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Influence of weather data on a fireball's dark flight

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The computation of the dark flight of a bright fireball requires knowledge of the atmospheric parameters. In particular wind and wind direction as a function of height are crucial for an accurate trajectory. In this paper we compare different sources of sounding balloon and model data, and study the effect on the dark flight.

1 Introduction

Meteors light up in the atmosphere between roughly 120 and 80 kilometres, fireballs a bit lower. Bright fireballs may not have entirely ablated at the point that they have decelerated so much that the ablation process no further occurs. The luminous trajectory ends and the remaining mass continues its so-called *dark flight*. The deceleration continues until the travel continues in free fall. At altitudes of approx. 30 kilometres the atmosphere becomes so dense that the lateral wind starts to have influence on the path, resulting in drifting the particle away from its nominal trajectory.

The computation of the dark flight of a bright fireball therefore requires knowledge of the atmospheric parameters (besides the wind also of pressure and temperature).

Bright fireballs nowadays get broad attention and are quickly being analysed by the many networks (FRIPON (Colas et al., 2020), Allsky7 (Hankey et al., 2020), EN (Spurny et al., 2017)[1], UKMon[2], DFN (Towner et al., 2021), GMN (Vida et al., 2021), etc.). Obviously, the data is needed quickly to enable quick recovery in case of potential meteorite dropper scenarios. We note that different data sets for the atmosphere are being used, apparently there is a broad choice, but which one is the right one to use?

In this paper we will compare different sources of sounding balloon and model data, and study the effect on the dark flight. Basis is the ablation and dark flight simulator *PyDAF* (Bettonvil et al., 2021).

2 Atmospheric parameters

For the trajectory of a meteoroid through the lower atmosphere generally the *Equation of motion* (Ceplecha, 1987) is used:

$$
\begin{aligned}
(\mathrm{d}v_l/\mathrm{d}h) &= (-\Gamma S\varrho v(V_1 + v_1) - 2\omega(v_x \sin\varphi + \\
&\qquad + v_h \cos\varphi \sin a_\mathrm{R}))/v_h \\
(\mathrm{d}v_h/\mathrm{d}h) &= (-\Gamma S\varrho v v_h - g + 2\omega \cos\varphi\,. \\
&\qquad .\,(v_l \sin a_\mathrm{R} + v_x \cos a_\mathrm{R}))/v_h \\
(\mathrm{d}v_x/\mathrm{d}h) &= (\Gamma S\varrho v(V_x + v_x) + \\
&\qquad + 2\omega(v_l \sin\varphi - v_h \cos\varphi \cos a_\mathrm{R}))/v_h\,,
\end{aligned}
$$

in which

$$\varrho = (3{\cdot}483676P/T) \times 10^{-4}\ \mathrm{g\,cm^{-3}}$$

v_h refers to the vertical velocity of the meteoroid, v_l to the horizontal velocity in the direction of flight, and v_x to the horizontal velocity perpendicular to v_l. V_l and V_x represent the two horizontal, perpendicular wind directions. ρ refers to the density of the air, which depend in turn on pressure *P* and temperature *T*. All those parameters are atmospheric parameters which we need to know as function of altitude. For an explanation of the other parameters in the equation of motion we refer to (Ceplecha, 1987).

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[1] https://www.dutch-meteor-society.nl

[2] https://ukmeteornetwork.co.uk

3 Atmospheric data: options

To retrieve atmospheric data at the time of a fireball, we have the following options:

- Weather (or sounding) balloons. Once every 12 (or sometimes 6) hours they are launched from specific meteorological stations (data available at e.g. *weather.uwyo.edu*)[3]. They give temperature, pressure and wind as function of altitude, have high temporal and spatial resolution and reach altitudes to 25 or sometimes 30 km.

- Weather models: usually used for forecasting.

  An example is ECWMF (among several others). They compute a prediction every 6 hours. E.g. available at *Windy.com.*

  Another example is WRF (Weather Research and Forecast model simulation tool) which gives options to run models yourself (provided that you have access to a powerful computer cluster). E.g. *Wetterzentrale.de*.

- Aeolus: a satellite designed to perform wind profile measurements. Unfortunately, the Aeolus spacecraft was decommissioned in 2023, and Aeolus-2 still in the planning phase.

- Doppler weather radars: provide wind measurements, but only to ~4 km altitude.

This leaves us only two options: balloons and models. Disadvantage of the balloons is that time and location of the measurement do generally not match with the time/location of the fireball. Disadvantage of model data is that public data is generally not very detailed (particularly at higher altitudes). Also, public data often doesn't go beyond 15 km of altitude (exception: *rucsounding.noaa.gov*[4] (GFS), with data up until ~50 km). They are also only available as prediction or a limited time in the past. For more, access to meteorologic institutes is needed.

4 A case study: The Dutch fireball of June 04, 2023

A recent fireball over the Netherlands was used to look deeper into atmospheric data sets. The fireball appeared on June 04, 2023, over the province of Zeeland, Netherlands around local midnight (22:10:03 UT). It was captured by the networks of FRIPON, Allsky7, GMN, DMS, and WGM. Although there is no consensus whether a meteorite would have dropped, a dark flight and strewn field was computed which serves as a good basis for our study.

Figure 1 shows the trajectory of the fireball, and the nearby sounding stations. The three closest are De Bilt (EHDB, 06260, NL), Essen (EDZE, 10410, D), Herstmonceux (03882, UK), 100 to 150 km away from the fireball, and further away Meiningen (10548, D), Nottingham (03354, UK) and Norderney (10113, D). Also, a WRF dataset is available, provided by (Vida, Devillepoix, 2023), which was run for the location of the fireball.

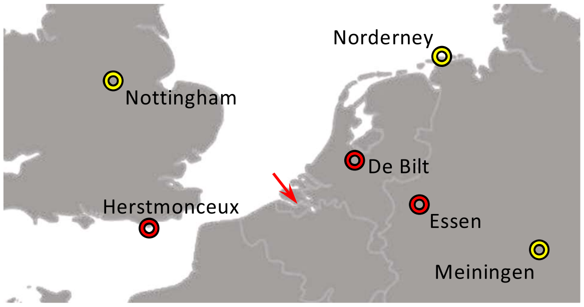

Figure 1 – Calculated impact point and nearby sounding stations.

The first thing to check is how the various atmospheric parameters vary from station to station (Figures 2, 3, 4, 5). Figure 2 shows the pressure as function of altitude for Essen, De Bilt and WRF. Curves are identical and lay nicely on top of each other. Figure 3 gives temperature as function of altitude, here is some slight variation visible, but still all three nicely match well. Figure 4 then shows the wind speed as function

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[3] There are both the old format (TEMP) and BUFR, the latter preferred.

[4] https://rucsoundings.noaa.gov

of altitude. Although one could say that the general pattern is the same, there is large scatter and at certain altitudes there are significant differences.

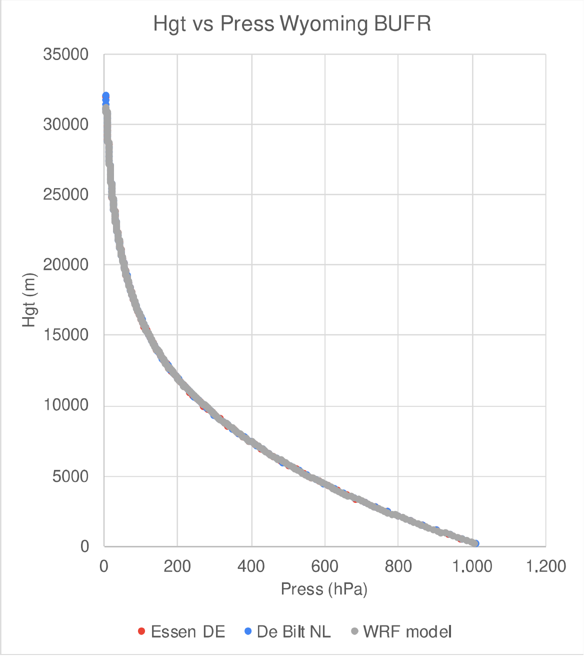

Figure 2 – Relation of pressure and altitude of stations Essen (orange dots), De Bilt (blue dots) and the WRF model (grey).

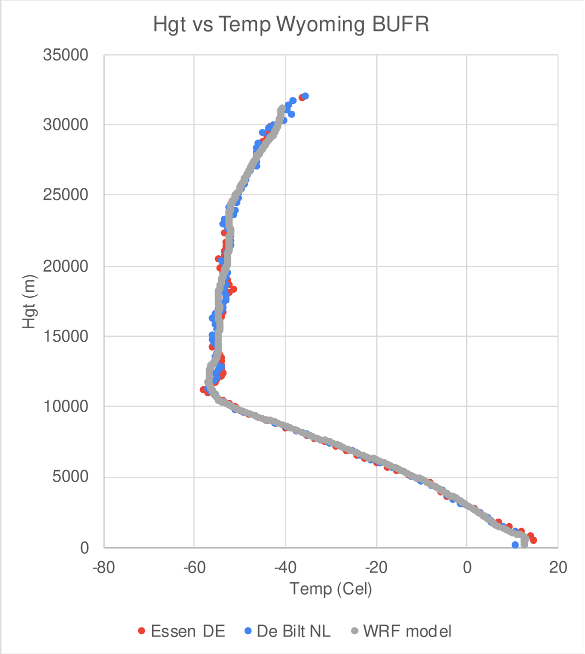

Figure 3 – Relation between temperature and altitude of stations Essen, De Bilt and the WRF model.

Below 10 km De Bilt has a systematic larger wind speed when compared to Essen. Most notable however is a twice higher wind speed at ~ 9 km computed by WRF compared to the sounding data. Clearly WRF predicts a hodograph wind maximum there which the sounding stations did not measure. Figure 6 finally shows the wind direction. Here all data do match overall, albeit with a large scatter.

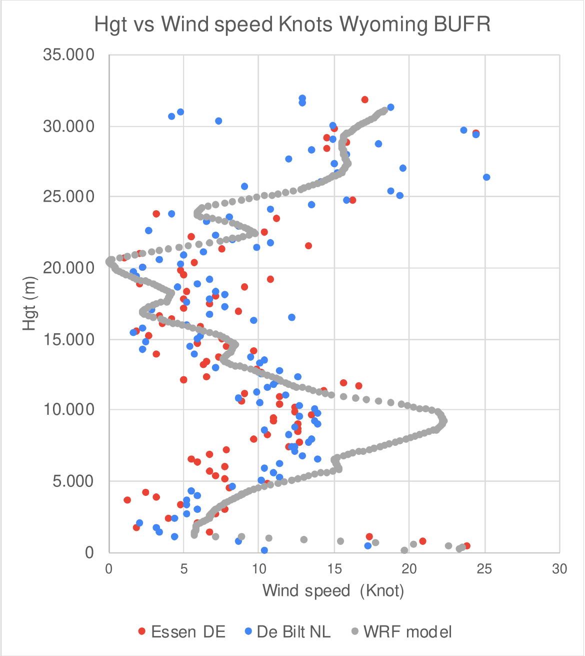

Figure 4 – Relation between wind speed and altitude of stations Essen, De Bilt and the WRF model.

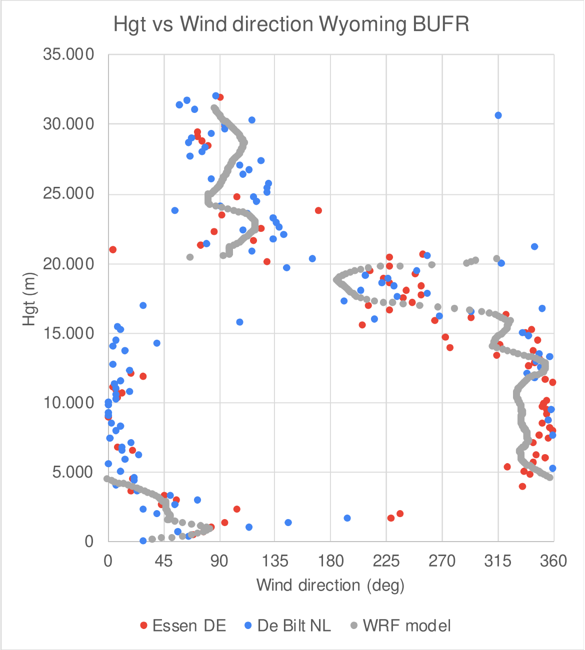

Figure 5 – Relation between wind direction and altitude of stations Essen, De Bilt and the WRF model.

Obviously, the two upper air data sets are not identical. But the differences in upper air data were considered as being small (RTV Drenthe, priv. comm.), justifying the use of station Essen (as initially applied to the fireball data).

The next step is to study the influence of the various data sets on the dark flight trajectory. We do that by running the dark flight code *PyDAF* and compute the geographic location of a fragment of a certain size for the fireball of June 04. We use the Allsky7 trajectory (Hankey, 2023).

Figure 6 shows the result. Shown are the geographic locations of 16 gram and 3 gram meteorites for sounding data and model data of all stations as mentioned in Figure 1. In dashed blue the ground projection of the trajectory is shown. The direction of the fireball was from top left to lower right. The wind pushed all meteorites to the right side of the trajectory.

As the smaller - 3 gram – meteorites decelerate faster than their 16 gram counterparts, they reach the ground closer to the terminal point of the fireball (i.e. towards the upper left corner of the picture). Also, we can see that because of the lower velocities the 3 gram fragments reach, thus spending more time in the atmosphere, wind gets more grip on them, and thus the differences between the different data sets increase.

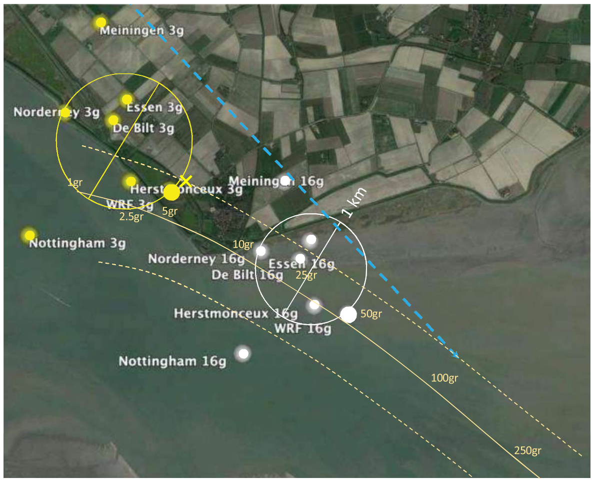

Figure 6 – Calculated impact points for the fireball of June 04, 2023, near Ellewoutsdijk, for two different sizes (16 gr -white; 3 gr – yellow) and different sounding (small dots) and model data (large dots). The circles represent an estimate of the spread in the impact point due to the slightly different weather parameters at the neighbouring weather stations or WRF model. In dashed blue, the ground projection of the trajectory is shown. Also is The impact points as carried out by GMN (Vida/Devillepoix, 2023) are also plotted (in light-yellow color).

There is no preferred direction in the spread of impact points: they simply tend to form a 2-dimensional cloud. Of course, the lateral shift (perpendicular to the fireball trajectory) is the more worrisome. An axial shift leads to the finding of meteorites with another size meteorite than predicted, a lateral shift either to success or no find at all.

Figure 6 also shows the computed dark flight computation as derived by GMN (Vida, Devillepoix, 2023) based on a Monte-Carlo run with the distribution coming from uncertainties in the luminous trajectory.

5 Discussion

Figure 6 shows obviously that the different data sets give different results. Even the three closest sounding stations De Bilt, Essen and Herstmonceux give differences of ~500 m. The stations further away (i.e., Norderney, Nottingham, Meiningen) show larger deviations. The impact point derived from the WRF data (indicated with a larger dot), is also off when compared to the three nearest stations. This likely is caused by the fact that the WRF model did predict high altitude winds (wind maximum), which the three stations did not measure.

The WRF-data impact points do match rather well with the central (solid) line of the GMN impact computation. It tells that the *PyDAF* and GMN code do give similar results.

If we would not know what data to take, thus select just ad-hoc a nearby sounding station or WRF data set, one might expect an uncertainty as indicated with the circle in Figure 6. It has a diameter of roughly 1 km (which excludes Nottingham and Meiningen, being the furthest ones), and is of similar magnitude as the uncertainty of the GMN result due to uncertainty in the luminous trajectory. But is it true that there is no preference? Can we decide for sounding data above model data, or vice versa?

To obtain more insight, we compared (for another date than the June 04 fireball), two WRF model outputs, run for the same location and same time (August 05, 00h UT), and provided by two different WRF calculations (Figure 7). The temperature profiles look similar, although not identical. In Figure 8 shows in more detail the wind profiles, with also the ECWMF model output shown. It is obvious that the three models give no identical predictions for both wind speed and direction. From this we conclude that model (forecast) data comes with its own uncertainty.

To gain further insight, we also compare a model output with a sounding balloon measurement, for the same location and same time (Figure 9, Station De Bilt, Nov. 04, 00h UT). At first they look quite similar, but also here we see some differences: the model predicts lower wind at lower altitude and stronger wind at high altitude.

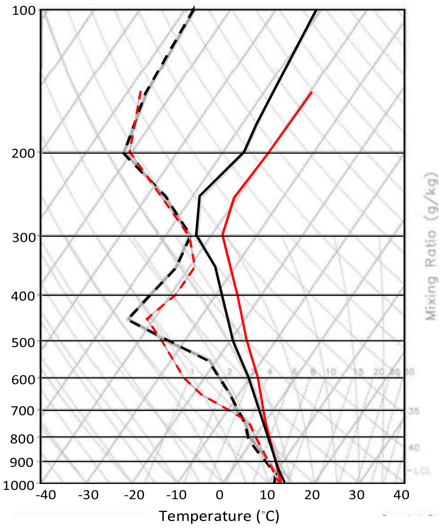

Figure 7 – Skew-T diagram of two WRF models (Wetterzentrale.de – black, Modellzentrale.de - red) for the same location, both on August 05, 2023, 00h UT. The solid curve represents temperature, the dashed curve the dew point temperature. Both models give similar results but are also not identical.

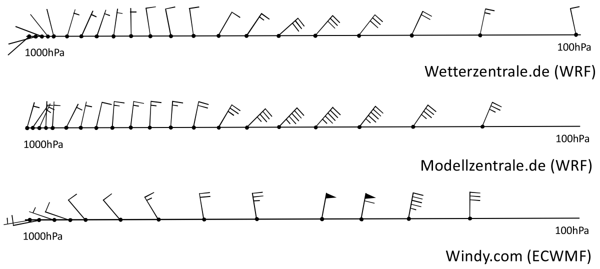

Figure 8 – Two WRF models and the ECWMF model for same location, same time. (August 05, 00h UT). Both wind strength and direction vary significantly.

Let's now have a closer look at the sounding data. Station De Bilt is the closest station; Herstmonceux and Essen lay on equal distance from the fireball on opposite sites. At first order, (and strengthened by the fact that the night was considered as a night without large differences within at least 100 km), it may be expected that the best sounding profile is the average between the two. This is indicated with the center of the white and yellow circle in Figure 6. Station De Bilt is located closely to this point. Therefore, the average seems a reasonable estimate which data to take. We note that the model is ~500 m away. But, as explained in the next section, this is not our final conclusion yet.

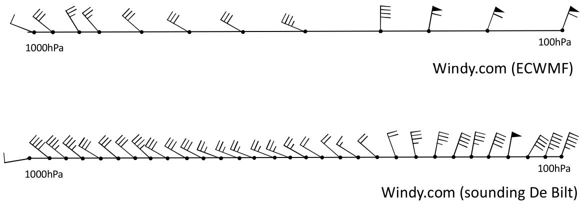

Figure 9 – Example of a WRF model and sounding measurement taking at the same location and same time. (De Bilt, Nov. 04, 00h UT). Wind directions agree reasonably well, wind strength vary slightly: the model predicts lower wind at lower altitude and stronger wind at high altitude.

6 Conclusions

Atmospheric data can both be derived from model data as well as sounding balloons. Whereas model data in principle can be computed for the location of the meteorite trajectory, for sounding data this is not the case and a nearby sounding station is to be selected. Also, the timing of the balloon sounding does generally not match the time of the fireball: typically, once every ~6 hours a balloon is launched.

We conclude from our case study, done on a fireball on June 04 in The Netherlands, that it quite matters which sounding station to take: wind speed and wind direction vary from station to station and are not negligible, even in this fortunate case where the atmosphere was stable and quiet, and the sounding data was taken at the time that the fireball appeared. Sounding measurements show differences and models, we conclude, however do vary too.

Our case study, lead to a spread in impact point of ~ 1 km, when putting all nearby stations and WRF data together. It is of the same order as the uncertainty caused by the luminous trajectory.

It seemed quite possible to average the nearby sounding stations, based on their distance to the fireball impact point. We note that the average differs half a kilometre from the one derived from the WRF. The fact that WRF predicted as only data set a wind maximum around 10 km altitude, with winds approximately twice at high might be the cause.

Despite the fact that the night did not show large differences over a large 100-200 kilometre area, we do one last check: check the data of sounding station Beauvechain (EBBE, 06458). The data is not available in BUFR format, and was therefore at first excluded in the study. Beauvechain turns out to show also a wind maximum at 10 kilometres. The wind at this altitude turns out having a NNW direction, thus coming quite exactly from the location of the fireball dark flight! We conclude therefore that there has been a narrow NNW wind stream, at the location of the fireball which was not present at the sounding stations De Bilt, Herstmonceux and Essen. Then, as final check, we convert the sounding data of Beauvechain to BUFR and compute the dark flight. It is indicated with a yellow cross in Figure 6: the impact point for Beauvechain and WRF match well, they are only 100 m apart. It changes our conclusion: in this case we prefer to use the WRF data set over the sounding data.

We conclude by stating that generally the choice what data to use, straight after a meteorite the fall, is thus not trivial. Based on the presented case study, we tend to conclude that it is best to use WRF data. Download the model data as quickly after fall as possible for the location of the dark flight, e.g. from *windy.com* (for high-resolution ECWMF data up to 13 kilometres and from *rucsounding.noaa.gov* (GFS) for the upper atmosphere). Compare the data with nearby sounding data to gain insight of consistency and fast variations (e.g. due to upper air wind patterns which are their dynamic and of local nature), as we saw in this case study. Clearly both data sets have their strengths and weaknesses.

It is to be noted that ~ 6 hrs after the sounding data is taken, model- and sounding data are merged, and models re-run (Colas, 2023). It. should then become the ideal data set for meteorite recovery. This would be an interesting check to do for this case study as well, a plan for future work.

Acknowledgments

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References

Bettonvil F., Bettonvil D. (2021). “Tests with a basic ablation and dark flight calculator”. *WGN*, **49**, pp.147-151.

Ceplecha Z. (1987). “Geometric, Dynamic, Orbital and Photometric Data on Meteoroids From Photographic Fireball Networks”. *Bulletin of the Astronomical Institute of Czechoslovakia*, **38**, 222

Colas F., (2023). priv. comm.

Colas F., et al. (2020). “FRIPON: a worldwide network to track incoming meteoroids”, A&A, **644**, A53, 23pp

Hankey M. (2023), priv. comm.

Hankey M., Perlerin V., Meisel D. (2020) “The all-sky-6 and the Video Meteor Archive system of the AMS Ltd.” *Planetary and Space Science*, **190**, article id. 105005.

Spurny, P., Borovička, J., Mucke, H. Svoreň, J. (2017). “Discovery of a new branch of the Taurid meteoroid stream as a real source of potentially hazardous bodies”, A&A, **605**, A68, 25 pp.

Towner M., et al. (2021). “The Australian Desert Fireball Network; overview and recent results”, *43rd COSPAR Scientific Assembly*. Held 28 January - 4 February, 2021. Abstract B1.2-0009-21 (oral), id.319.

Vida D., Devillepoix H., (2023). priv. comm.

Vida D., et al. (2021). “The Global Meteor Network - Methodology and first results”, *MNRAS*, **506**, Issue 4, pp.5046-5074