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Reentry Analyses from Serendipitous Radar Data

Benjamin G. Miller, Robby Keh, Yash Sarda, and Moriba K. Jah

Introduction

Public weather radar provided by the National Oceanic and Atmospheric Administration (NOAA) provides a way to automate detection, characterization, and impact site estimation of re-entering bodies. Meteorite falls are a well-documented phenomena, and are analyzed here to identify a methodology applicable to tracked and untracked satellites. Current meteorite reentry detections rely on eyewitness input and may cover only 0.3% of total reentries (Beech, 2003). This work covers the radar data analysis of the two meteorite fall case studies, including the Ash Creek event investigated by M. and J. Fries (2003), and identifies a set of characteristics for automatic real-time identification without eyewitness dependency. The algorithm has been validated for false positives against a 2 hour span of data covering the continental United States, encouraging further scaling of the process to full-scale operation. The exploration and development of algorithmic methodologies for detection and identification of resident space objects re-entering Earth's atmosphere through commonly collected weather radar data was supported by funding through the TexasView Research and Education Grant.

Methodology

The NOAA operates a series of 159 Weather Surveillance Radar 1988 (NEXRAD) Doppler radar stations across the continental United States as shown in Figure 1. Every 5-10 minutes, every station uploads a set of local scans across several altitudes to a public archive, each covering a 100*x*100 km horizontal area up to 8.4 km in altitude, with significant overlap. The "Level II" data products provided by each station include reflectivity, radial velocity, and spectrum width (or standard deviation of local velocity) measurements. While all three products can provide useful information, only radial velocity and spectrum width were considered here, as they measure the uniquely strong atmospheric shear from high-speed reentries which can persist throughout the long-period scans. To reduce low-altitude noise from weather or animal presence, the lower quarter altitudes of each scan set were ignored. The OpenCV module of Python was used to process data unpackaged by the Atmospheric Radiation Measurement Radar Toolkit (Helmus and Collis, 2016).

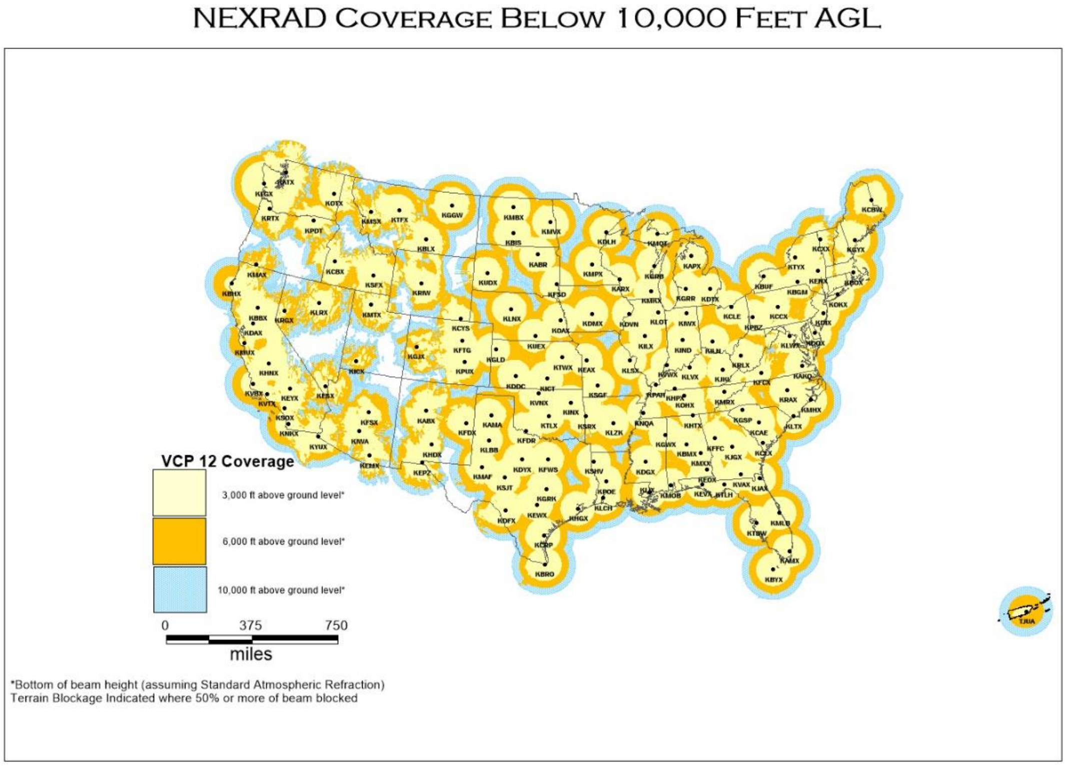

Figure 1: NEXRAD station map

As case studies, the meteorite falls from Ash Creek and Battle Mountain were analyzed (KFWS 02/15/2009 16:53:32 and KLRX 08/22/2013 06:17:04 respectively), and false positives were tested for across contiguous 24-hr periods. These cases were used to ensure feasibility of detection across a wide range of different reentry scenarios, as the Ash Creek fall had very coherent phenomena while the Battle Mountain fall had substantial dispersion. Successfully identifying these disparate events in a noisy atmospheric environment required a robust detection method, and so processing followed a multi-stage process as shown in Figure 2. Firstly, radial velocity was filtered based on a minimum speed, and radial acceleration gradients were then calculated as the spatial derivative of these velocities. A basic set of area, eccentricity, and spatial density filters were applied, and contour features were defined. If successful, contours were then calculated for the spectrum width data by applying the latter filter set. If both methods returned a detection, altitude-specific processing was performed iteratively on the spectrum width data by using a *2*iteration* pixel dilation filter and a reduced *eccentricity/iteration* requirement. The Cartesian positions relative to the radar station could then be converted to latitude, longitude, and altitude for Cesium-based plotting, permitting future integration with the ASTRIAGraph satellite visualization interface.

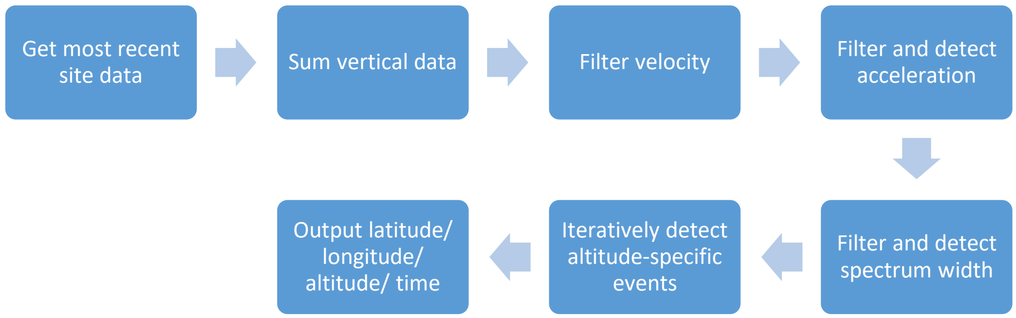

Figure 2: Reentry identification process

A tentatively feasible filter set was defined using the above process on the case studies, as will be later discussed, permitting an increase in experiment scale. A limited quantity of real-time data was acquired using the computing resources of the Texas Advanced Computing Center (TACC) for false positive testing to evaluate the potential functionality of full-scale operation. Data was retrieved every five minutes for two hours from all NEXRAD stations, resulting in around 22GB of raw data. These radar sets were then processed for detections in parallel as above.

The current dependencies of the image filter prevent true removal of all data leaks, prompting research into removing dependency on the Python module Matplotlib and moving towards a local process with internal image processing.

Results

The initial case studies were used to develop the empirically-derived filter set shown in Table 1, with Ash Creek's radar detections shown in Figures 3 and visualized in Cesium in Figure 4. Single iterations of the algorithm took an average of 30 seconds to complete with non-optimized programming, requiring an estimated 16 parallel processes to achieve real-time behavior.

The employed filter set successfully detected both case study events with no false positives in the initially tested six days, suggesting that the empirically-derived filter set is indeed effective for disparate fall phenomena (coherent versus dispersed bodies). Two detections were made for Ash Creek, but the velocity found by differencing the detections in a single 5-minute scan was an order of magnitude different than computed by Fries (56m/s compared to 7m/s), indicating that positional information itself is not valid for the identification of object velocities. As a topic for future research, it may possible to measure persistent turbulence and thereby characterize velocity. Similarly, it may be possible to exploit the shape of the turbulence regions in order to infer mass, and establish initial boundary conditions for trajectory analysis. However, for the purposes of this report, the issue bears no effect upon the accuracy of initial reentry detections.

Radial Velocity (m/s)	Spectrum Width (m/s)	Acceleration (m/s)	Min/Max Area (m^2)	Eccentricity	Density (% of Bounding Box)
20	10	8.75	1-5	0.3	30

Table 1: Empirically-derived filter settings

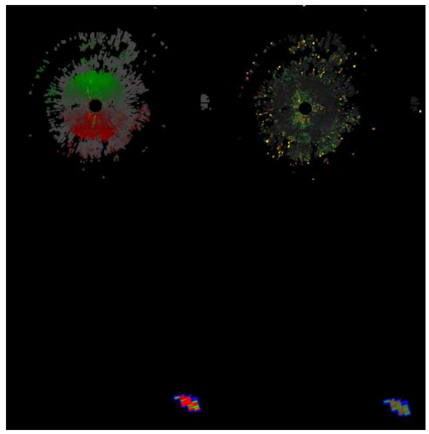

Figure 3: Detected phenomena for Ash Creek (outlined in blue). Left: radial velocity. Right: spectrum width

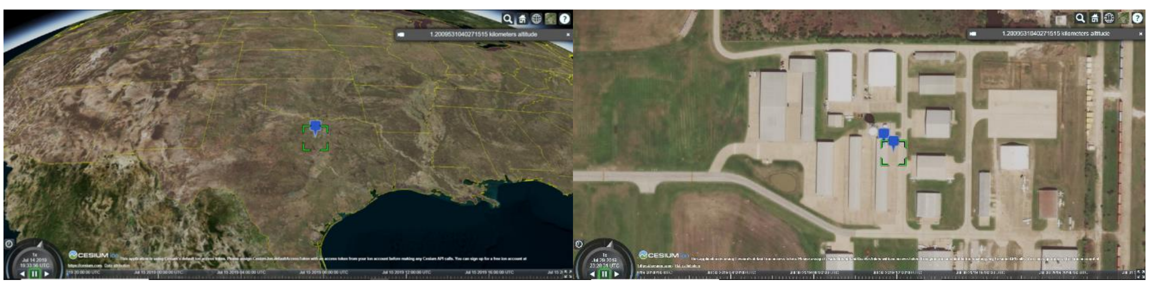

Figure 4: Ash Creek detection visualized in Cesium (2 altitudes)

Local case studies were insufficient to characterize whether or not the methodology was robust enough to weather and noise effects to permit continental-scale real-time operation, which demanded testing on TACC resources. In processing the aforementioned 2 hours of continental-scale radar data, no detections were made, suggesting a strong resiliency to false positives that will be further established through full-scale operation and analysis of additional known case studies.

Conclusion

While automating trajectory analysis from radar data will require future research into velocity and mass estimations using turbulence data, successful reentry detections have been made on case studies, with no false positives detected across a full 2 hour period of continental-scale data. By extracting latitude, longitude, and altitude of detected radar phenomena, re-entering meteorites and satellites can be plotted into a Cesium interface for simple user access, allowing improved meteorite retrieval and awareness of satellite reentry events. By removing the dependency on eyewitness input in defining meteorite falls, and in removing the need for a-priori orbital knowledge on re-entering satellites, the rate of change in the orbital population can be better defined for space situational awareness. Future work will attempt to construct an empirically-based predication table for impact dispersion of a body based on the detected phenomena, which may be used to augment current reentry analysis models and improve certainty in planned satellite deorbits.

References

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