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Dark-flight Estimates of Meteorite Fall Positions: Issues and a Case Study Using the Murrili Meteorite Fall

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Abstract

Fireball networks are used to recover meteorites, with the context of orbits. Observations from these networks cover the bright flight, where the meteoroid is luminescent, but to recover a fallen meteorite, these observations must often be predicted forward in time to the ground to estimate an impact position. This dark-flight modeling is deceptively simple, but there is hidden complexity covering the precise interactions between the meteorite and the (usually active) atmosphere. We describe the method and approach used by the Desert Fireball Network, detailing the issues we have addressed, and the impact that factors such as shape, mass, and density have on the predicted fall position. We illustrate this with a case study of Murrili meteorite fall that occurred into Lake Eyre-Kati Thanda in 2015. The fall was very well observed from multiple viewpoints, and the trajectory was steep, with a low-altitude endpoint, such that the dark flight was relatively short. Murrili is 1.68 kg with a typical ordinary chondrite density but with a somewhat flattened shape compared to a sphere, such that there are discrepancies between sphere-based predictions and the actual recovery location. It is notable that even in this relatively idealized dark-flight scenario, modeling using spherically shaped projectiles resulted in a significant distance between predicted fall position and recovered meteorite.

Unified Astronomy Thesaurus concepts: Meteorites (1038); Meteoroids (1040)

Supporting material: data behind figure

1. Introduction

Camera networks are used to observe fireballs, for the study of meteoroid orbits, and for the recovery of meteorites with known orbits. By recording the arrival of a fireball, one can calculate the arrival trajectory and hence the orbit and origin within the solar system. If the fireball is large enough that a meteorite falls, recovery of this is often a high scientific priority, as it represents a fresh solar system sample with a known origin. Several networks have been deployed historically, beginning with the Harvard photographic meteor program (Jacchia & Whipple 1956), with the first observed and recovered meteorite being Příbram from the Czech Fireball Network in 1959 (Ceplecha 1961).

Initially these systems were film based, but more recently digital systems have become predominant (e.g., Spurný et al. 2006; Colas et al. 2014; Howie et al. 2017). The practical techniques they operate on are to observe fireballs from multiple viewpoints and then triangulate these bright observations to derive a trajectory in the atmosphere (Ceplecha 1987; Borovicka 1990) and hence backtrack to calculate a heliocentric orbit. In the case of a putative meteorite, for recovery, one uses this bright-flight trajectory to calculate forward in time to give a predicted fall position on the ground—the so-called dark-flight analysis, allowing ground searches to then be carried out. The details of this dark-flight calculation are not often discussed in the literature, except in passing, usually implying that integration calculations were carried out. The calculation is done using the classical drag equation

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. (Equation (1)), but this simplicity hides more complex factors. For the starting conditions, what is the shape, mass, and density of the meteorite? How do these properties reflect in factors like the drag coefficient? What is the behavior of the atmosphere at that time and position? How are uncertainties propagated? Typically, bright-flight endpoints are 20–30 km altitude, so there is significant height and time that must be integrated through to get to the ground, and small errors can accumulate, resulting in significant errors in the predicted fall position compared to the actual landing site. This dark-flight calculation is also difficult to verify. By the very nature of dark flight, there are no observations to cross-check during descent, so the only criteria for successful modeling are location and characteristics of a recovered meteorite, and a failure to recover may be caused by factors unrelated to the dark flight.

1.1. Historical Review

In literature concerning meteorite recoveries, the precise method used for dark-flight prediction is discussed, but rarely in full detail. One early example was given in Ceplecha (1961), describing the Příbram meteorite fall, where the direction of the winds was a special case of blowing directly against the azimuth of the meteor trajectory, simplifying calculations. This predates the widespread use of computers, so calculations were integrated numerically by hand, which the authors describe as "laborious." Integration steps were every 100 m altitude, and drag coefficient was a function of Mach number, but fixed in the subsonic regime to a spherical value of 0.52.

Ceplecha (1987) (see also Ceplecha et al. 1998, p. 390) described their approach in some detail, following the discussion of triangulation methods, as an integration under atmospheric interactions and gravity. They used a Runge–Kutta

integrator with a fixed integration step of 10 m (so in space rather than in time) and assumed that after the apparent end of the luminous phase ablation has ceased and there is no fragmentation, such that meteorite shape does not change. The nearest observational data were used for atmospheric density and wind values, supplemented by a standard atmosphere model (CIRA 1972) if observations were incomplete. Drag coefficient was a function of Mach number (unspecified), with a scalar modifier for a nonspherical nature fixed by using the deceleration at the endpoint of bright flight. This scalar parameter is in contrast to their work focused on bright flight (Pecina & Ceplecha 1983; Ceplecha et al. 2000), where photometric mass is introduced and used to separate mass from a shape-density scalar.

Further publications on notable recovered meteorites briefly mention details of their approaches to dark flight: For the Lost City meteorite, McCrosky et al. (1971) carry out a numerical integration assuming a spherical rock, using a standard atmosphere, with a fixed drag coefficient of a sphere of 0.92 (in fact, comparable to the value of 0.52 for a sphere from Ceplecha (1961); the different values result from a different terminology). For the Innisfree meteorite recovery, Halliday et al. (1978) note that they use atmospheric data from the nearest balloon flight observations at Edmonton. Gritsevich et al. (2014) describe the Annama meteorite observations and recovery, with a Monte Carlo simulation of the dark flight using wind data provided by the Finnish Meteorological Institute. They describe their method in some detail and begin by fitting the later part of the observed bright flight, calculating forward and requiring any fragments to have an appropriate shape/density/mass to fit subsequent bright-flight observations. Most recently, Moilanen et al. (2021) have published details of their modeling approach to dark flight, which incorporates both bright-flight and dark-flight calculations with modeling of fragmentation events, in order to derive a strewn field estimate to aid in search and recovery. For the Desert Fireball Network (DFN) recovery of Bunburra Rockhole (Spurný et al. 2012), the paper summarizes the DFN approach as applied at the time; here we briefly describe the current DFN approach in more detail.

Some studies have also focused on the drag coefficient parameter; Zhdan et al. (2007) describe the drag coefficient of various meteorite shapes, as does Carter et al. (2011). Additionally, there are many studies on the general aerodynamic drag coefficients for hyper/super/subsonic objects, which we refer to in later sections.

2. Method

Here we describe the dark-flight modeling technique used by the DFN, discussing the details of some factors that affect the predictions. We illustrate this with the case study of the Murrili fireball.

2.1. Overview

The DFN data pipeline is almost completely automated, so it would be in principle possible to generate Weather Research and Forecasting (WRF) and dark-flight predictions for all triangulations seen. However, such an approach would overwhelm, without some method of filtering. Hence, the choice of which fireballs to investigate in detail is based primarily on the α - β criterion from Gritsevich (2007) and Sansom et al. (2019).

Further heuristics that are often considered are considerations of the final observed bright velocity and end height.

For dark-flight modeling, one starts with the classical aerodynamic drag equation:

$$\underline{F}_d = -\frac{C_d \rho S V_{\text{mag}}^2 \nu}{2m},\tag{1}$$

where \underline{F}_d is the drag force on the body, C_d is the drag coefficient, *m* is the body mass, *S* is the body cross-sectional area, \underline{v} is the unit velocity vector relative to the atmosphere (which includes any contribution from wind movement of the atmosphere) with a magnitude of v_{mag} , and ρ is the atmospheric mass density. Gravitational forces must also be calculated and included for a trajectory calculation.

This equation is used numerically; one integrates forward in time, initiating parameters from the last observed bright-flight position, consisting of position, velocity vector, and meteorite mass and shape. Figure 1 outlines the calculation steps involved. For every position, the appropriate environmental conditions (air pressure, temperature, density (or humidity), wind speed/direction, gravity vector) are either calculated or looked up in data tables. It is then possible to calculate the Knudsen number, the Reynolds number, and hence the drag coefficient throughout the descent of the body (see Table 1). Hence, we calculate forces on the body and accelerations, update position and velocity vectors using Newtonian mechanics, and account for any ablation effects that will change the mass and hence cross-sectional area, using a theoretical estimation (since there are no observations). For starting conditions, one can also include derived parameters from theoretical modeling of the bright-flight behavior: mass, meteorite shape, and plausible density. One can also impose the further condition that the transition from bright to dark-flight must be smooth; most importantly, this means that the rate of change of acceleration should be smooth from bright to dark flight (see Ceplecha 1987). The DFN approach for the core procedure is monotonic; we assume that shape does not change during descent and that there is no fragmentation (see Vinnikov et al. 2016). In reality, it is quite possible for fragmentation to occur during the dark flight, as seen in meteorites recovered with broken or missing fusion crust (Folinsbee & Bayrock 1961; Spurný et al. 2012). Only a small amount of ablation is predicted between the time after the meteorite ceases to be observed and the time where the velocity has dropped sufficiently for ablation to actually cease, and we implement this in code using the approximation of Passey & Melosh (1980), Equation (2). Typical values for this later ablation are predicted to be <1% of the final mass, which is a relatively small uncertainty compared to other factors.

In common with previously described methods for darkflight integration, the core of the DFN approach is a time-series integration. We have tested simple first-order time-step integration but get slightly better fidelity (in terms of matching fall positions of recovered meteorites) using a fourth-order Runge–Kutta integrator.

2.2. Complicating Factors

Dark-flight integration presents a unique testing problem, as there are no observations during descent that can offer insight as to the accuracy of the approach. The only "test" available is the recovery—or not—of the meteorite, as well as its final position with respect to the prediction. To compound this,



Figure 1. Flow schematic of dark-flight modeling.

nonrecovery of a meteorite may not indicate errors in darkflight modeling, as it may be a ground searching issue. The only other assistance one may get is serendipitous, nonvisual observations; in the case of a large meteorite, weather Doppler radar may detect the falling body or bodies (Fries & Fries 2010; Jenniskens et al. 2012), or if a seismic sensor is very close by, the impact may be detected. A specialist instrument such as an active RADAR or LIDAR would assist, but typical ranges are relatively small (few tens of kilometers), and such instruments are expensive and have not been deployed to date, to the authors' knowledge.

From theoretical modeling such as Sansom et al. (2017), or earlier work such as ReVelle (2005 and references therein), the shape, density, and mass are only partially constrained and are interlinked. However, one can apply some plausible constraints; it is reasonable to expect the density to be close to one of three typical values—approximately 2700 kg m⁻³ for an achondrite, 3500 kg m⁻³ for a chondrite, or 7500 kg m⁻³ for iron (Flynn 2005). Carbonaceous chondrites can have lower bulk densities, in the range of $\sim 1600-2800$ (Consolmagno et al. 2008) with a lot of sample-to-sample variation, but are less likely to survive bright flight owing to the fragility of that meteorite type and will correspondingly be very rare.

The meteorite shape alone is not usually independently accessible via modeling or observation. The shape may also vary during the bright-flight phase owing to ablation or fragmentation, although it is commonly assumed to be fixed during dark flight. (An exception is the dark-flight modeling of Vinnikov et al. 2016.) One approach, as taken by Ceplecha (1987) and similarly used for bright-flight modeling (Ceplecha et al. 2000; Revelle 2002; Sansom et al. 2015), is to combine these parameters of shape, density, and mass to generate a shape-density parameter (since none of these parameters can be independently constrained from observations) and then use values derived from bright flight as an input to dark-flight modeling. This approach in theory forces a smooth transition from bright to dark flight, and in practice it becomes an issue of observational errors close to the end of bright flight, which

 Table 1

 Detailing the Regimes and Derivations of Drag Coefficients Used in Dark-flight Calculations

Regime	Value	Symbols and Reference
Free molecular flow Kn > 10	$C_{d_free} = 2 + \frac{\sqrt{1.2}}{2V} \left[1 + \frac{V^2}{16} + 30 \right]$	Kn = Knudsen Number V = velocity, km s ⁻¹ (Khanu- kaeva 2003 Equation (3))
Hypersonic	$C_{d_hyper} = 0.92$	(For a sphere) (Masson et al. 1960)
Transitional from mole- cular flow to continuum $0.01 < Kn < 10$	Bridging function: $C_{d_trans} = C_{d_sub} + (C_{d_free} - C_{d_sub})e^{(-0.001*Re^2)}$	Re = Reynolds number (Khanu- kaeva 2003, Equation (6))
Within continuum regime $0.3 < M < 2.0$	Numerical interpolation using Re and Mach number to graphs and tables in Miller & Bailey (1979); "Sphere drag at Mach numbers from 0.3 to 2.0 at Reynolds numbers approaching 10^7 ," normalized to match the boundary conditions of C _d trans and C _d sub	
Where subsonic drag coef- ficient is	$C_{d_sub} = \frac{24}{\text{Re}} [1 + \exp(2.3288 - 6.4581\varphi + 2.4486\varphi^2) \text{Re}^{(0.0964 + 0.5565\varphi)}] \\ + \frac{\text{Re}^* \exp(4.905 - 13.8944\varphi + 18.4222\varphi^2 - 10.2599\varphi^3)}{\text{Re} + \exp(1.4681 + 12.2584\varphi - 20.7322\varphi^2 + 15.8855\varphi^3)}$	$\varphi =$ sphericity (Haider & Leven- spiel 1989, Equation (11))

Note. We have implemented this as a callable function in Python 3, available at www.github.com/desertfireballnetwork/DFN_darkflight

strongly influence the choice of values. The fall position prediction is critically related to the choice of drag coefficient (or shape-density factor) of the meteorite; values too low/high will produce over/undershoot in the fall site prediction. This is particularly a contributor very early in the dark flight, when the meteorite is super- and transonic, and is likely traveling nonvertically, as small changes in the choice of drag coefficient here result in large horizontal shifts in the predicted fall position. Once the meteorite is falling at terminal velocity, drag coefficient influences the velocity, and hence the time to fall, and controls the influence of winds. Drag coefficient is obviously a function of body shape, and this is usually handled as a scalar factor, by giving the meteorite the drag properties of a sphere as a function of conditions, and then a multiplier to a nonspherical shape (Ceplecha 1987; Zhdan et al. 2007). Shape, of course, also factors into angle of attack, which will give variation in drag coefficient and can even produce lift; however, the particular orientation of a meteorite in flight is unknown a priori, so no aerodynamic lift is assumed. Fragmentation can also cause deviation from the fall line by virtue of the fragmentation event adding transverse velocity to the object, deviating the trajectory (e.g., the Morávka meteorite; Boroviĉka & Kalenda 2003).

The details of the drag coefficient behaviors chosen do not appear to be discussed in detail in dark-flight papers, with the notable exception of detailed modeling such as Vinnikov et al. (2016). Apart from meteorite properties, drag coefficient is dependent on many conditions, such as the velocity, the Mach number, and the density of air, all of which vary in dark flight as one goes from the supersonic regime in low-density air to a subsonic regime in high-density turbulent air, close to the ground.

The DFN choice of drag coefficient is detailed in Table 1, extending the earlier table in Sansom et al. (2015), which focused more on bright-flight parameters. Values are generated in separate regimes initially: free molecular flow, and continuum regime. For dark-flight conditions, the regime is almost always continuum, which is further divided into hyper/ supersonic, transonic, and subsonic. Dark flight terminal falling is subsonic, which is further divided into turbulent and laminar conditions. The choice of regime is parameterized by Knudsen and Reynolds numbers. (The Knudsen number represents the ratio of molecular mean free path distance to a characteristic dimension.) In all cases related to dark flight, the Knudsen number indicates that calculations are in the continuum regime rather than the free molecular flow regime. The Reynolds number is relatively easy to calculate using the standard formulation, taking the characteristic length as the diameter of the meteorite, and when compared to the Mach number, one can choose the appropriate regime to estimate a drag coefficient.

As mentioned, the choice of value of the drag coefficient is critical in the early part of the dark flight; however, fortunately for meteorite recovery, the hyper- and supersonic values of drag are estimated to be relatively simple and only slowly changing over a variety of conditions.

In reality, the choice of drag coefficient is probably an approximation to a complex aerodynamic problem. In dark flight, the meteorite may be tumbling and ablating slightly early on, and complex shapes can generate lift or transverse forces shifting the trajectory. Post hoc estimation of the instantaneous drag coefficients and aerodynamic behaviors using a recovered meteorite shape and appropriate aerodynamic modeling software would make an interesting but complex study, which has not been done to our knowledge.

2.3. Atmospheric Wind Data

During the descent through the stratosphere and troposphere, the atmosphere is not quiescent. Upper atmosphere winds and density variations can deflect the falling meteoroid, such that the ground impact positions may be shifted by several kilometers. In particular, upper atmosphere phenomena such as jet streams are the major drivers of how the fall line is shifted relative to an analysis without considering winds. To predict these atmospheric properties, the DFN uses the NCAR atmospheric modeling system WRF version 4, with ARW dynamic core (Skamarock et al. 2019).¹ The WRF is a forecast model that incorporates real-world data (such as balloon flights) to model atmosphere dynamics, capable of being initialized from a global data set to generate mesoscale results at high spatial resolutions suitable for inputs into a dark-flight calculation. The WRF software generates a weather simulation product as a three-dimensional data matrix in a latitude/

¹ https://rda.ucar.edu/datasets/ds083.2/

longitude/height cuboid around the bright-flight endpoint. From the model, grid values are extracted for the atmospheric properties of relevance to dark flight. This includes the pressure, density, temperature, relative humidity, and horizontal wind speeds as a function of height, latitude, and longitude (in u, v coordinates), such that these can be interpolated during dark-flight modeling in 3D to precise locations. Since the WRF data cuboid is not necessarily north–south oriented, wind values must be extracted; this extraction therefore involves a coordinate transform, as WRF grids are not typically aligned with true north, and local verticals may also need to be corrected. For convention in our calculations, we define wind directions in degrees, with north = 0, east positive, with a positive wind magnitude in the direction of wind travel, not the wind's origin.

The primary use of the WRF tool is weather forecasting. The top-level forecast is done on a global matrix-extrapolating the state of the weather matrix, based on past observations using a physical model of the atmosphere, to the future. The global matrix is typically applied with a time step/resolution of 6 hr. This top-level product then initializes finer resolution modeling over a smaller area in order to achieve better precision in both time and space. To get a detailed (fine grid) forecast for a local area, a set of embedded domains is defined (typically four levels), increasing in cell size resolution, to finally achieve typically 1 km resolution around the bright-flight endpoint. Each domain is based on the physical model of the atmosphere, with the boundary states coming from higher-level matrix points. However, in the dark-flight modeling case, we are not forecasting but interpolating the past state of weather. We do this along the meteoroid dark-flight trajectory using a physical model of the atmosphere based on the observations rather than the forecast, using the archived data from the NCEP FNL Operational Model Global Tropospheric Analysis online data sets.² These archived snapshots contain constraints on the global weather conditions at each time step, with a 6 hr interval. When hindcasting the conditions, one starts with a snapshot and propagates the weather model forward in time (and at higher spatial resolution in the location of interest). The propagation has forcing conditions, such that the results generated must pass through the conditions recorded by later snapshots, including snapshots of times after the meteorite fall.

Due to the stochastic nature of the WRF numerical modeling software, slightly different results are produced each time it is run, even with the same input data, but the model outputs do not provide any error analysis. Variations arise from floating point precision, and from the limitations of the hardware and numerical libraries used. As its primary purpose is weather forecasting, the success of the modeling is evaluated by comparing the forecast with real weather observations. It is also worth noting that observational data for central Australia are somewhat sparse. To resolve this lack of defined error bars, for each studied case of possible meteorite fall we run models starting from different archived global snapshots, typically 0–6 hr, 6–12 hr, and 12–18 hr before the fall time, and then extract from the results the conditions and wind profile at the time of the meteorite fall. Comparison of these multiple cases highlights how stable the weather was, to explore uncertainties in the product introduced by the known errors in the observational data and the ability of the model to work for

specific weather situations. For example, a stable weather situation is more likely to give very similar sets of wind profiles, while a cold front passing shortly before the time of the fall can be expected to produce a lot more diversity in the vertical profile plots extracted from the three individual modeling products of the different time windows. The amount of profile variation provides insights as to how to constrain our Monte Carlo dark-flight simulations (as described below).

2.4. Implementation Details

For the DFN operations, we have implemented a dark-flight integrator in Python 3, using the SciPy, NumPy, and AstroPy libraries as needed (Astropy Collaboration et al. 2018; Virtanen et al. 2020). SciPy includes the core Runge–Kutta integrator function. We use the WRF-Python library provided by NCAR to access the data files produced by WRF, and several smaller libraries are used for geocentric coordinate transforms. The resulting tool takes as an input the results from a triangulation, plus putative meteorite characteristics, and a data file from a WRF scenario and produces time-position trajectories to ground. This tool can then be iterated over to investigate multiple scenarios, to produce likely fall positions for practical use for ground meteorite searching.

This dark-flight integration can be carried out in an Earth inertial coordinate system, or in an Earth Centre Fixed frame (where Coriolis force must be included as the atmosphere is coupled to Earth's rotation on short timescales), a geodetic Earth model is used, and the gravity vector is calculated as perpendicular to Earth's reference ellipsoid.

The resulting product of dark flight aims to predict a likely search area for a meteorite. The most basic result is a fall linea ground plot showing a line giving fall positions for a given range of proposed masses. For the DFN, a wide range of masses are modeled, to aid in searching planning; generally this range is much larger than the expected uncertainty of the final mass, which is obtained from bright-flight modeling (Sansom et al. 2020). This can be produced for multiple scenarios such as different assumed shapes or wind profiles, resulting in multiple fall lines. In Figure 2 we plot this simple case for the Murrili fall, discussed in more detail in the following section. We show two scenarios: idealized spherical and brick-shaped meteorites. Note the curved shapes of the fall line and the offset caused by shape choice; the curve is a result of the influence of the atmospheric winds, whereby drag coefficients are generally higher for smaller bodies.

For searching, of greater use is an impact probability scatter plot or heat map. To generate heat maps, a Monte Carlo approach is used, varying both the meteorite input parameters and the atmospheric variables. Monte Carlo modeling can be computationally expensive, but as a bare minimum, several scenarios can be calculated since the meteorite shape/density/ mass is estimated from modeling (Sansom et al. 2017) but not known with certainty. The dimensions of the Monte Carlo scatter can be used to inform the likely width of the uncertainty in the fall line, which allows searchers to prioritize their activities in the most time-efficient manner. To highlight all the subtleties and complexity involved, we describe in detail the analysis related to the Murrili meteorite fall (Sansom et al. 2020) below.

In comparison to this approach, Moilanen et al. (2021) also recently discussed and presented dark-flight calculations incorporating a wind model to estimate strewn field patterns.

² DOI:10.5065/D6M043C6



Figure 2. Fall line predictions from the Murrili bright-flight endpoint, assuming a chondritic sphere and brick, using the wind model 06:00 snapshot as described in the following section. The actual recovered fall position is marked with a black triangle.

Their approach for computation of individual trajectories is similar (in a sense necessarily due to the same physics) but differs in comparison to the DFN approach, whereby they start their integrations at a point where the fireball is best characterized, whereas DFN starts at the end of bright flight. Moilanen et al. (2021) carry out Monte Carlo forward modeling from within the bright flight, ensuring that generated objects fit the remaining luminous data, incorporating fragmentation. This approach requires more detailed formulation of ablation than the DFN, with the inclusion of fragmentation allowing the focus to be more on the whole strewn field rather than specific scenarios/fall lines.

3. Murrili Meteorite Fall as a Case Study, with Discussion

The Murrili fireball provides an interesting case study of the effects and importance of detailed modeling of the dark flight. The fireball that resulted in the Murrili meteorite occurred over Kati Thanda (Lake Eyre south) in South Australia at 2015-11-27T10:43:45.5 UTC. The fireball was observed by the DFN, and the meteorite was recovered within the following month. Hence, the recovered shape, density, and mass can be used to back-validate dark-flight modeling. Murrili is a fortunate case, as the scenario was quite ideal from the point of meteorite recovery (although the ground conditions were difficult): the fireball had a well-observed bright flight, almost equidistant between four DFN all-sky cameras that all captured the full event with high-quality data (Wilpoorina, William Creek, Nilpena, and Etadunna), supported by two more distant cameras at Billa Kalina and Mount Barry that also contributed. The trajectory was relatively steep, with a zenith angle of 21°.8, and the fireball penetrated deep into the atmosphere, to a low altitude of 18.0 km. The triangulation, modeling, and recovery are described in detail in Sansom et al. (2020).

The steepness and the low final altitude dramatically reduce the influence—and hence the associated uncertainties—of the local wind conditions, reducing the errors compared to less favorable examples, such as a shallow entry angle with an endpoint altitude that could be much higher (over 30 km in some cases). This combination of factors makes Murrili a case study where one can investigate the limitations of dark-flight modeling—the almost-ideal experimental situation should result in predictions that closely match the recovered fall position, provided that the model is accurate.

Further confidence for meteorite searching and fall position was given by aerial reconnaissance of the site, using a light aircraft from William Creek (by authors M.C. and B.D.), that observed a visible splash in the lake bed, at the area of the expected meteorite fall. Approximate coordinates from the light aircraft were used to begin ground searching. This single splash also supported the lack of significant fragmentation seen in the bright-flight images.

3.1. Constraints from Bright-flight Observations

The factors as mentioned above resulted in a low uncertainty in the end position and velocity, as detailed in Table 2.

As discussed in detail in Sansom et al. (2020), the final mass prediction was for a value of 1.9 kg, +/-0.4 kg, assuming a chondritic density of 3500 kg m⁻³. The best-fit modeling to the luminous trajectory using first the $\alpha-\beta$ approach of Gritsevich (2007) and Sansom et al. (2019) and then an Extended Kalman Filter (Sansom et al. 2015) was relatively smooth, showing no evidence of major fragmentation, and giving a shape change coefficient that matches well with typical values, so this event does not stand out significantly as indicating an unusual shape, or any strong deviation from expected path (such as might occur from lift or strong asymmetry).

Table 2										
Showing the	End	of Bi	right-flight	Parameters,	Used	for the	ne I	nitiation	of	Dark-
flight Calculations										

Date/Time	2015-11- 27T10:43:51.626 +/-0.05					
Longitude (deg east positive)	137.478 17 +/-50 m					
Latitude (deg)	-29.26534 + / -50 m					
Height above WGS84 (m)	17960 + / -40					
Velocity (m s^{-1})	3280 + / -210					
Zenith angle (deg from vertical)	21.80 + / -0.05					
Azimuth angle (deg; north = 0, clock- wise positive)	82.60 +/-0.05					

Note. See Sansom et al. (2020) for further details.

3.1.1. Single-object (Sphere) Dark-flight Integrations

We begin by considering an integration case and discuss the effects of factors such as wind modeling in the following sections. In Figure 3 we plot the calculated sphere drag coefficient (C_d) and fall velocity as a function of altitude. We see that C_d does change significantly during descent, as velocity and atmospheric density both vary, in particular early on when velocity is still dominated by the arrival velocity, rather than terminal effects. Dark flight encompasses the full supersonic to subsonic regime, and this illustrates the importance of varying C_d . Murrili is almost an ideal case, with short dark flight; this effect would be more pronounced for a meteorite at, say, a shallow angle, from a higher altitude.

In Figure 4 we show the idealized model trajectories viewed from above for several chondritic spherical masses, equivalent to generating the sphere fall line shown in Figure 2. This illustrates the effect of winds on fall position and how the fall line is constructed. Even in the case of Murrili, with a particularly low endpoint and steep trajectory, a 1 kg sphere is still deviated significantly in predicted fall position compared to a no-wind scenario.

3.2. Effects of Variation in Wind Profiles on Fall Lines

Wind data are generated using the WRF model. In the case of the Murrili meteorite, we used version v3.7.1 for the fall coordinate predictions prior to meteorite searching, and later v3.9.1 as it came available for rerunning of the initial analyses (Skamarock et al. 2008).

As is seen in Figures 2 and 4, the atmospheric winds distort and shift the fall line, in a mass-dependent manner. However, this wind profile used is a modeling prediction generated by WRF, with no way of being independently directly verified at this locale.

As mentioned, WRF can be initiated with archived global snapshots at six hourly intervals. Examination of the spread of profiles from these snapshots is one method to generate an estimate of the plausible variation in wind models to use within any Monte Carlo simulation. In Figure 5 we plot wind profiles from each WRF model run for comparison. Dominating westerly winds at altitudes 10–15 km are typical for the subtropical jet stream in the area of the fall. We plot results from three model runs based on different snapshots. Note that the winds are exceptionally strong at the 15,000 m levels, indicating a jet stream effect, and in fact greater than have been observed in most other cases investigated by DFN. There is also some variation between outputs from each snapshot.

Regional historical weather maps for this area of Australia for 2015 November 25–30 show a high-pressure region passing to the south of the fall area, with a change in general wind direction on November 26–28. The precise timing of this change may well have taxed the fidelity of WRF to carry out a high spatial-temporal resolution simulation far from actual archived weather observations.

One can investigate the gross effect of this wind variation by carrying out dark-flight calculation for Murrili for ordinary chondritic-density spheres using the results from each wind model, as shown in Figure 6.

There are significant variations between ground predictions from the wind models, typically 200-300 m between lines. This strong wind dependence is in part a consequence of the structure of the drag equation, where relative velocity is a squared factor (Equation (1)). In the bigger picture of conducting ground searches in the Australian outback, this can be an issue, as accepting such variations produces an unrealistically large search area that is not feasible to search (compounded by the other uncertainties discussed in the following sections). Ironically, it appears that although the Murrili triangulation scenario was ideal, dark-flight conditions were poor. Of some hope in the case of Murrili is that most plausible mass ranges-from bright-flight estimates (Sansom et al. 2020)-are close to the western edge of the fall lines, at the areas of most fall line curvature. So, in this case, this means that the area that needed to be searched was relatively constrained, regardless of the choice of wind models.

More generally, when wind model scenarios diverge, at one extreme one can elect to search all areas, or one can prioritize. For this and previous searches, when faced with this choice, the DFN has usually elected to focus on the penultimate/secondshortest WRF model outputs, in this case starting from the snapshot from 2015-11-27 00:00 UTC. This is purely an empirical choice, based on backward comparison of almost all of the DFN-recovered meteorites (and with hindsight a good match to Murrili as well; Spurný et al. 2012; Spurny et al. 2012; Sansom et al. 2020). This may be a result of the mechanics within WRF that implies that longer runs are needed for accuracy, to allow the WRF model to achieve numerical stability, whereas the longest simulations allow deviations from reality to accumulate. We lack the expertise in climate modeling to comment in detail, and this is clearly an area that needs further study and more data, as very few meteorites exist with both known precise endpoints and well-characterized, published, detailed shapes and densities. As such, our approach is to empirically use the penultimate wind model, ensuring that searching in the field is aware of the limitations of this approach. It is worth noting that it appears that Murrili is a particularly variable WRF scenario; in previous DFN searches the fall lines from different WRF snapshots are often closely overlapping, such that it is possible to search all scenarios within a reasonable time frame and a judgment on choice of wind profile is not required. In this case, it was fortunate that the fall was on a salt lake, allowing the use of quad bikes to search large areas relatively quickly in comparison to foot searching in a vegetated area.

However, wind is not the only uncertainty affecting fall position in dark-flight calculations; one must also consider shape and meteorite density, which can be partially constrained but is effectively unknown.



Figure 3. Modeled Murrili fall speed, and drag coefficient as a function of altitude.

3.3. Effects of Shape and Density

To investigate the effect of meteorite shape and density choices on predictions, Figure 7 plots dark-flight predictions for three different densities (2700, 3500, and 7500 kg m⁻³) and three different shapes (sphere, cylinder, and brick, as defined by Zhdan et al. 2007), compared to the 00:00 snapshot fall line. The changes in shape (which effectively changes drag coefficient) and density (which changes cross-sectional area for the same mass) have direct effects on the fall line position, and in this case (and in other cases seen by the DFN; Devillepoix et al. 2018) the choice of shape has a greater influence than meteorite mass or density prediction. For density variations, this results in the same mass falling on effectively the same fall line but translated along the line. This is also the case when changing shape from cylinder to brick; however, this shift is more extreme. From the DFN experience of recovered meteorites a $2.5 \times 1.5 \times 1$ brick shape will be an outlier; in general, recovered samples seem to be best fit by drag coefficients close to spherical. Furthermore, it is worth noting the dominance of shape choice: the effective drag coefficient is changed by a factor of 1-2 (Zhdan et al. 2007), and although density effects are varying comparably (through the crosssectional area), the shape effects dominate. This effective along-line shifting effect has advantages and disadvantages for searching. Traverse distance from the line that must be searched is essentially unchanged, but more of the line must be searched, given a particular mass range prediction, as shape

will shift this further along the line. However, since multiple scenarios overlap, several can be effectively searched at the same time.

3.4. Monte Carlo Studies of Fall Line Variations and Scatter

To combine all these factors and generate some understanding of the associated uncertainties that predictions would generate in the case of Murrili, we have carried out Monte Carlo simulations of dark-flight descents covering the following ranges:

- Mass in the range of 1.5–2.3 kg, based on pre-recovery predictions from (Sansom et al. 2020);
- 2. A density 3500 kg m^{-3} .
- 3. First with no atmospheric winds, then allowing variation of up to +/-5% in wind magnitude and direction for a wind profile, using the data based on the 00:00 snapshot, chosen for reasons discussed in Section 3.2. The 5% uncertainty is estimated from the deviation of the profile variations seen in Figure 5; a percentage approach was chosen rather than absolute variations—such as +/-2 m s⁻¹—as it was felt to better represent the uncertainties across the range of absolute wind speeds, which could vary from small to large as a function of altitude.
- 4. Meteorite shape can vary from spherical to a rounded brick shape—defined as $2.5 \times 1.5 \times 1$ brick dimensions with corners smoothed off, using the rationale and



Figure 4. Modeled trajectories of chondritic spheres for different masses in longitude and latitude, showing the influence of winds and atmosphere during descent, from Murrili bright-flight endpoint.

estimates of Zhdan et al. (2007), with the highest drag direction of the brick oriented in the direction of travel. For wind effects acting transverse to the oriented brick, we use the drag coefficients from Zhdan et al. (2007) for a cube-shaped object. (For nonspherical objects in supersonic regimes, the object usually settles into an orientation with the maximum cross section across the trajectory, giving the maximum drag coefficient, as detailed in Turchak & Gritsevich 2014 and references therein.)

These Monte Carlo ground positions are then displayed as scatter maps in Figure 8.

The ground scatter plots are very roughly the same location, although with greater scatter as wind due to wind. In overall dimensions, the scatter distributions are about 200 m orthogonal to the fall line, indicating a reasonable distance to search from the fall lines, and the rough length along the fall line of both scatters is 400 m, giving each a searchable area of about 0.2 km^2 .

3.5. Fall Line Prediction Compared to Meteorite Recovered Position

The previous sections describe the analysis that can be done before meteorite recovery, using shape approximations and wind model predictions. We now consider after the meteorite recovery, when the actual shape, mass, and density are known, and a newer version of the WRF is available. Despite the high quality of triangulation and the low endpoint of the bright flight, the fall position was ~40 m away from the preferred line prediction, and ~100 m along the line from a sphere-based prediction. This would at first glance appear excellent from a practical searching point of view, but for a less favorable fall with a higher endpoint this offset would be proportionally larger. For a shallower entry angle, fall line uncertainties also increase owing to greater horizontal travel at high velocity immediately after the end of bright flight, where any unknowns in the drag coefficient and shape contribute greatly. One should then investigate possible causes for this orthogonal offset: since many factors are constrained by the properties of the meteorite, one is essentially left with issues of wind model accuracy, a nonideal shape, or modeling issues such as choice of drag coefficient. The preceding analysis has focused on the data available prior to recovery, but for the following figures using post-recovery data, fall lines are plotted using a later recalculation of the wind models, using WRF v3.9.1, which has shifted the fall line predictions slightly, by about 100 m to the south.

The Murrili meteorite is shown in Figure 9. Its extents in the left panel are approximately $130 \text{ mm} \times 90 \text{ mm}$, while the thickness in the right panel is 70 mm. We round to the nearest 5 mm owing to fine detail irregular variations in surface features. The meteorite volume (obtained from a CT scan) is 474,731 mm³, giving an equivalent sphere radius of 48 mm (volumetric radius). Alternatively, the meteorite surface area is 40,299 mm², giving a sphericity of 0.71 or 0.73 depending on the definition used; the surface area of an equivalent-volume sphere over the surface area of the meteorite is 28,952/40,299, giving 0.71 (Pettijohn 1975), or alternatively, the equivalent-volume sphere is 96 mm/130 mm, giving 0.73 (Wadell 1935).

As part of the meteorite description studies prior to official classification, the meteorite was visually inspected, and we have reviewed the 3D CT scan data to investigate any fusion crust features that might hint at orientation or even changes in flow regime during descent—there are some possible flow lines, but they are very faint and quite subjective, and not completely compelling. Unfortunately, the meteorite fell into a wet salt lake in the Australian summer and so was buried for about a month in warm saltwater mud before recovery. The extensive weathering appears to have removed a lot of fine detail, preventing any firm conclusions about orientation. We have also reviewed the details of the impact site for insight into orientation, via images of the impact itself, and consideration of



Figure 5. Plot of wind profiles from each WRF model run for comparison. Dominating westerly winds at altitudes 10–15 km are typical for the subtropical jet stream in the area of the fall. The individual profiles are products of WRF runs starting from the snapshot 2015-11-26 18:00 UTC, 2015-11-27 00:00 UTC, and 2015-11-27 06:00 UTC.

the impact velocity. The impact appears roughly circular in form (Sansom et al. 2020), although the salt lake crust may break unevenly. Sansom et al. (2020) additionally state that the meteorite was buried 42 cm into the mud. However, the lack of knowledge of the properties of the ground, as needed for the appropriate projectile depth penetration equations (Young 1967, 1997), can generate a wide range of velocities, providing little guidance on reconstructing the impact velocity.

One can attempt to correct the spherical drag coefficient with some factor based on the known shape of the recovered meteorite. For nonspherical bodies, this problem has been studied in the context of dust settling rates, often in relation to industrial processes or environmental studies. See, for example, Connolly et al. (2020 and references therein), or Kleinstreuer & Feng (2013) for a review from a biomedical context. For settling rate studies, the Corey Shape Factor (CSF), $(d_{\rm min}/\sqrt{(d_{\rm max}*d_{\rm med})})$, where *d* is diameter (Corey 1949), is the most commonly used approximation and provides the most data for correlations between publications. For Murrili this evaluates to 0.64. However, one must exercise caution with using CSF outside of settling studies—a CSF of 1.0 describes a sphere, a cube, or several other regular solids, which all have different drag coefficients.

Freefall drag coefficient has also been derived as a function of sphericity from empirical and theoretical studies (Haider & Levenspiel 1989 and references therein). Within the DFN general dark-flight code implementation it is possible to explicitly specify sphericity (Table 1, forcing the use of Haider and Levenspiel, Equation (11)), overriding the default calculations for a sphere. Hölzer & Sommerfeld (2008) extend this formulation to include projectile orientation, by treating crosswise and longitudinal sphericity separately. To investigate



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Figure 6. Variation in fall line predictions for chondritic spheres due to variations in WRF wind model data, with the model snapshot shown in the legend. Numbers along the line indicate the mass on the ground. Some numbers are omitted for clarity on some lines, but the points shown correspond to matching mass markers on the lowermost curve. The final recovered meteorite fall position (1.68 kg) is also shown with a filled triangle.

and compare this, we have implemented their Equation (9) and then calculated Monte Carlo dark-flight simulations with Murrili falling teardrop oriented (low drag) and then flat oriented (high drag). We indicate these directions of travel with arrows $V_{\rm L}$ and $V_{\rm H}$ in Figure 9). In Figure 10 we show the results of these Monte Carlo simulations. We exactly specify the meteorite mass and density but permit initial vector variation and 5% wind uncertainties. For reference to previous figures we also display the 00:00 fall line (based on a spherical drag coefficient, but with the later WRF v3.9 wind model) and meteorite recovery location.

Considering the scatter points in Figure 10, we can see that fall orientation clearly will have an effect. The top panel shows that the high drag-oriented simulations are somewhat offset from the isotropic drag fall line and from the recovery position (triangular marker). The bottom panel of Figure 10 shows the vertically oriented (falling in a teardrop orientation, with lowest possible drag coefficient in the direction of travel) scatter as a closer match, intersecting the isotropic fall line but not intersecting the recovery position.

The actual position of the impact is close to the isotropic fall line, but \sim 400 m along the line from the 1.68 kg prediction (black square marker), which corresponds to an anomalously large mass (>5 kg). By beginning with a spherical isotropic object and keeping mass fixed at 1.68 kg, but reducing the drag coefficient in all directions (so using Table 2, but with a scalar reduction in forces as labeled), we generate the dashed/triangle line that is oblique to the isotropic fall line. This line also does not pass precisely through the impact point, and the closest approach is when drag is reduced by about 75% (so a scalar factor of 0.75) compared to a sphere. The closest approach distance is 44 m.

The relative lack of cross-track offset between the impact point and the isotropic sphere fall line may result from the wind modeling not matching reality: in general, isotropic drag changes from shape, density, or mass variations act to effectively shift objects either along the fall line or very close to it, rather than away from the line (the sphere and brick fall lines in Figure 2 are essentially the same line extended). Note also how the isotropic subsphere line in Figure 10 is subparallel to the sphere line, not at some arbitrary angle. The recovered meteorite does not precisely align with either of the isotropic lines; this offset is either from a small amount of nonspherical drag (aerodynamic shape effects such as angle of attack or lift) or most likely from just basic inaccuracies in the wind model.

Comparing the Monte Carlo point clouds for the two orientations, the two oriented point clouds do not bracket the spherical fall line, as one might initially imagine, as the influence of sphericity means that sideways wind effects are decoupled from vertical velocity. The difference between the centers of the clouds is shifted east and slightly south (from high to low drag), which corresponds to the general wind orientations of approximately 270° - 300° in the right panel of Figure 5. These point clouds can be thought of as representing

△ 1kg end points ---◇--- 00:00 snapshot fall line

Figure 7. Plot showing the effects of density and shape on final position of a hypothetical 1 kg object. Shapes plotted are sphere, cylinder, and brick (as defined in the text). Density of the object is constrained to 2700, 3500, and 7500 kg m⁻³. For comparison we include the fall line based on the 2015-11-27 00:00 UTC wind snapshot (3500 kg m⁻³ sphere, varying mass) and the impact point from Figure 4.

extremes on a spectrum of orientations, and some intermediate orientation value would lie in between these clouds. However, no intermediate value would pass through the actual impact site, which hints that perhaps the modeled wind data have some inaccuracy, most likely due to lack of real supporting measurements.

In both cases the diameter and scatter of the oriented Monte Carlo point clouds are smaller than the isotropic sphere scatter as seen in the bottom panel of Figure 8: we hypothesis that the sphere has a unique combination of properties of wind influence and vertical fall velocity; hence, the low-drag orientation is most influenced by the horizontal winds but vertically falls a lot quicker, with less time for the wind influence to act, and vice versa for the high-drag orientation.

In the top panel of Figure 10, the difference in position between the high-drag-oriented point cloud and the isotropic sphere fall line (and the impact point) appears relatively large, compared to the low-drag cloud. This appears somewhat counterintuitive, as one might expect the low-drag down orientation (which has a high drag sideways) to have bigger shift from the sphere line. This shift must result from the higher drag giving a longer dwell time (slower fall velocity), giving the winds greater influence.

Although the low-drag (vertical orientation) Monte Carlo simulation appears closer than the high-drag simulation to the recovery point, neither orientation overlaps this point. In the bottom panel of Figure 8, the Monte Carlo simulation of an isotropic sphere does, however, overlap the recovery point: the wind model can be compatible with an isotropic object but not an oriented fall, although an irregular shape with complex tumbling may effectively cancel out any orientation effects.

The above discussion has resulted in several possible scenarios that could reconcile the data with the modeling: wind models approximately correct, but with an isotropic shape having an anomalously low drag coefficient, or an isotropic shape where winds are lower or less influential than expected (or a reduced drag coefficient). Finally, an oriented shape falling seems less likely, as the wind models would have to be substantially incorrect, which is not supported by other recoveries, both DFN and other fireball networks around the world.

These possibilities are not exclusive, as the Australian outback real wind observations are sparse. A change of orientation during flight and even rotation could not be ruled out and might have the effect of damping the effects of orientation. Even in the low-drag scenario, strong horizontal winds would have the effect of altering the angle of attack of the falling rock, which will have aerodynamic effects. From this single event it is difficult to separate these possibilities, but

-O-00:00 snapshot fall line • 5m/s wind variation

Figure 8. Top: Monte Carlo results of 1.5–2.3 kg chondritic meteorite, 1000 runs, allowing initial shape to vary from sphere to rounded brick. Bottom: same as the top panel, but with wind variation of 5% allowed in direction and magnitude of the 00:00 snapshot-based wind profile provided by WRF. The simulations also allow variation in the initial vector from the end of bright-flight triangulation, using the uncertainties in Table 2.

analysis of further falls should show which is the appropriate formulation to use in future predictions.

These scatter plots, as well as the shape dependence of points along the fall line in Figure 7, illustrate both the need to search widely along an ideal fall line prediction and the dominance of shape in dark-flight modeling. Any shape characteristics available from bright-flight behavior will be most helpful, but detailed shape is unlikely to be known. In this context, the approach of Moilanen et al. (2021) of beginning the trajectory integration within the bright flight may yield useful results,

Figure 9. Murrili meteorite dimensions and shape. In both images, the black scale bar is 50 mm. Compared to a sphere, the rock is flattened and heart shaped, but almost teardrop from the side view. An STL file representing this shape is available as data-behind-the-figure. (The data used to create this figure are available.)

avoiding some of the shape issues. It is worth noting that within their Monte Carlo calculations Moilanen et al. (2021) have chosen wind variations comparable to values chosen here, albeit slightly larger; 10% versus 5% here. The reasonable match between Murrili basic predictions and the recovered fall position would tend to indicate that the wind model chosen in this case is probably sufficiently accurate (i.e., not the major source of uncertainty) and also that geometric errors in triangulation are relatively minor. Assuming a specific orientation during dark flight does not provide a best fit, but simple assumptions can be helpful in planning searching. In contrast to the spherical or lower drag coefficient here demonstrated, another DFN recovery, the Dingle Dell meteorite, landed 105 m from the fall line, but at a point along the line that corresponds to a cylindrical mass, with a drag coefficient significantly greater than spherical (Devillepoix et al. 2018, their Figure 10). However, we must note that Dingle Dell suffered from several complicating issues: the recovered meteorite has an angular broken surface, implying fragmentation, which was supported by the light curve; the entry angle was also shallow; and the endpoint was slightly higher (19.1 km). However, in both the Murrili and Dingle Dell cases the offset between fall lines and recoveries and the position along the line result in a search area that is relatively manageable from a logistical point of view.

4. Conclusions

For fireball camera networks, focused toward meteorite recovery, the calculation of the dark-flight trajectory after luminous observations is a critical step to sample recovery. This step is very difficult to test, due to the lack of observations during descent, with only the recovery (or not) of the meteorite providing a data point. The principles of dark-flight calculation are simple, based on a classical aerodynamic drag equation, but the calculation hides subtleties, particularly in the formulation of aerodynamic properties. We describe the details and approach taken to this problem by the DFN. The simplest output from a dark-flight calculation is typically a fall line, showing impact positions for a known range of hypothetical masses. From consideration of these lines and the effects of parameters, we find that the choice of meteorite shape is more important than density or mass choice, in terms of variation in ground position. These constraints in turn influence the ground searching strategy.

We illustrate this with a case study of the Murrili meteorite fall, recovered from Lake Eyre-Kati Thanda in 2015. Murrili is an ideal case for dark-flight study, as the optical observations and triangulation data were exceptionally good, with multiple DFN observatories relatively close by giving a range of viewpoints. Additionally, the meteor trajectory was steep, and the final height at the end of the luminous phase was at a relatively low altitude of 18 km, so the dark flight was relatively short, compared to many meteorite falls. However, winds were quite strong at this location, especially around the 15 km levels, so the dark-flight fall line was perturbed significantly. Given the known location of the meteorite impact point and the known shape, we investigate whether the meteorite had an orientation during fall, and we find that although the final position can be matched using an orientation with the lowest drag coefficient in the direction of travel rather than the highest, the fall position is best matched by assuming either a spherical shape and drag characteristics or a reduced drag sphere, where one assumes spherical properties and then artificially reduces the influence of atmospheric interactions (to about 75% in this case). A simple isotropic approach like this may provide a way forward to investigate weakly constrained shapes for observed falls; other falls seen by the DFN are also well matched with an isotropic shape, but not necessarily a pure sphere. We note from this that although Murrili is close to an ideal case for dark-flight modeling, it was still necessary to consider in detail the overall shape of the meteorite and the detailed atmospheric properties in order to get a good agreement between predicted and observed fall positions.

Further work would benefit greatly from detailed published data concerning the shape of recovered meteorites, in combination with precise details of the end of luminous

Figure 10. Monte Carlo simulations of Murrili (fixed at 1.68 kg, 3500 kg m⁻³) falling at different orientations. Top: the scatter for falling in a high-drag orientation (horizontal orientation in Figure 9); bottom: in a low-drag orientation (vertical in Figure 9), as indicated by fall direction arrows in Figure 9. Percent line is described in the text.

trajectory, so that aerodynamically realistic drag coefficients could be estimated and compared to the recovery positions. Extending this with reference to Moilanen et al. (2021), a swift way to provide these data would be more published details of strewn fields with shapes, masses, and locations of all samples collected. This could feed into a valuable tool for searchers to be able to rerun software to refine scenarios while in the field, once the first pieces have been recovered. In particular, specific recovered shapes, masses, and densities could be used to eliminate specific wind scenarios to refine the ground searching strategy in near real time.

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