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New IMO Radio and Visual Commission Directors
Esko Lyytinen: miner for out-of-this-world experience
SNMv3: new catalog of orbits from SonotaCo Network
Geminid fireball spectrum from 2020 shower maximum

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## Administrative



## Ongoing Meteor Work



## Front cover photo

This impressive fireball through clouds was recorded on 2021 May 28, at $04^{\mathrm{h}}28^{\mathrm{m}}$ UT ($22^{\mathrm{h}}23^{\mathrm{m}}$ MDT on May 27), from northern New Mexico, USA. Photo courtesy: Scott Roberts.

**Writing for WGN** This Journal welcomes papers submitted for publication. All papers are reviewed for scientific content, and edited for English and style. Instructions for authors can be found in WGN **45:1**, 1–5, and at `http://www.imo.net/docs/writingforwgn.pdf` .



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# News about IMO's Radio Commission and Visual Commission

*The IMO Council*

Due to health problems, Jean-Louis Rault has recently resigned as Director of the Radio Commission and as IMO Council member. We want to thank Jean-Louis for the many years of good service in both functions and we wish him a good recovery. Chris Steyaert is the new Director of the Radio Commission. Chris is a long time radio observer who has been arranging and publishing the Radio Meteor Observing Bulletin since its creation in 1993 and who regularly contributes radio meteor studies to the IMC and WGN. We are convinced that Chris will be an excellent Director and we wish him a lot of success in this new position. The e-mail address for any questions regarding radio meteor observations stays the same: `radio@imo.net`.

Rainer Arlt requested to be relieved of his duties as Director of the Visual Commission, and is succeeded by Jürgen Rendtel. We are very grateful to Rainer for all the good work that he has done for the Visual Commission and for IMO in general. Jürgen has been IMO President from 1988 until 2013, is IMO's all-time most diligent visual observer, and regularly publishes global analyses of visual observations. We are assured that Jürgen will be an excellent Director and we wish him a lot of success. The e-mail address for any questions regarding visual meteor observations stays the same: `visual@imo.net`.

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# The miner for out-of-this-world experience

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*'Let someone else praise you, and not your own mouth; an outsider, and not your own lips.'* [1]

Here we are, Esko, your sincere admirers – trying to conceive the extent of what you are and always has been for us – an inconceivable teacher, brilliant scientist, and a courageous pioneer pursuing new inspiring ways in science and life.

[1] Proverbs 27:2, Esko has mentioned it in several occasions as being his life motto.

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## 1 Introduction

This story is inspired by the life and work of our friend, collaborator, and co-author, Esko Lyytinen. A man of extraordinary mind. A one of his kind. With a life-long passion for science.

From a very early age Esko was fascinated by the stars and the universe. Esko was 14 when the Earth's first artificial satellite, Sputnik 1, was launched in 1957 and already at that age he could figure out exactly where and when to look to see it in the sky. He would get the whole family to look at it the very first night it was visible. While for the rest of the family it was a one night spectacle, Esko continued observing it as well as subsequent satellites. It may come as no surprise then that years later he named his first model of meteoroid stream formation "the satellite model of comets" (Lyytinen, 1999).

He outgrew his very first telescope quickly and built his own reflecting telescope. He ground the main mirror himself and managed to source an eyepiece. He built the frame with whatever leftover planks he could find. It was not pretty but it worked. Its scruffy appearance did not stop it being placed in a prime spot on the small balcony in the family's home. This inventive approach would be repeated many times with the various other contraptions he created throughout his life. Antennae, cameras, directional microphones, metal detectors and so on would be taped or glued together with whatever spare objects he could find or source to get the job done. Wherever they needed to go, be it the front of the house, on the roof, installed on a laptop, or literally attached to his own forehead, the look did not matter as long as the concept worked.

*Figure 1* – Esko on the photograph titled 'my first telescope' (source: Esko's own photograph album). We acknowledge great help especially by Olli Lyytinen with providing data, support and details from the family archive.

Esko's interests in photography, astronomy and amateur radio converged in the 60s when he started receiving weather satellite imagery with his equipment. This was at a time when others would see such images only rarely printed in newspapers. Esko was always extraordinarily capable of applying and combining his fields of knowledge to new problems and filling in the gaps by persistently educating himself.

As Maria Gritsevich recollects, "Due to the nature of my profession the list of highly motivated, sharp and smart people I have met is fairly long, however even in this 'list' Esko clearly makes a difference. His ability to think big, ease of giving up the 'old ways', and bravery and talent in inventing the new with inconceivable speed, in addition to dedication and persistence in achieving results, are truly unique."

While the far distance of space fascinated Esko, he was not enthusiastic about traveling long distances back on Earth. In November 1998 Esko had chosen to holiday with his family at Madeira over a 'meteor storm chasing' trip to China at the time when the Leonid meteor shower was predicted to peak and be most visible. He believed that his holiday location was far from the ideal spot to observe the Leonids; the peak of the shower was calculated to be at a time when the opposite side of the

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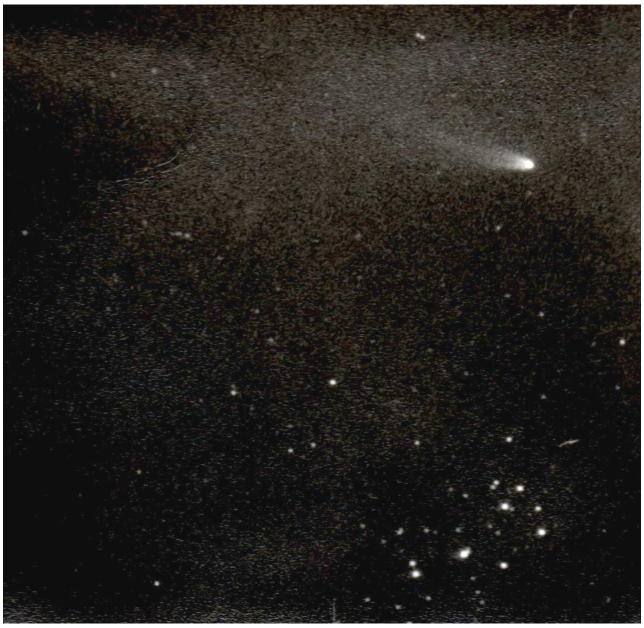

*Figure 2* – Photograph of the comet Seki-Lines of 1962 (photo taken by Esko on 16 April 1962, source: Esko's own photograph album).

*Figure 3* – Photograph of Esko made in July 2004 near Savonlinna, in Eastern Finland. The picture is taken during the comparison test with metal detectors – a commercial version (which Esko is holding) and the metal detector which Esko had made himself (on the ground). (Image credit: Markku Nissinen).

Earth was facing the dust trail that produced it. Nevertheless, Esko got up that night and to his surprise, and against the predictions, he was treated to a spectacular meteor shower, not only visible from an area not predicted but also earlier than expected.

As it turned out, the shower had peaked earlier than predicted and Esko was close to an ideal location to observe it. He was perplexed at how inaccurate and far "off-schedule" the predictions had been and set his mind to developing better comet dust trail models on his home computer. Soon after that, Esko indeed came up with an independent model of the formation and evolution of dust trails from comets (Lyytinen, 1999).

Markku Nissinen recalls his memories of Esko and his thoughts about working together: "I became acquainted with Esko in the late 90s when I was actively involved in the Meteor Section of the Ursa Astronomical Association. I was involved at first with Esko in the mathematical modeling of meteor showers and dust trails. I remember him as a very sympathetic and friendly person."

"I was personally very interested in emerging modern dust trail prediction methods in the late 90s, because I had been on a visual observing expedition with enthusiasts from the Meteor Section of Ursa to The Great Wall of China to see the anticipated Leonid 1998 'storm', which did not in reality materialize in the predicted way at all. There was only a small increase of rates at the predicted time."

"Then I met Esko and he offered me a possibility to be involved in modeling of the dust trails using the advanced model that he and Tom Van Flandern had originally developed (Lyytinen & Van Flandern, 2000). I refined the model with Esko further. We made improvements with Esko to non-gravitational processes in the model. It was very fascinating to see how the particles were affected by the model and see the numbers print out in the computer screen. It took quite a long time to model dust trails with the quite modest PC I had in those days."

"Then I was extremely proud to see how the media compared the models, like there was a competition going on between different dynamists. Esko's model produced one of the best predictions for the Leonids in 2001. I especially remember the interesting and popular articles of Leonids referring to the different models by Joe Rao in Sky & Telescope magazine."

Esko went on to successfully forecast and (post)-predict many meteor outbursts. His dust trail predictions yielded many important publications, including improved 2001 Leonid storm predictions from a refined model (Lyytinen et al., 2001). The work was continued and for the 2003 and 2004 predictions Esko teamed up with other researchers. Hence, different models were compared with older cometary trails (Vaubaillon et al., 2003). In the following years, much work was done to try to improve the predictions using possible changes from radiation pressure. Observed ZHR values were quite low, but different predicted dust trail encounters could indeed be recognized in the observations (Vaubaillon et al., 2004; Trigo-Rodríguez et al., 2006).

In 2000, Esko started a very fruitful collaboration with meteor astronomer Peter Jenniskens that led to 33 co-authored publications. "I first interacted with Esko leading up to the 2000 Leonids," recalls Jenniskens. "Esko analyzed the effects of radiation on the moving particles, which moved the dust trails near Earth's orbit enough to cause quite different predictions that year."

"Later that year, the Ursid meteor shower was expected to show an unusual meteor outburst, which occurred when the parent comet 8P/Tuttle was at aphelion, and Esko worked out why that was. We published our predictions of the peak time in Jenniskens & Lyytinen (2000) and the outburst was confirmed (Jenniskens & Lyytinen, 2001; Jenniskens et al., 2002)." Calculations on the Ursids by Esko and Markku Nissinen were published in a table in Jenniskens' book "Meteor Showers and Their Parent Comets" (Jenniskens, 2006).

"In the following years, I directed Esko's attention to long-period comet dust trails, like the one that caused the alpha Monocerotid outburst in 1995. Again, Esko was able to model key features of the observations. His results on long-period comets were published in the journal Icarus (Lyytinen & Jenniskens, 2003). Ever since I have turned to Esko for future predictions when a new long-period comet shower was seen. Esko predicted a shower from comet C/1976 D1 (Lyytinen & Jenniskens, 2003) and I traveled to South Africa to try to confirm that, but the weather and far southern declination of the radiant proved too big a challenge. Even this campaign led to greater collaborations. Examples being studies of the October Camelopardalids and the 2008 September Perseids (Jenniskens et al., 2005; Jenniskens et al., 2008a) Most recently, Esko found a clever way to use meteor shower observations to measure the orbital period of poorly observed long-period comet Grigg-Mellish (Jenniskens et al., 2020a)."

With the return of comet 8P/Tuttle in January 2008, close to the 2007 encounter, further modeling of the Ursid shower was carried out. In addition, there was even a prepared airborne observing campaign from NASA Ames Research Center to observe the Ursid shower over the Canadian arctic. This was fascinating and very inspiring for Esko to follow (Jenniskens et al., 2007c). This work found there were two predicted encounters with old trails, from years 1466 and 1533 and they were coinciding in time. The trail of 1466 produced an outburst in 2008. This allowed Esko to update the prediction by running the model with the increased number of particles (Lyytinen & Nissinen, 2009; Vaubaillon et al., 2009a; Vaubaillon et al., 2009b).

When comet 17P/Holmes exploded in October 2007, Esko immediately realized the possibility to observe the dust trail produced by the explosion in the future. In the 'Tähdet ja Avaruus' article of the comet explosion Esko suggested that a phenomenon "shaped like an hourgrass" may appear at the explosion site at the next revolution of the trail. Esko expected that this phenomenon may be a vivid reminder of the past explosion event. Unfortunately the phenomenon was too dim to be seen without a powerful telescope and this did not prove to be as amazing sight for the public as had been hoped, compared to if the trail would have been much brighter and easier to see (Lyytinen et al., 2014; Lyytinen et al., 2015).

When the material from the explosion had travelled half revolution to the other common node of the particle's orbits Esko and Markku had succeeded in observing the phenomenon in the southern sky using remote controlled telescopes at the Siding Spring Observatory in Australia (Lyytinen et al., 2013b; Lyytinen et al., 2013a). As Nissinen explains: "We had to use image reduction techniques in 2013 to detect the trail. We then succeeded in observing the bright phenomenon in the explosion point in the northern sky in the first revolution. Seeing the images of the dust trail was extremely rewarding. This time phenomenon was visible in telescope view without image reduction. The project is ongoing in 2021 and 2022 with the comet in perihelion in February 2021 and the comet approaching the explosion site in the fall of 2021."

The hobby-motivated research soon made Esko famous in the meteor, and later, in the planetary science community. Often he would be contacted concerning the annual shower calendar as well as his model calculations that he could graciously perform for meteor showers. He would readily share findings about meteor events he had analyzed as well as his ideas on meteoroid stream evolution.

Jürgen Rendtel recalls: "Esko provided me with numerous hints based on his meteoroid stream modelling for the annual IMO Meteor Shower Calendars over years. This also opened out into joint publications combining observational data and modelling results. Two examples are the September epsilon-Perseids and very recently the Aurigids (Rendtel et al., 2020). Their slightly enhanced rates in 2019 yielded to the conclusion that we might see another enhancement in 2021 – an occasion not only to look for the meteors but at the same time also to remember Esko as an enthusiastic motivator to observe usually weak showers."

Notably, already in 2003 Esko was invited to review and serve as an opponent of the PhD thesis defended by Jérémie Vaubaillon in the Paris Observatory in France (Esko declined the invitation for personal reasons). Later (in 2014) the International Astronomical Union (IAU) named the asteroid 15699 Lyytinen (1986 VM6) to highlight his long-term outstanding contribution to planetary science.[a]

From the very beginning Esko's meteor passion went beyond meteoroid streams, with observing meteors first by radio reflections from their ionized wake in the atmosphere, and later also visually with wide-angle video cameras. His degree in mathematics (Lyytinen, 1972) came in useful again when he started developing methods to solve the exact trajectory based on multiple observations from different observation points, which led to locating surviving meteorite fragments on the ground. This resulted in creation of sophisticated tools, such as the fb_entry program developed by Esko and used to analyze most of the Finnish fireball trajectories to date (Lyytinen & Gritsevich, 2013).

[a]A new proposal has been put forward to exceptionally name the Swedish iron case observed on November 7, 2020 following the last Esko's birthday on this planet as Esko Lyytinen. The present article comprises a lot of justifications for that exceptional reasoning. Even if not achievable, that will be an association that we will always carry with those of us who knew and worked with him.

Jeff Brower recalls: "My first contact with Esko was over 20 years ago. I had several questions about mAnalyzer, a software program for counting forward scatter echoes authored by Esko and his son, Olli. Esko's reply was several pages long with step-by-step directions and an explanation about how the program worked. I was very impressed with both, the thoroughness of his reply and with his mathematical reasoning inside the software. It was at this time I also noticed he was a fellow amateur radio operator, which gave us even more to discuss. Esko and Olli next produced JAnalyzer, a Java version that could run on Windows, Macs and Linux systems. I was a beta tester for Esko. It worked well and was a valuable tool for recording meteor echoes, aurora, and Sporadic E events."

In spring 2004, following several spectacular fireballs, the Finnish Fireball Network (FFN) was co-founded by Esko, Marko Pekkola and Jarmo Moilanen with the goal to collect video observations of meteor phenomena. Since the formation of the network, Esko has played a central role in its maintenance, development, and data analysis.

Markku Lintinen recalls: "I have known Esko only for the last three years in the context of the Finnish Fireball Network. I was very impressed by what you scientists have done and achieved! Esko was very welcoming and helpful to me, as I joined as the novice fireball camera operator. This was a rewarding experience to me – one relevant set of images for the November 7th Swedish iron meteorite fall in 2020 came from my Tampere west camera. Esko had used those images in his modelling. On December 11th he called me for some additional details of the images. I mentioned his significant efforts in this case and still remember clearly what Esko said about what motivated him: "This could be a once in a lifetime event!"

Earlier we talked about expanding the camera coverage in Tampere. I told Esko that my next camera candidate towards the west could be easily opened in order to access the imaging cell. That time Esko was experimenting with infrared daytime fireball images. I was willing to join and he sent me a piece of a filter that I glued in front of the cell. We didn't succeed in catching a daytime fireball but it was a rewarding experience otherwise – some nice thunderstorm pictures and landscapes with stunning clouds and night skies where stars were a bit challenging to identify because of different brightness in IR."

Esko would gladly engage in complex video calibration of any unknown camera if it happened to capture an interesting meteor case in any part of the world (Lyytinen & Gritsevich, 2016; Trigo-Rodríguez et al., 2015; Hildebrand et al., 2018; Larionov et al., 2018; Meier et al., 2020). In fact, when we received a physical dash-cam that captured a daylight Osceola fireball in the US, its robust study with stars on Finnish skies practically did not improve on Esko's previously made remote calibration of the camera.

Various smart techniques were proposed by Esko in processing meteor observations, including the height correction method to account for real atmospheric conditions (Lyytinen & Gritsevich, 2016). Similarly, the atmospheric refraction correction method allows for retrieving a fireball position with high accuracy without the need to consider at which distance from the observer (or height above the Earth's surface) the fireball is situated (Visuri et al., 2020).

Finland is a relatively small and not well-populated country, with an area elongated from south to north of $\sim 338\,000$ km$^2$. It is Europe's most heavily-forested country and subsequently it has one of the most difficult terrains for meteorite recovery. In addition, Finland's water area is vast: 187 888 lakes and ponds with an area of more than 500 m$^2$, as well as a total of 25 000 km of rivers. The total area of water bodies takes $\sim 10\%$ of the area of the country and forests take $\sim 74\%$ of the land area. Despite the effort, no meteorites from the observed falls were recovered in Finland within the last 50 years. Out of the 5 historically witnessed meteorite falls (and a total of 13 meteorite falls), the last one, Haverö, was collected in 1971.

Despite this, Esko played an essential role in the recovery of several meteorites abroad, including in the two neighboring countries of Russia and Sweden. The most prominent successful cases were the recoveries of 3 meteorite falls made with the engagement of the FFN: Annama, Ozerki and that of the asteroid 2018 LA, Motopi Pan (Gritsevich et al., 2014a; Gritsevich et al., 2014b; Trigo-Rodríguez et al., 2015; Lyytinen & Gritsevich, 2016; Kohout et al., 2017; Maksimova et al., 2020; Moilanen et al., 2021; Jenniskens et al., 2021). In addition, right post-predictions of the strewn field were made for the Chelyabinsk, Osceola, Flensburg meteorites, and more, including the Swedish iron case (close to Ådalen) observed on November 7, 2020. A number of important physical aspects were proposed and specified in treating the fireball trajectories including the dark flight stage (Moilanen et al., 2021).

Jarmo Moilanen recalls: "After I got my dark flight Monte Carlo code working in 2010 Esko delivered parameters of fireball trajectories to me. For most interesting cases Esko checked his calculations several times before he was satisfied with the result. All in all Esko provided the trajectory parameters for 52 fireballs observed in Finland by the Finnish Fireball Network and for 21 fireballs observed abroad. We also discussed and compared our results which helped me a lot in improving the dark flight model I was developing."

Jeff Brower brings another memory: "Around 2006 some local amateurs formed the British Columbia Fireball Network. The network consisted of a handful of participants with fisheye lenses to produce full sky survey video captures. Once we began capturing fireballs we turned to Esko for his help to determine the fireball's orbit and where the possible strewn field might be located. Esko graciously took on our request. He began by painstakingly calibrating several of our network cameras. Once the camera calibrations were done he could begin to work out the possible orbits of each fireball we recorded. No matter how overworked Esko was with co-temporal multiple fireball captures in Europe, he always managed to work on our small group's

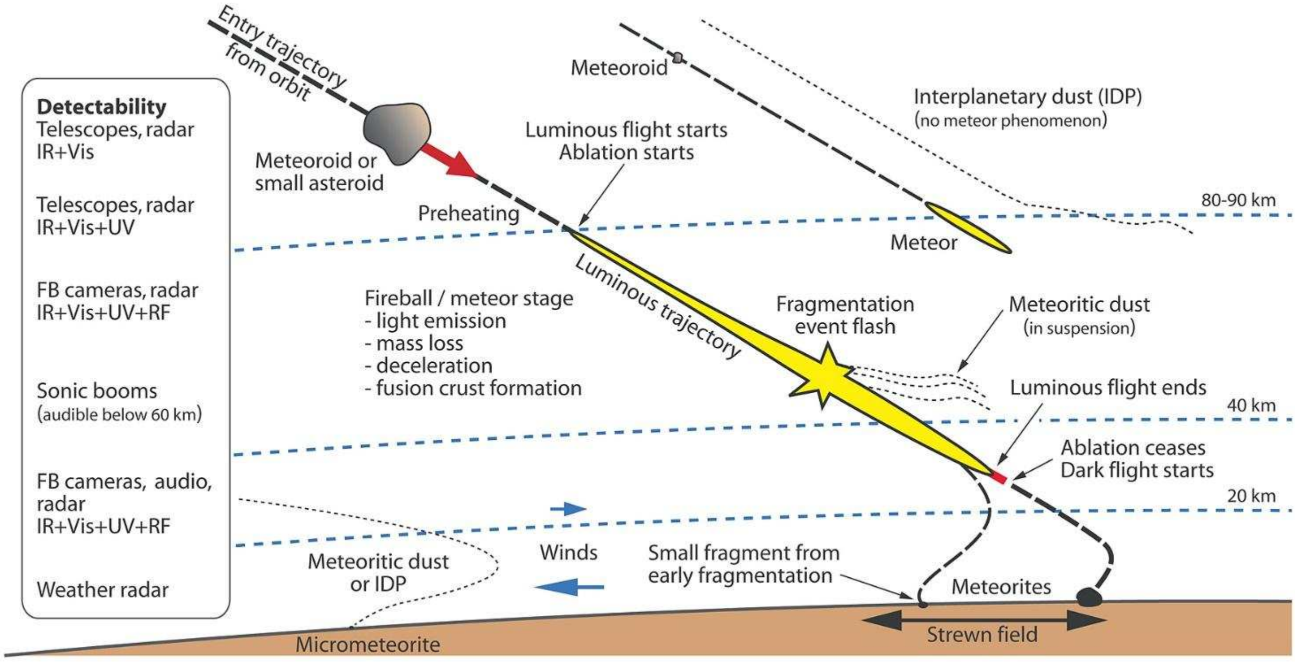


*Figure 4* – Different stages and phenomena related to a meteoroid entering the Earth's atmosphere, after Moilanen et al. (2021). One of the latest journal papers authored by Esko.

*Figure 5* – The Annama fireball – leading to the first meteorite recovery based on the Finnish Fireball Network observations. Photo from Kuusamo, Finland on April 19th 2014. (Image credit: Asko Aikkila)

requests for help. Esko's extensive work with our group paid off on September 5, 2017. Esko computed a probable fall site based on a single camera's capture from Rick Nowell's camera at College of the Rockies at Cranbrook, BC. Esko's calculations led to the recovery of multiple meteorites near Crawford Bay, British Columbia.[b]

Esko's email from May 29, 2014 (when he just got the information on the first fragment of Annama being recovered) reads: "Dear Maria, I find this almost unbelievable !!!! :) ..." "...I think that you now deserve, and I also good sleep, hope that this will not prevent us to sleep :)" was in one of the emails the following day.

The most enjoyable emails that some of us received were from times when Esko was up at his summer house

*Figure 6* – The photograph of the first recovered fragment of the Annama meteorite taken by Esko the same day as it arrived to Finland, 1st of June 2014 (Esko biked to MG the same day to see the sample and this is when he used his phone to make this picture of the sample lying on the kitchen table). The sample was later given to the Ural Federal University meteorite collection in Russia.

in the small town of Vesanto in central Finland. Esko made lists of ideas and experiments that he would try once he was up at Vesanto. His first email upon arrival stating he made the trip OK were then quickly followed by a flurry of emails for the next 4 or 5 weeks about his various experiments and which ones worked and which didn't. These were usually followed by his thoughts on what could be done to improve the results.

It was while he was up at his summer place that Esko would engage in his latest attempts of pushing both radio and video methods of meteor detection. His temporary modification of his video camera to push the infrared end led to fascinating videos of nocturnal birds and waterfowl migrations and aurora. Although these may not have always been the results, Esko was looking for the most; they were unique and charming nonetheless. Esko was a true tinkerer as seen in a photo of

[b]"Lyytinen got a result of the fireball flight, which was only half a mile away from the second modelling published later on by the Canadians." (Suominen, 2017) Suominen, Mikko "A Finnish expert assisted in finding meteorites in Canada" (2017) `https://www.avaruus.fi/uutiset/tahtiharrastus-ja-taivaanilmiot/suomalaisasiantuntija-avusti-meteoriittien-loytamisessa-kanadasta.html`

*Figure 7* – The photograph of the second recovered fragment of the Annama the day it was donated for the display at the Finnish Museum of Natural History.

*Figure 8* – Esko Lyytinen, Maria Gritsevich and the Annama meteorite fragment just placed on the museum display. (Images credit: Jarmo Moilanen).

a bay of UHF antennas duct taped to a hockey stick. Despite its comical look, it allowed Esko to pursue his goals quicker and, as always, it worked.

Esko's time in Vesanto was also a period of enjoying nature, swimming, mushroom and berry picking. He would gladly engage in translating and teaching Finnish (also) during that time: *kantarelli* mushrooms, *mustikka*, *puolukka*, *mustaherukka* berries, and which were *kypsä* or not. One could keep a record comparing berry conditions in Vesanto along with discussions on the current weather patterns for each summer. Esko was like that, finding a common interest in just about anything we talked about, be it VLF, ultrasound, audio recordings of meteors, space-based observations, or hunting for micrometeorites.

On the topic of meteorite falls, Esko also became a very important collaborator to many researchers abroad. One prominent example is joint work with the Spanish Fireball Network. Josep Trigo-Rodríguez recalls: "As he was in charge of the Finnish Fireball Network we were both in contact with each other every month. We exchanged information about fireball events because we were convinced that some large bolides are produced by rocks detached from their parent asteroids or comets. Our papers together on this subject was a product of great cooperation. He was a really bright amateur astronomer, and achieved with us an excellent team job."

Manuel Moreno-Ibáñez continues: "I met Esko when I was a PhD student and I owe a good part of my PhD title to him. He provided a lot of support when I was working in exploiting the capabilities of the $\alpha$-$\beta$ model – dimensionless meteor trajectory analysis that was introduced to the meteor community some time ago and was about to reach its maturity (Moreno-Ibáñez et al., 2016; Moreno-Ibáñez et al., 2017; Raja-Halli et al., 2016; Gritsevich et al., 2016b; Gritsevich et al., 2017a; Sansom et al., 2019; Moreno-Ibanez et al., 2020). Indeed, his proposal to adjust the observed meteor height values according to the corrected atmospheric pressure, resolved with grace multiple issues that deemed very complex at first and thus, reinforced the capabilities of this methodology (Lyytinen & Gritsevich, 2016)."

"All in all, Esko was always there. Even if I was a student with a lot of skills to be learnt and shameless to bother anyone, he would gladly reply to every email, including his interesting points of view and various approaches to my requests. I had the chance to meet him when I spent a couple of months in Helsinki as part of my research formation. That was during the summer 2015. Esko was as kind and supportive as his emails demonstrate, and he always seemed to have striking ideas to share regardless of where conversation would have taken us. He would always show the excitement of a child when sharing with me fireball images from the FFN. He was the vivid example any student would love to follow and I did indeed use on the cover of my PhD thesis two of the awesome fireball images Esko has provided me with (Moreno-Ibanez, 2018)."

"Esko was very active in meteor research even after he retired, and his contribution to this field is well-known and very valuable: it ranges, for instance, from the development of software tools to the prediction of outbursts of different meteor showers. In particular, I am very grateful that he could test my meteoroid orbit calculation software" – adds José Maria Madiedo.

After the publication by Trigo-Rodríguez et al. (2007) that analyzed the ability of large meteoroids from asteroid 2002 $NY_{40}$ to give rise to meteorite-dropping bolides, this study was presented at the LPSC congress (Trigo-Rodríguez et al., 2008). One of the following papers focused on the outburst experienced by the $\gamma$-Ursae Minorids in 2010 (Madiedo et al., 2013). The work analyzed the first ever recorded emission spectrum by a member of this shower and it was also presented at the EPSC congress held in 2011 (Madiedo et al., 2011c).

In 2010 and 2011 two contributions were presented to the Meteoroids congress (Madiedo et al., 2011b) and the EPSC congress (Madiedo et al., 2011a), respectively. Both of them described a software tool that was developed to derive, among other information, meteor atmospheric trajectories and meteoroid orbits. Esko tested some parts of that software tool to validate them. Esko would gladly engage in testing, using or even improving the software – be it the '$\alpha$-$\beta$ model' (Gritsevich, 2009; Lyytinen & Gritsevich, 2016), orbit determination with 'Meteor Toolkit' (Dmitriev et al., 2015;

Dmitriev et al., 2015) or anything else. In fact, the diversity of different ideas and tools that Esko had and used will significantly impress many.

In 2013 an analysis of a potential meteorite-dropping fireball spotted over the south of Spain in 2011 was presented at the LPSC (Rodriguez et al., 2013). A software tool developed by Esko (fb_entry) was unique and very helpful to obtain information about this single-station event. Esko has also contributed to the book published in 2017 (Blanch et al., 2017). This was a chapter in the book "Assessment and Mitigation of Asteroid Impact Hazards" (Trigo-Rodríguez et al., 2017) focused on the detection and analysis of nocturnal and diurnal bolides from Ebre Observatory in Spain.

Yet Esko was certainly much more than his extensive meteor work. Even though he lived in Helsinki for most of his life and was always very capable with technology, he loved being in nature, a lifestyle he had gotten used to in his childhood. Most summers he would retreat to the family summer house in Vesanto, situated by the lake and surrounded by thick forests. He would fish and forage for food, collect the birch sap in spring and could concentrate on his research and hobbies in peace. In addition to astrophotography, Esko also loved photographing nature and birds in particular and was also active in bird ringing in his earlier years. One of the themes that kept Esko extremely excited was the search for planet X.

In 2010 he participated in developing the iPhone application "Hear Birds Sing". It changed the frequency of high-pitched sounds, like grasshoppers and high-pitched birds, to lower frequencies, which would be better hearable in real time by people with reduced hearing abilities, a challenge that Esko himself faced in later life. The users could have heard the sounds of high-pitched animals that otherwise would be impossible to hear using headphones without applying a delay. This application was popular in the App Store and was heavily in use around the world for a long time. Unfortunately, it is not available any more. Esko has also developed an Android version of this application.

*Figure 9* – Photograph of Esko hearing birds sing taken right outside the family summer house in Vesanto in 2011 (image credit: Leena Elliot).

Many of you, dear readers, may have scratched your head by this point wondering, "Wow! If this was what Esko achieved in retirement, then what did he engage with in his professional career?!" That, however, is another story entirely and would require a larger volume. :) The story that has been just explained here is truly unique. Because of its unusual nature it may not resemble a stretch of biography what could have been originally envisaged, but truly captures the contributions Esko made to our lives and also to science.

After reading the original draft of this article Janne Pyykkö from FFN has commented – "Wow, that was a really exceptionally fascinating text. I want to thank the writers / contributors who very well catched the spirit of Esko for his life-long passion of producing new ideas as well as experimenting and developing them. The true friendship that Esko also provided me in some situations is so very well captured in the text. Well done, and thank you for letting me feel good for being a part of this compassionate society." – As long as the reader's impression runs along these lines, we feel that our intention for writing down this story is fulfilled!

Beyond science, Esko was a loving father, husband, and grandfather; a slightly introverted, private man who was always helpful to others, a sincere giver/sharer and a real mentor to many of us, and presumably to the many others that he knew. Besides his great enthusiasm he always had empathy, modesty and (only) kind, optimistic and positive words in what he wrote or spoke. Even on his very last Christmas Eve day Esko's messages were "Sairaalassa kaikki hyvin. Everything well. Hyvää Jouluattopäivää ☺🙏" (in the morning) and "Kiitos Maria !💥🎄" (in the afternoon). Esko certainly already is and will be greatly missed. Over the past years Esko taught us much about both meteors and life in general. The last lesson Esko taught was the hardest lesson of all; how harsh it makes us feel to lose such a great friend, such a brilliant mind, and how much rethinking it demands.

## References


Blanch E., Trigo-Rodríguez J. M., Madiedo J. M., Lyytinen E., Moreno-Ibáñez M., Gritsevich M., and Altadill D. (2017). "Detection of Nocturnal and Daylight Bolides from Ebre Observatory in the Framework of the SPMN Fireball Network". In Trigo-Rodríguez J. M., Gritsevich M., and Palme H., editors, *Assessment and Mitigation of Asteroid Impact Hazards: Proceedings of the 2015 Barcelona Asteroid Day*, volume 46. page 185.

Dmitriev V., Lupovka V., and Gritsevich M. (2015). "Orbit determination based on meteor observations using numerical integration of equations of motion". *Planetary and Space Science*, **117**, 223–235.

Dmitriev V., Lupovla V., Gritsevich M., Lyytinen E., and Mineeva S. (2015). "Orbit determination and analysis of meteors recently observed by Finnish Fireball Network". In *European Planetary Science Congress*. pages EPSC2015–598.

Gritsevich M., Dmitriev V., Vinnikov V., Kuznetsova D., Lupovka V., Peltoniemi J., Mönkölä S., Brower J., and Pupyrev Y. (2017a). "Constraining the Pre-atmospheric Parameters of Large Meteoroids: Košice, a Case Study". In Trigo-Rodríguez J. M., Gritsevich M., and Palme H., editors, *Assessment and Mitigation of Asteroid Impact Hazards: Proceedings of the 2015 Barcelona Asteroid Day*, volume 46. page 153.

Gritsevich M., Kohout T., Grokhovsky V., Yakovlev G., Lyytinen E., Vinnikov V., Haloda J., Halodova P., Michallik R., Penttilä A., Muinonen K., Peltoniemi J., Lupovka V., and Dmitriev V. (2013). "A Comprehensive Study of Chelyabinsk Meteorite: Physical, Mineralogical, Spectral Properties and Solar System Orbit". In *AAS/Division for Planetary Sciences Meeting Abstracts*, volume 45. page 205.01.

Gritsevich M., Lyytinen E., Grokhovsky V., Vinnikov V., Kohout T., and Lupovka V. (2013). "Orbit, trajectory, and recovery of Chelyabinsk meteorite". *Meteoritics and Planetary Science Supplement*, **76**.

Gritsevich M., Lyytinen E., Grokhovsky V. I., Vinnikov V., Kohout T., Lupovka V., and Dmitriev V. (2013). "The Chelyabinsk Meteorite Orbit, Trajectory and Recovery". In *European Planetary Science Congress*. pages EPSC2013–1071.

Gritsevich M., Lyytinen E., Hankey M., Meier M. M. M., Matson R., and Fries M. (2017b). "Atmospheric trajectory and orbit of the Osceola meteorite". In *European Planetary Science Congress*. pages EPSC2017–995.

Gritsevich M., Lyytinen E., Hankey M., Meier M. M. M., Matson R., and Fries M. (2017c). "Atmospheric Trajectory and Orbit of the Osceola Meteorite (January 24, 2016)". In *80th Annual Meeting of the Meteoritical Society*, volume 80. page 6188.

Gritsevich M., Lyytinen E., Kohout T., Moilanen J., Midtskogen S., Kruglikov N., Ischenko A., Yakovlev G., Grokhovsky V., Haloda J., Halodova P., Lupovka V., Dmitriev V., Peltoniemi J., Aikkila A., Taavitsainen A., Lauanne J., Pekkola M., Kokko P., and Lahtinen P. (2014a). "Analysis of the Bright Fireball over Kola Peninsula on April 19, 2014 Followed by Successful Meteorite Recovery Campaign". In *77th Annual Meeting of the Meteoritical Society*, volume 77. page 5369. no. 1800.

Gritsevich M., Lyytinen E., Moilanen J., Kohout T., Dmitriev V., Lupovka V., Midtskogen V., Kruglikov N., Ischenko A., Yakovlev G., Grokhovsky V., Haloda J., Halodova P., Peltoniemi J., Aikkila A., Taavitsainen A., Lauanne J., Pekkola M., Kokko P., Lahtinen P., and Larionov M. (2014b). "First meteorite recovery based on observations by the Finnish Fireball Network". In Rault J. L. and Roggemans P., editors, *Proceedings of the International Meteor Conference, Giron, France, 18-21 September 2014*. pages 162–169.

Gritsevich M., Silber E. A., Lyytinen E., Moreno-Ibáñez M., Trigo-Rodríguez J. M., Muinonen K., and Penttilä A. (2016a). "Meteoroid Impact Hazard based on Atmospheric Trajectory Analysis". In *American Geophysical Union, Fall General Assembly*. pages P43B–2104.

Gritsevich M., Silber E. A., Lyytinen E., Moreno-Ibáñez M., Trigo-Rodríguez J. M., Muinonen K., Penttilä A., and Silber R. E. (2017d). "A New Approach to Estimate Meteoroid Impact Hazard Based on Atmospheric Trajectory Analysis". In *Lunar and Planetary Science XLVIII*. page 2471. no. 1964.

Gritsevich M., Vinkovic D., Schwarz G., Nina A., Koschny D., and Lyytinen E. (2016b). "Meteor Observations as Big Data Citizen Science". In *American Geophysical Union, Fall Meeting*, volume 2016. pages ED21C–0794.

Gritsevich M. I. (2009). "Determination of parameters of meteor bodies based on flight observational data". *Advances in Space Research*, **44:3**, 323–334.

Hildebrand A. R., Hanton L. T. J., Ciceri F., Nowell R., Lyytinen E., Silber E. A., Brown P. G., Gi N., Jenniskens P. M. M., Albers J., and Hladiuk D. (2018). "Characteristics of a Well Recorded, Bright, Meteorite-Dropping Fireball, British Columbia, Canada, September 4, 2017". In *49th Lunar and Planetary Science Conference*. page 3006.

Jenniskens P. (2005). "October Camelopardalids". *CBET*, **309**.

Jenniskens P. (2006). *Meteor Showers and Their Parent Comets*. Cambridge University Press. p. 643.

Jenniskens P., Albers J., Tillier C. E., Edgington S. F., Longenbauch R. S., Goodman S. J., Rudlosky S. D., Hildebrand A. R., Hanton L., Ciceri F., Nowell R., Lyytinen E., Hladiuk D., Free D., Moskovitz N., Bright L., Johnston C. O., and Stern E. (2018). "Detection of meteoroid impacts by the Geostationary Lightning Mapper on the GOES-16 satellite". *Meteoritics and Planetary Science*, **53:12**, 2445–2469.

Jenniskens P., Brower J., Martsching P., Lyytinen E., Entwistle D., and Cooke W. J. (2008a). "September Perseid meteors 2008". *CBET*, **1501**.

Jenniskens P., Gabadirwe M., Yin Q.-Z., Proyer A., Moses O., Kohout T., Franchi F., Gibson R. L., Kowalski R., Christensen E. J., Gibbs A. R., Heinze A., Denneau L., Farnocchia D., Chodas P. W., Gray W., Micheli M., Moskovitz N., Onken C. A., Wolf C., Devillepoix H. A. R., Ye Q., Robertson D. K., Brown P., Lyytinen E., Moilanen J., Albers

J., Cooper T., Assink J., Evers L., Lahtinen P., Seitshiro L., Laubenstein M., Wantlo N., Moleje P., Maritinkole J., Suhonen H., Zolensky M. E., Ashwal L., Hiroi T., Sears D. W., Sehlke A., Maturilli A., Sanborn M. E., Hyskens M. H., Dey S., Ziegler K., Busemann H., Riebe M. E. I., Meier M. M. M., Welten K. C., Caffee M. W., Zhou Q., Li Q.-L., Li X.-H., Liu Y., Tang G.-Q., McLain H. L., Dworkin J. P., Glavin D. P., Schmitt-Kopplin P., Sabbah H., Joblin C., Granvik M., Mosarwa B., and Botepe K. (2021). "Asteroid 2018 LA, impact, recovery and origin on Vesta". *Meteoritics & Planetary Science*, **56**, 844–893.

Jenniskens P. and Lyytinen E. (2000). "Possible Ursid outburst on December 22, 2000". *WGN, Journal of the International Meteor Organization*, **28:6**, 221–226.

Jenniskens P. and Lyytinen E. (2001). "2000 Ursid outburst confirmed". *WGN, Journal of the International Meteor Organization*, **29**, 41–45.

Jenniskens P. and Lyytinen E. (2001). "Dynamical Models of Meteoroid Streams in Relation to Recent and Upcoming Leonid and Ursid Showers". In *American Astronomical Society, Division of Dynamical Astronomy Meeting*, volume 32. page 01.06.

Jenniskens P. and Lyytinen E. (2001). "No outbursts from comet C/2000 WM1 (LINEAR)". *WGN, Journal of the International Meteor Organization*, **29**, 35–37.

Jenniskens P. and Lyytinen E. (2003). "Possible meteors from comet C/1976 D1". *IAUC*, **8079**.

Jenniskens P. and Lyytinen E. (2005). "Meteor showers from the debris of broken comets: D/1819 W1 (Blanpain), 2003 WY25, and the Phoenicids". *The Astronomical Journal*, **130:3**, 1286–1290.

Jenniskens P. and Lyytinen E. (2014). "Possible new meteor shower from Comet 209P/LINEAR". *CBET*, **3869**.

Jenniskens P., Lyytinen E., and Baggaley J. (2020a). "An outburst of delta Pavonids and the orbit of parent comet C/1907 G1 (Grigg-Mellish)". *Planetary and Space Science*, **189**.

Jenniskens P., Lyytinen E., and Bemer C. (2015). "Potential meteor shower from comet C/2015 D4 (Borisov)". *CBET*, **4127**.

Jenniskens P., Lyytinen E., Brower J., and Yrjölä I. (2007a). "Ursid meteors 2007". *CBET*, **1188**.

Jenniskens P., Lyytinen E., de Lignie M. C., Johannik C., Jobse K., Schievink R., Langbroek M., Koop M., Gural P., Wilson M. A., Yrjölä I., Suzuki K., Ogawa H., and de Groote P. (2002). "Dust trails of 8P/Tuttle and the unusual outbursts of the Ursid shower". *Icarus*, **159:1**, 197–209.

Jenniskens P., Lyytinen E., Jehin E., and Marsden B. (2004). "NEO 2003 EH_1, the Quadrantid Shower Parent". *35th COSPAR Scientific Assembly*, **35**, 612.

Jenniskens P., Lyytinen E., and Johannink C. (2017a). "October Camelopardalid meteors 2017". *CBET*, **4443**.

Jenniskens P., Lyytinen E., Johannink C., Odeh M., Moskovitz N., and Abbott T. M. C. (2020b). "2019 outburst of 15-Bootids (IAU#923, FBO) and search strategy to find the potentially hazardous comet". *Planetary and Space Science*, **181**.

Jenniskens P., Lyytinen E., Nissinen M., and Jenniskens P. (2006a). "Geminid and Ursid meteors 2006". *CBET*, **773**.

Jenniskens P., Lyytinen E., Nissinen M., Yrjölä I., and Vaubaillon J. (2007b). "Strong Ursid shower predicted for 2007 December 22". *WGN, Journal of the International Meteor Organization*, **35:6**, 125–133.

Jenniskens P., Lyytinen E., Nissinen M., Yrjölä I., and Vaubaillon J. (2007c). "Ursid meteors 2007". *CBET*, **1159**.

Jenniskens P., Lyytinen E., and Sugimoto H. (2017b). "Ursids meteors 2016". *CBET*, **4363**.

Jenniskens P., Lyytinen E., Vaubaillon J., and Maslov M. (2008b). "Perseid meteors 2008". *CBET*, **1464**.

Jenniskens P., Lyytinen E., and Watson P. S. (2013). "Predicted possible outburst of Gamma Delphinid meteors". *CBET*, **3553**.

Jenniskens P., Lyytinen E., and Williams G. V. (2017c). "Potential new meteor shower from comet C/2015 D4 (Borisov)". *CBET*, **4403**.

Jenniskens P., Moilanen J., Lyytinen E., Yrjölä I., and Brower J. (2005). "The 2005 October 5 outburst of October Camelopardalids". *WGN, Journal of the International Meteor Organization*, **33:5**, 125–128.

Jenniskens P., S. N., Ueda M., McBeath A., Vandeputte M., Lyytinen E., Yrjölä I., Moilanen J., and Brower J. (2006b). "Ursid meteors 2006". *CBET*, **788**.

Jenniskens P., Sato I., Lyytinen E., and Vaubaillon J. (2007d). "Perseid meteors 2007". *CBET*, **1019**.

Jenniskens P., Yrjölä I., and Lyytinen E. (2007e). "Orionid meteors 2007". *CBET*, **1107**.

Jenniskens P., Yrjölä I., and Lyytinen E. (2007f). "Orionid meteors 2007 [this text replaces that on Cbet 1107]". *CBET*, **1108**.

Kohout T., Gritsevich M., Lyytinen E., Moilainen J., Trigo-Rodríguez J. M., Kruglikov N., Ishchenko A., Yakovlev G., Grokhovsky V., Haloda J., Halodova P., Meier M. M. M., Laubenstein M., Dimitrev

V., and Lupovka V. (2015). "Annama H5 Meteorite Fall: Orbit, Trajectory, Recovery, Pe-trology, Noble Gases, and Cosmogenic Radionuclides". In *78th Annual Meeting of the Meteoritical Society*, volume 78. page 5209. no. 1856.

Kohout T., Haloda J., Halodová P., Meier M. M. M., Maden C., Busemann H., Laubenstein M., Caffee M. W., Welten K. C., Hopp J., Trieloff M., Mahajan R. R., Naik S., Trigo-Rodriguez J. M., Moyano-Cambero C. E., Oshtrakh M. I., Maksimova A. A., Chukin A. V., Semionkin V. A., Karabanalov M. S., Felner I., Petrova E. V., Brusnitsyna E. V., Grokhovsky V. I., Yakovlev G. A., Gritsevich M., Lyytinen E., Moilanen J., Kruglikov N. A., and Ishchenko A. V. (2017). "Annama H chondrite–Mineralogy, physical properties, cosmic ray exposure, and parent body history". *Meteoritics and Planetary Science*, **52:8**, 1525–1541.

Larionov M. Y., Kruglikov N. A., Pastukhovich A. Y., Gritsevich M. I., Lyytinen E., Muravyev L. A., and Grokhovsky V. I. (2018). "Analysis of the Bright Fireball over the Ural Region of Russia on March 6, 2018". In *81st Annual Meeting of the Meteoritical Society*, volume 81. page 6302. no. 2067.

Lyytinen E. (1972). "Eräiden riemannin pintojen luokkien säilyminen kvasikonformikuvauksessa".

Lyytinen E. (1995). "Using the Kreutz comets in the search for Planet X". *Meta Research Bulletin*, **4**, 56–62.

Lyytinen E. (1999). "Leonid predictions for the years 1999–2007 with the satellite model of comets". *Meta Research Bulletin*, **8**, 33–40.

Lyytinen E. (2015). "On the Thermal Stability of the LENR Tube". `https://e-catworld.com/2015/08/02/on-the-thermal-stability-of-the-lenr-tube-esko-lyytinen/` .

Lyytinen E. (2016a). "Fireball over Finland on 11 May 2016 at 21:03 UT". *eMeteorNews*, **1:2**, 64.

Lyytinen E. (2016b). "October Camelopardalis outburst model comparisons in the years 2005, 2016, 2017". *eMeteorNews*, **1:4**, 135–136.

Lyytinen E. and Gritsevich M. (2013). "A flexible fireball entry track calculation program". In Gyssens M. and Roggemans P., editors, *Proceedings of the International Meteor Conference, 31st IMC, La Palma, Canary Islands, Spain, 2012*. pages 155–167.

Lyytinen E. and Gritsevich M. (2014). "Specification of atmospheric density profiles for the fireball observations in Finland". *Finnish Geodetic Institute, Space Geodesy, Academia*, page 325.

Lyytinen E. and Gritsevich M. (2016). "Calibration of occasionally taken images using principles of perspective". In Roggemans A. and Roggemans P., editors, *International Meteor Conference Egmond, the Netherlands, 2-5 June 2016*. page 159.

Lyytinen E. and Gritsevich M. (2016). "Implications of the atmospheric density profile in the processing of fireball observations". *Planetary and Space Science*, **120**, 35–42.

Lyytinen E. and Jenniskens P. (2003). "Meteor outbursts from long-period comet dust trails". *Icarus*, **162:2**, 443–452.

Lyytinen E. and Jenniskens P. (2020). "Likely alpha Monocerotids (AMO#246) outburst on the morning of November 22, 2019". *eMeteorNews*, **5:1**, 11–12.

Lyytinen E., Lehto H. J., Nissinen M., Jenniskens P., and Suomela J. (2013a). "Comet 17P/Holmes dust trail". *CBET*, **3633:1**.

Lyytinen E. and Nissinen M. (2009). "Predictions for the 2009 Leonids from a technically dense model". *WGN, Journal of the International Meteor Organization*, **37:4**, 122–124.

Lyytinen E., Nissinen M., and Lehto H. J. (2013b). "Comet 17P/Holmes: originally widely spreading dust particles from the 2007 explosion converge into an observable dust trail near the common nodes of the meteoroids' orbits". *WGN, Journal of the International Meteor Organization*, **41:3**, 77–83.

Lyytinen E., Nissinen M., Lehto H. J., and Suomela J. (2014). "Dust trail of comet 17P/Holmes". *CBET*, **3969**.

Lyytinen E., Nissinen M., and Oksanen A. (2015). "Dust trail of comet 17P/Holmes". *ATel*, **7062**.

Lyytinen E., Nissinen M., and Van Flandern T. (2001). "Improved 2001 Leonid storm predictions from a refined model". *WGN, Journal of the International Meteor Organization*, **29:4**, 110–118.

Lyytinen E. and van Flandern T. (2004). "Perseid one-revolution outburst in 2004". *WGN, Journal of the International Meteor Organization*, **32**, 51–53.

Lyytinen E., van Flandern T., Jenniskens P., Vaubaillon J., Sato I., and Maslov M. (2007). "Leonid meteors 2007". *CBET*, **1115**.

Lyytinen E. J. and Van Flandern T. (2000). "Predicting the strength of Leonid outbursts". *Earth Moon and Planets*, **82**, 149–166.

Madiedo J. M., Trigo-Rodríguez J. M., and Lyytinen E. (2011a). "Data analysis software for video meteor observing networks". In *EPSC-DPS Joint Meeting 2011*, volume 2011. page 67.

Madiedo J. M., Trigo-Rodriguez J. M., and Lyytinen E. (2011b). "Data Reduction and Control Software for Meteor Observing Stations Based on CCD Video

Systems". In Cooke W. J., Moser D. E., Hardin B. F., and Janches D., editors, *Meteoroids: The Smallest Solar System Bodies*. page 330.

Madiedo J. M., Trigo-Rodríguez J. M., Lyytinen E., Dergham J., Pujols P., Ortiz J., and Cabrera J. (2013). "On the activity of the $\gamma$-Ursae Minorids meteoroid stream in 2010 and 2011". *Monthly Notices of the Royal Astronomical Society*, **431:2**, 1678–1685.

Madiedo J. M., Trigo-Rodriguez J. M., Lyytinen E., and Pujols P. (2011c). "On the activity of the gamma-Ursae Minorids meteoroid stream on 2010 and 2011". In *EPSC-DPS Joint Meeting 2011*, volume 2011. page 65.

Maksimova A. A., Petrova E. V., Chukin A. V., Karabanalov M. S., Felner I., Gritsevich M., and Oshtrakh M. I. (2020). "Characterization of the matrix and fusion crust of the recent meteorite fall Ozerki L6". *Meteoritics and Planetary Science*, **55:1**, 231–244.

McBeath A., Lyytinen E., Langbroek M., and Matson R. D. (2014). "Exceptionally persistent fireball over the british isles 2012 september 21, 21h55m-21h58m ut". *WGN, Journal of the International Meteor Organization*, **42:3**, 106–115.

Meier M. M. M., Gritsevich M., Welten K. C., Lyytinen E., Plant A. A., Maden C., and Busemann H. (2020). "Orbit, Meteoroid Size and Cosmic History of the Osceola (L6) Meteorite". In *14th European Planetary Science Congress*. pages EPSC2020–730.

Moilanen J., Gritsevich M., and Lyytinen E. (2021). "Determination of strewn fields for meteorite falls". *Monthly Notices of the Royal Astronomical Society*, **503:3**, 3337–3350. `https://doi.org/10.1093/mnras/stab586`.

Moreno-Ibáñez M., Gritsevich M., Lyytinen E., Silber E. A., Silber R. E., and Trigo-Rodríguez J. M. (2017). "Revised Masses for the Canadian Meteor Network Fireballs". In *80th Annual Meeting of the Meteoritical Society*, volume 80. page 6218.

Moreno-Ibáñez M., Gritsevich M., Trigo-Rodríguez J. M., and Lyytinen E. (2016). "Current progress in the understanding of the physics of large bodies recorded by photographic and digital fireball networks". In Roggemans A. and Roggemans P., editors, *International Meteor Conference Egmond, the Netherlands, 2-5 June 2016*. page 192.

Moreno-Ibanez M. (2018). *Impact hazard associated with large meteoroids from disrupted asteroids and comets*. PhD thesis, Universitat Autònoma de Barcelona, Departament de Física. ISBN: 9788449084522, 189 p.

Moreno-Ibanez M., Gritsevich M., A. S. E., and Trigo-Rodriguez J. M. (2020). "Physically based alternative to the PE criterion for meteoroids". *Monthly Notices of the Royal Astronomical Society*, **494:1**, 316–324.

Oberst J., Heinlein D., Gritsevich M., Lyytinen E., Flohrer J., Margonis A., Lupovka V., Dmitriev V., Schweidler F., Peltoniemi J., and Grau T. (2014). "The extraordinary grazing fireball over Central Europe on March 31, 2014". In *European Planetary Science Congress*, volume 9. pages EPSC2014–745.

Raja-Halli A., Gritsevich M., Näränen J., Moreno-Ibáñez M., Lyytinen E., Virtanen J., Zubko N., Peltoniemi J., and Poutanen M. (2016). "Meteor detections at the Metsähovi Fundamental Geodetic Research Station (Finland)". In Roggemans A. and Roggemans P., editors, *International Meteor Conference Egmond, the Netherlands, 2-5 June 2016*. page 230.

Rendtel J., Lyytinen E., Molau S., and Barentsen G. (2014). "Peculiar activity of the September epsilon-Perseids on 2013 September 9". *WGN, Journal of the International Meteor Organization*, **42:2**, 40–47.

Rendtel J., Lyytinen E., and Vaubaillon J. (2020). "Enhanced activity of the Aurigids 2019 and predictions for 2021". *WGN, Journal of the International Meteor Organization*, **48:5**, 158–162.

Rodriguez A., Madiedo J. M., Lyytinen E., Ortiz J. L., Castro-Tirado A. J., Trigo-Rodríguez J. M., and Cabrera J. (2013). "A Potential Meteorite-Dropping Fireball Recorded over Spain in 2011". In *44th Lunar and Planetary Science Conference*. page 1101. no. 1719.

Sansom E. K., Gritsevich M., Devillepoix H. A. R., Jansen-Sturgeon T., Shober P., Bland P. A., Towner M. C., Cupák M., Howie R. M., and Hartig B. A. D. (2019). "Determining fireball fates using the $\alpha$-$\beta$ criterion". *The Astrophysical Journal*, **885**, 115.

Trigo-Rodríguez J. M., Betlem H., and Lyytinen E. (2005). "Leonid meteoroid orbits perturbed by collisions with interplanetary dust". *The Astrophysical Journal*, **621:2**, 1146–1152.

Trigo-Rodríguez J. M., Bottke W. F., Campo Bagatin A., Tanga P., Llorca J., Jones D. C., Williams I. P., Madiedo J. M., and Lyytinen E. (2008). "Is Asteroid 2002NY40 a Rubble Pile Gravitationally Disrupted?". In *39th Lunar and Planetary Science Conference*. page 1692. no. 1391.

Trigo-Rodríguez J. M., Dergham J., Gritsevich M., Lyytinen E., Silber E. A., and Williams I. P. (2021). "A numerical approach to study ablation of large bolides: Application to Chelyabinsk". *Advances in Astronomy*, **2021**. Article ID 8852772, 13 pages. `https://doi.org/10.1155/2021/8852772`.

Trigo-Rodríguez J. M., Gritsevich M., and Palme H., editors (2017). *Assessment and Mitigation of Asteroid Impact Hazards*. Springer International Publishing.

Trigo-Rodríguez J. M., Llorca J., Lyytinen E., Luis Ortiz J., Sánchez Caso A., Pineda C., and Torrell S. (2004). "2002 Leonid storm fluxes and related orbital elements". *Icarus*, **171:1**, 219–228.

Trigo-Rodríguez J. M., Lyytinen E., Daniel C. J., Madiedo J. M., Castro-Tirado A. J., Williams I., Llorca J., Vítek S., Jelínek M., Troughton M., and Gálvez F. (2007). "Asteroid 2002NY40 as a source of meteorite-dropping bolides". *Monthly Notices of the Royal Astronomical Society*, **382:4**, 1933–1939.

Trigo-Rodríguez J. M., Lyytinen E., Gritsevich M., Moreno-Ibáñez M., Bottke W. F., Williams I., Lupovka V., Dmitriev V., Kohout T., and Grokhovsky V. (2015). "Orbit and dynamic origin of the recently recovered Annama's H5 chondrite". *Monthly Notices of the Royal Astronomical Society*, **449:2**, 2119–2127.

Trigo-Rodríguez J. M., Vaubaillon J., Lyytinen E., and Nissinen M. (2006). "Multiple station meteor observations: an international program for studying minor showers exploring imo potentiality". *WGN, Journal of the International Meteor Organization*, **34:2**, 40–44.

Trigo-Rodriguez J. M., Vaubaillon J., Ortiz J. L., Castro-Tirado A., Llorca J., Lyytinen E., Jelínek M., de Ugarte Postigo A., Sanz P. S., Aceituno Castro F. J., Francisco J., Sánchez C. A., Bernal G. A., Erades J. P., and Ocaña F. (2005). "Orbital Elements of 2004 Perseid Meteoroids Perturbed by Jupiter". *Earth Moon and Planets*, **97:3-4**, 269–278.

Vaubaillon J., Atreya P., Watanabe J., Sato M., Maslov M., Moser D., Cooke B., Lyytinen E., Nissinen M., Asher D., and Jenniskens P. (2009a). "Leonid meteors 2009". *CBET*, **2019:2**.

Vaubaillon J., Lyytinen E., Nissinen M., and Asher D. J. (2003). "The 2003 Leonid shower from different approaches". *WGN, Journal of the International Meteor Organization*, **31**, 131–134.

Vaubaillon J., Lyytinen E., Nissinen M., and Asher D. J. (2004). "The unexpected 2004 Leonid meteor shower". *WGN, Journal of the International Meteor Organization*, **32:5**, 125–128.

Vaubaillon J., Maslov M., Moser D., Cooke B., Lyytinen E., Nissinen M., and Asher D. (2009b). "Leonid meteors 2009". *CBET*, **2019:3**.

Vaubaillon J., Sato M., Moser D., Cooke W. J., Maslov M., and Lyytinen E. (2011). "Draconid meteors 2011". *CBET*, **2819**.

Visuri J., Lyytinen E., Sievinen J., and Gritsevich M. (2020). "Correcting the Atmospheric Refraction of Fireball Observations at Low Elevation Angles and Significance of the Correction". In *14th European Planetary Science Congress*. pages EPSC2020–526.

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# Ongoing Meteor Work

## SNMv3: A Meteor Data Set for Meteor Shower Analysis

*SonotaCo*[1], *T. Masuzawa, T. Sekiguchi, T. Miyoshi*[2], *Y. Fujiwara, K. Maeda, S. Uehara*

A new version of SonotaCo Network Meteor data set (SNMv3) that contains 353 231 orbits from a 14-year period (2007–2020) was created. It was re-computed from 2 609 106 single station video meteor observation of Sonotaco Network in Japan. Using observation error propagation with error reducing process, the radiant direction error was precisely evaluated for each orbit, and 50% of orbits had an error below 1.0°. By long term constant observation from the same region, distortions related to the age of the moon and weather conditions were reduced. Although there remain the geographical limitations, it has the consistency and precision that are required for meteor shower analysis. As a sample, a subset that contains 128 228 of higher-accuracy orbits was made and used for a new meteor shower clustering project J14. It showed more compact concentrations of meteor shower radiant directions than ever. All observations have been made by volunteer observers organised via a social network system on the Internet. It has reached one of its goals. This data set is planned to be published on the IAU MDC Meteor Database, and will be usable for all researchers in the world.

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### 1 Introduction

SonotaCo Network simultaneous video meteor observation over Japan began on 2007 January 1. It has continued without interruption through to 2021. As the result of the first 2 years, the standard data for 34 meteor showers, including 12 new showers were determined and published (SonotaCo, 2009). At the same time, the observed meteor orbit data from every year has been published on the Internet as SonotaCo Network Meteor data set (SNM) for 14 years (SonotaCo, 2021). It was the first archive of exhaustive meteor orbits that were observed by continuous uniformed multi station video observation. SNM became the largest meteor orbit data set in 2016 (Jenniskens et al., 2016), and has been used in more than 50 meteor investigations around the world.

In recent years, high-resolution equipment has started to be used. SonotaCo developed observation error computation method on stacked observations (SonotaCo, 2016), and error reducing method for more than 2 simultaneous observations (SonotaCo, 2017). In 2021, a new project named J14 whose aim is the creation of high-precision meteor shower catalog has begun. In this, the re-computation of all stacked observation results from 2007–2020, using those two methods, has been carried out and the new version of SonotaCo Network Meteor data set (SNMv3) has been completed and contains 14 years of results with reliability information.

This paper describes the results of new methods on the large data set, and the features of SNMv3.

### 2 Observation hardware

Table 1 shows typical observation system used in SonotaCo Network. In 2007, all cameras were National Television System Committee (NTSC) format video cameras. High definition (HD: 1920 × 1080) system was developed in 2010, 4K system (3840 × 2160) 30p was developed in 2014, Cinema 4K (4096 × 2160) 60p system was developed in 2020. HD or higher resolution cameras are gradually increasing. Despite accounting for less than 15% of all cameras at the end of 2020, by the selection of simultaneous observation, it is contributing for the improvement of the accuracy.

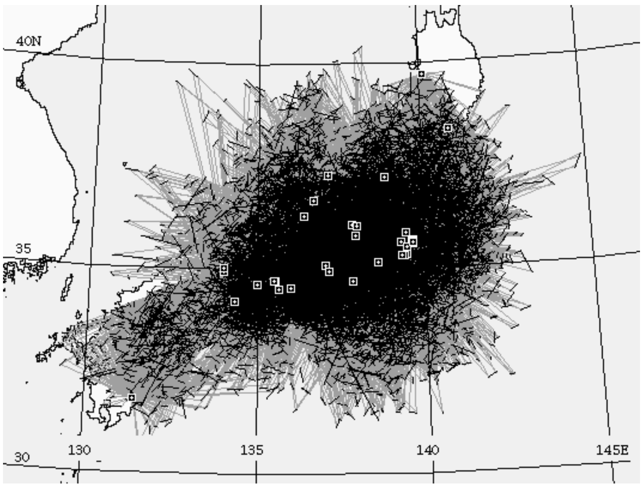


*Figure 1* – Observing stations and meteors ground tracks 2020.

Most of the observers use multiple cameras to cover wider area with higher accuracy. The total number of camera identification codes registered during the 14 years was 429. Almost one quarter of them operated continuously throughout the 14 years.

### 3 Stations and observers

Figure 1 shows the location of observing stations in 2020. The area under observation ranges between 32°–39° N, 130°–145° E. The difference in the area across the years has been small. The number of stations has been 20 to 30 throughout this period.

All observations have been made by volunteer observers organised on a social network system on the Internet. Table 2 shows the regular observers and their

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*Table 1* – Typical observation system hardware.

| type | camera | gain/ISO | lens variation | video format | resolution | frame rate exposure time | typical accuracy (0.3 pixel) | required CPU |
|---|---|---|---|---|---|---|---|---|
| SD (mono) | Watec 902 H2 Ultimate | 32 db | 2.6 mm F1.0 – 12 mm F0.8 | NTSC (analog) | 720 × 480 | 59.94i 17 ms | 0.02 degree (8 mm lens) | 1 thread 2.0 GHz |
| HD (mono) | Imaging Source MDK33GX290e | 36 – 42 db | 2.6 mm F1.0 – 6.0 mm F1.4 | Y800 (GigE) | 1920 × 1080 | 30.0p – 54.0p 33 – 19 ms | 0.1 degree (6 mm lens) | 2 core 4 thr. 3.6 GHz |
| HD (color) | Panasonic DMC-GH3 | ISO 12800 | 25 mm F0.95 | UYVY (HDMI) | 1920 × 1080 | 59.94i – 59.94p 17 ms | 0.007 degree (25 mm lens) | 2 core 4 thr. 3.6 GHz |
| 4K30p (color) | Sony ILCE7s | ISO 51200 | 20 mm F2.8 – 85 mm F2.8 | UYVY (HDMI) | 3840 × 2160 | 29.97p 33 ms | 0.005 degree (20 mm lens) | 4 core 8 thr. 3.6 GHz |
| C4K60p (color) | Panasonic DC-BGH1 | ISO 51200 | 16 mm F1.4 – 25 mm F0.95 | UYVY (HDMI2) | 4096 × 2160 | 59.94p 17 ms | 0.004 degree (16 mm lens) | 8 core 16 thr. 3.6 GHz |

*Table 2* – Observers (*1) and number of meteor observations in 14 years.

| Observer | Location ID (*2) | Ns (*3) | Nm (*4) |
|---|---|---|---|
| Toshihiro Masuzawa | Nagano1 | 361 312 | 163 507 |
| SonotaCo | Tokyo1 Tokyo8 Sizuoka3 | 226 744 | 111 698 |
| Takashi Sekiguchi | Saitama1 | 379 036 | 105 109 |
| Hiroyuki Inoue | Kanagawa1 TokyoB | 185 792 | 64 519 |
| Masayoshi Ueda | Osaka3 | 201 596 | 56 156 |
| Hiroshi Yamakawa | Ishikawa2 | 145 420 | 43 466 |
| Terunori. Miyoshi (*5) | Kagawa1 | 101 138 | 35 001 |
| Toshio Kamimura | Niigata2 | 132 651 | 34 690 |
| Yasunori Fujiwara | Osaka4 Nara3 TokyoA | 132 578 | 33 852 |
| Ada | Chiba2 | 72 683 | 32 866 |
| Koji Maeda (*6) | Miyazaki1 Miyazaki3 Miyazaki4 Miyazaki5 Fukuoka1 | 331 570 | 29 562 |
| Kazuhiko Yoneguchi | Ishikawa5 | 59 845 | 26 451 |
| Naoya Saito | Tokyo6 | 46 191 | 25 009 |
| Hideaki Muroishi | Ishikawa1 | 47 915 | 23 010 |
| Yasuo Shiba | Hyogo3 | 32 121 | 20 912 |
| Satoshi Uehara | Osaka1 | 105 838 | 20 078 |
| Junichi Yokomichi | Okayama1 Okayama4 | 64 898 | 19 065 |
| Junichi Nakai | Tokyo5 Saitama4 | 35 461 | 14 976 |
| Sadao Okamoto | Aichi3 | 24 783 | 15 424 |
| Chikara Shimoda | Nagano4 | 23 861 | 12 541 |
| Hiroshi Kawakami | Nagano5 | 13 248 | 9 511 |
| Tetsuya Nakamura | Toyama1 | 13 931 | 5 611 |

(*1) Regular observers who have observed more than 5000 simultaneous meteor observations in 14 years.
(*2) Location ID is the prefecture name of the station in Japan and the serial number in it.
(*3) Ns: Number of all single station observations.
(*4) Nm: Number of observations that have simultaneous multi station observations and orbit computed.
(*5) Sanbonmatsu High School
(*6) The Nippon Meteor Society

observation count who have observed more than 5000 simultaneous meteors in 14 years.

## 4 Basic statistics of the set

The total number of single station observations during the 14 years was 2 609 106 and the number of simultaneously observed meteors was 353 231.

Figure 2 shows annual observation count. 20k to 30k meteors have been regularly observed during the 14 years. This reduces the distortions due to changes in planetary positions, the age of the moon and weather conditions.

Figure 3 shows the number of sporadic meteors in each 1° solar longitude span. It shows the seasonal change in observable night hours and the scatter due to weather-related factors. Each 1° solar longitude was averaged over 14 years and this reduced the scatter to nearly 30%. The dip caused by rainy season in Japan called “Tsuyu” was predicted, but no other seasonal climate effects or annual changes in sporadic meteors were apparent in the data.

Figure 4 shows the distribution of absolute magnitude of all observed meteors. Since the differences in sensor sensitivity between the cameras was small, the

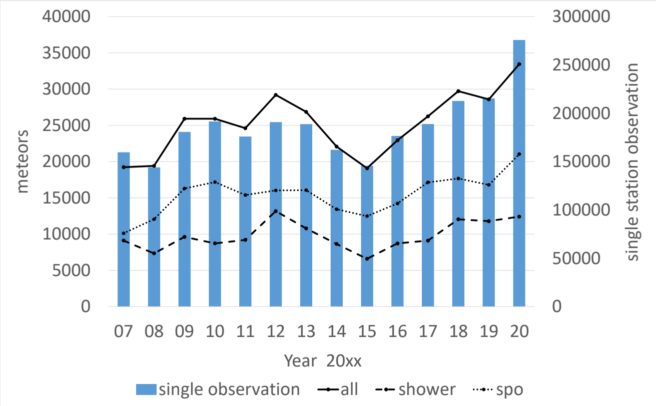


*Figure 2* – Annual observation count. Sporadic meteors are classified by J14 meteor shower catalog (SonotaCo et al., 2021) under the condition of radiant direction coefficient on standard deviation 4.0, and velocity coefficient 5%, solar longitude allowance ±5.0 degree.

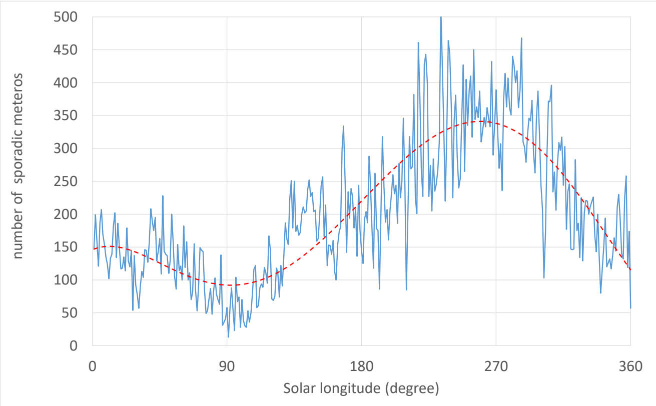


*Figure 3* – Number of sporadic meteors in one solar longitude span on high-accuracy Er1Ev5 set. Dashed line shows the 5th order fitted curve.

limiting magnitude was determined by the size of field of view (FOV) and the aperture of the lens, and not by the sensor resolution.

## 5 Accuracy issues on data processing

The major purpose of the re-computation on SNMv3 is to get reliable accuracy values that can be used in the selection of orbits that shows more compact concentrations of meteor showers.

The error information processing of SNMv3 is based on the observation error propagation (SonotaCo, 2016). On the error propagation, the overall reliability of the accuracy is dependent on the reliability of the observation error as the input of the propagation.

On the processing pipeline of SonotaCo Network, the fixed star images on video frames are intensified by real time digital processing of the capturing software and stored as a bitmap file linked to each video file. It improved the limiting magnitude of reference stars by almost 2 magnitude and contributed the improvement of the accuracy on variety of weather conditions or non-rigid camera mount. The consequence of this was that the required CPU speed for the capturing stage became very high, as can be seen in Table 1, and we could not use compressed video format used in IP cameras or most of security cameras.

The second factor on the accuracy was the use of pole direction of the plane that involves the meteor trajectory and the station (SonotaCo, 2007). It is obtained by least square method on all the observed directions and is used for triangulation. On this process the linearity error comparing with great circle on the celestial sphere is computed and minimized.

These two error values enabled the uniform handling of variety of camera, lens, or resolution. As for the orbit accuracy criterion for meteor shower clustering, through preliminary experiment, we decided to use two values of Er and Ev. Er is the standard deviation of center angle of the radiant direction on equatorial coordinate (SonotaCo, 2016). Ev is the percentage of standard deviation of geocentric velocity. The limitation on of those values showed reasonable effect as follows.

Figure 5 shows the distribution of Er. 50% of the orbits are within the error of 1.5°. Though 10% of orbits have error larger than 3.5°.

Figure 6 shows the distribution of Ev. 50% of orbits have the error of less than 1.5%, 10% of orbits have error larger than 8%.

On this re-computation, the exhaustive error computation of all possible combinations among the simultaneous observations (SonotaCo, 2017) was done. Of the 353 231 meteors, 115 401 were observed by more than 2 stations simultaneously. By the selection of the combination of simultaneous observations, the error values for 886 611 meteors were improved and the

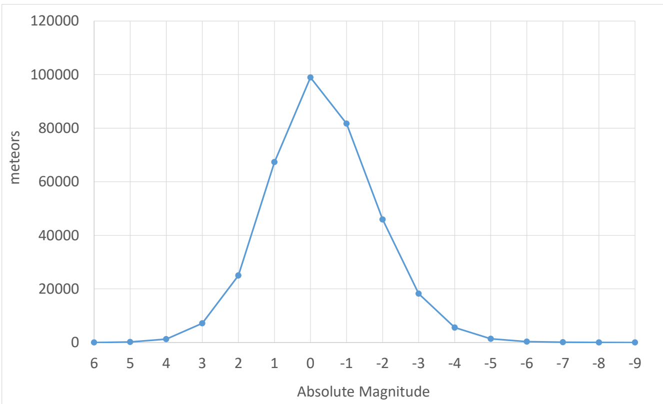


*Figure 4* – Absolute magnitude of observed meteors.

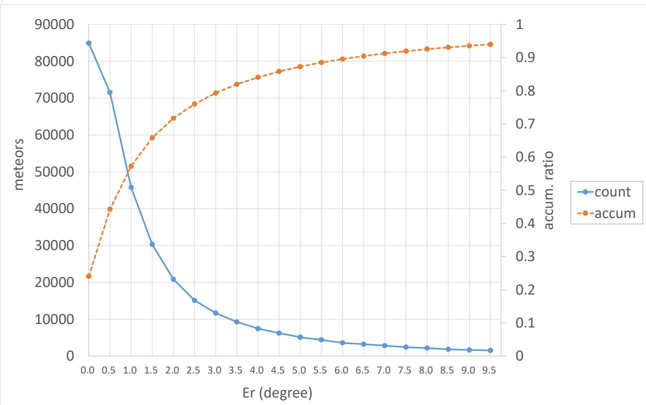


*Figure 5* – Radiant direction error (Er) distribution.

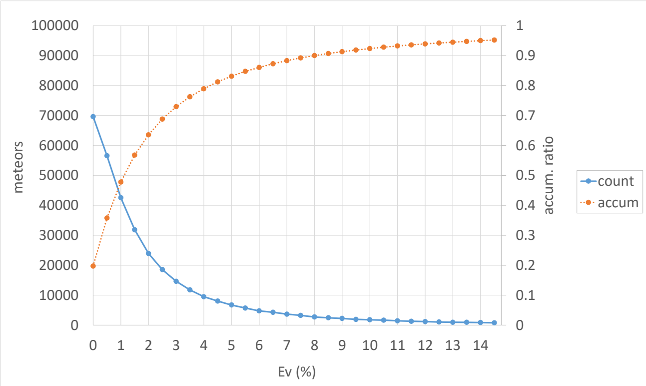


*Figure 6* – Geocentric velocity error (Ev, %).

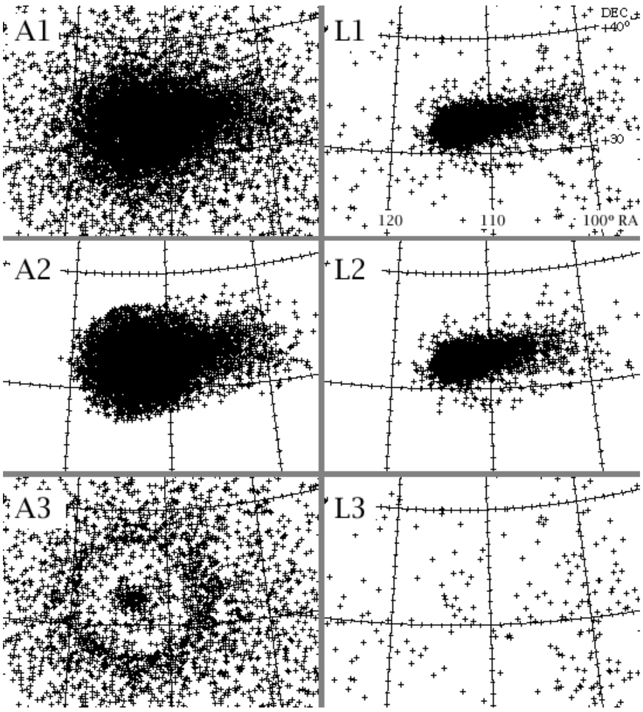


*Figure 7* – Accuracy limitation effect on shower meteors. Radiant plots in range of solar longitude 246–264° around Geminids shower. A1: all accuracy all meteors; A2: all accuracy shower meteors; A3: all accuracy sporadic meteors; L1 limited accuracy all meteors; L2: limited accuracy shower meteors; L3: limited accuracy sporadic meteors. Limited accuracy condition: $Er < 1.0°$, $Ev < 5.0\%$, Er: standard deviation of center angle of the radiant direction on equatorial coordinate, Ev: percentage of standard deviation of geocentric velocity.

average Er changed from 1.69° to 0.86°. Used number of simultaneous observations is decreased from 4.23 to 2.48. Although the exhaustive computation on all possible combination requires factorial order of computation, this result showed the benefit of more than two simultaneous observations.

## 6 Accuracy and shower concentration

Generally, the adequacy of a meteor shower clustering is reflected in the distribution of 'sporadic' meteors that left over from the shower meteor assignments. When the clustering condition of a shower is too severe, partial enhancements are left behind in the sporadic meteor distribution like ghost of the shower, and if the condition is too loose, a 'hole' is created in on the sporadic distribution. On a low accuracy set, it is very difficult to set a proper condition.

Figure 7 shows the accuracy limitation effect on a same condition of shower meteor clustering. On the all accuracy set, the concentration is vague and there is clearly a ghost of shower meteors on the sporadic meteor distribution. The outer vague circle on the sporadic distribution of all accuracy is caused by radiant direction error and the center concentration is caused by velocity error. On the contrary, error managed Er1Ev5 subset, the diameter of the shower meteor concentration is reduced to almost half of original, and the flat distribution of sporadic meteors is obtained.

Figure 8 shows the Er limitation effect on the period of solar longitude 208°–218°. On the lower threshold, it shows the more compact distribution of ORI, NTA, STA shower orbits.

Figure 9 shows radiant of all-accuracy 353 231 orbits. Figure 10 shows a sample of high-accuracy subset Er1Ev5 that is used for new shower clustering project J14. It contains 128 228 orbits that have original radiant direction error Er-org (Er before combination selection) $\leq 1.0°$ and geocentric velocity error $Ev < 5.0\%$. Figure 11 shows Er1Ev5 on the apex centered ecliptic coordinate. On both figures Er1Ev5 shows clear and sharper concentration of shower meteors. There are multiple unknown concentrations, which will be identified by future research.

## 7 Conclusion

On the meteor shower analysis, the accuracy of the orbit is prime requirement for the orbit data, but the number of the un-biased instances must also be sufficient for fair statistical significance. These requirements can only be met via long-term error-managed regular observation. Through the 14 years of observer's efforts, SNMv3 has possibly become a basic data set for this. The improvement in the accuracy looks like the revealing of noisy cloud of uncertainty. SonotaCo Network, a social network system on the internet, a gathering of scientific volunteers, has reached one of its goals. This data set is planned to be published on the IAU MDC Meteor Database (Neslusan et al., 2020), and will be usable for all researchers in the world. The deeper nature of SNMv3 will be studied on the succeeding projects.

## Acknowledgements

There were almost one hundred observers who upload their observations, but not being listed as the regular observer. A list of all observers is attached to each yearly data set. We appeal sincere respect for their contribution. Also, we would like to note that the use of our past SNM data by many researchers in the world has encouraged us and gave us the motivation for the continuation. At the last, we would like to thank T. Jopek and L. Neslušan who have opened a way to publish our data on IAU MDC meteor data base.

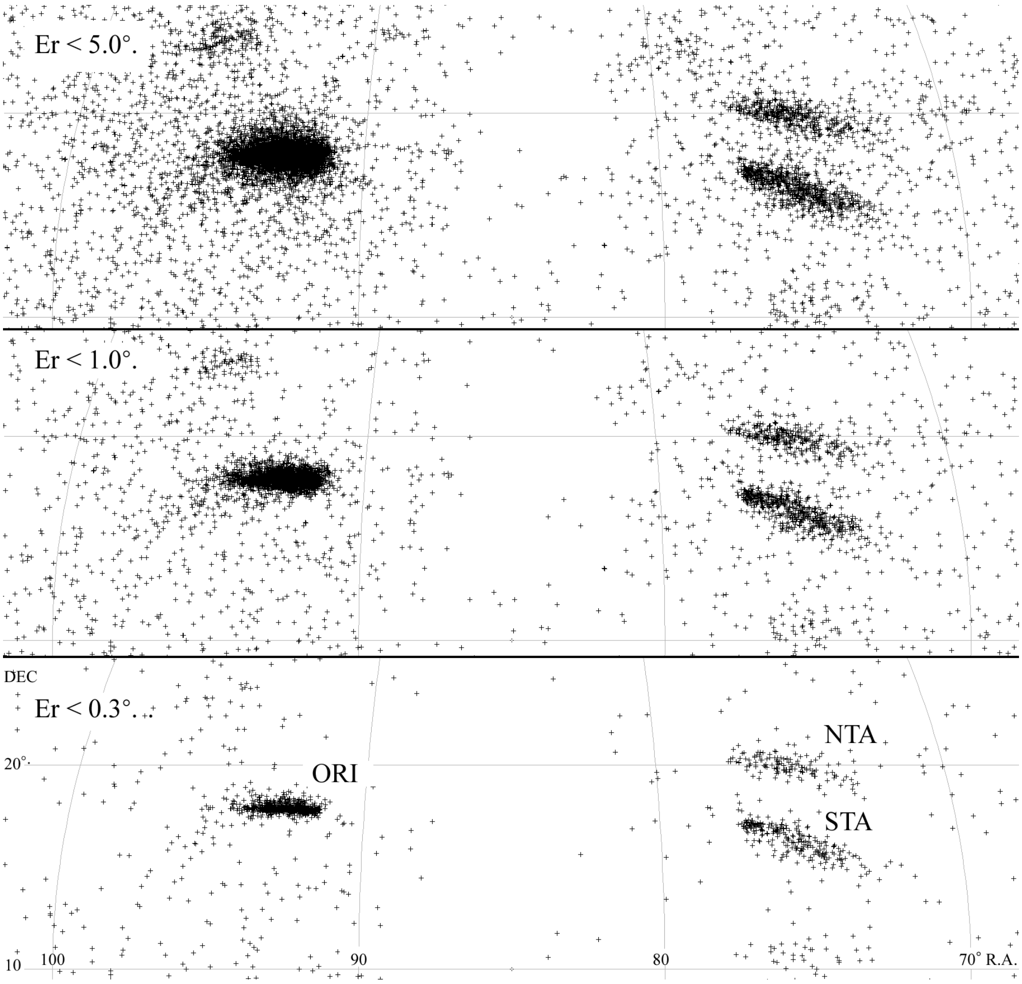


*Figure 8* – Shower concentration on different Er limitation. Radiant plots in rage of solar longitude 208–218°. ORI, NTA, STA concentration.

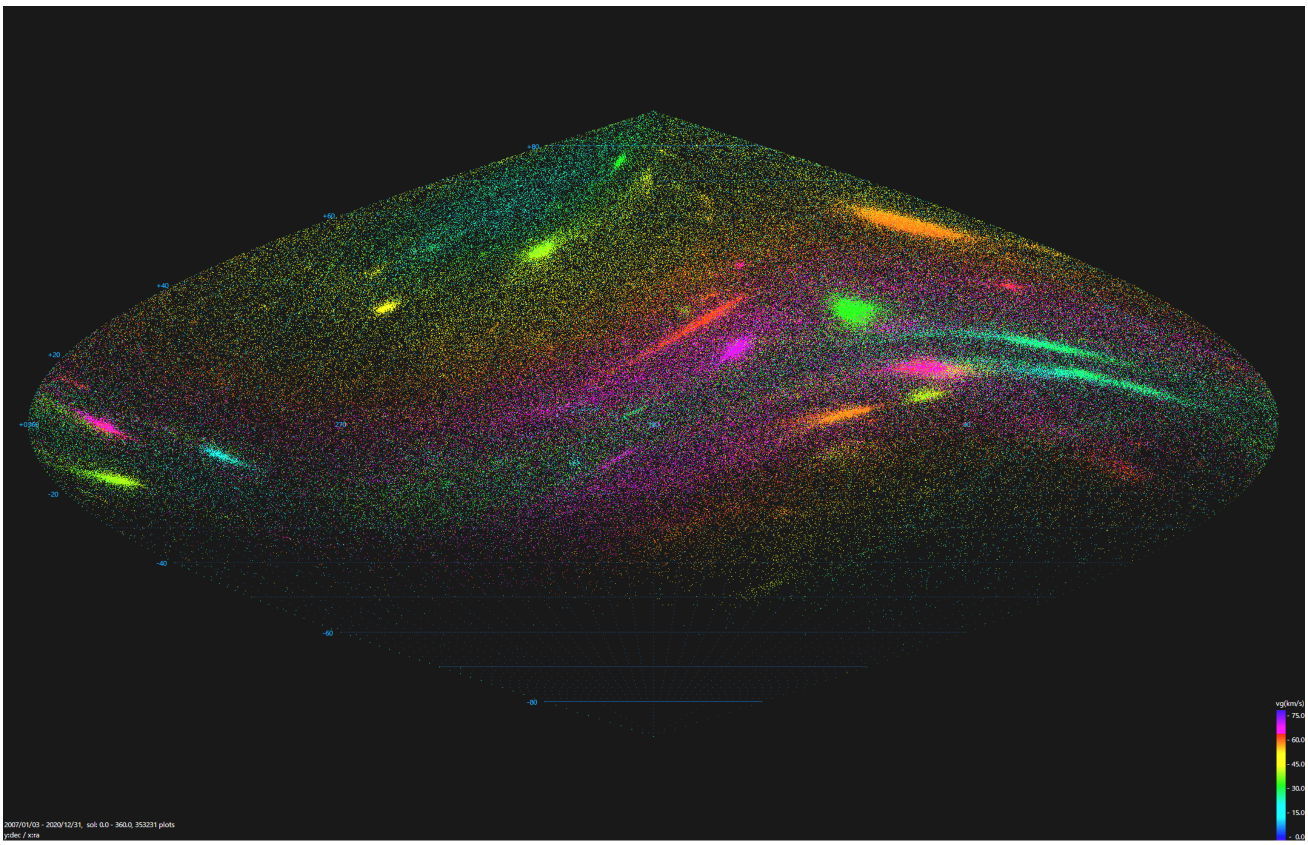

*Figure 9* – SNMv3 all accuracy 353 231 radiant equatorial coordinate plot.

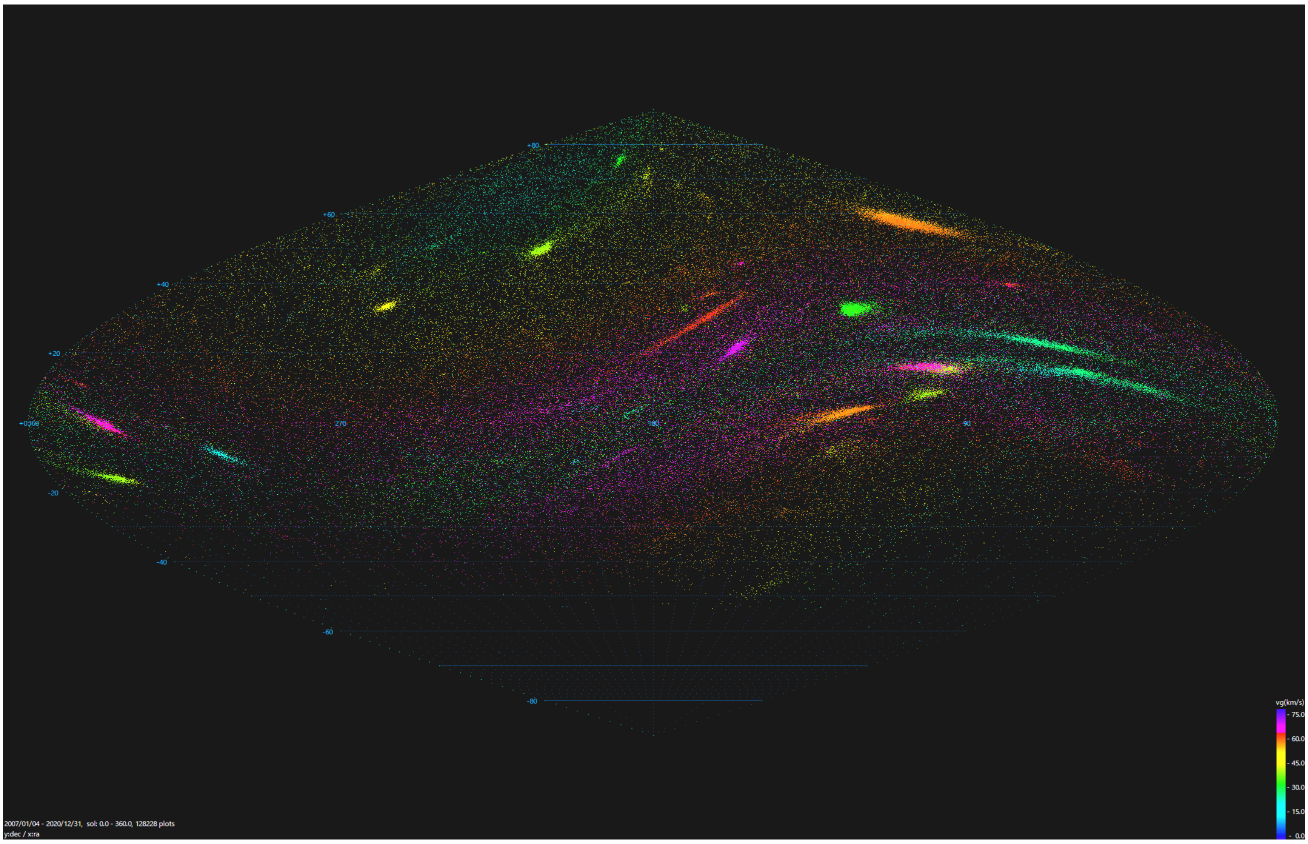


*Figure 10* – SNMv3 Er1 Ev5 128 228 radiant equatorial coordinate plot.

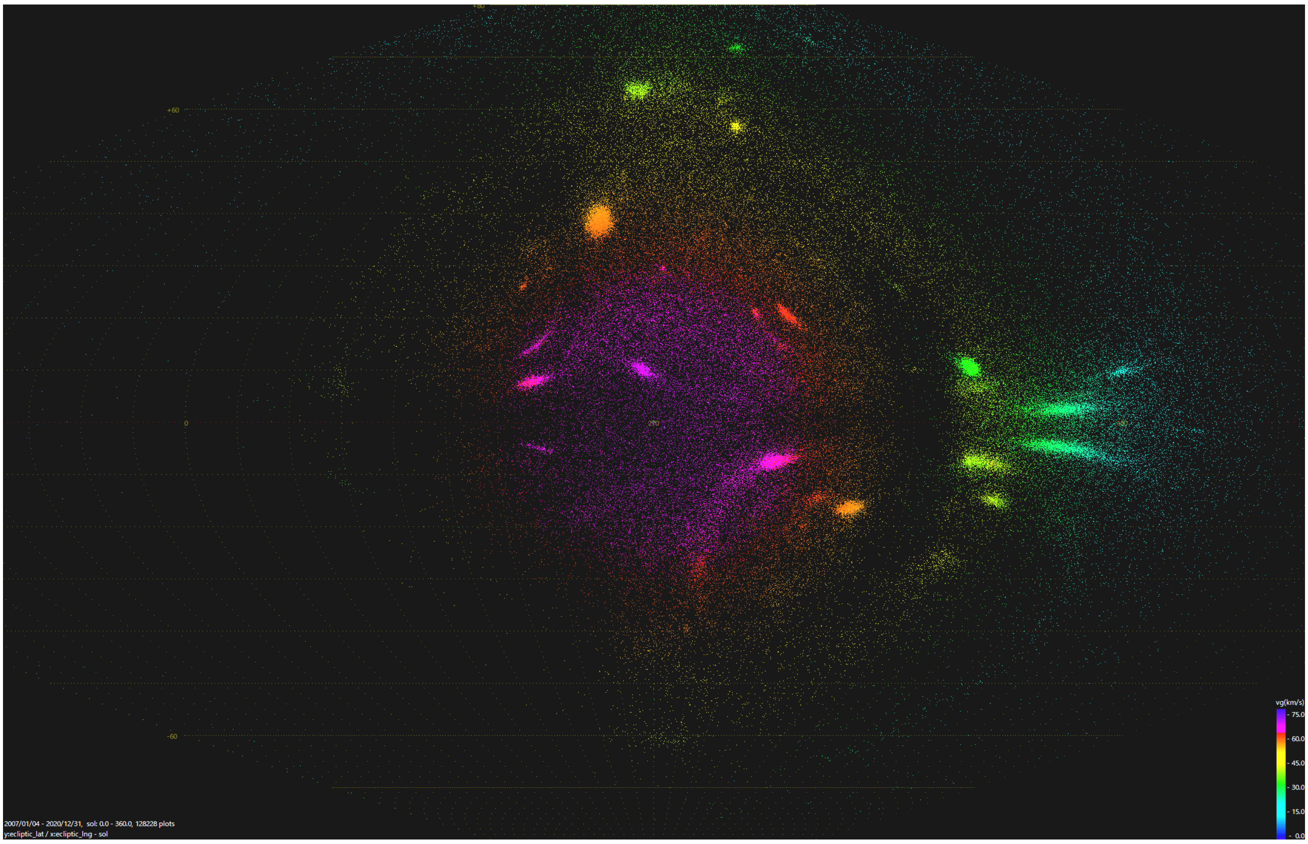


*Figure 11* – SNMv3 Er1 Ev5 128 228 apex center ecliptic coordinate plot.

## References

Jenniskens P., Nénon Q., Gural P. S., Albers J., Haberman B., Johnson B., Holman D., Morales R., Grigsby B. J., Samuels D., and Johannink C. (2016). "CAMS confirmation of previously reported meteor showers". *Icarus*, **266**, 355–370.

Neslusan L., Porubcan V., Svoren J., and Jakubik M. (2020). "On the new design of the IAU MDC portal". *WGN, Journal of the International Meteor Organization*, **48:6**, 168–169.

SonotaCo (2007). "UFOOrbitV2 Users Manual". `http://sonotaco.com/soft/UO2/UO21Manual_JP.pdf` .

SonotaCo (2009). "A meteor shower catalog based on video observations in 2007–2008". *WGN, Journal of the International Meteor Organization*, **37:2**, 55–62.

SonotaCo (2009-2021). "SonotaCo Network Simultaneously Observed Meteor Data Sets (SNM20xx)". `https://sonotaco.jp/doc/SNM/index.html` .

SonotaCo (2016). "Observation error propagation on video meteor orbit determination". *WGN, Journal of the International Meteor Organization*, **44:2**, 42–45.

SonotaCo (2017). "Exhaustive error computation on 3 or more simultaneous meteor observations". *WGN, Journal of the International Meteor Organization*, **45:5**, 95–97.

SonotaCo, Uehara S., Sekiguchi T., Fujiwara Y., Maeda K., and Ueda M. (2021). "J14: A Meteor Shower and Cluster Catalog". *WGN, Journal of the International Meteor Organization*. (to be submitted to WGN).

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# Spectrum of a Geminid fireball

*C. Zhang*[1,2]*, C. J. Wu*[1]*, Q. Z. Ye*[3]*, G. W. Li*[1]*, K. Zhou*[4]

We present a fireball spectrum recorded by a 50 mm $f/1.8$ lens with an objective prism during Geminids meteor shower in 2020.

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## 1 Introduction

The Geminids meteor shower originates from near-Earth asteroid (3200) Phaethon, an asteroidal object that exhibits mass loss activity near its perihelion. Spectroscopic observation of the Geminid meteors provides clues to the composition of Phaethon and spaceweathering effects on the meteoroid body. Earlier studies have revealed a sodium-poor composition of the Geminids meteors (e.g. Borovička, 2001; Kasuga et al., 2005; Borovička, 2010; Neslušan, 2015). Here we report our spectroscopic observation of a bright Geminid fireball during the Geminids activity in 2020.

As a pathfinder of the Luoshan project which plan to operate a network of wide-angle meteor spectrograph over China, we used a Canon EOS 6D DSLR with 50 mm $f/1.8$ lens equipped with an objective prism as described Cheng & Cheng (2011). The prism has a 35° wedge angle. Its surface is coated by a $MgF_2$ layer to reduce reflection. We used an ISO of 3200 and an exposure time of 10 seconds. Frames were saved in a lossy JPEG format in order to reduce the readout time and improve the observation efficiency.

We recorded six Geminid meteors during the available observation time of four hours. But only one spectrum is of good quality, and reported in this paper. The fireball was recorded on 2020 December 13, at $19^{\mathrm{h}}05^{\mathrm{m}}$ (UT). The fireball track started with faint O I at 557.7 nm followed by the Na D-lines and Mg lines. The entire meteor track extended over 15°.

To extract the spectrum for analysis, we firstly rotated the original image to make the dispersion direction be parallel to the X-axis of the image and then trimmed to the section that contains the spectrum. We then convert RGB values to brightness of image using the expression derived by Stokes et al. (1996): $L = 0.2126 \times R + 0.7152 \times G + 0.0722 \times B$, where $L$ is the raw pixel value and $R$, $G$ and $B$ are the values of three primary colors read from the image, respectively. Finally, we derive the instrument brightness at the seven spots marked in Figure 1 by subtracting the sky background at the same rows of the image. The spectrum is then wavelength-calibrated using a third-order function fitted to the positions of the strongest emission lines (e.g. Borovicka, 1994; Ward, 2015) identified from the spectrum. The final extracted spectrum is given in Figure 2, and the Na/Mg ratio variation at different height are given in Table 1.

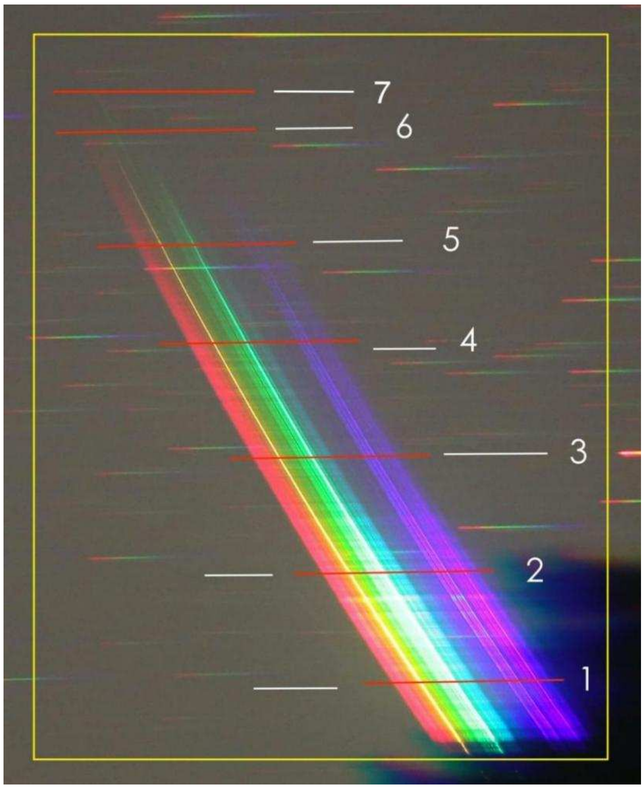


*Figure 1* – The fireball spectrum with seven spots.

*Table 1* – The Na/Mg ratio variation at different height.

| Position | Na/Mg ratio |
|---|---|
| 01 | 0.92 |
| 02 | 0.92 |
| 03 | 0.86 |
| 04 | 0.84 |
| 05 | 1.16 |
| 06 | / * |
| 07 | / * |

* the Mg line is strongly affected by Fe lines nearby.

The fireball spectrum recorded during the Geminids meteor shower in 2020 shows an unexpected result in the ratio of the emission lines of Na/Mg. This may be an individual case. It is possible that the fireball was not a Geminids meteor. We believe it to be a Geminid for the faint trail in the high atmosphere, and the position it corresponds with respect to others. However, if there are more Geminids fireball spectra data, this problem may be solved.

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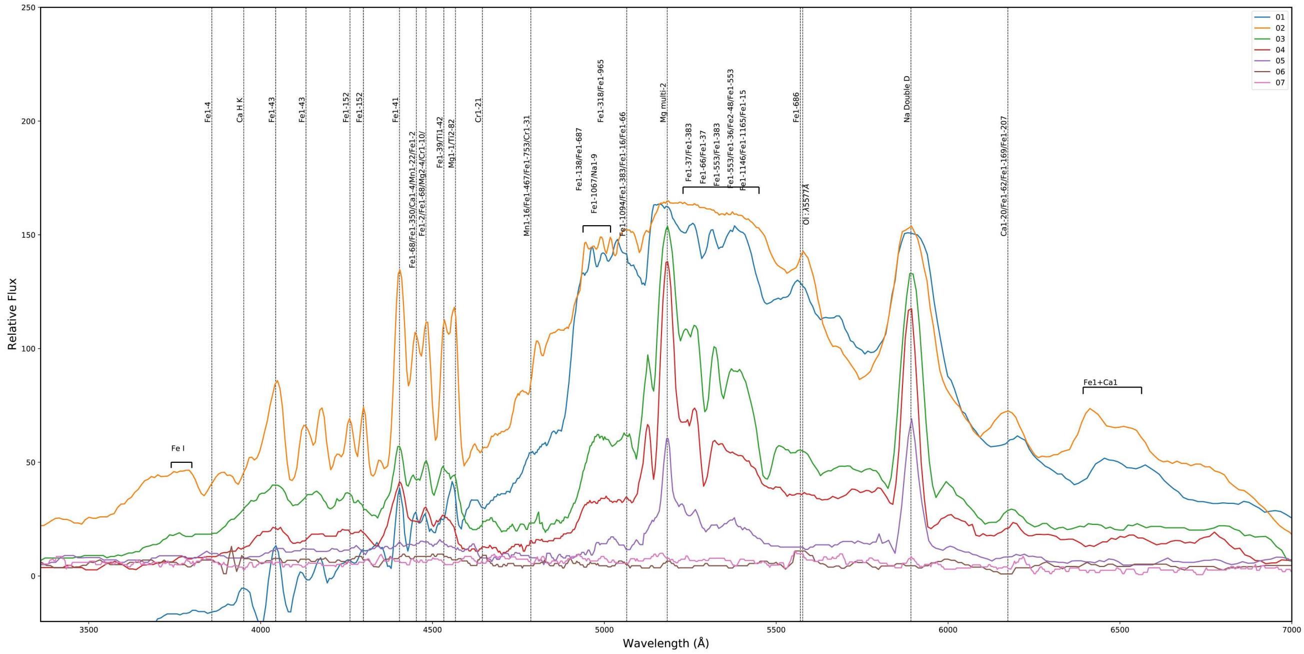


*Figure 2* – The 1D spectrum of fireball with identified emission lines.


## Acknowledgements

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## References


Anderson M., Motta R., Chandrasekar S., and Stokes M. (1996). "A standard default color space for the internet – sRGB". In Buckley R., editor, *Color and Imaging Conference, 4th Color and Imaging Conference Final Program and Proceedings*. Society for Imaging Science and Technology, pages 238–245(8). (also published at `https://www.w3.org/Graphics/Color/sRGB.html`).

Borovicka J. (1994). "Line identifications in a fireball spectrum". *Astronomy and Astrophysics Supplement Series*, **103**, 83–96.

Borovička J. (2001). "Video spectra of Leonids and other meteors". In Warmbein B., editor, *Meteoroids 2001 Conference*, volume 495 of *ESA Special Publication*. pages 203–208.

Borovička J. (2010). "Spectroscopic Analysis of Geminid Meteors". In *Proceedings of the International Meteor Conference, 26th IMC, Bareges, France, 2007*. pages 42–51.

Cheng S. and Cheng S. (2011). "Meteor spectral observation with DSLR, normal lens and prism". *WGN, Journal of the International Meteor Organization*, **39:2**, 39–46.

Kasuga T., Watanabe J., and Ebizuka N. (2005). "A 2004 Geminid meteor spectrum in the visible-ultraviolet region. Extreme Na depletion?". *Astronomy and Astrophysics*, **438:2**, L17–L20.

Neslušan L. (2015). "A summary of the research of Geminid meteoroid stream". *Contributions of the Astronomical Observatory Skalnate Pleso*, **45:1**, 60–82.

Ward B. (2015). "Meteor spectroscopy during the 2015 Quadrantids". *WGN, Journal of the International Meteor Organization*, **43:4**, 102–105.


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# Geminid fireball spectrum

Spectrum of a Geminid fireball recorded on 2020 December 13, at at $19^{\mathrm{h}}05^{\mathrm{m}}$ UT. The spectrum is described in paper on page 71. Image courtesy: Chao Zhang.