GNSS with Satcom Networks to Dramatically Improve Space Situational Awareness

PrincipalAuthor: Charles F Radley(1), Thomas M Eubanks(1)

(1)Space initiatives Inc, 572 Burlington Ave NE, Palm Bay, Florida, 32907 U.S.A.  cfr@space-initiatives.com

ABSTRACT

- With current technology prediction errors in Low Earth Orbit (LEO) are frequently greater than the estimated separation distance between objects undergoing conjunction. Current predictions are thus frequently false alarms, and real collisions have been missed resulting in expensive losses. The February 2009 collision between the active Iridium 33 and the inert Kosmos-2251 was predicted to have a miss distance of 584 metres, but this was less than the error, and so the prediction was ignored, and the actual collision and destruction of Iridium-33 came as a complete surprise.
- As well the inherent errors in existing ground-based measurements of spacecraft, a significant problem for satellite tracking and collision prediction is the lack of coverage of ground stations. Less than 20% of the Earth’s surface area is suitable for siting ground stations [plus a limited number of isolated island sites].
- For example, for BDS [a Chinese navsat system], inadequate ground stations and the poor distribution of the network have limited the accuracy of BDS orbit determination [1].
- The increasing flux density of orbital objects is driving the community to improve orbital determination of all space objects, or as many as possible. Recently studies have determined that collision prediction accuracy can be greatly improved for spacecraft who carry on board GNSS transponders. We are developing a system using autonomous tracking devices (an application of our Pixie nanospacecraft) which are attached to a host satellite and communicate accurate location data autonomously of the main spacecraft. The data collected is sent to a central Earth station via an established satellite relay from the device. This intersatellite link is available continuously without regard to the position of the host satellite relative to the Earth’s surface (e.g., whether it is over regions with no tracking stations). Consequently, positional and velocity data of the host satellite is available without gaps, allowing greatly improved knowledge of the orbital parameters and position of the host satellite versus existing methods. The attached device contains several sensors including a GPS or GNSS receiver, which allows determination of the host spacecraft position accurate to within 10 metres or better, compared with one kilometre (or worse) for conventional ground station methods. The improved knowledge of spacecraft position will allow greatly improved predictions of collisions between space objects, by orders of magnitude versus the existing technology, and yet is cheaper than the less accurate methods using ground stations.
- It is difficult to quantify the economic damage due to space object collisions since commercial operator might not publish all collision events, preferring to keep them confidential. Nevertheless, it is widely agreed that economic impact can be severe. In addition, damage to the International Space Station is a major concern, it is the largest “target”. Furthermore, it is becoming increasingly difficult to correctly identify the increasing number of satellites. There have been recent launches of multiple spacecraft on a single vehicle in which radio contact was not established with many of the objects, and hence it has become impossible to identify them. This is a concern for several reasons, including liability. Attaching Pixies will resolve this problem.
- Over time, the improvement in knowledge of space object position by installing the Pixie black boxes will reduce the number of collisions by improving positional knowledge accuracy and reducing the number of false alarms. Collision avoidance maneuvers can be planned and executed in a more controlled and reliable manner, reducing expenditure of propellant. Once Pixies have been successfully demonstrated then it is entirely possible that the international community could mandate the use of Pixie black boxes to be attached to all spacecraft, in a similar manner than Flight Data Recorders and Cockpit Voice Recorders are mandated on most passenger aircraft.
- The large quantity of new more accurate space object positional data generated will facilitate new methods for organizing large numbers of rapidly moving space objects. New algorithms will be developed to optimize multi-dimensional positional knowledge and situational awareness. Artificial intelligence would be appropriate to leverage the new data pool. Improved conjunction predictions will be facilitated, and
probabilistic risk assessment methods should be applied to assist decision making, e.g.
- when to initiate collision avoidance maneuvers. Potentially this decision making could be automated.

1 Problem description

1.1 Inaccuracy of TLEs

Table-1: Known Spacecraft Collisions versus Predictions

<table>
<thead>
<tr>
<th>Date of Collision</th>
<th>First Object</th>
<th>Second Object</th>
<th>Predicted Miss</th>
<th>Predicted Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>Cosmos-1275 debris</td>
<td>Cosmos-1934</td>
<td>512 metres</td>
<td>1 in 50,000</td>
</tr>
<tr>
<td>1996</td>
<td>Cerise</td>
<td>Ariane-1 Debris</td>
<td>882 metres</td>
<td>1 in 2 Million</td>
</tr>
<tr>
<td>Feb 2009</td>
<td>Iridium-33</td>
<td>Cosmos-2251</td>
<td>584 metres</td>
<td>1 in 500,000</td>
</tr>
</tbody>
</table>

Source: Thompson, R, “A Space Debris Primer”, Crosslink, Fall 2015

There has never been a single instance of a successful prediction of a collision of any two spacecraft. Nevertheless, collisions have occurred (e.g. Table-1) and the predictions of those conjunctions were significantly in error. The US Government Stratcom publishes collision probabilities which do not have confidence level assigned to them, and without statistically meaningful confidence levels, the probabilities published mean very little. As far as we can determine the algorithms and methods for deriving the predicted miss distances have never been published, and the computational methods have never been subjected to any independent review nor validation. Yet these data are widely used by the community of spacecraft operators.

The warnings of collisions predicted by the widely used sources are almost entirely false alarms. They are most likely resulting in a large number of unnecessary COLA maneuvers, which is burning up a great deal of valuable propellant and reducing the commercial lives (and revenue generation) of many spacecraft.

There is no definitive data on the accuracy of the Stratcom conjunction predictions, however anecdotal reverse analysis suggests that the one-sigma error is of the order of two kilometres. This error will vary according to a number of factors, such as uncertainty in air-drag coefficients, uncertainty in atmospheric density, and the time since the last positional fix measurement.

There seem to be plans to improve the accuracy of the predictions by various ways, but most of these involve high capital costs such as improving ground-based radar, lidar and optical telescope assets. There is also a plan for Space Based Visual Sensors for monitoring deep space and geosynchronous objects [3].

Another problem which is currently unsolvable using conventional methods, is the identification of multiple cubesats. Cubesats have standardized form factors, e.g. 1U, 2U, 3U, 6U etc. Cubesats with identical form factors cannot be uniquely identified by radar signatures, since they appear identical. This has been a problem on several recent launches. From an Electron Launch from New Zealand five cubesats remain unidentified (NMTSat, CeReS, CubeSail, RSat-P, ALBUS - December 2018) [2]. In 2017, eight cubesats deployed form a Russian Soyuz remain unidentified, and from a Falcon-9 launch from Florida (December 2018, 12 cubesats unidentified) [4]. In each case multiple cubesats were deployed from the vehicle, and they many failed, an infant mortality problem. As a result, it has been impossible to identify which spacecraft was which. This in turn has impeded efforts to recover the spacecraft, since the owner-operators have no idea which of the spacecraft to point their antennas towards.

Andrew Abrahamson at Aerospace corporation published a novel approach which will greatly improve the accuracy of conjunction predictions for suitably equipped spacecraft [5]. The paper includes data which shows a considerable improvement in the accuracy of prediction of collisions for a spacecraft equipped with a GNSS (e.g. GPS) receiver, versus a non-cooperating spacecraft. He considers a scenario with covariance of 10 metres (1σ) for the GNSS equipped spacecraft, versus 100 metres (10σ) covariance for the non-cooperating spacecraft. For a predicted miss distance of 50m, the probability falls from approx. 5E-04 to 1E-07, a factor of about 5,000 improvement. For large miss distances the accuracy improvement is considerably better, and literally goes off the chart in the Figure-4 of that paper.

Kelso et al. performed a comparison of cooperative and non-cooperative tracking data for Global Positioning System satellites and found that cooperative tracking data reduced mean positional error by 88 percent.[6]
1.2 TLE aging.

Kelso informed me the following (slightly edited for brevity): “TLE age matters for several reasons. First, a TLE is an estimate with error. Some of that error is in the observations and some is in the force model mismatches. There can also be error in the process of deriving an estimated orbit from fitting the observations to the force model. All errors grow with time.

There are lots of missing forces in SGP4. Drag modeling is very limited and not dynamic and solar radiation pressure is non-existent. And there is zero accommodation for maneuvers (which can be both intentional or the result of changes in attitude).

How susceptible a particular satellite is to these errors depends on things like size (bigger objects are easier to observe), mass (more massive objects are less susceptible to drag and solar radiation pressure), whether the spacecraft is operational (which means it might maneuver and can control attitude), and what type of orbit. These factors vary satellite to satellite and day to day and should be assessed according to mission objectives.

TLEs should be less than a day old and typically are for many—about 1,450 of the 2,200 active satellites (see https://celestrak.com/NORAD/elements/active.php). 18 SPCS updates to try to keep the difference between the observations and TLE predictions within 5 km for LEO and 50 km for GEO 90% of the time. When the age starts going up, one should expect to see accuracy degrading, particularly for conjunction assessment. We advise whenever TLE age rises above 2 days so that operators can look at how that affects accuracy for their missions (see https://celestrak.com/NORAD/elements/history.php)”[7].

Informal discussion with community stakeholders highlights the following: in 2014 Stratcom TLE were improved by using a new version called EGP TLEs, at least one user has reported order of magnitude improvement in accuracy, however there are reports that 5km errors are still commonplace. Furthermore, some claim that the TLEs are inherently limited and not a valid basis for accurate conjunction predictions, and that a full ephemeris (with state vectors) with covariance is preferable. Furthermore, some claim that TLEs which are more than 2 days old are essentially useless for predictive conjunction analysis.

2 Proposed Solution

At Space Initiatives Inc we are developing a system for cooperative tracking by using autonomous tracking devices (an application of our Pixie nano-spacecraft) which are attached to a host satellite and communicate accurate location data autonomously of the main spacecraft. The data collected is sent to a central Earth station via an established commercial satellite relay from the device. This intersatellite link is available continuously without regard to the position of the host satellite relative to the Earth’s surface (e.g., whether it is over regions with no tracking stations). The additional of a continuous downlink (via commercial network) is a significant enhancement over the design proposed by Abrahamson which relies on ground stations. Most of the commercial networks were designed and built to support terrestrial users and not to support spacecraft. Nevertheless, it has been found that they work adequately for spacecraft in practice. A large quantity of data has been accumulated by at least two satellite operators, Globalstar and Iridium which demonstrates that adequate data links can be established with minimal outages. These data have not been published and indeed have been provided to the author under non-disclosure agreements, so cannot be discussed in detail in this open paper. We also had discussion with one other commercial satellite operator who has successfully demonstrated intersatellite links but cannot to disclose their identity at this time.

In the case of Iridium, at least two spacecraft types have demonstrated the method, i.e. the NASA Thedsat, and the Tokyo University EGG spacecraft. In the case of Globalstar, a series of “Thinsat” spacecraft have operated using simplex downlink via Globalstar.

Using such commercial downlinks has several advantages versus the more common method of using ground stations. Primarily, the downlink is available 24/7 with minimal gaps or outages, versus a single ground station which can only view any given LEO spacecraft for a matter of minutes (less than an hour) per day, and on some days never. A large expensive network of many ground stations is required to achieve coverage adequate for accurate positional tracking, and even then, it is impractical (prohibitively expensive) for commercial operators to put ground stations in most of the ocean areas which cover most of the Earth’s surface. While low cost leased ground tracking networks are available at UHF they appear less available at other frequencies.
By using the Pixie type technology with GPS data continuously downlinked to a common repository on a 24/7 basis, the problem of lack of data and out of data will be greatly mitigated. Continuous positional knowledge accurate within 10 metres will become routine, we speculate that the probability of collisions will reduce by orders of magnitude (quantitative analysis has not yet been performed). With the proliferation of tens of thousands of spacecraft in LEO, predicted collisions probabilities are becoming alarmingly high, such as reported in the recent Amazon Kuiper constellation FCC filing. There is an urgent imperative for the community to invest in Pixie type technology, and for regulators to mandate such devices be installed and activated on all spacecraft. The additional cost of these devices and the associated data subscription costs are minimal compared to the respective overall spacecraft constellation system cost.

3 Future plans

Over a period of years, after releasing the initial MVP, SII has a roadmap plan to roll out a series of increasingly capable and sophisticated devices, with enhanced and augmented versions of the basic Pixie product. For example, an on-board Chip-scale atomic clock (commercially available) will allow on board calibration of GPS timing signals received and increased accuracy.

In addition, on board differential GPS measurement will also allow increased accuracy.

We will try to educate regulators of the value of the Pixie system.

Further analysis is needed to quantify the benefits of Pixie technology.

Currently it will only be possible to attach Pixies to new satellites and upper stages which have not yet been launched. Despite that, in the longer term we would like to develop a system to retrofit Pixies and attach them to RSOs which are already in orbit. We feel this will be safer, easier and cheaper than trying to destroy or deorbit these spacecraft. Using chemical rockets to rendezvous with each of the many objects in orbit (requires very large delta-vee and propellant expenditure) is prohibitively expensive and therefore impractical. Some propellant-free options are available, especially promising is electrodynamic tether propulsion, which has been successfully demonstrated on a number of experimental missions in orbit and on sounding rockets. In this approach a reasonably long conducting tether (e.g. a few kilometers) passes a current in a loop generating a magnetic field which interacts with the Earth’s magnetic field and generates a controllable force.

Such an electrodynamic tether vehicle could over time maneuver to rendezvous with a large number of RSOs and attach Pixie devices to them. The RSO’s could be inoperative, and thus the Pixie footprint would be extended across a large population of RSO’s and significantly improve ability to accurately track these objects.
Fig. 1. Early Pixie Design Developed via Royal Observatory Belgium Subcontract for ESA/ESTEC AIM COPINS.

Fig. 2. Example of possible ISS Experiment.
4 Conclusions
Technology now exists for small devices which can be inexpensively attached to host spacecraft to achieve 10 metres positional accuracy (from on-board GNSS receiver) versus a few kilometres for currently available TLEs. Furthermore, the problem of TLE aging can be greatly mitigated by downlinking the positional data 24/7 via commercial satellite networks, which is also inexpensive, and in many cases cheaper than building and operating a network of ground stations. We expect this improvement in satellite ephemerides will be significant and result in greatly improved accuracy of conjunction predictions. The consequent reduction in false alarms will reduce the need for unnecessary COLA maneuvers which in turn will greatly reduce wasteful consumption of valuable propellant and prolong the lifetimes of the spacecraft. We suggest that the community of spacecraft operators and the government regulators in spacefaring nations should invest in such technology. The modest investment will have considerable benefits. The SII company has a roadmap of increasingly sophisticated enhancements to this technology.

5 ABBREVIATION AND ACRONYMS
18 SPCS - 18th Space Control Squadron
AIM – Asteroid Impact Mission
COLA – Collision Avoidance
COPINS - CubeSat Opportunity Payloads
EGP - Enhanced General Perturbations
GNSS – Global Navigation Satellite System
GPS – Global Positioning System
MVP – Minimum Viable Product
NDA – Non Disclosure Agreement
RSO – Resident Space Object
SGP4 - Simplified General Perturbations propagator – version 4
SSA – Space Situational Awareness
SII – Space Initiatives Inc
Stratcom – US Strategic Command
STM – Space Traffic Management
TLE – Two Line Element set

6 REFERENCES

6.1 Sample References


[2] McDowell J. Twitter.com, planet4589, “5 payloads from the last Electron launch (NMTSat, CeReS, CubeSail, RSat-P, ALBUS) have not been heard by their owners since soon after launch, so there’s no way to tell which tracked object is which cubesat”, March 4 2019.


