Design and implementation of Stellar Intensity Interferometry on the ASTRI Mini-Array

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For the ASTRI Mini-Array SI^3 Work Package

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Outline

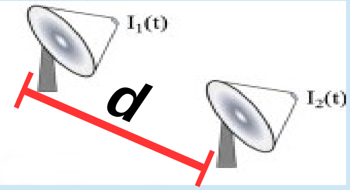
- Science: Potential goals
- ASTRI SI^3: Design
- ASTRI SII: Program implementation

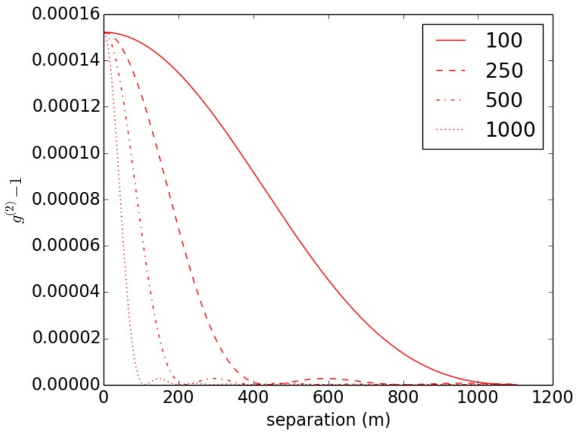
Stellar Intensity Interferometry with the ASTRI Mini-Array

Intensity Interferometry

Technique based on the measurement of the 2nd order spatial correlation of the radiation intensities of a star measured at two telescopes

The main observable is the *(discrete) degree of coherence*





$$|\gamma|^2 = \frac{\langle \Delta I_1 \Delta I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle}$$

Degree of coherence of a source with angular size **θ** (in μarcsec) as a function of the telescope separation **d**

Stellar Intensity Interferometry (SII) with ASTRI

The ASTRI Mini-array provides a suitable infrastructure for performing SII measurements

Main goal: Achieving optical imaging with resolution of **~100 microarcseconds** using the **long multiple baselines (36)** of the 9 ASTRI SSTs

Stellar Intensity Interferometry: calculating g2 in photon counting

$$g^{(2)} = N_{T1\text{-}T2}\, N / (N_{T1}\, N_{T2})$$

N_{T1}, N_{T2} = number of photons detected at the two telescopes in interval T
$N_{T1\text{-}T2}$ = number of simultaneous detections in small time bins dt in T
N = T/dt (number of bins in interval T)

$g^{(2)}$ is calculated in all intervals of an acquisition and values are then averaged

The optical design of ASTRI SI3 allows us to perform **measurements at zero baseline** using the detectors in the quadrants A, B, C, D

$$g^{(2)} = N_{X\text{-}Y}\, N / (N_X\, N_Y)$$

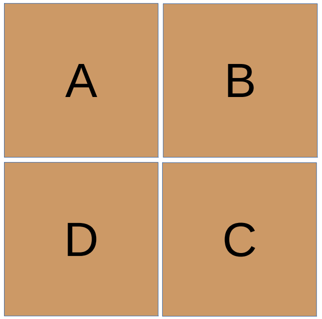
[X, Y] are combinations of the quadrants

Calibrated value of $g^{(2)}$ (important to remove systematics at zero baseline)

$$g^{(2)} = 1 + g^{(2)}(\text{narrow}) - g^{(2)}(\text{wide+ND1})$$

Narrow band filter (II): **440 nm CW, 3 nm FWHM**
Wide band filter + 10x attenuator: **440 nm CW, 30 nm FWHM + ND1**

Strategy follows closely the one implemented in the Asiago intensity inteferometer (Zampieri et al. 2021)



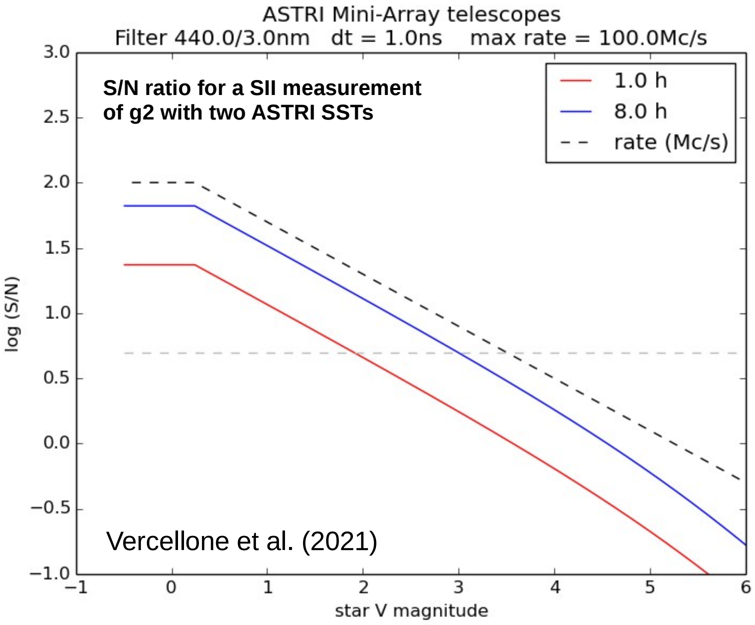
Stellar Intensity Interferometry with the ASTRI Mini-Array

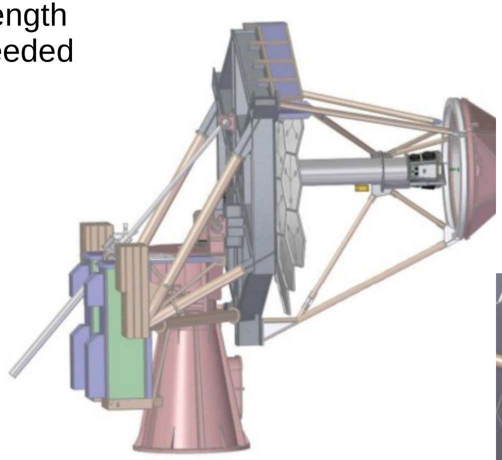
The ASTRI Stellar Intensity Interferometry Instrument (SI^3) is conceived to *measure the 2nd order discrete degree of spatial and temporal coherence (g2) of a star*

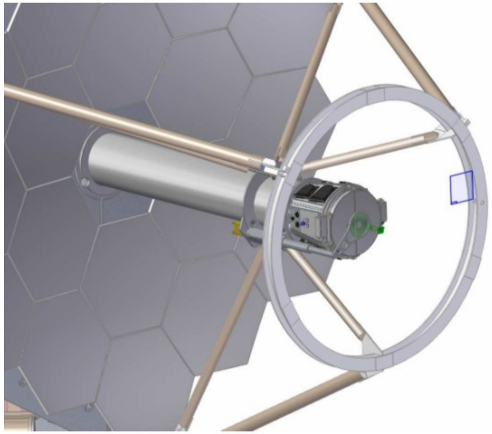
Photon counting approach, performing the correlation off-line

To this end, accurate measurements (**~1 ns**) of single photon arrival times in a narrow optical wavelength range (**~5 nm**) are needed

ASTRI Stellar Intensity Interferometry Instrument



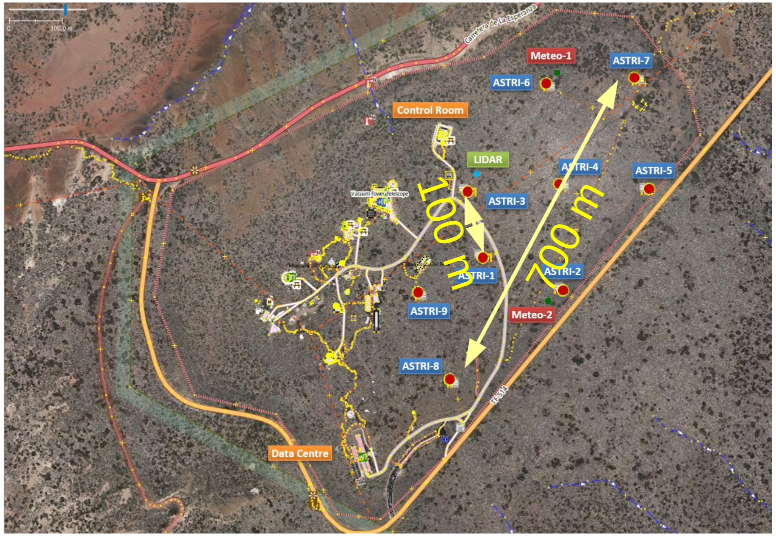


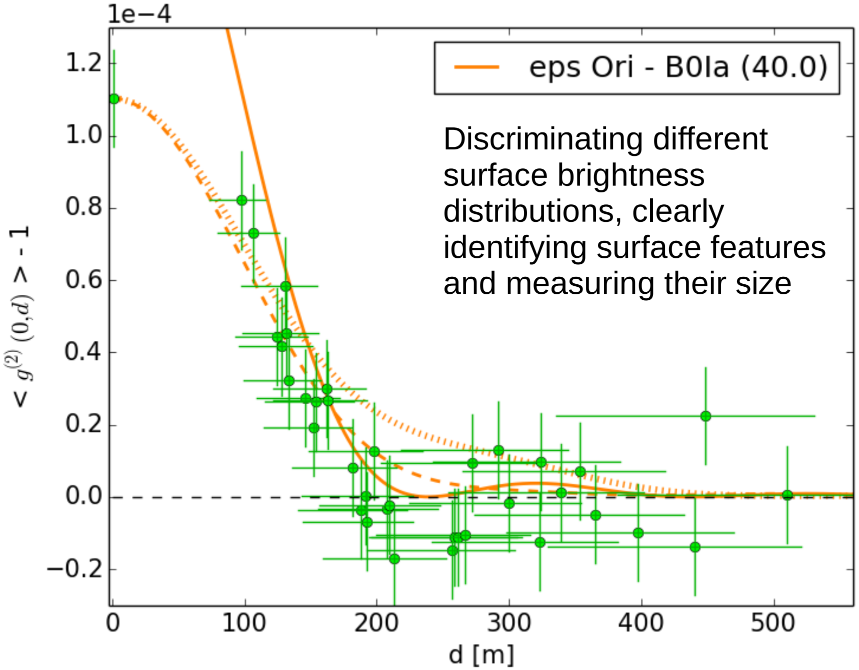


Stars with magnitude V < 3 are observable with the ASTRI SSTs in < 24 hours with a S/N > 5

Stellar Intensity Interferometry: calculating g2 (0,d)

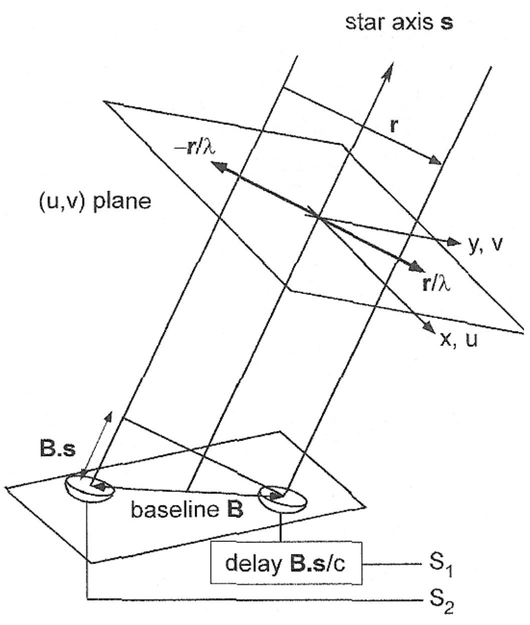
Determining the radius and surface features in early (B-through-F) type stars
Measurements over many baselines provide a tightly sampling of g2(d)



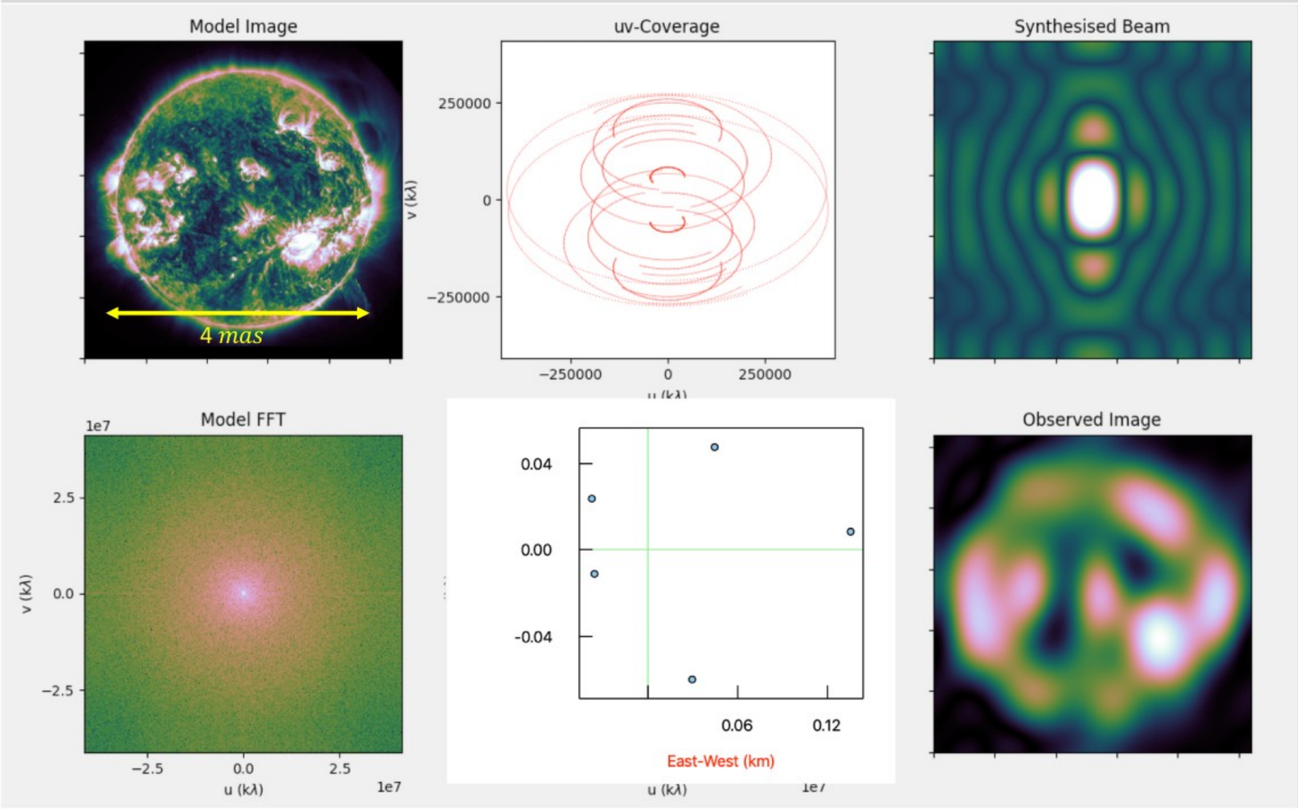


Stellar Intensity Interferometry: image synthesis

Synthetised image produced on the (u, v) plane, modelled with FFT methods to reconstruct the actual image



g2 measurements referred to the (varying) baseline projected on the (u, v) plane



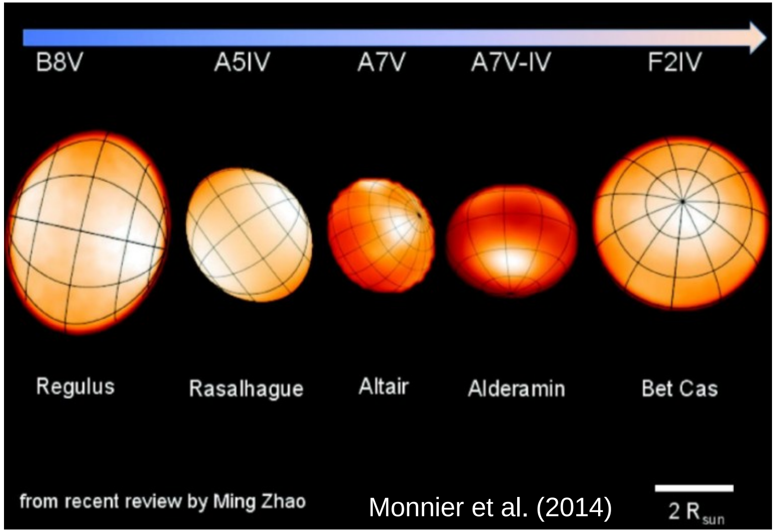
Simulated 8 hours SII Observation

4 VERITAS Telescopes + pSCT

420 nm

Only includes FFT Sampling effects

Stellar Intensity Interferometry with the ASTRI Mini-Array: Imaging rapid rotators



The ability to image the surface is the superior method to unambiguously measure the shape of a star

The more baselines used, the more model independent an image will be (CHARA has 6 telescopes, ASTRI MA has 9 tel.)

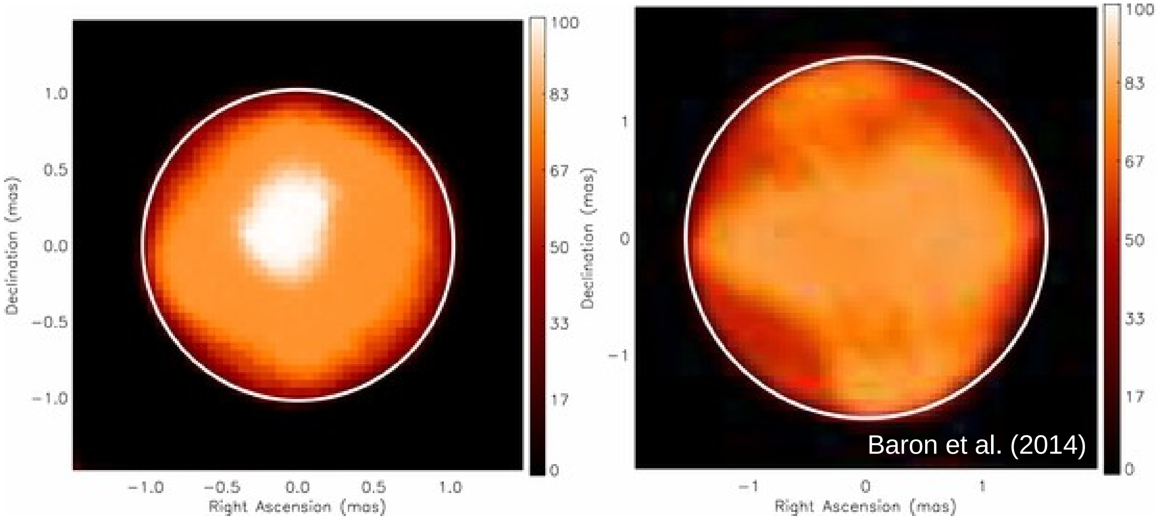
CHARA observations show that no rapid rotators have temperature contrasts as high as expected, inconsistent with any von Zeipel-like gravity darkening prescription assuming uniform rotation

Unexpected fast rotation of evolved sub-giants (Che et al. 2011)

Importance for stellar evolution:
- independent measurement of the star rotational speed
- revealing differential rotation (and meridional circulation)
- properly placing rapid rotators on the HR diagram
- understanding core-envelope coupling

ASTRI SI^3 can measure the oblateness of many A-type and B-type stars in visible light, extending the sample collected with CHARA

Stellar Intensity Interferometry with the ASTRI Mini-Array: Imaging bright spots with the highest angular resolution



CHARA/MIRC IR (H band) image of **RS Per (M3.5Iab) and T Per (M2Iab)**

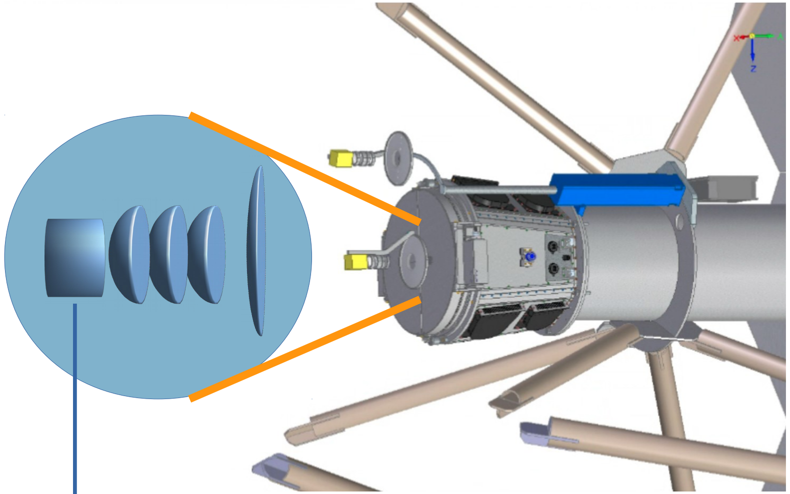
A visible light image of **Betelgeuse (M2Iab)**, taken with VLTI/SPHERE on 2019 Dec 26 (Montargès et al. 2020), revealed a substantial dimming in the southern hemisphere (Dupree et al. 2020)

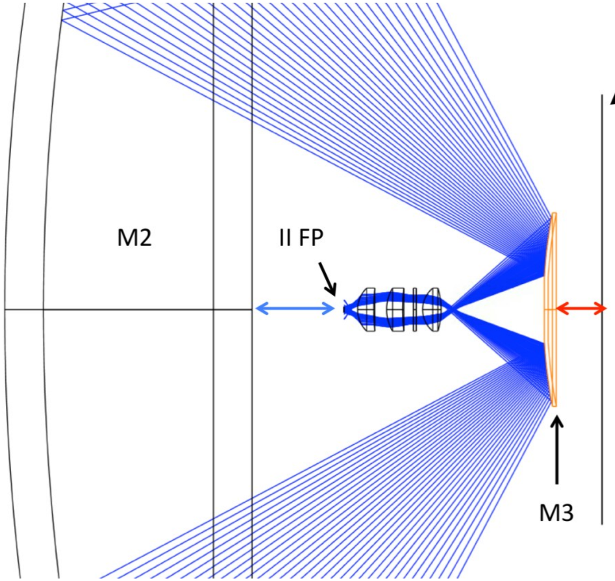
Bright spots and dimmer areas are present and are caused by temperature variations

Importance for stellar evolution:
They provide evidence of large convective cells/motions on the stellar surface

ASTRI SI^3 can resolve bright spots on smaller stars, pushing the limits of the present capabilities of interferometry (see e. g. Roettenbacher et al. 2018)

ASTRI SI^3: The Instrument





Focal Plane Optics

Convex spherical mirror
+ spherical lenses
+ narrow-band filters

60 Mcounts/s max rate
500 MB/s max data rate
~ 100 ps time res.
< 10 ns double hit res.

Focal Plane Module
(Optics + Detector +
PRE-Front End Electronics)

Placed on top of
the camera
with a positioning arm

Front End Electronics

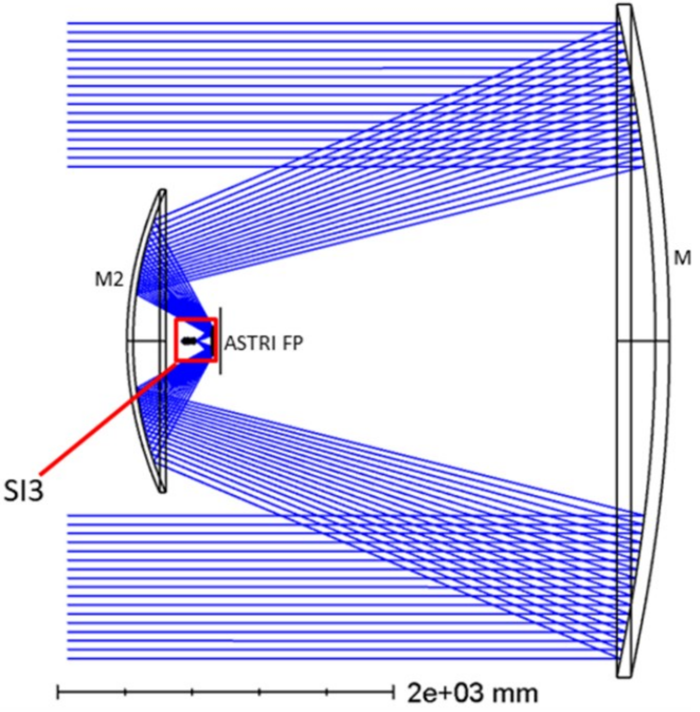
Signal conditioning + power
distribution + control

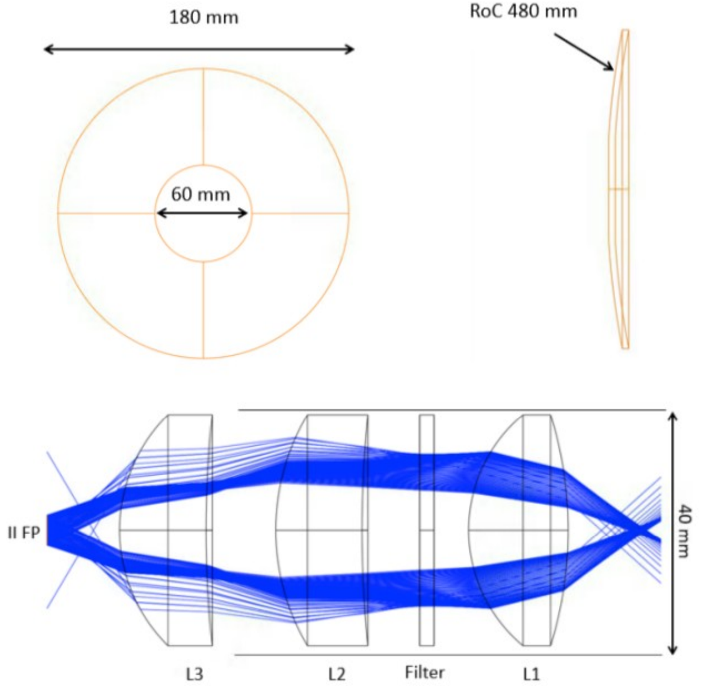
Back End Electronics

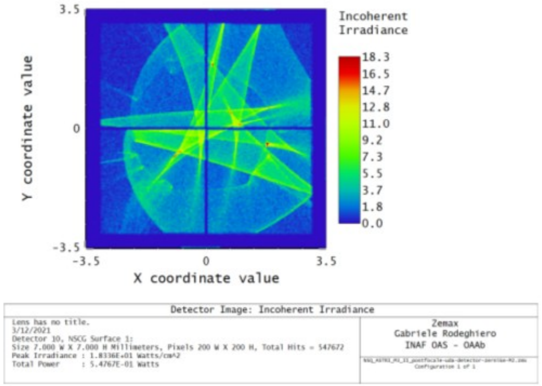
Data acquisition

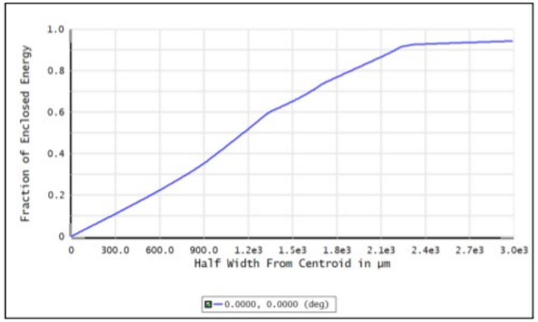
ASTRI SI^3: Focal Plane Optics

- **Convex spherical mirror (M3) + 3 spherical lenses**
- **Narrow-band filters**:
  CW: 440-500 nm – FWHM: 3-8 nm
- **Deployment and stability tolerances:**
  +/- 1 mm in x, y, z
  +/- 0.07 deg tilt x and y





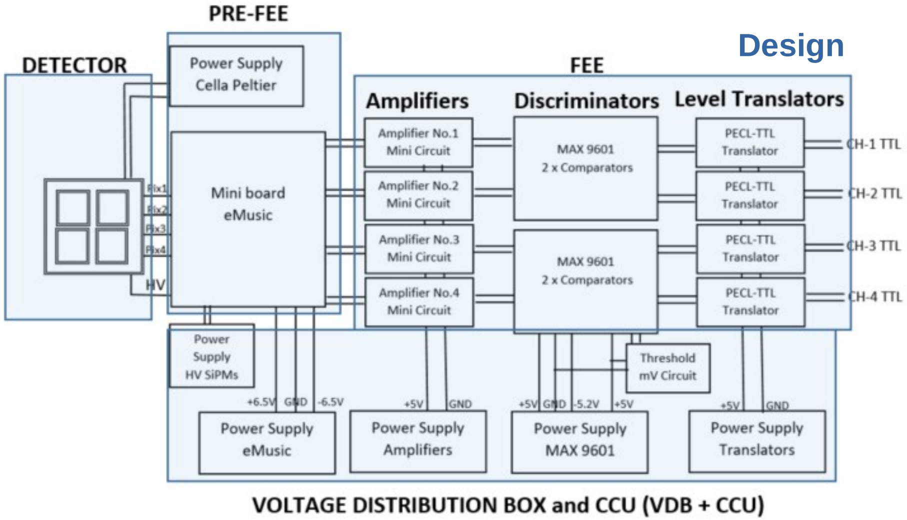




ASTRI SI³: Front End Electronics

Mini-Array

Design



Test: dark

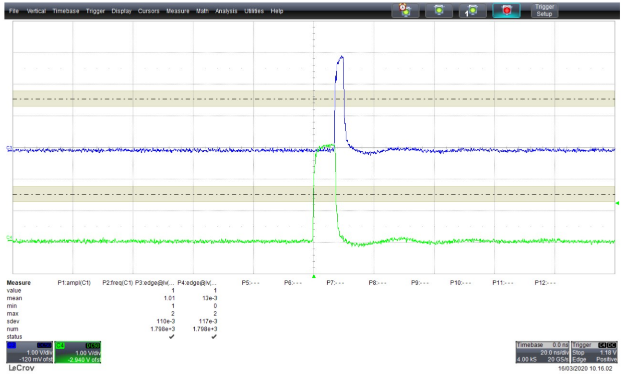
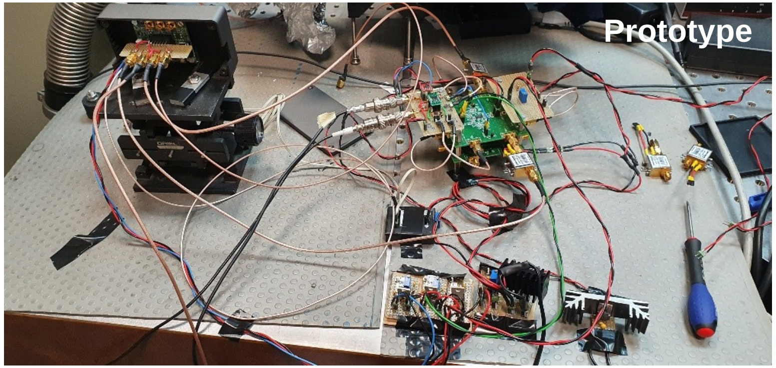
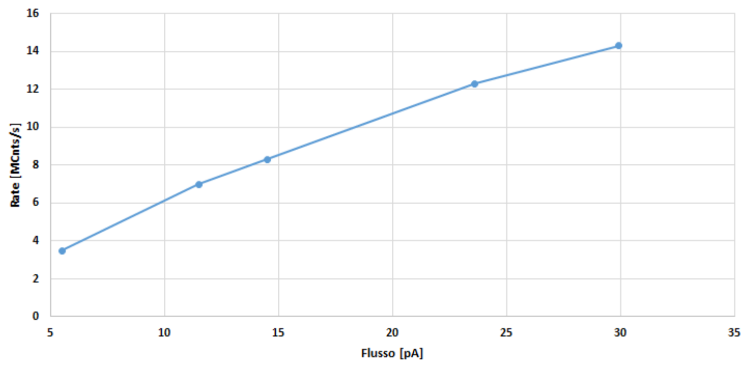


Figura 37. *Segnali digitali all'uscita del comparatore per i due canali con relativa durata. Base tempi 20 ns/div*

Double pulse resolution ~10 ns per channel and < 10 ns between different channels



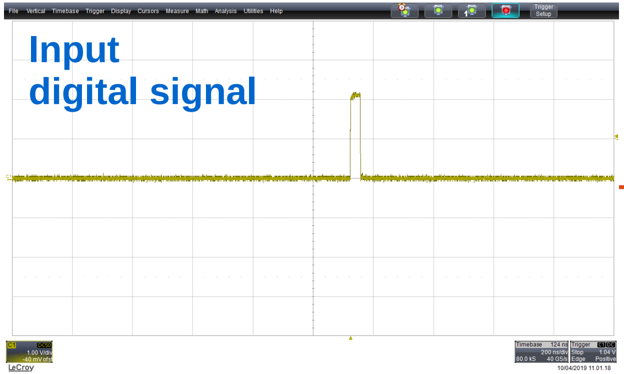
Test: illuminated



Almost linear response up to ~60 Mcounts/s (4 channels)

ASTRI SI^3: Back End Electronics

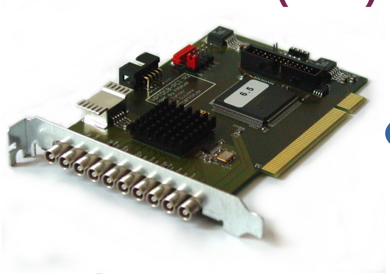
Mini-Array



Input
digital signal

x4

Time-to-Digital
Converter (TDC)



60 Mcounts/s max rate
500 MB/s max data rate
~ 100 ps time res.
< 10 ns double hit res.
< 50 ps jitter

Industrial PC (IPC)

To storage

~ 4 Gb/s

PPS signal
Clock reference signal

Time Distribution
Unit (TDU)

ASTRI SI^3: Team

ASTRI SI^3 – Organization Chart

Positioning Sub-system (C. Gargano)	Optics Sub-system (G. Rodeghiero)	Detector Sub-system (G. Bonanno)	PRE-FEE +FEE Sub-system (G. Bonanno)	VDB+CCU Sub-system (G. Bonanno)	BEE Sub-system (L. Zampieri)	Acquisition and control Sub-system (L. Zampieri)	Science data processing Sub-system (L. Zampieri)	AIV (L. Zampieri)
C. Gargano	G. Naletto	G. Bonanno	G. Bonanno	G. Bonanno	G. Naletto	P. Bruno	M. Fiori	M. Fiori
L. Lessio	C. Pernechele	G. Romeo	P. Bruno	L. Paoletti	L. Zampieri	M. Fiori	L. Zampieri	L. Zampieri
	G. Rodeghiero		A. Grillo	G. Romeo		G. Naletto		
			G. Romeo			L. Zampieri		
			M. Timpanaro			+ members of the ASTRI Mini-array soft./hard. team		

PRE-FEE: Pre Front End Electronics
FEE: Front End Electronics
VDB: Voltage Distribution Board
CCU: Control and Communication Unit
BEE: Back End Electronics
AIV: Assembly Integration and Verification

- Work Package within the framework of the ASTRI project (ASTRI Project Office directly involved)
- All technological areas (optics, electronics, mechanics) well covered at present
- Main INAF Institutes involved: OA Padova (0.65 FTE), OA Catania (1.1 FTE), IASF Palermo (0.2 FTE), OAS Bologna (0.1 FTE)
- Close collaboration with Univ. Padova (0.3 FTE), INFN Roma Tor Vergata and other national and international Institutes/working groups (e.g. MAGIC, VERITAS, CTA)

SII with the ASTRI Mini-Array: Schedule of next activities

Original schedule delayed by 3-6 months because of delays in the delivery of components for the prototype (missing basic components/raw materials)

Program – Framework: 2021-2023

ASTRI SI³

* Critical assessment of the design
* Documents for Preliminary Design Review:
    - **Science Requirements document (ASTRI-INAF-SCI-7400-001)**
    - **Concept Design document (ASTRI-DES-7400-001)**
    - **System Requirements document (ASTRI-INAF-SPE-7400-002)**
* Preliminary Design Review
* Science data processing software/activities (dedicated pipelines)
* Starting realization prototype, and testing it (Serra La Nave, Asiago)
* Completing documentation
* Detailed Design Review
* Contributing to the design of an SII instrument for CTA
* Building the instruments
* AIV (El Teide)

Science

* Presentation of the instrument to a wider Community
* Science data simulation
* Contributing to the CTA SII science
* Selection scientific cases, programs and targets