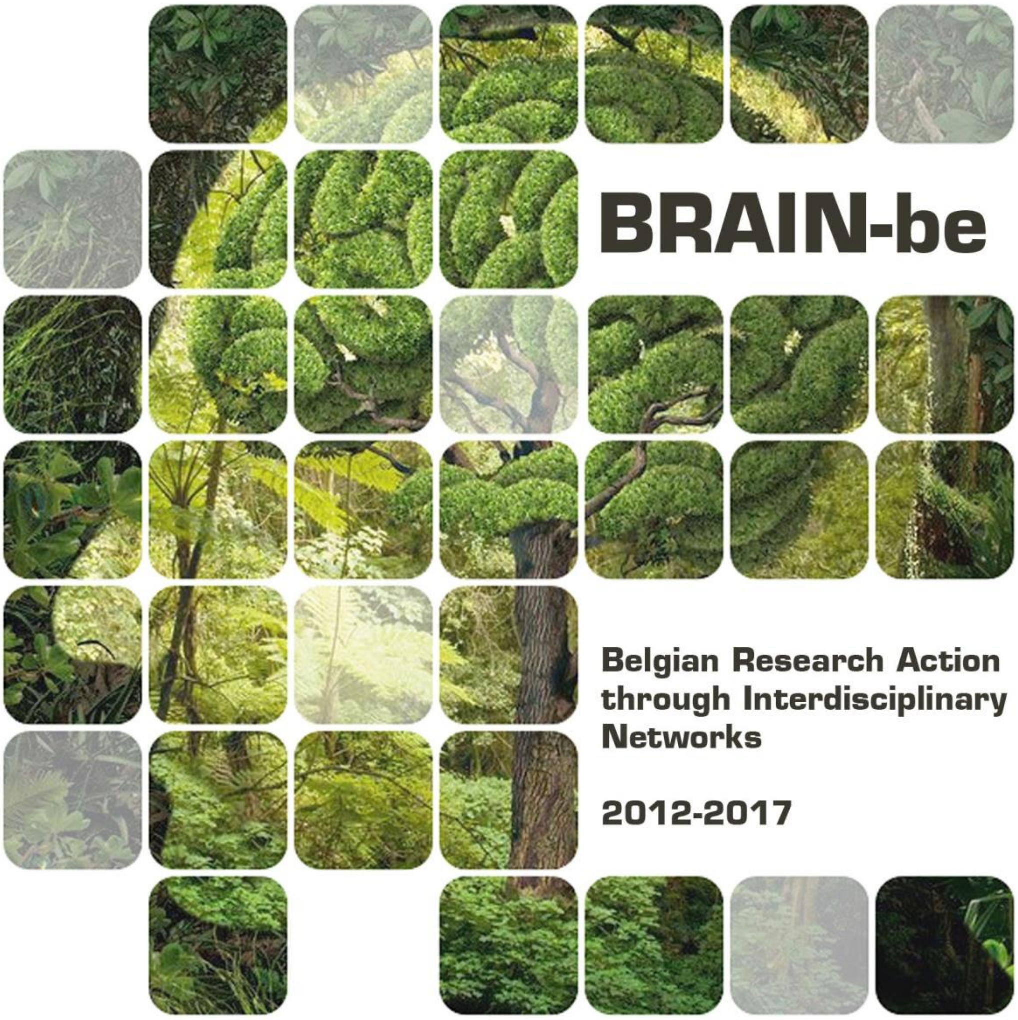

METRO

Banen van meteoren en hun oorsprong

Trajectoires des météores et leurs origines

Trajectories of meteors and their origin

H. Lamy (BIRA-IASB) – J. De Keyser (BIRA-IASB) – T. Magin (VKI) – B. Dias (VKI) – F. Bariselli (VKI)

NETWORK PROJECT

METRO

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Trajectories of meteors and their origin

Contract - BR/143/A2/METRO

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ABSTRACT

Context: Meteoroids enter the Earth's atmosphere constantly. They represent a hazard for spacecraft in orbit and are of great interest for the hypersonic re-entry of objects.

Objectives: Since 2010, BIRA-IASB has developed a unique network of radio receiving stations, BRAMS, for forward scatter radio observations of meteoroids. VKI has experience with modelling spacecraft re-entry and is extending this expertise to the entry of meteoroids. The objectives are to combine the expertise to 1) develop the tools to analyse the data from the BRAMS network, 2) to develop models to simulate the hypersonic entry of meteoroids, and 3) to combine data and models to better understand the meteor phenomenon and to estimate meteoroid trajectories and initial masses.

Conclusions: During this project the BRAMS network has been expanded and upgraded. Many tools to analyse BRAMS data were created. VKI developed models for the entry of small meteoroids (at high altitudes, so mostly kinetic models) and larger ones (going deeper into the atmosphere, so mostly fluid models). The methods to retrieve the trajectories of meteoroids from BRAMS data only have not yet reached a sufficient maturity to combine with the outputs from the VKI modelling. However, some interesting results have been obtained.

Keywords: Meteors – Meteoroids – Radio observations - Modelling

1. INTRODUCTION

Millions of meteoroids fall every day in the Earth's atmosphere, most of them being tiny dust grains. The cumulative daily mass of these objects deposited in the atmosphere is of the order of tens of tons. They play an important role in many fields. In the upper atmosphere, they influence the chemistry and they allow sampling the temperatures and winds in a region inaccessible via balloons or spacecraft. Outside of the atmosphere, they also pose a potential threat for all spacecraft and astronauts in orbit. They also allow studying the evolution of the interplanetary dust complex and specific comets or asteroids crossing the Earth's orbit. The complex physics of ablation of these objects when they enter the atmosphere at hypersonic velocities is also a topic of great interest for the re-entry of spacecraft or man-made debris.

With this METRO project, we proposed to study meteoroids using radio data collected by the BRAMS network, a network of Belgian radio receiving stations using forward scatter techniques to detect and characterize the meteoroids. The network comprises one dedicated transmitter and a large number of receiving stations spread all over the Belgian territory. Forward scatter means that the transmitter and the receivers are not at the same location, unlike a classical meteor radar. A continuous radio wave is sent by the transmitter and might be reflected on ionized meteor trails produced by meteoroids ablating in the atmosphere. Depending on the geometry, several receiving stations can record the reflection of these radio waves, the so-called meteor echoes. Radio observations of meteoroids have two advantages over optical / video observations. First, they can be run continuously, including during daylight and independently of most weather conditions. In addition, they are sensitive to smaller particles, which constitute the bulk of meteoroids, and therefore they detect many more objects. A BRAMS receiving station typically detects 1500 to 2000 meteor echoes per day. One of the main goal of this project was to develop tools to analyze the huge amount of data generated by the BRAMS network.

The work of analyzing the BRAMS data was carried out at BIRA-IASB. Given the large amount of data generated by the network, the first goal was to develop algorithms to automatically detect the meteor echoes and disentangle them from all other spurious signals, mostly coming from reflections of the radio waves on aircraft flying nearby the transmitter. Another important objective was to reconstruct trajectories of meteoroids from multiple observations at various receiving stations and see how accurate these reconstructions are by comparing them with observations coming from networks of optical cameras such as CAMS or FRIPON. And a third important goal was to study the power profile (power versus time) of the underdense meteor echoes (the majority of the echoes detected by BRAMS and produced by small particles). From this power profile, the ionization at the specular reflection point can be determined and multi-station observations can then provide a profile of the ionization along the meteoroid path.

Therefore, the ability to predict the ionization intensity and the dissipation rate of the plasma trail becomes essential for the correct interpretation of the radio signal. However, current approaches are drastically simplified and disregard collisional effects in the rarefied gas. For this reason, sophisticated models were used at VKI to provide a detailed description of the meteoroid degradation process and those physico-chemical phenomena that drive the dynamics of the ablated vapor around the body and in its plasma trail. First, the gas behavior and the ionization process were studied by simulating the molecules directly at the kinetic scale. For bigger meteoroids that can reach lower altitudes, the effect of radiation and the resulting luminosity of the event has been considered. In a second step, a procedure to examine the neutralization of the extended trail has been designed and applied. Also, particular attention has been devoted to the investigation of gas-surface interactions. This investigation was supported by ground experiments in the VKI plasma wind tunnel. Each improvement in the modelling is expected to impact not only our understanding of the physical problem but also the estimates on mass fluxes and the statistical outcome of the collected observational data.

2. STATE OF THE ART AND OBJECTIVES

Meteoroids are small planetary bodies (from 1 m across down to micron-size grains) orbiting the sun with fast speeds relative to Earth, which makes them hard to detect in situ with space-borne instruments or with remote sensing techniques. The most convenient detector at hand is Earth itself as our planet is continuously bombarded by meteoroids that burn up in the atmosphere at typical altitudes of 90-110 km, creating the meteor phenomenon ("shooting stars"). They also create an ionization trail along their path in the Earth's atmosphere and the density of electrons inside these trails is large enough (compared to the local electron densities in the ionosphere at these altitudes) to reflect VHF (Very High Frequency 30-300 kHz) radio waves. From the properties of these meteors, one can glean information about the progenitor meteoroids.

The present project focused mostly on radio meteor observations and what can be learned from them. For that purpose, the unique data set from the BRAMS radio meteor network was used. BRAMS (Belgian RAdio Meteor Stations, a project carried out since 2010 by BIRA-IASB and mostly funded by the Solar-Terrestrial Center of Excellence) relies on forward scattering of radio waves. A dedicated beacon located in Dourbes transmits radio waves that are reflected off meteor ionization trails and received by approximately 30 stations across the country. It monitors the whole sky above Belgium and turns it into a giant detector for the meteoroid population in the Solar System. The receiving antenna located in Uccle is shown in Figure 1. It is worth noting that BRAMS is a very active Pro-Am collaboration since most BRAMS stations are hosted by astronomical public observatories or radio amateurs.

Figure 1: the receiving antenna at the station in Uccle

Each BRAMS station typically records between 1500 and 2000 meteor echoes per day. An example of BRAMS observations is provided in Figure 2, showing the various types of reflections (various meteor echoes, reflections on airplanes) or the direct (tropospheric) signal coming from the beacon.

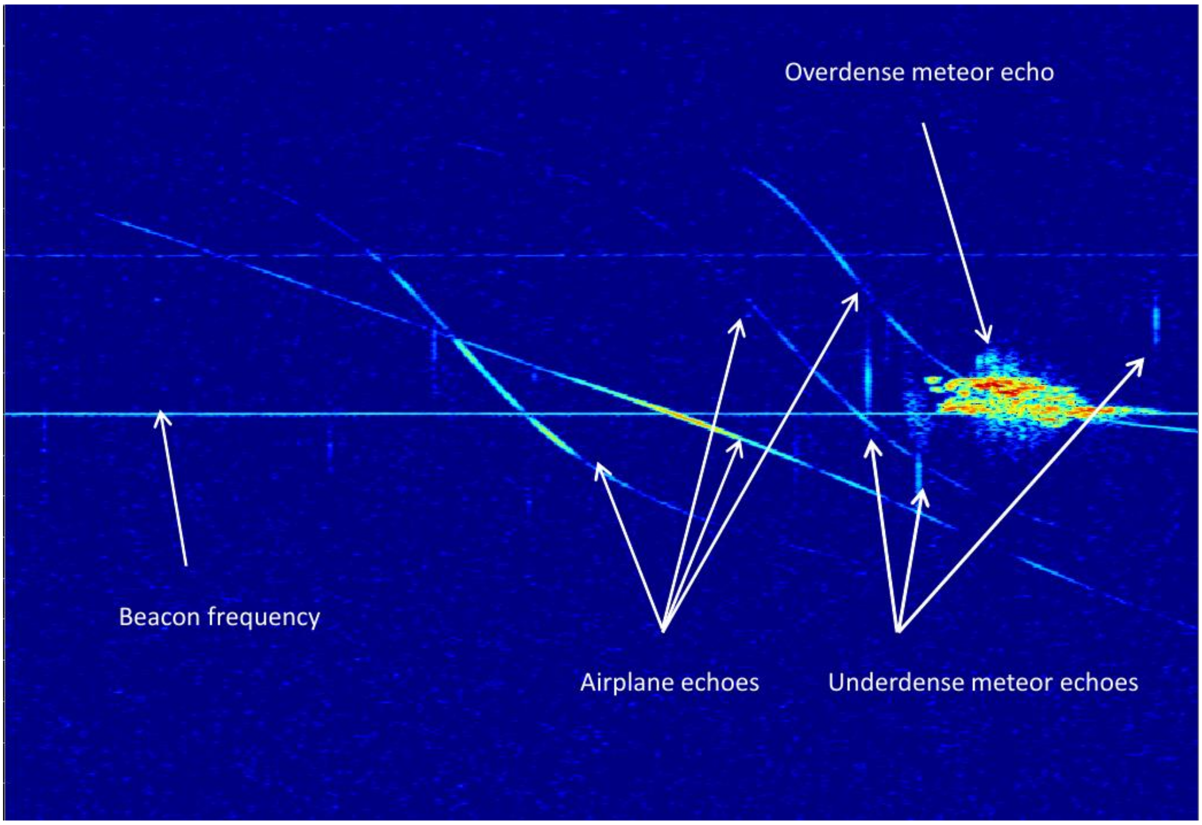


Figure 2: Typical BRAMS spectrogram. The horizontal axis represents time and covers 5 minutes. The vertical axis gives frequency and displays a 200 Hz range centered on the direct signal from the beacon. Power is color-coded.

One of the main objectives of the project is to determine the trajectories of meteors in the sky above Belgium from data continuously acquired by the BRAMS network. Computing such trajectories in an automatic way for the large number of meteors recorded by BRAMS is a first challenge that has to be addressed. This is possible because all BRAMS receiving stations are equipped with GPS clocks, which allow accurate time synchronization. For a number of meteors, it is also possible to obtain meteor speed. Combining speed and meteor trajectory, one can trace back the orbit of the meteoroid.

Another objective is to obtain an ionization profile along the meteoroid path from multi-station observations of the same meteor. This can be done using the peak power of underdense meteor echoes and the signal from the BRAMS calibrator, a device that has been designed and built in-house and that provides a very stable reference amplitude. This ionization profile can then be used in conjunction with an ablation model, which provides among others the mass loss rate dm/dt along the path if the trajectory and initial speed are known. This mass loss rate profile can be used to estimate the ionization profile along the path as they are linked together via the (poorly known) ionization efficiency parameter. The comparison of the computed ionization profile and the estimate of the electron densities in several points along the trajectory can provide an estimate of the initial mass of the meteoroid by using optimization methods.

A long-term objective is to compute fluxes of meteoroids, i.e. a number of objects in a mass (or size) range passing through a unit surface and per unit time. This is extremely relevant for spacecraft in orbit and is therefore important for space agencies in order to decide their shielding strategy for the instruments or the crucial parts of a satellite. To go from the raw BRAMS data to eventually fluxes of meteoroids is a long and complex process. A first step is to compute the observability function (OF) which tells us how many meteoroids can be detected for a given transmitter-receiver configuration and a given radiant for the objects. This has never been done before for a forward-scatter system and is therefore a challenging and long-term task.

Another important aspect is the comparison of radio observations with optical observations. The former are sensitive to a larger range of masses including many objects that cannot be detected with optical observations. But for those meteoroids which can be detected by radio and optical observations, the goal is to combine the observations to 1) use the trajectories and speed measurements coming from the optical observations to facilitate the use of radio observations, 2) to compare the reconstruction of trajectories coming from radio data obtained with BRAMS with those obtained from video networks such as CAMS-Benelux or FRIPON, 3) to study the ionization efficiency.

The foundations of the physical theory of meteors have been laid in the first part of the 20th century, Scientists have mainly focused on the development of synthetic models. These models are agile and based on algebraic relations, and they condense the complexity of the problem in a few free physical parameters. This intrinsic simplicity made them suitable for parametric studies and fitting of observational curves. However, these models are oversimplified, often based on a zero-dimensional approach, and disregard non-equilibrium phenomena such as rarefied gas or radiative heat transfer effects. At the same time, past computational studies have tackled the formation and the dissipation of the plasma trail as two separate problems. They never accounted for the whole picture in a self-consistent way. Also, past simulations have included only basic kinetics and simplified vapor mixtures. Besides observations, from this moment onward, further progress in this discipline is likely to be achieved mainly via computer simulations. Studies relying on synthetic theories, exact approaches, and non-dimensional analysis are of paramount importance, yet they struggle to lead to firm conclusions. Difficulties principally arise from the intercoupling of phenomena and multiscale physics. Important factors risk being neglected solely for mathematical expediency.

Therefore, one of the goals of this project was to develop comprehensive physico-chemical models and methodologies for the description of the meteor phenomenon in the rarefied and continuum regimes, with application to radio detection. By doing so, we wanted to reduce the initial uncertainties relevant to i) the input of metals in the chemistry of the upper atmosphere, ii) the resulting ionization efficiencies and plasma dissipation rates, which are necessary for a correct interpretation of radar and radio detection measurements.

3. METHODOLOGY

Work Package 1: Observations and data analysis

WP 1.1: Meteor count & data selection

Several algorithms were tested over the years with the goal of maximizing the number of detection of meteor echoes (therefore decreasing the number of false negatives, FN) and minimizing the number of false detections (false positives, FP). Roughly speaking, the false negatives are mostly due to faint meteor echoes for which additional detailed analysis is difficult because of the poor signal-to-noise ratio. The number of false positives is mainly due to multiple airplane reflections overlapping each other and producing signals mimicking underdense meteor echoes, the majority of meteor echoes detected with the BRAMS network.

The most efficient methods are trying to detect meteor echoes in spectrograms and not in raw data. They are based on the fact that most underdense meteor echoes have a much larger frequency (vertical) extent in spectrograms than other signals due e.g. to airplane reflections or direct signal from the beacon. A Matlab procedure was developed to use a median vertical filtering (see an example in Figure 3). This was the topic of several internships with students from the University of Brussels (2016, 2018 and 2019). The results were presented at several international conferences.

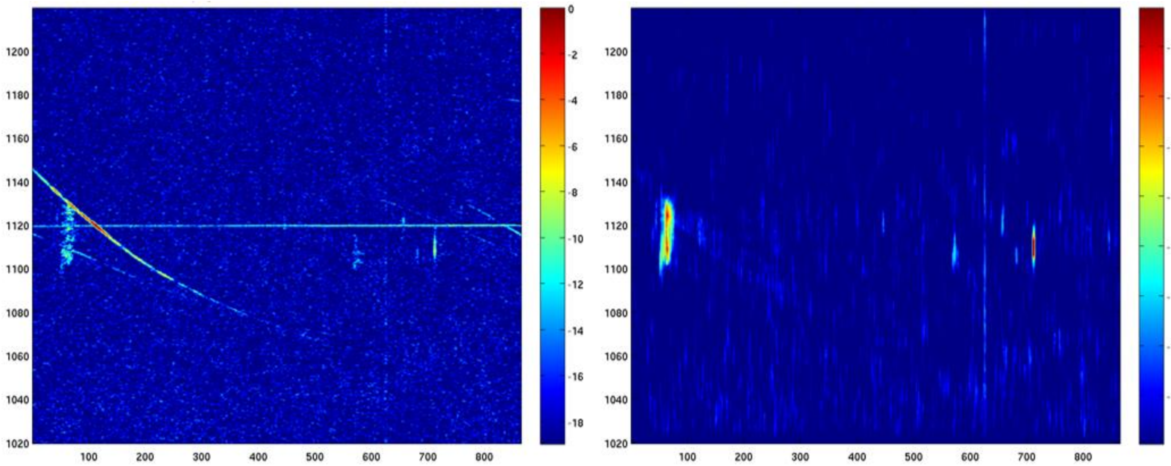


Figure 3: Example of a spectrogram (left) and the result after using a median vertical filtering (right).

Another method was tested in collaboration with the University of Antwerp and is based on the use of neural networks (NN). A large data set of BRAMS data was used to feed various types of NN in order for them to learn how to distinguish meteor echoes from other spurious signals. For that a data base with correct identification of meteor echoes needs to be used (see below). The NN gives good results in terms of FP and FN (see an example in Figure 4) but needs to be adjusted for spectrograms where reflection on military airplanes occur. A special data set is currently produced to teach the NN with these special sets of data. This was the topic of a Master Thesis at University of Antwerp (2019).

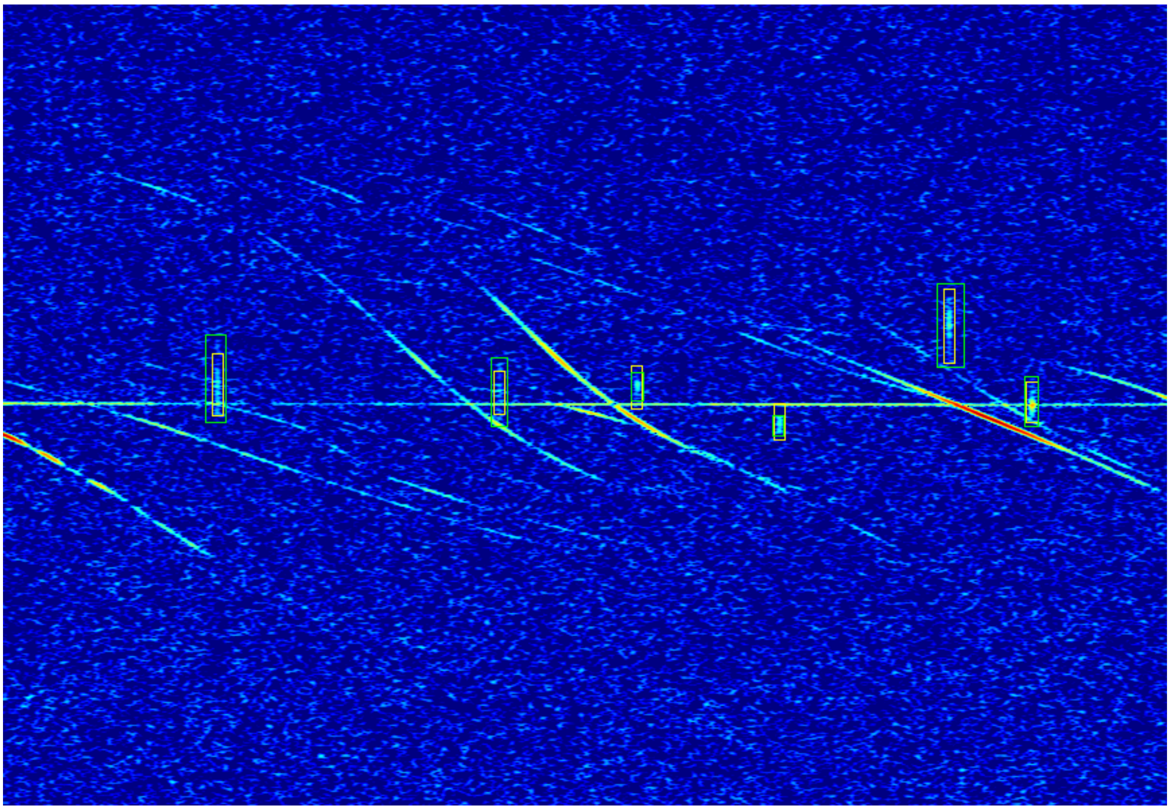


Figure 4: An example of a spectrogram analyzed with Neural Networks. The Yellow rectangles come from the manual counts done by the users of the Radio Meteor Zoo, a citizen science project. The green rectangles are the outputs of the trained NN. The agreement is nearly perfect in this case.

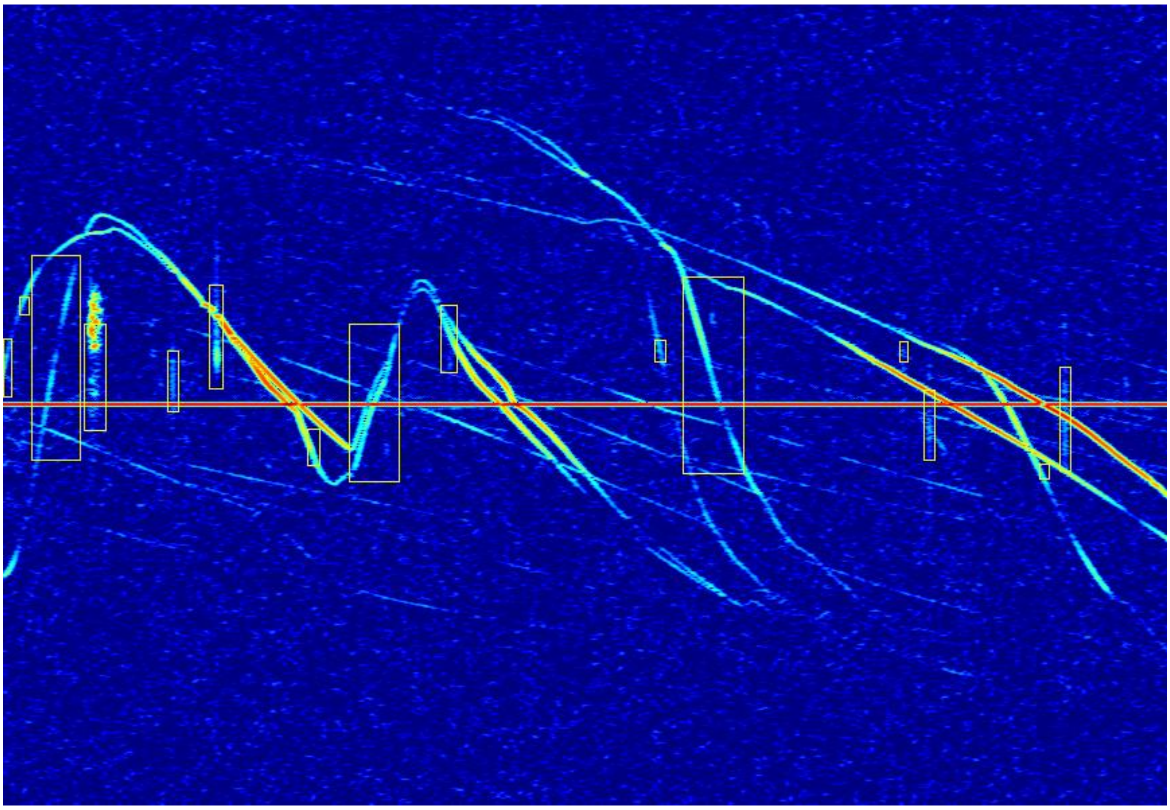


Figure 5 : A spectrogram with many complex reflections due to military airplanes. The yellow rectangles are the outputs of the trained NN. Several FPs are visible because the network was not trained to identify these specific signals.

Among the radio meteor echoes, a small percentage are due to bigger meteoroids producing so-called overdense meteor echoes, which appear much more complex in spectrograms and with a duration, intensity and shape that can vary a lot. The algorithms described above fail to automatically identify some of these overdense meteor echoes, most of the time because they consider one such complex echo as many individual meteor echoes, creating a lot of FPs. The problem is particularly striking during meteor showers, when a lot of these complex overdense meteor echoes occur. In this case, the best detector still remains the trained human eye. Therefore, the idea arose to create a Citizen Science project, called the Radio Meteor Zoo, https://www.zooniverse.org/projects/zooniverse/radio-meteor-zoo, in collaboration with Zooniverse (https://www.zooniverse.org), which provides the platform and online support. This project has been very successful, both in terms of outreach and providing valuable scientific results. See for example Figure 6. In the context of this work package, the identification of meteor echoes in spectrograms from the users was e.g. used to feed the NNs.

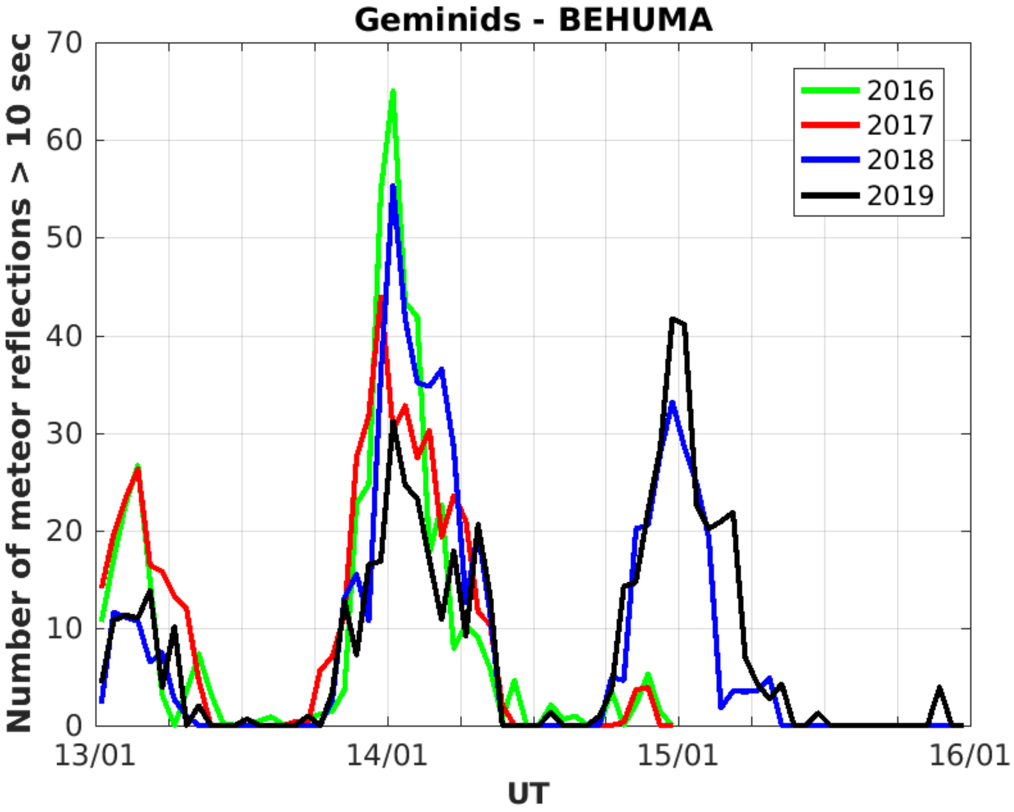


Figure 6 : Results obtained with outputs from the Radio Meteor Zoo. The plot shows the estimated activity of the yearly Geminids meteor shower, from 2016 to 2019, based on the number of meteor echoes with a duration larger than 10 seconds.

WP 1.2: Multipoint trajectory determination

Retrieving the meteoroid trajectory from multi-observations with various BRAMS stations is not an easy task. This comes partly from the fact that the transmitter sends a radio wave without any type of modulation and that the receiving station uses 3-element Yagi antennas which are not directional. Therefore, when a meteor echo is detected at a BRAMS receiving station, we have no information about the direction of arrival of the signal (direction of the specular reflection point on the meteoroid path) nor about the range of distance that the wave has travelled from the transmitter to the reflection point and then to the receiver.

A first geometrical attempt was made using a method proposed by Nedeljkovic (2006). The principle is based on the idea that the reflection of the radio wave (at least for underdense meteor echoes) is specular, which implies that most of the power of the meteor echo recorded at a BRAMS receiving station comes from one point along the trajectory called the specular reflection point. The position of this point only depends on geometrical parameters, namely the meteoroid trajectory and the geographical positions of the transmitter (Tx) and the receiver (Rx). It is the point of the trajectory that is tangential to an ellipsoid whose foci are Tx and Rx. When the trajectory is known, finding the position of this point is a simple mathematical problem with an analytic solution. But the trajectory is a priori unknown. So Nedeljkovic (2006) suggested to search for trajectories that are tangential to n ellipsoids if the meteor has been detected by n different stations. Matlab codes were developed using this idea and simulations were made with a limited number of stations. Results were presented at the International Meteor Conference in 2016. This method needs to be tested with more stations.

Table 1 – Number of remaining trajectories using the altitude criterion. Three stations are considered: U = Uccle, O = Ottignies and S = Seneffe. z_p is the altitude of the specular reflection points.

	$95 < z_p < 110$ km
U	65631
O	65344
S	67870
U & O	61186
O & S	57003
U & O & S	54734

A second method uses timing and has been implemented only recently. We are working in collaboration with Dr. Gunther Stober from University of Bern for this method. It consists in minimizing the total distance traveled by the radio wave from transmitter to the various reflection points and eventually to the transmitter. One station is chosen as reference. The position of the reflection point for this station provides 3 unknowns. The position of the reflection points for the other stations depends on the speed of the object, which provides 3 additional unknowns. We also need 2 time measurements corresponding to the delay necessary to travel from the reference specular point to another one. In total we have 8 unknowns and therefore we need 8 stations, which will provide accurate delays Δt between occurrence of meteor echoes. In order for this method to be successful, clusters of BRAMS stations geographically close to each other need to be created in order to maximize the number of stations which detect the same object at slightly different times. Since the method involves solving a set of non-linear equations, 8 stations is only a minimum; the more stations, the better the accuracy. We have recently installed additional new BRAMS stations in Limburg, with a total amount of currently 7 stations in the neighborhood (~ 30 km) of Genk. Additional locations have been considered and we expect to have 10-12 stations soon. The method will then be heavily tested. Other clusters in Belgium will be installed later on if the method proves to be successful.

A third method is possible when one of the receiving stations which detect a meteor echo is the interferometer in Humain. This station is different from the rest of the network in the sense that it uses 5 similar Yagi antennas in a specific configuration described by Jones et al (1998). The receivers used for this station are AR-5001 which accept a common external reference disciplined by GPS clocks. This allows us to measure the phase of the signals arriving at each antenna, contrary to all the "classical" receiving BRAMS stations which use ICOM-R75 receivers. The combination of the different phases allows us to reconstruct the direction of arrival of the meteor echo with an accuracy of 1°. A great deal of effort was put in the development of this interferometer, both in terms of hardware (accurate measurements of the electric length of the cables, accurate distances in 3D between the phase centers of the antenna, etc) and software. This was also partly the topic of two internships with students from University of Brussels, one in 2017 for the development of the Matlab codes (see an example of result in Figure 7), the other one in 2019 about the calibration of the interferometer using signals from a transmitter flying on a drone, using reflections from airplanes whose position and speed are determined using ADS-B signals recorded with specific material, and finally using data from the optical network CAMS-Benelux (see below). Results were presented at the International Meteor Conferences in 2017 and 2019. The method using data from the station in Humain with data from additional stations nearby has still to be implemented. We are actively looking for stations geographically closer to Humain in order to maximize the chances to have enough common detections.

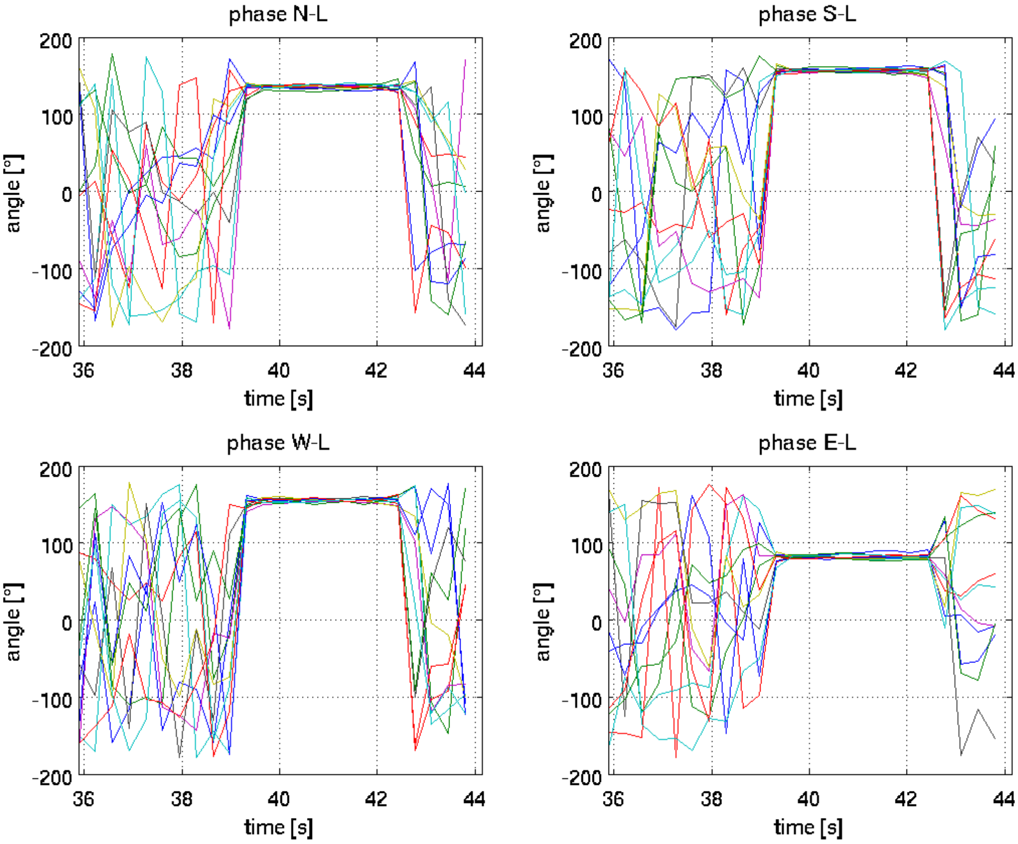


Figure 7 : Data obtained with the radio interferometer in Humain. The phase differences between the central antenna (called L here) and the four other antennas (North/South/West/East) are shown. During the meteor echo, the phase differences become extremely coherent and the combination of these four phase differences allow us to retrieve the direction of arrival of the meteor echo. The different colors correspond to various frequency bins belonging to the meteor echo.

Although none of the three methods is currently fully operational, significant progress has been made with at least two of the three. The network is also currently densified with the addition of new receiving stations in order to either create a cluster of stations geographically close to each other (important for methods 1 & 2) or to have more stations around the interferometer in Humain (important for method 3). Note that, in parallel to the BRAMS network, we are also building an in-house meteor radar in Dourbes, next to our BRAMS transmitter. The frequency of this radar will be very close to the one of the BRAMS transmitter (49.97 MHz). The receiving part of the radar is an interferometer similar to the one in Humain (see Figure 8). With the additional information of the range, this radar system will provide the position in 3D of the specular reflection point for a meteor echo. Since the distance between Dourbes and Humain is only 60 km, there will be a reasonably large fraction of meteor echoes that will be detected by both interferometers (and the additional stations). For these meteoroids, the reconstruction of the trajectories will be easier.

Figure 8: the receiving part of the future meteor radar in Dourbes is an interferometer similar to the one installed in Humain. The transmitter will be an antenna and a grid similar to the BRAMS transmitter and is located in the background at around 200 meters from the interferometer.

WP 1.3: Verification of BRAMS trajectories

The idea was to validate the reconstruction of meteoroid trajectories using BRAMS data by comparing with those coming from more traditional optical networks. In Belgium, we have cameras from two such networks : CAMS (Camera for All-sky Meteor Surveillance)-Benelux and FRIPON (Fireball Recovery and InterPlanetary Observation Network). We have been contributing actively to the CAMS-Benelux network by installing and running four cameras on a daily basis (one at BIRA-IASB in Uccle, two in the Geophysical Center in Dourbes, and one in Humain). We have also installed a FRIPON camera on the roof at BIRA-IASB and helped with the installation of another one at the University of Liège. CAMS-Benelux aims at detecting meteors down to typically magnitude +5 and at reconstructing very accurate trajectories and speeds in order to detect new minor meteor showers and to find their parent bodies. FRIPON is dedicated to the observation of fireballs with the goal to reconstruct their trajectories, to identify their parent bodies and to find potential meteorites on the ground.

Since the algorithms for retrieval of meteoroid trajectories with BRAMS data are not fully operational yet, a direct comparison with the trajectories obtained with optical networks such as CAMS-Benelux were not possible. However, studies combining CAMS-Benelux and BRAMS data have been carried out. Using trajectories and speed data coming from CAMS-Benelux observations, we computed the theoretical positions of specular reflection points for each BRAMS receiving station as well as the theoretical times of appearance and compared these with meteor echoes in spectrograms and raw data. This provided excellent agreement between the observations and the theory, providing strong support for the ability to use these data for further analysis (see below). Of course, such an analysis can only be applied to a handful of meteoroids that produce signals bright enough to be detected by CAMS cameras (typically ~ magnitude +5) and not too bright as those objects will produce overdense meteor echoes for which the specularity condition might not apply strictly. Comparisons were made using more than 200 trajectories obtained by the CAMS-Benelux network on the night from 4 to 5 October 2018.

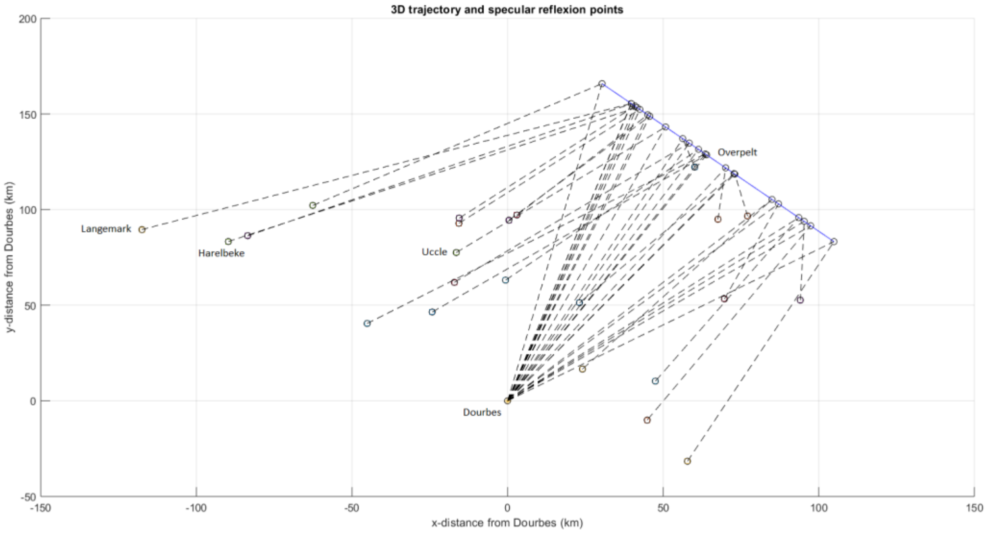


Figure 9: Example of a CAMS trajectory from night 4 to 5 October 2018. The dots correspond to BRAMS receiving stations active that night. The positions of the specular reflection points along the meteoroid trajectory have been computed.

Some comparisons were also made with the FRIPON data, in particular in order to understand why some fireballs are producing strong overdense meteor echoes visible by all BRAMS stations, while others are barely visible (see Figure 10). Also, the occurrence of head echoes or not, sometimes with positive or negative frequency shifts, were analyzed using trajectories provided by the FRIPON network.

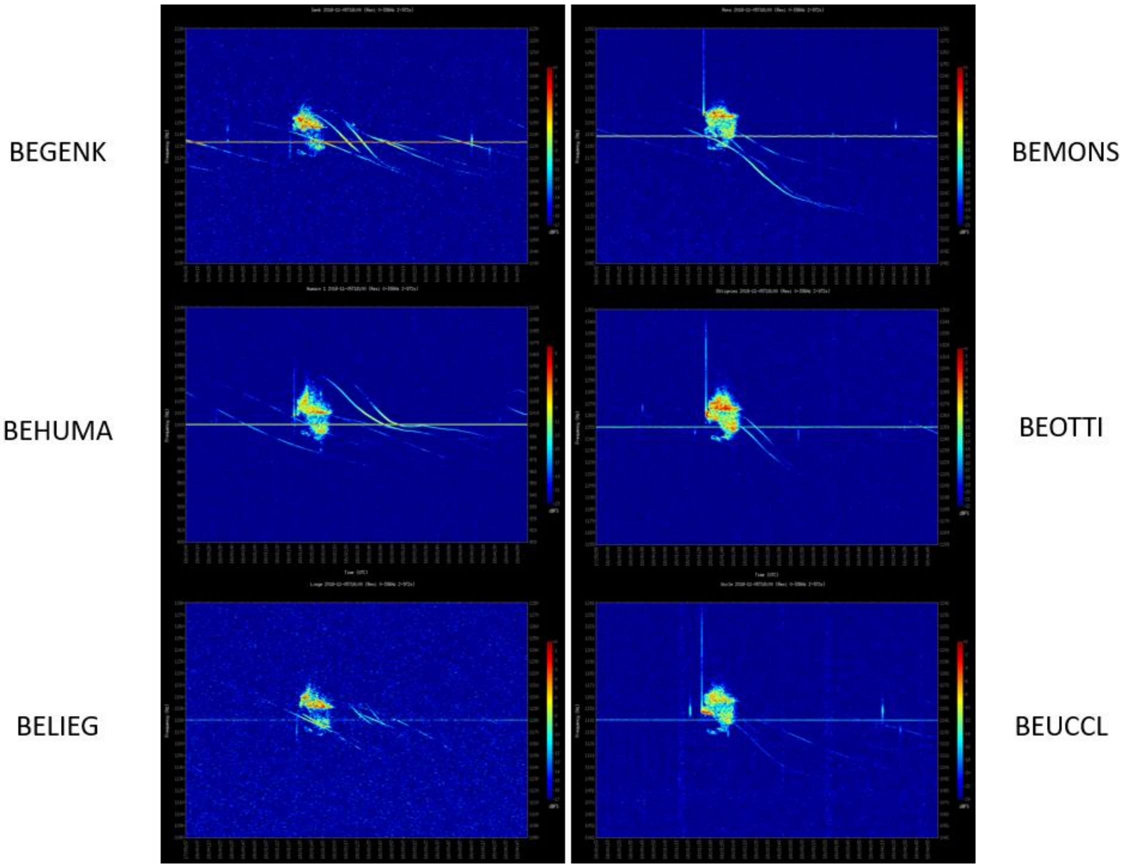


Figure 10: BRAMS observations of a fireball detected by the FRIPON cameras in Belgium on 05/11/2018.

WP 1.4: Observability conditions

A given configuration transmitter (Tx) – Receiver (Rx) cannot detect all meteor echoes at any time. The specularity condition and the geometry play a fundamental role. In particular, during meteor showers, the position of the radiant is critical. Very few meteoroids belonging to the meteor shower can be detected if the radiant is low on the horizon or close to the zenith. The Observability Function (OF) is a tool that takes these geometrical factors in account and that allows to correct the observed numbers to a flux of meteoroids. C and Python codes have been developed to calculate the OF for a given meteor shower and a given configuration Rx-Tx at any time of the day.

The OF should also include technical parameters such as the gains of the transmitting and receiving antenna as well as the sensitivity of the receivers. A lot of work was done to fully characterize the Tx, both the antenna and the power amplifier. The emitting pattern of the antenna was fully characterized using a payload specifically designed and attached to a captive weather balloon flying at various positions around the antenna. For the receiving antennas, a lot of modeling has been made and led to the conclusion they should be oriented vertically instead of tilted to point towards an altitude of around 100 km above the transmitter. In summer and fall 2018, all antennas were set up vertically and all BRAMS receiving stations were investigated to better adapt the antennas and to estimate the local noise level. All these data will soon be included in a much more complete OF.

WP 1.5: Meteor flux model and elemental mass deposition rate

The goal here was to combine BRAMS data with simulation results from VKI (see WP2). The CAMS/BRAMS comparisons described above were carried out with this goal in mind. From the CAMS data, meteor echoes at different receiving stations were unambiguously identified in spectrograms. We have then automatically classified the meteor echoes in 3 categories: 1) those spectrally isolated, 2) those superimposing spectrally with the direct signal from the transmitter, and 3) those superimposing spectrally with airplane echoes. For the first category, we just need to filter out the noise, which was done using Blackman filters. For the second category, we cannot filter out the direct signal from the beacon as we would also filter out part of the meteor echo itself. We have instead developed a technique to reconstruct the direct signal and subtract it from the raw data before filtering the noise. This method proves to work perfectly for the interferometer in Humain as these receivers are extremely stable due to the use of an external reference disciplined by GPS clocks (see Figure 11). For all the other BRAMS stations, the results vary from very good to moderate depending on the propagation conditions and other factors. In the latest and future BRAMS stations, a new type of receiver is used, which allows an external reference (contrary the ICOM-R75 receivers) and therefore this technique can be used in the future for all meteor echoes. For the third category, developments are still being pursued.

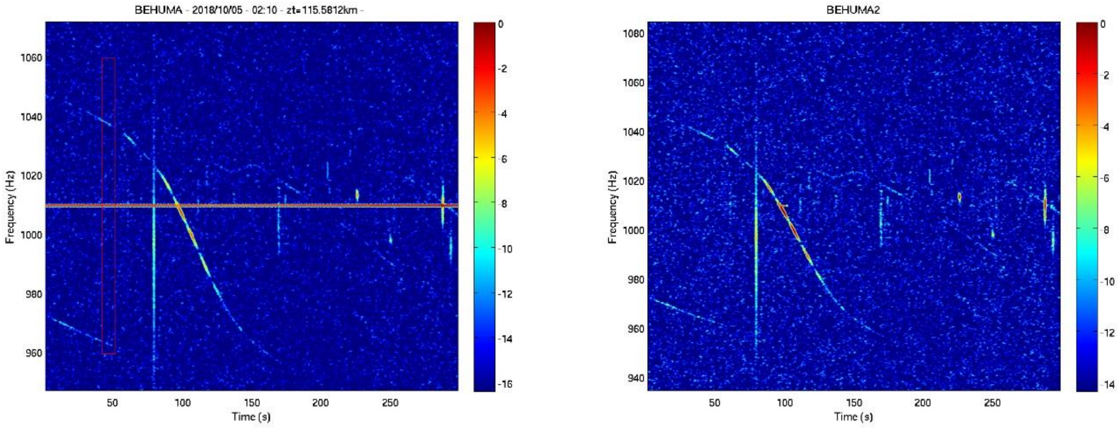


Figure 11: example of subtraction of the direct signal from the beacon on a spectrogram from Humain. Left : raw spectrogram. Right : spectrogram after the subtraction

Once these meteor echoes have been cleaned in the raw data, we obtain a power profile (see Figure 13). For underdense meteor echoes, using an extension to the forward case of Mc Kinley's formula valid for meteor radar, we can obtain the ionization (in electrons/meter) at the specular reflection point. For that we need to know the geometry (trajectory provided by CAMS data) and the gain of the antenna (see WP 1.4). For multi-station observations of the same meteoroid, a profile of the ionization along the meteoroid path can be obtained.

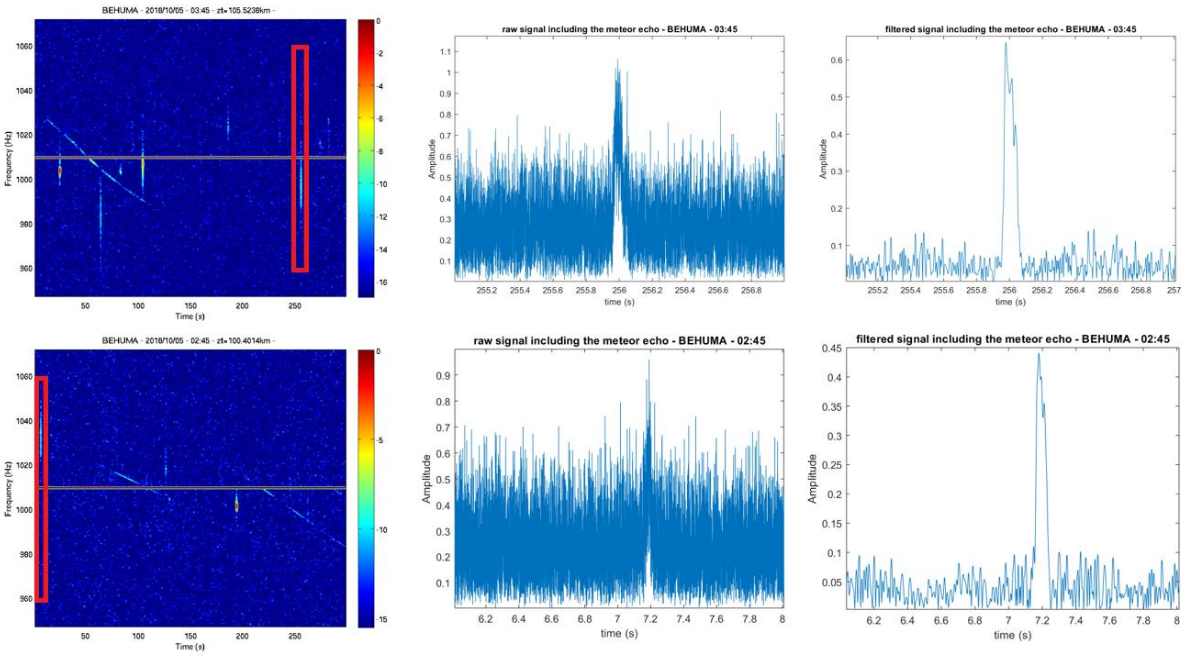


Figure 13 : two examples of underdense meteor echo power profiles. Left : the spectrogram and the corresponding meteor echo surrounded by a red rectangle. Middle : the raw BRAMS data corresponding to the time interval inside the red rectangle. Right : the filtered raw BRAMS data. The power profile of the meteor echoes are clearly visible.

The ionization is directly related to the mass deposition during the ablation process of the meteoroid. Therefore, using an ablation model with a known trajectory (here given by CAMS) and speed, and assuming a reasonable composition, a mass deposition profile can be computed for various values for the initial mass of the meteoroid. A fit was then computed between a theoretical ionization profile and the data estimated from BRAMS observations. This was the topic of a Master Thesis at the University of Liège in direct collaboration with BIRA-IASB and VKI. Part of this work was also continued during an internship bu another student from the University of Brussels in 2019.

WP 1.6: Detailed analysis of meteor reflections

We have unfortunately never really seen Fresnel oscillations so far in our BRAMS data. At least, we have not been able to make completely sure that they are not artifacts of the filtering process. So making estimations of the meteoroid speed using this method has not been tested yet. The computation of the ionization profile determined from the peak power of underdense meteor echoes has already been discussed above (see WP 1.5).

We have started working on the exponential decay of meteors to relate it to temperature in the mesosphere. Again, this has to be done with trajectory retrieval in order to relate the altitude of the reflection point to this temperature estimate. A collaboration has been also initiated with the university of Bern to estimate mesospheric winds from Doppler shifts of meteor echoes in the spectrograms.

WP 1.7: Visual meteor brightness curve and spectroscopy

We have not been able to make progress with this spectroscopy part. We have not procured material or acquired a solid experience. This field is still not completely mature yet. For the time being, spectroscopic observations are still limited to very bright meteors and can thus be applied at this moment only to fireballs, which are not the main target of the BRAMS network. Therefore, so far, we have relied on previous work and a priori knowledge about the composition of the meteoroids.

Work Package 2: Simulations

WP 2.1: Meteor simulation for low altitudes

Meteor simulations have been done at the VKI using a stagnation line fluid code coupled to a material ablation code using the Mutation++ library and a radiative heat transfer code. Fluid codes are applicable for relatively large particle size and high atmospheric density; in practice below roughly 70 km altitude. Thermodynamic and transport properties are available for the relevant species of the atmosphere and meteor ablation products in the Mutation++ database. Results obtained are compared and checked against the literature to validate the quality of the simulation.

WP 2.2: Meteor simulation for high altitudes

Meteor simulations have been set up using a Direct Simulation Monte Carlo (DSMC) code available at VKI; the code has been coupled to a model of the upper atmosphere where rarefied gas effects (gas kinetic effects) are important, including ions and electrons. The DSMC simulations have been carried out by means of the SPARTA code suitable for complex 3D geometries; this code includes complex physico-chemical models for internal energy relaxation and chemical reactions.

Work Package 2.3: Ionization trail

A Lagrangian solver for nonequilibrium reacting flows has been developed. The solver acts as a chemical reactor following a fluid particle along pre-computed streamlines, integrating the governing equations with initial conditions picked from the first point of the streamline. This tool allows to draw a map of the free electrons in the tail of the object and to assess its characteristic time of dissipation, which is crucial for the interpretation of data obtained through radio detection by BRAMS.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

Work Package 1: Observations and data analysis

WP 1.1: Meteor count & data selection

A huge set of data has become available and archived at BIRA-IASB with nearly 10 years of data for some BRAMS stations. An important outcome of the METRO project is *the need for better calibration in order to obtain a consistently uniform high data quality*.

The quality of these data has already been improved and we continue to do so, e.g. by adding a device called the BRAMS calibrator (developed in-house at BIRA-IASB) that allows to convert power measurements of meteor echoes from dimensionless units to watts, which is crucial to the study of ionization along the meteoroid path. The network has also been constantly extended and upgraded in order to produce high-quality data. The next generation of stations using new type of receivers (RSP2 digital receivers instead of the commercial ICOM-R75 analog receivers) will provide even better data, e.g. thanks to the additional use of an external reference.

A second recommendation is that *automatic techniques are needed to process the large amounts of data produced by BRAMS*.

The BRAMS data are available online on our website (https://brams.aeronomie.be) and can be downloaded via a tool called the BRAMS viewer. Monitoring tools have also become available online such as the BRAMS data availability or the BRAMS monitoring tool.

Two algorithms for automatic detection of meteor echoes have been developed with good results in terms of False Positive and False Negatives on most spectrograms. They are in their final evaluation and still open to improvement but a first implementation is planned soon to produce daily activity curves for each BRAMS station.

These algorithms produce good results during days without meteor showers, the so-called background days with mostly sporadic underdense meteor echoes. During meteor showers, the Radio Meteor Zoo, launched in August 2016, has allowed us to study activity curves of the most active meteor showers during several years in a row. The results have been presented at several international conferences.

Our work with the BRAMS data has *shown the importance of an active Pro-Am collaboration*. Indeed, most of our receiving stations are hosted by radio amateurs, amateur astronomers, public observatories or universities. We have regularly new candidates interested to welcome a new BRAMS station. This will be extremely useful in our goal to densify the network in order to have local clusters of stations able to detect a lot of meteoroids and allow a reconstruction of their trajectory.

WP 1.2: Multipoint trajectory determination

The problem of multipoint trajectory determination has proved to be more difficult than we envisaged before, in particular because one has to consider different problem settings. Also, *the multipoint trajectory determination problem appears to be closely coupled to the spatial organization of the observation network*. We have worked on 3 methods:

- One based purely on geometrical factors. It needs to be tested more with a larger number of stations but with the state of the BRAMS network at the time of the tests, it was clear that the network was not dense enough and that not enough BRAMS stations were detecting the same meteors because the corresponding specular reflection points are either at too high altitude (resulting in not enough ionization to produce a signal strong enough to be detected) or at too low altitude (and therefore is a point that is never reached by the meteoroid which is fully ablated at higher altitudes).
- One based on geometrical factors and timing. The same comment applies. We need at least 8 stations detecting the same object at slightly different times. However, with the state of the network, it was not often the case. Therefore we have started adding new BRAMS stations and forming clusters of receiving stations geographically close to each other. This is the case at the beginning of 2020 with the installation of several new stations in Limburg. These methods will then be tested again. For this method, we benefit from a recent collaboration with University of Bern, initiated in fall 2019.
- A third method needs less stations (only 4) but needs to include the BRAMS interferometer in Humain as one of them. Therefore a great effort was put in terms of hardware and software to develop this station and calibrate it. The station is fully active and calibration tests have been encouraging but not yet reaching the desired accuracy ($<1°$) for the direction of arrival of the meteor echoes. The method therefore has not been tested yet.

In the coming months, we will continue developing these 3 methods since reconstructing the BRAMS trajectories is of paramount importance for most applications developed during this project.

Also, in parallel, we are installing a meteor radar in Dourbes, built in-house at BIRA-IASB. This radar will have an interferometer similar to the one in Humain. The use of the two interferometers for the common meteor echoes will provide a fourth method of reconstructing trajectories. The data from the radar itself in combination with future BRAMS stations nearby Dourbes will also be another way to provide trajectories.

WP 1.3: Verification of BRAMS trajectories

We have carried out a study combining CAMS-Benelux and BRAMS data, which has *validated the theory behind meteor trajectory determination with BRAMS based on the specular reflection hypothesis and the ensuing limitations on the heights of reflection points*, by checking the occurrence of meteor echoes in BRAMS spectrograms and the timing of the meteor echoes in the BRAMS raw data. We have developed techniques to filter the noise and subtract the direct signal of the beacon in order to obtain the power profiles of meteor echoes from BRAMS raw data. Additional work is pursued in order to subtract adequately from the meteor echoes the signal coming from the reflection of the radio wave on airplanes but this is a challenging task. From the power profiles, the ionization at the specular reflection points can be obtained using a formula from Mc Kinley (1961) extended to forward scatter case. The geometry must be known (and therefore the trajectory of the meteoroid) which limits currently the applicability of this method to joint CAMS / BRAMS observations. But since the BRAMS network detects many more meteor echoes than optical networks, the need for trajectories coming solely from BRAMS data is obvious. The rest of the method is ready.

The future verification of BRAMS trajectories with those obtained using data from CAMS-Benelux or FRIPON will be easy as we are actively cooperating with these networks.

WP 1.4: Observability conditions

The Observability Function (OF) for meteor showers based on purely geometrical factors is nearly ready. A great deal of effort has also been done in parallel to accurately measure the gain patterns of the transmitting and receiving antennas. A careful characterization of the receiving chain has also been done. All these parameters determine the sensitivity of a given receiving station at a given time. In summary, *all the parameters are available for an end-to-end Observability Function for BRAMS*, covering the entire detection chain.

WP 1.5: Meteor flux model and elemental mass deposition rate

The mass of the initial meteoroid can be estimated using ablation models or more sophisticated models like those developed at VKI (see WP2). These models predict mass deposition rates along the meteoroid path, which can then be compared to ionization curve from multi-point observations with BRAMS receiving stations.

Given the present network configuration and the status of the multipoint trajectory computations, *it is too early to contribute to meteor flux models*.

WP 1.6: Detailed analysis of meteor reflections

Fresnel oscillations are very rarely seen in BRAMS data. When oscillations are seen, work is still carried out to investigate whether they are due to the ionization along the meteoroid path or are artifacts due to the filtering.

Peak power measurements have been done for underdense meteor echoes in the case of CAMS/BRAMS joint observations. This requires knowledge of geometry (given by CAMS observations), calculation of the position of the specular reflection point, automatic identification of the meteor echo, filtering of the meteor echo in the raw data, determination of the peak in relative units, and transformation to watts using the reference signal from the BRAMS calibrator.

Exponential decay has been measured for a few underdense meteor echoes. However, the use of these exponential decays to provide mesospheric temperature measurements still has to be carried out.

Another study is planned with university of Bern to use Doppler shifts of meteor echoes in spectrograms to produce maps of mesospheric winds above Belgium.

In summary, the *first steps have been set as to a more detailed analysis of individual meteor echoes*, but more is to come.

WP 1.7: Visual meteor brightness curve and spectroscopy

There was no attempt yet to link the ionization curve obtained from multi-stations observations with BRAMS and compare them to the meteor brightness curve provided e.g. by the CAMS-Benelux network. This task will be done soon.

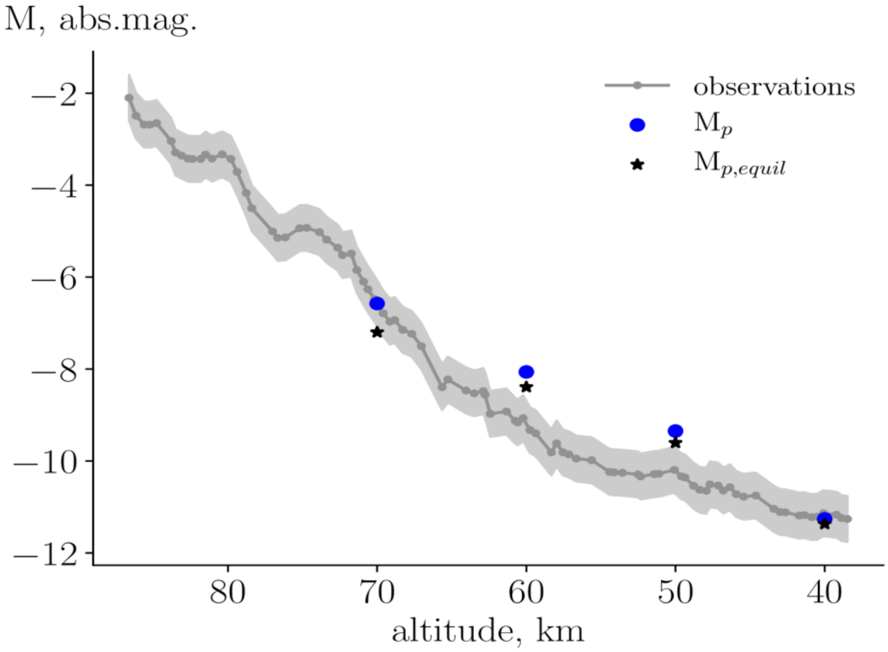
Spectroscopy of meteors is still an emerging field and linked only to fireballs so far. We have no experience with this field yet but we have been following recent developments presented e.g. during International Meteor Conferences.

Work Package 2: Simulations

Work Package 2.1: Meteor simulation for low altitudes

Luminosity calculation of meteor entry based on detailed flow simulations in the continuum regime

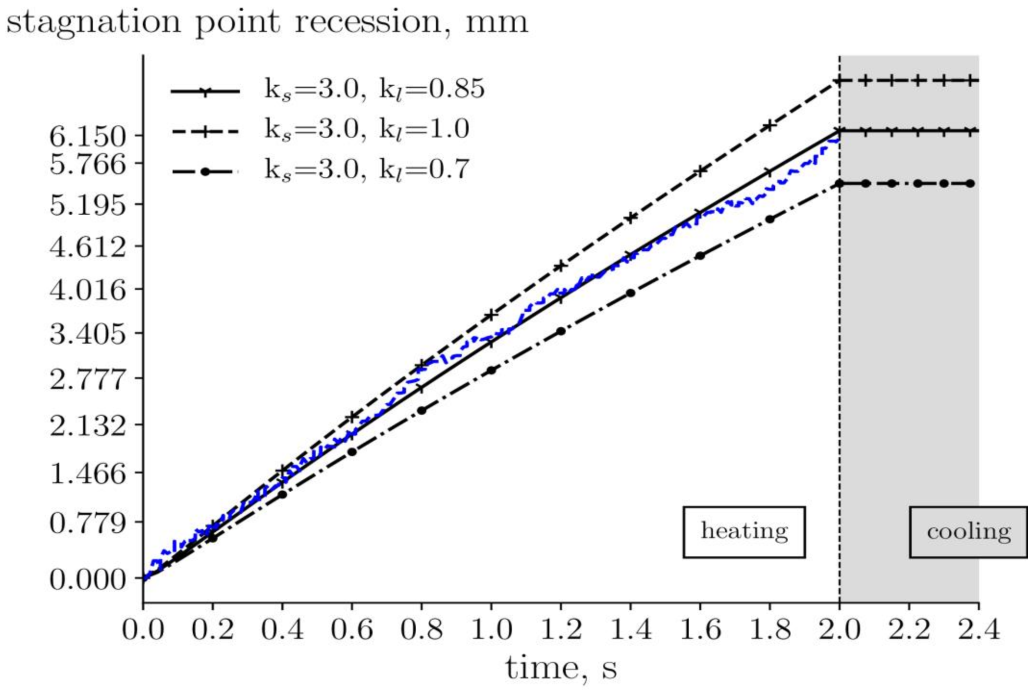
Composition, mass, and trajectory parameters of meteors can be derived by combining observations with the meteor physics equations. The fidelity of these equations, which rely on heuristic coefficients, significantly affects the accuracy of the properties inferred. The objective is to present a methodology to compute the luminosity of meteor entry based on detailed flow simulations in the continuum regime. The methodology consists in solving the Navier-Stokes equations using state-of-the-art physico-chemical models for hypersonic flows. It includes accurate boundary conditions to simulate the surface evaporation of the molten material and coupled flow-radiation effects. Such *detailed simulations allow for the calculation of heat transfer coefficients and luminous efficiency*, which can be incorporated in the meteor physics equations. Finally, the Radiative Transfer Equation is integrated over a line-of-sight from the ground to the meteor to derive the luminosity magnitude. The developed methodology has been applied to simulate the Lost City bolide and to derive the luminosity magnitude, obtaining a good agreement between numerical results and observations. The computed color index is more prominent than the observations. This is attributed to a lack of refractory elements in the modeled flow, such as Ca, that might originate from the vaporization of droplets in the trail, a phenomenon currently not included in the model.



Absolute magnitude luminosity of the Lost City bolide; comparison between the observations and the numerical results using standard and modified boundary conditions.

A model for meteoroid ablation including melting and vaporization

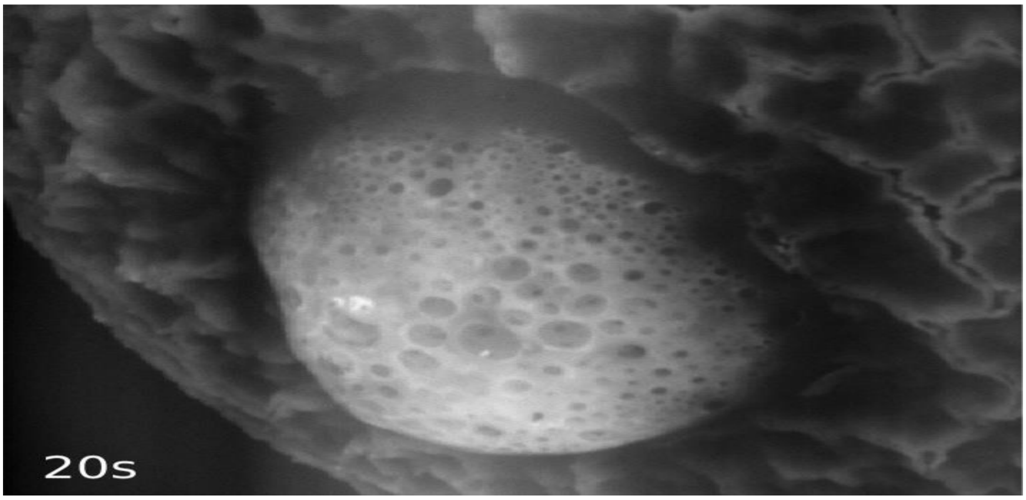
Meteor influx and its physical properties can be estimated based on observations using heuristic models for ablation. These models suffer from a lack of validation and physical description of the flow and material fields, as well as their coupling. A model has been developed for meteoroid ablation including melting and vaporization, where both flow and material are coupled. The model has been applied to ground experiments carried out at the arc jet facilities at NASA Ames Research Center. These experiments reveal a substantial effect of the shear ablation on the ablation process, which the heuristic models do not describe. Due to scarce data on physicochemical material properties at high temperatures, a sensitivity analysis has been performed, showing that the material *thermal conductivity and viscosity are essential parameters for the shear ablation process*. It is also observed that *the direct evaporation phenomenon is negligible compared to the mass lost by shear ablation*. The models are used to compute an effective heat of ablation six times smaller than the one reported in the literature. These models can be applied to study meteor trajectories and to improve coefficients used in heuristic models.



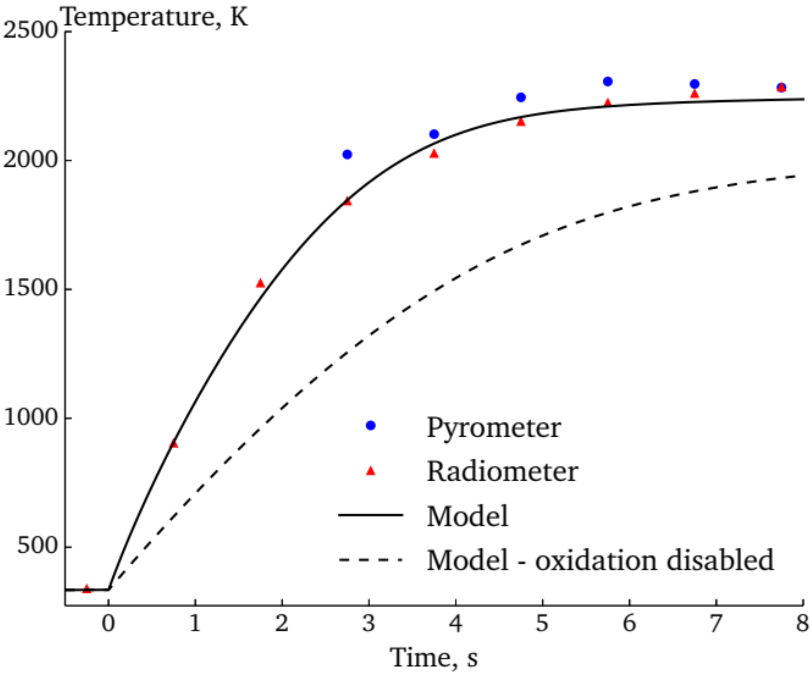
Recession of the stagnation point during the test and after the test for different material properties. The blue curve is the recession of the stagnation point determined from the video camera data.

Analysis of meteoroid ablation based on plasma wind-tunnel experiments, surface characterization, and numerical simulations

Meteoroids largely disintegrate during their entry into the atmosphere, contributing significantly to the input of cosmic material to Earth. Yet, their atmospheric entry is not well understood. Experimental studies on meteoroid material degradation in high-enthalpy facilities are scarce and when the material is recovered after testing, it rarely provides sufficient quantitative data for the validation of simulation tools. *The thermo-chemical degradation mechanism of a meteorite has been investigated in a high-enthalpy ground facility able to reproduce atmospheric entry conditions*. A testing methodology involving measurement techniques previously used for the characterization of thermal protection systems for spacecraft has been adapted for the investigation of ablation of alkali basalt (employed here as meteorite analog) and ordinary chondrite samples. Both materials have been exposed to a cold-wall stagnation point heat flux of 1.2 MW m^-2. Numerous local pockets that formed on the surface of the samples by the emergence of gas bubbles reveal the frothing phenomenon characteristic of material degradation. Time-resolved optical emission spectroscopy data of ablated species allowed us to identify the main radiating atoms and ions of potassium, calcium, magnesium, and iron. Surface temperature measurements provide maximum values of 2280 K for the basalt and 2360 K for the chondrite samples. A material response model has also been developed by solving the heat conduction equation and accounting for evaporation and oxidation reaction processes in a 1D Cartesian domain. The *simulation results are in good agreement with the data collected during the experiments*, highlighting the importance of iron oxidation to the material degradation.



Snapshot after 20 s of the surface of the ordinary chondrite experiment in the VKI Plasmatron facility. From "Analysis of meteoroid ablation based on plasma wind-tunnel experiments, surface characterization, and numerical simulations", WP 2.1.



Comparison of the surface temperature measurements with the numerical simulation of the thermal response of an ordinary chondrite. Exothermic heterogeneous reactions play an important role and have a significant impact on the simulations. From "Analysis of meteoroid ablation based on plasma wind-tunnel experiments, surface characterization, and numerical simulations", WP 2.1.

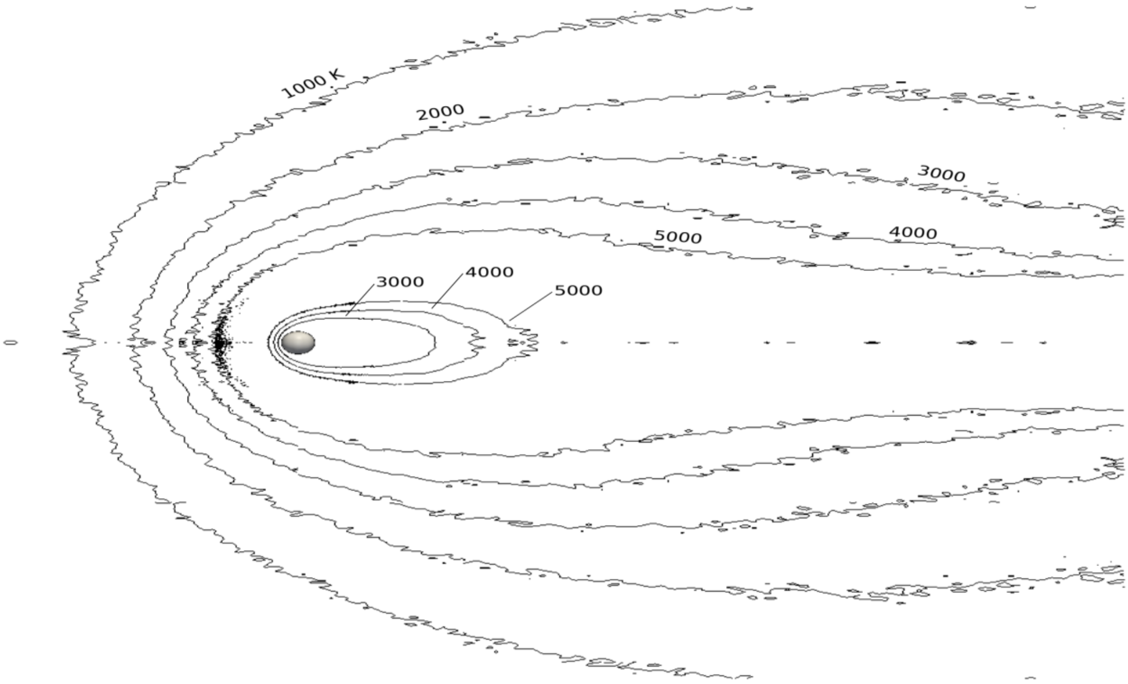
Meteoroid atmospheric entry investigated with plasma flow experiments: petrography and geochemistry of the recovered material

Melting experiments attempting to reproduce some of the processes affecting asteroidal and cometary material during atmospheric entry have been performed in a high enthalpy facility. For the first time with the proposed experimental setup, the resulting material has been recovered, studied, and compared with natural analogues, focusing on the thermal and redox reactions triggered by interaction between the melt and the atmospheric gases under high temperature and low pressure conditions. Experimental conditions were tested across a range of parameters, such as heat flux, experiment duration, and pressure, using two types of sample holders materials, namely cork and graphite. A basalt served as asteroidal analog and to calibrate the experiments, before melting a H5 ordinary chondrite meteorite. The quenched melt recovered after the experiments has been analyzed by µ-XRF, EDS-SEM, EMPA, LA-ICP-MS, and XANES spectroscopy. The glass formed from the basalt is fairly homogeneous, depleted in highly volatile elements (e.g., Na, K), relatively enriched in moderately siderophile elements (e.g., Co, Ni), and has reached an equilibrium redox state with a lower Fe^{3+}/Fe_{tot} ratio than that in the starting material. Spherical objects enriched in SiO_2, Na_2O and K_2O concentrations were observed, inferring condensation from the vaporized material. Despite instantaneous quenching, the melt formed from the ordinary chondrite shows extensive crystallization of mostly olivine and magnetite, the latter indicative of oxygen fugacity compatible with presence of both Fe2+ and Fe3+. Similar features have been observed in natural meteorite fusion crusts and in micrometeorites, implying that, at least in terms of maximum temperature reached and chemical reactions, *the experiments have successfully reproduced the conditions likely encountered by extraterrestrial material following atmospheric entry*.

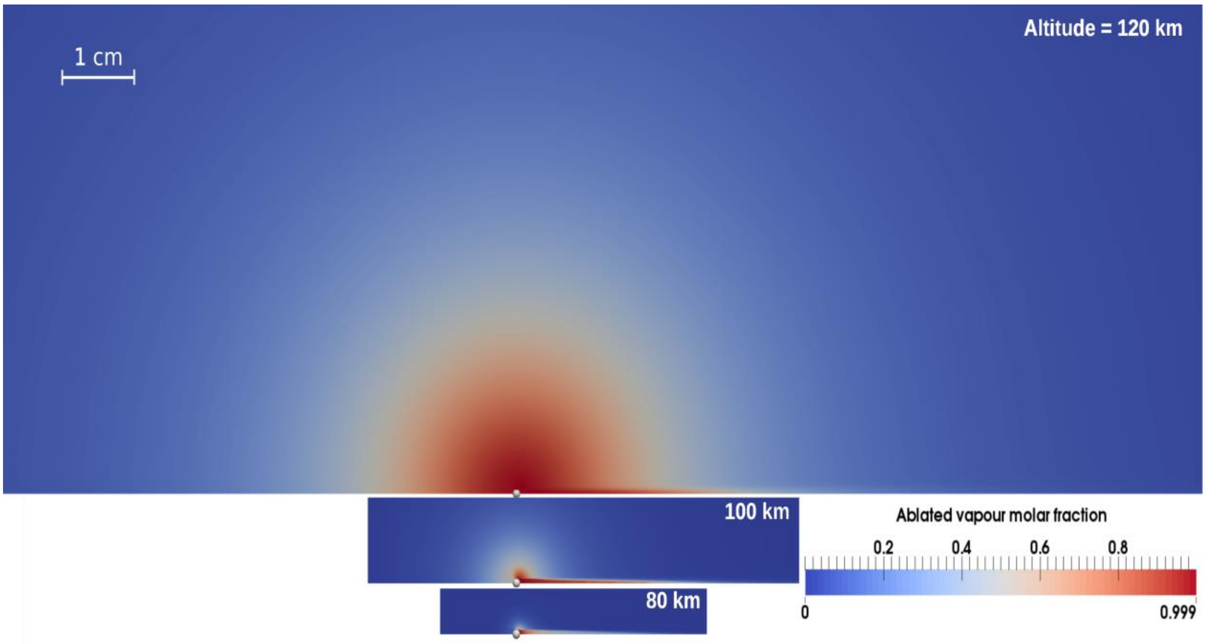
Work Package 2.2: Meteor simulation for high altitudes

Aerothermodynamic modelling of meteor entry flows

Due to their small size and tremendous speeds, meteoroids often burn up at high altitudes above 80 km, where the atmosphere is rarefied. Ground radio stations allow us to detect the concentration of electrons in the meteoroid trail, which are produced by hyperthermal collisions of ablated species with the freestream. The interpretation of these data currently relies on phenomenological methods, derived under the assumption of free molecular flow, that poorly accounts for the detailed chemistry, diffusion in the vapour phase, and rarefied gas effects. The direct simulation Monte Carlo (DSMC) method has been employed to analyse the detailed flowfield structure in the surroundings of a 1 mm meteoroid at different conditions, spanning a broad spectrum of Knudsen and Mach numbers, and the resulting ionization efficiencies have been extracted. For this purpose, the DSMC method has been coupled with a kinetic boundary condition which models evaporation and condensation processes in a silicate material. Transport properties of the ablated vapour are computed following the Chapman–Enskog theory starting from Lennard–Jones potentials. Semi-empirical inelastic cross-sections for heavy- and electron-impact ionization of metals are computed analytically to obtain steric factors. *The ionization of sodium is dominant in the production of free electrons, and hyperthermal air–vapour collisions play the most important role in this process. The ionization of air, classically disregarded, contributes to the electron production as significantly as* *ionization of magnesium and iron*. Finally, it is proposed that DSMC could be employed as a numerical experiment providing ionization coefficients to be used in synthetic models.



Vibrational temperature of the mixture at 80 km altitude for 1 mm body flying at 32 km/s. The freestream flows from left to right.



Fields for the ablated vapour molar fraction for three different altitudes of detection: 80, 100, and 120 km. The wall temperature is 2000 K, the diameter of the body 1 mm, and its velocity 32 km/s. The freestream flows from left to right.

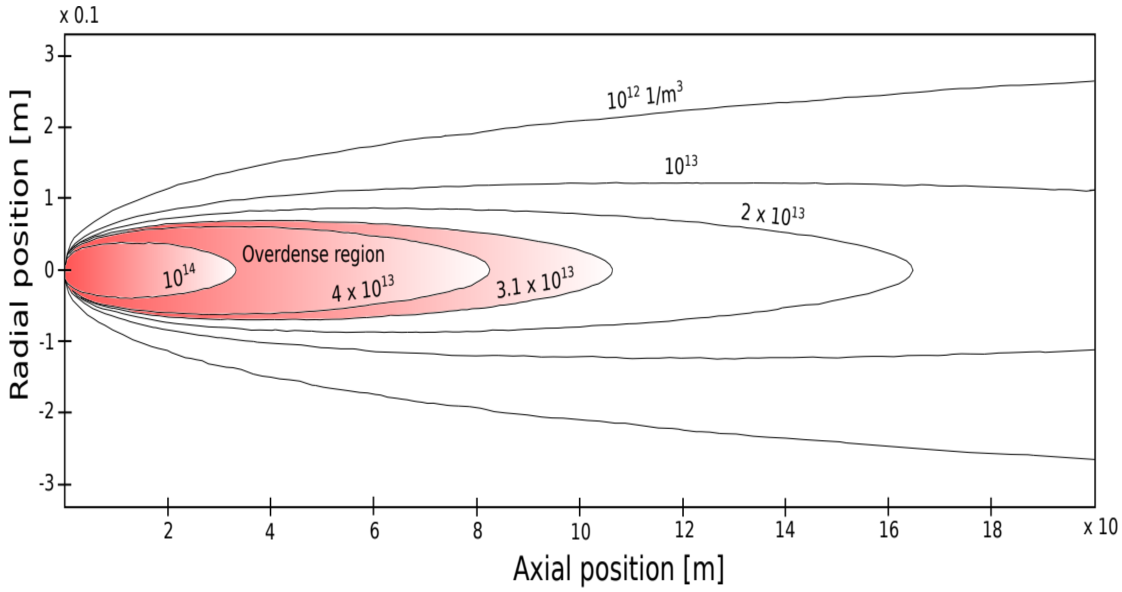
Work Package 2.3: Ionization trail

Lagrangian diffusive reactor for detailed thermochemical computations of plasma flows

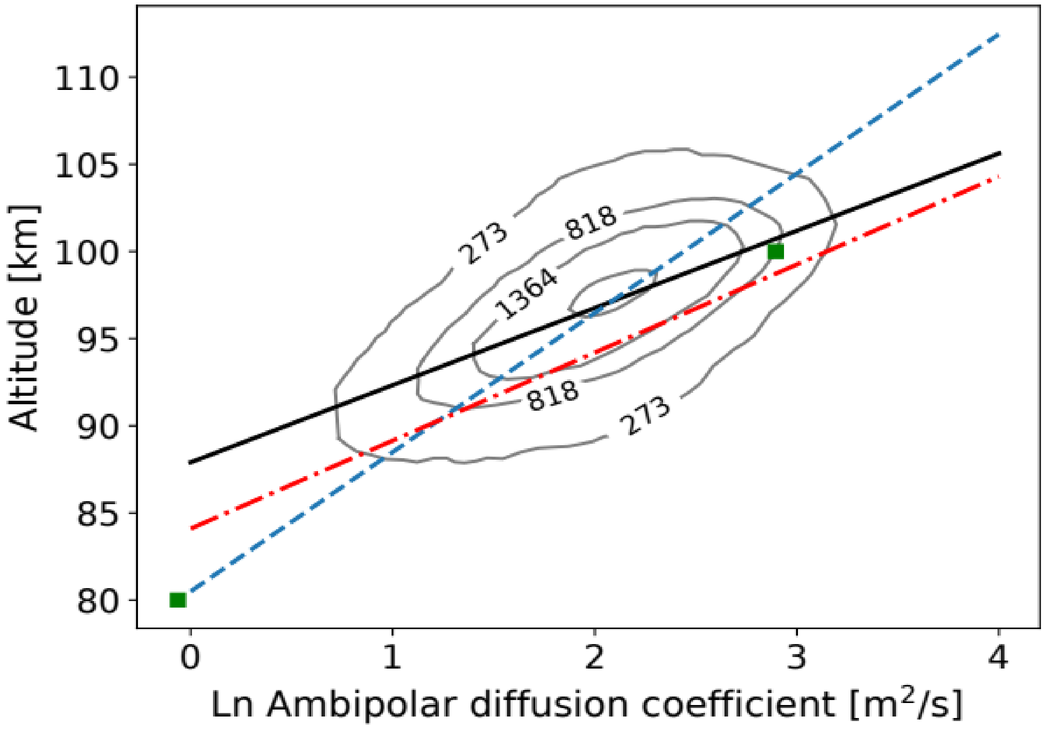
The simulation of thermochemical nonequilibrium for the atomic and molecular energy level populations in plasma flows requires a comprehensive modeling of all the elementary collisional and radiative processes involved. Coupling detailed chemical mechanisms to flow solvers is computationally expensive and often limits their application to 1D simulations. We develop an efficient Lagrangian diffusive reactor moving along the streamlines of a baseline flow simulation has been developed to compute detailed thermochemical effects. In addition to its efficiency, the method allows us to model both continuum and rarefied flows, while including mass and energy diffusion. The Lagrangian solver is assessed for several test cases including strong normal shockwaves, as well as 2D axisymmetric blunt-body hypersonic rarefied flows. In all the test cases performed, the *Lagrangian reactor improves drastically the baseline simulations*. The computational cost of a Lagrangian recomputation is typically orders of magnitude smaller with respect to a full solution of the problem. The solver has the additional benefit of being immune from statistical noise, which strongly affects the accuracy of DSMC simulations, especially considering minor species in the mixture. The results demonstrate that the method enables applying detailed mechanisms to multidimensional solvers to study thermo-chemical nonequilibrium flows.

A self-consistent method for the simulation of meteor trails with application to radio observations

Radio-based techniques allow for meteor detection 24 hours a day. Electromagnetic waves are scattered by the electrons produced by the ablated species colliding with the incoming air. As the electrons dissipate in the trail, the received signal decays. The interpretation of these measurements entails complex physical modelling of the flow. A procedure is proposed to compute extensive meteor trails in the rarefied segment of the trajectory. This procedure is a general and standalone methodology, which provides meteor physical parameters at given trajectory conditions, without the need to rely on phenomenological lumped models. One starts from fully kinetic simulations of the evaporated gas that describe the nonequilibrium in the flow and the ionisation collisions experienced by metals in their encounter with air molecules. These simulations are employed as initial conditions for performing detailed chemical and multicomponent diffusion calculations of the extended trail, in order to study the processes which lead to the extinction of the plasma. In particular, one focuses on the evolution of the trail generated by a 1 mm meteoroid flying at 32 km/s, above 80 km. *The ambipolar diffusion coefficient and the electron line density are retrieved and the outcome of the computations are compared with classical results and observational fittings.* Finally, the electron field is employed to estimate the resulting reflected signal, using classical radio-echo theory for underdense meteors. A global and constant diffusion coefficient is sufficient to reproduce numerical profiles. A good agreement is found when the extracted diffusion coefficients are compared with theory and observations.



Contour plot of the electron number density at 80 km altitude. The overdense region is highlighted . We have assumed a wavelength of 6 m, which corresponds to a radio frequency equal to 50 MHz. For this condition, the region extends up to 100 m in the axial direction and 5 cm in the radial direction. Axes are not to scale and the freestream flows from left to right.



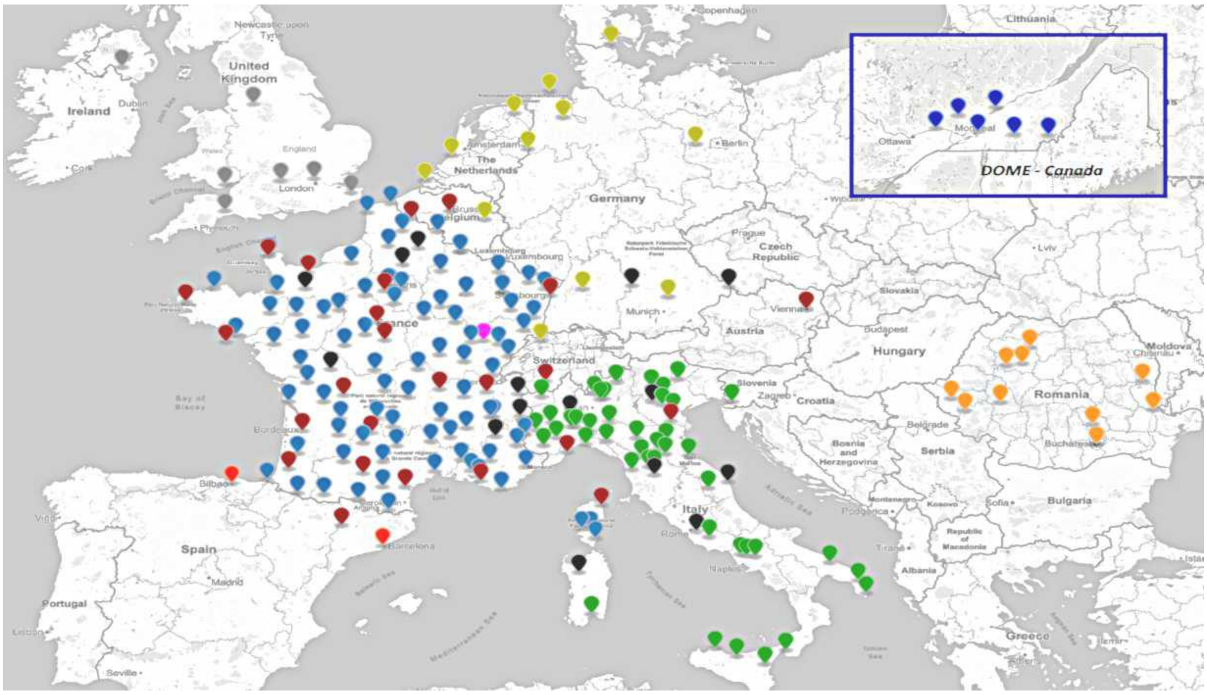
Base-10 logarithm of the ambipolar diffusion coefficient in function of the altitude. Comparison between numerical simulations from present work (marker green) and fits to observed radio signal decays: Greenhow (1961) blue dashed line, Jones (1990) red line, Galligan (2004) black line. Contour lines from the AMOR data correspond to the number of detections.

Work Package 3: Implications for planetology

Work Package 3.1: Meteoroid orbit analysis

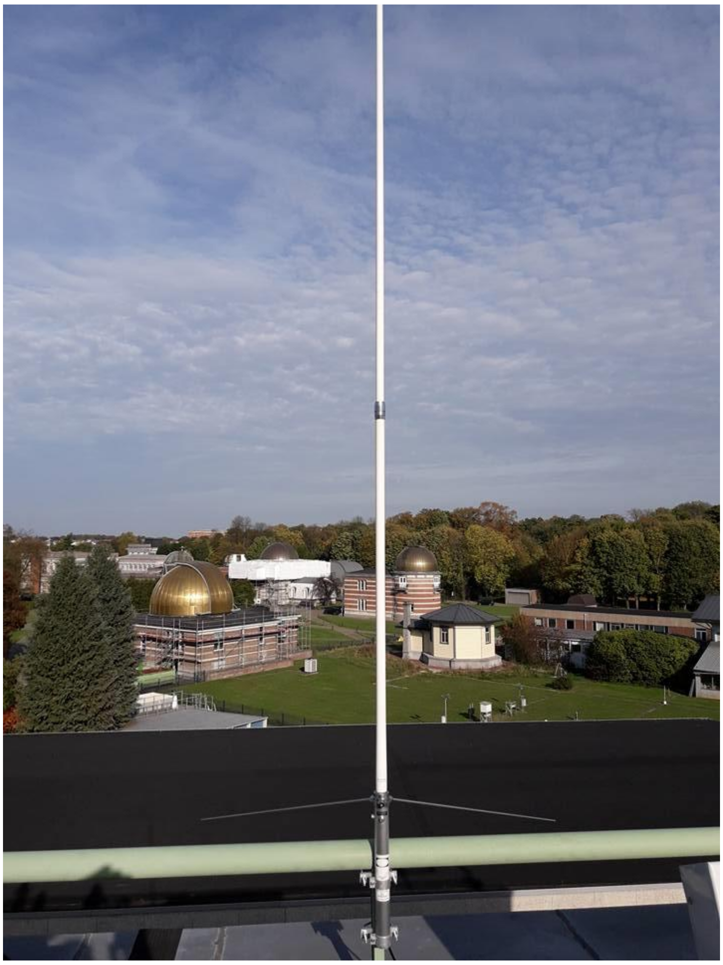
Context: Until recently, camera networks designed for monitoring fireballs worldwide were not fully automated, implying that in case of a meteorite fall, the recovery campaign was rarely immediate. This was an important limiting factor as the most fragile - hence precious - meteorites must be recovered rapidly to avoid their alteration.

Aims: To overcome this limitation, a fully automated camera network called FRIPON (Fireball Recovery and InterPlanetary Observation Network; PI: F. Colas) has been designed and deployed over a significant fraction of Western Europe and a small fraction of Canada. As of today, it consists of 150 cameras covering an area of about 1.5 × 106 km2.



FRIPON network map as of end 2019. The color code is the following: 1. Blue: FRIPON-Vigie-Ciel, optical stations (France), 2. Red: Coupled optical camera and radio receiver stations, 3. Black: Stations under development, 4. Green: PRISMA (Italy), 5. Light Orange: MOROI (Romania), 6. Yellow: FRIPON-North (Northern-Europe), 7. Grey: SCAMP (United Kingdom), 8. Dark blue: DOME (Canada), 9. Dark Orange: SPMN (Spain), 10. Pink: GRAVES radar.

FRIPON camera installed in 2017 on the roof of BIRA-IASB in Uccle



Antenna of the FRIPON-radio station installed in 2018 on the roof of BIRA-IASB in Uccle.

Methods: The FRIPON network has been monitoring meteoroid entries since 2016, allowing the characterization of their dynamical and physical properties. In addition, the level of automation of the network makes it possible to trigger a meteorite recovery campaign only a few hours after it reached the surface of the Earth.

Results: Nearly 4,000 meteoroids have been detected so far and characterized by FRIPON. The distribution of their orbits appears bimodal, with a cometary population and a main belt one. Sporadic meteors amount to about 55% of all meteors. A first estimate of the absolute meteoroid flux (mag < -5 ; meteoroid size ≥~1 cm) amounts to 1250 /year/106 km2. Such a value is compatible with previous estimates (Halliday et al. 1996). Finally, the first meteorite was recovered in Italy (Capodanno, January 2020) thanks to the extended FRIPON network.

Summary

The METRO project has significantly helped to advance the BRAMS system into an internationally recognized research facility with a lot of growing potential. The project has provided a stimulus in three areas:

- Improvements in the BRAMS hardware: better calibration, recommendations for the best localization of new observing sites
- Improvements in the data treatment through the development of automated data processing tools
- Improvements in the scientific interpretation of the data
- Strengthen active collaborations with the optical networks developed in Belgium such as CAMS-Benelux and FRIPON.

At the same time, the simulations and the laboratory experiments that have been conducted have led to a further strengthening of Belgian expertise in the area of hypersonic re-entry, a topic of strong interest for spaceflight.

The METRO project has offered a number of side results:

- Strengthening pro-am collaboration, involving public observatories and amateur astronomers in the BRAMS network, which are known to be all involved in advancing STEM education.
- Boosting the development of the Radio Meteor Zoo, a citizen science project, offering the interested citizen and taxpayer to be directly involved in the research activities.
- Offering the opportunities for 6 students to perform a BRAMS related project, supporting 1 Master Thesis, and 2 PhD theses to be involved in this research topic.

5. DISSEMINATION AND VALORISATION

Work Package 1: Observations and data analysis

The BRAMS data are available on our website (https://brams.aeronomie.be) or on-demand.

We have presented the results during several international conferences:

1. **BRAMS: a new facility to characterize meteoroids and their interactions with Earth's atmosphere**, Lamy, Hervé; Ranvier, Sylvain; Anciaux, Michel; Gamby, Emmanuel; Calders, Stijn; Tétard, Cédric; De Keyser, Johan, EGU General Assembly 2016, held 17-22 April, 2016 in Vienna Austria, id. EPSC2016-11624
2. **The Radio Meteor Zoo: searching for meteors in BRAMS radio observations**, Lamy, H.; Calders, S.; Tétard, C.; Verbeeck, C.; Martinez Picar, A.; Gamby, E., European Planetary Science Congress 2017, held 17-22 September, 2017 in Riga Latvia, id. EPSC2017-714
3. **Study of the Quadrantids 2016 using BRAMS data**, Lamy, Hervé; Verbeeck, Cis; Calders, Stijn; Martinez Picar, Antonio; Tétard, Cédric, 20th EGU General Assembly, EGU2018, Proceedings from the conference held 4-13 April, 2018 in Vienna, Austria, p.6698
4. **The Radio Meteor Zoo: involving citizen scientists in radio meteor research**, Calders, Stijn; Lamy, Hervé; De Keyser, Johan; Verbeeck, Cis; Martinez Picar, Antonio; Tetard, Cédric, European Planetary Science Congress 2018, held 16-21 September 2018 at TU Berlin, Berlin, Germany, id.EPSC2018-148
5. **Computing mass indices of meteor showers with BRAMS data**, Lamy, Hervé; Anciaux, Michel; Verbeeck, Cis; Tétard, Cédric; Calders, Stijn; Martinez Picar, Antonio, European Planetary Science Congress 2018, held 16-21 September 2018 at TU Berlin, Berlin, Germany, id.EPSC2018-976
6. **Over-dense radio meteor reflections in a forward scatter set-up**. S. Calders, J. De Keyser, H. Lamy. Poster 2261 at the EGU General Assembly 2019, Vienna, Austria, 7-12 April 2019
7. **Radio and optical observations of meteors with the BRAMS and CAMS-BeNeLux networks**, Lamy, H.; Anciaux, M.; Ranvier, S.; Calders, S.; Calegaro, A.; Verbeeck, C.; Martinez Picar, A.; Johannink, C.; De Keyser, J., American Geophysical Union, Fall Meeting 2019, abstract #P21F-3440

The presentations given during the METRO annual meetings are available on our website: https://brams.aeronomie.be/metro

Several students did also an internship at BIRA-IASB and worked with BRAMS data:

1. Comptage manuel et automatique des échos de météores dans les données BRAMS, Nicolas Englebert, rapport de stage, année académique 2016-2017, ULB
2. Automatic meteor detection for the BRAMS network, Maxence Draguet, rapport de stage, année académique 2017-2018, ULB
3. Calibration and analysis of BRAMS interferometer data at BIRA-IASB, Margaux Stocq, rapport de stage, année académique 2017-2018, ULB

4. Development of methodology to analyse BRAMS and CAMS meteor observations and confronting them with numerical simulations, Thomas Chauvaux, Master Thesis, ULg (co-sponsored by BIRA-IASB and VKI).
5. Calculation of the mass index of meteor showers using BRAMS data, Quentin Gontier, rapport de stage, année académique 2018-2019, ULB
6. Calibration of BRAMS interferometer, Léa Planquart, rapport de stage, année académique 2019-2020, ULB
7. Study of coordinated radio and optical observations of meteors with BRAMS and CAMS networks, Pierre-Yves Duerinck, année académique 2019-2020, ULB

The Radio Meteor Zoo (www.radiometeorzoo.be) is a citizen science project, which allows citizen scientists to analyze BRAMS spectrograms obtained during meteor showers. More than 10000 users are registered and analyze nearly 500 000 images in 4 years. 25 meteor showers were analyzed including Perseids, Draconids, Geminids, Quadrantids, Lyrids, etc... Beside the scientific return, it is also a wonderful way to valorize the BRAMS network and do public outreach about meteors and radio observations in general.

The BRAMS project is an active Pro-Am collaboration with most of our receiving stations hosted by radio amateurs, public observatories or universities. Every year we have organized the BRAMS annual meeting where everyone involved in the network is invited and can learn about the latest progress of the project. The presentations are available via the news section on our website: https://brams.aeronomie.be/NewsManage/news_recent

Work Package 2: Simulations

We presented the results during several international conferences:

1. **A coupled DSMC-SPH solver to study atmospheric entry ablation in presence of a rarefied gas phase**. Bariselli, F., Frezzotti, A., Magin, T., Hubin, A., VI International Conference on Particle-Based Methods, Barcellona, Spain, October 2019
2. **A coupled DSMC-SPH solver to study atmospheric entry ablation in presence of a rarefied gas phase**. Bariselli, F., Frezzotti, A., Magin, T., Hubin, A., 11th Ablation Workshop, Minneapolis, USA, September 2019
3. **Ionization coefficients resulting from the direct molecular simulation of meteor entry flows**. Bariselli, F., Frezzotti, A., Magin, T., Hubin, A., Meteoroids 2019, Bratislava, Slovakia, June 2019
4. **Fusion crust and atmospheric entry of ordinary chondrites, a comparison between experiments and nature**. Pittarello, L., Goderis, S., Soens, B., Mckibbin, S., Bariselli, F., Barros Dias, B. R., ... Claeys, P, XV Congresso Nazionale di Scienze Planetarie (pp. 144). Societa Geologica Italiana, 2019
5. **Aerothermodynamic modelling of meteor entry flows in the rarefied regime**. Bariselli, F., Boccelli, S., Magin, T. E., Frezzotti, A., Hubin, A., 2018 AIAA Joint Thermophysics and Heat Transfer Conference, Atlanta, GA, USA, AIAA 2018-4180, 2018
6. **Multiphase modeling of liquid droplets in rarefied gas flows by means of a coupled DSMC-SPH solver**. Bariselli, F., Frezzotti, A., Magin, T., 31st International Symposium on Rarefied Gas Dynamics, Glasgow, UK, July 2018

7. **Development of a coupled DSMC-SPH solver for the study of melting in rarefied gas flows**. Bariselli, F., Frezzotti, A., Magin, T., Hubin, A. 3rd European Conference on Non-Equilibrium Gas Flows, Strasbourg, France, March 2018
8. **Redox reactions in meteoroid atmospheric entry reproduced in plasma experiments**. Pittarello, L., Giuli, G., Goderis, S., Soens, B., Mckibbin, S., Bariselli, F., ... Claeys, P., European Planetary Science Congress 2018 [EPSC2018-271], EPSC, 2018
9. **Meteorite Atmospheric Entry Reproduced in Plasmatron II: Iron Oxidation State Change Probed by Xanes**. Giuli, G., Lepore, G. O., Pittarello, L., Mckibbin, S., Goderis, S., Soens, B., Bariselli, F., ... Claeys, P., European Planetary Science Congress 2017 [EPSC2017-998], EPSC, 2017
10. **Experimental characterization of meteoric material exposed to a high enthalpy flow in the Plasmatron**. Zavalan, F. L., Bariselli, F., Barros Dias, B. R., Helber, B., & Magin, T., European Geosciences Union General Assembly 2017 (pp. 997). European Geosciences Union., 2017
11. **Meteorite atmospheric entry reproduced in Plasmatron**. Pittarello, L., McKibbin, S., Goderis, S., Soens, B., Bariselli, F., Barros Dias, B. R., ... Claeys, P., Meteoritical Society 79th Annual Meeting [6062], 2017
12. **Development of a melting model for meteors**. Dias, B., Bariselli, F., Turchi, A., Frezzotti, A., Chatelain, P., Magin, T. E., 2016, 30th International Symposium on Rarefied Gas Dynamics, Victoria, BC, Canada, 1786(1):160004, 2016
13. **Atmospheric entry of meteors**, T. Magin, 30th International Symposium on Rarefied Gas Dynamics, Victoria, Canada, 2016
14. **I. Simulation of atmospheric entries of meteors, II. Plasmatron wind-tunnel experiments**, T. Magin, International School of Quantum Electronics, 61st course: Hypersonic Meteoroid Entry Physics, Erice, Italy, 2017
15. **Stagnation-Line Simulations of Meteor Ablation**, Dias, B., Turchi, A., Magin, T., 45th AIAA Thermophysics Conference, Dallas, TX, USA, AIAA 2015-2349
16. **Towards a physics-based model for meteor interaction with Earth atmosphere**, Dias, B., Turchi, A., De Keyser, J., Lamy, H., Magin, T., 12th European Space Weather Week, Ostende, Belgium
17. **Detailed modeling of meteor entry at low altitudes**, Dias, B., Turchi, A., Scoggins, J.B., Magin, T., Meteoroids 2016, Noordwijk, the Netherlands, June 2016
18. **Detailed shock layer physics of a meteor entry**. Dias, B., Scoggins, J.B., Magin, T., A. 3rd European Conference on Non-Equilibrium Gas Flows, Strasbourg, France, March 2018
19. **Shock layer radiation of an evaporating meteor**, Dias, B., Scoggins, J.B., Magin, T., European Planetary Science Congress, Berlin, Germany, September 2018
20. **Non-equilibrium meteor entry: in search of the coefficients of interest to improve meteor modelling**, Dias, B., Scoggins, J.B., Chatelain, P., Magin, T. Meteoroids 2019, Bratislava, Slovakia, June 2019
21. **Numerical simulation of a H5 chondrite radiative field: comparison with the experiments performed at the VKI plasmatron facility**, Dias, B., Scoggins, J.B., Soucasse, L., Riviere, P., Soufinani, A., Magin, T., 8th International Workshop on Radiation of High Temperature Gases for Space Missions, Madrid, Spain, March, 2019

6. PUBLICATIONS

Work Package 1: Observations and data analysis

Peer reviewed:

1. **Calibration of fish-eye lens and error estimation on fireball trajectories: application to the FRIPON network**, Jeanne, S.; Colas, F.; Zanda, B.; Birlan, M.; Vaubaillon, J.; Bouley, S.; Vernazza, P.; Jorda, L.; Gattacceca, J.; Rault, J. L.; Carbognani, A.; Gardiol, D.; Lamy, H.; Baratoux, D.; Blanpain, C.; Malgoyre, A.; Lecubin, J.; Marmo, C.; Hewins, P., Astronomy & Astrophysics, Volume 627, id.A78, 11 pp., 2019.

Other:

2. **Recent advances in the BRAMS network**, Lamy, H.; Anciaux, M.; Ranvier, S.; Calders, S.; Gamby, E.; Martinez Picar, A.; Verbeeck, C., Proceedings of the International Meteor Conference, Mistelbach, Austria, 27-30 August 2015, Eds.: Rault, J.-L.; Roggemans, P., International Meteor Organization, ISBN 978-2-87355-029-5, pp. 171-175
3. **Directional pattern measurement of the BRAMS beacon antenna system**, Martínez Picar, A.; Marqué, C.; Anciaux, M.; Lamy, H., Proceedings of the International Meteor Conference, Mistelbach, Austria, 27-30 August 2015, Eds.: Rault, J.-L.; Roggemans, P., International Meteor Organization, ISBN 978-2-87355-029-5, pp. 177-179
4. **The Radio Meteor Zoo: a citizen science project**, Calders, S.; Verbeeck, C.; Lamy, H.; Martínez Picar, A., Proceedings of the International Meteor Conference, Egmond, the Netherlands, 2-5 June 2016, Eds.: Roggemans, A.; Roggemans, P., ISBN 978-2-87355-030-1, pp. 46-49
5. **Retrieving meteoroids trajectories using BRAMS data: preliminary simulations**, Lamy, H.; Tétard, C., Proceedings of the International Meteor Conference, Egmond, the Netherlands, 2-5 June 2016, Eds.: Roggemans, A.; Roggemans, P., ISBN 978-2-87355-030-1, pp. 143-147
6. **Numerical simulation of the BRAMS interferometer in Humain**, Martínez Picar, A.; Marqué, C.; Verbeeck, C.; Calders, S.; Ranvier, S.; Gamby, E.; Anciaux, M.; Tetard, C.; Lamy, H., Proceedings of the International Meteor Conference, Egmond, the Netherlands, 2-5 June 2016, Eds.: Roggemans, A.; Roggemans, P., ISBN 978-2-87355-030-1, pp. 175-178
7. **The Radio Meteor Zoo: Involving citizen scientists in radio meteor research**, Calders, Stijn; Lamy, Herve; Martinez Picar, Antonio; Tetard, Cedric; Verbeeck, Cis; Gamby, Emmanuel, Proceedings of the International Meteor Conference, Petnica, Serbia, 21-24 September, 2017 Eds.: Gyssens, M.; Rault, J.-L. International Meteor Organization, ISBN 978-2-87355-031-6, pp. 13-15
8. **First observations with the BRAMS radio interferometer**, Lamy, Herve; Tetard, Cedric; Anciaux, Michel; Ranvier, Sylvain; Picar, Antonio Martinez; Calders, Stijn; Verbeeck, Cis, Proceedings of the International Meteor Conference, Petnica, Serbia, 21-24 September, 2017 Eds.: Gyssens, M.; Rault, J.-L. International Meteor Organization, ISBN 978-2-87355-031-6, pp. 132-137

9. **Overview of major shower observations 2016—2017 by the BRAMS network**, Verbeeck, Cis; Lamy, Herve; Calders, Stijn; Tetard, Cedric; Martinez Picar, Antonio, Proceedings of the International Meteor Conference, Petnica, Serbia, 21-24 September, 2017 Eds.: Gyssens, M.; Rault, J.-L. International Meteor Organization, ISBN 978-2-87355-031-6, pp. 138-144
10. **BRAMS radio observations analyzed: activity of some major meteor showers**, C. Verbeeck, H. Lamy, S. Calders, C. Tétard, A. Martinez Picar, Proceedings of the International Meteor Conference, Pezinok-Modra, Slovakia, 2018, August 30 – September 2, Eds Regina Rudawska, Jürgen Rendtel, Charles Powell, Robert Lunsford, Cis Verbeeck, André Knöfell, International Meteor Organization , ISBN 978-2-87355-032-5, pp. 100-105.
11. **Towards an autonomous BRAMS network**, S. Calders , H. Lamy , M. Anciaux , S. Ranvier , A. Martinez-Picar , C. Verbeeck, Proceedings of the International Meteor Conference, Pezinok-Modra, Slovakia, 2018, August 30 – September 2, Eds Regina Rudawska, Jürgen Rendtel, Charles Powell, Robert Lunsford, Cis Verbeeck, André Knöfell, International Meteor Organization , ISBN 978-2-87355-032-5, pp. 131-133.
12. **Properties of meteoroids from forward scatter radio observations**, H. Lamy, in 61st Course Hypersonic Meteoroid Entry Physics of the Ettore Majorana Foundation, Eds Gianpiero Colonna, Mario Capitelli, Annarita Laricchiuta, 2019.
13. **BRAMS forward scatter observations of major meteor showers in 2016–2019**, C. Verbeeck, H. Lamy, S. Calders, A. Martınez Picar, A. Calegaro, Proceedings of the International Meteor Conference, Bollmannsruh, Germany, 2019, October 3 – 6, Eds Urska Pajer, Jürgen Rendtel, Marc Gyssens and Cis Verbeeck, International Meteor Organization , ISBN 978-2-87355-032-5, pp. 27-31.
14. **The Radio Meteor Zoo: identifying meteor echoes using artificial intelligence**, Stijn Calders, Stan Draulans , Toon Calders, Hervé Lamy, Proceedings of the International Meteor Conference, Bollmannsruh, Germany, 2019, October 3 – 6, Eds Urska Pajer, Jürgen Rendtel, Marc Gyssens and Cis Verbeeck, International Meteor Organization , ISBN 978-2-87355-032-5, pp. 32.
15. **Calibration of the BRAMS interferometer**, H. Lamy, M. Anciaux, S. Ranvier, A. Martinez Picar, S. Calders, A. Calegaro, C. Verbeeck, proceedings of the International Meteor Conference, Bollmannsruh, Germany, 2019, October 3 – 6, Eds Urska Pajer, Jürgen Rendtel, Marc Gyssens and Cis Verbeeck, International Meteor Organization , ISBN 978-2-87355-032-5, pp. 33-38.
16. **The BRAMS receiving station v2.0**, Michel Anciaux, Hervé Lamy, Antonio Martinez Picar, Sylvain Ranvier, Stijn Calders, Antoine Calegaro, and Cis Verbeeck, proceedings of the International Meteor Conference, Bollmannsruh, Germany, 2019, October 3 – 6, Eds Urska Pajer, Jürgen Rendtel, Marc Gyssens and Cis Verbeeck, International Meteor Organization , ISBN 978-2-87355-032-5, pp. 39-42.

Work Package 2: Simulations

Peer reviewed:

1. **Lagrangian diffusive reactor for detailed thermochemical computations of plasma flows**, Boccelli, S., Bariselli, F., Dias, B., Magin, T. E., Plasma Sources Science and Technology, 28(6):065002, 2019
2. **Analysis of meteoroid ablation based on plasma wind-tunnel experiments, surface characterization, and numerical simulations**, Helber, B., Dias, B., Bariselli, F., Zavalan, L. F., Pittarello, L., Goderis, S., Soens, B., McKibbin, S. J., Claeys, P., Magin, T. E., The Astrophysical Journal, 876(2):120-134, 2019
3. **Meteoroid atmospheric entry investigated with plasma flow experiments: petrography and geochemistry of the recovered material**, Pittarello, L., Goderis, S., Soens, B., McKibbin, S. J., Giuli, G., Bariselli, F., Dias, B., Helber, B., Lepore, G. O., Vanhaecke, F., Koeberl, C., Magin, T. E., Claeys, P., Icarus, 331:170-178, 2019
4. **A model for meteoroid ablation including melting and vaporization**, Dias, B., Turchi, A., Stern, E. C., Magin, T. E., Icarus, 345:113710, 2020
5. **Aerothermodynamic modelling of meteor entry flows**, Bariselli, F., Frezzotti, A., Hubin, A., Magin, T. E., Monthly Notices of the Royal Astronomical Society 492(2):2308-2325, 2020
6. **Luminosity calculation of meteor entry based on detailed flow simulations in the continuum regime**, Dias, B., Scoggins, J. B. , Magin, T. E, Astronomy & Astrophysics, 635, A184, 2020

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ANNEXES

Publications are attached.