Applications of AMOS meteor all-sky detection system for space debris research

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ABSTRACT

The All-Sky Meteor Orbit System (AMOS) is an automated system used for the detection and orbit determination of meteors. AMOS has been developed and is operated by the Faculty of Mathematics, Physics and Informatics of the Comenius University in Bratislava, Slovakia (FMPI CU) and the system currently consists of two major parts, the all-sky AMOS-Cam and AMOS-Spec. AMOS-Cam is a global system of cameras which monitor meteor activity around the world, nowadays five stations are located in Slovakia, two in Canary Islands, two in Chile and two in Hawaii. The AMOS-Spec is a video system connected to AMOS-Cam for the systematic spectroscopic observations and detection of meteor spectra. It is currently worldwide distributed with one station in Slovakia, one in Canary Islands, two in Chile and one in Hawaii. Expansion of the observation network is planned in the future in central and eastern Slovakia as well as in South Africa and Australia. Network distribution secures large sky coverage, Northern and Southern hemispheres observed simultaneously, and the trigonometry used by two stations helps to accurately determine the atmospheric trajectory, which then leads to the pre-atmospheric heliocentric orbit and eventually to estimate whether the meteor belonged to a certain meteor shower or to a sporadic background.

In our work we will present the AMOS network and its sub-systems. The output data products will be discussed in detail and the focus will be put on AMOS's application in space debris domain. We will discuss the astrometric and photometric reduction process, as well the procedures used for the spectrum and reflective spectrum analysis. The work will be demonstrated on several real cases captured during AMOS nominal operation.

1 INTRODUCTION

The All-Sky Meteor Orbit System (AMOS) system primary focuses to capture meteors. However, specular glints detections of Low Earth Orbit (LEO) objects, objects orbiting on geocentric orbits with mean elevation below 2,000 km above the Earth surface, are quite common during the AMOS observations. Such data can extend the AMOS system capabilities to space debris research as well. This research mostly focuses on the extraction of the astrometric, photometric and spectroscopic measurements from these observations. Detected debris comes in three categories: 'specular periodical flashes', 'diffuse repetitive flashes' and 'diffuse continuous line-like trails'. First two categories can provide information about the rotational state of the objects. The 'specular periodical flashes' are also ideal for spectrum identification during specular reflections. Raw reflective spectrum and properties of the reflective surface can then be determined thanks to such observations.

Light sensitivity of AMOS-Cam system can be compared to human eye and camera astrometric precision ranging from 0.03 to 0.05 degrees which for meteor can result in tens of meters of uncertainty for the meteor's atmospheric trajectory. For the less bright space debris records the uncertainty will be even greater. Therefore, the system will work for good quality object identification but considering the operating limitation, the astrometric measurements are expected to be a secondary outcome. This is not the case for the re-entry events which can be captured by the AMOS system. Thanks to its geographical distribution and output data types, astrometry and spectra, the AMOS-Cam and AMOS-Spec in the AMOS worldwide network can be used to support re-entry events modelling by monitoring the parent body's fragmentation during the re-entry, calculating the fragments' trajectories in the atmosphere and measuring their spectra by performing the spectral analysis of the fragments, analysis developed by FMPI.

1.1 Space debris

Space debris represents all the man-made objects in geocentric orbit which no longer serve useful purpose like upper stages of launch vehicles, non-functional satellites, debris created during explosions, tiny fragments of paint or mechanical parts released after impacts or due thermal stress. Since late fifties the number of orbital debris has risen by millions and now pose a growing threat for future space research. Commonly, space debris is observed by radar or optical telescopes, special cases of LEO debris, large in diameter and bright when reflecting light from the Sun, can be detected by all-sky cameras.

1.2 LEO population

Low Earth Orbit (LEO) space debris is located ~200 – 2 000 km above Earth's surface. Objects in this altitude are still affected by Earth's atmosphere and are slowly pulled back towards the Earth. Such pieces will eventually after different lifetimes burn in the atmosphere or fall back down to the Earth, depending on objects properties such as size and density. Observing satellites low in altitude, affected by gravitational pull, comes with a difficulty since the effect of atmospheric drag will change the mean motion properties. However, in the night sky LEO type of debris are mostly bright and visible to detect by all-sky cameras which offer a prompt way to observe them.

1.3 Re-entries

AMOS is primary developed to observe phenomena called meteor. Meteor is a luminous event of a meteoroid particle in the atmosphere. When this particle interacts with the atmosphere, it leads to the ablation of the body and air ionization, eventually causing the particle to vaporize. These particles collide with the atmosphere with high relative velocities between 11 up to 71 km/s. Re-entry is a similar event as meteor but is caused by an artificial object, usually accompanied with a break-up event of the parent body. Because of their small re-entry velocities ≤ 10 km/s, only large objects such as satellites, upper stages or space stations, re-entries can be visually observed from the surface. Over the years, several campaigns have been organized to monitor the dynamics of the parent body's break-up, atmospheric trajectory and in some cases their fall location [1]. These events can be sometimes also visually confirmed by sightings [2].

2 AMOS System

All-Sky Meteor Orbit System is an automated and remotely controlled system of cameras used mostly for detection and orbit determination of meteors. The system currently consists of two major parts, the all-sky AMOS-Cam and AMOS-Spec/AMOS-Spec-HR.

Both AMOS-Cam and AMOS-Spec are worldwide distributed, as shown in Fig. 1 (left). Red cross illustrates an area where AMOS-Cams are located, five stations can be found in Slovakia, two operate in Canary Islands, two in Chile, two in Hawaii. Expansion of the observation network is planned in the future in central and eastern Slovakia as well as in south Africa and Australia, denoted by blue crosses. Wide range distribution is important mostly for trigonometry when observing meteors, in order to determine the heliocentric orbits and estimate whether the meteor belonged to a certain meteor shower or to a sporadic background.

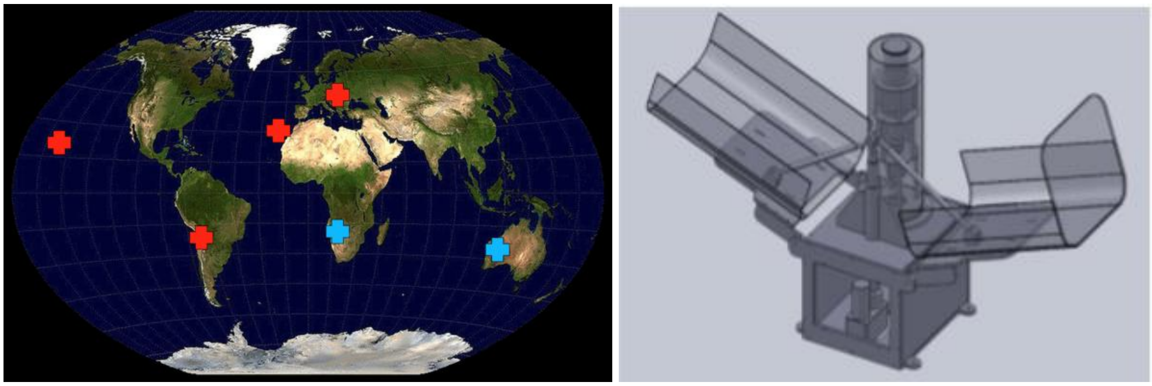

Fig. 1 Left: AMOS meteor network global distribution; right: Model of AMOS-Cam including the protecting cover

2.1 AMOS-Cam

AMOS-Cam is a system of cameras which monitor meteor activity in the all-sky meteor monitoring system. The camera consists of a fish-eye lens, image intensifier, projected lens and digital camera, operating computer with hard-drive, weatherproof enclosure, temperature, humidity and light sensors. The overall design of the AMOS-Cam with its protecting housing is shown in Fig. 1 (right). The AMOS-Cam primary focuses to capture meteors however detection of other objects occurs on regular basis. Therefore, it can be used for other purposes as well, such as meteorological, geophysical or satellite observations.

Data obtained from the cameras can come in form of short videos with digital resolution of 1600x1200 pixels and field of view being 180°x140°. Its light sensitivity can be compared to a human eye and the astrometric precision ranges from 0.03-0.05 degrees which could for a meteor result in tens of meters of trajectory uncertainties. Overall the camera can detect meteors with magnitudes higher than 4th [4].

2.2 AMOS-Spec and AMOS-Spec-HR

The AMOS-Spec is a video system for the systematic spectroscopic observations and detection of meteor spectra. It is aimed to study spectra and physical properties of meteoroids in -1 to -10 magnitude range. Despite that the high resolution of more advanced photographic spectrographs cannot be achieved with a large field of view spectral camera, this system provides a balance between sufficient spectral resolution, astrometric precision and statistical advantage of the video detection sensitivity. 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 [3]. Such capabilities can be applied directly onto space debris spectral observations and re-entry observations. Within the video system two types of spectral cameras are installed within AMOS network, AMOS-Spec and AMOS-Spec-HR. AMOS-Spec is only installed at the Astronomical and Geophysical Observatory in Modra, Slovakia (AGO), while AMOS-Spec HR is installed in Canary Islands, Chile and Hawaii. Example of the AMOS-Spec-HR capturing a meteor spectra in the composite image and its processed calibrated spectra are shown in Fig. 2.

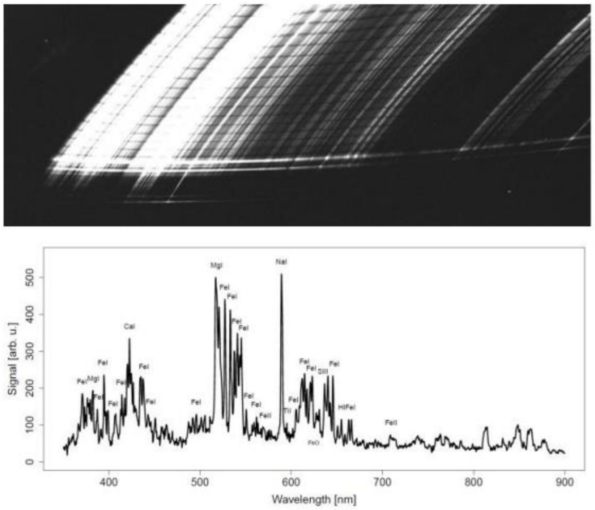

Fig 2. Bright fireball spectrum captured by AMOS-Spec-HR on La Palma, Canary Islands (top) and the extracted spectral profile (bottom) [3]

For space debris research we identified several different products to be obtained from the AMOS system. These are listed in Tab. 1. For space debris spectroscopy the qualities of AMOS-Spec, located at the Astronomical and Geophysical Observatory (AGO) in Modra, Slovakia, had been evaluated so far. The main display of AMOS-Spec components consists 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 arc-min/pixel and frame rate of 12 fps. 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 and -1.0 for meteor spectra. AMOS-Spec-HR has a new higher resolution spectrograph with display component of these spectrographs 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 arc-min/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].

Tab 1. AMOS system products with related methodology which can be obtained for space debris objects

Object	Methodology	System	Product	Comment
LEO object	astrometry	AMOS-Cam	astrometric position	Astrometric positions can be used for the object identification; orbit determination/ improvement of LEO is not applicable due to the low astrometric accuracy of AMOS-Cam (~ 2 arc-min)
LEO object	photometry	AMOS-Cam	light curves; time of specular glint	Photometry can be used to extract the light curves of observed objects; limiting magnitude is up to 5th mag; specular glints can be used to determine the apparent rotation period
LEO object	spectroscopy	AMOS-Spec / AMOS-Spec-HR	reflectance spectra	The final product is a reflectance spectrum which contains the information about the object's surface; the resolution of the spectrum is 1.3 nm/pixel and 0.5 nm/pixel
Re-entry	astrometry	2 x AMOS-Cam	atmospheric trajectory,	By using triangulation the atmospheric trajectory of the re-entering object can be calculated; in case of fall, this product helps to identify the impact area
Re-entry	photometry	AMOS-Cam	light curve	Light curve can help to identify specific moments when and how the break-ups occurred
Re-entry	spectroscopy	AMOS-Spec / AMOS-Spec-HR	spectra	Spectra of the whole event can be monitored; acquired can be spectra as a function of time

3 LEO objects observations

Capturing a bright LEO satellite during both AMOS-Cam and AMOS-Spec observations is quite common. This extends the use of the AMOS system to space debris observation as well. So far, a successful method of satellite identification from the recorded AMOS data had been developed, by evaluating the coordinates, position angle and angular velocity of the recorded satellites. Future extend of the research to debris astrometry, photometry and spectroscopy is desired and hereby evaluated.

3.1 Astrometry, photometry, identification

Astrometric reduction is performed using tool UFOAnalyzer [5]. 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 is performed. For space debris the uncertainties vary depending on the type of the recorded event, with differences for specular flashes and diffuse continuous line-like trails. If the recorded objects are bright and their positions are measured within a span of few seconds, an accurate tracklet can be extracted. These types of records can be used for astrometry purposes; however, these events are rather rare. Majority of records are of bright flashes in short-span videos, these objects can be identified but it is difficult to predict their trajectory based on AMOS-Cam measurement. This could be due to the combination of effects; starting from low signal to noise ratio of the targeted object, up to the uncertainties in the prediction of ephemerides. Overall the discrepancies between the measured and observed positions can be up to one degree. Therefore, the system will work for good quality object identification, however considering the operating limitation, the astrometric measurements are expected to be used for identification rather than cataloguing purposes.

Object identification itself is performed by astrometric measurements. These are compared with the ephemerides calculated with the FMPI's internal tool SatEph [15] which is built based on the SGP4 model [6]. The software uses the Two-Line Elements (TLE) set obtained from the public catalogue [7] to calculate the exact position of the object for given observer and observation epoch. This tool allows user to select appropriate object, e.g. object with required angular velocity, and visualize its position compared to the telescope's pointing. SatEph provides the user with the additional information such as elevation above the horizon, phase angle, observer-object range, etc.

As previously mentioned, most commonly detected objects are bright 'specular periodical flashes' which are ideal for spectrum identification during specular reflections. Raw reflective spectrum and properties of the reflective surface of such objects can then be determined. These types of AMOS-Cam records can be used for photometric measurements. AMOS-Cam photometric uncertainty (8 bits digital cameras) is in the order of 0.1 magnitude in the range of (+5; -1) magnitudes in visual band for non-saturated objects.

3.2 Reflectance spectroscopy

The space debris specular periodical flashes records from AMOS-Spec spectral camera are ideal events to acquire the reflectance spectra. So far, 55 of such events had been recorded and analysed, out of which 23 cases of leading quality were identified and distinguished according to the duration, brightness and completeness of the record and whether single or double first order of the spectra is detected. All these cases, their zero and first orders, are plotted in a composite AMOS-Spec image in Fig. 3.

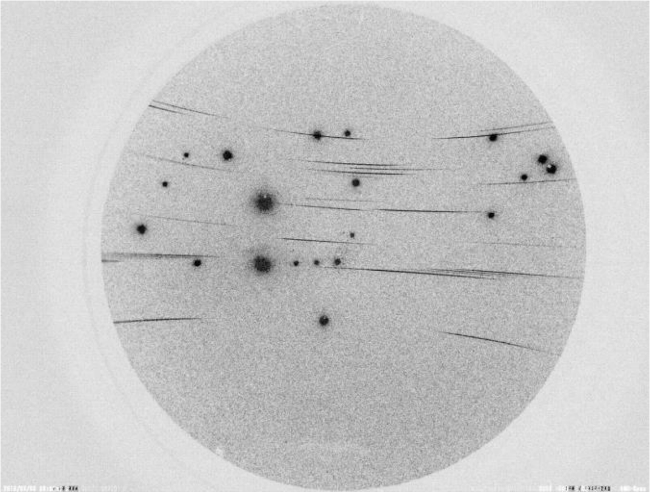

Fig 3. Composite image containing 23 samples of the reflectance spectra frames acquired by AMOS-Spec system.

The process of analysing the reflectance spectra will be demonstrated on the experimental examples of two very bright satellites ERS 1 (COSPAR ID 91050A) and ERS 2 (95021A), ESA's former European Remote Sensing satellites. Two events were recorded by the AMOS-Spec, one on 15th of April 2018 and one on 3rd of February 2018 respectively at AGO. The process of obtaining the reflectance spectra from raw AMOS-Spec images will be hereby described.

Image reduction

First, the image reduction is performed by applying the master flatfield and dark frames on the images. Additionally, the subtraction of the background is applied to remove the mask of the surroundings such as trees and observatory's dome. All these calibrations steps were acquired by using ImageJ software tool [8].

Intensity extraction

The spectra analysis starts with extracting the relative intensities (gray values) [ADU] as a function of position [pix] from the frame Fig. 4 (top). This is done also by using ImageJ. Two examples of such extracted information are plotted in Fig. 4 (bottom), namely for ERS-2 and ERS-1 detected by AMOS-Spec during nights 3rd of February 2018 and 15th of April 2018, respectively. Two type of information is plotted, the original signal marked by red color and smoothed signal marked by blue color.

Pixel to wavelength scaling

Essential step is to scale the measured pixel values into the wavelength. For meteor events this is done by using known spectral lines [9]. However, those lines are missing for specular reflections of debris objects. Therefore, to perform such scaling, we had to use scaling obtained from a meteor event which occurred at the similar position of the camera that ERS's specular flashes, as illustrated in Fig. 5.

ERS 2 - 20180203 ERS 1 - 20180415

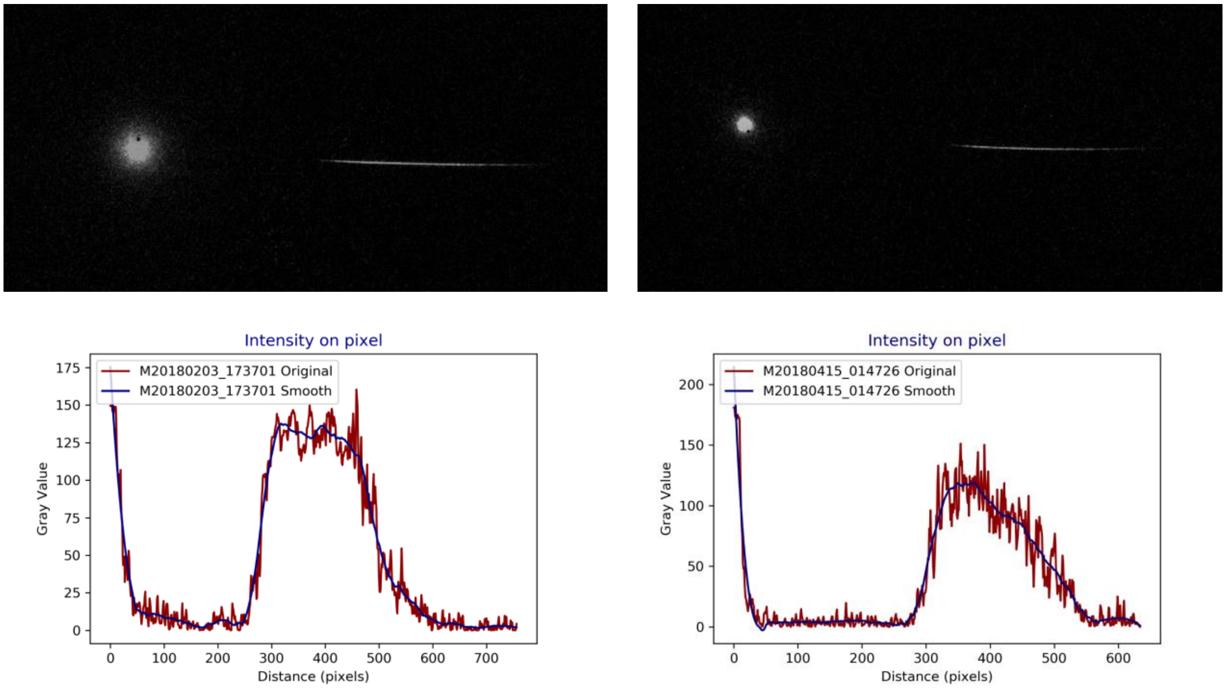

Fig 4. ERS-2 and ERS-1 detections (top) and their raw extracted spectra (bottom) captured by AMOS-Spec during nights 3rd of February 2018 and 15th of April 2018, respectively.

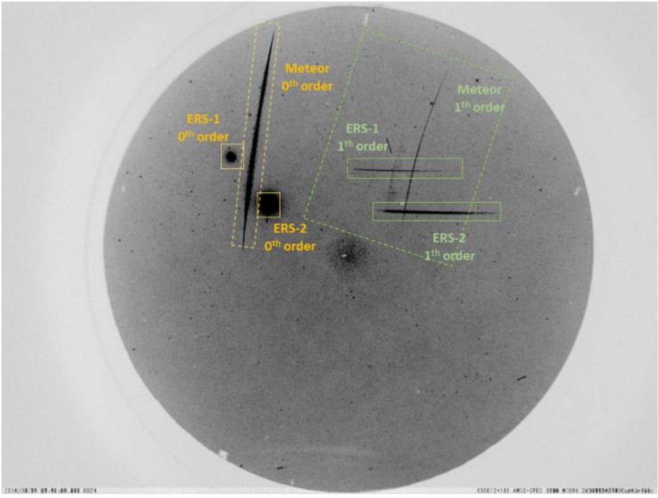

Fig 5. Composite image of ERS-2 and ERS-1 detections along with the meteor detections used for the scaling of the pixels to wavelength.

Via comparison scaling technique, using the absorption spectral lines of the meteor M20160206_2056 (Fe I; 438.3 nm, Na I; 589.2 nm and absorption line in ERS 2 spectra around 716.2 nm) the two satellites pixel distances were recalculated into wavelengths. Positions of the satellites vs meteors are relatively close, about 50 pixels on x-axis, however the uncertainties in this technique are unknown as the geometry of the spectral camera changes depending on the position of the object. The resultant curves are in the range of visible spectra, within the absorption lines, satisfactory. Outside this range in the area of low spectral sensitivity the precision is unclear. In the future a diffraction map can be extrapolated from the meteor spectra or an experiment with a neon calibration lamp can be performed to make sure that the conversion from pixels into wavelengths is exact in all ranges of the spectrum. Obtained spectra are plotted in Fig. 6.

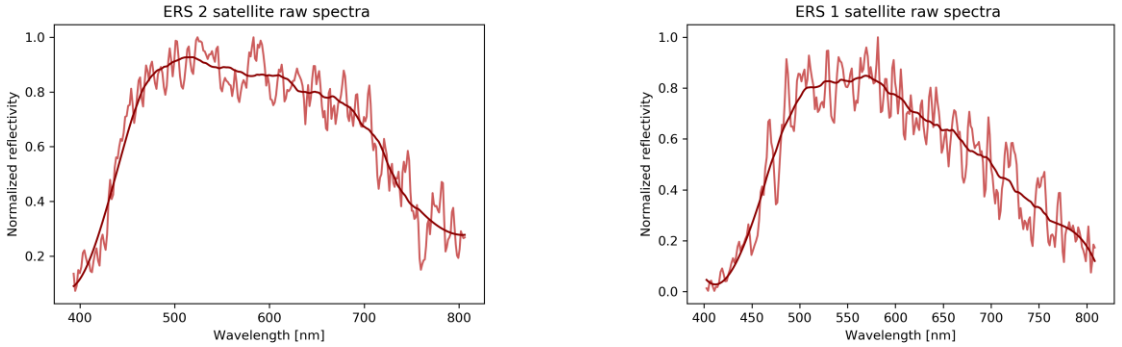

Fig 6. The raw satellite spectra of ERS-2 (left) and ERS-1 (right) scaled to wavelength.

Correction for the atmospheric effects

Influence of the earth atmosphere and atmospheric extinction is to be added in the future according to the Atmospheric Transmission Model. This is not done at the moment and will be part of our future work.

Camera sensitivity correction and solar spectra division

To obtain reflectance spectra it is necessary to correct the data by the calibration curve which accounts for the sensitivity of the AMOS-Spec camera and then to divide the spectra by the solar analogue to obtain the relative reflectance spectrum. In this case we have used 2000 ASTM Standard Extraterrestrial Spectrum E-490 in the wavelength range of 300 – 1000 nm, where solar spectral irradiance is based on the satellite surface characteristics and modelled spectral irradiance [10]. The two calibration curves are presented in Fig. 7.

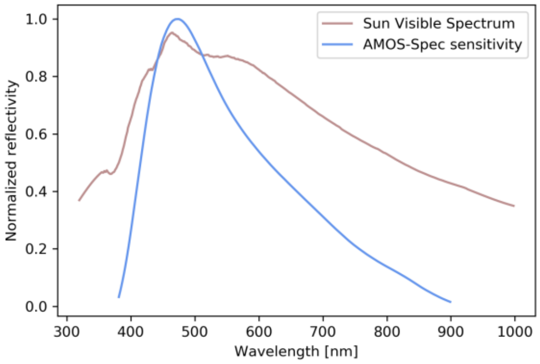

Fig 7. Normalized solar spectral irradiance (red line) and AMOS-Spec sensitivity calibration curve (blue line)

The raw satellite spectra is now corrected by the two aformentioned normalized curves to obtain final reflectance spectra. The reflectance spectra of two analysed satellites ERS-2 and ERS-1 are shown in Fig. 8. The final curve is the green curve, where in both cases there is a minimum in 400 nm wavelengths and curves are considerably increasing towards 700 nm where they peak and are much noisier, in the area of red spectrum. Both ERS satellites were made of very bright materials with good reflectivity, such as copper [11] (Fig. 9), and thus in theory it fulfils our expectations that the spectrum peaks in the red area of wavelengths [12], however the data is for now purely experimental. Further experiments are to be conducted with more AMOS-Spec debris recordings, enhancing the measuring technique and hoping to observe and study different materials correlating to different reflectance spectra.

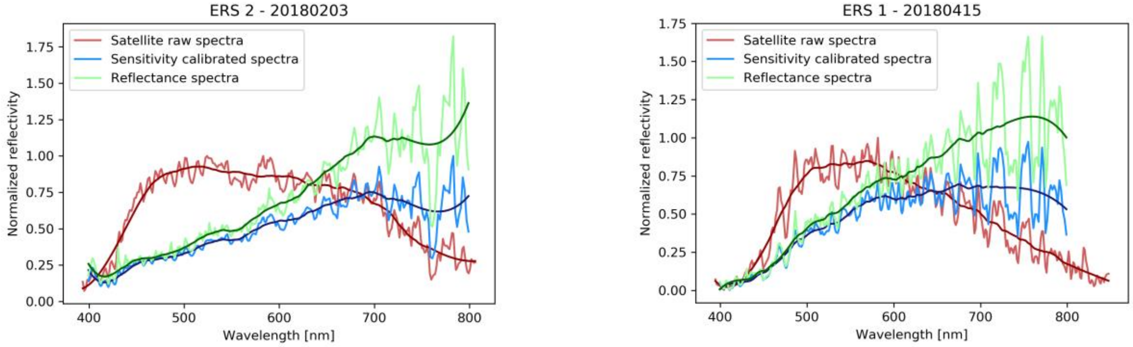

Fig. 8 Reflectance spectra of two bright satellites ERS 1 and ERS 2, red curve shows the raw spectrum with no calibration, blue line is spectrum calibrated by the AMOS-Spec sensitivity and green curve is the desired reflectance spectrum corrected by solar spectrum

Fig. 9 Artist’s illustration of ESA satellite ERS-2 [11]. High specular glints are expected to be caused by the reddish copper alloy protective foil

3.3 Re-entries, trajectory

Since AMOS-Cam cameras were originally built for meteor observations and debris re-entry events in their nature resemble a meteor fall in the atmosphere, AMOS can be further used for debris re-entry observations. Thanks to the far-reaching coverage of AMOS global meteor network, AMOS-Cam can spot and record such events instantly at different locations on earth. The output data can be used for astrometric, photometric and spectra measurements, so the AMOS-Cam together with AMOS-Spec/AMOS-Spec-HR can be used to support re-entry events modelling. This includes monitoring the parent body’s fragmentation during the re-entry, calculating the fragments’ trajectories in the atmosphere and measuring their spectra by performing the spectral analysis of the fragments. So far, two re-entry events, or candidate events, have been identified in the AMOS archive.

Case of M20160809_001049_AGO-TEST

This case has been already reported in [3]. In August 8, 2016 at 00:10:50 UTC a meteor was detected over several Europeans states. AMOS-Cam system located at the AGO Observatory was able to observe only a part of the luminous trajectory for duration of 6.5 s (Fig. 10, left). This is already unusual duration for a meteor event. Thanks to the multiple sites observations we were able to determine the atmospheric trajectory of the meteor (Fig. 10, right).

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.

Case of 052757_AMOSCHI-SP

During the night of 10th of March 2018 AMOS-Cam in Chile detected an event which lasted for more then one minute. This event has been recorded but due to the high storage demand for the far located camera system filter removed the record from archive. However, the image composition of the event could be restored and is plotted in Fig. 11 (left). The luminous path is in the South part of the sky moving most likely from top (West) to bottom (East) of the frame. Same event has been recorded by the European Southern Observatory (ESO) APICAM all-sky camera system installed at the ESO Paranal Observatory, Chile. This is shown in Fig. 11, right. The luminous path is in the top (South) part of the frame.

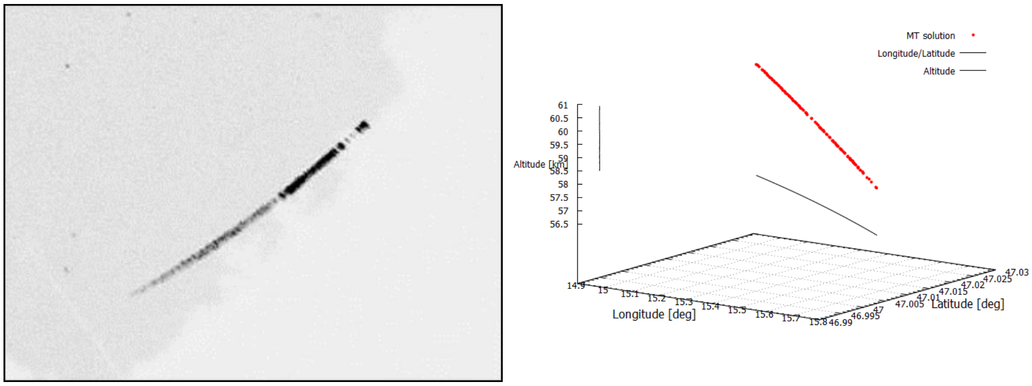

Fig. 10 Left: Luminous path of possible re-entry event over the lower right horizons on negative composite image from AMOS-Cam video record from AGO station on August 8, 2016 at 00:10:50 UTC (left); Right: Calculated atmospheric trajectory of possible reentry event on August 8, 2016 from double-stations observation from AGO Modra and amateur observer Martin Popek, Nýdek, Czech Republic

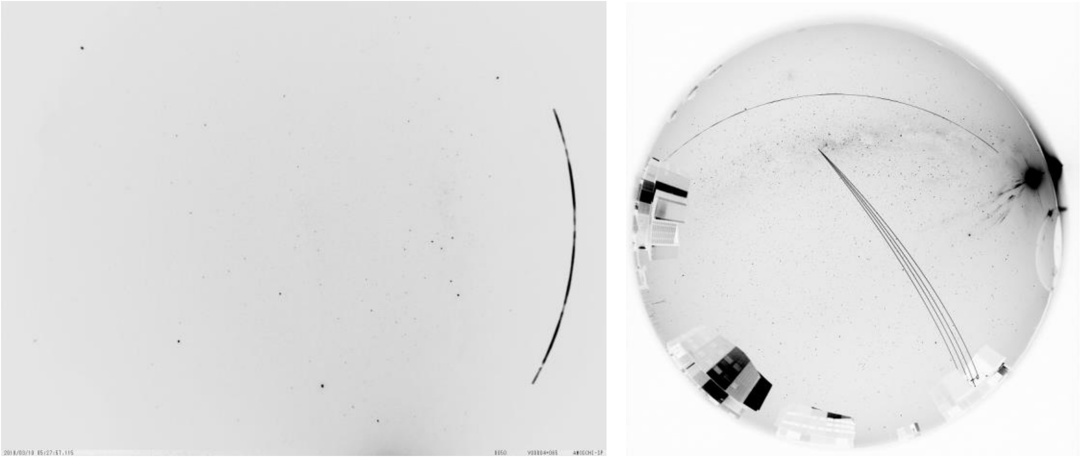

Fig. 11 Luminous path of a re-entry event over the lower right horizons on negative composite image from AMOS-Cam video record from Chile-SP station (March 10, 2018 at 05:27:27 UTC) (left) and image from APICAM all-sky camera video record from ESO Paranal Observatory, Chile (March 10, 2018 at 05:26:12 UTC (right)

According to the United States Strategic Command web site [14], there was event which correlates with the location and time of the recorded event. A re-entry of upper stage CZ-3B R/B (17078B) occurred at time 2018-03-10 05:29:00 UTC above a geographical point 24°42'00.0"S 61°18'00.0"W. This is also shown in Fig. 12.

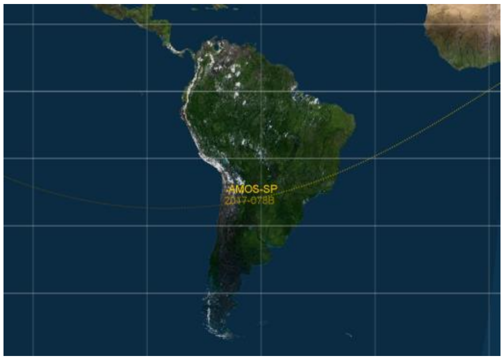

Fig. 12 Geographical configuration between the AMOS Chile-SP station and the re-entry point of upper stage CZ-3B R/B (17078B) according to [14]. Image rendered by SatEph program [15].

4 CONCLUSION

The extent of AMOS system to space debris research was hereby evaluated. AMOS-Cam records of LEO objects are well suited for object identification, however due to the system limitations or limitations of UFO Analyzer software (development of own processing tool is in progress) astrometric measurements are expected to be secondary outcome. Interesting will be future evaluation of AMOS-Cam photometric measurements. Since majority of space debris AMOS records were specular periodical flashes ideal for spectrum identification the effectivity of AMOS-Spec use for space debris spectroscopy was investigated. Experimental method to extract reflectance spectra was developed and tested on two satellite records of ERS 1 and ERS 2. Method is to be enhanced in the future and more AMOS-Spec videos are to be inspected aiming to create a catalogue of reflectance spectra types with respect to the surface properties of the captured objects. Next application of AMOS-Cam and AMOS-Spec would be to observe re-entry events which in nature resemble meteor behavior and hence can be very well treated by AMOS system measuring software. To conclude, AMOS provides a wide area of different applications which can be used in space debris research, the range of which remains under investigation.

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