Adapting a Planetary Science Observational Facility for Space Situational Awareness

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ABSTRACT

The Desert Fireball Network (DFN) 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 12 months in a harsh environment, and storing all imagery collected over that period. They are intelligent imaging systems, using neural network algorithms to recognize and report fireball events. An automated data reduction pipeline delivers orbital data and meteorite fall positions. Currently the DFN stands at 50 observing stations covering ~2.5 million km^2. A sub-set of the existing stations will be upgraded with a parallel camera package using 50mm prime lenses. Paired stations will allow triangulation. The high resolution array would deliver a ~Gpixel tiled image of the visible sky every 10 sec, at 20 arcsec resolution, with a limiting magnitude of ~13 in a 10 sec snapshot. There are benefits in transient astronomy (optical flashes associated with gamma-ray bursts; flares from sources that generate ultra-high energy cosmic rays), and space situational awareness. The hardware upgrade would extend the resolution of the DFN into the V=11-12 magnitude range for objects in LEO, allowing us to observe significant activity during the terminator period. The result would be a wide field array, capable of triangulation, with a 3500km baseline enabling a larger terminator observing window.

1. INTRODUCTION

Meteorites produce a bright fireball as they transit the atmosphere. Deriving precise orbits for meteorites requires high quality photographic observations of a fireball from a number of locations. This occurred for the first time by chance in 1959. Cameras set up to monitor meteor streams in the Czech Republic recorded a brilliant fireball on 7th April 1959 [1]. That fireball resulted in the Příbram meteorite. Subsequently it was realised that there was the potential here to explore an entirely new field of research: scientists now had a method for recovering meteorites with orbits, and determining a spatial context for meteorites – their origins in the solar system – via observations of the fireball. Since then a dozen projects – professional and amateur – have pursued the goal of recovering meteorites with known orbits (e.g. [2,3]). This scientific effort yielded 10 rocks. Although the numbers are small, even this handful generated fundamental insights: the early work provided the proof that meteorites come from the asteroid belt. But why so few? All these projects were sited in the temperate zone of the northern hemisphere: vegetated areas where recovery efficiency is marginal. Deserts are one of the few places on Earth where meteorite recovery is straightforward. This was the driver behind the Desert Fireball Network (DFN).

2. THE DESERT FIREBALL NETWORK

The DFN currently has 50 observatories across 2.5 million km^2 of outback Australia (Figure 1). In addition to the observing hardware, logistics for dark-sky sites (power, sensor platforms, data connection) are all in place. It is a distributed system with components co-ordinating and communicating to observe a class of solar system objects that we cannot see in any other way. An automated software pipeline handles data reduction. A meteorite was successfully recovered from Lake Eyre on 31st December 2015, using that pipeline. By end-2015 we had built a supercomputer database for storage, allowing us to process our entire archive. By February 2016 we had reduced our complete fireball dataset, deriving precise orbits for >300 bright fireballs: the largest single dataset of its kind ever collected (Figure 2). With a larger area and minimal cloud cover we see ×10 more sky than any other system, with higher resolution cameras, and automated data reduction, in an area that is well suited to meteorite recovery. Low rainfall means that recovered samples will be pristine (even brief exposure to rain can degrade the primordial record that they contain [4]). The unique potential of the DFN was fundamental in forging a formal Australia-NASA partnership in planetary and exploration science. This partnership has allowed us to develop collaborative relationships with US colleagues that are central to maximising project science return going forward, including expansion overseas.

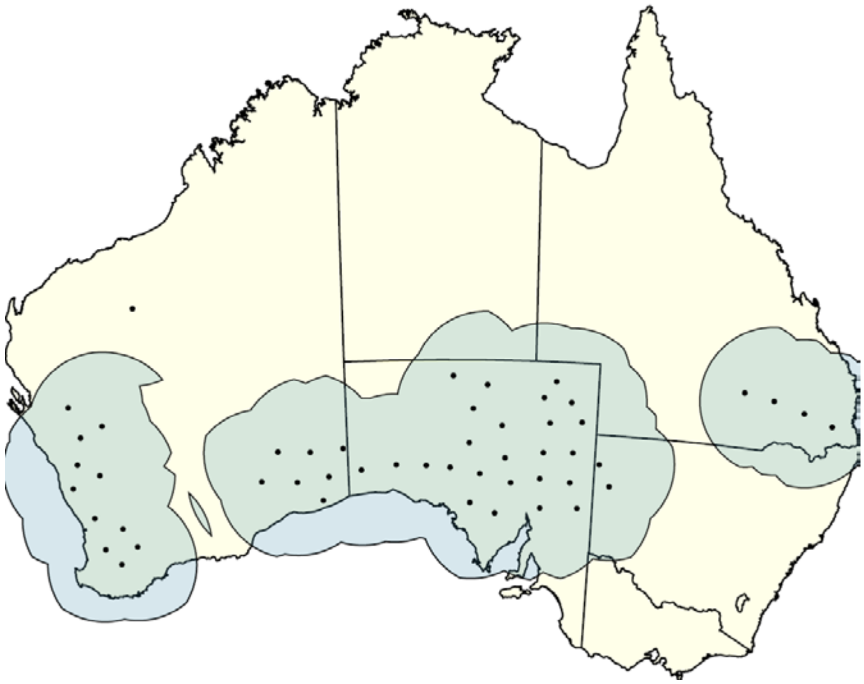

Figure 2. The Desert Fireball Network across Australia, showing positions of observatories and observing area.

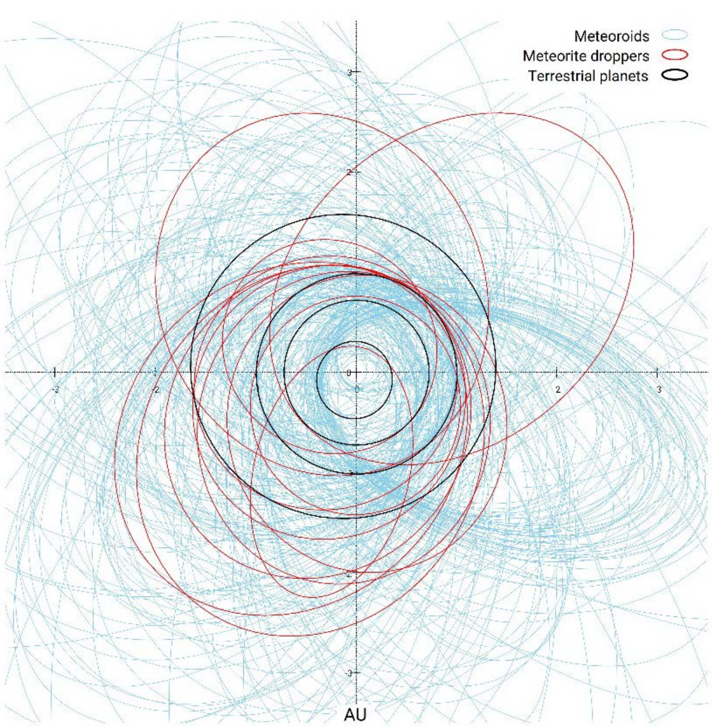

Figure 2. Orbits for DFN fireballs and meteorites as of March 2016

The DFN can revolutionise our understanding of the dynamics, origin and evolution of asteroidal and cometary debris; record space debris fireballs; track satellites and rocket launches (Figure 2). It will deliver transformative science across many areas. One example is defining a spatial context for meteorites. Reading the record in meteorites is like trying to interpret the geology of a continent using random rocks found in a backyard. Meteorites sample the entire compositional diversity of the inner solar system, but with no way to match rock to outcrop, that potential is wasted. The DFN can provide the outcrop data that will let us realise the potential that meteorites have to offer, and interpret the record they contain. Our Lake Eyre meteorite recovery demonstrated that every link in the data collection and analysis pipeline works.

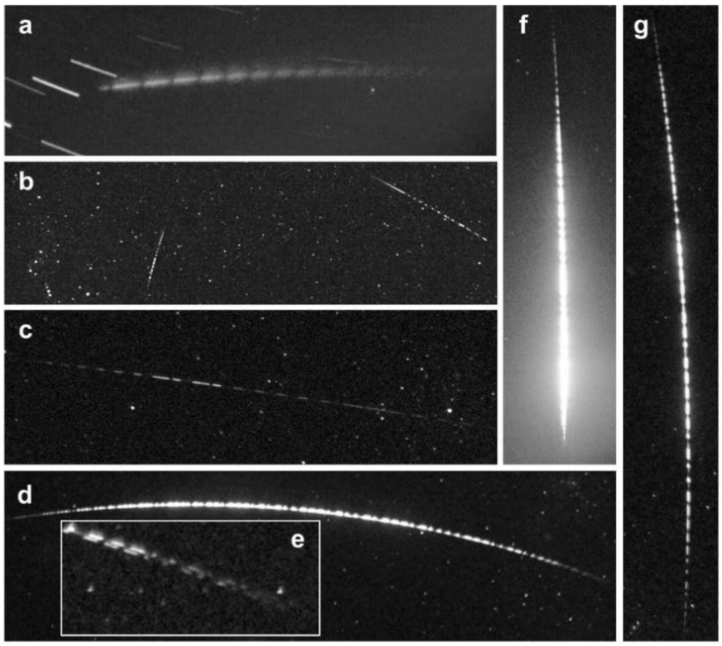

Figure 3. Selection of DFN images: a) tracking a LEO to geostationary boost; b) 2 fireballs in same 30 sec image; c) outer solar system comet fragment; d) resolution of imagery: tracking individual fragments; f) fireball from Lake Eyre meteorite; g) fireball from another fall: 11 await search.

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. Our fireball observatories are fully autonomous intelligent imaging systems, capable of operating for 12 months in a harsh environment without maintenance, and storing all imagery collected over that period, modifying observations based on cloud condition, and automatically recognizing and reporting fireball events using neural network algorithms. Precise timing is required for orbit determination. We invented a method to embed absolute millisecond timing data into long exposures [5], an innovation that we have patented [*Patent pending AU2016900714*]. This advance enabled a cheaper system, without sacrificing sensitivity or data quality, allowing us to build a larger array for the same cost. A larger array meant more data, which drove development of an automated data reduction pipeline [6-9] that allows us to analyse our entire archive, and generate a complete orbital dataset for large debris (Figure 2). Supercomputer data storage of network imagery enables rapid post-processing and analysis of the entire dataset.

A larger array – hardware innovation: The original hardware concept was an iterative development, built around astronomy CCDs, alongside photomultipliers for precision timing. We invented something radically new: a shutter system within the lens of each observatory encodes a unique non-repeating DeBrujin sequence into each fireball (Figure 4), providing accurate, absolute embedded timing information (to 0.4 ms) for the duration of the trajectory [5]. This advance allowed for a much cheaper system, built around interchangeable high resolution DSLRs: highly modular, simple to upgrade and maintain, without any sacrifice in sensitivity or data quality [10,11]. Each system includes a Nikon D810 36Mpixel camera with a fish-eye lens providing all-sky coverage, 2x8TB hard disks (sufficient to record a complete 12 month dataset), low-light video, and embedded PC. Camera software controls system hardware, permitting customisation of camera settings and scheduling operations; monitoring cloud conditions and internal environment, adjusting exposures accordingly; handling networking; and processing imagery (neural network algorithms detect fireball events). The package is fixed to a stable platform, with independent comms and solar power. A typical station is shown in Figure 5. The DFN is comprised of 50 of these stations, allowing for continual monitoring of the sky over a 2.5 million km^2 area.

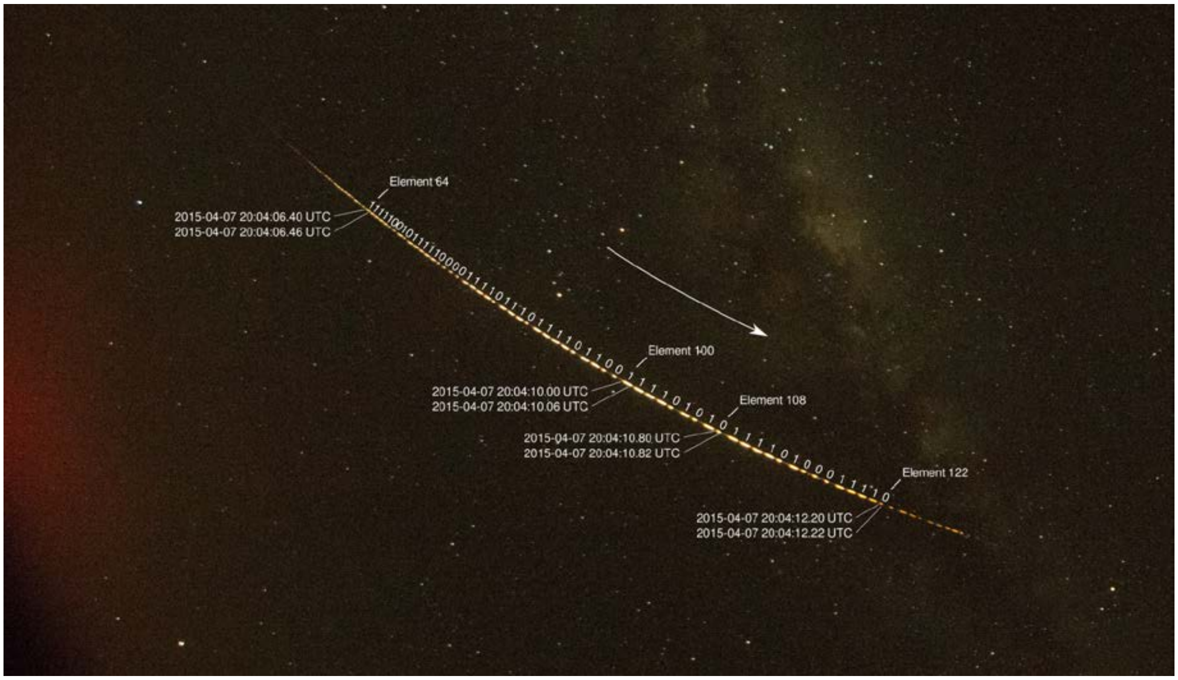

Figure 4. A shutter system within the lens encodes a non-repeating DeBrujin sequence into a fireball, absolute embedded timing and velocity information.

Figure 5. DFN observatory at Mt. Ive Station, South Australia.

Reducing all of the data - software innovation: A larger network area, together with increased sensitivity of the digital systems, gave rise to a rate of data acquisition that required an automated digital pipeline for data reduction. Data reduction in earlier projects which employed high resolution cameras (necessary to minimise errors in fall position) has been labour intensive. In practice, this has meant that >95% of fireballs are not analysed, or data published. Our automated data reduction pipeline [6-9] was completed by October 2015. Software detects fireball trajectories in pixel coordinates, and converts them to celestial coordinates, at sub-arcminute precision, by automatically identifying surrounding stars, and using them as a referencing system. Our approach to fireball modelling is also radically innovative. There have been iterative improvements in this area for 50 years but none are amenable to automation (or allow error propagation). We model changing meteoroid mass using particle filters, and additional methods from Guidance Navigation and Control (Figure 6). Once ablation stops, a WRF atmospheric wind model with a ~100m resolution mesh is created around the area of the fireball to calculate a fall position and probability map. The data pipeline enabled the recovery of a third DFN meteorite on 31st December 2015, from Lake Eyre. By February 2016 we had derived orbits for every fireball from 18 months of observations. We can now go from raw fireball imagery, to trajectory, orbit, and initial fall position of a meteorite, in ~15 minutes.

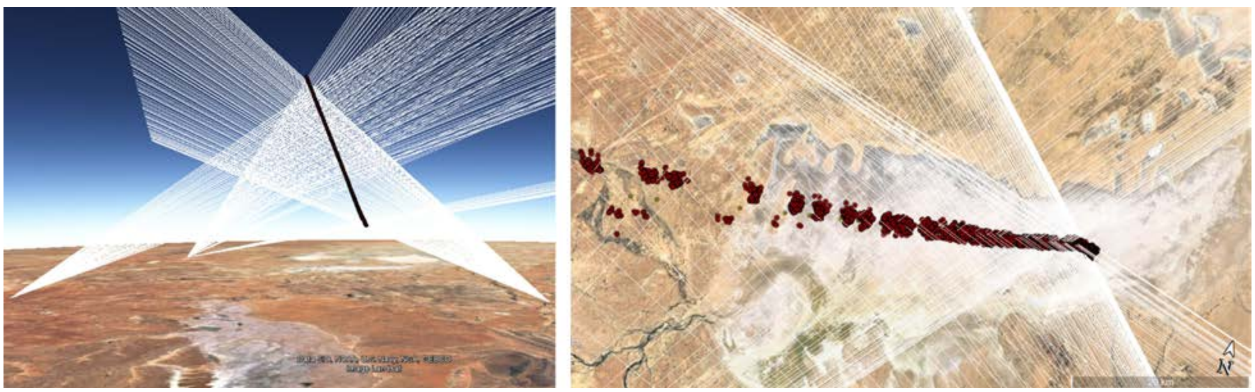

Figure 6. Modelling changing meteoroid mass, velocity, and trajectory using particle filters.

Storing all of the sky: The DFN currently collects ~50,000 images per night. Our automated data pipeline detects and reports fireball events, immediately downloading fireball imagery via Telstra NextG network. But the observatories record all imagery – not only fireballs – on 2x8TB hard disks. Rather than delete non-fireball images as initially intended (99.99% of the imagery), we developed a data management system that capitalises on preferential access to Pawsey Centre supercomputer facilities for Curtin University academics and geoscientists. An allocation of 1 petabyte storage allows all hard disk data to be ingested into a purpose-built archive – a supercomputer database of 15 million images – completed end-2015. It dramatically simplifies post-processing and analysis of our dataset. But a continuous record of the sky, over a large fraction of a continent, contains much more than fireballs. It is a high resolution archive of all of the sky, all night, every night, at 30 second intervals, from multiple locations. It is a unique resource. Thus far we have identified and tracked satellite burns to geostationary orbit, novae and supernovae. It prompted us to explore whether the DFN architecture and/or data archive could be of value to other fields.

3. A HARDWARE UPGRADE FOR ASTRONOMY AND SPACE SITUATIONAL AWARENESS

Here we discuss potential applications for astronomy and space situational awareness. Although the DFN was built for planetary science applications, its unusual design gives it the unique ability to address astrophysical problems across a range of scales in terms of duration, cadence and luminosity. Most optical astronomical transient surveys have a narrow field of view and low cadence which means that they cannot track continuity of objects across adjoining fields or in time. The unique capability of the DFN is that it observes the *entire* night sky, *all* the time. As a high cadence network with all-sky capability and a long operation cycle it accesses astronomical events with durations from ten seconds through to the lifetime of the network, or for space situational awareness as a wide field sensor with high cadence. As a distributed network it can monitor and track satellites without downtime for weather. The large baseline extends observations during the terminator period. Most importantly – for both applications – we can leverage the entire existing infrastructure from a continent-scale observational network that has already been constructed.

Implications for astronomy: A low-cost upgrade to the existing Fireball Network stations has already been prototyped and field tested. It has sufficient sensitivity to reach predicted luminosities of target events in the Local Universe, with a single 10 sec snapshot reaching, for instance, the *least*-luminous known optical gamma-ray flashes to a distance of 0.95 Gpc, equivalent to a look-back time of 17% of the age of the Universe. Images stacked over 40 minutes have sufficient sensitivity to detect hypernova explosions to >50 Mpc. With an adapted data reduction pipeline, the Desert Fireball Network can be expanded to a parallel function as a novel, powerful, astronomical facility, with unique capability. Primary research targets here would be studying gamma ray burst optical emission (although GRBs were discovered in the Cold War era, we still do not fully understand the physics of the brightest electromagnetic events in the universe), extremely rare classes of supernovae, electromagnetic radiation accompanying gravitational waves, counterparts to fast radio bursts and ultra-high energy cosmic ray and TeV energy photon events, as well as Galactic archaeology with variable stars, and microlensing.

Implications for space situational awareness: As it stands, the DFN offers two principal benefits in space situational awareness. The NASA Orbital Debris Program Office conducts a survivability analysis on all large satellites. NASA uses two models in this process, both of which are highly theoretical with limited calibration data. The DFN routinely observes re-entering debris. With the existing DFN we can provide calibration data to NASA allowing it refine these re-entry models. In addition, the DFN is currently able to track satellite burns to geostationary orbit. But the hardware upgrade that will extend the resolution of the DFN into the V=13 magnitude range offers would significantly expand its potential for SSA. We would observe significant LEO activity during the terminator period. V=13 in a 10sec exposure translates to approximately V=11 for an object in LEO (without post-processing) – approaching 'cubesat-class' objects. In addition to triangulation, with a continuous network coast-to-coast, we have a much larger terminator observing 'window'. The niche for this type of novel optical surveillance paradigm would be as a wide field detector capable of generating a self-starting catalogue, detecting planned (maneuvers) or unplanned (collisions) changes in orbit as soon as possible after they occur. Developing algorithms to process all the data for thousands of targets per night, in close to real time, is a significant challenge, but having the hardware in place would provide a clear path along which technologies and systems can be assembled, trialed and integrated, for a proof-of-concept.

Hardware upgrade: To build the upgraded facility a simple hardware increment is required. A sub-set of the existing stations will be upgraded with a parallel camera package comprising a 36Mpixel Nikon D810A, equipped with a Sigma 50mm f1.4 lens, and sufficient memory (5x8TB hard disks) to record the sky at high cadence. We have built, installed, and field-tested a prototype version of this unit. An individual system covers ~1/25th of the visible sky. With 28 systems we have the flexibility to tile the visible sky, with sufficient overlap to allow for triangulation. As with the existing system, the upgrade package is highly modular: cameras, hard disks, or complete systems, can be changed by individuals on-site in minutes. The entire array would deliver a ~Gpixel image of the visible sky every 10 sec, at 20" resolution. The prototype upgrade packages with Nikon D810 deliver a single camera snapshot (10 sec exposure) sensitivity of 13th magnitude. For photometry, in preliminary testing we achieve an RMS of ~2.5%. These are results of initial trials. We expect to improve as we gain further insights into the performance of our system. Finally, the systems used in the array will employ the Nikon D810A – a version of the D810 optimized for astrophotography. We anticipate an improvement in sensitivity with this system for astronomical applications.

Real-time data pipeline: The upgraded facility would employ a modified version of the existing Fireball Network data pipeline. To find candidates while minimizing CPU power requirements, each station pipeline will perform only image alignment and comparison of each frame with a series of previous images to generate a list of new sources in real-time. Once the data are collated, during camera downtime in the day, the automatic fireball triangulation algorithm, upgraded with a minor planet search service and satellite database, will generate a near-real-time list of triangulated targets and geostationary positions, potentially allowing for rapid ground-based follow-up in the event that unscheduled maneuvers are observed.

Data archive and offline pipeline: Every frame from the expanded facility will be archived. Data from each stations hard disks will be ingested onto the existing HPC datastore to provide a searchable archive. The offline pipeline will perform a full astrometric extraction of each frame (using tools such as SExtractor), rather than the simple image differencing employed by the real-time system. In this rigorous approach, all the objects identified and calibrated by the photometric and astrometric pipeline will be catalogued to a fully searchable database – an extension of the existing DFN database.

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