SEA Prize PhD in Instrumentation, Computing and Technological Development in Astronomy and Astrophysics (2017-2018)

“PANIC, una cámara infrarroja de gran campo para el Observatorio de Calar Alto”

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PhD thesis:

"PANIC, una cámara infrarroja de gran campo para el Observatorio de Calar Alto"

(PANIC, a wide-field infrared camera
for the Calar Alto Observatory)

UNIVERSIDAD DE GRANADA

Defence: December, 2018

Outline

1. Introduction
2. Objectives
3. Requirements and Specifications
4. Design of PANIC
5. Implementation and Verification of PANIC
6. PANIC's Performance

1. **Introduction**

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

6. PANIC's Performance

Max-Plank-Institut für Astronomie
(MPIA-MPG)
Heidelberg, Germany

- Mechanics
- Cryogenics
- Electronics
- Detectors

Instituto de Astrofísica de Andalucía
(IAA-CSIC)
Granada, Spain

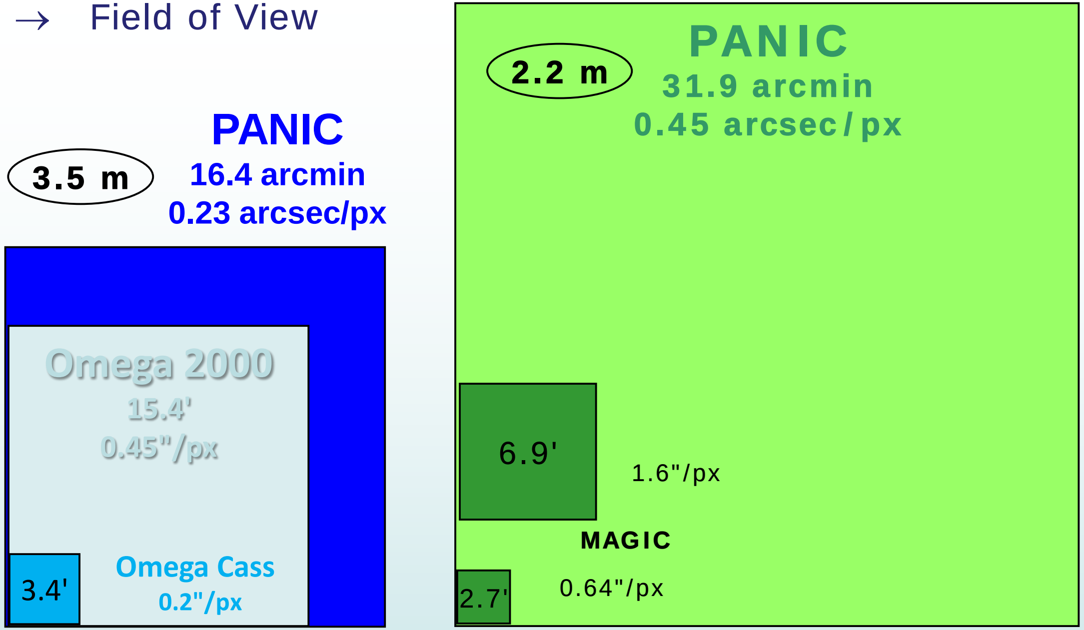
- Optics
- Software

PAnoramic Near Infrared Camera for Calar Alto

- A wide-field infrared camera for the 2.2 m and the 3.5 m telescopes
- 1st instrument in the Program of development of new instrumentation in collaboration between IAA and MPIA

- PI: Matilde Fernández (IAA-CSIC)
- PI: Klaus Meisenheimer (MPIA)

→ Field of View



Instrument	Spectral range (μm)	Pixel scale (arcsec/pix)	FoV (arcmin²)	Operation started	Telescope / Location	Science community
NEWFIRM	1-2.4	0.4	780 / (28×28)	2010	Mayall (4 m) / Kitt Peak (USA) Blanco (4 m) / Cerro Tololo (Chile)	USA
WFCAM	1-2.5	0.4	780 / (28×28)	2005	UKIRT (3.8 m) / Hawaii (USA)	USA / Hawaii / NASA
WIRCAM	0.9-2.5	0.3	460 / (21.5×21.5)	2006	CFHT (3.6 m) / Hawaii (USA)	Canada / France / Hawaii
Omega 2000	0.8-2.4	0.45	235 / (15.4×15.4)	2003	CAHA (3.5 m) / Almería (Spain)	Germany / Spain
PANIC	0.8-2.5	0.45 0.23	940 / (30.7×30.7) 240 / (15.6×15.6)	2015	CAHA (2.2 m) / Almería (Spain) CAHA (3.5 m) / Almería (Spain)	Germany / Spain

Scope of PANIC: Science projects

- General purpose wide-field imager
- Useable for surveys
- Not tailored to a special application

· Solar system: Comets, searches for transneptunians & minor bodies.

· Stellar evolution: Brown dwarfs, accretion disks of young stars, post-AGBs, exoplanets, supernovae searches, asteroseismology.

· Galactic astronomy: Large-scale structure of the Milky Way and the Galactic components in hidden areas.

· Extragalactic astronomy: Cosmic evolution in the z range 1.5 – 2.0: photometric redshifts in the redshift desert (narrow band filters in clean windows of z and J reducing the background sky, GRBs at high redshift, GRB host galaxies.

· Clusters and Superclusters of galaxies at intermediate redshift: Search for objects with strong IR excess, Selection of candidates for supermassive starbursts , Broad band + narrow band filter imaging matching the redshifted Hα line.

· Morphology of nearby galaxies

1. Introduction

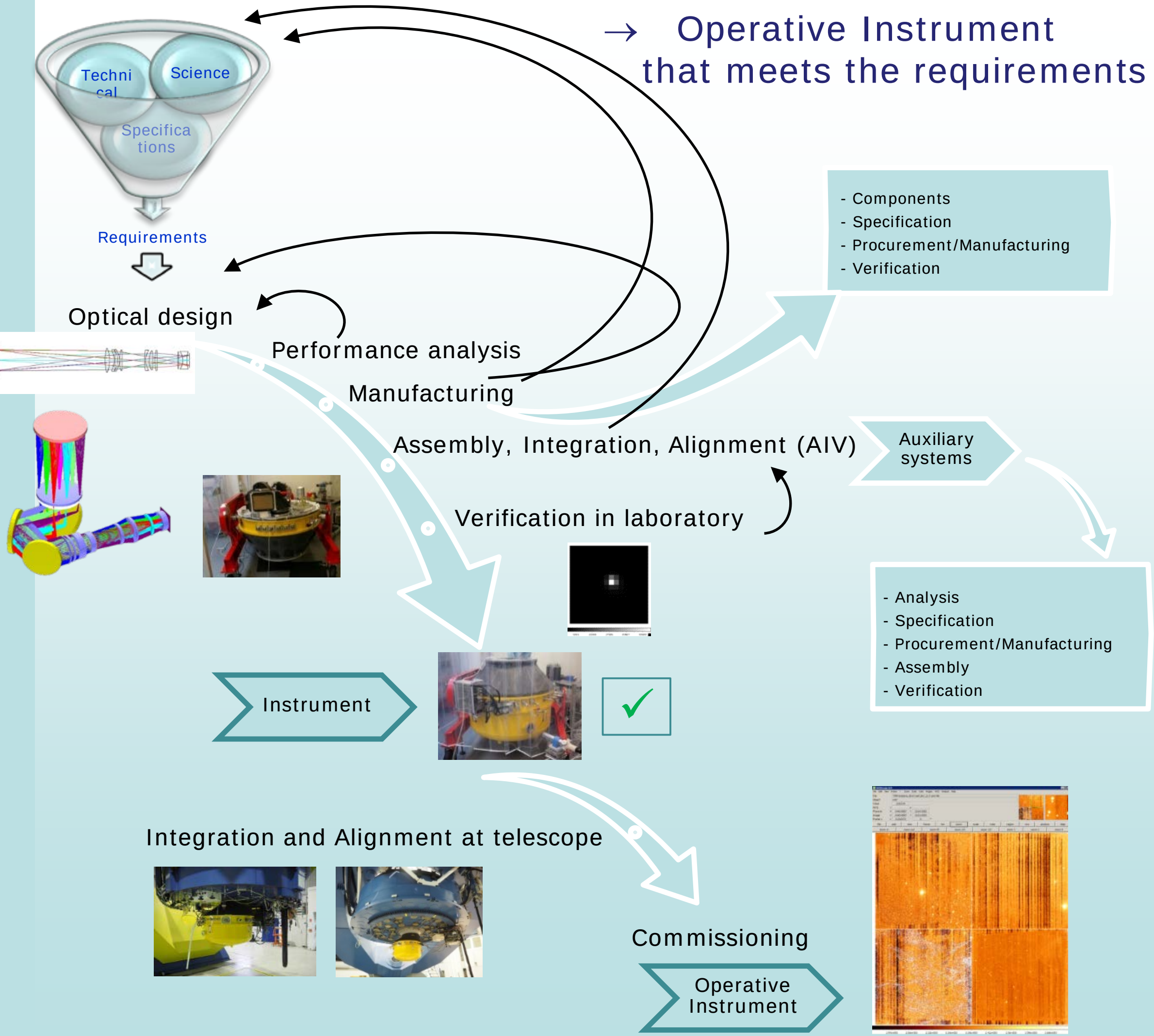
2. Objectives

3. Requirements and Specification

4. Design of PANIC

5. Implementation and Verification of PANIC

6. PANIC's Performance



Project timeline

Kick-off	10/2006	Requirements Collection and Specifications definition
PDR	11/2007	Preliminary Design Phase
FDR Optics	09/2008	Final Design Phase
FDR Mechanics Cryo, Electronics	12/2009	Final Design Phase
FDR Software	02/2010	Final Design Phase
MAIV	05/2009-08/2014	Subsystems Manufacturing and Acceptance AIV phase and Final tests at laboratory
First light	10/2014	Instrument alignment with telescopes
Commissioning	10/2014-03/2015	Instrument verification at both CAHA telescopes

1. Introduction

2. Objectives

3. Requirements and Specifications

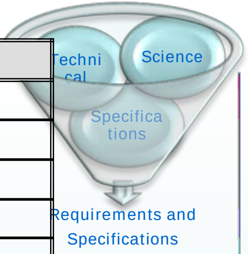
4. Design of PANIC

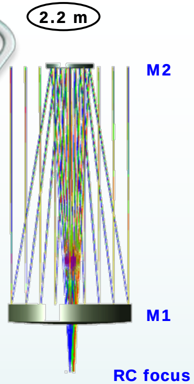
5. Implementation and Verification of PANIC

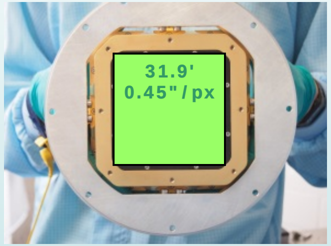
6. PANIC's Performance

→ High Level Requirements

Parameter	Requirement
Telescope	T22
Focal Station	Cassegrain Focus
Operation mode	Direct Imaging, over the whole FoV
Wavelength range	(0.8 – 2.45) μm
Filters	Broad band: **Z Y J H K_s** Narrow band: ~1%
Pixel scale	0.45 arcsec/px
FoV	(32×32) arcmin, for 0.45 arcsec/px
IR Detector	4K x 4K mosaic of 2x2 HAWAII-2RG 18 μm pixel 2.5 μm cut-off
Entrance pupil	Telescope primary mirror
Pupil image available	Cold stop
Thermal background	S/N maximum, specially in K band
Operating conditions	80 K (liquid nitrogen) vacuum
System focusing mechanism	Telescope secondary mirror
Second pixel scale	0.25 arcsec/pixel / FoV 18 arcmin
Camera optics solution	Mono-beam/Refractive/non-collimated stage







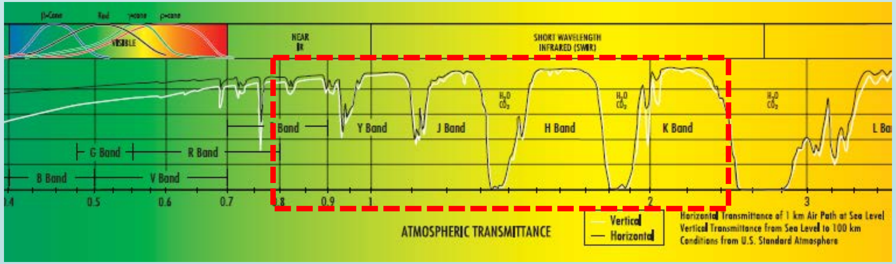


Imagen: Raytheon Vision Systems

→ High Level Requirements

→ System Specifications

Parameter	Requirement
Image Quality, for 0.45 arcsec/px	$D_{EE80} \leq 0.9$ arcsec=2 px
Image Quality, for 0.25 arcsec/px	$D_{EE80} \leq 0.75$ arcsec=3 px
Distortion	≤ 1.5 %
Ghosts: Relative intensity Size at the detector	$\leq 10^{-4}$ ≥ 10 arcsec
Narrow-band filters: max λ_c shift	≤ 0.3 %
Optical Transmission	Maximize
Instrument Weight	≤ 400 kg
Instrument length from the telescope focal plane	≤ 110 cm

1. Introduction

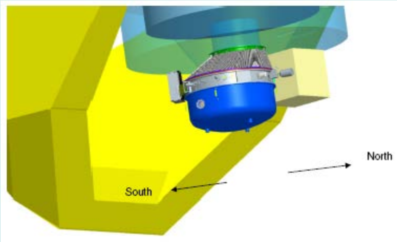
2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

6. PANIC's Performance



1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

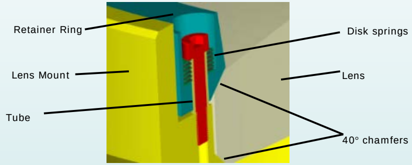
6. PANIC's Performance

→ High Level Requirements

→ System Specifications

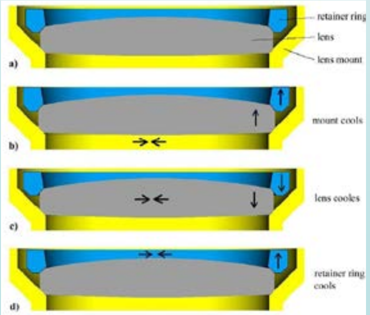
→ Other Requirements

- Maximization of the S-N in K band
  - Field Stop: cold
  - Aperture Stop: cold
  - Stray light: Baffling, optics manufacturing.
- Pupil re-imager



→ Detailed Specifications

- Optical materials [n(λ,T), CTE(T)]
- Tolerances: manufacturing, positioning, integration
- Interfaces with other subsystems
- Lens mounts: mechanical design
- Iterations with manufacturers
- Cryostat window
- Space between lenses
- Packing: folding



1. Introduction

2. Objectives

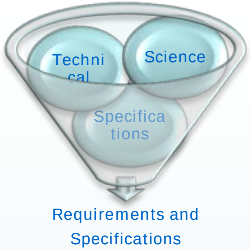
3. Requirements and Specifications

4. Design of PANIC

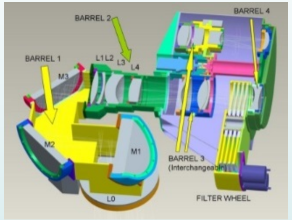
5. Implementation and Verification of PANIC

6. PANIC's Performance

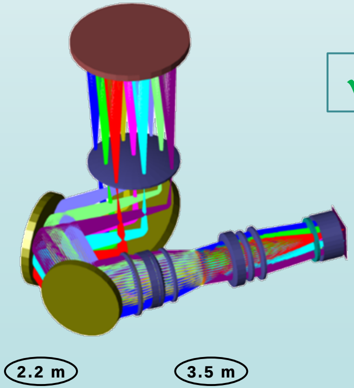
Optical System Implementation



Preliminary Optical Design



Final Optical Design



✓

Build the Instrument

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

4.1. Optical system development

4.2. Preliminary Optical Design

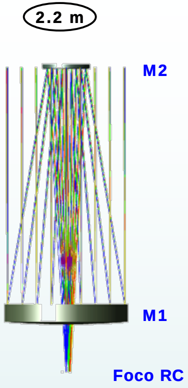
4.3. Final Optical Design

5. Implementation and Verification of PANIC

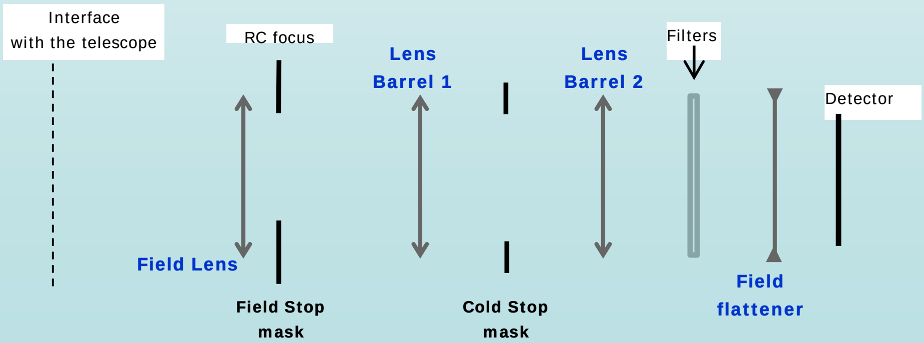
6. PANIC's Performance

A) Optical Design **Approach**

Parameter		PANIC optical configuration	
		0.45 arcsec/px	0.25 arcsec/px
Infrared detector	px	4096x4096	
Space between detectors	px	147	
Pixel size	µm	18	
Plate scale	arcsec/px	0.45	0.25
	arcsec/mm	25.0	13.9
FoV	px	4096+147	
	mm	76.374	
	arcmin	31.82	17.68
Lateral Magnification	adim	0.4685	0.8433
Effective focal length	mm	8251	14851
Focal ratio, F#	adim	3.750	6.75



B) The **Initial** Optical System



1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

4.1. Optical system development

4.2. Preliminary Optical Design

4.3. Final Optical Design

5. Implementation and Verification of PANIC

6. PANIC's Performance

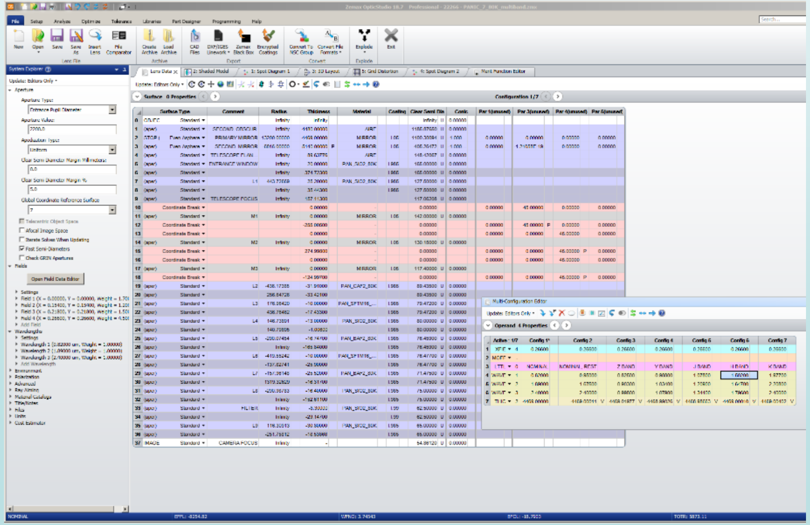
A) Optical Design **Approach**

B) The **Initial** Optical System

C) Optical system **Model**

- Object
- Entrance Pupil: localization and size
- FoV
- Wavelength range
- Magnification
- Plate Scale
- Optical materials:
  - n (λ, T)
  - CTE (T)

- Constrains: Temperature, telescope, focus mechanism.
- Field Stop and Aperture Stop: localization and size



D) Optical System **Optimization**

- Variables set up
  → RoC, Thickness, Materials
- Merit figures
  → Image Quality
  → Optical Distortion
- Constrains Set up
  → Mechanical
  → Optical

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

4.1. Optical system development

4.2. Preliminary Optical Design

4.3. Final Optical Design

5. Implementation and Verification of PANIC

6. PANIC's Performance

A) Optical Design **Approach**

B) The **Initial** Optical System

C) Optical system **Model**

D) Optical System **Optimization**

E) Optical system **Evaluation**

- Merit figures: Performance
- Constrains fulfilment
  - Mechanical
  - Optical
- Margin for errors

F) **Error Budget**

$$\sigma^2_{instrument} = \sigma^2_{\substack{nominal\\design}} + \sigma^2_{\substack{optical\\manufacture}} + \sigma^2_{\substack{integration/\\assembly}} + \sigma^2_{uncompensated} + \sigma^2_{thermal} + \sigma^2_{motion}$$

- Sensitivity $\rightarrow$ worst offenders $\rightarrow$ compensators
- Tolerances $\rightarrow$ Budget
  - Manufacturing Errors
  - Assembly and alignment Errors
- Final performance Prediction $\rightarrow$ Montecarlo analysis

Error	σ (μm)	Verification
Nominal Optical Design	5.22	Optical Design: nominal (T22+PANIC)
Lenses manufacturing	4.33	200 Montecarlo (PANIC+ lenses manufacturing) rms spot radius: 5.22 to 6.78 (μm)
Assembly / Integration / Alignment	6.10	200 Montecarlo (PANIC+subsystem) rms spot radius: 5.22 to 6.37 (μm)
Non compensable	0.66	200 Montercarlo (PANIC+indix+Abbe) Numerical model (glasses inhomogeneity) rms spot radius: 5.22 to 5.26 (μm)
Thermal	1.72	Numerical model (thermal gradient) rms spot radius: 5.22 to 5.50 (μm)
Movement	0.92	200 Montercarlo (PANIC+mechanical flexions) rms spot radius: 5.22 to 5.30 (μm)
Margin	0.50	
Total	**9.36**	≤ 10.03 μm

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

4.1. Optical system development

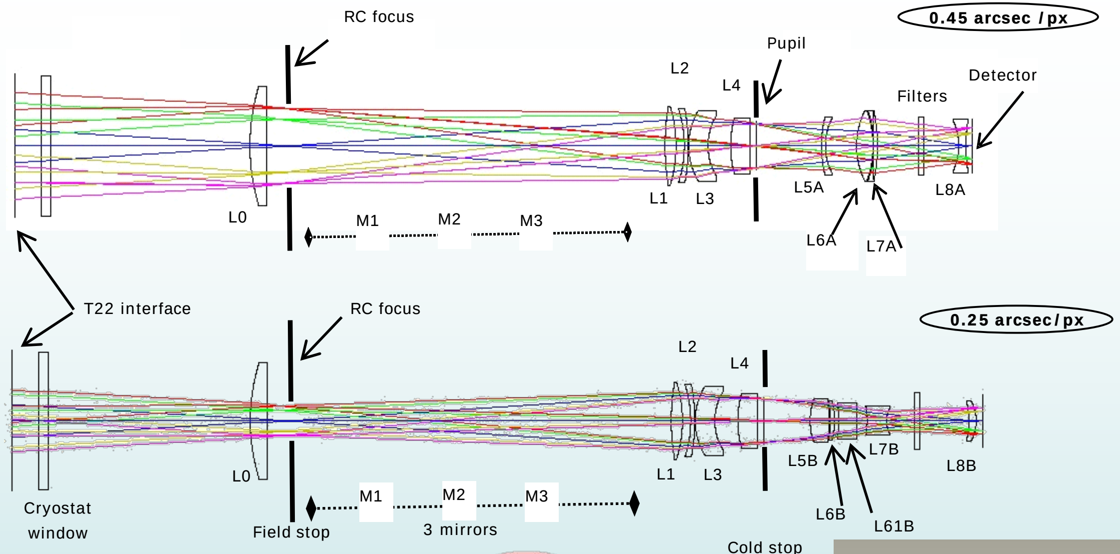
4.2. Preliminary Optical Design

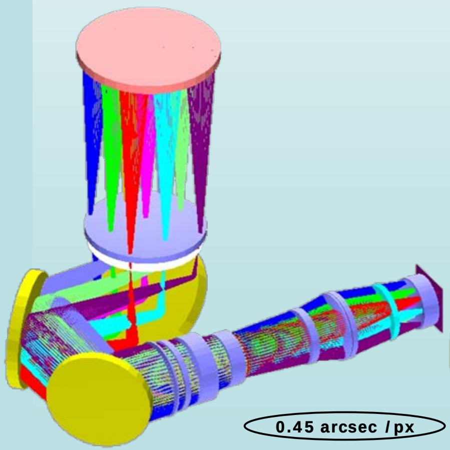
4.3. Final Optical Design

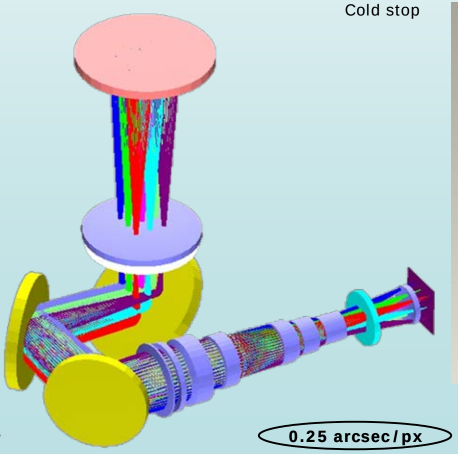
5. Implementation and Verification of PANIC

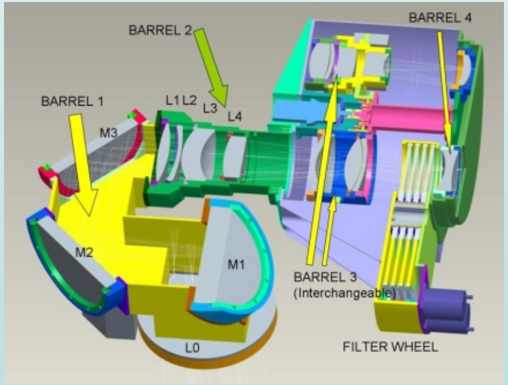
6. PANIC's Performance

• PDR Optical Design









• FDR Optical Design

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

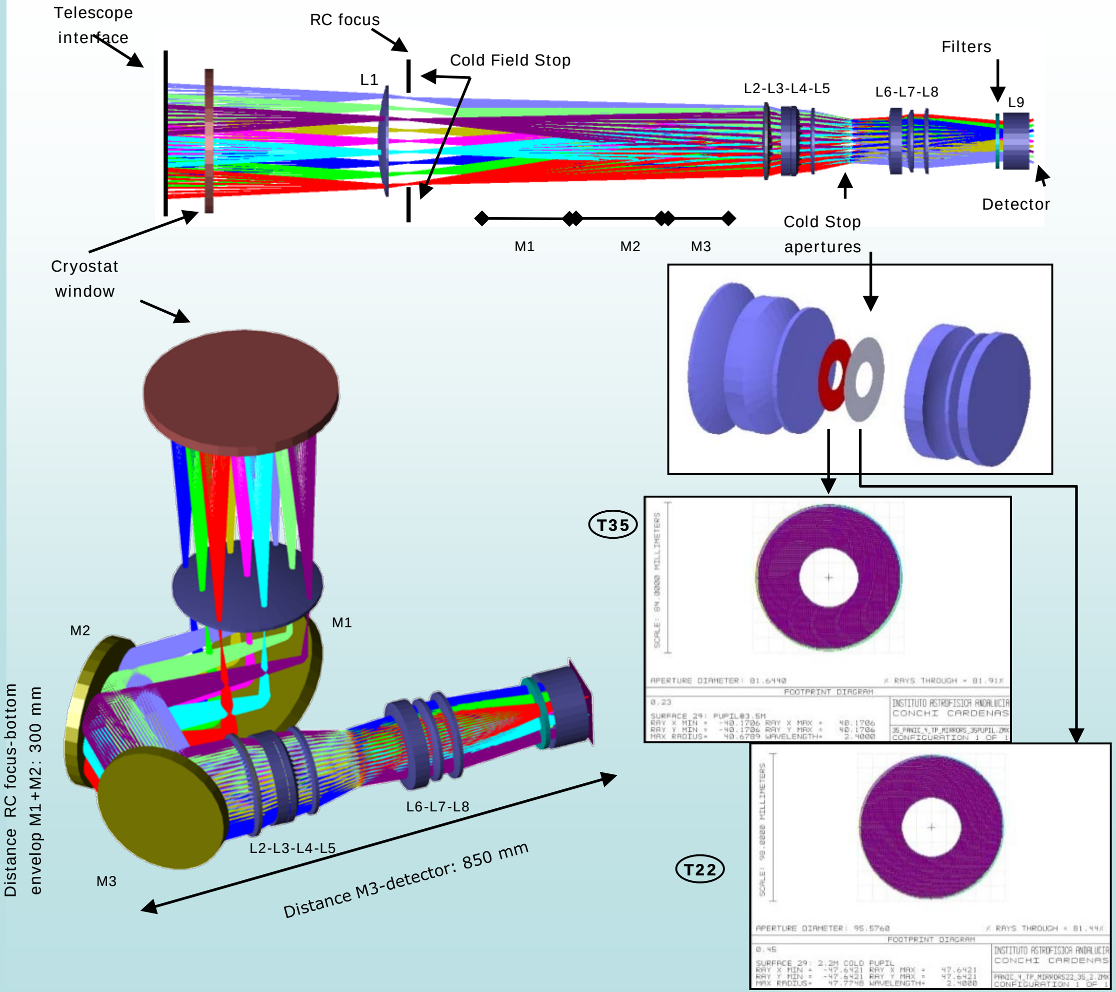
4.1. Optical system development

4.2. Preliminary Optical Design

4.3. Final Optical Design

5. Implementation and Verification of PANIC

6. PANIC's Performance



1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

4.1. Optical system development

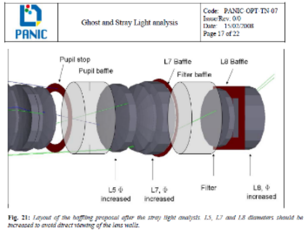
4.2. Preliminary Optical Design

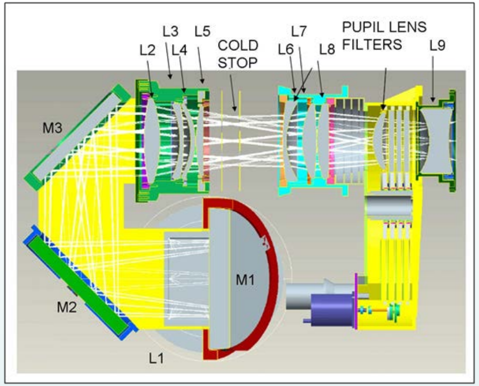
4.3. Final Optical Design

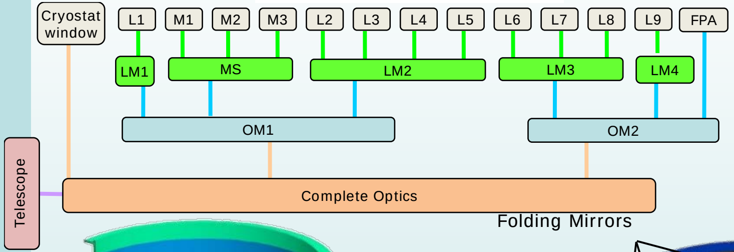
5. Implementation and Verification of PANIC

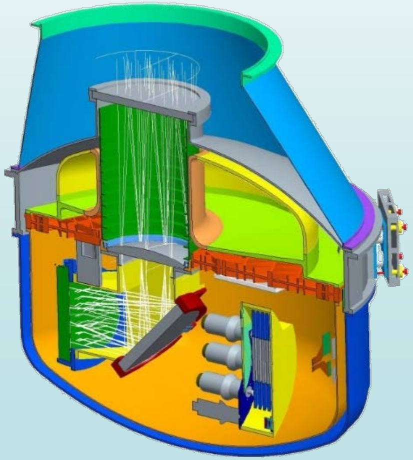
6. PANIC's Performance

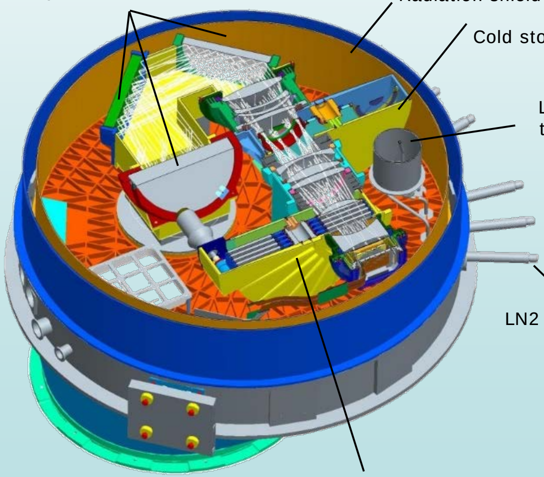
- Interaction between Optical Design and Mechanics-Cryogenics











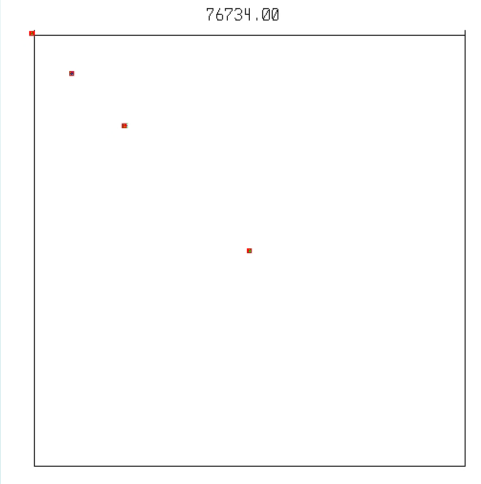
Diameter: 1100 mm
Height: 1000 mm
Weight: 385 kg
Optical bench diameter: 1050 mm

Image quality

2.2 m telescope

Requirement: $D_{EE80} \leq 2$ px	
λ range	D_{EE80} (pix)
Z	1.12
Y	0.91
J	0.99
H	1.35
K	1.81
Polychromatic	1.47

on sky FoV = 31.6 arcmin



Polychromatic

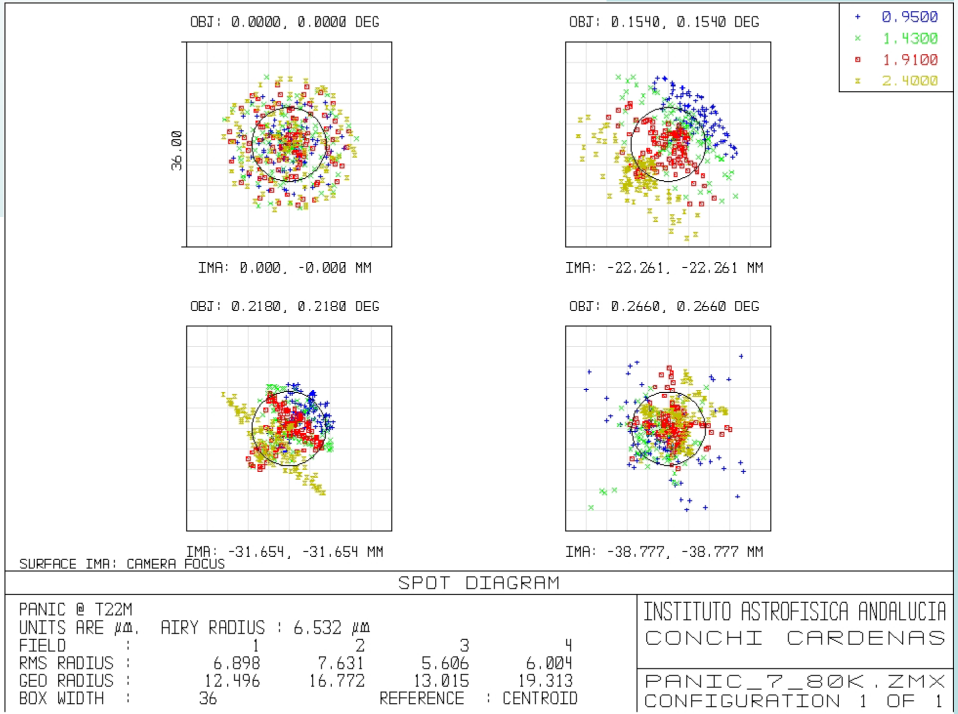
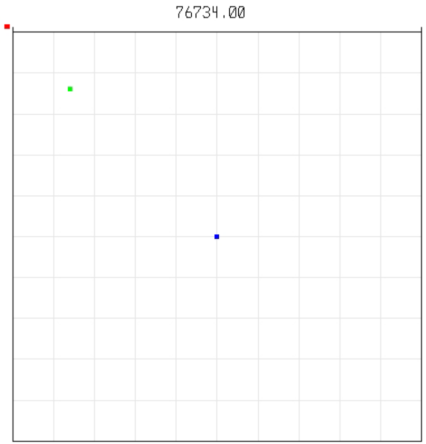


Image quality

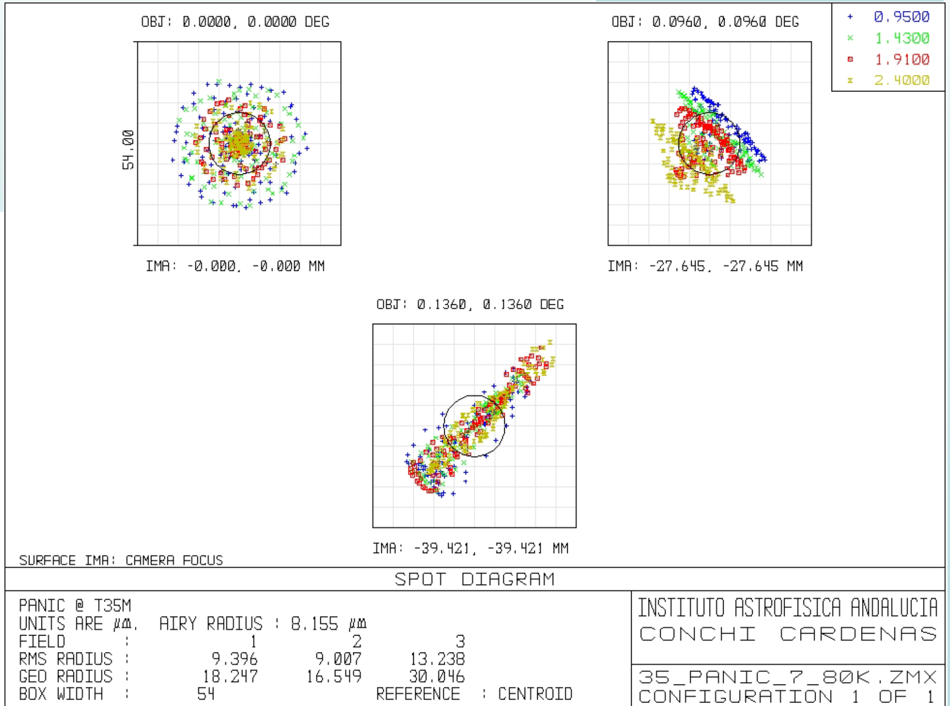
3.5 m telescope

Requirement: $D_{EE80} \leq 3$ px	
λ range	D_{EE80} (pix)
Z	1.72
Y	1.72
J	1.80
H	1.94
K	2.18
Polychromatic	1.97

on sky FoV = 15.9 arcmin



Polychromatic



1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

4.1. Optical system development

4.2. Preliminary Optical Design

4.3. Final Optical Design

5. Implementation and Verification of PANIC

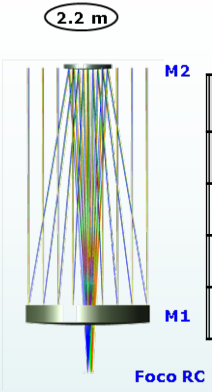
6. PANIC's Performance

• Performance

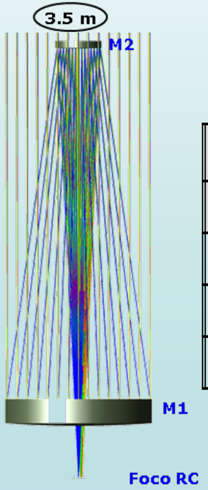
Parameter	Requirement	PANIC
Wavelength range	(0.8 – 2.42) µm	✓
System	Within a cryostat	✓
Temperature (liquid nitrogen)	~ 80 K	✓
Pressure	10^{-6} mbar	✓
Focus mechanism	Telescope secondary mirror	✓
Optical system solution	Refractive	✓
Optical surfaces	Spherical and flat Minimize number of aspherics and conics	Spherical and flat ✓
Elements	2 barrels for cold stop re-imaging 2 flat-fields	✓
Lenses mechanical constrains	Implementation of chamfers at the edge Edge thickness ≥ 6.5 mm	✓
Broad-band filters	**Z**, **Y**, **J**, **H** y $\mathbf{K_S}$	✓
Narrow-band filters	FWHM/λ_c 100 ~ 1%	✓
Narrow-band filters, λ_c shift	≤ 0.3 %	✓
Re-imagined System Entrance Pupil	Physically available to introduce a cold stop within the camera optical track	✓
Image quality for the re-imagined System Entrance Pupil	Flux loss in K band: < 10%	< 2% ✓
Aperture stop	Cold	✓
Cold stop diameter degradation	≤ 3 % in K band	✓
Field Stop	Cold	✓
Stray Light reduction	Optimized for K band	✓
Ghosts: relative intensity	< 10^{-4}	✓
Ghosts: size on the detector	> 10 arcsec (in case of relative intensity violation)	✓
Back focal distance	> 10 mm	✓
Length focal plane - bottom	≤ 110 cm	✓
Weight	≤ 400 kg	385 kg ✓
Transmission	> 45 % (complete wavelength range)	~ 50.6 % ✓
Distortion	≤ 1.5 % (complete wavelength range)	< 1.42 % ✓
Lateral magnification	0.4685 ± 0.0025	0.468 ± 0.003 ✓

1. Introduction
2. Objectives
3. Requirements and Specifications
4. Design of PANIC
4.1. Optical system development
4.2. Preliminary Optical Design
4.3. Final Optical Design
5. Implementation and Verification of PANIC
6. PANIC's Performance

- Performance



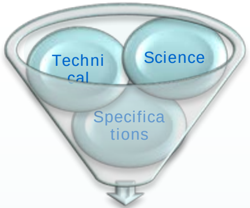
T22		
Parameter	Requirement	PANIC
Plate scale	(0.450 ± 0.007) arcsec/px	(**0.445** ± 0.003) **arcsec/px** ✓
FoV, square	(32.0 ± 1.0) arcmin	(**31.6** ± 0.3) **arcmin** ✓
Image quality, D_{EE80}	≤ 2 px = 36 μm = 0.900 arcsec	**≤ 1.5 px** = 26.4 μm = 0.65 arcsec ✓



T35		
Parameter	Requirement	PANIC
Plate scale	(0.226 ± 0.004) arcsec/px	(**0.224** ± 0.002) **arcsec/px** ✓
FoV, square	(16.1 ± 0.5) arcmin	(**15.88** ± 0.11) **arcmin** ✓
Image quality, D_{EE80}	≤ 3 px = 54 μm = 0.678 arcsec	**≤ 2.0 px** = 35.5 μm = 0.45 arcsec ✓

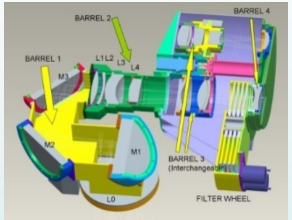
Optical System Implementation

1. Introduction
2. Objectives
3. Requirements and Specifications
4. **Design of PANIC**
5. Implementation and Verification of PANIC
6. PANIC's Performance

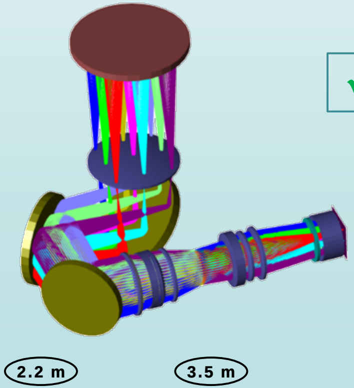


Requirements and Specifications

Preliminary Optical Design



Final Optical Design



Build the Instrument

PANIC's Components

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

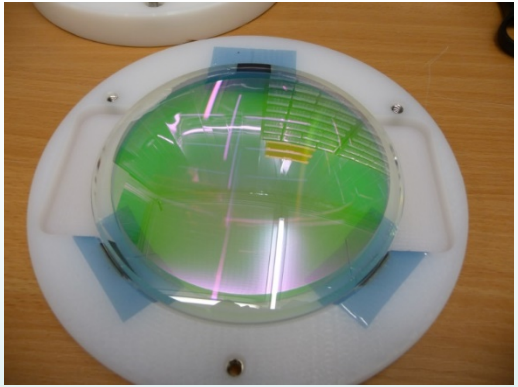
6. PANIC's Performance

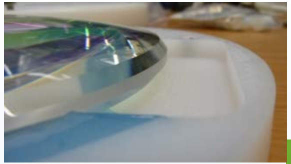
Auxiliary systems designed for PANIC

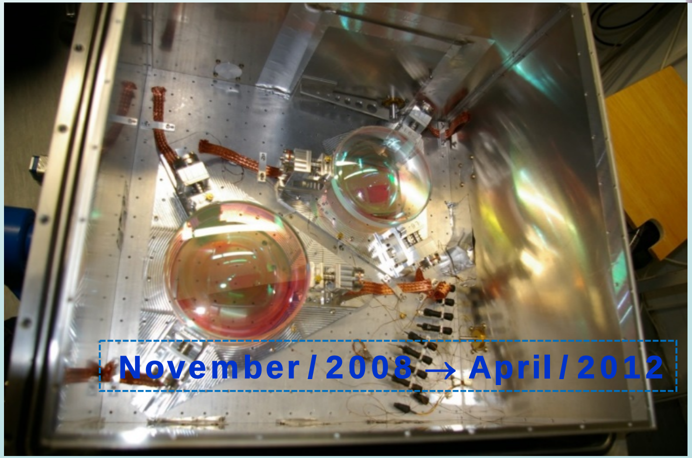
November / 2008 → April / 2012

PANIC's Components

- Lenses and Cryostat window







1. Introduction
2. Objectives
3. Requirements and Specifications
4. Design of PANIC
5. **Implementation and Verification of PANIC**
   - **5.1. Components: Manufacturing and Acceptance**
   - 5.2. Instrument in the Laboratory: AIV and Final tests
   - 5.3. Instrument at Telescope: Alignment and Verification
6. PANIC's Performance

PANIC's Components

- Lenses and Cryostat window
- Folding Mirrors

1. Introduction

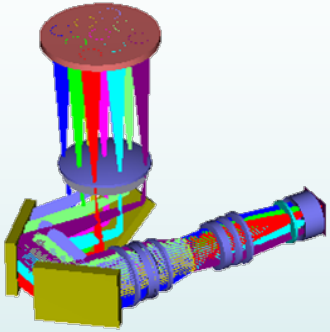
2. Objectives

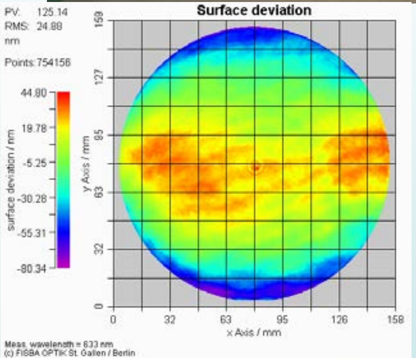
3. Requirements and Specifications

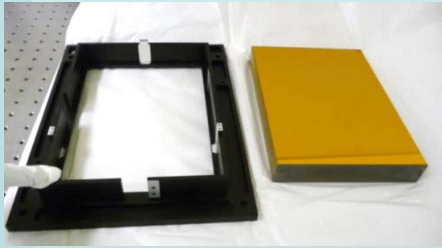
4. Design of PANIC

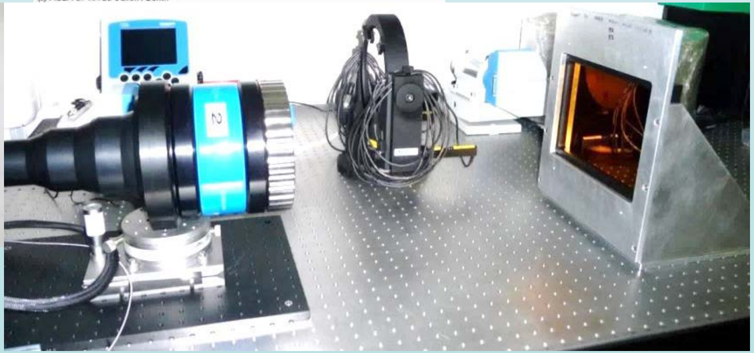
5. Implementation and Verification of PANIC

5.1. Components:









6. PANIC's Performance

PANIC's Components

- Lenses and Cryostat window
- Folding Mirrors
- Science Filters

Filtro	λ_c (μm)	FWHM (μm)	T (%)
Z	0.877	0.095	> 80
Y	1.020	0.100	> 70
J	1.250	0.160	> 80
H	1.635	0.290	> 80
K_S	2.150	0.301	> 80
H_2	2.122	0.032	> 65

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

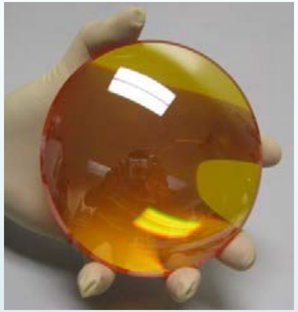
5.2. Instrument in the Laboratory: AIV and Final tests

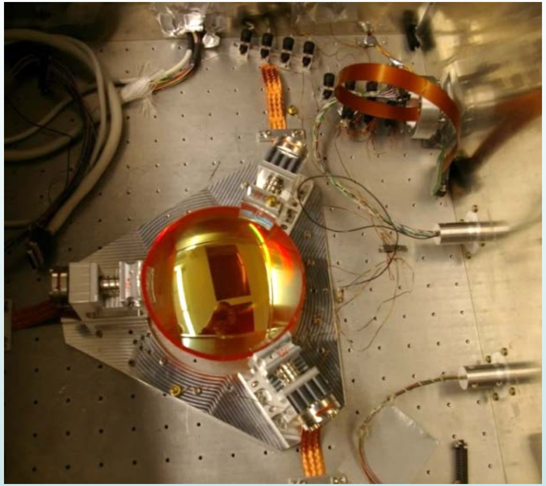
5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

PANIC's Components

- Lenses and Cryostat window
- Folding Mirrors
- Science Filters
- Pupil Imager Lens





1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

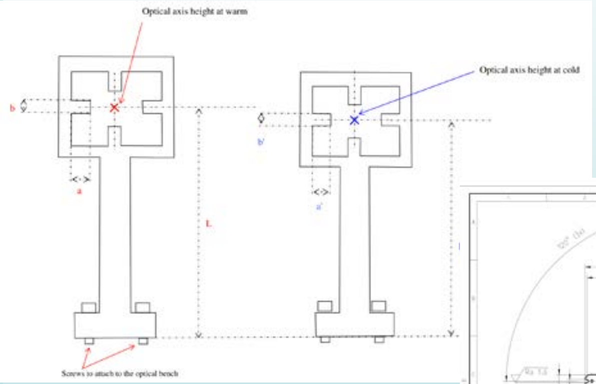
6. PANIC's Performance

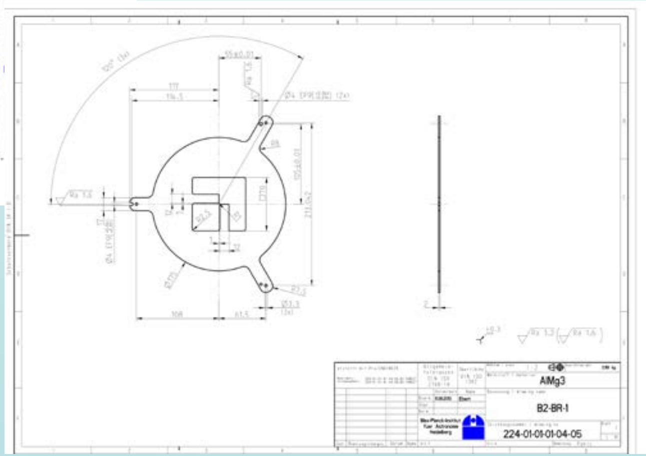
PANIC's Components

- Lenses and Cryostat window
- Folding Mirrors
- Science Filters
- Pupil Imager Lens

Auxiliary systems designed for PANIC

- Alignment targets (at warm, alignment DEC X and DEC Y)





1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

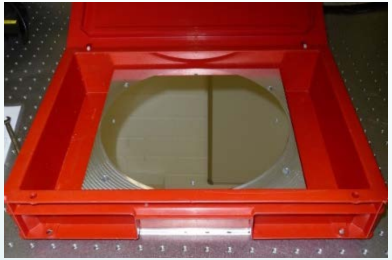
5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

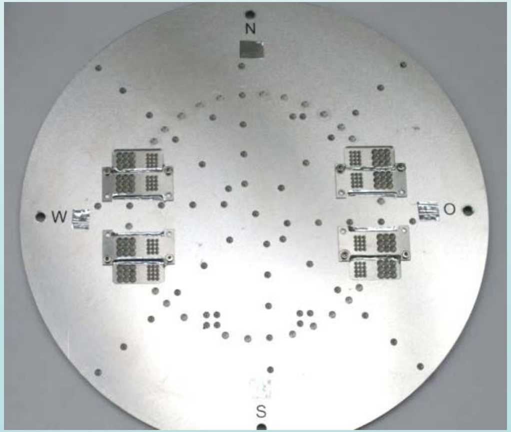
PANIC's Components

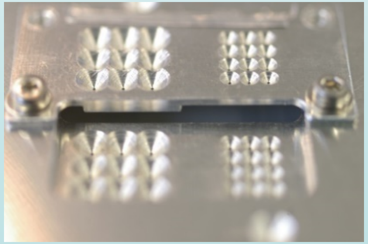
- Lenses and Cryostat window
- Folding Mirrors
- Science Filters
- Pupil Imager Lens



Auxiliary systems designed for PANIC

- Alignment targets (at warm, alignment DEC X and DEC Y)
- Auxiliary mirrors (at warm, alignment Tilt X and Tilt Y)
- Auxiliary cryostat exit window (for opto-mechanical axis verification at cold)
- Focal mask (for detector positioning at the instrument focus)





1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

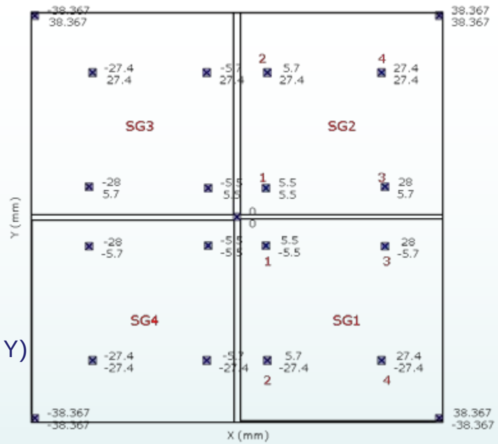
5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

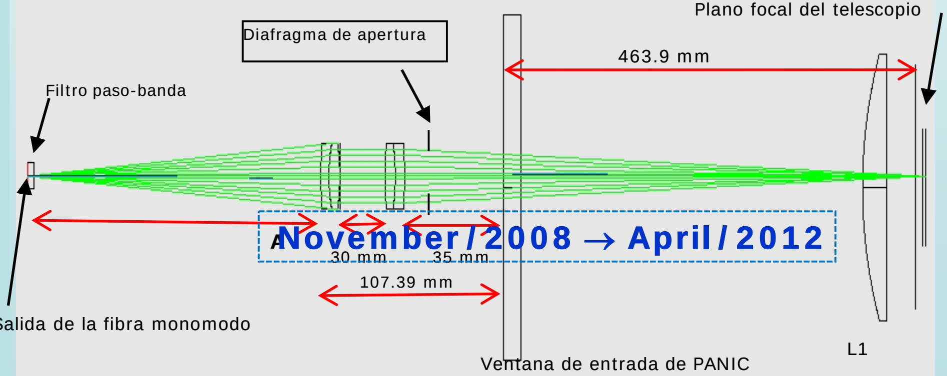
PANIC's Components

- Lenses and Cryostat window
- Folding Mirrors
- Science Filters
- Pupil Imager Lens



Auxiliary systems designed for PANIC

- Alignment targets (at warm, alignment DEC X and DEC Y)
- Auxiliary mirrors (at warm, alignment Tilt X and Tilt Y)
- Auxiliary cryostat exit window (for opto-mechanical axis verification at cold)
- Focal mask (for detector positioning at the instrument focus)
- Star Simulator (for instrument image quality measurements at laboratory)



November / 2008 → April / 2012

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

Subsystem level

May / 2010 → August / 2014

- **Folding Mirrors Structure**

Tilt X,Y ≤1.2 arcmin

System level

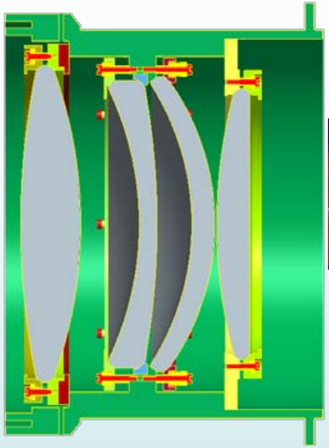
Static conditions:
Tilt X = (5 ± 1) arcsec
Tilt Y = (15 ± 7) arcsec

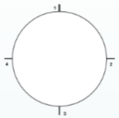
Dynamic conditions:
Tilt X,Y ≤ 20 arcsec

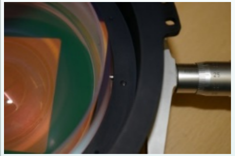
Subsystem level

May / 2010 → August / 2014

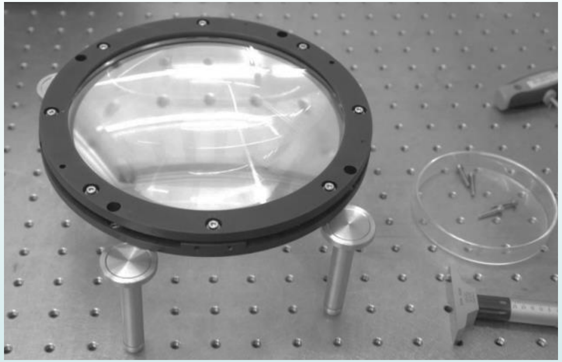
- Folding Mirrors Structure
- **Lenses**







DEC X, Y ≤ 50 μm



1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

Subsystem level

May / 2010 → August / 2014

- Folding Mirrors Structure
- Lenses
- **Filters** and **PIL**

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

Subsystem level

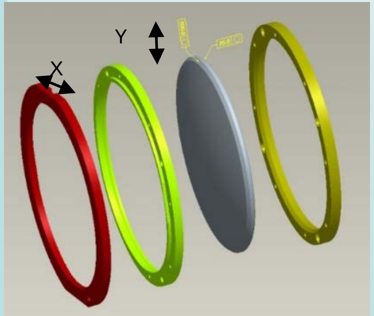
May / 2010 → August / 2014

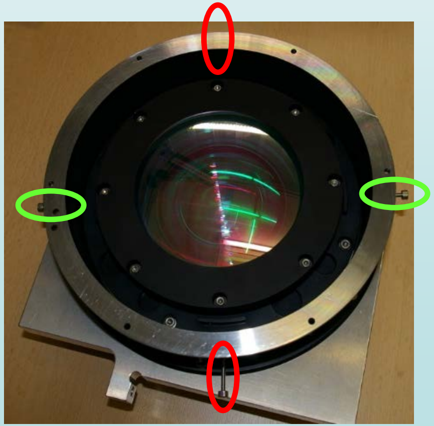
- Folding Mirrors Structure
- Lenses
- Filters and PIL

System level

- **Operation temperature** changed: from 80 K to **95 K**
- Final optical design: Feedback with the optical as-built parameters

  → **As-built Optical model**
- Calculation of the mechanical **compensators**: **L2-L3 and L7-L8 distances**
- **Lenses Barrels:** mechanical **compensators, decentering L2 and L6**





1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

Subsystem level

May / 2010 → August / 2014

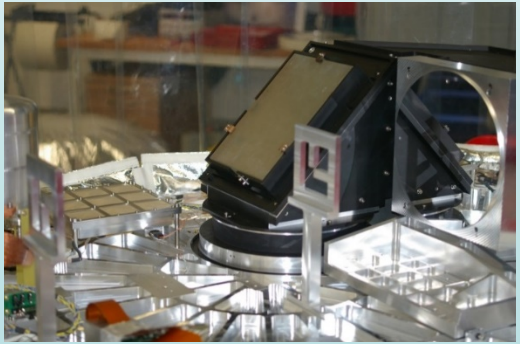
- Folding Mirrors Structure
- Lenses
- Filters and PIL

System level

- **Operation temperature** changed: from 80 K to **95 K**
- Final optical design: Feedback with the optical as-built parameters

→ **As-bu**

- Calculation of the mechanical **compensators**: **L2-L3 and L7-L8 distan**
- **Lenses Barrels:** mechanical **compensators, decentering L2 and L6**
- **Opto-mechanical axis alignment at warm** and **verification at cold**



1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Subsystems: Manufacturing and Acceptance

Subsystem level

May / 2010 → August / 2014

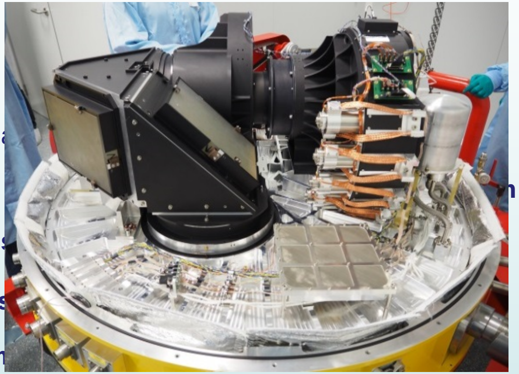
- Folding Mirrors Structure
- Lenses
- Filters and PIL

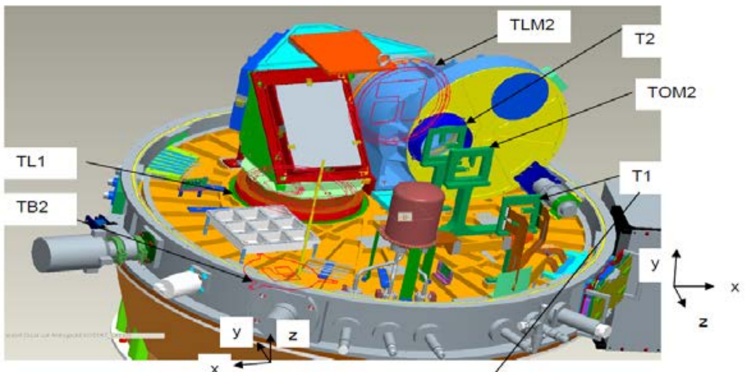
System level

- **Operation temperature** changed: from 80
- Final optical design: Feedback with the optica

nodel

- Calculation of the mechanical **compensators**
- **Lenses Barrels:** mechanical **compensators**
- **Opto-mechanical axis alignment at warm**
- **Complete instrument alignment at warm** and **verification at cold**





9 cryogenic cycles

Common Opto-mechanical axis:
DEC X/Y → 100 – 50 μm
Tilt X/Y → 1 -1.5 arcmin

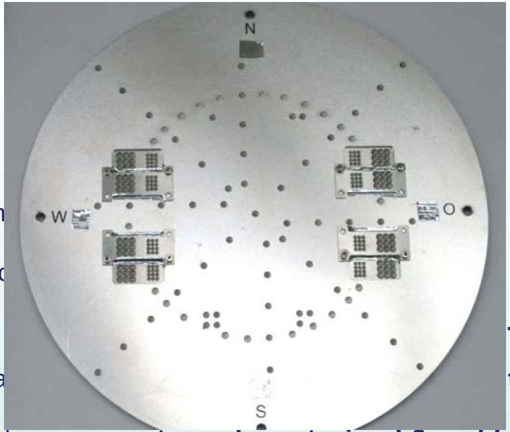
1. Introduction
2. Objectives
3. Requirements and Specifications
4. Design of PANIC
5. Implementation and Verification of PANIC
5.1. Components: Manufacturing and Acceptance
5.2. Instrument in the

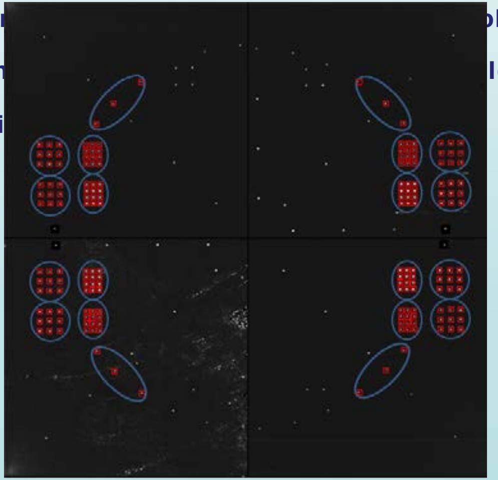
Subsystem level

- Folding Mirrors Structure
- Lenses
- Filters

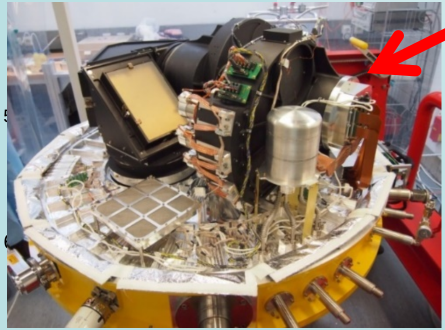
System level

- **Operation temperature** ch
- Final optical design: Feedbac **-built Optical model**
- Calculation of the mechanica **tances**
- **Lenses Barrels:** mechanical **compensators, decentering L2 and L6**
- **Opto-mechanical axis alig** **old**
- **Complete instrument align** **l**
- **Mosaic of detectors: positi**





Focus < 50 µm
Tilt X,Y < 1.2 arcmin



+4 cryogenic cycles

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

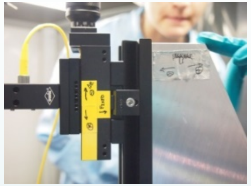
5.2. Instrument in the Laboratory: AIV and Final tests

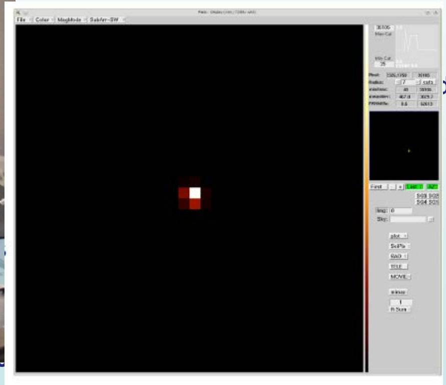
5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

Subsystem level

May / 2010 → August / 2014





- **Complete instrumen**
- **Mosaic of detectors:**
- **Image quality tests at laboratory (<u>before</u> transportation)**

FWHM → 0.9 – 2 px
As predicted by the as-built optical model

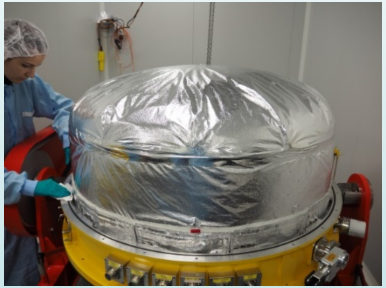
Instrument performance confirmed

- **Dismount to transport PANIC to CAHA !!**

We go to the telescope !!!

- **Reassembly after transport**






1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

October / 2014 → March / 2015

- Reassembly after transport
- **Image quality tests at laboratory (<u>after</u> transportation)**

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

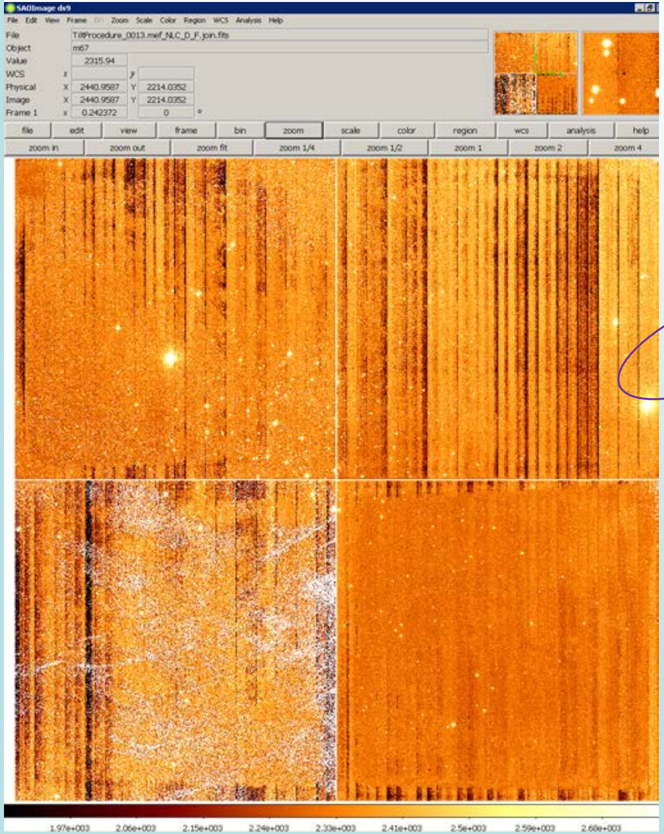
5.2. Instrument in the Laboratory: AIV and Final tests

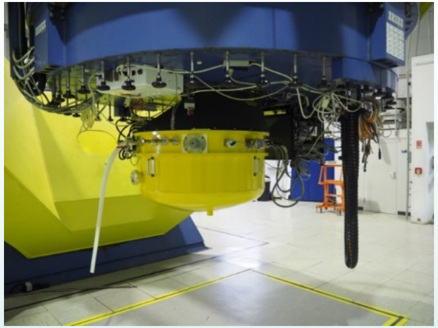
5.3. Instrument at Telescope: Alignment and Verification

6. PANIC's Performance

October / 2014 → March / 2015

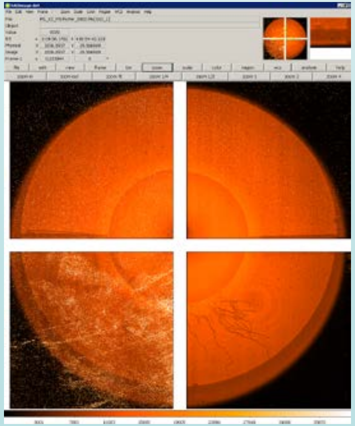
- Reassembly after transport
- Image quality tests at laboratory (after transportation)
- **At 2.2 m telescope: alignment**





3 iterations

T22: PIL mode



1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

5.1. Components: Manufacturing and Acceptance

5.2. Instrument in the Laboratory: AIV and Final tests

5.3. Instrument at Telescope: Alignment and Verification

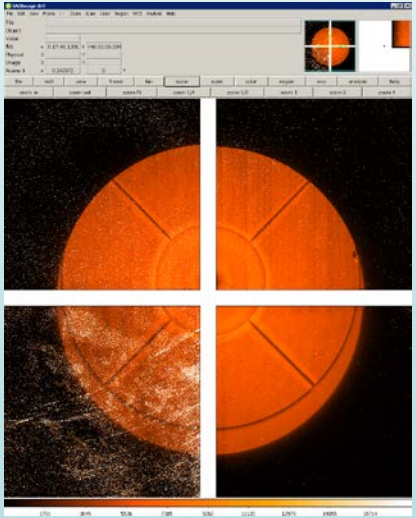
6. PANIC's Performance

October / 2014 → March / 2015

- Reassembly after transport
- Image quality tests at laboratory (<u>after</u> transportation)
- At 2.2 m telescope: alignment
- **At 3.5 m telescope: alignment**

2 iterations

T35: PIL mode



1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

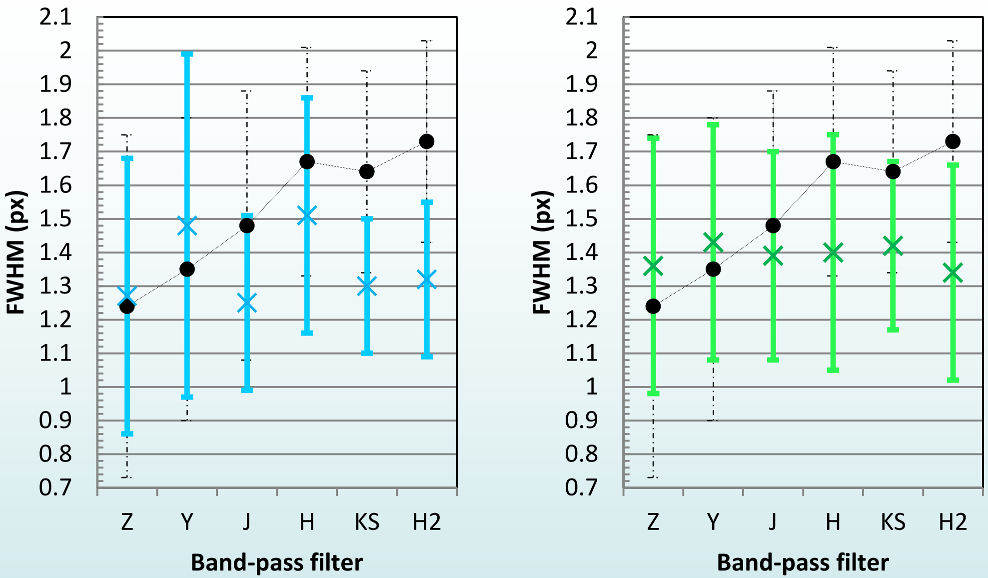
5. Implementation and Verification of PANIC

6. PANIC's Performance

6.1. Image Quality in the laboratory

6.2. Filters Set

6.3. Commissioning at both telescopes



- as-built Optical model

x Experimental data at laboratory: before transport

x Experimental data at laboratory: after transport

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

6. PANIC's Performance

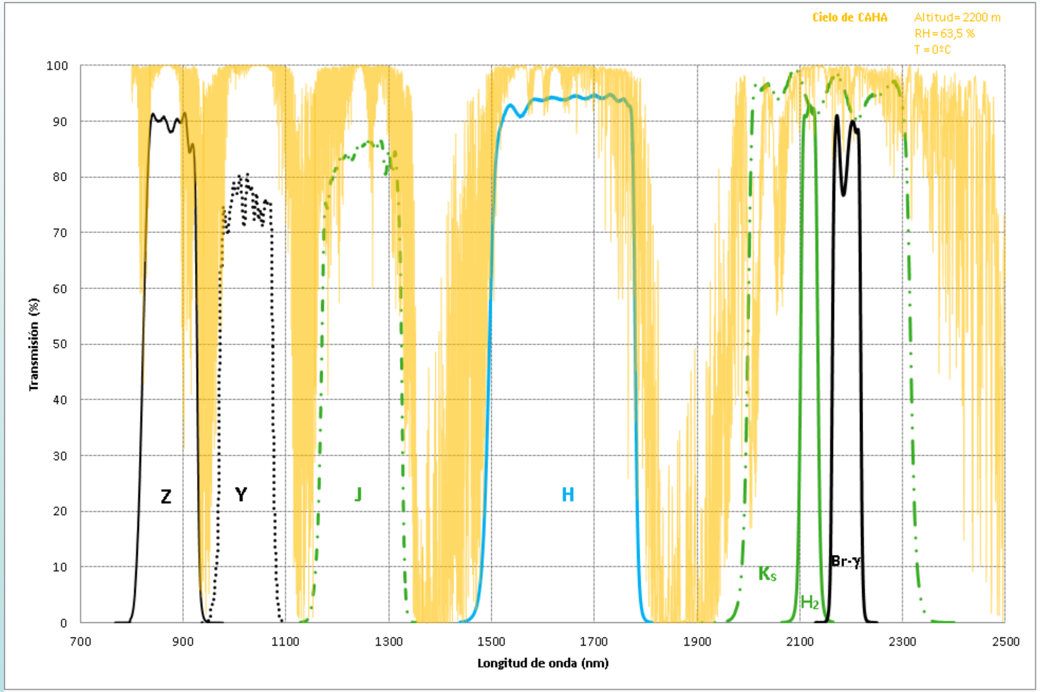
6.1. Image Quality in the laboratory

6.2. Filters Set

6.3. Commissioning at both telescopes

		Position					
		1	2	3	4	5	6
Wheel	#1	**Y**	**H**	**PIL**	Blank	**J**	Open
	#2	**Z**	**Ks**	Blank	H_2	dummy	Open
	#3	dummy	dummy	Blank	dummy	dummy	Open
	#4	dummy	dummy	Blank	dummy	**Br-γ**	Open

8 free slots !!



Operation temperature: 100 K

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

6. PANIC's Performance

6.1. Image Quality in the laboratory

6.2. Filters Set

6.3. Commissioning at both telescopes

T22		
PANIC performance	Expected **As-built Optical system**	Measured (M) Derived from measurements (D)
Lateral magnification	0.4676 ± 0.0014	(D) 0.470 ± 0.020
Focal ratio, F#	3.7434 ± 0.0016	(D) 3.76 ± 0.17
Plate scale	(0.4456 ± 0.0022) arcsec/px	(M) (**0.4484** ± 0.0017) **arcsec/px**
FoV, square	(31.65 ± 0.15) arcmin	(M) (**31.67** ± 0.11) **arcmin**
Image quality, D_{EE80}	(25.9 ± 0.6) μm = (1.44 ± 0.03) px (≤ 2 px)	(D) **≤ 2 px**
Distortion	≤ (1.332 ± 0.016) %	(M) **≤ 0.73 %**
Gap between detectors	≤ 167 px = 75 arcsec	(M) ~ 156 px = 70 arcsec
Pupil image diameter (on the detector)	(72.4 ± 0.9) mm	(M) ~ 71.5 mm

T35		
PANIC performance	Expected **As-built Optical system**	Measured (M) Derived from measurements (D)
Focal ratio, F#	4.6744 ± 0.0022	(D) 4.70 ± 0.21
Plate scale	(0.2239 ± 0.0013) arcsec/px	(D) (**0.226** ± 0.009) **arcsec/px**
FoV, square	(15.90 ± 0.09) arcmin	(D) (**16.0** ± 0.8) **arcmin**
Image quality, D_{EE80}	(32.4 ± 0.8) μm = (1.80 ± 0.04) px (≤ 3 px)	(M) **≤ 2 px**
Distortion	(1.381 ± 0.020) %	(D) **≤ 0.73 %**
Gap between detectors	≤ 167 px = 38 arcsec	(D) ~ 156 px = 35 arcsec
Pupil image diameter (on the detector)	(55.7 ± 0.6) mm	(M) ~ 55.3 mm

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

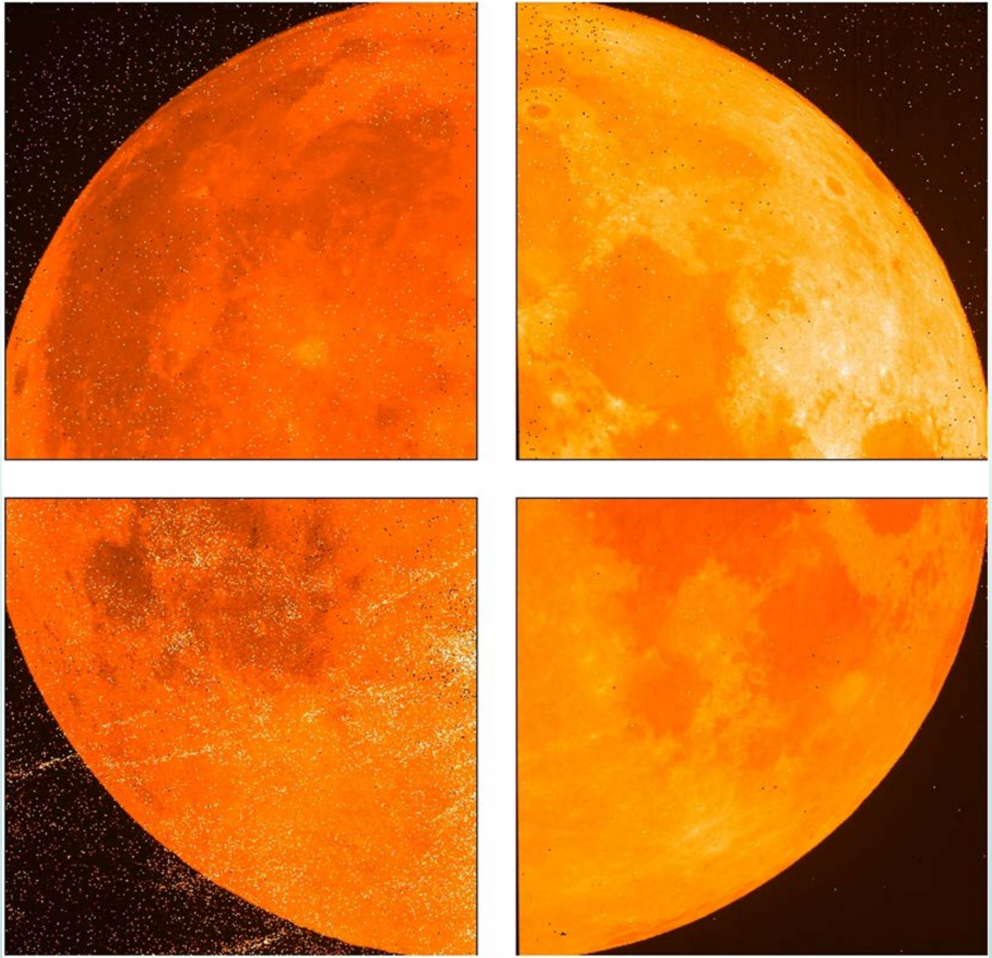
5. Implementation and Verification of PANIC

6. PANIC's Performance

6.1. Image Quality in the laboratory

6.2. Filters Set

6.3. Commissioning at both telescopes



First light image, full Moon: T22, H2, 30 arcmin

1. Introduction

2. Objectives

3. Requirements and Specifications

4. Design of PANIC

5. Implementation and Verification of PANIC

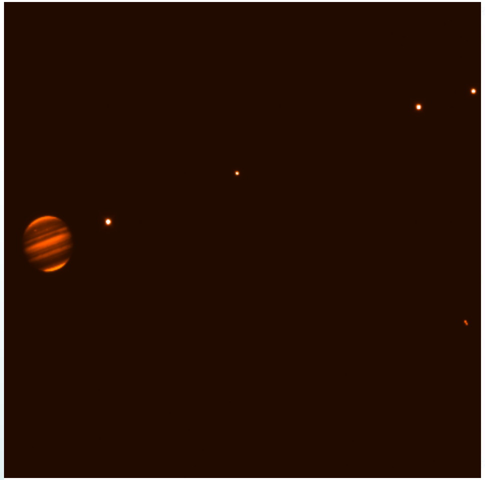
6. PANIC's Performance

6.1. Image Quality in the laboratory

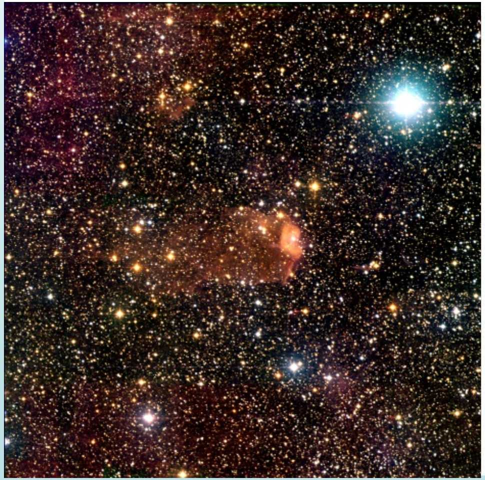
6.2. Filters Set

6.3. Commissioning at both telescopes

Jupiter: T35, H2, 8 arcmin

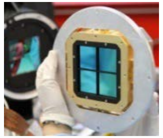


ECX6-21, T22, JHKs, 15 arcmin
Fernando Comerón et al. (in preparation)



DR18, T22, JHKs, 15 arcmin
Fernando Comerón et al. (in preparation)

Infrared bright source RAFGL5475, T22, JHKs, 15 arcmin
Fernando Comerón et al. A&A 622, A134 (2019)



Mosaic 2×2: HAWAII-2RG

18 µm/px

(76.5 × 76.5) mm

→

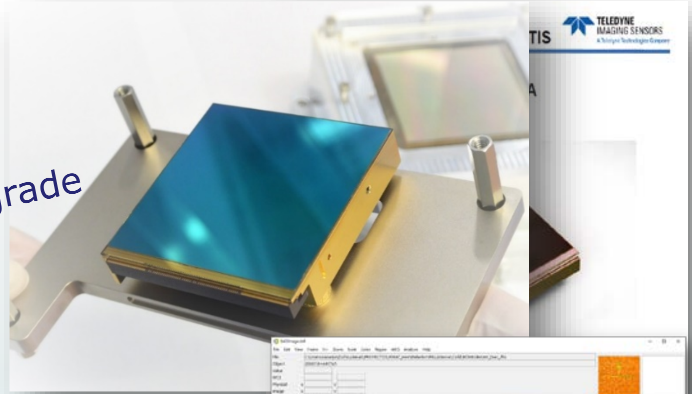
HAWAII-**4RG**
4k x 4k

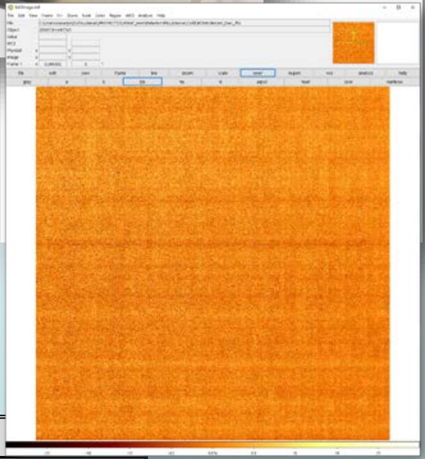
15 µm/px

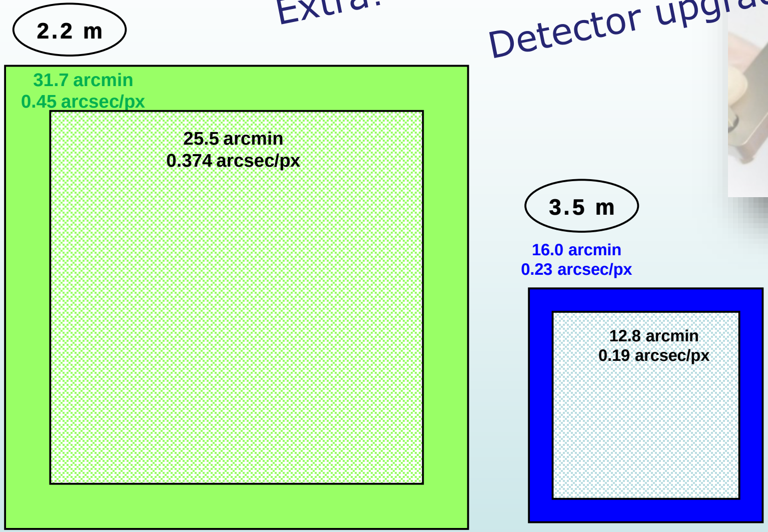
(61.4 × 61.4) mm

Extra!

Detector upgrade







PANIC performance		
Parameter	**T22**	**T35**
Monolithic Infrared Detector	Array 4096 × 4096 px HAWAII-4RG, *cut-off* 2.5 µm , 15 µm/px	
Plate scale	(**0.3737** ± 0.0014) **arcsec/px**	(**0.188** ± 0.008) **arcsec/px**
FoV, square	(**25.5** ± 0.1) **arcmin**	(**12.8** ± 0.5) **arcmin**
Image quality, D_{EE80}	(25.9 ± 0.6) µm = (1.73 ± 0.04) px (≤ 2 px)	(32.4 ± 0.8) µm = (2.16 ± 0.05) px (≤ 3 px)

¡Gracias!

· Concepción Cárdenas Vázquez: conchi@mpia.de

· Thesis available at: http://digibug.ugr.es/handle/10481/54456

· This talk in English at EAS 2020 annual meeting: https://youtu.be/q53OWQD87tg?t=3263

· PANIC web site: http://panic.iaa.es