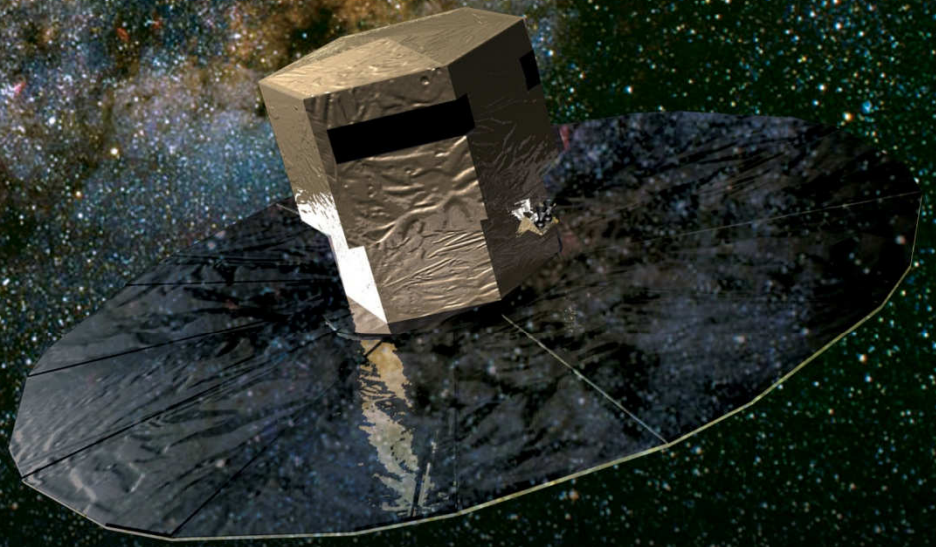
The Gaia project

Jordi Torra on behalf of the Gaia Group

Universitat de Barcelona

ICC/IEEC

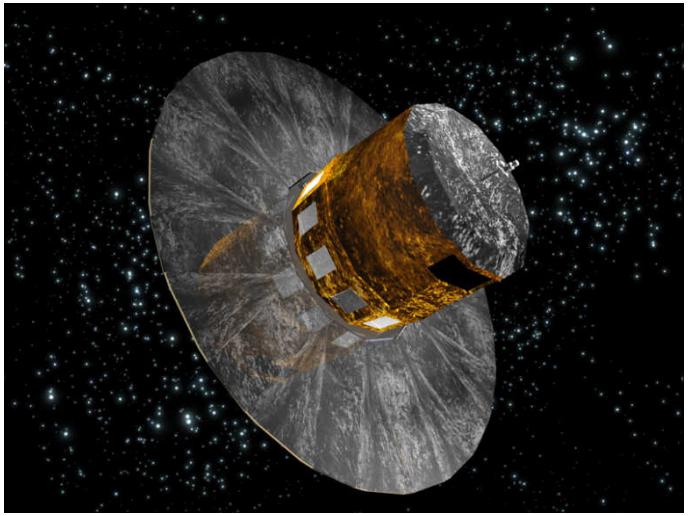


IX RES, 23rd September 2015

Launch December 19 2013 09:12:19 UTC

- First 1h43m: First signal acquisition and automatic start-up sequence monitoring

- OK transmitter, gyroscopes, PLM bipod release, CPS priming, thermal control configuration

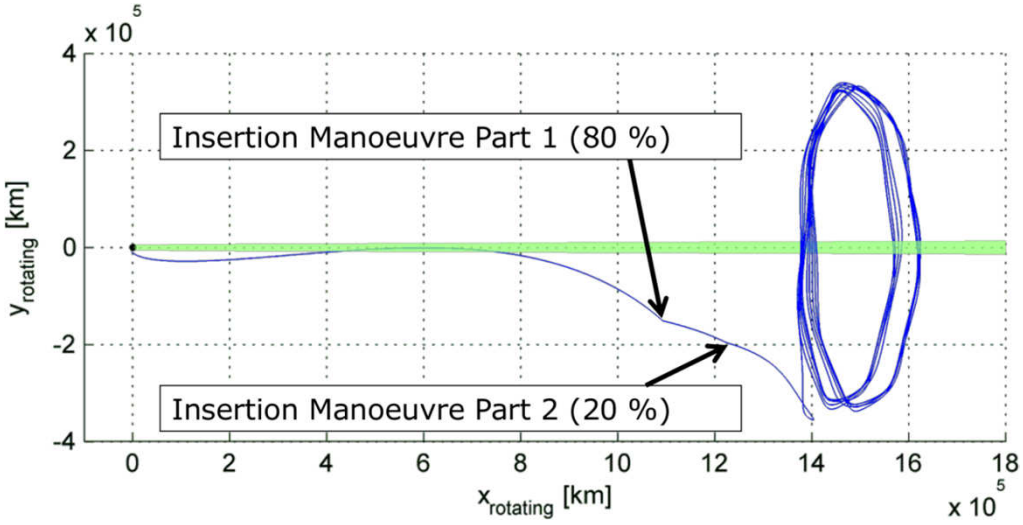


DSA deployment end 10:38 UTC

Gaia Calendar

- Gaia is the*Cornerstone Mission 6* in "Horizon 2000+" (ESA)

- Approved in 2001
- **2001-2003:** Phase A (feasibility studies)
- **2005-2006:** Phase B (detailed design)
- **2006-2013:** Phase C/D (construction)
- **19 Dec-2013: Launch**
- **July 2014 - 2018:** nominal operations (+1yr extension).
- Orbit around L2
- **2013-2022:** data reduction

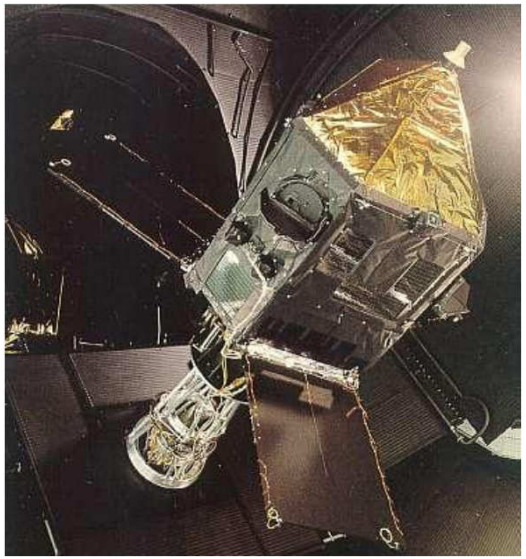


Gaia: global astrometry mission

Gaia's main science goal is to unravel the dynamical and chemical evolution of the Galaxy – back in time to its formation – and to study its kinematics, dynamics, and structure

A large 3D survey of the Milky Way (and beyond)

Based on Hipparcos principles (large angle, global astrometry) and success



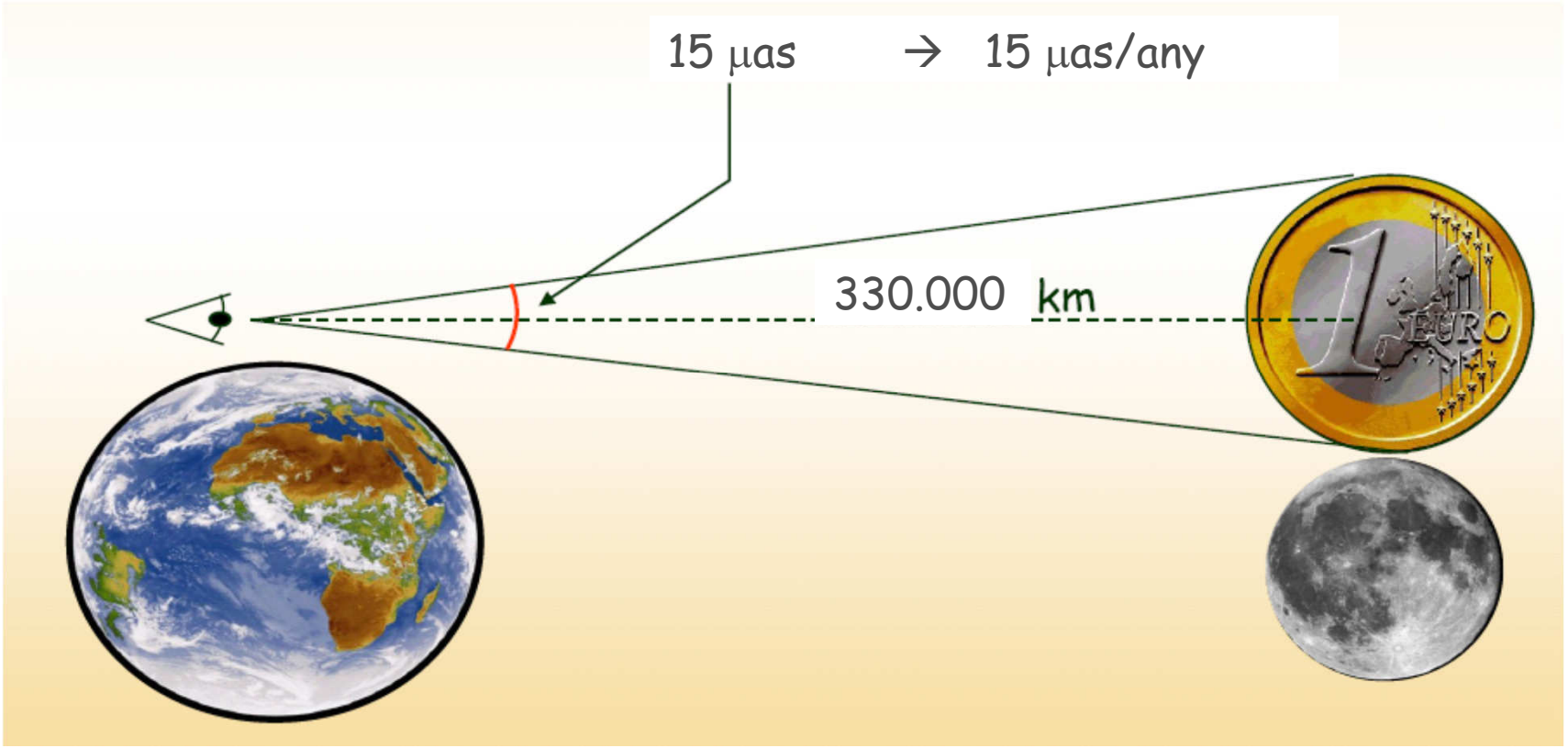
Hipparcos: launched Aug. 1989
Operations: 1988 -1993
Data reduction: 1988 -1997
European leadership

Gaia capabilities

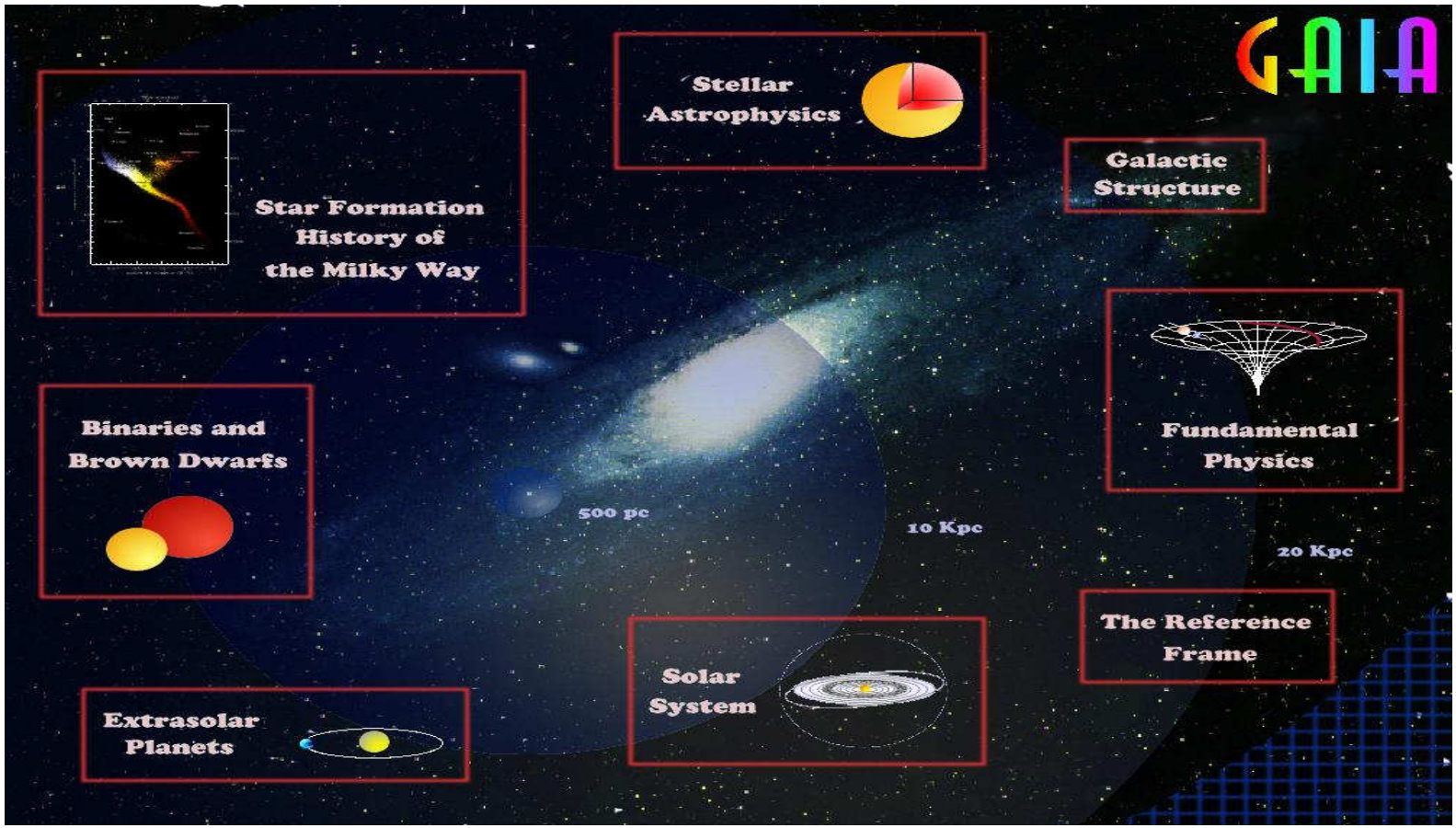
- Positions, proper motions and parallaxes for 1 billion stars (G < 20)

- Low resolution spectrophotometry for 1 billion stars, allowing estimations of Teff, logg, Av and [Fe/H]

- Radial velocities for 150 million stars (G < 16)
- Atmospheric parameters, reddening and rotational velocities for 5 million stars (G < 12)
- Detailed chemical abundances for 2 million stars (G < 11)


15 μas → 15 μas/any
330.000 km
1 EURO

Scientific Goals

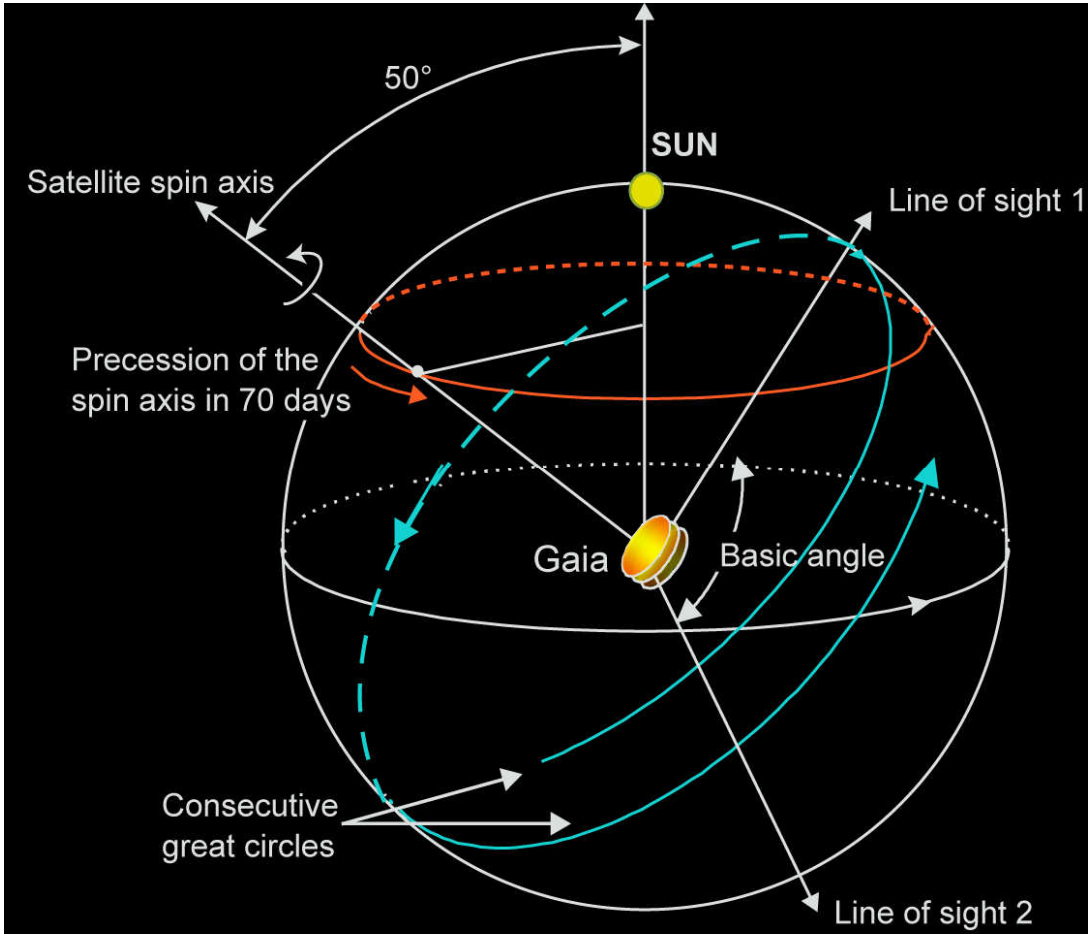


Two Challenges:

- To build the satellite:
  - Thermal and mechanical stability
    =>CCDs operate at ~ -110ºC
    =><1mK at focal plane
    =>~μK in the torus
  - High precision
  - The largest focal plane + TDI sinchronized with rotation

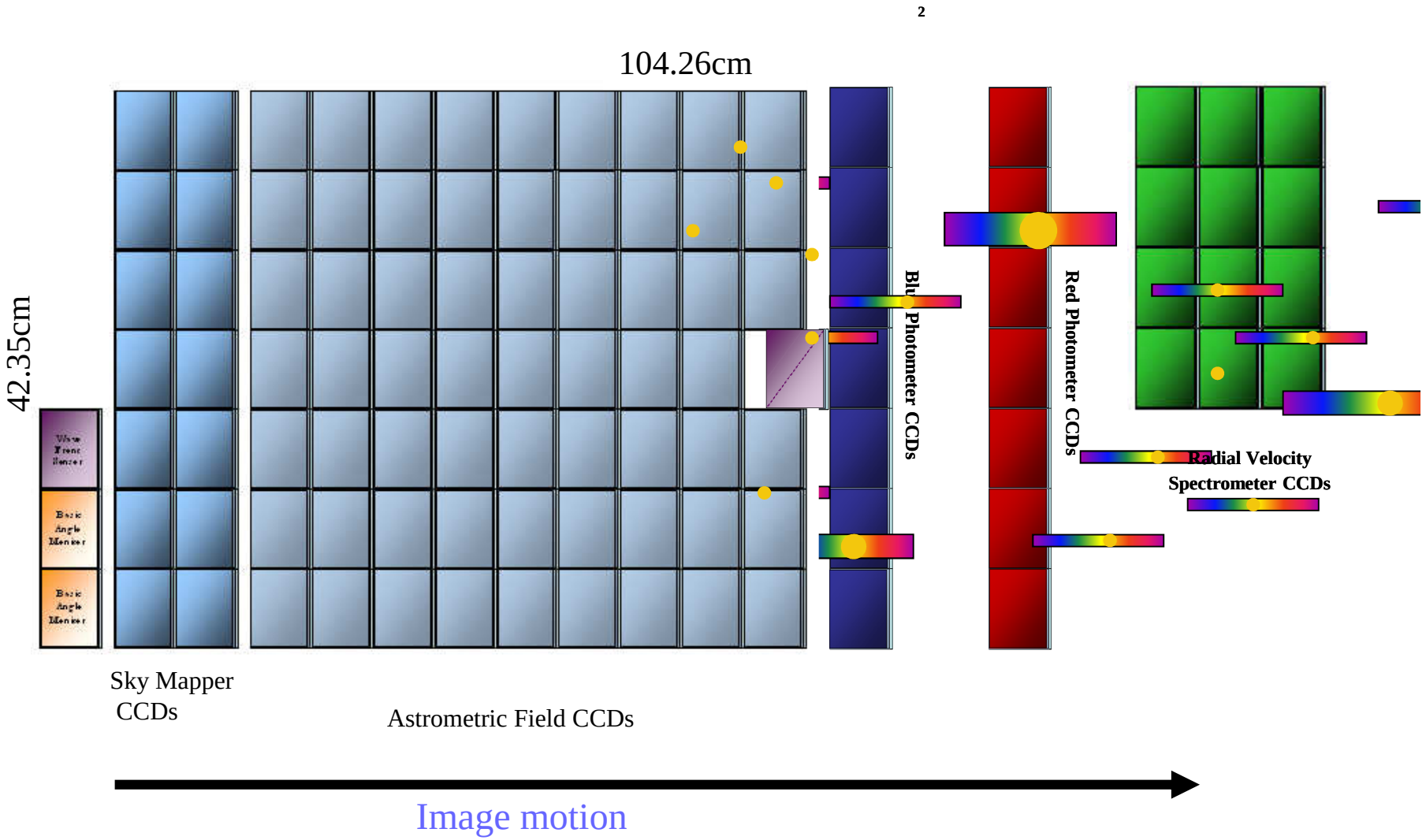
- Data processing:
  - Complex relationship as astrometry, photometry and spectroscopy
  - ~1 PetaByte of data, $10^{20\text{-}21}$ flop
  - μas accuracy, 0.1 μas = 10^{-13} rad
  - Hipparcos approach (flat files, sequential process) not possible

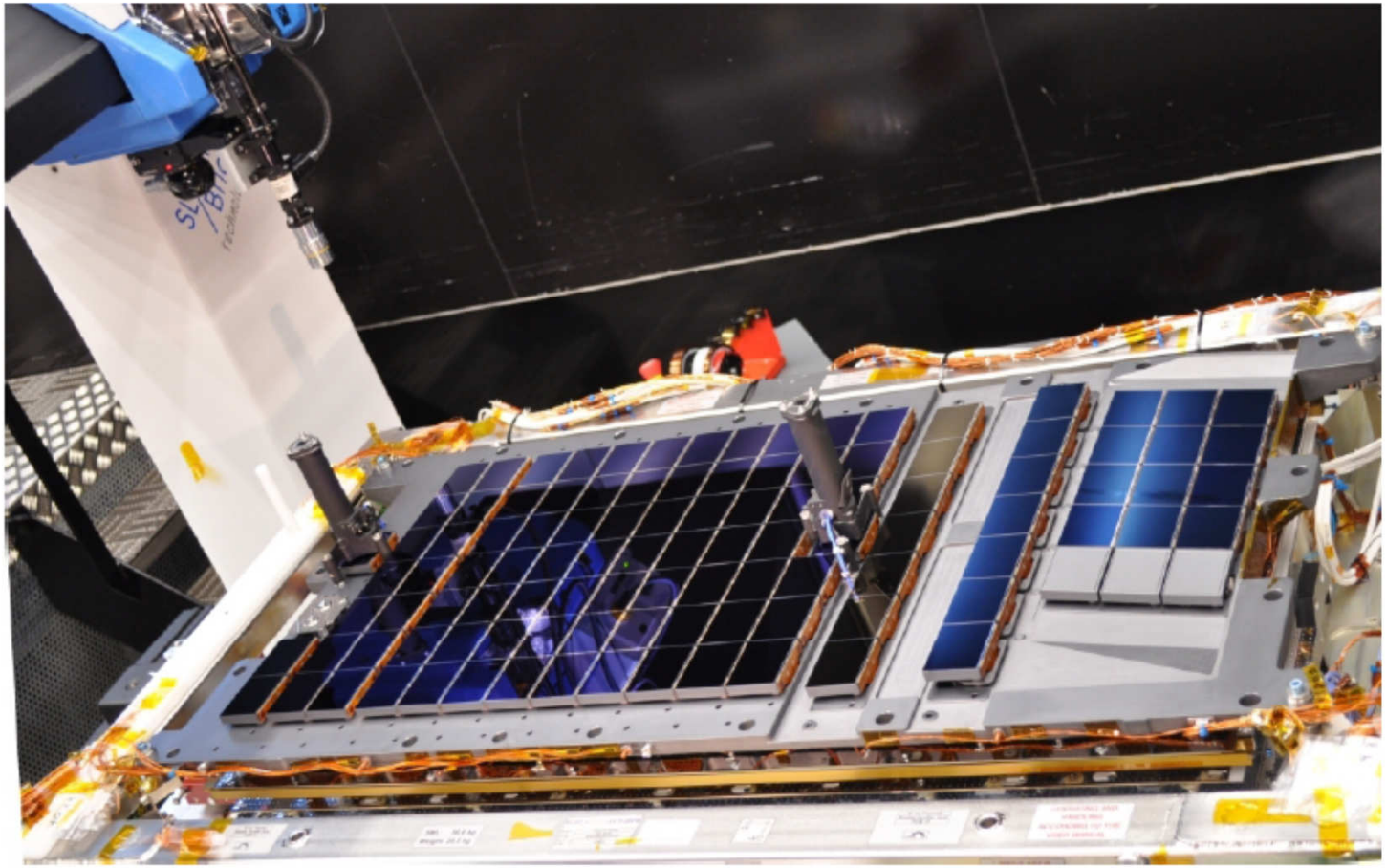
Scan law


50°
SUN
Satellite spin axis
Line of sight 1
Precession of the
spin axis in 70 days
Gaia
Basic angle
Consecutive
great circles
Line of sight 2

Telescopes, focal plane

106 CCDs , 938 million pixels, 2800 cm², 0.75 sqdeg
CCDs: 4500x1966 pix, operated in TDI mode



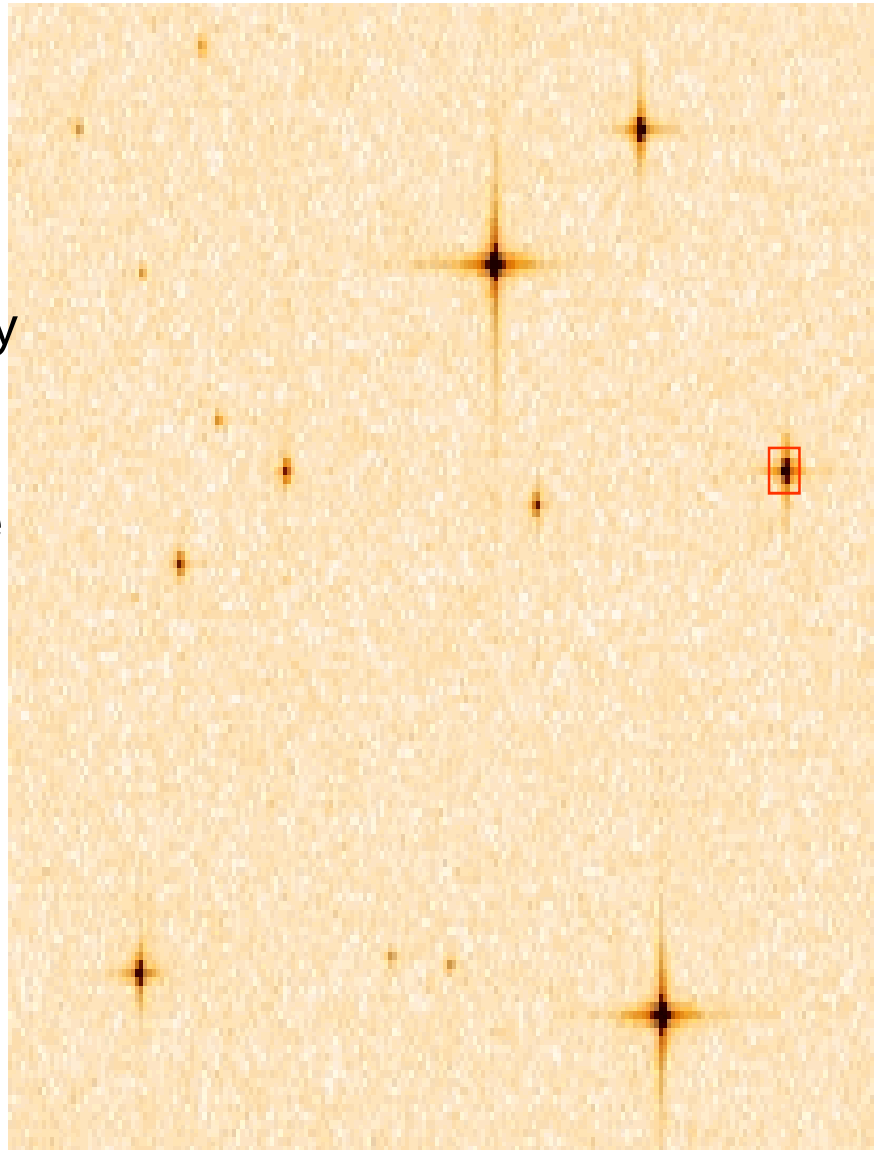


Images courtesy EADS-Astrium

Windowing

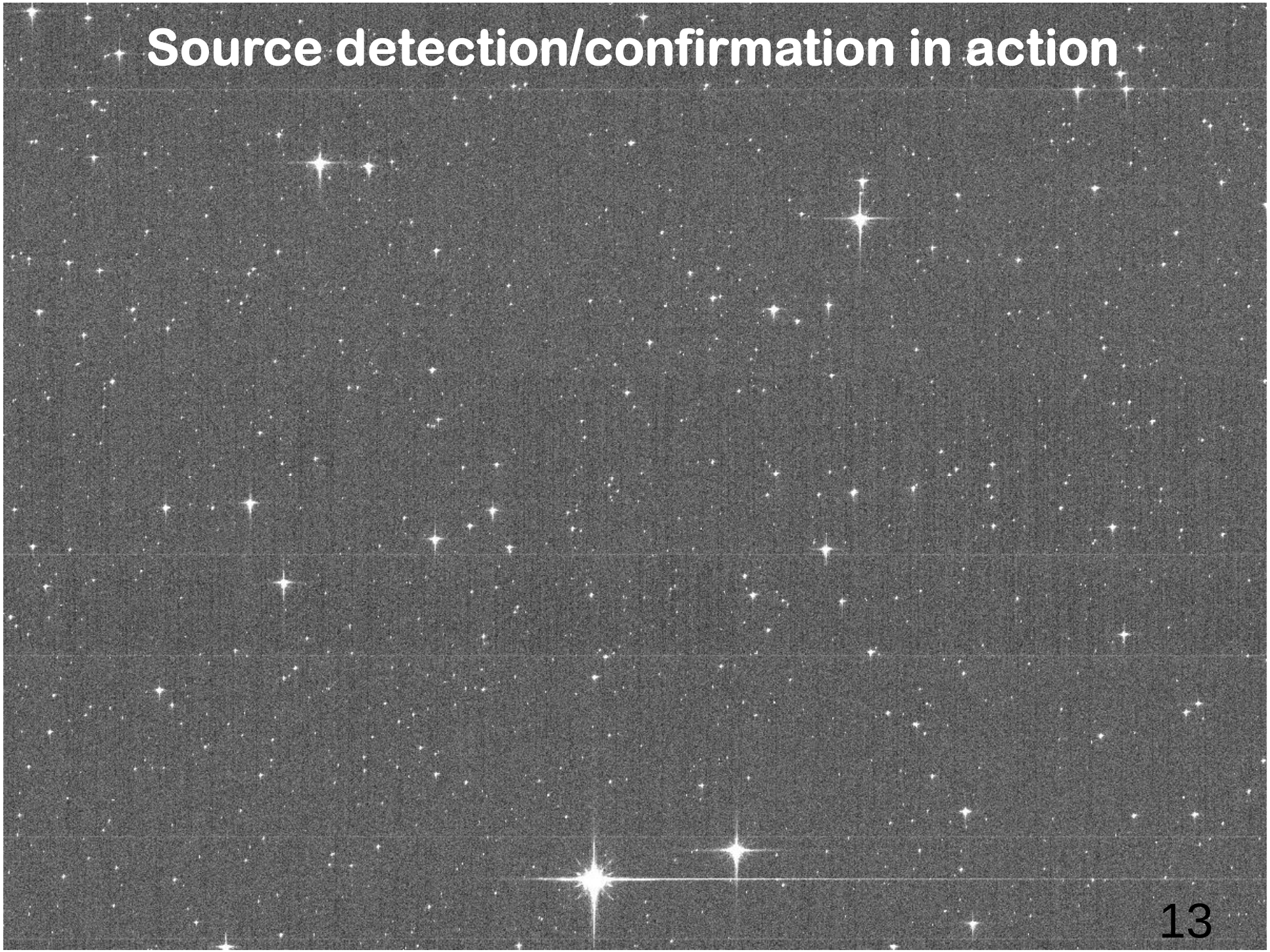
N = 45 10^6 obs/day

Not all the pixels are readed

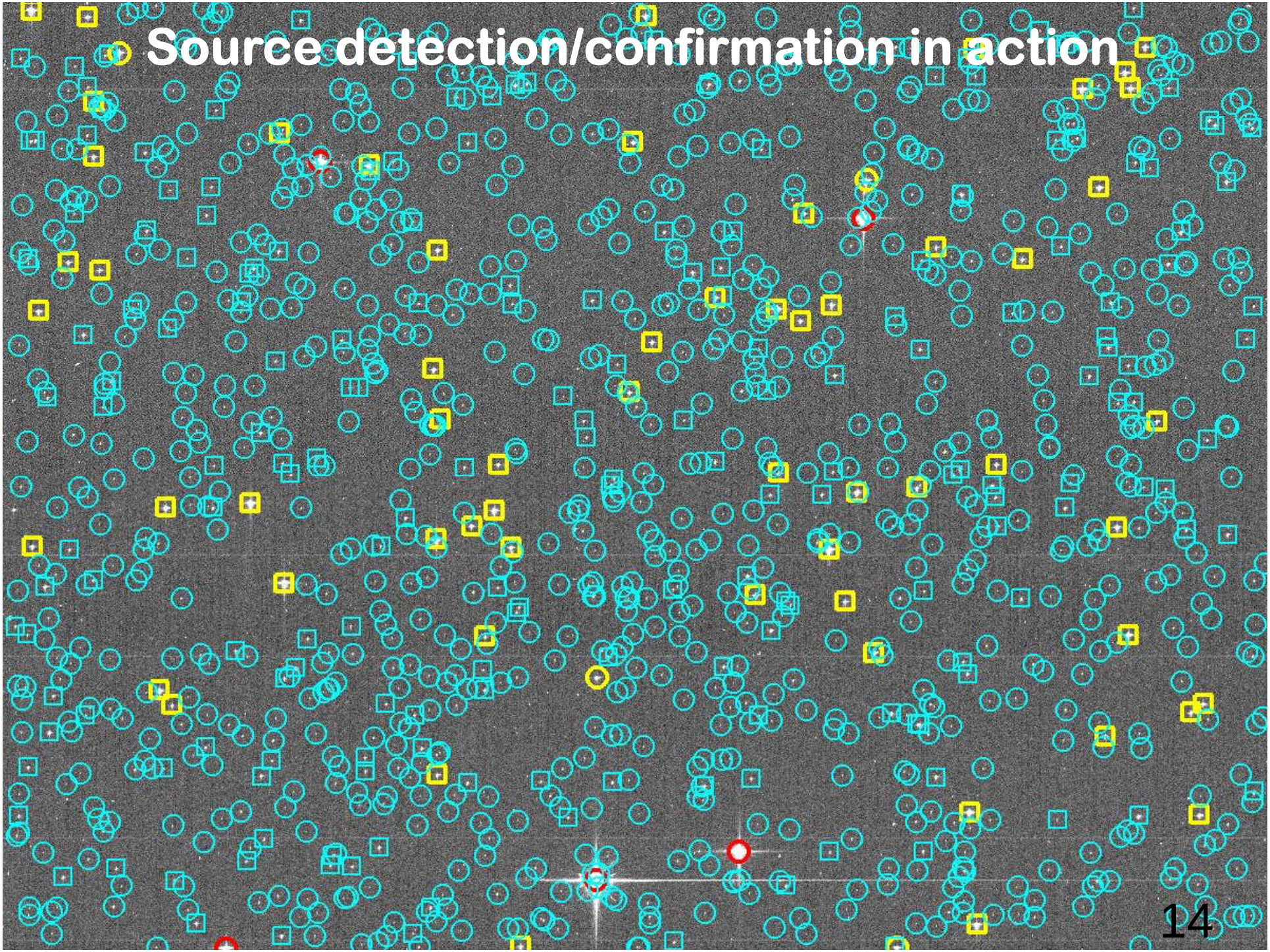


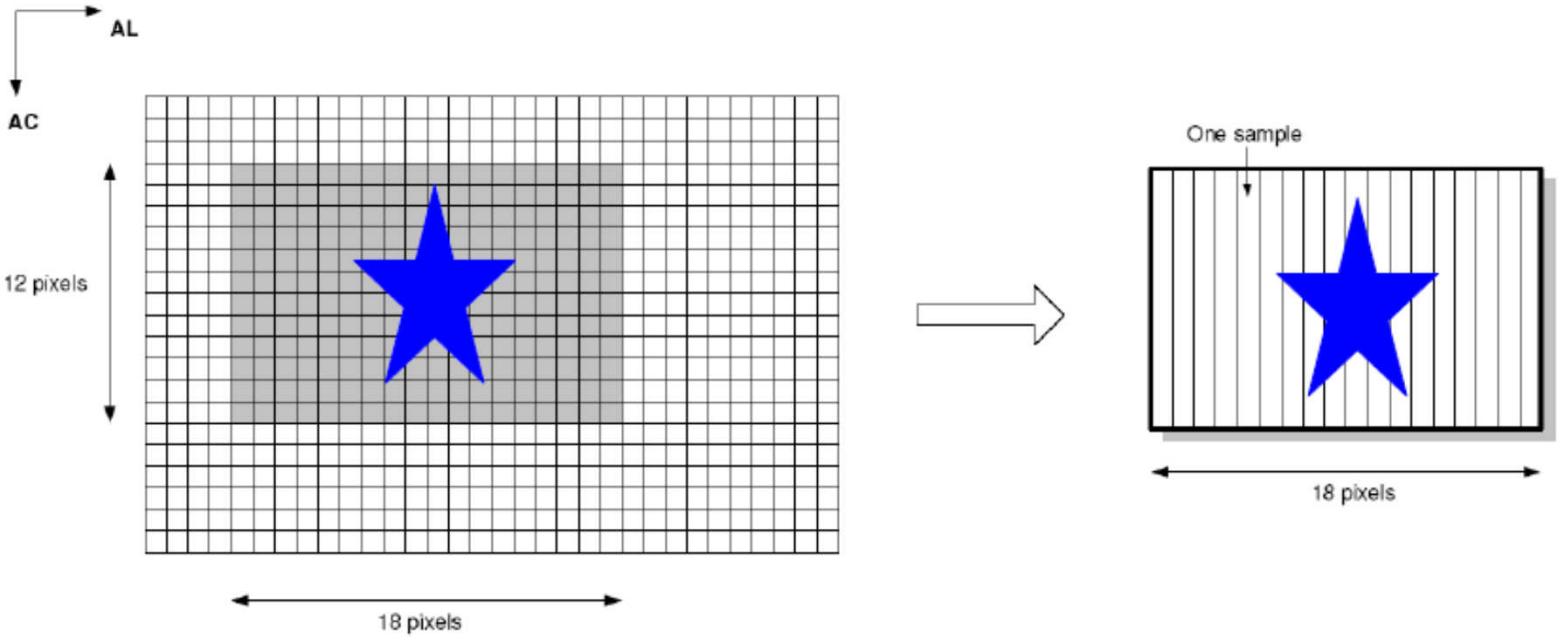
Window (in red): to be downloaded for each object detected and confirmed

Source detection/confirmation in action



Source detection/confirmation in action

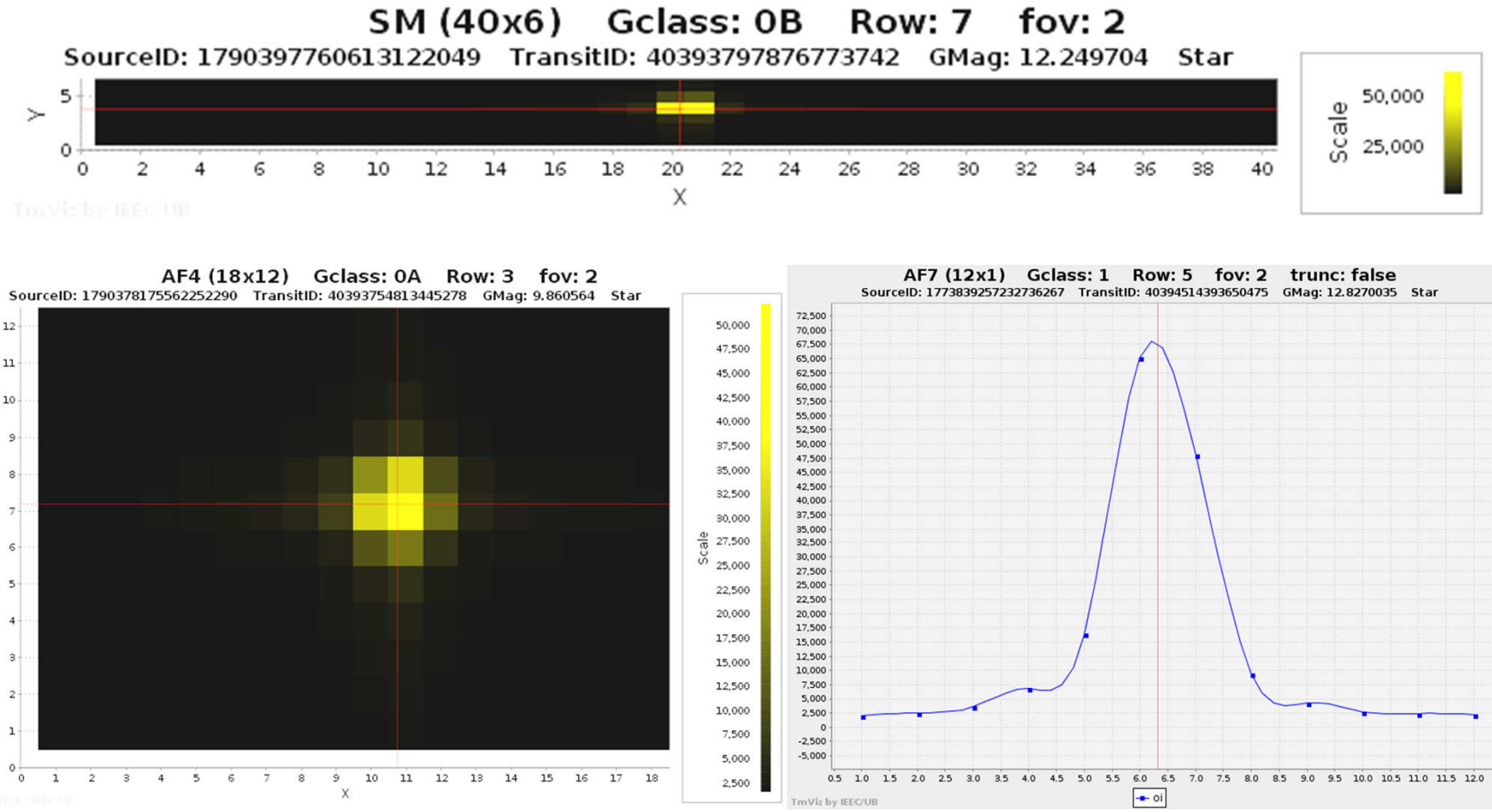




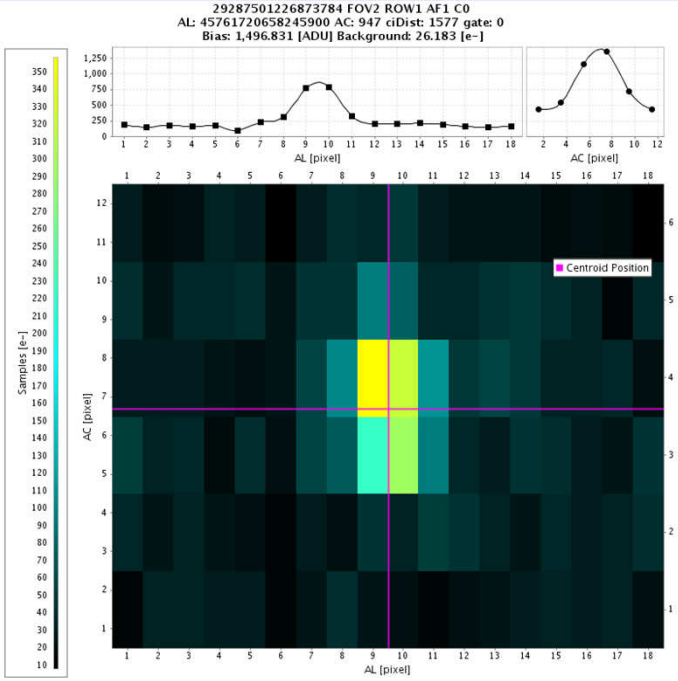
Example:

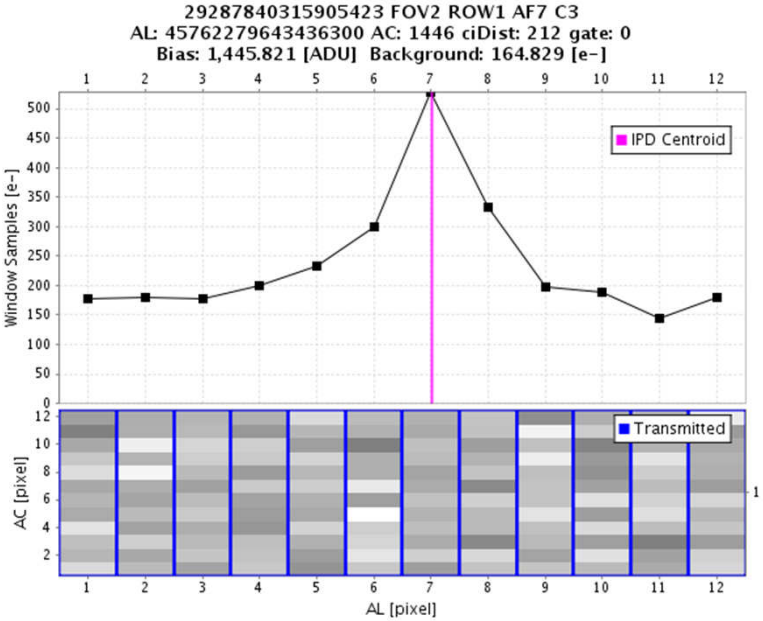
- The required window around the star covers 18×12 CCD pixels
- The read window is composed of 18 along-scan samples of 1×12 pixels
- Only the 18 electron-count sample values are sent to the ground

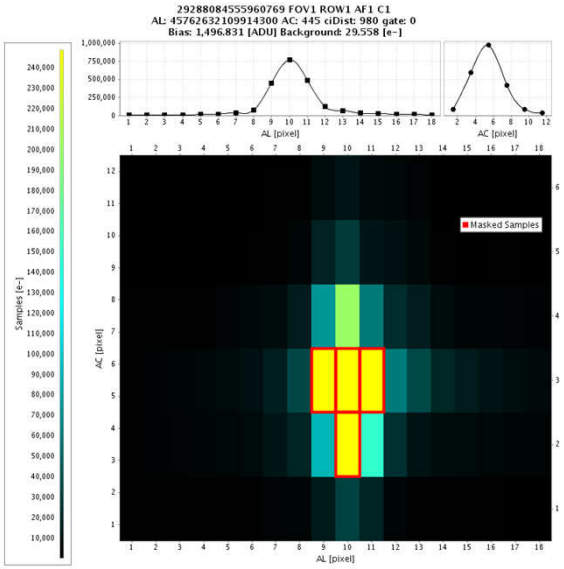
Positions, G magnitude



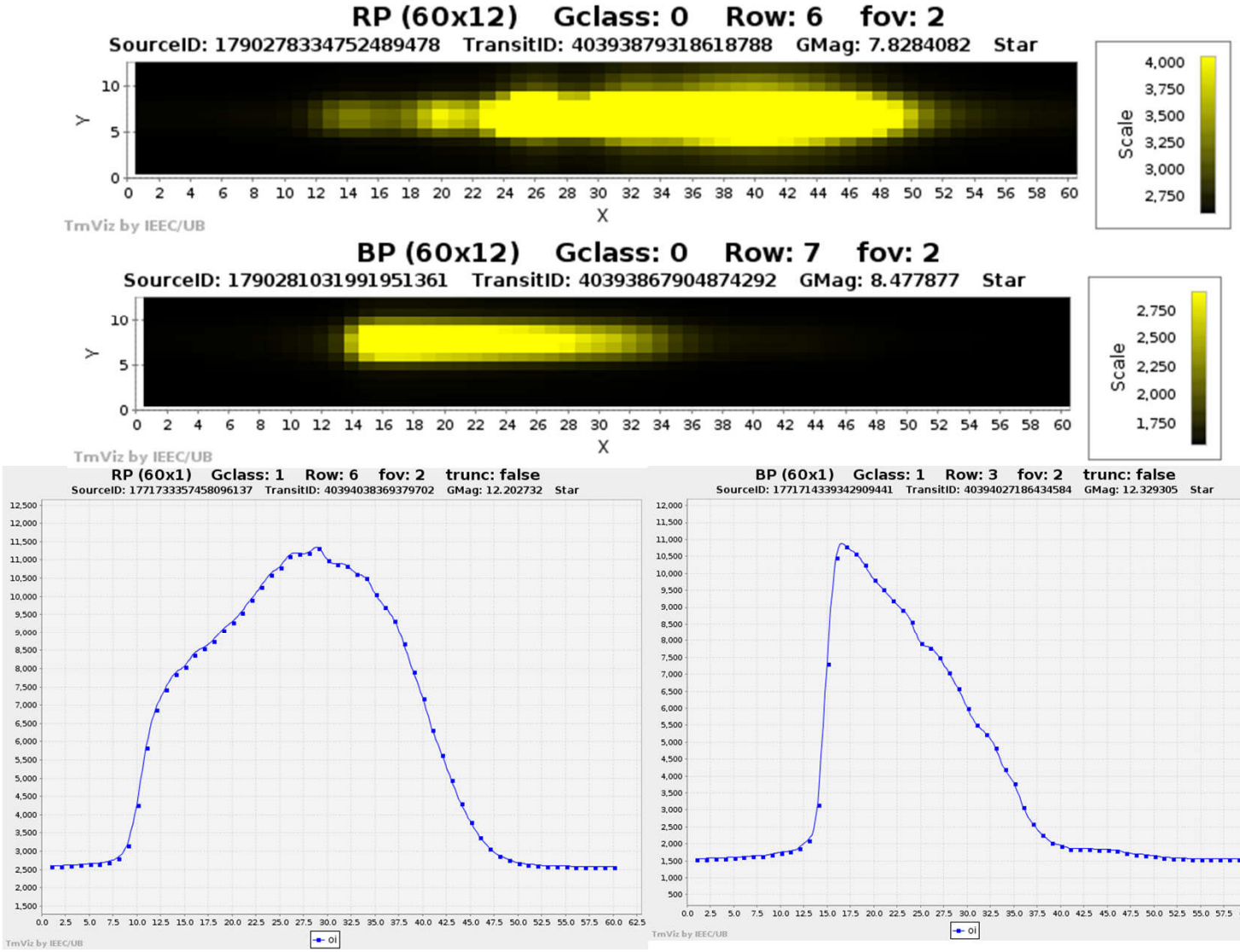
(9 measures in each transit)

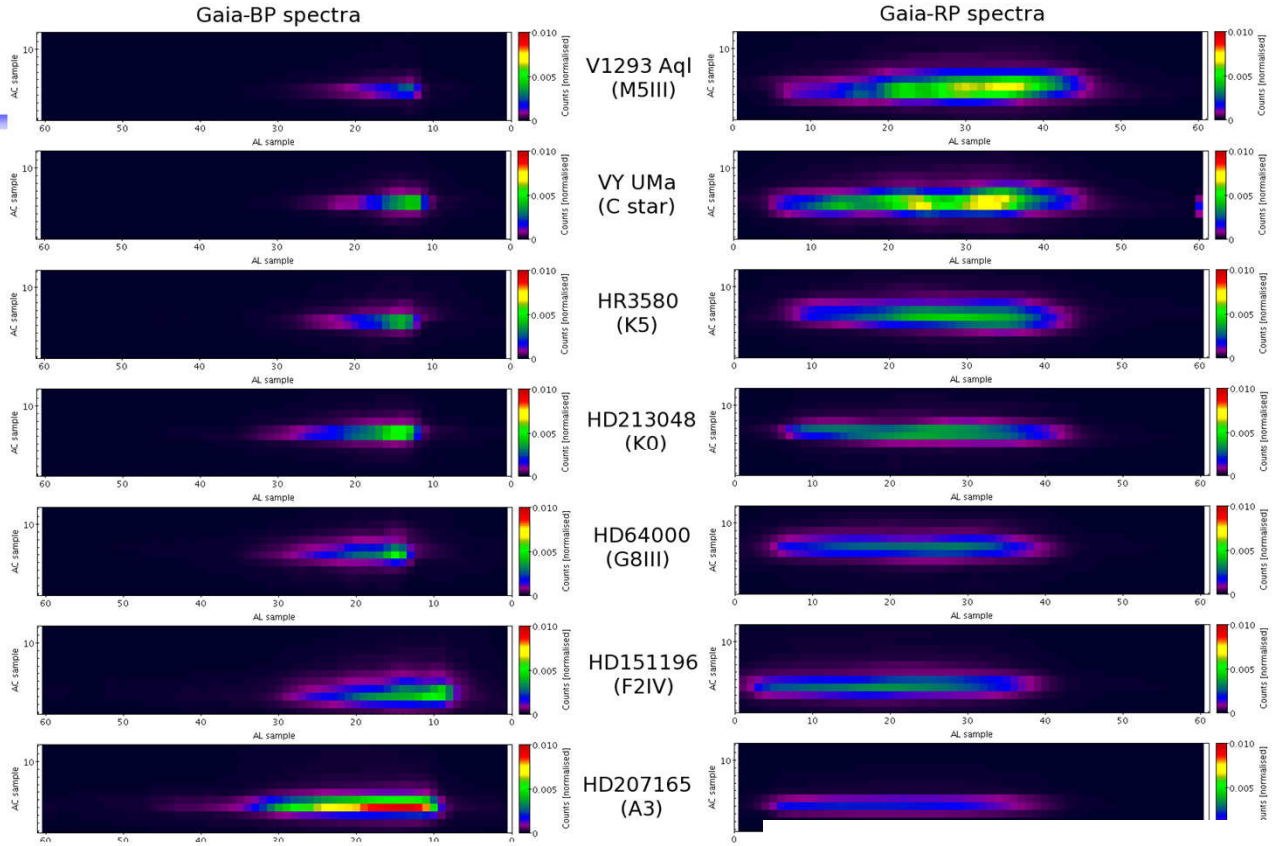

2928750122687378 4 FOV2 ROW1 AF1 C0
AL: 45761720658245900 AC: 947 ciDist: 1577 gate: 0
Bias: 1,496.831 [ADU] Background: 26.183 [e-]
Samples [e-]
AL [pixel]
AC [pixel]
Centroid Position

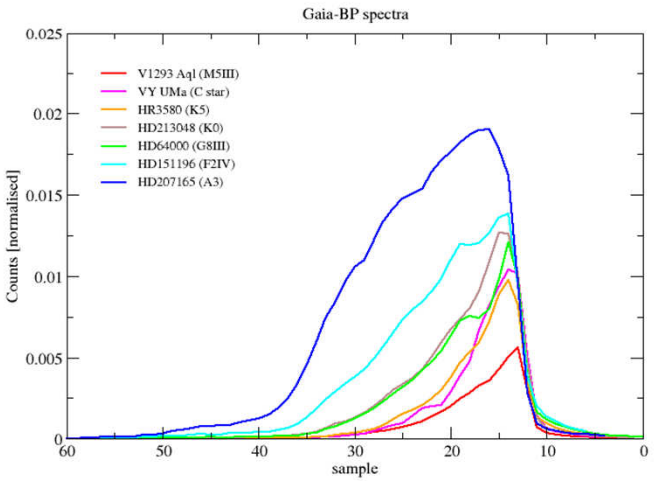

29287840315905423 FOV2 ROW1 AF7 C3
AL: 45762279643436300 AC: 1446 ciDist: 212 gate: 0
Bias: 1,445.821 [ADU] Background: 164.829 [e-]
Window Samples [e-]
IPD Centroid
Transmitted
AC [pixel]
AL [pixel]

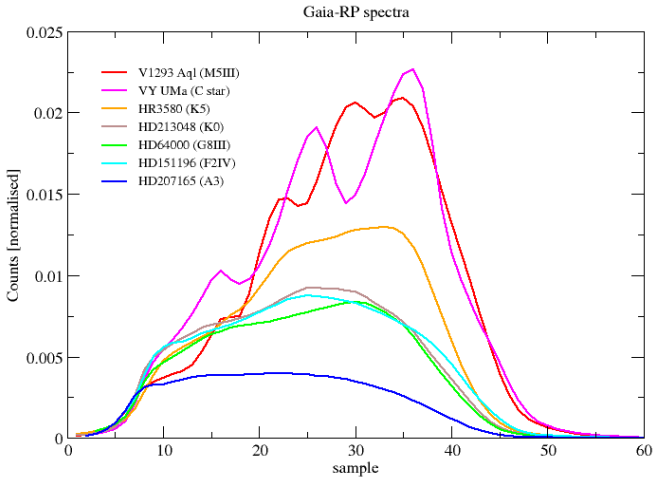

29288084555960769 FOV1 ROW1 AF1 C1
AL: 45762632109914300 AC: 445 ciDist: 980 gate: 0
Bias: 1,496.831 [ADU] Background: 29.558 [e-]
Samples [e-]
AL [pixel]
AC [pixel]
Masked Samples

BP, RP Photometry

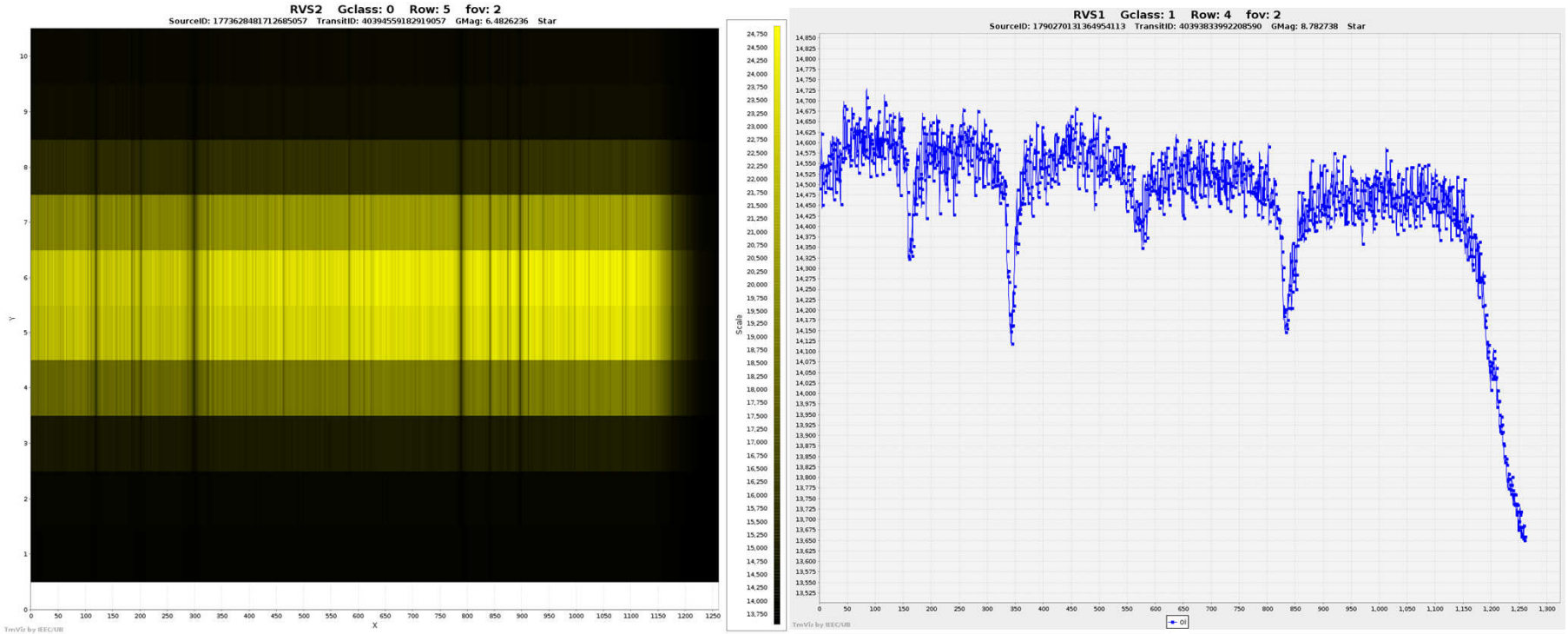


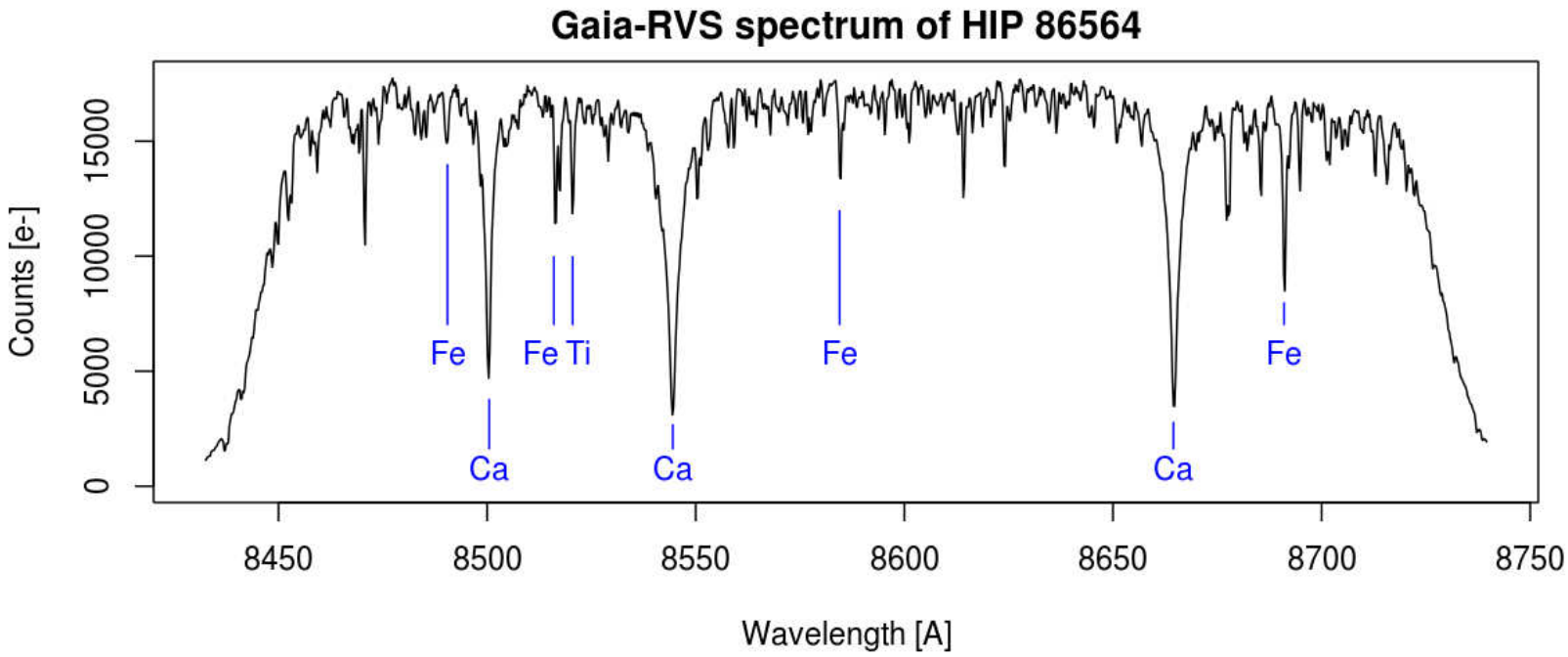

Gaia-BP spectra
Gaia-RP spectra
V1293 Aql (M5III)
VY UMa (C star)
HR3580 (K5)
HD213048 (K0)
HD64000 (G8III)
HD151196 (F2IV)
HD207165 (A3)
AC sample
AL sample
Counts [normalised]

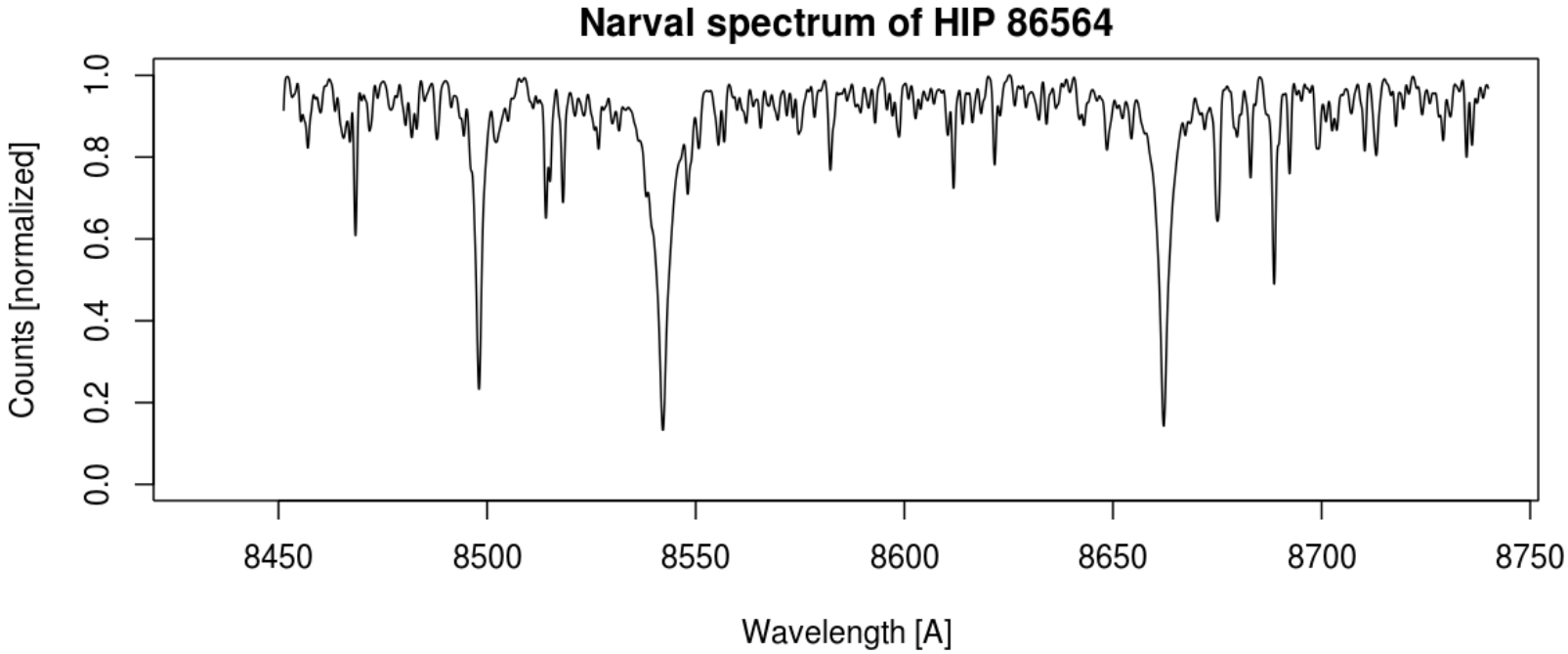

Gaia-BP spectra
V1293 Aql (M5III)
VY UMa (C star)
HR3580 (K5)
HD213048 (K0)
HD64000 (G8III)
HD151196 (F2IV)
HD207165 (A3)
Counts [normalised]
sample


Gaia-RP spectra
V1293 Aql (M5III)
VY UMa (C star)
HR3580 (K5)
HD213048 (K0)
HD64000 (G8III)
HD151196 (F2IV)
HD207165 (A3)
Counts [normalised]
sample

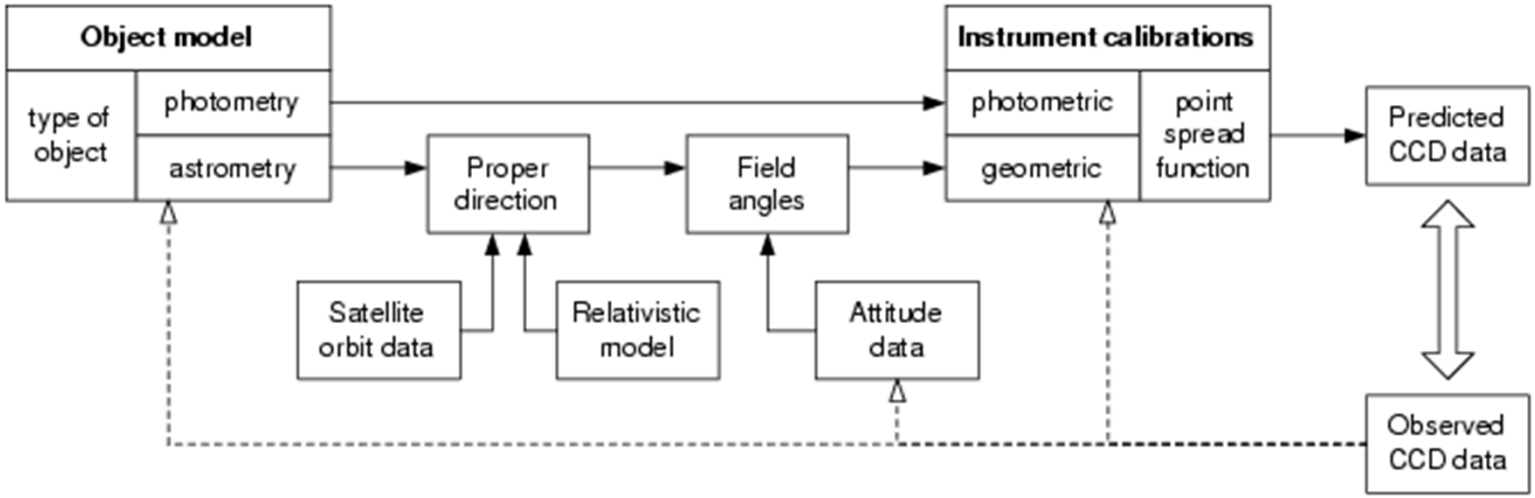
Spectrum, radial velocities




Gaia-RVS spectrum of HIP 86564
Counts [e-]
0
5000
10000
15000
Fe
Fe Ti
Ca
Ca
Fe
Ca
Fe
8450
8500
8550
8600
8650
8700
8750
Wavelength [A]


Narval spectrum of HIP 86564
Counts [normalized]
0.0
0.2
0.4
0.6
0.8
1.0
8450
8500
8550
8600
8650
8700
8750
Wavelength [A]

Data Analysis: Concept and Requirements



$$R_l(\boldsymbol{s}, \boldsymbol{a}, \boldsymbol{c}, \boldsymbol{g}) = \eta^{obs}(t_l \mid \boldsymbol{c}) - \eta^{calc}(t_l \mid \boldsymbol{s}, \boldsymbol{a}, \boldsymbol{g}, \aleph)$$

Calibration parameters (AL/AC positions of CCDs, etc)

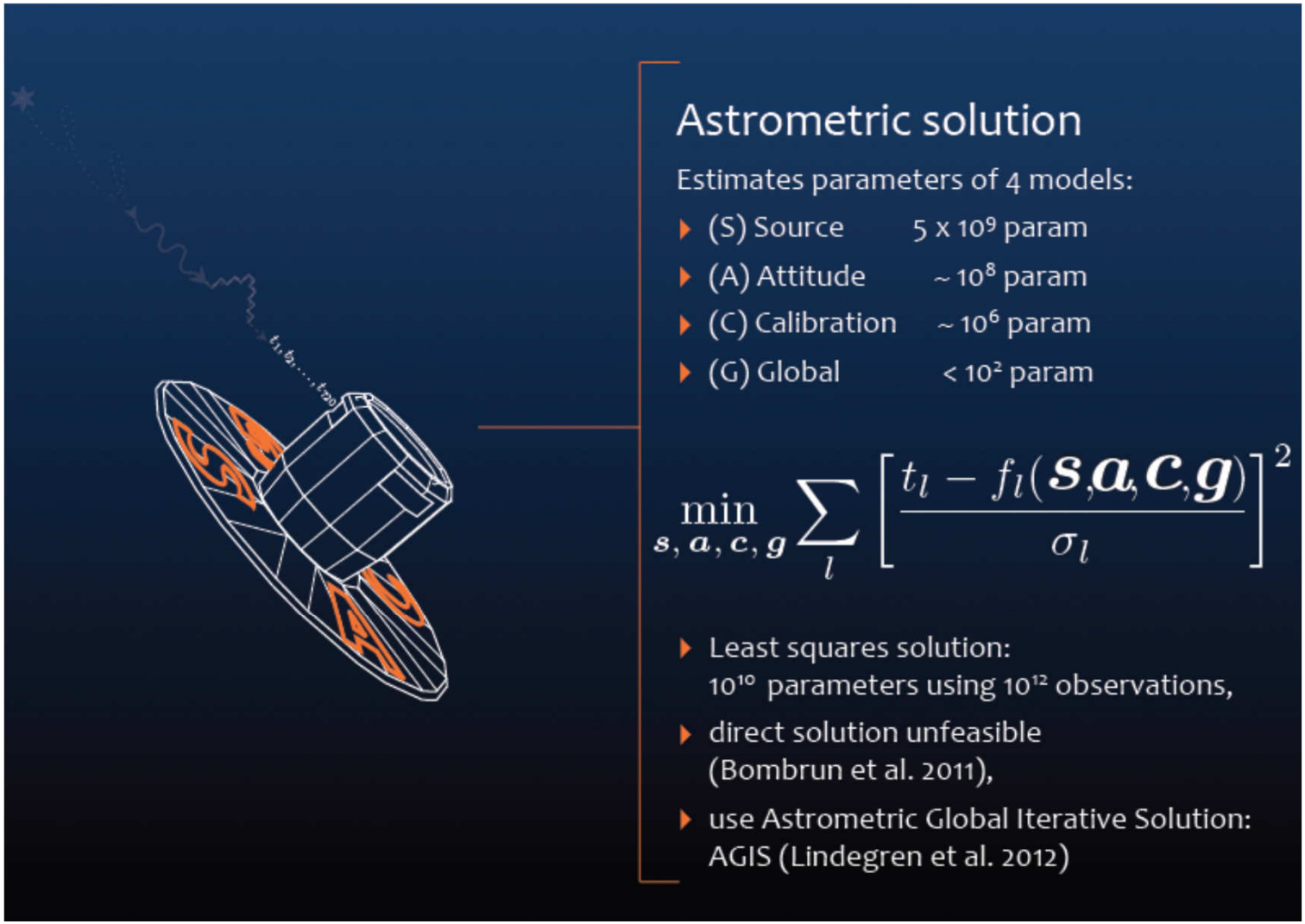
Source parameters (α_0, δ_0, π_0, μ_α, μ_δ)

Attitude parameters (spline coefficients)

Global parameters (e.g., PPN γ)

Auxiliary parameters (e.g. Ephemeris)

t_l: Time of observation *l*


Astrometric solution
Estimates parameters of 4 models:
(S) Source 5 x 10^9 param
(A) Attitude ~ 10^8 param
(C) Calibration ~ 10^6 param
(G) Global < 10^2 param
$\min_{s,a,c,g} \sum_l \left[\frac{t_l - f_l(s,a,c,g)}{\sigma_l}\right]^2$
Least squares solution:
10^10 parameters using 10^12 observations,
direct solution unfeasible
(Bombrun et al. 2011),
use Astrometric Global Iterative Solution:
AGIS (Lindegren et al. 2012)

Astrometric Global Iterative Solution

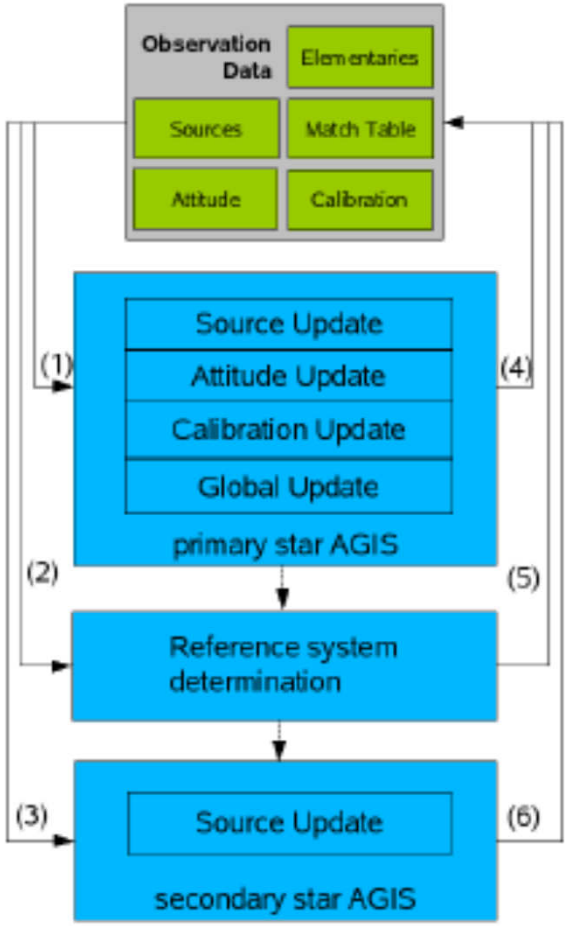
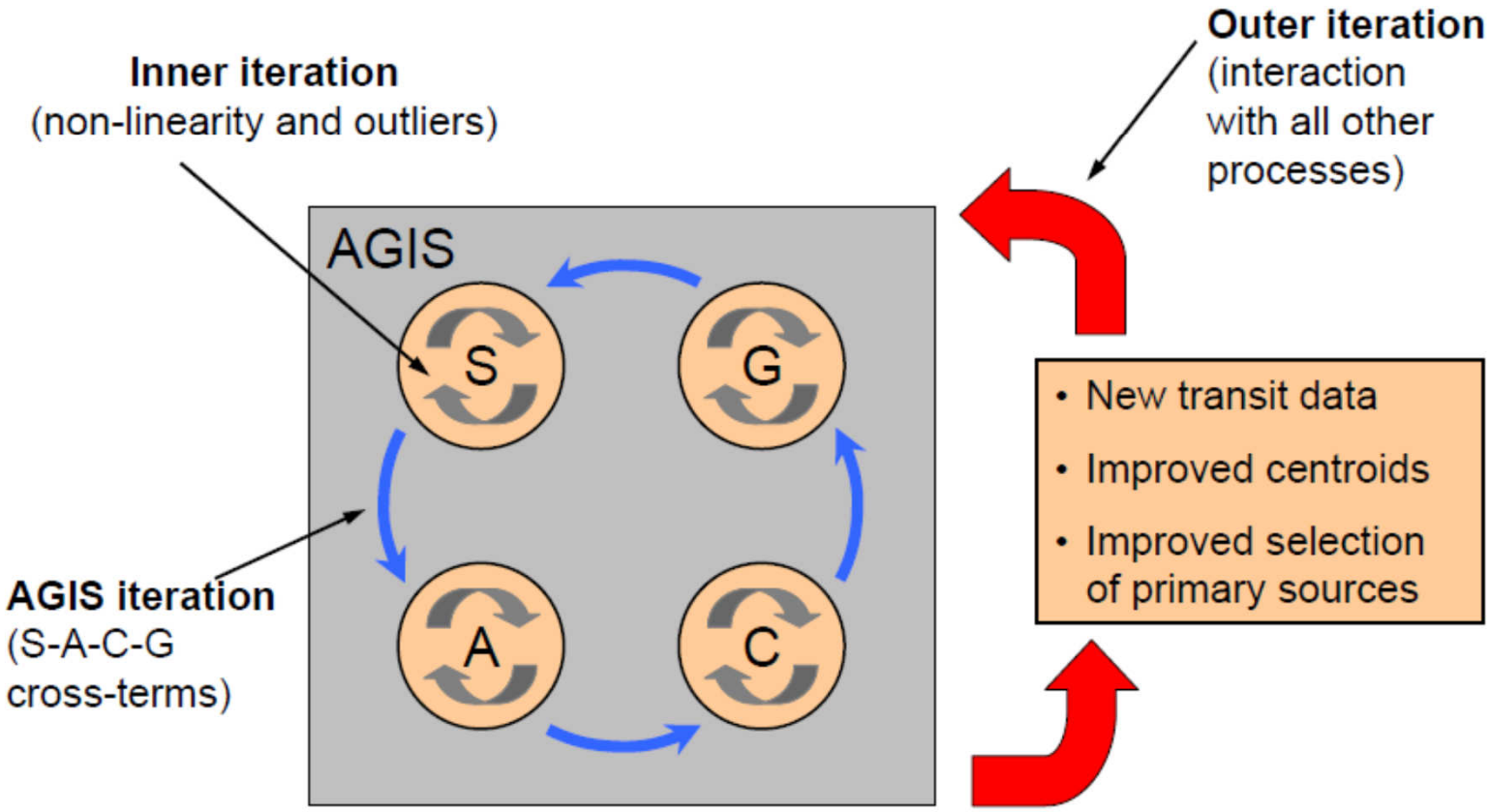
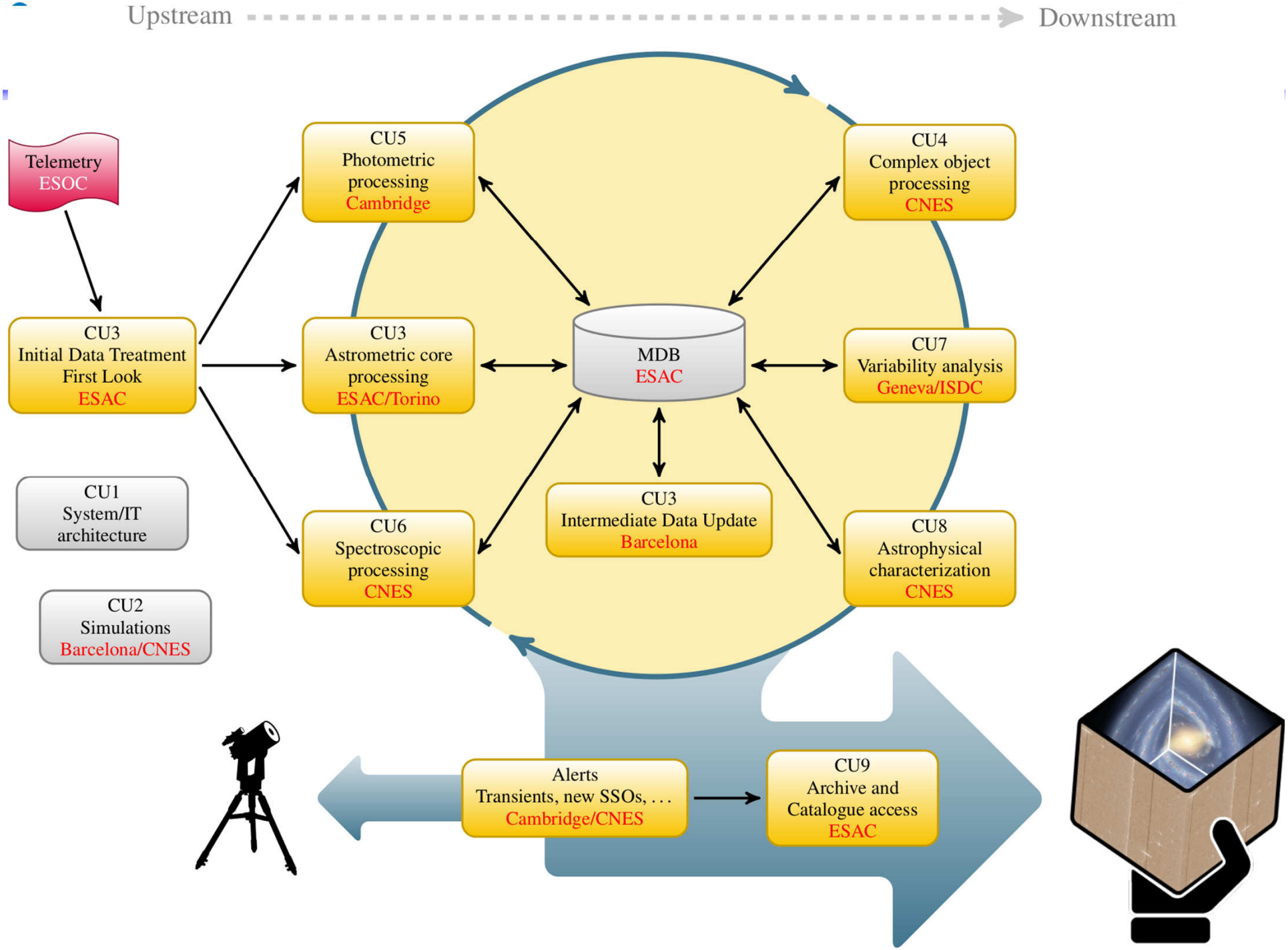


FIGURE 1: Functional overview of AGIS processes and top-level data flow

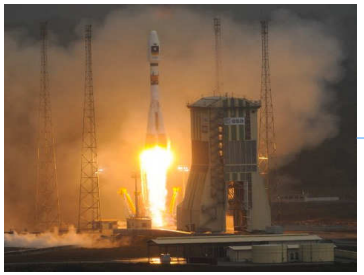
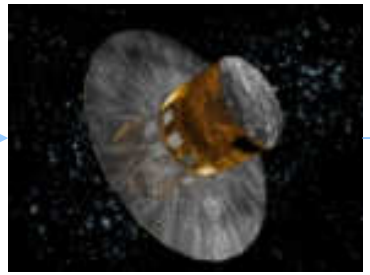
- 100 milion stars
- Model for secondary stars
- Not fitting to the model: CUx
- Improved after new data are available => Data Updating

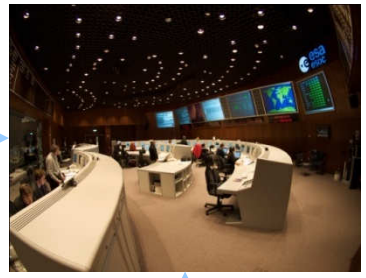
Intermediate Data Update




Upstream
Downstream
Telemetry
ESOC
CU3
Initial Data Treatment
First Look
ESAC
CU1
System/IT
architecture
CU2
Simulations
Barcelona/CNES
CU5
Photometric
processing
Cambridge
CU3
Astrometric core
processing
ESAC/Torino
CU6
Spectroscopic
processing
CNES
MDB
ESAC
CU3
Intermediate Data Update
Barcelona
CU4
Complex object
processing
CNES
CU7
Variability analysis
Geneva/ISDC
CU8
Astrophysical
characterization
CNES
Alerts
Transients, new SSOs, . . .
Cambridge/CNES
CU9
Archive and
Catalogue access
ESAC

Industry/ESA CSG/ESOC



(2013)

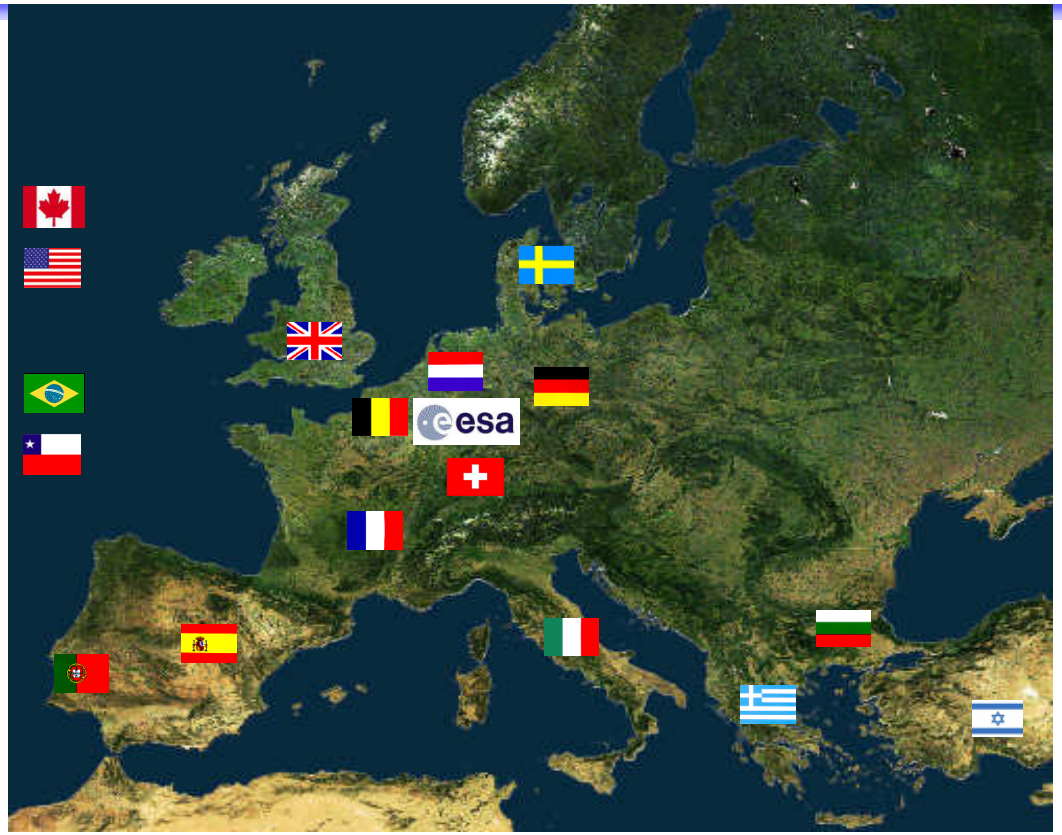
One consortium: the DPAC

The final responsibility of the Mission is in the hands of ESA

Data reduction is a responsibility of the scientific community, funded by the member states

Data Processing and Analysis Consortium (DPAC)

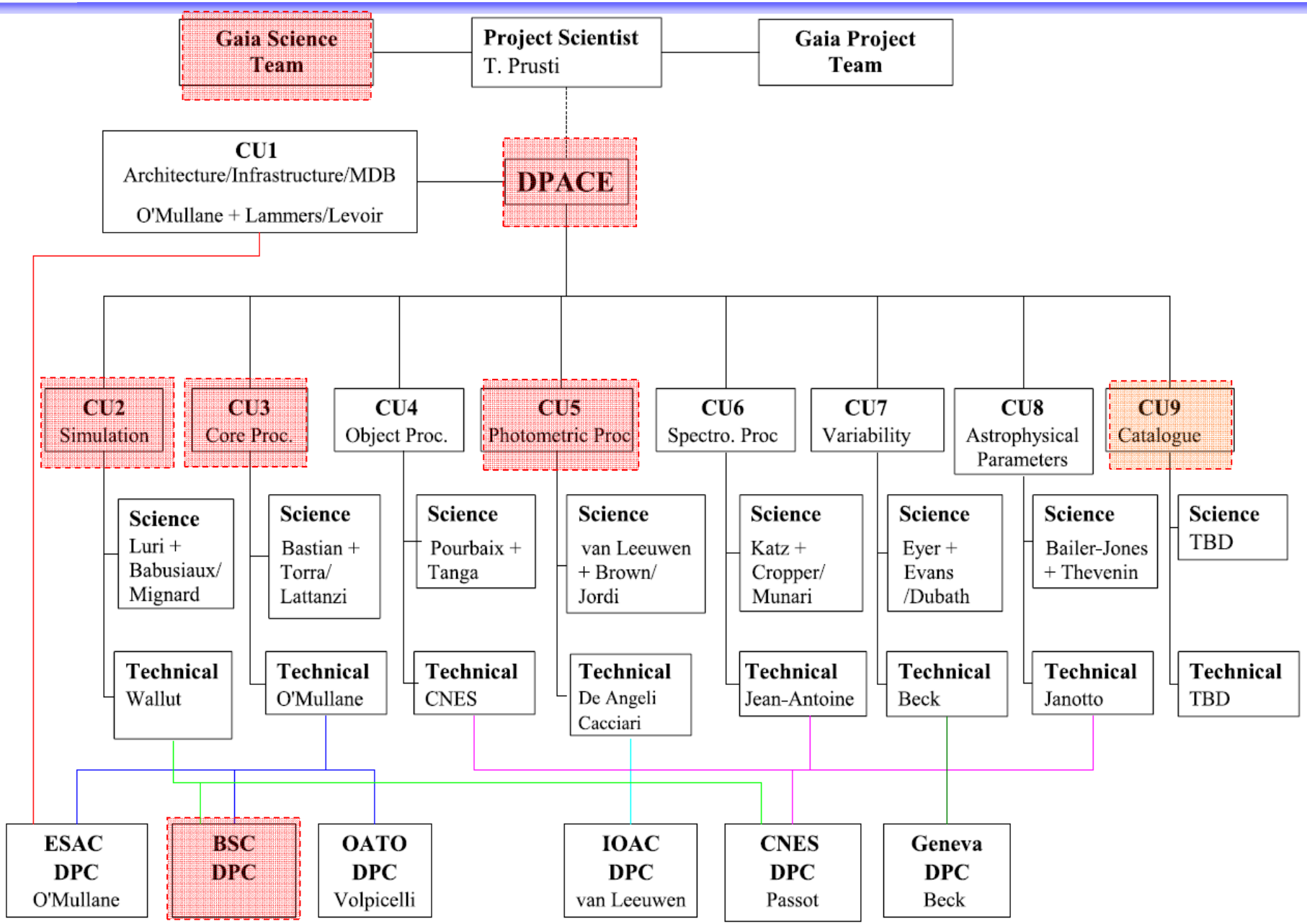
- 459 members
- 24 Funding Agencies



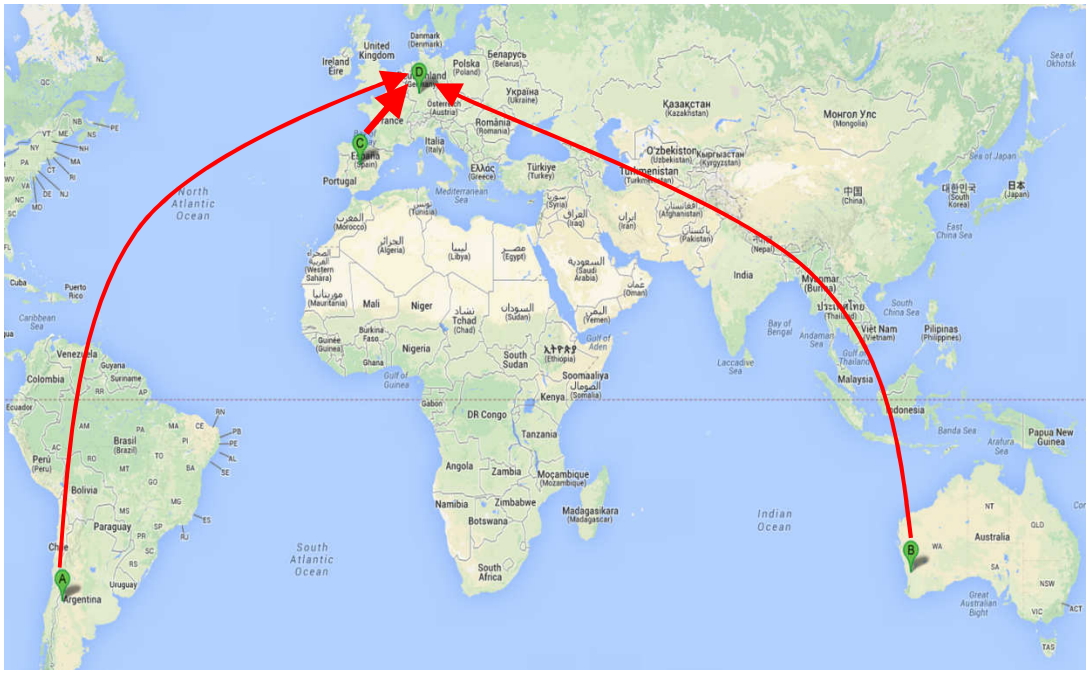
- With a 5 years mission, ~33% of DPAC cost will be dedicated to Operations

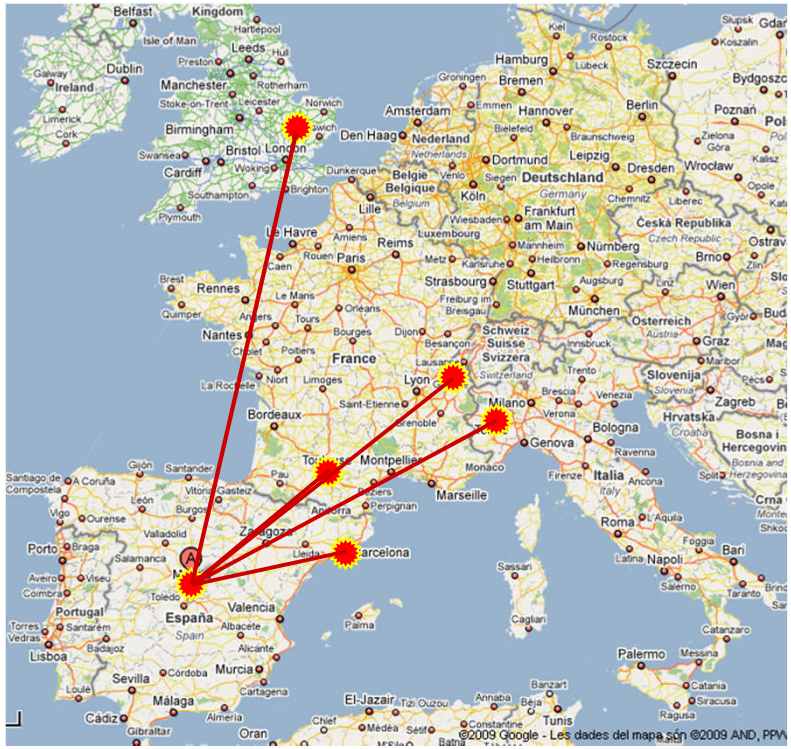
MLA duration: 2007-2022
FTEs/year up to 2011: 270
Average yearly cost: ~30Meuros
Global cost: ~500M€

Data Processing and Analysis Consortium (DPAC)



Data collection and distribution





Tasks at BSC (I)

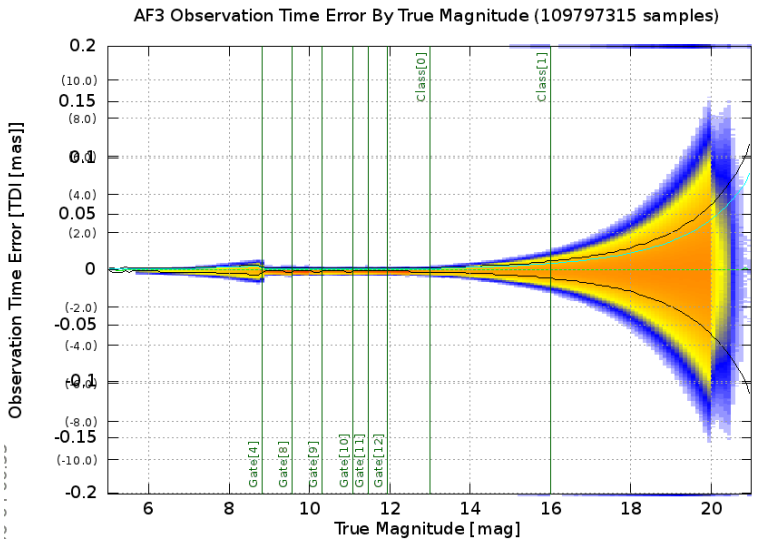
- Simulations for testing the whole Gaia-DPAC processing chain:
  - High-realism simulation of the Gaia instrument - GASS
  - High-realism simulation of the Gaia catalogue - GOG

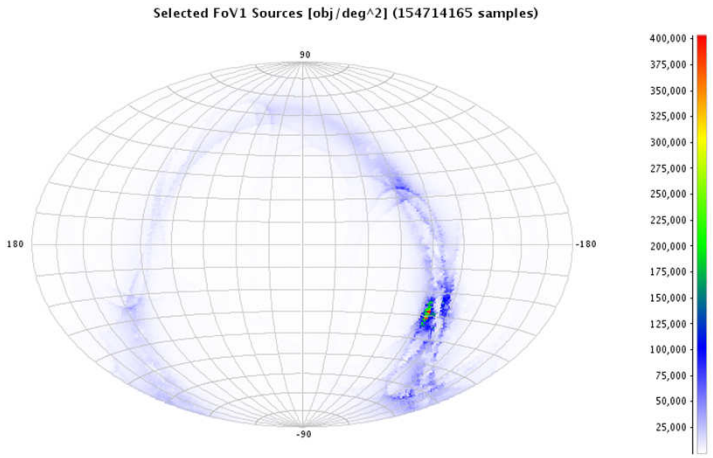
- Provision of:
  - Full-scale sky simulations for Operations Rehearsals – testing of the main Scientific Critical software involved in the daily processing of Gaia Telemetry stream.
  - Reduced density simulations covering long term periods for the testing of the whole Gaia data processing chain

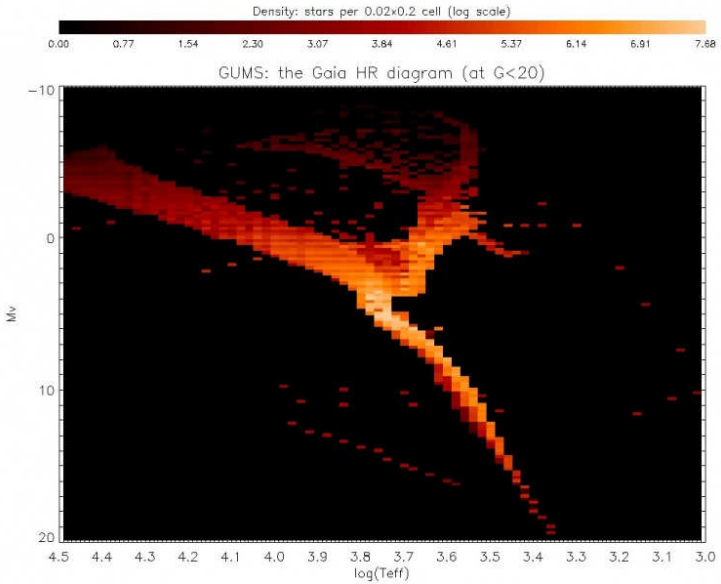
Achieved Milestones

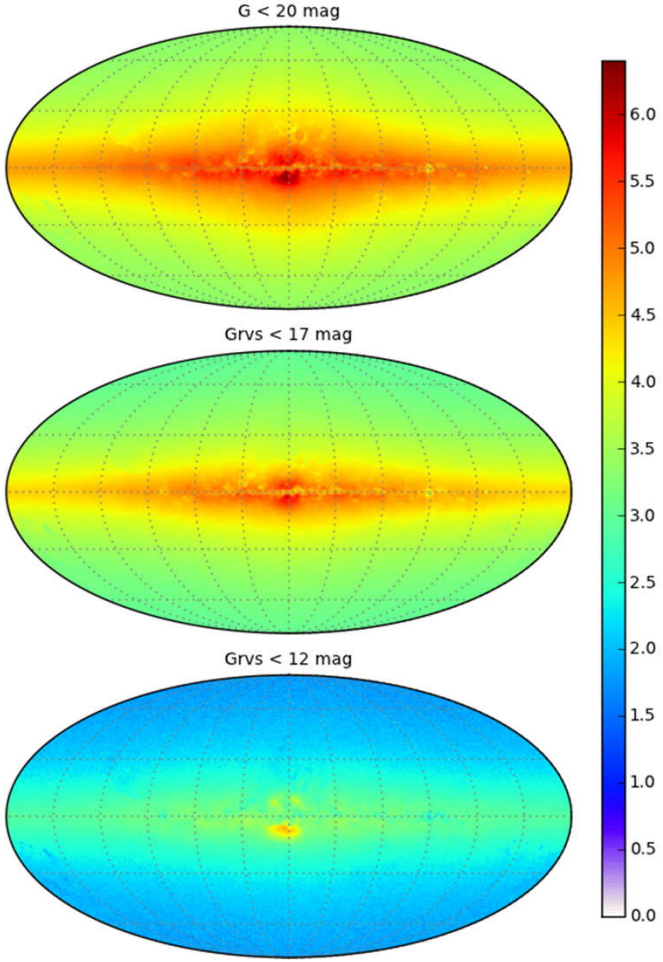
Scientific milestones:

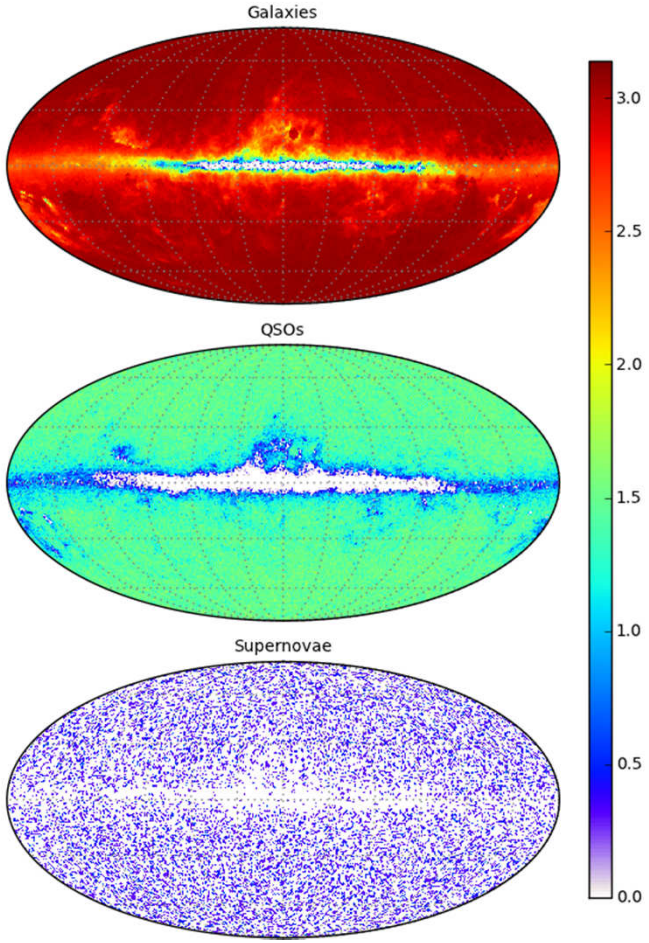
- Large mission simulations using realistic Universe Model
- Simulation of telemetry for rehearsal campaigns before Gaia launch
- 1,2 bilions sources catalogue
- Simulation of epoch and combined (final) data using GOG
- Simulations of RVS (spectra) data








G < 20 mag
Grvs < 17 mag
Grvs < 12 mag
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0


Galaxies
QSOs
Supernovae
3.0
2.5
2.0
1.5
1.0
0.5
0.0

Computational Products:

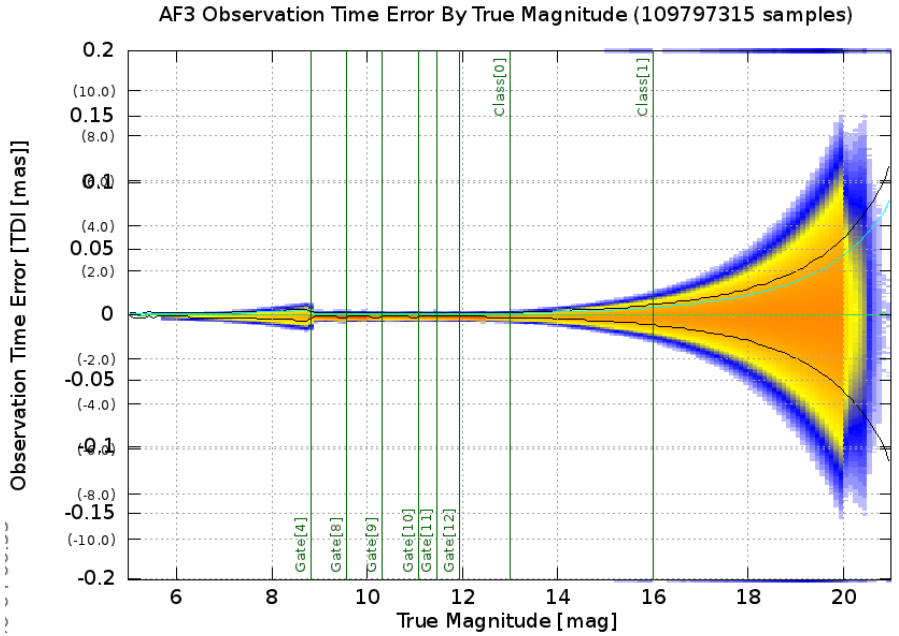
- GASS (telemetry simulation)
  - >20 datasets, from few days to 5 years at reduced density
  - 4 Operational rehearsal dataset (several days of full density telemetry).
  - Several TB of data generated

- GOG (object generator)
  - 2 full sky simulations
  - >30 datasets (special objects, partial sky, etc)
  - Several TB of data generated

Tasks at BSC (II)

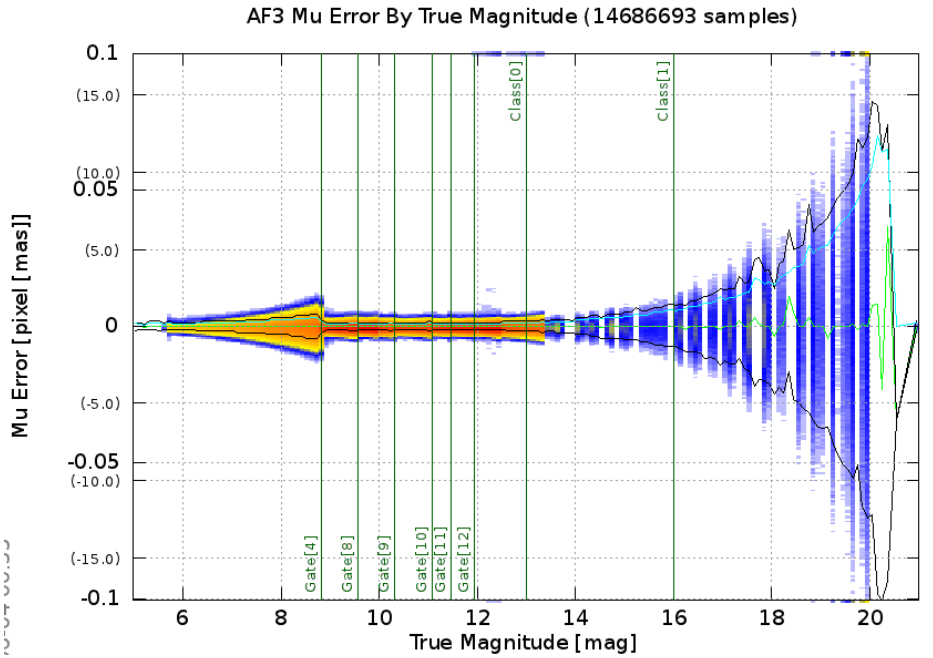
- Raw data re-processing and calibration system – Intermediate Data Updating (IDU)
- Detailed design and first implementation
- Assessed feasibility of concept and correct integration in the whole Gaia processing chain
- Test on 1.5 years of downsized data (700M observations, equiv. 8 days mission) in just 5 days using up to 84 MareNostrum II nodes
- Running some IDU-processes on real data (XM, Detection Classifier)

Data products



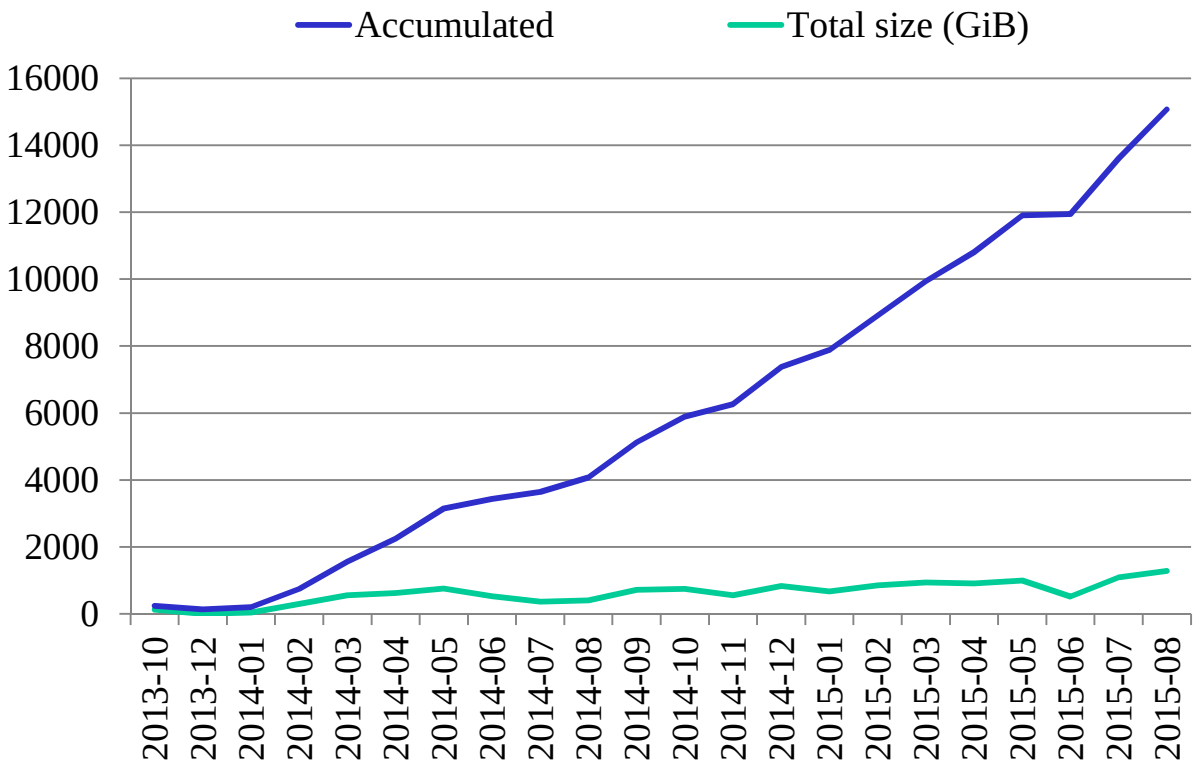
Gaia raw data re-processing system (IDU)

Determination of the along-scan and across-scan positions of the observations



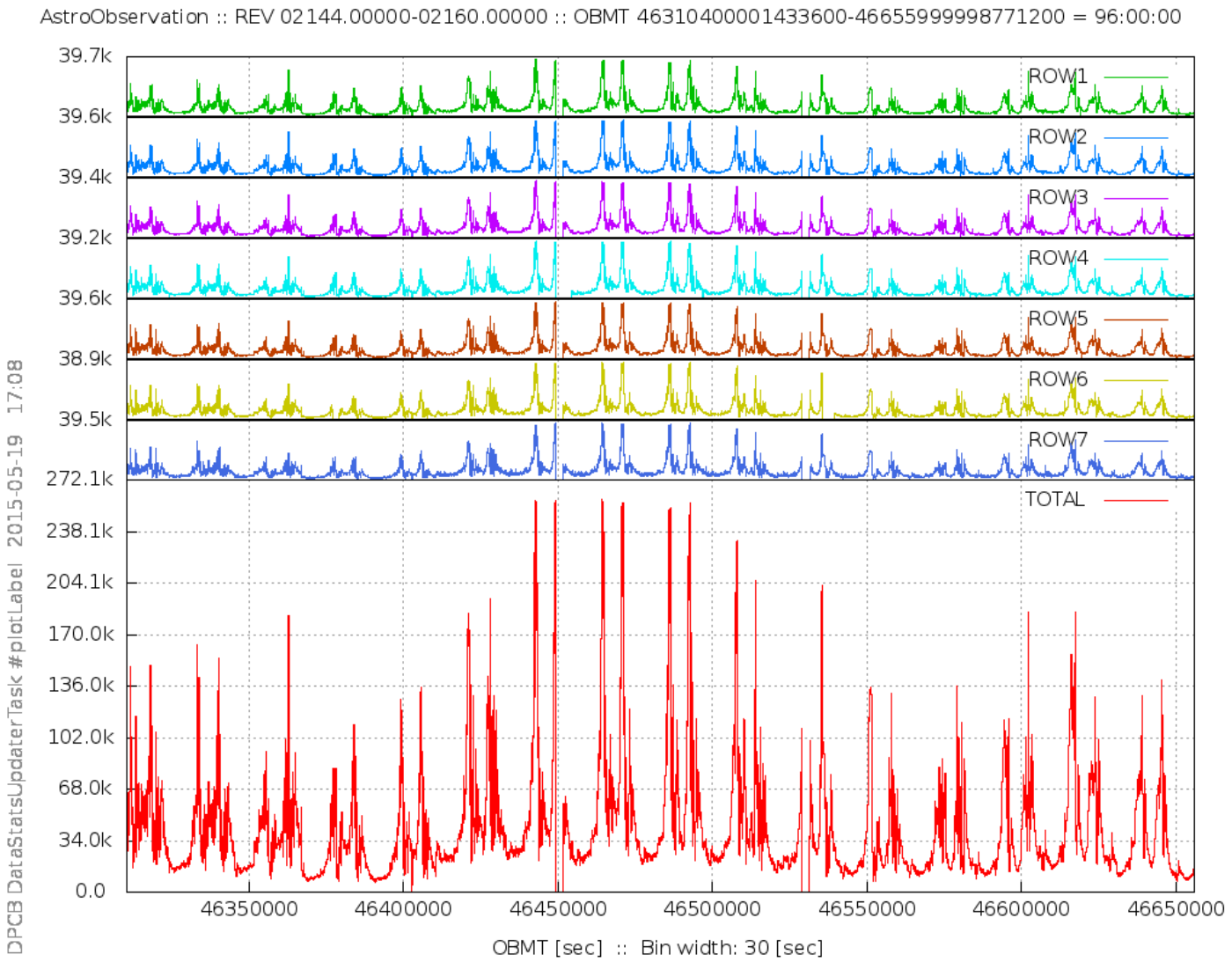
Data at DPCB

Month	Files received	Size (GB)
2013-10	5	122.00
2013-12	776	4.57
2014-01	9332	37.04
2014-02	106283	293.35
2014-03	188574	551.45
2014-04	211658	618.56
2014-05	210585	760.64
2014-06	139968	525.15
2014-07	104357	367.12
2014-08	119372	399.26
2014-09	166881	720.89
2014-10	181099	747.33
2014-11	151642	558.27
2014-12	194144	832.54
2015-01	175661	671.55
2015-02	295839	849.09
2015-03	219903	936.65
2015-04	212863	906.69
2015-05	246223	1000.00
2015-06	95550	519.81
2015-07	243699	1090.00
2015-08	211013	1280.21

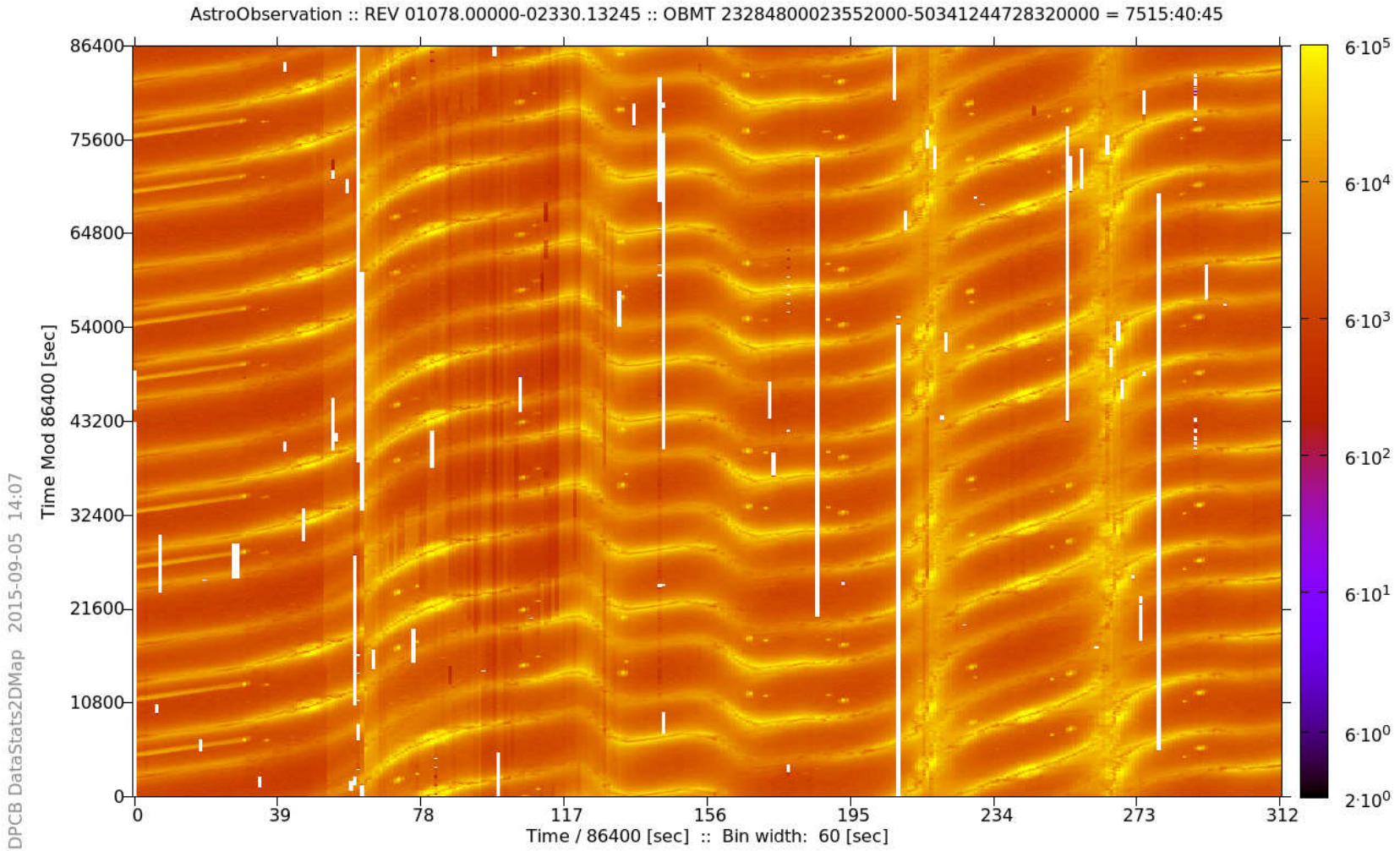


AstroObservations (AO) in operations:
Total size: 10,417 GB

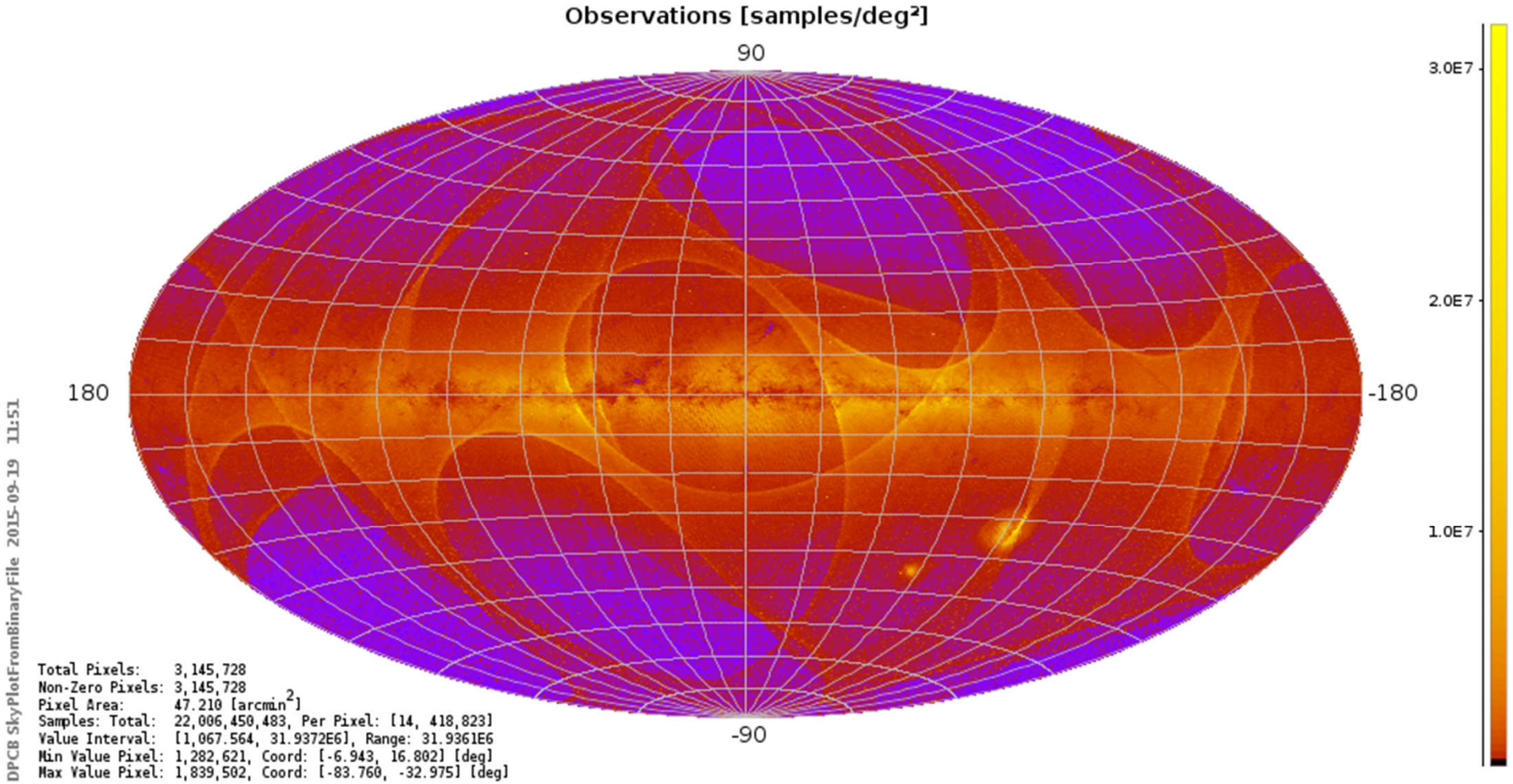
AO received by time (4 days)



AO received by time (10 months)

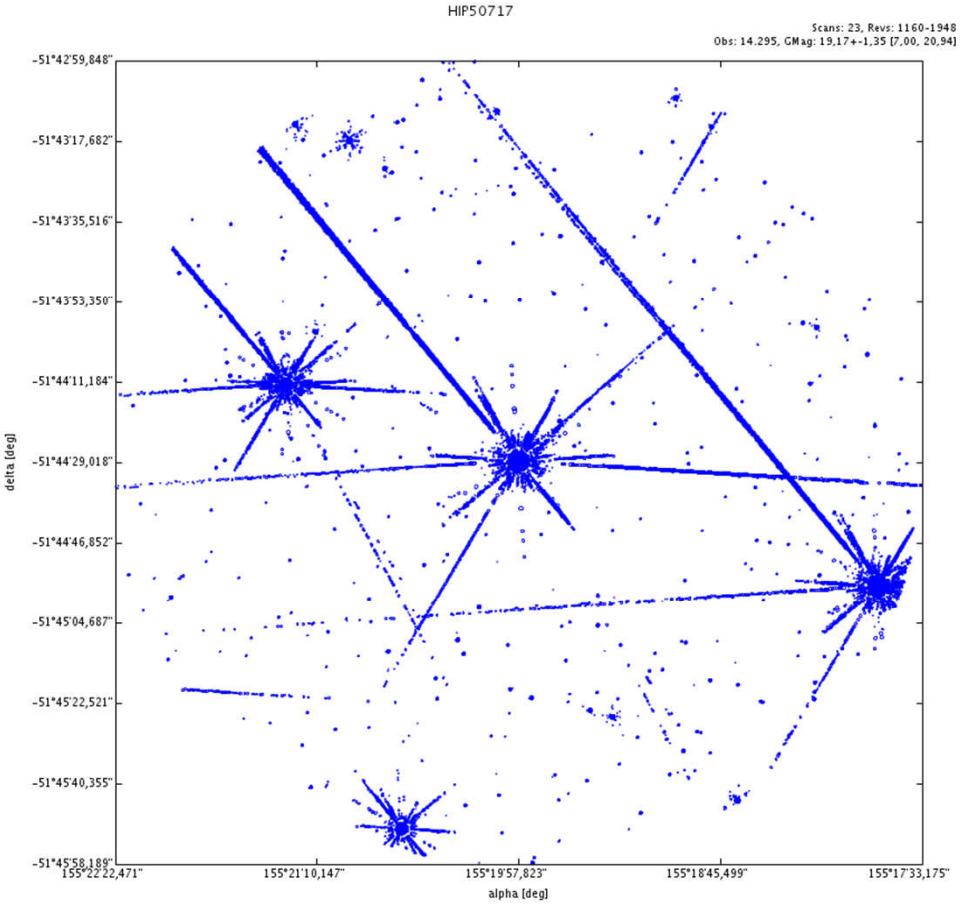


Accumulated AO during (10 months)

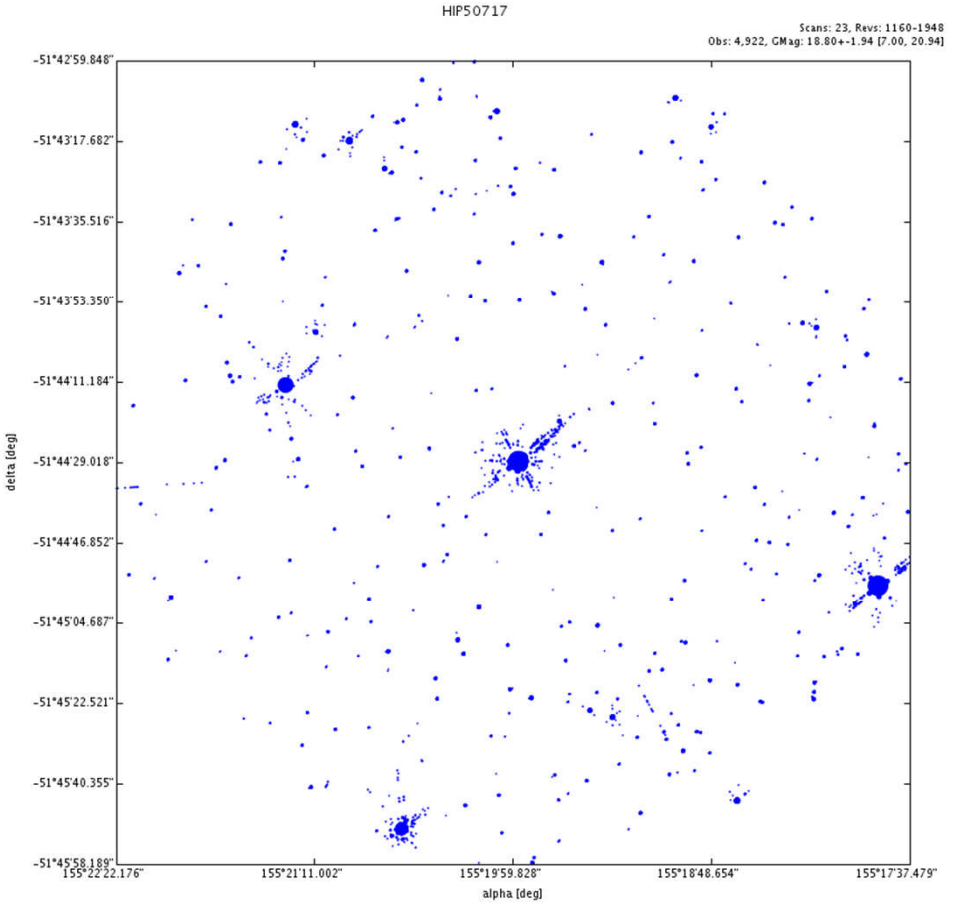


Detection Classifier

Hipparcos 50717

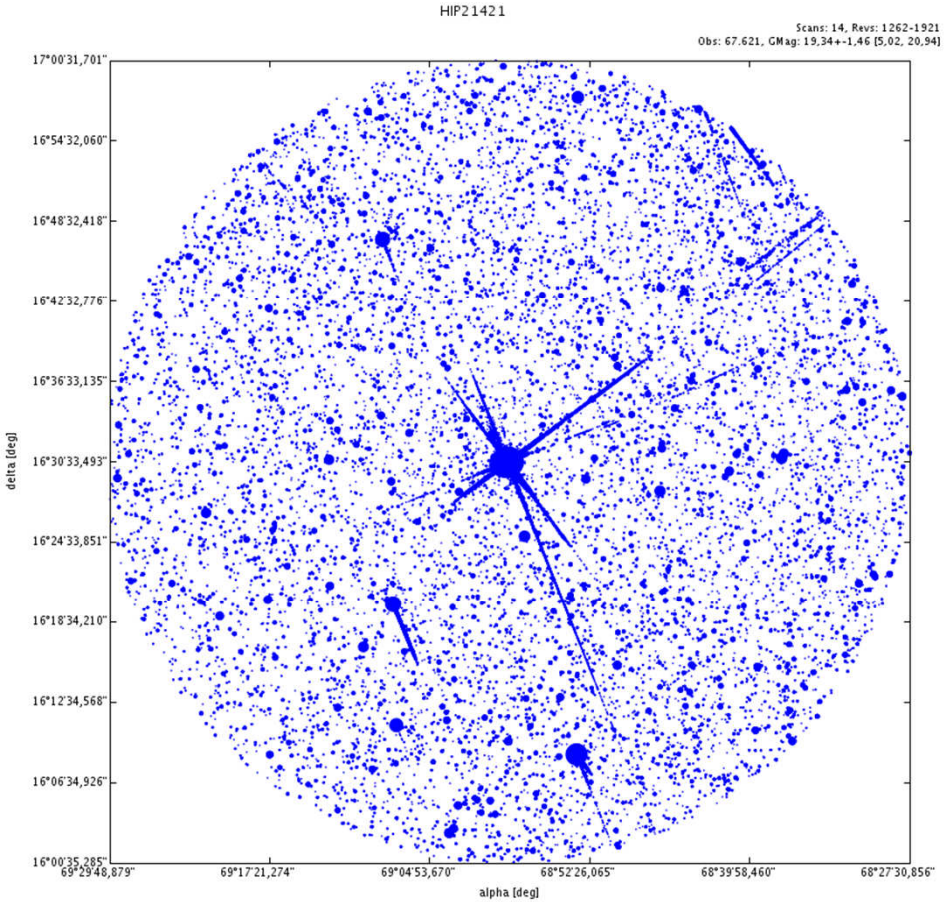


Without filtering spurious detections

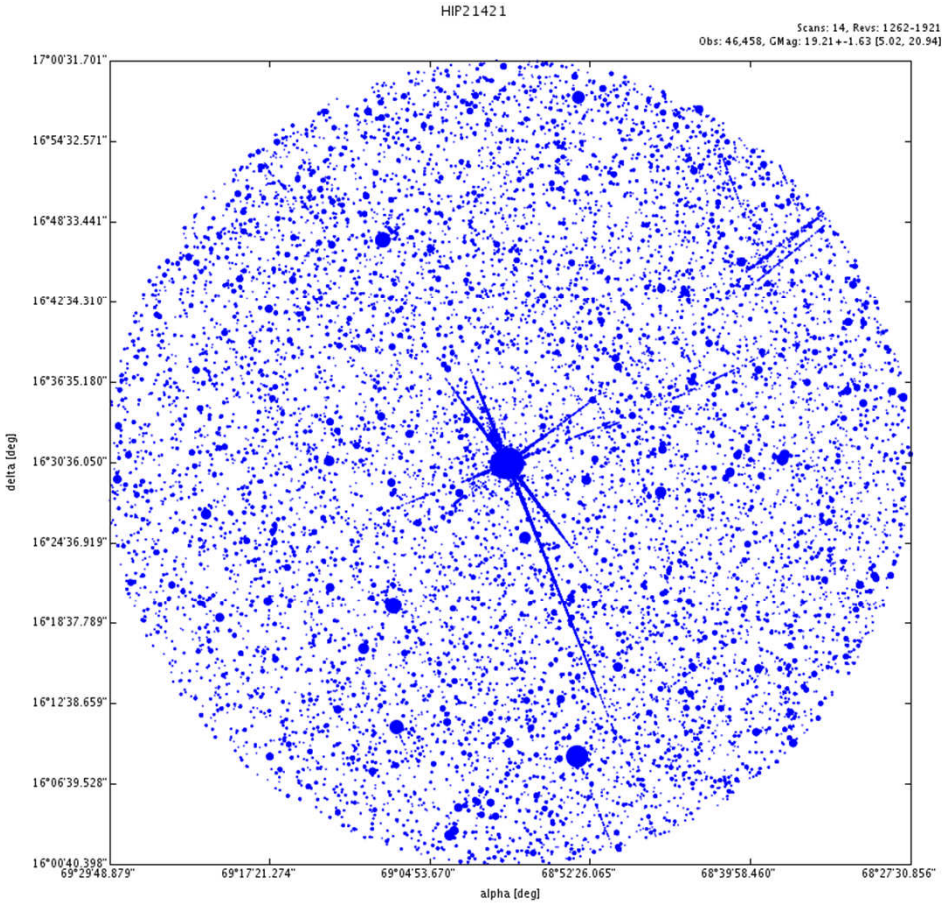


Filtering spurious detections

Hipparcos 21421



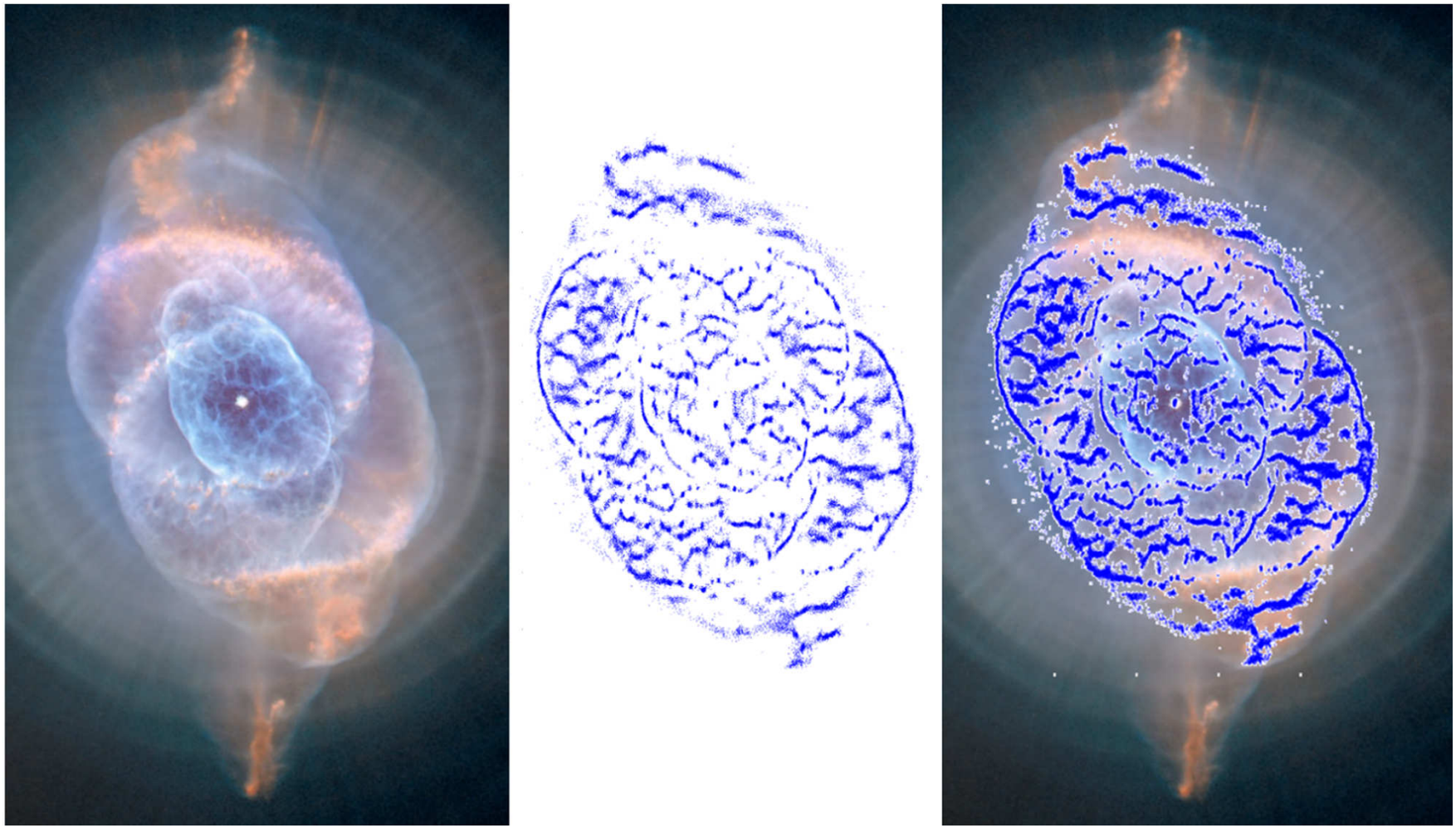
Without filtering spurious detections



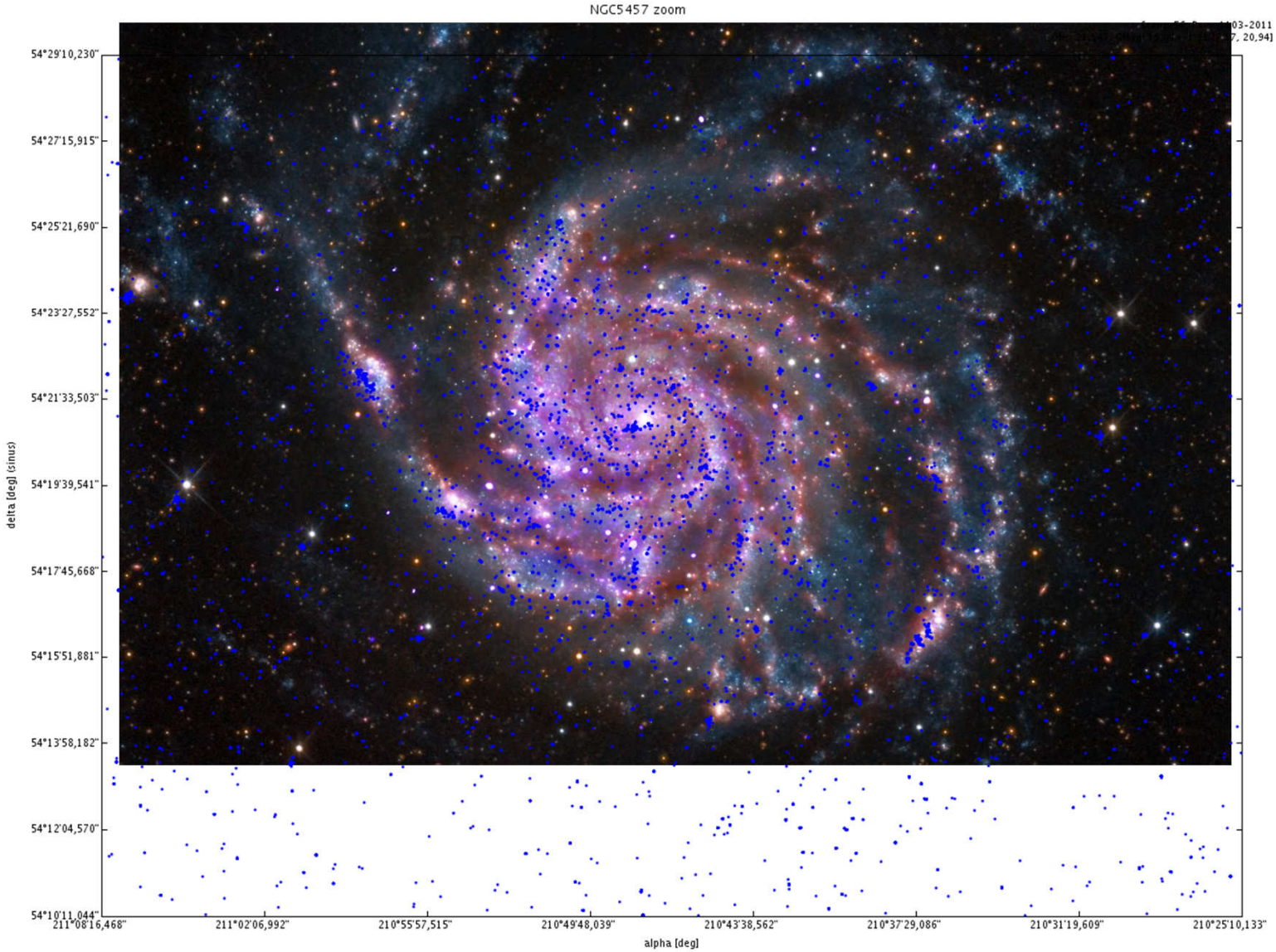
Filtering spurious detections

Extended objects

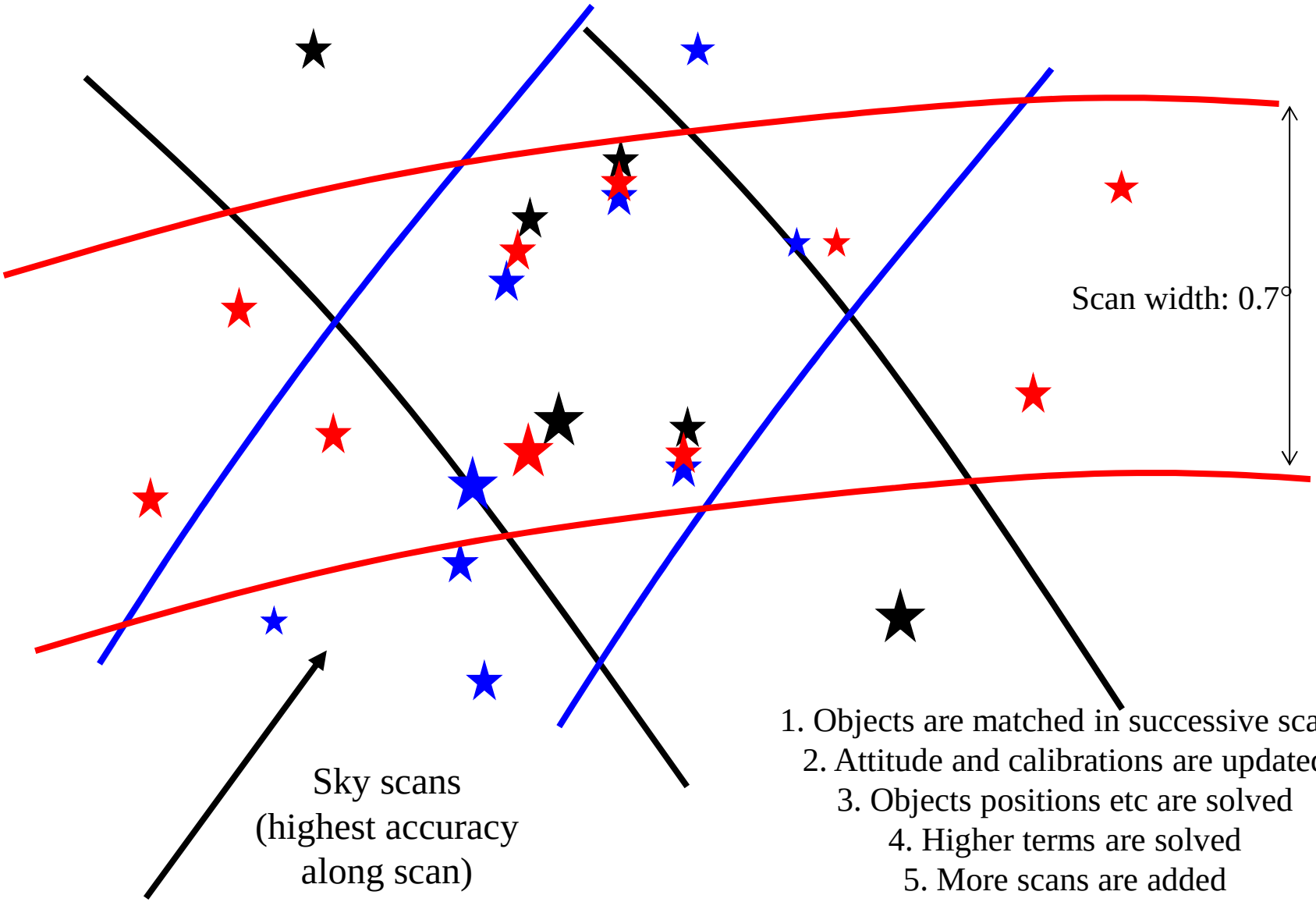
Cat's Eye Nebula. NGC6543



Pinwheel Galaxy, NGC5457

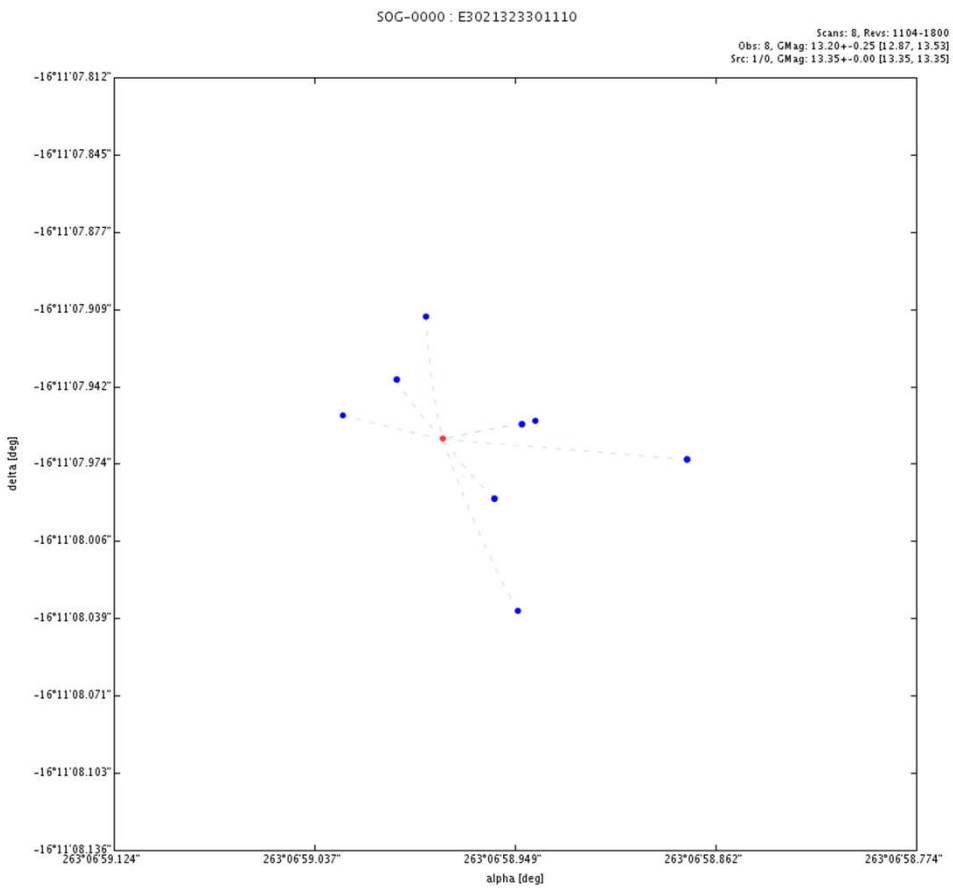


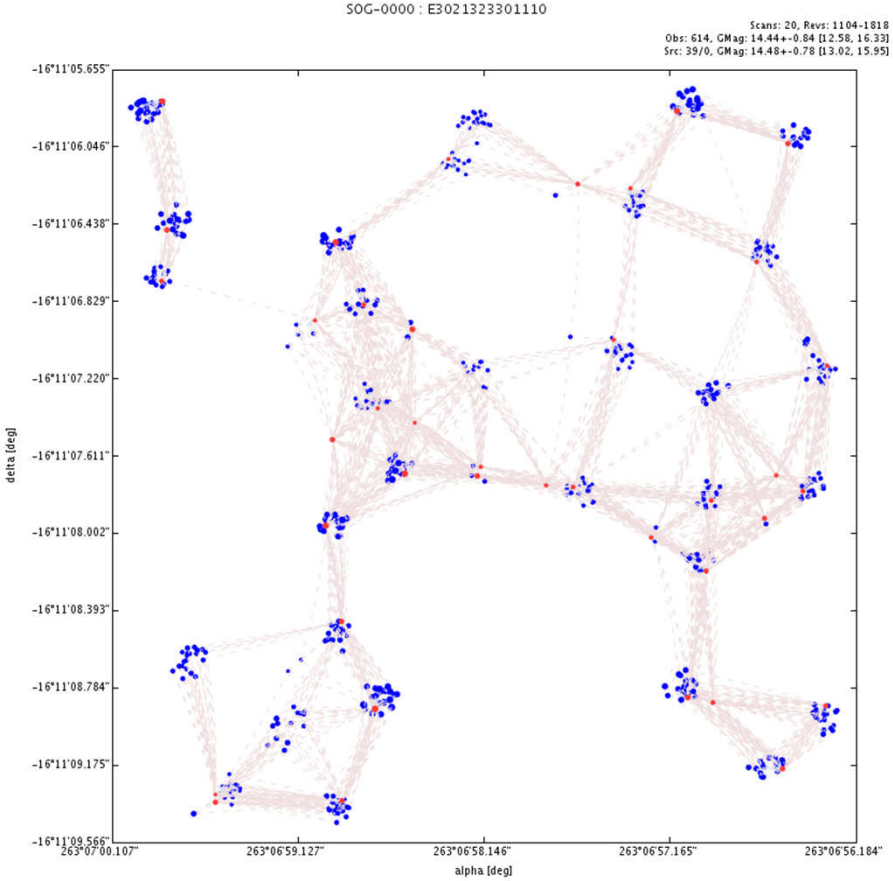
Cross-matching observations



1. Objects are matched in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc are solved
4. Higher terms are solved
5. More scans are added
6. System is iterated

XM resolution





XM resolution is currently under heavy development to improve handling of complex cases. This will most likely lead to higher CPU requirements.

After 11 months of Nominal Operations:

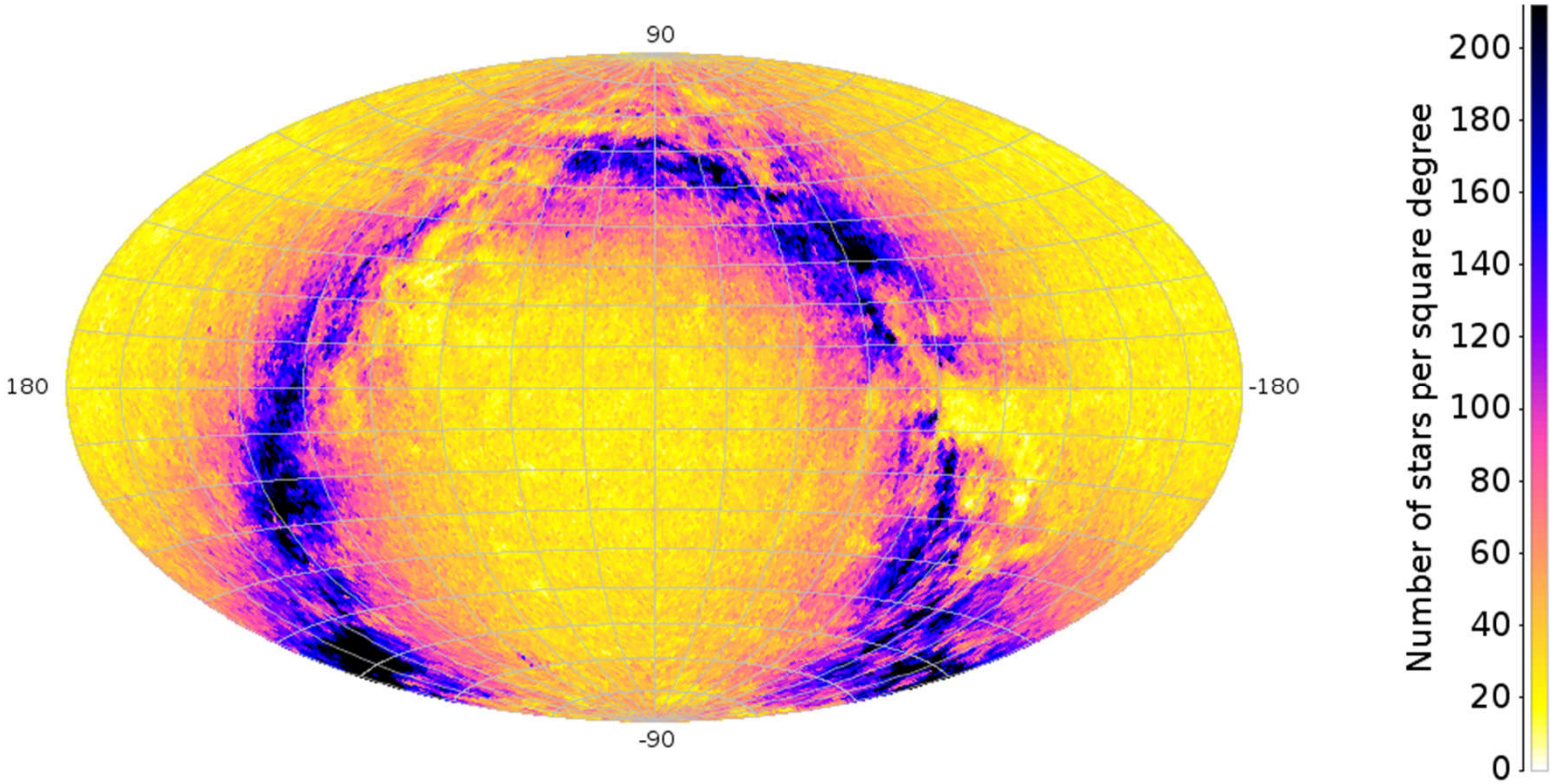
Nominal mission time:	**340 days**
Raw data received:	**~9 TB (~26GB/day)**
Astro/photometric transits received:	**> 22 billion (~64M/day)**
Astrometric CCD measurements:	**> 220 billion**
Photometric CCD measurements:	**> 44 billion**
Spectroscopic transits received:	**> 1.5 billion (~4.5M/day)**
Spectroscopic CCD measurements:	**> 4.5 billion**
Main DB size:	**~70 TB**

Data release scenario

http://www.cosmos.esa.int/web/gaia/release

First release: Summer 2016	• **Positions** (α,δ) and **G-mag** for single-like stars (90% of the sky) • **Ecliptic pole** data during commissioning • the **Hundred Thousand Proper Motions (HTPM)** catalogue based on the Hipparcos stars → **Tycho-Gaia (TGAS)**?
Second release: Early 2017	• **Positions, proper motions, parallaxes** and **G-mag** (90% of the sky) • **Integrated XP photometry for sources with Astrophysical parameters** estimated with appropriate standard errors. • **Mean radial velocities for stars** with non-variable radial velocity (90% of the sky)
Third release: 2017/2018	• Astrometric solutions + radial velocity + orbital solutions for **binaries** (2 months – 75% of the observing time) • Object **classification and astrophysical parameters**, together with **XP and RVS spectra** for well-behaved objects. • **Mean radial velocities** and **atmospheric parameter** estimates for non-variable stars.
Fourth release: 2018/2019	• **Variable star classifications and parameters** as available, and the epoch photometry • **Solar system results** with preliminary orbital solutions and individual epoch observations • **Non-single** star catalogue
Final release: 2022	• **Full** astrometric, photometric, radial velocity catalogue • All available **variables and non-single** stars solutions • Source **classifications** (probabilities) + multiple **astrophysical parameters** derived from BP/RP, RVS and astrometry for **stars, unresolved binaries, galaxies and quasars**. Some parameters may not be available for faint(er) stars. • List of **exoplanets**. • All **epoch and transit data** for all sources • All **Ground Based Observations** made for data processing purposes (or links to it)

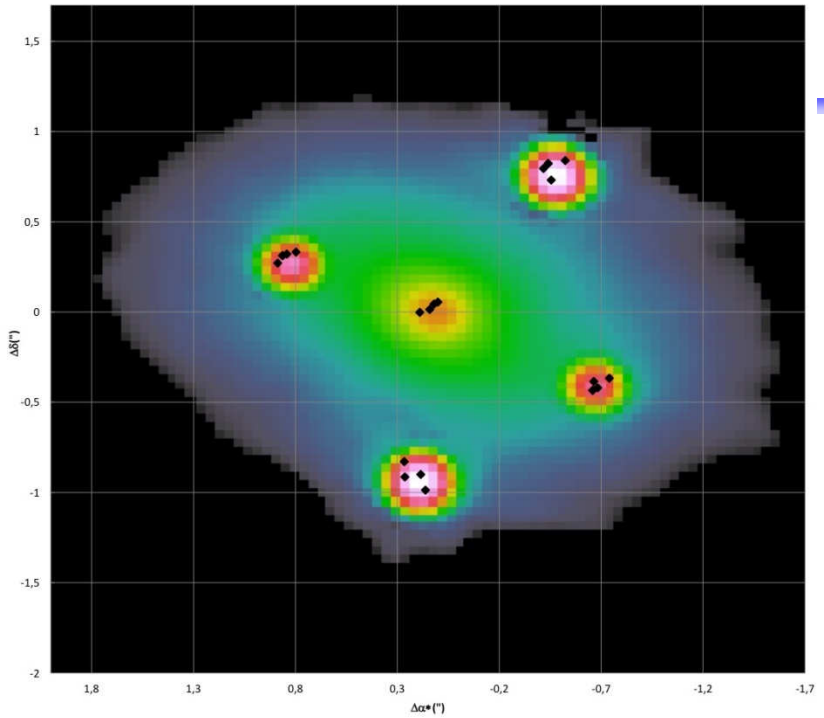
Tycho Gaia Astrometric Solution (TGAS)



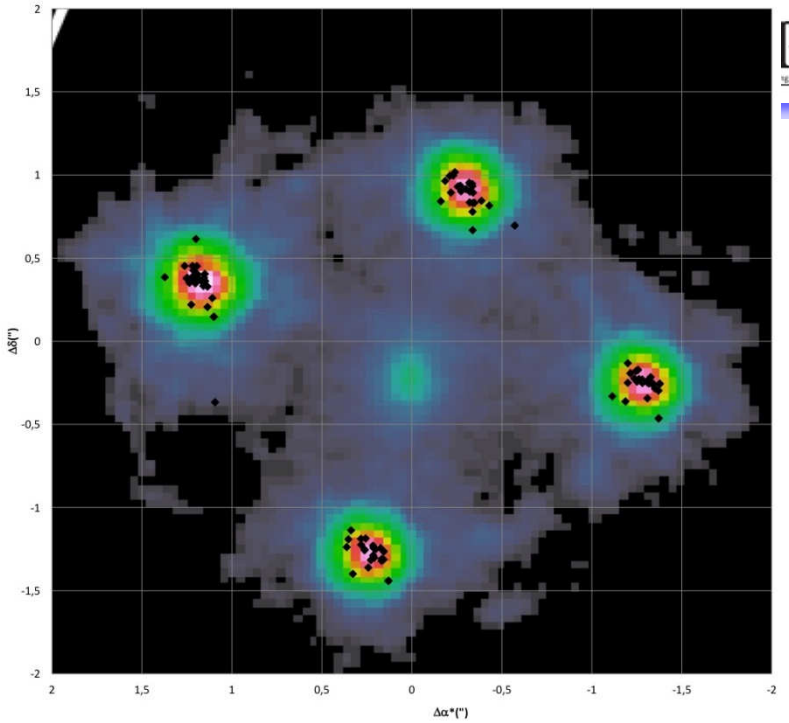
- Tycho: 2.5 milions stars
- 6 – 12 month of Gaia observations: two parameters
- Sub-mas accuracy for positions, pm parallaxes

Conclusions

- Gaia operating nominally around L2 with all the instruments
- Ground-segment working (reception, input data)
- DPAC daily systems working. Almost all the systems running
- BSC. IDU runs started. Full IDU execution beg. 2016
  Simulator activities finished
- Added complexity due to “instrumental” problems
- Calibrations and BAM under analysis (also adding complexity)
- First data release + TGAS in mid 2016



Q2237+030 Einstein's Cross



HE0435-1223

Gravitational lensing detected by Gaia placed over HST images.
QSOs are very distant (10^9 ly). Lensing produced by a galaxy some 100 Mpc away.
Astrometric accuracy < 100 mas