OPTICALFENCE: SUPPORTING SST WITH OPTICAL TRIANGULATION

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ABSTRACT

Outline. We present the OpticalFence network concept aimed at providing low-cost optical observational data for objects in LEO (200-2000km).

Motivation. The goal of developing the OpticalFence system is to fill the gap between optical MEO/GEO monitoring and radar-based LEO observations with an robust and economical solution that is modular, expandable and able to provide not only angular and velocity information about the observed object, but also range.

System overview. The designed system consists of multiple-station segments distributed around the globe along local meridians that provide 3D state and velocity vectors of objects crossing a common volume of space that are seen by at least two stations. The 3D vectors are obtained with optical triangulation. We present the theory behind the concept, simulation studies, actual implementation and conclusions drawn from the obtained observational results.

Hardware. The OpticalFence observing stations use mostly off-the-shelf components, are virtually maintenance free and contain almost no moving parts. They are optimized for deployment in remote areas. The network concept is built around edge and cloud computing paradigms. Data streams from the cameras are processed in real time with heavily optimized on-board software. A key feature of the system is time synchronization – all cameras operating in the network are triggered by an external device that is GPS-synchronized, guaranteeing that all image sequences are taken at the same moment of time, down to microsecond precision.

Software. Image-related data processing is done on-board the devices. Once a moving object is detected, a small region of interest including the object and its immediate surroundings are packed into a binary file and uploaded to the cloud or further data synthesis. There, all detections are cross-correlated and events that satisfy certain matching criteria are merged using the triangulation technique to provide final position and velocity measurements in space. Finally, detections are cross-referenced against a known catalogue and identified, where possible. On-going work includes neural-network based image processing for increased precision and robustness, as well as TLE-prediction based synthetic tracking to increase sensitivity.

Summary. The presented system is modular, easily upgradeable – in terms of both software and hardware and provides a novel approach SST data delivery for LEO.

1 INTRODUCTION

Rapid development of sensitive, high resolution and high speed CMOS cameras have opened new horizons to precise wide-field observations during the recent years. With properly chosen optical systems such instruments can fill the existing gaps combining high efficiency with reasonable precision. Efficient orbital surveying of the LEO objects was a domain of large radar systems like GRAVES [1] such systems are very sensitive but also very expensive. Optical observations were typically limited to observing particular objects with small telescopes to make a precise astrometric measurements from a single site.

OpticalFence is the first reliable attempt to make usable optical surveying system for satellites and space debris exploiting optical triangulation. It is an evolvement of an idea of video fireball networks widely used for observation of meteoroids entering the Earth atmosphere. Optical Fence is also a derivative of the OmniSky project [2], an observing network created to observe space debris during deorbit phase. A network of three OmniSky stations is currently operational, observing the sky over south-eastern Poland, with expected altitudes below 70 kilometres. Optical networks developed for satellite detection must be usable on much wider range of altitudes. As opposed to meteoroids, objects orbiting the Earth, sooner or later will appear at the some particular part of the sky which allows to avoid observing the entire sky with less precise all-sky optical systems. The goal of developing the OpticalFence system is to fill the gap between existing optical systems monitoring MEO/GEO objects and expensive radar systems used typically for LEO surveying. Optical Fence solution is modular, expandable and is able to provide not only angular data but also the distance to the observed objects.

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2 SYSTEM OVERVIEW

OpticalFence is a network of observing stations resembling a fireball network used to observe meteoroids entering the Earth atmosphere. However, typical distances between stations are much larger because of the larger and more differentiate altitudes of the observed satellites. Also, the network geometry must be specifically adapted to some certain requirements.

OpticalFence is composed of multiple pairs of observing stations. Typical system may consist two stations with typical distance close to 1500 km (A, B) or may be supplemented by two additional stations placed in the center locations(C, D). This way we can observe using a single pair of stations (A-B) or three pairs (A-B,A-C,D-B). All stations are located roughly along the same meridian and observe the common volume of space located in-between. This way satellites observed by all stations will be illuminated the same way, with the same phase angle, we expect similar apparent brightness for every station. Because of the large vertical field of view (15x56 degrees) all satellites are detected along the meridian, at the altitudes between 200 and 2000 kilometres. Additional pairs of station can be used to improve performance at lower altitudes while the main pair is best suited for high LEO observations.

The satellite's position is determined using triangulation method – with two observing stations we can easily calculate exact position of the object – two half-lines originated at both observing stations and directed to observed object will intersect at the object coordinates (perfect case). With expected astrometric errors both half-lines will miss each other with very small distance with object located in the middle of the path perpendicular to both lines. This way we can measure the exact location of the observed satellite at specified time, precisely measured using GPS receiver. For every satellite fly-by whole sets of cartesian coordinates are available after calculations, such data are sufficient to determine the position, velocity (state vector). Orbital elements of the observed satellite can be calculated directly from the state vector and time. At the end the object is identified (if possible) by comparison with recent TLE data.

According to simulations every properly arranged pair of stations can observe and produce TDM [3] files for at least few dozen unique satellites per night. Observations are done mostly during two observing windows – one just after the sunset and another one at the end of the night. For the system located at the medium geographical latitudes observations are possible whole night during the local summer, when the Earth shadow is located low over horizon.

3 HARDWARE

OpticalFence network consist of multiple observing stations mounted in various locations along the common meridian. Every station is a remotely operated unit prepared for maintenance free operation, the only requirement is AC power and Internet connection available on the observing site. OpticalFence station is a man-size unit consisting of air conditioned cabinet and observing head with six optical windows on the top. Six industrial PC computers are mounted inside the cabinet, every computer is responsible for data processing of the corresponding digital camera. The cameras and PC computers can be remotely power cycled using a watchdog controller. The cabinet also contains various power adapters, a UPS, temperature and humidity sensors and other required power distribution elements. There is also GPS receiver connected to dedicated triggering circuit used to initiate video frames every 0.2s. An efficient air conditioner mounted on the sidewall makes it possible to use the station in every conditions including temperatures up to +50 Celsius degrees.

The observing head is mounted on top of the cabinet, it contains six digital cameras with lenses, connected to the computers using the USB 3.1 interface cables. The cameras and lenses are protected against direct sunlight using specifically designed moving shutter located between the lenses and optical windows. The head is designed to make a synthetic vertical field of view as described in the previous paragraph. The entire head can be tilted and rotated to obtain the required azimuth and altitude of the FOV.

Figure 1. Two OpticNode stations – Alpha 1 (on the left) located in the western part of Poland and Alpha 2 (on the right) at Kryoneri Observatory, Greece

4 SOFTWARE

OpticalFence software is built around edge and cloud computing paradigms, with image processing done onboard of the stations and with final processing on the cloud service.

4.1 Station firmware

Satellite trail detection and initial processing are being realized using onboard station firmware which is installed on internal PC computers. A video stream from the camera is captured by the firmware and then processed. All moving objects are detected, extracted from the background and buffered for further processing. Morphological and geometrical tests allow only trails representing actual satellites to be used for further processing. At this stage the satellite trail is represented by a sequence of a few dozen or few hundred images of the moving satellite. An initial processing allowing for data size reduction is applied at this stage. Detection frames are cropped around the satellite streak forming small 16-bit images (ROI-s), position of the ROI is stored to later image reconstruction. Centroids of the satellite streak are precisely measured in cartesian coordinates then converted to horizontal coordinates of the object using real time updated astrometric solution. From all available data the 3-dimensional FITS file is created, such file contains all ROI images and binary table with corresponding data like cartesian and azimuthal coordinates, pixel intensity, centroids positions (leading point, trailing point and center). Data from GPS video trigger are combined with corresponding frames, this way the frame timing has sub-microsecond precision. All other important data like station coordinates, station and camera designation etc are stored in the FITS header. The firmware creates also preview FITS files for diagnostic purposes (Fig 2.), typically once per hour. Such processing allows to maintain reasonable size of the transferred files despite of large amount of data processed on the station side. OpticalFence is able to detect and process multiple objects at once, even if the multiple objects are detected on the same camera.

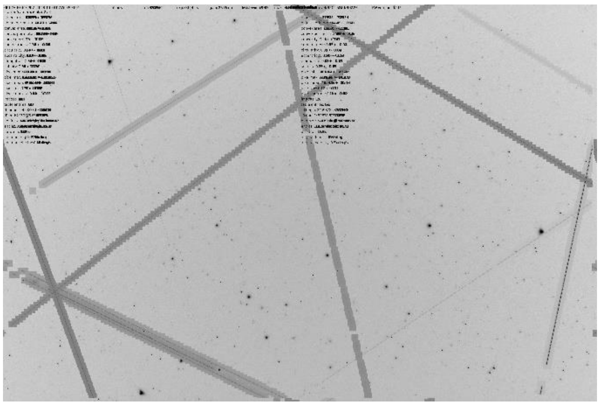

Figure 2. Detected satellite trails registered by single camera during 10 minutes of observations superimposed on preview image, 01.01.2023.

4.2 Cloud Service

All data from the OpticalFence stations are sent to server with MinIO storage and then captured by the cloud service for further processing. From every properly selected pair of incoming FITS files a set of satellite positions can be calculated. There is a large amount of incoming files and two stage selection is required for proper work. The first stage is time based selection, from all satellite detections with common time span a groups are formed. Such groups may be formed by accidental time convergence of unrelated detections or may contain true detection of the same satellite from two observing station. To filter out all accidental pairings the geometrical test is performed as the second stage, from every two points of the examined pair the initial triangulation is performed to check the possible distance between the line of sights (station-object half-lines). The pair is accepted only if mean distance fall below the threshold.

For each selected pair positional computations are performed, every pair of positions with the same GPS time stamp can be converted to cartesian coordinates of the observed satellite thus the result of computations for multiple ROI FITS files is a set of satellite positions with corresponding timestamps. Such set of positions can be used for state vector and orbit determination, as described in Section 2. For each calculated pair with all positions available the identification is performed. Observed coordinates of the object are compared with ephemerides of the satellites calculated from recent TLE file. If the measured and expected positions are properly matched the additional altitude test is performed to rule out any accidental matching. All results are stored in the database, for every calculated set of positions a TDM file is created containing angle and distance data (somewhat similar to radar measurements).

5 OPERATION

At the beginning of 2023 two OpticalFence networks are operational. The first one, OpticNode is owned and operated by Cilium Engineering. This network consist of two observing stations. The northern station is located in western Poland, the second, southern station is located at Kryoneri Observatory, Greece. The main axis of the network is slightly inclined with respect to the meridian, the distance between stations is almost 1700 km. The second network has been deployed for the Polish Space Agency and consist of three main components – European, African and Australian. Each segment of this network is composed of four stations – two in the outer locations and two in the middle, creating multiple pairs with base close to 1500km and close to 500-700km.

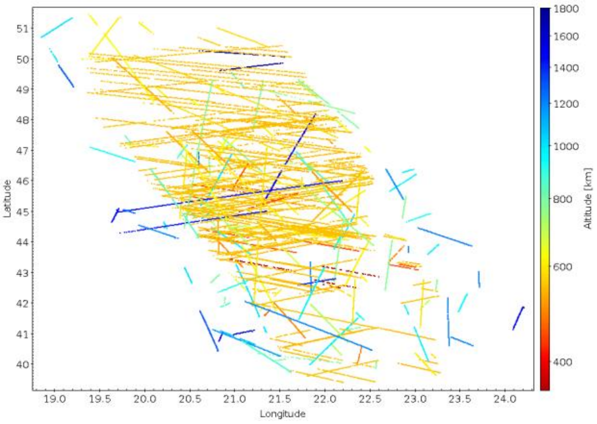

Figure 3. OpticNode results, one night of observation. 243 satellites were identified, majority of them belonging to Starlink constellation. This is a typical shape of the common volume of space observed by OpticNode.

OpticalFence is a very efficient system which is able to hundreds of unique objects per night. An example presented in Fig. 3 shows the results obtained by OpticNode sensors during the single night close to the summer solstice, when the Earth shadow is located low over horizon and system can observe for the whole night. 23 900 individual points were calculated. After object identification 243 unique satellites were found in the data. 172 satellites belong to the Starlink constellation, clearly visible on the graph as a large group of east-west oriented trajectories with typical height just below 550km. Remaining 71 objects represents all other satellites with highest observed altitude 1685 km.

During the first months of observations we found that OpticalFence is able to observe objects at altitudes at the wide altitude range. The highest observed objects (mostly rocket stages) on highly eliptical orbits were observed at the height larger than 6500km. On the other hand, satellites few weeks before deorbitation have been observed at altitudes close to 240 kilometres. Limiting stellar magnitude of the system is close to +11m, practical size limit is close to 1m at altitudes above 1500km and a few tenths of a meter for lower altitudes. Positional precision of the system is directly dependent of the image scale, geometrical configuration of the system and object altitude/distance, typically several meters for 200km orbits and is as good as 150m for 2000km. Examination of the collected data shows that precision at the level of 80-100m at 2000 km can be achieved with good geometrical conditions. Precision of 30m is achieved at best conditions for the Starlink satellites at 549km altitude.

6 SUMMARY

Optical Fence is an innovative project involving modern CMOS technology to create an efficient system for optical surveying of the satellites and space debris. First months of operations have shown that even the simple network created with two stations is able to detect few several hundred unique objects per night. On-going work includes neural-network based image processing for increased precision and robustness as well as TLE-prediction based synthetic tracking to increase sensitivity.

Finally, it is worth to mention that the system costs are significantly lower when compared to typical surveying projects. OpticalFence should be deployed in large numbers to improve observability of the space objects and provide data for SST services.

7 REFERENCES

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