SIMULATION OF PAST BREAKUP EVENTS AND THE CORRELATION WITH ACTUAL RADAR DETECTIONS

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ABSTRACT

Fortunately, large breakups in LEO are relatively rare. Only three have occurred in the last ten years which have deposited more than 100 cataloged objects. The chance to study these breakups is equally rare. Statistical radar observations have provided useful data, but scores of unidentified debris remain in historic radar data. The potential for greater understanding of past breakups exists if only these unknown pieces can be linked to these events. Through the simulation of known breakups, a range of possible radar range and range rates can be used to fence in possible detections. Correlation of historic radar data which falls within these limits makes the likelihood high that detected pieces that fit these parameters originate from the simulated parent body.

The Haystack radar, using a staring campaign with long periods of observation, has the potential to view a large range of orbits encompassing many potential past breakups. Several known satellite breakups were simulated, producing a broad group of debris objects. The orbits of this debris were examined for Haystack radar interception, and equivalent Haystack radar range and range rates were determined. From these simulated debris detections, a range of possible parameters was established. Simulation of the debris cloud as it passed through the Haystack radar beam provided a sample space from which to draw possible evidence of breakup fragments. Detection candidates which were previously unidentified were marked and the probability of these detections originating from the known parent body was computed with the intention of gathering a more complete record of detected breakup debris to improve the understanding of the event.

1. INTRODUCTION

Breakup cloud characteristics, though simple in concept, are difficult to determine in a concrete manner. In the event of an on-orbit breakup, such details as how energetic the breakup was, fragment ejection velocities, and the exact time at which the breakup occurred can be quite elusive. Data pertaining to the characteristics of objects ejected from an explosion have been gathered in the past and yield a basis from which on-orbit breakups are modelled. From these past data and knowledge of the parent orbit, simulation of the on-orbit explosive event may be formed for the purpose of understanding how to capture such processes using ground radar observation. Simulation of a breakup can be accomplished in many different fashions. One such method is that of generating a random cloud of debris many different times to determine statistical evidence of detection. When examining past radar detections though, it becomes useful to know the entire range of particles that could be generated and detected. The purpose of this paper is to characterize the entire feasible pool of detections of past breakups for the purpose of revisiting recorded radar observations in search of previously unrecognized debris related to known breakups.

Debris data is not taken continuously or at regular intervals by the Haystack radar. Often Haystack is not available for debris measurements for weeks or even a few months after a breakup. Additionally, the radar may not be operating at the right time of day to capture debris from the breakup. For this reason, each opportunity becomes incredibly valuable when attempting to discern particles from a specific breakup from the debris environment. The measured quantities at Haystack include range and range-rate from which orbits are estimated. The technique used in this paper involved looking at on-orbit breakups from the parent body perspective, and matching the attributes of possible breakup particles with debris detected by the Haystack radar.

The big question when analyzing a breakup is how many particles are generated, and with what velocity they were ejected from the source. Rather than use a specific breakup model, the simulation used in this paper systematically examines a range of _v magnitudes which act on the full range of exit vectors from the parent body. If one were to assume an explosive _v about an orbiting body, and propagate a single fragment with this intensity from the object, then an orbit from a single piece of debris from a breakup would be simulated. If instead one were to take n objects with equal explosive magnitude, but each with a different exit direction about the source, a general overview of the result at that particular breakup _v is produced.

The radar detection characteristics of the generated debris cloud from a breakup provided the means to establish a boundary about possible detections by ground-based instruments. In this study there are four characteristics of debris particles which are used: 1) time of breakup, 2) time of radar observation, 3) ground radar detected range rate, and 4) ground radar detected range. Breakup time determines the distribution of the cloud about the parent body's orbit, time of observation links the debris detected to the time range allowed for the radar beam to pass through the total cloud, and the ground radar range and range rate information yields the details of the orbit of a detected object. An object detected by Haystack that fits within these constraints is considered a possible correlation to breakup.

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2. BREAKUP SIMULATION METHOD

A breakup can be adequately simulated by the instantaneous application of differential velocities (Δv) to the resulting debris pieces. The in-plane _v component produces changes in the semi-major axis and eccentricity of the orbit while the out-of-plane component produces changes in inclination. The orbits form a narrow band, or toroid, immediately after the breakup. The location in space where the breakup occurred, or the breakup point, is common to the orbits of all generated fragments immediately after an event. This results in a "pinch point". All ejected fragments will pass through or near this point on their next orbit and for a number of revolutions afterwards. Up to a few days after the breakup, the pinch point is the ideal volume to monitor in order to detect the majority of debris generated. It is often not within the range of available ground based sensors though. Differences in orbital period quickly spread the debris along this toroid. Typically within a day debris is spread along its entire circumference. Small perturbations in individual orbits, primarily caused by the oblatness of the Earth, cause this toroid to spread out over time. Eventually the orbits spread completely around the Earth, although this process typically takes several months to several years to occur depending on the details of the breakup.

Since debris is distributed along the toroid so quickly, the width of the toroid is important when the debris cloud passes over a ground-based radar. As the Earth rotates the beam sweeps through inertial space. The orbit plane of each fragment remains relatively fixed, while the Earth rotates beneath it, exposing the breakup plane only twice per day. The outer most orbit planes correspond to earliest and latest observation times. These orbital planes fence in the possible candidates by time of observation.

2.1. Debris Field Generation and Radar Detection

Each fragment simulated is done so with only the velocity vector. Mass and size characteristics were ignored, in favour of isolating only the _v imparted on the simulated particle at the time of ejection. By analyzing the range of conceivable magnitudes, along with the entire range of ejection directions from the parent, the widest dispersion of orbits is obtained. In analyzing a breakup, examination of the orbit plane about which the parent body existed prior to the breakup provides a basis from which to assume the range over which any feasible breakup particle may enter. The assumptions used for the two breakups analyzed in this paper were: the breakup $\_v_{max}$=500 m/s, and the reported time of breakup was within ±0.5 hr of reality. Though breakup times reported are often considered accurate to within minutes, the possibility of error should not be precluded as error could include additional correlations. The value of ±0.5 hr is used in order to explore what time of breakup error would do to the resulting correlation pool.

The key details which must be addressed for correlation with a breakup are: time of breakup, time of debris cloud observation by the radar, and the shape and population of the debris cloud. If a detected particle matches these criteria, it is feasible though not certain that the particle is associated with the breakup. In implementing the time of breakup error, scenarios are computed over a breakup time range, generated in increments of 0.05 hours. This allowed for a good spread of simulated detections from which to draw a conclusion on correlation with actual detections. The point at which these particles enter their orbits, from the parent body's, limits how the cloud may spread. The time of breakup determines at which point along the orbit of the parent body the fragments are ejected. For eccentric orbits, a _v imparted at apogee will affect the orbit much differently than one imparted at perigee. In addition, for both eccentric and circular orbits the point in the orbit at which the cloud is ejected determines the fragment apogee and perigee positions. In using a range of times which encompass the real point at which the breakup occurred, it is possible to examine a range of possible clouds, assuming pieces are detected and fit the established range of parameters from simulation.

The time of breakup should not be confused with the time of observation. Time of observation represents the time at which the radar beam passed through the orbit plane of the particle. Variation of the time of breakup changes the orbital distribution of the breakup cloud. The data presented in this paper is from a single fraction of a day at which detections of the estimated debris cloud by the Haystack radar were possible.

The third unknown, the velocity at which particles are expunged from the parent body, is meant to encompass the bulk of possible ejections. As will be laid out in Section 3, ten magnitudes are used: _v = 50 through 500 m/s, at 50 m/s increments. This provides a method of determining possible ejection _v. The cloud increases uniformly from small to large _v, where the 500 m/s cloud has the most dispersion of the generated clouds. The number of particles is ignored, as the question answered is not distribution, but the range of possible particle ejections. Once the simulation is performed, data from Haystack observations is overlaid to identify particles that meet the possibility criteria.

2.2. Debris Cloud Propagation

The breakup is modeled by first taking a randomized generation of particles emanating from the center of the parent body at the time of breakup. For each simulation, a fixed _v magnitude was selected and applied to a uniformly distributed set of exit vectors from the source. In the instant of the explosion, this is effectively a sphere of vectors with the same magnitude projecting from the parent body. Each generated cloud uses only one ejection velocity, allowing the analysis to be graded by explosive _v alone. Generating a uniform distribution can only be accomplished in a few configurations. Much like the cartographer's problem of mapping a spherical coordinate system onto a 2-D plane, the cloud's higher latitudes compress together while the lower latitudes have large gaps between points. Instead, a Monte Carlo sample randomized about the solid angle is taken, centered at the parent body, and a collection of unit vectors representing the debris exit directions is formed. With this randomly generated vector distribution created, assigning impulse velocities to each vector demonstrates the effect of breakup _v. Fig. 1 shows the simulated distribution of orbits using a breakup _v=500 m/s. The parent body orbit and breakup point are from the historical breakup of 2001-049D, satellite 26960 in the U.S. Space Surveillance Network (SSN) catalog. As the debris cloud propagates from the point of breakup, it forms a band of orbits about the original parent.

2.3. Orbital Distribution and Propagator Error

Each debris particle, generated at the estimated time of breakup, was propagated using the SGP4 algorithm. It does not include an actual solar flux model, but instead uses a fitted drag rate based on an empirical fit. For this reason any particles dipping into the atmosphere become unreliable and are rouge points in the correlation charts. This study involves only well-behaved groupings of fragments. Only those that are unaffected by drag are used. The end result is a study on objects orbiting in stable, long-term orbits with a reasonable accuracy for modeling each object's orbital plane.

Figure 1. Simulated Debris Cloud

3. RADAR CORRELATION WITH BREAKUPS

This paper limited detection to within 30 days after an event, due to large errors introduced in propagating simulated particles for longer. Given that a particle is detected in this time and it possesses the radar detection characteristics of an object that could have a trajectory linked back to the parent at breakup, then it is a possible fragment. It should be emphasized that a radar detection with matching criteria is only possibly related to the breakup and may in fact be from an unrelated source.

3.1. Haystack Radar Geometry

The Haystack radar, operated by MIT Lincoln Laboratory, is located in Massachusetts, USA at a Latitude and Longitude of 42.6˚ N and 288.5˚ E. The pointing characteristics for the gathered data were 75˚ elevation, and 90˚ azimuth. The radar operates with a full-width half-max (3dB intensity) of approximately 0.058˚. It has a detection range of 2000 km, and can detect particles as small as 3mm (below 500 km). The radar operates in a staring mode, which means the dish is fixed at the same elevation/azimuth. Haystack operates at a 10.0 GHz frequency and peak power of 400 kW. The simulation assumes that any fragment orbit plane passing through the beam was detected.

3.2. Debris Correlation Method

Correlation of detected debris is accomplished by fencing in the detections to match five criteria: 1) time of breakup, 2) time of observation, 3) range, 4) range rate, and 5) matching both range and range-rate to the simulation. This process involves matching detected debris with a cloud generated from an estimated time of breakup. The time of observation with range, with range rate, and range with range-rate charts (see Section 4), must include the detected debris in order for the debris object to meet the simulated constraints of the breakup. The time range is important because the orbit plane, as described previously, precesses at a specific rate. Relative to a point on the Earth, the breakup cloud contains particles that arrive early and late, due to each individual orbit plane. Time range is established by the leading particle, or beginning of the time fence, and by the trailing particle which closes the range of possible observations. Similarly range and range-rate function to detail the particle with respect to the detected particle's orbit. The point at which the Haystack radar hits each particle's orbit determines how high, and at what velocity relative to the beam a particle will be detected.

Contours form within the simulated orbits which limit the possible matches from observation. The radar charts used are 2-D representations of a 3-D cloud, and thus cause some dissimilar orbits to overlap. The final check is to ensure that a radar detection lies at the same position as the particles similar to it in the simulated debris cloud. This is accomplished by generating two charts: 1) Time vs. Range, with Range Rate contours, and 2) Time vs. Range Rate, with Range contours. The contours establish isotropic zones, limiting detected particle orbit parameters within the simulated cloud. If all five of these details line up, a unique "mapping" of the particle is established, which gives credibility to the link between a detected particle and a known breakup.

4. POSSIBLE DETECTIONS BY THE HAYSTACK RADAR

Two historical breakups, 2001-049D (SSN 26960) and 1990-110G. (SSN 21012), were examined during the course of this study. Each occurred within a month of Haystack operation times. 26960, a particularly large breakup, was a PSLV (Polar Satellite Launch Vehicle) rocket body which was assessed as a propulsion breakup. Haystack did not take measurements until 26 days later. 21012 was a Proton Ullage Motor under the COSMOS 2109-2111 mission, where the assessed cause of breakup was also propulsion related. Haystack was not active until 17 days after the 21 Feb 2003 breakup.

4.1. 26960 Breakup

The PSLV breakup was particularly large, with 326 objects catalogued. The fourth stage of the PSLV, after successfully delivering two satellites to polar orbits, had a propulsion system failure which resulted in the many debris objects reported. The breakup time was estimated at ~11:40GMT on the 19th of December 2001. At the time of breakup, 26960 had an inclination of 97.9˚, and an eccentricity of 0.01.

In Figs. 2-7, using only the breakup time from the breakup report, simulations of the observation were taken during the afternoon of January 20, 2002. As expected, particles with smaller _v produce a smaller grouping contained within the boundaries of values for particles with larger _v. The lower _v groupings always intersect higher _v groups, thus higher _v particles may exist in lower _v circles. If a detected object is included in more than one group, this means that it could possibly be any _v scenario that it intersects. For example: a detected object is included in the 100 m/s group, but just on the edge of it. By default, it is also included in the 500 m/s group (because the lower _v groupings always remain within higher _v groupings). The possible scenarios established include _vs ranging from 50 m/s to 500 m/s. The results of the PSLV analysis show that under the originally reported breakup time of 11:40 GMT five detected objects possibly correlate to the 26960 breakup. In order to match all criteria, these objects would have had to be ejected with minimum _vs of 200-300 m/sec.

It should be noted in Fig. 2 that Haystack detections are grouped in relatively narrow range rate bands while the variation for higher _vs in the simulated data is quite broad. Although this is only an example and the shape of the simulated pattern varies depending on the parent orbit and time/location of the breakup, it seems likely that few particles are ejected at the highest _vs.

The minimum _v cloud from which a correlation could be extracted was the 300 m/s. Figs. 6 and 7 depict the this cloud separated into contours of range rate and range from the simulated population of orbits. The final criteria for a correlated object is that the detection must lie within the proper contour of the simulated cloud. Of the five detections singled out as possible correlations, only one met with the proper contour, while the other four were invalidated because their range and range rate characteristics were not at the right place within the simulation. The validated radar detection had a range rate of -0.481 km/s, as shown in Fig. 6, which is within the defined simulation range. Fig. 7 matches this objects range of 642.48 km with the contour range of 600 – 700 km.

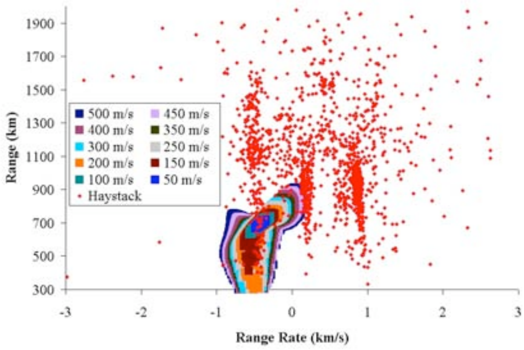

Figure 2. Range Rate vs Range of all Haystack detections with 26960 Simulation Overlaid

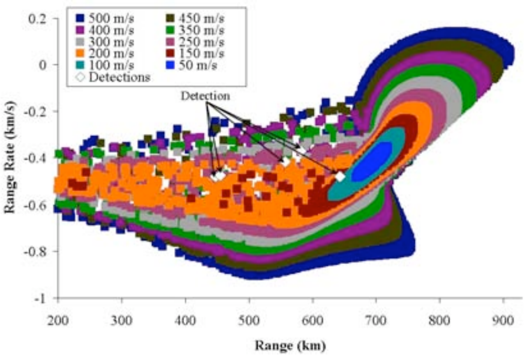

Figure 3. Range vs Range Rate by ejection _v

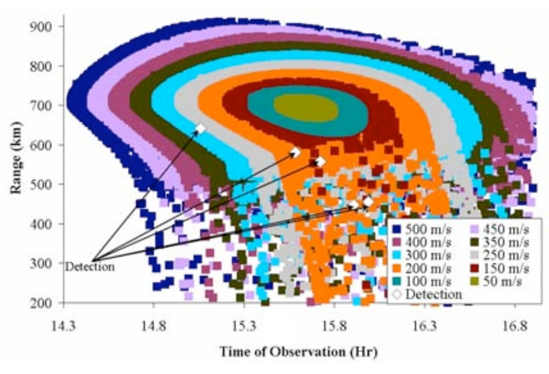

Figure 4. Time vs Range by ejection _v

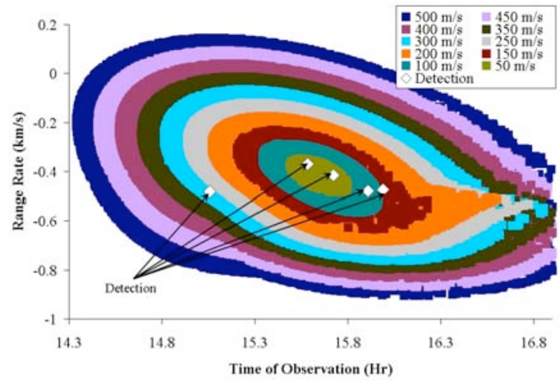

Figure 5. Time vs Range Rate by ejection _v

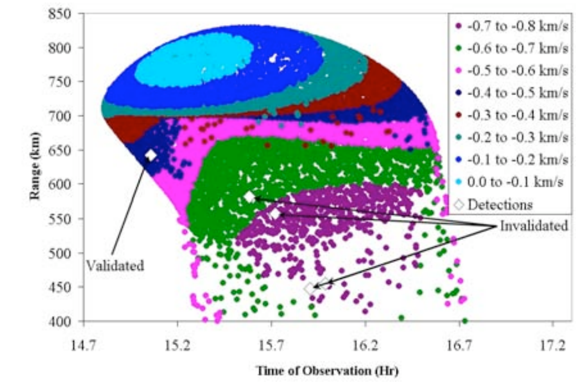

Figure 6. Time vs Range for 300 m/s Cloud, with Simulation Range Rate Contours (see Fig. 4)

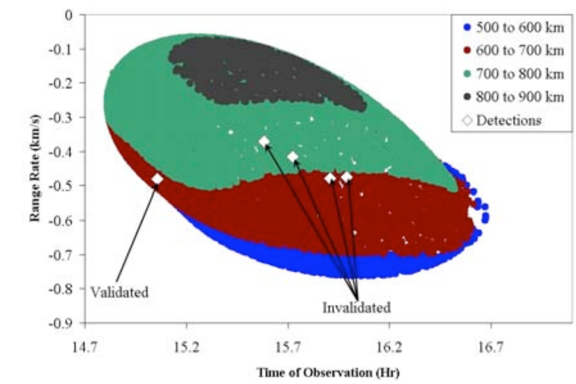

Figure 7. Time vs Range Rate for 300 m/s Cloud, with Simulation Range Contours (see Fig. 5)

Assuming that the provided breakup time was only an estimate, the breakup was simulated over a range of times. Reported at 11:40 GMT, the breakup cloud was generated starting at 11:10 GMT. A simulation was performed, and the breakup time was modified by 0.05 hour increments up to 12:10 GMT, repeating the simulation at each increment. As Figs. 8-10 show, using a range of breakup times includes a much larger pool of possible detection events. With the additional swaths of possibilities, 4 additional detections are included. It should be noted that objects that begin to reenter the atmosphere exit the well-defined region representing the bulk of possible observations. This accounts for the noisy features appearing below a range of 600 km.

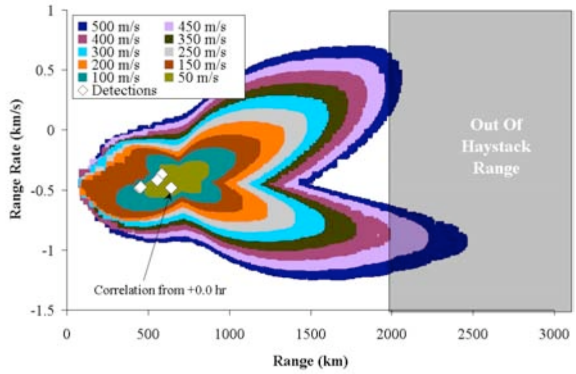

Figure 8. Range vs Range-Rate for varying breakup times

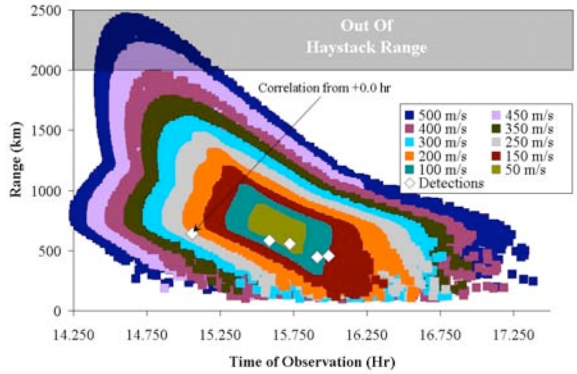

Figure 9. Time vs Range for varying breakup times

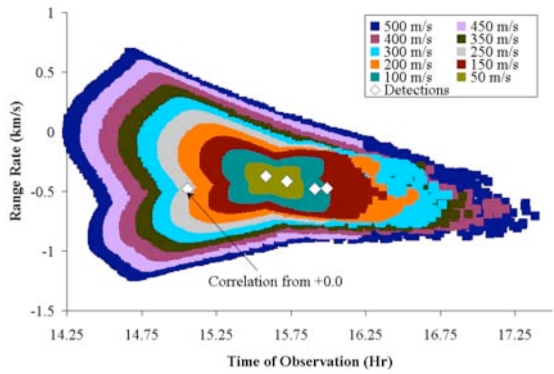

Figure 10. Time vs Range-Rate for varying breakup times

4.2. 21012 Breakup

The second object analyzed involved a Proton Ullage motor, SSN 21012. This breakup occurred February 21, 2003 at approximately 03:00 GMT, where the cause of this event was again assessed to be an explosion in the propulsion system. This was a much smaller event and only 1 additional debris object was cataloged. At the time of breakup the inclination of 21012 was 65.38˚, and was in a particularly eccentric orbit with e = 0.564. Figs. 11-16 depict the radar observations for 21012 using only the breakup time given by the breakup report. Only one possible correlation meets the criteria for a fragment detection and it would require a very high breakup _v, in the range of 450-500 m/sec.

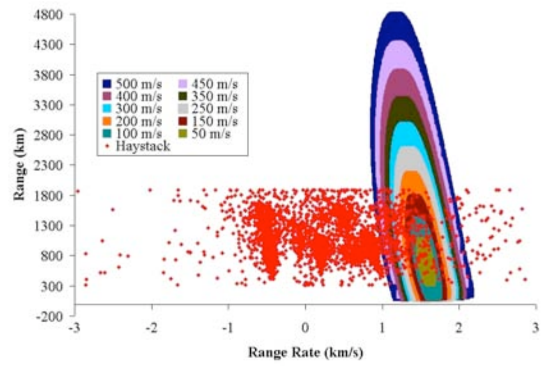

Figure 11. Range Rate vs Range of all Haystack detections with 21012 Simulation Overlaid

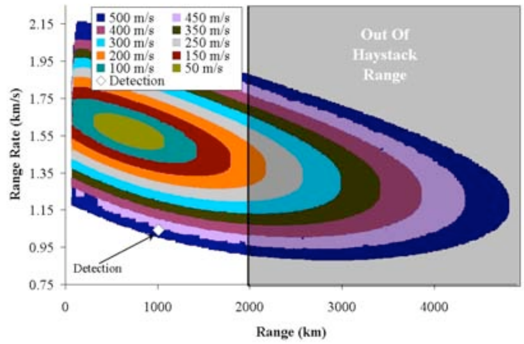

Figure 12. Range vs Range Rate by ejection _v

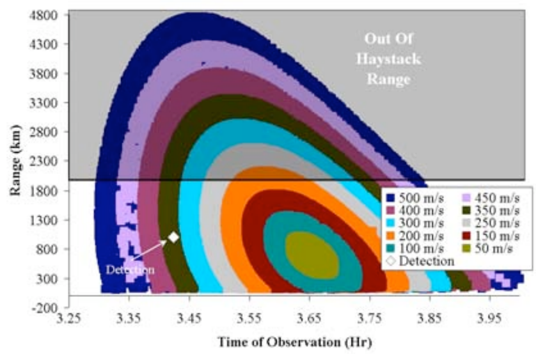

Figure 13. Time vs Range by ejection _v

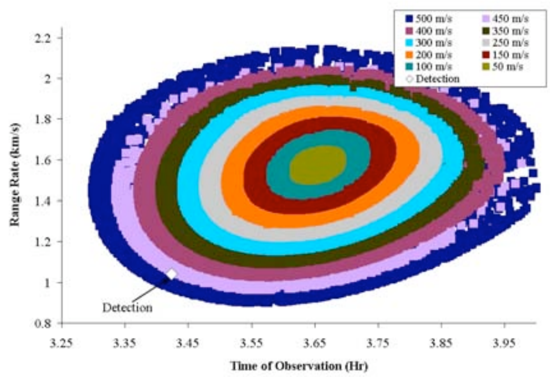

Figure 14. Time vs Range Rate by ejection _v

Using the minimum _v cloud of 450 m/s, the simulated cloud contours were examined, as shown by Figs. 15 and 16. The detection was rejected, as both the range and range rate of the detected object did not fit within the simulated pool of orbits. In Fig. 15, the detection had a range rate of 1.042 km/s, but lay in the grouping of 1.7 – 2.3 km/s. The range, at 1006.41 km, lay just shy of the grouping of 200 – 2200 km; however, without a proper range rate, the correlation would not work.

In this case, the assessed breakup time was particularly important. Because a _v imparted near the apogee would have a drastically different effect on the distribution of debris than one imparted near perigee, a variety of simulation breakup times were necessary. Varying the time of breakup does not reveal any additional radar detections which possibly correlate to the breakup; however, it does illustrate the sensitivity of variation in the breakup time for highly eccentric orbits with respect to the simulated cloud shape under detection conditions by Haystack, shown by Figs. 17-19.

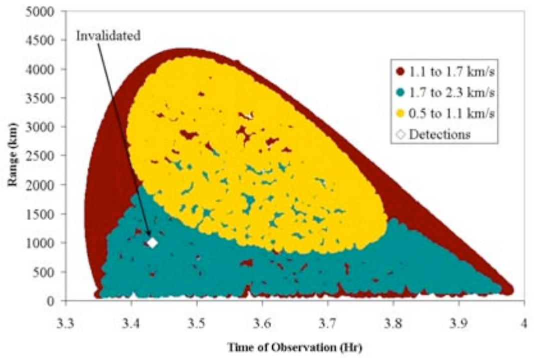

Figure 15. Time vs Range for 450 m/s Cloud, with Simulation Range Rate Contours (see Fig. 13)

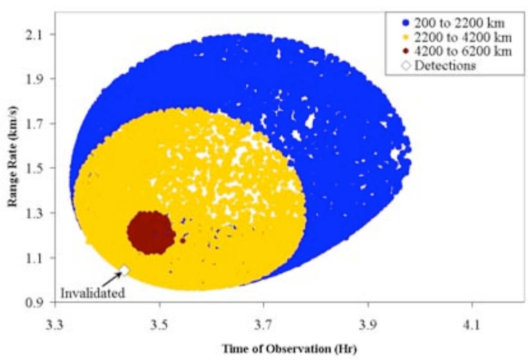

Figure 16. Time vs Range Rate for 450 m/s Cloud, with Simulation Range Contours (see Fig. 14)

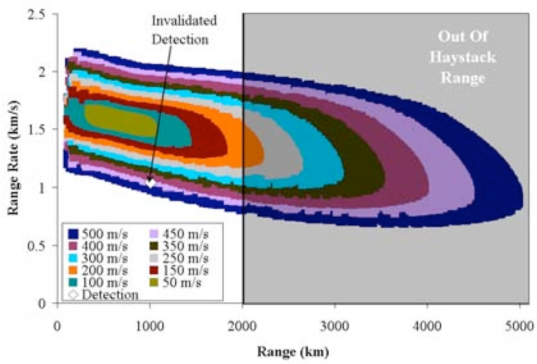

Figure 17. Range vs Range-Rate

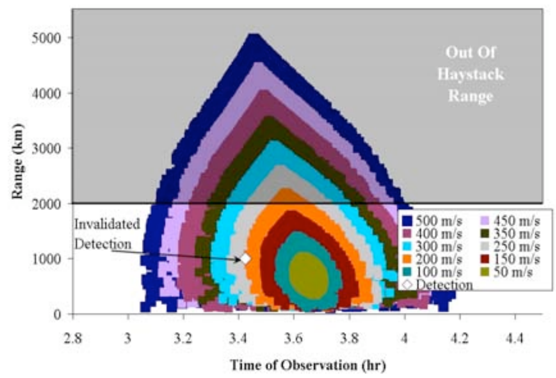

Figure 18. Time vs Range

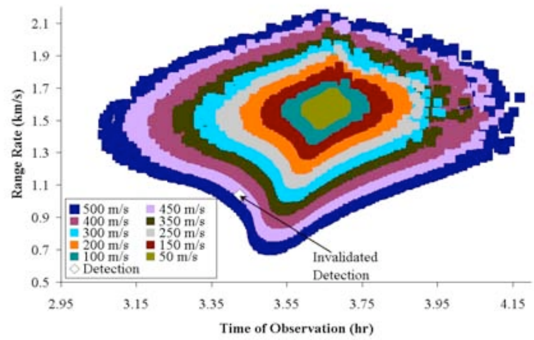

Figure 19. Time vs Range-Rate

5. CONCLUSION

This analysis serves to connect breakup parameters such as time of breakup and the _v imparted to debris with parameters measured by ground sensors such as the Haystack radar. Radar detections that lie within the parameters established by the range, range rate, and time of observation data presented represent possible breakup fragments, but the correlation is not definitive. These detections lie in the same plane as the breakup and have similar orbits as compared to estimates of the range of particles ejected by the event.

6. REFERENCES

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