missions.[7] These recommendations include:

- Filing launch and deployment plans with the JSpOC well in advance of those activities
- Providing maneuvering capability to the CubeSat if possible
- Designing the CubeSat such that its operational life accounts for the majority (at least 66%) of the total orbital life

- Keeping CubeSats far away from inhabited spacecraft such as the International Space Station
- Informing the JSpOC of the physical parameters of the CubeSat, including size, maneuverability, solar panels, etc.
- Providing orbit determinations during early orbit operations to enable conjunction assessments
- Applying identification markers (physical or signal-based) that would operate for at least two months

The final bullet point (and several others) would be more than adequately addressed via the introduction of GPS transponders. They provide a far more efficient, accurate, and reliable source of satellite identification, and redirect the burden of detection, tracking, and identification away from a non-cooperative tracking network and back to the satellite owner/operator. This permits the DoD and others to concentrate on other objects of higher interest. Even more resources are saved for small objects that are on the edge of trackability; sometimes, these objects show up on non-cooperative tracking network sensors, and sometimes they don't— even when the sensors are looking directly at them (which is especially vexing). Transponders also permit positive identification of space objects, rather than relying upon the forensic association that occasionally confuses one object for another (known as cross-tagging).

The Ideal System

In addition to establishing the need for a space object GPS transponder system, as discussed above, it is also helpful to define the ideal attributes of such a system and a concept of operations. Prior to launch, GPS transponders could be attached to all space objects intended for release by a launch vehicle or spacecraft (even debris). The transponder should be standardized, such that one can be quickly swapped for another and can be integrated onto the spacecraft hours before launch. Figure 5 presents an overview of the system. Once activated, the transponder will transmit a unique serial number in addition to the GPS data (position, velocity, and time). Other precision navigation and timing systems, such as Galileo, GLONASS, or BeiDou, could be used as well. The transmitted signal will be received by either ground-based or space-based receivers and forwarded
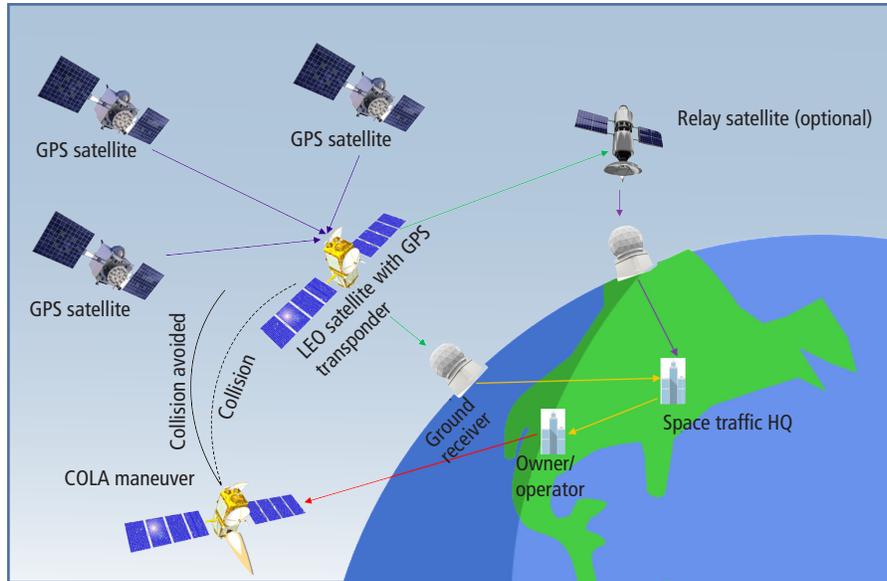
Figure 5: Overview of GPS transponder system.

other transponding spacecraft and also reduce the ability of potential adversaries to perform orbit determination using the raw signal. Due to the small size of this data packet, transmission of the message would last only a fraction of a second.

Size, Weight, and Power

The GPS transponder should be as small and lightweight as possible. A reasonable target size would be $8 \times 8 \times 3$ cm or smaller, with a mass of 100–200 grams or less. Figure 6 illustrates a first-generation GPS transponder prototype constructed by The Aerospace Corporation that is roughly $8.6 \times 9.4 \times 3.2$ cm with a mass of 285 grams. Future prototypes are planned to shrink that size significantly (to roughly half the size of a deck of playing cards). The device has a self-powered mode (solar cell and battery) as well as an optional input for power and data from the host spacecraft. It has an omnidirectional antenna (to account for a tumbling host) and can close the link at distances in excess of 2,000 km—thereby covering all of LEO. The device will be thoroughly tested to ensure it does not cause undue RF interference. The Aerospace Corporation is creating an industry-wide working group to further explore this form factor and better determine the needs and constraints of all stakeholders involved. Specifications can then be adjusted to accommodate any concerns raised by spacecraft owner/operators (including CubeSats).

to a central space traffic coordinator. Orbit determination will use the reported GPS data, and conjunction assessments will be performed on all space objects (with and without transponders). Finally, spacecraft owner/operators will be warned by the space traffic coordinating authority of upcoming conjunctions, and an appropriate response can be coordinated. Initially, the system would be restricted to objects in low Earth orbit (LEO), as it is straightforward to acquire GPS signals and transmit low-power messages to the ground. Since LEO is the most congested orbital regime, it makes sense to design a system to operate in this environment first. A follow-on system could be designed at a later time to cover other orbital regimes.

Message Format

The transponder message should be standardized to make the system interoperable and manufacturer agnostic. This could be accomplished via industry consensus or by national/international agreement. At a minimum, a single message should contain the transponder serial number, the timestamp, and the GPS data. Error-checking data may be included where appropriate, as well as ancillary data containing optional sensor information from the transponder and state information from the host spacecraft (e.g., is the host alive or thrusting?). The message could be encrypted to prevent reception by unauthorized entities. Spread-spectrum technology would help avoid packet collisions between

Modes of Operation

There are three modes of operation that a GPS transponder should support. They are:

- **Normal Mode** (optional). The transponder is receiving a modest amount of power from the host vehicle. It acquires GPS data at regular intervals (e.g., once a minute) and transmits it immediately. Navigation, timing, and sensor data could be passed back to the host vehicle if requested. Also, a periodic "I'm alive" signal could be sent to the transponder indicating the status of the host.

- **Thrust Mode** (optional). This mode is nearly identical to the Normal Mode except for a few minor alterations. The main difference is that the data rate of the transponder will increase (e.g., once per second) to allow for a rapid and data-rich reconstruction of the thrusting trajectory. This will also quickly indicate any unexpected results in the maneuver and permit rapid recalculation of conjunction screenings. The host will send a flag to trigger the transponder to switch to this mode via the optional data port.

- **Debris Mode** (mandatory). This mode is the most technically challenging but is also the most important. It assumes no power nor attitude control from the host vehicle. Instead, the transponder will charge an internal battery from a small photovoltaic cell mounted on the top surface of the unit. The meager power produced by the solar cell precludes the transponder from collecting a large amount of GPS data and transmitting it to the ground instantly. Instead, the transponder spends most of its time in "sleep mode." Occasionally, it will wake up, gather and store the GPS data, and fall back to sleep. When there is sufficient power, and a ground site is in view, the transponder will wake up and transmit all the data stored in its buffers. In this way, the necessary data is transmitted in a power-deprived environment with the introduction of a modest amount of latency—on the order of a couple hours. This mode permits the transponder to be completely independent of its host. If a host spacecraft separates from the launch vehicle, fails immediately, and remains in orbit for decades, it would still be tracked by the GPS transponder.

The transponder will maintain custody of any LEO object—even a brick. It should also be able to do this for several decades and be tolerant of radiation effects. Since a typical spacecraft can last 10 years or more and is then allowed 25 years for disposal, the ideal transponder should be designed to last three to four decades.

Ancillary Data

While optional, it may be highly beneficial for the host spacecraft to provide a means of communication with the transponder. There is no reason why the transponder could not be used as a supplemental (even primary) navigation unit for the host, thereby offering additional
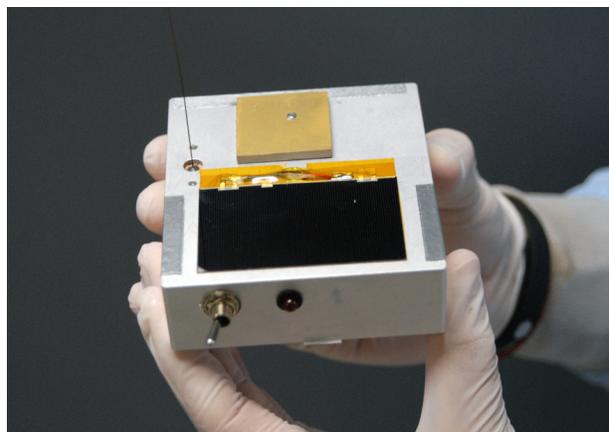

Figure 6: The Aerospace Corporation's first working GPS-transponder prototype.

benefit. Other data that would be useful for space traffic management may also be useful to the host vehicle. Several sensors have become so small that their impact on size, weight, and power is negligible, while the additional benefit is significant. Micro accelerometers and gyroscopes, for example, would be highly useful in determining the orientation of the spacecraft and informing more accurate atmospheric drag models. Reentry predictions would be much more accurate using this data. Furthermore, that same data could be utilized by other spacecraft conducting active debris removal missions. Remotely and autonomously measuring the tumble rate of a non-cooperative target vehicle is challenging and potentially hazardous. Creating a mechanism for that data to be provided to the debris-removal spacecraft would be highly beneficial and greatly enhance the safety of such a mission.

The Coordinating Authority

It is important to have a robust and reliable ground architecture capable of receiving, processing, and disseminating the transponder signals in a timely manner. To that end, trades between the number and location of ground receivers should be weighed against total system cost. With the advent of low-fidelity onboard (on the transponder) orbit determination, it should be possible to trade the size of the ground infrastructure for latency using a store-and-forward concept of operations (an interrogation signal is also a viable alternative). Over time, the system could evolve to reduce latency with additional ground sites. Also, while directional antennas have advantages in terms of signal gain, it is preferable

to design the system with omnidirectional ground receivers. In this way, the ground system does not require a precomputed trajectory. All that is required is line-of-sight to the host spacecraft and a postprocessing algorithm that continuously listens for impromptu transponder messages.

There are several different concepts for how a space traffic coordinating authority will work and who would best implement it. In general, there are four different approaches, each with their own pros and cons:

- an intergovernmental space traffic authority that is likely run by the United Nations Committee on the Peaceful Uses of Outer Space or similar body;
- a civil space traffic authority created with jurisdiction over all assets launched or operating in markets involved with the host nation;
- a commercial or nonprofit company that is granted authority on behalf of a national or international governing body;
- an open-source approach built upon volunteer satellite watchers (e.g., amateur radio) and open sharing of data on a public website.

Each option raises questions of cost, authority, quality, and accountability. Due to the nature of space, an international authority may be preferable to one with only national influence. This is the approach taken in the maritime domain. Conversely, it may require ample financial resources and setup time to agree to and implement a government-run system. A quicker and less expensive option may be the creation of a volunteer or corporate space traffic management organization; however, such an entity may suffer from quality, accountability, and authority problems. Nevertheless, there is precedent in the aviation domain of several countries for a commercial or nonprofit traffic management entity. An extension of the Space Data Association may be a good fit for this option.[8] Of course, there is no reason why the space traffic coordinating authority could not evolve over time from one approach to the next, nor why it should not look like a mixture of the options stated above. Market forces, safety concerns, and stakeholder needs will dictate the final approach.

One final concern is understanding what entity holds the encryption keys to transponder messages. One option is to leave all messages unencrypted, but this comes with several operational security concerns as well as privacy issues. Most would agree that the spacecraft owner/operator should have access to the transponder data—but should everyone? If the data is encrypted, then who has the ability to decrypt it? Should that ability be vested in the transponder manufacturer, the space traffic coordinator/authority, an international body, nations in conflict, or solely by the owner/operator of the spacecraft? Those who hold the keys to the kingdom also hold the power.

Alternative Approaches

The discussion above outlines the desired traits for an ideal GPS transponder, but these decisions are not yet universally accepted, as the space community is only beginning to discuss the need for transponders. It is recommended that a GPS transponder working group be created, consisting of representatives from the DoD, civil, commercial, academic, and international communities. The goal would be to codify transponder requirements into a single, industrywide set of best practices and standards. Until there exists an industry-wide agreement on the requirements for transponders, several other methods for performing some or all of the stated objectives should be considered.

> *There is no reason why the space traffic coordinating authority could not evolve over time....*

Some methods focus on passively enhancing the radar return signal from a hard-to-track object via the addition of reflective thin films and slightly larger retro-reflectors. Even something as simple as a deployable metal measuring tape can act as a dipole antenna and significantly increase the radar return. Other approaches focus on the identification of the satellite by coding a liquid crystal display to modulate a serial number when the space object is illuminated by radar or lasers, with the returns detected by ground receivers or telescopes. Some approaches shrink the electronics even further (100 grams for example) and concentrate on returning

a faint identification signal to large ground receivers whenever the host receives an interrogation request. In this case, the package is extremely small, runs off stored battery power, and can last up to two months. Finally, another approach focuses on transmitting transponder data optically rather than using RF energy. The optical signal would be received by telescopes on the ground on clear nights.[9] Each technology has advantages and disadvantages that must be closely scrutinized. It is likely that one technology would be appropriate for one specific niche area (e.g., 1U CubeSats), but not others (e.g., rocket bodies).

Finally, an approach that should be seriously considered is the idea of self-reporting. Several spacecraft have mission requirements that call for the use of onboard GPS navigation. This capability could be repurposed into a "virtual" GPS transponder, thereby saving the size, weight, and power costs of a traditional transponder. For this concept to work, the virtual transponder must meet all the standards of a physical transponder (including a debris mode) and should be verified and validated by an independent third party. If all the requirements are satisfied, there is no reason why a virtual transponder could not work well and greatly benefit all parties involved in space traffic management.

Shaping the Future

To fully appreciate the benefits of a GPS transponder, it is helpful to imagine what the future might look like, after the space community has invested in this technology. How would transponders influence the evolution of spaceflight? Below is a list of fringe benefits that might apply.

- *Trust and Confidence-building Measures.* By international treaty, nearly all ships at sea are required to have transponders. This greatly clarifies the maritime environment and helps others determine the intent of a vessel. If the vessel is running dark, it usually has nefarious intentions and is easy to prosecute. Could the same apply to the space domain?

- *Active debris removal.* Debris removal is a risky business, but will probably be standard practice in the future. International law does not make it clear when a third party is permitted to salvage or dispose of a space object.[10] The GPS transponder allows for communication between it and the host vehicle. If the transponder has not communicated with the host for a predetermined period, then the host could be legally considered dead and subject to space salvage rights. This is an easy and unambiguous test for establishing the salvageability of space objects. Additionally, extra sensors for rotation rate or acceleration, easily included on the transponder, could greatly assist a vehicle in removing a non-co-operative space object.

- *Risky Phases of Space Flight.* The transponder should prove valuable in enhancing the safety of risky phases of spaceflight to include launch, reentry, rendezvous and proximity operations, debris removal, and human spaceflight. Launch collision avoidance could be conducted on-the-fly, and improved reentry predictions could be made to enhance safety.

- *Liability.* The transponder can be used to keep a record of activities in space. Everything from RF interference, to collisions, to debris creation can be monitored either fully or in part via transponders. Anomaly resolution and attribution would also be improved.[11]

- *Space Traffic Management Zones.* Should all orbits be treated with identical rules? There are several air traffic management zones that are largely defined by the aircraft's equipment, rating, transponder, and economic activities. Should a similar system be established for space?[12]
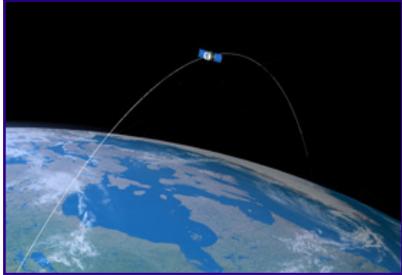
Conclusion

Space is becoming increasingly contested and congested; innovative methods are needed to improve space traffic management. Collisions in space involve long-term economic costs that are difficult to fully calculate and extend far beyond the scope of the primary parties involved. Currently, the costs of debris creation and collision avoidance are typically passed on to unrelated third parties, thereby creating an inefficient market. Additionally, the costs associated with tracking and navigating satellites are often not borne by the spacecraft owner/operators but rather by the DoD. The forecasted increase in launch rates eliminates the status quo as a viable option, due to the overwhelming number of conjunction warning messages that will occur. Clearly, a more accurate method for tracking and orbit determination is required.

A GPS transponder system has the potential to solve many of today's space traffic management challenges. Such a system would quickly identify satellites, reduce positional uncertainty, improve conjunction screening, and facilitate tracking of a thrusting space object. This is accomplished in several different modes of operation, with the most technically difficult (albeit important) focused on debris. This debris mode should be capable of tracking a dead spacecraft for several decades until it is properly disposed, thereby correcting for the inefficiently allocated costs of debris creation, collision avoidance, and tracking that would otherwise be absorbed by society. Spacecraft operators would glean the additional benefit of receiving data provided by the transponder (supplementing or replacing their own navigation system) as well as avoiding the costly research and development of such a system themselves. Indeed, standardization could open up a whole new competitive market for navigation hardware and services. There is no reason to wait until space is populated with thousands of New Space actors. The space community needs a robust and reliable means for reporting highly precise positions, identifying satellites, and tracking thrusting spacecraft. Now is the time to act to achieve the maximum benefit offered by GPS transponders for space traffic management.

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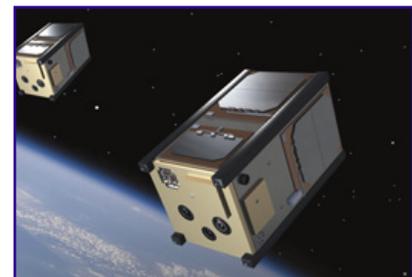**Public-Private Partnerships: Stimulating Innovation in the Space Sector**

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