AMSNEXRAD
Automated Detection of Meteorite Strewnfields in Doppler Weather Radar

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Abstract— For several years meteorite recovery in the United States has been greatly enhanced by using Doppler weather radar images to determine possible fall zones for meteorites produced by witnessed fireballs. While most fireball events leave no record on the Doppler radar, some large fireballs do. Based on the successful recovery of 10 meteorite falls 'under the radar', and the discovery of radar on more than 10 historic falls, it is believed that meteoritic dust and or actual meteorites falling to the ground have been recorded on Doppler weather radar[1].

Up until this point, the process of detecting the radar signatures associated with meteorite falls has been a manual one and dependent on prior accurate knowledge of the fall time and estimated ground track. This manual detection process is labor intensive and can take several hours per event.

Recent technological developments by NOAA now help enable the automation of these tasks. This in combination with advancements by the American Meteor Society[2] in the tracking and plotting of witnessed fireballs has opened the possibility for automatic detection of meteorites in NEXRAD Radar Archives. Here in the processes for fireball triangulation, search area determination, radar interfacing, data extraction, storage, search, detection and plotting are explained.

Keywords—Fireballs, Meteors, Meteorites, Doppler, Radar, AMS, American Meteor Society

1. Introduction

1.1. What is NEXRAD?

NEXRAD or Next Generation Radar is a network of Doppler weather radar stations operated as a joint project by NOAA, the USAF and the National Weather Service. The network was established by 1997 and all data from all stations has been archived since that time and is available online. Each radar station creates a file that spans 1 sweep for each elevation angle in the radar. A new file is generated every 5-10 minutes and available online in almost real time. The data structure is comprised of 720 rays per sweep that radiate from the radar's location. Each ray contains 1000s of gates or pixels that are spread out by approximately .25km within the ray. Each gate contains numerous data values that represent reflectivity, radial velocity and other values. Each radar stations covers a radius of 300km. The network is made up of over 160 stations and 2 or more radar stations cover nearly every inch of the United States.

1.2. NEXRAD Meteorite Recovery

The NEXRAD meteorite recovery process was discovered and pioneered by Jeff Fries, Marc Fries and Rob Matson. Since 2009 this method is responsible for 11 recovered meteorite falls. Radar signatures associated with more than 10 historic falls have also been found and several suspected radar falls have been identified, but not recovered. The list of NEXRAD identified meteorites is:

- Unnamed, AZ (2016)
- Osceola, FL (2016)
- Mount Blanco, TX (2016)
- Creston, CA (2015)
- Addison, AL (2012)
- Novato, CA (2012)
- Battle Mountain, NV (2012)
- Sutters Mill, CA (2012)
- Mifflin, WI (2010)
- Lorton, VA (2010)
- Whetstone Mountain, AZ (2009)
- Ash Creek, TX (2009)
- Grimsby, ONT (2009)
- Red Canyon Lake, CA (2007)
- Berthoud, CO (2004)
- Park Forest, IL (2003)
- Monahans, TX (1998)
- Portes Valley, NM (1998)
- Kitchner, ONT (1998)
- Elbert, CO (1998)
- Worden, MI (1997)

The manual process requires the analyst(s) continually monitor the AMS website and other news sources keeping an eye out for large falls that are characteristic of meteorite dropping fireballs. These characteristics include reports from dozens or hundreds of witnesses and reports of sonic booms. Once a potential fall is identified the analyst must:

- Determine the time and place of fall
- Identify radar stations within range of fall zone
- Download data files for each radar station before and after the fall (+/-30 minutes)
- Visually examine images presented from radar files for each time period and cut angle (usually 6 or more) and locate potential meteorite clouds near the time and place of the fall.

Once a radar return has been found, an exhaustive review of all sweeps and stations for multiple times is completed and all matching relevant signatures are compiled and saved into a single KMZ file. This manual process can take several hours when a fall happens, and requires that analysts review candidate falls that aren't meteorite droppers. While effective, the process is time consuming and requires 100s of hours of volunteer work from Marc Fries, Rob Matson and other members of the community.

2. Automation Opportunity

Three recent technologies have converged to create an opportunity for automation of the NEXRAD Meteorite Recovery process. These are: the AMS Fireball Reporting and API system; NOAA's 'Big Data' project which migrated all NEXRAD data to the Amazon Web Cloud; Pyart – a python library created by NOAA that allows programmatic reading and plotting of NEXRAD data files.

2.1. AMS Fireball Reports and API

The AMS Fireball Reporting Program captures data from eyewitnesses of fireballs and in most cases is capable of determining the time and location of fireball events within a small margin of error.[3] The when and where of every fireball event logged by the AMS is programmatically available through the AMS Data APIs (JSON).

2.2. NOAA NEXRAD on AWS Cloud

Prior to the 'Big Data Project', NEXRAD files were available on a request basis – meaning a web request with a station, date and time had to be submitted and then a few minutes later the file would be delivered. While possible, automated data access was disjointed. By moving the archive to Amazon Web Service (AWS), every file from every station is now available on a cloud drive that can be mounted to a local computer. This level of data access allows seamless searching and copying of data files from the archive.

2.3. Pyart Python Library

NOAA has also created a robust python library called Pyart that is designed to access NEXRAD and other radar data files. With the Pyart libraries NEXRAD files can be programmatically opened, plotted, decoded and scanned.

3. Automated Process

The automated detection process has several parts. First the time and place of the fall must be identified. A script monitoring the AMS APIs triggers the radar scan when new worthy events occur. Next, the NEXRAD stations and files within 300km of the event are identified and the time relevant files are downloaded. Plots for each radar, cut angle and time slice are then automatically created and presented on a single page view. The raw data inside the file is then decoded and exported to a MYSQL database where it is then aggregated and examined for auto-detection. A more detailed explanation of each process follows.

3.1. Determine Time and Place of Fall

The automated detection process starts with eyewitness reports logged to the AMS system. Each witness enters their location, the time they saw the fireball and the elevation and azimuth angles for the starting and ending point of the fireball. The AMS system computes the intersections of all of the witness sightings with each other, averages the results and produces a trajectory estimate that is usually <50km accurate. By averaging all of the submitted times, and then re-averaging only those times that are within 15 minutes of the original average, a revised time estimate can be computed that is usually within a 1-2 minutes of the actual fall. This information is accessible from the AMS API and a script can be coded to automatically check for new events each day. Armed with the time and place of the fall, relevant NEXRAD files can then downloaded, plotted and searched.

3.2. Download Files

After the script has determined the end point of the fall it identifies all NEXRAD stations within 300km of the fall location. The AWS directories are traversed and scanned and all files within +/- 30 minutes of the fall time are automatically downloaded.

3.3. Simple Plots

A plotting program using MATPLOTLIB is run and a graphic map plot of the radar is created for each station, sweep and time increment. Each of these plotted files is arranged on one easy to view page. From this page, the entire hour time period across all radar stations can be visually scanned in a minute or less. The total number of plots needed to properly review radar data associated with a fall equals the total number of radars queried (3-5) times the number of cut angles in each radar (6-15) times the number of time intervals scanned (3-6) or a number between 54 and 450. Complicating the manual review process further, is the need to compare images from one time period to another. Having all of these images pre-created and presented with the trajectory information on a single page expedites the review process greatly.

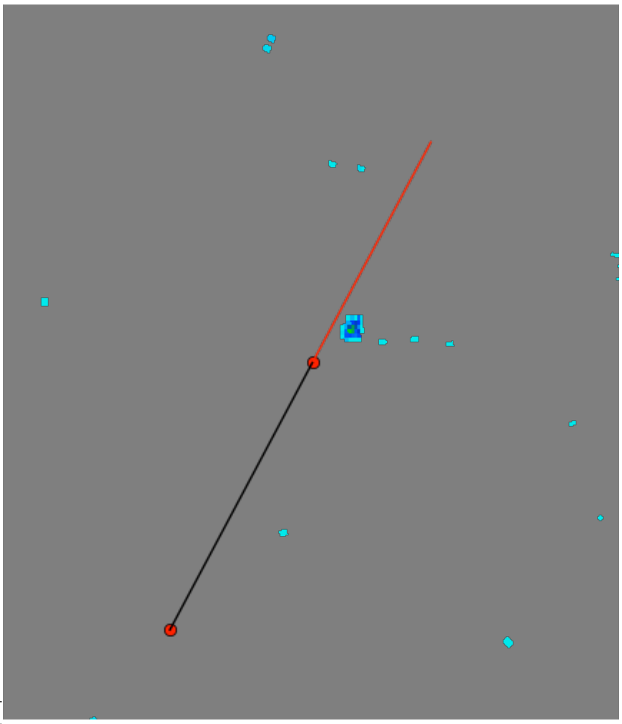
4. [

Figure 1 – Reflectivity Image and Fireball Trajectory for Osceola Meteorite, 2016

4.1. *Raw Data Extraction*

A deeper scan of the data is executed after the simple plots are created. Data for each file is structured in a multi-dimensional array by sweep, ray and gate. Each gate or pixel holds the following values: gate time, gate longitude, gate latitude, gate altitude, reflectivity (+/-), differential reflectivity (+/-), radial velocity (+/-), spectrum width and, differential phase. These values are extracted from the binary data file and saved to a text file for later loading and analysis in MYSQL. Only pixels within the geographic bounding box of the fall location are extracted from the file. This bounding box is dependent on the trajectory of the fall, but can vary from 2500 to 10,000 square KM. The size of the search area is derived from the distance between the dark flight point and the geometric impact point resulting in larger search areas for shallow fireballs. This search box distance can be increased when the trajectory is more uncertain.

4.2. *Raw Data Aggregation and Detection*

The extracted raw data is loaded into a MYSQL database and aggregated by geographic sector. The entire bounding box is cut into 10x10 KM squares and values are assigned for the total reflective gates inside each square for each radar, sweep and time slice. Sectors with no reflective gates are given 0 values. Non-reflectivity data values are also averaged in a similar way. A recursive program then scans through the data and computes the average change of each radar, sweep, time slice and sector to the value before and after it. These averages are called the forward rolling average and the backward rolling average. Once the data is structured in this way, queries can be run to detect the most anomalous, irregular and transient reflectivity bursts within the geographic search area and time of the fall.

Sector: 62
Gate Average Increase Factor: 114.0

Reflectivity History For KVAX

Sweep	1501	1510	1520	1529	1538	1548
0	0	0	0	20	0	0
1	0	0	0	0	0	0
2	0	0	0	10	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	3	0	0	0

Reflectivity History For KJAX

Sweep	1507	1517	1527	1537	1547
0	0	0	4	8	4
1	0	0	0	0	0
2	0	0	52	0	2
3	0	0	30	0	0
4	0	0	22	0	0
5	0	0	2	0	0
6	0	0	0	0	4
7	0	0	0	0	0

Figure 2 – Reflective Gates Table showing detection of Osceola Meteorite from two radars.

4.3. *Final Presentation*

Once all data has been extracted and modeled and all image files have been created the data is placed inside a KML that includes layers for witness and trajectory information, plots of all radar sweeps organized by sweep and time and the colored sector output. Ideally once the system is fully operational, these KMZ files as well as an email or text notification will be automatically sent within a few hours of a fall occurring.

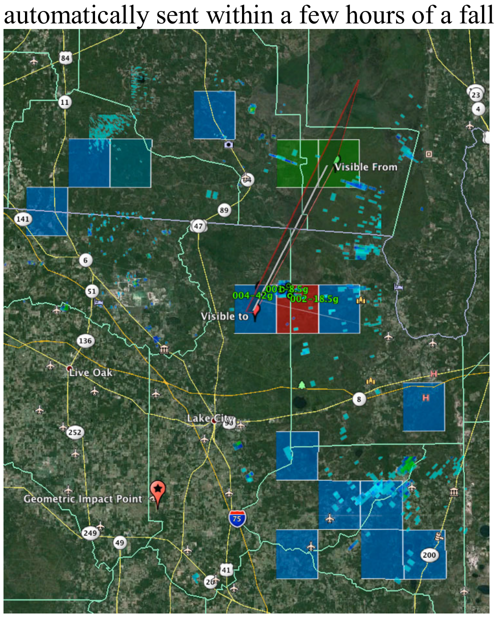


Figure 3 – Trajectory, Sector Detection Output and Radar Overlays for Osceola Meteorite Fall, 2016

5. Signature Detection & Time Values

Auto-detection of most known events is successful without constraining the data values beyond their record counts, meaning the current detection system does not consider the values held by each reflective pixel or the other field values that are present. The NEXRAD system is dual polarized radar with one beam oscillating vertically and the other oscillating horizontally. Data collected from these radars can be used to differentiate precipitation types. Rain, snow and hail have different signature values. With study, data comparison and analysis it should be possible to identify a data signature specific to meteorites. NEXRAD radars are scientific instruments that capture data on meteorites falling through the air and this data set, at this level of detail has never been studied before.

Additional specific time values are also present when the raw data is examined. Each gate record holds the exact time it was recorded to the microsecond. When the exact time of the fall is known, and meteorite reflections exist, the difference in time between the end of illuminated flight and the presence of the radar return can be easily calculated. This time difference can then be used to infer the size of the meteorites caught by the return.

6. Next Steps & Planned Enhancements

The computer code to accomplish all that has been described has been written and is working, but more work is needed to speed up and fully automate the process. The current program is CPU intensive and requires significant run time to build all of the files and extract and analyze all of the data. By re-working the program to utilize parallel processing and distributed computer architecture the speed will be greatly increased. A production hardware environment to run the program and house the data also needs to be secured. At that point, the program will be run against the archive of AMS fireball events. It will also be setup to monitor new events as they occur.

Additionally, the developers of PYART have added support for Rainbow radar files, which are commonly used throughout Europe and other parts of the world. With this development, it is possible to extend radar meteorite recovery capabilities to the international community. The biggest challenge to making this a reality is determining who the weather authority is for each country and how to obtain the data files from that agency.

Acknowledgment

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