# A METHOD FOR ESTIMATING METEORITE FALL MASS FROM WEATHER RADAR DATA.

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**Introduction:** Techniques such as weather RADAR, seismometers, and all-sky cameras allow new insights concerning the physics of meteorite fall dynamics and fragmentation during "dark flight", the period of time between the end of the meteor's luminous flight and the concluding impact on the Earth's surface. Understanding dark flight dynamics enables us to rapidly analyze the characteristics of new meteorite falls. This analysis will provide essential information to meteorite hunters to optimize recovery, increasing the frequency and total mass of scientifically important freshly-fallen meteorites available to the scientific community. We have developed a mathematical method to estimate meteorite fall mass using reflectivity data as recorded by National Oceanic and Atmospheric Administration (NOAA) Next Generation RADAR (NEXRAD) stations. This study analyzed eleven official and one unofficial meteorite falls in the United States and Canada to achieve this purpose.

**Methods:**

Two approaches have been attempted: an empirical assessment of the historical relationship between fall mass and RADAR reflectivity, and an analytical assessment of mass from RADAR returns by mathematical estimation.

*Empirical Approach.* RADAR Data from known meteorite falls was retrieved from the NOAA database utilizing NOAA's Weather and Climate Toolkit (WCT) and quantified in terms of the absolute value of total reflectivity per radar sweep by summing the reflectivity value associated with each meteorite pixel, and compared to Meteoritical Society database values for meteorite mass recovered. The resulting totals were graphically analyzed to discover any possible trends between reflectivity and recoverable meteorite mass. See Results, Table 1 for values.

*Analytical Approach.* The calculation uses RADAR pulse properties to find the total reflecting mass and then applying a correction to account for falling masses that evade RADAR detection. RADAR reflectivity power returned to the RADAR ($P_R$, measured in decibels, or dBZ) is a measurement of total power reflected from an object back to the RADAR. $P_R$ can be used to calculate the reflectivity (z) of that return according to the RADAR equation [1]:

$$P_R = \frac{\pi P_E G^2 \theta \phi h |K|^2 l z}{1024\, ln(2) \lambda^2 r^2} \qquad RADAR\ Equation$$

where $P_E$ is emitted power, $G$ is antenna gain, $\theta$ and $\phi$ are antenna beam width in horizontal and vertical planes, respectively, $h$ is pulse length, $|K|^2$ is the target dielectric factor, and $r$ is distance to target [1]. This form of the RADAR equation assumes a diffuse target that fills the radar beam, which is the best estimate for the small meteorites that show up most prominently in NEXRAD imagery. Most variables of the RADAR equation are accounted for by NEXRAD system constants with the exceptions of $P_R$, $z$ and $|K|^2$.

By combining the RADAR equation and a commonly used meteorological equation for precipitation ($z = nD^6$), it was possible to formulate the following equation to quantify the number of meteorites "seen" in a particular RADAR sweep:

$$n = (0.2742)\frac{z_m \rho^2}{m^2} \qquad (Equation\ 1)$$

where $n$ is number of meteorites, $\rho$ is meteorite density, $m$ is mass of meteorites belonging in the RADAR sweep, and the constant accounts for NEXRAD system constants and the assumed geometry of spherical meteorites. To simplify the equation, it was assumed that meteorites are spherical and of uniform density. As you may notice, the z variable for reflectivity in Equation 1 has been modified to $z_m$. $z_m$ is the raw reflectivity data multiplied by a calibration constant accounting for the differences between the dielectric factors ($|K|^2$) for water and meteorite material ([2] and [3] provided the proper meteorite dielectric values). The reflectivity totals are displayed as both z and $z_m$ in Table 1.

To acquire the necessary values for Equation 1, extensive dark flight modeling analysis of each fall was required. To find the mass of meteorite pieces belonging in the scanned portion of the fall, many fall details and theories of projectile motion were used to calculate mass distribution. Dr. Fries's dark flight model, JÖRMUNGANDR (acronym: Just because ÖRMUNGANDR) mathematically predicted the mass of the pieces present at each scan time and altitude. Fall details consisted of fireball terminus altitude, terminus time (with seconds accuracy), initial velocity, initial angle below the horizontal, initial direction, meteorite density [4], scan times (with seconds accuracy), scan altitude, local wind velocity, atmospheric density and atmospheric temperature. These details were obtained through the searching and analysis of video and published literature meteorite records [5,6], seismometer records, and fall location-specific weather balloon data. For scan time, it was necessary to correct a technical bug in the NOAA freeware with a procedure developed by Dr. Rob Matson before proceeding with the calculations.

Each sweep's JÖRMUNGANDR determined mass, known density (dependent on meteorite type) and totaled $z_m$ value were used with Equation 1 to calculate the number of meteorites of that mass present in the scan. The resulting data for number of meteorites per RADAR sweep was plotted versus the corresponding mass values to produce histograms of RADAR observable mass distribution. From this point, it is necessary to estimate the total mass distribution of the meteorite falls to include masses that do not appear on RADAR. Two power law fitting methods (Strict Fitting for small falls with $z_m$ values under 1500 dBZ and Morávka Fall Based Fitting [7] for large falls above 1500 dBZ) were used to fit the histograms and estimate the quantity of masses missed by RADAR in between scan revolutions according to the mass range of the fall. Two fit types were necessary upon recognition that it is likely there is a fundamental variation in the fragmentation behavior of "large" vs "small" meteorite falls.

ite recovery. The three falls showing high (above 10%) recovery efficiency in Table 1 and Figure 1 were located on search-friendly terrain with high search participation, showing the correlation between ideal search conditions and high recovery rate. For example, Creston is 22% because one large meteorite was recovered on the side of a road for what was otherwise a very small fall. Under typical conditions, it can be expected that less than ten percent of a meteorite fall is recovered for scientific study.

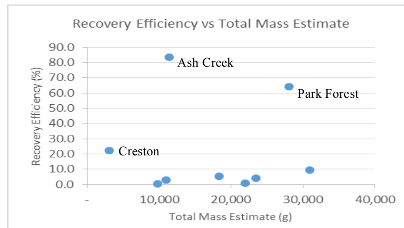


**Figure 1:** Scatter Plot Showing the Distribution of Recovery Efficiency vs Fall Size.

We present these data with the caveat that an additional calibration is currently in progress. RADAR reflection from some meteorite fragments fall in the Mie region of optical scattering, where particle size and RADAR wavelength produce an interference effect. Accounting for Mie scattering should improve the fit to observed particle size and improve the fidelity of the measurement. We will present this refinement in a future publication.

| Fall | Meteorite Type[a] | Recovered Mass (g)[a] | Reflectivity Z (dBZ) | Corrected Reflectivity Zm (dBZ) | Fit Type | Total Mass Estimate (g) | Recovery Efficiency (%) |
|---|---|---|---|---|---|---|---|
| Ash Creek (2009) | L6 | 9500 | 1592.5 | 3992.0 | Moravka | 11,394.20 | 83.4 |
| *Mifflin (2010)* | *L5* | *3580* | *1565.5* | *3924.3* | *n/a* | *n/a* | *n/a* |
| Battle Mountain (2012) | L6 | 2900 | 1422 | 3564.6 | Moravka | 30,940.30 | 9.4 |
| Osceola (2016) | L6 | 991 | 711 | 1774.8 | Moravka | 18,366.90 | 5.4 |
| Park Forest (2003) | L5 | 18000 | 670 | 1679.5 | Moravka | 28,068.90 | 64.1 |
| Mount Blanco (2016) | L5 | 36.2 | 546 | 1368.7 | Strict | 9,832.00 | 0.4 |
| Sutter's Mill (2012) | C | 993 | 467 | 1206.4 | Strict | 23,457.50 | 4.2 |
| *Indian Butte (1998)* | *H5* | *1721* | *246* | *608.1* | *n/a* | *n/a* | *n/a* |
| Lorton (2010) | L6 | 330 | 220 | 551.5 | Strict | 10,979.20 | 3.0 |
| Grimsby (2009) | H5 | 215 | 204.5 | 504.5 | Strict | 21,915.10 | 1.0 |
| Creston (2015) | L6 | 688 | 82.5 | 206.8 | Strict | 3,081.90 | 22.3 |
| *AZ Unnamed (2016)* | *LL?* | *n/a* | *82* | *250.9* | *Strict* | *20,023.20* | *n/a* |

**Table 1**: Summary of Known and Estimated Values for the Studied Meteorite Falls
[a]Classification by the Meteoritical Society, published in the Meteoritical Society Bulletin.

**Results & Discussion:** Of the eleven official meteorite falls used in this study, full analysis was possible for nine. Mifflin produced an unreasonable fit that is under investigation, and Indian Butte is an old (1998) event that uses earlier RADAR parameters that do not compare well to more modern events. The method presented in this study is a fundamentally new tool to aid fresh meteorite recovery. As shown by the results obtained for the unnamed AZ fall (2016) on the bottom row of Table 1, with access to reflectivity data it is possible to develop a generalized estimate of fall mass before any meteorites are recovered. These models and estimates provide a glimpse into the mysterious nature of meteor dark flight by describing and quantifying in-flight mass distribution. The numerical products of this study also provide new insight into meteorite recovery.

It is the hope of this study that this method can be utilized and improved upon to supplement the amount of freshly fallen meteorites available to the scientific community in the future.

**References:**

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