Observation error propagation on video meteor orbit determination

SonotaCo [1]

A new radiant direction error computation method on SonotaCo Network meteor observation data was tested. It uses single station observation error obtained by reference star measurement and trajectory linearity measurement on each video, as its source error value, and propagates it to the radiant and orbit parameter error by Monte Carlo simulation method. The resulted error values on a sample data set showed reasonable error distribution that enables effective selection on the accuracy. A sample set of selected orbits obtained by this method revealed sharper concentration of shower meteor radiants that we have not ever had. The published SonotaCo Network simultaneously observed meteor data sets will be revised to have this error value on each record and be opened for public with its computation program in near future.

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1 Introduction

On the determination of a meteor shower set, we need enough number of low-biased orbits that have higher accuracy than natural distribution of shower meteors. By the developments of automated video meteor observation systems, long term observation with high constancy and continuity became possible. On the SonotaCo Network, that has been operated over 9 years, there stacked over one and half million single station observations. From this, over 200 000 orbits were reduced as simultaneous observation and were published as SonotaCo Network simultaneously observed meteor data sets (SNM) (SonotaCo, 2016). By these observations the bias problem on optical meteor observation, which are caused by weather condition, moon age, and solar longitude limitation of night time, is now almost overcome. But its measurement accuracy problem has not been solved satisfactory yet. In 2014, though the data processing of a new meteor shower April alpha Capricornids (IAU#752 AAC), a new radiant error computation method was tried and it showed quite reasonable standard deviation of radiant direction (SonotaCo et al., 2014). If we got the fair uncertainty of each orbit on large database, we can select orbits using each accuracy and get the revealed sharper image of radiant map. Thus, the implement of the new error propagation function on our orbit computation tool UFOOrbitV2 (UO2) (SonotaCo, 2007b) was planned. This paper reports its method and the result of its evaluation using a subset of SonotaCo Network data base.

2 Past approach

Generally, the uncertainty of computed results should be got from mathematical error propagation of measurement error. On the SonotaCo Network, single station measurement software UFOAnalyzerV2 (UA2) (SonotaCo, 2007a), the observation error was automatically measured on each event by using the reference stars on same video. But the error propagation has not been done because there are least square methods in the reducing process on which the error propagation using covariance computation is difficult. Instead of error propagation, UO2 has provided some quality selection methods such as threshold on duration or cross angle. They were effective to reject orbits that has very bad accuracy, but were not enough to sharpen the concentrations of shower meteors. On the CAMS (Jenniskens et al., 2011), though it uses assumed observation error, the error propagation using Monte Carlo simulation method was done and uncertainty of results were estimated. Hence, though it may require large quantity of computation, Monte Carlo simulation based on the actual observation error was expected to produce reliable uncertainty on SonotaCo Network data.

3 Observation error

The most dominant error factors on video meteor observation is the error on the determination of center direction of the bright object's image. Experimentally, the weighted center computation using the brightness of pixels on a video field gives around 10% of object's diameter. So there can be a method that use assumed uncertainty (such as 0.3 pixel) as the source error value, but in this experiment, we tried to use the actually measured error values on each observation. This error appears both of reference star position measurement and meteor position measurement. On UA2, the former error is called FOV adjustment error d (expressed as "ddeg" on UA2) and is measured on each video as the average distance from reference fixed star imaged position to its of star catalog. To have the generality on the variety of FOV size and resolution, all measured position in pixels are firstly converted to equatorial coordinate directions in degrees and all computation is done on it. This conversion uses 11 plate parameters including parameters for lens distortion, focus plane curvature, optical center offset, and pixel X/Y aspect ratio and so on. On the typical case of a clear night, there are 50 to 100 reference stars automatically recognized on each video, and d became $0\overset{\circ}{.}01$ to $0\overset{\circ}{.}1$ typically ($0\overset{\circ}{.}01$ corresponds to 0.1 pixel of 60° FOV NTSC system). The latter error is called trajectory linearity error c (expressed as "cdeg" on UA2) and is measured as the residual on the least square method of straight line fitting to the observed trajectory (computation of a plane that contains trajectory line and observing point). It

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depends on the size of the luminescence of a meteor, the c usually becomes $0.^{\circ}01$ to $0.^{\circ}1$. The actual distribution of these values can be known from published SNM. These two values with the number of reference stars are included in the network hub data and also in the output of UO2. They have been stacked since 2007. On this experiment, the summation of both observation error on each meteor $e = d + c$ was used as the source observation error value for the error propagation.

4 Error Propagation

There are multiple observation factors that may dominate the final error in the orbit determination process. The major factors are, duration time (number of video frames), physical distance from the station to the meteor trajectory, cross angle among the simultaneous observation planes (geographical relation among stations and the meteor trajectory), and the singular point effect of velocity when it is near to the escape velocity of solar system and it of the Earth. The dominant factor is different on each meteor, and any of them can amplify the observation error up to infinite. Cross interaction among the factors also exists. On this complex situation, usual error propagation using variance or covariance is very difficult, but the Monte Carlo simulation method with enough number of trials will produce the appropriate error values on the results.

On this experiment, the whole propagation process was divided into two stages. One is the computation of observation plane pole on single station data, and the other is the rest part of radiant and orbit computation using multi station data. The reason of this dividing is to fix the error of each single station result that might be used in multiple combination among the simultaneous observations. On the implementation of Monte Carlo method, to ensure the re-computability, the seed of artificial random numbers is fixed for each stage of each meteor. On each stage, 1000 times computations using random error on input were done, and the standard deviation of outputs were computed over obtained 1000 results. And finally, as the accuracy measure, the standard deviation of angle distance around the mean radiant direction Er was computed for each orbit. Er shows the uncertainty of radiant direction by one value, and it does not have scale bias like Right Ascension error that has scale dependency on the Declination.

5 Evaluation on an actual sample

Sample data set

The evaluation of this new method was done using a subset of actual SonotaCo Network observation data. The subset is all meteors that were observed in 1° solar longitude range of $283.^{\circ}0$ to $284.^{\circ}0$ in 10 years (2007 to 2016). It is the peak period of Quadrantids (QUA) shower. There were 16 374 single station observations data. 7047 of them composed simultaneous observations and by using the same quality conditions on UO2 as usual SNM making, 2662 meteor orbits data set S with error values was obtained. Figure 1 shows the major part of its radiants distribution.

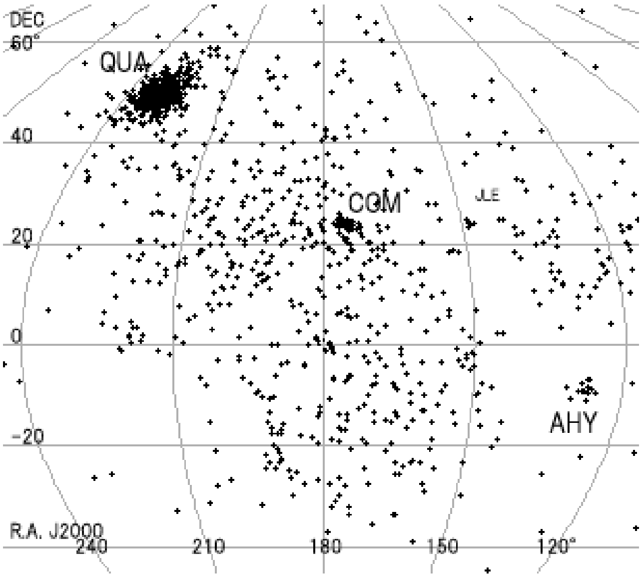

Figure 1 – All radiants in $\lambda_{\odot}$ range $283.^{\circ}0$ to $284.^{\circ}0$ of 10 years.

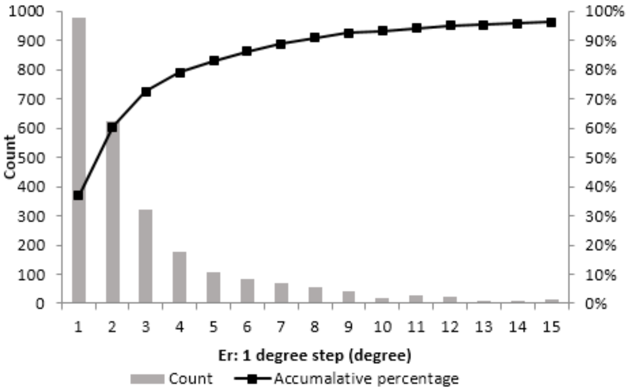

Figure 2 – Distribution of radiant error Er on sample data set.

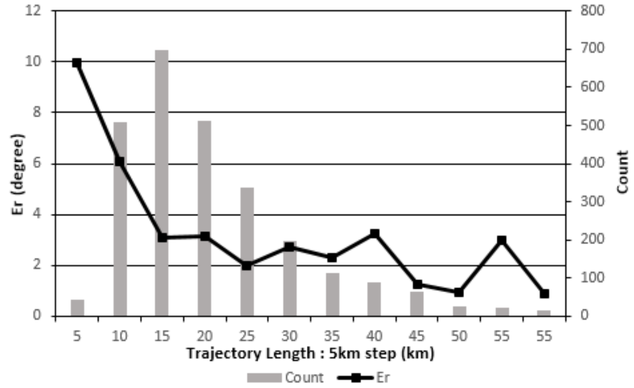

Figure 3 – Correlation between Er and the trajectory length.

Er distribution

Figure 2 shows the Er distribution of on S. It shows 90% was under 8°, and 60% was under 2°. It is well matched to the sense that we have experienced on the

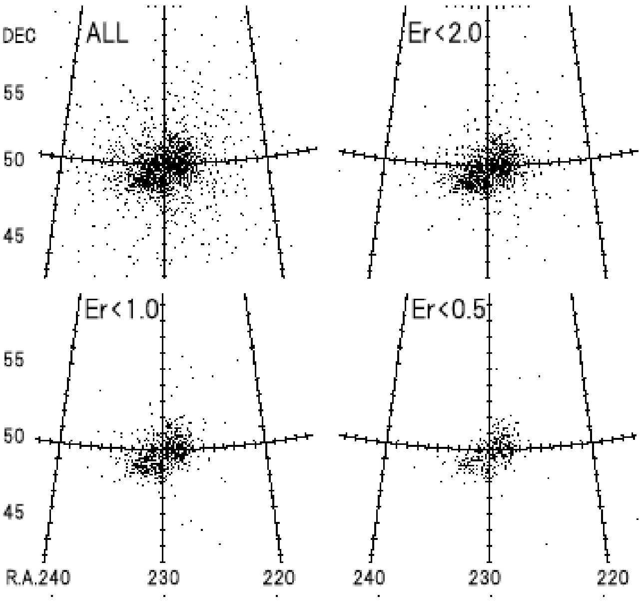

Figure 4 – Concentration of QUA shower meteors.

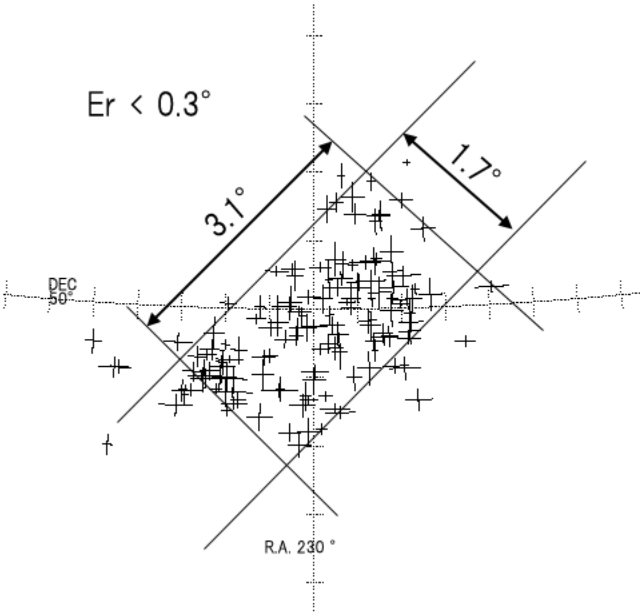

Figure 5 – QUA Radiant distribution on $1^\circ\lambda_\odot$ range.

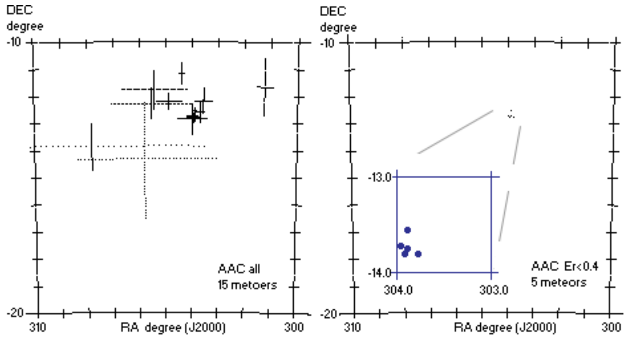

Figure 6 – *Er* restriction on April alpha Capricornids meteors.

Limitation of *Er*

If *Er* is properly expressing the observation uncertainty, and the uncertainty is not enough smaller than natural distribution of shower meteors, then selection on the results using the limitation of *Er* will sharpen the concentration of shower meteor distribution. Figures 4 and 5 show the QUA meteor shower concentration on some *Er* limits. The sharpness of the concentration is increasing along with the decrease of error limit. It is relatively clear on $Er > 1\overset{\circ}{.}0$, but the still continues down to $Er > 0\overset{\circ}{.}3$. And finally we got $1\overset{\circ}{.}7 \times 3\overset{\circ}{.}1$ natural distribution of QUA meteor radiants of $1^\circ\ \lambda_\odot$ range. This result encourage us to use *Er* value for the future research. For example, if we adopt this method to the AAC meteor shower on 2014, we get $0\overset{\circ}{.}3 \times 0\overset{\circ}{.}4$ radiant area at $Er < 0\overset{\circ}{.}4$ shown in Figure 6. It might be one of the most compact shower radiants concentration that we have ever seen. Figure 7 shows the result of $Er < 1\overset{\circ}{.}0$ limitation on *S*. Comparing with Figure 1, the limitation clearly sharpens the concentrations of shower meteors.

On these samples, the orbit selection using *Er* looks very effective and promising. We can use appropriate *Er* limit according to the purpose of the research. But there, we should be careful about the possibility multiple results computation among more than 2 stations simultaneous observation. And it suggests even restricting the error under 2°, we will get over 130 000 precise orbits during 10 years of our observation.

Correlation between *Er* and error source factor

As a sample of correlation between *Er* and an error source factor, Figure 3 shows the correlation between meteor trajectory length and *Er*. It shows clear correlation where $Er > 3\overset{\circ}{.}0$. It means the rejection of too short trajectories is effective for rejecting the orbits that have very bad accuracy. But it also shows the difficulty of selecting high accuracy results, such as $Er < 2\overset{\circ}{.}0$, by a single source factor.

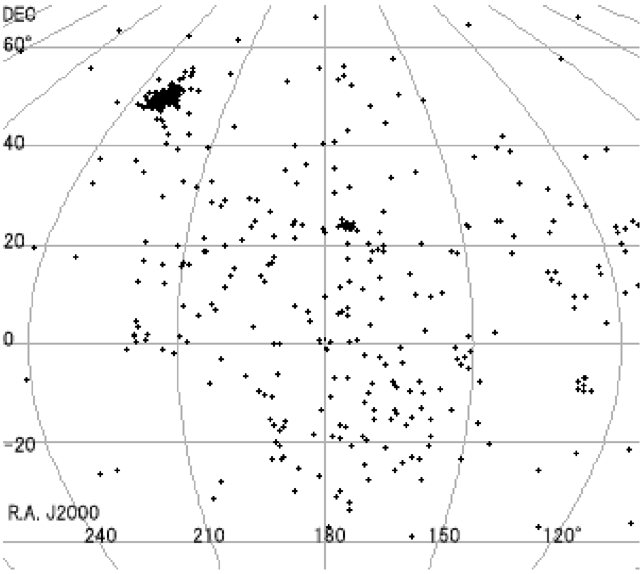

Figure 7 – Selected radiants $Er < 1\overset{\circ}{.}0$ on *S*.

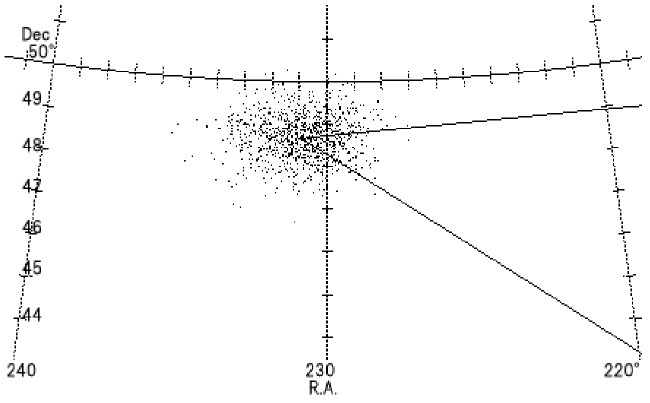

Figure 8 – Typical simulated error distribution of an actual meteor (20130103_114512, $Er = 1\overset{\circ}{.}02$).

of the observation bias that this selection might cause. It might be bias on the trajectory length, or objects weight.

Simulated Error Distribution

Figure 8 shows the typical simulated error distribution around the observed radiant. It is an actual sample of one QUA meteor (2013 January 3 at $11^{h}45^{m}12^{s}$ UT, $Er = 1\overset{\circ}{.}02$, $\sigma\text{RA} = 1\overset{\circ}{.}33$, $\sigma\text{Dec} = 0\overset{\circ}{.}54$). There are 1000 plots of simulated results and two straight lines showing the observed trajectory direction of each station. The cross angle between two trajectory direction was $37\overset{\circ}{.}8$, and there is small anisotropy along with the common trajectory direction. This sample suggests a not enough cross angle always causes anisotropic distribution.

Figure 9 shows another sample of highly accurate observation (2012 January 4 at $15^{h}28^{m}29^{s}$ UT, $Er = 0\overset{\circ}{.}09$, $\sigma\text{RA} = 0\overset{\circ}{.}06$, $\sigma\text{Dec} = 0\overset{\circ}{.}06$). This meteor was observed by 4 stations simultaneously. The distances from the trajectory to the stations are almost same and are less than 200 km. The cross angle of trajectory direction among stations is over 88°. It was almost ideal case. But yet some anisotropy can be seen. It seems 3 observations from one side (along with the Dec axis) might contribute to narrow the distribution of that direction (UO2 utilizes all simultaneous observation by least square method to decide the observed radiant).

These samples suggest that the anisotropy of error distribution around the radiant can happen depending on cross angle or any asymmetricity on each observation.

6 Conclusions

The observation error propagation shows reasonable error distribution that can be used for the effective selection of orbits. The selected orbits of actual shower meteors shows very sharp concentration that we could not see ever. The new error computation method can be adopted to not only newly observed orbits, but also stacked large quantity of SonotaCo Network data, and is expected to produce many new findings. The updated version of UFOOrbitV2 that contains this error propagation function will be opened to public in near future with the updated SNM data base that has error values for each orbit.

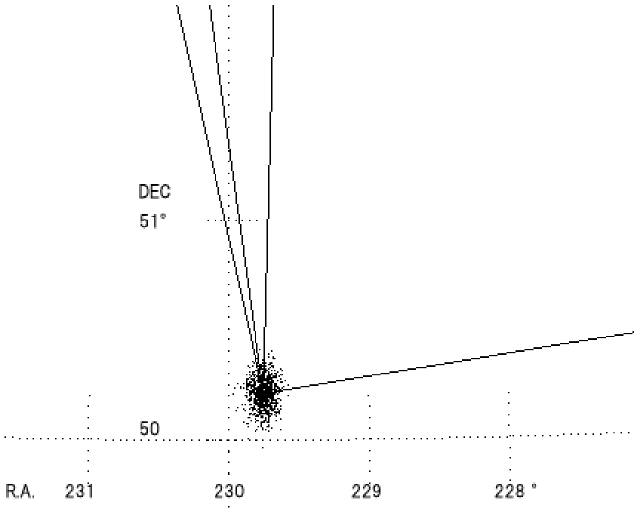

Figure 9 – Simulated error distribution of a highly accurate observation (20120104_152829, $Er = 0\overset{\circ}{.}09$).

Now we have the last piece of automated video meteor observation system. It will show us precise distribution of actual Earth colliding objects. SonotaCo Network activity on the internet over 10 years, now reaches to one of its scientific goal.

Acknowledgements

Without the large quantity of observation by the SonotaCo Network members, nothing would have happened. Its observation accuracy is increasing year by year. It is the result of observer's continuous efforts. I appeal my best appreciation and respect for the observers who are listed in the SNM note files.

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