OMNISKY: WIDE ANGLE MULTI-CAMERA STATION NETWORK CONCEPT FOR RE-ENTRY DETECTION

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ABSTRACT

Approximately 400 man-made objects of size larger than 10 cm re-enter the Earth's atmosphere every year – the majority of these are never observed. Typically, the only way we know that they are no longer in orbit is because they are not observed any more in an expected location at a given time. OmniSky is a concept network of multi-camera sensors that are designed to detect re-entries of objects larger than 1 cm over an area covered by a grid of observing stations. Based on extensive simulations, including a realistic in-orbit population model and historical weather data, we have estimated that a 16-station network covering roughly the area of Poland will detect 4.6 re-entry events per year. Various hardware and on-board software approaches have been considered during the design and feasibility study phase. The resulting network will be integrated into one system by the means of tailored cloud services. The need of detecting and characterizing re-entry events is justified by the requirements of space commercialisation, satellite mega-constellations, space law evolution and the emerging market of space insurances. Additionally, a single OmniSky station is a versatile tool that can be used for other complementary activities, also during the day: weather monitoring (including cloud detection for solar farms), environmental monitoring (e.g. forest fires, bird migration), drone observing, amateur astronomy, night-time cloud detection for astronomical observatories.

Keywords: re-entry; camera; fireball; all-sky.

1. INTRODUCTION

The main objective of the project presented in this paper was to design and develop OmniSky, a modular hardware and software platform dedicated to observing the entire visible sky during day and night in a fully autonomous way with cloud services-based data management and processing optimised for re-entry detection. OmniSky, due to its versatility, can become a base platform for a wide range of observing activities depending on the selected configuration. The base design consists of a weather-proof enclosure that houses the cameras, the main processing unit, a dedicated power supply, protection circuitry and communication interfaces. OmniSky can be equipped with one or more camera modules, each with its own processing sub-system and lens.

The core of the SST Segment is the catalogue of all objects that orbit the Earth, and one of the most important tasks is the maintenance of this catalogue. This includes not only potential collision between satellites and space debris but also possibilities of uncontrolled re-entry. It is very important to not only predict and observe when large pieces of space debris re-enter the atmosphere but also to capture as many events as possible, even the faintest ones those that are not even catalogued. The concept of the network is shown in Fig. 1. In Sec. 2 we describe the methodology behind re-entry observations, in Sec. 3 we describe existing networks of similar observing stations, in Sec. 4 we present the design details of the OmniSky station. Section **??** describes the software architecture of the proposed system. In Sec. 6 we describe our simulation framework that was used to verify that the design meets the requirements and to analyse deployment scenarios. We summarize in Sec. 7.

2. METHODOLOGY

The OmniSky concept had been strongly influenced by experience in fireball networks that have been described in detail in Sec. 3, as well as cloud monitoring systems. Factors that characterise the equipment used in fireball networks are sky coverage, limiting magnitude, resolution (or image scale) and imaging technique (photographic, CCD or video). The types of fireball detection stations can be divided into several groups.

1. All sky stations with fish-eye lenses and high resolution detectors (CCD or dSLRs). These have low

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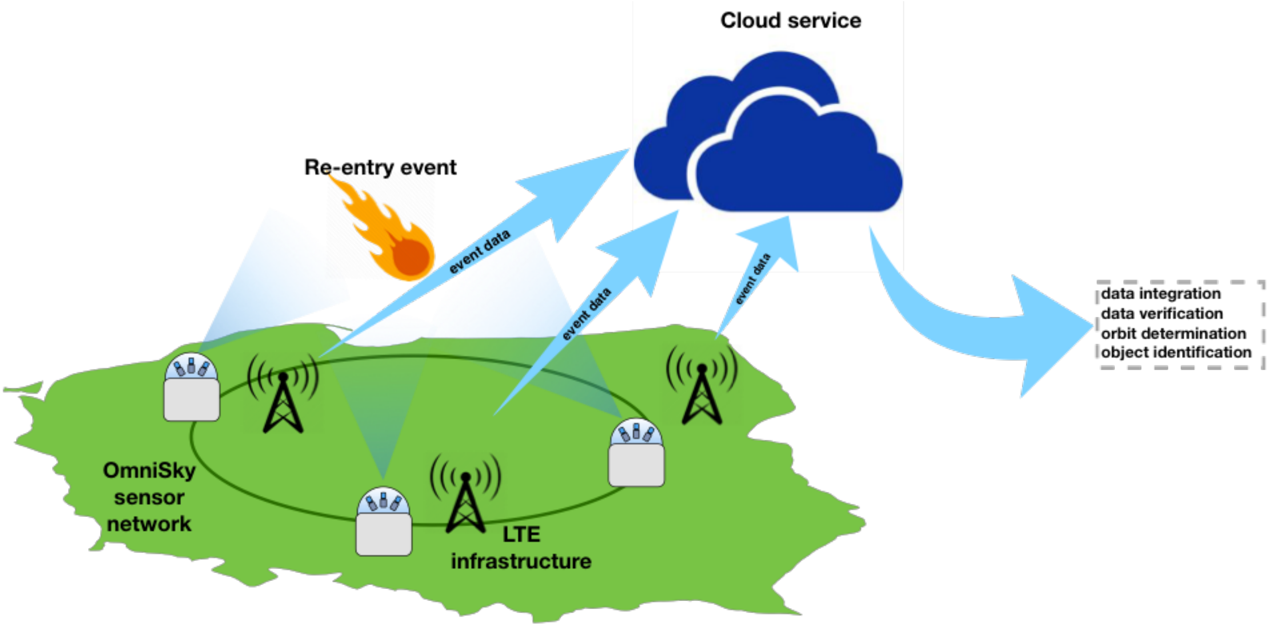

Figure 1. OmniSky concept. The sensors are designed so that they can operate on 3G networks. Data acquired by the stations is processed in real-time and potential re-entry events are transferred to the cloud for further computing and integration with data from other sensors.

limiting magnitude and are not suitable for recording fragmentations due to low frame rates.

2. All sky stations with video cameras – these are low resolution and have low limiting magnitude.
3. Narrow field video stations (e.g. CAMS, see Sec. 3) high resolution but small field of view.

The OmniSky station is designed so that it has the advantages of all three approaches described above:

- almost all-sky setup thanks to an array of cameras,
- limiting magnitude for re-entry events at least +4 mag, can be increased to +6 mag,
- image scale ca. 2 arcminutes per pixel – comparable to best fireball networks,
- video recording with up to 30 fps allowing to trace fragmentation with full detail,
- combined resolution of 8 MP.

We have formulated the following requirements that need to be met by the network of newly designed stations.

1. A network of OmniSky stations shall detect all observable (perfect weather and astronomical night) re-entries of objects 1cm in size and larger above the area covered by the network.
2. The average precision of all trajectories detected above the area covered by the network shall be 50m. The trajectory term corresponds to the visible part of the patch observed instrumentally by Omnisky camera (this is not the precision of the possible dark-flight trajectory which is significantly affected by upper atmosphere winds).
3. The station and the network shall be designed in such a way to optimise hardware, deployment and operating costs.
4. The station shall be a standalone unit with on-board image processing capabilities, satisfying the edge computing paradigm.
5. The network shall be managed by cloud services that are responsible for inter-station data processing and network supervision.

In the following section we present a thorough review of existing fireball networks that influenced the design of OmniSky. These networks are at the same time candidates for future integration with OmniSky.

3. EXISTING NETWORKS

Photographic observations of meteors, conducted in order to catch the highest number of bright phenomena, have a lot of history. The technique of such observations is not simple. If you want to gather the biggest amount of information about a given phenomenon, including its orbit, the trajectory in the atmosphere and the place of its potential fall, you have to observe it at the same time from at least two stations which are positioned at least several dozen of kilometres apart.

The first group of scientists who used such a method on a large scale were two astronomers: Luigi Jacchia and Fred L. Whipple. In 1939-1951 on Harvard University they started a basic survey of the sky, based on fast Schmidt-Baker cameras. However, the aim of their work was to determine the orbits of the highest number of phenomena, not finding their places of fall. That's why their instruments were very sensitive but with a relatively narrow field of view [7].

After finishing the project in 1951 the work of Whipple and Jacchia was continued in the former Czechoslovakia, led by astronomers from the observatory in Ondřejov. The year 1959 was a breakthrough in the development of the Czech and European fireball network. On 7th April exactly the Czechoslovakian stations registered the route of flight for a bolide of -19 mag. Thanks to the photographic observations they managed to determine the orbit and the place of its potential fall and, as a result, they found very quickly four meteorites near Pribram [3].

3.1. European Fireball Network

The Pribram meteorite made the European community aware of the value of a fireball network which would cover the widest area possible. In 1963 the Czechoslovakian stations were transformed into a beginning of the *European Fireball Network (EN)*. Five years later Germany joined that project and in 1978 the same did Holland.

Still the Czech stations remain the best and the most efficient link of EN. They are positioned almost perfectly across the whole territory of the country, keeping the average distance of about 100 km. Every cloudless night ten stations observe the sky, never missing a meteor brighter than -3 mag which happens to fly over the territory of the Czech Republic [13, 15].

The Czechs have also invested in their equipment the biggest amount of money. Each of their automatic photographic stations is able to work for a month without any human maintenance. It is equipped with the Zeiss Distagon 3.5/30mm fish-eye lens which, combined with the Ilford 100-400 ASA film and 9×12 cm format provides a 180-degree angle of view and allows to determine the position of every phenomenon with the precision of 0.01 of a degree. The efficiency is the problem of Czech stations (for slower phenomena their reach limiting magnitude of -3; -4 mag for faster ones) and their significant cost (the price tag for the lens itself is about 6,000 Euros). Recent improvements of Czech stations and newly developed Australian Desert Fireball Network stations are described in [14]. Recently, EN stations were upgraded and so called DAFO (digital autonomous fireball observatory) were implemented. Each DAFO contains the Canon EOS 6D camera with Sigma 8 mm f/3.5 fish-eye lens and an electronic LCD shutter for speed determination. Older analogue stations are still operational, thus all EN stations are equipped with sensors of both types working independently.

The statistics of the Czech network from the last years show that about 45% of nights in the Czech Republic are clear enough to ensure the work of at least two stations. In that period one can register on average 32 bolides every year; averagely almost one of them is able to force its way through the atmosphere and result in a meteorite fall. Its place of the fall can be determined with utmost precision [11].

3.2. Polish Fireball Network

Poland and the Czech Republic share similar climate but Poland's territory is four times bigger. A simple extrapolation of the Czech statistics indicates that a regular fireball network in our country would allow to register over 100 bolides a year; 2-3 of them would have a chance to withstand the atmosphere and finish with a meteorite fall. Such conclusions were the beginning of a project called the Polish Fireball Network, initiated in 2004 by the *Comet and Meteor Workshop* (PKiM - Pracownia Komet i Meteorów in Polish) and Nicolaus Copernicus Astronomical Centre.

The first instrument conducting a regular bolide patrol was a set of four analogue Canon T50 cameras with fast 1.4/50 lenses. On 20th February 2004 it registered the first bolide - the EN200204 Łaskarzew. It happened that exactly the same phenomenon was registered by the Czech station situated on Lysa Hora, which belonged to the European EN network. Combined data from Poland and the Czech Republic allowed to determine the meteorite's orbit, trajectory, and the place of its potential fall. The results of that analysis were described in [16].

PKiM, seeing the continuous development of electronic detectors of images, have been trying from the very beginning to make the fireball network rely on digital photographic technique and sensitive video cameras. In order to find the best instruments for astronomical observations we conducted a big test of CCTV industrial cameras. The results of that test were described in [21]. The best price/quality ratio offered sets of Tayama, Mintron and Siemens cameras with 1/3" detectors with a resolution of 768×576 pixels, equipped with Ernitec or Computar f/1.2 4 mm lenses. Such a set features a field of view of 62×48 degrees and the limiting magnitude for meteors up to 1-2 mag. The fact that one station, in order to cover the whole sky, should have 7-8 cameras is a drawback of such a solution. Limited budget meant that the best stations were equipped with only 2-3 cameras. It is worth to mention that this cheap equipment is sill widely used in PFN stations. About 40 such cameras are still in operation. Low PAL resolution connected with cheap lenses causes many problems. In case of bright fireballs we deal with strong saturated areas which are additionally deformed by optical off-axis aberrations. This causes serious problems with proper determination of the centroid of the fireball and produces serious errors in trajectory and brightness determination. Moreover, these errors are difficult to estimate. This is the reason why some of our results differ from results obtained by more accurate and significantly more expensive equipment used in EN stations.

Obtaining the Polish NCN[1] grant in 2013 was a milestone in the development of PFN. Currently, the network consists of 35 stations with more than 75 cameras. Still, almost half of them are old and cheap models working in PAL resolution. Thanks to previous grant funds it was possible to acquire about 15 highly sensitive models of Mintron still operating in PAL resolution. However, these cameras, equipped with lenses with a focal length of 6 mm being as fast as f/0.75 (detector size 1/2" giving a field of view around 60 deg), are very efficient in registration of weaker meteors.

In case of fully digital cameras, only models with a resolution of 1920×1200 pixels were within budget limits. Full HD resolution combined with 180 deg field of view given by fish-eye lenses gives insufficient angular resolution for precise astrometry. Therefore, the decision was made that one station will consist of two sensitive cameras FullHD DMK 33GX236 (sensor 1/2.8"), each equipped with Tamron lens with a focal length of 2.4 mm and f/1.2. Each camera gives a field of view 127×83 degrees (diagonal fov is 150 deg), so the two cameras cover nearly the entire useful part of the sky and give the required precision of meteor path detection and high number of stars needed to obtain good quality astrometry. Eight such stations have been built.

During last two years several interesting digital cameras appeared on the market. One good example is DMK 33GX174, which is FullHD (1920×1200 pix) camera, but it has a relatively large sensor (1/1.2") with high image quality, large dynamic range and low noise. In combination with the high-quality Japanese VST 1.8/6mm lens, this represents a highly efficient combination, well suited for spectroscopic observations.

3.3. SonotaCo Network

SonotaCo Network is the network consisting of 100 high sensitivity cameras located in 25 stations across Japan. It is run by amateur astronomers. It started its operation in 2007. The typical equipment consists of high sensitivity monochrome CCD video camera (WATEC 100N or WATEC 902H2U), CS-mount lens 3.8-12mm f/0.8 with field of view from 30 do 90 degrees. The video format is 720×480 or 640×480 AVI digitalised from analogue NTSC signal (29.97 frames per second, interlaced).

[1]National Science Centre

Motion detection software called UFOCapture is used and it allows video recording from a few seconds before the trigger. The meteor measurement software UFOAnalyzerV2 and the orbit computation software UFOOrbitV2 are used for all multi-station events. The typical accuracy of single-station observation measurement is 0.03 deg for the direction and 0.5 seconds for the absolute timing.

In years 2007-2008 the SonotaCo Network recorded 293702 meteors with 39208 of them being multi-station events allowing precise determination of their trajectories and orbits. Currently the network records from 160000 to 180000 single station meteors per year and 19000 to 27000 multi-station simultaneous observation orbits per year [12].

3.4. Fireball Recovery and Interplanetary Observation Network

The French network called FRIPON (Fireball Recovery and InterPlanetary Observation Network) was founded by ANR (Agence Nationale de la Recherche) in 2013. Its aim is to connect meteoritical science with asteroidal and cometary science in order to better understand the Solar System formation and evolution. The main idea is to set up an observation network covering all the French territory to collect a large number of meteorites (one or two per year) with accurate orbits, allowing us to pinpoint possible parent bodies. About 100 all-sky cameras are going to be installed forming a dense network with an average distance of 100 km between stations. To maximize the accuracy of orbit determination the optical data are mixed with radar data from the GRAVES beacon received by 25 stations [4].

The FRIPON uses circular fish-eye lenses to cover the whole sky. The cameras are based on Sony chip ICX445 (resolution 1288×964 pix) working at 30 frames per second, allowing a good efficiency for low light measurements at night but also a very short exposure time for daytime observations.

An optical network is very efficient for measuring fireball geometry, but determination of velocity is less easy with only a few points on fish eye images. However, speed is essential for semi-axis measurement and, therefore, fundamental for pinpointing the origin of fireballs and their possible parent bodies. Thus the radar echoes of the GRAVES beacon dedicated to measuring low altitude satellites are used. The beacon is usable all over France, a 200 km spacing being sufficient for radio observatories, so only 1/4 of the optical stations will have radio equipment. The goal is to measure relative speed with the Doppler effect.

3.5. Cameras for Allsky Meteor Surveillance (CAMS)

The Cameras for All sky Meteor Surveillance (CAMS) was set up by the team of Peter Jenniskens and Pete Gural to validate minor meteor showers. The project was funded by NASA Planetary Astronomy program in July 2008. At the beginning, two CAMS platforms were planned with 20 cameras each, installed at Fremont Peak Observatory and Lick Observatory, both in California USA.

The first light for CAMS took place on 2010 November 11 with 22 of the 40 cameras operational at only two sites of the three sites planned. In April 2011 the third station at Lick Observatory was finally operational. The sites are 54-64 km apart. The cameras that contribute to a meteor trajectory are recorded, and the effective survey area is known at all times [8].

In June 2011 one-camera version of CAMS were ready for testing. This setup would allow amateurs to join the CAMS project. This happened in August 2011, when the first Single Camera CAMS station based on Watec 902 H2 Ultimate became operational. In the next years several Single Camera CAMS stations were installed in Belgium, Netherlands and New Zealand. Up to 2014 the CAMS project had collected 232000 meteor orbits. There are 203 cameras in operation at the beginning of December 2017.

The MeteorScan software package [6] is used to detect the meteors and retrieve the astrometric data. The software works on video sequences of 256 frames (NTSC, 29.97 frame-per-second). The temporal propagation history of the meteor is recorded and preserved the astrometric accuracy for equatorial coordinate calibration. The averaged frames typically contain 70-200 stars brighter than 8 mag allowing to obtain astrometric accuracy at the level of $\sim$1 arc min. The good quality photometry is obtained in the magnitude range from $+5$ to -5 mag.

3.6. Southern Ontario Meteor Network

As part of the Western Meteor Group's Southern Ontario Meteor Network (SOMN) sensor suite seven all-sky video systems designed to automatically detect bright fireballs were developed. The SOMN currently consists of 13 cameras, located throughout South Western Ontario, and in Ohio (USA). The all-sky video network component of the SOMN was developed originally from hardware and software supplied by Sandia National Labs as part of their sentinel camera network. The intent was to use a dense array of all-sky cameras (with spacing of order 50-100 km) to record many meteors from multiple stations. The intent is to use the moderate precision metric data for comparison with other instrumental recordings of the same event and to act as a "trigger" for other instruments in the SOMN [20].

To record fireballs with these video systems, the All Sky and Guided Automatic Real-time Detection (ASGARD) software was developed. It detects video meteors in real-time and automatically analyse them to produce video and image summary files. For multi-station detections, atmospheric trajectories and heliocentric orbits are also determined by using some extra software.

The cameras used for each station are HiCam HB-710E SONY Ex-view HAD (1/2" size) CCD cameras equipped with a Rainbow L163VDC4 1.6-3.4 mm f/1.4 circular fish-eye lens. The cameras are housed inside a simple enclosure with a clear acrylic dome. The enclosure has a thermostat for heating during winter and a fan system to circulate air and prevent dewing of lenses or the dome. A photosensor attached to each camera which shuts off the unit during the day. The video signal from the camera (NTSC, 29.97 frames per second) in a 640×480 format is captured by a Brooktree 878A frame-grabber card in a PC, processed, and then streamed to disk. Timing information (based on the system time when a hardware interrupt from the capture card occurs) is calibrated against a US GlobalSat BU-353 USB GPS receiver using the Network Time Protocol (NTP) software. Instead of simply correcting the system clock periodically (which allows it to drift between updates), NTP will adjust the clock rate to ensure the clock is always accurate to better than one frame time. When extreme accuracy is desired, NTP can use a pulse per second (PPS) signal to obtain times accurate to ~ 10 microseconds.

3.7. Desert Fireball Network

The Desert Fireball Network (DFN) is a network of cameras in Australia. It is designed to track meteoroids entering the atmosphere, and recover meteorites. It currently operates 49 autonomous cameras, spread across Western Australia and South Australia: Nullarbor plain, WA wheatbelt, and South Australian desert, covering an area of 2.5 million km^2. The project started in 2006 with analogue cameras (Bland et al. 2006). Subsequent to the first analogue phase and recovery of two meteorites during that time, the DFN expanded into an automated digital fireball network [1].

Currently, the DFN observatories use consumer, digital, single reflex, full frame 36 Mpix cameras with 8mm stereographic fish-eye lenses covering nearly the entire sky from each station. The observatories take one long exposure image every 30 seconds for the entire night. After capture, automated event detection searches the images for fireballs, and events are corroborated on the central server using images from multiple stations.

The DFN has recovered four meteorites with highly accurate trajectory and orbital data so far [2].

3.8. NASA All-sky Fireball Network

The NASA All-sky Fireball Network is a network of cameras set up by the NASA Meteoroid Environment Office (MEO) with the goal of observing meteors brighter than -4 mag. The network currently consists of 17 cameras, 6 of which are placed in locations in north Alabama, north Georgia, southern Tennessee, and southern North Carolina. Another 3 are in the northern Ohio/Pennsylvania area, 5 are located in southern New Mexico and Arizona, and 3 are in Florida [5].

The cameras in the network are low-light black and white video cameras working in NTSC resolution and equipped with circular fish-eye lenses. The housing of the camera has a thermostat for heating during winter and a fan system to circulate air and prevent dewing of lenses or the dome. The system works under the ASGARD (All Sky and Guided Automatic Real-time Detection) software.

3.9. Spanish Meteor Network

The SPanish Meteor Network (SPMN) also known as Spanish Fireball Network was born in 1997 in order to study interplanetary matter, and recover fresh meteorites for direct study in laboratories. Up to now, the SPMN has promoted the recovery of two meteorites: the L6 ordinary chondrite Villalbeto de la Pena (2004) and the eucrite Puerto Lapice (2007).

The network is still growing at a good rate with fundings received from our different research projects, and public funds. In 2010 the network had about 25 video and CCD stations monitoring the atmosphere for bright fireballs occurred over Portugal, Spain, north of Morocco and south of France. The SPMN developed the first high-resolution CCD all-sky cameras applied to fireball monitoring in the world. The SPMN all-sky systems are able to record meteors from magnitude $+1/+2$. The very good limiting stellar magnitude of the cameras provide enough comparison stars to make astrometric and photometric measurements of faint meteors and fireballs with an accuracy of 1.5 arcminutes [18, 19].

Starting from 2006 several new video stations were installed within SPMN. All of them are based on an array of high sensitivity video cameras that perform a continuous monitoring of the night sky by covering an atmospheric volume enclosed within a radius of more than 500 km under ideal conditions. Most of these cameras are manufactured by Watec (Watec Co. Japan) and because of their high sensitivity (0.0002 lux at f/1.4) image intensifiers are not necessary [10].

3.10. OmniSky versus others

The OmniSky design presented in this paper offers an image scale of 2-3 minutes per pixel i.e. the same as the best all-sky sets equipped with high resolution digital cameras and which are used by the European Fireball Network and Desert Fireball Network. In contrast to these networks, however, OmniSky is video-based, thus offers a better limiting magnitude (in this case even a factor of several hundred) and the possibility of detailed examination of fragmentation of the observed event and separate analysis of specific fragments (in the case of photographic techniques they merge into one trail).

In comparison to other video-based all-sky solutions (e.g. FRIPON, SOMN), OmniSky gives a much better resolution of the acquired images, still keeping the possibility of observing almost the whole celestial hemisphere with a much better limiting magnitude. It allows not only to detect more events but gives the possibility to obtain much better astrometric precision due to the significantly larger number of imaged stars.

The resolution and the expected astrometric precision of OmniSky stations will be comparable to the results obtained by narrow-field video stations networks like SonotaCo and CAMS. In contrast to sensors used in these networks, OmniSky has a much larger field of view.

Finally, OmniSky is unique with regard to the proposed cloud services and edge computing approach. Dealing with high volume video streams generated on-board the stations due to camera arrays is a challenge but at the same time an opportunity to develop new-generation modular sensors that can be easily upgraded.

4. STATION DESIGN

The OmniSky station is a modular hardware platform that is based mostly on off-the-shelf industrial components with made-to-measure software. The station consists of four FullHD cameras equipped with 8 mm f/1.4 lenses and multiple network, computing, power and sensor devices (Fig. 3, 2).

4.1. Mechanical design

The cameras are housed under a custom dome with UV-filter openings. This solution, although slightly more complicated and expensive, has several benefits over a fully transparent acrylic dome. (1) Thanks to an opaque dome with precisely positioned openings, the inside of the dome will be minimally exposed to external heating. (2) A photographic UV filter is flat and plane-parallel, thus reducing the risk of unwanted image distortions that could occur in case of an acrylic dome. (3) No internal reflections will occur. Cameras are mounted on custom arms with hinges that allow them to be positioned inside the dome. The dome itself is attached to the top of an industrial IP66-rated enclosure with DIN-rail mounted components.

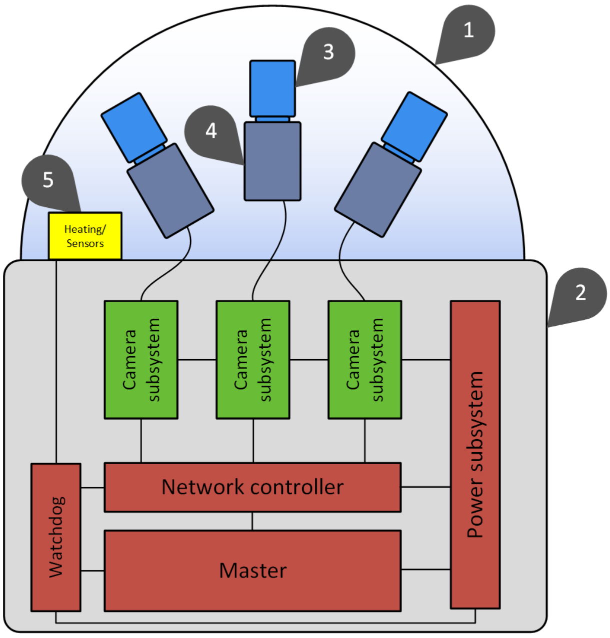

Figure 2. OmniSky station hardware architecture concept. 1 – camera and lens housing; 2 – electronics' housing; 3 – camera lens; 4 – camera; 5 – heating/sensors module.

4.2. System design

The system design can be divided into several sections reflecting all major functionalities.

- Power section – consists of power supplies, UPS, power line protection, devices providing all required voltages required across the device.
- Network section – consists of networking devices such as LTE router, Ethernet switch, GSM antenna, Ethernet link protection and cabling.
- Watchdog section – system watchdog is a dedicated controller providing low level logic such as power management, devices control and sensor hub.
- Imaging section – consists of four camera subsystems with links to cameras and master controller.
- Sensors, heater – additional devices such as temperature and humidity sensors, light sensors, dome flanges heating.

Components have been chosen to satisfy I/O requirements. The devices are powered either by 24V DC or 5V DC lines. The power section is designed in such way that it can be supplied either by 230VAC mains power line or external 24V DC. The 24V DC external power supply can be provided by solar panels. A solar-power module will need to supply power for 24/7 operation with external battery support. The on-board UPS is designed to prevent damage to the instruments in case of short power interruptions only.

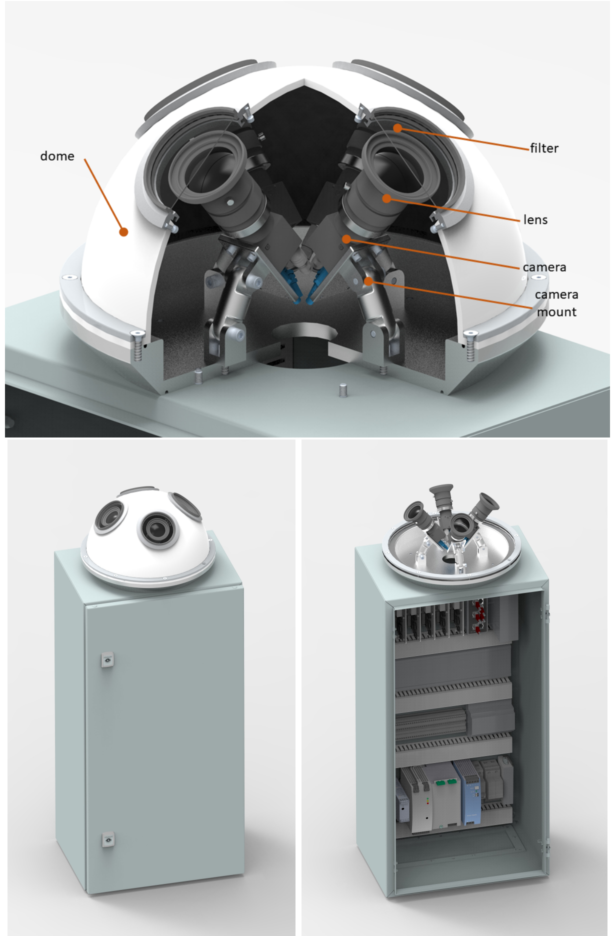

Figure 3. OmniSky station design renderings: dome details (left), full assembly (centre), interior (right)

4.3. Station firmware

There are five single board computers (SBC) housed in the enclosure – one per camera plus a master device. The SBCs are responsible for image acquisition and image processing. Because of the high data rate, the firmware has to be heavily optimised to allow for real-time image processing. Extensive use of multi-threading is required. Upon detection, processed data is transferred to the master computer that then converts the data to an appropriate format and finally transfers it to the cloud services for further processing. This approach satisfies the edge computing paradigm that is well suited for the type of operation. The top level information flow is presented in Fig. 5.

By design, all image processing will be done on board the station. The following features need to be supported:

- camera control and image acquisition,
- motion detection and object detection,
- object tracking,
- re-entry detection and tracklet generation,

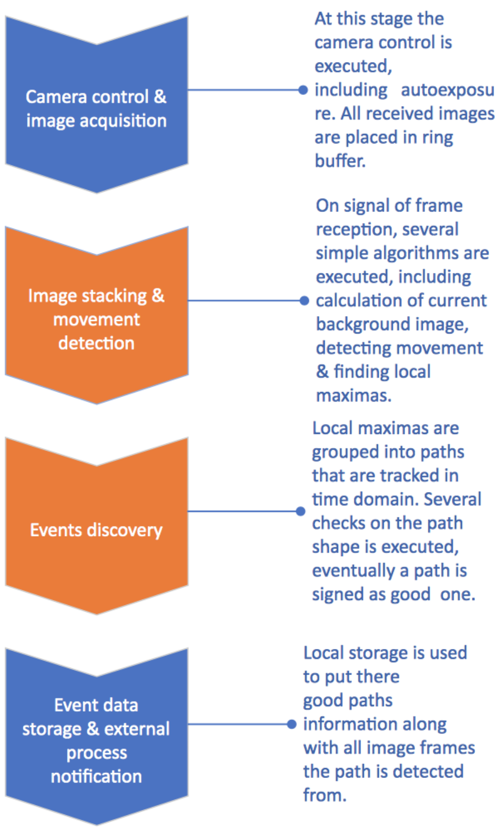

Figure 4. Generic application flow.

- astrometry image generation,
- preview image generation.

The generic application flow is shown in Fig. 5.

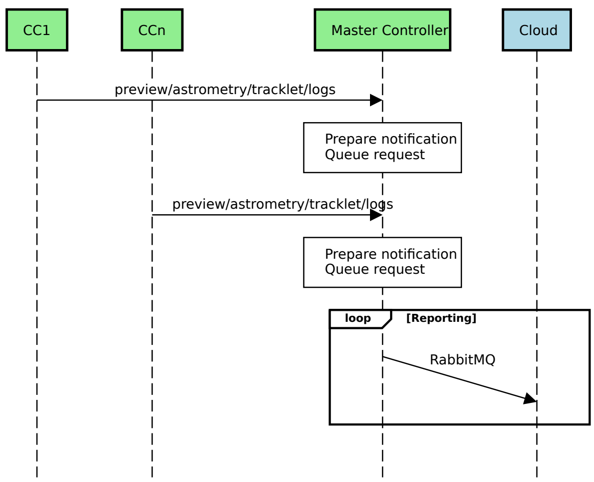

Figure 5. Generic application flow. CCns are the camera controllers.

The software and hardware design are backed by extensive test-bed operation and software mocks that have been used to verify that the requirements are met.

5. CLOUD SERVICES

Cloud services are a crucial component of the proposed OmniSky network. To reach high flexibility and satisfy the established requirements a micro-service architecture backed up with RabbitMQ decoupled messaging system has been designed. Docker containers in a virtualised environment are used whenever possible. They are deployable to the public cloud infrastructure and managed in the agile, iterative application lifetime management cycle.

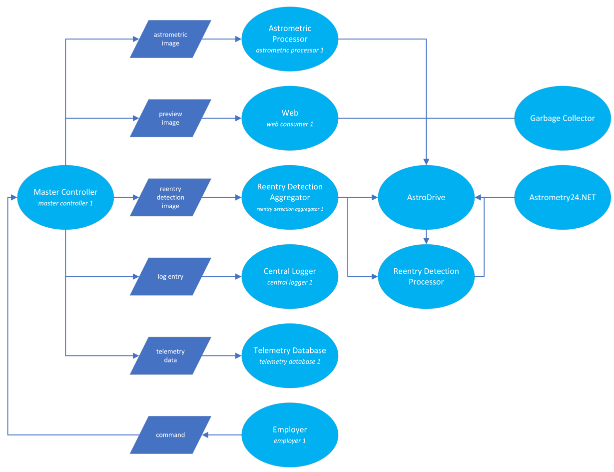

Figure 6. High-level station-cloud interaction.

The cloud services are responsible for data integration and processing. Once the station detects a re-entry event, raw but limited (only to the essential) and strongly compressed data is transferred to the cloud. There, the image data is further processed and the re-entry trajectory is computed if the event has been detected by at least two stations. Data flow between the station and cloud is shown in Fig. 6.

The following aspects have been covered by the cloud services design: cloud-station communication and messaging, data storage, FITS handling, database schema, data structure and flow for orbital elements' calculation, OmniSky station and data management user interfaces and security.

The conceptual approach to preparing the OmniSky system (that is: the station(s) and the aggregating cloud service) is in line with the up-to-date *intelligent cloud and intelligent edge* paradigm. An OmniSky station (the *intelligent edge* component) monitors, processes and prepares the data to be ingested by the management system (the *intelligent cloud*).

This approach has been proven successful with the authors' work dedicated to the operation and management of the networks of robotic, optical telescopes and thus receives much from the tools and solutions:

- Abot - command and control system for network of robotic optical observatories [17],
- AstroDrive - storage, visualisation and simple analysis of the optical data in the web browser [9],
- Astrometry24.NET - astrometric web service providing fast, precise, astrometric solutions for SST and NEO [9].

Cloud services in OmniSky are responsible for:

- continuous communication with the OmniSky station,
- triggering orbital solution processing when enough data is being retrieved from the OmniSky stations,
- single-stop access (through a web-UI) to manage and oversee the state of the stations,
- configuring and monitoring of the station,
- securing, authentication and authorizing users and clients,
- visualization of the stored the data.

We decided on the following solution due to its flexibility and fit to the requirements of OmniSky: microservice architecture backed up with the RabbitMQ decoupled messaging system with topic pattern in the virtualised environment using Docker containers on the cloud-side. The data retrieved from the OmniSky stations as well as the products of the orbital solution generation shall be stored in a relational database.

Because of the architectural decisions the cloud-based system for OmniSky shall be cloud-provider-agnostic, yet the current environment is deployed to the Microsoft Azure cloud system.

The approach to the communication in the OmniSky system aligns with the Internet-of-Things (abbr. *IoT*) paradigm and with the selection of RabbitMQ as the messaging framework allows for a great flexibility in terms of selecting the client (that is: the OmniSky station) environments. RabbitMQ defines the message layout that forms *a protocol* and due to its maturity and versatility provides easy means for introducing clients to virtually any platform. Currently, the clients communicate with the use of a Python-based wrapper around the RabbitMQ protocol. The use of RabbitMQ+Python enables the system to communicate and receive data from networks other than OmniSky. In this spirit the analysis of adherence to theNEar real-time MOnitoring system (abbr. *NEMO*) is one of the ongoing tasks.

There are two mechanisms for authentication within OmniSky:

- machine-to-machine (abbr. *M2M*) authentication, that is the authentication of communication between the station and the cloud due to the fact of happening in the so-called *assumed-secure* communication will use a native RabbitMQ user/password communication with the configuration of allowed Internet address range and MAC filtering
- user authentication, that is the authentication of the users external to the system (human-users and applications communicating with the system on the human-users' behalf) will rely on the OAuth2.0/OpenID Connect approach. This is a *de facto* standard in current Internet applications and provide for the means of reliability and continuity of the approach.

A note shall be made that due to the fact of the *device flow* extension in OAuth2.0 and the recent, active development of the `rabbitmq-auth-backend-oauth2` plugin by the core RabbitMQ team we have been investigating the possibility to bring the whole authentication to OAuth.

6. DEPLOYMENT AND OPERATION

Re-entry events are observed the same way as natural meteors are. Although the angular resolution of a single camera is relatively low compared to typical telescope setups, using triangulation allows an average precision of the re-entering object's trajectory of 50 m to be reached. The main difference between re-entries of natural and man-made objects is that the latter are faint events – a 10 cm object will be visible as a -1 mag event, while a 1 cm object will be visible as a 6 - 6.5 mag event.

A software environment for re-entry simulation has been prepared to evaluate various design and deployment options. This step was crucial to refine system requirements and formulate an operation scheme for the network. The simulation software allows one to compute the detection rate of de-orbitations, their brightness, trajectory precision and observability. The input parameters are: network technical parameters, grid separation, object population and weather data. It is also possible to take into account weather statistics for a given geographical region.

A number of deployment scenarios of a network of stations were considered. The target network configuration, assuming perfect weather, needs to detect re-entries of objects 1 cm and larger, that take place above the area covered by the network. This is the fundamental requirement. Deployment simulations carried out within this activity include different configurations of station parameters and grid spacing. It has been shown that the optimal network covering the territory of Poland should consist of 16 stations. The global and total yearly number of re-entries has been determined to be 11 400 (1 cm and larger). Figure 7 shows the simulation results for three network variants. Obtained precision in trajectory computation is shown in Fig. 8.

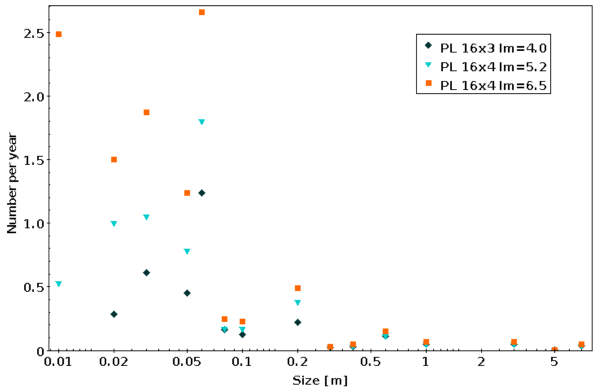

Figure 7. Re-entry rate as a function of object size – based on ESA's MASTER suite using the Business as usual scenario with time range from 2018/05/01 to 2028/05/01. Three variants are presented. The target network has 16 stations with 4 cameras each and a limiting magnitude of 6.5 (PL 16x4 lm=6.5).

Additionally, based on the simulation results, we have shown that currently existing fireball networks are not efficient in detecting re-entries of man-made objects. The main reasons are: insufficient magnitude reach, low angular resolution, low temporal resolution, inadequate software.

OmniSky, by design, addresses the above issues by means of dedicated hardware, software and cloud services.

7. SUMMARY AND HIGHLIGHTS

The project has shown that it is feasible to setup a ground-based network to detect re-entries of 1 cm and larger objects. The detection efficiency is strongly dependant on the area that the network covers and the local weather conditions. The 16-station network should observe 4.6 events per year assuming realistic weather conditions.

To detect more events, a larger network will need to be deployed. It may be possible to upgrade existing fireball networks with new hardware and software and at the same time greatly improve the coverage. The detection rate will increase linearly with the area covered. Additionally, southern parts of Europe provide extra gain due to more favourable weather conditions.

In the era of space commercialisation, satellite mega-constellations, space law evolution and emerging market of space insurances, the costs of ground-based re-entry monitoring is justified. It should be part of risk management and regular SST activities. Data obtained from observed re-entries will provide valuable information that may also be used as feedback for re-entry prediction calculations.

The OmniSky station is a versatile tool that can be used for other complementary activities, also during the day: weather monitoring (including cloud detection for solar farms), environmental monitoring (e.g. forest fires, bird migration), drone observing, amateur astronomy, night-time cloud detection for astronomical observatories.

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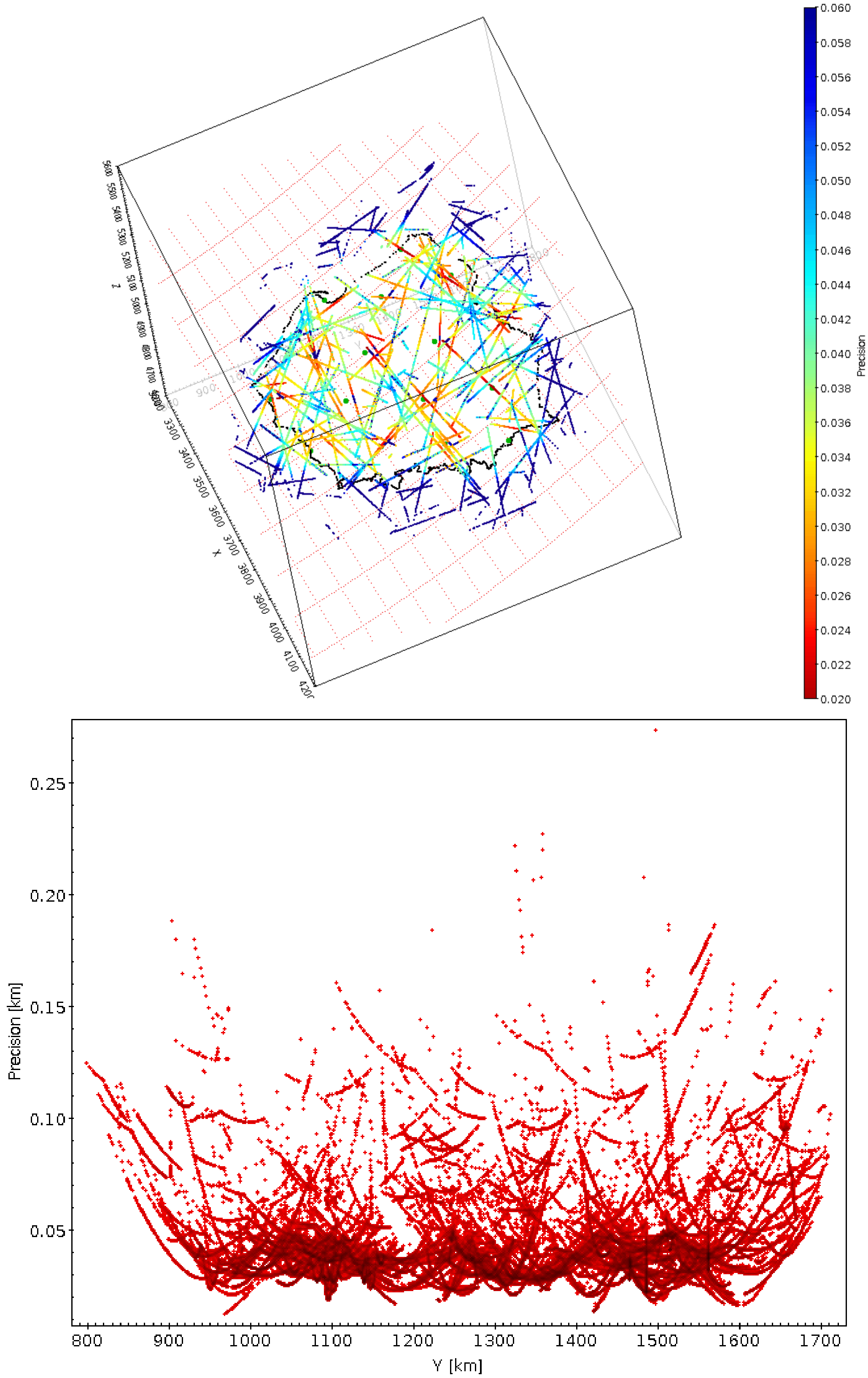

Figure 8. Precision of trajectory computation for a 16-station network covering the territory of Poland. Top: positional precision, colour scale adjusted to show details of the most precise trajectories; X, Y and Z axes as well as the precision bar, are scaled in kilometres. Bottom: positional precision (vertical axis) plotted against the Y Cartesian coordinate (horizontal axis); arcs visible on the graph represent trajectory points (each trajectory forms a separate arc). Most of the trajectories reach 20m-30m precision, there is one trajectory with significantly better precision (at Y=970), in this case we have the terminal point of the large de-orbit event very close to the observing station, at low altitude.

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