Autonomous sensor network for detection and observation of meteors

Ana Vodopivec and Hakan Kayal

Dept. Aerospace Information Technology, University of Würzburg, Germany
`vodopivec@uni-wuerzburg.de` and `hakan.kayal@uni-wuerzbuerg.de`

This paper describes the project ASMET for detection and observation of meteors and other transient sky phenomena (TSP), in particular with the application of some of the satellite technologies on Earth with respect to harsh environmental conditions (heating, cooling, power supply) and autonomy (portability, remote control, redundancy, sensors, network, reporting).

1 Introduction

The Space Technology Department as a part of the Chair for Aerospace Information Technology of the University of Würzburg is engaged in the development, construction, and operation of space systems, especially in the field of small satellites for scientific applications and higher autonomy as well as the search for extraterrestrial intelligence (SETI) and the exploration of Unidentified Aerospace Phenomena (UAP). Sky observations are reported by individuals who may not have a strong scientific or technical background or who lack the adequate equipment necessary to record an event in the sky just when and where it occurs. Since the location and time of a meteor is largely unknown, it is necessary to have as many small and particularly cost-effective systems as possible. At the University of Würzburg, an Experimental Sensor Platform (ESP) for this purpose was set up in 2008 and is continuously being improved (see Figure 1). Similar systems for the detection of the Transient Lunar Phenomena (TLP) are also developed within the group (Mohn et al., 2015).

Most of the meteors—caused by natural objects that dive into the Earth's atmosphere at high speed, glow, and disintegrate—appear suddenly and unpredictably. Similarly to the UAPs and TSPs, neither the location nor the time of occurrence can be planned (except some known meteor showers). An important challenge is to detect the meteor phenomenon at all. In many cases, there are no wide-area monitoring systems that could detect a meteor. Therefore, it is necessary that an autonomous network of sensors is established for detection and observation in inaccessible and uninhabited areas.

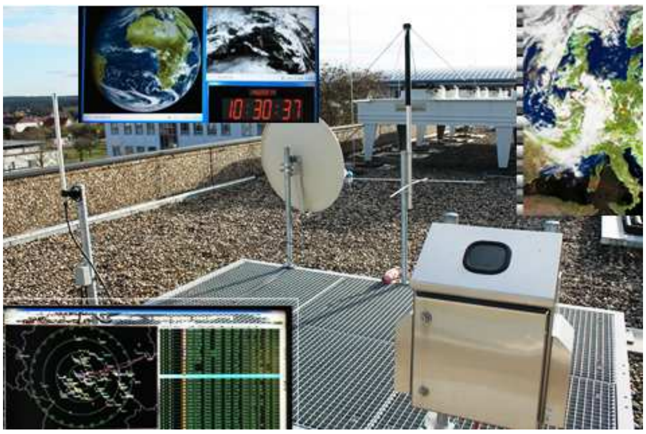

Figure 1 – Outdoor platform of the ESP and screenshots of received data from weather satellites and airplanes.

The primary goal of the project ASMET is to develop and test a system for autonomous detection and observation of meteors with the following system goals:

- continuous and reliable detection, observation, recognition, and recording of the phenomenon;
- real-time alarm function;
- low maintenance requirements due to autonomy;
- remote control capability;
- self-sufficiency;
- multiple data transmission and networking.

Since the system goals have a lot in common with space technology, especially with the development of autonomous satellites, the user requirements and functional requirements listed in Tables 1 and 2 are derived from the system goals according to space engineering standards.

2 Project requirements

2.1 User and functional requirements

The specific functional requirements of the ASMET system are derived from the user requirements and from the meteor characteristics. For example, the functional requirement FR0600, "The system should be able to detect the meteors that persist for at least 2 seconds" is a detailed derivation from the user requirement UR0300, "The system should be able to autonomously recognize at least meteors from observed sky phenomena". Some of the meteor phenomenon characteristics relevant for the project are categorized and highlighted in Table 3.

Table 1 – User requirements.

Nr.	Description	Priority	Fulfilled
UR0100	The system must detect short-term sky phenomena		yes
UR0200	Observation with the system must be possible day and night, 24/7		yes
UR0300	The system should be able to detect at least meteors from observed celestial phenomena autonomously	high	no
UR0400	The system should be able to detect at least as well as the healthy human eye	high	no
UR0500	The system should cover the entire sky of a location	high	yes
UR0600	There must be at least 2 systems at different locations		no
UR0700	The optical frame rate should be adjustable	med.	yes
UR0800	The system should be suitable for all weather conditions	med.	partly
UR0900	The system should be able to deal with light pollution and thus reduce false alarms	med.	no
UR1000	The system should be able to observe other short-term phenomena	med.	no
UR1100	The system can work in modes with different settings	med.	partly
UR1200	After detection, the system may lead another instrument in the direction of the phenomena	low	no
UR1300	The system must be able to send an alarm (short message) to the user upon detection		partly
UR1400	The system must be able to store the user data (images, videos, measured data, ...) redundantly and non-volatilely		partly
UR1500	The detection metadata shall be available to the user no later than 3 minutes after detection	high	no
UR1550	The payload data should become available to the user at the latest after 24 hours of remote detection	med.	no
UR1600	The system should back up the detections of at least 7 past days in offline mode	high	no
UR1700	The system must remain capable of communicating throughout Europe under environmental conditions		
UR1750	The system should be able to detect reliably under environmental conditions throughout Europe	med.	no
UR1780	The system should remain capable of communicating worldwide under environmental conditions	low	no
UR1800	The system should be portable	med.	no
UR1900	The system should have a permanent, 24/7 self-sufficient energy supply	high	no
UR2000	The system is to be constructed modularly	low	yes
UR2500	The system should be expandable with additional sensors	low	yes
UR2900	The system design must remain within the budget		yes

Table 2 – Functional requirements.

Nr.	Description	Source	Priority
FR0100	The system must be able to detect TSPs in the wavelength range from 380 nm to 780 nm	UR0100 UR0400	
FR0200	The system should be able to record the TSPs for for a period of at least 1 sec. to at least 2 min.	UR0100 UR0400	high
FR0300	The system should be able to detect the TSPs with a magnitude of at least +4	UR0100 UR0400	high
FR0400	The system should be able to detect the TSPs at night in min. 110 km height above ground	UR0200	high
FR0500	The system should be able to detect the TSPs during the day in min. 80 km height above ground	UR0200	high
FR0600	The system should be able to detect the meteors that persist for at least 2 sec.	UR0300	high
FR0700	The system is designed to provide a minimum sky coverage of 360° × 150°	UR0500	high
FR0800	The system should remain capable of communication between 36°–64° N and −30°–36° E	UR1700 UR1750	high
FR0900	The system should remain communicative at temperatures between −30° C and +60° C	UR1700 FR0800	med.
FR1000	The system should have a max. of 8 kg weight and max. hand luggage dimensions for expeditions	UR1800	med.
FR1100	The system should be able to detect at least 8 meteors at the same time	UR0400 FR0200	med.

2.2 Meteor and system characteristics

There are many meteor characteristics (e.g., size, texture, brightness, origin, radiant, frequency). According to the latest IAU definition[1], in the context of meteor observations, any object (original body) causing a meteor can be termed a meteoroid, irrespective of size.

ASMET system should be able to record meteors not fainter than magnitude +4 (FR0300) since most of the meteors detected are not fainter than +5 magnitudes (Campbell-Brown, 2016). The aim of the ASMET system is not only to perform meteor detection at night, but also to detect daylight meteors. Till now, daylight meteors have mostly been captured by radar observations since they are daytime- and weather-independent. However, nowadays much better cameras are available with higher dynamic range, higher sensitivity, and lower noise. With the benefit of integrated sensor data, reduction of false detections by a neural network, and appropriate dynamic calibration of the system that works seven days a week, twenty-four hours a day (UR0200) the daylight meteors detection must also be possible.

2.3 Further properties and boundary conditions

There are many different measuring methods available to obtain the relevant meteor data. In this initial project, the ASMET system should mimic, and ideally surpass, the human eye's detection capabilities, as required by user requirement UR0400, "The system should be able to detect at least as well as the healthy human eye" (Table 1). Therefore, we should first analyze observation performance of the healthy human eye (spatial resolution, FOV, wavelength, light value, limiting magnitude, frames per second, size, distance, and frequency). Then we can derive from the user requirement, e.g., UR0400, the next functional requirement, e.g., FR0300, "The system should be able to detect the TSPs with a magnitude of at least +4", and so on, as listed in Table 2.

In the next projects, following project ASMET, some other rarely interlinked meteor characteristics, e.g., radiometric, acoustic, electrical, and astrometric will be simultaneously collected for the same meteor case to generate new knowledge and to reach secondary project goals (described in Section 4).

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[1] `https://www.iau.org/static/science/scientific_bodies/commissions/f1/meteordefinitions_approved.pdf`.

Table 3 – Meteor phenomenon categorization based on Sumners and Allen (2000), Beatty (2006), Hanslmeier (2007), and Brown et al. (2013).† The table entries most relevant to us are those referring to objects with an average diameter in the range of 30 μm to 10 m.

Average Diameter (As big as)	Average Mass (Ablation)	Average Frequency	Name/Effect
$< 30\ \mu$m	$< 1\ \mu$g	100/second	Dust/Micrometeorite
30 μm–1 mm	1 μg–2 mg (all decay)	> 10/second ($> 100\,000$/day)	Meteoroid/Telescopic meteor ($> +5$ m)
1 mm–1 cm (sand grain/pebble)	2 mg–2 g (all decay)	1/second (> 1000/day)	Visual meteor (-2–$+6$ m.), > 1 g TNT
1 cm–50 cm (boulders/rock)	2 g–250 kg (mostly decayed)	1/hour (> 10/day)	Fireballs (< -2 m.), 1 kg–0.6 kT TNT
50 cm–1 m (microwave)	250 kg–1 T (mostly decayed)	1/day	Bolides (< -4 m.), 0.6 kT–1 kT TNT
1 m–10 m (car)	1 T–1.5 kT (icy/stony decay, iron not)	1/10 years	Asteroids/Superbolides (< -17 m.), > 0.6 kT TNT
10 m–50 m (house)	1.5 kT–200 kT	1/100 years	Local disaster, 1–600 MT TNT
50 m–100 m (soccer field)	200 kT–1.6 MT	1–2/1000 years	Regional disaster, 1 GT TNT
100 m–1 km (small village)	1.6 MT–1 GT	1/50–500 000 years	Continental disaster, > 1 GT TNT
1 km–10 km (small town)	1 GT–1.6 TT	1/10–100 million years	Mass extinction 1 TT–1 PT TNT
> 10 km	> 1.6 TT	< 1/billion years	Planet disaster

† See also Footnote 1 and `http://lexikon.astronomie.info/TNT/TNT.html`.

3 System concept

Meteor observations are mostly based on optic and radio methods. ASMET's rough optical system concept consists of six basic functional groups (see Figure 2):

1. optical system (camera, heatable cover, and further sensors;
2. communication system (alarm, metadata, payload data, further stations);
3. computer system (board, data processing, archiving, distribution, and analysis);
4. thermal system (heating and cooling);

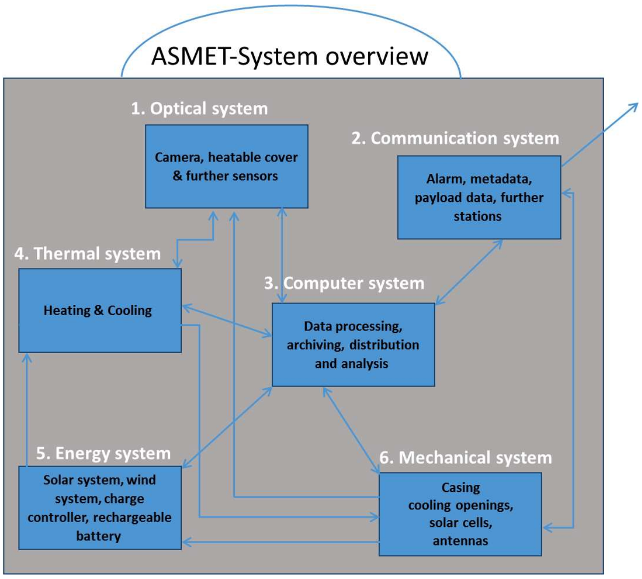

Figure 2 – ASMET system overview with relationships between functional groups.

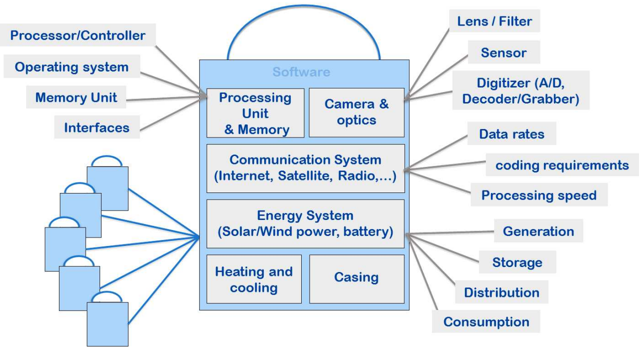

Figure 3 – ASMET functional groups with individual components and aspects.

5. energy system (solar and wind system, charge controller, rechargeable battery); and
6. mechanical system (casing, cooling openings, solar cells, antennas).

Optional additional sensors can also be added: rain sensor, wind gauge, seismic sensor, hygrometer, temperature measuring instruments, etc.

Based on the rough system concept, we develop a detailed top-down description of the individual components (Figure 3) for each of the six functional groups in the following subsections.

3.1 Functional group "Optical system"

A typical optical system consists of the following components:

- external contactor (transparent glass dome, dome heating, temperature, rain, humidity sensor, O-ring, twilight switch module);

Table 4 – Optical and computer system concepts.

Concept A	Concept B	Concept C
Common products	Custom embedded	Futuristic technologies
Components off-the-shelf	Multi-sensor cams	Dynamic, neuron processing
Fisheye cam	Camera array	DAVIS sensor
Single Board (industrial) PC	Intelligent camera base unit	SNAP neuron processor
Prototype 1	Prototype 2	Next projects

- camera system (fisheye lens/lens, aperture, image intensifier, imaging lens/filter, (CCD or CMOS) sensor/camera, digitizer (A/D converter, decoder/grabber); and
- internal housing (lightweight, plastic) due to modularity (UR2000), adaptability, and easy interchangeability (with the opening for the supply of CPU hot air for drying the fish eye and dome and connected cables).

There exist basically three approaches to video observation of the entire sky: reflective (curved) mirrors, fisheye lenses, and camera array. In the future, the development of Dynamic and Active-pixel VIsion Sensors (DAVIS) could play an important role for high-speed vision applications (Tedaldi, 2016). We decided to study two system concepts (Table 4): Concept A with fisheye lens Cam (MATRIX VISION mvBlueFOX3) and Concept B with four embedded 130° Cams (VRmagic VRmS-12/BW-COB M12 IR-Cut).

3.2 Functional group “Communication system”

In order to get a rough estimate of the communication needs, we use a simple (best guess) calculation of the frequency and usual duration of the meteor phenomenon. Furthermore, we want to distinguish, as with other M2M applications, between “control” and “monitoring”. The aspect of “system tracking” is not relevant to the ASMET project because the individual systems are stationary and do not move. “Control” requires a bidirectional low rate communication (telemetry data, such as Alarm-E-Mail with thumbnails, and telecommands, such as camera settings), and “monitoring” requires unidirectional high-rate transmission of event videos (e.g., meteors). Assuming that there are usually about 30 meteors per day (and night) with an average duration of 4 seconds, 120 seconds of transmitted payload data (video material) will be transmitted. Assuming an HD camera with at least 30 fps and a resolution of $1920 \times 1080 = 2\,073\,600$ pixels results in 3600 (120 s × 30 fps) frames per day with 9.3 MB (12 bit × 3 color depth for RGB, CMOS × resolution = $12 \times 3 \times 2\,073\,600 = 74\,649\,600$ bit) per frame results in 33 GB/day and multiplied by 30 days requires 1 TB of non-volatile memory (SSD) per month. Each video would add 10% overhead in meta-information (timestamp and possibly other sensor data) for internal communication and backup of all payload data. For external communication, however, only one event per day, of a length of 4 s, is sufficiently interesting (fireball, unrecognized event) to be uploaded to the server via satellite (push). Then, this takes 120 frames with each uncompressed frame of 9.3 MB, which results in at least 1.2 GB/day (including meta-information). In addition, the users could find a pair of thumbnails worth exploring and manually request further (uncompressed) videos (pull, via low rate communication). Such a video upload takes up to 30 minutes via commercial providers such as skyDSL2+ FLAT L Premium (upload 6 Mbit/s). In summary, there are four possible transfers to users:

- text-alarm only per e-mail;
- text-alarm per e-mail, with preview image attached;
- compressed video (system-AI decides to send);
- uncompressed video (user decides).

Communication channels and interactions with other observation stations will be developed in further work based on communication in satellite swarms.

3.3 Functional group “Computer system”

3.3.1 Hardware-functional scenario

After we decided to install a single board (industry) PC in ASMET and to compare different models, we decided to use Axiomtek’s Pico-ITX Embedded Board[2] for the first prototype. We have compared the following criteria with regard to the fulfillment of primary objectives: CPU, graphic, data handling (operating system, SATA), communication channels (ethernet, USB, PCI), expandability and energy budget. Further prototypes are to be equipped with cheaper and more energy-efficient SBCs, such as LattePanda and Raspberry PI 3/Module. In Concept B, we use the D3 Intelligent Camera Platform[3], which is available in combination with the four VRmagic Cams.

3.3.2 Software-functional scenario

For meteor detection and analysis, it was decided to write our own custom software. There are countless examples of similar software (ASGARD, Sandia, MeteorScan, MetRec, UFOCapture, WSentinel, AstroRecord, AstroVideo, Lucam Recorder, Meteor44, Motion, CMN_binViewer, UFOID with cascade classifier, Recap, and other OEM software and

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[2] `http://www.axiomtek.com/Default.aspx?MenuId=Products&FunctionId=ProductView&ItemId=8931&upcat=137`.

[3] `https://www.vrmagic.com/vrmagic-imaging/oem-solutions/camera-platforms/`..

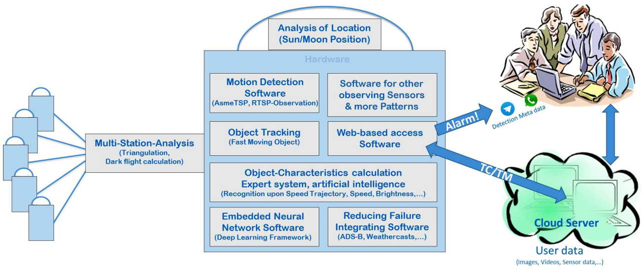

Figure 4 – ASMET Basic software concept.

detection algorithms), but we have decided to develop AsmetTSP software for university use for further customization and to improve existing ideas. Basic framework of the AsmetTSP software is a GUI programmed by students in C++ with QT-Cross-platform software development for embedded and desktop and OpenCV-Open Source Computer Vision Libraries for motion detection and analysis. This software is gradually being updated with sensor data and trained neural networks (Figure 4). We also use the common software UFO-Capture as reference software.

3.3.3 Data storage, distribution and archiving

On the basis of user requirements (Table 1), the data concepts for storage, distribution, and archiving are worked out, e.g., the system should back up the detections of at least 7 past days in off-line mode, the detection metadata shall be available to the user no later than 3 minutes after detection, and the payload (full) data should become available to the user 24 hours after remote detection at the latest.

3.4 Functional group “Thermal system”

Regarding to a very harsh environment, heating and cooling aspects will be tested and gradually improved in the first prototype (Figure 5).

Figure 5 – First Prototype ASMET1.

3.5 Functional group “Energy system”

Power system with Sun module, rechargeable battery, solar controller, Webbox-LCD for online monitoring and long-term statistics, as well as fuses and lightning protection have been set up. In the next prototype, more attention has to be paid to include the full number of 3 solar panels and consider more low-power components, to evaluate the self-sufficient operation capabilities.

3.6 Functional group “Mechanical system”

A sketch of the housing for the first prototype (Concept A) was custom-made by us and commissioned to a company for production. Regarding Concept B, we will design the array mount for VRmagic cameras so that with 20° elevation and four overlapping fields of view, we can cover the entire sky.

4 Conclusion and outlook

This paper is a description of the Project ASMET and its prototyping and testing phase. More detailed analyses and further prototypes are in preparation to integrate the “observation” and “analysis” of meteors and other transient celestial phenomena in better quality.

The task of the observation procedure is to set up and use autonomous observation systems with different kinds of sensors and algorithms to detect such transient phenomena as meteors are. The task of the analysis procedure is to analyze the meteor phenomenon itself but also all surrounding aspects like weather, air and space traffic, and astronomical situation, and to compare and combine these data with the results from other networked stations. This makes it necessary to have integrated and networked intelligent systems for observation, detection, and analysis with the specific time and location of the observation. By autonomous and synchronous observation of the same meteor from different locations with several different methods (e.g., optical and radio), including neural network analysis, more precise results can be extracted.

In addition to the primary project goals, the following secondary goals as next steps for future developments and subsequent projects are also considered:

- full autonomy;
- opening up of hard-to-reach, sparsely populated areas to the observation network;
- supplementation by additional instruments/sensors (e.g., environmental sensors);
- analysis and calculation of the trajectory and orbit;

- acquisition of comprehensive scientifically based data on so-called Unidentified Aeronautical Phenomena (UAPs) and their detection.

Long-term goals, in addition to education of university students, are to give students the opportunity to carry out interdisciplinary and practice-oriented research with their own prototypes resulting in diverse topics for final studies.

The currently available low-power single-board PCs and measuring instruments for sky observation have more performance and they are also more precise and lower-priced than before, which can be clearly seen, e.g., in the rapid development of the market for the commercial AllSky 360° HD 3D VR Cams with one or more lenses[4]. The open source software with countless libraries, databases and advances in autonomous driving and flying systems is also developing better and smarter than ever, e.g., the newest version of OpenCV supports deep neural networks (“createCaffeImporter”), as well as new and improved algorithms for important functions such as calibration, optical flow, image filtering, segmentation, and feature detection[5]. Novel end-to-end artificial intelligence products as system-on-chip (SOC) with dedicated Neural Compute Engine vision processing unit (VPU) and dedicated hardware accelerator for deep neural network inferences are appearing more and more on the market.

Area-wide, multistational observations will also allow orbital distributions to be determined. The atmosphere strongly reduces both the UV and IR range so that the best data in this range may come from cameras on small satellites[6] (meteors were also observed on other planets). Combining all of these aspects can help us to develop better methods to measure more accurate meteor characteristics optically and with all other methods.

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