Observed peaks in satellite conjunctions with debris populations

Bruce W. Rabalais
DigitalGlobe, Inc., Longmont, CO 80503

Abstract

During routine collision avoidance activities for the DigitalGlobe imaging satellite constellation, periodic peaks in the quantity of close approaches have been observed between WorldView-2 and the Cosmos 2251 and Iridium 33 debris populations. Investigation showed that the debris populations from previous on-orbit collision or fragmentation events tend to remain somewhat grouped in ascending nodes for years after the event, allowing some portions of the population's dynamics to be modeled as a group. The population's ascending nodes can be fit to a circular normal distribution, and using simple linear regression on the calculated mean nodes, relative motion between WorldView-2 and the debris clouds can be predicted. This modeling methodology is demonstrated using the debris populations from the former Cosmos 2251 and Iridium 33 populations, and the observed peaks in WorldView-2's daily conjunction notices are shown to coincide with the satellite's passage through the debris populations in a head-on fashion, as indicated by the operational satellite's ascending node being 180 degrees opposite the cloud's mean ascending node. The derived debris cloud model is also used to predict the next peaks in WorldView-2's conjunction frequency with opposing passages through the two noted debris populations. Discussion is also provided concerning the lack of such conjunction peaks between WorldView-2 and the Fengyun-1C population, even though WorldView-2 and the original Fengyun-1C satellite were at similar altitudes.

1. Introduction

DigitalGlobe (DG), Inc. owns and operates a constellation of five high-resolution imaging satellites in sun-synchronous orbits and at various altitudes: WorldView-1 at 496 kilometers (km), WorldView-2 at 770 km, GeoEye-1 at 684 km, Ikonos at 684 km, and QuickBird at 450 km. Conjunction analysis and collision avoidance with orbital debris have been a regular and daily part of DG's satellite operations since late 2009, using supporting data generously made available by the Joint Space Operations Center (JSpOC), a subset of the United States Strategic Command, under the Joint Functional Component Command for Space (JFCC Space). All data in this report comes from JSpOC's support of DG's collision avoidance activities, and is used by permission of JSpOC.

In the context of this paper, a *conjunction* is defined as the mutual approach of two on-orbit objects to within a specified distance threshold, such as a debris object approaching an operator's active satellite. The size of the threshold can be specified from a variety of criteria, but qualitatively, it should be large enough to provide awareness of objects within the vicinity of an operator's asset, but small enough to filter out most events of extremely low likelihood of actual collision. In the overwhelming majority of scenarios, a conjunction notification indicates a need for caution and increased awareness, but is not necessarily a sign of imminent danger.

In 2009, an unintentional collision between an active Iridium satellite and a deactivated Russian Cosmos satellite destroyed both satellites, and also resulted in the release of thousands of small debris objects [1]. In addition, in early 2007, the Chinese government conducted an anti-satellite experiment that involved shooting down a decommissioned Chinese weather satellite, releasing thousands of small debris objects into the 800-km orbit altitude [2]. As the resulting debris clouds from these events slowly dissipate and re-enter Earth's atmosphere over the course of centuries, the individual debris particles frequently experience close approaches with other satellites operating in the Low Earth Orbit (LEO) environment, resulting in periodic collision avoidance activities to ensure the safety of the live satellites. The interaction of WorldView-2's orbit with the debris clouds from these events are the subject of this paper.

Over several months of operation in 2011, it was noted that WorldView-2 (WV-2) often experienced spikes in the number of conjunctions reported per day, specifically with the Iridium 33 and Cosmos 2251 debris clouds. Knowing that the two progenitor satellites had occupied orbits in similar altitudes to WV-2, DG analysts undertook a study to attempt to correlate the peaks in conjunction activity with the expected evolution of debris clouds from collisions similar to that experienced by the Iridium and Cosmos satellites in 2009. The intent of the study was to show that the observed spikes in conjunction activity are an expected phenomenon, and could be predicted to some degree. As a contrasting element, debris from the Fengyun 1C event does not exhibit spikes with WV-2, even though the progenitor was at a similar altitude. This event is discussed, though not explicitly included in the study.

2. Data Collection and Modeling

Figure 1 shows nearly three years of WorldView-2 conjunction events with the Cosmos 2251 and Iridium 33 debris collections, depicting the number of close approaches experienced per day, and excluding objects not directly included in the three debris clouds under consideration. Though some base level of conjunctions with the Cosmos and Iridium clouds are always present, the previously-mentioned peaks are quite apparent. The apparent drop-off from late 2012 is due to a decrease in WV-2's conjunction distance threshold.

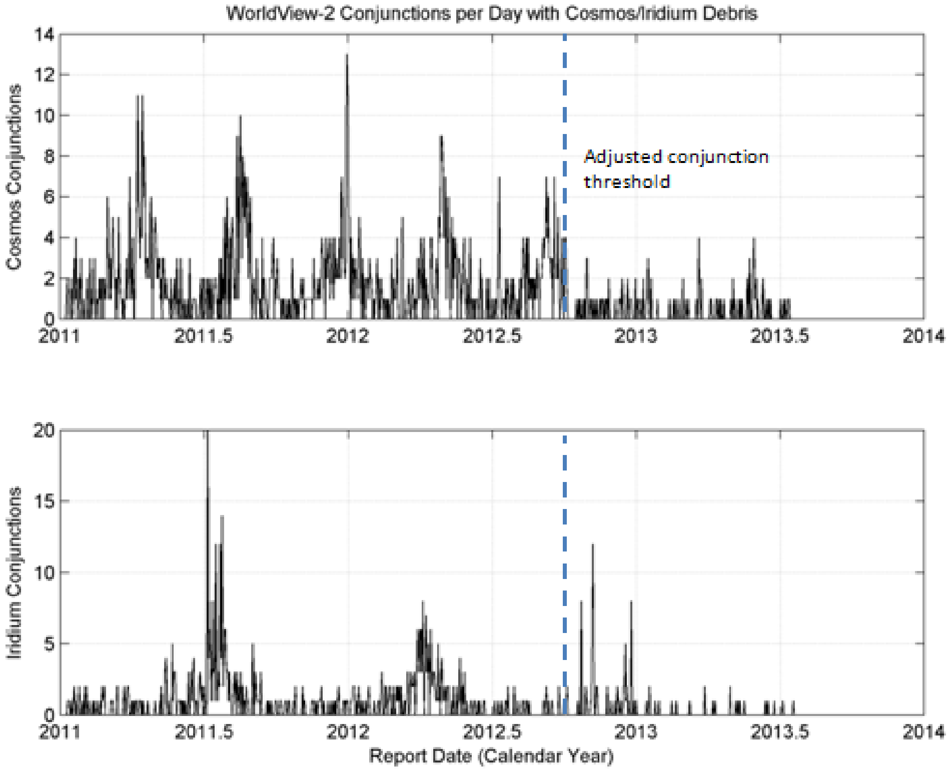

Fig. 1. Conjunctions/day of WV-2 with Cosmos and Iridium debris objects, showing periodic peaks in conjunction activity. The reduced conjunction activity after 09-22-2012 is due to adjustments in the conjunction threshold distance.

Qualitatively, immediately after a fragmentation event, the resulting debris will spread along the original object's orbit path, resulting in a toroidal distribution within a few days of the event. Over the course of months to years, simulations [3] show that the toroidal distribution will eventually disperse into a shell as the orbit planes of the individual fragments slowly drift away from the original orbit plane. The drift is due primarily to orbit perturbations such as atmospheric drag and central body non-sphericity operating on the initial velocity differences of the debris particles produced by the fragmentation event. One consequence of this evolution is that while the cloud is in the toroid shape, other satellites should exhibit increased conjunction activity as they pass through the debris cloud. If the orbits of the satellite and the cloud have differing nodal precession rates, then intuitively, the number of close approaches should show an increase as the satellite and cloud orbits come into head-on configurations, occurring when the ascending nodes of the satellite and debris orbit planes are in 180-degree opposition of each other. This is the phenomenon used by this study to explain the observed periodic peaks in WV-2's conjunction reports for the Cosmos and Iridium clouds.

To analyze and characterize “snapshots” of the debris clouds at various times, it was necessary to use two-line element (TLE) databases collected over the past three years as part of routine collision avoidance activities. These are produced by JSpOC on a daily basis, and can be propagated for short periods using a publicly available SGP4 propagator [4]. While the low-order nature of the SGP4 theory discourages the use of TLEs for high-precision collision avoidance, the TLEs still make an excellent resource for determining the overall crowdedness of LEO and the general behavior of debris populations. Since downloading the TLE database was manually performed on an as-needed basis, the data available to the study was sparse over most of the 2.5 years of the study, but still quite adequate for the task. To study the RAANs of objects within the debris clouds, each of the 66 available TLE databases was filtered for all objects belonging to the Cosmos and Iridium debris populations. Those objects that did not actually cross the WV-2 orbit were also excluded. Each remaining TLE was then evaluated to the epoch date of its database (a few hours at most). In this fashion, it was possible to represent the state of the entire populations of the debris clouds at the 66 epochs of the TLE databases. No propagation was performed *between* the 66 epochs.

Detectable debris objects from the Cosmos and Iridium clouds number into the thousands, and a method was needed to characterize and model the clouds as collections of similar orbits rather than individual objects. One obvious initial approach was to define a “mean” RAAN of a collection of objects, and then observe how all the ascending nodes behaved relative to the mean. As a start, a mean RAAN was defined by finding that angle that maximized the sum of the cosines of the differences between the mean RAAN and the collection of RAANs:

$$f(\bar{\Omega}) = \sum_{i} cos(\Omega_i - \bar{\Omega})$$

$$\frac{df}{d\bar{\Omega}} = 0 \xrightarrow{yields} tan(\bar{\Omega}) = \frac{\sum_i sin(\Omega_i)}{\sum_i cos(\Omega_i)}$$

where $\bar{\Omega}$ denotes the mean RAAN of a collection of debris objects, and Ω_i denotes the RAAN of a particular object within that population. The reason for using the cosine function above is that the cosine of the difference of two angles is at its maximum value when the angular difference is zero, and at its minimum when the angular difference is at 180 degrees. However, since the above formula is just as likely to find a minimum as it is a maximum, a second derivative check is always required.

A mean RAAN alone is not enough to describe a cloud, even at this level of investigation, since as the cloud evolves, its RAANs will eventually spread through the circle, and any conclusion based on the calculated mean will eventually be misleading or erroneous. Some sort of indication of distribution around the mean is needed to add confidence to any analysis. To this end, histograms of the dispersions of the cloud RAANs around their means were constructed, shown in figure 2. Both clouds clearly hint at something with the appearance of a normal distribution, though Cosmos is much more dispersed than Iridium.

From examination of the histograms, it seemed that while the clouds were clearly dispersing, there was still enough structure to explain the observed conjunction peaks. It also seemed that a normal-like distribution would be appropriate as a first-order approximation for further refinement of our definition of mean node, and for a quantitative measure of nodal dispersion; however, normal distributions are only defined on the open real line, not on the closed intervals described by circles. A more appropriate choice seemed to be the von Mises, or circular normal distribution [5]. The von Mises distribution has a definition of mean that is functionally equivalent to the earlier definition, and additionally, has an easily calculated shape parameter that is analogous to the standard deviation in the linear normal distribution. Given these similarities, it was decided to proceed with using the von Mises distribution to further characterize the clouds for analysis, though it should be noted that the Cosmos histogram of figure 2 does show an as-yet-unexplained asymmetry of about 25 degrees between the average and peak values.

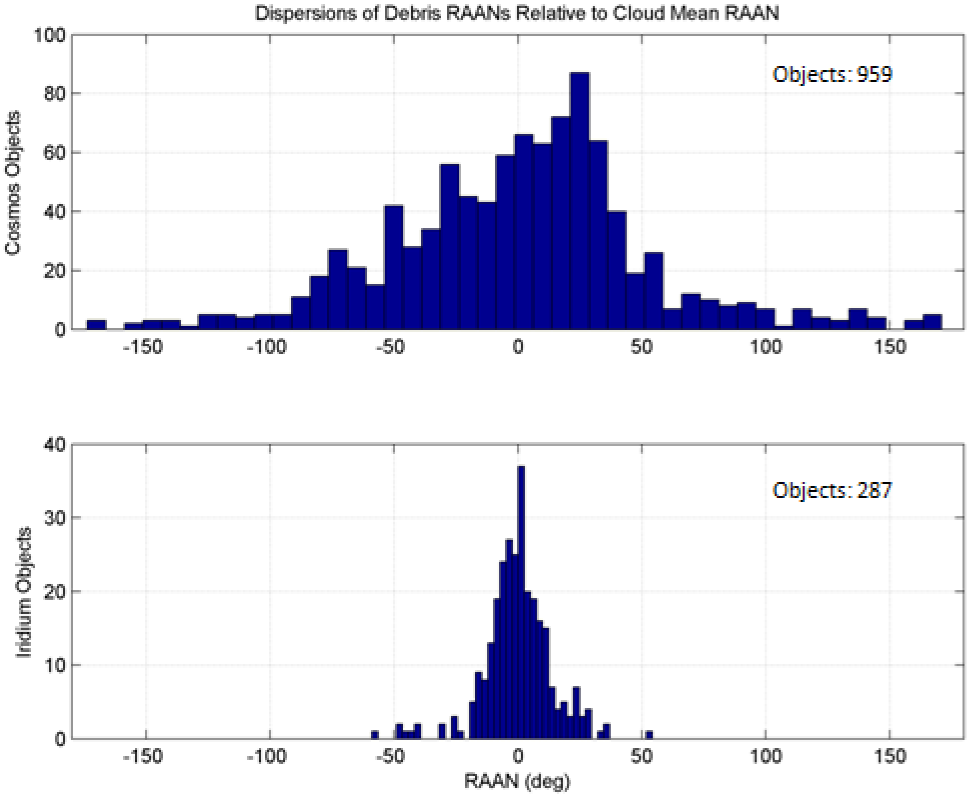

Fig. 2. Distribution of individual debris object RAANs about the clouds' mean RAANs, epoch 2011/09/14. Only objects crossing WV-2's orbit altitude are included.

Recall that the primary intentions with the model are to: a) define a mean ascending node for the debris clouds, and b) obtain some quantitative measure of the time-dependent dispersion of the clouds. The von Mises mean has already been discussed as being equivalent to what we've previously defined, and needs no further attention. The time behavior of the von Mises shape parameter, typically denoted κ, is captured in figure 3 for each of the two debris clouds, as a function of the TLE database epoch. The shape parameter is large for tightly-packed populations, decreasing to zero as the population eventually spreads to a uniform distribution, and this is reflected in figure 3 by a gradually decreasing κ value as later TLE databases are examined. The Cosmos and Iridium populations are quite different from each other, which is interesting, considering that their formations date to the same collision event.

3. Fitting the Debris Data to the Model

For attempting to match the state of the debris clouds in the TLE databases with the observed periodic peaks in WV-2's conjunctions, the key parameter to model and predict is the delta of the ascending nodes, or specifically the ifference between WV-2's ascending node and the calculated mean ascending node of the cloud. When this parameter reaches 180 degrees, WV-2's orbit plane will be in a position to encounter the majority of the debris cloud in a head-on configuration. All three progenitor satellites were at similar altitudes as WV-2 (one reason for the high number of debris conjunctions with WV-2, as opposed to other satellites in the DG constellation), but Cosmos 2251 and Iridium 33 were at significantly different inclinations, leading to a large difference in nodal precession rates. One would expect the delta node to change rapidly for these analyses, and perhaps even be dominated by linear motion. Therefore, the delta angle between the mean node of a debris cloud and WV-2's ascending node will be conceptualized as a function of time, with the end desire of predicting when it is 180 degrees, and explaining the observed conjunction peaks.

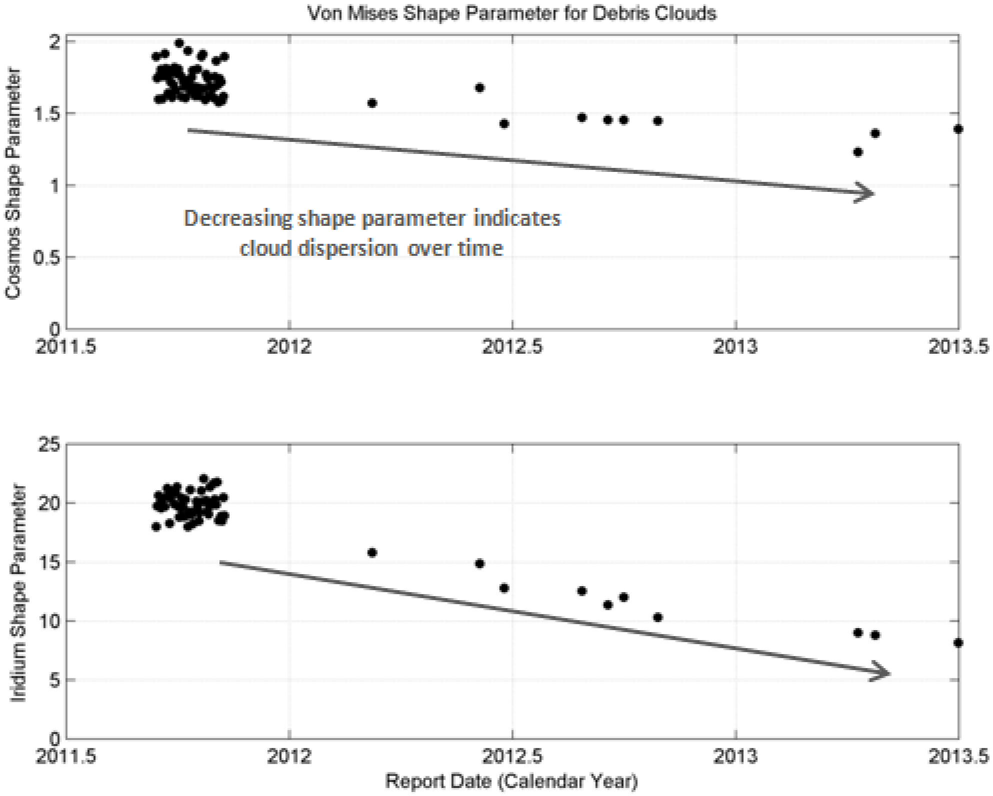

Fig. 3. Decreasing von Mises shape parameter shows cloud RAANs are continuing to disperse. Shape parameters approach zero as the distribution becomes uniform.

To achieve the desired angle as a function of time, each of the 66 TLE databases were processed and only those objects belonging to one of the three debris clouds and crossing WV-2's orbit were selected. For each TLE database, the publication date was used as an epoch, and all the selected TLEs (including WV-2) were propagated to the database epoch using a public version of the SGP4 propagator [4]. The debris population was fit to a von Mises distribution for purposes of calculating a mean node, and the delta node between the cloud mean and WV-2 was calculated. Afterwards, a linear regression technique was used to fit the delta node as a first-order polynomial of time (being careful of branch cuts in the angle space). As seen in figure 4, the fit was surprisingly good, considering the simple regression methodology and the effective negligence of all perturbations higher than the secular nodal precession.

Once the regression was complete and shown to be sufficient for the stated purpose, it then became a simple matter to determine the predicted dates at which the delta node would achieve 180 degrees and head-on planar conjunction between WV-2 and the clouds' mean orbit planes. The periodicity of the Cosmos planar conjunctions is roughly 128 days, and that of the Iridium cloud is about 258 days. Figure 5 shows predicted dates projected onto the actual conjunction report data discussed earlier, showing reasonable visual agreement between the analysis and observation. In operational practice, it was noted that the Cosmos predictions were consistently several days early, while the Iridium predictions were quite accurate. The author believes the Cosmos inaccuracy is due to the asymmetric skew in the histograms of figure 2.

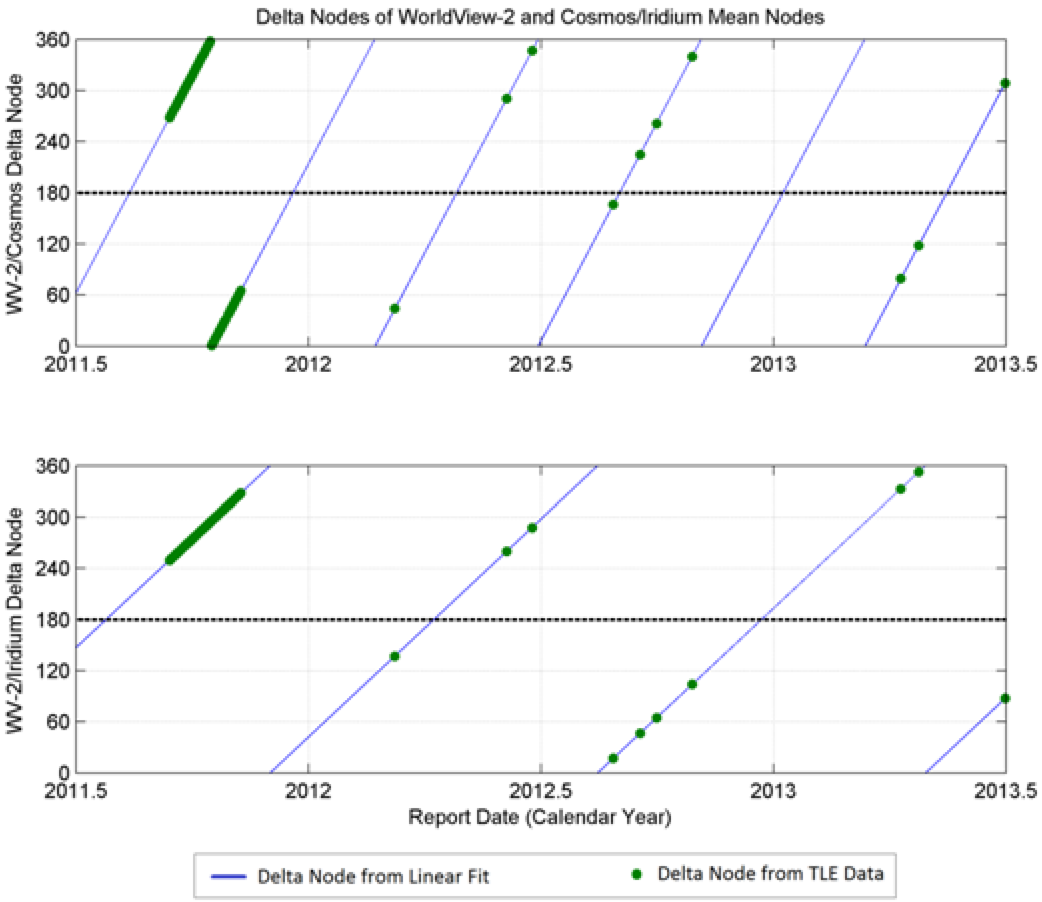

Fig. 4. Delta angle between WV-2's RAAN and debris clouds' mean RAANs as function of time, showing linear fit from measured TLE data. As the function crosses 180 degrees, satellite-debris conjunction activity should increase.

It was noted during investigation of the peaks phenomenon that WV-2 has no observable conjunction peaks with the Fengyun-1C debris cloud, though it does see a near-constant daily level of Fengyun activity. Further investigation of the Fengyun incident reveals that when viewed as a whole, the debris cloud's mean RAAN still follows the sun-synchronous pattern of the progenitor, which gave a local mean time of descending node (LMTDN) of roughly 7AM. Since WV-2 is orbiting at an LMTDN of 10:30AM, roughly 55 degrees removed from Fengyun-1C, both orbit planes would precess at the same rate, and no peaks would be expected. That said, the subset of the cloud that intersects WV-2's orbit has spread from the cloud mean quite a bit, and is now currently in the same 10:30AM descending node as WV-2, and the latter now travels within and parallel with a portion of the debris cloud. This "travel-with-the-flow" behavior apparently reduces the total number of potential conjunctions, as seen in actual observation. The author believes this is due to the much larger synodic periods introduced by the near-coplanar orbits, stretching out interactions between the satellite and the individual debris objects of this band of the cloud over a much longer period.

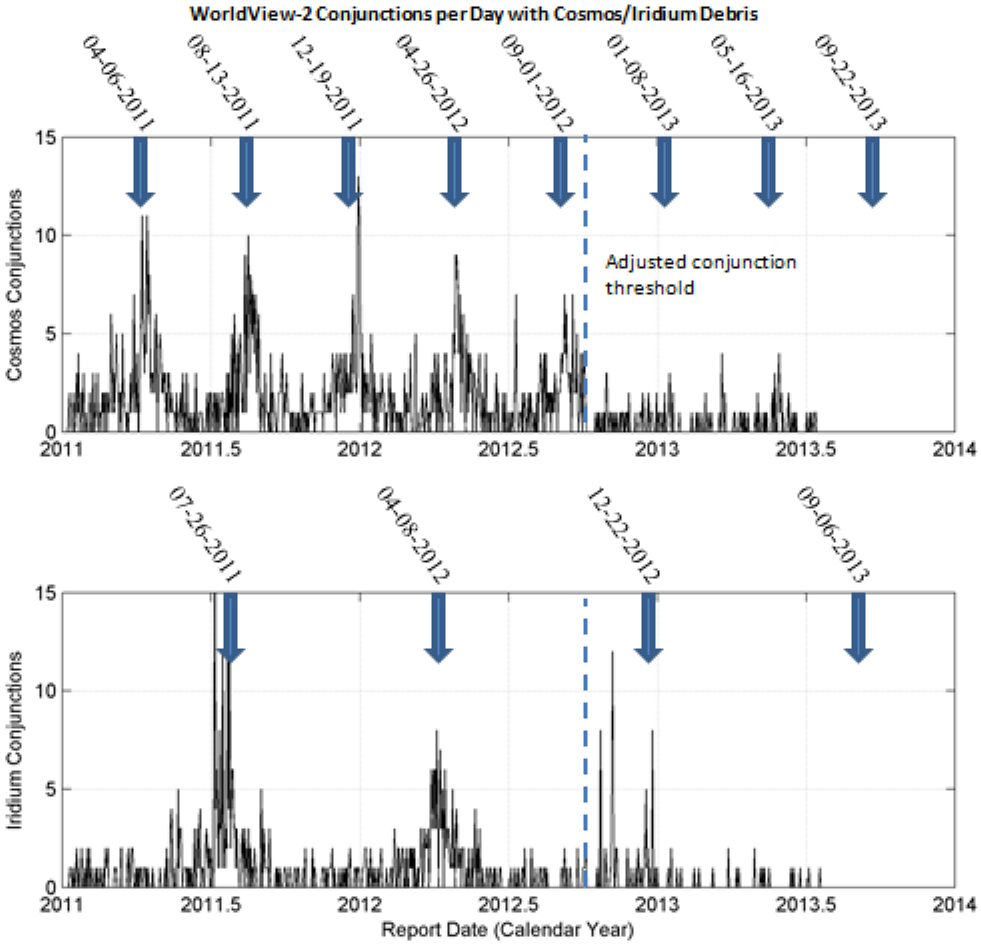

Fig. 5. Predicted peak activity times superimposed upon observed daily conjunction frequency. The reduced conjunction activity after 09-22-2012 is due to adjustments in the conjunction threshold distance. Data cutoff is 07-23-2013.

4. Conclusion

The observed conjunction peaks between WV-2 and the Cosmos/Iridium debris clouds have been shown to be an expected by-product of the clouds' continuing orbit evolution, and the lack of such peaks with the Fengyun cloud has been explained as a feature of the comparable sun-synchronous orbits of WV-2 and Fengyun 1C. In addition, the expected spreading of the clouds' ascending nodes over time has been demonstrated with the shape parameter of the von Mises distribution. Finally, short term predictions of future peak observations have been made. It has been noted that the asymmetry in figure 2 is an indicator the symmetric von Mises distribution is not necessarily the best fit for the problem. Future work will involve determining an ascending node population model more able to capture the observed asymmetry in the Cosmos ascending nodes.

5. Acknowledgements

DigitalGlobe would like to thank the JSpOC organization for monitoring the near-Earth orbit environment, for making the debris orbit data available for critical conjunction analysis and collision avoidance, for their continued support of DigitalGlobe collision avoidance activities, and for permission to publish this paper using their TLE data. This study would not have been possible without JSpOC's continuing commitment to the Space Situational Awareness field.

References

[1] Wright, D., “Colliding Satellites: Consequences and Implications,” Union of Concerned Scientists, 2009

[2] David, L., “China’s Anti-Satellite Test: Worrisome Debris Cloud Circles Earth,” Space.com, 2007

[3] Pardini, C., Anselmo, L., “Evolution of the Debris Cloud Generated By the Fengyun-1C Fragmentation Event,” International Symposium on Space Flight Dynamics, 2007

[4] Vallado, D., et al, “Revisiting Spacetrack Report #3”, AIAA 2006-6753

[5] Fisher, N.I., *Statistical Analysis of Circular Data*, Cambridge University Press, Cambridge, United Kingdom, 1993