Final Presentation of “Assessment Star Tracker for Asteroid Search”

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TERMA

ALLIES IN INNOVATION

Study Overview

- Study name:

  Assessment of Star Tracker use for Asteroid Search

- ESA contract:

  ESA contract 4000105591/12/NL/AF

- Budget: 150 k€

- Study duration: March 2012 to May 2013

Study Objectives

To assess the potential of using Star Trackers in ESA missions currently in operation, or planned in the future, to work as a “payload of opportunity” that can be used to carry out observations with scientific or engineering interest. In particular the activities looked to:

- Define a case study i.e. a specific operational scenario involving the search for NEO’s in orbits fully inside the Earth's orbit.
- Investigate, as a test case, how to modify an existing, flying Star Tracker’s software to enable scientific use of the Star Tracker imaging data in such operational scenario.
- Demonstrate the proof of concept by a S/W update for the existing Star Tracker presently in operation.
- Analyze how other current or future ESA missions could be used to test the operation of a Star Tracker for imaging purposes, and recommendations on possible modifications of Star Tracker H/W and/or S/W to enable scientific or engineering use of the data, as either a background task or by using a redundant non active unit.

Study Technical Requirements

ID	Requirement Text
R1	The software shall be made in a form that makes it possible to upload it, as a patch, to a presently flying STR.
R2	The patch shall be resident in RAM only, such that the STR, after a power cycling (off/on), shall boot up in the nominal STR configuration and be functioning as an unmodified Star Tracker as before the upload had been performed.
R3	The patch shall be fully compatible with the receiving unit on the spacecraft, and any other units which may be affected by this modification.
R4	Allow reading out and transmit to ground full frame images at full resolution.
R5	Allow integration times up to at least 10 minutes. If this is not possible due to hardware limitations a routine to sum consecutive images to reach an equivalent integration time shall be made.

ID	Requirement Text
R6	The target limiting magnitude for the STR after modification shall be 15 at a signal/noise = 5.
R7	Allow cosmic ray suppression by making pixel by pixel median for a programmable number of consecutive exposures/frames (typically 3). This function shall be possible to enable/disable. (This function must be executed before an image summation, if implemented as described under point R4 above, or alternatively be combined with this function).
R8	Allow sending the full frame in many small packets at a controlled packet rate, in order not to overload the interface/CPU of the receiving unit. This rate shall be adjustable.
R9	The software shall include an algorithm for data compression (preferably lossless).

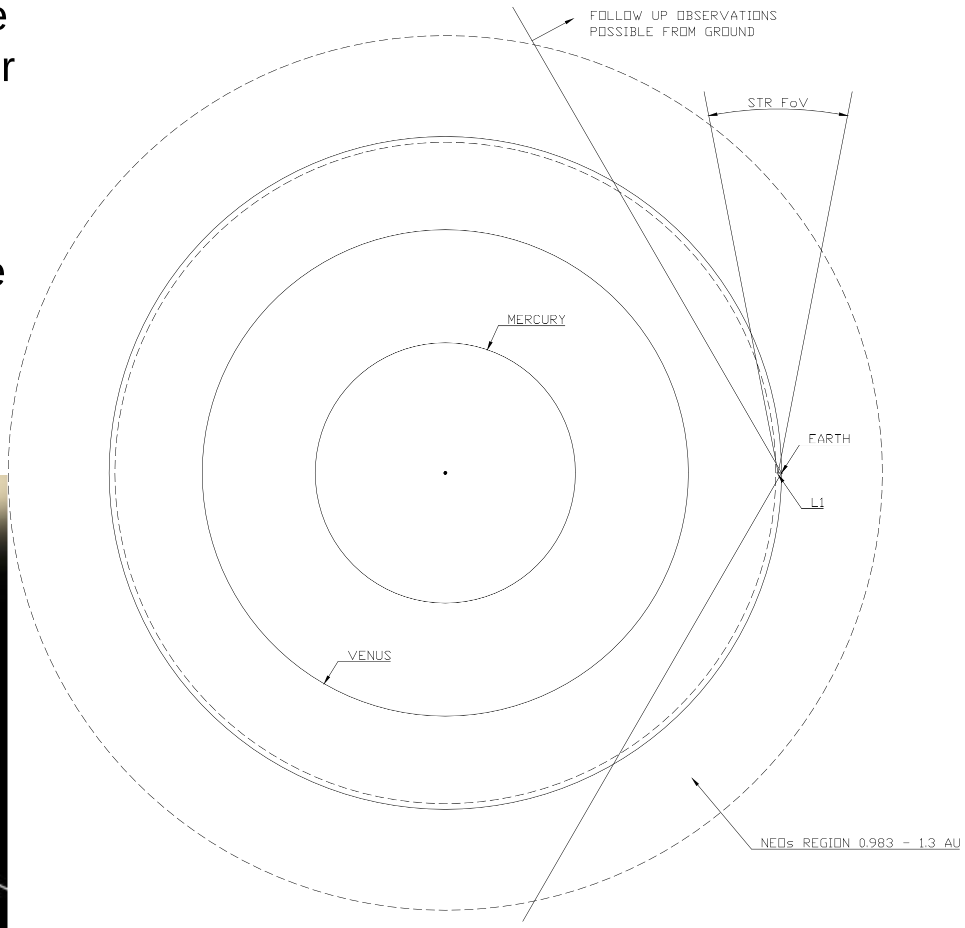
Analysis of Operational Scenario

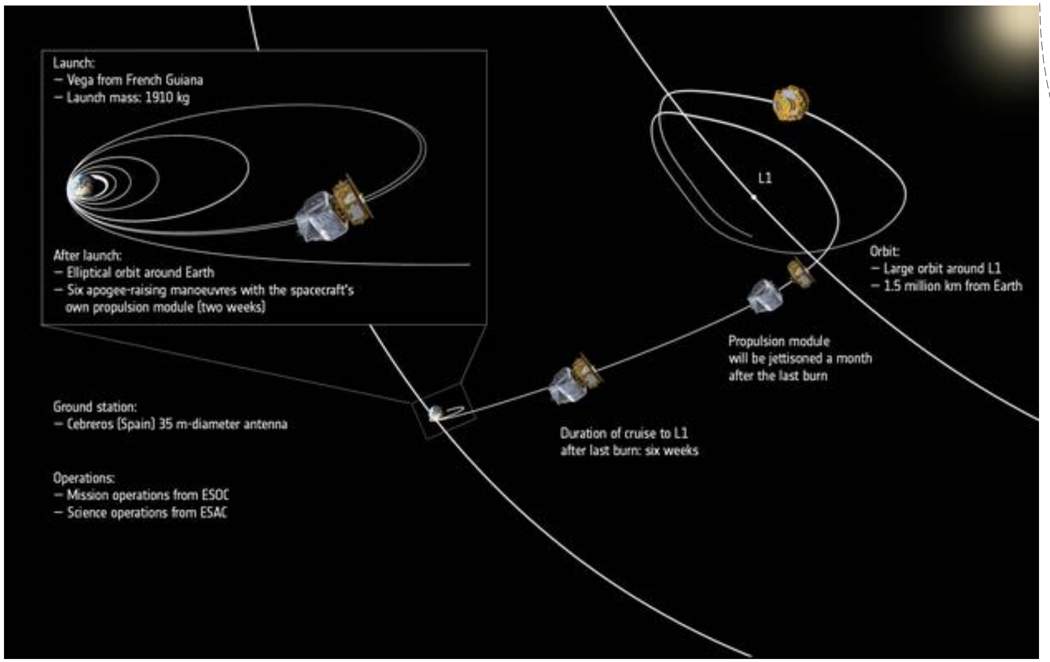
The following slides provides an overview of a candidate operational scenario:

- Selected ESA Mission
- Terma HE-5AS Star Tracker presentation
- Asteroid detection

Lisa Pathfinder Mission

A heliocentric orbit with a semi major axis in the range 0.5 AU to 0.72 AU (Venus) would definitely be ideal for a dedicated mission with a narrow FOV instrument searching for Inner-Earth-Objects. However, for proof of concept with a large FOV star tracker, the Lisa Pathfinder orbit around L1 with a heliocentric distance of 0.99 AU has an important advantage concerning detection verification.





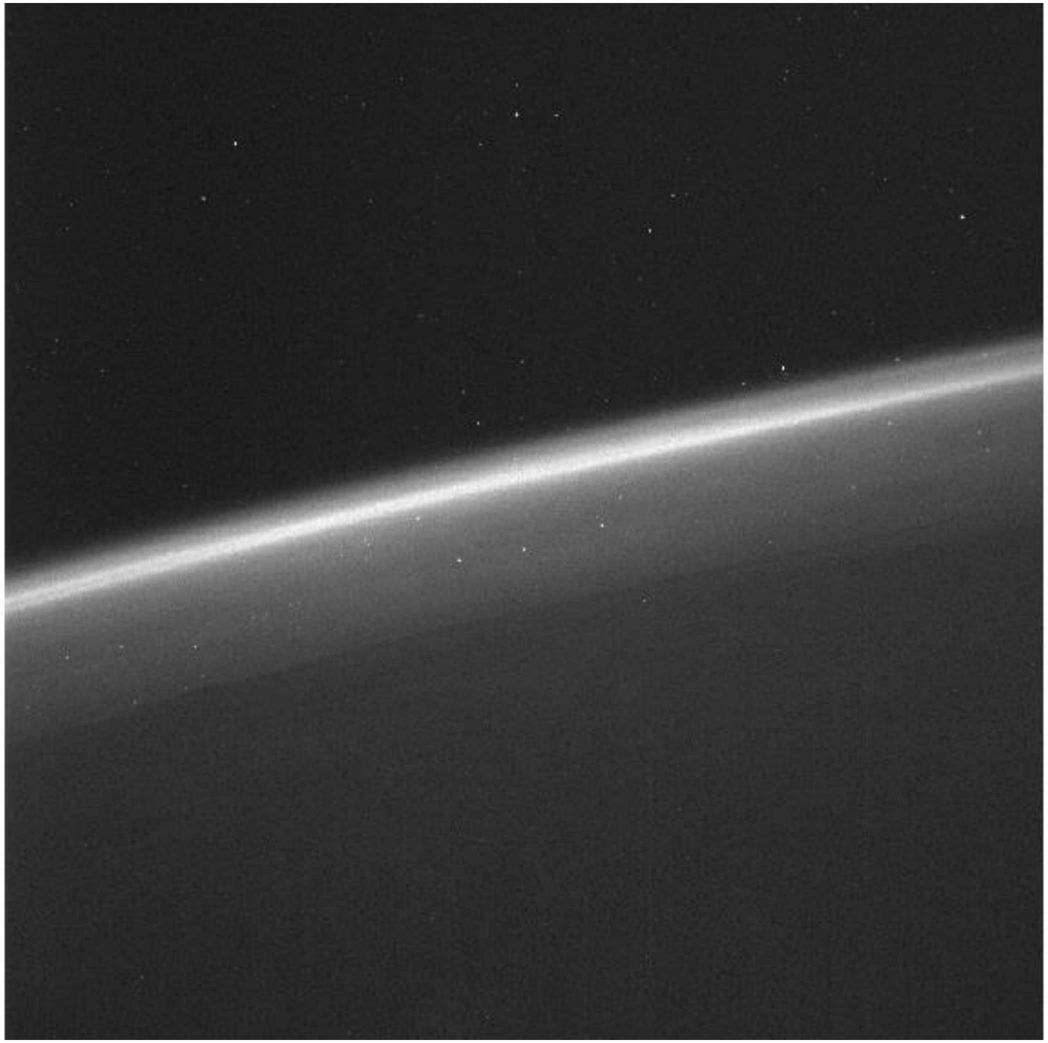
The LPF mission was successfully launched on Dec. 3 2015. “L1” was reached on Jan 22 when also the propulsion module was separated.

Lisa Pathfinder Mission

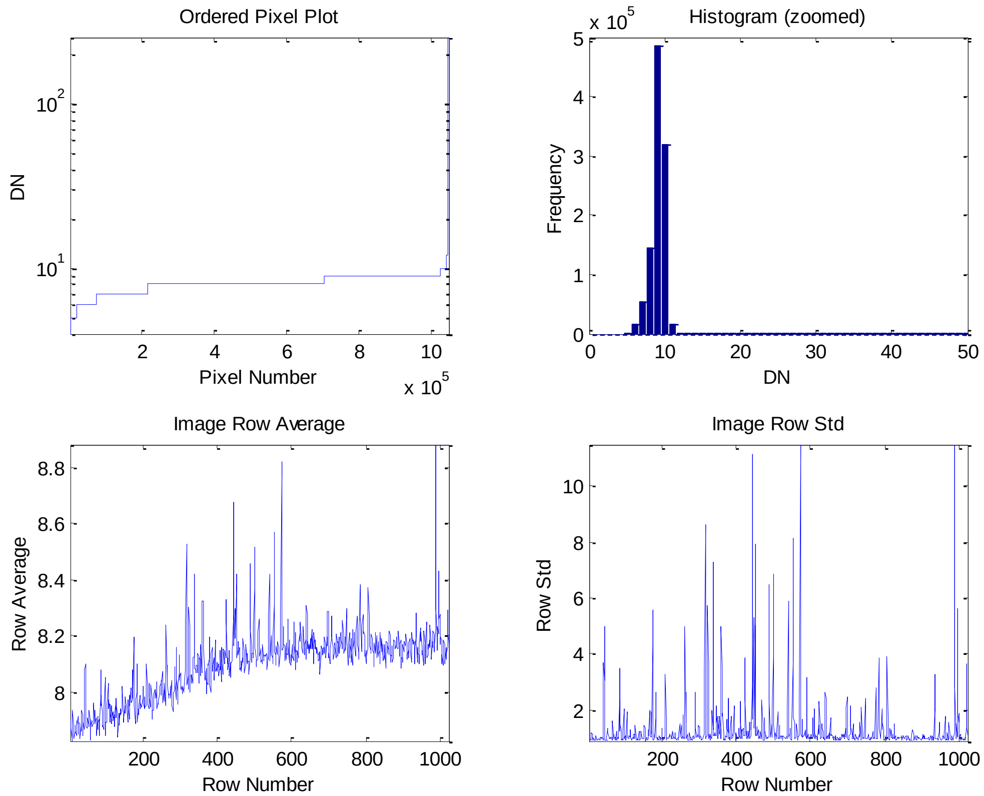
Terma Star Trackers

LPF Star Tracker Status

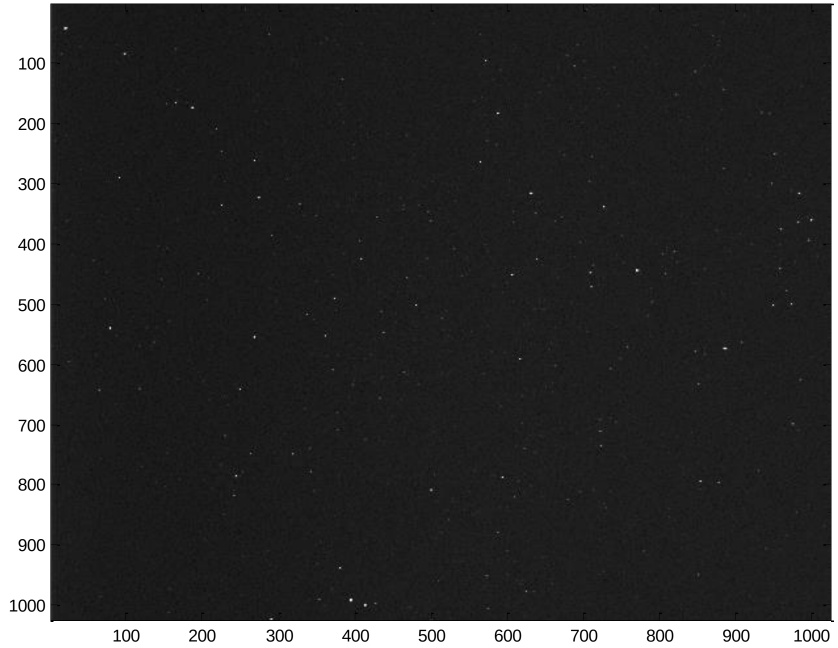
The LPF star trackers have already observed a NEO…very near:



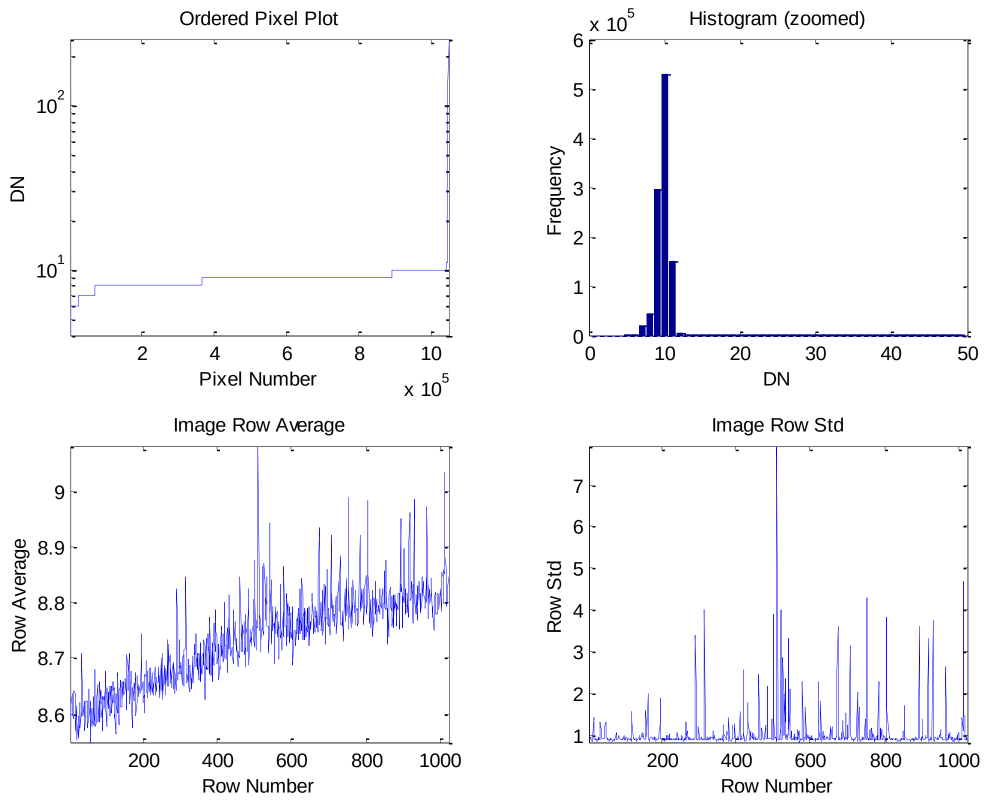
LPF Star Tracker Status (AST1)



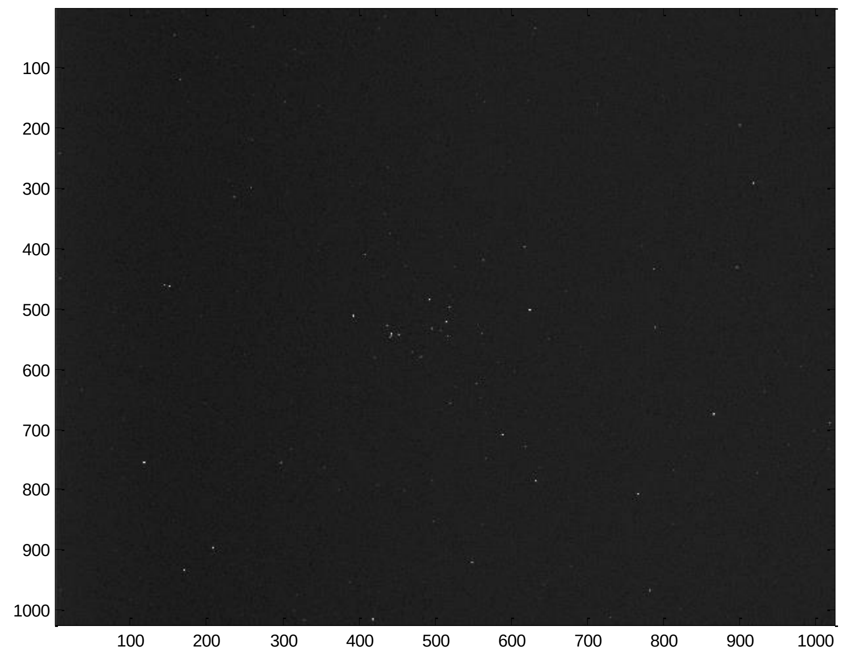
In-orbit image dump
CCD temperature: -8 degC
Captured en-route to L1



LPF Star Tracker Status (AST2)

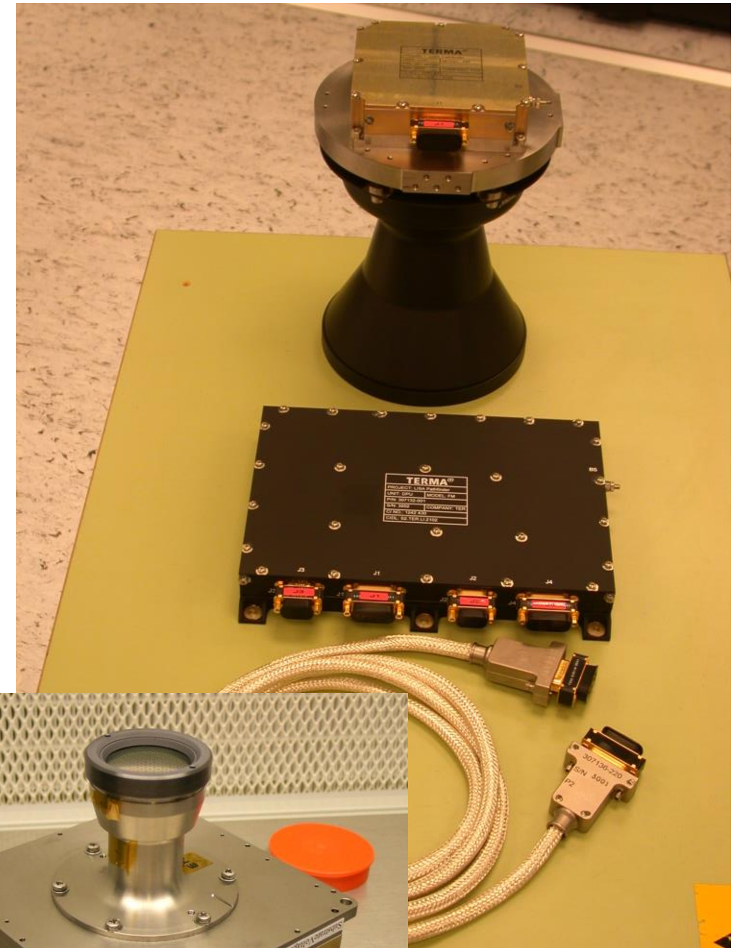


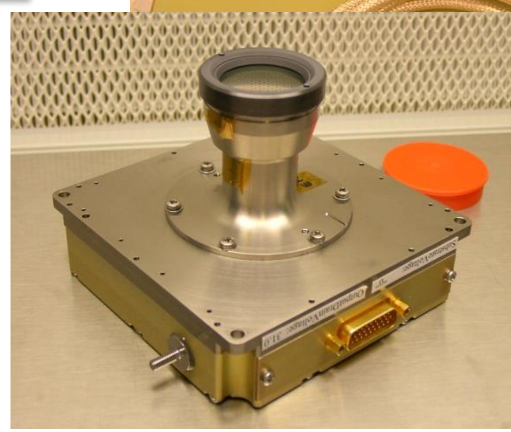
In-orbit image dump
CCD temperature: -8 degC
Captured en-route to L1



The Terma HE-5AS Star Tracker

Detector	CCD47-20, FI AIMO, Frame transfer
Resolution	1024 x 1024 pixels
Pixel size	13 µm
Full well capacity	Linear up to 100.000 e-
Dark current (293 K)	< 100 e-/s/pixel (typical 50)
DCNU (1σ)	40 e-/s/pixel
PRNU (1σ)	1 % of mean
FOV	21.6 x 21.6 deg2
Focal length	35 mm
IFOV	77 arcsec/pixel
Aperture	22 mm
Pixel readout freq.	1 MHz
Frame store	6.2 ms
Readout noise	30 e-
ADC specification	Resolution: 8 bit Gain: 4 – 72 e-/LSB (nominal 50) Offset: 0 – 8192 e-
Mass	1.0 kg
Power consumption	1.5 W





Optics PSF

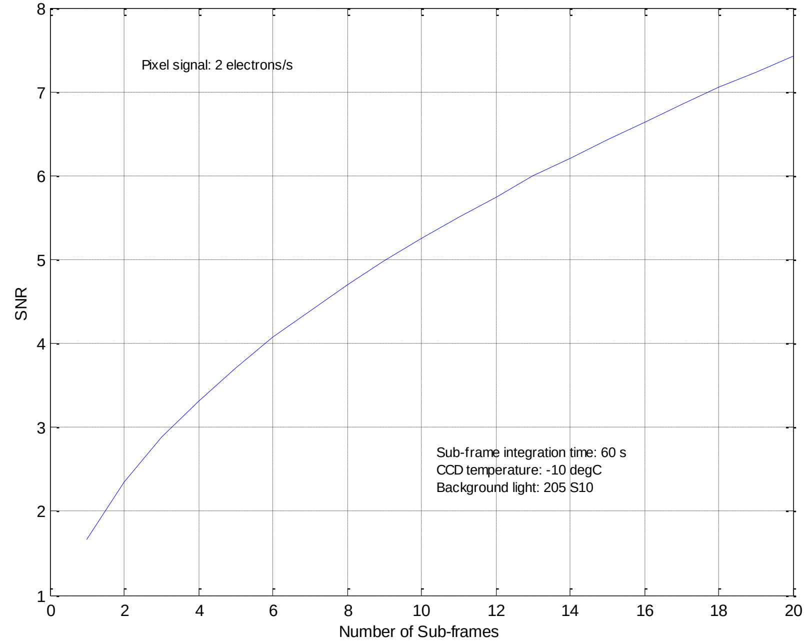
3.4%	11.5%	3.4%
11.5%	38.4%	11.5%
3.4%	11.5%	3.4%

Asteroid Detection SNR

$$SNR = \frac{\sqrt{n}\, S\, T_{Int}}{\sqrt{(S + N_{BG} + N_{DC})\ T_{Int} + N_{RO}^2 + N_{ADC}^2}}$$

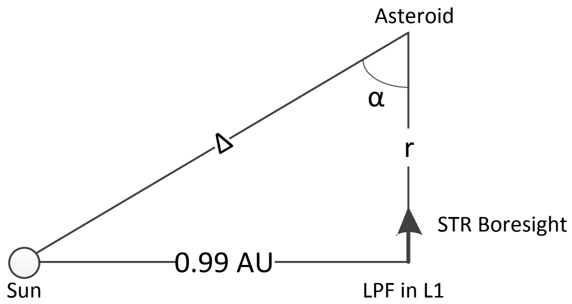
S is the pixel signal originating from a star or asteroid, T_{Int} is the sub-frame integration time and n the number of sub-frames that are added to make a long exposure. N_{BG} is the background signal originating from Zodiacal light and faint stars. N_{DC} is the CCD dark current, N_{RO} the readout noise and finally N_{ADC} the quantization noise originating from the analogue to digital conversion.

Requirement:
SNR>5 for a V15 Asteroid ->
10 sub-frames each 60 s



Asteroid Brightness

Asteroid apparent magnitude m and absolute magnitude H relates as follows (http://www.britastro.org/asteroids/dymock4.pdf):



$$m = H + 5\log(r\Delta) - 2.5\log\left[(1-G)e^{-3.33\left(Tan\left(\frac{\alpha}{2}\right)\right)^{0.63}} + Ge^{-1.87\left(Tan\left(\frac{\alpha}{2}\right)\right)^{01.22}}\right]$$

STR Sensitivity	Detectable Absolute Magnitude 90 deg Sun Phase	Detectable Asteroid Size (albedo 0.25 – 0.05)		
		1 AU	100 LD	1 LD
m_v = 11.7	H = 8.5	50 – 120 km	13 – 30 km	130 – 310 m
m_v = 12.7	H = 9.5	35 – 75 km	9 – 19 km	90 – 190 m
m_v = 13.7	H = 10.5	20 – 50 km	5 – 12 km	50 – 120 m
m_v = 14.7	H = 11.5	13 – 30 km	3 – 8 km	35 – 80 m
m_v = 15.7	H = 12.5	8 – 19 km	2 – 5 km	20 – 50 m

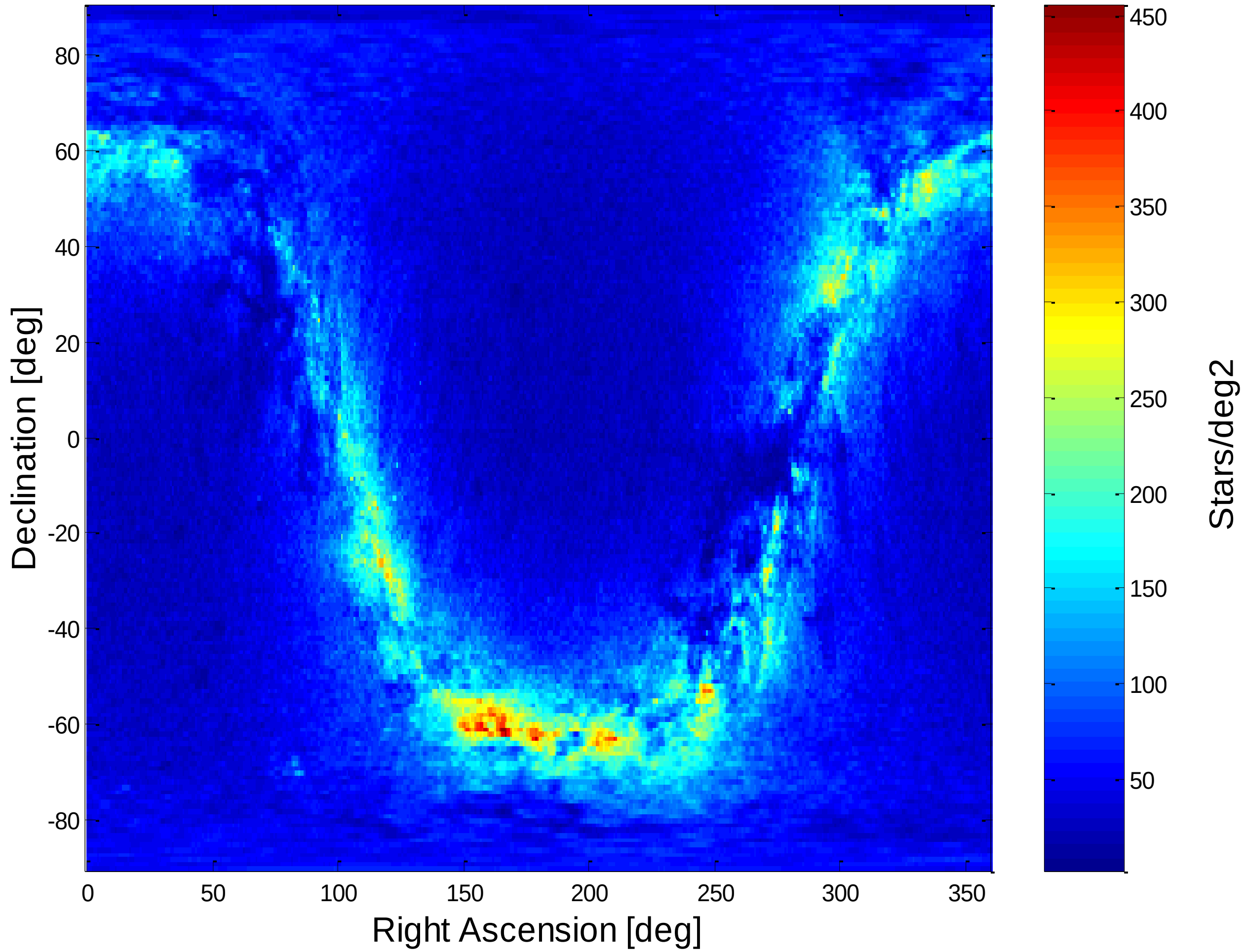
(data are taken from the NASA web site: http://neo.jpl.nasa.gov/glossary/h.html)

Simulated Asteroid Detection

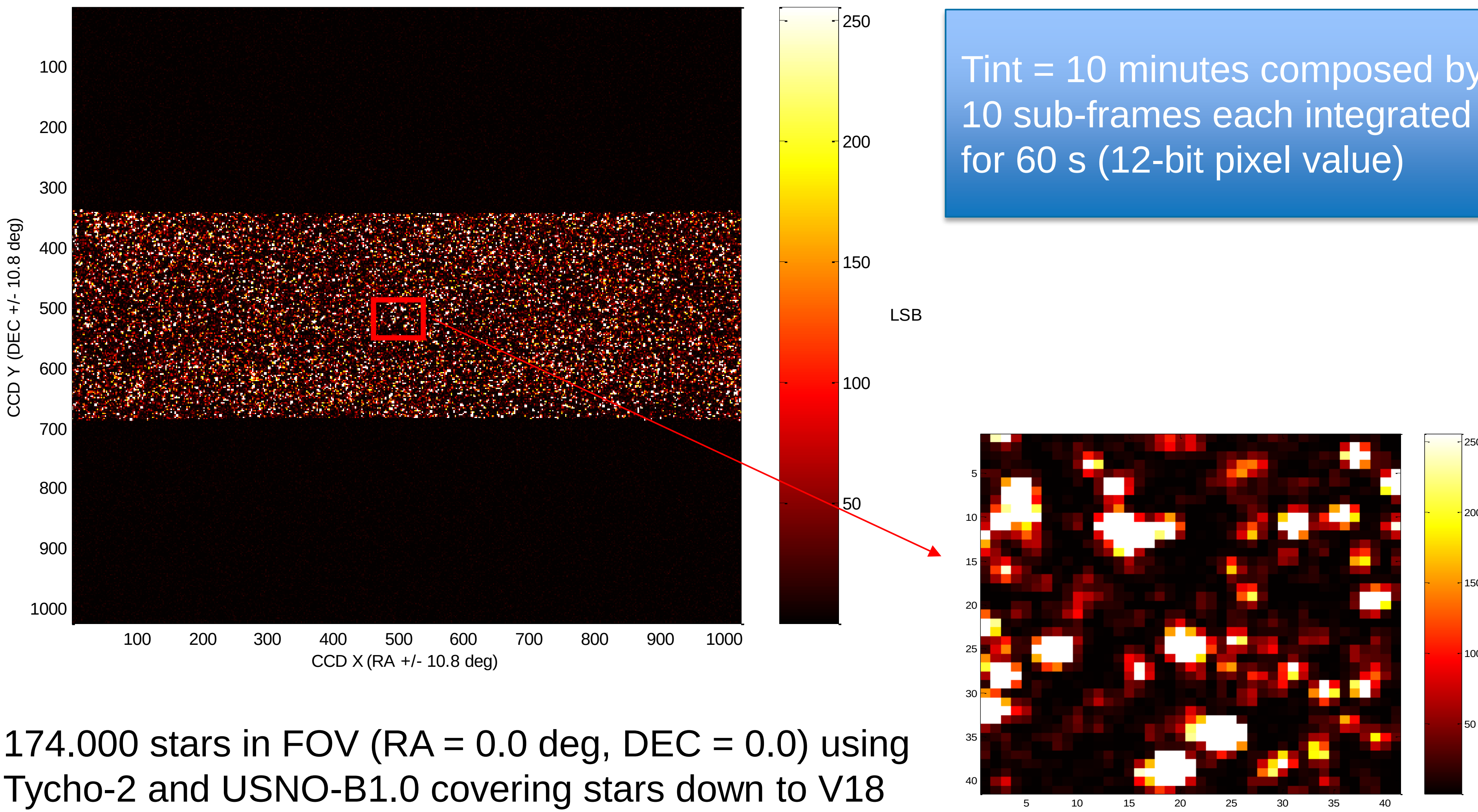
- The high number of background stars makes Asteroid detection from single raw images very difficult. It is therefore suggested to carry out raw image subtraction before the actual Asteroid search.
- Raw image translation/rotations will be required prior to subtraction due to the non-zero S/C rotation around the Sun vector. The mis-alignment can be determined by computing the attitude of each image
- A simulation has been carried out in order to investigate the feasibility of the subtraction method. Three images were generated each containing a visual magnitude 14 Asteroid separated by 5 pixels from image to image. The image attitudes have been shifted 0.1 pixels from each other in order to simulate the residual mis-alignment from the individual image translation/rotation.
- The background removal by subtraction can possible be improved by using the median of all aligned images in an observation series (except the image used to subtract from). This process will not remove CCD hot pixels mainly caused by proton radiation in-orbit which to a large extent, can be mitigated by running the CCD cold (<-10 degC).

Stars in FOV

Tycho-2 Star Density (99 % complete down to V11, 90 % complete down to V11.5)



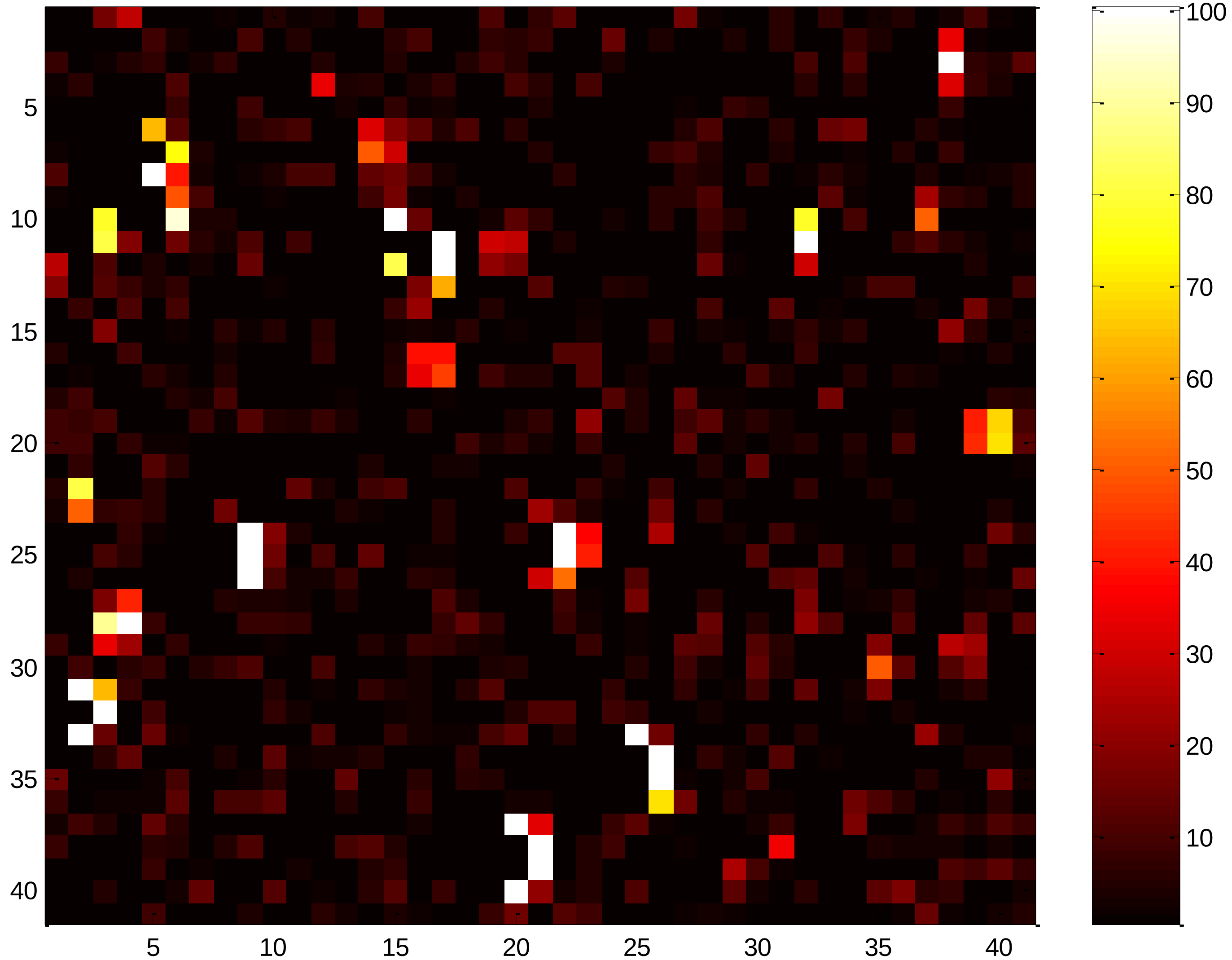
Simulated Image



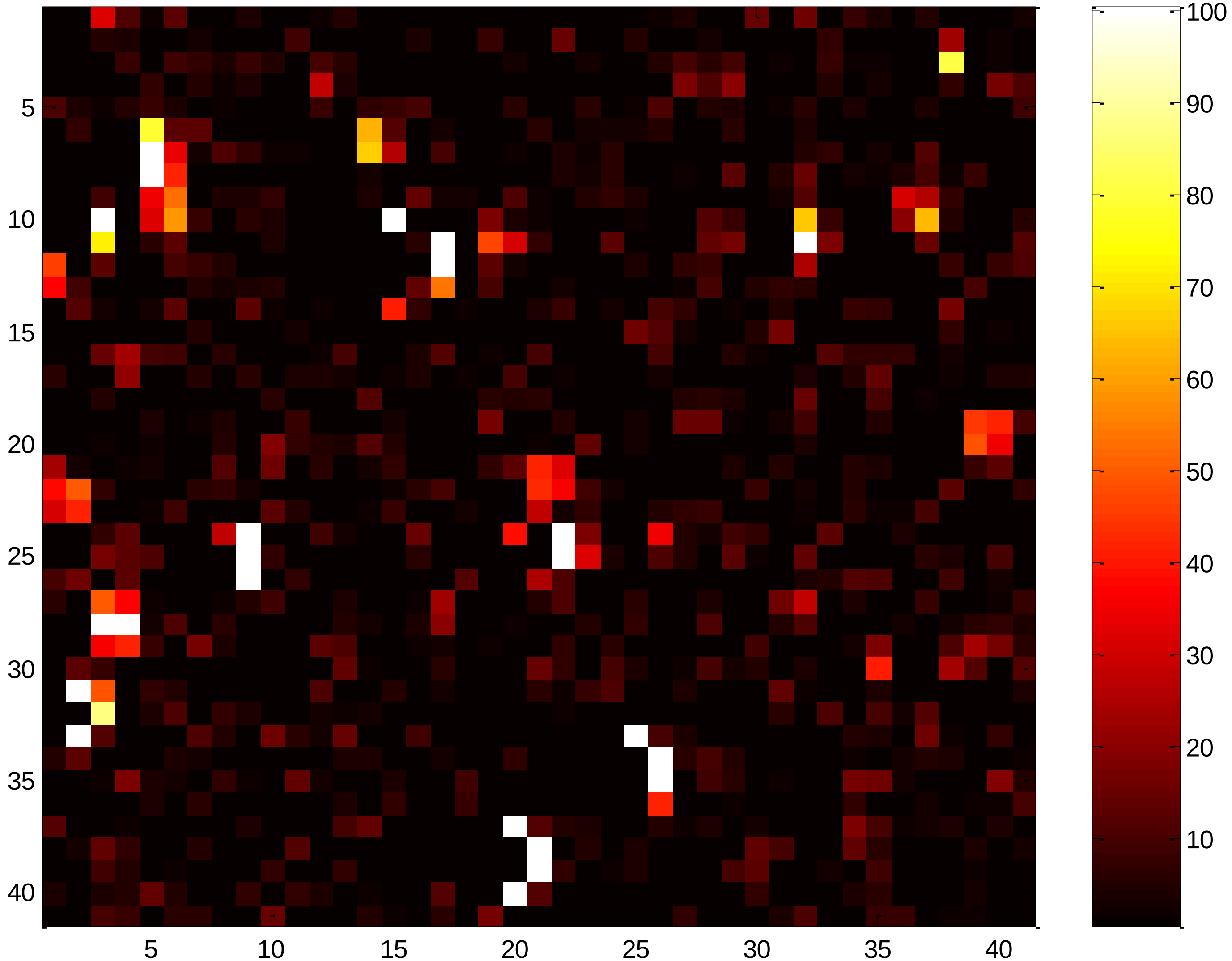
Tint = 10 minutes composed by 10 sub-frames each integrated for 60 s (12-bit pixel value)

174.000 stars in FOV (RA = 0.0 deg, DEC = 0.0) using Tycho-2 and USNO-B1.0 covering stars down to V18

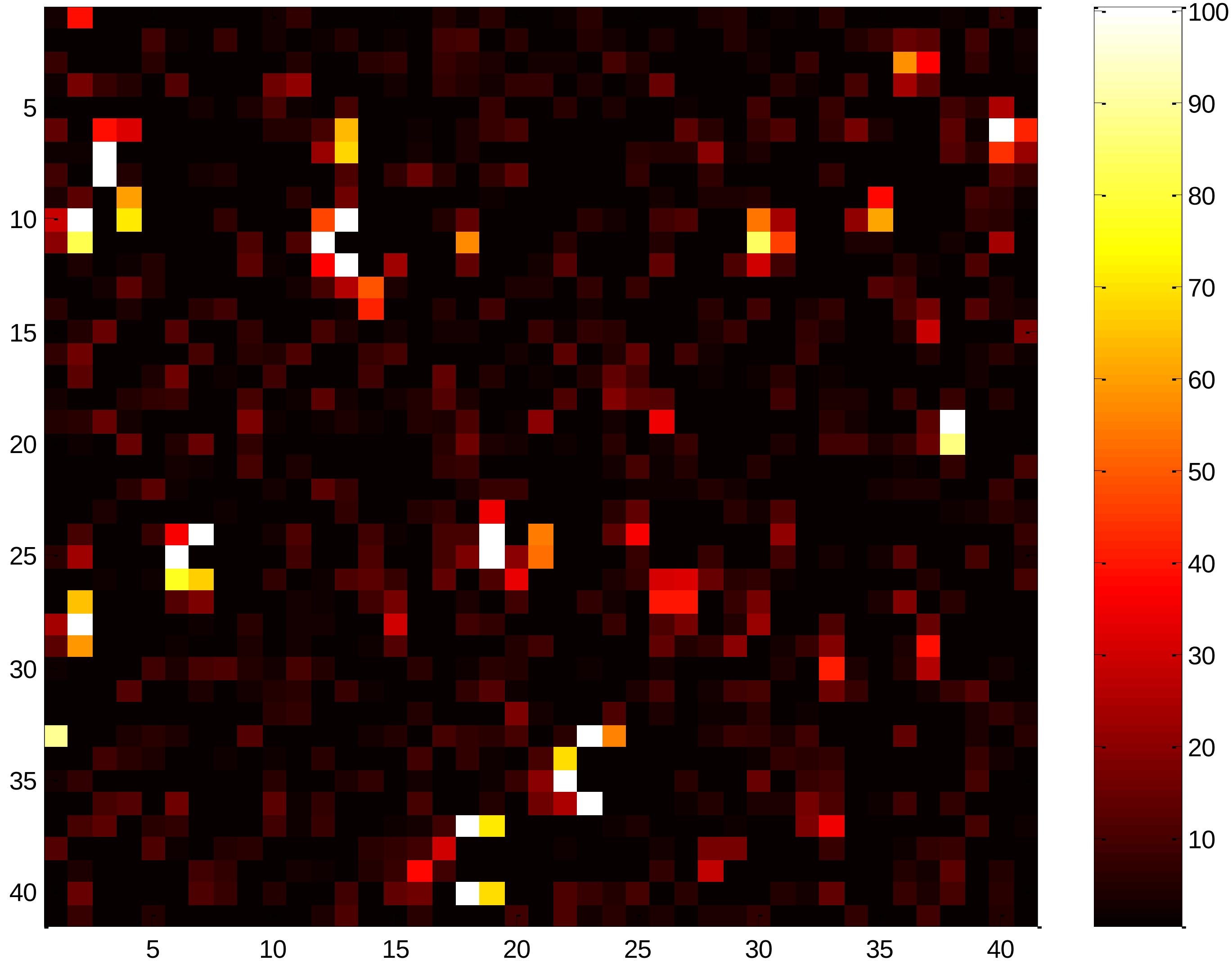
Simulated Asteroid Detection by Image Subtraction



Simulated Asteroid Detection by Image Subtraction



Simulated Asteroid Detection by Image Subtraction



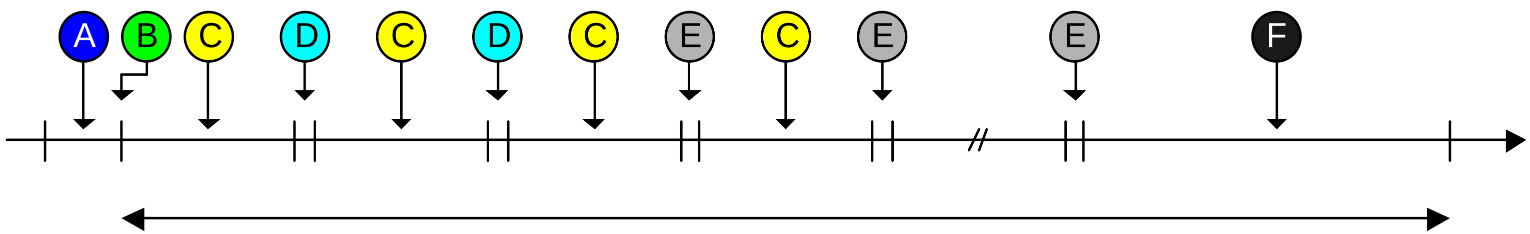
Software Patch Overview

The following slides presents an overview of the SW patch:

- Software Patch Functionality
- Software Patch Properties and Operations
- Software Patch Image Buffers and Compression
- Software Patch Operating Parameters
- Software Patch Performance
- Software Patch Test

Software Patch Functionality

- Capture a series of raw images (sub-frames)
- Cosmic suppression is done after first 3 sub-frames and then for every new sub-frame.
- Each of the sub-frames are 8 bit per pixel whereas the resulting image is 12 bit.
- Time between exposures must be short to ensure very little apparent motion of asteroid.
- Resulting image is compressed and dumped upon user request.



Example: 10 sub-frames each integrated for 60 s, window size 1024 x 341 pixels (1/3 frame)
10*C + 2*D + 8*E + F = 10*60 + 2*2 + 8*3 + (1024*341*30/2)/19200 = 900 s (15 min)

A Setup image dump parameters (window definition, # of sub-frames, sub-frame integration time, cosmic suppression ON/OFF)

B Command image sequency start

C Sub-frame exposure (e.g. 60 s)

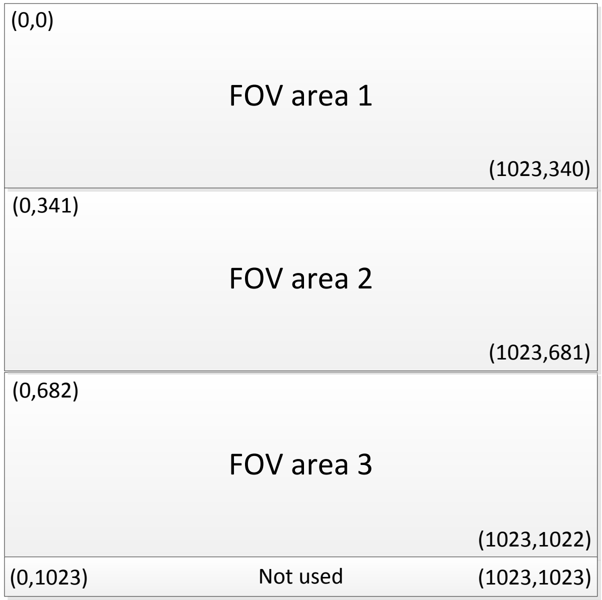
D Sub-frame readout and temporary store (approx. 2 s)

E Sub-frame readout and temporary store, perform median filtering on three previous sub-frames, add image (approx. 3 s)

F Dump image via Spacecraft interface (transmission time ≈ (30 bits / 2 pixels) * n pixels / 19200 bits/s)

Software Patch Properties and Operations

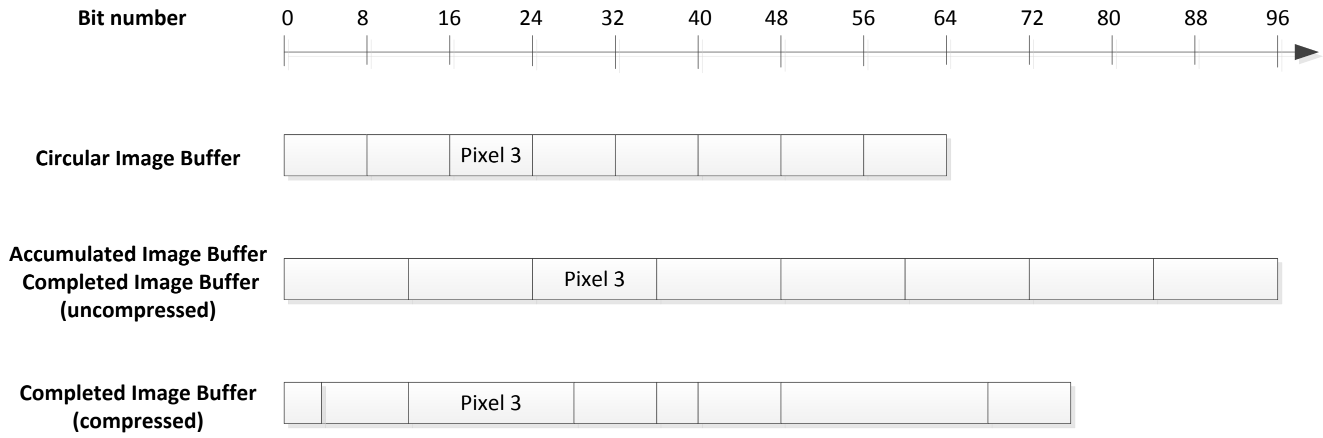
- RAM patch only:
  - Existing STR ASW and its operating parameters in NVM is not modified.
  - Power-cycling or commanding a STR reset loads the existing STR ASW.
- When patch is applied, the STR only supports Standby Mode.
- Patch uses a subset of existing TC and TM packets:
  - ***StrLoadMemory*** TC: Used for modification of memory mapped operating parameters.
  - ***StrDumpImage*** TC: Used for requesting acquisition and processing of a series of sub-frames for a specified FOV area all the way up to the compressed resulting image. The sub-frame size is 1024 x 341 pixels.
  - ***StrDumpMemory*** TC: Used for commanding a downlink of the resulting image as a series of **StrMemoryDump** TM packets.



- Normal housekeeping via ***StrHkTm*** TM packet is not modified by the patch.

Software Patch Image Buffers and Compression

- Three new buffers introduced by patch:
  - **Circular Image Buffer***:* Area 1 used for CCD image acquisition and areas 2-4 used for storage of the previous 3 sub-frames.
  - **Accumulated Image Buffer***:* Used for the accumulated image data for a configurable number of sub-frames.
  - **Complete Image Buffer***:* Used for storage of the complete frame ready for downlink.
- Pixels are stored back-to-back in the image buffers:



- Image compression is using pixel-by-pixel Huffman encoding with the related variable-length code table stored on-board. The table is derived on ground based on simulated images, currently optimized for 10 sub-frames and a 60 sec sub-frame integration time.

Software Patch Operating Parameters

Name	Description	Value
RequestedFrames	Number of frames to acquire and process when the **StrDumpImage** TC is executed.	Range: 1-16 Default: 10
CosmicRay	Flag indicating if cosmic ray suppression is enabled or disabled. For the cosmic ray suppression to work as intended, the number of requested frames must be to 3 or higher.	Range: 0-1 Default: 1
Compress	Flag indicating if Huffman compression of the Complete Image is enabled or disabled.	Range: 0-1 Default: 0
IntegrationTime	Integration time in seconds for each of the acquired frames.	Range: 1-120 Default: 60
Gain	CHU ADC gain used for the acquired frames.	Range: 1-255 Default: 171
Offset	CHU ADC offset used for the acquired frames.	Range: 1-255 Default: 43
MedianThreshold	Threshold for the maximum difference between the pixel value and the calculated median. If exceeded, the pixel is considered to have been subjected to a cosmic ray event.	Range: 1-255 Default: 50
FramesForMedian	Number of frames for calculating the median used in the cosmic ray suppression.	Range: 3-4 Default: 3
DumpPeriode	Number of TCPs to wait between each **StrMemoryDump** TM. A value of 0 means that the TM packets are transmitted back-to-back.	Range: 0-255 Default: 0

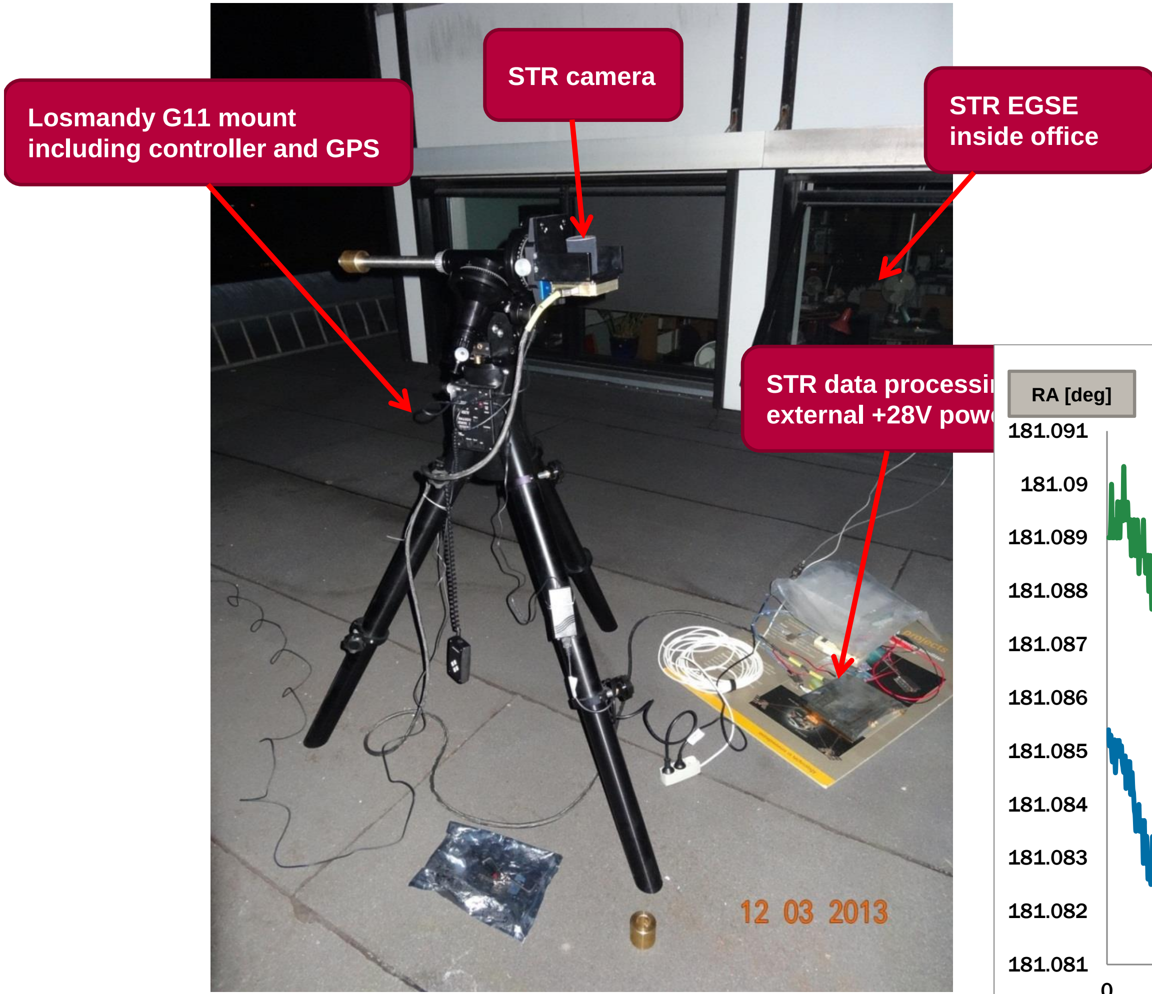
Software Patch Performance

- Execution time of the **StrDumpImage** TC depends on the setting of *RequestedFrames* and *IntegrationTime*, but the initialization, readout, accumulation and compression adds some processing overhead:

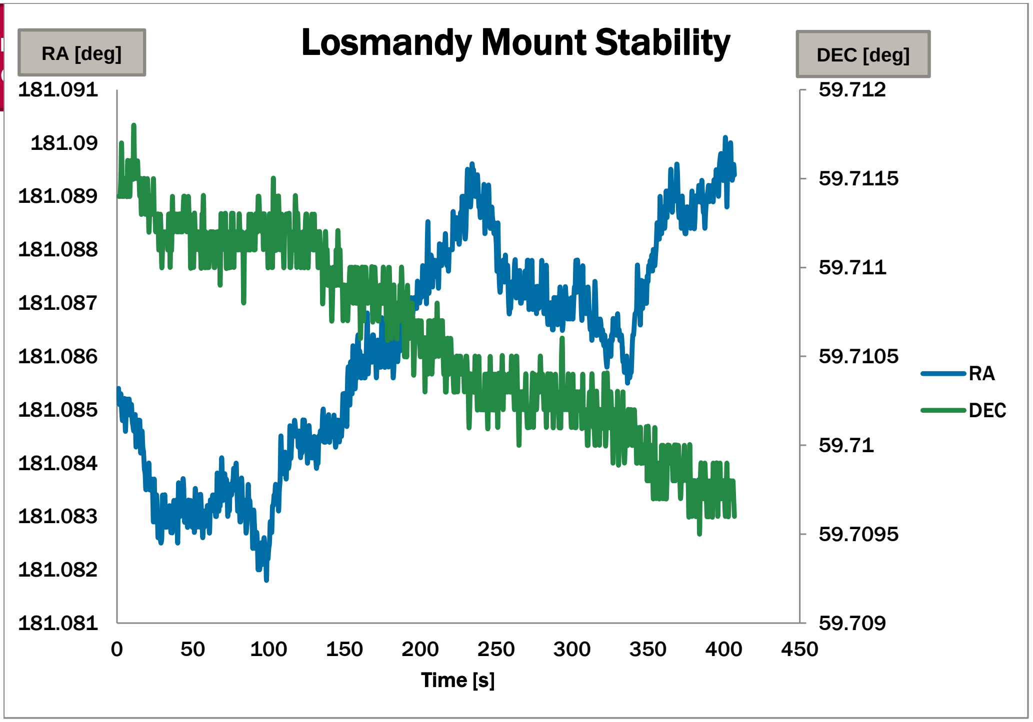
Test ID	RequestedFrames	CosmicRay	FramesForMedian	Compress	Overhead
1	10	0	-	No	29 sec
2	10	1	3	No	41 sec
3	10	1	4	No	86 sec
4	10	0	-	Yes	43 sec
5	10	1	3	Yes	55 sec
6	10	1	4	Yes	100 sec

- Cosmic ray suppression testing:
  – Showed in tests to be more efficient when using 4 instead of 3 sub-frames for median.
  – Number of corrected pixel values were 40 and 59 with 3 and 4 sub-frames.
- Image compression testing:
  – Dedicated off-line Huffman Decompression Utility developed and used for validation of compressed resulting images.
  – Showed in tests that a compressed image took up 67% of the uncompressed image.

Night Sky Test (setup)



Right Ascension stability: 29 arcsec
Declination stability: 8 arcsec

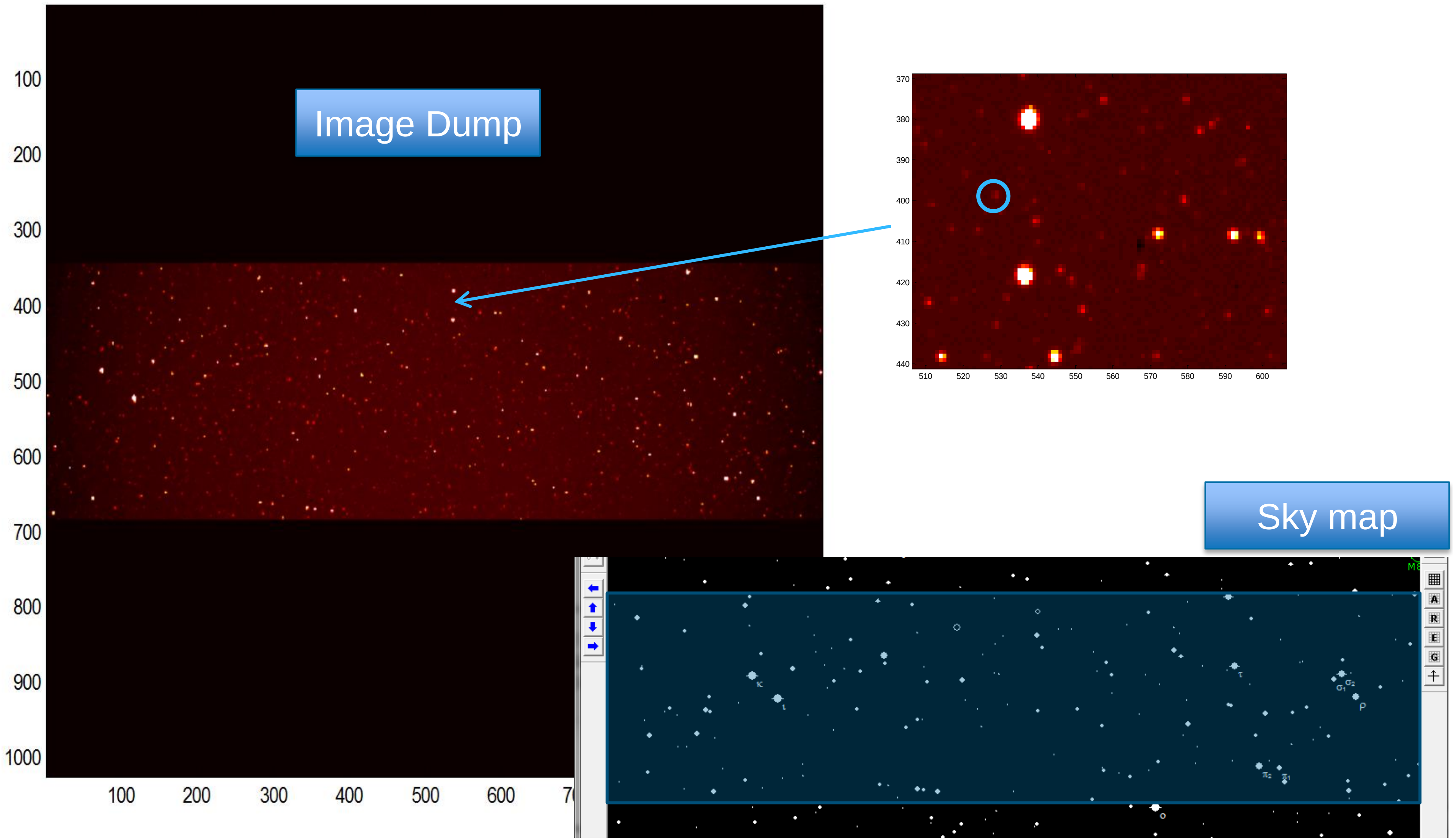


Night Sky Image

Image parameter settings:

- FovArea: 2 (center part of the FOV, see page 10 in the manual)
- RequestedFrames: 10
- CosmicRay: disabled
- Compress: disabled
- IntegrationTime: 10 s (we had to limit the sub-frame integration time from 60 s to 10 s due to “city” airglow, the image offset adjustment saturated at 60 s integration time)
- Gain: 255 (actual gain = 46 e/DN derived)
- Offset: 110
- MedianThreshold, FramesForMedian: N/A
- DumpPeriod: 0

Star Match Example



Star Match Example

Example (star marked with blue circle on plot above):

- Star name: TYC 3809-1505-1
- Brightness and color: V_J10.66 (V_T10.78 and B_T12.02), $(B\text{-}V)_J$=1.053 -> T≈4600 K
- Image coordinates: line 395 to 401, row 526 to 531

Stars of visual magnitudes 10-11 are clearly detectable in the recorded image. This provides strong evidence of visual magnitude 14-15 objects to be detectable with no airglow and 10x60 s integration time (instead of 10x10 s).

Raw pixel values						Constant background removed (250 DN)					
247	243	237	239	229	230	0	0	0	0	0	0
248	233	257	252	246	251	0	0	7	2	0	1
235	253	267	263	248	243	0	3	17	13	0	0
256	268	355	446	290	260	6	18	105	196	40	10
235	252	370	512	295	257	0	2	120	262	45	7
245	250	268	289	275	248	0	0	18	39	25	0
252	274	270	245	257	259	2	24	20	0	7	9

Brightness ≈ 820 DN
Estimated brightness assuming 24 mm aperture, 100 s integration time, 50 e/DN gain, 4600 K and V10.66: ≈ 830 DN -> excellent agreement!

Conclusions

- The “Assessment of Star Tracker use for Asteroid Search” has been successfully conducted and a very small Software patch has been developed and tested during both laboratory and night sky testing.
- The proposed ESA Lisa Pathfinder mission carrying two identical HE-5AS Terma STRs seems to be very well suited as a demonstrator mission for the search of Asteroids using large FOV STRs. The primary STR can be operated in normal star tracking mode whereas the redundant unit can be configured for asteroid search. Both unit should be operated at -10 degC preferable even colder in order to mitigate CCD radiation degradation
- It has been analyzed that the HE-5AS sensitivity will allow for search of Asteroids with visual magnitude down to 15 as required by the SOW.
- A viable Asteroid search strategy using image subtraction has been analyzed with promising results even with the presence of a vast amount of stars in the large FOV.
- Lisa Pathfinder must be stable pointing or feature a very low angular rate in order to perform long image integration exposures without significant smearing. Observation in the direction of the Milky-way makes Asteroid detection difficult due to the relative large FOV.