Methods of Processing Geosynchronous Breakups

Zach Slatton

HQ AFSPC/A3/6Z, 18th Space Control Squadron

Robin Thurston

18th Space Control Squadron/OL-D

ABSTRACT

This paper presents methods of processing geosynchronous breakups that have been developed over decades by 1st Command and Control Squadron (1 CACS), 1st Space Control Squadron (1 SPCS) and 18th Space Control Squadron (18 SPCS). The paper reviews how 18 SPCS detected and verified the breakup of a Breeze-M rocket body on Jan 16, 2016, and reveals two unpublicized breakups of possible EKRAN payloads in the early 1980's. 18 SPCS has developed these analytical methods on behalf of Air Force Space Command, in support of US Strategic Command's (USSTRATCOM) Joint Functional Component Command for Space (JFCC SPACE), which is charged with executing USSTRATCOM's presidentially-assigned space operations mission.

1. INTRODUCTION

The geosynchronous (GEO) belt is a challenging regime to maintain, primarily because of the decrease in detectability due to the range of the object residing in this orbit. For radars, the detectability is inversely proportional to R^4. For optical sensors, the detectability is inversely proportional to R^2. For this reason, most of the debris in the GEO region is tracked primarily by optical sensors. Optical sensors have limitations due to weather and solar exclusion cycles. They also do not have a range component to their observations, which increases the time needed to perform accurate initial orbit determination. These difficulties make the GEO region a sparse data environment. While a breakup in low earth orbit (LEO) would be detected within hours, a GEO breakup, depending on the longitude, could take months to detect due to the low observability of the pieces.

There have been eight events in the geosynchronous (GEO) region that are considered possible breakups. However, only four have been confirmed, and one has no identified pieces associated to the parent, leaving it in doubt.

Table 1. Breakups of Geosynchronous Objects (As of May 31, 2018)

Name	SCC	Date	Confirmed	# Published Pieces	# Unpublished Pieces
TITAN 3C TRANSTAGE	2222	30 Sep 1987		0	0
TITAN 3C TRANSTAGE	2868	14 Feb 1994		0	3
TITAN 3C TRANSTAGE	3432	21 Feb 1992	X	28	5
TITAN 3C TRANSTAGE	3692	28 Feb 2018	X	12	16
EKRAN 2	10365	25 Jun 1978	X	4	4
EKRAN 4	11561	23 Apr 1981		0	13
EKRAN 9	13554	23Dec 1983		0	16
BREEZE-M	41122	16 Jan 2016	X	6	0

2. GEOSYNCHRONOUS ORBITAL BELT STUDY (GOBS)

In the 1980s, the Geosynchronous Orbital Belt (GOBS) program was developed to create a database of geosynchronous objects. The follow up, GOBS 2 [2], was developed to sort out objects in the 75 degree east longitude trough, and GOBS 3 extended the functionality to the rest of the GEO belt [3] [4]. 18 SPCS finds GOBS 3 invaluable for maintaining objects in the GEO belt. GOBS 3 works by propagating the orbital plane of every GEO TLE in the catalog to a common epoch. It then compares the plane, longitude, and relative energy values. Since the plane is such a stable parameter, this technique has located objects that have been lost for decades. By using a common epoch, GOBS 3 also finds objects that are related to each other, such as apogee kick motors, sensor covers and debris from breakups.

3. GEOPOP

A few flaws were found with GOBS 3, however. The common epoch that is used is Jan 1 1987, and it is hardcoded into the program. It also doesn't use the SGP4 constants and it truncates some of the calculations. As the current time gets further from the common epoch, these errors become more significant and generate less accurate results. For these reasons, GEOpop is being developed by 18 SPCS as a supplementary program to GOBS 3. GEOpop uses SGP4 to propagate the GEO TLEs to a user defined common epoch. The default common epoch is to the beginning of the current day. The program then uses the same plane matching algorithm as GOBS 3 to match the planes of all GEO objects to the object of interest. To find the difference in orbital plane (DOP) of two objects [3]:

$$W_x = \sin(i) * \cos(RAN) \tag{1}$$

$$W_y = \sin(i) * \sin(RAN) \tag{2}$$

$$DOP = \sqrt{(\Delta W_x)^2 + (\Delta W_y)^2} \tag{3}$$

Where i is the inclination and RAN is the right ascension of the ascending node.

Objects that are related will have small DOP values assuming that the objects have not changed their plane.

The FENGYUN 2G AKM, 40369, was chosen as a comparison test of GEOpop vs. GOBS 3. As seen in Tables 2 and 3, the DOP values are much better for GEOpop. For GOBS 3 there was another unrelated piece as the second closest piece, whereas GEOpop had the only two pieces from the launch as the best matches.

Table 2. GOBS 3 Results for 40369

SATNO	Name	Rank	DOP
89592	FENGYUN 2G DEB (Uncatalogued)	1	0.057
40367	FENGYUN 2G	3	0.062

Table 3. GEOpop Results for 40369

SATNO	Name	Rank	DOP
89592	FENGYUN 2G DEB (Uncatalogued)	1	0.0007
40367	FENGYUN 2G	2	0.0008

GEOpop also has plotting functionality. It can plot Inclination vs. Right Ascension of the Ascending Node (RAN) or W_y vs. W_x for the entire deep space orbit population or just the closest matches for an object of interest.

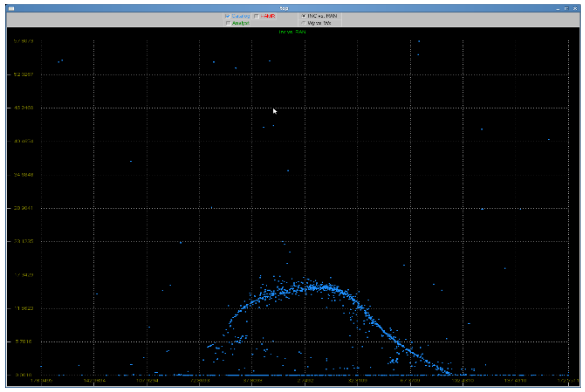

Fig. 1. Inclination vs. RAN of GEO Population

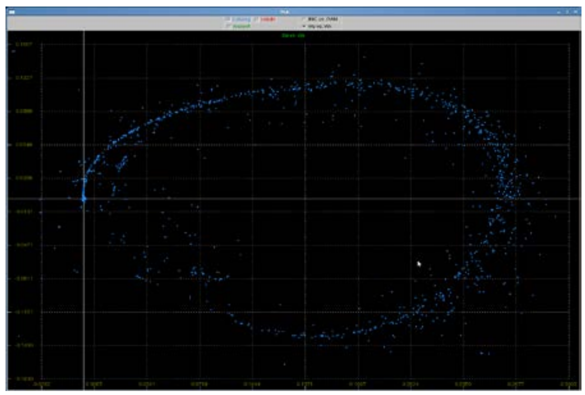

Fig. 2. W_y vs. W_x of GEO Population

4. ELSET PLOTTER

The ELSET Plotter allows the user to plot the historical TLEs together in a scatter plot to see trends in the orbital elements over time. Multiple objects can be plotted together making it ideal for object comparison. Figs. 3 and 4 show TLE histories vs. time of breakup objects and their debris.

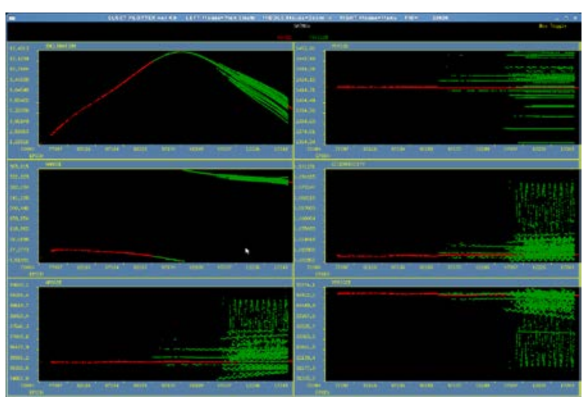

Fig. 3. Debris Plot of 3432

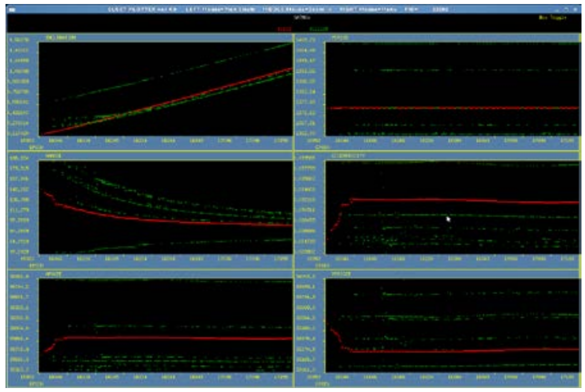

Fig. 4. Debris Plot of 41122

5. PROPAGATION

The Astrodynamics Support Workstation's (ASW) special perturbations (SP) propagator does extremely well in propagating the inclination and RAN backwards in time. Some reverse propagations are good for decades in plane. Using the SP propagator, a propagated TLE history can be created and plotted on the ELSET Plotter, which aids in finding lost objects, filling in gaps of history, and visualizing trends in breakup debris with short histories.

6. WATERFALL PLOT

The waterfall plot shows longitudes and latitudes of tracks of observations and ephemeris points. For a radar sensor, the range from the sensor to the satellite is given. For an optical sensor, the altitude of the satellite is assumed to be GEO.

$$\vec{r} = \rho * \hat{\rho} + \vec{R} \tag{4}$$

$\vec{r}$ is the satellite position in ECI coordinates.

ρ is the range from the sensor to the satellite.

$\vec{R}$ is the sensor position in ECI coordinates.

$$\hat{\rho} = \begin{bmatrix} \cos(\delta_t) * \cos(\alpha_t) \\ \cos(\delta_t) * \sin(\alpha_t) \\ \sin(\delta_t) \end{bmatrix} \tag{5}$$

δ_t is the topocentric declination

α_t is the topocentric right ascension.

To find the range, the problem becomes a ray-sphere intersection [5], where the radius of the sphere is at the GEO belt or 42164km. The problem is simplified by assuming the center of the sphere is at the center of the earth. The solution of the range then becomes a quadratic equation where the solution(s) is:

$$\rho_{GEO} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{6}$$

$$A = \hat{\rho}_{x+}^2\hat{\rho}_{y+}^2\hat{\rho}_z^2 \quad (7)$$

$$B = 2\hat{\rho}_x\vec{R}_x + 2\hat{\rho}_y\vec{R}_y + 2\hat{\rho}_z\vec{R}_z \quad (8)$$

$$C = \vec{R}_x^2 + \vec{R}_y^2 + \vec{R}_z^2 - 42164^2 \quad (9)$$

For sensors inside the GEO belt, which will be any ground based sensor, $B^2 - 4AC$=0, which means that there is one solution for range. For sensors outside the GEO belt looking into the GEO sphere, $B^2 - 4AC$>0, and there will be two solutions for range. For sensors outside the GEO belt looking outside the GEO sphere, $B^2 - 4AC$<0, and there will be no solution for range. Once the range is found, equation (4) can be solved to determine a latitude and longitude.

Using this method, 18 SPCS detected and confirmed the breakup of the BREEZE-M breakup two days after the event. To determine the time of the breakup 18 SPCS used conjunction assessment software [6].

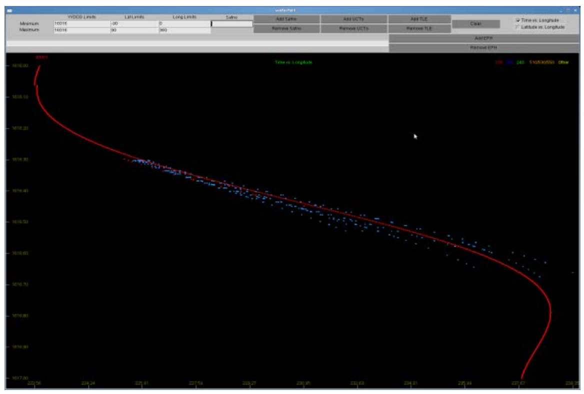

Fig. 5. Time (Reversed) vs. Longitude for 41122 Breakup

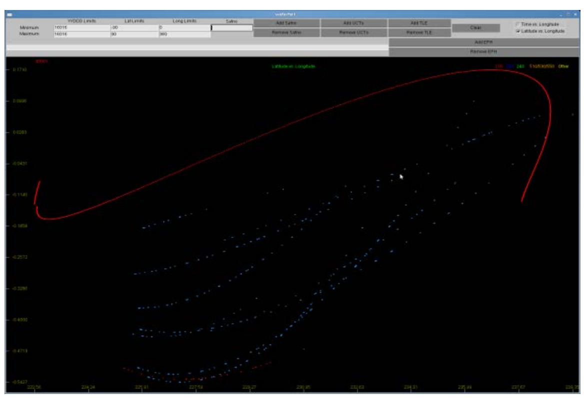

Fig. 6. Latitude vs. Longitude for 41122 Breakup

7. DISCOVERY OF TWO ADDITIONAL EKRAN BREAKUPS

Participants at the 7th European Conference on Space Debris [1] stated that there are two unreported GEO belt breakups. These can be seen in the Inclination vs. RAN plot of GEOpop. The full public catalog is in blue, and the debris pieces of the breakups are in white.

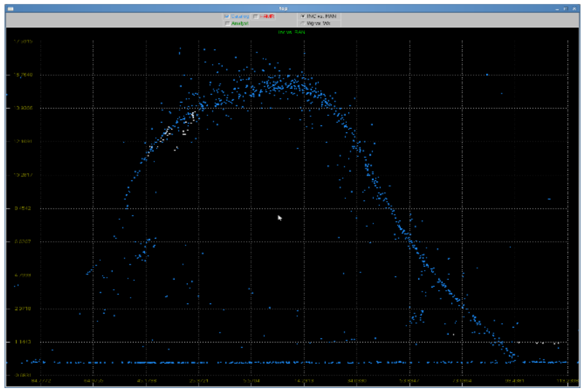

Fig. 7. Inclination vs. RAN with Breakup Debris Added

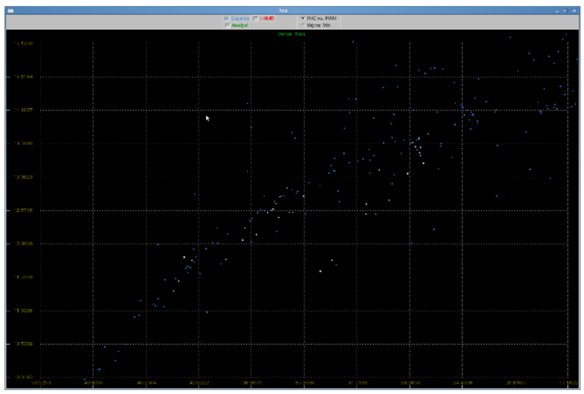

Fig. 8. Inclination vs. RAN Unknown Breakups

These two breakups correlate to EKRAN 4 (SCC 11561) and EKRAN 9 (SCC 13554). Best estimates place the breakup of EKRAN 4 on April 23, 1981 and the breakup of EKRAN 9 on December 23 1983. These objects were not well maintained by the SSN at the time due to poor coverage in that region of the GEO belt. Once sensor capabilities and coverage of the region improved, 18 SPCS discovered more debris pieces and correlated them to their respective parents by using GOBS 3. EKRAN 2 was confirmed by the owner to have broken up on June 25, 1978 due to a battery explosion. If EKRAN 4 and EKRAN 9 have indeed broken up, they may have suffered a similar fate.

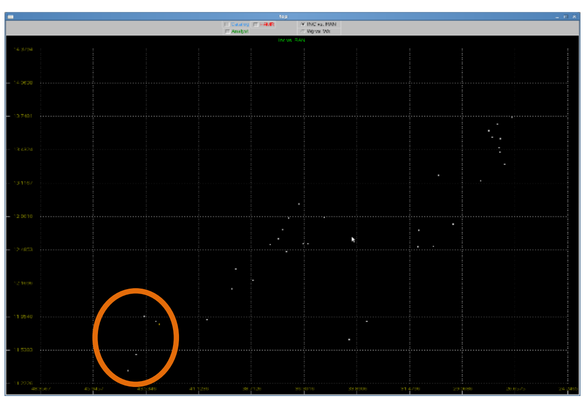

Fig. 9. Inclination vs. RAN for EKRAN 2 Debris

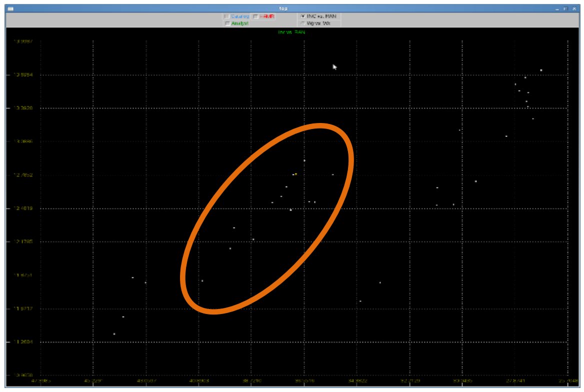

Fig. 10. Inclination vs. RAN for EKRAN 4 Debris

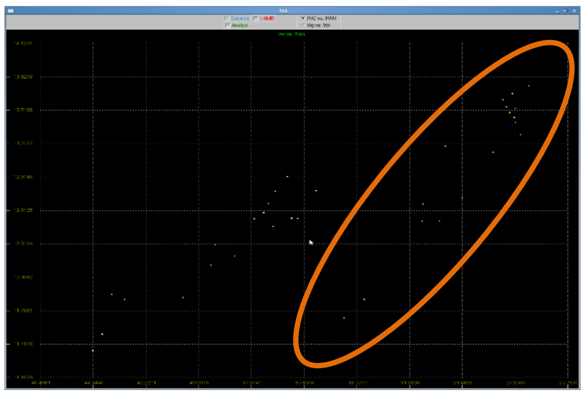

Fig. 11. Inclination vs. RAN for EKRAN 9 Debris

8. TITAN 3C TRANSTAGE BREAKUPS

Of the thirty entries in the SSN catalog listed as TITAN 3C TRANSTAGE, twenty-two have had anomalous events. 3432 is the only confirmed breakup from this family due to the large number of associated trackable pieces, and its good fortune of being tracked as it broke up. It also experienced a large change in its orbital period due to the energy of the breakup. 2222 and 2868 also had jumps in period of several minutes, which require a significant amount of energy, and were actually much larger than the jump experienced by 3432, leading 18 SPCS to conclude that these objects may have also broken up.

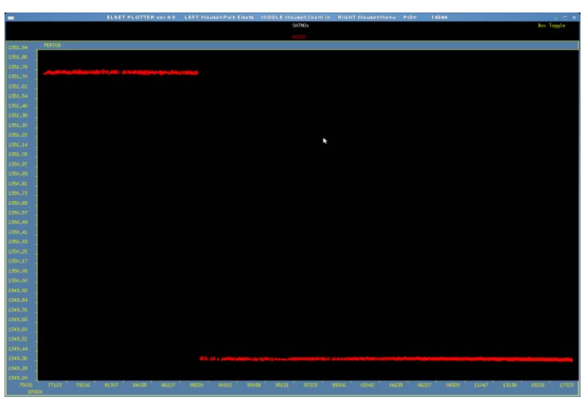

Fig. 12. Period vs. Time for 2222

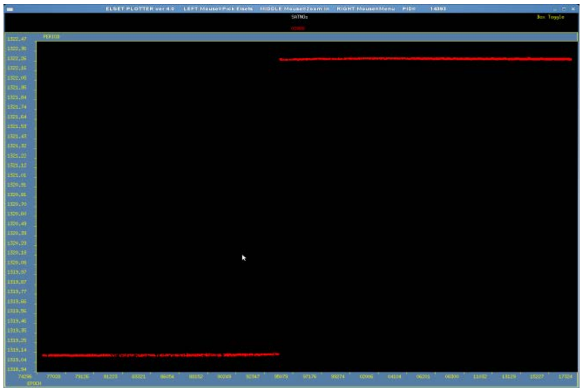

Fig. 13. Period vs. Time for 2868

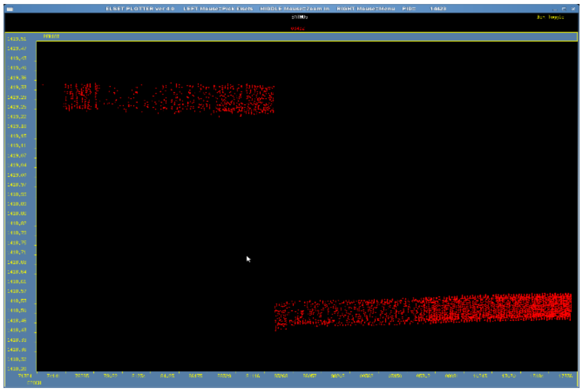

Fig. 14. Period vs. Time for 3432

On day 064 of 2018, several uncorrelated tracks (UCTs) were found that belonged to 3692. It had experienced an anomaly that changed its period by an entire minute.

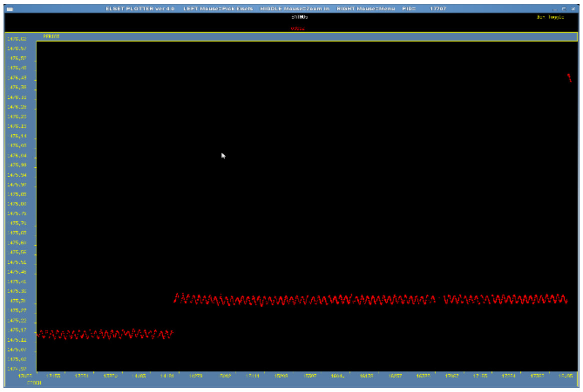

Fig. 15. Period vs. Time for object 3692

A week later, on day 074, an unknown object was found by 18 SPCS with a period of around 100 minutes higher than that of 3692 that correlated in GEOpop with a DOP of 0.00797. It was determined that the object likely came from 3692. 18 SPCS analysts then used ASW's conjunction assessment software and Astrodynamic Standard's Breakup Analysis Module (BAM) [6] to find a time of breakup of day 059 at 2100z. The separation velocity was around 71 m/s meaning that the event was energetic. 18 SPCS is expecting to find more pieces in the future.

9. AMC-9

While not considered a breakup, the AMC-9 debris causing event is worth mentioning because it allowed 18 SPCS to take advantage of relationships with commercial and other US government agencies. When Applied Defense Solutions (ADS) discovered an anomaly with AMC-9 through open source information, they were able to task passive RF and electro-optical systems to investigate previous collections taken on AMC-9 by their assets. Pieces were then noticed coming off of the satellite. ADS then notified 18 SPCS of the event through a contract with the National Space Defense Center (NSDC). A few days later outgassing occurred and then stopped. Since the owner, Société Européenne des Satellites (SES), is a member of the Commercial Integration Cell (CIC) collocated with 18 SPCS, any information on the event was freely passed back and forth between 18 SPCS, NSDC, and SES. As of July 2017 SES has regained some control of AMC-9 and expects to begin disposal operations. The pieces, though bright, are assumed to be high area-to-mass ratio (HAMR) objects and are not expected to be well maintained.

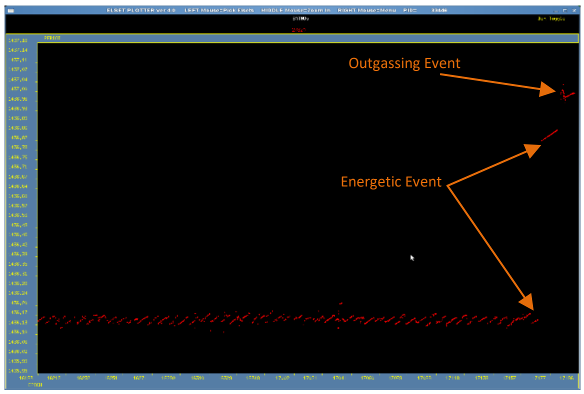

Fig. 16. Period vs. Time for AMC-9 event

10. CONCLUSION

Catalog maintenance of the geosynchronous regime continues to be a challenge at 18 SPCS. However, with the addition of new analytical capabilities, 18 SPCS can more accurately correlate GEO debris to fragmentation events. Using these methods 18 SPCS can better detect, track, and correlate geosynchronous breakups.

11. REFERENCES

[1] Agapov, Vladimir, “Expanding Knowledge on Real Situation at High Near-Earth Orbits” in Proceedings of the 7th European Conference on Space Debris ESA/ESOC, Darmstadt, Germany, April 2017.

[2] “Geosynchronous Orbital Belt Study II Final Report.” Technical Report. Lockheed Missiles and Space Company. Colorado Springs. 17 November 1986. Electronic scan.

[3] “Geosynchronous Orbital Belt Software GOBS III Report.” Technical Report. Lockheed Missiles and Space Company. Colorado Springs. 31 October 1988. Electronic scan.

[4] “Geosynchronous Orbital Belt Study GOBS III Update.” Technical Report. Lockheed Missiles and Space Company. Colorado Springs. 4 August 1987. Electronic scan.

[5] “Ray-Sphere Intersection” Ray-Tracing Formulas. Northeastern University. Web. 06 June 2017

[6] Slatton, Zach, et al., “Methods of Predicting and Processing Breakups of Space Objects” in Proceedings of the 7th European Conference on Space Debris ESA/ESOC, Darmstadt, Germany, April 2017