# AMOS - THE SLOVAK WORLDWIDE ALL-SKY METEOR DETECTION SYSTEM

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## ABSTRACT

AMOS, the All-Sky Meteor Orbit System, is a system dedicated to automatic detection and orbit determination of meteors. The system has been developed and operated by the Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava, Slovakia (FMPI CU). At current stage of development, the AMOS system consists of two different parts, the all-sky AMOS-Cam and AMOS-Spec. AMOS-Cam is designed for meteor detection and observation, but adjustable for meteorological, geophysical, aviation or satellite observations.

## 1 OVERVIEW OF AMOS SYSTEM

The AMOS-Cam cameras systematically monitor meteor activity in the Slovak Video Meteor Network (SVMN) at four locations. There are currently six cameras installed outside the Slovakia, two at locations in Canary Islands, two at locations in Chile and two at locations in Hawaii. The network is about to be expanded in central and eastern Slovakia, as well in south Africa and Australia. The operation of cameras is semi-automatic and needs electric power and internet connection. The AMOS-Cam system is also available in a portable configuration, and can be quickly relocated to any desired destination for a given meteor shower campaign or be a part of an airborne mission.

The AMOS-Spec is the automatic and possible remotely controlled video system for the detection of meteor spectra. The AMOS-Spec program has been created with the intention of carrying out systematic spectroscopic observations. At the same time, the meteoroid trajectory and pre-atmospheric orbit are independently measured from data collected by the AMOS-Cam network. This, together with spectral information, allows us to find the link between the meteoroid and its parent body, from both dynamical and physical characteristics. Five AMOS-Spec systems have been deployed so far; one in Slovakia, one at Canary Islands, two in Chile and one at Mauna Kea, Hawaii.

We present the technical characteristics of AMOS-Cam and AMOS-Spec systems. We discuss systems processing routines, output data products and scientific outputs. In addition, the wide field of view and global coverage of the AMOS network allows us to detect space debris atmospheric reentry events. An example of such an event is demonstrated.

## 2 TECHNICAL SPECIFICATIONS AND LOCATIONS

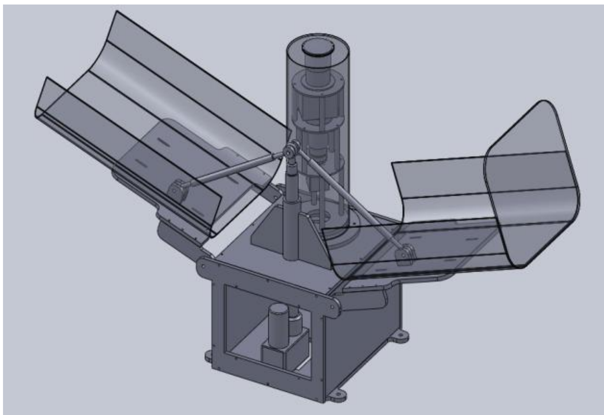

*Figure 1. AMOS-Cam system with open outer housing*

### 2.1 AMOS-Cam

AMOS-Cam (All-sky Meteor Orbit System Camera) is an image-intensified all-sky meteor video system originally developed (Fig. 1) for the Slovak Video Meteor Network in 2007 at the Astronomical and Geophysical Observatory (AGO) Modra, Comenius University [1], [2].

The system AMOS consists of four major components: a fish-eye lens, image intensifier, projection lens and a digital video camera. The resulting field of view of AMOS is 180° × 140° (Fig. 2) with the image resolution of 8.4 arcmin/pixel with video frame rate of 15 fps (DMK23U274). The most recent version of AMOS is using digital cameras with the resolution of 6.75 arcmin/pixel and frame rate of 20 fps (DMK41AU02). Limiting magnitude for stars is about +5 mag for a single frame, the detection efficiency is lower for moving objects approx. +4 mag due to the trailing loss. The operations of cameras are automatic and are remotely controlled through internet. The entire system is protected by outer and inner enclosures and is secured

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by environmental detectors for temperature, humidity, rain and illumination of the sky. AMOS can automatically operate even during full Moon which does not saturate most of the field of view and only raises the level of sky background and lowers the limiting magnitude. AMOS itself needs DC current for its operation with the voltage of 24V [2].

Although the system was primarily designed for meteor observation, it could be used for meteorological, geophysical, aviation or satellite observations as well. The inner part of the system is portable and fully operational by itself, weighting only 6.5 kg and with the height of 50 cm and base width of 25 cm. Portable configuration is suitable for man-assisted operation and ground or on-board operations. The outer enclosure was tested for extreme weather conditions in a wind tunnel up to the wind speed of 52 m.s$^{-1}$ in a closed configuration. The test proved that the system is able to operate and be aerodynamically stable up to 32 m.s$^{-1}$ [3].

Currently, four AMOS-Cams exist as a Slovak Video Meteor Network (SVMN) at locations of AGO Modra, Arborétum Tesárske Mlyňany (ARBO), Kysucké Nové Mesto Observatory (KNM) and Važec is operated by the Comenius University in Bratislava. The direct distance between individual stations ranges from 80 to 150 km and are operated remotely. Additional stations in Central and Eastern Slovakia will increased the area of the network in the near future. The current performance of an individual AMOS camera within SVMN is equal to detection of approximately 10,000 single-station meteors per year and about 50 transient luminous events like sprites or elves and about hundreds of satellite flares, glints. Currently, we operate additional AMOS cameras abroad, specifically on Canary Islands with cooperation with Instituto de Astrofísica de Camarias (IAC), in Chile (SpaceObs and Paniri Caur Observatories) and in Hawaii (IfA Univ. of Hawaii, SMA of CfA). Each location operates a pair of AMOS-Cam systems and one AMOS-Spec for meteor spectroscopy (Fig. 3, 4).

Astrometry from AMOS yields a standard astrometric uncertainty of 0.03–0.05° that translates to the accuracy of several tens or hundreds of meters for a meteor atmospheric trajectory, when the detailed all-sky reduction described in [4] and [5] is performed. Photometric uncertainty (8 bits digital cameras) is in the order of 0.1 magnitude in the range of (+5; -1) magnitudes for non-saturated objects. We are developing algorithm for the reduction of saturated objects such as fireballs with larger uncertainties up to 1 magnitude. Improved trajectory software MT and detection software AMOS are also under development. Currently, we use UFOCapture software for meteor detection.

*Figure 2. AMOS all-sky composite image from San Pedro de Atacama station, SpaceObs, Chile, 2016*

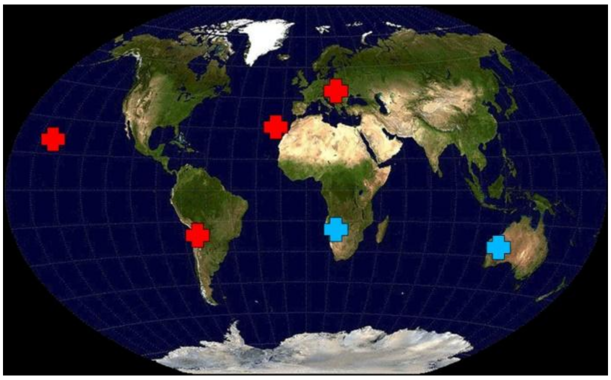

*Figure 3. AMOS global network. Red crosses are locations with operating cameras (10 AMOS-Cam, 5 AMOS-Spec) and blue crosses are planned stations*

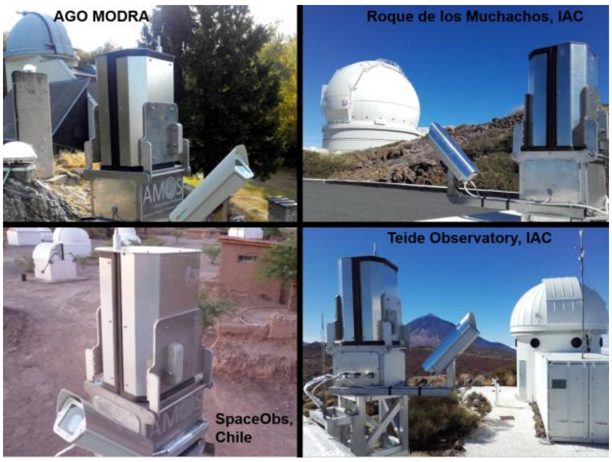


*Figure 4. AMOS global network, examples of AMOS-Cam together with AMOS-Spec installations at AGO Modra, Slovakia (upper left), SpaceObs, Chile (lower left) and Canary Islands installations (on the right)*

*Figure 5. AMOS-Cam operating during night observation with open outer shell on Haleakala Observatory, IfA University of Hawaii*

Our aim is to develop a global network for 24 hours continuous monitoring of the influx of relatively faint meteors and characterization of weak meteor showers along with their parent bodies identifications and composition characterization.

## 2.2 AMOS-Spec

The AMOS-Spec program [6], [7] is aimed to study spectra and physical properties of meteoroids in -1 to -10 magnitude (mm-dm) range. Meteor spectroscopy has been gaining popularity among professional and amateur astronomers in recent years, due to the accessibility of simple video-based systems providing lower-resolution meteor spectra. The precision and high resolution of earlier photographic spectrographs e.g. [8] cannot be achieved, but this is partially compensated by the sensitivity of the video systems. The intention of the AMOS-Spec and AMOS-Spec-HR (High-resolution Spectrograph) spectral program is to provide balance between sufficient spectral resolution, astrometric precision and statistical advantage of the video detection sensitivity (Fig. 6).

It has been shown that lower resolution spectra can be used to study the composition of meteoroids based on the variations of relative intensities of the main meteor emission multiplets of Mg I - 2 (representing the silicate content in meteoroids), Na I -1 (volatiles) and Fe I - 15 (metals and silicates). This is the basis of the spectral classification of primarily smaller meteors introduced by [9]. In addition, multi-station observations can be used to determine the trajectories, orbits and light curves of studied meteoroids, which can be further applied to deduce physical properties, such as the material strength, dynamic pressure or density of meteoroids. Obtaining such set of parameters for a large number of observations provides us with a complex insight of the population of meteoroids in the Solar System. For known meteoroid streams, it also suggests implications for the structure and properties of their parent comets and asteroids.

The AMOS-Spec is a semi-automatic remotely controlled video system for the detection of meteor spectra located at the Astronomical and Geophysical Observatory (AGO) in Modra, Slovakia. The main display components consist of 30 mm f/3.5 fish-eye lens, image intensifier, projection lens and digital camera (DMK 51AU02). This setup yields a 100° circular field of view (FOV) with a resolution of 5 arcmin/pixel and frame rate of 12 fps.

The incoming light is diffracted by a holographic grating with 1000 grooves/mm placed above the lens. The spectral resolution of the system varies due to the geometry of the all-sky lens with a mean value of 1.3 nm/px. The system covers the visual spectrum range of approximately 370–900 nm. The spectral response curve of the AMOS-Spec system was determined by measuring the known spectrum of Jupiter and calibrated lamps. The typical limiting magnitude of the system for meteors is approx. +4 mag, while only meteors brighter than approx. -1 mag can be captured along with its spectrum. More details about the properties and capabilities of the AMOS systems can be found in [10].

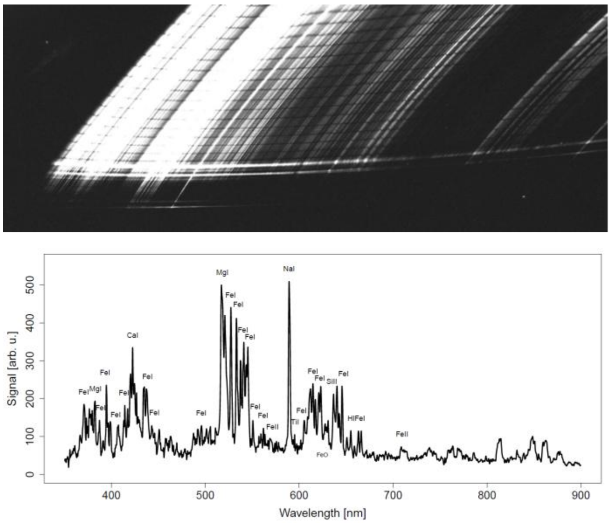


*Figure 6. Spectrum of a bright fireball captured by AMOS-Spec-HR system on La Palma, Canary Islands on March 13, 2017 at 21:56 UTC. Below, the extracted spectral profile displaying numerous spectral lines, with only the brightest emission multiplets noted. The spectral profile is not corrected for spectral sensitivity and was obtained from one non-saturated frame*

Since 2015, the AMOS network has been expanded into global scale by installation of two systems on Canary Islands (Teide Observatory, Tenerife; Roche de los Muchachos Observatory, La Palma) and two in Chile 2016 (Space Obs, San Pedro; Paniri Caur Observatory, Chiu-Chiu). The recent installation (Fig. 5) took place in September 2018 at Haleakala and Mauna Kea Observatory, Hawaii. To provide simultaneous spectral observations, new higher resolution spectrographs were employed to accompany existing AMOS stations in Tenerife and San Pedro, Chiu-Chiu and Mauna Kea.

Display component of these spectrographs is based on a 6 mm f/3.5 lens, high definition digital Point Grey camera providing 60 × 45° FOV with a resolution of 1.76 arcmin/pixel and frame of 15 fps. The applied 1000 grooves/mm holographic diffraction grating results in spectral resolution of 0.5 nm/pixel. The typical limiting magnitude of the system is approx. +3 for meteors and -1.5 for meteor spectra.

## 3 POSSIBLE APPLICATIONS OF AMOS FOR SPACE DEBRIS REENTRY EVENTS

Eventually, AMOS system can monitor other luminous events in the night sky besides meteors. There are several examples of lightning and sprites or other Transient Luminous events (TLE) detections. Another examples are detected airplanes, satellites and space debris. However, we eliminate non-meteors by a filter set to remove slow-moving targets, that would significantly increase the number of total detections. But in principle, the filter can be removed in special cases. Bright satellite flares along with their spectra are often observed. In some cases, we have detected reentry events. As an example, we can mention a case from August 8, 2016 at 00:10:50 UTC over several Europeans states (Fig. 7, 8, 9).

We were able to observe only a part of the luminous trajectory for (6.5 seconds) of the body from two sites, AGO Modra by AMOS instrument and narrower field of view meteor/sprite camera of amateur astronomer Martin Popek from Nýdek, Czech Rep. The movement of the body was primary from West to East. We have determined the atmospheric trajectory, where the observed beginning height was 60.7 km and end height was 58.3 km above the Earth. The luminous curve shows several flares, which suggested the fragmentations or break-ups.

However, we would need more accurate data from our network to reliably confirm the particular reentry object in this case. This event serves as an example of a possible similar reentry event observation in the future, whether it will occur in the location within the reach of AMOS network, or will be predicted and dedicated observation will be planned with a portable version of AMOS cameras.

## 4 CONCLUSIONS

In our work we presented AMOS, the All-Sky Meteor Orbit System, which is a system dedicated to automatic detection and orbit determination of meteors. The system has been developed and is operated by the Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava, Slovakia (FMPI).

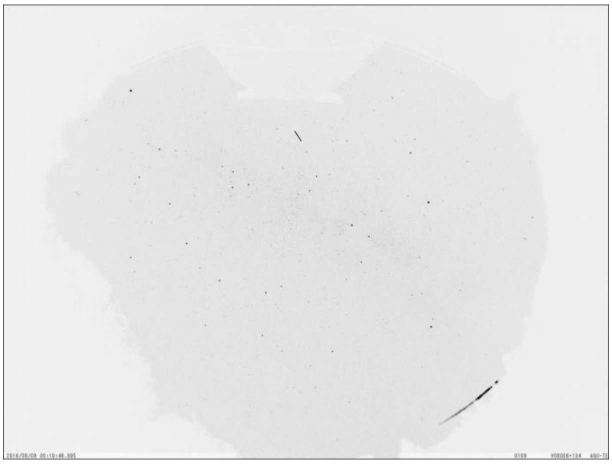

*Figure 7. Luminous path of possible reentry over the lower right horizons on negative composite image from AMOS video record from AGO Modra station on August 8, 2016 at 00:10:50 UTC*

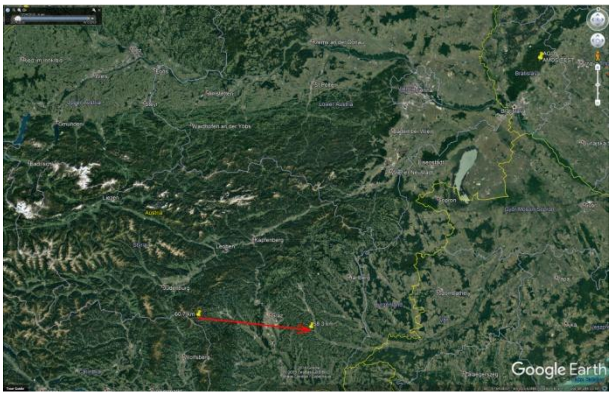


*Figure 8. Projection of luminous path over Austria near Graz of possible reentry event on August 8, 2016*

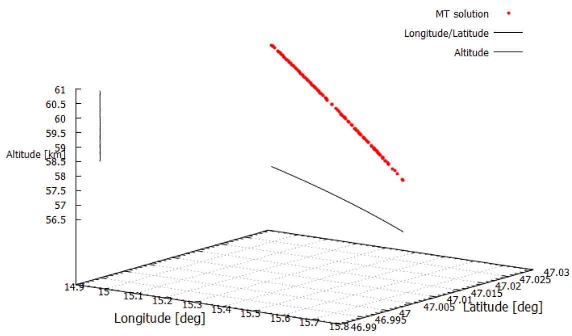


*Figure 9. Calculated atmospheric trajectory of possible reentry event on August 8, 2016 from double-stations observation from AGO Modra and amateur observer Martin Popek, Nýdek, Czech Republic*

FMPI CU operates five AMOS cameras in Slovakia and six cameras abroad, specifically on Canary Islands with cooperation of IAC, in Chile (SpaceObs, Paniri Caur Observatories) and in Hawaii (IfA Univ. of Hawaii, SMA CfA). Each location has a pair of AMOS cameras and one or two AMOS-Spec for meteor spectroscopy.

AMOS network can provide scientific data for detected meteors daily, including visual magnitude, astrometric position, spectra, atmospheric trajectory and heliocentric orbit. All these physical and dynamical characteristics help to better understand the meteoroid population.

Additionally, AMOS system can monitor other luminous events in the night sky besides meteors. There are several examples of lightning and sprites or other Transient Luminous events (TLE) detections. Another examples are detected airplanes, satellites and space debris. In the past, we have detected several satellite's flares, even with their spectra. We can measure astrometric and photometric data for space debris. In some cases, we have detected reentry events.

AMOS network is planned to expand in years 2019/2020 to additional locations such as Australia and Africa, extending this way its celestial coverage. Once achieved, the extension will provide constant monitoring of the meteoroid flux interacting with the Earth's atmosphere. The higher coverage will also increase the number of detections of satellites and reentries.

## 5 ACKNOWLEDGEMENT

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