METEORITES ORBITS RECONSTRUCTION BY OPTICAL IMAGING (MOROI) NETWORK

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Abstract. An wide range, all-sky camera network is an effective infrastructure for the detection of atmospheric entries of natural (meteoroids) or artificial bodies (space debris). The *Meteorites Orbits Reconstruction by Optical Imaging* (MOROI) is an all-sky network operated by the Astronomical Institute of the Romanian Academy. Here we present the overall architecture of the network that became operational on mid-2017 and the preliminary results on atmospheric trajectory and orbit reconstruction of multi-station events. The 20-station network is expected to be fully operational by the end of 2018.

Key words: meteors – meteorites – asteroids – celestial mechanics – orbits.

1. INTRODUCTION

Today, more than 780 000 asteroids and comets have been discovered and many thousands are discovered every year. Most of these objects orbit in the Main Belt, a region of the Solar System located between the orbits of Mars and Jupiter, but not all of them are so far from the Earth. The current population of Near Earth Objects (NEO) totals more than 18 250 asteroids and few periodic comets. Near-Earth Asteroids (NEA) are a population of asteroids whose Earth-crossing or approaching orbits have perihelion distances $q \leq 1.3$ A.U. Among this population there is a sub-class of Potentially Hazardous Asteroids (PHA) represented by objects with a diameter larger than 140 m that may approach the orbit of Earth within 0.05 A.U. or less (7 500 000 km, or 20 lunar distances). Dynamical calculations show that the typical lifetime of a NEA is much shorter than the age of the Solar System. They are constantly removed from the inner region of the Solar System in a few million years, ending their lives by falling into the Sun, by impacting the terrestrial planets, or by acquiring high eccentricity, ejection orbits (Farinella *et al.*, 1994). The interest

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in studying NEAs is mostly driven by the significant risk they pose to Earth during the threatening close approaches and, more recently, by their relative accessibility for the space missions dedicated to their exploration and in the future, to their exploitation (mining). Given their sizes, from meters to tens of kilometers, NEA display the entire array of geophysical processes that shaped the Main Belt. With 1 909 NEAs classified as PHA on June 2018, the danger of a catastrophic impact in a foreseeable future is non-negligible.

The near-Earth space hosts critical civilian and military infrastructure vulnerable to meteoroids impact. Meteoroids are objects of asteroidal or cometary origin but significantly smaller than asteroids, having diameters between 30 μm and 1 m. Meteoroids are produced by asteroids collisions, cometary activity or disintegration, rotational fision of low strength asteroids (rubble-pile structure) via YORP or during the close planetary approaches of asteroids by tidal mechanism. Most of the objects entering the atmosphere detonate without hitting the ground. Using eight years of space based observations, Brown *et al.* (2002) estimate from the 300 bolides recorded during this period that the Earth is impacted on average every year by an object of 5 kt of energy while 10 Mt, Tunguska-like events, occur on average every 1 000 years.

Given their origins and their production mechanism, the study of meteoroids population impacting the Earth atmosphere is essential for understanding and evaluating the risk of impacts from asteroidal and cometary population.

2. THE MOROI NETWORK

The IAU meteor showers database published by Division F (Planetary Systems and Bioastronomy) currently holds 957 showers including 112 establised ones. Meteor showers are mostly associated with comets and their activity or even disintegration during the inner Solar System passage. There are however meteor showers firmly associated with (active) asteroids like Geminids and Quadrantids linked to (3200) Phaethon and (196256) 2003 EH1 respectively (Dumitru *et al.*, 2017). In addition to meteor showers there exists a population of sporadic meteoroids that is not well understood since they do not share a common origin. A typical meteor (the luminous phenomenon) is produced by the atmospheric passage of meteoroids with diameters within 0.1 and 20 cm. Depending on the initial meteoroid velocity, the heating followed by ablation is initiated at different altitudes eventually leading to a complete disintegration of the object. For larger objects or lower initial velocities, the thermal ablation process does not completely remove the initial mass since it will stop at $\sim$ 3 km/s (Borovička, Spurný, and Brown, 2015). The surviving fragment continues on the trajectory without visible light emission, this last segment being called *the dark flight*. Its duration can reach up to few minutes in contrast to the luminous segment of the trajectory that lasts few seconds. Precise, multi-station observations of the meteor allow the reconstruction of the trajectory and, by providing the initial conditions of the dark flight, may estimate the final landing ellipse for the surviving fragment(s).

An eventual recovery of meteorites has important scientific benefits since laboratory analysis can determine essential parameters like their structure, chemical compositions and radiometric age. This data may be used to infer the composition of the primordial nebula, the distribution of water and organics in the Solar System and to provide important constraints on the geological evolution of the meteorite parent body.

First systems of sky survey dedicated to meteors detections using photographic plates/films were deployed in the 1960s and early 1970s in Czechoslovakia and Germany later forming the European Fireball Network (Ceplecha and Rajchl, 1965; Ceplecha *et al.*, 1973). Outside Europe there were the Prairie Network (McCrosky and Boeschenstein, 1965) and the *Meteorite Observation and Recovery Project* - MORP (Halliday, Blackwell, and Griffin, 1978). Modern sky survey systems use high quantum efficiency, sensitive CCD cameras and automated software for meteors detection. This leads to an increase in the number of accurately determined meteoroids orbits thus allowing the identification or confirmation of new meteor showers, the linking of meteors with their parent bodies and the characterization of meteorites producing fireballs. Some of these systems are: NASA All-sky Fireball Network (Cooke and Moser, 2012), NASA/SETI Cameras for Allsky Meteor Surveillance - CAMS (Jenniskens *et al.*, 2011), Camera for Better Resolution Network - CABERNET (Colas *et al.*, 2011), All-sky Meteor Orbit System AMOS (Tóth *et al.*, 2015), Fireball Recovery and Interplanetary Observation Network - FRIPON (Colas *et al.*, 2014) and Italian network for meteors and atmospheric studies - PRISMA (Gardiol, Cellino, and Di Martino, 2016).

The Meteorites Orbits Reconstruction by Optical Imaging - MOROI network is operated by the Astronomical Institute of the Romanian Academy. The project begun in 2016 following the installation of the most eastern FRIPON camera in Bucharest. After an initial array of three cameras had been deployed on Transylvania for testing and validation on early 2017, the network was extended to 10 cameras as of June 2018 (Fig. 1). Ten more cameras will be installed to achieve the final configuration of the MOROI network.

At the hardware level, MOROI uses the same all-sky cameras as FRIPON and PRISMA network: 1.2 Mp Gigabit CCD (ICX 445) and a 1.25 mm F/2 fisheye lens. In fast rate mode (30 fps) the cameras provide the necessary temporal resolution for an accurate reconstruction of the meteor trajectory. Each station runs Ubuntu Linux 16.04 LTS. An 1 TB HDD is used for the bulk of data (stacks, cap-

Fig. 1 – The MOROI network map as of June 2018.

tures, events). The software for image acquisition and meteor detection software is *freeture* (https://github.com/fripon/freeture). Giving the heterogenous network infrastructure on MOROI sites, all the nodes run *openvpn* and are aggregated into a private network for easier management and IT automation: mass update on nodes, mass deployment of *freeture* configuration files for parameter tunning (regular captures, scheduled captures for bright satellites passes detection etc.), OS configuration and tuning and overall network health monitoring. The daily volume of data generated by a single station is of 7 GB for the 1 minutes stacks and an additional 1 GB for each detection event. Lossy compression of generated *fits* images is an available option if long term storage of data is necessary. Finally, all the relevant data is gathered for inspection and validation on the project website http://observer.astro.ro:8080.

The astrometric calibration procedure starts from *long* exposure images of 5 seconds in which we can reliably detect stars up to magnitude 5 (for dark sites). Star positions extracted using the IRAF *daofind* procedure are matched with their horizontal coordinates (azimuth and altitude) by fitting a simple polynomial radial distortion function for zenith distance. The typical error of match for altitudes greater than 30° is of the order of 0.1°.

The procedure of trajectory reconstruction (Ceplecha, 1987) for multi-station observations uses the meteor positions automatically extracted by the detection software. The image coordinates of the meteor are converted to azimuth and altitude using the parameters obtained in the calibration procedure and further to geocentric equatorial coordinates system to determine the average plane containing the meteor trajectory and each station. The average geocentric trajectory is then found at the intersection of these two (or more) planes. All astrometric calculations are carried out using the NOVAS C library routines (Kaplan *et al.*, 2010).

The multi-station events are automatically identified by coincidence detection

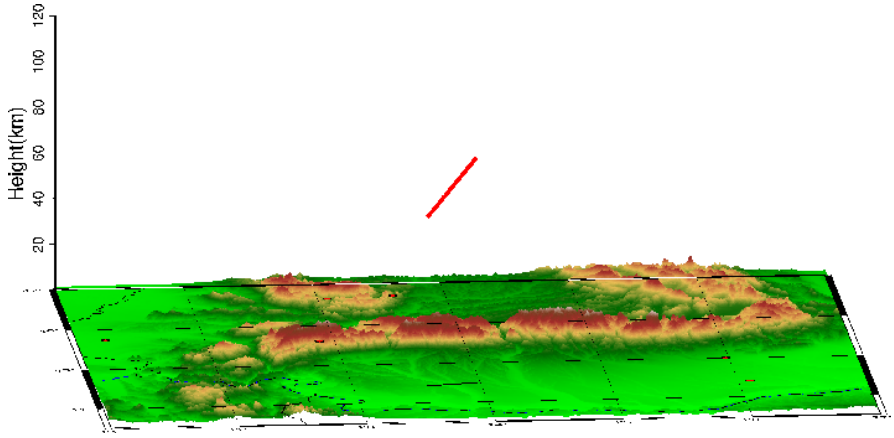

Fig. 2 – The reconstructed trajectory of a Lyrid meteor detected on 2018/04/22 at 22:11:28 UTC. The meteor, detected from Bucharest and Berthelot, was visible from 98 to 73 km altitude. Radiant coordinates and meteor velocity match well the expected values of the Lyrids meteor shower. The image was produced using the Generic Mapping Tools (Paul *et al.*).

with every station running a Network Time Protocol server for time synchronization. The data obtained by the trajectory reconstruction software (the beginning and the end heights, the velocity, the radiant and a graphical representations of the atmospheric trajectory (Fig. 2)) are distributed to the network core e-mail list.

As of June 2018 the MOROI network detected 197 meteors brighter than magnitude 2 with the detection limit set by the 33 ms exposure time. There were also recorded 23 multi-station event detections (20 double, 3 triple).

3. FIRST RESULTS

We provide, as an example of typical results expected to be produced by the network, the atmospheric trajectories and orbits reconstruction of two Lyrids meteors detected on April 2018 (Table 1). The Lyrids are a low ZHR (10) meteor shower active in the period April 16 - 26, with a maximum around April 21 - 22. The stream, associated with the comet C/1861 G1 Thatcher, is known to produce outburst of $>$ 100 ZHR with a period of 12 years (Jenniskens, 1995). The stream has a finer structure with short and long period components from $2.3 < a < 3.9$ to $23.6 < a < 32.0$ (Porubčan and Kornoš, 2008) possibly caused by resonances with giant planets. The two detected Lyrids have similar beginning and end heights and a geocentric velocity of $\sim$ 48 km/s. We can observe that the computed orbital elements are in agreement with those of the parent body thus validating the entire chain of data reduction. Although the errors in the heliocentric velocity are the most important source of uncertainty in semi-major axis determination we note the identification of two different

Table 1

Atmospheric trajectory and orbits reconstruction of two Lyrids meteors. The orbital element of the shower parent body are provided for comparison

	2018/04/22/ 22:11:28	2018/04/21 23:32:12	C/1861 G1 (Thatcher)
H begin (km)	98	94 0	
H end (km)	73	79	
V_g (km/s)	48	47.95	
Ω°	32.47	31.56	31.86
ω°	212.64	210.8	213.45
a A.U.	26.77	5.58	55.68
i°	82.78	81.44	79.77
e	0.965	0.831	0.983

period Lyrids.

In order to further investigate the behaviour of the two components, we generated, for each orbit, 40 clones uniformly distributed in mean anomaly, a structure typical for meteor streams. The clones were integrated for a period of 100 000 year centered on the present in the framework of an accurate Solar System model using a Bulirsch-Stoer numerical integrator (Nedelcu *et al.*, 2014).

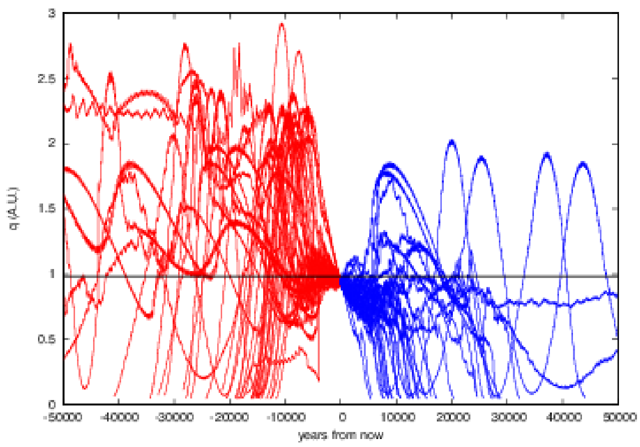

Fig. 3 – Perihelion evolution of the short period component clones for the 100 000 years.

The clones of the short period meteor display a marked chaotic behaviour with less than 10% of clones surviving outside the 100 000 year period (Fig. 3). The most likely scenario of evolution is their removal as the result of their close approaches to Sun. This result can be used to constrain the probable age of the stream. In contrast, most of the clones of the meteor from April 22 remained on the near-Earth space for the entire run (Fig. 4).

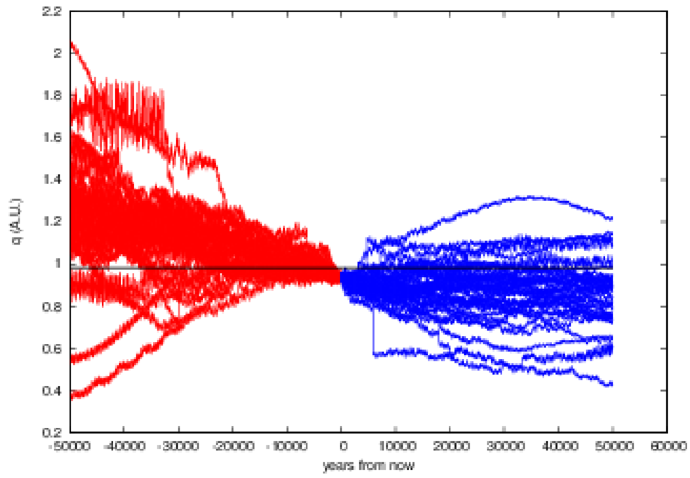

Fig. 4 – Perihelion evolution of the long period component clones for the 100 000 years.

4. CONCLUSIONS

The MOROI network is expected to achieve its upgraded, 20-station configuration, by the end of 2018. As of June 2018 we detected 197 meteors brighter than magnitude 2. During its first year of operation we recorded 23 multi-station events (20 double and 3 triple detections). Automated tools provide, for multi-station events, the estimation of the beginning and the end heights, of the velocity and the radiant of the meteor alongside a graphical representation of its atmospheric trajectory. Preliminary results on two Lyrids meteors were presented as a validation of the data reduction chain.

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