

# **FireOPAL: Continental-scale Coordinated Observations of the OSIRIS-REx Flyby**

**Trent Jansen-Sturgeon<sup>1</sup>, Benjamin Hartig<sup>1</sup>, Phil Bland<sup>1</sup>, Greg Madsen<sup>2</sup>, Matthew Bold<sup>3</sup>,  
Robert Howie<sup>1</sup>, James Mason<sup>3</sup>, Rod Drury<sup>2</sup>, & Dane McCormack<sup>2</sup>**

*<sup>1</sup>Space Science & Technology Centre, School of Earth and Planetary Sciences, Curtin  
University, GPO Box U1987, Perth, Western Australia 6845, Australia*

*<sup>2</sup>Lockheed Martin Space, 8 Brisbane Avenue, Barton, Canberra, ACT 2600, Australia*

*<sup>3</sup>Lockheed Martin Advanced Technology Center, 3251 Hanover St., Palo Alto, CA 94304, USA*

## **ABSTRACT**

OSIRIS-REx is a NASA sample-return mission to asteroid Benu. On 22<sup>nd</sup> September 2017 it performed an Earth gravity-assist (EGA) manoeuvre with favourable viewing opportunities from Australia. The closest approach occurred over Antarctica and it passed over Australia with an altitude of 42,000 – 73,000km. 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. Approximately 2,000 images of the spacecraft were acquired from each site as it transited over Australia & New Zealand. This dataset, for a single object on a single pass, is unprecedented. It enables 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 allows us to evaluate the degree to which target geometry can be reconstructed from lightcurves.

## **1. BACKGROUND**

### **1.1 The Desert Fireball Network**

The Desert Fireball Network (DFN), a continent scale observatory, monitors the Australian sky for the bright fireballs produced by meteoroids as they enter the atmosphere. The main objective of this project is to recover meteorites that can be traced back to their parent bodies through rigorous regression analysis. By capturing imagery of meteoroid events from multiple locations simultaneously, the DFN is able to determine the pre-entry orbit and fall site of meteorites, providing valuable insights into the history of the solar system.

The imaging system for the fireball observatories, a Nikon D810 DSLR and a Samyang 8 mm f/3.5 UMC Fish-eye CS II lens, continuously capture 27 second exposures every 30 seconds throughout the night. These observations are synchronized to GNSS time through an innovative technique of embedding absolute timing data into the long exposure images with millisecond accuracy [1]. This method provides the precise timing required for trajectory analysis and orbit determination.

Designed to withstand the harsh Australian outback, each of the 52 remote sites operates completely autonomously and can continuously collect and store data for up to two years without intervention. The data set collected through this project is unprecedented, with over three terabytes of data collected by the Australian network every night. An additional 40 observatories are currently being managed by the thirteen partner networks that form the Global Fireball Observatory (GFO). This instrument provides a large number of opportunities beyond the original project scope. For example, the network was uniquely situated to constrain the brightness of the GW170817 gravity wave detected by the Advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO) [2]. It also has applications in many other areas, including weather monitoring and detecting astrometric transients.

## 1.2 Adaption for Space Situational Awareness

In addition to meteoroids, the DFN observes a variety of spacecraft phenomena: including satellite streaks, engine burns to geostationary orbit and rocket launches. It was determined that with minor hardware adaptations, the remote observatories could prove a useful instrument for space situational awareness (SSA). The initial test of this was conducted by deploying three modified DFN systems north of Perth, Western Australia, having replaced the fish-eye lens used for all sky fireball detections with an 85mm rectilinear lens. Conducted in partnership between Curtin University and Lockheed Martin, this small network represented the first trial phase leading to the development of the FireOPAL network. The details of the ongoing development and hardware of the FireOPAL project can be found in [4], [5] and [6].



Fig. 1. A full installation of two completed FireOPAL observatories.

The distinct advantage of the GFO as a foundation for an optical SSA network is the engineering heritage and existing infrastructure. The observatories provide a rigorously tested control system, with independent power and network connectivity, that can host a variety of sensors and instruments in remote off-the-grid locations. This allows

for a distributed architecture for the potential SSA instrument, providing large baselines for triangulation, an extended terminator observation window (with stations at different longitudes) and provides resistance to weather interference [3]. With a global network, a distributed instrument provides persistent data collection at a fraction of the cost of an equivalent radar system. The main challenge in adapting the DFN observatories for SSA is the selection of an appropriate sensor/lens combination; the OSIRIS-REx flyby provided an exceptional opportunity to verify the performance of the leading hardware options.

### **1.3 OSIRIS-REx**

The Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) is a NASA operated sample return mission to the near-Earth asteroid 101955 Bennu - chosen due to its proximity to the Earth and its carbon rich composition. It began its journey on the 8th of September, 2016, and returned to perform an Earth slingshot maneuver on the 22nd of September, 2017. Fortunately, Australia was in a very advantageous spot for viewing this flyby event - both in proximity and time. This provided an excellent setting to assess the FireOPAL proof-of-concept against a known object with reliable telemetry.

## **2. OBSERVATION CAMPAIGN**

### **2.1 Portable SSA Observatories**

To observe the OSIRIS-REx flyby from multiple sites around Australia and New Zealand, we needed to design a lightweight alternative to FireOPAL while still providing the same functionality. This motivated the design of a portable semi-autonomous SSA observatory, comprised of an off-the-shelf D810 Nikon camera, a 85mm/105mm lens, a tripod and a custom triggering box. The focus of the campaign was the data collection, without the need for weather proofing, autonomous ongoing operation or image processing onboard. This allowed the system to be stripped down to the essential components. Without the need for a solar power system, processor or heavy steel stand the unit could be transported in a small case as carry on luggage.

The portable SSA units were assembled from components manufactured for DFN observatories. The triggering box contained the circuitry from a DFN observatory, including a GPS receiver. This unit actuated the shutter of the DSLR camera with a millisecond accurate signal, for 4 second exposures every 6 seconds, synchronising the observations across the portable network and enabling more diversity in post-processing. This reduced the functionality to that of a GNSS synchronised triggering mechanism, avoiding the complexity and power requirements of a networked system cable of onboard data management and analysis.

### **2.2 Site Selection**

To decide on the locations of our portable SSA observatory, we had to consider multiple factors including weather, ease of access, light pollution, operator safety (remote-factor) and optimised OSIRIS-REx viewing. The rough viewing locations were first established based on increasing our observational baseline in both the along-track and cross-track directions to improve the orbit prediction. Next these locations were refined based on local light pollution levels, and ease of access; primarily determined through the location of regional airports. Before committing to the chosen site however, we needed to keep up-to-date with the local weather and make alternative arrangements if it looked unfavourable. Fortunately, out of the 12 chosen sites, only Adelaide and Cairns were affected by poor sky conditions and were changed to Broken Hill and Mt Isa at the last minute.

The observation team was comprised of eight DFN team members and five partner universities; Charles Darwin University (CDU), University of Southern Queensland (USQ), Macquarie University (MQU), Australian National

University (ANU) and Monash (MON). Each university handled their observations locally while the DFN team covered the remote locations; identified in Fig. 2 by the university abbreviations or the International Air Transport Association (IATA) codes of the regional airport respectively. In the unique case of Darwin, a DFN team member joined the CDU team to run dual observations from the location allowing a direct comparison of the performance of an 85mm and 105mm lens.



Fig. 2. The strategically positioned observation sites for the OSIRIS-REx viewing campaign.

### 2.3 Pointing

With our observation locations selected, we needed to know where to aim our semi-autonomous portable SSA cameras to capture the passing of the OSIRIS-REx satellite as it slingshots around the Earth. To determine the correct altitude and azimuth for the camera to point, we estimated using NASA's HORIZONS system as a guide - downloading sufficient altitude and azimuth information for every site.

In an attempt to minimise the number of camera re-pointings while still keeping OSIRIS-REx in the center of the field of view, we segmented the predicted alt/az coordinates into 5 degree windows starting from when OSIRIS-REx became brighter than 15th magnitude until it reached the local horizon. This procedure was implemented using a python script, recording the centre of these observation windows along with their timestamp. This resulted in the observatories having to be manually re-pointed every 20 min at the beginning of the night and as often as every 4 min by the end - due to the increased apparent angular speed as OSIRIS-REx performed its flyby maneuver. From these observations, streaks can be detected and light curves constructed, aiding in the revelation of OSIRIS-REx's true trajectory.

### 2.4 Extracting Light-curves

The process of streak identification and light-curve extraction is more-or-less the same as that used for 'LEO/MEO' analysis in the FireOPAL pipeline [4]. This involves aligning, smoothing, and subtracting consecutive images to

highlight potential streaks within the current image. To remove the majority of artifacts and further identify statistically significant streaks, the smoothly varying background sky signal is removed and appropriate filters are applied based on the dynamics of the desired object. The stars in the region around an identified streak are used for astrometric calibration and photometric analysis.

To generate light-curves, a very narrow box is constructed to outline the uncovered streak. The apparent flux is then estimated as a function of position along the streak, providing photometric information that could perhaps determine rough size and possible spin rates of the satellite. More details about the pipeline processing and calibration can be found in [4], [5], and [6].

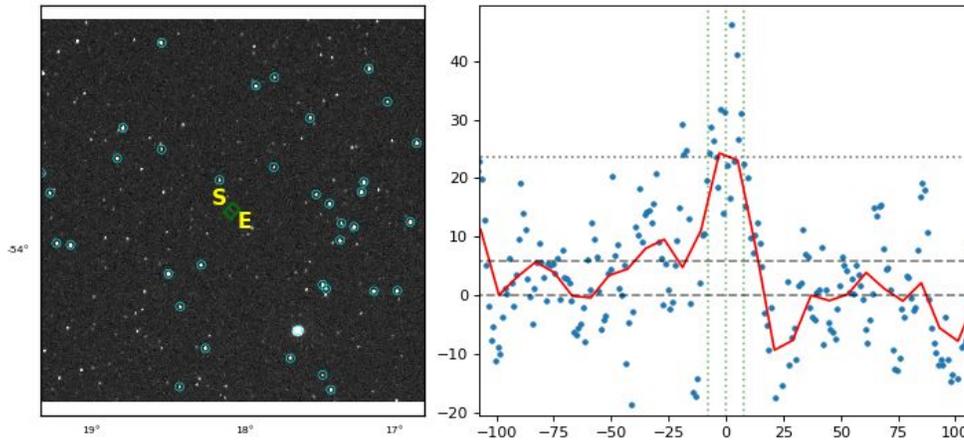


Fig. 3. An example of the light curves produced for each OSIRIS-REx streak.

In the case of OSIRIS-REx, the detection threshold was lowered to ensure all possible sightings of the satellite were captured and analysed. While this did lead to an increased number of unwanted artifacts, these could be eliminated knowing the rough trajectory path of OSIRIS-REx from any point on the ground.



Fig. 4. A series of five OSIRIS-REx streaks with timesteps from our Perth node.



Fig. 5. Stacked OSIRIS-REx streaks from a single pointing, lasting 288 seconds, from the Perth observation site.

Every portable FireOPAL unit managed to capture different amounts of OSIRIS-REx streaks due to varying ambient sky brightness and weather conditions. So far, we have analysed over 3,200 measurements of OSIRIS-REx as it performed its slingshot maneuver around the Southern Hemisphere, as shown in Fig. 6, with this number set to increase with further streak detection analysis.

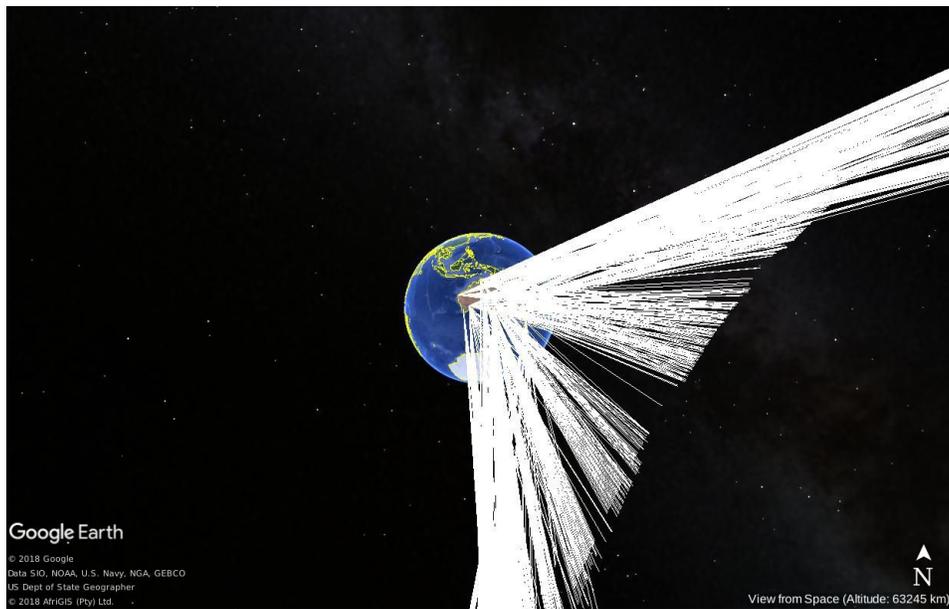


Fig. 6. Observation rays of OSIRIS-REx from the portable SSA cameras extending into space.

## 2.5 Orbit Determination

From the detected streaks, we can obtain where OSIRIS-REx is in the sky (ra/dec) and at what time (epoch). However we are missing all range information - a typical problem for optical SSA tracking. Although, unlike ordinary optical observatories, our network of portable SSA cameras are all triggered at the exact same time thanks to GPS synchronization, allowing us to extract range information using triangulation. The triangulation factor assists in making a more accurate orbit estimate over a shorter observation window, not only because of the increased data density, but due to the multiple perspectives that aid in constraining the trajectory.

Usually satellite orbits are determined using a least squares approach that involves fitting an orbit to a set of observations, or in other words minimising the perpendicular distance between the observed lines-of-sight and the predicted orbit. OSIRIS-REx proved to be a special case of orbit determination due to its hyperbolic trajectory with respect to Earth, as opposed to the typical elliptical orbits of the Earth bound satellites. However it is easily handled given the right set of generalised orbital equations.

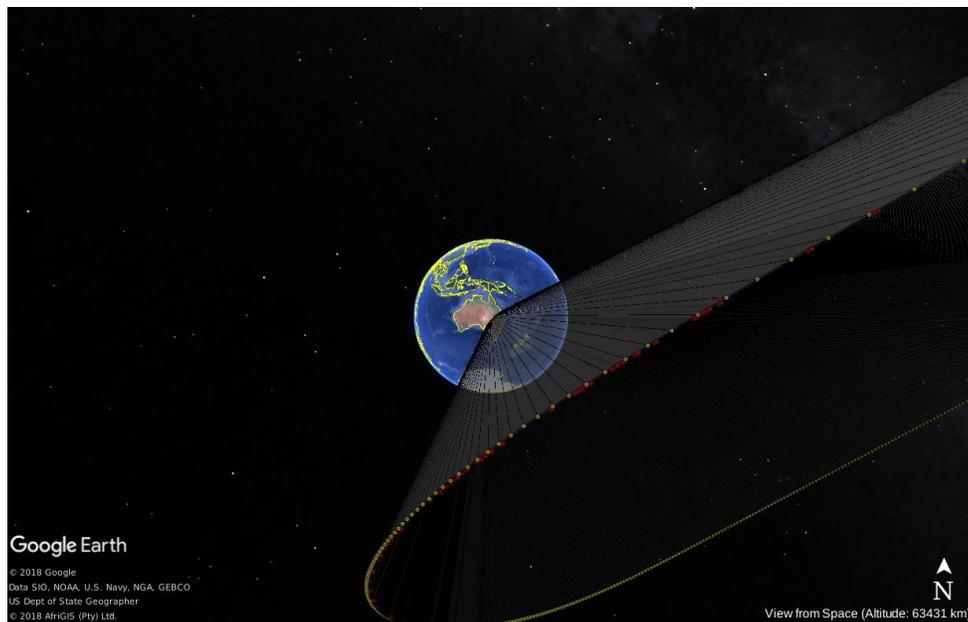


Fig. 7. The fitted orbit of OSIRIS-REx (red) given the captured observations against HORIZONS predicted orbit (yellow). The apparent odd shape of the slingshot is due to its portrayal in a non-inertial reference frame.

## 2.6 Hardware Limitations

The stripped down units provided a valuable tool for the observation campaign, however performance of the imaging system was suboptimal due to the heavy dependence on operator intervention and weather related impacts. The track of the flyby meant that the DSLR would need to be repointed throughout the viewing window, which introduced significant risks that in a permanent installation would be automated. Defocusing the lens, inadvertently adjusting DSLR settings and accidentally disconnecting cables, were a few of the obstacles the operator needed to avoid while repointing the tripod.

The power and memory provisions, which are typically abundant in DFN installations, were managed through multiple replacements of the DSLR batteries and memory cards, again introducing difficulty for the operator working hastily to minimise downtime within the viewing window. The replacement of the steel stand, designed to

withstand gusts of wind, with a lightweight off-the-shelf tripod, resulted in a few images compromised by the decreased stability. Fortunately, all of these issues represent obstacles previously addressed in the development of the DFN and have contributed to the significant increase in performance in the current FireOPAL network compared to the portable test units.

### 3. SUMMARY

The advantageous location of Australia & New Zealand for observing OSIRIS-REx provided the perfect target for testing a continent scale SSA instrument. Despite the compromises made to create a portable and lightweight unit, an unprecedented data set was collected for a single pass, providing a benchmark for the performance of the FireOPAL pipeline. With 11 Australian and 1 New Zealand site, the test maximised the opportunity for large baseline triangulations. The light curves collected for the spacecraft grant an opportunity to evaluate the potential for the reconstruction of target geometry. The campaign confirmed the capability of the DFN modified for SSA, with determined orbits in agreement with predictions.

### 4. REFERENCES

1. Howie, R.M. et al., How to Build a Continental Scale Fireball Camera Network, *Experimental Astronomy*, Vol. 43 (3), 237-267, 2017. doi:10.1007/s10686-017-9532-7
2. Andreoni, I. et al., Follow Up of GW170817 and Its Electromagnetic Counterpart by Australian-Led Observing Programmes, *Publications of the Astronomical Society of Australia*, Vol. 34, e069, 2017. doi:10.1017/pasa.2017.65
3. Bland, P.A. et al., Adapting a Planetary Science Observational Facility for Space Situational Awareness. *Proceedings of AMOS*, 2016.
4. Madsen, G.J. et al. FireOPAL: Technical Performance and First Results. *Proceedings of AMOS*, 2018.
5. Bland, P.A. et al. FireOPAL: Toward a Low-Cost, Global, Coordinated Network of Optical Sensors for SSA. *Proceedings of AMOS*, 2018.
6. Bold, M. et al. FireOPAL: Analysis of One Million High Time Resolution Optical Light Curves. *Proceedings of AMOS*, 2018.