A Search Method for Meteor Radiants

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This article presents the results of a study whose goal it was to develop a method to search for new showers. The method inputs are meteor orbits provided by data from video-monitoring networks. As a result, the method proved to be effective in providing a list of new potential showers. The method consists of five data-analysis and processing steps. This study and development provided an important tool for the search of new showers. Up to the present moment, the method enabled the identification of more than a hundred new potential showers.

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1 Introduction

In 2017 the BRAMON (Amaral et al., 2017) meteor video-monitoring network began its search for new meteor showers. This activity led to the research and development of a new method. The search used input orbits of meteors provided by the BRAMON database and by other meteor video-monitoring networks, such as: EDMOND (Kornoš et al., 2014a; Kornoš et al., 2014b; EDMOND, 2018), and SonotaCo (SonotaCo, 2009; SonotaCo, 2018).

2 Description of the Method

The method consists of a processing procedure, split into five steps, which at the end generates a list of new potential showers. The steps comprise of following: 1 – Orbits of sporadic meteors (meteors not belonging to any specific shower (Ceplecha et al., 1998)) are clustered using clustering algorithms like the DBSCAN algorithm (Ester et al., 1996) – *Density-based spatial clustering of applications with noise* (Sugar et al., 2017); 2 – The orbit clusters discovered in the first step undergo a process of combinatorial analysis that groups the orbits that have the characteristics of a shower; 3 – The results of step 2 are then validated against the list of known showers of the IAU Meteor Data Center (MDC, 2018). The resulting product is a collection of orbits that are strong candidates for new showers; 4 – The step 4 candidates undergo a refinement process that looks for additional members of the showers and tries to determine the shower center (average orbit located at the point with the highest concentration of shower orbits), which are then validated against the MDC database; and 5 – New methods are used to better understand the shower and its relation with other nearby showers. The steps of the proposed method are described below:

Step 1 — Finding similar groupings of orbits

A clustering algorithm is used to evaluate a list of previously extracted meteor orbits. In this work the DBSCAN algorithm was used but it could also be used others clustering algorithms (taking advantage of the characteristics of each). To optimize the process only orbits that are classified in the database as sporadic meteors should be used. Each element of the list has the following orbital parameters: RA, DEC, solar longitude, geocentric velocity, semi major axis (a), eccentricity (e), periapsis distance (q), argument of periapsis (ω), longitude of the ascending node (Ω), and inclination (i).

As described in Southworth & Hawkins (1963) the orbit of a meteor can be represented as a point in a 5-dimensional space, and the similarity between them can be assessed by calculating the distance between these points. Thus, the DBSCAN algorithm can be used to separate orbit clusters, and the distance between different orbits is calculated by the similarity between them.

The output of DBSCAN is a set of orbit clusters. The orbits of each cluster are considered to be neighbors and they have similar orbital characteristics.

In order to analyze if one orbit is similar to another, mathematical methods that calculate the orbital dissimilarity between two orbits can be used. These methods measure the extent to which two orbits are dissimilar, i.e., the lower the result, the more the orbits are similar. As an example, the method of Drummond (D), (Drummond, 1981; Galligan, 2001; Jopek et al., 2002) was used, whose implementation of the formula uses the orbital parameters e, q, ω, Ω, and i.

This implementation of DBSCAN uses the D_{maxc}, minPoints, and minClusterSize input parameters, which are described below.

D_{maxc} represents the maximum limit of the D criterion to determine if an orbit is considered a neighbor of another orbit. That is, if the D test returns a value lower than D_{maxc} the two orbits are considered neighbors.

DBSCAN uses the *core point* concept. The minPoints parameter represents the minimum amount of neighbors that a point must have to be considered a *core point*.

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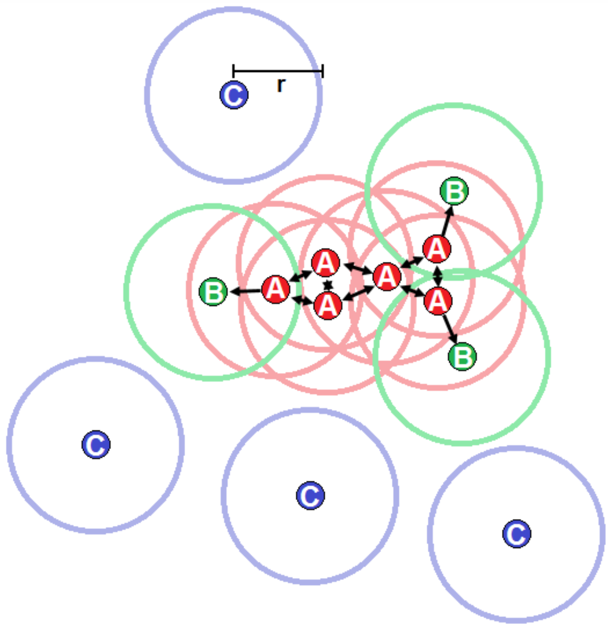

Figure 1 – Red points are *core points* (MinPoints= 3), green points are reachable points, and the blue point is noise. D_{maxc} is represented by the radius of the larger circles.

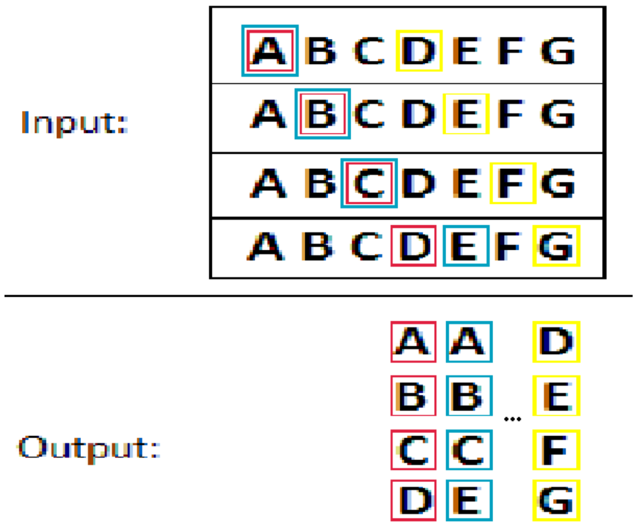

Figure 2 – Representation of the execution of the simple combination algorithm. In this example the orbits are represented by letters (AB. . . G). The input represents a cluster and the output the possible combinations. The ShowerMin parameter is 4.

The minPoints parameter directly impacts how "dense" a set of orbits should be in order to be considered a cluster. Points that are neighbors of a core point, but do not satisfy the minPoints parameter, are also part of the cluster and are called reachable points. Points that are not core points or reachable points are considered noise, see Figure 1.

In order to be considered a cluster, the group comprising the core points and the reachable points must be greater than or equal to the minClusterSize parameter.

Each cluster that is found is not necessarily a shower. It may have no shower or it may have several. This depends on how the orbits are distributed and the parameters used in DBSCAN. The use of a high D_{maxc} can lead to false clusters (obits that are not really similar will be grouped as a cluster). Tests performed indicate that good D_{maxc} values are between 0.04 and 0.07 (Using these values it was possible to find most known showers). Values close to 0.01 and 0.02 can be used to find filaments within dense clusters (This value can dissolve a large clusters in severals small clusters. Only the denser orbits groups survive. In these cases filaments pertaining to the same shower can be exposed).

Step 2 — Combining the Elements of a Cluster

After the clusters are found by DBSCAN, an algorithm that performs a simple combination in each cluster find in Step 1 must be executed. The input parameters of this combination are: Cluster, ShowerMin, ClusterSizeMax, and D_{maxa}.

The ShowerMin parameter defines the size of the groupings that are used by the simple combination algorithm. A cluster smaller than the ShowerMin parameter is discarded. In the tests performed, ShowerMin was configured with values 6 and 8.

The Figure 2 represents the output of a simple combination of an input cluster. In Figure 2 the red, blue, and yellow columns in output represent the results of the first, second, and last iteration of the algorithm, respectively.

Clusters larger than the ClusterSizeMax parameter are split into smaller groups, because the combinatorial analysis algorithm has $N!$ computational complexity, and therefore, very large clusters take a long time to process (we use values under 60 in our tests). However, this number can be increased depending on the available computational power.

Another way to reduce cluster sizes is running DBSCAN with small values of D_{maxc} and larger values of minPoints, as this can break down a large cluster into several smaller ones.

Each grouping found by the combinatorial analysis must undergo a validation test that aims to determine whether they constitute a possible shower or not. In this test, an *average orbit* is generated using all the orbits of the grouping. That is, each parameter (e, q, ω, Ω, and i) of this average orbit is calculated as the mean of the respective parameter of all the orbits of the grouping. A D test is then performed for each of the orbits of the grouping against its average orbit. If the result of each of the D tests of this procedure is lower than the D_{maxa} parameter, this grouping is considered a shower.

Due to the characteristics of this simple combinatorial analysis, the output list of new potential showers may contain several combinations of groupings, which sometimes differ by only a single orbit (like 'ABCD' and 'ABCE' in Figure 2), since they actually belong to a single shower. In this case the groupings can be combined, thus forming a shower with a larger number of elements. This recombination is performed in step 4.

Step 3 — Validation against IAU MDC

The groupings that are considered potential showers are validated against the showers currently found in the MDC list. This validation is done by performing the D test between the average orbit of each grouping and the orbital parameters of each of the showers in the MDC list. The average orbit is calculated as the arithmetic mean of the orbital elements of the meteors of the same grouping.

If the result of the D test is greater than D_{maxiau} (the study considered $D_{maxiau} = 0.22$. This value represents a safe margin to say that the orbits of the two showers are different enough to be considered two different showers), the grouping is considered a new shower candidate.

If the result of the D test is lower than D_{maxiau}, other parameters such as solar longitude, RA, DEC, and geocentric velocity are tested. If these parameters differ by a large amount (like 30–40%), the result is also considered a new shower candidate, otherwise the grouping is discarded. This is an interesting test since there may be showers with the same orbital characteristics, but with different other parameters (like solar longitude in Eta Aquariids and Orionids).

Step 4 — Refinement and Confirmation

The first 3 steps can be performed automatically, i.e., no manual steps are necessary. The output of the third step is a list of candidate groupings for new showers. In step 4, each of these candidates is manually tested in an attempt to find all the orbits that belong to the shower, an attempt is also made to find the best average orbit, i.e., the location of the largest concentration of orbits of the shower (the center of the shower). This method was named "Lapdeitor".

It has 3 parameters: Initial average orbit, D_{maxl}, and N, which represents the number of iterations desired. The algorithm executes N iterations, and each iteration searches the database for orbits distant less than D_{maxl} from the average input orbit (in the first interaction the initial average orbit is used). The orbits that are found are added to a list, and a new average orbit is calculated from the mean of the orbits of that list. This new average orbit is then used as the input orbit of the next iteration.

If the orbits are concentrated near the average orbit, at each iteration more orbits near the center are returned in the search, thus increasingly influencing the calculation of the average orbit. As a consequence, the average orbit will tend to migrate gradually towards the average orbit representing the shower center.

At the end of N iterations, the average orbit tends to be closer to the highest concentration of orbits of the shower. Figure 3 graphically depicts the behavior of the data returned at each iteration of the algorithm. The plot symbolically represents the concentration of orbits around the shower center, in relation to the D value.

The N value must be large enough so that interactions $N-1$ and N have the same result.

The D_{maxl} value must be chosen carefully. Exceedingly high values might return false centers, especially if the average orbit is close to two centers. A graphical representation of this behavior is shown in Figure 4.

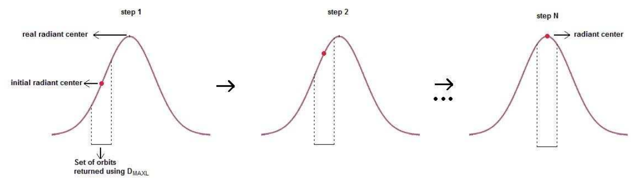

Figure 3 – Representation of steps 1 to N of Lapdeitor.

Large D_{maxl} values may also prevent small centers from being found. This can happen if two centers are close to each other and one is much larger than the other. On the other hand, exceedingly small values can prevent the convergence of the average orbit to the nearest center.

The distribution of shower orbits does not always follow the same pattern. Some showers have well concentrated orbits and others are more sparse. Thus, the D_{maxl} parameter must be chosen according to the characteristics of the shower. The Break-point+ and Valideitor methods (which will be presented in Step 5) can help to understand the characteristics of each shower and so help to choose a suitable value for the D_{maxl}.

To minimize problems, Lapdeitor must be run multiple times, and at each time smaller values of D_{maxl} should be used. By doing that it is possible to find the center of a shower more accurately.

During the execution of Lapdeitor, it is possible to generate an XY graph, in which the X axis corresponds to the current iteration and the Y axis corresponds to the number of orbits found from the list of orbits using the D_{maxl} value in the search.

After finding the probable center of the shower, it is necessary to perform a new verification in order to validate if the orbits of the center actually belong to a shower. The test verifies if the shower center is represented by at least 6 orbits. It also tests the center's average orbit against the existing showers in the MDC database. This need arises from the fact that the average orbit of the center may now be displaced relative to the initial average orbit of the shower, which had al-

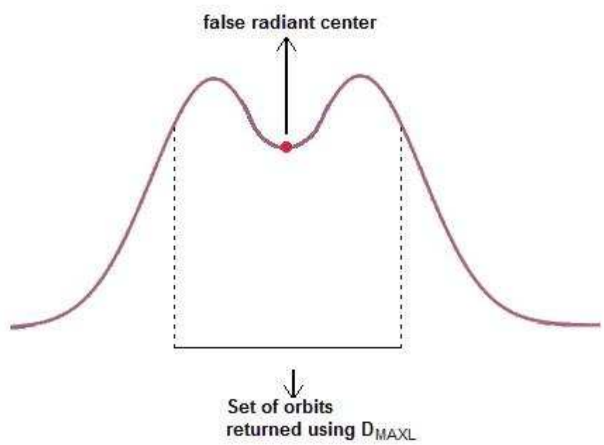

Figure 4 – False center returned when D_{maxl} is too large.

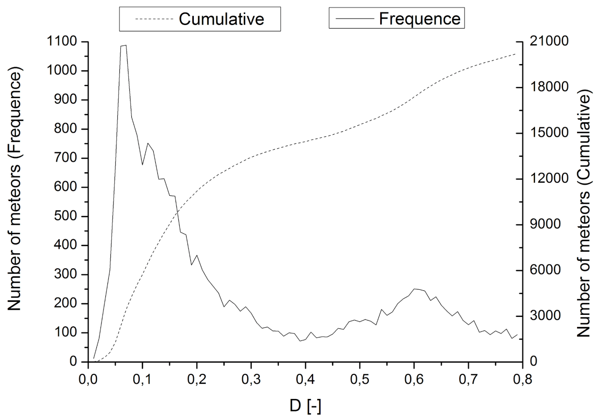

Figure 5 – Southern Taurids Break-point.

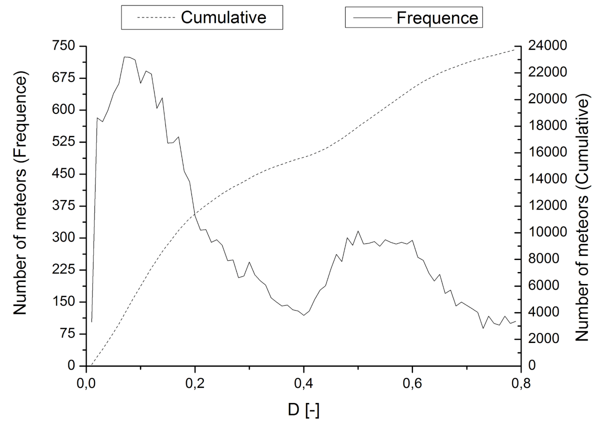

Figure 6 – Southern Taurids* Break-point.

ready been checked against the IAU list in step 3. Each shower that passes the tests can then be considered a new shower.

In order to demonstrate the use of Lapdeitor, all steps of the process were executed for the Southern Taurids shower. Table 1 shows the results of Lapdeitor for this shower. The last MDC report was used as initial orbit in Lapdeitor, and the result was the average orbit of Southern Taurids*. Figures 5 and 6 show the break-point (Welch, 2001; Neslušan et al., 2013) plots using the D criterion for both average orbits (Step= 0.01). It is possible to see that the Southern Taurids* plot (to the right) has a steeper slope at low D. This indicates that it is closer to the actual center of the shower. It is also possible to see that Southern Taurids* encompasses more orbits in total.

Step 5 — Shower Characteristics and Final Validation

At the end of the fourth step, a set of new showers is found, each representing a concentration of orbits around an average orbit. It is also known that the average orbit is far from showers known by the MDC. These characteristics alone would be enough to confirm a new shower, however, to exercise caution, it is necessary to understand how the shower's orbits are distributed and what their relation with nearby showers is.

Following that, new showers can be submitted to new methods that aid in understanding and validating their characteristics. The first method is a break-point variation. The second is a totally new method, called Valideitor, both being related and complementary to each other. In addition, the shower orbits can be represented in 3D, thus dismissing any uncertainties that may still persist.

Break-point+

The break-point implementation uses as its input the orbital values of a shower in addition to the following parameters: D_{initial}, D_{final}, D_{current} and Step. The algorithm executes a number of iterations, and in the first iteration the value of D_{current} is equal to D_{initial}, and at the end of each iteration the Step value is added to D_{current}. This process is repeated until D_{current} becomes larger than D_{final}.

In each iteration, the algorithm goes through the list of orbits from the catalogs searching for orbits whose D test value between itself and the orbital values of the input shower is lower than or equal to D_{current}. The number of orbits that satisfy this parameter is then added to a linear plot. This result is shown by the dotted lines in Figure 5.

A second line is also implemented (it is represented by the solid lines in Figure 5). This line represents the change in the number of orbits in an iteration relative to the previous iteration.

In Figure 7 we can see that the inflection point of the dotted lines is approximately at $X = 0.2$, this is the break-point. We can also see that after the break-point, even for large values of X, few orbits are added to the dotted line, which shows that the orbits of the shower are concentrated near its average orbit (the more concentrated, the lower the break-point).

However, the break-point method has problems when analyzing a shower that has other showers nearby, in the sense of orbital proximity. This problem is further aggravated if one of the nearby showers is much larger than the shower being tested, in such cases, the plot may show several inflection points or none at all.

To minimize this problem, the break-point+ method is proposed. In this method the orbits used in the break-point are filtered out. This filter uses the RA/DEC coordinates of the shower as the center point, and a spherical cap with radius equal to R is drawn. Only those orbits whose RA/DEC fall inside the cap area shall be considered in the break-point. We can see in

Table 1 – Southern Taurids Result.

Name	Solar Longitude	RA	DEC	V_g	a	q	e	ω	Ω	i
Southern Taurids	211.3	42.8	10.6	27.0	1.85	0.368	0.807	114.8	31.3	5.4
Southern Taurids*	221.01	52.72	15.36	27.92	2.02	0.354	0.822	115.09	41.01	5.26

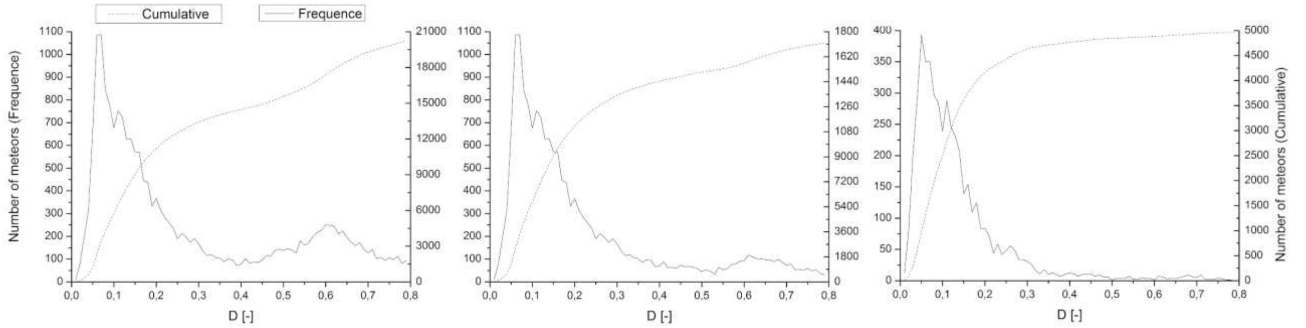

Figure 7 – Variation of the R parameter in the Break-point+ of the Southern Taurids shower. From left to right: $R = 360$, 50 and 10 degrees were used.

Figure 7 how the variation of the R parameter impacts the result of break-point+.

The break-point plot with $R = 10$ degrees shows a clearer picture (with fewer inflection points in the plot), making it easier to understand the distribution of orbits in relation to the average orbit. This happens because the filter eliminates showers that are too distant (in RA/DEC) to the average orbit of the shower being analyzed. The R value can be different for each shower. It must be chosen so that only a few shower's orbits are missed, while also limiting the influence of other showers. The R parameter also must be chosen with a value large enough to accommodate the drift of the radiant.

Valideitor

In order to better understand the relation between a shower and other showers close to it (in the orbital and chronological sense), a new method was proposed. This method is called Valideitor and it was designed to analyze, over time (day to day), the number of orbits that belong to a given shower. To determine if an orbit belongs to a shower, the D test is performed between this orbit and the average orbit of the shower. If the result is lower than a given D_{maxv}, usually the break-point value or a value close to 0.21, the orbit is considered as belonging to the shower.

Over time, and as the shower's peak approaches, the number of orbits that fit to the shower tends to increase, and therefore a peak can be seen in the plot.

To prevent the plot from growing indefinitely, a reduction factor is applied, thus, after the shower's peak date, the number of orbits tends to decrease and the plot tends to a minimum.

With this method it is possible to see the distribution of the orbits over time, and also how these orbits fit to the shower.

The method also allows us to understand the distribution of orbits that are near the shower, but that do not fit into it. This provides a better understanding of the characteristics of the shower and its neighborhood. As an example, Figure 8 shows the result of Valideitor for the Geminids shower. In this figure, a radius of 10 degrees with respect to the shower center was analyzed. We can see that the shower's peak is concentrated, and it stands out among the orbits that do not belong to the shower.

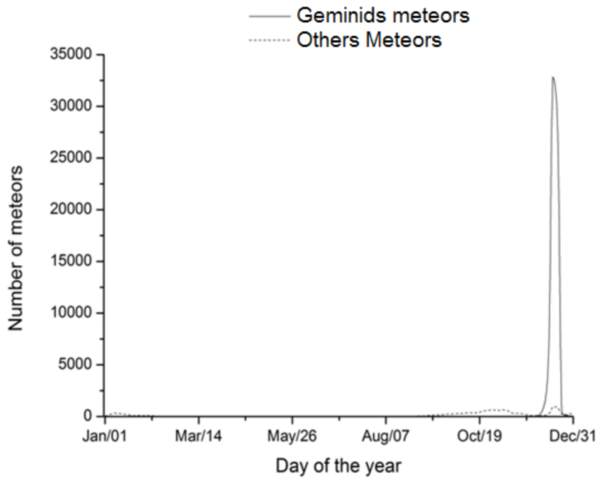

Figure 8 – Valideitor of the Geminids Shower. The X axis represents the days of the year and the Y axis represents the number of orbits. The solid line represents the orbits that fit the shower ($D_{maxv} = 0.21$ was used), and the dashed line represents the orbits that did not fit the shower.

In the implementation of this method the same RA/DEC filter described in the Break-point+ method was used, and the following parameters were provided as input: D_{maxv}, InitialDate, FinalDate, CurrentDate, and DateDelta.

The method consists of executing a number of iterations. In the first iteration, the CurrentDate parameter is set to InitialDate, and at the end of each iteration the current date is incremented by one day (this parameter can be changed). The iterations continue until CurrentDate is equal to FinalDate. At each iteration the following steps are performed: (i) A list called CurrentList is created. This list includes all the orbits whose dates have the same day/month as the CurrentDate (disregarding the year), (ii) A D test is performed between each of the orbits in the CurrentList and the shower's orbit. If the result of the D test is lower than D_{maxv}, the orbit is added to a new list called ShowerList; (iii) A point is added to the plot corresponding to the number of orbits currently in the ShowerList. This point represents the number of orbits that belong to the Shower; (iv) Another point is added to the plot corresponding to the number of elements in the CurrentList less the number of elements in the ShowerList. This point represents the number of orbits that do not belong to the

```
Radiant: 928732 Passed the IAU test
_20141217_044837  264.948334  105.564255  6.930053  39.412121  7.385394   0.970038  0.221284  125.04615   84.9483870000001  31.151657  256
_20141217_070349  265.043884  107.358086  4.97564   39.617413  5.714485   0.961153  0.221992  125.461235  85.0439450000001  35.504627  258
_20151215_042653  262.643677  107.713669  2.681762  36.367138  1.989476   0.888704  0.22142   130.328644  82.6439060000002  37.579353  1691
_20151216_064759  263.760864  104.469002  8.888292  38.509533  5.860625   0.962696  0.218626  125.864883  83.761139         26.694635  1696
_20161211_234126  260.146759  101.153145  7.001359  41.309399  11.428244  0.982964  0.19469   128.199753  80.1465149999998  36.1661    4955
_20161214_005538  262.232056  102.312508  7.072981  41.184856  30.626831  0.993153  0.209702  125.40374   82.2317959999998  34.176571  4987
Radiant: 928733 Passed the IAU test
_20141217_044837  264.948334  105.564255  6.930053  39.412121  7.385394   0.970038  0.221284  125.04615   84.9483870000001  31.151657  256
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_20151216_064759  263.760864  104.469002  8.888292  38.509533  5.860625   0.962696  0.218626  125.864883  83.761139         26.694635  1696
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Radiant: 928734 Passed the IAU test
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_20151215_042653  262.643677  107.713669  2.681762  36.367138  1.989476   0.888704  0.22142   130.328644  82.6439060000002  37.579353  1691
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_20171212_031641  260.038208  101.696289  7.536115  38.16703   3.604663   0.942422  0.207548  128.801559  80.0384980000002  30.447754  8366
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Figure 9 – Output from step 3. The lines of the orbits are represented by the parameters: orbit capture date, solar longitude, RA, DEC, V_g, a, e, q, ω, Ω, i and line of the input file.

Shower; and (v) All orbits whose capture date is earlier than CurrentDate minus DateDelta are removed from the ShowerList. This is the plot's reduction mechanism. DateDelta must be proportional to the duration of the shower. Values between 7 and 15 days were used for this parameter in the tests performed.

Search for Parent Bodies

The last task of step 5 is trying to find the parent body or bodies that created the shower. For that, a simple method to search for the parent body is executed, using as its input the orbital parameters and the D_{maxp} parameter. The algorithm reads the orbital parameters from a file provided by the Jet Propulsion Laboratory (JPL, 2018), which has hundreds of thousands of orbits of celestial bodies in the solar system, and performs a D test between these orbits and the input orbit.

The search returns all records in the JPL file for which the D test is lower than D_{maxp}. With this result, retroactive simulations are performed in order to validate if these elements belong to the parent body of the shower.

3 Application of the Method

To demonstrate the new method, a test was performed through which an existing shower was rediscovered, more precisely the December Monocerotids (MON) shower, whose orbital elements were intentionally removed from the MDC list used in step 3.

Step 1 was executed using the BRAMON database (with 6 805 orbits). In this step, 106 clusters were found using the parameters $D_{maxc} = 0.07$, minPoints= 5, and ClusterSize= 6. Step 2 was executed using the parameters ClusterSizeMax= 35, ShowerMin= 6, and $D_{maxa} = 0.07$. As a result, 1 394 534 combinations of 6 orbits were found that meet the criteria that characterize a shower. These combinations were then validated against the MDC database using $D_{maxiau} = 0.22$ and 132 combinations were found as candidates of new showers. Analyzing these 132 combinations, 125 corresponded to groups that fit the expected orbit of the MON shower. In Figure 9 three of these groups of orbits are shown.

Table 2 lists the average orbit generated from the first group (928732 in Figure 9).

By executing step 4, the average orbit can be refined using Lapdeitor with $D_{maxl} = 0.07$, and the BRAMON, SonotaCo, and EDMON databases. Line 1 of Table 3 lists a new average orbit found by this method, which closely resembles the known orbit of the MON shower published in the last MDC report (line 2 of Table 3).

By performing a search for all records distant up to D = 0.05 from the new orbit and from the MON shower, it was shown that a search using the new orbit returns more elements than the current MON orbit, 800 compared to 782. In other words, the method not only rediscovered the shower, but it also managed to define an orbit that is closer to the center of the shower.

4 Conclusions

Over a short period of time the new shower search method has demonstrated its strong capability to find new showers. Until the present date, this method has been responsible for the discovery of 121 new showers, that have already been submitted to the Meteor Data Center (in *pro tempore*). The presentation and detailing of these new showers will be carried out in a next article. This represents more than 12% of all showers ever discovered. The method is capable of finding and improving large previously known showers, but it stands out in the search for small showers.

After decades of continuous searches for new showers, most of the large showers have already been identified and published. Currently, the search is focused on small showers and on showers that come from the same region of the sky as other previously discovered showers. Visual identification methods may not be able to identify such showers, however, this new search method uses orbital data, and is thus capable of identifying showers in these scenarios.

The new method uses orbital data, clustering algorithms, combinatorial analysis, validation against the MDC database, mechanisms of refinement and validation of showers, as well as resources to search for possible parent bodies. It is also able to perform the search for new showers by simultaneously using the capture databases of several meteor video-monitoring networks.

Table 2 – Average orbit of the group (928732). The parameter values were rounded in order to accommodate the table.

Name	$\lambda_\odot$	RA	DEC	V_g	a	q	e	ω	Ω	i	Line
_20141217_044837	264.9483	105.6	6.9	39.41	7.39	0.2213	0.9700	125.046	84.948	31.15	256
_20141217_070349	265.0439	107.4	5.0	39.62	5.71	0.2220	0.9612	125.461	85.044	35.50	258
_20151215_042653	262.6437	107.7	2.7	36.37	1.99	0.2214	0.8887	130.329	82.644	37.58	1691
_20151216_064759	263.7609	104.5	8.9	38.51	5.86	0.2186	0.9627	125.865	83.761	26.69	1696
_20161211_234126	260.1468	101.2	7.0	41.31	11.43	0.1947	0.9830	128.200	80.147	36.17	4955
_20161214_005538	262.2321	102.3	7.1	41.18	30.63	0.2097	0.9932	125.404	82.232	34.18	4987
Average:	263.1293	104.8	6.3	39.40	10.50	0.2146	0.9598	126.717	83.129	33.55	—

Table 3 – Average orbit after Lapdeitor (using the BRAMON, EDMOND, and SonotaCo databases).

Radiant	$\lambda_\odot$	RA	DEC	V_g	a	q	e	ω	Ω	i
Radiant Found	258.72	101.17	8.7	40.9	15.03	0.189	0.977	129.3	78.7	34.7
MON	258.5	100.5	7.9	41.5	13.4	0.19	0.985	128.9	78.5	35.8

In addition to the search for new showers, the method also offers two mechanisms that help to improve the understanding of showers, Valideitor and Break-Point+. These new mechanisms provide important data to better understand the showers and how they relate to each other. The combination of these mechanisms and the possibilities they offer make the new method unique and capable of boosting the study of showers.

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