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Stereoscopic meteor observation: Determining satellite bus and formation parameters requirements

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ABSTRACT

The Institute of Space Systems (IRS) of the University of Stuttgart and the TU Berlin are planning a mission to observe meteors and dust particles using a formation of two small satellites. In this paper, we analyse the formation and satellite parameters to optimize the scientific output of the meteor observation. The stereoscopic observation of meteors allows calculating the corresponding meteor trajectory. The potential output of a meteor observation strongly depends on the configuration of the satellite formation (orbit, satellite distance) and the satellite bus parameters (knowledge of satellite position and attitude). Therefore, a simulation, based on the trajectory algorithm of the Meteor Orbit and Trajectory Determination Software (MOTS), is conducted, in order to calculate the accuracy of the meteor trajectory depending on those parameters. Furthermore, different meteor properties are taken into account to evaluate the influence on the accuracy of the calculated trajectory. According to our simulations, the satellite attitude knowledge has a huge influence on the trajectory accuracy, while the position knowledge is less relevant. Furthermore, the simulation allows calculating the ideal satellite distance with a minimal trajectory error for a specific orbit. The trajectory error is ~200 m, when typical errors on satellite position and attitude knowledge (7”) are used.

INTRODUCTION

The FACIS missions

The Institute of Space Systems (IRS) of the University of Stuttgart and the TU Berlin are planning a joint mission to observe meteors and dust particles using a formation of two small satellites of approximately 30 kg each in low earth orbit. The satellite bus is based on the TUBiX20 platform developed by TU Berlin while the IRS provides the payload and the data downlink system. The scientific objectives are dust measurements using a miniature dust sensor and meteor observation with a camera system. In this paper, we analyse the ideal formation as well as satellite parameters to optimize the scientific output of the meteor observation.

Space-based stereoscopic meteor observation

The stereoscopic observation of meteors allows to calculate the corresponding meteor trajectory and thus, to determine the parent body. Furthermore, the meteor flux is measured. This data can be used to improve prediction models to assess the danger of meteoroids hitting satellites. Furthermore, meteor observation contributes to the exploration of our solar system. A space-based meteor observation can aid ground-based observations, which are limited by the weather condition and coverage. A satellite instrument can potentially observe more meteors and meteor showers which are difficult to observe from ground due the weather condition and location of most ground based system. For example the meteor shower Quadrantids is not well observed due to usually bad weather conditions in January. The data of a satellite based instrument could contribute to the characterization of this shower.

The potential output of a meteor observation mission strongly depends on the constellation of the satellite formation and the satellite bus parameters. As stated in a previous paper (see [1]), the distance and orientation of the two satellites influence the number and the mass of meteors which can be observed from two satellites. For the scientific output of the mission not only the number of meteors, but also the accuracy of the meteor trajectory calculated from the images and the satellite position and orientation matters. The trajectory of the meteor is back propagated, to determine the orbit of the meteoroid, which is necessary to determine the parent body of the meteoroid. An accurate trajectory results in an accurate orbit and determination of the parent comet. Therefore, it is important to know, how the parameters of satellite formation (distance and altitude) as well as satellite bus (knowledge of orientation and position) influence the trajectory calculation. This information is crucial to develop a mission concept. Therefore, a simulation is conducted, in order to calculate the accuracy of the meteor trajectory depending on satellite formation (distance and altitude) and satellite bus (knowledge of orientation and position) parameters.

TRAJECTORY SIMULATION

Before outlining the simulation approach, it is important to understand how meteor trajectories are measured. Ground based meteor observation systems, e.g. the *Canary Island Long-Baseline Observatory* (CILBO, see [2]), consists of at least two cameras at different locations with overlapping field of views (FOV). The trajectory can be calculated with the knowledge of the camera position and orientation as well as the meteor observation time. When using satellites, several issues arise compared to ground based systems: First, the observing satellites change position during the observation and the measurement of the position is erroneous. Second, the attitude of the satellite, and therefore the orientation of the camera, is only known with finite accuracy. Both values are needed to calculate the trajectory and therefore influence the trajectory accuracy. In a previous analysis the influence of the satellite attitude knowledge accuracy was estimated using CILBO data (see [1]). Further analysis is required to confirm the preliminary results and also to evaluate the effect of the position knowledge accuracy on the trajectory accuracy. Besides these satellite bus parameters, the effect of the formation parameters (satellite distance and orbit altitude) on the trajectory error should be evaluated.

This evaluation is done, by adapting a meteor trajectory algorithm for ground based to spaced based meteor observation. In our simulation the *Meteor Orbit and Trajectory Software* (MOTS) algorithm (see [3]) is used to determine the effect of different parameters on the calculated trajectory. This algorithm is successfully used for evaluating CILBO data and is well documented. After adapting the algorithm in a Python script, a meteor with settable properties (velocity, direction, position) is generated as well as the position of the two satellites. The needed parameters to calculate the meteor trajectory are the position of the two satellites as well as the meteor position during different time steps. Different error sources can now be applied to these values, in order to simulate the effect of e.g. a satellite position knowledge error on the final trajectory. Before describing the simulation setup in more detail, the MOTS algorithm is briefly explained.

The MOTS algorithm

The MOTS algorithm is a software program developed by D. Koschny et. al. which calculates the trajectory of a meteor observed from two ground based stations. Only a short description on the working principle can be given here, please refer to [3] for more details. Generally, the algorithm uses the position of the two stations, their viewing directions and the (two dimensional) position of the meteor to calculate the three dimensional meteor position. See Figure 1 for visualization. The algorithm works as follows: First, a plane is constructed from a point inside the plane and a normal vector of the plane. The point in this plane is the position of Station 2. The normal vector is calculated by calculating the cross product of two vectors. The two vectors are the viewing directions from Station 2 to the meteor in different frames. The meteor position as seen from Station 2 is derived from the camera orientation. In order to improve the normal vector, the average cross product of all possible vector combinations is used and the average taken as the normal vector. This is only possible, if the meteor is visible in more than three frames. The length of the normal vector is not yet known, because an observation from one station is not sufficient to calculate a three dimensional position. The data of the first Station is required, to calculate the meteor position. This is done by calculating the intersection between the plane and the viewing vector to the meteor as seen from Station 1 (vector from Station 1 to the meteor). The intersection point is calculated for all frames in which the meteor is visible from Station 1. In doing so, the three dimensional meteor position is calculated for different points in time. Furthermore, this process is repeated with the roles of Station 1 and 2 reversed. The trajectory is calculated by fitting a line through the calculated meteor positions. The timestamp of each frame is essential, to calculate the velocity and the trajectory of the meteor.

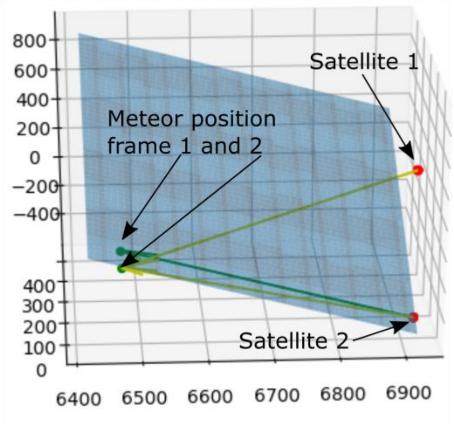

Figure 1: Visualization of the MOTS algorithm. Shown in blue is the plane calculated with satellite 2 as part of the plane and the two vectors (green and yellow) from satellite 2 to two meteor positions. The intersection of this plane with the viewing direction to one meteor as seen from satellite 1 gives the three dimensional position.

For our simulation the algorithm is adapted: Station 1 and 2 are replaced with Satellite 1 and 2. The satellite position is known via GPS, the meteor position as seen from a satellite, can be calculated from the satellite position and attitude. The MOTS algorithm is basically used as described above. In contrast to ground based observations, the satellite moves during the observation. Therefore, the average satellite position is used to set up the plane. After all meteor positions are calculated, a line is fitted through all positions. For comparison, the trajectory error is calculated in the same way as in the CILBO project: The median distance of the calculated meteor position and the fitted line is used as the trajectory error. A shorter median distance means the line could be fitted better to the positions. The line and the trajectory error is calculated two times, the second with the reversed roles of Satellite 1 and 2. The mean error of both trajectory errors is used for the evaluation and called simply trajectory error.

Simulation setup

The simulation consists of two Python scripts: The first one calculates the trajectory with the according settings; the second one evaluates the data. The simulation principle is as follows: First, the meteor position is calculated from given properties at different times during the event duration. The settable properties include lateral and horizontal angle, speed, altitude, position and duration. A simple linear motion is assumed for the short time the meteor is visible. This simulated meteor position is hereinafter called the true meteor position, which is used as a reference. From this reference, the meteor position as seen from each satellite is derived. Currently this is done by applying a random error to the true position. In reality, this would be derived from the satellite attitude. The two satellites are positioned close to the meteor, with the same and settable distance from the meteor trail. The satellite position is set in a way that the middle point of the meteor trail is perpendicular to the satellite position. The satellite orbit can be set as well. From those settings, the satellite position is calculated for the same times (true time) as used for the meteor position. Those positions are hereinafter referred to as the true satellite position. All positions in the simulation are given in X, Y, Z coordinates, with the earth centre as the zero point (see Figure 2).

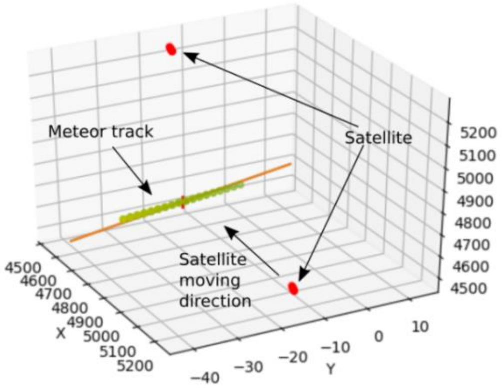

Figure 2: Visualization of the satellite and meteor track

This basic setup allows the calculation of the trajectory, the necessary data (satellite position, meteor position as seen from the satellite and time of observation) is given in the simulation. However, the calculated trajectory from stereoscopic meteor observations is affected by different errors. In this simulation the effect of the satellite position and attitude knowledge accuracy as well as clock accuracy are evaluated. All three errors can be set independently in the simulation. Before calculating the meteor positions with the MOTS algorithm, the input data is altered by a settable error. The error is given as the minimal and maximal deviation (in percent) between the true value and the measured value by the satellite. Three errors can be set: satellite position, meteor position and clock error.

Table 1: Simulation parameter naming convention

Reference parameter	Parameter with error
True meteor position	Satellite meteor position
True satellite position	Satellite position
True time	Satellite time

The meteor position as seen from the satellite (including the error) is called the satellite meteor position. The satellite position as measured by the satellite (including the error) is called the satellite position. The time as seen from the satellite (including the error) is called the satellite time (see Table 1). Technically, the error is calculated by randomly generating a number between the given low and high percentage for each true meteor and satellite position as well as each satellite time step. This number is the random percentage error for this specific position or time step. The percentage error is now multiplied with the true (satellite and meteor) position or time. This gives the random absolute error, which is added to the true position/time and finally gives the position/time as seen from the satellite.

As stated earlier, the effect of satellite bus parameters (position, attitude and time knowledge) on the trajectory should be evaluated. The bus parameter position knowledge is directly evaluated by setting the error on satellite position. The second error which should be investigated is the satellite attitude knowledge accuracy. This value is derived by calculating the angle between the true meteor position and the meteor position as seen from the satellite (see Figure 3). Therefore, the error on the satellite meteor position is treated as the satellite attitude knowledge accuracy. This is valid, since in reality the meteor position is calculated from the satellite attitude.

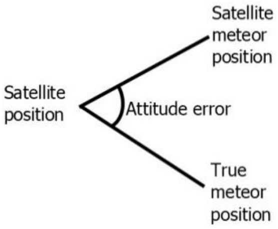

Figure 3: The attitude error as an angle between true and satellite meteor position as seen from the satellite

The bus parameter time knowledge can be directly set as the clock error, similar to the satellite position error. However, the clock error is not used directly in the calculations. Instead this error influences both, satellite and meteor position and can be seen as an additional error to both positions: When calculating the satellite position, orbital mechanic is used to calculate the position for different times. Herefore, the satellite time, which includes the error, is used and affects the satellite position. This simulates the clock error, which comes into effect when assigning a timestamp to a frame. This timestamp is erroneous, but important to derive the satellite position during exposure. Thus, the clock error reduces the satellite position accuracy. The clock error also influences the satellite meteor position: The difference between true time and satellite time is used to calculate the moving distance of the meteor during this time. Depending on the offset, this distance can be positive or negative and is added to the satellite meteor position which further effects this value. This simulates the inaccuracy of the frame timestamp, which is necessary to derive the satellite attitude during exposure. Both positions (meteor and satellite) as seen from the satellite are used as input values for the algorithm.

Simulation and evaluation

As explained in the previous section, the satellite bus parameters are evaluated by setting the according errors. The formation parameters should be evaluated as well. Therefore, orbit altitude and satellite distance can be set as well. The simulation is done for different orbits. While for the FACIS mission an orbit altitude between 300 and 565 km is planned, the simulation includes also higher and lower orbits. For each orbit, different satellite distances are simulated. Each combination of orbit and distance is a separate simulation which is run 200 times to get good average values. This is necessary, because the errors are randomly assigned. The standard settings for the parameters are stated in Table 2.

Table 2: Simulation settings

Parameter	Setting
Meteor altitude	100 km
Meteor speed	40 km/s
Meteor start angle	45°
Meteor lateral angle	90°
Meteor slope angle	60°
Exposure time	1/6 s
Orbit altitude	200-700 km
Satellite distances	1-10°
Simulation runs for each setting	200
Low error satellite position	8e-6%
High error satellite position	4e-5%
Low error meteor position	5e-5%
High error meteor position	8.03e-5%
Low error clock	0.004%
High error clock	0.005%

The errors were chosen to represent realistic values: The satellite meteor position error results in an average angle between true meteor position and satellite meteor position of about 7″ which is a typical satellite attitude knowledge accuracy. The satellite position error results in an average position error of about 170 m, which is a very conservative value for GPS accuracy. The satellite time is set to be accurate between 4 ms to 5 ms. Values not changed include meteor altitude (100 km), meteor speed (40 km/s), duration of meteor event (2 s) and exposure time (1/6 s). Some values (e.g. meteor angles) were changed only for dedicated simulations, to evaluate their effect. Generally, the evaluation is done by plotting the trajectory error against the distance between the satellites (satellite distance) for each orbit. The trajectory error is the median distance between calculated meteor positions and trajectory line, the lower the error the better a line could be fitted through the calculated meteor positions (see Section "The MOTS algorithm"). The simulation is also used to evaluate the effect of each error and their combination. This is done by setting two or one of the errors to zero.

RESULTS

Effect of orbit altitude

In Figure 4 the trajectory error is plotted against the distance between the satellites for different orbit altitudes. As can be seen, there is a minimal error depending on the satellite distance for each orbit. The higher the orbit, the higher the distance between the satellites must be in order to achieve a minimal trajectory error. Since the minimal trajectory error is in the same order of magnitude for each orbit, this value is used to compare the effect of different error sources (e.g. position error) and the magnitude of each error. This is achieved by calculating the mean minimal trajectory error over all orbits and comparing this value between different scenarios.

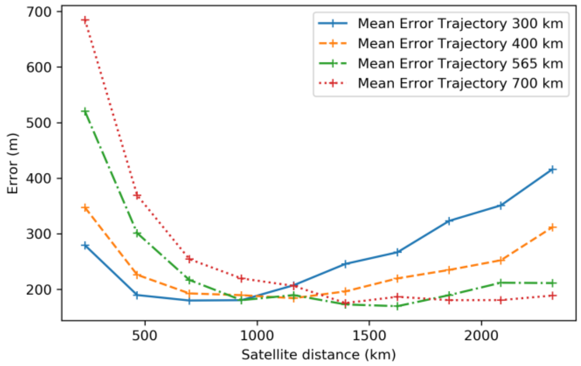

Figure 4: Trajectory error for different orbits and satellite distances

Effect of satellite attitude knowledge

In the simulation a typical satellite attitude knowledge error of 7” should be used. As mentioned before the satellite attitude knowledge is derived by calculating the angle between the true meteor position and the meteor position as seen from the satellite. The angle is set with the low and high meteor position error. By setting all other errors to zero, only the effect of the satellite attitude knowledge error can be evaluated. Before evaluating the results, it has to be ensured, that the attitude knowledge error is about 7”. This is done by calculating the angle between true and satellite meteor position for each orbit. As shown in Figure 5, for all orbits the attitude knowledge error is in the same order of magnitude. The attitude knowledge error is calculated at the distance between satellites which results in the minimal trajectory error.

The minimal trajectory error is about 140-170 m for a 565 km orbit and an attitude knowledge of 7”. This trajectory error is in the same order of magnitude as the estimation derived from the CILBO data base (120 m to 240 m trajectory error for 7” satellite knowledge error, see [1]). When comparing the trajectory error from the simulation and the CILBO data, it has to be taken into account, that the estimation from the CILBO data is also influenced by other errors, e.g. the determination of the meteor position in one image. This results in an overestimation of the trajectory error. However, in the simulation other errors also degrade the trajectory error, e.g. the movement of the satellite during the observation. All in all, the estimation from the CILBO data and simulation are consistent and can therefore be assumed to be correct.

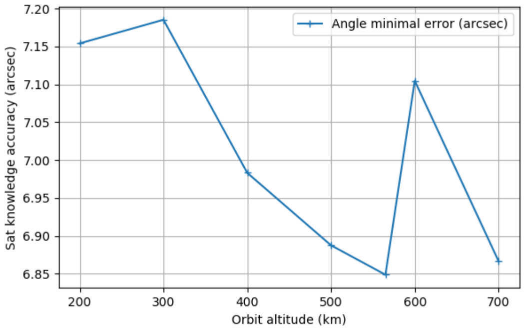

Figure 5: Angle between true meteor position and calculated meteor position from each satellite at the minimal trajectory error. This is treated as the satellite knowledge accuracy which is independent and almost constant for all orbit altitudes

Effect of satellite position knowledge

The effect of the satellite position knowledge error is evaluated the same way as the attitude knowledge: Meteor position and clock error were set to zero and the high/low error for satellite position were set to result in a conservative satellite position error of about 170 m. Unsurprisingly, a higher position error results in a higher trajectory error. The satellite position error of about 170 m, results in a trajectory error of about 60 m. For comparison, the mean trajectory error for the CILBO data is between 12 and 260 m, which includes all errors.

Effect of meteor properties

The meteor track is described by two angles: The slope angle is the angle between meteor track and the horizon (re-entry angle). The lateral angle describes the angle between meteor track and X-axis and thus effects the projection of the meteor track on the sensor. Since the satellites move along the X-axis, with a 90° lateral angle the meteor moves perpendicular to the moving direction of the satellites (see Figure 2). Both angles influence the calculation of the trajectory, therefore the minimal trajectory error was calculated using different angles. For all other settings the standard values as ones stated in Table 2 were used.

The lateral angle was set to 30, 60 and 90° respectively. As shown in Figure 6, a higher lateral angle results in a higher trajectory error. Therefore the chosen angle of 90° represents the worst case.

The slope angle was varied between 10 and 60°. A higher slope angle results in lower trajectory errors (see Figure 7). This means, the standard slope angle of 60° for the simulation does not represent a worst case. The additional trajectory error between the chosen angle of 60° and the 10° angle is about 55 m.

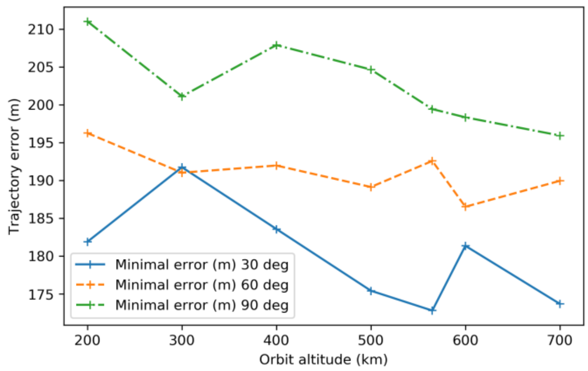

Figure 6: Minimal trajectory error for a simulation with different meteor lateral angles

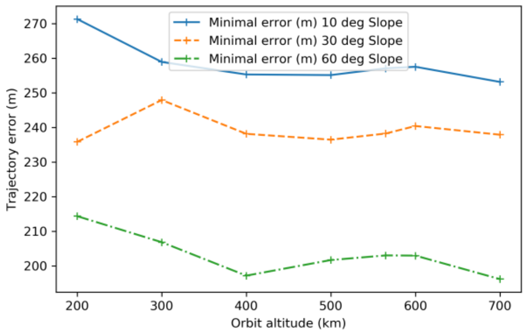

Figure 7: Minimal trajectory error for a simulation with different meteor slope angles

Effect of different error sources combinations

In the previous sections, the effect of single errors and meteor properties was evaluated. In this section, combinations of realistic values for each error source (position and attitude knowledge as well as clock accuracy) are simulated and the effect compared to each other. The results are shown in Table 3. For the baseline run, all errors are set to zero. Case 1 includes the effect of the clock error on the satellite position, while in case 2 the meteor position is also effected by the clock error. For the position and attitude cases, only the error for satellite position respectively the satellite meteor position are taken into account. The last three cases are combination of the above mentioned settings. For each case, the not mentioned errors are set to zero. As can be seen in Table 1, the clock error has the lowest influence, but in the same order of magnitude as the satellite position error. By far the highest influence has the attitude error, which is represented by the satellite meteor position. This becomes also clear when looking at case 1 and 2: When taking into account the effect of the clock error on the satellite meteor position, the trajectory error increases significantly. The errors do not add up linear, which is due to the fact, that the errors can cancel each other out due to the random nature of the error.

Table 3: Influence of different errors sources on trajectory error for realistic error magnitudes and a 565 km orbit

Case	Case number	Mean min. trajectory error (m)	Mean sat. distance min. error (km)
Baseline	0	0. 46	239
Clock error	1	11	1541
Clock error and clock error on meteor position	2	60	1847
Position error	3	62	930
Attitude error	4	171	894
Attitude and position error	5	169	929
Attitude, position and clock error	6	171	895
Attitude, position, clock error and clock error on meteor position	7	200	1133

When using realistic but still conservative errors for satellite position and attitude knowledge as well as the clock accuracy, the trajectory error is about 200 m. This error could increase up to 255 m, if the worst case slope angle is used. This is an estimate of the trajectory error to be expected from the satellite bus parameters for a stereoscopic meteor observation. This assumes the satellites have the ideal distance to minimize the trajectory error and the MOTS algorithm is used for calculation. It has to be noted, that the trajectory error is higher in a real application due to additional errors not included in the simulation. For example, the determination of the photometric centre of a meteor on the image sensor further increases the trajectory error.

For each error case, the ideal satellite distance with a minimal trajectory error was also calculated (see last column of Table 3). There is no relation between trajectory error and ideal distance, a higher error does not result in a higher distance. One reason is that for the first cases (Cases 0 to 3), the trajectory error does not change much above a certain satellite distance (see Figure 8). Therefore, the ideal satellite distance is not obvious and has no effect on the trajectory error given a high enough distance.

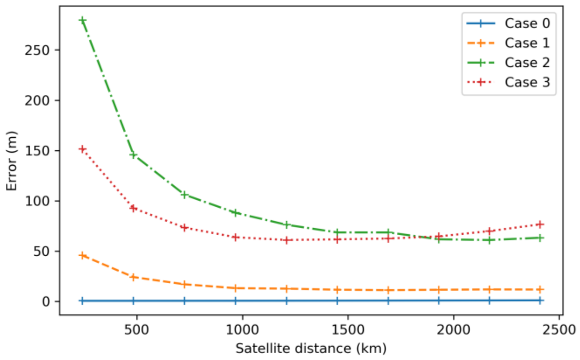

Figure 8: Trajectory error vs satellite distance for a 565 km orbit at the different error cases (0-3)

For the error cases 4 to 7, the ideal distance can be determined more accurately, because a clear minimum exists (see Figure 9). In those cases the trajectory error increases again after reaching the minimum. Therefore, it is important for the satellite formation to keep the ideal distance. However, it has to be noted that the minimum is not sharply defined and a small deviation from the ideal distance does not increase the trajectory error much. The ideal distance for minimal trajectory error at different orbits is summarized in Table 4.

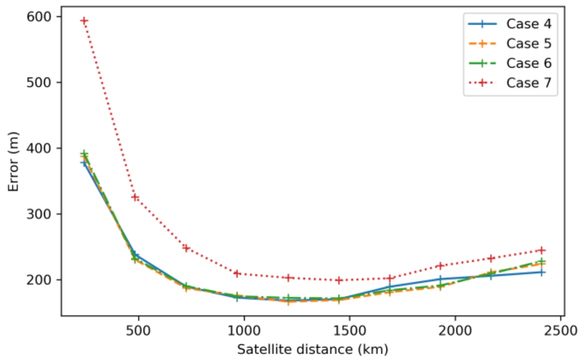

Figure 9: Trajectory error vs satellite distance for a 565 km orbit at the different error cases (4-7)

Table 4: Ideal satellite distance for different orbits taking into account all errors

Orbit (km)	Mean sat. distance min. error (km)
200	459
300	698
400	945
500	1198
565	1450
600	1457
700	1723

IDEAL FORMATION PARAMETERS FOR METEOR DETECTION

In order to generate useful scientific data, the FACIS mission must fulfil two requirements: First, generating a large data base by observing as many meteors as possible. Second, the measurements must be accurate. The distance between the satellites influences both requirements. As shown in this paper, the distance must be in a certain range, to minimize the trajectory error. Thus the distance influences the accuracy of the measurements. The number of observed meteors is, among others, influenced by the distance as well: A higher distance allows for a higher tilt angle of the satellite cameras, which results in a larger area covered by both cameras and consequently increases the number of detected meteors. However, a higher distance also reduces the number of detected faint meteors due to the higher distance between meteor and camera. Therefore, it has to be evaluated which distance is ideal for the number of observable meteors and compare this result with the ideal distance for trajectory calculation.

The *Simulator for Wide Area Recording of Meteors from Space* (SWARMS) software was used and adapted to simulate the meteor detection rates depending on the satellite orbit, satellite distance and tilt angle (see [4] and [1]). According to those simulations, the satellite tilt angle should be at least 25°. The tilt angle describes the angle between camera optical axis and Nadir, an angle of 0° would mean the camera points at Nadir. The satellite distance is calculated from the satellite tilt angle, in order to maximize the area covered by both camera field of views. The ideal distance for coverage at a 565 km and a 300 km at a 25° angle using a 12 mm focal length lens is about 614 km and 246 km respectively. Both values are lower than the ideal distance for trajectory calculations which are 1450 km and 698 km respectively. In order to observe as many meteors as possible and also calculating an accurate trajectory, the satellite tilt must be increased. With a tilt angle of 40° for the 565 km orbit, the ideal distance for the number of observed meteor is 1411 km. This means, a distance suitable for trajectory calculation and number of observed meteors is feasible. For the 300 km orbit the highest possible tilt angle of 42° results in an ideal distance for the number of observed meteors of 575 km, which is close to, but still significantly different from the ideal distance for trajectory calculation. The tilt angle cannot be increased further, because the camera field of view would exceed the horizon.

A consequence of the higher tilt angle and increased distance for the meteor observation is the reduced number of observed faint meteors. Due to the higher distance between the two cameras, a faint meteor can only be detected by one camera. The distance to the other camera is too high and not enough light reaches the camera. Therefore, the satellite distance could be slightly reduced, in order to observe more faint meteors. As shown before, the trajectory error is low for a certain range of satellite distances. A slight reduction of satellite distance would increase the number of faint meteors observed, while still allowing an accurate trajectory calculation.

SIMULATION USING SWARMS METEOR DATA

The previous simulation used fixed values for the meteor and satellite properties for each simulation. Furthermore, the meteor always appeared in the middle of both satellites. This approach is useful to evaluate the effect of each parameter systematically and derive requirements for the satellite bus and formation. In order to get an idea of the trajectory error for real observations, meteors appearing in different distance to the satellite with various properties must be simulated. Therefore, the meteor properties from the previous mentioned SWARMS simulations are used. In this simulation the mean meteor properties (speed, re-entry and lateral angle) are set and varied using a Gaussian distribution with settable standard deviation. Each property is randomly assigned to a meteor. Furthermore, the meteors are positioned at various locations on a grid.

After the SWARMS simulations were conducted, each detected meteor with the according properties is exported into a file. This file is imported into the trajectory simulation and the trajectory error is calculated using the meteor properties (position, re-entry and later angle) as well as satellite properties (position and attitude) and satellite formation parameters (orbit and satellite distance) from the SWARMS simulation. As before, an error is applied to the satellite position, satellite meteor position and clock.

The SWARMS simulation was conducted for a 565 km orbit, a mean re-entry angle of 62° with 22° deviation and a mean later angle of 90° with 20° deviation. Meteors down to a mass of 0.01g were simulated. The meteor speed was assigned according to the European Cooperation for Space Standardization (ECCS) standard (see [5]). The tilt angle of the satellite was set to 10, 25 and 35° respectively. The satellite distance was set to maximize the area covered by both satellite cameras. This means the distance was optimized to maximize the number of observed meteors.

For each tilt angle a separate trajectory simulation was conducted with the according settings and data from the SWARMS simulation and the errors on satellite position, satellite meteor position and clock. For evaluation the mean, maximal and minimal trajectory error was calculated. The results are shown in Table 5.

Table 5: Results of the trajectory simulation using data and settings from the SWARMS simulation

Tilt angle (degree)	Mean trajectory error (m)	Max trajectory error (m)	Min trajectory error (m)	Satellite distance (km)
10	303	4610	109	218
25	182	2061	120	614
35	192	1528	130	1036

As can be seen in Table 5, the mean trajectory error for all tilt angles is in the same order of magnitude as in the previous simulations. However, there is a strong variation of the trajectory error as shown in Figure 10. For some meteors the trajectory error exceeds 500 m. This is likely due to some unfavourable combination of meteor properties and location.

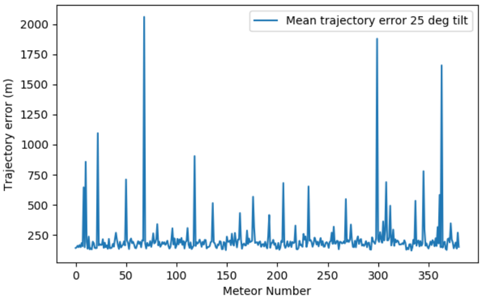

Figure 10: Variation of the trajectory error (25° tilt angle)

Furthermore, for the larger tilt angles (25 and 35°) the trajectory error is lower than for the small tilt angle of 10°. The reason for this is the lower and not ideal distance of the satellites. For the higher tilt angles the satellite distance is closer to the suitable range for reducing trajectory error (see Figure 4).

All in all the trajectory simulation using the SWARMS data shows that the trajectory error estimated for specific meteor properties and location is applicable for various meteor properties as well. Furthermore, even without setting the satellites to the ideal distance for trajectory determination, the mean trajectory error is still in a range suitable for scientific meteor observations.

CONCLUSION

The trajectory simulation presented in this paper was successfully used to evaluate the effect of satellite position and attitude knowledge error on the trajectory. The error on the trajectory for a satellite attitude knowledge error of 7″ is about 170 m for a 565 km orbit. The position error degrades the trajectory accuracy by about 62 m. The total expected trajectory error for a typical meteor and a formation in a 565 km orbit is about 200 m. While this value is a suitable assessment of the expectable scientific performance, the trajectory error for a real observation is likely to be higher. This is due to the fact that some error sources are not taken into account. Furthermore, in this simulation the meteor occurs in the middle of both satellites. In reality this is not the most likely situation. Therefore, another simulation using different meteor properties and position from the SWARMS simulation was conducted. According to this simulation, the trajectory error is still in the same order of magnitude.

The simulation is also used, to evaluate the effect of orbit altitude and to calculate the ideal satellite distance. The ideal satellite distance depends on the orbit altitude, the higher the orbit, the higher the satellite distance needs to be in order to achieve the highest possible trajectory accuracy. However, the trajectory error is low for a certain range of altitudes. For the current FACIS orbit (300 km to 565 km) a satellite distance between 500 km to 1800 km results in a suitable trajectory error (see Figure 4). Furthermore, the simulation with the SWARMS data shows that the trajectory error does not increase significantly despite optimizing the satellite distance for coverage and not trajectory calculation. The distance for ideal coverage is in the range of suitable distances for trajectory determination.

In the future, more error sources which influence the trajectory accuracy must be evaluated. This includes for example the determination of the meteor position on the CCD chip and the effect of exposure time on the determination of this position as well as on the determination of meteor speed.

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