SIRIS

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ENS

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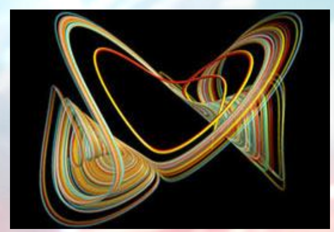
LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

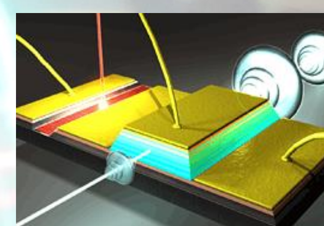
Before 2019

LKB
Laboratoire Kastler Brossel

LPS
Laboratoire Physique Statistique



LPA
Laboratoire Pierre Aigrain



LPT
Laboratoire Physique Théorique

LRA
Laboratoire Radio-Astronomie

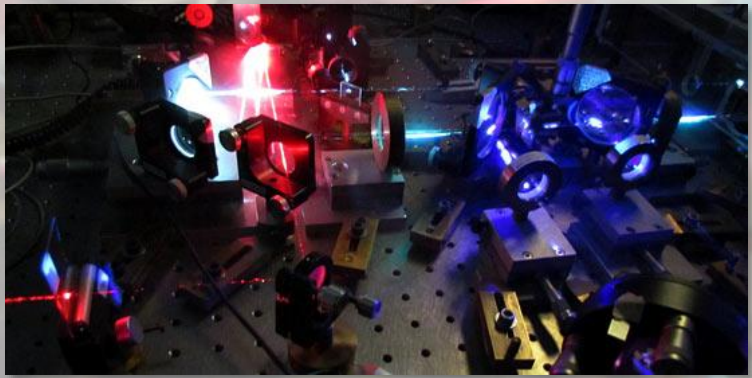
Quantum Materials and Devices (ex LPA)

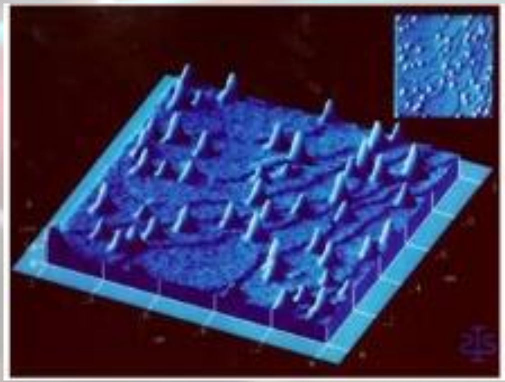
The scientific research in condensed matter and related techniques focuses on:

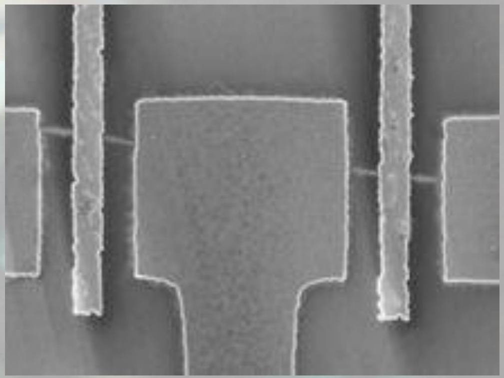
quantum dots and microcavities of semiconductors, mesoscopic conductive structures, superconducting thin films, single molecules of carbon (nanotubes, graphene) or biological (DNA).

These Experimental researches are divided into three experimental research fields:

- Optical and far-infrared (or TeraHertz) properties of nanostructures
- Transport and mesoscopic systems
- Biophysics

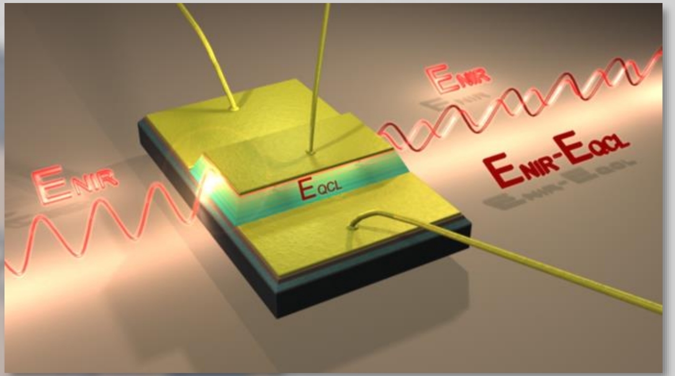




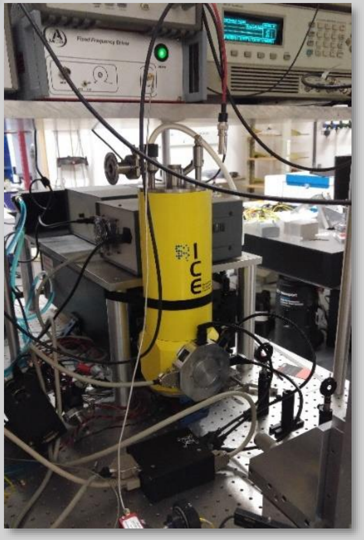


Early Motivations and Initial Selections

Motivations :
- Mixing waves SWIR-TeraHertz →
- Nanotubes Photoluminescence up to 1.5 µm
- Quantum dots beyond the µm



Constraints :
- Detection up to 1,6 µm
- Weak signals => Low noise readout
  High QE (Quantum Efficiency)
  Long Exposure Time
- Long Exposure Time => cooling system to avoid Dark Signal
- IR Sensor Price

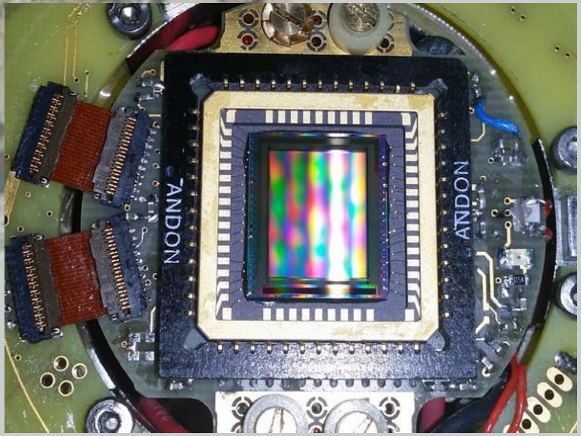


Solutions :
- Some hybrid IR sensors manufacturers that operate at 77K : Raytheon, Rockwell, Xenics ,.. but overpriced and especially the contact/ communication too complicated.
- Paper from NIT(New Imaging Technologies) which speak about one of their InGaAs hybrid sensor that operate at 77K..... is it the one ?!!

nit
A World Class Supplier of CMOS Sensors™

InfraRed InGaAs Camera SIRIS prototype

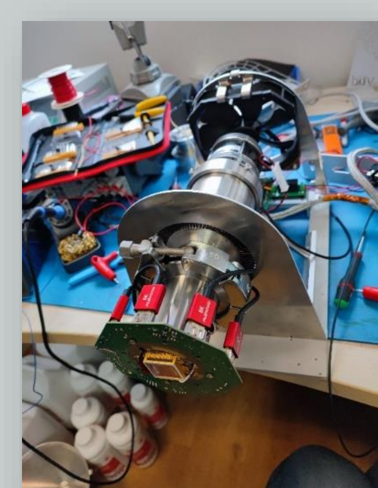
- **NSC1601 (640*513)**
- **0,9µm – 1,7µm avec un QE up to 80%.**
- **Cooled from ambiant to 77K by a vibration free cryocooler**
- **Dark signal : <10 e^-/s at 120K**
- **Well Depth : >150 k e^- (linear dynamic/CTIA mode)**
- **Readout Noise : <5 e^- (with NDRO)**
- **Global Shutter (ITR/IWR), NDRO (Non Destructive ReadOut).**
- **Mode Lin/log or CTIA : ie Full Linear.**
- **True ROI on chip, real time tunable.**
- **200fps (full frame), up to 10kfps (ROI 25x25)**
- **Tps de pose de 1µs à >1h (à 100K).**
- *Possibility of uHDR (ultra High Dynamic Range).*
- *Possibility of adaptative optics with one sensor.*
- **Liaison PC par « Camera Link »**



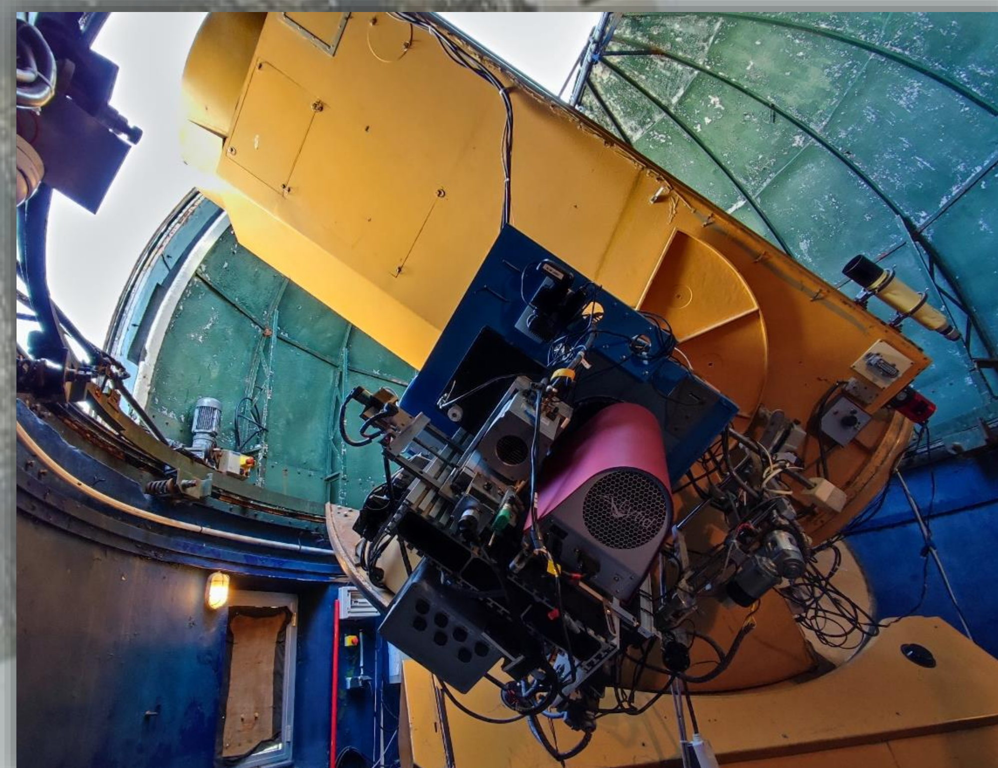
SIRIS : SWIR Camera commercialized by LYTID

The SIRIS camera is industrialized by the company LYTID, with ‘savoir faire’ licensed to LYTID by CNRS.

Lytid



The first SIRIS built by Lytid



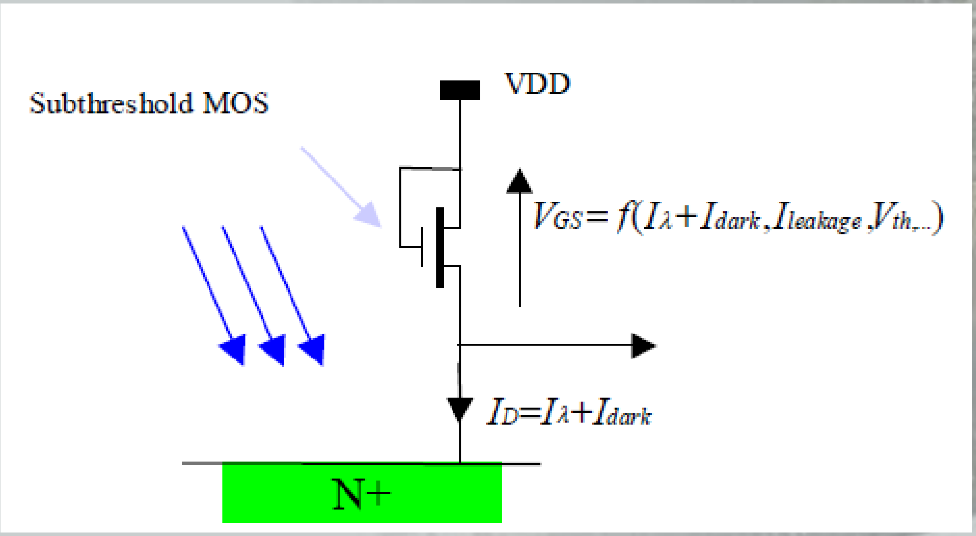
PTB
Physikalisch-Technische Bundesanstalt
National Metrology Institute

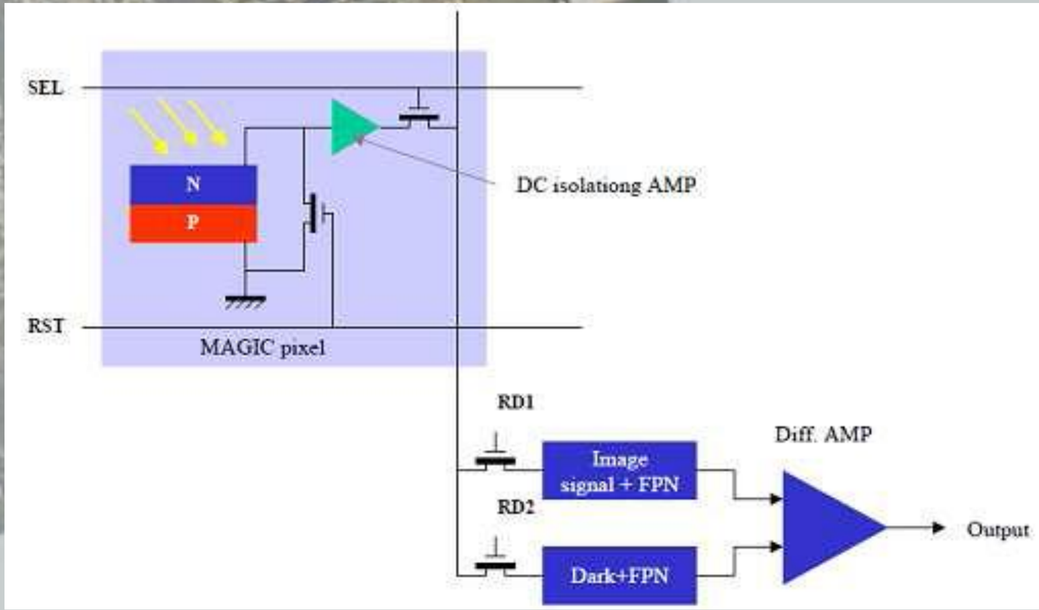
Optical nuclear spectroscopy of ^{229}Th group

CMOS version Wide Dynamic Range (WDR)

The conventional logarithmic image sensors operate with a photodiode in a photoconductor mode and create the log response between V_{GS} et I_{drain} with a MOS in Subthreshold mode (or even in weak inversion).

The Log-PV Pixel NIT: a photodiode in photovoltaic mode with in // a MOS transistor for the Reset to a reference and subtract the FPN



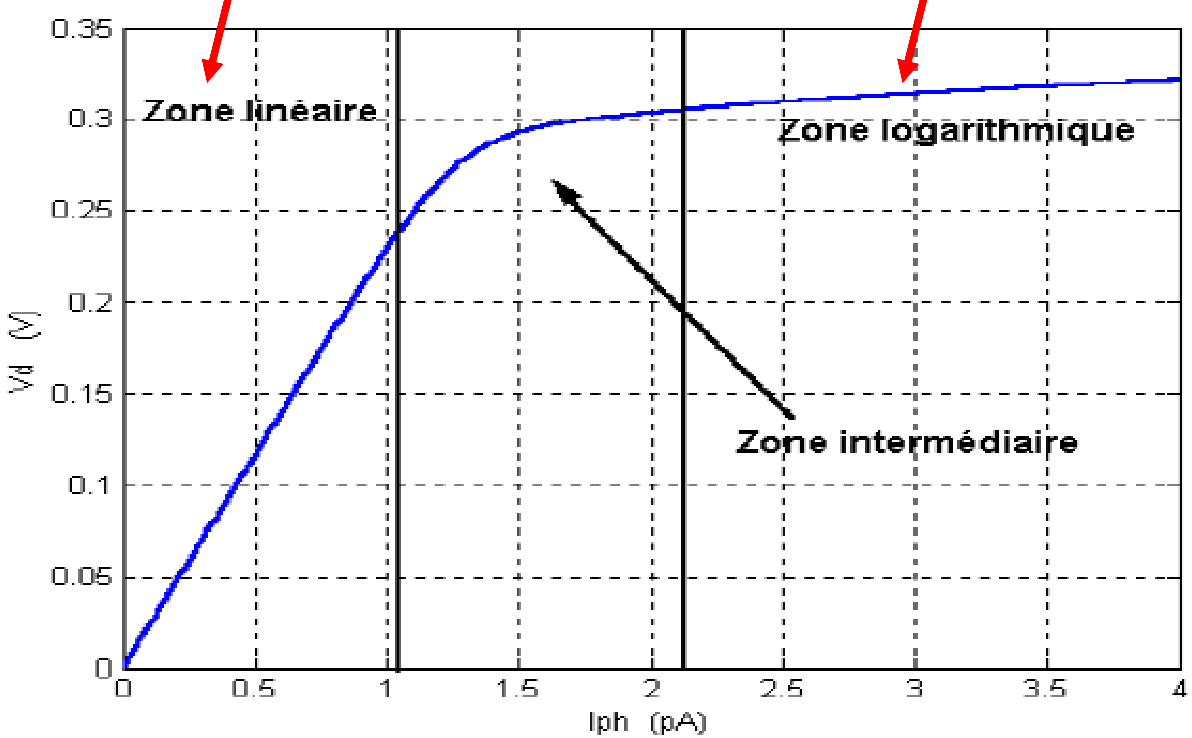


CMOS version Wide Dynamic Range (WDR)

$$V_d(t) = I_{ph}\frac{t}{C_e}$$

Avec Rd très grande

$$V_d(t) = U_T \ln\left(\frac{I_{ph}}{I_s}\right)$$



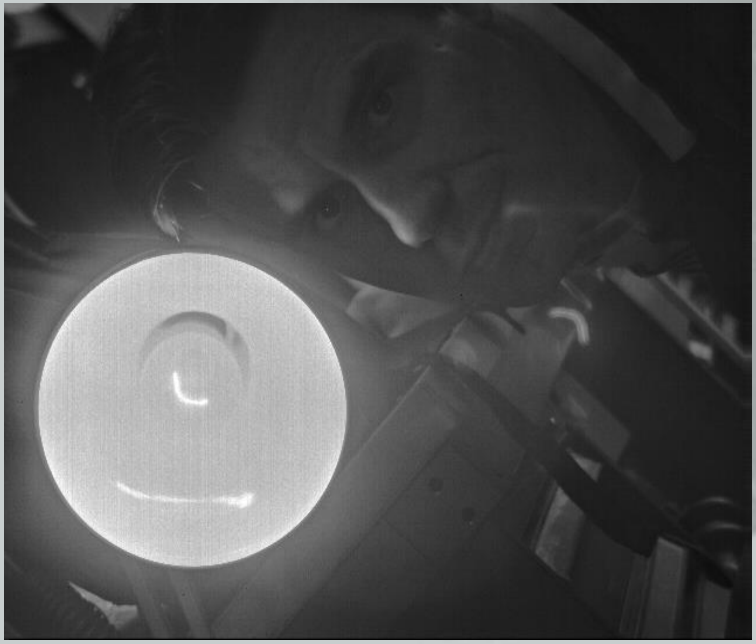
Réponse avec Texp = 20ms

- La tension thermique $U_T = 26mV$
- Condensateur de jonction $C_e = 86\,fF$
- Le courant de saturation inverse $I_s = 0{,}017\,fA$

'Capteur d'image logarithmique avec compensation "on-chip" du bruit spatial fixe'. Karine MATOU / 2003

CMOS version Wide Dynamic Range (WDR)

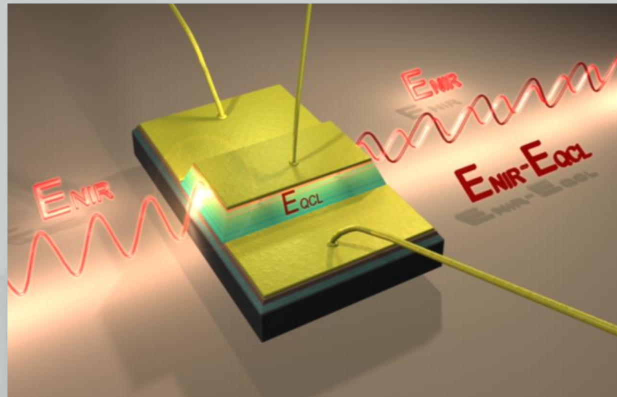
$$V_D = V_T \ln \frac{I_\lambda + I_s}{I_\lambda e^{-\frac{(I_\lambda + I_s)t}{V_T C_D}} + I_s}, \text{ where } V_T = \frac{kT}{q}$$



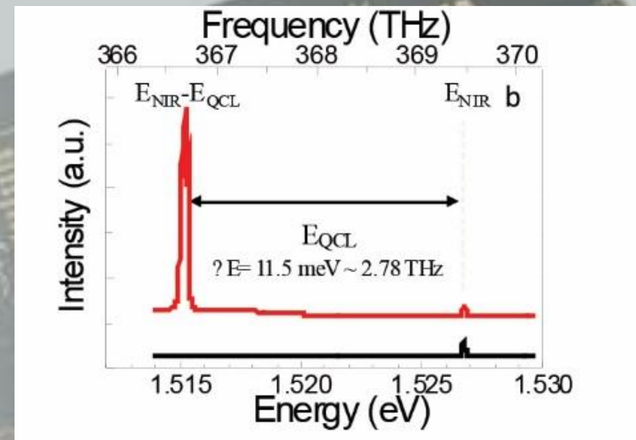
Log response V_D with linear part lead by C_D. We exploit this linear response for accumulation operating (for low and very low light) and in the same image, we can have the 'log' response for the photon high flow and linear response for pixels that are not saturated under low photon flux.

First experimental utilization

Quantic cascade laser (QCL)



Geometry schematic and experimental principle



SWIR + TeraHerz
High intensity peak measured E_{NIR}-E_{QCL} 11.5meV, 2,78 THz

Transmitted spectrums with QCL respectively switch off (black curve) and switch on (red curve)

Mixed SWIR-TeraHertz waves

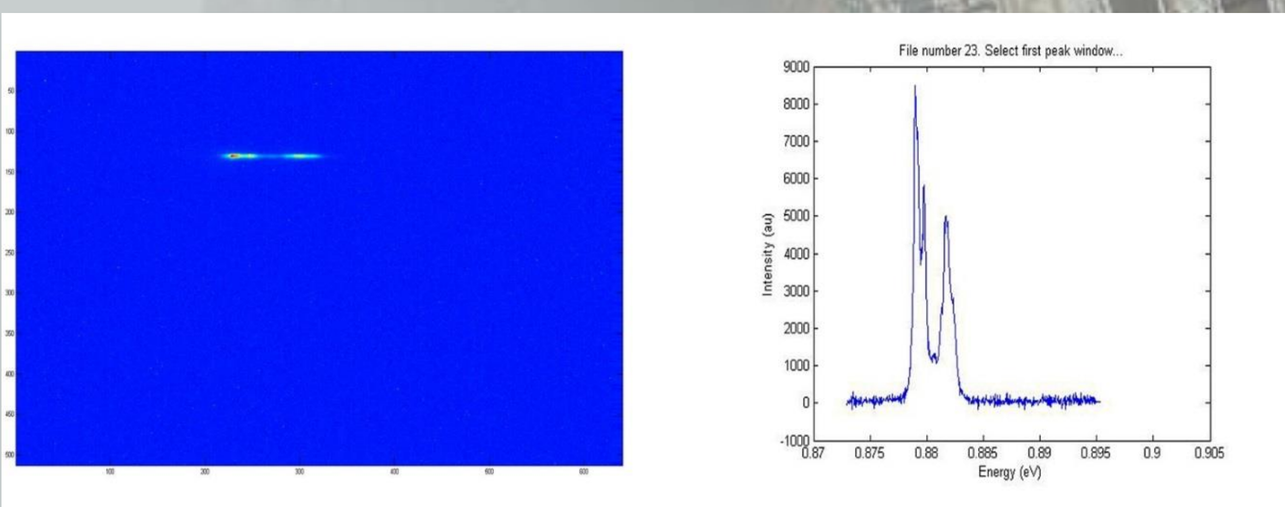
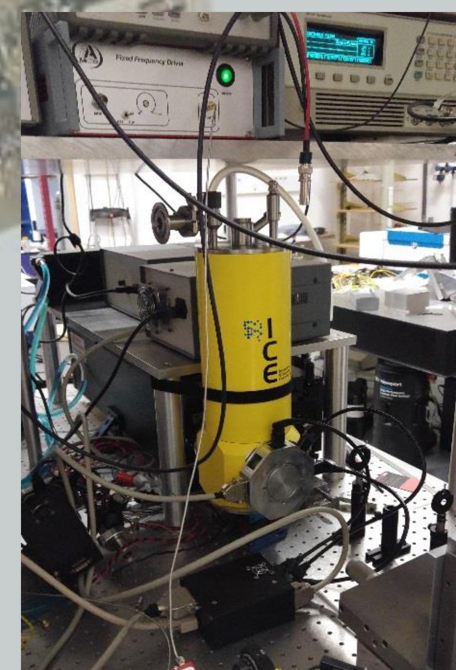


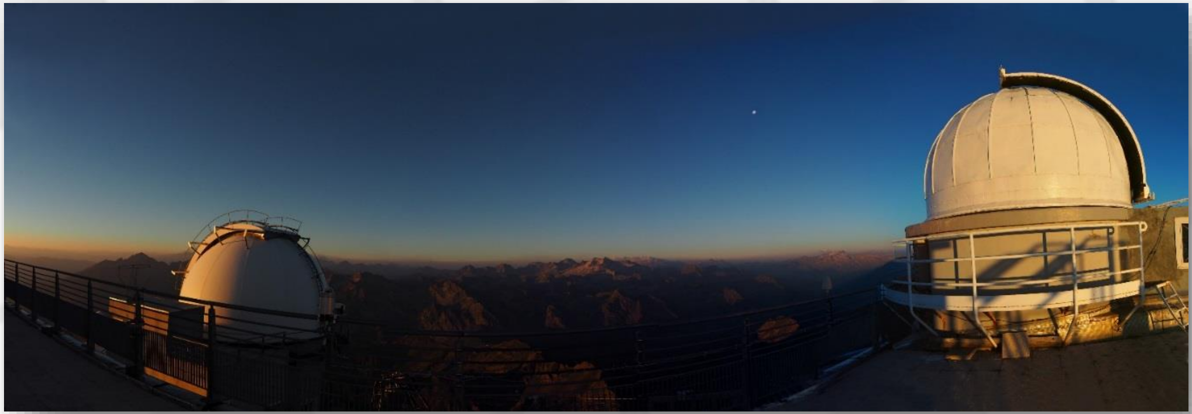
Image and profile obtained using the UHDR camera



First Results in Astronomy

APPLICATION CASE : ASTRONOMY PIC DU MIDI

- Pic du Midi' observatory at the top of French 'Pyrénées'.
- Altitude : 2876m.
- One of the best site around the World for it's very turbulence conditions (when the weather is good !!! ;-))
- We have as much telescope time as we need (it's 'unique' !)



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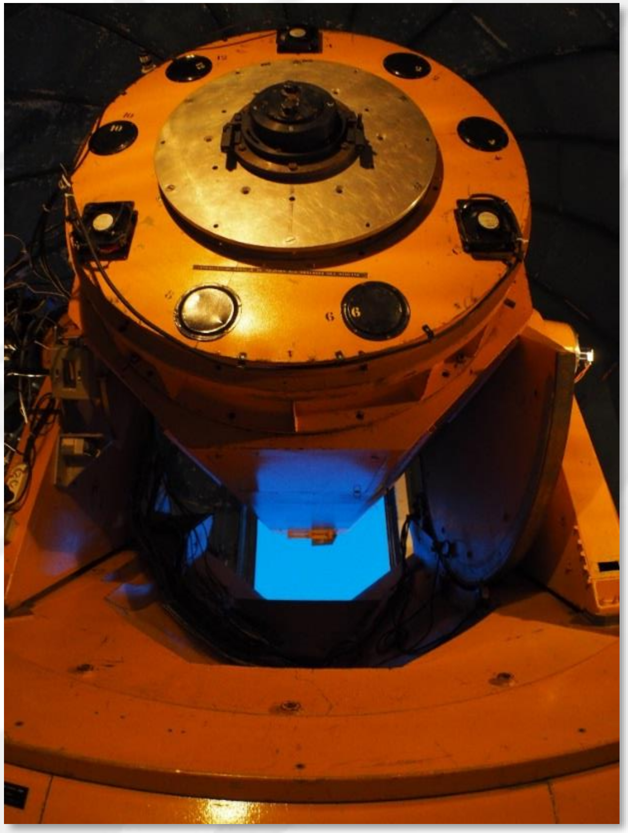
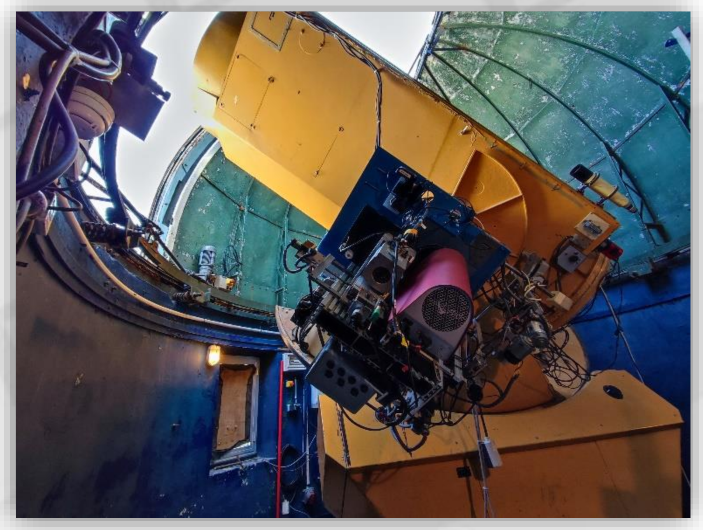
T1m at 'Pic du Midi'

T1m Telescop at the Pic du Midi:

- **1 meter of diameter.**
- **Optical formula: Cassegrain.**
- **Camera on Nasmyth focal plane.**
- **F17 (17m focal length).**
- **Filters:**
  - **J (1250nm,200nm fwhm).**
  - **H (1630nm,300nm fwhm).**
  - **Z' (>900nm).**
  - **Other narrow band filters with 50nm fwhm : 925, 975, 1000, 1100, 1175, 1275, 1575**





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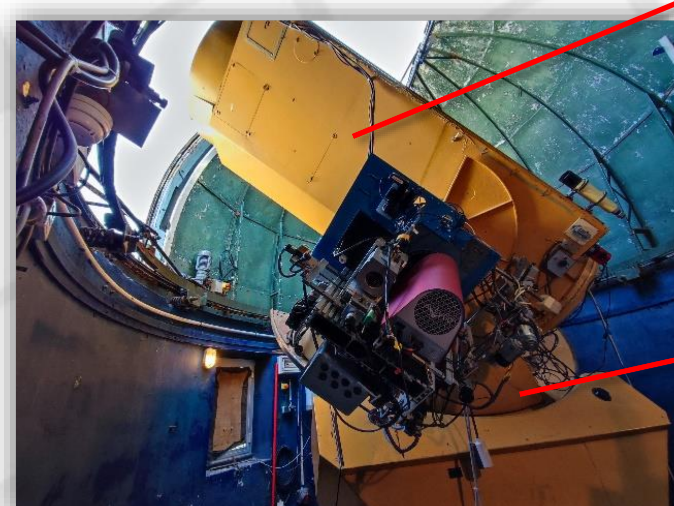
T1m at 'Pic du Midi'

The SIRIS Camera on the T1m:

- **640*512 pixels,15µm*15µm pixel size.**
- **Wavelength range : 0.9-1.7µm**
- **RON : $<150e^{-}$ (low gain)**
- **FOV : 1.94'*1.55'**
- **Scale : 0.18''/pixel**



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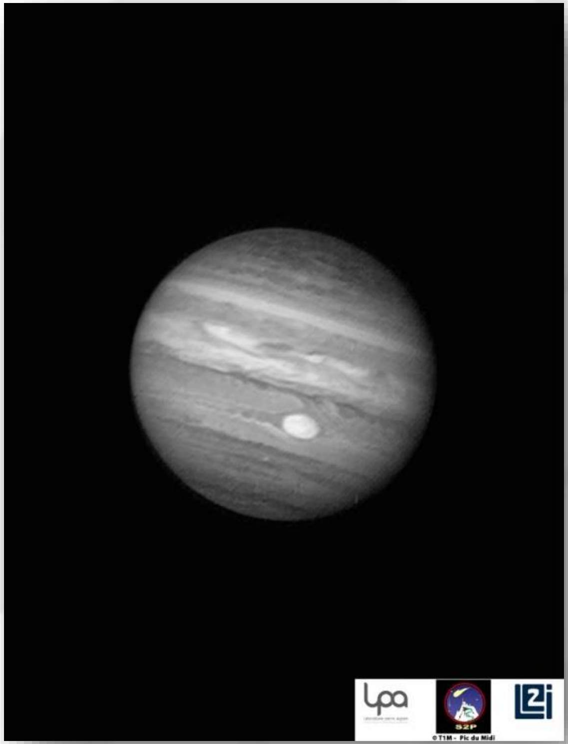
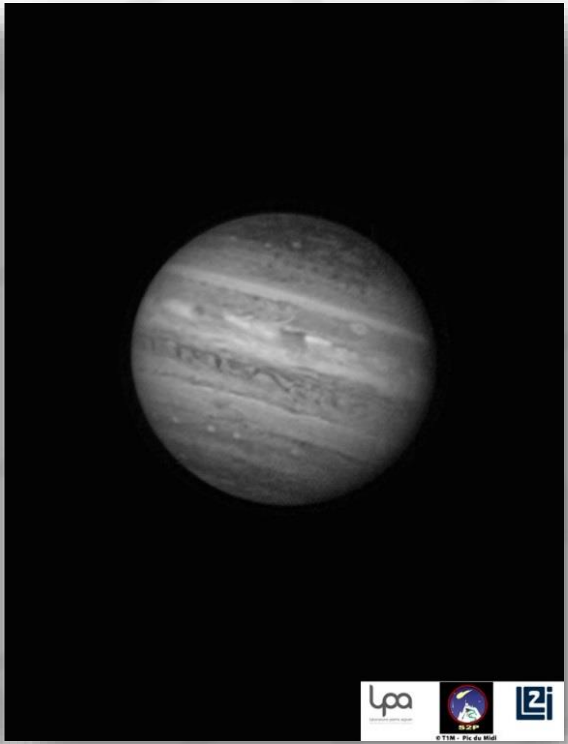
APPLICATION CASE : ASTRONOMY PIC DU MIDI

JUPITER

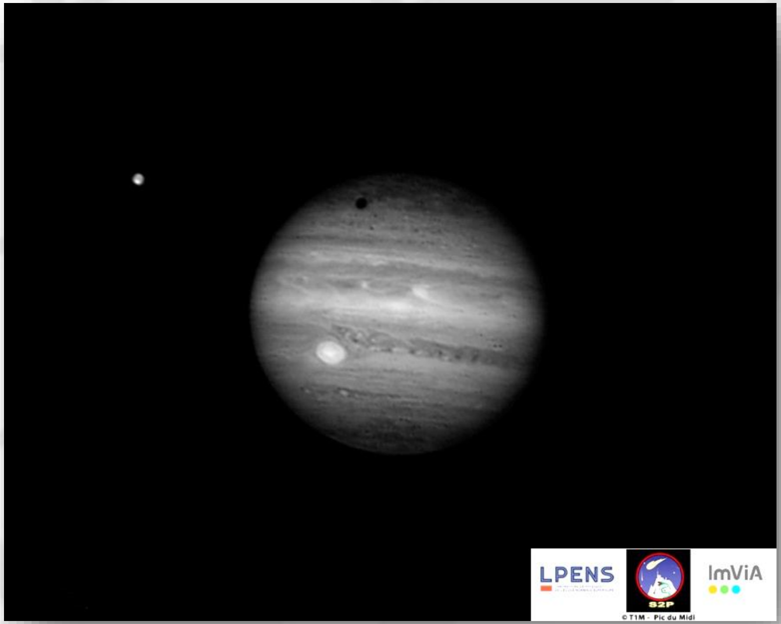
Classical stack with selection of the best images taken from one acquisition sequence : linear mode.



Filter J,



Filter H,



Filter H,

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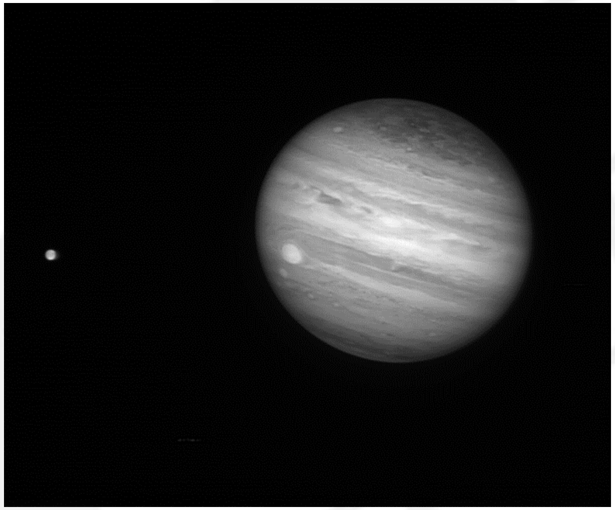
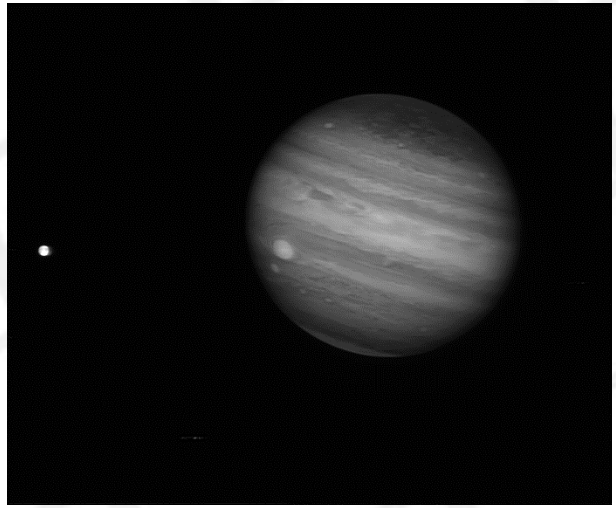
APPLICATION CASE : ASTRONOMY PIC DU MIDI

JUPITER

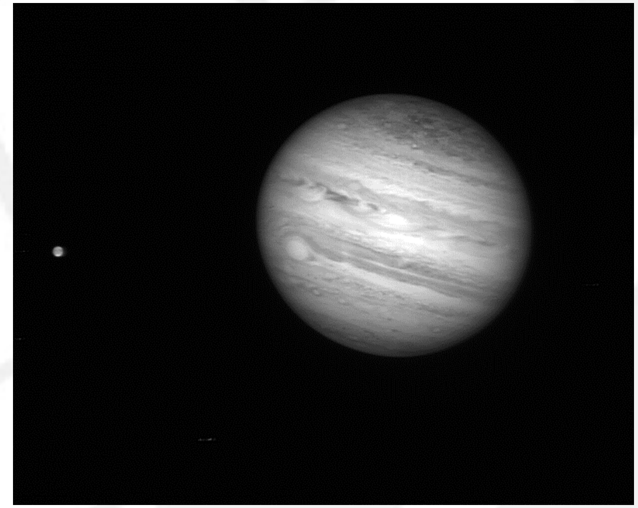
Classical stack with selection of the best images taken from one acquisition sequence : linear mode.



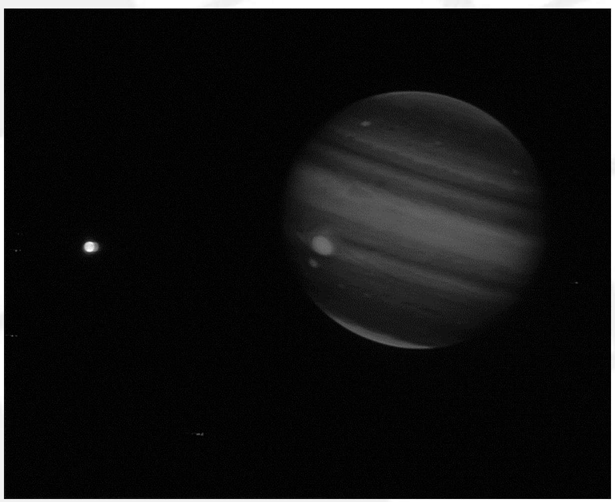
975nm 60ms (CTIA G2)



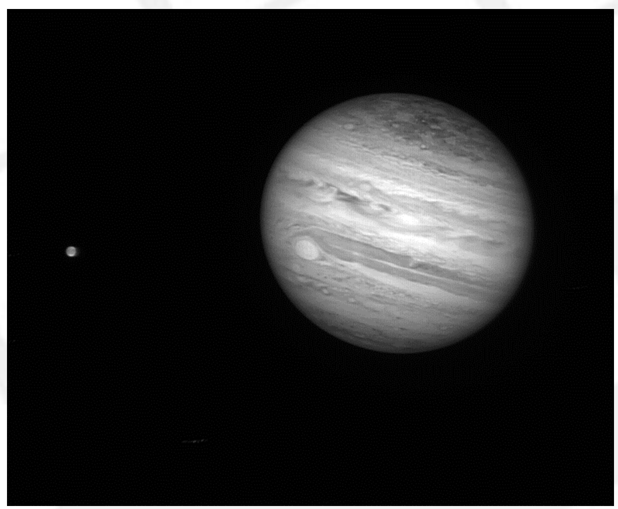
1000nm 100ms (CTIA G2)



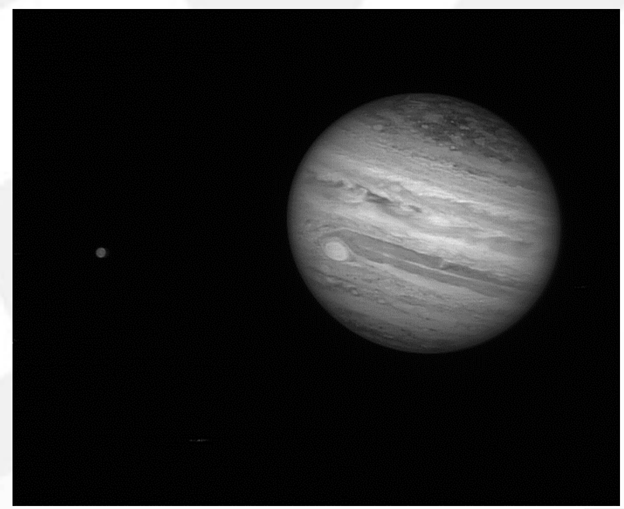
1100nm 100ms (CTIA G2)



1175nm 1000ms (CTIA G2)



1275nm 60ms (CTIA G2)



1575nm 60ms (CTIA G2)

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APPLICATION CASE : ASTRONOMY PIC DU MIDI

JUPITER

Filter J, Jupiter in Linear (CTIA) response stack of 40 exposure of 5s each with NDRO readout noise reduction

Filter J, Jupiter in Linear-Log response stack of 80 exposure of 2s each with NDRO readout noise reduction

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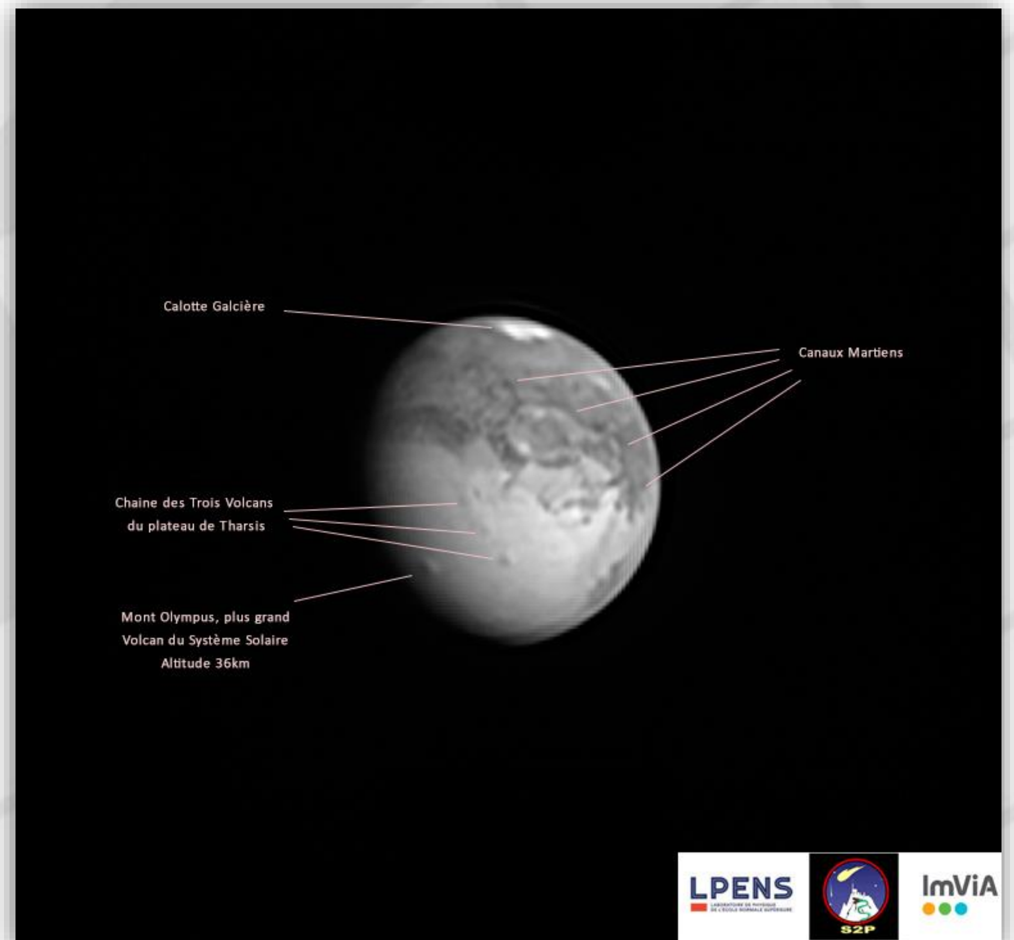
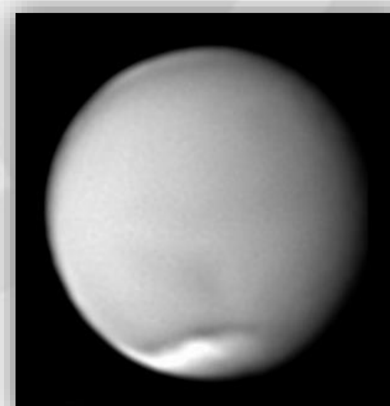


Filter J, Mars classical stack in CTIA mode, 100ms sub exposure

Mars

Filter J, Mars during global sand storm in summer 2018



Mars during the same nigth taken in visible range

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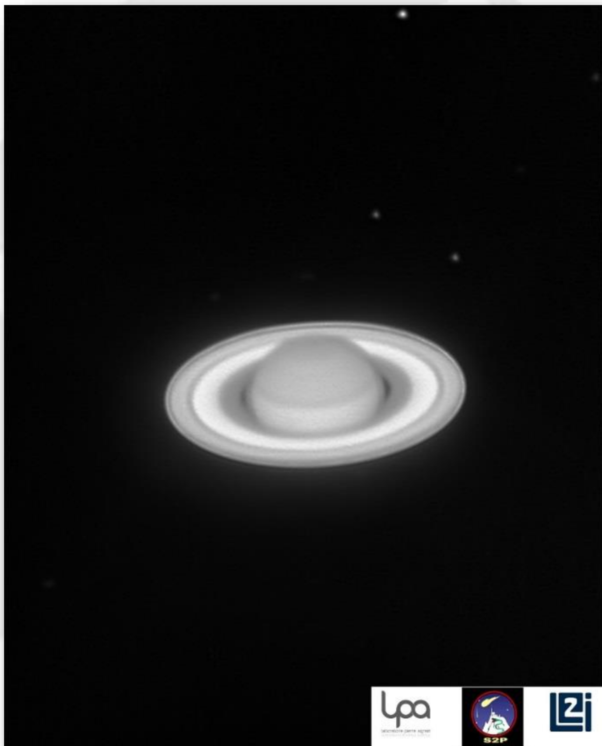
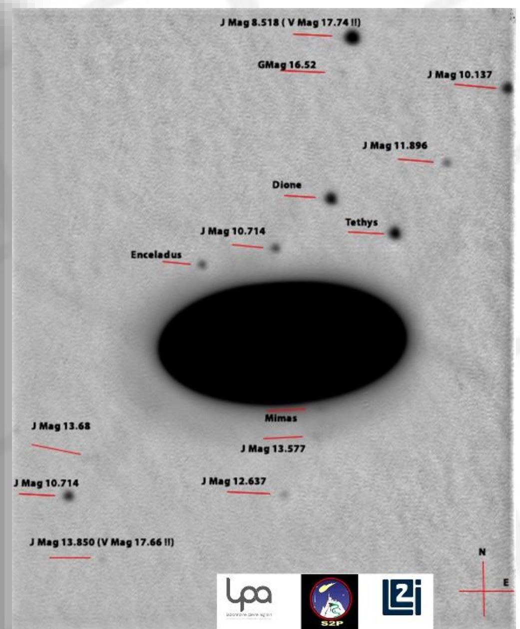
APPLICATION CASE : ASTRONOMY PIC DU MIDI





Filter J, J Mag up tu 13.8 and Hencke division, lin-log readout mode with 4s exposure time

SATURNE

Filter J, classical stack 50 ms sub_exposure

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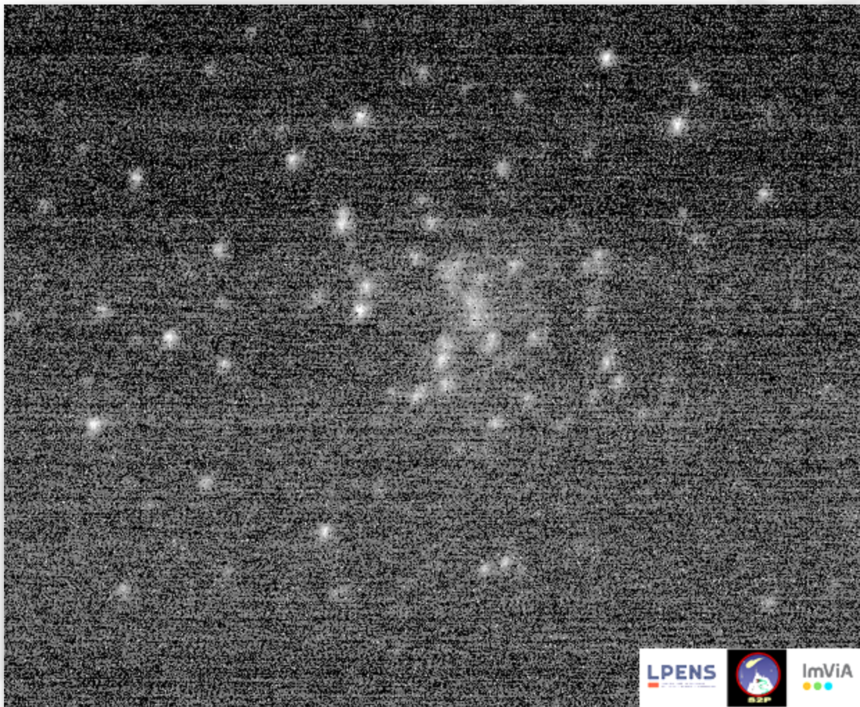
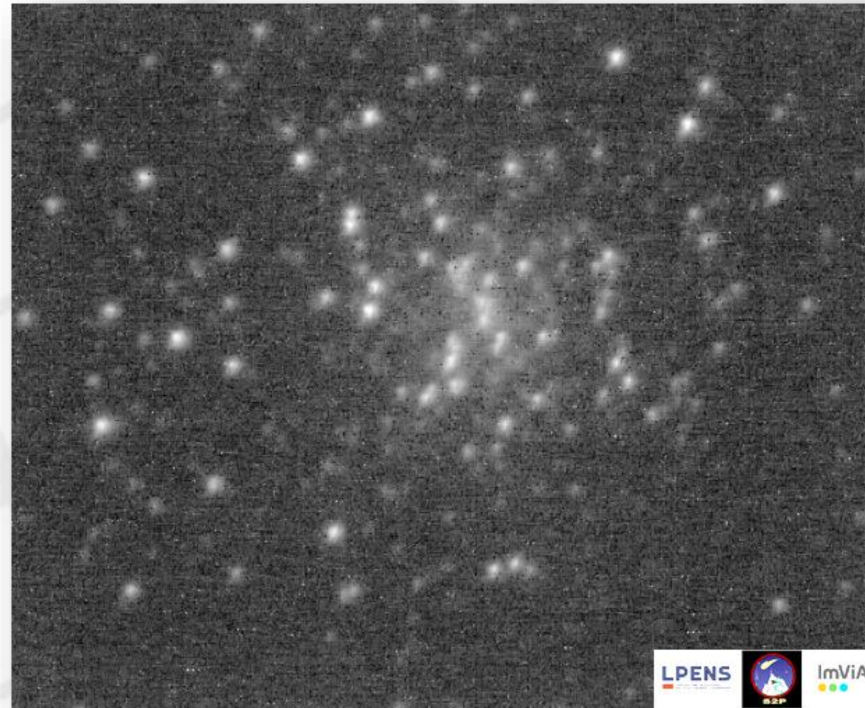
APPLICATION CASE : ASTRONOMY PIC DU MIDI

M15

Same acquisition of 1s: comparison of just one classical readout or with NDRO for noise reduction during this acquisition





M15 1s exposure, classical mode with single readout at the end of exposure

M15 1s exposure, very same exposure as left one, but taking account of NDRO during exposure. (100NDRO)
Here a gain of about 2 Mag, ie a SNR rises by a factor >6.25

M15 2s exposure time , taking account of 400NDRO gain of about 3 mag.

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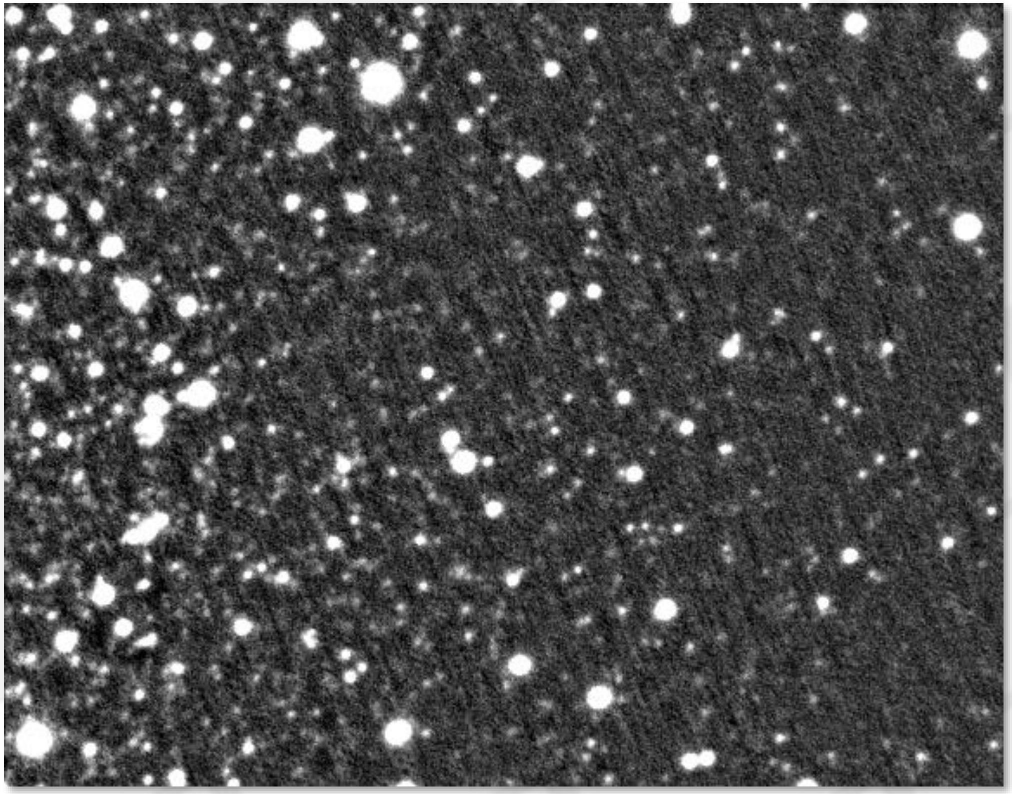
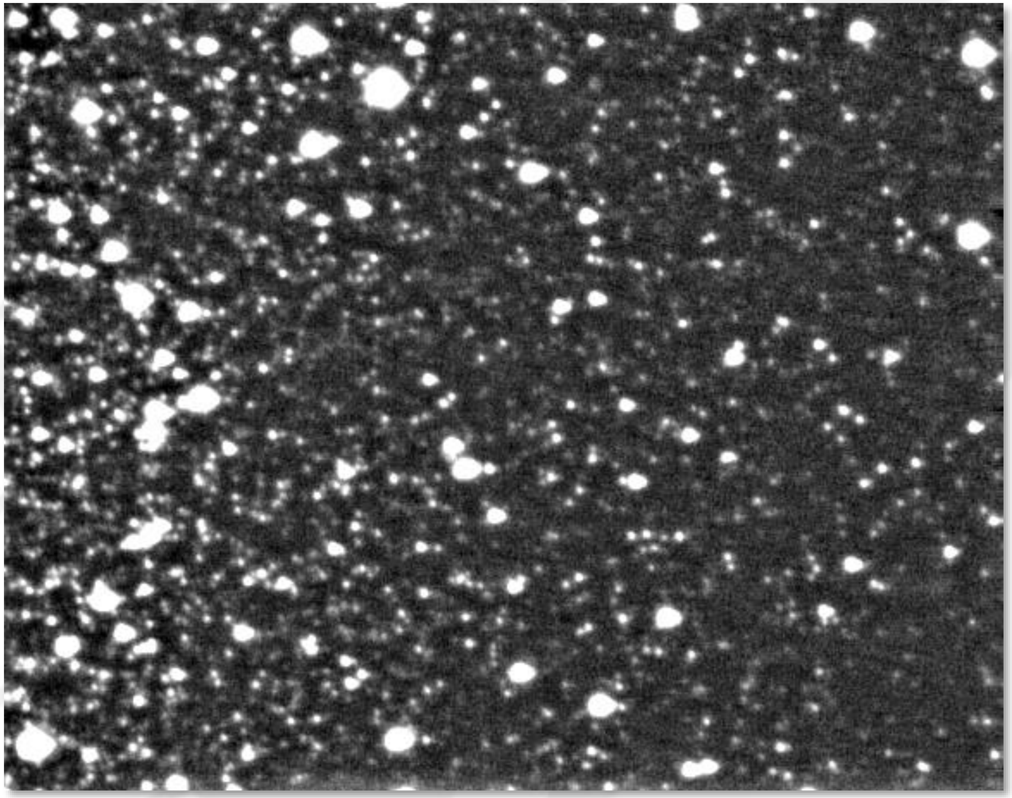
M13

A close view away from the center of M13. Same acquisition of 30 exposures 8s: stack: comparison between Siris and the Ninox640SU from Raptor.



Stack of 30 exposures of 8s from Ninox640SU Raptor SWIR Camera



Stack of 30 exposures of 8s from our SIRIS SWIR Camera. Mag19 in J band is visible on this image.

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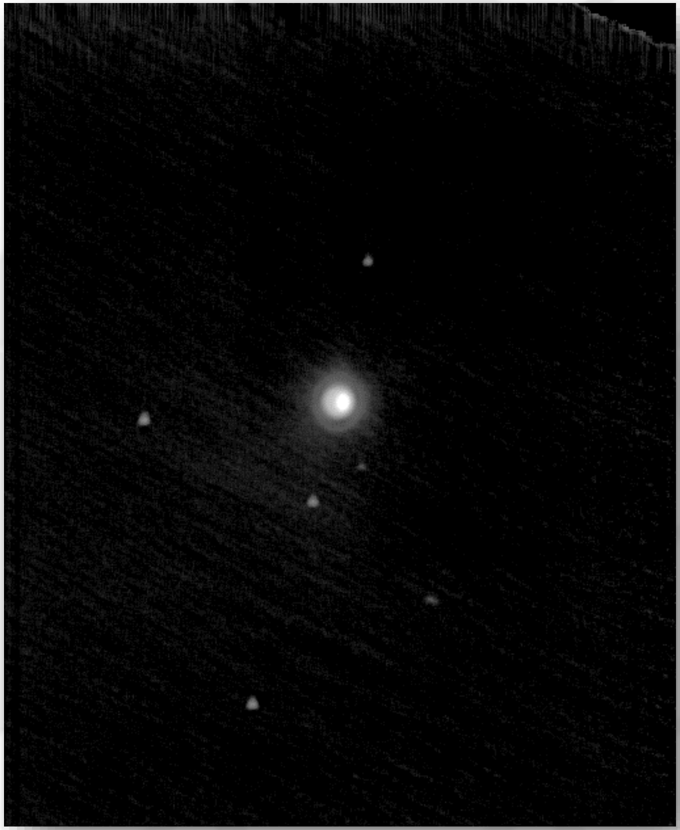
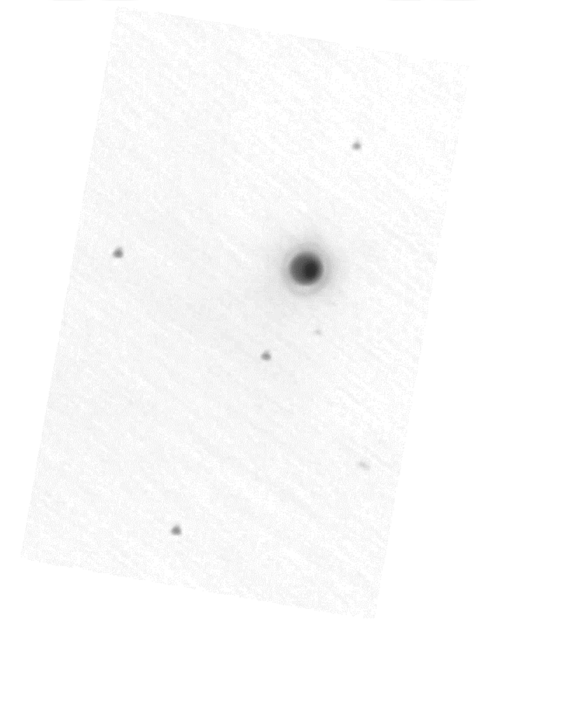
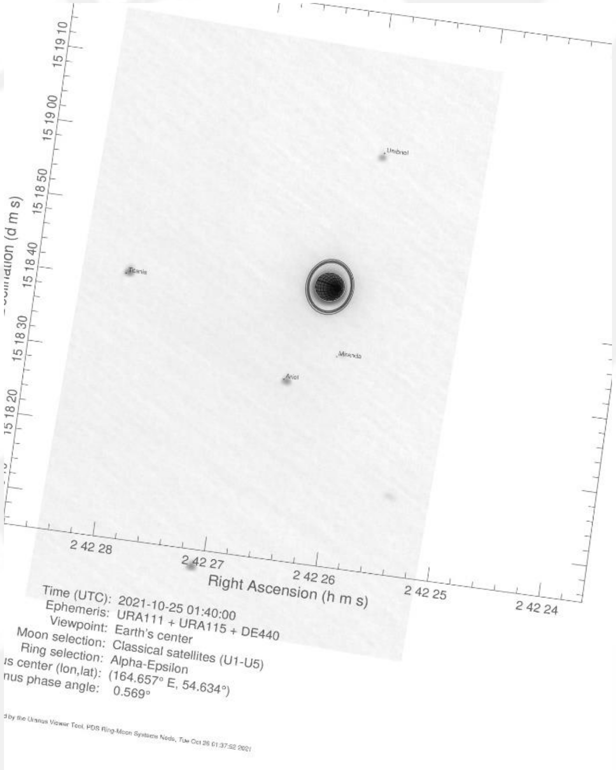
Uranus



Filter J, Uranus (CTIA) NDRO readout noise reduction, stack of 500 exposure of 600m. 24 October 2021. We can see satellites, pole clouds, and rings !





Same image, inverted, and surimpose with position with the ephemeride of Uranus satellites and rings … rings confirmation!

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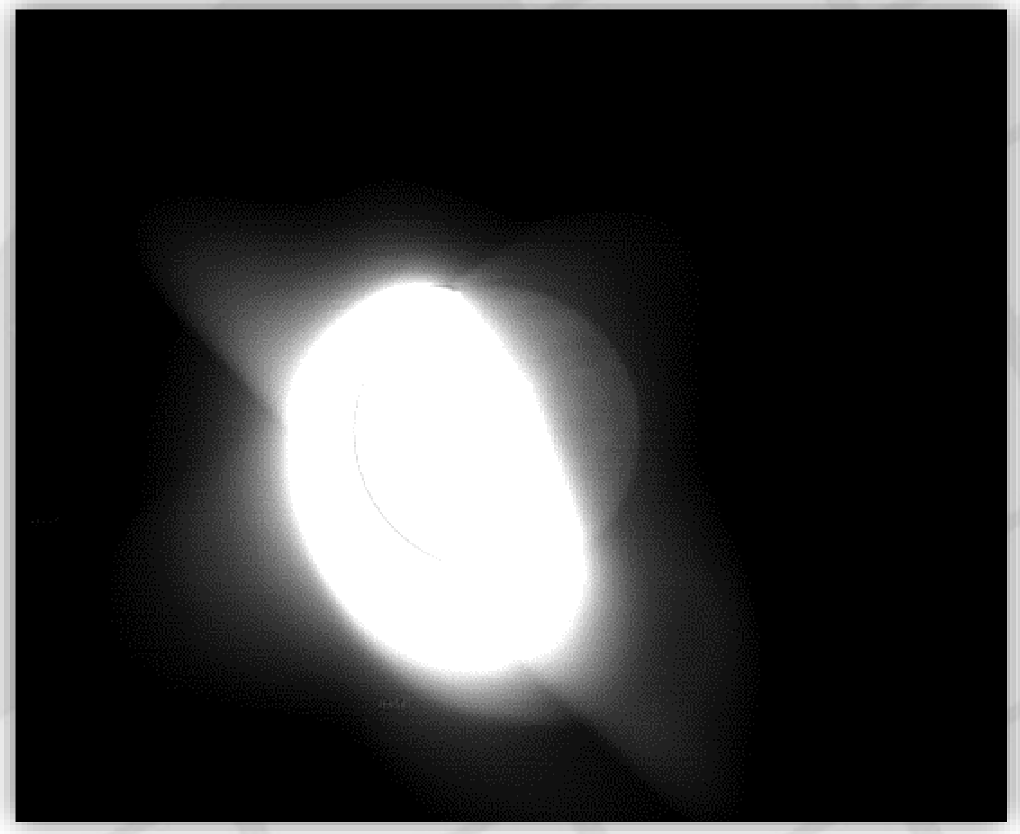
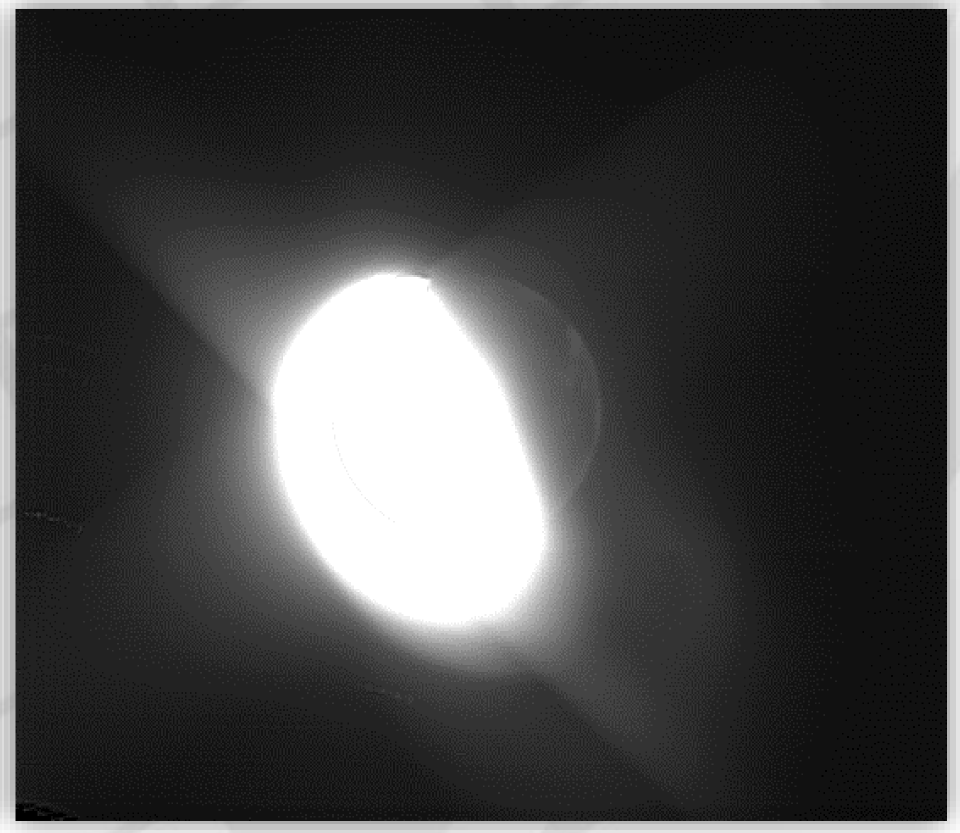


Venus 1175nm



Venus, 1275nm

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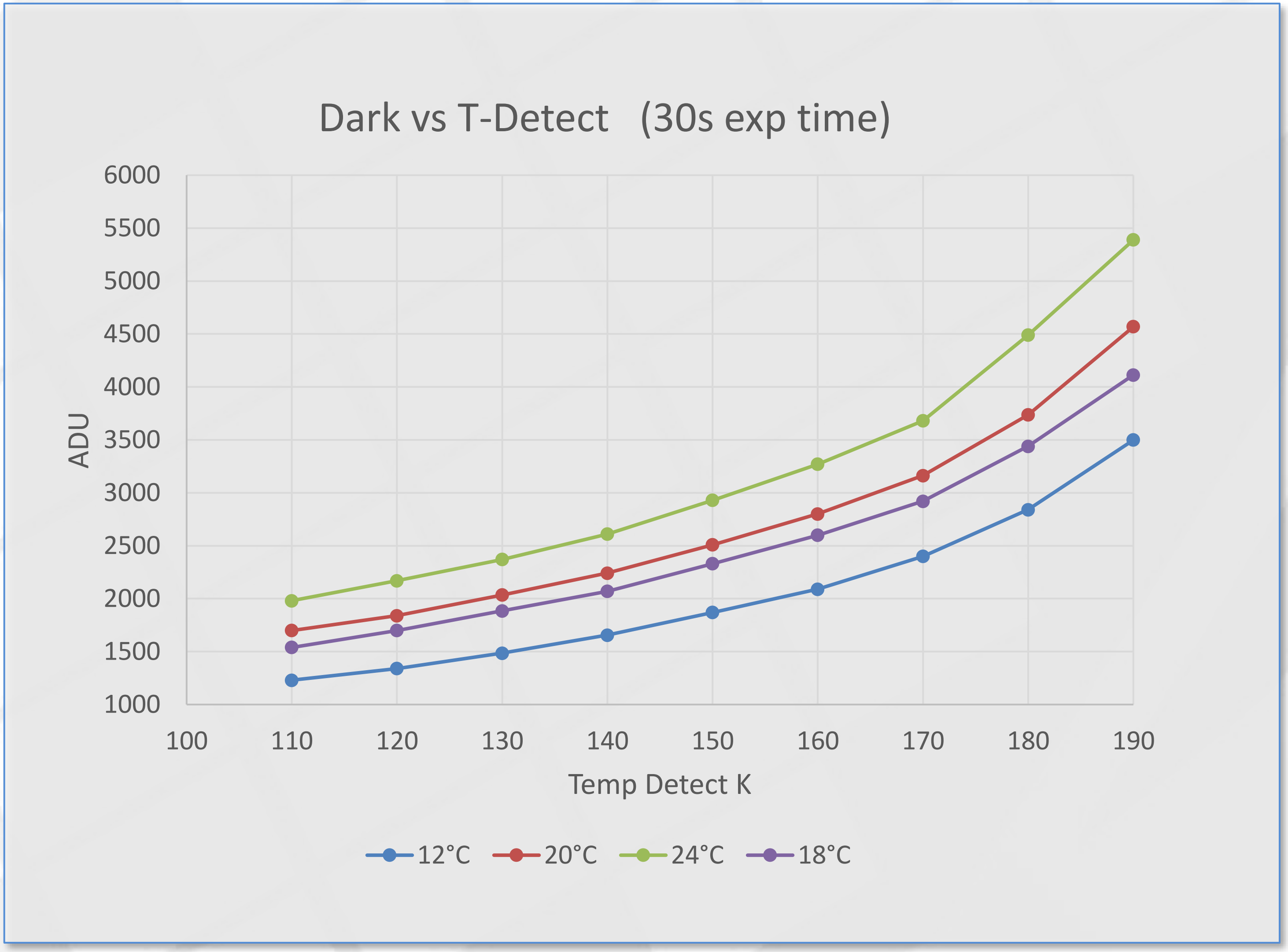
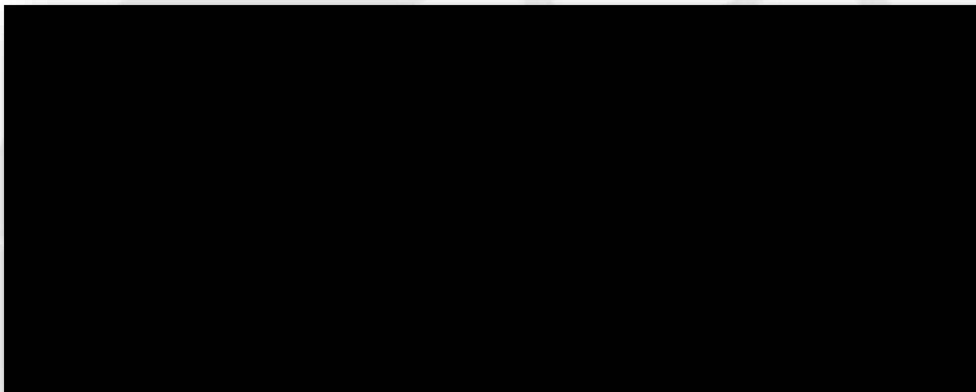

Dark vs T-Detect (30s exp time)
ADU
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
100
110
120
130
140
150
160
170
180
190
Temp Detect K
12°C
20°C
24°C
18°C

Two Patents

uHDR (Ultra High Dynamic Range)

Patent R28732FR (2016) Darson & al : "Haute Dynamique Rapide sur une Pose par Lectures Adaptatives Non Destructives",



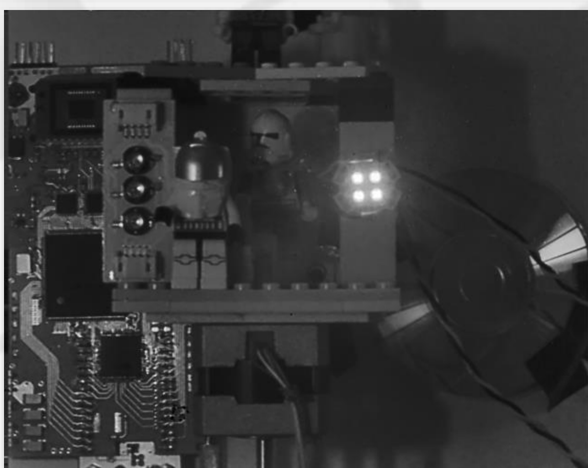
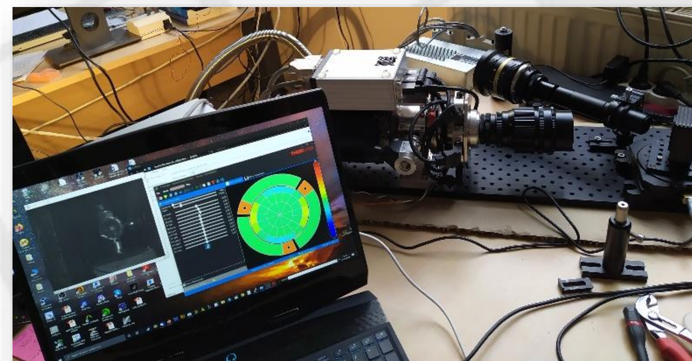
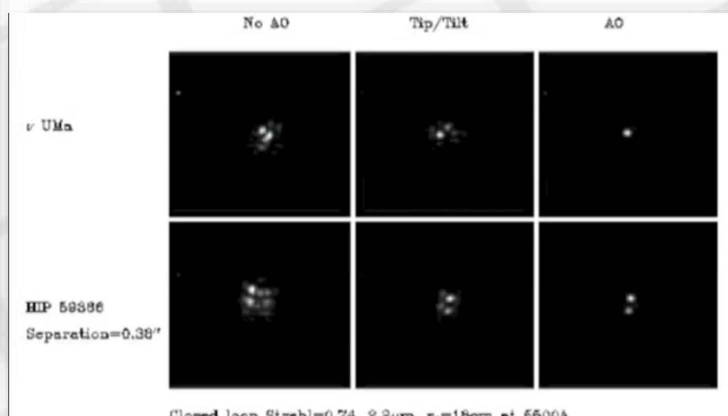


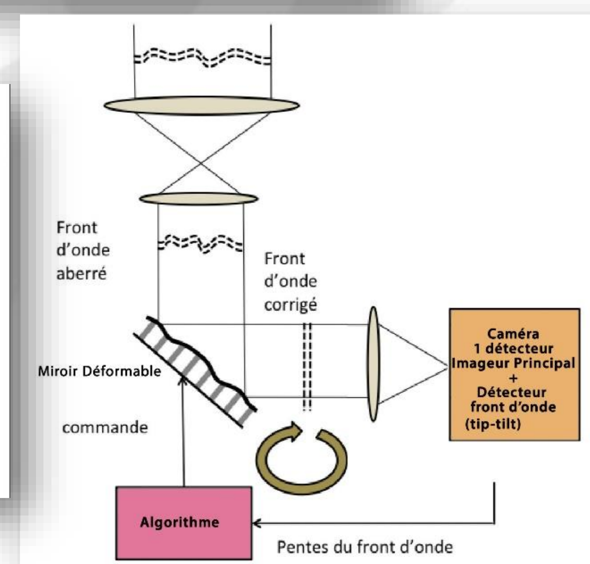
Image UHDR résultante (sur 32NDRO)_ >100millions de niveau de gris.

One sensor Adaptativ Optic Imaging System

Patent 376594D38439 2019 , Darson & al ,« PROCÉDÉ D'ACQUISITION D'UNE IMAGE AVEC UNE OPTIQUE ADAPTATIVE »





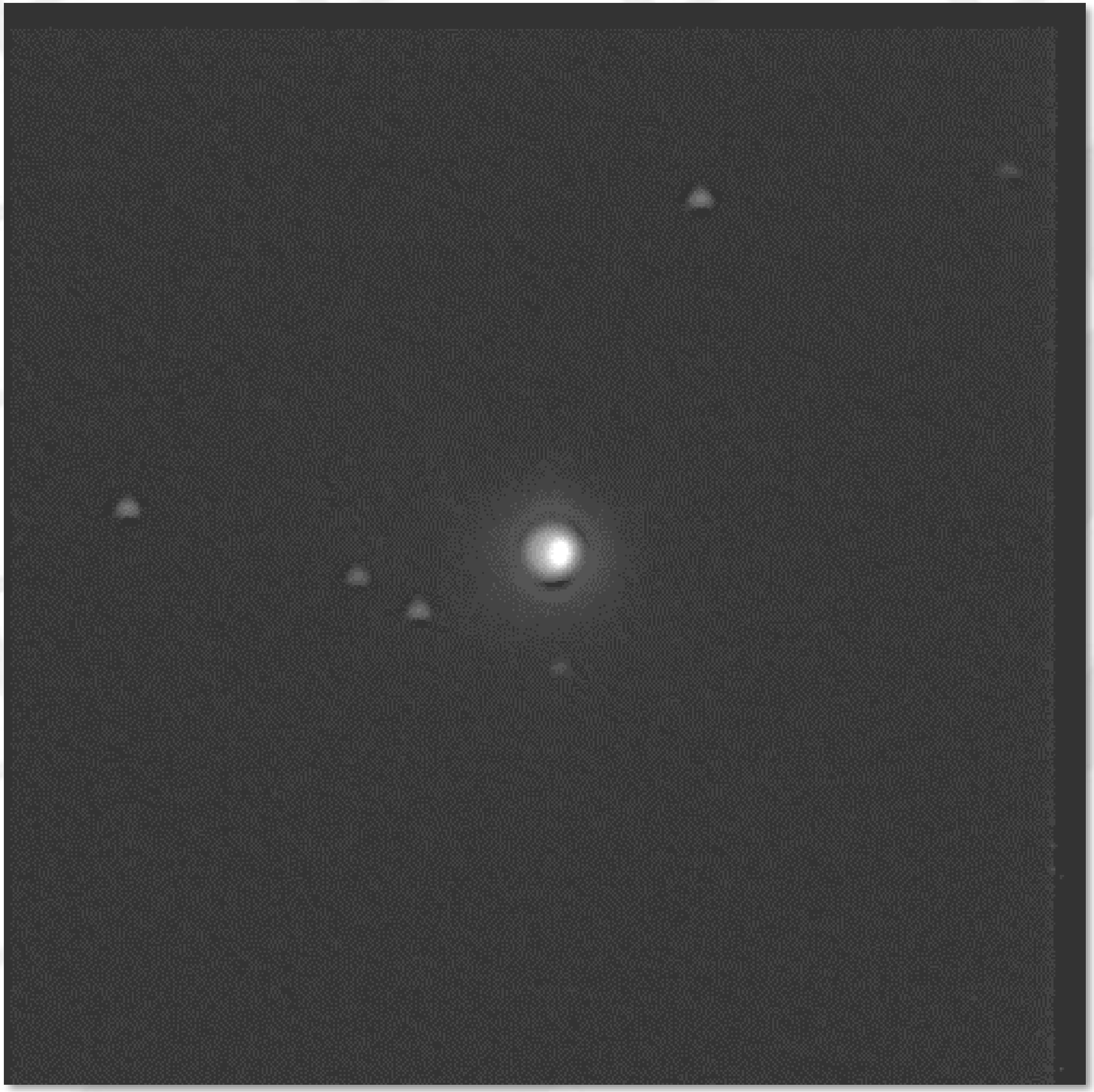


Questions ?

First Results in Astronomy

APPLICATION CASE : ASTRONOMY PIC DU MIDI

Uranus



Filter J, Uranus (CTIA) NDRO readout noise reduction, stack of 500 exposure of 600ms. Animation during 4 nights began 24 October 2021. We can see satellites, pole clouds, and rings !

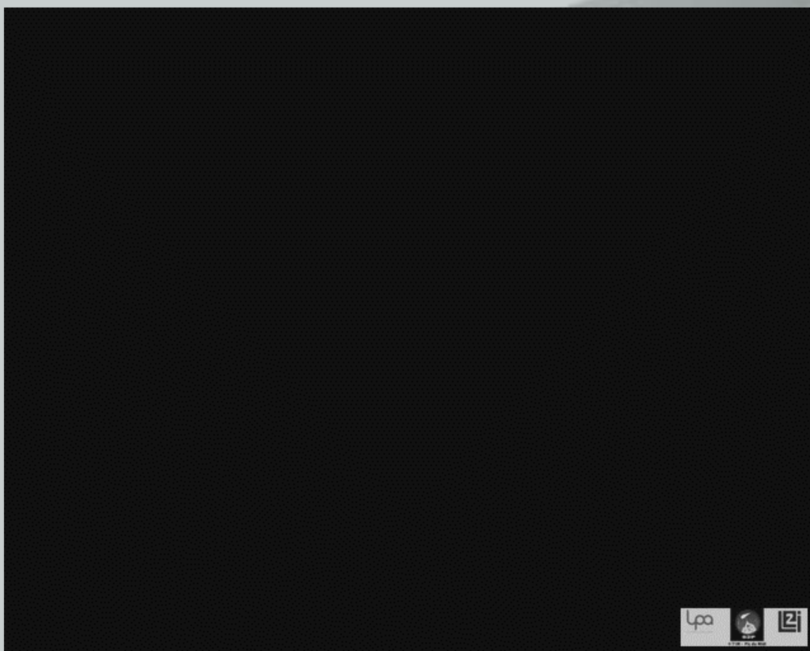
LPENS
©T1M - Pic du Midi
ImViA

First Results in Astronomy

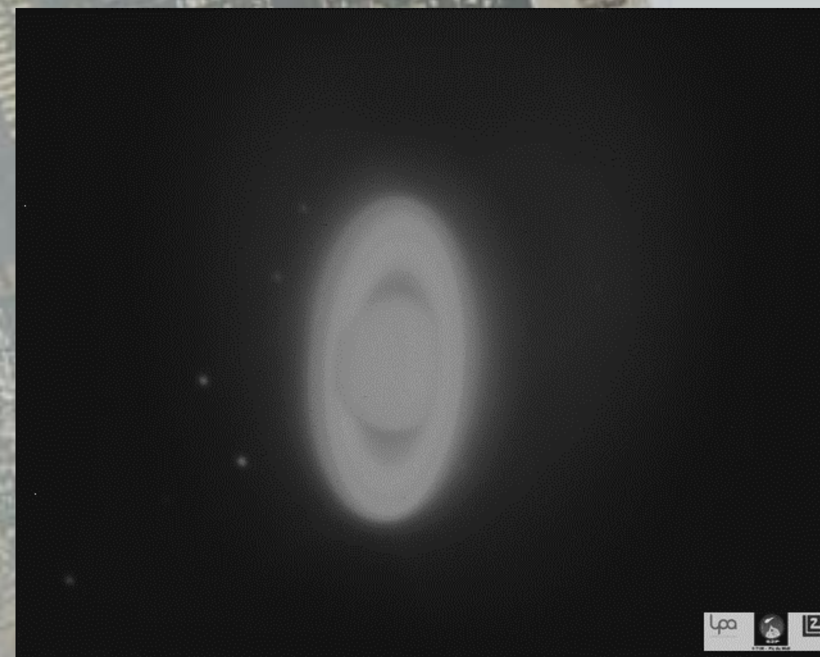
Au Pic du Midi sur le T1m

SATURNE

'live' of NDRO during sequence of exposures



'live' of sequence of 2,5s exposures with 480 NDRO during each of them. Strong turbulence conditions. When Saturn saturate its linear part and transit into 'log' we retrieve real time information : space (x,y) and time data. Meanwhile low signals in linear parts continues to accumulate.



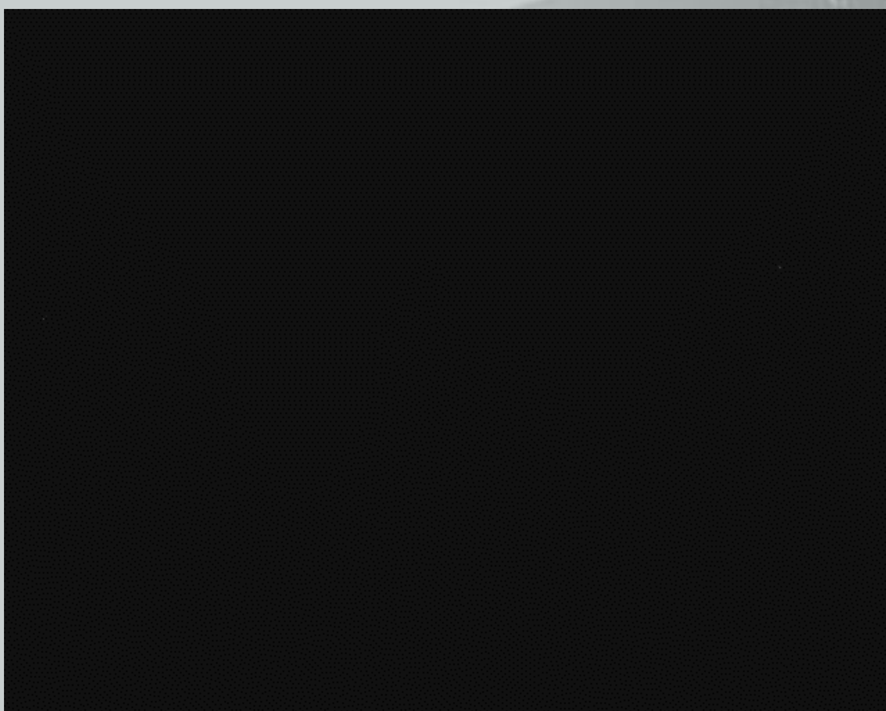
Same as left video but with better turbulence conditions and with 250NDRO during 1,25s exposures.

First Results in Astronomy

APPLICATION CASE : ASTRONOMY PIC DU MIDI

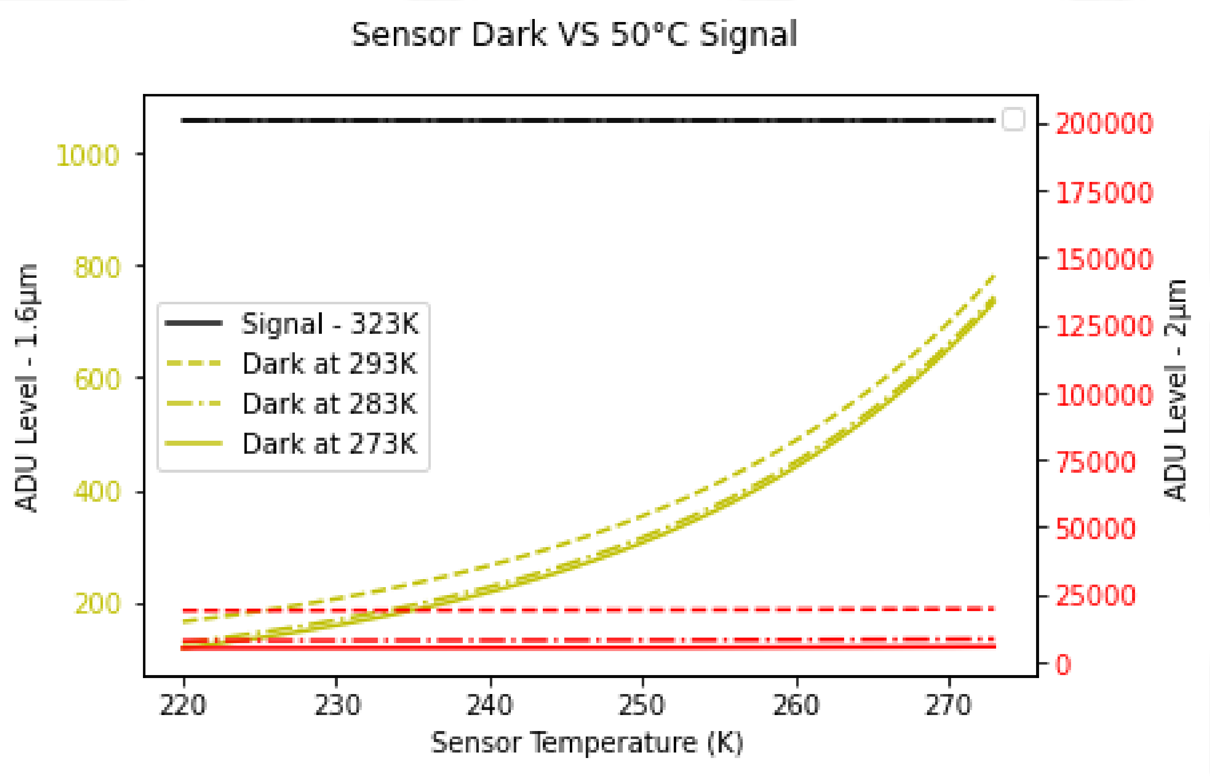
Gamma Sagittae

sequences of 250 NDRO (1,2s equivalent exposure)



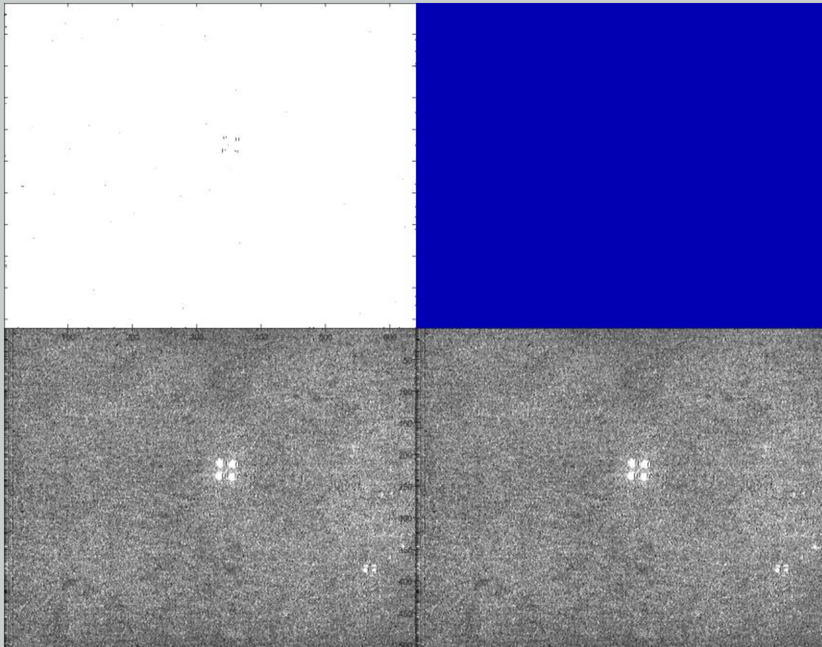
Sirius-a et Sirius-b

sequences of 300 NDRO (1.5s equivalent exposure)

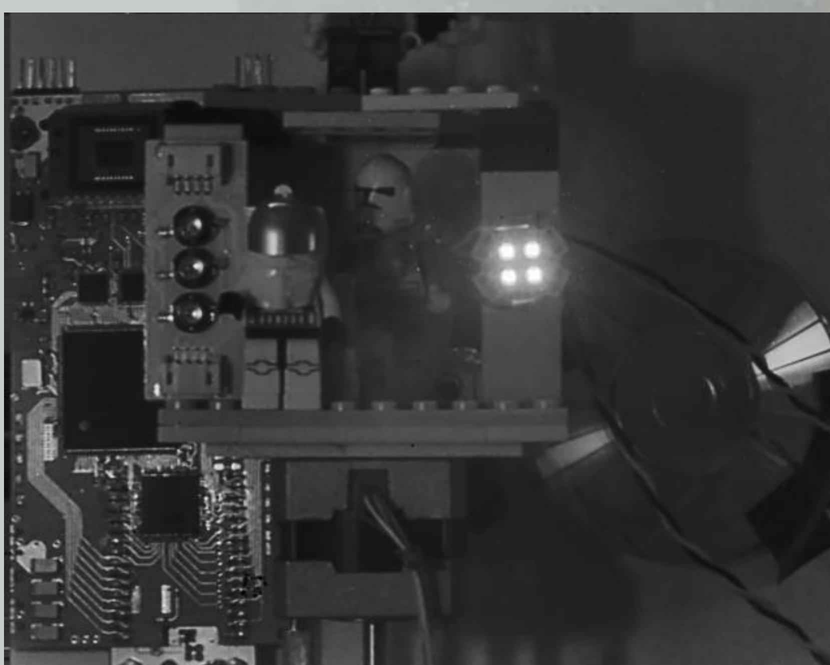


Sensor Dark VS 50°C Signal
Signal - 323K
Dark at 293K
Dark at 283K
Dark at 273K
ADU Level - 1.6µm
1000
800
600
400
200
ADU Level - 2µm
200000
175000
150000
125000
100000
75000
50000
25000
0
220
230
240
250
260
270
Sensor Temperature (K)

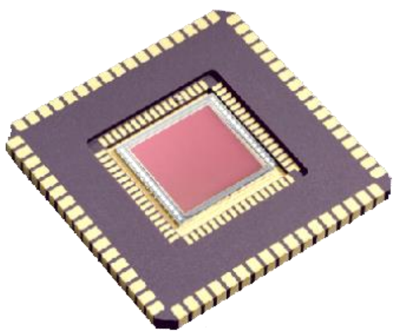
uHDR : Ultra High Dynamic Range



Real Time, low cost memory and CPU, High Dynamic Range image generation that automatically adapt acquisition time, dynamic to the incident photon flux.
‘No’ limitation for the final dynamic.



Context HDR



Specific sensor

Multi exposure with classical sensor

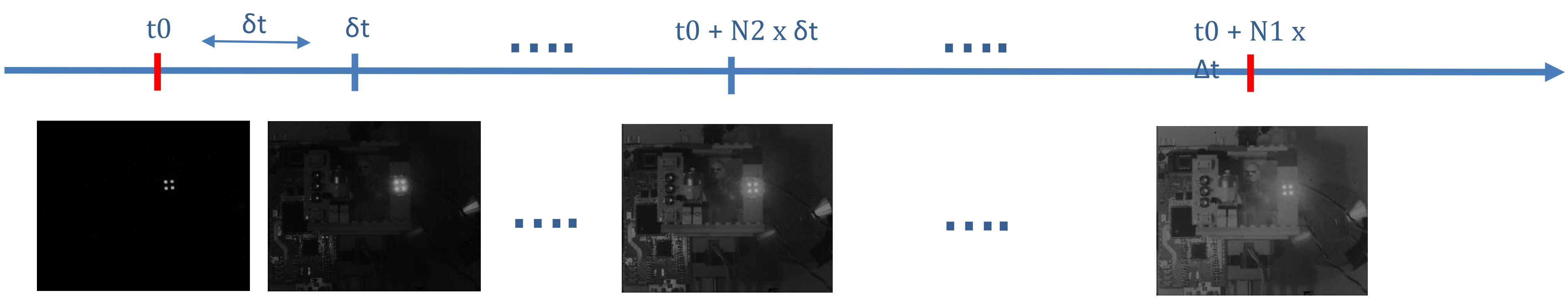
Native log sensor:
no image saturation

For Linear response

Main idea : Merging the two solutions access
to weak as well as high signals

Multi-Readout during a single exposure

Previous approach: One image reading, charges destroyed, image reset

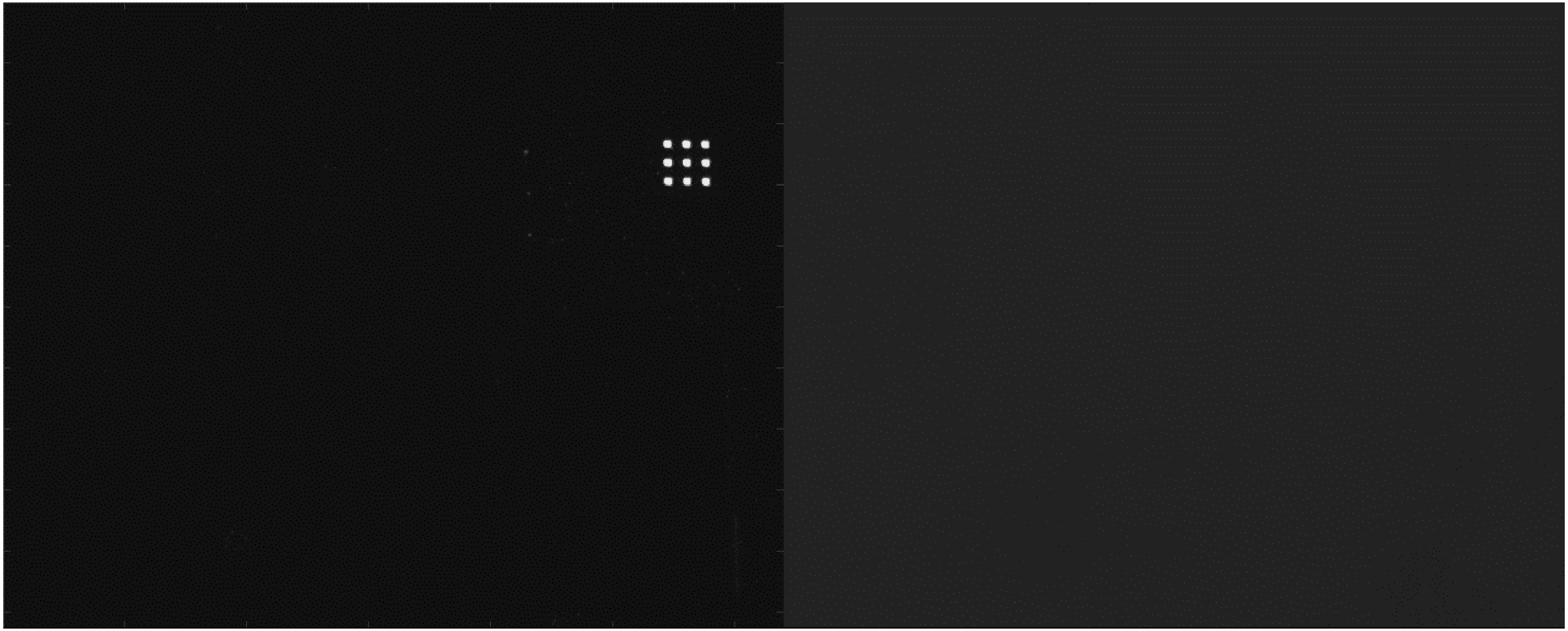


Different exposures nevertheless all acquisitions based on Non-Destrcutive Read Out (NDRO)

Main advantage : frame rate only depend of the longest exposure time not the number of exposures !

Main limitation: data bandwidth between image sensor and processing memory

Debevec or Specific Algorithm

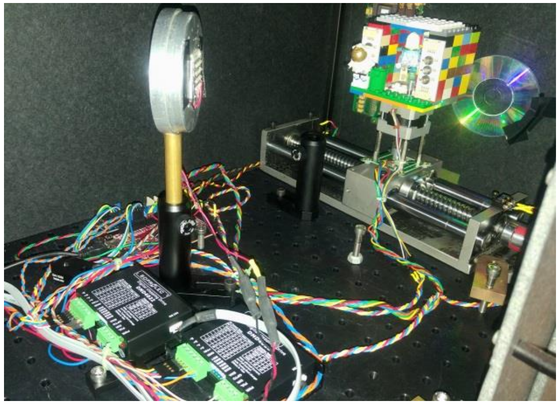


Different exposures (61 frames)

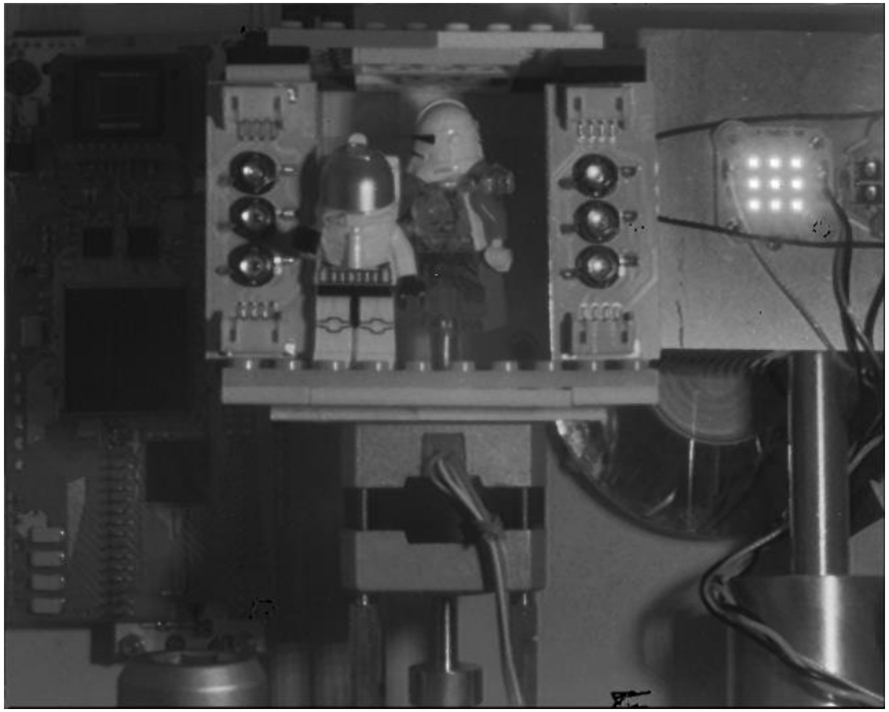
NRDO image contribution

A specific algorithm pattern which enables memory resources to be reduced and therefore high number of exposures to be done

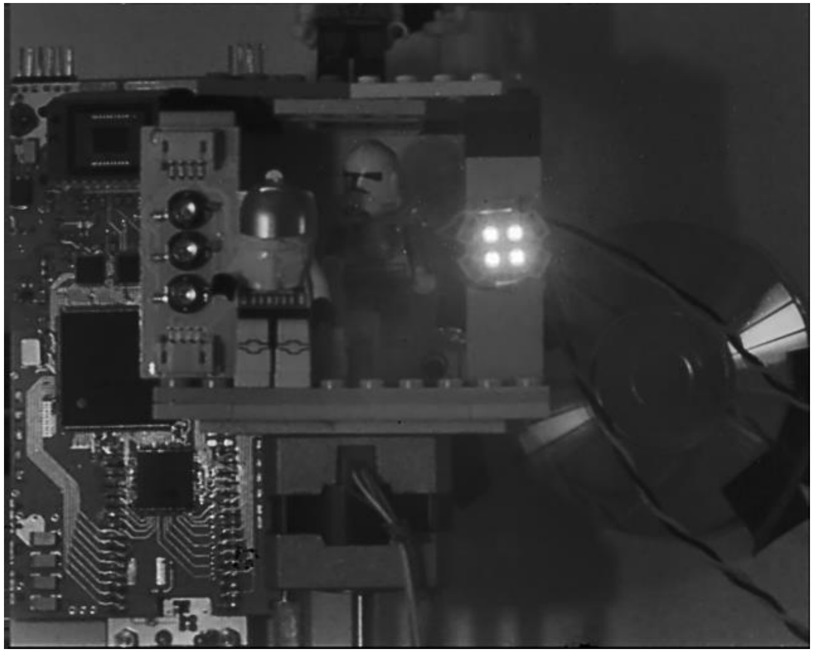
UHDR reconstruction result



Video scene with controlled motion



50 millions grey levels, 154dB



200 millions grey levels, 166dB

HDR Resulting video

Log/lin
NDRO
+12dB
Vs Lin
NDRO

Lin
NDRO

Log
NDRO
High
expo

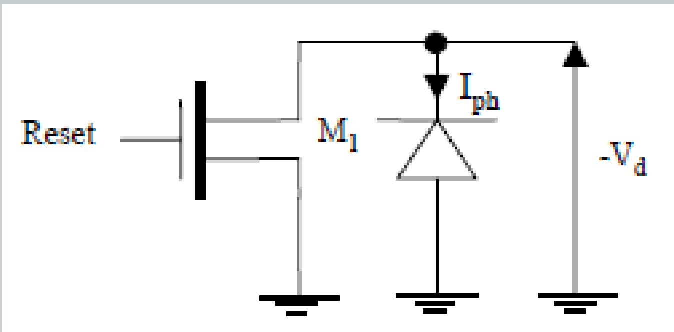
Log
NDRO
Low
expo

HDR Resulting video

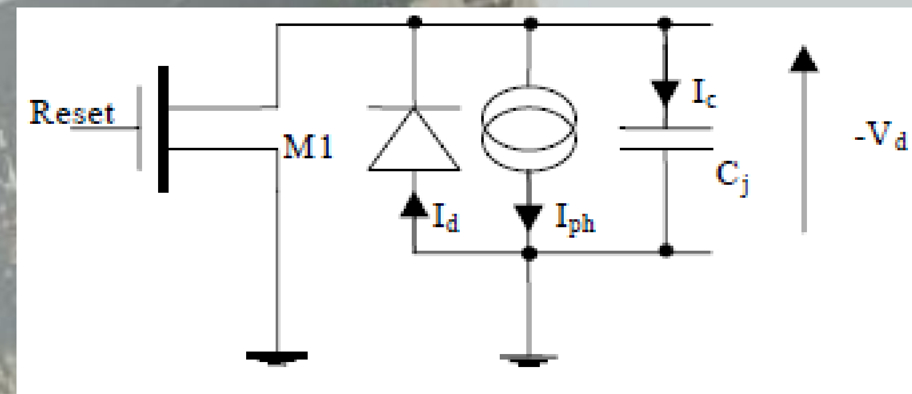
Video with HDR reconstruction with NDRO during exposures

Video with normal exposures and the intrinsic logarithm behavior of NIT sensor

CMOS version Wide Dynamic Range (WDR)



Electrical diagram Log-PV photoreceptor



Electrical diagram Log-PV photoreceptor with the equivalent model of a photovoltaic photodiode

$$V_d(t) = U_T \ln\left(\frac{I_{ph}+I_s}{I_{ph}e^{-\frac{t}{R_dC_e}}+I_s}\right)$$

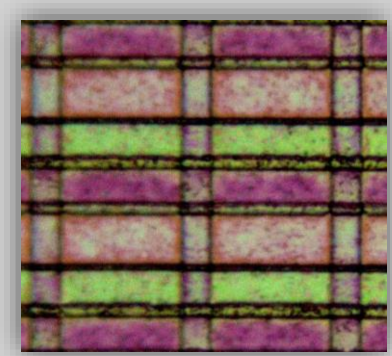
Time response function with R_d junction dynamic resistor.

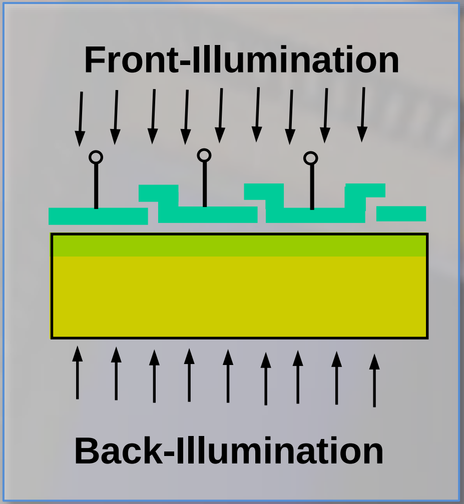
$$V_d(I_{ph}) = \frac{I_{ph}T_{exp}}{C_e} + U_T \ln\left(\frac{I_{ph}}{I_{ph}+I_s e^{\frac{T_{exp}}{R_dC_e}}}\right)$$

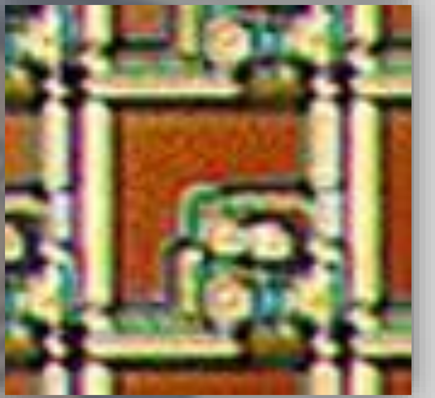
Exposure time fixed at Texp and Iph>>Is

CCD vs CMOS

Differences between CCD and CMOS (here APS, Active Pixel Sensor)







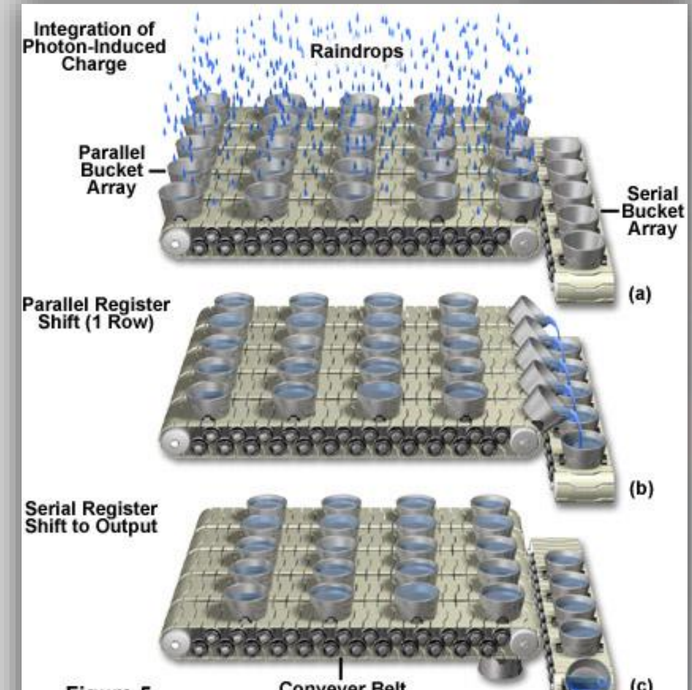
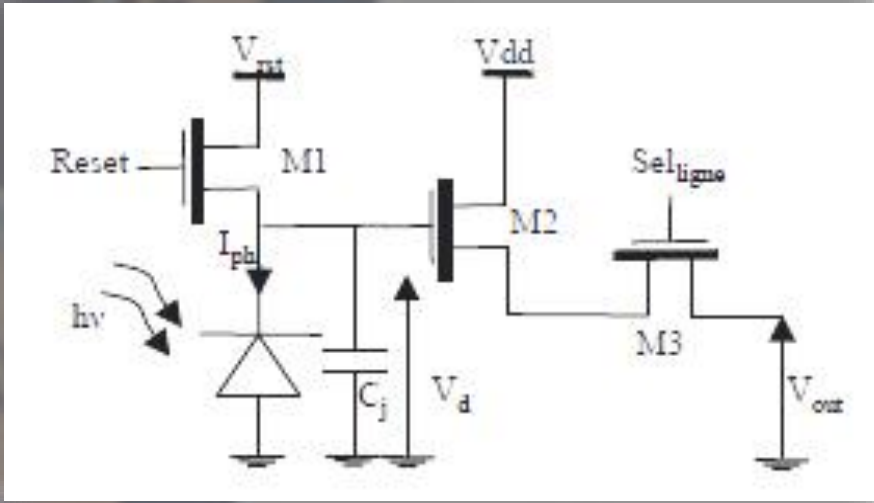


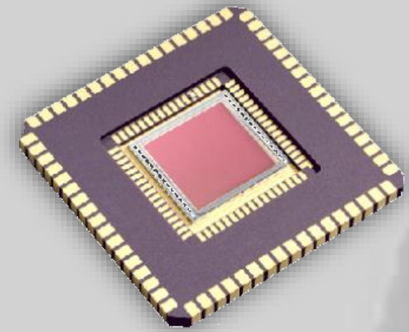
Figure 5

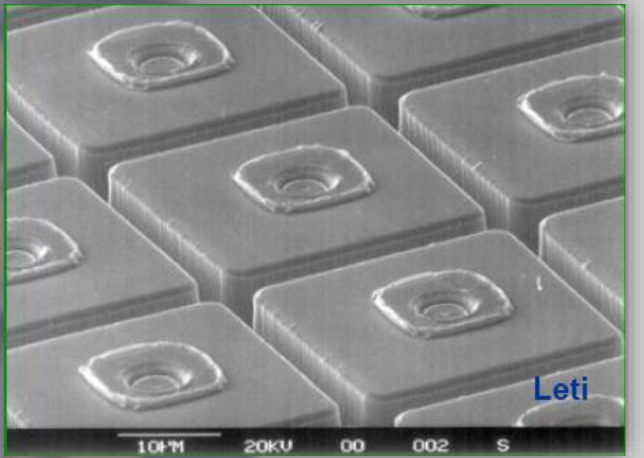
Bucket Brigade CCD Analogy

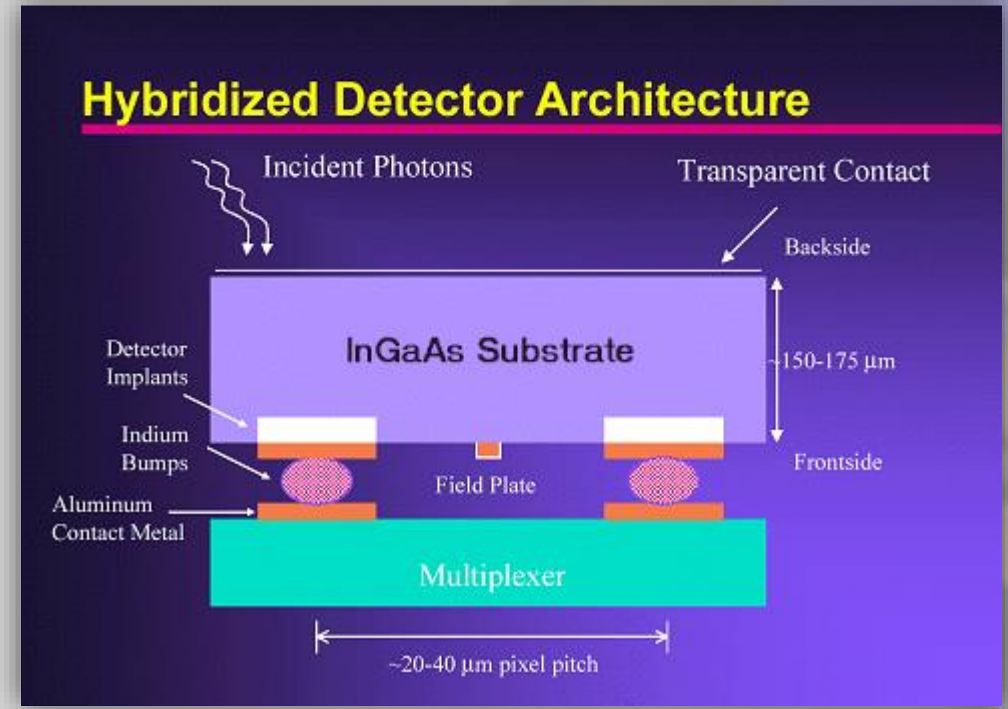


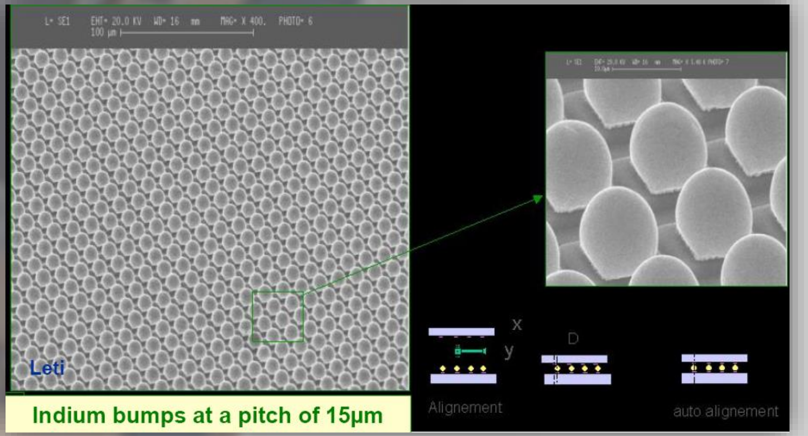
APS pixel structure with photodiode and integration mode

ROIC CMOS hybridized with InGaAs = IR sensor

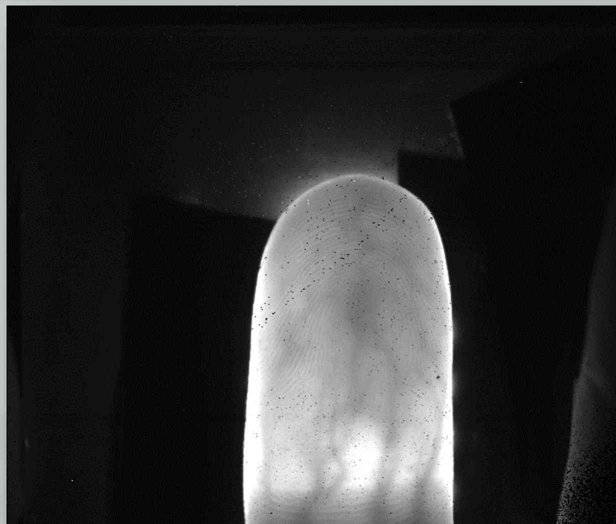






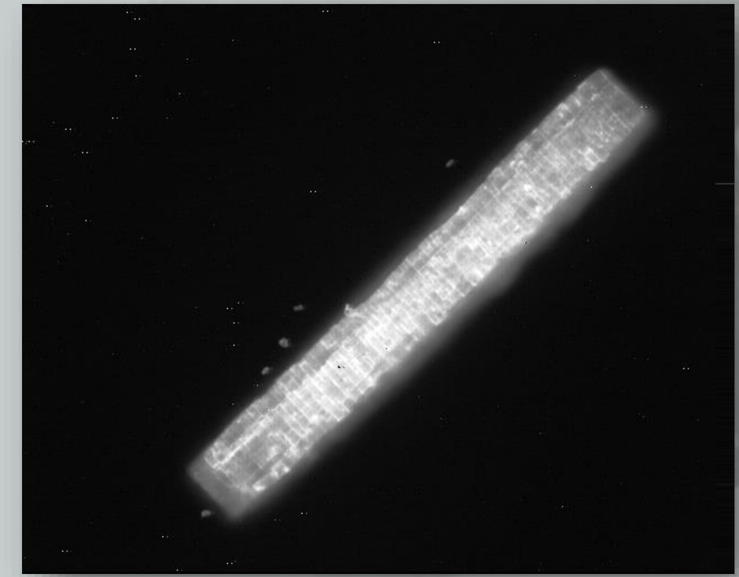


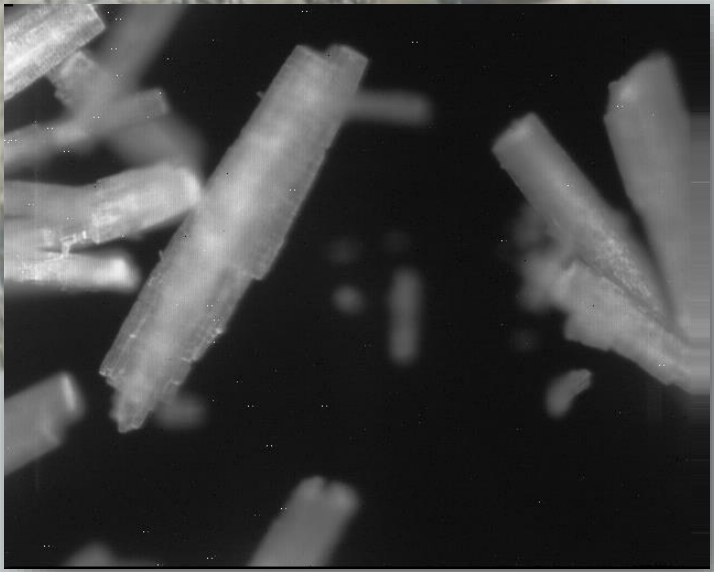
InfraRed InGaAs Camera : Biological and Medical Applications



5ms exposure, FPA InGaAs Cooled, LED at 940nm behind the finger

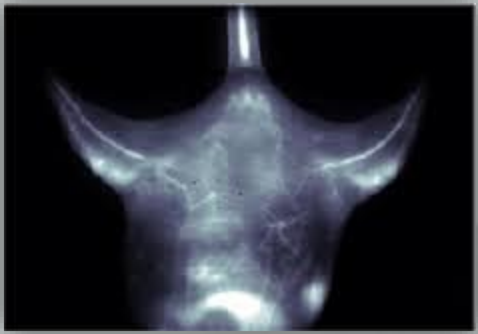
5ms exposure, FPA InGaAs Cooled, LED at 940nm in front of the hand



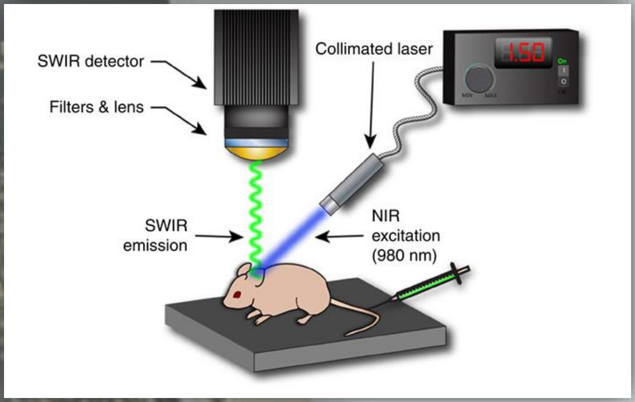


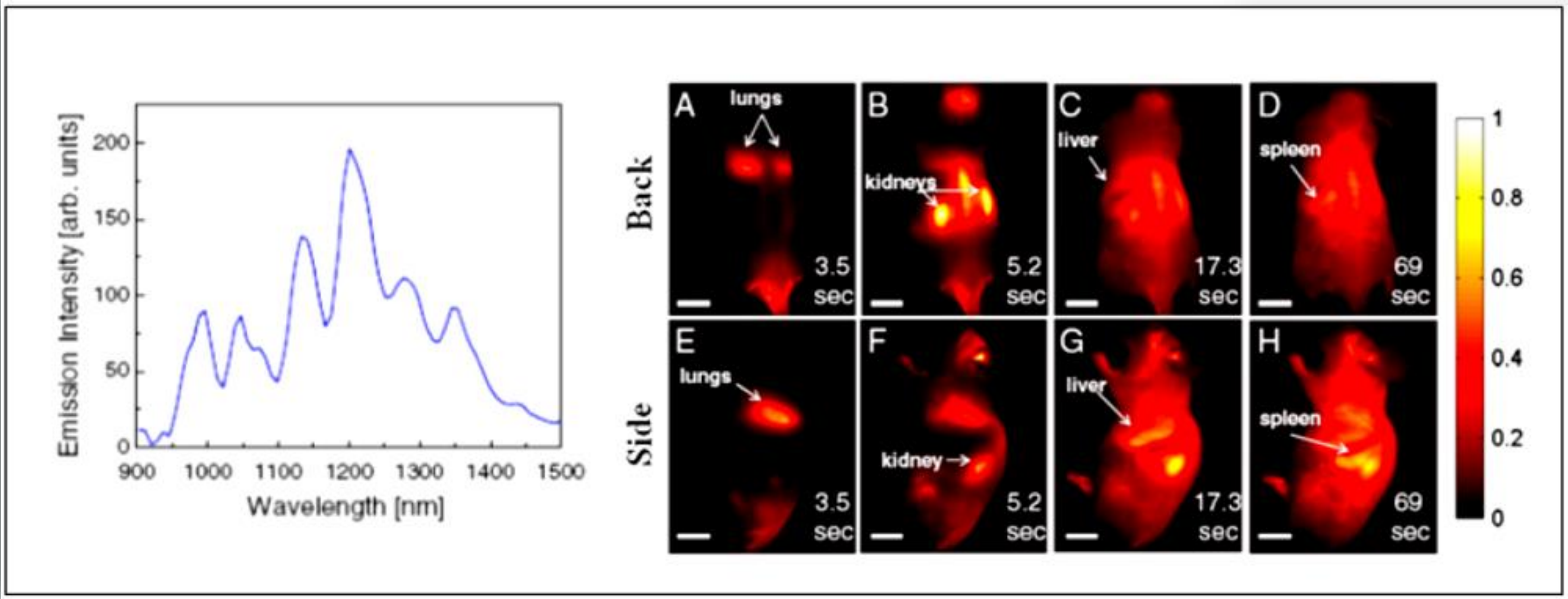
Lanthanides NanoCrystals / SWIR fluorescence taken under ZEISS microscop

InfraRed InGaAs Camera : Biological and Medical Applications



NIR luminescent nanomaterials for biomedical imaging tumoral investigation





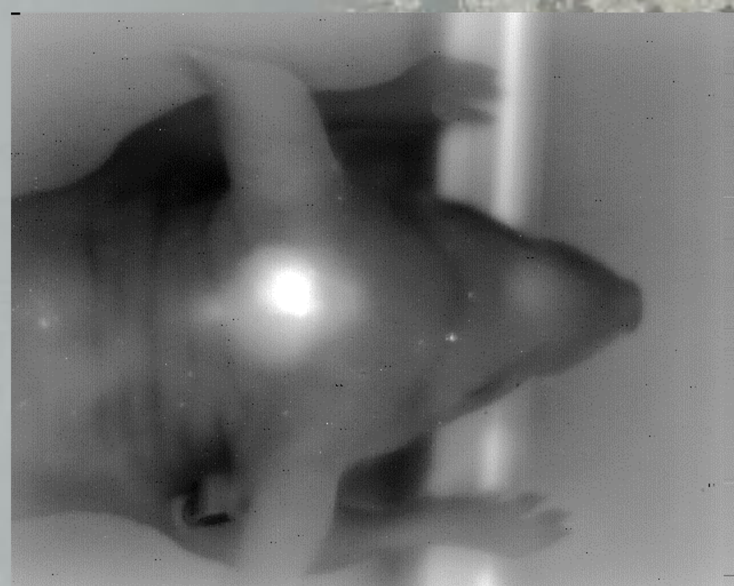
Left panel: Fluorescence spectrum of DSPE-mPEG functionalized SWNTs excited at 808 nm, showing several emission peaks in the NIR II ranging from 1000–1400 nm. Right panel: Frames from video imaging of mice injected with SWNTs.

Nanomaterials 2012, 2(2), 92-112, Chai-Hoon Quek and Kam W. Leong

InfraRed InGaAs Camera : Biological and Medical Applications

100ms exposure, UV excitation, Lanthanid response 975nm

100ms exposure, UV excitation, Lanthanid response 975nm



100ms exposure, UV excitation, Lanthanid response 975nm-1500nm, Broadband detection