Commercial Space Situational Awareness – An investigation of ground-based SSA concepts to support commercial GEO satellite operators

Mark A. Skinner
Boeing LTS
Thomas M. Kelecy, Stephen A. Gregory, Joseph P. Toth, and Dennis Liang
Boeing LTS
Dean Yamanaka, Stan Kent
Boeing Satellite Systems, Customer Operations Support Center
Rodney Tjoelker and Dragos Margineantu
Boeing Research & Technology
Audrey L. Allison
Boeing Frequency Management Services
Christopher Heiberg
Boeing Space & Intelligence Systems

Abstract

The geostationary Earth orbit (GEO) satellite belt* is a unique "place" above the earth affording a continuous line-of-sight to satellite uplink and downlink stations. The volume defined by this belt is large, but available slots are limited.

During the course of the space age, this volume has become more crowded, as humankind has launched more and more satellites into this particular orbital regime, and satellites that suffered incapacitating anomalies and space debris have remained in the belt. The latter pose a hazard since they are uncontrolled, and with no capability for debris removal, the only way for satellite operators to avoid collisions with space objects is to maneuver. Knowing when and where to maneuver requires *space situational awareness* (SSA). Discussions with commercial satellite operators have led to the identification of a need for a targeted source of observations of active satellites, as well as space debris and inactive satellites, in this orbital regime.

This paper reports on an investigation of the applicability of well-established SSA approaches to support the interests of commercial GEO satellite owner-operators. We identify prominent issues and concerns of the commercial satellite community and explore ground-based SSA methods to address these interests.

*In this work we will refer to the geostationary *ring* as the altitude at which the orbital period exactly matches the rotation of the earth, with zero eccentricity and zero inclination, such that the object appears exactly fixed in the sky from an earth-based observer, and the geosynchronous *belt*, as, similarly to the geostationary ring, that volume where the orbital period is almost synchronous with the rotation period of the earth, and the inclination and eccentricity are not constrained to being zero. Though this implies an unlimited region for geosynchronous objects, the limitation of launch geometries and perturbations constrain the geosynchronous objects to a "band" around the earth.

1. Space debris near GEO

The year 1963 saw the dawn of the commercial satellite era with the launch of the first GEO satellite, Syncom 2. Geosynchronous satellite communications have since provided many benefits to mankind. However, "as a result of past activities in space, a massive amount of space debris – non-functional and uncontrolled objects – has been left in Earth orbit and this poses a serious challenge to the sustainability of outer space" [1]. Fig. 1 below illustrates the concentrations of tracked, man-made objects in Earth orbit, with a concentration of objects evident in the neighborhood of the GEO ring.

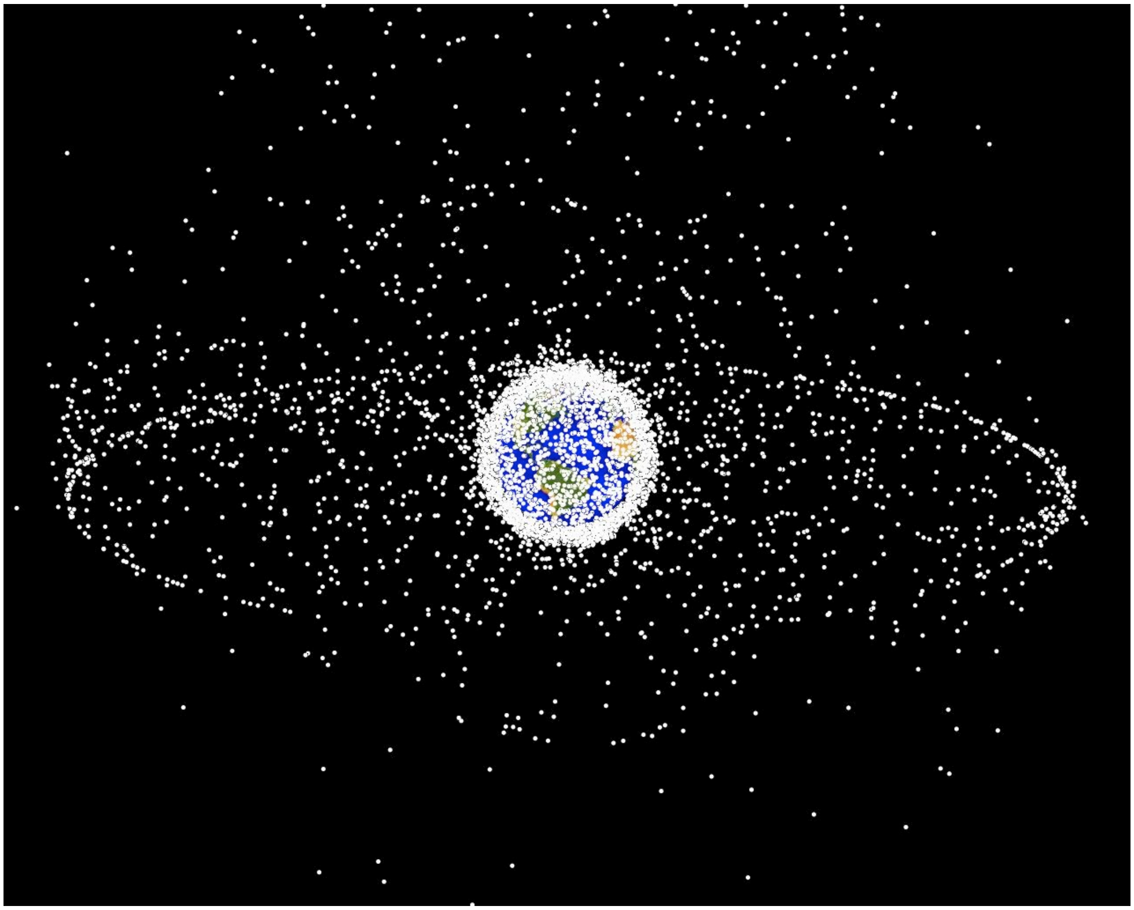

Fig. 1. Computer generated images of objects in Earth orbit that are currently being tracked. Approximately 95% of the objects in this illustration are orbital debris, i.e., not functional satellites. The dots represent the current location of each item. The orbital debris dots are scaled according to the image size of the graphic to optimize their visibility and are not scaled to Earth. This image was generated from a distant oblique vantage point to provide a good view of the object population in the geosynchronous region (around 35,785 km altitude). Note the larger population of objects over the northern hemisphere is due mostly to Russian objects in high-inclination, high-eccentricity orbits. Image and caption courtesy of the NASA Orbital Debris Program Office [2].

One source of larger debris in the GEO ring is the population of non-functioning payloads and upper stages that were placed into the GEO ring, but were not able to be disposed of into orbits higher than GEO (as is the current practice) upon their end of life. These objects are trapped in or both of the two gravitational wells ("pinch points") that are caused by the gravitational anomalies (more specifically, perturbations related to the tesseral components of the spherical harmonic expansion of the earth gravitational model) of the Earth at the equator [3]. Objects that are trapped in one (or both) of the wells oscillate back and forth, passing through the wells, the period and amplitude of the oscillations being dependent on the specific orbital geometry. The objects thus trapped are primarily defunct payloads, including the first commercial GEO communications satellite, Intelsat-1 F1 ("Early Bird") [4]. Table 1 [5] summarizes the trapped object population. Fig. 2 shows, for the western pinch point (105° W), how the number of trapped objects has increased over the decades.

Table 1. The oblateness of the earth causes the existence of two stable gravitation wells [3] which 'trap' non-station-kept objects in the geostationary ring. The trapped objects are mostly old payloads [5].

Characteristic	75° East Well	105° West Well	Trapped in Both Wells
<u>Payload</u>: Radugas (29), Gorizonts (9), Ekrans (8), etc	83	39	15
<u>Rocket Body</u>: Largely Proton-K Fourth Stages	17	0	3
<u>Debris</u>: 2006 Feng Yun and 1978 Ekran 2	2	0	0
<u>Total</u>	102	39	18

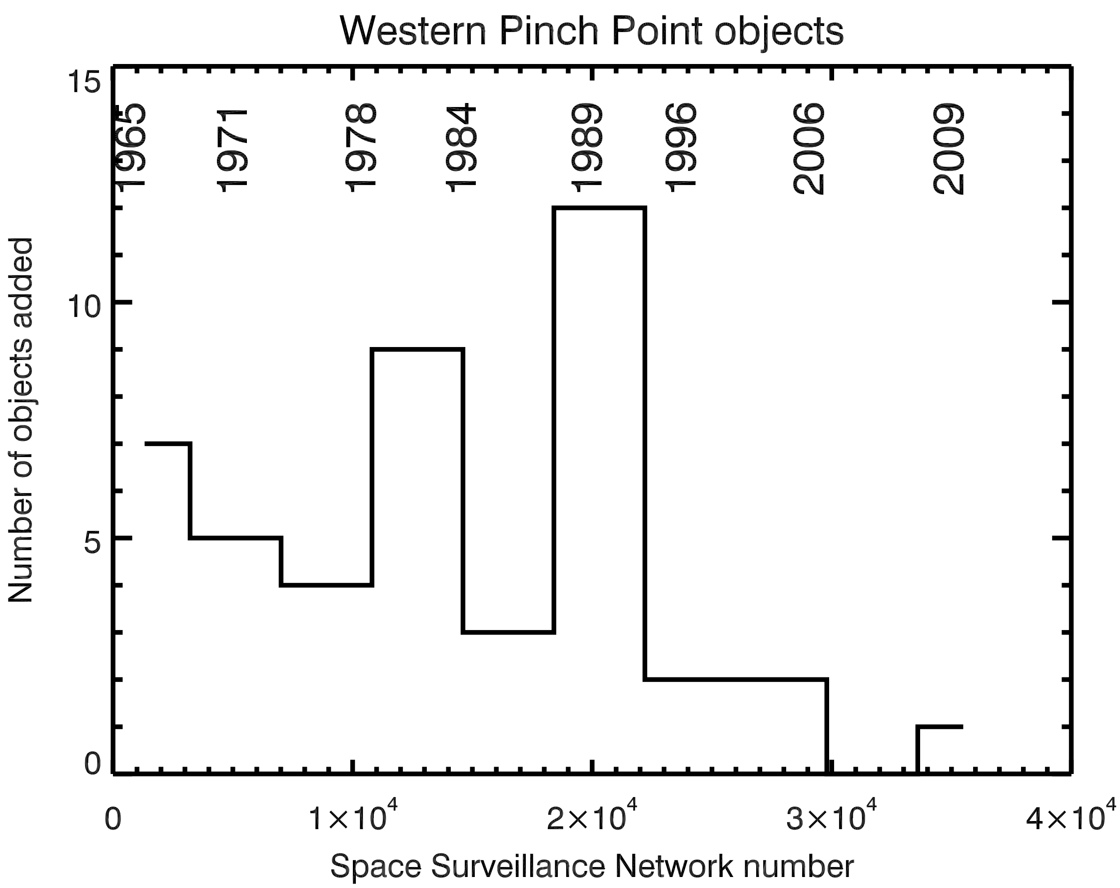

Fig. 2 shows how the number of objects trapped in at 105° W has increased over the years. About 40 objects are trapped and oscillate about the western pinch point [5]. The date (in years) for the launch of various objects is to be seen below the upper abscissa on the graph.

The trapped objects represent a variety of ages (~45 years) and sizes (up to a factor of 30 in size difference), as well as a number of manufacturers and launching states. As may be seen in Fig. 2, the trend has been for fewer objects to become trapped over the years, as operators follow improved “best practices”. However, the trapped objects will remain in GEO, and constitute a continuing threat to operational spacecraft.

Besides the larger (greater than a few square meters in cross sectional area) tracked objects found in the public domain catalog [6], observational campaigns estimate ~500 unknown, un-cataloged debris objects brighter than 18.5 visual magnitudes (about 29 cm in size assuming an albedo of 8%) in the geostationary ring [7]. This figure does not include high area-to-mass (HAMR) objects that drift through the GEO ring, nor does it include large station-kept satellites that are not included in the public catalog.

In addition to the objects enumerated above that exist in, or drift above or below the GEO belt, there is another class of objects shown in Fig. 3 that are also of concern. These objects have high area-to-mass ratios, and their orbital elements can change on time-scales of weeks to months by solar radiation pressure, which causes them to periodically pass through the GEO belt [8, 9,10,11].

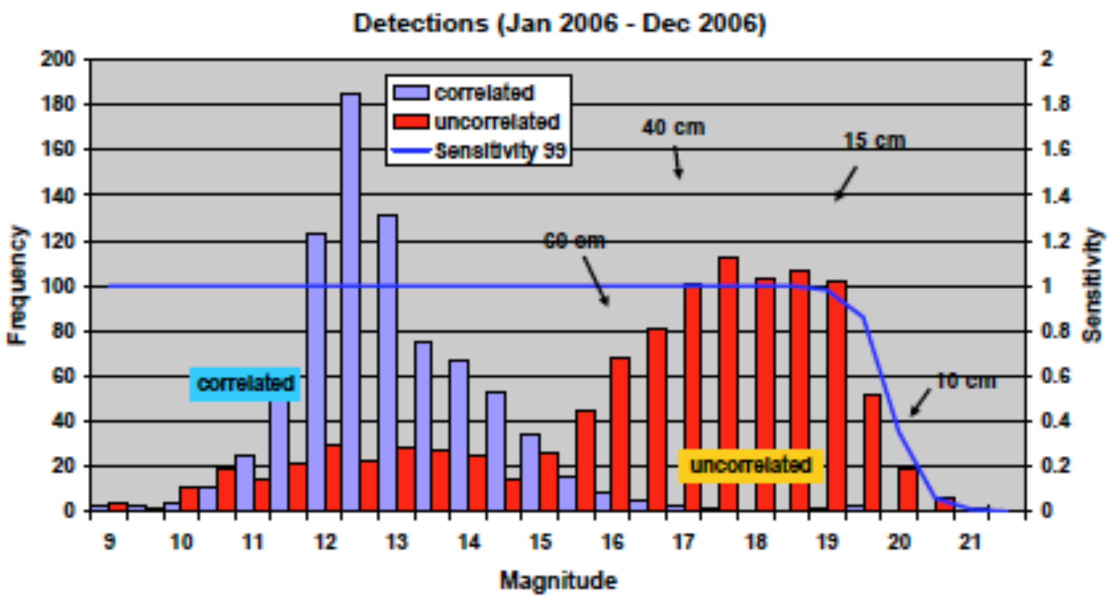

Fig. 3 shows the distribution of objects that can be correlated (in blue) with the public catalog, as well as a new population of faint objects that are not found in the catalog (in red). The right-hand distribution of uncorrelated objects contains the high area-to-mass (HAMR) objects [8].

As the HAMR objects are mostly visibly faint and far away, with orbital element values that change over shorter time-scales (weeks), it is generally difficult to detect and track them consistently; they are easily “lost”. Additionally, as the origin of these objects is unknown, and they cannot be traced back to a particular satellite launch, they are usually excluded from the public domain catalog [6].

2. Orbital congestion and interference.

The GEO belt is an important location for a wide variety of commercial and military satellite users, but is especially important for communications satellite users. The global satellite industry is a $189.5 billion industry. Of the more than 1,000 operational satellites in orbit, 54% are communications satellites (38% commercial and 16% military or civil government)[12]. Forty-two per cent of existing satellites are in a geosynchronous orbit [13]. As illustrated in Fig. 4, the geostationary orbit is densely occupied, particularly over land-masses where communications services are most developed or most sought after by paying customers. All satellites require access to radiofrequency spectrum resources to enable them to communicate with the ground to support their operations and their mission. Typically, commercial communications satellites utilize globally harmonized spectrum allocations in the L, S, C, Ku, and Ka-bands, portions of which have been allocated to satellite services use by nation states based on the decisions of various world conferences of the International Telecommunication Union (ITU), a specialized United Nations body that facilitates use of radiofrequency spectrum and orbital resources. Access to these resources is subject to coordination and notification requirements to ensure that other operators will not receive harmful interference from the proposed project [14]. Technology and physics dictate how close individual satellites can be to each other without causing interference. This is true not only with regard to physical proximity for avoiding collisions, but also avoidance of causing harmful interference to each others' radiofrequency communications systems.

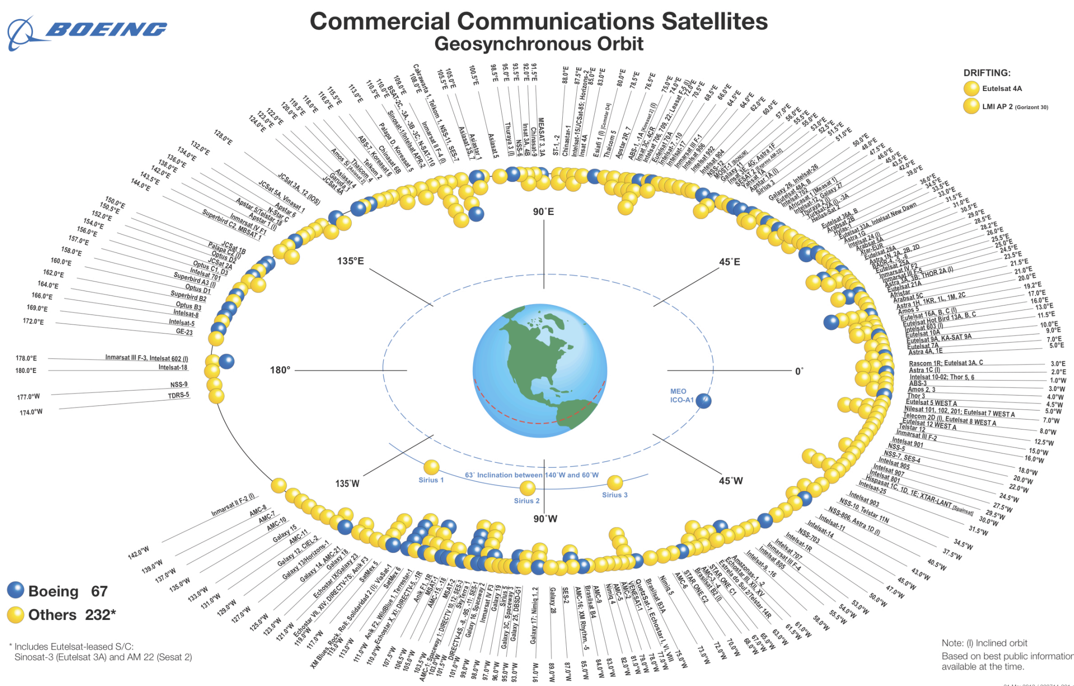

Fig. 4, an historical illustration of the distribution of commercial communications satellites in the GEO orbit [15].

This orbital congestion at GEO has led to a number of challenges. Chief among them is obtaining rights to an orbital slot to accommodate a new satellite in a congested region of the GEO arc. In addition to the orbital congestion resulting from the growing numbers of operational satellites is the fact that many proposed satellite projects that have been filed into the ITU's coordination process remain un-built, but are still maintained in the records as if real. This problem of "reservation of capacity without actual use" was once known as "paper satellites" or now, the "virtual satellite" problem. Administrations have filed coordination requests with the ITU for more orbital positions and frequency assignments than are actually needed, either for purposes of maximizing flexibility, warehousing resources for future use, frustrating competition, or, perhaps, trying to cash in.

Virtual satellites remain an endemic problem for satellite operators. Although the ITU has made great strides to address this, including adopting a cost recovery scheme that charges operators for the coordination and notification filings they make, the number of satellite filings continues to grow. The ITU and its members struggle to find workable and agreeable approaches to effectively managing access to the geostationary orbit. This "regulatory" hazard is one aspect to the difficulties with space operations in the GEO belt.

3. Satellite aging

A modern communications satellite is a complex system involving numerous subsystems that have finite lifetimes due to mechanical wearing (e.g., sun-tracking solar panel bearings, momentum wheels, etc.), limited propulsion resources (gas jets or similar), and carefully engineered thermal surfaces, which can be subject to degradation due to space "weathering" [16] or collisions with small debris.

Aging can be viewed as a continuous slight degradation of the performance of some surface (e.g., weathering of thermal surfaces), or it can be a discrete event, punctuated by "anomalies" (i.e., a critical component on the satellite fails). Even though satellite subsystems are instrumented with sensors that provide "housekeeping" data, not everything can be sensed, and sometimes the housekeeping data stream is unavailable. It is important that GEO satellites remain functional until the end of their useful life when they can be re-orbited into a "graveyard" orbit; deplete their stored energy sources; and be decommissioned. A satellite that is not property disposed of only becomes a new element of the debris picture.

4. Mitigation of the hazards

One method to reduce the probability of collision of satellites with debris objects is to remove the debris from the orbital plane of the active satellites. This concept, active debris removal, is being discussed and studied by the international community [1]. However, given the difficulty and expense of removing significant amounts of debris from the GEO ring, this is probably not a tenable solution for the near-term [17].

International efforts are underway to promulgate standards and best-practice guidelines for space actors [18], which will aid in decreasing the amount of orbital debris introduced into the GEO orbit. This will help to contain the debris growth problem. However, this will not prevent the possibility of an existing defunct payload shedding debris objects, nor will it prevent two larger pieces of debris colliding and creating a cloud of smaller debris objects. Activities of "rogue" nations, as well as unexpected failures and/or anomalies of operational satellites, also present potential hazards that must be anticipated and which commercial SSA must be prepared to handle.

The current strategy for active payloads to avoid collisions is to obtain orbit information about objects in space, and then to propagate the various orbits, and their uncertainties, forward in time, and to estimate the probability of collision between two objects (a conjunction assessment). This orbital information generally is sourced by USSTRATCOM and delivered on the Space-Track.org website [6], although a disclaimer does warn about the ineffectiveness of using the available two-line element sets on the public site for conjunction assessment. The Joint Space Operations Center (JSpOC) does offer more "detailed" data to satellite operators on request [6], but there have been reports of the unreliability of these detailed data [19, 20]. Additional factors adding to the unreliability of the current situation is that maneuvers (*e.g*., for station-keeping) are not accounted until after the fact [21], nor is the uncertainty in the prediction quantifiable in a statistical fashion.

Most satellite operators derive positions in space (orbital information) for their own geosynchronous satellites using a technique known as ranging. But, as the satellites are fixed, it is hard to determine an orbit using only data from a fixed ranging site, as the relative positions of the satellite and the ground site change by very little over time. Usually, satellite operators combine the ranging data with azimuth and elevation angle data from a high gain antenna that is 'locked-on' to the satellite's maximum signal strength. Orbital information gleaned in this fashion only has an accuracy of about 0°.01 (36 seconds of arc) [22]. This positional knowledge is adequate for a single satellite with no close neighbors for ordinary station-keeping purposes. However, for satellites on-orbit close to one another, it is possibly too crude a measurement for safety of flight. In these cases, a second, geographically distant ranging station is utilized to provide more accurate positional knowledge.

To enhance the quality and timeliness of satellite orbit information, a number of operators have joined together to form the "Space Data Association" (SDA) [23]. Its vision is to create a clearing-house for members to exchange information that would overcome some of the issues surrounding the *ad hoc* exchange that had evolved to that point in time. Fig. 5 illustrates the situation before the SDA was organized, and what tits eventual desired outcome would be.

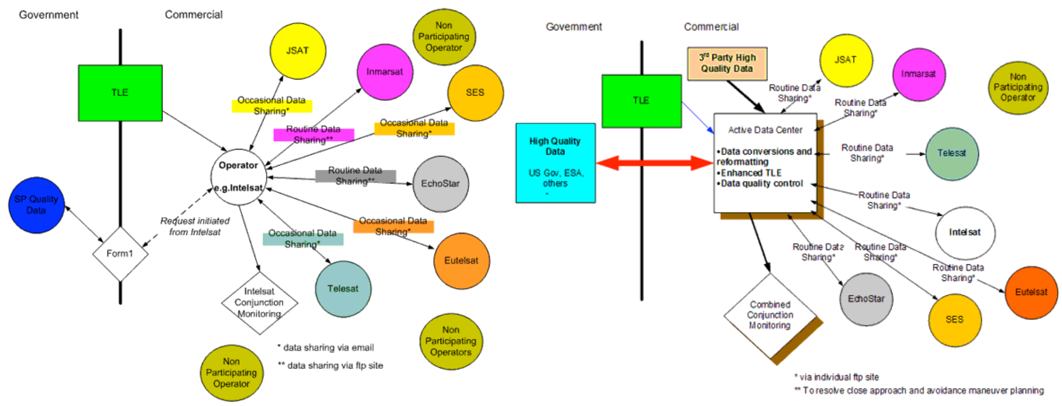

Fig. 5 shows the *ad hoc* sharing of satellite information before the founding of the SDA (left), as well as the vision for future sharing of data amongst various entities in the future (right) [21, 23].

How well the sharing model works is dependent on the accuracy and timeliness of the data to be shared, and in Fig. 5 this shortcoming is indicated by the unconnected nodes labeled "non-participating operators." In addition to the satellite operators that could potentially share orbital data but chose not to participate, there is the entire population of space debris previously described. Information on some of these objects may be supplied by the publicly available two-line element sets (TLEs), but with the same caveats as described above. A new entry point for information not currently available publically is the box at the top of the right hand side of figure 5 labeled "3rd Party High Quality Data."

One problem that the SDA does not solve, nor cannot solve, is the problem of the "virtual" satellites; are these fictitious entities "tying up" valuable GEO belt locations that could be utilized by real satellites? By virtue of the membership charter, member shared-data may not be used for regulatory purposes [24]. However, individual owner/operators may be assisted in dealing with regulatory issues with externally-provided observations of satellites and satellite "slots" in GEO.

An R&D effort is underway to better understand the requirements for 3rd party high quality data that would be of utility to satellite operators. Boeing has been in discussion with the SDA regarding how the data we would collect on active satellites and orbital debris could supplement and enhance existing operator ranging data, as well as conjunction assessment data. Field data (observations of satellites) have been collected to validate assumptions, and to understand what is and what is not effective [25].

Boeing's approach has been to couple a small commercially-available optical telescope with a sensitive, low-light camera, and conduct observations of "cooperative" satellites (such that we can receive accurate positional information for the time periods of our observations), as well as developing techniques to search for space debris in and near the GEO ring, but with unknown orbital parameters [26]. We have collected optical telescope data of sufficient accuracy (sub-arcsecond) to be useful in improving the covariance (uncertainties) of conjunction assessments [27], with a goal of making the uncertainties more representative of the prediction errors.

During the course of collecting positional information on space objects, a large set of photometric data on the satellites and space debris detected will also be obtained. If the data are properly calibrated, valuable information can be gleaned from the light-curves of the space objects [28]. Trend analysis of a long-term periodically-monitored photometric data set can assist in detecting changes to an operating satellite, an example of which may be seen in Fig. 6 [29]. These data sets, and changes that occur in the properties of the reflected light signal over time may also be useful with the resolution of any periods of anomalous behavior by the satellite, which may greatly aid the satellite owner/operator in understanding on-board operating problems. Additionally, similar light-curve analysis of the optical signatures of debris objects can reveal information about them, including area-to-mass-ratio, apparent sizes, and possibly material composition [9, 30, 31], which may aide in indentifying the material properties of the debris, and possibly their source of origin [10].

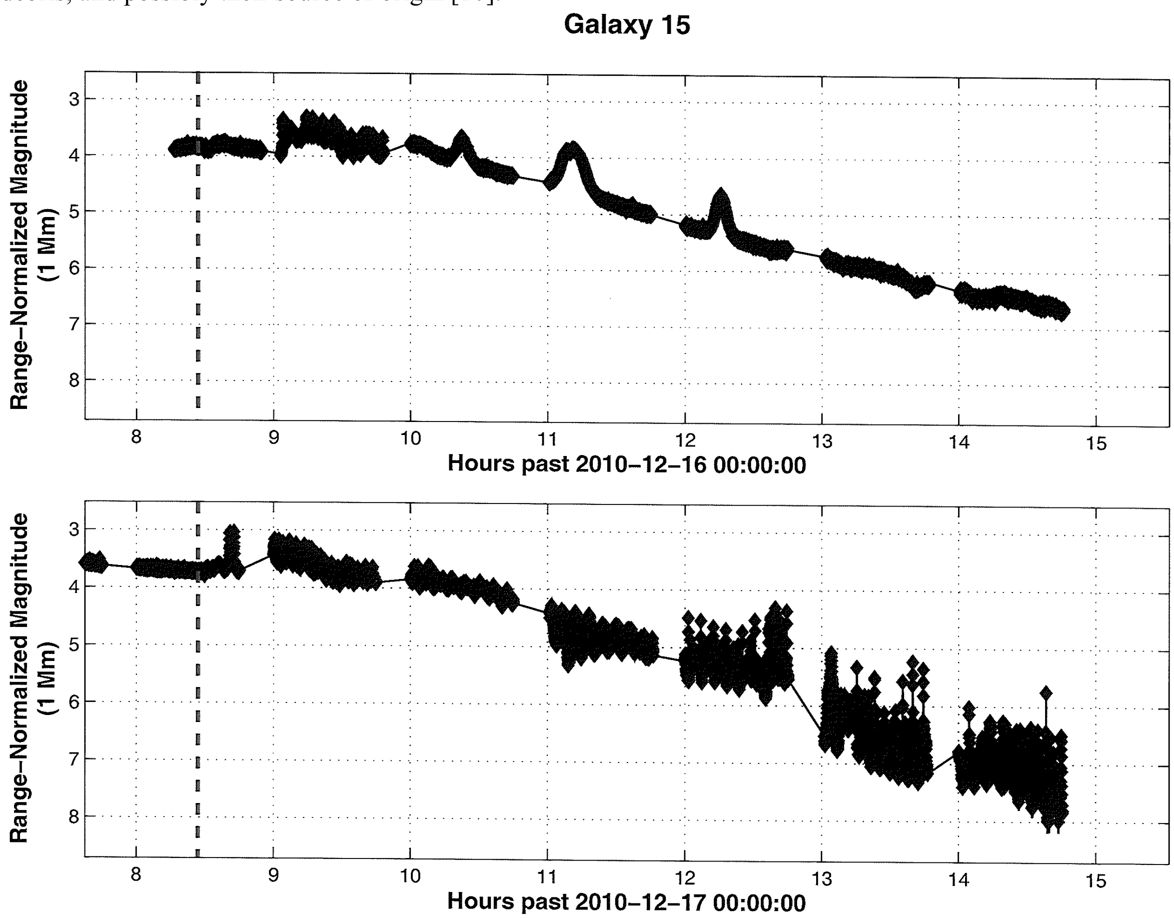

Fig. 6 shows the brightness signatures from Maui collected on Galaxy-15 prior to, and during, the loss-of stability off-pointing event. [29]

5. Summary

There exists a large number of uncontrolled space objects residing in and passing through the geostationary belt which are potentially hazardous to existing and future operational satellites in that orbit. Currently, there is no viable active debris removal effort to reduce the number of uncontrolled objects in these orbits, and current and near-term best practices for satellite operators and launching states only seek to minimize the number of new debris objects. Thus, the best strategy for a satellite operator is to seek the most accurate and current information on objects in the vicinity of its satellites. Previously, this was accomplished almost exclusively through data provided by the US Space Command. Recently, several satellite owners and operators have combined to share their knowledge of their own satellites, namely their current positions and anticipated maneuvers. To augment these current sources of satellite information, Boeing has conducted tests of satellite observing systems, to investigate whether it could provide information on operating satellites and space debris in the GEO environment that would be of utility to commercial satellite owners and operators. We have found that the data we can collect and the techniques that we use to analyze the data allow us to aid the satellite owners and operators with information that is sufficiently timely and accurate to enhance their knowledge of the situation in the vicinity of their satellites. Fig. 7 outlines a potential architecture for this process.

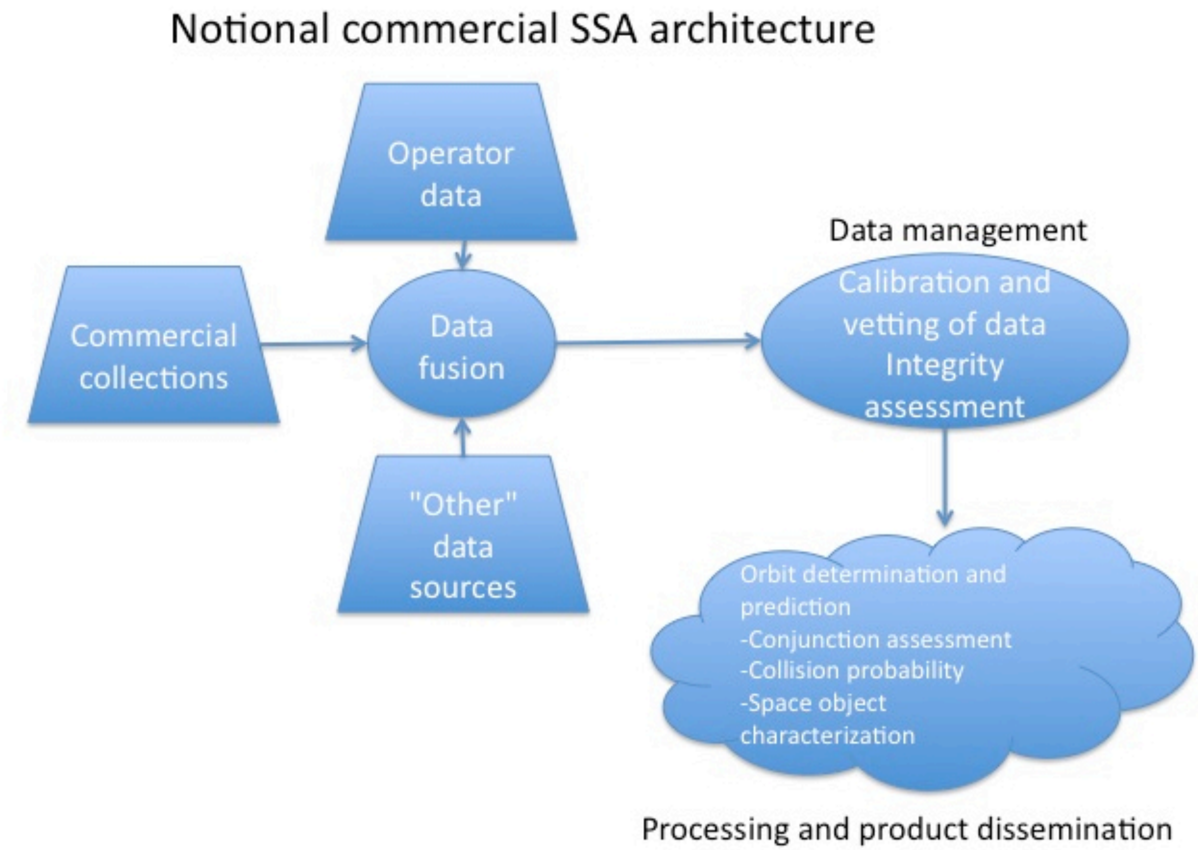

Fig. 7 outlines a notional architecture for data collection and processing flow for commercial SSA.

6. References

1. UN Office for Outer Space Affairs, COPUOS Scientific and Technical Subcommittee, 49th session, "*Active Debris Removal - An Essential Mechanism for Ensuring the Safety and Sustainability of Outer Space,*" A/AC.105/C.1/2012/CRP.16, Vienna, 6-17 February 2012.

2. http://orbitaldebris.jsc.nasa.gov/photogallery/beehives.html, accessed 4/12/2012.

3. Taylor, E.A., *Orbit Theory and Applications*, General Electric training material, http://www.cdeagle.com/, 1991.

4. Choc, R., Flohrer, T., and Bastida, B., "*Classification of Geosynchronous Objects*," Issue 13, ESA/ESOC, February 2011.

5. McKnight, D. & Di Pentino, F, "*New Insights on the Orbital Debris Collision Hazard at GEO*", IAC-11-A6.2.6, 62nd International Astronautical Congress, Capetown, South Africa, October 2011.

6. http://www.space-track.org, administered by the United States Strategic Command. Accessed 4/12/2012.

7. Jehn, R., Ariafar,S., Schildknecht, T., Musci, R., Oswald, M., "*Estimating the number of debris in the geostationary ring*," Acta Astronautica **59** (2006), pp. 84 – 90.

8.Schildknecht, *et al*., "*Properties of the High Area-to-mass Ratio Space Debris Population in GEO,*" AMOS Technical Conference, Wailea, Hawaii, September, 2005.

9. Skinner, M.A., *et al*., "*Time-Resolved Infrared Spectrophotometric Observations of HAMR objects in GEO,*" Acta Astronomica, **69** (2011), pp. 1007-1018.

10. Skinner, M.A., *et al*, "*Further Analysis of Infrared Spectrophotometric Observations of High Area to Mass Ratio (HAMR) Objects in GEO*", Acta Astronautica, in press.

11. Liou, J.-C., and J. K.Weaver, "*Orbital Dynamics of High Area-To-Mass Ratio debris and their distribution in the geosynchronous region*". Proc. 4th European Conference on Space Debris (ESA SP-587). April 2005, ESA/ESOC, Darmstadt, Germany, p. 285

12. Satellite Industry Association. 2013. State of the Satellite Industry Report. Online at: http://www.sia.org/wp-content/uploads/2013/06/2013_SSIR_Final.pdf [Accessed 3 July 2013].
13. Satellite Industry Association. 2012. *State of the Satellite Industry Report.* Online at: http://www.sia.org/wp-content/uploads/2012/06/Final-2012-State-of-Satellite-Industry-Report.pdf [Accessed 15 July 2012].
14. Allison, Audrey, "Paper Satellites, Virtual Satellites: Managing Satellite Orbital and Spectrum Resources in an Increasingly Competitive and Congested Environment," Diss. International Space University, 2012. (*publication pending*).
15. Boeing. *Commercial Communications satellites in geosynchronous orbit.* Online at: www.**boeing**.com/defense-space/space/bss/launch/980031_001.pdf *[accessed 15 June 2012].*
16. Jorgensen, K., Okada, J., Guyote, M., Africano, J., Hall, D., Hamada, K., Barker, E., Stansbery, G., and Kervin, P., Reflectance Spectra of Human-made Objects, 2004 AMOS Technical Conference, Wailea, Maui, Hawaii, 8 – 12 September 2004.
17. McKnight, D., "*Pay Me Now or Pay Me More Later: Start the Development of Active Orbital Debris Removal Now*," AMOS Technical Conference, Wailea, Hawaii, September, 2010.
18. United Nations Office for Outer Space Affairs, COPOUS Scientific and Technical Subcommittee, 49th session, "*Report of the Scientific and Technical Subcommittee on its forty-ninth session*," A/AC.105/1001, Vienna, 6-17 February 2012.
19. Ferster, W., "*JSPOC Conjunction Alerts Could Be Improved, Group Says*," Space News, 9 March 2012
20. Morring, F., "*USAF Notices Unreliable on Orbital Risks,*" Aviation Week, 24 February 2012.
21. Chan, J., DalBello, R., "*Data Sharing to Improve Close Approach Monitoring and Safety of Flight*," 3rd IAASS Conference, 21-23 October, 2008
22. Rosengren, M., De Vincente-Olmedo, J., and Pedersen, F., "*Keeping track of geostationary satellites*," ESA Bulletin **119**, Chapter 8, August 2004, pp. 64-68.
23. Chan, *et al*. "*Data Sharing to Improve Close Approach Monitoring and Safety of Flight*," Fifth European Conference on Space Debris, Darmstadt, Germany, March 2009.
24. D'Uva, Andrew**, "***HOW SDA PROTECTS YOUR DATA AND YOU."* SDA Users Meeting: General Forum. 12 March 2012, Washington DC. WWW.SPACE-DATA.ORG. Accessed 26 June 2013.
25. Skinner, *et. al*., "*Hazards at GEO: The Space Debris population in the vicinity of the GEO belt and mitigation of its impact on commercial satellites*," 30th AIAA International Communications Satellite Systems Conference (ICSSC), **ICSSC 172**, September 24-27, 2012, Ottawa, Canada.
26. Bloch, J. and Rast, R., "*Space Surveillance One Photon at a Time*," 2007 AMOS Technical Conference, Wailea, Maui, Hi, September 2007.
27. Chan, Joseph, Intelsat, personal communication, January 2012.
28. Skinner, M., Payne, T., *et al*, "*IR Spectrophotometric Observations of Geosynchronous Satellites,*" 2007 AMOS Technical Conference, Wailea, Maui, HI, September 2007.
29. Hall, Doyle, "*AMOS Galaxay 15 Observations and Analysis*," 2011 AMOS Technical Conference, Wailea, Maui, HI, September 2011.
30. Hall, Doyle T., *et al*., "*Time-Resolved I-Band Photometry of Calibration Spheres and NaK Droplets*", Journal of Spacecraft and Rockets, Vol. 44, No. 4, July-August 2007, 910-919.
31. Skinner, et al., "*Time-Resolved Infrared Spectrophotometric Observations of IRIDIUM satellites and related Resident Space Objects*," IAC-09-A6.1.17, International Astronomical Congress 60th meeting, 12-16 October 2009, Daejeon, Republic of Korea.