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# Project ASTRAL: All-sky Space Telescope to Record Afterglow Locations

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**Abstract.** ASTRAL is a project incorporating a wide-field optical telescopes on board of a small satellite dedicated to the whole-sky detection of a variety of rapid astronomical phenomena, particularly optical flashes associated with gamma ray bursts (GRB). Those flashes only visible optically (so called "orphans"), as well as those preceding associated GRBs, cannot be detected in the current triggering mode of the world wide GRB Coordinates Network (GCN). Hence ASTRAL would have a unique opportunity to trigger a follow-up multi-frequency study via GCN. ASTRAL consists of a set of 13 wide-field cameras (each with $FOV = 70^o$) equipped with 4096x4096 CCDs. The detection method is based on the Digital Blink Comparator mode, with a template of a complete sample of $\sim 2$ million stars down to $12^m$, precisely measured in the HIPPARCOS and TYCHO-2 missions. Supernovae, novae and nova-like explosions, fast variable AGNs, flare stars, and even new comets would be promptly detected as well. Monitoring of Near-Earth objects (NEO) is of special interest. Thus ASTRAL would also be an original working prototype of the prospective major space mission to monitor on-line all the sky - a high priority instrument of the 21st Century astrophysics.

**Key words:** Space Astronomy – Gamma-Ray Bursts – Variable Stars: Flare Stars – Comets

## 1 Introduction

Gamma-ray bursts (GRBs) remain one of the great mysteries in astrophysics. Although there have been measurements of the energetics of some bursts through redshift determination (e.g., Kulkarni et al. 1998), there is little firm knowledge of how the energy is produced. In fact, the total production is still uncertain by approximately 2 or 3 orders of magnitude because of the unknown level of postulated collimated jets (van Paradijs et al. 2000). Additionally, the total number of GRBs studied optically remains small. It recently became evident that the Gamma-ray burst (GRB) could appear to the observer only in optics (so called *orphan*, see Rhoads 1998), or optical flash could even precede GRB (Beloborodov 2001). Such optical flash associated with GRB can not be picked up early enough by the current GRB Coordinates Network (GCN). Even SWIFT, apparently so powerful mission having an on-board optical telescope, is unable to do it. This way we possibly miss an important clue to resolve the mystery of GRB, the most powerful and extraordinary fast exposition in the Universe.

So a problem is to build up an optical telescope which catches an optical transient (OT) and trigger other observatories in the GCN like way. It preferably should be an all-sky system, independent of the common Earth based restrictions: weather, day/night and Moon-phase illumination effects, various false lightnings and regular light pollution, - thence a space based mission. A probative ground-based system, which watches a FOV = $17^o \times 20^o$ synchronously with HETE-2, was recently installed (Pozanenko et al. 2004), but it evidently has the all severe restrictions mentioned above.
We propose here project ASTRAL - a space system, which, being compact and relatively cheap, provide an independent and early detection of various optical flashes on the whole sky sending an instant alert to other multiwavelength observatories including the gamma-ray ones (Tsarevsky et al. 2004).

## 2 Motivations and scientific objectives

### 2.1 Motivations of creating ASTRAL

MOTIVATION 1:
The total number of GRBs studied optically remains small. Moreover, for the short GRBs (with T < 2 s) there is almost no detection of optical afterglow. In fact, there is still only one optical detection covering an gamma-ray burst – the truly spectacular flash of GRB 990123 detected by ROTSE with the following characteristics (Akerlof 1999):
measured optical vs gamma-ray light maximum delay 22 s;
initial afterglow's detection: $11.7^m$ V;
maximum: $8.9^m$ V;
the power law decline down to the ROTSE detection limit $14.3^m$ V.
This detection level of GRB 990123, $\leq 12^m$, has been chosen as a basic parameter of ASTRAL - its detection ability. It would possibly give quite small rate of detection, but we should persue a new quality data to obtain: small in quantity, they could give a crucial knowledge about GRB nature. As listed below, ASTRAL would also detect a vast number of various other objects of high astrophysical interest.

MOTIVATION 2:
Gamma-ray bursts are believed to emit synchrotron or inverse Compton radiation from material moving at ultrarelativistic velocities. The resultant strong Lorentz beaming of the emission will decrease as the shocked material slows down. If the ultrarelativistic bulk flow is a collimated jet, radiation at wavelengths longer than gamma rays, believed to be produced by this slower material, will be emitted through a larger solid angle (Rhodes 1998). This suggests a population of *orphans* - optical bursts with timescales similar to GRBs but more frequent and with no gamma-ray signature.

MOTIVATION 3:
A search for optical flashes independent of GRB triggers, particularly those which could *precede* GRBs and thus would provide important diagnostics for the GRBs and their environments. Such 'pre-glows' were predicted by Beloborodov (2001), and strongly emphesized by Paczynski (2001). B. Paczynski also stressed that a search for optical flashes independent of GRB triggers would provide important diagnostics for the GRBs and their environments.

### 2.2 Scientific objectives of Project ASTRAL

In brief, scientific objectives of ASTRAL are to monitor in the whole sky and detect promptly a wide variety of rapid optical astronomical phenomena (fast transients and outbursts) that last from less than a day to as short as a second. A complete list of the scientific objectives is as follows:

**Gamma-ray bursts** (GRB):
– GRB afterglows.
– GRBs visible only in optics ('orphans').
NB: Impossible to detect them in current ALERT mode of GCN.

– 'Pre-glows' - optical flashes preceding the GRB event.
NB: Also impossible to detect them in current ALERT mode of GCN.
– GRB afterglows accompanied with associated SN bursts (e.g., Galama et al. 1998).

**Supernova explosions** (SN):
– SN in our Galaxy.
NB: Due to SN birth rate (e.g., Lozinskaya 1992),
at least ten SNs have been missed in our Galaxy since Kepler's SN 1604.
– SN in the nearest galaxies, e.g., in Magellanic Clouds.
– SN in distant galaxies.
– SN-GRB prominent, possibly genetic associaton (see above).

**Novae and nova-like stars** (N):
– N in our Galaxy.
– N in Magellanic Clouds.

**Flare stars**:
– Flares of the UV Ceti, U Gem and RS CVn type variables
(e.g., a spectacular radio-optical flare of UV Ceti reported by Lovell 1974).

**Active galactic nuclei (AGN)**:
– Fast violent variability of the BL Lac related sources
(like SDSS $J124602.5 + 011318.8$, see Gal-Yam et al. 2002).

**In the Solar System**:
– Detection of new comets (as well as their bursts).
– Fireballs (at the low orbit of perigee only).
– Monitoring of approaching near-Earth asteroids.
– Experimental satellite tracking.

Thus a wide range of astrophysical flaring optical events could be caught even at the $12^m$ level providing their early detection, independent calibrated optical monitoring and immediate prompt to other observatiories to catch it up.

## 3 PAYLOAD DESCRIPTION

### 3.1 Detection concept

An automated digital version of classic Blink Comparator (BC), a powerful tool to find variable objects. Optical flare appears in the digital BC mode as a new or considerably brightened source above the noise limited level, NLL, $\sim 0.5^m$. All other (constant) sources in the field will be suppressed (i.e., deducted against the template provided).
Template:
A sample of the objects in the whole sky down to a certain threshold magnitude.
Must be:
- complete;
- precision photometry provisioned;
- variable stars content to be very well known;
- compatible with optical unit (by the FoV size and CCD parameters), see below.

An adequate template already exists as the All Sky Compiled Catalogue (ASCC-2.5) compiled by Kharchenko (2002). It consists of 2,041,518 stars as a compilation of the HIPPACOS, TYCHO-2 and other space and ground missions; and
- complete up to V $= 12.0^m$ ;
- capacity: 200 MB (i.e. $\sim$ 20 MB per each Optical Unit, see below);
- an average on-sky density: 1 star per 60 sq. arcmin, or $<$ 1 star per 5 sq. arcmin in a crowded field (e.g., Milky Way). Hence 1 arcmin resolution of ASTRAL seems to be an adequate choice.

Such coordinate precision is good enough to identify ASTRAL's detection in the triggered follow-up. Indeed, it is considerably better than the error boxes of the current high energy triggers (like HETE-2),

and pretty consistent with SWIFT coordinate precision.
The template will probably be steadily improved in limiting magnitude (up to $13 - 14^m$) via further astrometry/photometry studies, along the ground based missions like ASAS (Pojmanski 1997) and 'Pie of the Sky' (Wrochna et al. 2002), and, possibly, space missions like GAIA or DIVA.
Routine on-board frame processing could also be provided.

### 3.2 Optical system design

A set of 13 optical units (OUs) to cover a whole sky (a 'hedgehog' like design).
Each OU consists of a wide–field camera (Sec. 3.3.1) and a CCD unit as recording device (Sec. 3.3.2).
Blind spot on the sky: $50^o$ wide, possibly directed to the Sun (hence only 5 % of the sky not covered at the time of observation).
Illumination from the Earth/Moon to be prevented mechanically/electronically.

### 3.3 Optical Unit (OU)

3.3.1. A wide-field camera with $FOV = 70^o$.
Optical design:
A Wide-Field camera, simplified, not fully achromatic (Popov 1988).
Aperture: $\oslash$ 100 $mm$.
Flat field:
angular $70^o$ ; linear 60 × 60 mm (using a focon type field reducer).
Part of the sky covered by each camera: $\sim 1/10$.
Overlap with the neighboring camera: $\sim 10^o$.
(which means an overlap of 20 % of the sky area).
Number of stars brighter than $12^m$ in the field of the unit: $\sim$ 250.000
(stored as a template in the on-board unit's memory).
Angular resolution: 5 arcsec in optics; 1 arcmin on CCD
(depending of number of pixels, and of pixel size).
Weight:
- Optics 1.0 kg (net). NB: Foam glass to be used for mirrors.
- Framework 1.3 kg.
- Total: 2.3 kg.

3.3.2. CCD unit
CCD device: Lockheed-Martin matrix 4096x4096, low DC, low blemished
(16 mln pixels; $\sim$ 1 arcmin/px at the focal plane, >10 pxs per point like source).
Pixel size: $15 \times 15$ $\mu$.
Die size: $60 \times 60$ $mm$.
QE: $60 - 80$ % around $550 - 800$ nm.
Cooling: Passive, 100 K (of outer space).
Prototype: LNA cooling system of 'Radioastron'.
Wavelength Range: from 400 to 900 nm.
Filter: Unfiltered.
Dynamic Range: $10^4 - 10^5$.
Readout time: 1 $s$.
Unit weight: 0.4 kg.
Number of units: 13.

### 3.4 Modes of observations: detection; monitoring.

Detection mode:
An early detection of various optical flares above $12^m$ around the sky (basic ALERT mode).

Post-detection mode:
On-source, with possibly better time resolution
(to be chosen automatically depending of the detected source brightness).
Monitoring mode:
Continuous on-source monitoring, with better sensitivity/time resolution.
Fireball-like detection mode of moving object.

### 3.5 Limiting magnitude

Detection mode: $12^m$ (due to the template provisioned, see Sec. 3.1).
To be steadily improved along further photometric/astrometric studies.
Post-detection mode: Variable (depending of integration time).
Monitoring mode: $\sim 19^m$ in 30 min integration.

### 3.6 Timing resolution

Detection mode: 30 s.
Post-detection mode: up to 1 s
(to be chosen automatically depending on brightness of the detected source).
Monitoring mode: arbitrary.

### 3.7 Orbit

A variety of orbits to be considered, e.g.:
- eccentric, with a major axis directed from the Sun;
- polar, circular $\sim 1000$ km.

Easy launchable orbit to be chosen if required by technical circumstances.

Examples:
Perigee altitude: 350 km.
Apogee altitude: $2000 - 40000$ km.
Period of revolution: 24 h (and more).

### 3.8 Stabilization/Pointing

The solar oriented 3-axis stabilization.
Calibrated pointing knowledge: 6-10 arcsec ($1\sigma$).
Re-pointing Rate: Nil!

### 3.9 On-board computer

CPU, with a direct access via telemetry.
13 microprocessors, one per each Optical Unit (in parallel).
Memory:
- CPU 2 GB.
- Mcp Unit: 64 MB.
- Re-programming and template updating (via telemetry).

### 3.10 Telemetry: Uplink - Downlink

Uplink.
Command line:
Rate: 4 kb/s
Schedule: 12 min/day, once per day.
Downink:
Low rate ALERT mode: 4 KB/s
Schedule: switch-on by the inner ALERT command.
Data transfer: 1.0 MB/s
Schedule: 12 min/day, once per day.
Possible regime: To be incorporated into and supported by the GCNetwork.
GTS location (FedSat II case): main – Adelaide.
Mobile tracking antenna: Sydney (e.g., AAO/ATNF/TIP site),
or elsewhere in the campaign mode.

### 3.11 Power & Weight & Cost Budget

Power:
Optical Unit microprocessor system: 1 Wt
Total for MCP units: 15 Wt
Payload, total: Low ( $<$ 20 Wt )
NB: Huge power saving due to absence of re-pointings.
Weight:
A set of 13 optical cameras: 30.0 kg (2.3 kg x 13)
A set of 13 CCD units: 5.2 kg (0.4 kg x 13)
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Total: 35.0 kg.
Cost:
Optical Unit: $ 100 K
CCD Unit : $ 120 K
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Total per Unit: $ 220 K
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Total per Optical System: $ 2.9 M (13 units).
Hardware Modeling and Software design: $ 4.0 M.
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Total Cost of the payload (estimated): $ 10.0 M.

## 4 Summary and Conclusion

We briefly describe a specific space mission - Project ASTRAL - dedicated to the whole-sky detection of a variety of rapid astronomical phenomena, particularly optical flashes associated with gamma ray bursts (GRB). Those flashes only visible optically (so called "orphans"), as well as those preceding associated GRBs, cannot be detected in the current triggering mode of the world wide GRB Coordinates Network. ASTRAL incorporates a set of the wide-field optical cameras on board a small satellite. Supernovae, novae and nova-like explosions, fast variable AGNs, flare stars, and even new comets would be promptly detected as well. Being compact and relatively cheap, ASTRAL would provide an independent and early detection of various optical flashes on the whole sky sending an instant alert to other multiwavelength observatories. This way ASTRAL would be a working prototype of the prospective major space mission to monitor on-line all the sky - a high priority instrument of the 21st Century astrophysics.

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