Absolute astrometry
In the next 50 years

The astrometric foundation of astrophysics

Erik Høg - 2016

Niels Bohr Institute - Copenhagen

- ***Two Gaia-like missions: performance, science***
- *Long-period exo-planets only by astrometry*
- *Only ESA can decide – it must happen in 20-30 years*

  The lesson from history

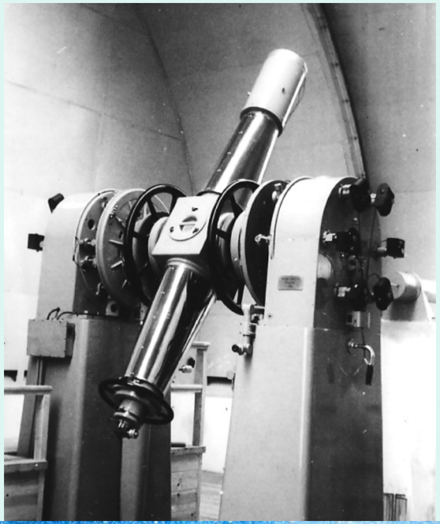
Presentations, e.g., for Astronomische Gesellschaft 2013 and 2014
by Norbert Zacharias at the IAU General Assembly in Hawaii in August 2015
Seminar in Lund in October 2015
Meeting in Bogota in September 2016

Astrometry

Positions & proper motions & parallaxes

Absolute vs relative astrometry

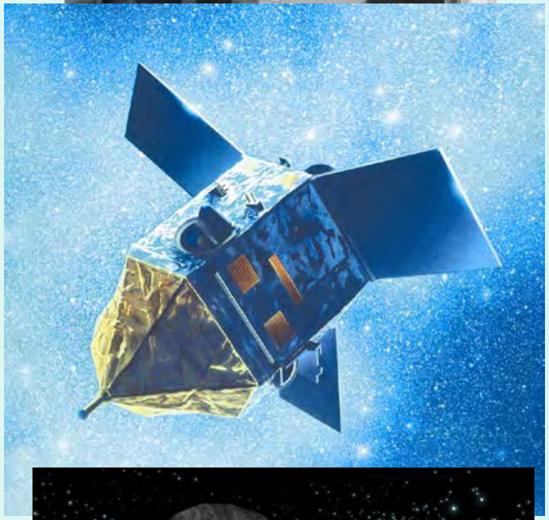
all-sky vs small-field astrometry



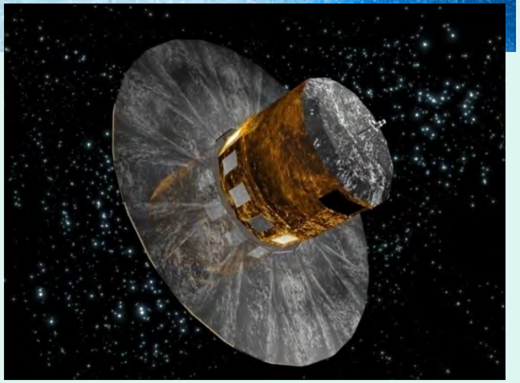
Absolute optical astrometry:

1705- ~1990 by meridian circles

1989-1993 by Hipparcos satellite



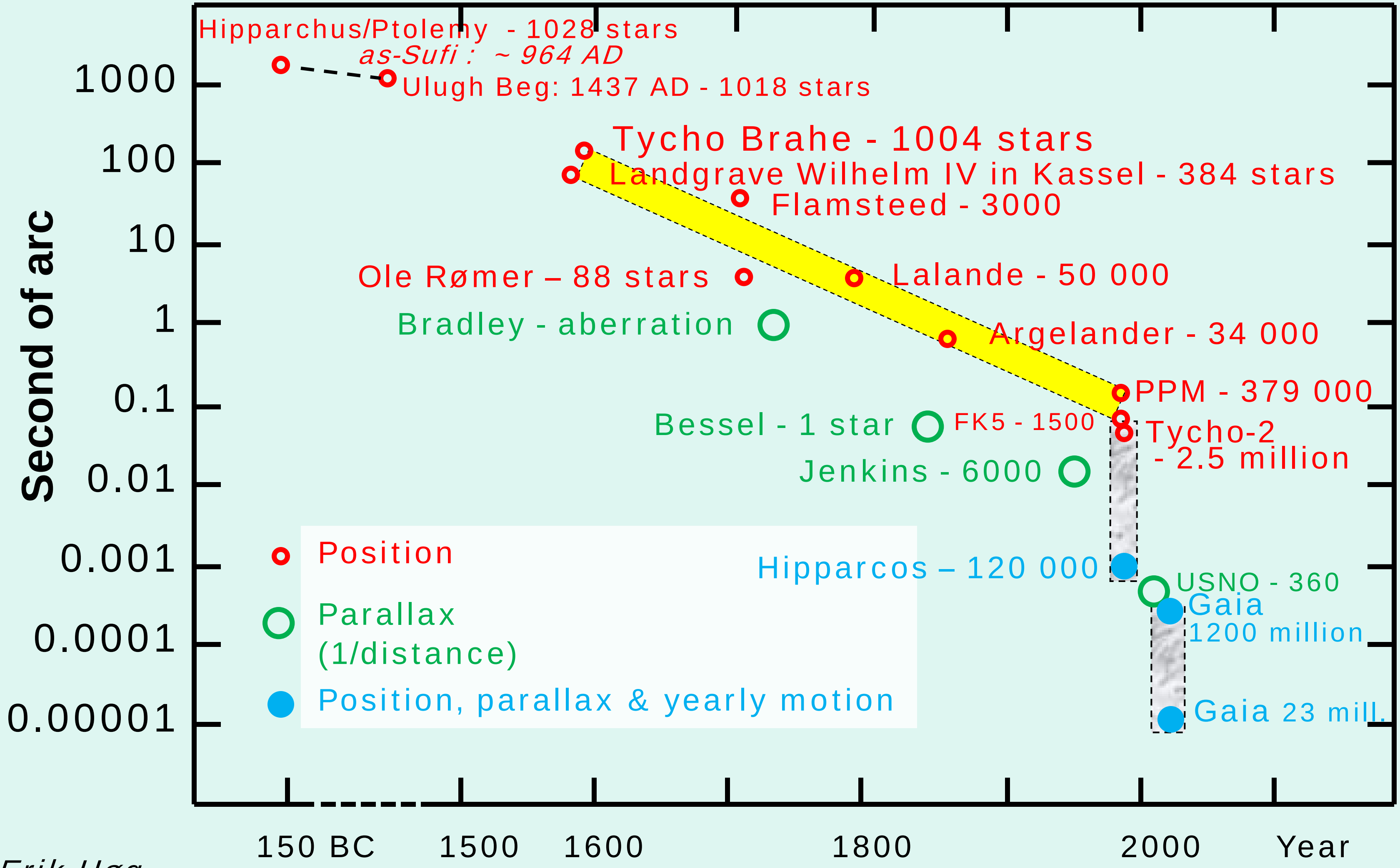
2013… by Gaia satellite



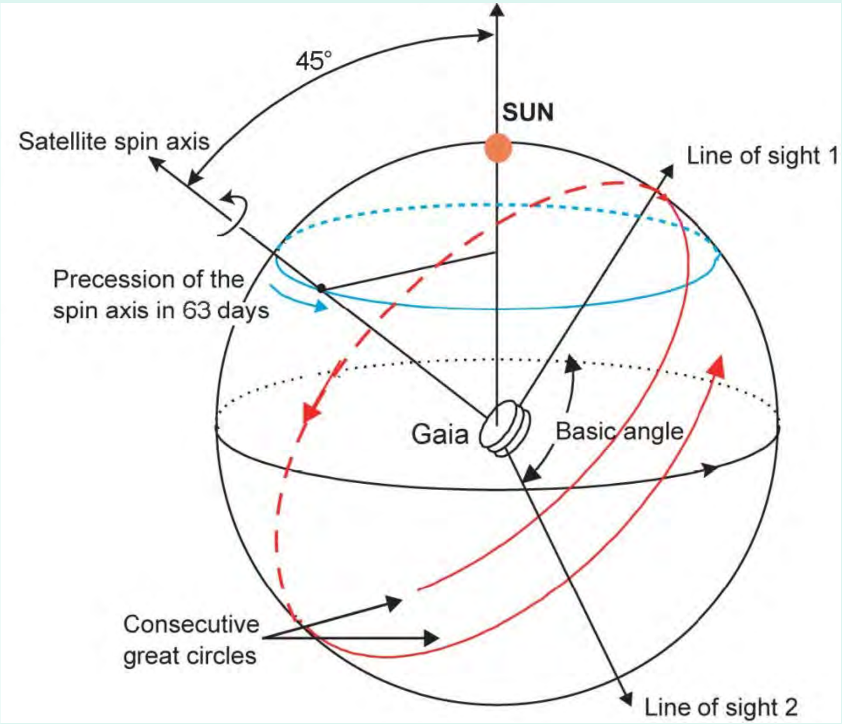
Future for all-sky astrometry

Gaia successor needed by 2033…

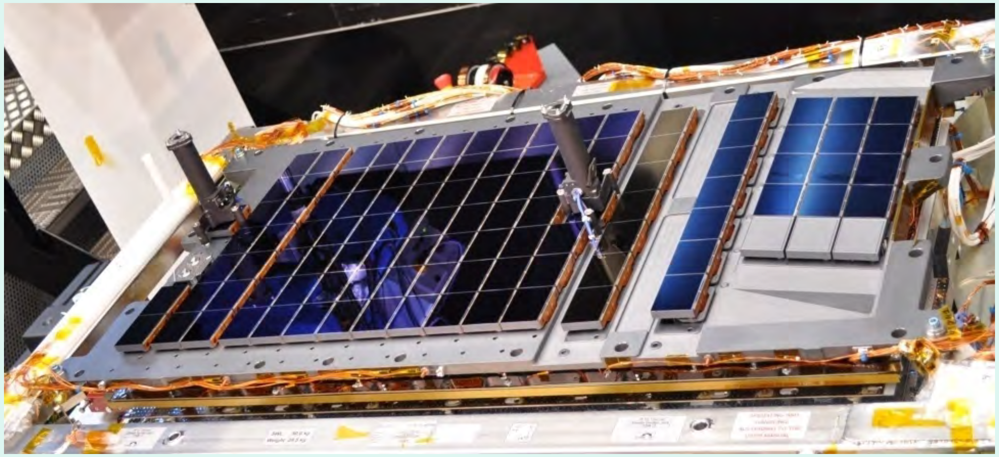
Astrometric Accuracy during 2000 Years



Erik Høg
1995/2016



Gaia Measurement principle



Gaia capabilities

Resolution of the images 0.”1, comparable to Hubble Space T.

Gaia will map the entire sky with this detail to 20th magnitude!

Telescopes and payload of Gaia = 3rd large Roemer

Final design 2005 – One focal plane - Launch December 2013

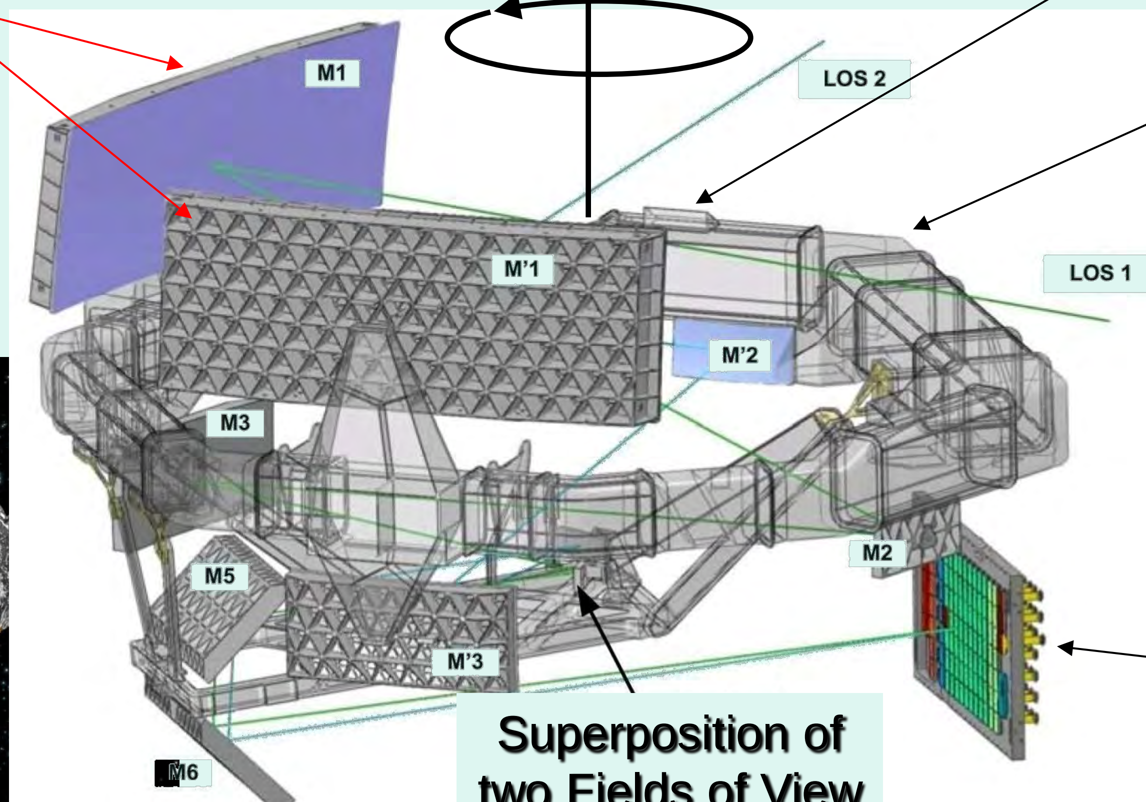
Two SiC primary mirrors

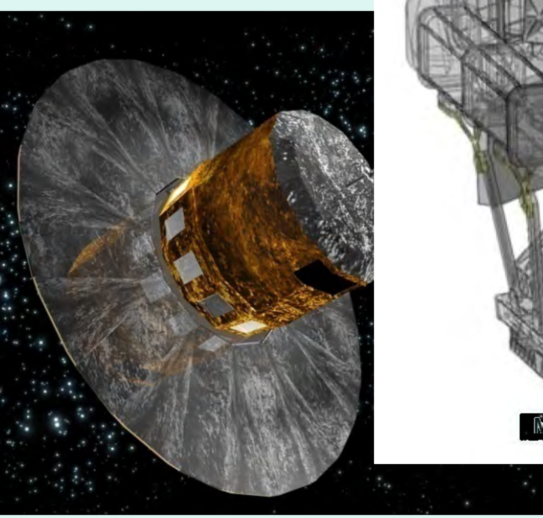
$1.45 \times 0.50\ m^2$ at 106.5°

Rotation axis (6 h)

Basic angle monitoring system

SiC toroidal structure (optical bench)





Superposition of two Fields of View

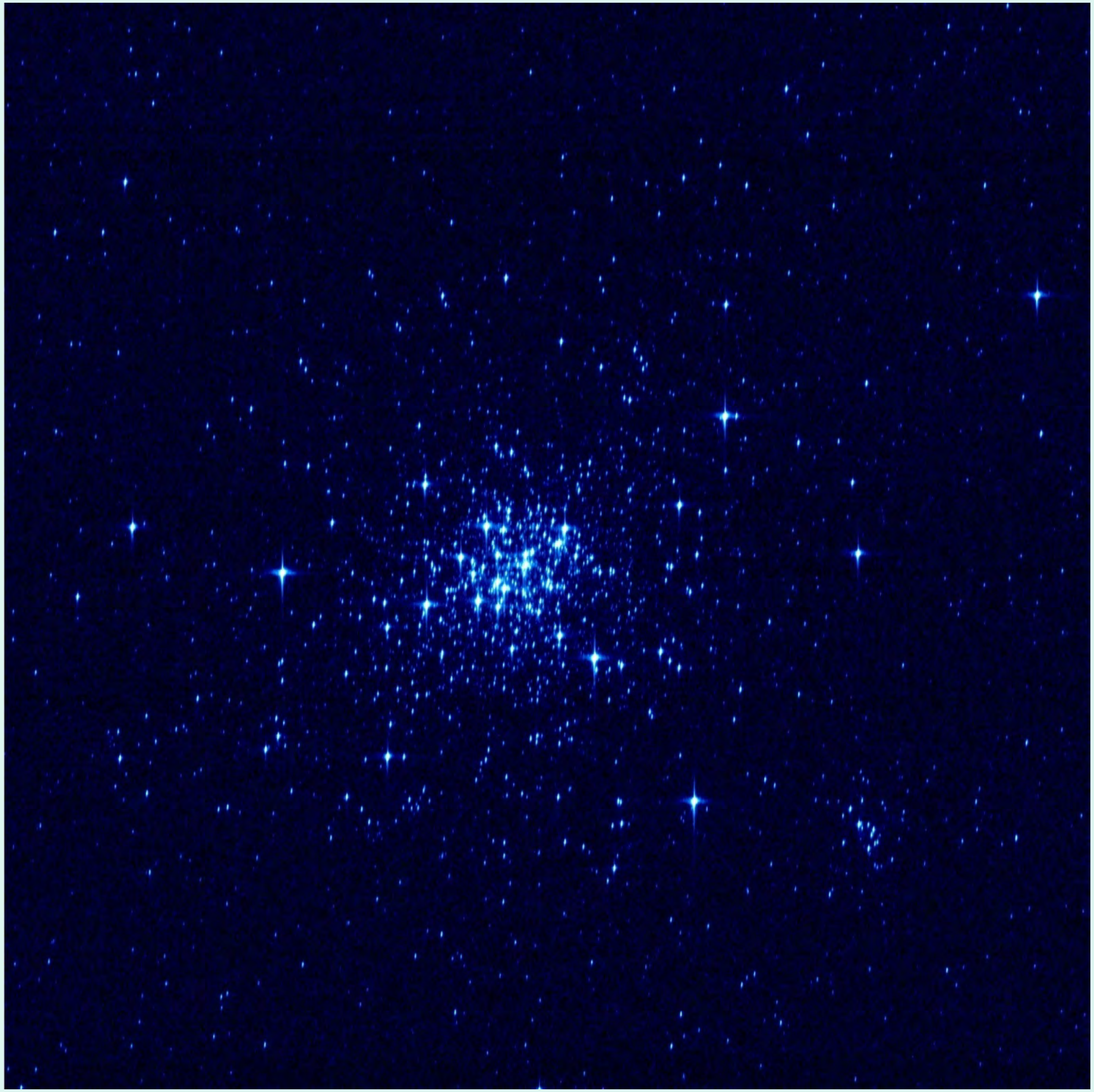
Combined focal plane (CCDs)

F = 35 m

Two anastigmatic off-axis telescopes

Figure courtesy EADS-Astrium

Gaia M1 and torus 2011



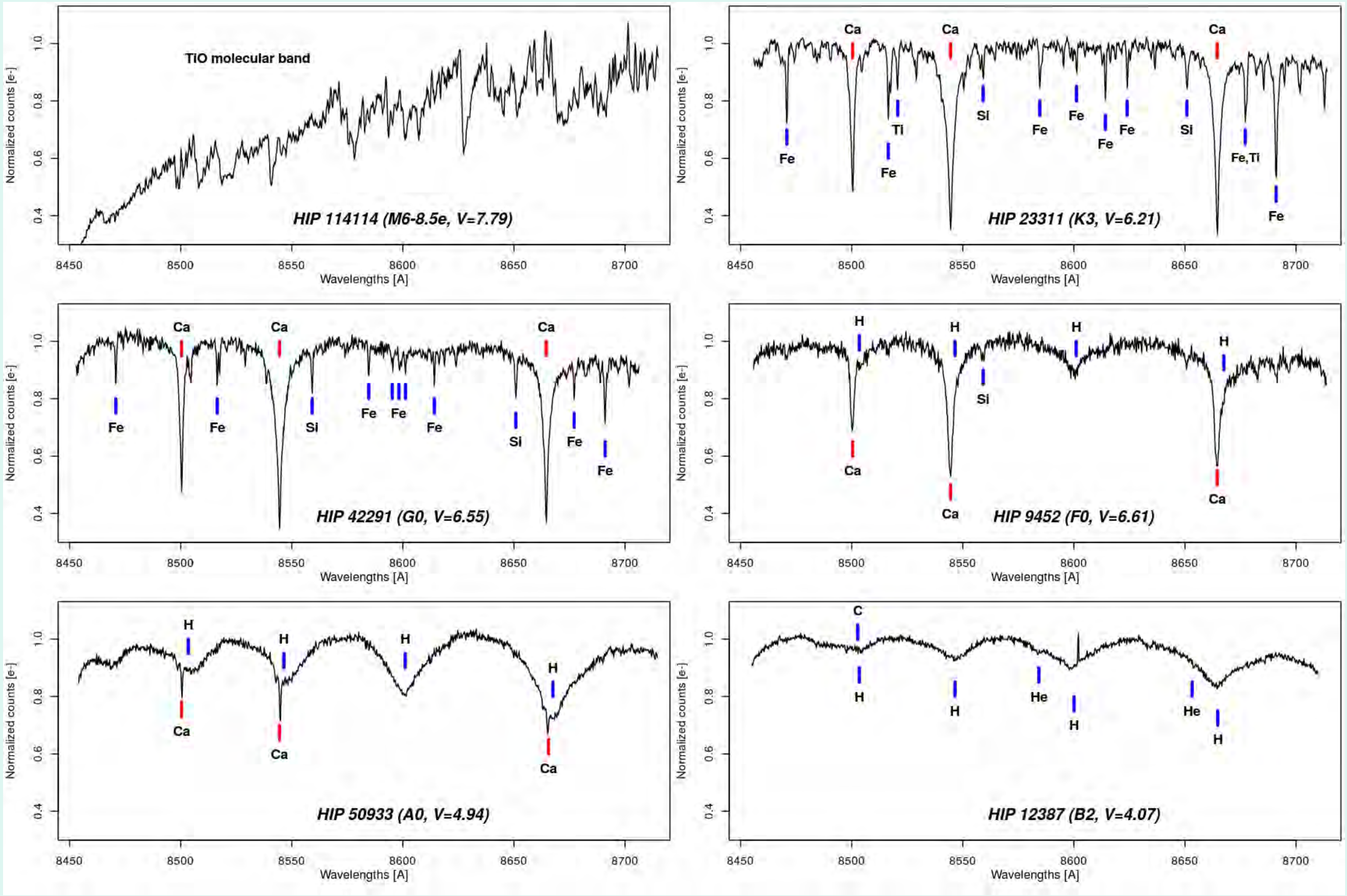
First image from Gaia
February 2014

NGC 1818
Globular cluster in LMC

2.85 second integration
212×212 arcsec^2

Spectroscopy

27 nm at the Ca-triplet: 845–872 nm



Stray light science impact (G2V star)

Pre-launch predictions

V-magnitude	Astrometry (parallax)	Photometry (BP/RP integrated)	Spectroscopy (radial velocity)
6 to 12	5-14 μas	4 mmag	1 km/s
15	24 μas	4 mmag	3 km/s
16.5			13 km/s
20	290 μas	40 mmag	

Stray light impact (noise contribution only)

V-magnitude	Astrometry (parallax)	Photometry (BP/RP integrated)	Spectroscopy (radial velocity)
6 to 12	5-14 μas	4 mmag	1 km/s
15	25 μas	5 mmag	13 km/s
16.5			
20	540 μas	60 (BP) – 50 (RP) mmag	

Calculations by: D. Katz, C. Jordi, L. Lindegren, J. de Bruijne

How Gaia began

- *August 1989: Hipparcos launched*
- *Data reduction occupied us all, also me,*

  but a visit to USSR in 1990 gave me impuls:
- 1990-91 dialogue with Russian colleagues
- *Proposal Høg 1992:*

  Scanning mission with ***CCDs : Roemer***

After Gaia – what then???

Høg 2014b, Interferometry from Space: A Great Dream

A Gaia successor in 20 years

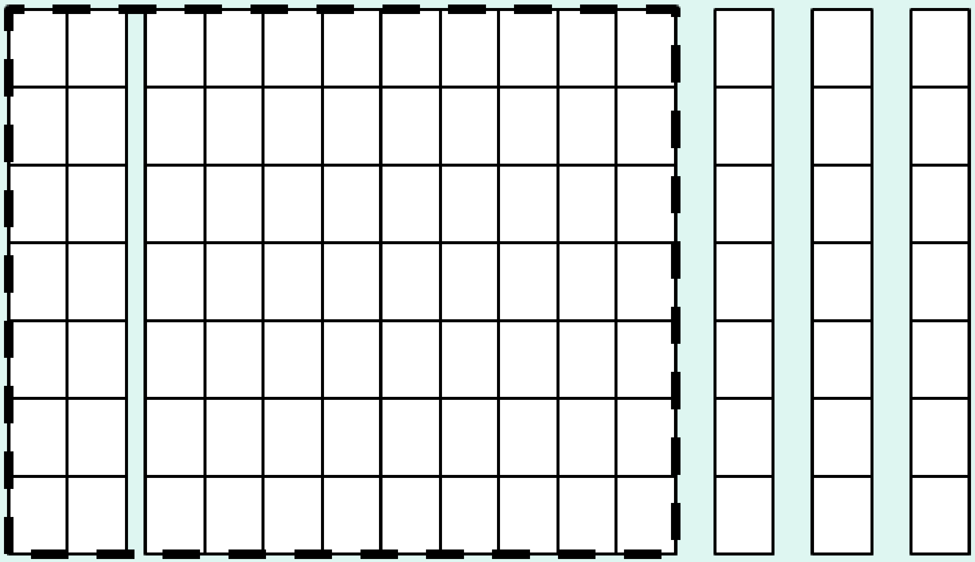
Similar astrometric performance as Gaia
Building on Gaia results

Proper motions with 10 times smaller errors using Gaia positions as 1st epoch

Parallaxes unaffected by motion in binaries

High-resolution photometry 140 mas FWHM

Gaia Successor Focal Plane



Sky mappers and astrometric CCDs inside the dashed rectangle are the same as in Gaia

Filter photometry with 3 bands

Sky Mappers Astrometric Field Photometry 3 Colours

Erik Høg 2014

Høg E. 2015, Absolute astrometry in the next 50 years.

http://arxiv.org/abs/1408.2190

34 pages with the science cases

Near-Infrared Astrometry - new July 2015

Goes deeper in obscured regions than Gaia CCDs

About 4 mag fainter than Gaia with a given astrometric accuracy for late spectral types in regions with A_V = 10 mag and 0.8 mag fainter on not obscured M2V stars

Astrometric focal plane with
***tunable HgCdTe = MCT* sensors**

Study and development of NIR sensor for TDI mode
Høg, Knude & Mora 2015, *Astrometric performance of a NIR option*
https://dl.dropbox.com/u/49240691/GaiaNIR.pdf

Application to ESA in Sept. 2016
https://dl.dropbox.com/u/49240691/GaiaNIR4a.pdf

The astrometric foundation of astrophysics

Top science

from new Gaia-like mission vs. a single Gaia:

- *Imaging of radio/optical sources etc. :*
  Positions 50 years from now >20 times smaller errors
- *Dynamics of Dark Matter etc. from stellar proper motions:*
  Tangential velocities with 10 times smaller errors
  in 30 times larger volume
- *Stellar distances in >3 times larger volume*
- *Exoplanets: Periods up to 40 years, vs. Gaia P<10 yrs*
- *Quasars only by zero motions: 100 times cleaner sample*
- *Solar system: orbits, asteroid masses…*
- *Astrometry and photometry with 0.”1 resolution*
- *Astrometric binaries. Common proper motion pairs. Etc. etc.*

Optical reference frame

Imaging of radio/optical sources

Gaia frame at G=20 mag:

σ = 1.8 mas in 2026, 8.8 mas in 2066 from Gaia

σ = 0.4 mas in 2066 Gaia1+2

Telescope D=50meter aperture, resolution 2.8mas at λ=560 nm

The frame should be 10 x better: 0.28 mas

Høg 2015: Sections 3 and 4

Høg 2014a, Future Reference Frames

Dynamics of Dark Matter etc. from stellar proper motions

Tangential velocities with 10 times smaller errors than from Gaia in 30 times larger volume for a give type of stellar tracer

Høg 2015: Section 2.5

Stellar distances

Parallaxes with Gaia accuracy
in >3 times larger volume

Parallaxes in binaries:
1) unaffected by the orbital motions
2) better chromatic corrections from
the high resolution photometry

Gaia: *1% error on trigonometric distances for 10 million stars*
80% of Gaia stars to 20 mag >20% error on trig. distances
Thus: Photometric distances needed:
Colour indices -> absolute mag; then apparent mag + extinction -> ***distance***

Photometric distances

*Colour indices -> absolute mag; then apparent mag + extinction -> **distance***

*Distances for normal single stars **~20% errors in 2015**, dwarfs & giants*
Santiago et al. 2015 based on Hipparcos parallaxes

***Gaia: 1% accuracy** of distances for 10 million stars =>*
1) Better luminosities for studies of stellar structure and evolution
2) Better calibration of absolute magnitude, extinction etc.
3) 3-D map of interstellar clouds =>> better extinction

*=> Distances for normal single stars **~10% errors by 2025***

*Distances for giants and some other types **~2% errors by 2025***

Section 1.3 and
Høg 2015b, An overview of photometric distances.

Long-period exoplanets only by astrometry

Periods up to 10 years by Gaia
Periods up to 40 years by Gaia1+2

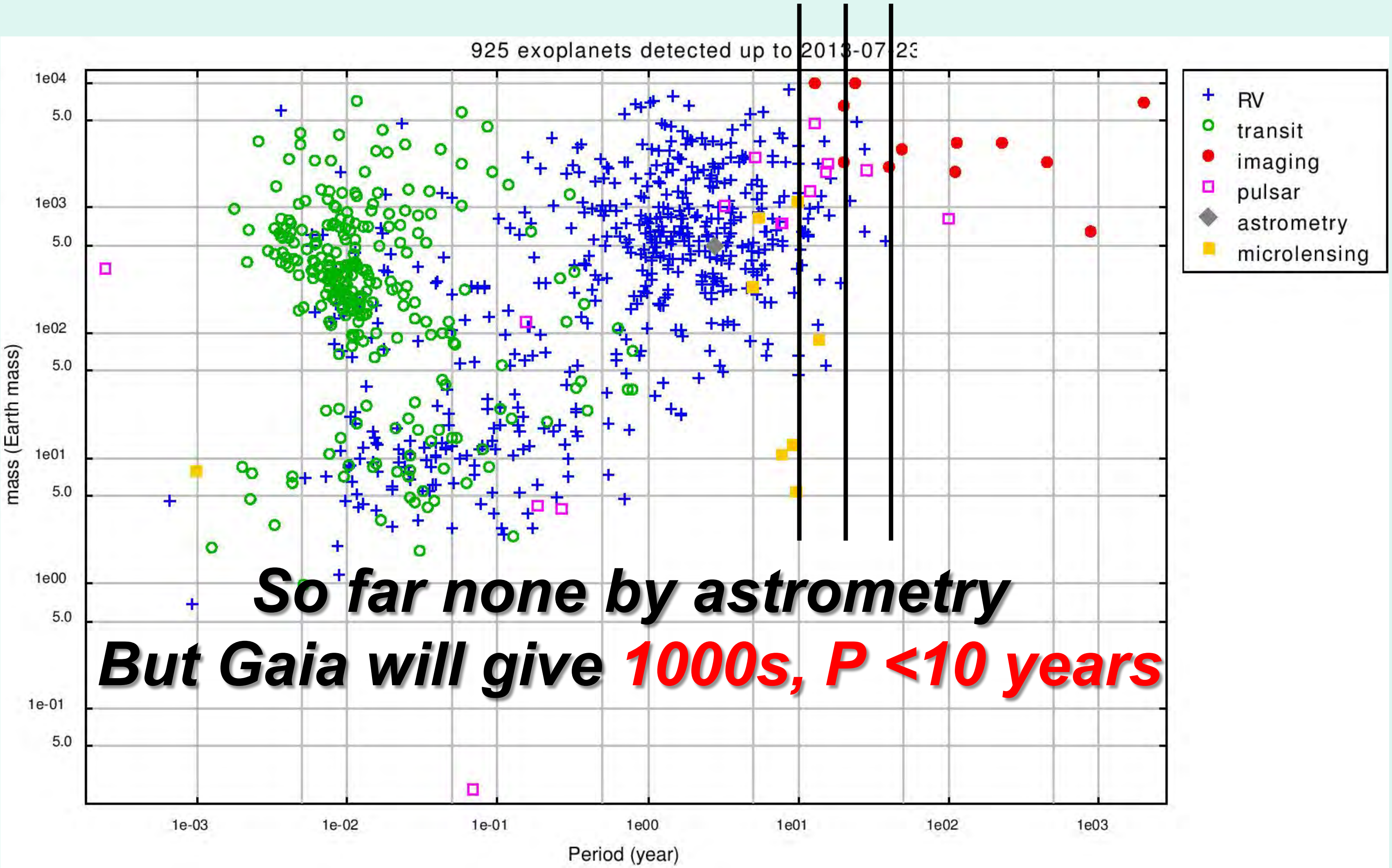
Inventory with 1000s of exoplanet systems
Migration theories are missing observational basis

Details …

Høg 2015: Section 2.6

The 925 known exoplanets in 2013

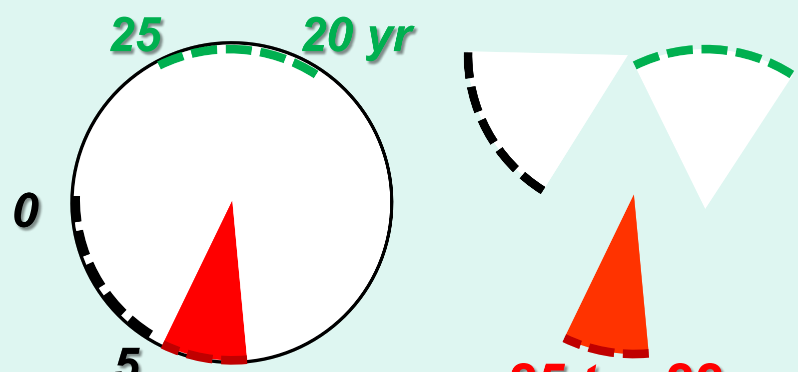
10 20 40 years



So far none by astrometry

But Gaia will give 1000s, P <10 years

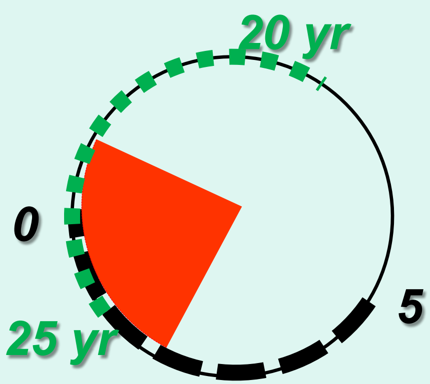
P = 30 yr like Saturn



5 year Gaia1+2 missions

-25 to -22 yr =3 year Hipparcos mission

P = 12 yr like Jupiter



3 year Hipparcos: t= -25 to -22 yr

5 year Gaia1: t=0-5 yr

5 year Gaia2: t=20-25 yr

Orbit well covered => all elements

Long, 10 year, missions wanted

Planetary systems

- *Some long-period planets migrate from beyond the snowline inwards through the habitable zone*
- *How many? How heavy?*
- *What effect on the habitable planets?*
- *Theories of migration have no observational basis about the planets before or during their migration*
- *The Gaia1+2 detections => comprehensive theory of the evolution of planetary systems*
- *No other technique can compete with Gaia1+2*

Quasars only by zero motions

10 times better proper motions in 2 dimensions
$\Rightarrow$ 10x10=100 times cleaner sample
Long-term radio p.m. of QSOs have s.e. ~0.010 mas/yr according to Fig.2 of Titov et al. 2011

Clean samples over most of the sky

Also other extragalactic point sources than QSOs

Høg 2015: Section 2.4
Heintz, Fynbo & Høg 2015, AstronAstrophys

Solar system and small-field astrometry

Orbits, asteroid masses…

Høg 2015: Section 2.8
Høg & Kaplan 2014,
Solar system and small-field astrometry

Astrometry and
photometry with 0."1 resolution
Section 2.3

Astrometric binaries. Sect. 2.6
Common proper motion pairs. Sect. 2.7

Etc. etc.

Gaia successor

Must be decided in 5-10 years to fly in 20-30 years
before the astrometric experience from Gaia is lost in Europe

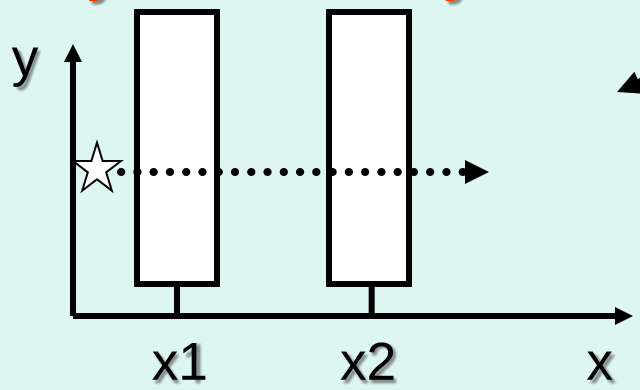
Only ESA can do all-sky space astrometry!

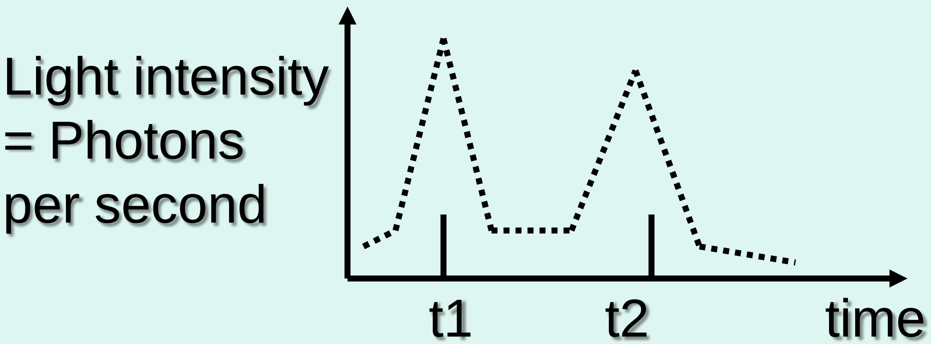
After 1978   USSR/Russia, USA, Japan tried in vain
Only in ESA can astrophysicists be convinced
Even the approval of Hipparcos in 1980 was a near miss!

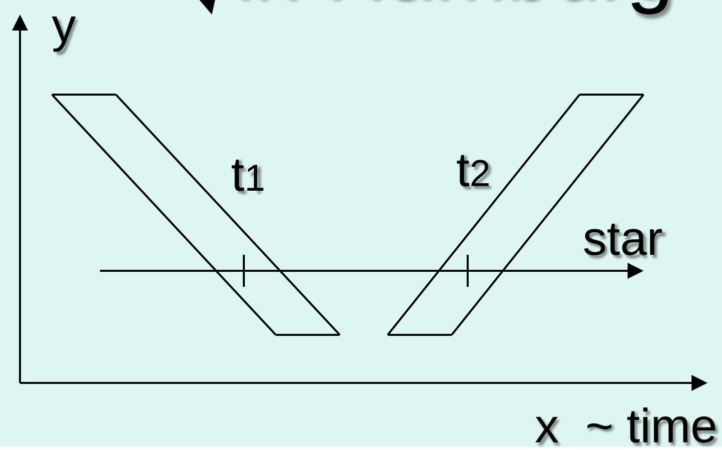
The process from 1925 to 1980 depended
1)   on support from the large astrometric community in Europe and
2)   on 7 persons : If one of these 7 individuals had been missing
Hipparcos would not have been approved in 1980 – and probably never as shown in
Høg 2011, Miraculous approval of Hipparcos in 1980: (2), and
Høg 2011b, Astrometry lost and regained

Slits + Photon counting vs. Time
=> Astrometry + Photometry

Ideas 1960 in Hamburg





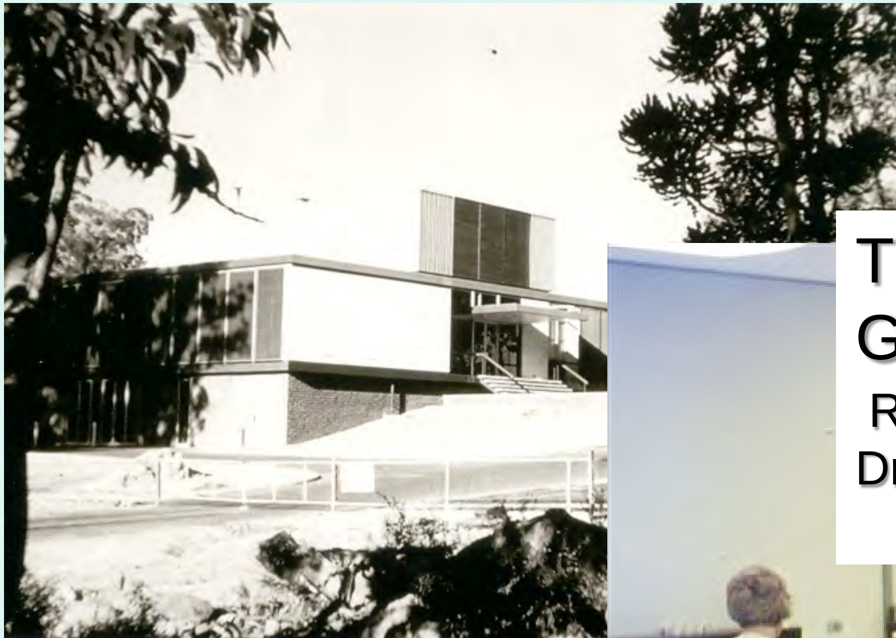


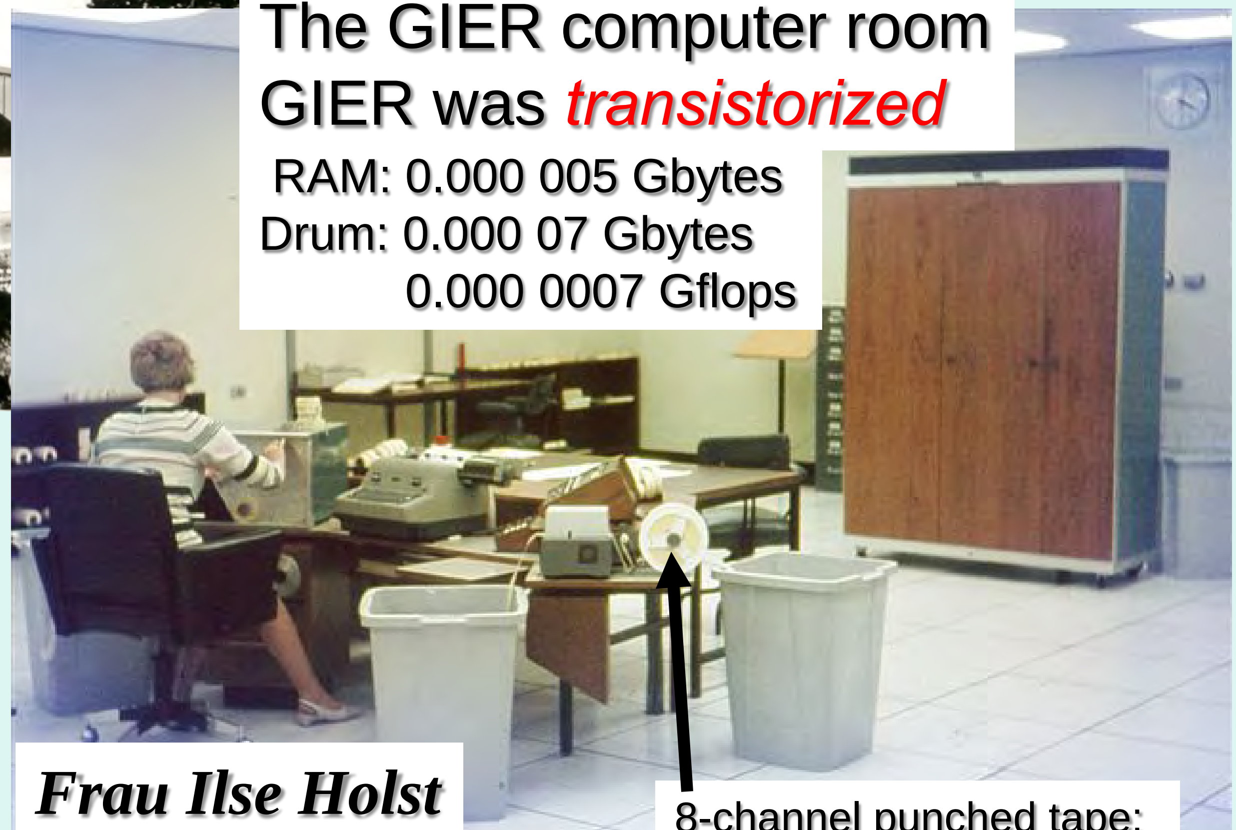
In France called: *Une grille de Høg*

B. Strömgren 1925: slits
Atomic bombs 1957 : Counting techniques
E. Høg 1960 : Slits + counting >>>
implementation on meridian circle in Hamburg

Otto Heckmann
Immediate support

Perth Observatory – 1967-72-80





The GIER computer room
GIER was *transistorized*

RAM: 0.000 005 Gbytes
Drum: 0.000 07 Gbytes
0.000 0007 Gflops

Frau Ilse Holst

8-channel punched tape:
0.000 1 Gbytes

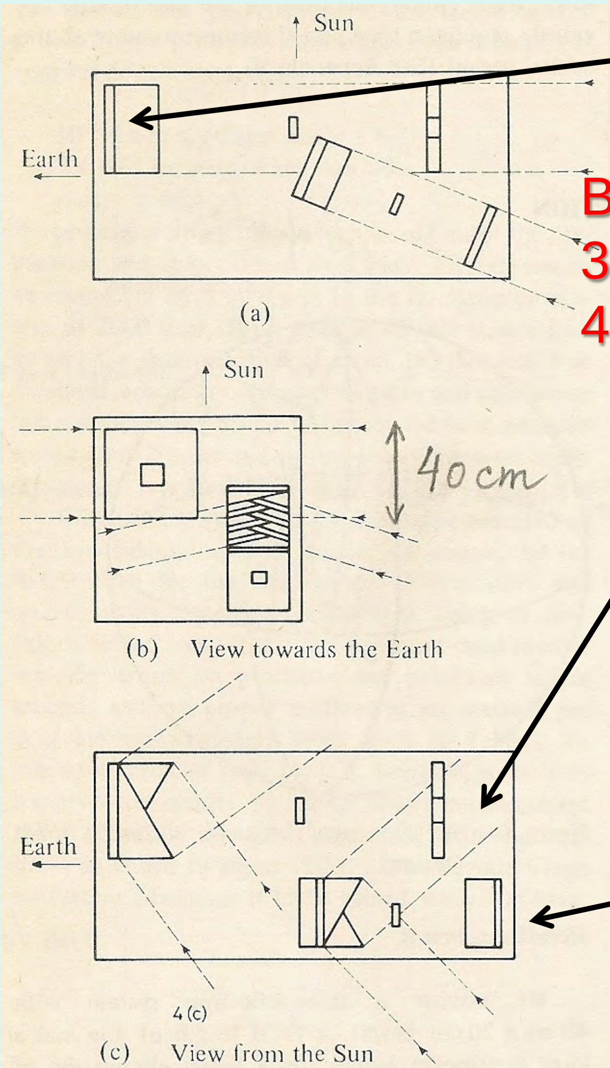
Space astrometry : A French vision

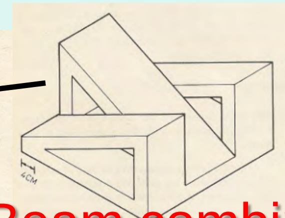
- Ideas and work in France 1964-74 Nice, Grasse, Paris, Lille: Pierre Bacchus, Strasbourg, and CNES in Toulouse; there was no space astrometry activity outside France in this period
- Pierre Lacroute 1967: Presentation in Prague
- Jean Kovalevsky 1974: European project

Pierre Bacchus & Pierre Lacroute (1985)

Jean Kovalevsky (2005)

Design of a scanning satellite

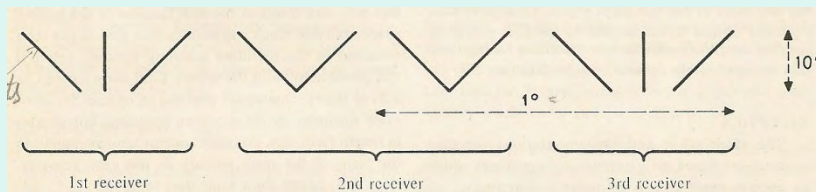


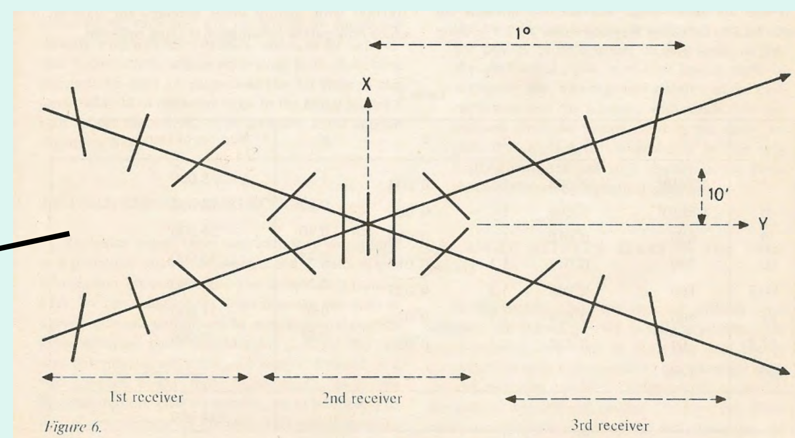


Beam combiner
3 parts
45 degrees

- Lacroute 1974:

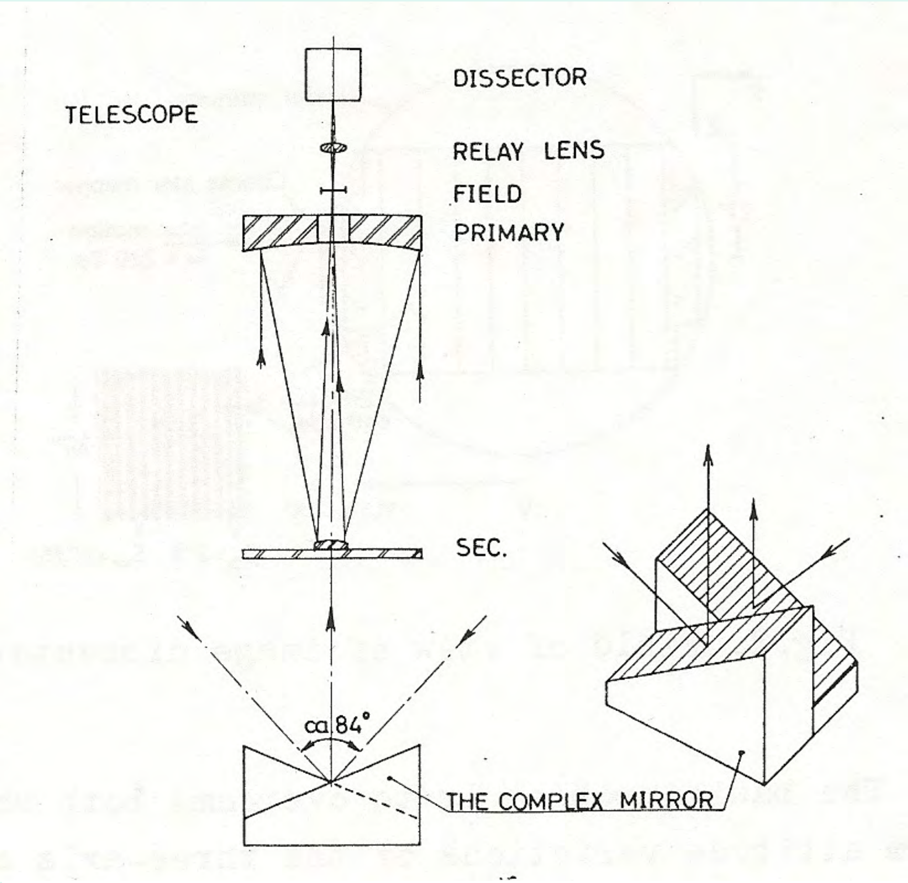
Expected 300 000 stars ~3 mas
with 40x40 + 30x30 cm apertures
Two-dimensional measurement
6 Photomultiplier tubes





Frascati 1974 in ESRO SP-108

Design of a scanning satellite



IAU GA 1976, Highlights of Astr., p.361

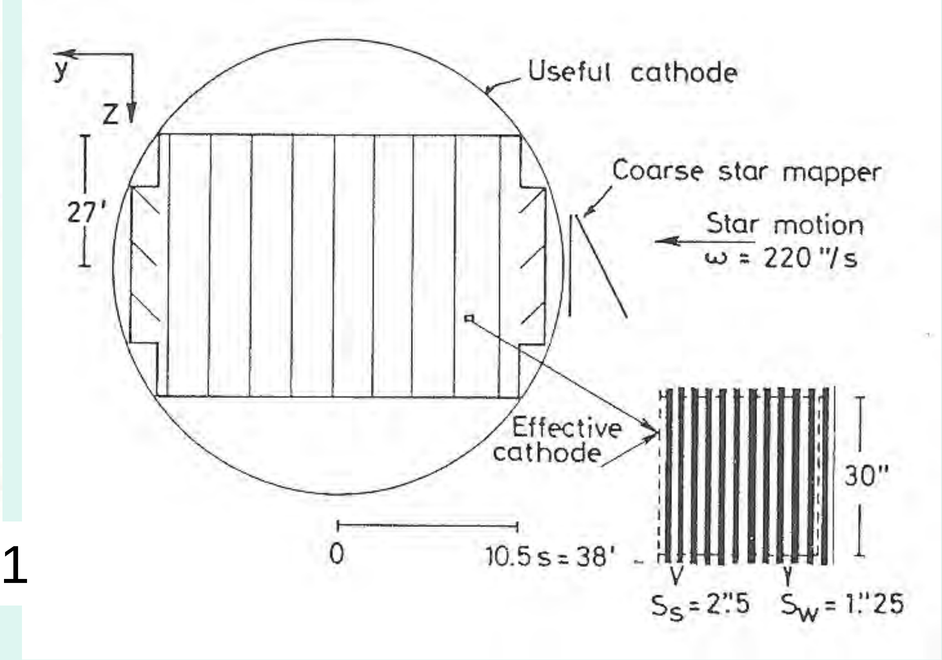
- Høg 1975-1976:

Expected 100 000 stars ~4 mas

with 16x16 cm aperture

One-dimensional measurement

One image dissector tube + one PM



Seven key persons 1925-1980 – a chain

B. Strömgren 1925: Slits + photo cell
E. Høg 1960: Slits + counting
O. Heckmann 1960: Immediate support, director of Hamburg Obs.
P. Lacroute 1967: Go to space
J. Kovalevsky 1974: European project - ESA
E. Høg 1975: New design of mission
L. Lindegren 1976: Data reduction
ESA 1980: Hipparcos approval
Ed van den Heuvel in ESAs AWG (EXUV mission, C. de Jager!)
www.astro.ku.dk/~erik/History.pdf

Hipparcos mission launch 1989 final results 1997
Resources: Astrophysicists' approval in 1980
~500 million Euro for ESA
>200 scientists + several hundred engineers++
20 years work

Seven key persons 1925-1980

3 astrophysicists

Bengt Strömgren

Erik Høg

Otto Heckmann

Pierre Lacroute

Jean Kovalevsky

Lennart Lindegren

Edward van den Heuvel

Two Gaia-like missions

Only ESA and astrophysicists can decide – must fly in 20-30 years

i.e. approval within 5 - 10 years

Høg E. 2015, Absolute astrometry in the next 50 years.
http://arxiv.org/abs/1408.2190
34 pages with the science cases