FireOPAL: Toward a Low-Cost, Global, Coordinated Network of Optical Sensors for SSA

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ABSTRACT

FireOPAL is a new, distributed network of standalone, optical sensors that is designed to monitor a large number of artificial satellites simultaneously, providing wide area surveillance and precision tracking in near real time. FireOPAL observatories are fully autonomous intelligent imaging systems, taking high resolution images at high cadence, capable of operating for 24 months in a harsh environment without maintenance. An onboard processing system detects and calibrates the results, delivering thousands of measurements each night of angles, range, and light curves for objects in LEO, MEO, and GEO. The results are reported within seconds of the observations, with all imagery and other data products stored onboard. FireOPAL observations are synchronised over a distributed geographic network - this enables range estimation through triangulation, significantly reducing uncertainties in orbit determination and catalogue maintenance. The network reports measurements to a central server capable of providing alerts of anomalous behaviour and other warnings within minutes of the observations. FireOPAL measures apparent angular coordinates with an accuracy of a few arcseconds; absolute time within milliseconds; absolute flux to within 10%, and detects point sources with visual magnitude of ~16 or brighter. When orbits for both LEO and GEO objects are propagated forward more than one day, the predictions match the observations to better than one pixel. FireOPAL traces a direct engineering heritage to the Desert Fireball Network (DFN), an Australian planetary science observational facility designed to track meteoroids entering the atmosphere, determine pre-entry orbits, and pinpoint fall positions for recovery by field teams. FireOPAL observatories are the end result of 6 years development of hardened optical systems for the DFN. Each unit is designed to maximise sensitivity and functionality within a cost effective package that minimises build, maintenance and servicing costs. Networked together, the result is a system that can easily be scaled to arbitrary size, allowing for persistent observations with a high level of disruption tolerance.

1. INTRODUCTION

The Desert Fireball Network (DFN) is the world's largest planetary science observational facility. It is designed to track meteoroids entering the atmosphere, determine pre-entry orbits (their origin in the solar system), and pinpoint fall positions for recovery by field teams. Fireball observatories are sited at remote dark-sky sites across Australia - logistics for power, sensor platforms, and data connection are in place. Each observatory is a fully autonomous unit, taking 36MP all-sky images (with fisheye lenses) throughout the night, capable of operating for 24 months in a harsh environment, and storing all imagery collected over that period, modifying observations based on cloud condition. They are intelligent imaging systems, using neural network algorithms to recognize and report fireball events. Precise timing is required for orbit determination. We invented a method to embed absolute millisecond timing data into long exposures [1]. This advance enabled a cheaper system, without sacrificing sensitivity or data quality, allowing us to build a larger array for the same cost (currently the DFN stands at 50 observing stations covering ~2.5 million km^2). A larger array meant more data, which drove development of an automated data reduction pipeline [2-5] that delivers orbital data and meteorite fall positions, and that allows us to analyse our entire archive, and generate a complete orbital dataset for large debris. Supercomputer data storage of network imagery enables rapid post-processing and analysis of the entire dataset.

Figure 1. Two FireOPAL systems deployed in South Australia.

The DFN is a continent-wide machine that can automatically analyse and reduce its raw observations, and output high-quality trajectory and orbit data with propagated errors. At the scale of an individual observing station our design requirement was for an autonomous unit that a non-specialist could install; that was capable of operating for extended periods with minimal human intervention; that could meet IP65 criteria; that was highly modular and simple to upgrade; and that was cost effective (enabling a large array) without impacting data quality. Our final requirement was that the unit should deliver a dataset that was amenable to automated data reduction. We met those goals. This concept – a distributed optical network of hardened sensors built from COTS components, capable of triangulating events and processing data in real time – was the starting point for the development of the FireOPAL system.

2. FireOPAL OBSERVATORIES

FireOPAL (Fireball OPtical ALert) observatories are standalone, weather-hardened systems housing a COTS camera, with a high resolution prime lens, a GPS receiver, and an embedded PC. The cameras is a full frame 36MP CMOS sensor (current FireOPAL iterations employ cooled cameras). The observatories are solar powered with battery storage, and are capable of 3G/4G, wireless, satellite modem, or Ethernet connectivity. They differ from DFN units in a number of ways. They are significantly higher spatial resolution, and come with a high performance multi-core PC, allowing complete real time onboard processing of all imagery. When coupled to a 105mm lens, the field of view is approximately 20° x 12.5° with 10 arcseconds/pixel. They are designed to function as a coherent network, to monitor a large number of artificial satellites simultaneously, and provide wide area surveillance and precision tracking in near real time. FireOPAL observatories take 5 second exposures, with observations synchronized and time-stamped to millisecond precision across the entire network. Synchronised observations over a large distributed geographic network enables range estimation through triangulation. This has the effect of reducing uncertainties in orbit determination by up to an order-of-magnitude, compared to single-look observations, allowing us to derive precise orbits from COTS lenses and sensors. 30TB of hard drive space allows all imagery and other data products to be stored onboard. The entire package is designed to be low cost, and easy to deploy. The observatories are capable of operating completely autonomously for 24 months in a harsh environment without maintenance.

3. DATA PROCESSING

Each FireOPAL observatory reports measurements to a central server in near real time, which are then used for orbit determination and catalogue maintenance. The observatories are fully autonomous intelligent imaging systems, taking high resolution images at high cadence. An onboard processing system detects and calibrates the results, delivering thousands of measurements each night of angles, range, and light curves for objects in LEO, MEO, and GEO. The results are reported within seconds of the observations. The network reports measurements to a central server capable of providing alerts of anomalous behaviour and other warnings within minutes of the observations. Further details on the processing system can be found in elsewhere in these proceedings [6].

4. TESTING THE SYSTEM

OSIRIS-REx is a NASA sample-return mission to asteroid Bennu. The spacecraft, built by Lockheed Martin, has dimensions of 2.44 × 2.44 × 3.15m. On 22nd September 2017 it performed an Earth gravity-assist (EGA) manoeuvre with favourable viewing opportunities from Australia. Although the closest approach occurred over Antarctica, it passed over Australia with an altitude of 42,000 – 73,000km. The OSIRIS-REx EGA provided an excellent test of the components of the FireOPAL system: a spacecraft with well constrained dimensions, materials, and orbit, presenting a faint target at high altitude. Detection would be challenging, but if successful then it would enable us to perform a detailed evaluation of position / range errors for triangulated observations. In addition, lightcurve information from multiple viewing angles for a target of known size and composition would allow us to evaluate the degree to which target geometry can be reconstructed from lightcurves. The FireOPAL team built an Australia-wide observation campaign around the EGA. Observers flew to 11 sites around Australia, and one in New Zealand, to take observations. The distribution of sites was chosen to maximise opportunities for triangulation. The portable units used for the EGA do not have the computing resources and storage of a full FireOPAL observatory, but they do have the same imaging system, and all data collected was subsequently processed using the same pipeline that runs onboard a full observatory.

Although the spacecraft streak was only 10-15 pixels long, and around 15th magnitude, it was accurately measured in ~50% of images (where stellar crowding and sky noise were relatively low). FireOPAL hardware was capable of resolving it, and our automated image processing pipeline detected the spacecraft, determined its position, and generated a lightcurve (Figure 2). Triangulated datasets allowed us to determine an orbit (Figure 3). In all, approximately 13,000 images of the spacecraft were acquired as it transited over Australia & New Zealand. This dataset, for a single object on a single pass, is unprecedented.

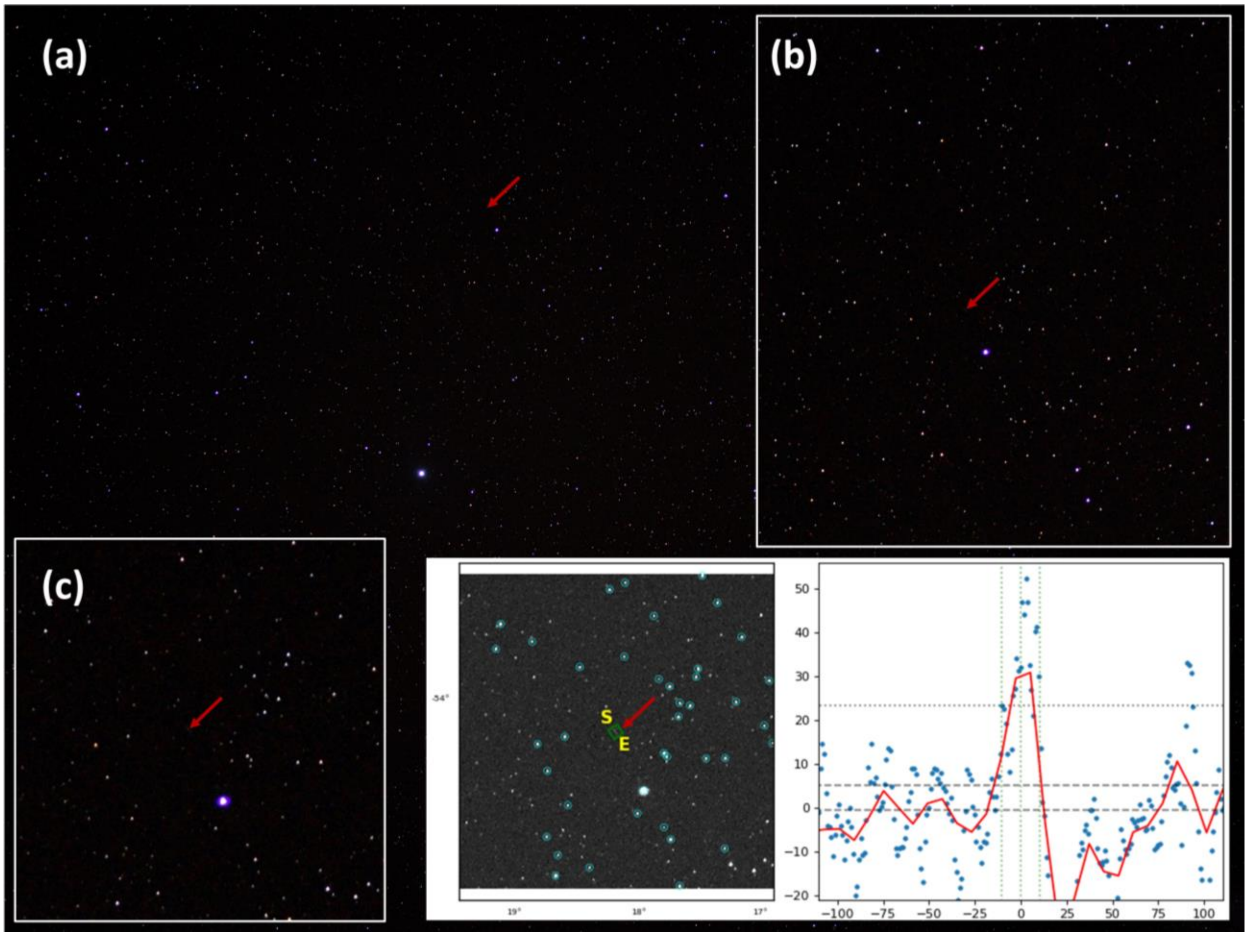

Figure 2. Capability of the FireOPAL system illustrated by observation campaign for OSIRIS-REx EGA: automated detection and tracking of a 2.5m spacecraft at 60,000km altitude. Full size image (a); zoom context images (b & c); detection, astrometric calibration, and lightcurve.

5. PERFORMANCE

FireOPAL delivers highly accurate track information, with cross-track and along-track angles with an accuracy of a few arcseconds. Typical residuals for objects in GEO are 1 arcsec. One test that we performed involved building orbits from our own observations, propagating them forward 24 hours, and then comparing how well our predictions match our observations. In many cases, for both LEO and GEO, the match is at the ~ pixel level (Figure 4). The system delivers high time resolution light curves for streaks, with photometry accurate to around 10%. Over the past few months, the system has recorded more than one million light curves of satellites which are used to deduce properties such as size, tumbling, composition, pattern of life, etc.

We currently have eleven FireOPAL observatories deployed around Australia. Six units are located at five clustered sites in central South Australia. Another five units are located in a cluster near the centre of Western Australia. These form our prototype network and are used to estimate the performance and capabilities of a much larger

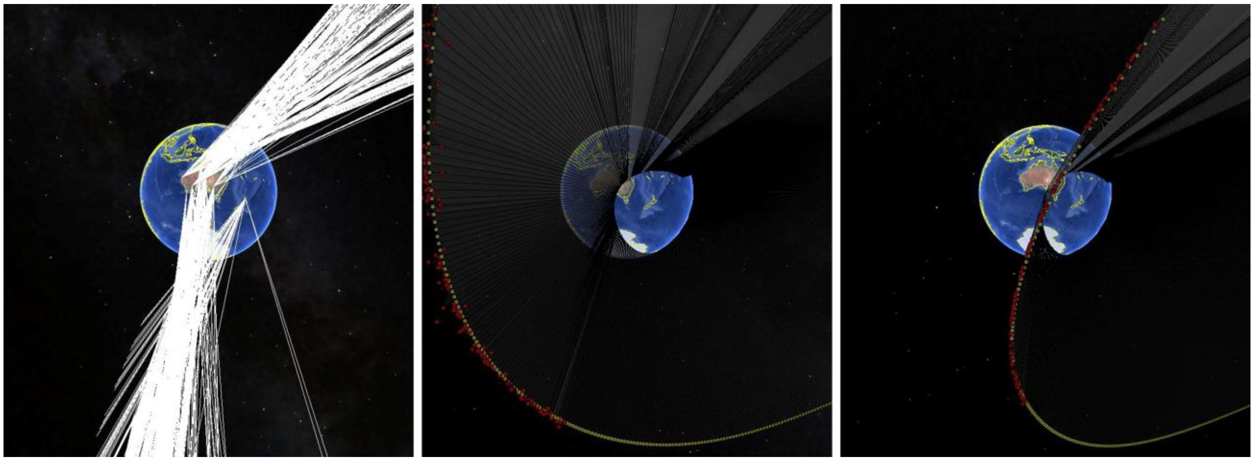

Figure 3. Lines of sight from multiple observations points across Australia and New Zealand for the OSIRIS-REx EGA; correlated pointwise triangulated positions for OSIRIS-REx (red) versus predicted position from telemetry (yellow; scatter is from range error); comparison looking down line of sight.

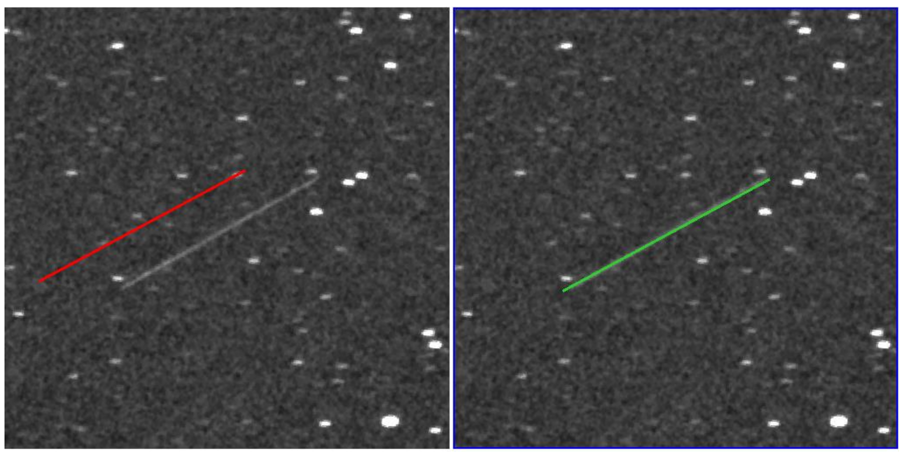

Figure 4. Comparison of orbit predictions from space-track and FireOPAL observations. The greyscale images are identical in each panel and subtend 1° by 1°. The image taken at 5 June 2018 20:04:10UTC from a South Australian site. The images are centered on a LEO streak that is well correlated with ASIASAT 2 PKM (SSN# 23725), a rocket body in a highly eccentric orbit. The left panel shows the predicted location of this object (red) using the most recently available TLE (at the time) from space-track; the TLE epoch was 22.4 hours older than the image epoch. The space-track prediction is offset from our observation by about 9.8arcmin in the along-track direction (~60 pix) and 5.3arcmin in the cross-track direction (~33 pix). The panel on the right shows the predicted location of the object (green) using an orbit to FireOPAL observations that were taken across the network on the previous night: 70 observations spanning 20.9 hours, latest observation was 26.3 hours older than the image. Our prediction is offset from the observation by 9.2arcseconds (<1 pix) in the along-track direction, 22.5arcsec (~2 pix) in the cross-track direction.

network of sensors. In the clusters, each sensor is separated by about 100km and are pointed at overlapping regions of the GEO belt. This enables imaging of the same objects from multiple sites at exactly the same time. On a typical night, each unit will take around 4,000 images.

If we consider a single observation period (1 June – 15 August 2018), we found that our current 'LEO/MEO' processing (streaks) detected around one million objects. 'GEO' processing (slowly moving point sources) detected ~700,000 objects (Figure 5). GEO processing involves stacking 60 frames (10 minutes) for GEO processing. The number of GEO measurements reported each clear night by each camera is about 1,000. We have a capture rate of around 90% for GEO [6]. The 10% that were 'missed' are likely due to a combination of unfavourable viewing angle of the satellite, the satellite is intrinsically faint, or its position was coincident with detector artefacts or other sources of noise.

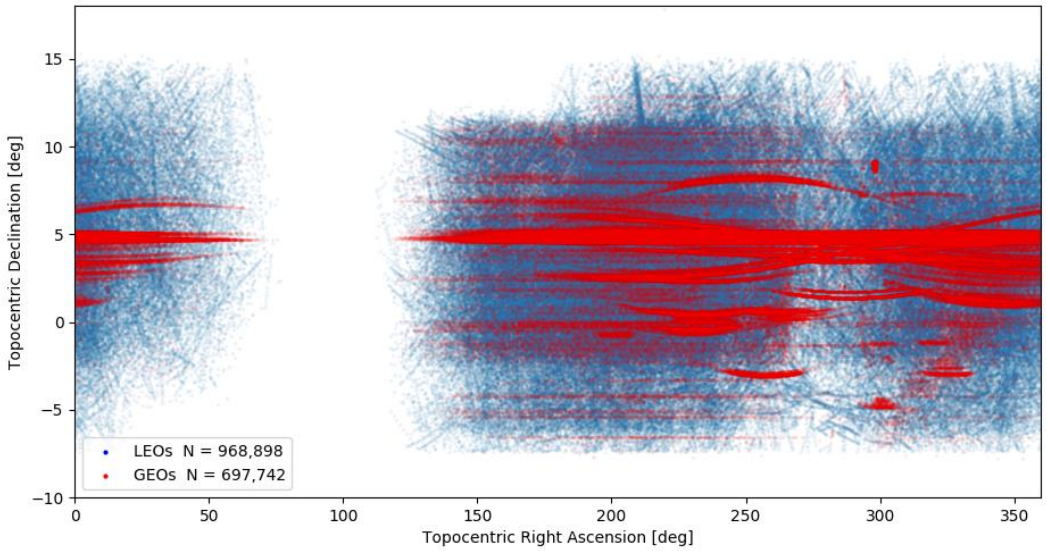

Figure 5. Apparent angular coordinates for LEOs and GEOs observed from all sites in the prototype network between 1 June – 15 Aug 2018. The gap near RA = 100° is middle of the day. The gap in LEOs near RA=275° is near midnight (LEOs in shadow). The diminished number of GEOs near RA=275° is due to noisy background from Galactic plane.

Finally, the near real triangulation of satellite positions and precision orbit propagation for hundreds of objects per hour across the network allows us identify anomalies and off larger, more sensitive, exquisite detectors for follow-up observations on the same pass. Our experiments are discussed in detail elsewhere [6]. They have been extremely successful. In one, we demonstrated that FireOPAL can detect a satellite, form tracks as seen across the sensor network, fit an orbit to all the tracks, and then perform a 'live' handoff to another sensors - all occurring within minutes of the initial detection. Where the objects were still visible (they had not set), they all appeared right in the middle of the small (<1°) field of view. A more difficult challenge is to build orbits, propagate them for 24 hours or more, and then task a larger sensor. Over a two week period in June 2018 FireOPAL orbits from the previous night were handed off to the DSTG sensor for automatic scheduling for observation for the current night. More than 90% of the orbits handed off were successfully imaged by the DSTG sensor and appeared in the middle of their field of view (with respect to the other 10%, one issue was that we had to downgrade our orbits to less accurate TLEs in order to drive the DSTG sensor control system; another was that objects on highly eccentric orbits, that had very low perigees (<400km) and were subject to significant atmospheric drag, had larger errors).

6. SUMMARY AND FUTURE WORK

The FireOPAL system is designed to be a cost effective optical SSA solution that tracks objects in LEO, MEO, and GEO. Our observatories can be mass produced, are simple to deploy and maintain, and can operate autonomously in remote environments for extended periods. Although the imaging systems in an observatory are comparatively low cost and low resolution (compared to larger telescope solutions), multiple, synchronized, triangulated observations deliver highly accurate orbits – comparable to results from exquisite (single look) optical sensors. The additional benefit is that a distributed network is disruption tolerant, unaffected by weather, images a large fraction of the sky, and extends the optimal terminator observation period. A FireOPAL optical fence, covering the entire GEO belt, with triangulation and redundancy, can be built from a network of a handful suitably placed observatories. Several fences, distributed at different latitudes, can be built for a fraction of the cost of a single one-metre class telescope. It is our goal to build a global system that can follow objects multiple times per day, is capable of catalogue maintenance for a large fraction of all satellites and is able to detect anomalous events in space as they occur.

7. REFERENCES

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