Cooperative Tracking Aid for Space Domain Awareness

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ABSTRACT

Since the dawn of the space age the ability to track Resident Space Objects (RSOs) has been of paramount interest. Historically, traditional tracking methods relied upon government organizations tracking RSOs via state-owned and operated ground-based radar and electro-optical telescopes. While this methodology sufficed for decades, recent changes in the space environment warrant a reconsideration of traditional approaches to Space Domain Awareness (SDA). Recently, near-Earth-space has become increasingly congested and contested. Proliferated constellations are now commonplace increasing the number of active satellites by an order of magnitude. Many of these satellites frequently conduct low-thrust and sometimes autonomous maneuvers which break the traditional assumptions of Keplerian dynamics that undergird traditional SDA methods. Additionally, multi-satellite deployments and other non-traditional operations are making it more difficult to prevent cross-tagging, provide positive identification of specific satellites, and maintain custody of all satellites in space.

Other environments, such as the aviation (ADS-B) and maritime (AIS) domains, have dealt with similar challenges. These domains evolved over the decades towards a cooperative tracking system that offers many advantages over a non-cooperative approach. Positive ID, increased density of safely operating vehicles, and improved operational efficiencies are all benefits realized with a cooperative approach in these domains. Currently, there is no parallel for cooperative tracking in the space domain. The intent is to show that a similar approach, adapted for the unique features of the space domain, would work within a low Size, Weight, Power, and Cost (SWaP-C) constraint.

This paper illustrates Lockheed Martin's modeling and simulation of a cooperative tracking system concept and provides an overview of a working prototype from a hardware, software, and CONOPS perspective.

1. INTRODUCTION

1.1 Space Congestion and Contestation

There is near-universal consensus that the space domain is increasingly congested and contested with an accelerating growth curve. Figures 1 – 3 quantify this claim [1]. Figure 1 demonstrates an increase in individual payloads deployed over the last seven years. Figure 2 quantifies a historic shift away from exclusively single-satellite deployments to multi-satellite deployments occurring annually. Figure 3 illustrates the steep rise in the number of cataloged objects over the last twenty years. The number of active satellites has ballooned from a historical average of a couple thousand to over eight thousand and rising. This is partially attributed to "new space" companies launching proliferated constellations consisting of several thousand satellites. Many of these satellites conduct autonomous maneuvers using low-thrust propulsion that voids the traditional assumptions of Keplerian orbit determination.

The value of space assets is predicted to increase in line with the proliferation of satellites. Researchers and space insurance companies [2] predict that by 2030 there will exist tens of thousands, possibly as many as 100,000, active satellites in LEO. These organizations estimate a present-day value of $38 billion and $280 billion by 2030. The researchers claim that projected losses from increased collision risk will rise from $65 million today to $1.9 billion by 2030. This estimate does not include losses incurred from a response to a potential collision which force satellite operators to incur various costs including 1) time to evaluate conjunction warning, 2) coordination with the opposing satellite operator, 3) collision avoidance (COLA) maneuver planning and execution, 4) satellite mission lifespan reduction due to diminished fuel reserves, and 5) temporary loss of mission while the satellite conducts the maneuver and recovery thereafter.

Congestion is not the only way space is changing. The United States has recognized that space is now a warfighting domain. The Defense Intelligence Agency compiles a list of unclassified threats to the space domain in its annual report [3], including radiofrequency jammers, kinetic kill vehicles, lasers, robotic arms, chemical sprayers, and microwave devices. Many of these technologies are dual-use and are beneficial for both civil and military applications. Unfortunately, it is often difficult to distinguish the intent of a RSO using exclusively non-cooperative tracking technology.

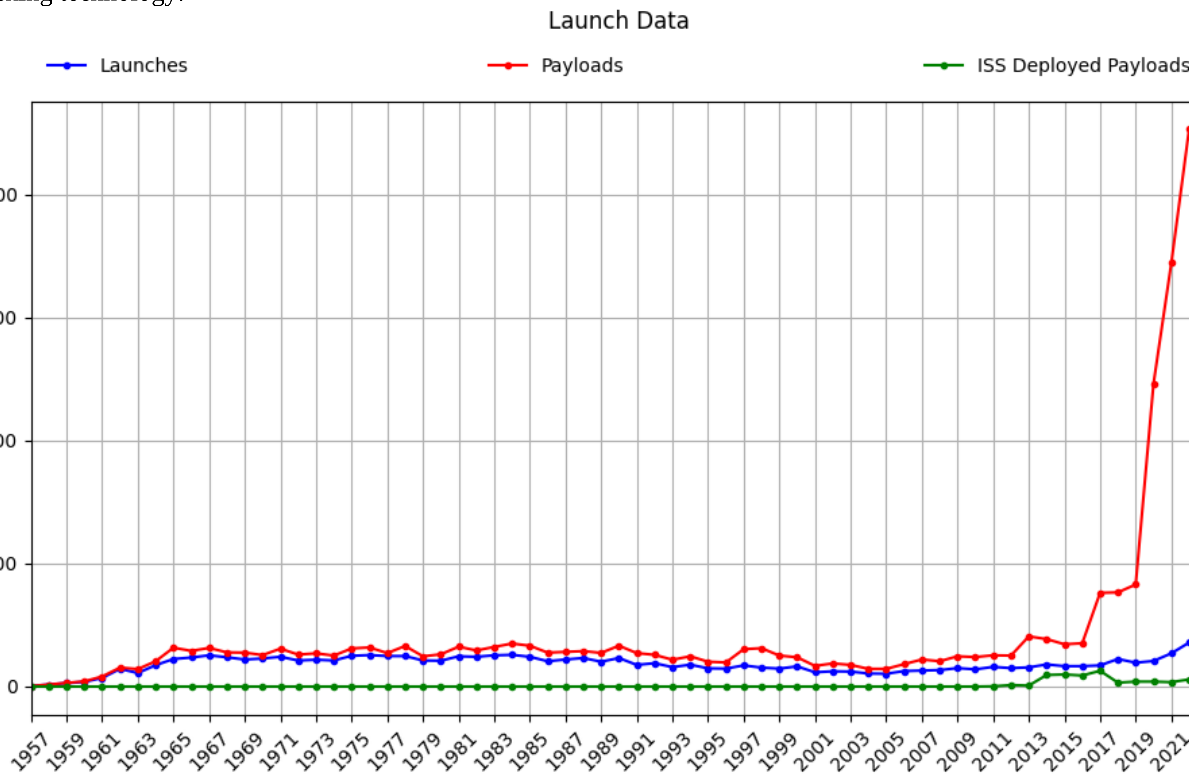

Fig. 1. Annual Deployment of Payloads Increased Exponentially in Last Seven Years

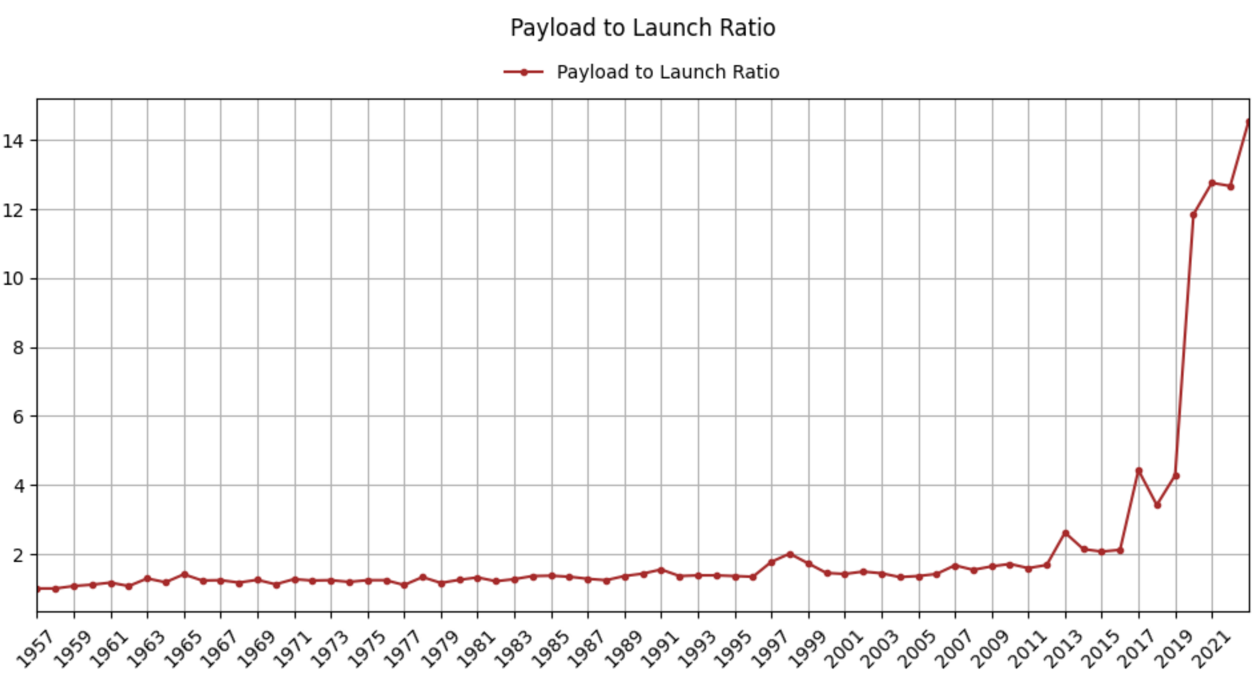

Fig. 2. Annual Payload to Launch Ratio Increased Exponentially in Last Seven Years

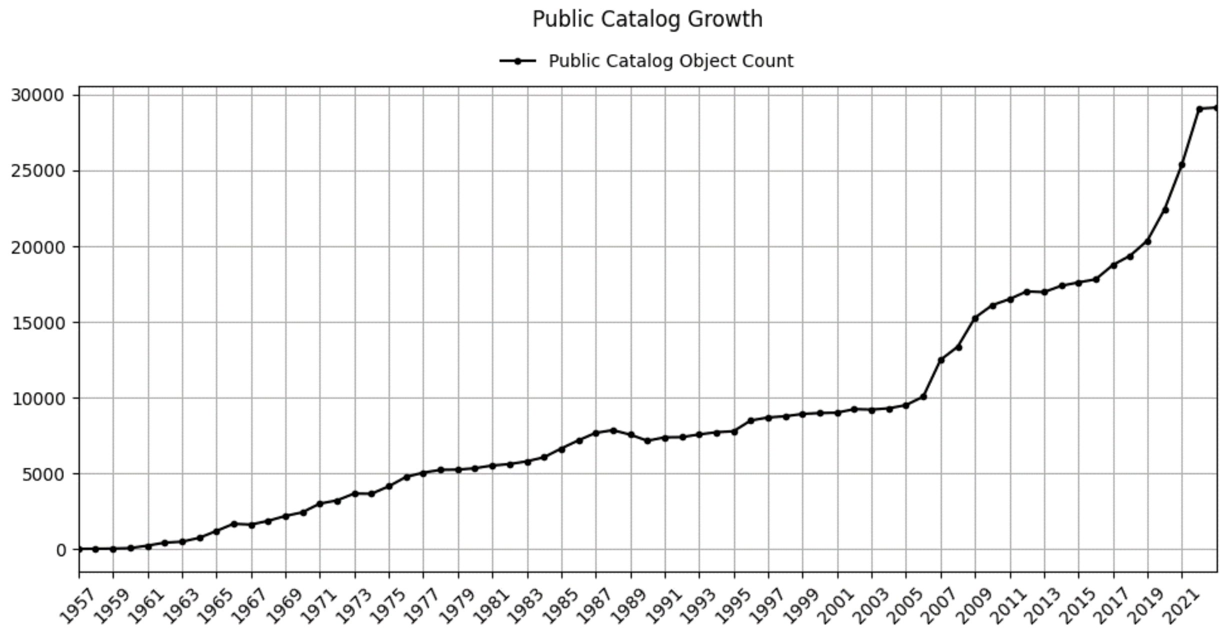

Fig. 3. Public Catalog Shows Number of Tracked Objects Tripled in Last Twenty Years

1.2 Domain Awareness in Terrestrial Domains

Since the launch of Sputnik in 1957, the primary method of SDA has been comprised of non-cooperative observations. Typically ground-based radar and electro-optical telescopes provide observations to maintain custody of space objects. The term "custody" refers to the ability of the surveillance network to predict where the satellite will be in the future with sufficient accuracy that new observations can be acquired to update the orbital state. This work is intended to formulate an augmentation or even a partial replacement of these traditional systems following the example of the aviation and maritime domains.

The aviation domain has a long history of tracking and identification technologies. In the 1920's and 1930's, traffic management was conducted via pencil, paper, chalkboards, and verbal radio updates. World War II introduced RADAR tracking for the first time which had both positive and occasionally negative consequences on allied forces. Friendly-fire incidents were mitigated via the introduction of on-aircraft Identify Friend or Foe (IFF) technology [4]. The governance of RADAR tracking dominated post-war civil air traffic management. While RADAR was excellent at providing range and bearing it was poor at providing accurate altitude information and was often unable to provide positive identification. Due to these deficiencies and increasing air traffic, airframes were equipped with a RADAR-activated transponder which broadcast the aircraft's identity and altitude[1] each time the transponder was interrogated by the RADAR system [5] [6]. By the late 1990's and early 2000's RADAR systems gave way to new technology that became known as Automatic Dependent Surveillance Broadcast (ADS-B) which used an on-board GPS/GNSS receiver to accurately calculate the aircraft's position, speed, and heading and broadcast that information[2] to Air Traffic Control. ADS-B technology provides more accurate position estimates of the aircraft which improves search and rescue missions and increases efficiency in airspace management since more aircraft can safely co-exist within congested airspace (e.g., approach for landing at an international airport) [7]. This resulted in more aircraft landings per hour in the world's busiest airports compared with rates seen prior to ADS-B technology. Furthermore, ADS-B technology is now an international standard implemented in dozens of countries across the world including China.

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[1] The altitude was measured by a barometric pressure gauge onboard the aircraft.
[2] Which, as with earlier transponders, also included the aircraft's tail number thereby providing positive identification

The aviation domain is not the only environment where active transponders are used. The maritime environment utilizes Automatic Identification System (AIS) to accomplish the same objectives described above. The International Maritime Organization states that "… all ships of 300 gross tonnage and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages, and passenger ships irrespective of size to be fitted with an automatic identification system (AIS)." [8]

While exceptions exist (e.g., small vehicles operating in uncontrolled space), most vehicles capable of international travel are outfitted with a GPS transponder device. While the original intent of transponders was for improved safety and traffic management, a byproduct of this technology are improvements to national security. A nation no longer needs to rely upon RADAR and radio communication to establish the identity and intent of a vehicle with an active transponder. Exceptions to this transponder requirement exist for military ships and aircraft who, by the necessity of their missions, are permitted to choose when to activate or turn off their transponder. While this seems to be a loophole, it can be used to a government's advantage. In a world where the norm is for civil or commercial vehicles to transpond, the detection of a non-transponding vehicle, or a vehicle with an improperly functioning transponder, would immediately raise suspicion and warrant additional scrutiny to evaluate the nature and intent of such a vehicle.

2. PROPOSED SOLUTION: GPS TRANSPONDERS

Inspired by the aviation and maritime domains, this paper will attempt to formulate a similar solution for the space domain. This solution must respect the fundamental differences between the aviation/maritime domains and the space domain. The authors are cognizant of other technologies that may address part of the solution space and are deserving of consideration in a separate publication [9] [10] [11] [12]. This paper does not intend to minimize nor detract from those worthy endeavors.

2.1 Desired Features

When considering a new technology, it is helpful to list the desired features prior to formulating the solution. To obtain the maximum utility, this new space tracking technology should be able to:

- Quickly obtain and maintain custody of a RSO with < 10-meter RSS covariance at state epoch. This is one to two orders of magnitude smaller than obtained via traditional tracking methods and useful for improved conjunction assessment.
- Quickly and unambiguously obtain positive RSO identification even in a cluttered environment (e.g., multi-satellite deployments, proliferated constellations, debris clouds, etc.).
- Maintain custody (tens of meters) of maneuvering RSOs before, during, and after a maneuver. Such maneuvers may be finite or impulsive, low or high thrust, short or long in duration, and pre-planned or autonomous in nature.
- The device must be self-contained and survivable since a non-functioning RSO does not rapidly exit the space domain in the same way a failed aircraft would rapidly exit the air domain. The service must persist for the entire orbital life of the RSO, or as long as practical, regardless of the health status of the RSO. This includes the case when an RSO is non-functional at launch.
- The system must not be influenced by weather conditions, eclipse conditions, nor rely upon the need for *a priori* RSO orbit knowledge. Such *a priori* orbit knowledge defeats much of the utility of a transponder and can easily be rendered impotent should the RSO conduct a maneuver or find itself in an unexpected situation relative to third party expectations.

2.2 General Approach

A physical transponder device affixed to a satellite prior to launch and deployment[3] can meet these objectives. The device consists of the following components:

- GPS receiver and antenna
- Radio used to transmit data to a receiving network
- Battery to power the transponder
- Photovoltaic cell for independent source of power should the host be unable or unwilling to supply it
- Circuitry to coordinate and drive the components listed above
- Optional sensors as space allows (e.g., inertial measurement unit)

2.3 Drawbacks

It is important to discuss the undesirable consequences of such an approach. These consequences include:

- A non-zero impact to the host RSO in terms of the SWaP of the transponder device (opportunity cost)
- The existence of an RF transmitter which implies a regulatory burden as well as interference concerns
- The existence of a small battery that could lead to thermal runaway or an energetic explosion in rare cases
- The non-zero monetary cost of the device

Specific design for a GPS transponder will need to address these drawbacks to minimize the cost to the host entity.

3. USE CASES

3.1 CONOPS Analysis

Multiple test cases were created to assess the performance of different GPS transponder capabilities and CONOPS. The simulations were chosen to highlight common, challenging scenarios that are improved with cooperative tracking data. Orbit Determination Toolkit (ODTK) and Systems Toolkit (STK) [13] were utilized to simulate GPS position observations at different measurement cadences with varying levels of measurement uncertainty. This represents different measurement acquisition CONOPS and accuracies of onboard GPS solutions. The data was post-processed to assess satellite position uncertainty and verify OD solution consistency throughout the scenarios.

3.2 Improved Conjunction Warning Assessments

A congested space environment poses high costs on satellite operators to assess COLA events. False positive warnings (i.e., collision predicted but does not occur) may waste valuable resources such as time, money, or propellant if a satellite maneuvers unnecessarily. A more dangerous false negative can occur when a collision event is missed by operators, resulting in a potential loss of mission.

Nine conjunction events in LEO were simulated by varying miss distance and relative speed as shown in Table 1. Both satellites involved in the conjunction event were assumed to have an active GPS transponder onboard that processed position measurements every 30 minutes with 100-meter (1σ) gaussian noise. This represents an inexpensive GPS receiver that provides noisier measurements than anticipated with real hardware. Eight days of transponder data was processed to allow the sequential filter to reach steady state. The last measurement occurred 48 hours prior to the time of close approach (TCA) representative of a two-day conjunction prediction period as shown in Figure 4. Additional post-processing demonstrated the position uncertainty was consistent with the simulated data.

MISS DISTANCE	RELATIVE SPEED
0 meters (collision)	15.1 km/s (head-on)
100 meters (miss)	9.2 km/s (out-of-plane)
1 kilometer (miss)	0.3 m/s (overtaking)

[3] A transponder device could also be attached to a RSO after its deployment but that comes with complications that are outside the scope of this paper and best addressed in follow-up work.

Table 1. Conjunction Event Conditions

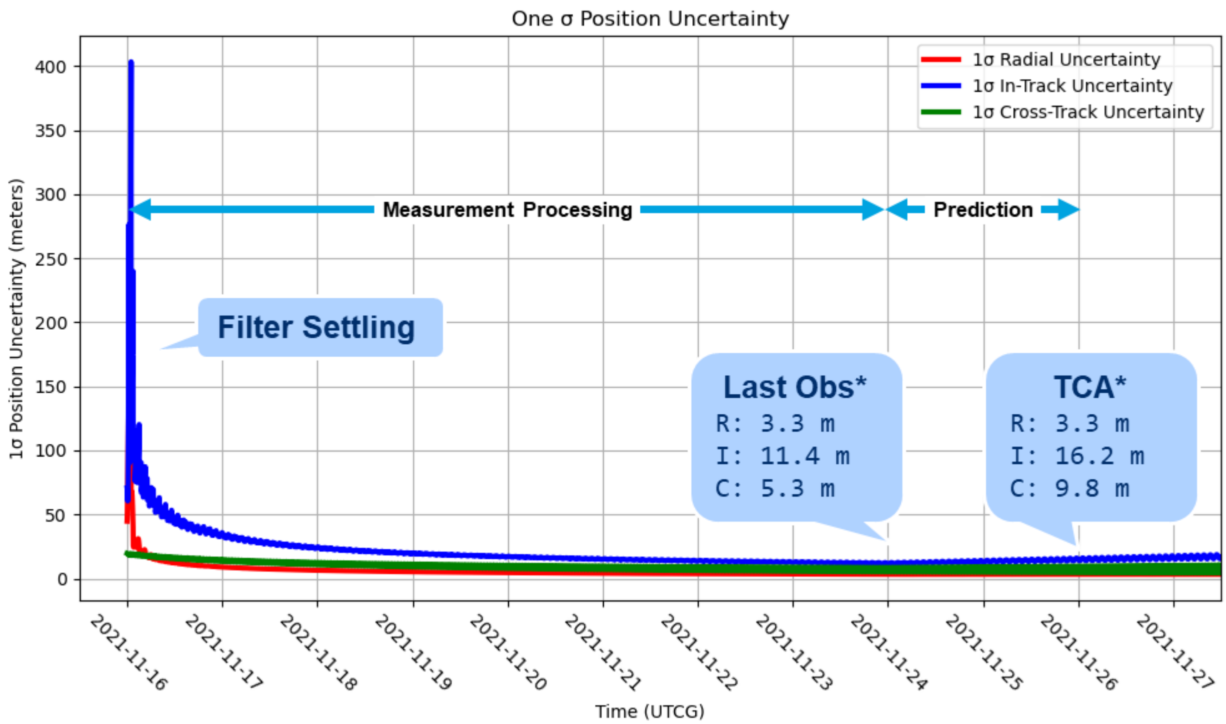

Fig. 4. Position Uncertainty Over 8 Day Measurement Processing and 2 Day Covariance Prediction Span

The STK Conjunction Analysis Tool was utilized to assess the estimated miss distance and probability of collision (P_c) between satellites. The NASA maneuver threshold of P_c > 1e-4 (1 in 10,000) [14] was used to determine if the close approach was predicted to result in a collision. Figure 5 shows the correctly predicted outcome two days prior to TCA in all nine test cases. All nine cases would be concerning using traditional SDA resources. The results show false positive and false negative conjunction warnings could be nearly eliminated if transponders were in use.

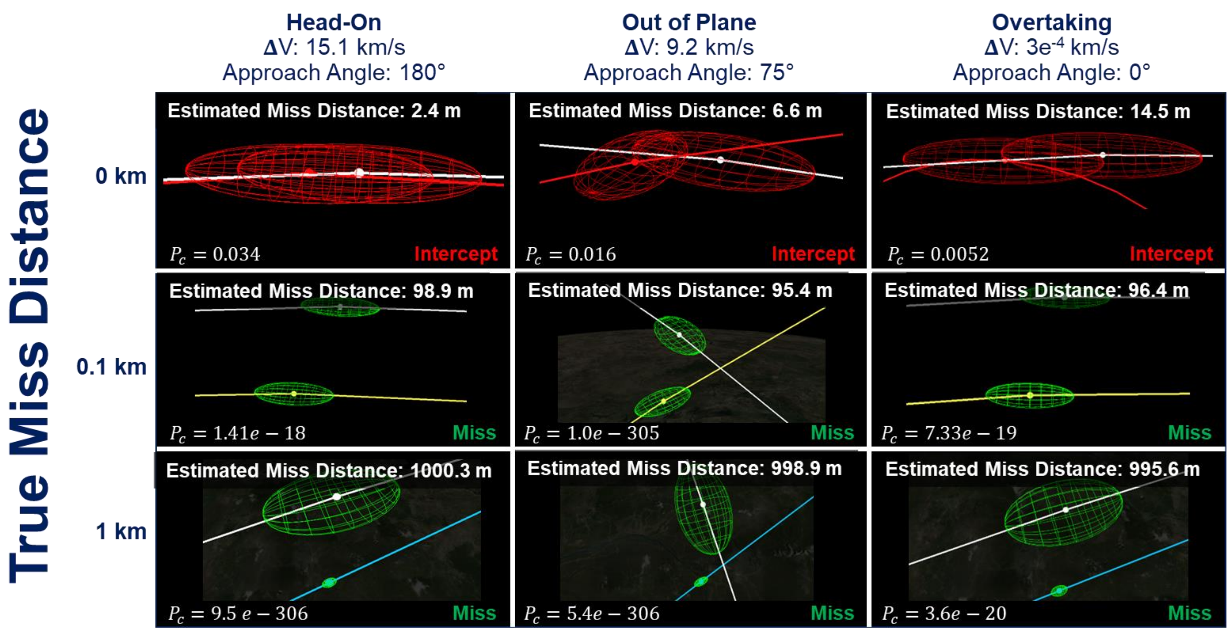

Fig. 5. Results Showing Correct Collision Outcome Predictions Two Days Prior to TCA in All Nine Test Cases

3.3 Positive Identification After Multi-Satellite Rideshare Deployments

An exponential increase of payloads included per launch has occurred over the last decade. For example, in 2017 a polar satellite launch vehicle deployed 104 satellites into low earth orbit – including 101 cubesats which were deployed over a period of 10 minutes [15]. While satellite launch operators often provide the estimated time and location of deployments for each payload, this can be insufficient for satellite operators to positively identify their payload. This is particularly challenging when there are dozens of similarly sized payloads deployed concurrently.

Operators may face temporary or permanent loss of mission if they are unable to identify their spacecraft. Aerospace America published an article in 2020 about the Miniature X-ray Solar Spectrometer 2 (MinXSS-2) cubesat built by University of Colorado in Boulder that faced this issue. The spacecraft was initially acquired by the university ground station after it was deployed from a rideshare launch. The cubesat was deployed amongst dozens of other satellites within a few minutes of each other, allowing the ground station to successfully contact the MinXSS-2 during early operations since multiple satellites were within the communication beam. After the satellites started to drift apart due to natural orbit perturbations, the university team was no longer able to communicate with MinXSS-2 since they did not know which satellite belonged to them. Since this satellite was not identified in the public space catalog, CU Boulder operators were left to try to find their spacecraft without assistance. They successfully made contact with MinXSS-2 about a month later, just before the spacecraft failed. [16]

Satellite operators across industry, academia, and government face similar risks to maintaining reliable tracking and communication with their spacecraft when deployed from large rideshare launches. In some cases, payloads are not identified in the public space catalog for weeks or months after deployment as shown in Figure 6 supported by data obtained via the public catalog [1]. A recent real-world rideshare mission inserted over 140 small satellites into LEO. While nearly 70% of the satellites (identified or otherwise) were added to the public catalog one day after launch, less than 25% were positively identified after five days. It took nearly four months for all payloads to be added to the space catalog, and even a year after launch, nine satellites had not been positively identified by name.

Instead, what if each of these satellites were equipped with GPS transponders? How quickly could all satellites be positively identified after deployment? A subset of 59 satellites from this launch were simulated starting within 6 kilometers of each other with no other *a priori* information besides a state vector for the launch vehicle. Two different GPS transponder CONOPS were simulated to assess positive identification capabilities: 1) every 30 minutes with 100-meter (1σ) gaussian noise and 2) every 10 minutes with 10-meter (1σ) gaussian noise. Deployment is a critical mission event, so the transponder would transmit more frequently than during average operations.

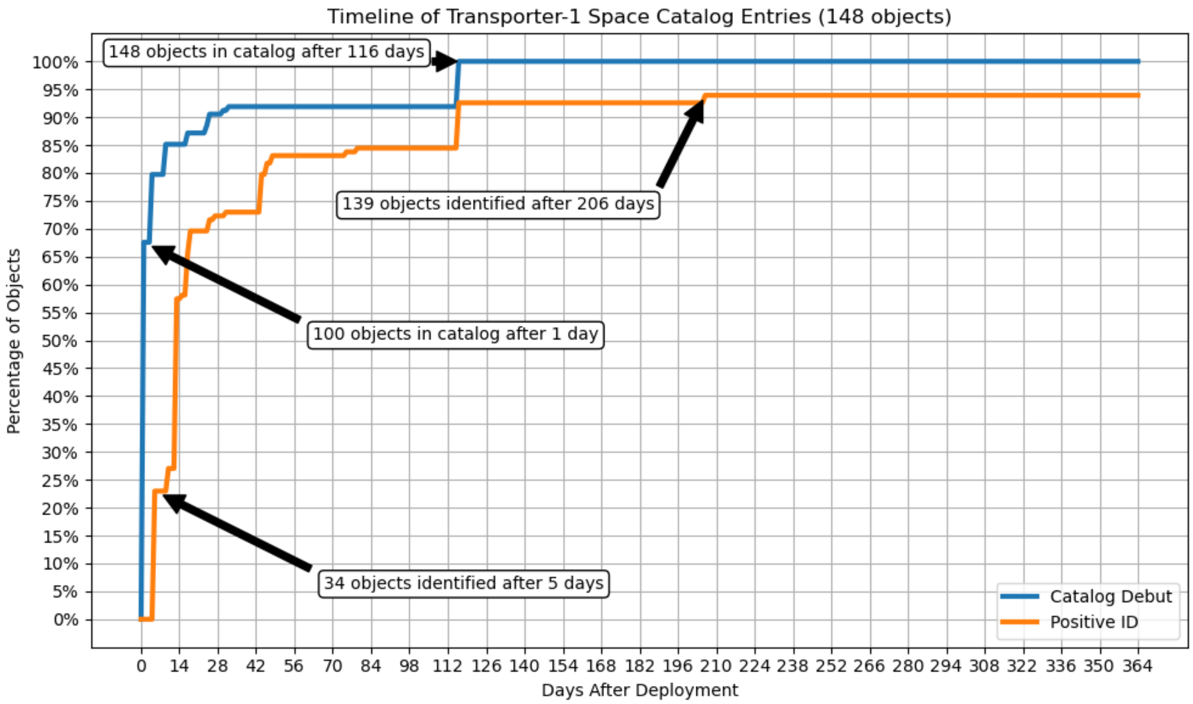

Fig. 6. Timeline of a Recent Rideshare Mission in the Space Catalog

Starting 30 minutes after deployment, each satellite's transponder would generate measurements on a regular cadence and transmit the data to a ground station. Satellite positive identification was assumed to occur when the covariance estimates for each satellite no longer overlapped with each other, so that each state could unambiguously be associated with a single payload. Figure 7 shows that both transponder CONOPS enable > 95% of the payloads to be identified within 90 minutes of the initial GPS transponder data generation.

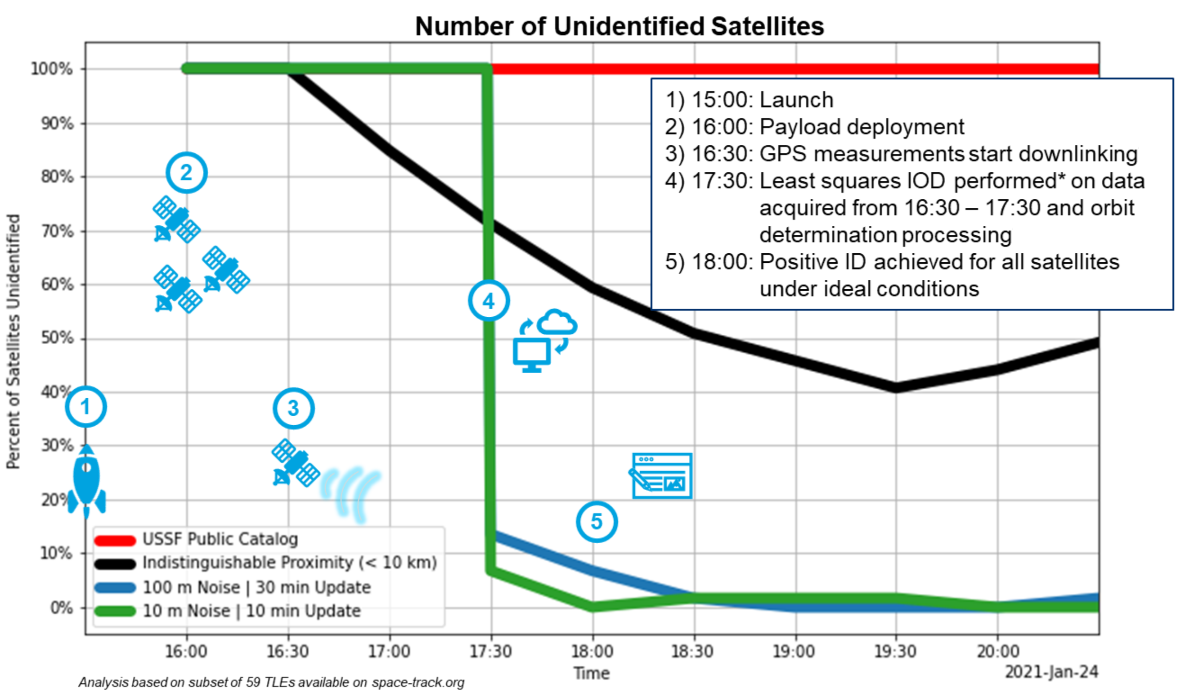

Fig. 7. Positive satellite ID achieved within 90 minutes with GPS transponder data processing

3.4 Custody of Maneuvering Satellites

Estimating accurate state vectors while satellites are actively maneuvering can be challenging using non-cooperative means of tracking. Multiple satellite trajectories containing maneuvers of different magnitudes, directions and durations were created using STK. GPS measurements for these trajectories were simulated using ODTK with different measurement cadences and measurement uncertainties to assess the effectiveness of different CONOPS. The position uncertainty during and after the maneuvers was generated to show the impact of GPS transponder data. Results from a 50 m/s impulsive maneuver and a 5 m/s low thrust (30 hrs. to complete) finite maneuver are shown in Figures 8 and 9. Maneuver estimates were simulated assuming a 10% maneuver magnitude uncertainty and 1° pointing uncertainty for the maneuvers. GPS position measurements were simulated with gaussian noise varying from 10 m to 1000 m 1σ at different cadences varying from every 10 minutes to once per day.

Processing position measurements more than every 12 hours resulted in divergence during the estimation process and yielded poor estimation results. In all cases the position uncertainty decreased close to steady state within four to five measurements. Even a transponder with a poor GPS fix providing 1 km accuracy measurement every 90 minutes can provide sub kilometer tracking accuracy throughout a low thrust, long duration maneuver as shown by the green curve in Figure 9.

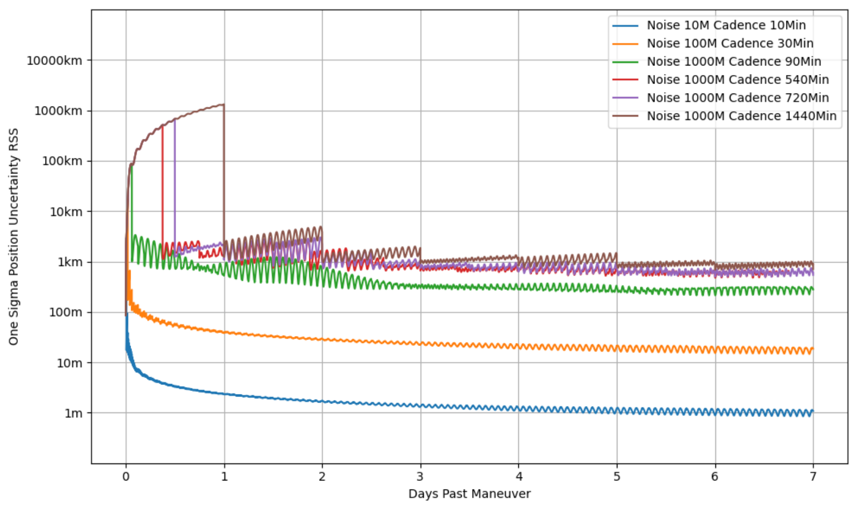

Fig. 8. Position Uncertainty Recovery from 50 m/s Impulsive Maneuver

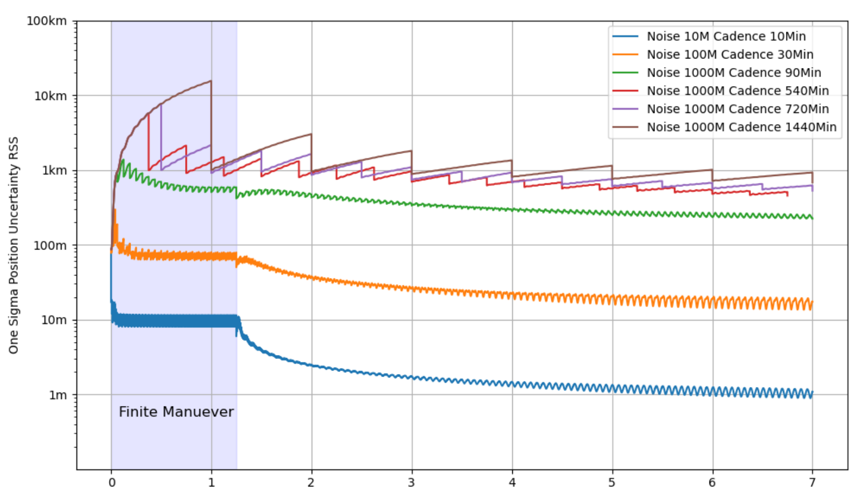

Fig. 6. Position Uncertainty Recovery from 5 m/s Low Thrust Finite Maneuver

3.5 Other Use Cases

There are also more experimental use cases that could be of value depending on the circumstances. For example, it is well known that the prediction of reentry of a naturally decaying satellite is exceedingly difficult to accomplish with any degree of precision. Typically, the uncertainty associated with such predictions is ± 20% of the “time to go”, or the time between element set epoch and the reentry prediction epoch. This translates to several revolutions around the Earth only one day prior to reentry. The dissemination of timely reentry warning is challenging for any land, air, or sea assets that could be within the debris footprint. Not only do transponders provide more frequent and higher quality data, but they could quickly flag attitude/tumble changes that are critical to generating accurate predictions. Furthermore, an onboard inertial measurement unit could also be triggered to provide near-real-time warning of the initiation of a terminal reentry phase of the flight and relay such data to salient government agencies to provide appropriate terrestrial warnings.

4. HARDWARE DESIGN

While there are other approaches to designing a GPS transponder [17] [18], Lockheed Martin has taken an innovative approach to streamline the transponder design such that the drawbacks listed in the previous section are minimized for potential hosts including cubesat operators.

4.1 Lockheed Martin’s Early Prototype Design

The Lockheed Martin prototype is comprised of mostly commercial-off-the-shelf (COTS) components to control cost. The ITAR[4]-restricted GPS receiver is interchangeable with an inexpensive, hardware-identical, and inexpensive version that is appropriate for ground tests and mockups if desired. The radio is in the 433 MHz amateur radio band and is designed to be ultra-low cost for hobbyists. The radio hardware and software are compatible with the TinyGS open-source satellite network [19] which grants access to well over one thousand ground stations located globally. The radio is specially designed for Internet of Things (IoT) applications and leverages Long Range (LoRa) technology which can close the link on a low data rate transmission over very long distances at very low power levels. The prototype transponder can be powered by either the host satellite or by photovoltaic cells attached to the top of its enclosure. The device has a mass of a around 150 grams and is approximately 9 x 8 x 1 cm although those dimensions are planned to be reduced with subsequent prototypes. The device is resilient to single event upsets via the ability to reboot every few hours which clears such errors. The device also contains additional sensors such as a smartphone-grade IMU[5], light sensor, and barometer. See Figure 10 for an overview of the subsystems involved. The cost of component parts is less than $1,000.

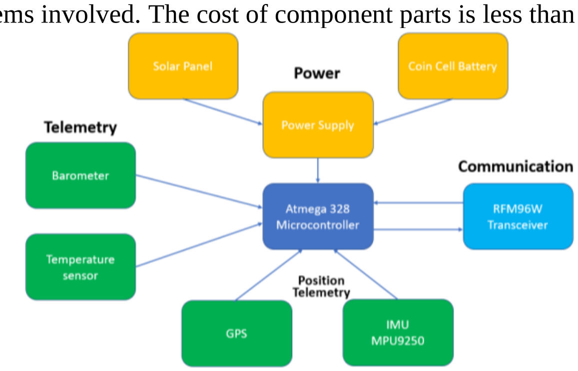

Fig. 10: GPS Transponder Subsystem Diagram

[4] International Traffic in Arms Regulations (ITAR) bans the export of items that could be used by third parties to create weapons. For GPS receivers, ITAR restrictions apply for conditions where the receiver is either above 60,000 feet in altitude or moving at a ground speed greater than 1,000 knots. Both conditions are met for RSOs thereby requiring an ITAR-restricted GPS receiver and the associated recordkeeping.

[5] Useful for detecting changes in tumble/rotation rates as well as acceleration due to drag, maneuvers, or debris collision.

A surprising amount of effort was needed to develop thoughtful inhibits for the prototype transponder. Traditional inhibits include a “Remove Before Flight” tag (included in this prototype), and various burn wires or mechanical switches that are released at deployment. In the case of this prototype, the engineers needed to assume that they would not have access to the host’s deployment device. They could not rely on the host to send a “wakeup” signal to the transponder[6] since infant mortality rates are uncomfortably high and the transponder must operate even if the host is dead on arrival.

The solution was a combination of sensors that determine when the spacecraft is deployed within the space environment. A simple barometric sensor was used to confirm the satellite was in the vacuum of space while a light sensor must also be triggered to confirm that the host satellite is not stowed within a deployment mechanism. Finally, a software timer is triggered once the previous two inhibit conditions are met to allow for cases where the deployment mechanism exposes the transponder to sunlight. In this case the timer would be set to slightly longer than the planned timeline for satellite deployment and is mission configurable. Finally, all of these inhibits, except the remove before flight pin, can be bypassed by the host satellite should it be alive and able to send commands directly to the transponder via digital communication over a small, optional, wiring harness. During the transponder’s active mission, the radio will never transmit unprompted but first must receive an interrogation signal from the ground network. This is a form of inhibit that ensures a malfunctioning transponder will never become an unstoppable/irreparable source of RF interference.

The core of the Transponder design lies with power management techniques. There are three different modes that the Transponder operates in with different power footprints:

- Normal Mode: The GPS Transponder wakes up, calculates a GPS fix, and listens for a radio interrogation command at a regular and rapid cadence on the order of every few minutes. This state is triggered either when the battery is almost full or when the Transponder is receiving about one watt of power from the host vehicle. Since the Transponder is experiencing a power surplus it is very active in this mode.
- Survival Mode: This mode is triggered either when the host vehicle is not providing power or when the Transponder’s battery charge falls below a given threshold (say 75%). In this case the Transponder will spend more time in a low-power sleep mode and increase the duration between GPS fix generation. It can store a time series of GPS fixes in a buffer and decide to transmit only when it has calculated that it has enough energy to successfully do so. Survival mode will become progressively more restrictive as the reserve energy in the battery approaches a zero state of charge. The philosophy is that sporadic data generated/transmitted every few hours/days is better than nothing.
- Emergency Mode: This mode is triggered when the GPS Transponder has sensed a “concerning event” that is so unusual it favors rapid data generation/transmission over self-preservation. This mode would typically be triggered by an unusual reading in the IMU indicating a debris collision event has occurred, a component of the satellite exploded, or the satellite is in the final stages of atmospheric reentry. In these situations, priority is placed on rapidly waking up, generating GPS and other sensor data, and transmitting upon the earliest opportunity.

4.2 Electronics Package

The entire hardware package is integrated in a custom printed circuit as pictured in Figure 11. The board is enclosed within a modest aluminum structure to provide a moderate degree of radiation shielding and a surface to mount the solar panel and antenna. The populated circuit board has a mass of 30 grams and consumes around one watt of power on average. The processor is a standard ATMEGA 328P and is typically programmed using the Arduino IDE.

[6] A “wakeup” command from the host will still activate the transponder. It simply is not relied upon as the only activation option.

Fig. 11: Lockheed Martin's GPS Transponder Circuit Board (Left) and Prototype Transponder (Right)

5. GROUND SYSTEM

As stated earlier, the goal of the GPS Transponder is to be as simple, inexpensive, and low SWaP as possible to minimize the impact to the host while still offering superior-quality data. The LoRa transceiver is constructed following the instructions provided by the TinyGS system [19]. TinyGS was selected due to its open-source nature, inexpensive design, and access to a large scale of ground network terminals. Construction of a single ground terminal is all that is required to participate in this ground network – our station is named "GriffinStation" and is located just outside of Pittsburgh, PA, as shown in Figure 12.

Data received by any given ground station is automatically shared with every other ground receiver via the internet. In this way, the construction of a single ground receiver permits the use of several hundred ground sites spread across the world. If the host is uncomfortable with sharing their transponder data on the internet, the data can be encrypted.

This technology allows for seamless transition as the number of on-orbit transponders grows. Initially, the TinyGS system offers an ultra-inexpensive option for supporting a few dozen satellites. As demand increases, it is expected that a separate but similar system, based upon the TinyGS approach, would be implemented to support many satellites and the associated increase in network traffic.

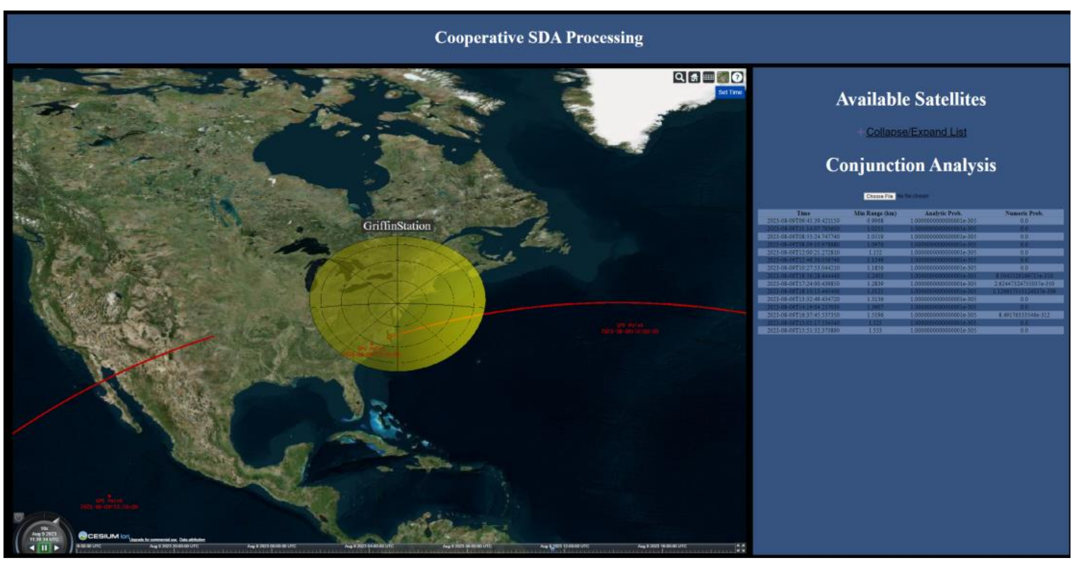

Fig.12: Griffin Station Data Display Screenshot

6. FUTURE WORK AND SUMMARY

6.1 Future Work

There is a great deal of additional technical and non-technical work to further develop this concept. On the technical side, a further iteration of prototyping is needed to refine the device, improve resiliency, lower cost, improve packaging, and so forth. A first flight test would be warranted to demonstrate the concept and conduct operational tests. Further exploration of interesting applications of the GPS transponder are also of merit. For example, there is ample opportunity for hosted transponders to aid in the recovery or post-mortem of satellites that prematurely fail on orbit. The transponder could be used as a back-door recovery device via a "reboot" command relayed through its radio. It could also listen and store host state-of-health information which may be accessed and downlinked to the ground during times of anomalous host activity which is often unavailable with current operations. The transponder could be engineered to act as a dead man switch that triggers a separate de-orbit device in the event of a premature host satellite failure. It could also be used to monitor satellites capable of rendezvous and proximity operation activities as this capability is dual civilian and military use and would be of interest to spacefaring nations.

There are also many non-technical details to work out when attempting to set up a ubiquitous system of space transponders. A detailed business case needs to be formulated to ensure the approach can be self-sustaining from an economic perspective. Coordination issues also arise at the national and international level. Using precise positional information to screen for conjunctions and other operational hazards requires information sharing with some (inter)national clearinghouse and all the associated mechanics involved with data curation, pedigree, integration, and satellite operator communication.

6.2 Summary

The space environment continues to evolve in complexity with increased congestion and contention of this critical domain. Significant improvements to spaceflight safety can be obtained through widespread adoption of small, inexpensive, and low-SWaP transponder devices. It has been demonstrated that such hosted GPS transponder devices can be made inexpensively and offer substantial advantages over other available methods of Space Domain Awareness (SDA) in line with the modern approach in the aviation and maritime domains. This approach offers one to two orders of magnitude improvement in precision orbit knowledge relative to traditional methods. This benefits conjunction assessment, multi-satellite deployments, positive identification issues, autonomous maneuvering, and a wide array of other operational challenges related to rapid and accurate SDA.

7. ACKNOWLEDGEMENTS

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