The road
from meridian circles to Gaia and beyond

By Erik Høg

On 3 February 2021

Universität Potsdam (online)

Based on the presentation for the AG
in Stuttgart on 17 September 2019

The road
from meridian circles to Gaia and beyond

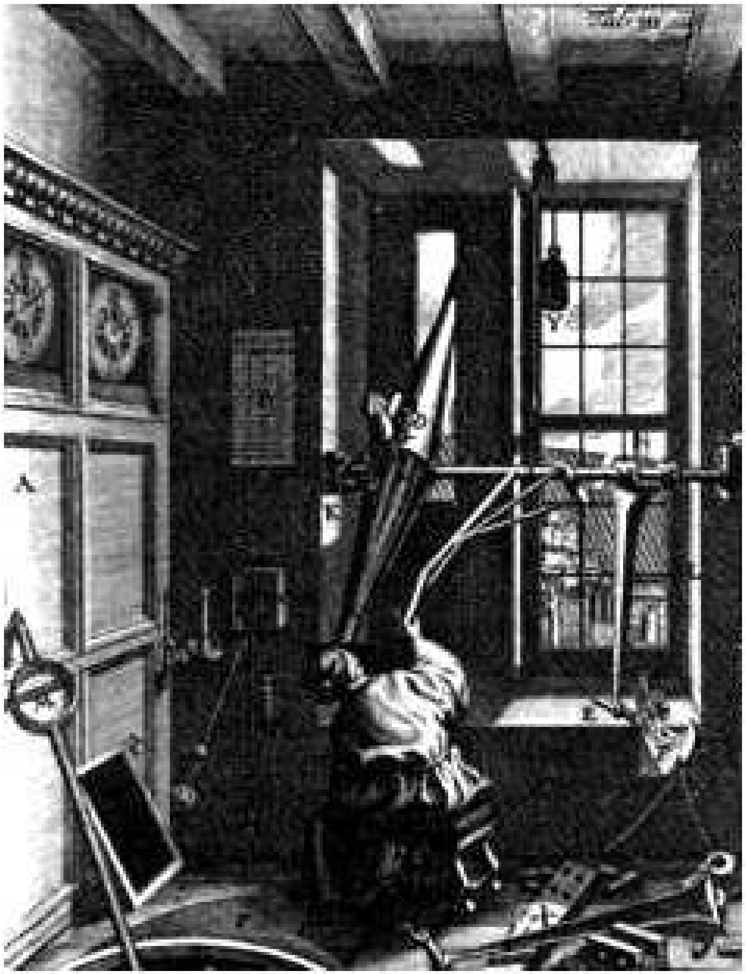
By Erik Høg

On 16 March 2021

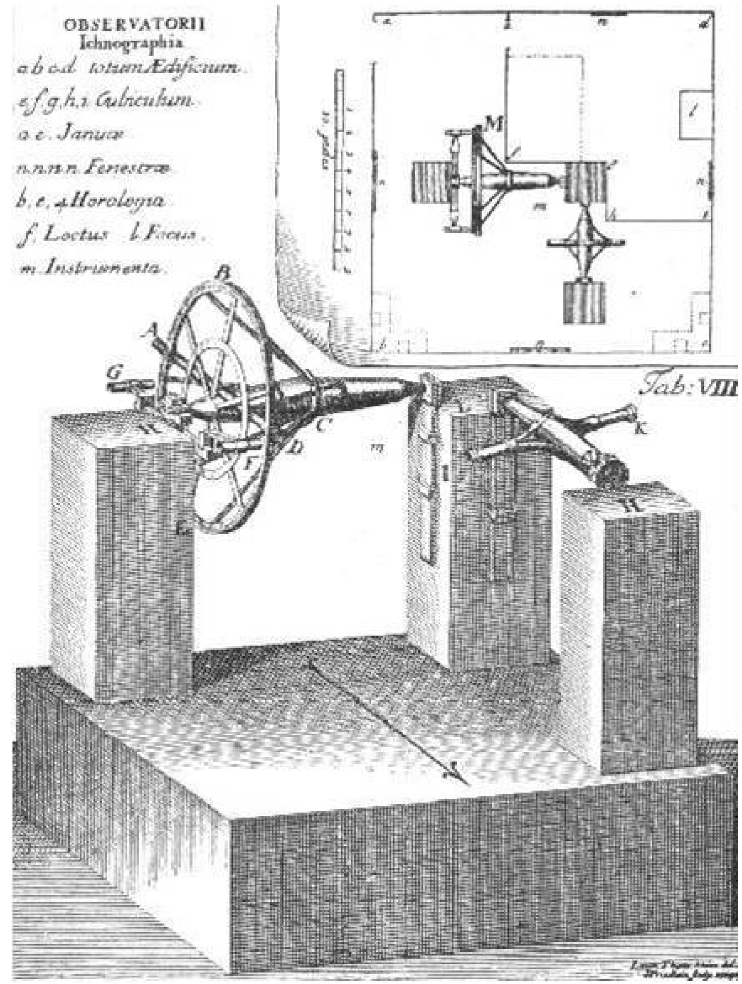
University of Perth (online)

Based on the presentation for the AG
in Stuttgart on 17 September 2019

Ole Rømer in Copenhagen



Transit Instrument ~1685

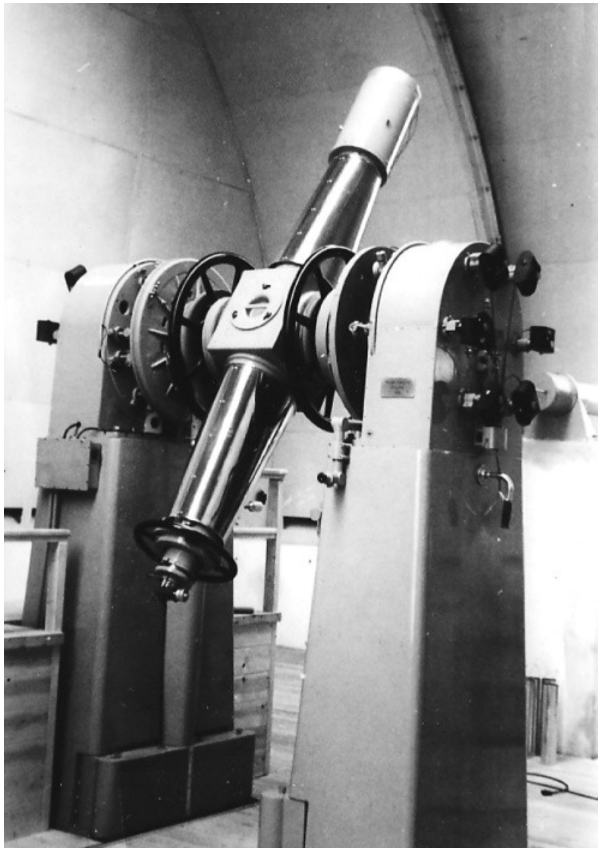


Meridian Circle 1705

Astrometry

positions & motions & parallaxes

are required in all branches of Astrophysics



Absolute optical astrometry

with meridian circles 1705-1990

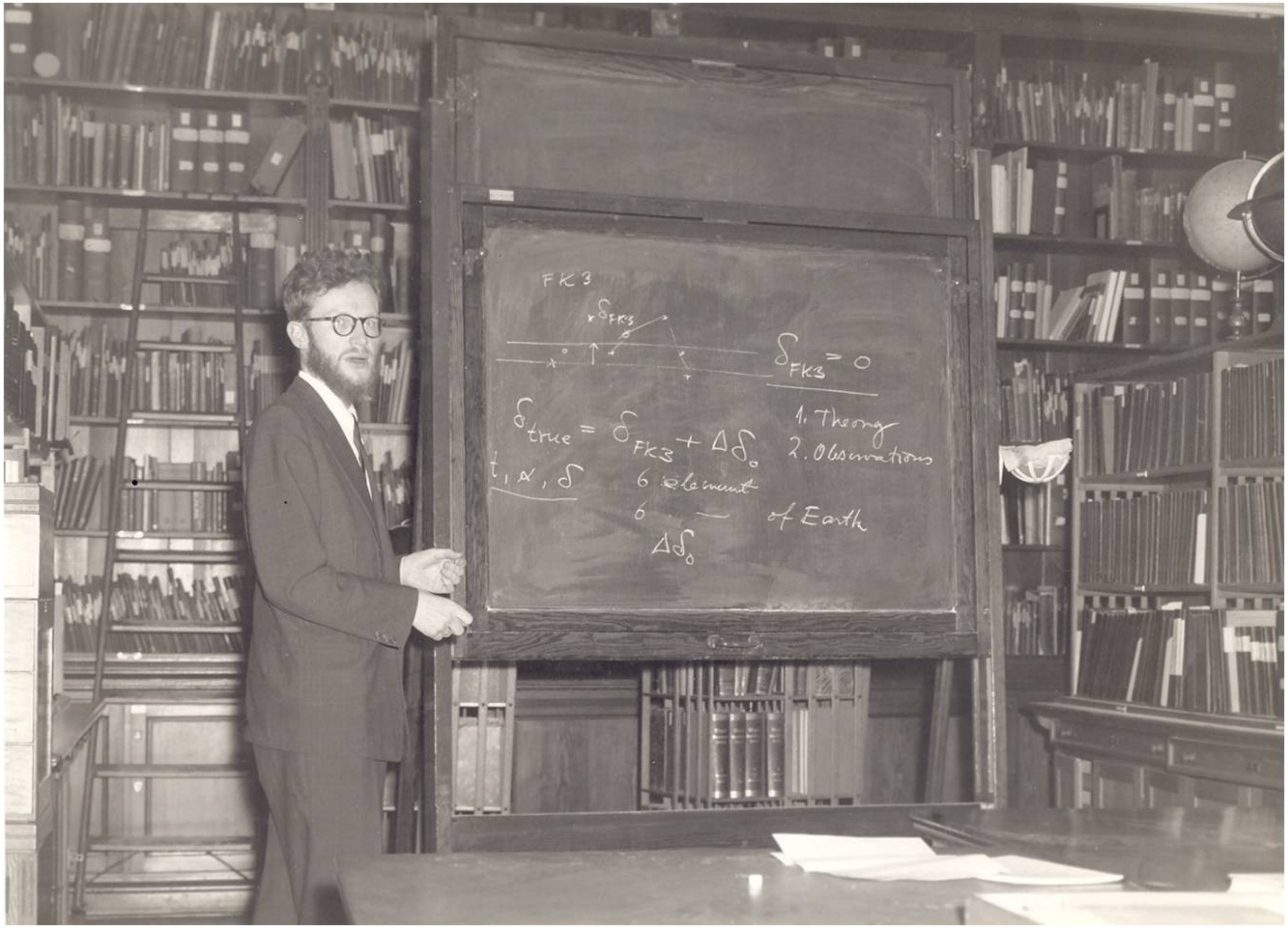
accurate positions of ~100 000 stars obtained in total

Invented and used by Ole Rømer from 1705

A new meridian circle was ordered by Bengt Strömgren in 1940 for a new Danish observatory. It was erected 1953 at **Brorfelde 50 km from Copenhagen.**

As a student of 21 years I was sent to work with this instrument. I became fascinated by astrometry. – From 1958 I stayed in Hamburg wanting of course to become an astrophysicist.

– But 1960, 27 July something happened …



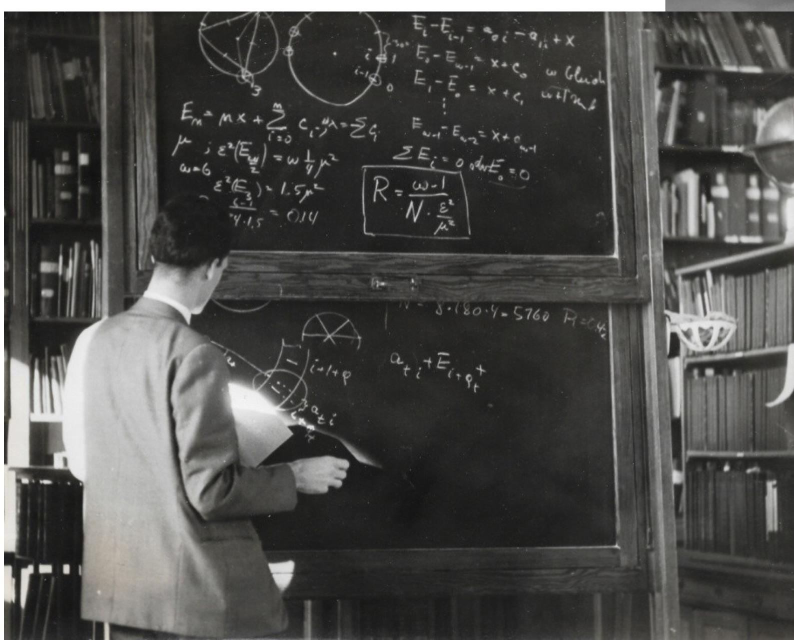
1958: Peter Naur in Hamburger Sternwarte

He left astronomy entirely in 1959 and soon became the first Danish professor of computer sciences. - ALGOL 60

Naur received the Alan Turing award in 2005

2010: Peter Naur - I met him again!
And often thereafter

Front row:
Brosterhuis, ?, Rahim, Kox, Voigt, Wellmann, Schwassmann,
Otto Heckmann, first director of ESO,
Larink, Beyer



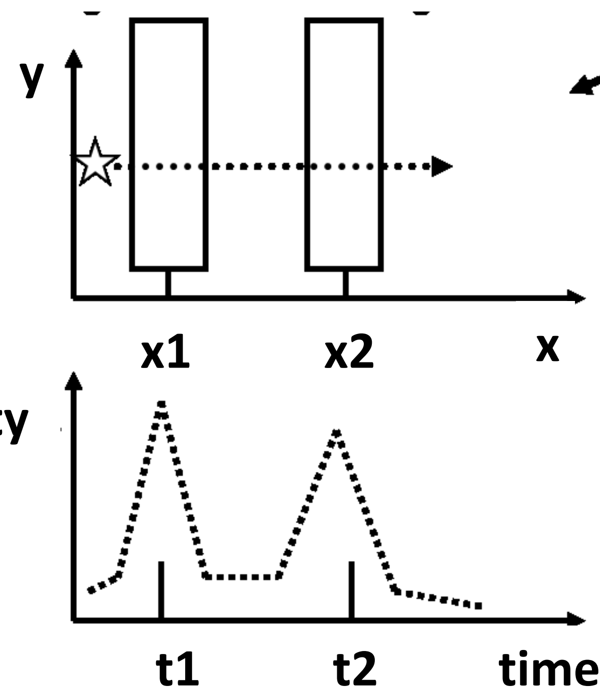
1959-60: Hamburg – Colloquium in the library and daily lunch in the basement. – Spectra, digitization of measurements! DESY visits.

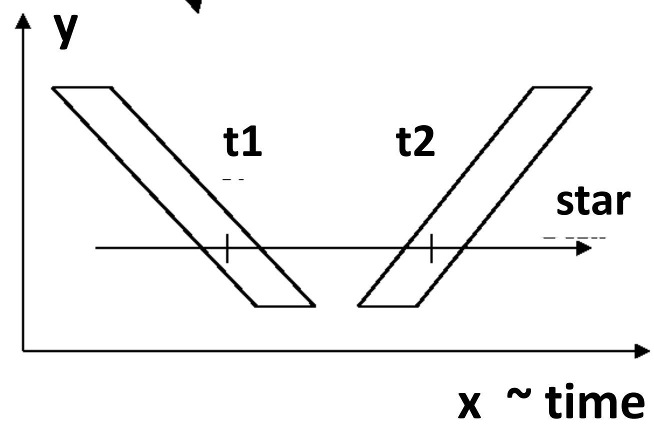
1960: Photon counting astrometry

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

Ideas Høg 1960
In Hamburg

Light intensity
= Photons
per second

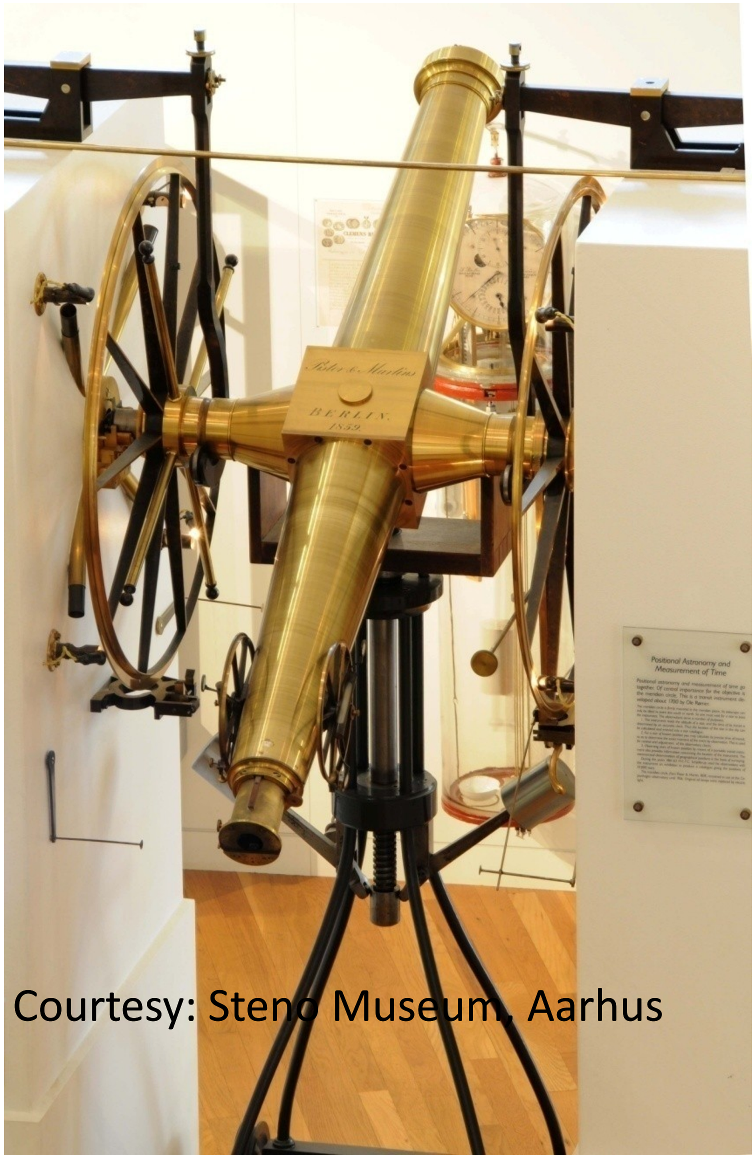




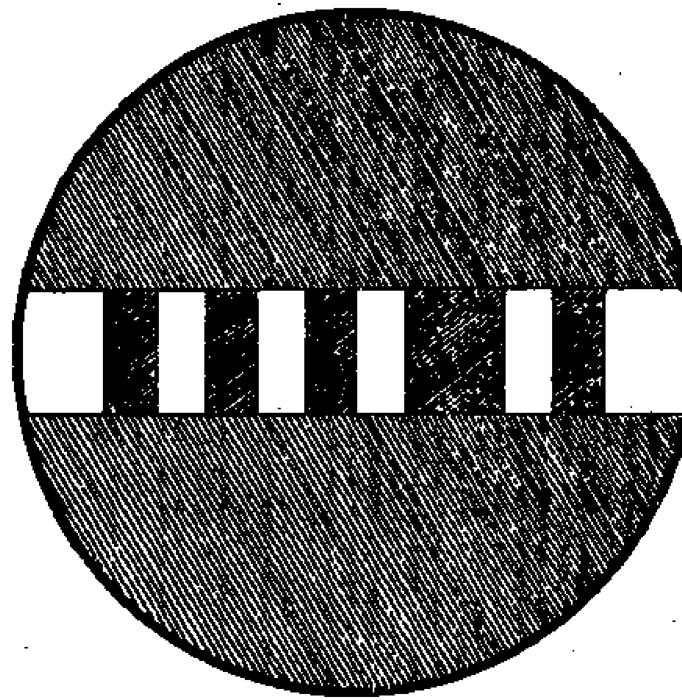
In France called: ***une grille de Høg***

- **The new astrometric method was implemented on the Hamburg meridian circle 1960-67. - It was operated for 5 years in Perth (Western Australia) resulting in 1976 in a catalogue of 25,000 stars with an accuracy of ±150 mas**

Copenhagen meridian circle
Photoelectric astrometry begins in 1925



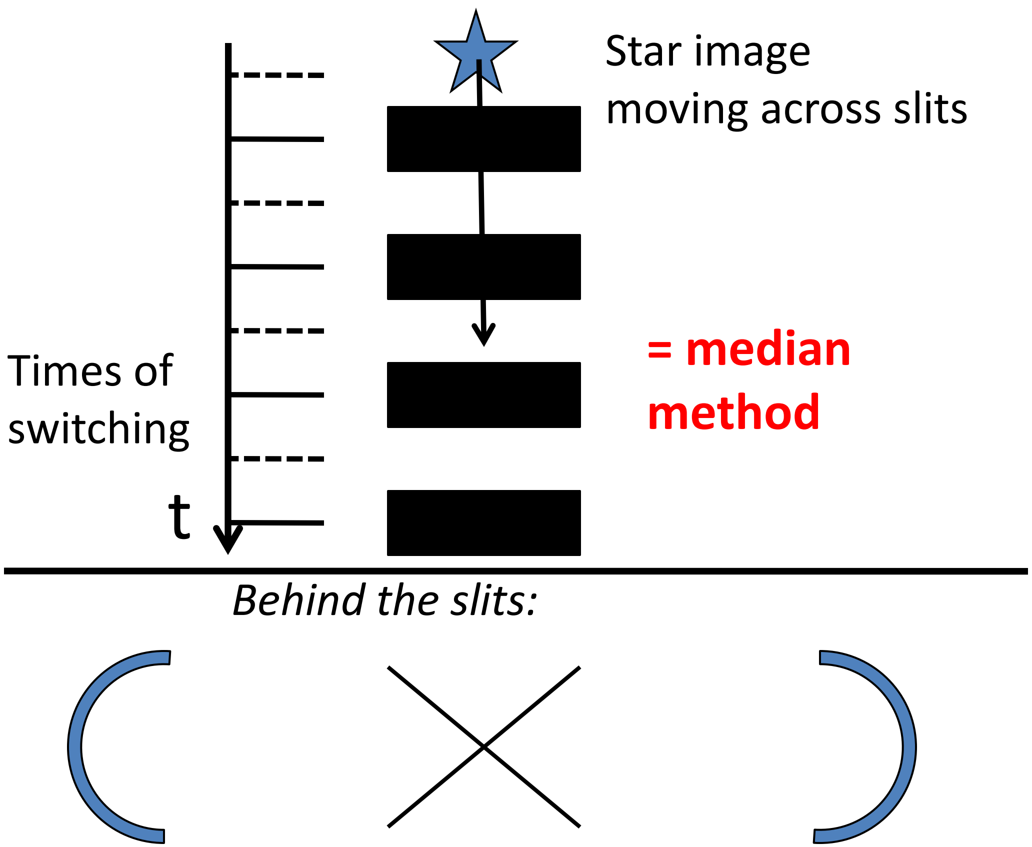
Courtesy: Steno Museum, Aarhus



Bengt Strömgren 1925
Experiments with
photoelectric recording of transits
In: Vierteljahrsschrift der
Astronomischen Gesellschaft

Switching mirror and integration

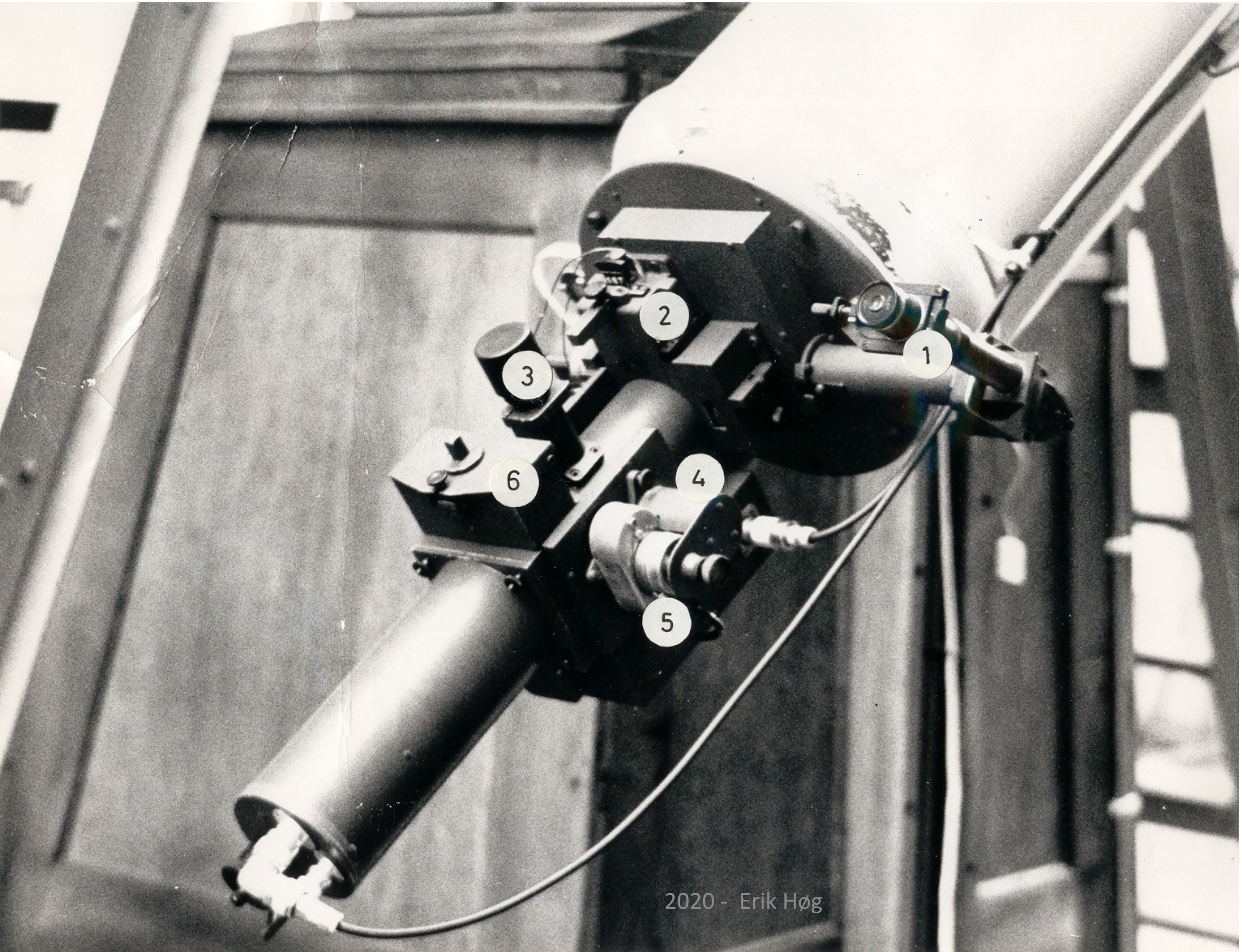
proposed 1933



Bengt Strömgren (1957)

Photon counting techniques learnt when I was a soldier in 1956

Hamburg – First photon-counting micrometer on a meridian circle 1966

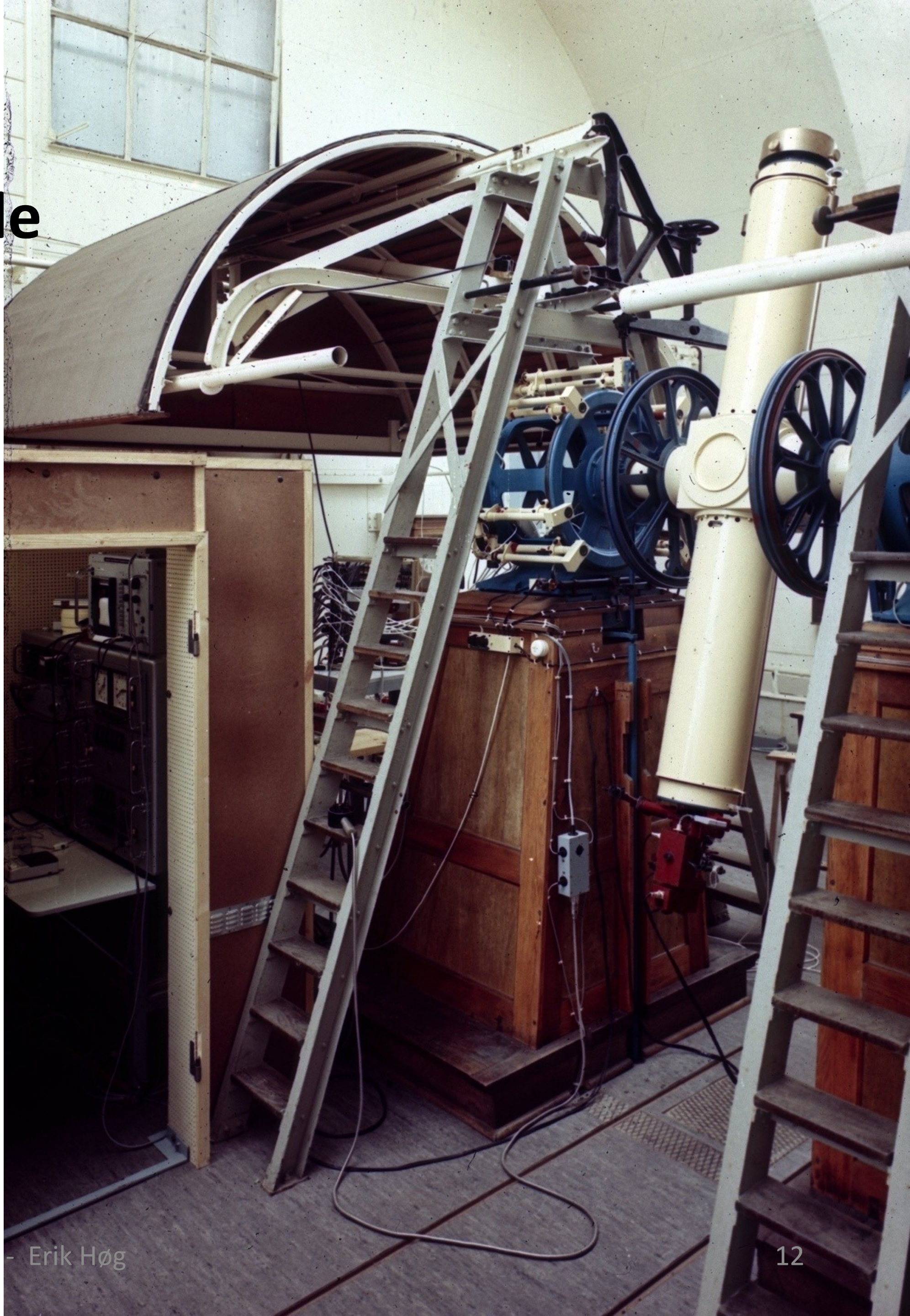


Hamburg 1966
The Repsold meridian circle

Ready for Perth

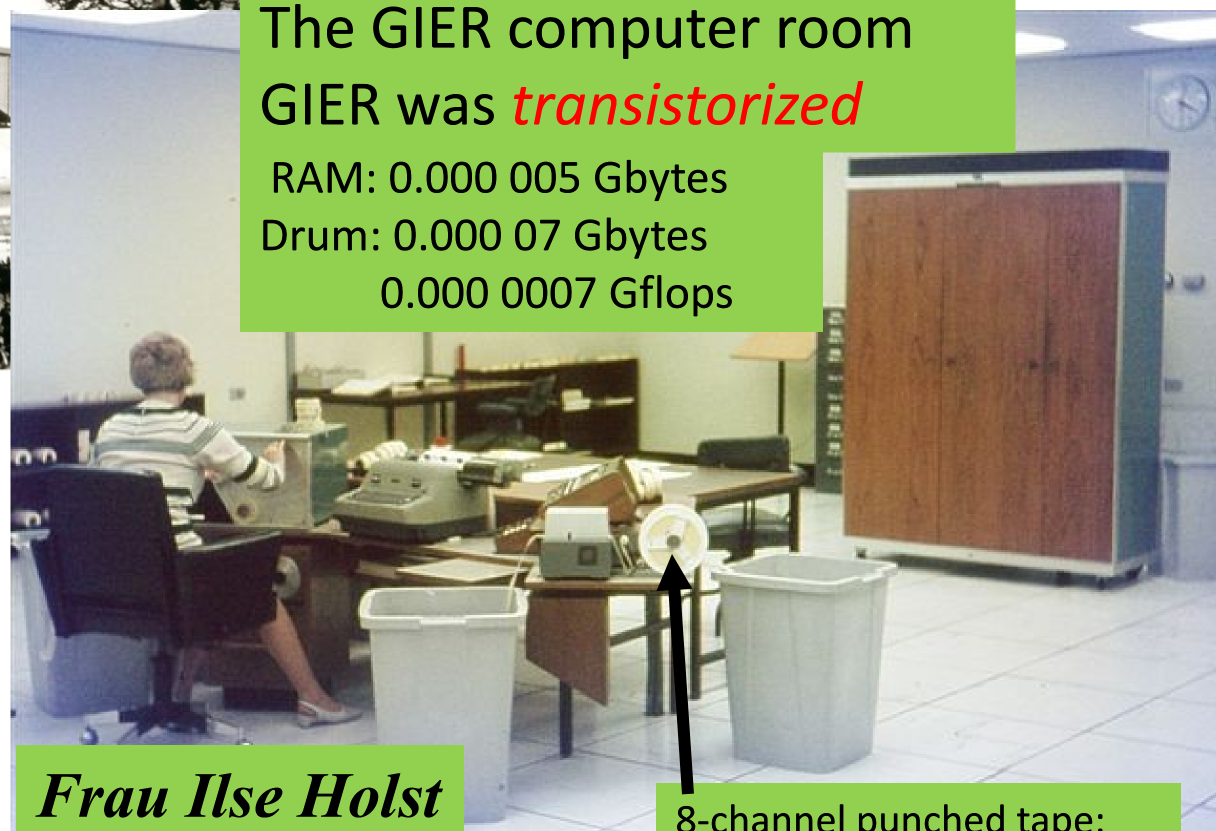
Semi-automatic:
Manual setting of telescope
Photoelectric measurement
 of declination circle and star
Recording on punched tape

Høg E. 2014, Astrometry 1960-80: from Hamburg to Hipparcos. Proceedings of conference held in Hamburg in 2012, Nuncius Hamburgensis, Beiträge zur Geschichte der Naturwissenschaften, Band 24, 2014.
http://arxiv.org/abs/1408.2407



Perth Observatory – 1967-72-80

All programmes
in ALGOL 60



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

Great changes in Hamburg…
So I returned to Denmark in 1973.

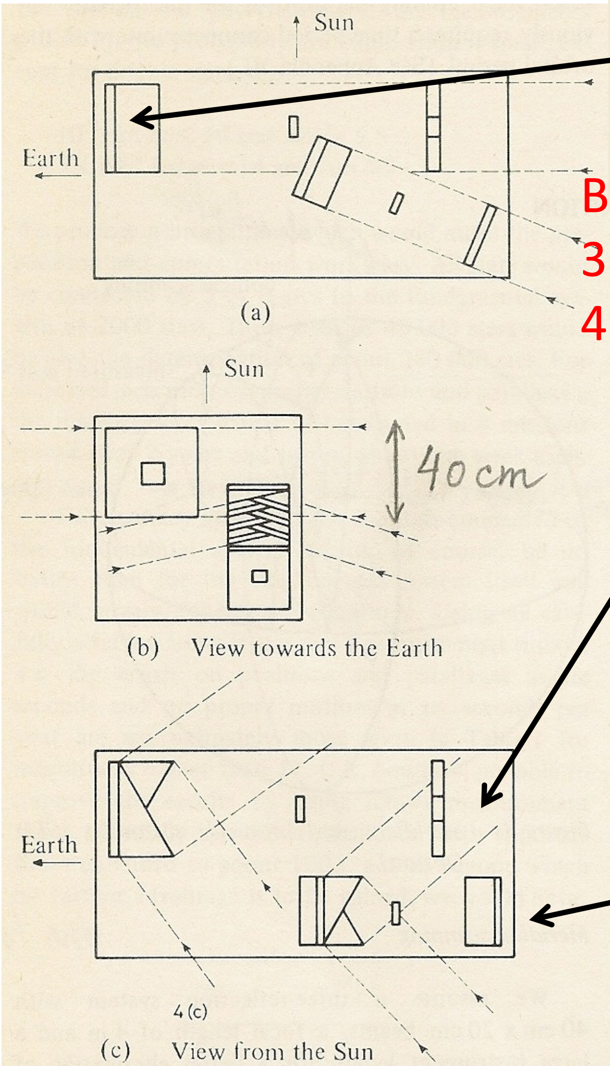
Much later in Hamburg:
Gudrun Wolfschmidt:
Nuncius Hamburgensis

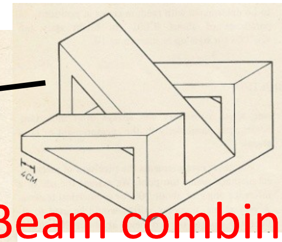
Photon counting astrometry in space

In France, the new method was adopted as basic for the great vision of a space-based astrometric mission by Pierre Lacroute, the father of space astrometry.

His work 1964-74 led him to propose a scanning satellite with a split mirror

Design of a scanning satellite

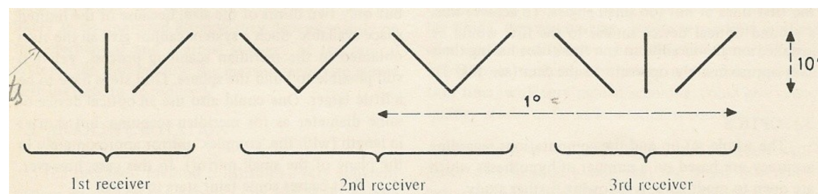


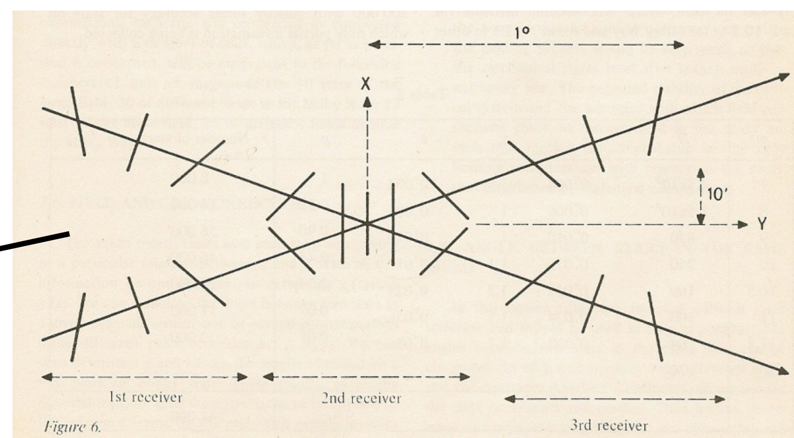


Beam combiner
3 parts
45 degrees

- 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

Beam combiners and mission

Features later adopted for Hipparcos in red, G=Gaia

- Lacroute 1965-1974:

Scanning satellite - G
with a beam combiner - G
Two-dimensional measurement
Beam combiner of 16, 5 or 3 parts
Slit systems
Only photomultiplier tubes (PMs)
Passive attitude control
Spin axis related to orbit

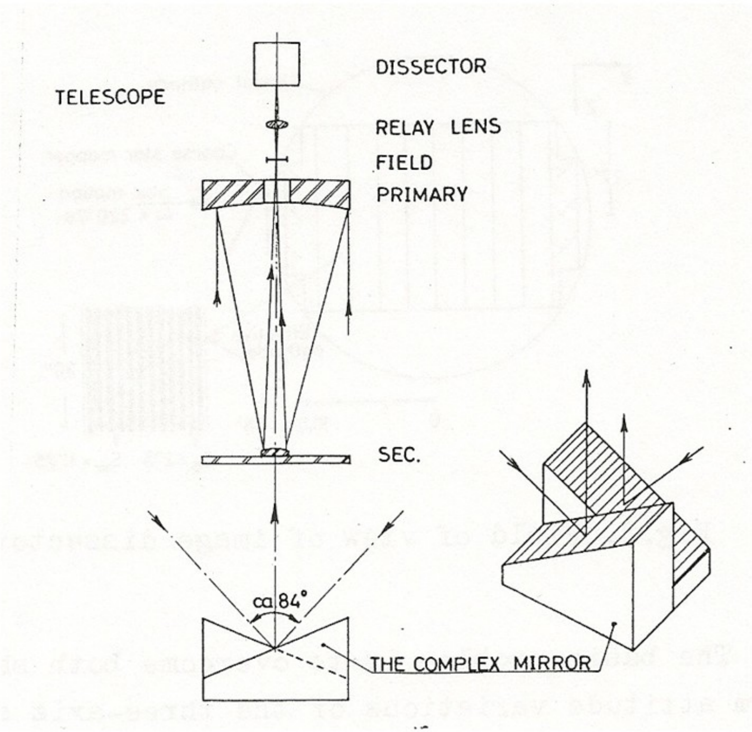
Lacroute also considered
a Spacelab option

First meeting of the ESA study group in Paris on 14 October 1975

- Høg 3 Dec. 1975:

One-dimensional measurement - G
Beam combiner of 2 parts - G
Change its angle from 45 deg – G
Active attitude control - G
Spin axis revolves around sun – G
Modulating grid
Image dissector tube
Star mapper with one PM
Input catalogue
Perhaps the best
I ever did for astronomy

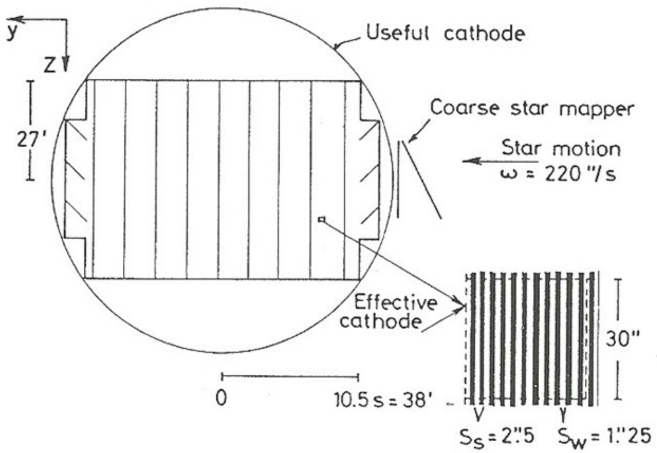
1975: Hipparcos design



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



1976: Lennart Lindegren joined

1980: Hipparcos approval, 1981: Michael Perryman project scientist

1989: Launch, 1997: Catalogue with 118 000 stars ±1 mas ±1 mas/year

2017: 2400 citations of the Hipparcos Catalogue

Prize from Astronomische Gesellschaft for Instrument Development - 2019

Erik Høg Lennart Lindegren Michael Perryman

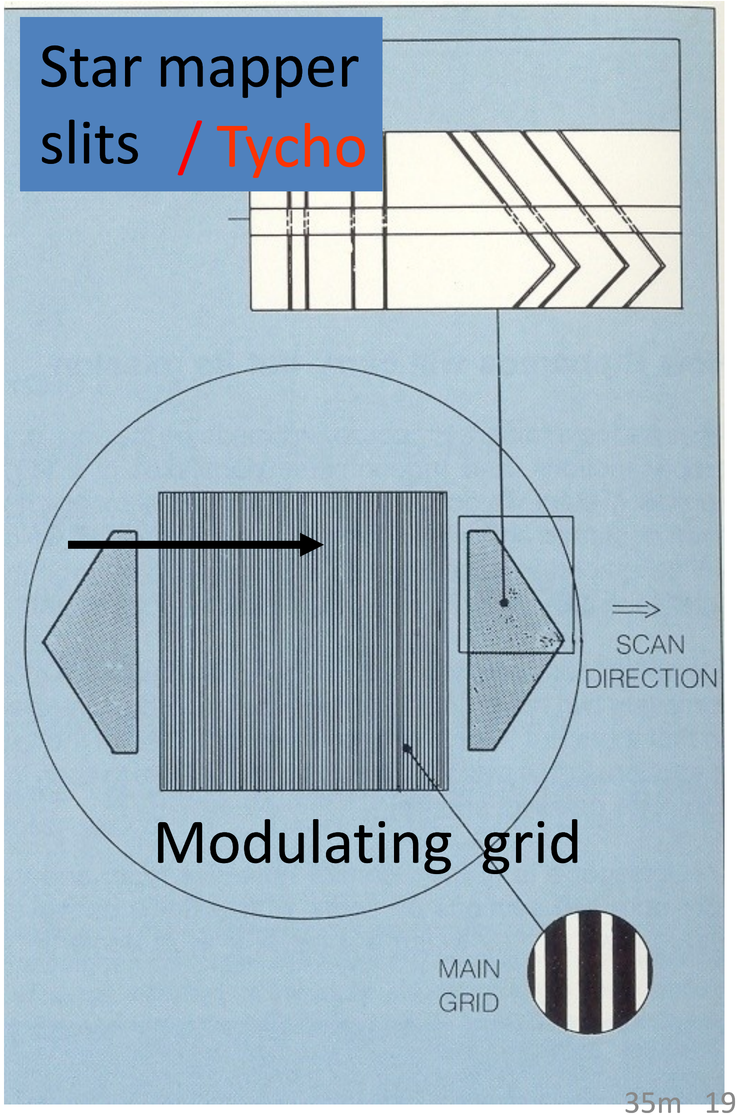
President of AG

Joachim Wambsganß

Hipparcos and Tycho 1975-2007

- Focal plane of
  Hipparcos – Tycho:

- New mission design Høg 1975
- Mission approval Feb 1980
- Tycho proposal Høg 1981
- Launch 1989
- Catalogues 1997 & 2007
- Tycho-2 Catalogue in 2000
  2.5 million stars
  2000 citations by 2020



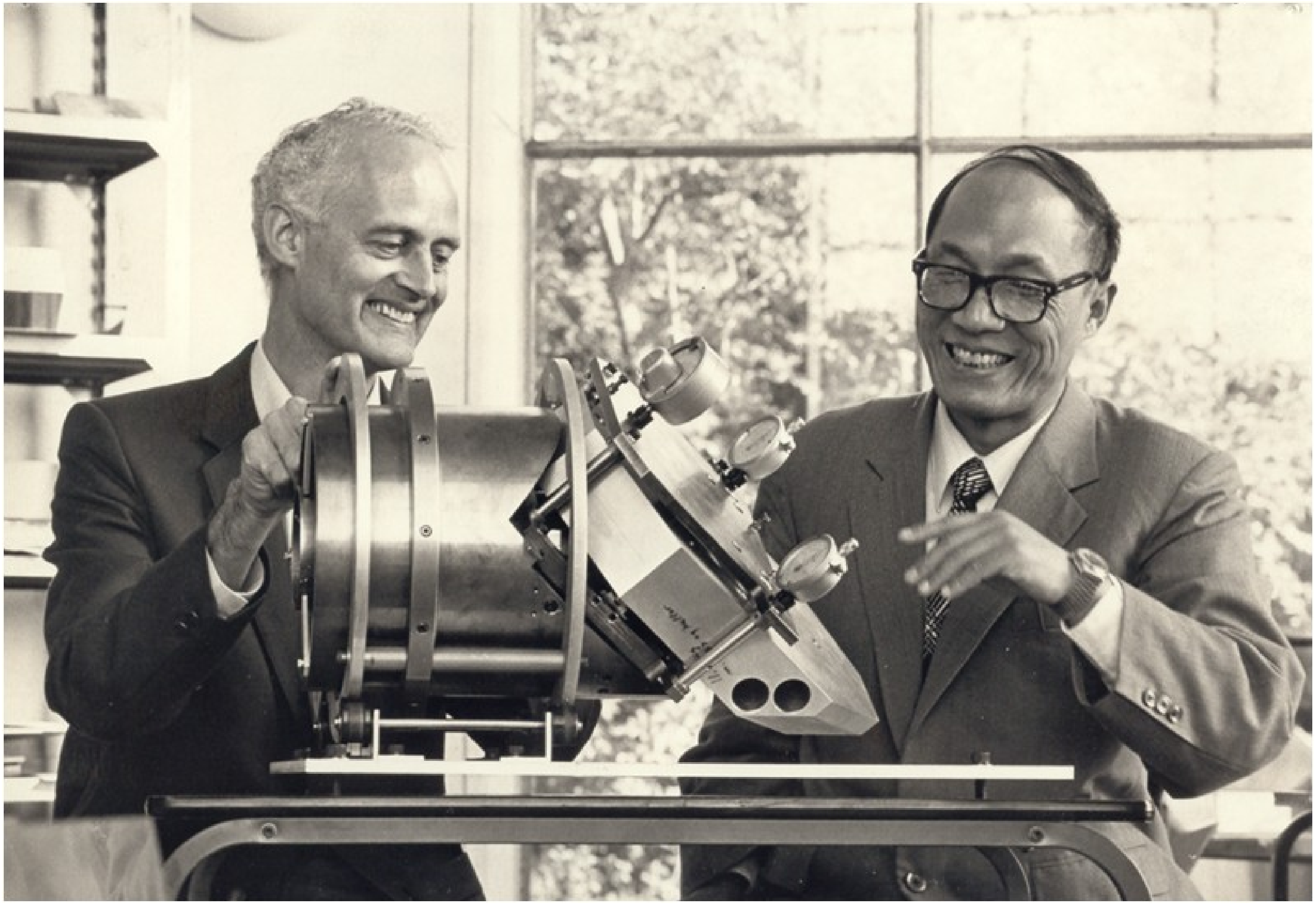
1984: At Uraniborg, Tycho Brahe's Observatory

Michael Yoshizawa Li

Lennart

1981: Model of the new type of meridian circle with Dr. Hu Ningsheng visiting from Nanjing

The idea goes back to ~1970…



1993: Meeting of the Tycho Consortium at Strasbourg Observatory

1989-92: design of a new mission in collaboration with Russian astronomers and Lennart Lindegren

Høg E. 2011, **Astrometry history: Roemer and Gaia**
http://arxiv.org/abs/1105.0879

In the USSR by 1989
three successors to Hipparcos proposed

Lomonossov : 1 m Ø, F=50 m pointing telescope 1 mas

REGATTA-ASTRO : scanning, 10 mas accuracy

AIST : 2 telescopes, 0.25 m Ø, scanning, 1 mas

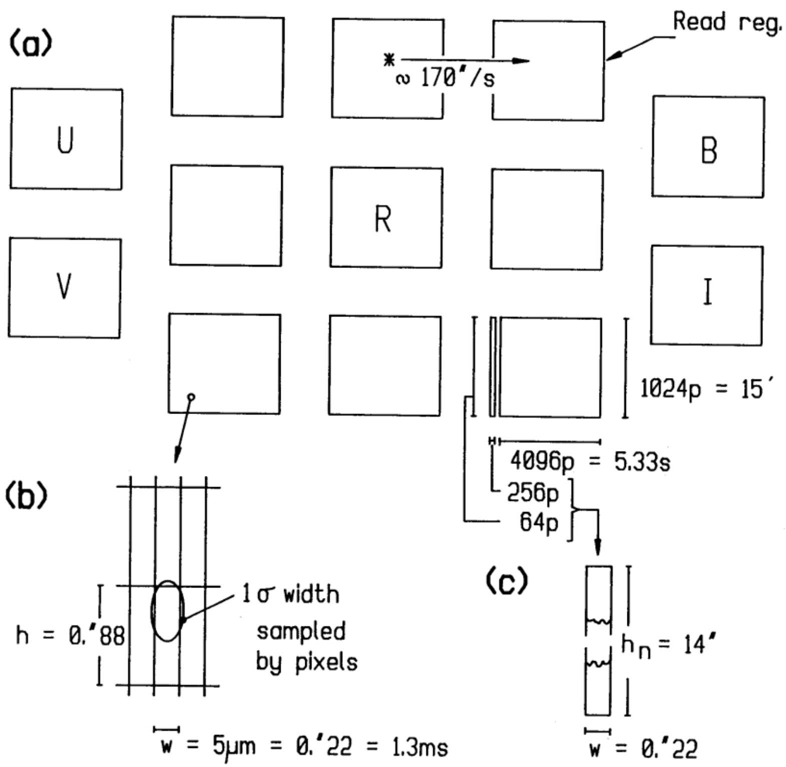
All three aimed for launch before 1997
and >1 mas accuracy – similar to Hipparcos

Aim: Get very accurate proper motions for the 100 000 Hipparcos stars

Dialogue with Russians 1990-91
Here on a visit to Copenhagen in 1991

Valeri Makarov : 7 years Tycho/Tycho-2 in Copenhagen then USA

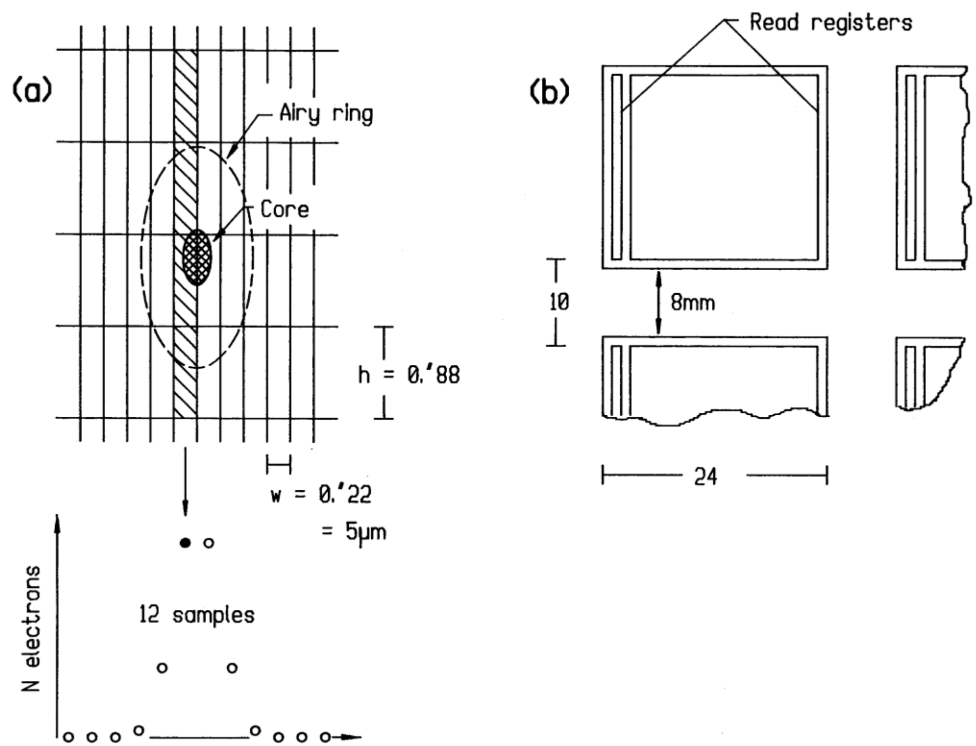
Focal plane of Roemer - Høg Sept. 1992 presented at an IAU Symposium in Shanghai



CCDs, direct imaging, elongated pixels, TDI, short CCDs for bright stars, sampling windows

Always reporting in the Hipparcos Science Team …

Sampling and CCDs

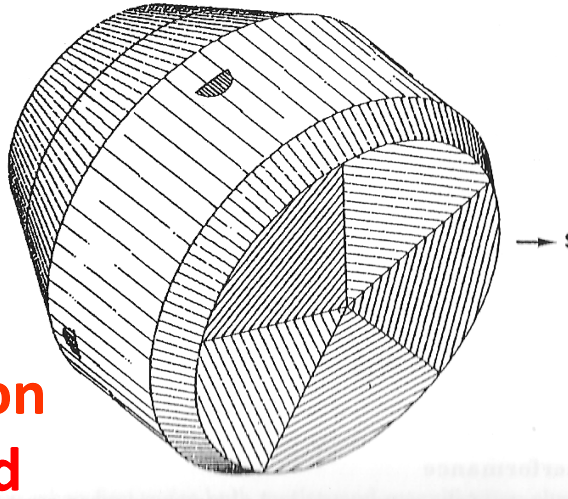


2 telescopes 26 cm Ø
5 years mission
Astrometry +-0.1 mas at 14 mag
Photometry +-0.006 mag in V …

1992: Symposium in Shanghai
Entertainment evening

Roemer mission with direct imaging on CCDs proposed by Høg in September 1992

In May 1993, Roemer was proposed as M3 mission
M3 = Third Medium Size ESA Mission
by Lindegren et al.



Proposal rated highly by the ESA advisory committees – scientifically
the highest rank of all medium-sized missions
by the Astronomy Working Group
But it was then referred to a Cornerstone Mission
if 10-20 muas could be demonstrated

- and we got that accuracy with Gaia launched in 2013

Innovations in Roemer 1992
comp. with Hipparcos and retained in Gaia

1. CCDs = high QE
2. Direct imaging, no modulation
3. Rectangular pixels corresponding to optical resolution
4. Time Delayed Integration (IDT) mode

5. Short CCDs for bright stars
6. Sampling: Windows for reading CCDs and transmission
7. Astrometry + multicolour photometry
8. Much higher accuracy ~ 10x ~ 100 muas

These 8 innovations are retained in Gaia

Roemer proposed as M3 mission in 1993

Roemer meeting March 1993 in Copenhagen : *Kovalevsky, Lindegren, Halbwachs, Makarov, Høg, van Leeuwen, Knude – missing here: Bastian, Gilmore, Labeyrie, Pel, Schrijver, Stabell, Thejll*

1999: Hipparcos consortia leaders receive the ESA Director of Science Medal *for outstanding contribution to the science programme*

Catherine Turon Jean Kovalevsky Lennart Lindegren Erik Høg

1993-98 Optical interferometry

September 1993: GAIA proposed by Lindegren & Perryman

We all believed in interferometry for space astrometry

ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

MAY I **1996**, PAGE 579

Astron. Astrophys. Suppl. Ser. **116,** 579-595 (1996)

GAIA: Global astrometric interferometer for astrophysics

L. Lindegren[1] and M.A.C. Perryman[2,3]

[1] Lund Observatory, Box 43, S-22100 Lund, Sweden
[2] Astrophysics Division, European Space Agency, ESTEC, Noordwijk 2200AG, The Netherlands
[3] Sterrewacht Leiden, Postbus 9513, 2300RA Leiden, The Netherlands

Received July 11; accepted October 4, 1995

1998: Study by industry taught us it was ***not good at all !***

We then returned to ***direct imaging on CCDs as in Roemer***

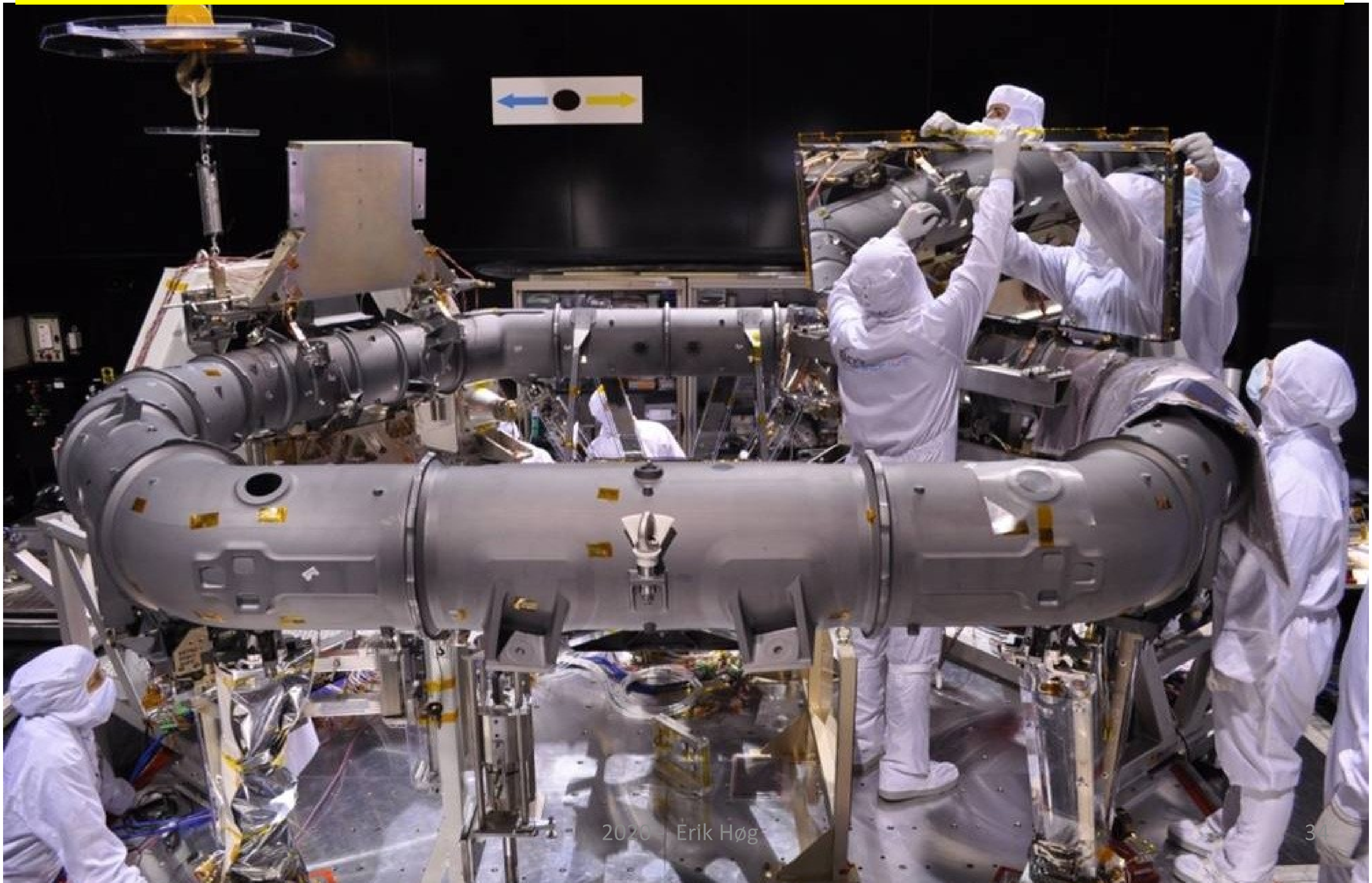
Høg E. 2014, **Interferometry from Space: A Great Dream**. In: Asian Journal of Physics Vol. 23, Nos 1 & 2 (2014), Special Issue on History of Physics & Astronomy, Guest Editor: Virginia Trimble. http://arxiv.org/abs/1408.4668

1995-2007: Design of Gaia

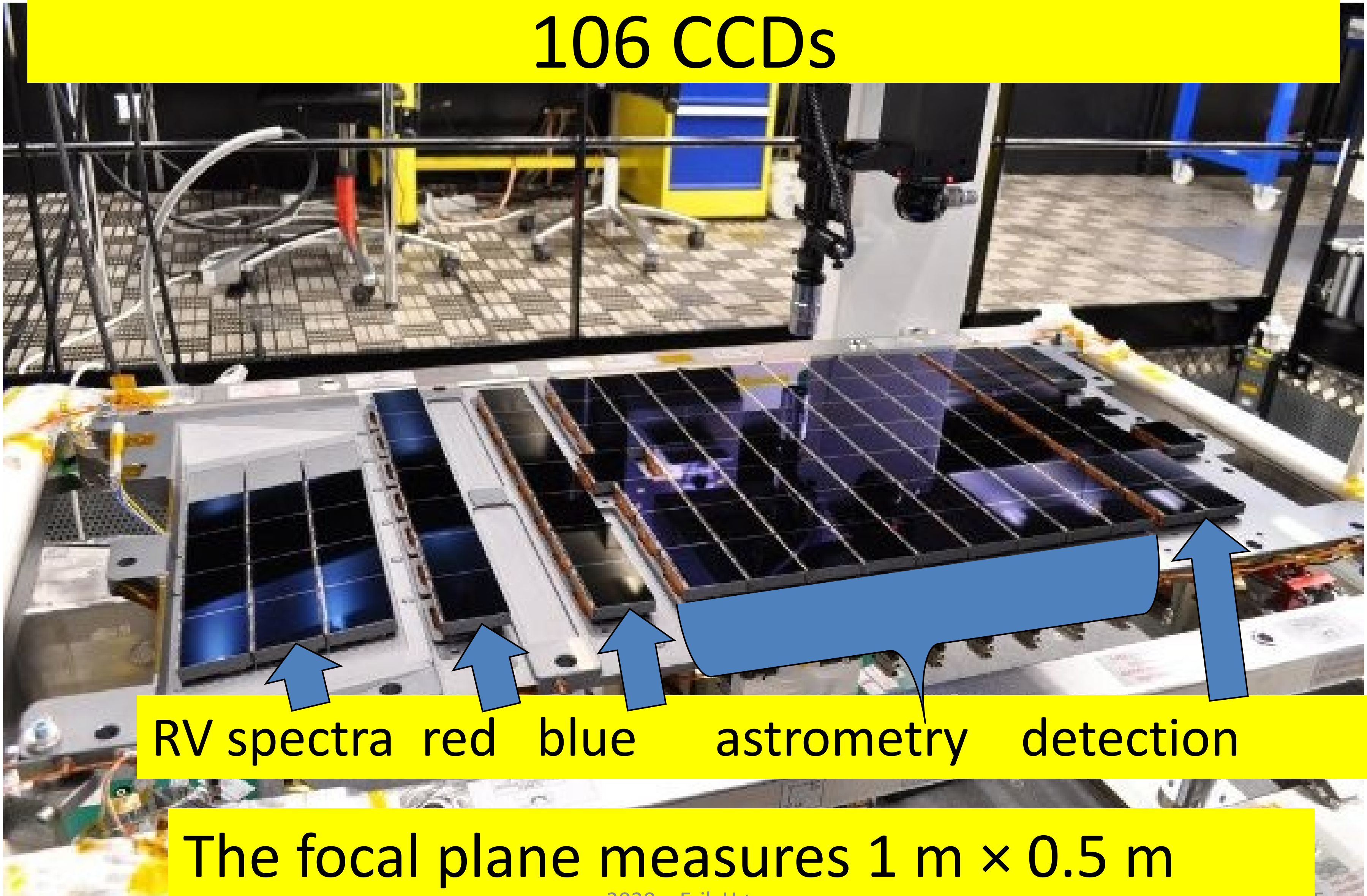
Here only some of my own work:

- Defined science cases: Galactic objects as a function of magnitude; Astrometric microlensing;…
- Designed 1995 a new optical **interferometric** system for GAIA
- This design was adopted by **Ulrich Bastian** for the **German DIVA mission**
- Served as member of the Gaia Science Teams chaired by **Michael Perryman**
- Was leader of the Photometry Working Group
- Designed the sampling of data from CCDs for mapping

Gaia M1 and torus 2011

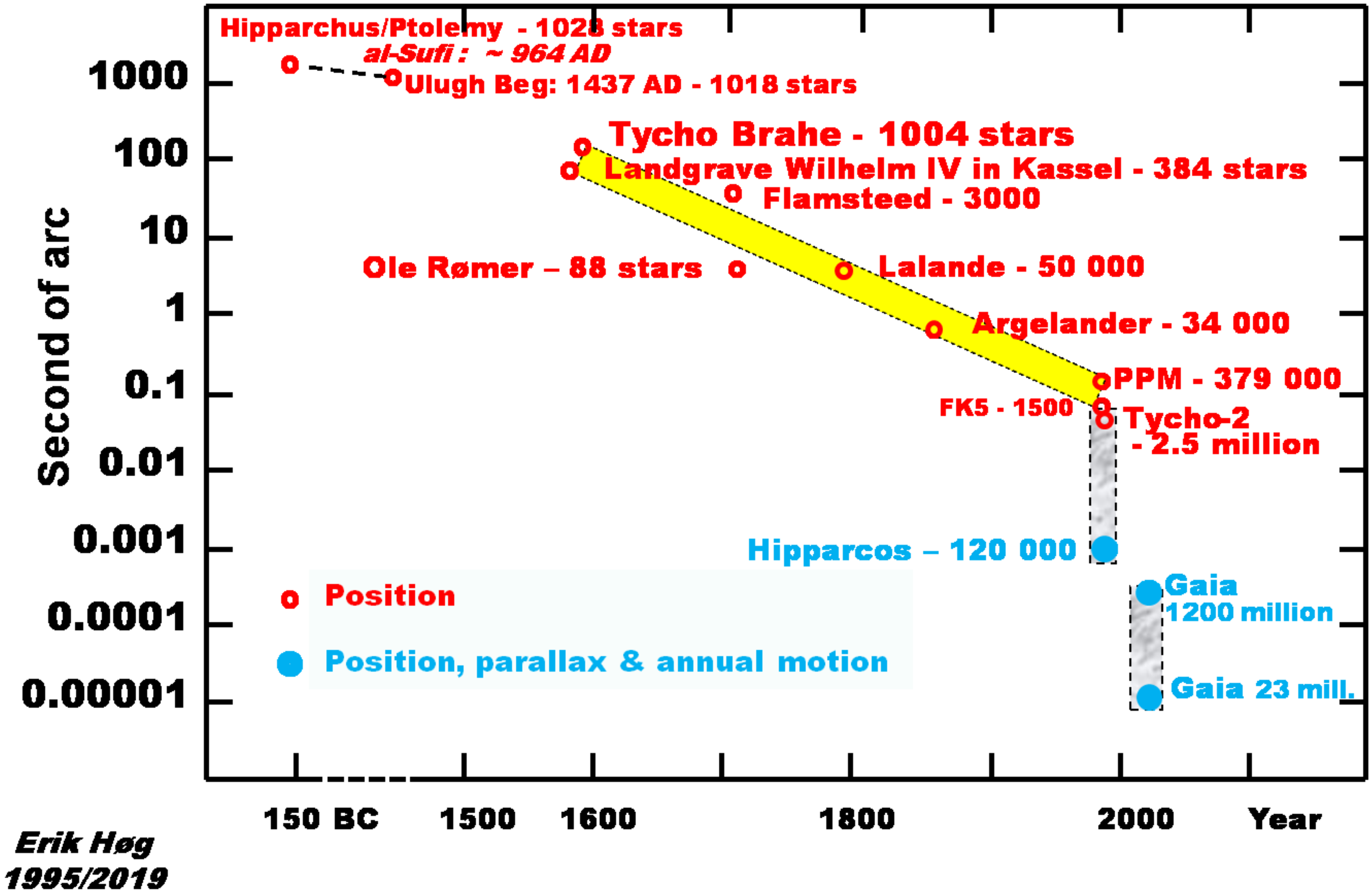


Gaia focal plane June 2011
106 CCDs



The focal plane measures 1 m × 0.5 m

Astrometric Accuracy during 2000 Years



2013: Gaia successor in 20 years

Similar astrometric performance as Gaia

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

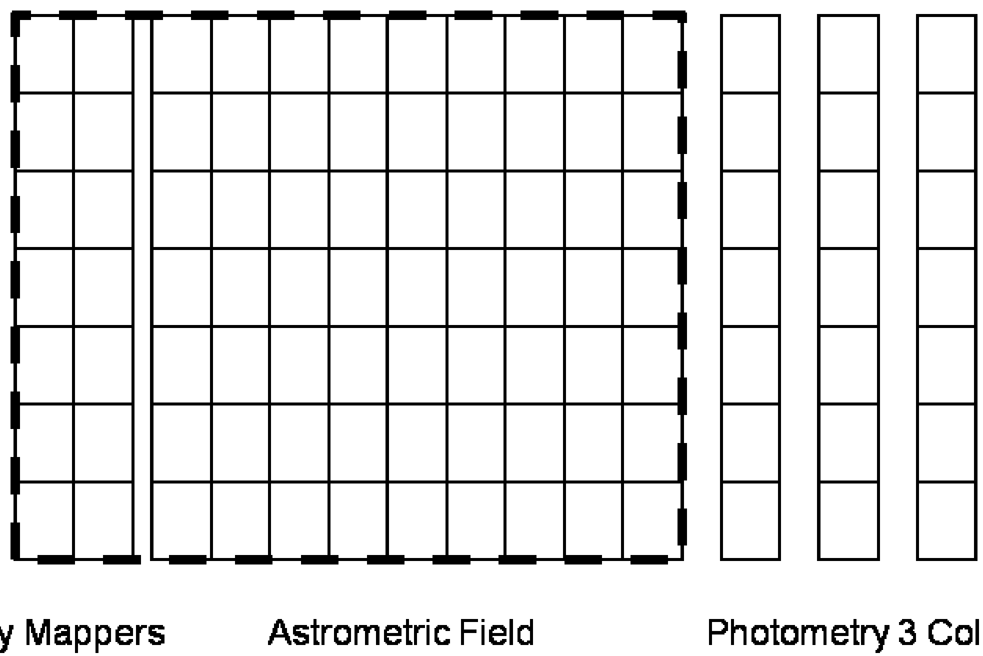
Parallaxes unaffected by motion in binaries

High-resolution photometry 140 mas FWHM

Altogether:

A new astrometric foundation of astrophysics

Gaia Successor Focal Plane



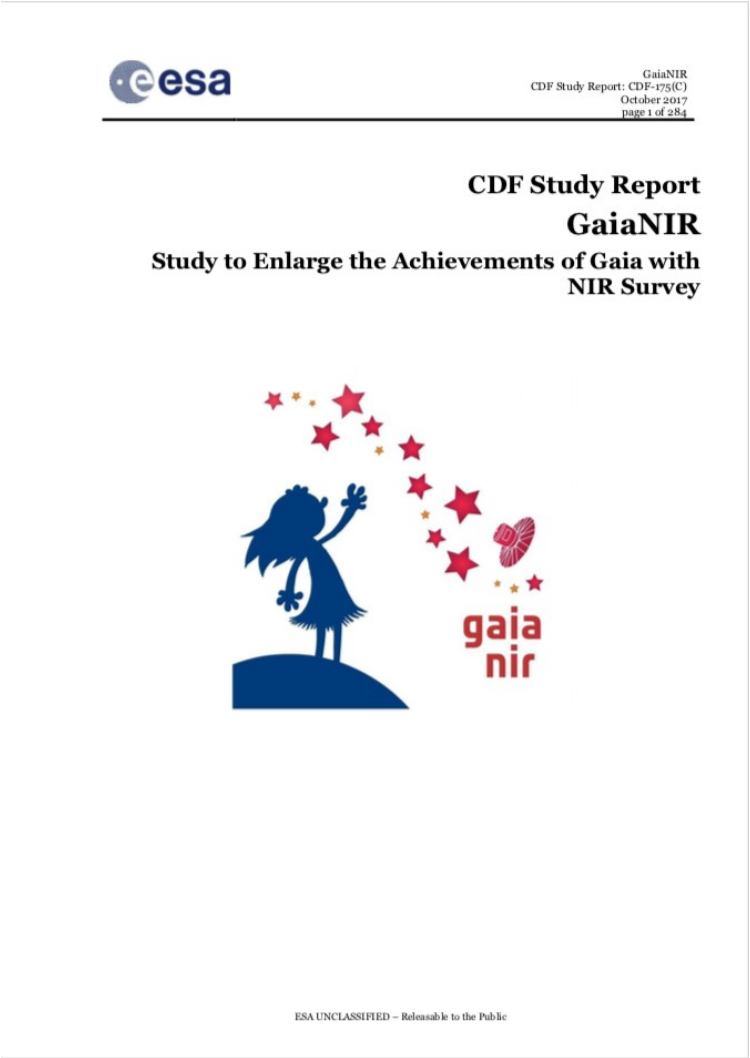
Sky mappers and astrometric CCDs inside the dashed rectangle are the same as in Gaia

Filter photometry with 3 bands

Erik Høg 2014

Technology Proposal

- In 2016 ESA announced a call for new and innovative science ideas for future space missions.
- 26 proposals were received and 3 were selected for further study - including NIR global astrometry.
- In late 2017 ESA conducted a Concurrent Design Facility (CDF) study of our proposal and the results were published in early 2018.



esa

GaiaNIR
CDF Study Report: CDF-175(C)
October 2017
page 1 of 284

CDF Study Report

GaiaNIR

Study to Enlarge the Achievements of Gaia with NIR Survey

gaia nir

ESA UNCLASSIFIED – Releasable to the Public

ESA Telescope

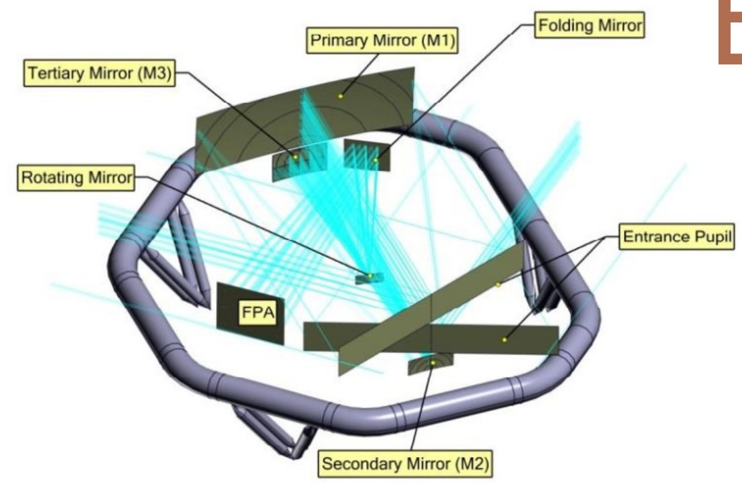


Figure 5-34: GaiaNIR optical surfaces and the light path

GaiaNIR is based on a off-axis f=35m Korsch telescope as is Gaia, but differs in:

- The mirror surfaces are simple conics to simplify manufacturing, alignment and test.
- Entrance pupil is at a flat folding mirror in front of the primary instead of on the primary mirror itself.

The optical path of the telescope is composed of:

- Primary mirror
- Secondary mirror
- Tertiary mirror
- 4x Flat mirrors:
  1) At the entrance pupil (2 defining the BA)
  2) Folding mirror (after the exit pupil).
  3) At the exit pupil (de-spin mirror)

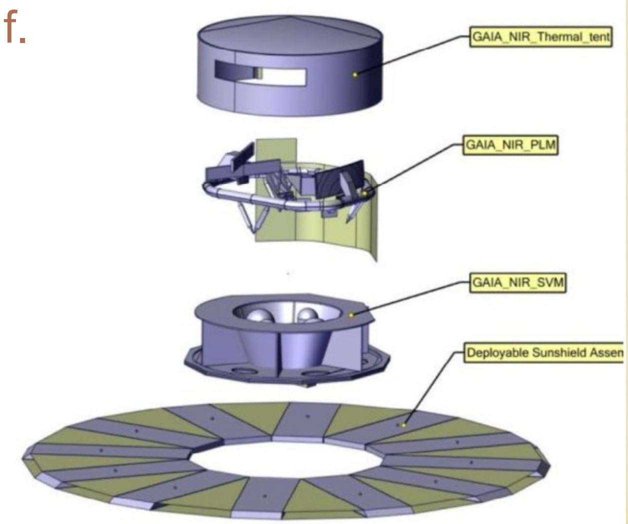
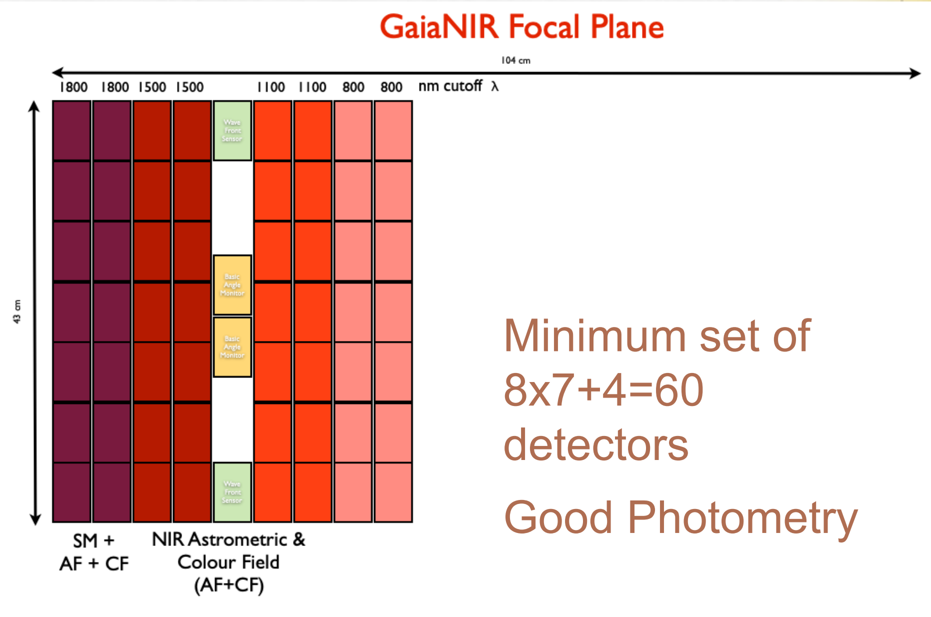


Figure 6-2: Gaia-NIR Spacecraft main elements

Detectors & filters

- NIR sensors (400–2500 nm) were considered with and without TDI mode. HgCdTe (MCT) materials are most promising for Optical and NIR sensors.
    - **Electron initiated Avalanche PhotoDiodes (e-APDs)**
    - Charge generation in MCT - silicon substrate for charge accumulation and transfer to next pixel - readout only occurs once at the end of pixel transfers.
- **Cooling strategy must be passive (~80K).**
- Focal plane with just one type of detector with different λ cutoffs.
- No SMs - track motion of stars instead
- Filter photometry 4-band -
    - λmin = 400nm (substrate removal)
    - λmax= (800, 1100, 1500, 1800) nm cutoff.
- No Spectrograph !



2014: Gaia successor with NIR for obscured regions and red objects

Until 2018 we thought of an ESA-only mission but…

2019: International GaiaNIR with partners in ESA, USA, Japan and Australia proposed to ESA for study:

Hobbs D. et al. 2019 **arXiv:1907.12535**

Høg, E., Hobbs, D. 2019, **Gaia Successor with International Participation.** Five pages at http://www.astro.ku.dk/~erik/xx/GaiaSucc2019.pdf

A new reference and a note on astrometry

Gaia successor with NIR

Hobbs D., Brown A., Høg E., ... Vaccari M (30 authors) 2021,
All-sky visible and near infrared space astrometry.
In: Experimental Astronomy, 61 pp
At: https://doi.org/10.1007/s10686-021-09705-z or as a PDF
here https://link.springer.com/content/pdf/10.1007/s10686-021-09705-z.pdf.

This presentation was focused on
absolute optical astrometry from space
Other kinds of high-precision astrometry are also important:
Radio astrometry by interferometry
Relative astrometry e.g. with HST, the Hubble Space Telescope