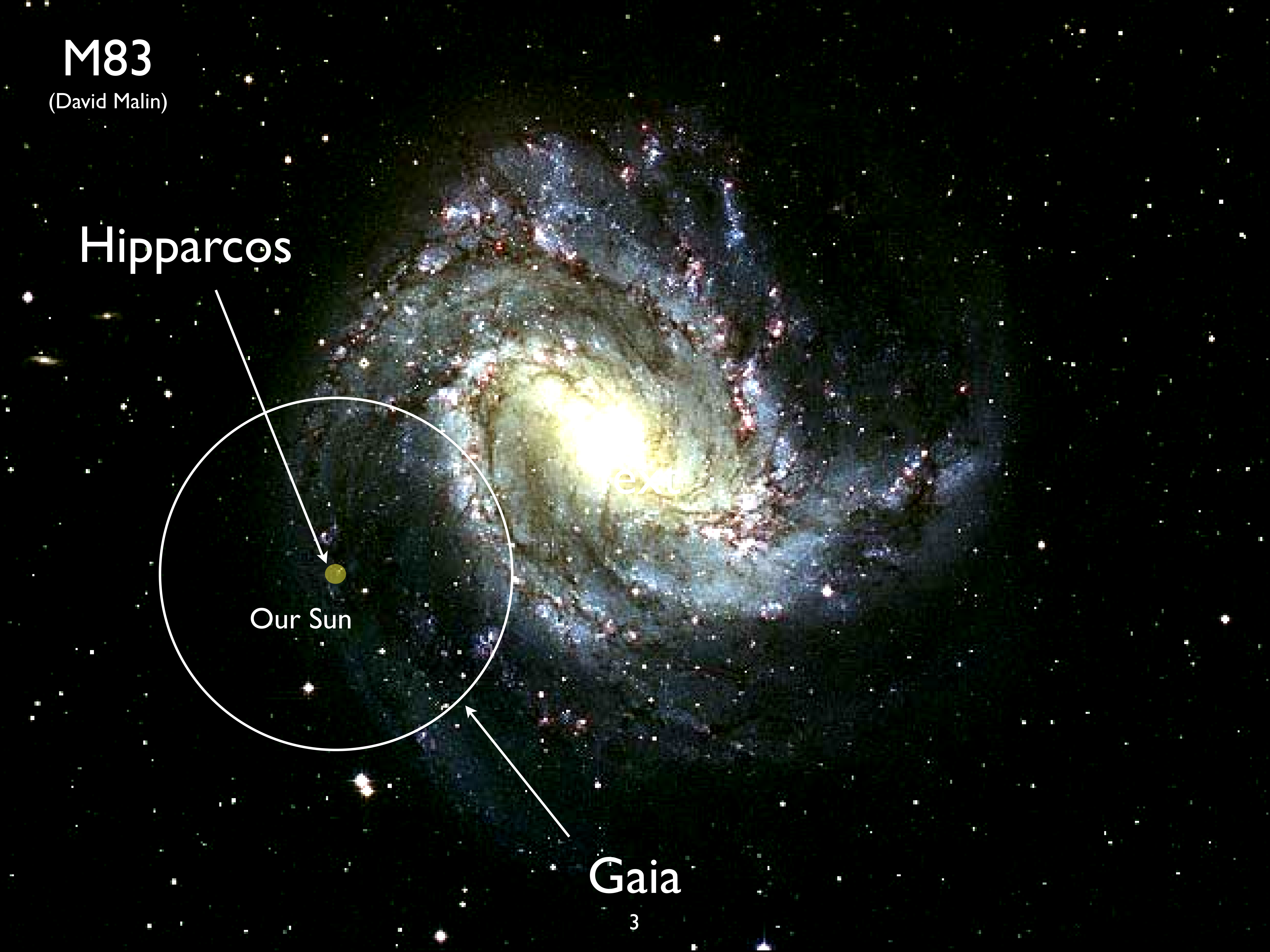
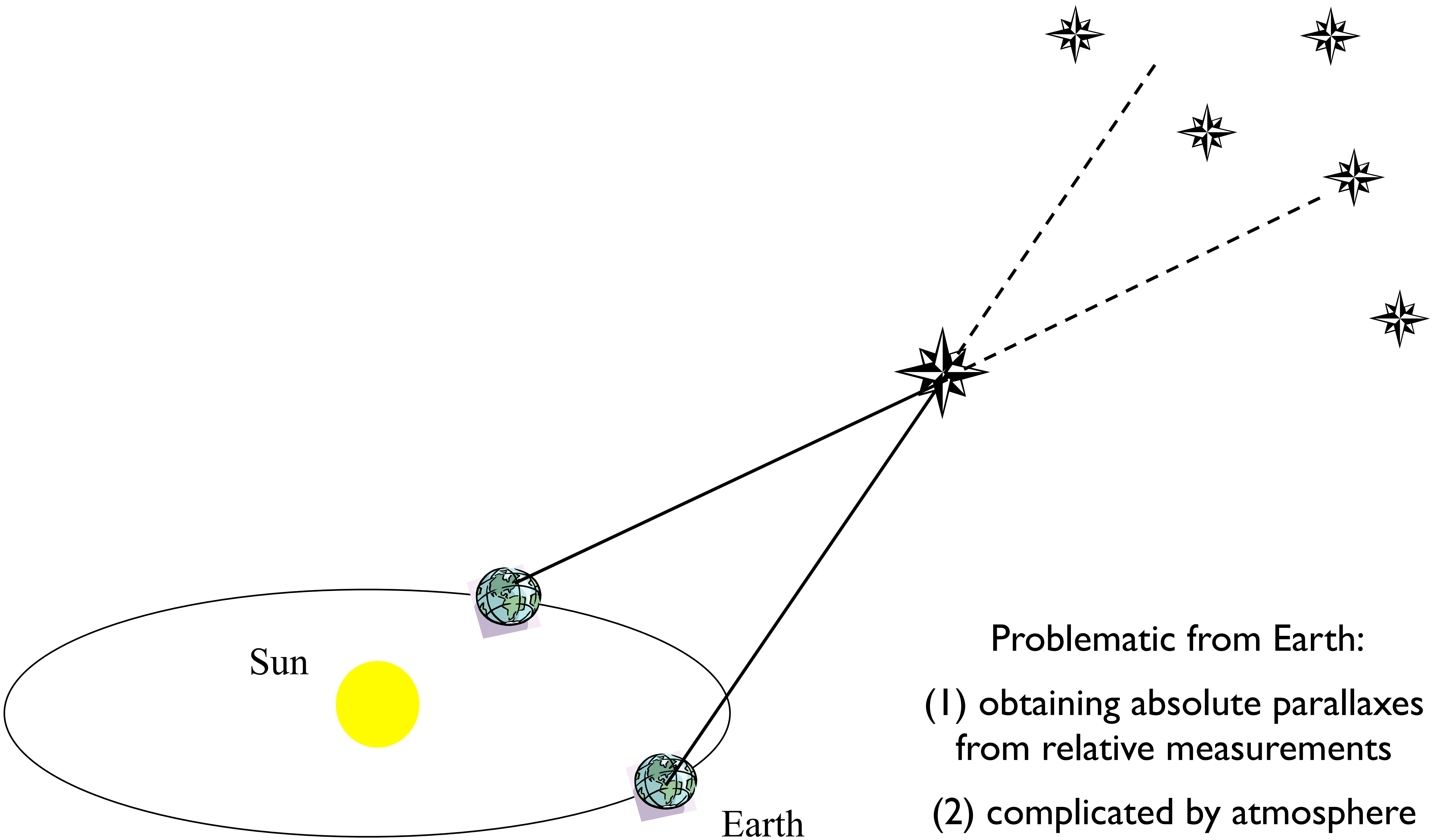
Principles and design of Hipparcos and Gaia

Michael Perryman

(Erlangen, 8-10 October 2014)


M83
(David Malin)
Hipparcos
Our Sun
Gaia

Parallax measurement principle…



Problematic from Earth:

(1) obtaining absolute parallaxes from relative measurements

(2) complicated by atmosphere [+ thermal/gravitational flexure]

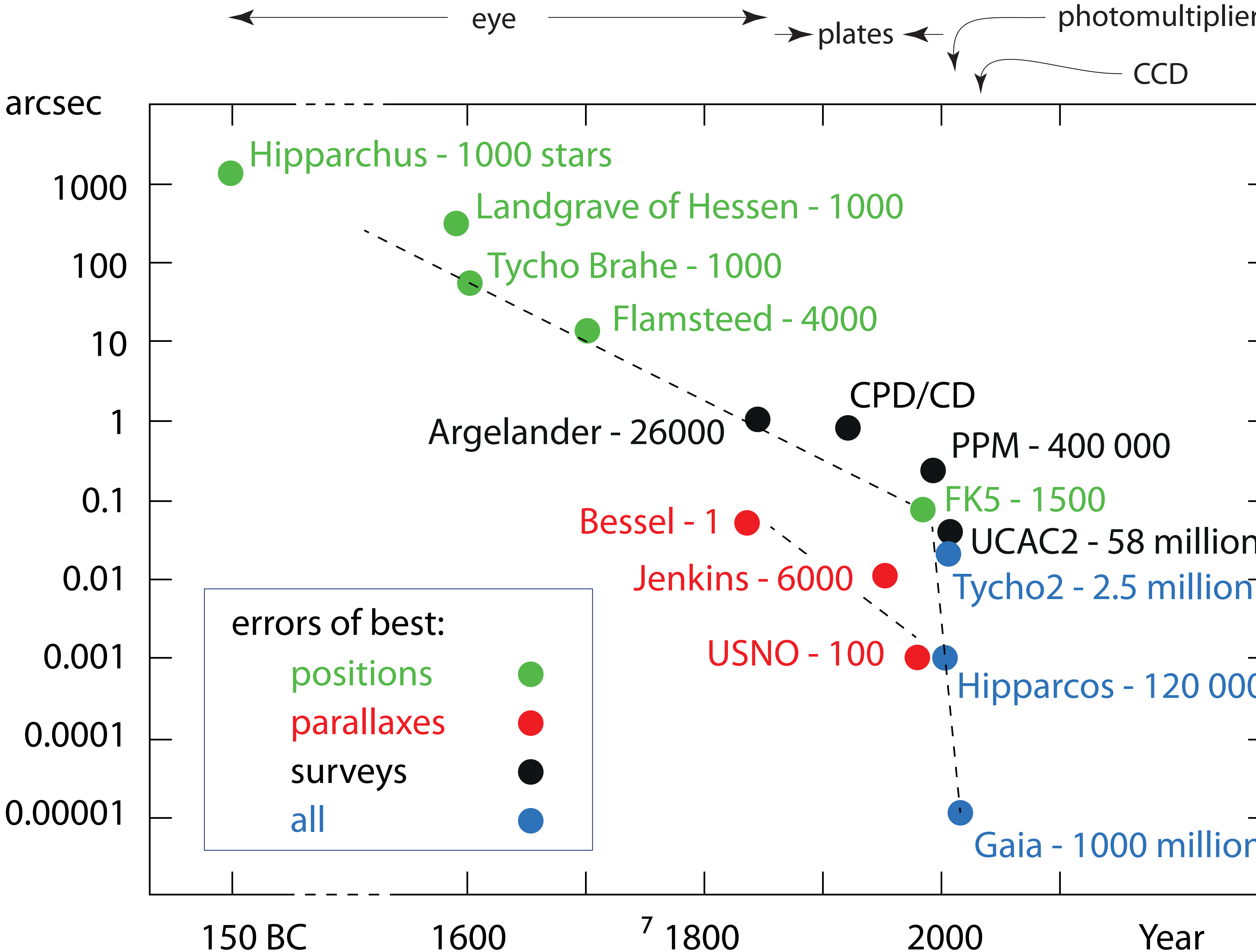
(3) no all-sky visibility

Some history: the first 2000 years

- 200 BC (ancient Greeks):
    - size and distance of Sun and Moon; motion of the planets
- 900–1200: developing Islamic culture
- 1500–1700: resurgence of scientific enquiry:
    - Earth moves around the Sun (Copernicus), better observations (Tycho)
    - motion of the planets (Kepler); laws of gravity and motion (Newton)
    - navigation at sea; understanding the Earth's motion through space
- 1718: Edmond Halley
    - first to measure the movement of the stars through space
- 1725: James Bradley measured stellar aberration
    - Earth's motion; finite speed of light; immensity of stellar distances
- 1783: Herschel inferred Sun's motion through space
- 1838–39: Bessell/Henderson/Struve − the first parallaxes
- 1880–1990: photographic and meridian circle catalogues

The History of Astrometry, Perryman 2012: European Physical Journal H37, 745-792

Accuracy over time



Over the last 100 years, bigger telescopes measure:

- fainter stars (billions)
- more star motions (millions)
- more star distances (few thousand)

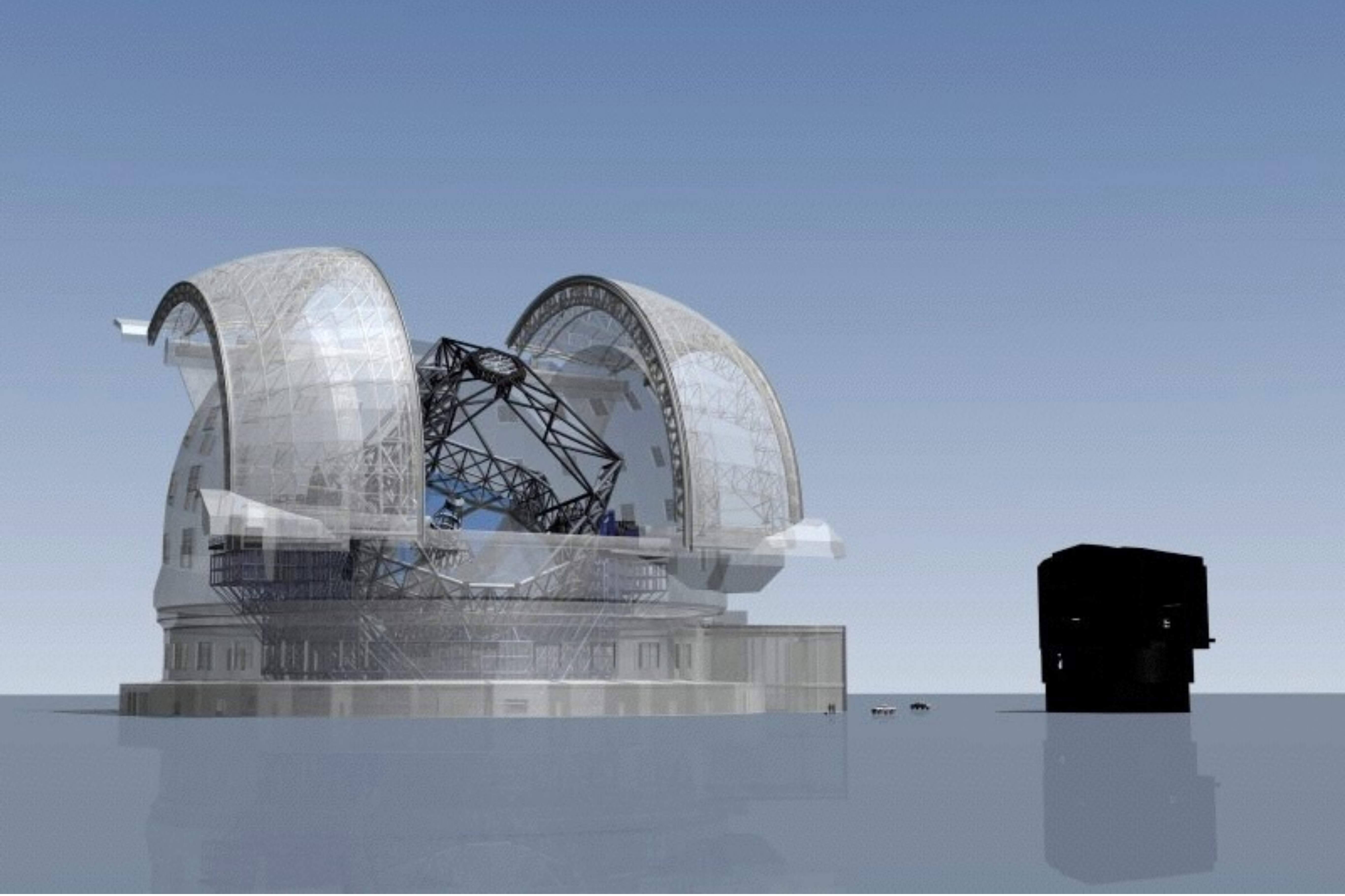
The Astrographic Catalogue 1887 – 1930/1964

...measurements made and recorded by hand!

Yerkes refractor
~ 1900

Schmidt telescopes ~1950–1980

European Southern Observatory, Chile ~2000

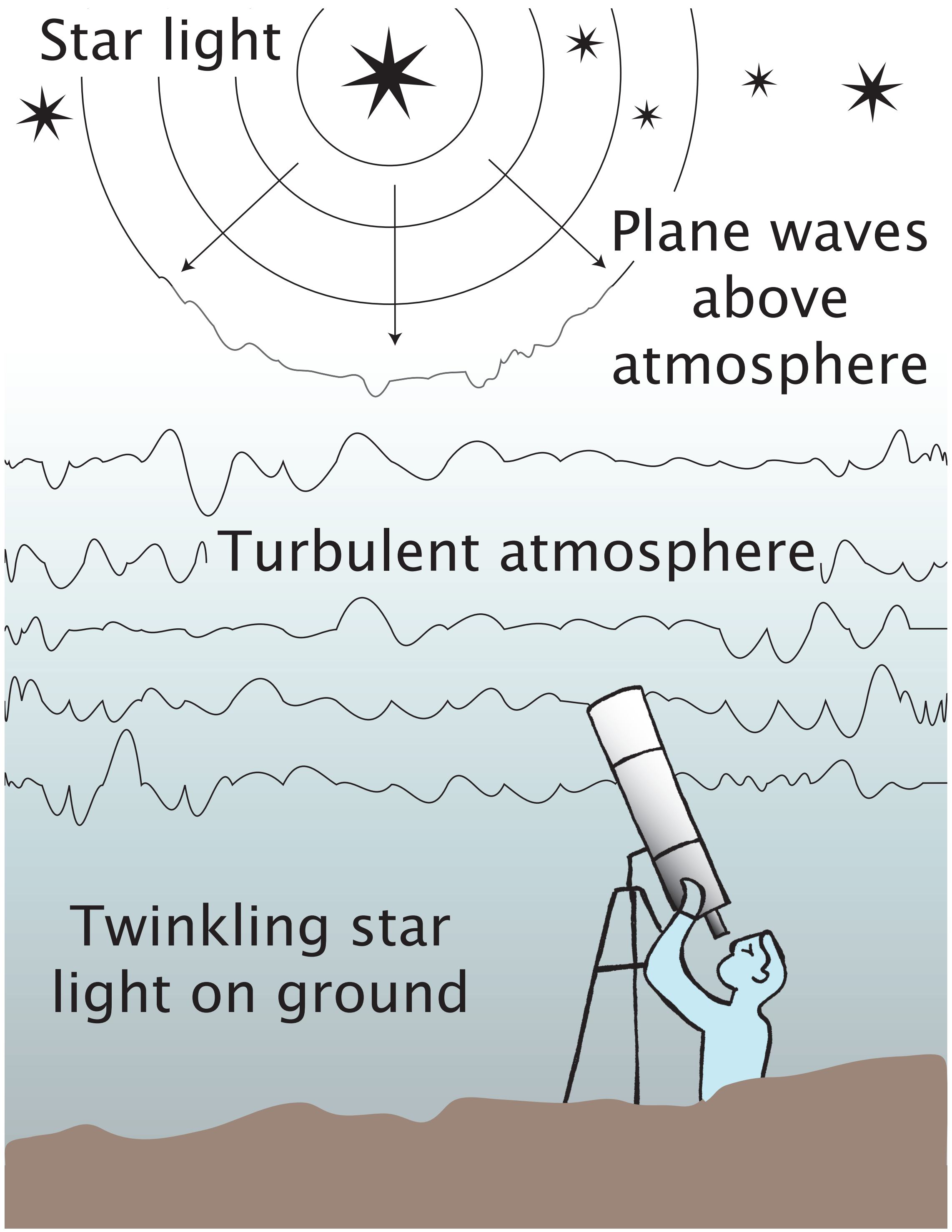


European ELT (Extremely Large Telescope) ~ 2020

...but it remains all but impossible to measure star distances from Earth, beneath its phase-perturbing atmosphere...

Stellar Distances and Motions: principles and numbers

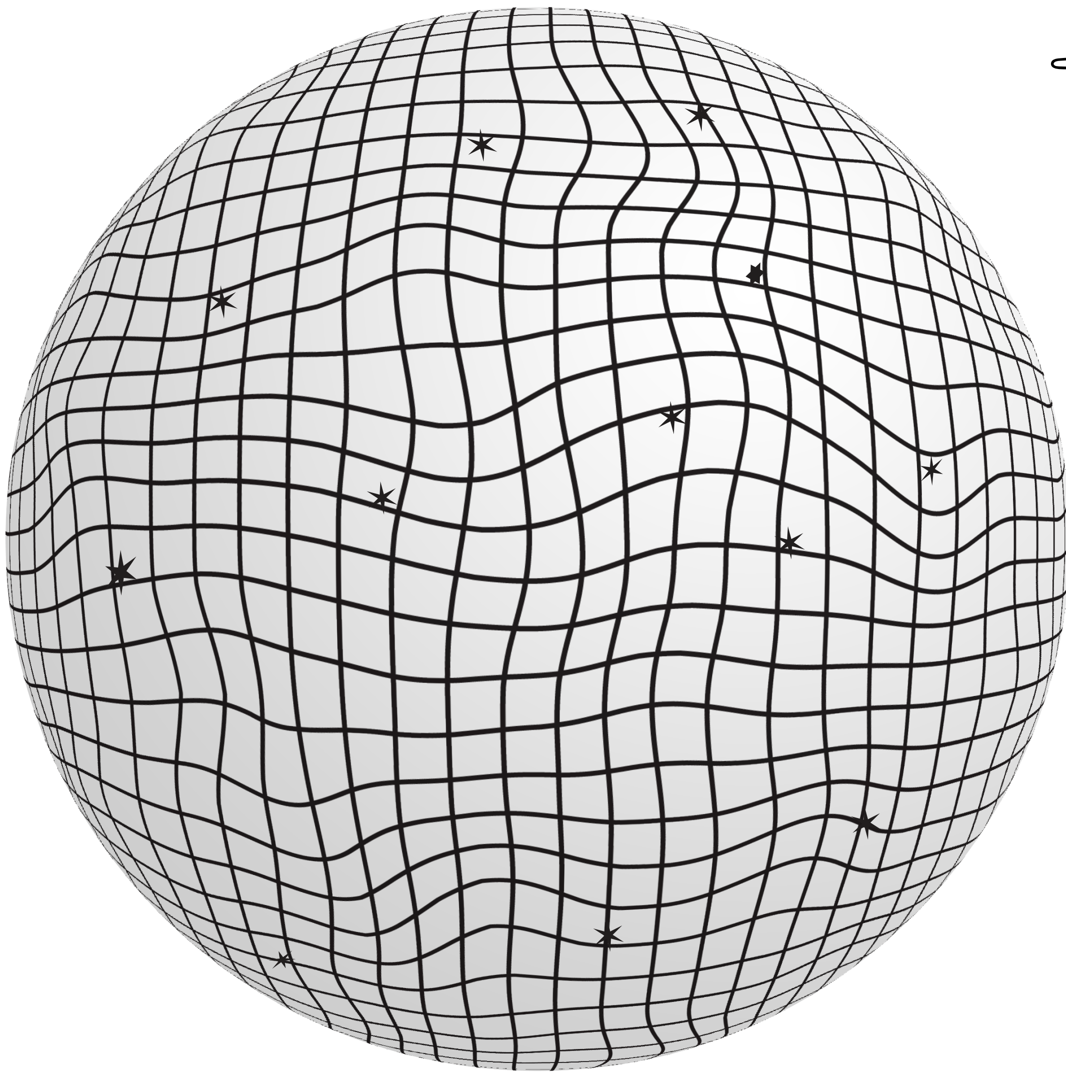
- star distances are determined trigonometrically, using Earth's annual orbit around the Sun as baseline
(INPOP06: 149 597 870 691 m, recently defined by IAU as 149 597 870 700 m)
- star distance of 1 pc gives a parallax of 1 arcsec
- nearest star is ~1 pc ≈ 3.26 light years = 3×10^{16} m
- Galactic centre ≈ 8 kpc ≈ 30,000 light years; requires 10 μas at 10% accuracy
- stars move through space at ~30 km/s, equivalent to ~0.1 arcsec/yr at a distance of 100 pc



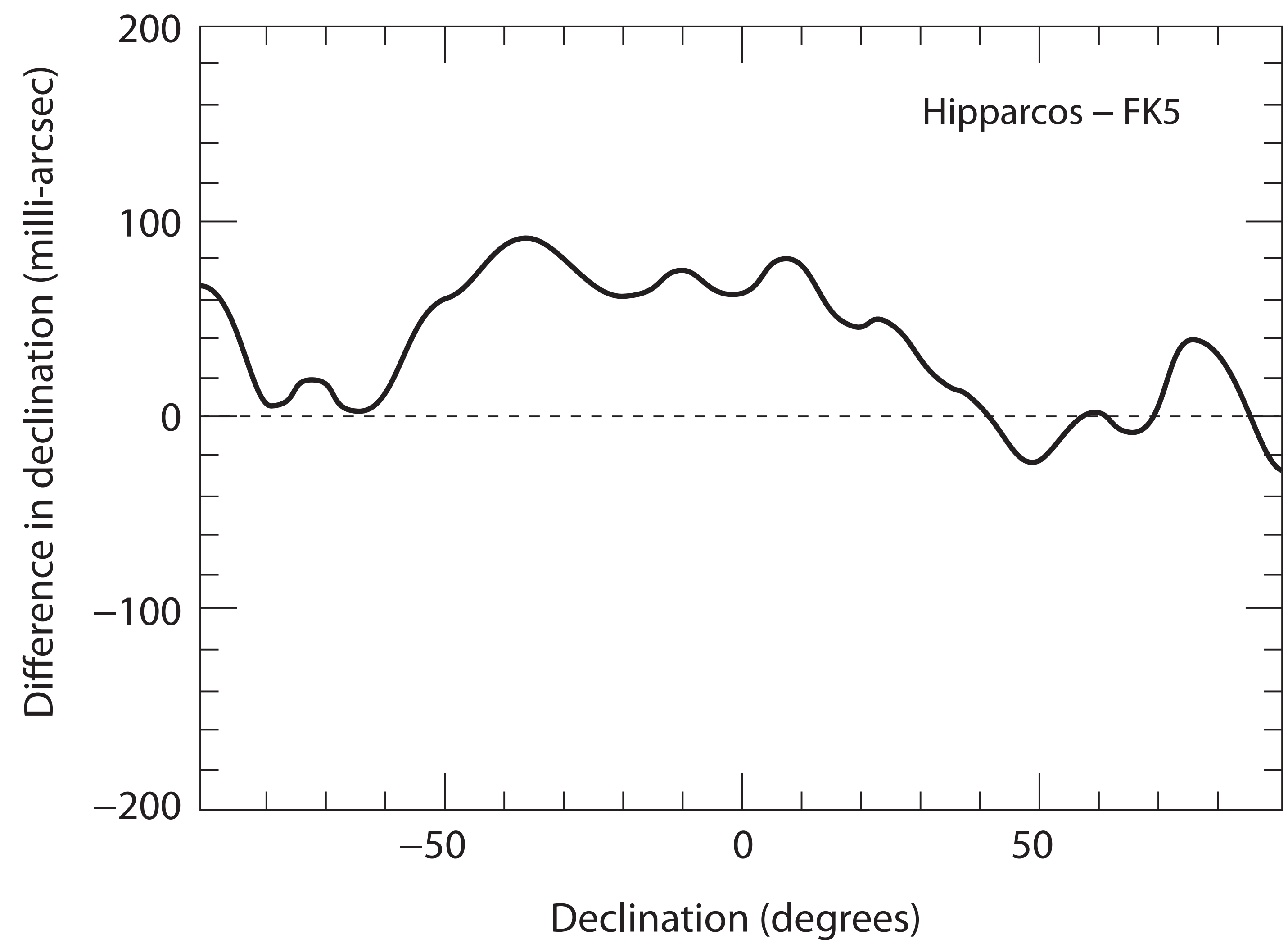
This is the problem...

These are the angles...

☞ schematic of a distorted reference frame



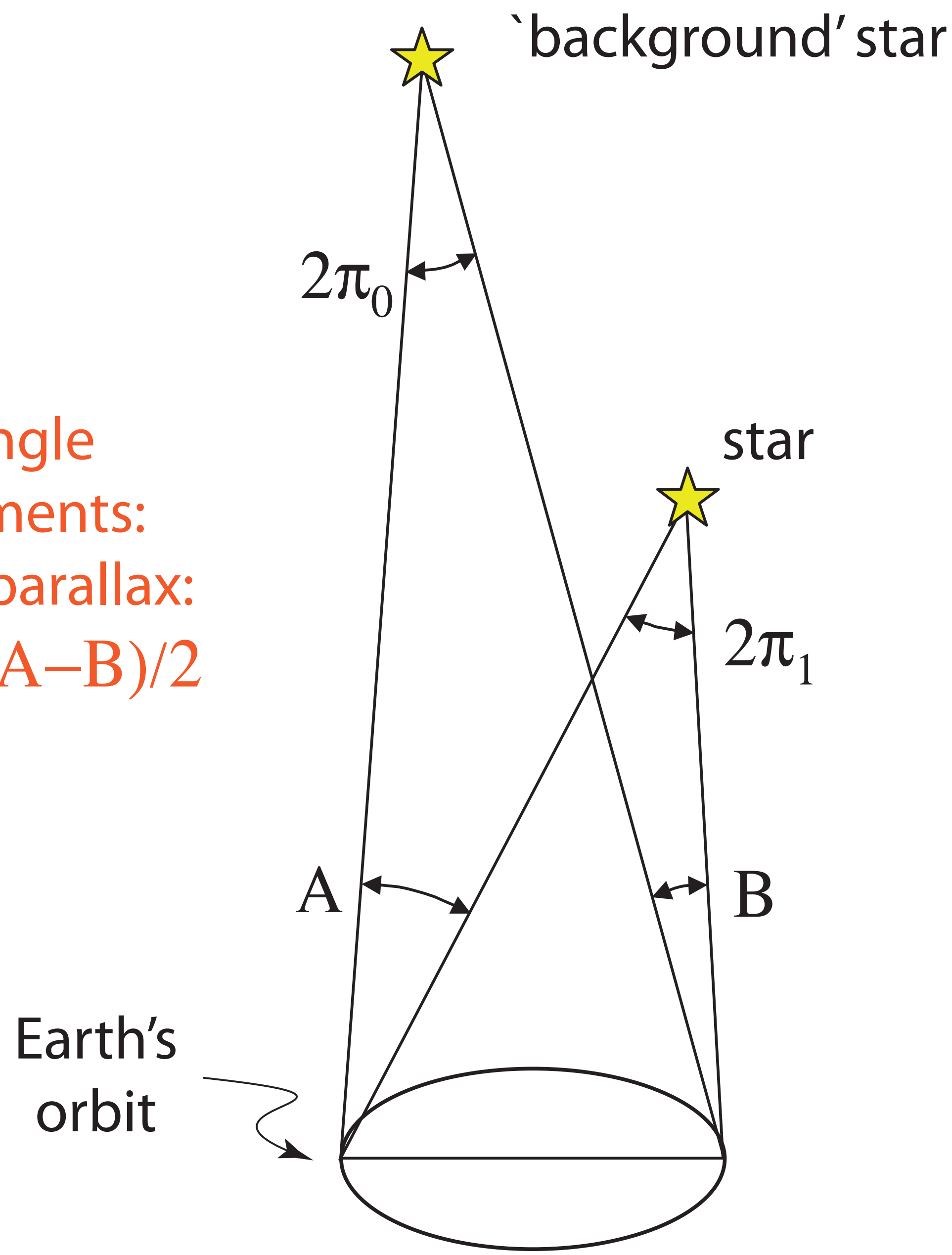
...it has proven impossible to eliminate these local distortions from small field observations (photographic plate or CCD), even using the method of 'block adjustment' (Eichhorn 1988)



Hipparcos − ground-based (FK5) systematic errors (Schwan 2002)

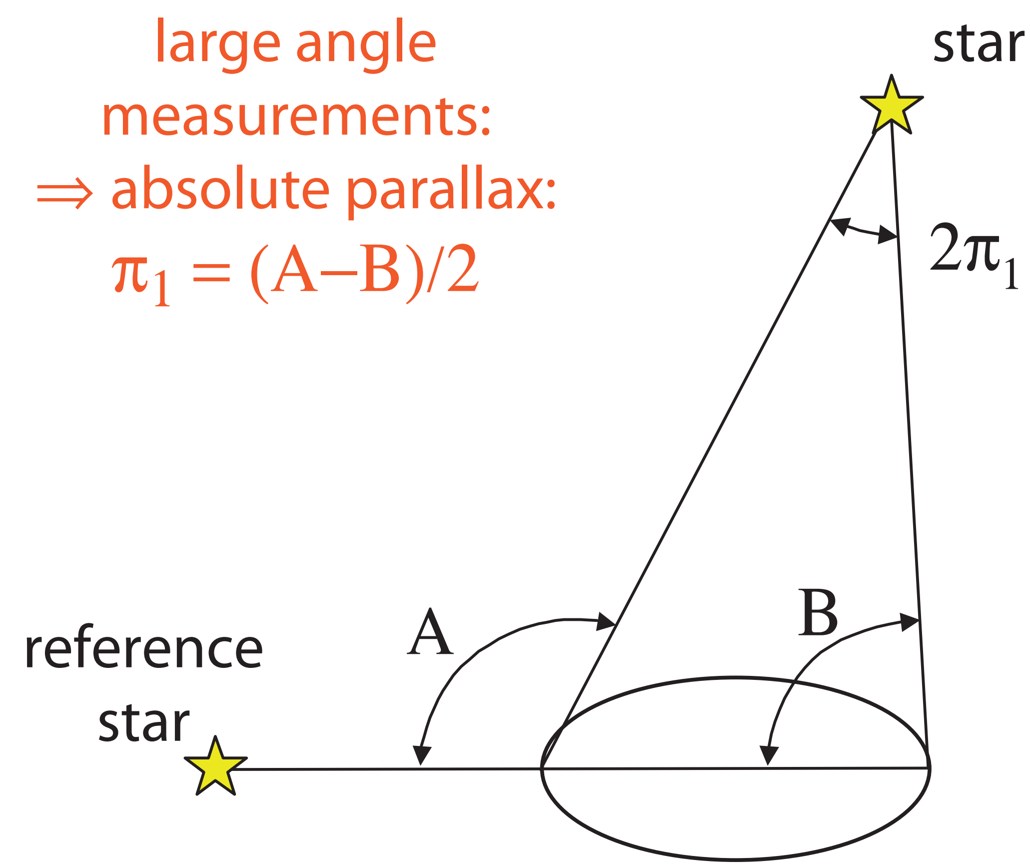
Measurement principle

small angle measurements:
⇒ relative parallax:
$\pi_1 - \pi_0 = (A{-}B)/2$



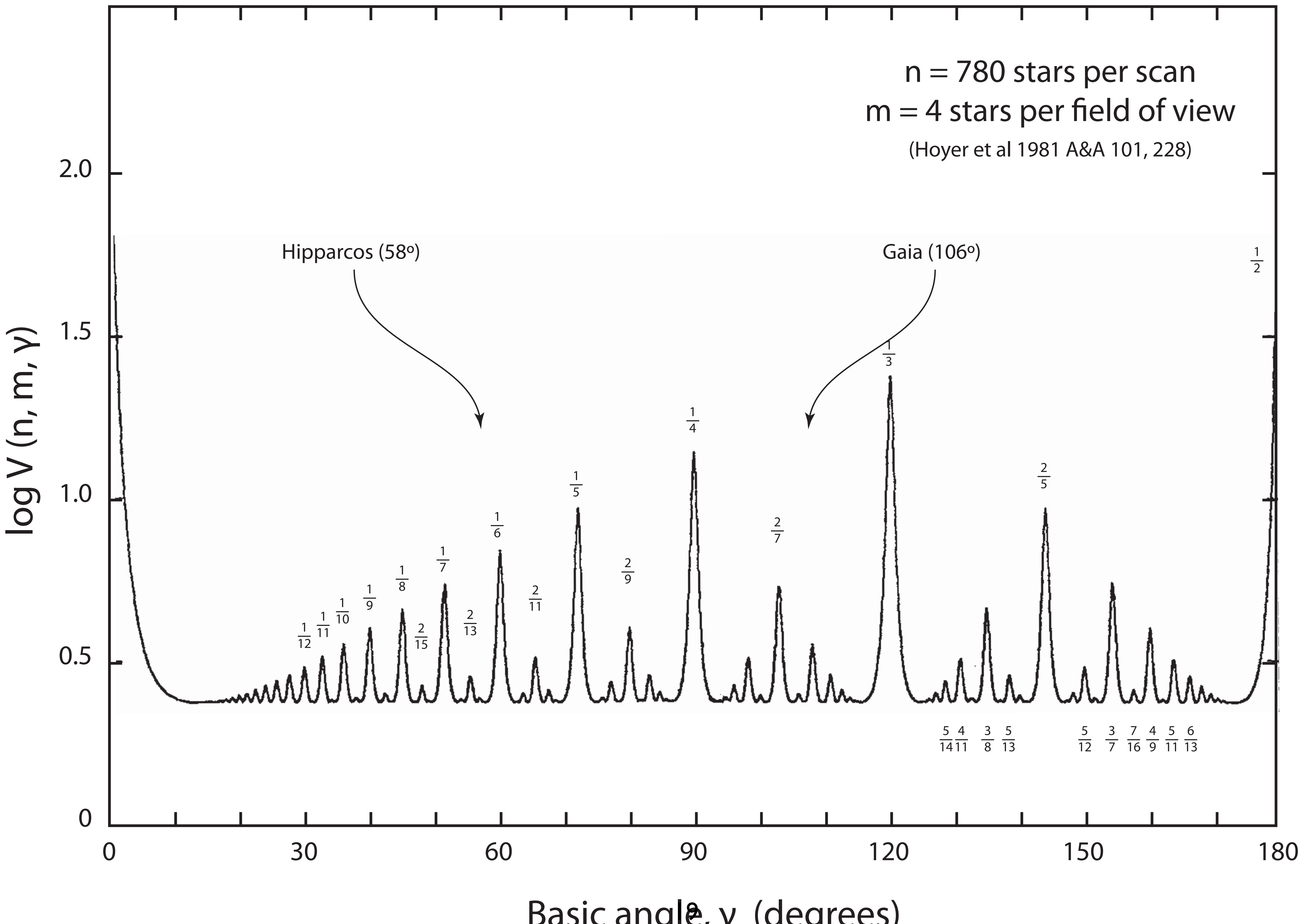
ground, or HST−FGS etc

large angle measurements:
⇒ absolute parallax:
$\pi_1 = (A{-}B)/2$



Hipparcos, Gaia

The basic angle follows from the great-circle rigidity...



Principle (1/3): one star, showing effects of proper motion and annual parallax

Principle (2/3): three stars in same region of sky: parallaxes in phase

Principle (3/3): three stars in each of two regions of sky: parallaxes out of phase

Hipparcos

proposed (Lacroute): 1968
accepted by ESA: 1981
launched: 1989
operated: 1989-1993
catalogue published: 1997

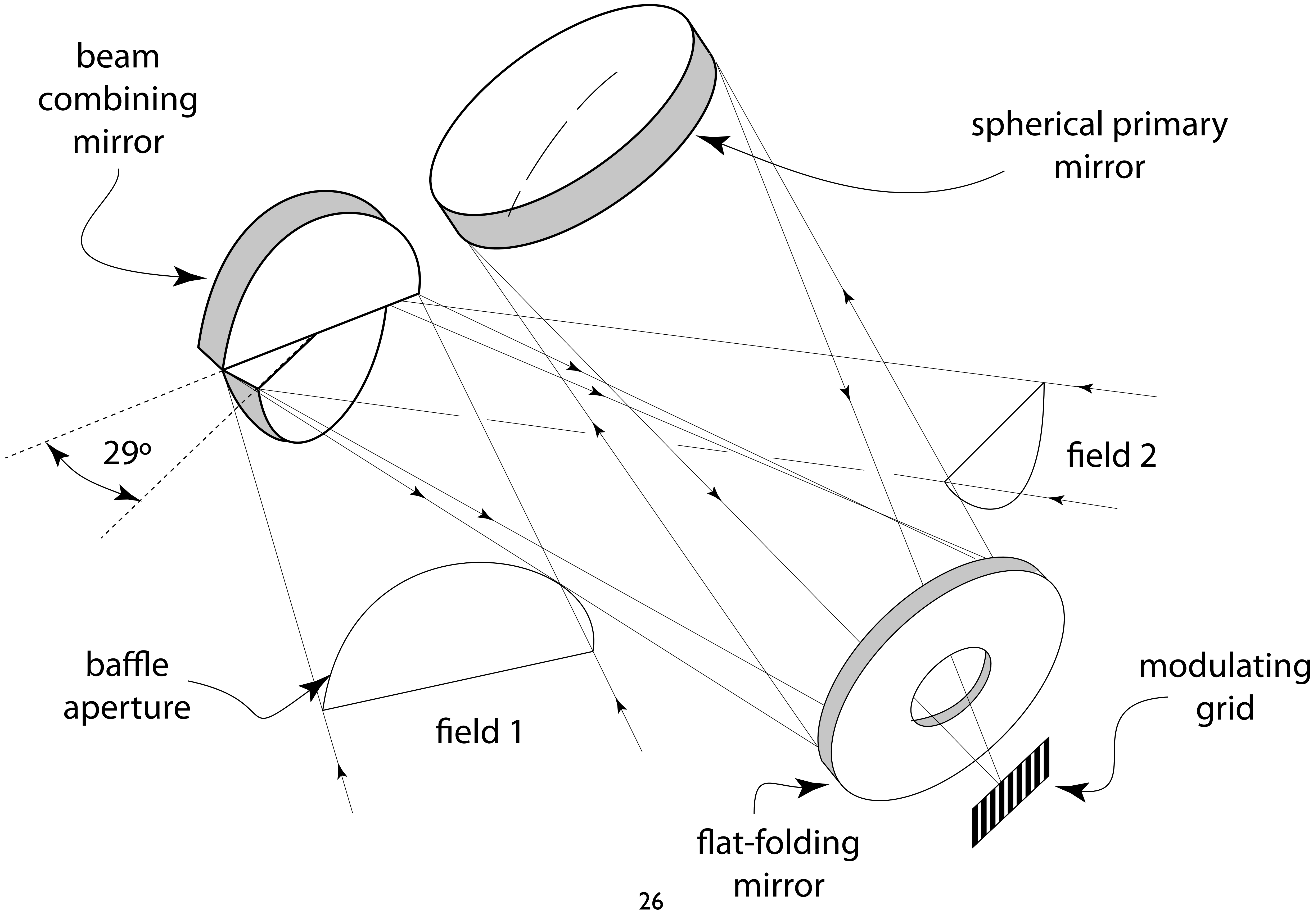
Early discussions, Bordeaux 1965

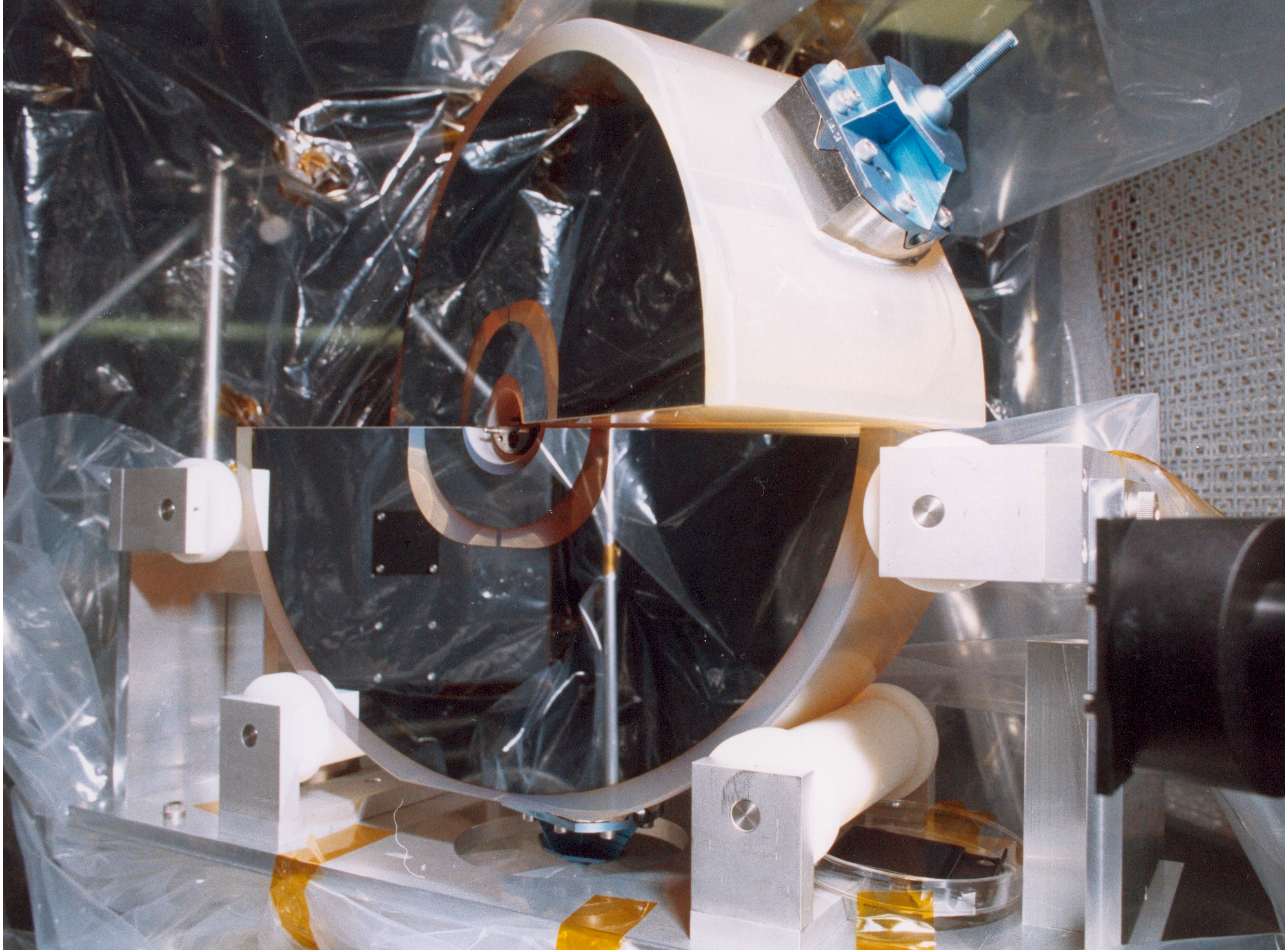
- Physics underpinning positional measurements:
  - the stellar distances (parallaxes): used to convert apparent quantities (notably magnitude) to absolute values (luminosities)
  - the space motions (angular, eg mas/yr), converted to linear space velocities (km/s) for kinematics and dynamics (absence of V_{rad})

- Main problems in making these measurements from ground:
  - the Earth's atmosphere (+ gravitational flexure +thermal variations)
  - determining an all-sky reference star grid such that:
    - the proper motions are (largely) free of systematics
    - the parallaxes are <u>absolute</u> (rather than relative)

- Justification for making these measurements from space:
  - measurements <u>above</u> the atmosphere
  - the consequent ability to make <u>large-angle</u> measurements
  - the resulting provision of <u>absolute</u> parallaxes

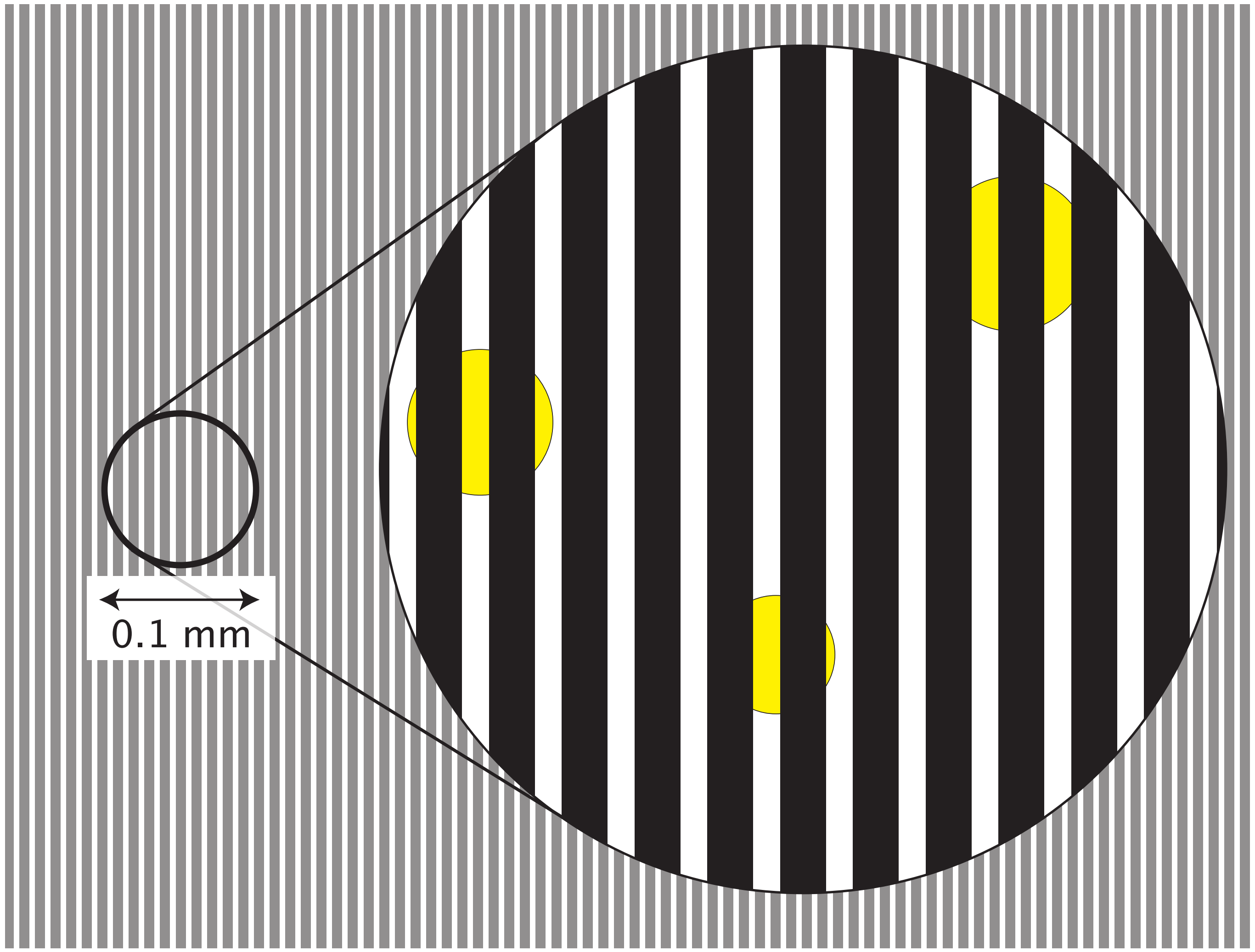
Hipparcos optical design





The 30 cm diameter beam combining mirror (now in National Maritime Museum, London)

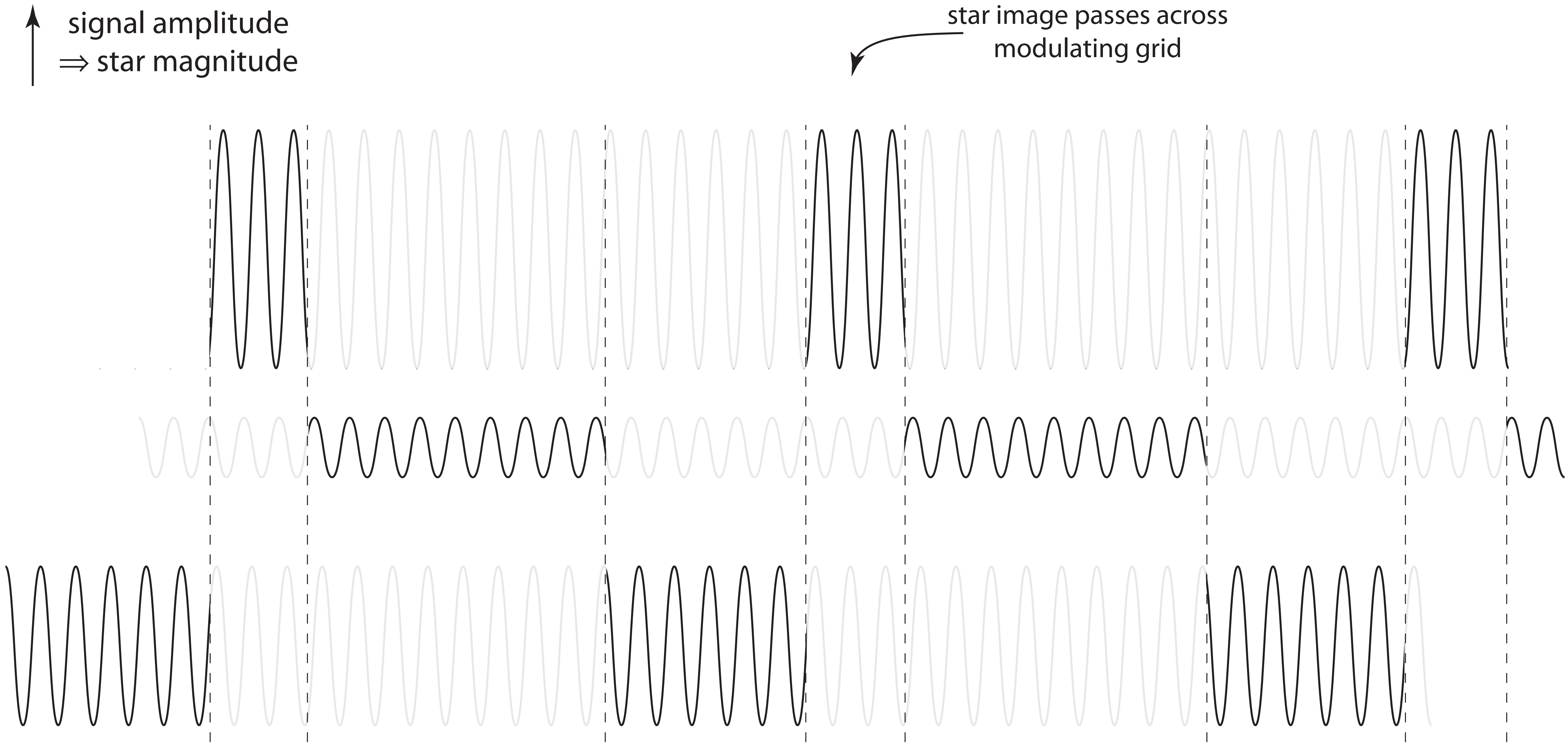
Hipparcos: measurements at the focal plane



- a high fidelity modulating grid
- 2688 grid lines
- about 2.5 cm x 2.5 cm
- grid period = 1.208 arcsec on sky

- star images pass behind grid
- detector with piloted field of view sampled the modulated signal by switching rapidly between star images several times per sec
- both fields of view are sampled
- modulation intensity → star magnitude
- relative signal phase → along-scan separation (modulo grid period and γ)
- star positions established to ~1 arcsec *a priori*, to allow detector piloting, and to resolve the grid period ambiguity in the relative separation
- signal digitised at 1200 Hz, sent to ground

Image dissector tube piloting

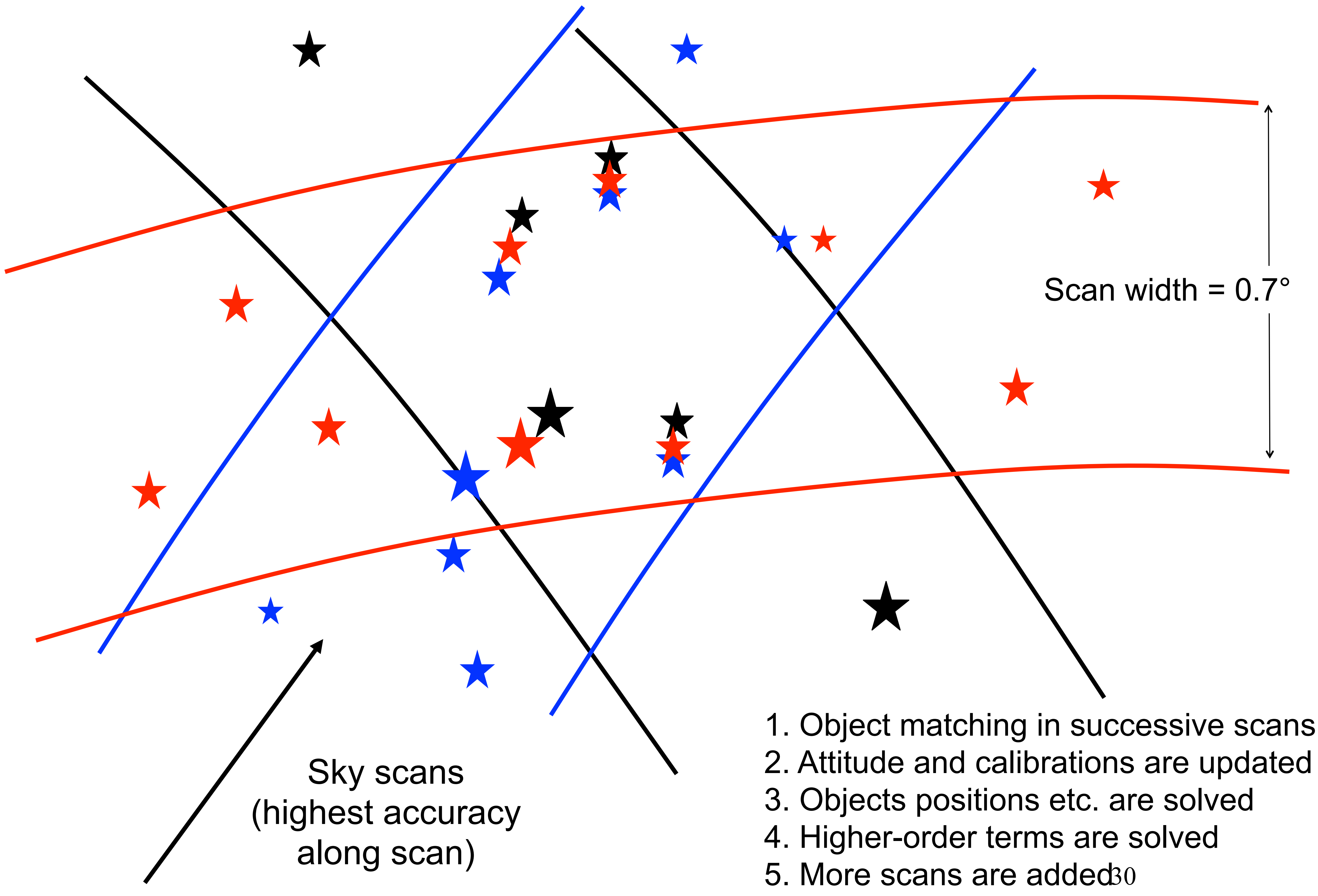


* requires star positions a priori
* dwell period ∝ star magnitude
* switching frequency = f(structural modes)

phase difference ⇒ along-scan separation,
modulo grid period (~1.2 arcsec) and basic angle (γ ~58^o)

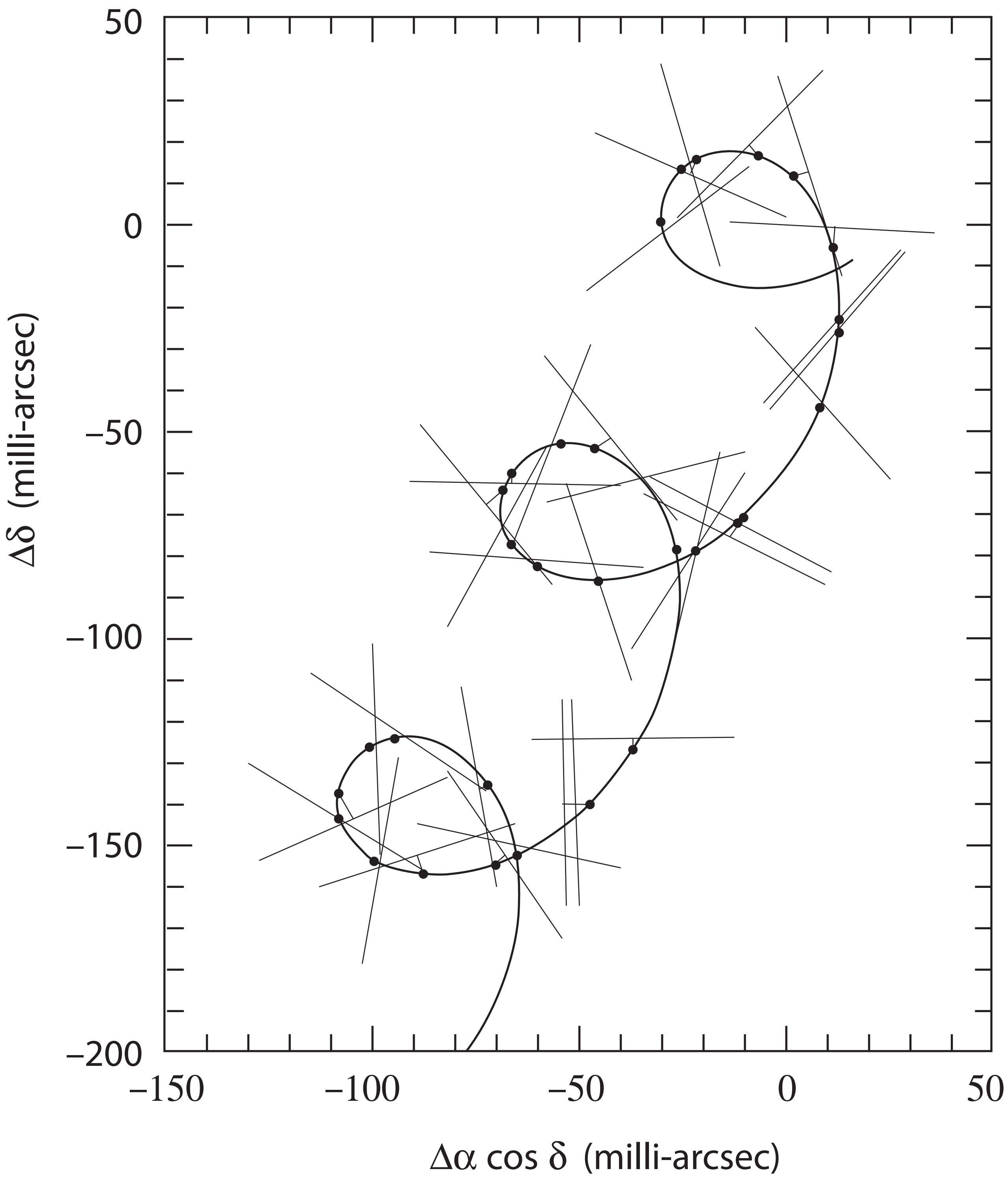
second harmonic (A,ϕ) ⇒ binary star (Δm, $\Delta\theta$)

Star Observing Principles: Hipparcos & Gaia

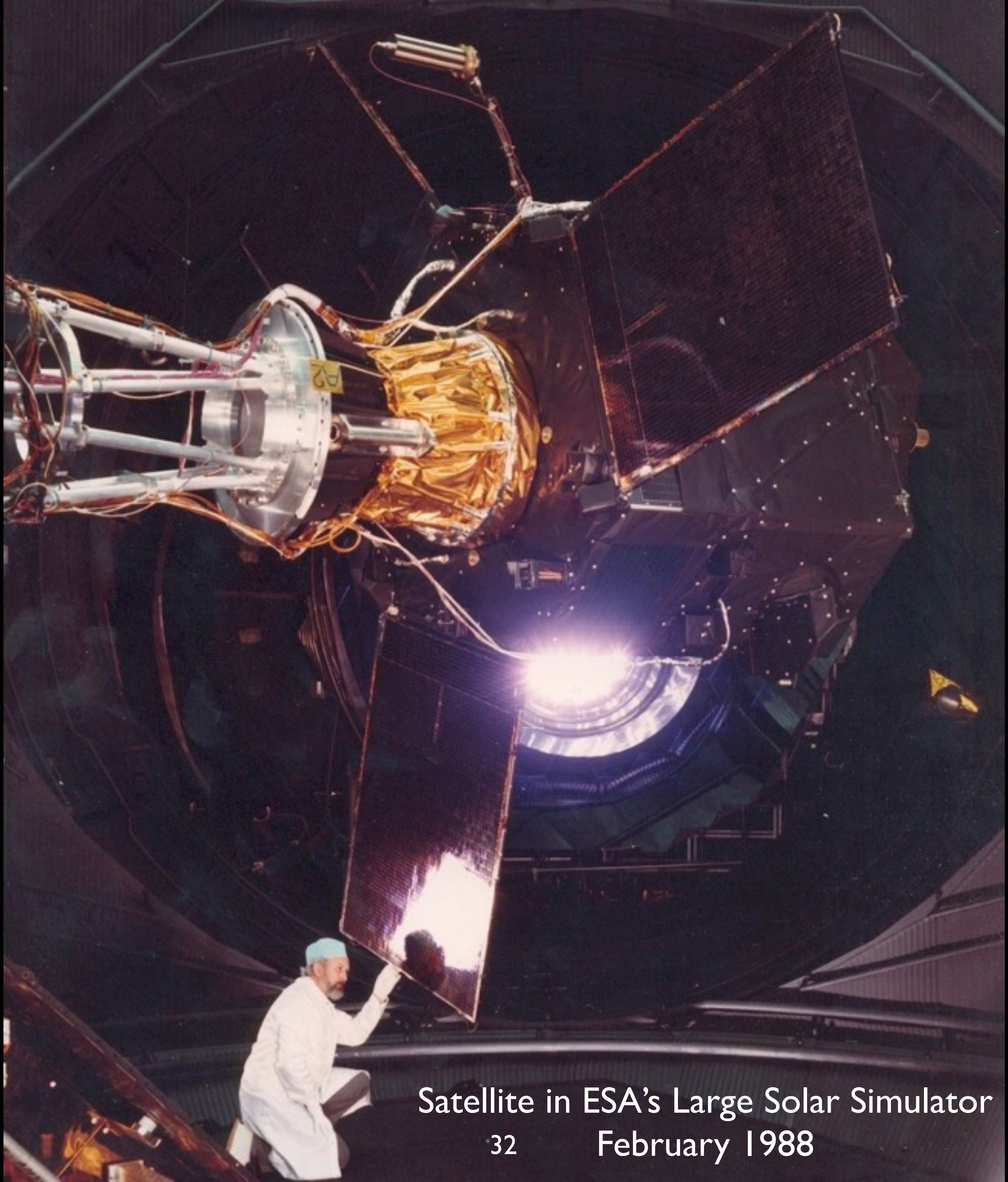


1. Object matching in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc. are solved
4. Higher-order terms are solved
5. More scans are added
6. System is iterated

Data Analysis: Principles



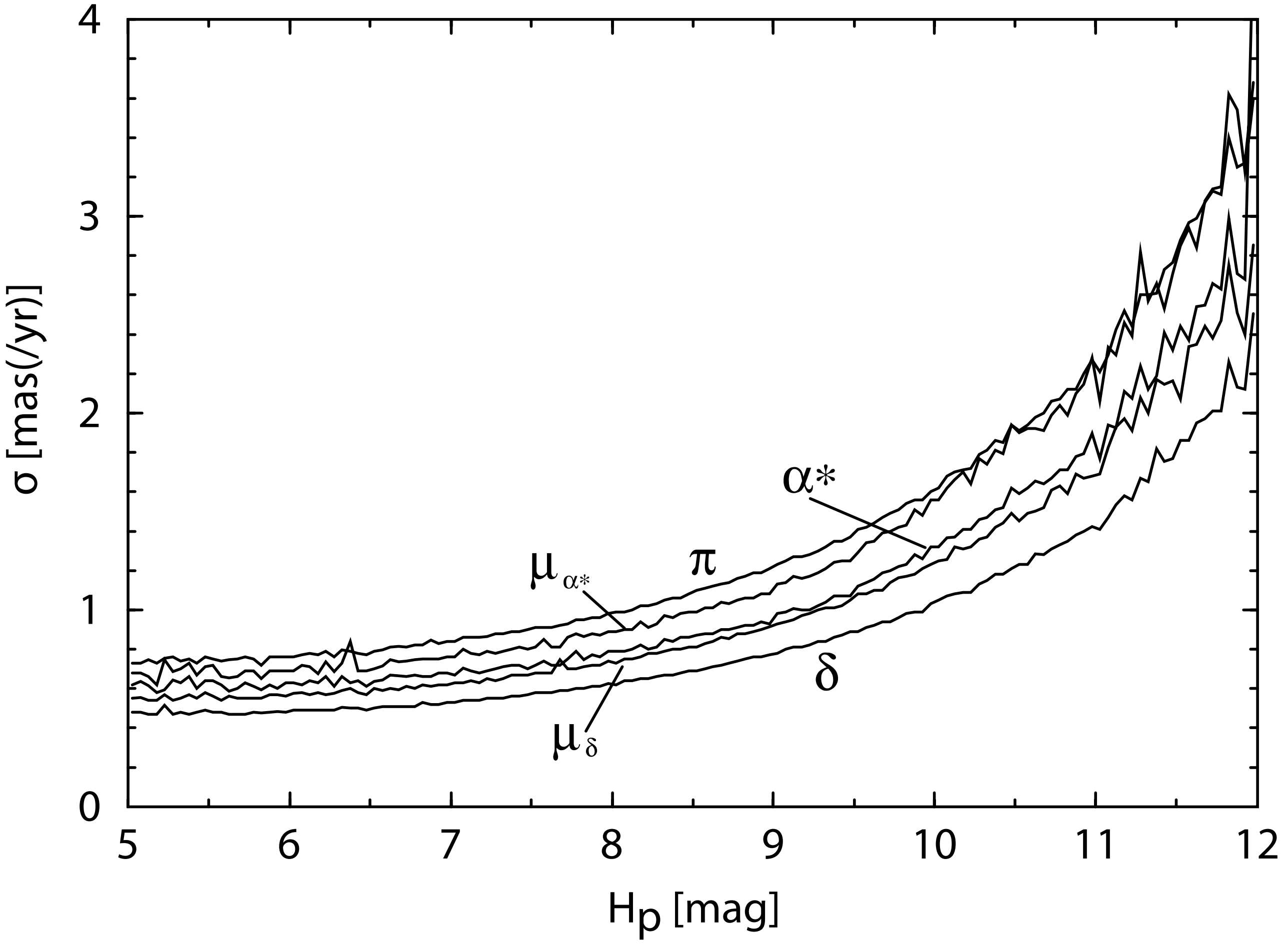
- as the satellite traces out a series of great circles on the sky, each star is (effectively) instantaneously stationary
- each star has a 2d position (abscissa and ordinate) projected onto that great circle
- in principle one should solve for both coordinates
- in practice, only the projection along the great circle (abscissa) dominates the 'great-circle solution'
- least-squares adjustment gives the along-scan position of each star at that epoch
- all great circles (12 hr duration) over the entire 3-year mission are then 'assembled'
- a star's position at any time *t* is represented by just five parameters: position (*xy*), proper motion components (μ_x, μ_y), parallax (π)

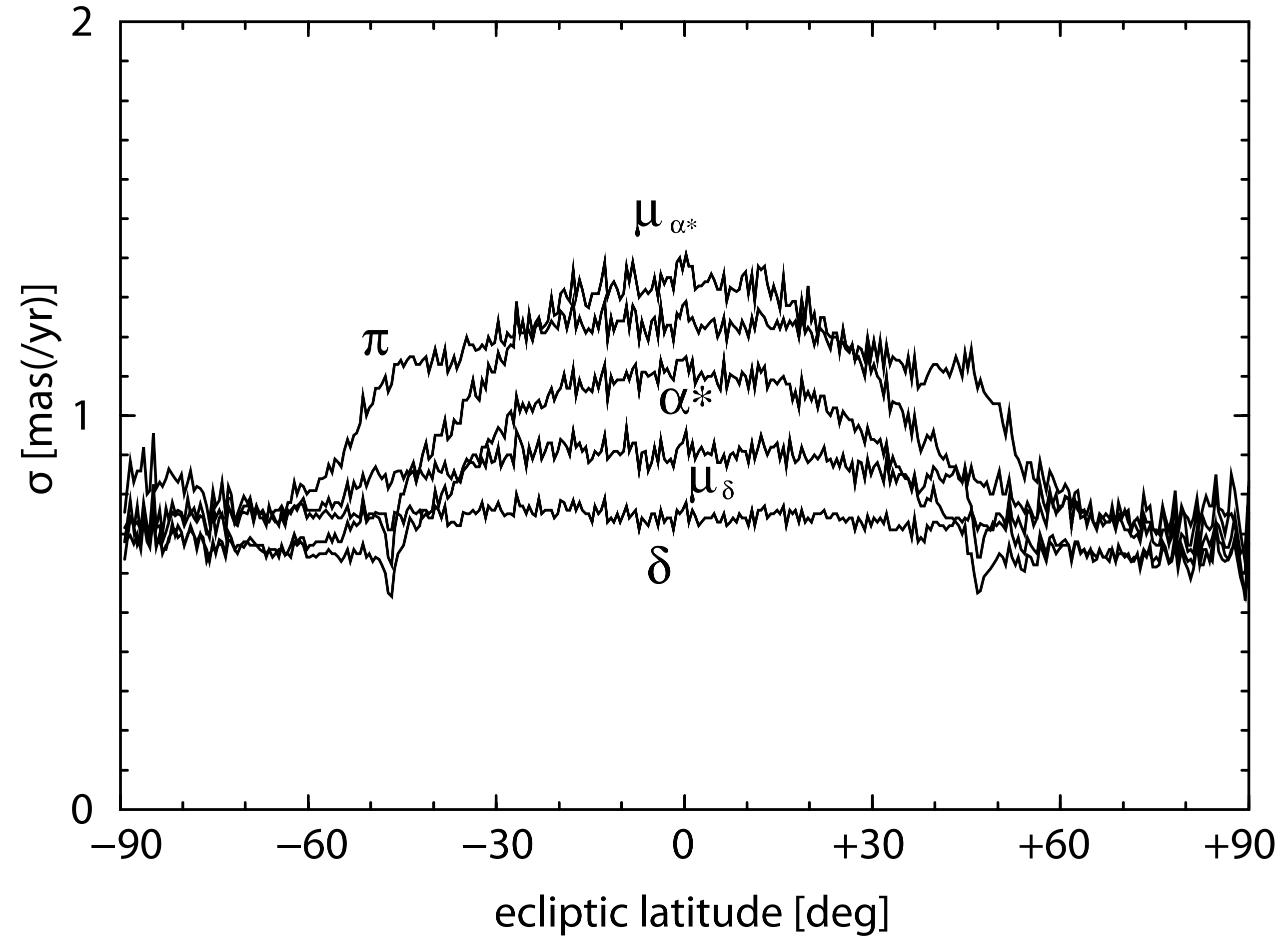


Satellite in ESA's Large Solar Simulator
February 1988

Numerical results

A catalogue of 118,000 stars (published 1997):
each of the 5 parameters determined to ~1 milliarcsec





Some limitations of Hipparcos

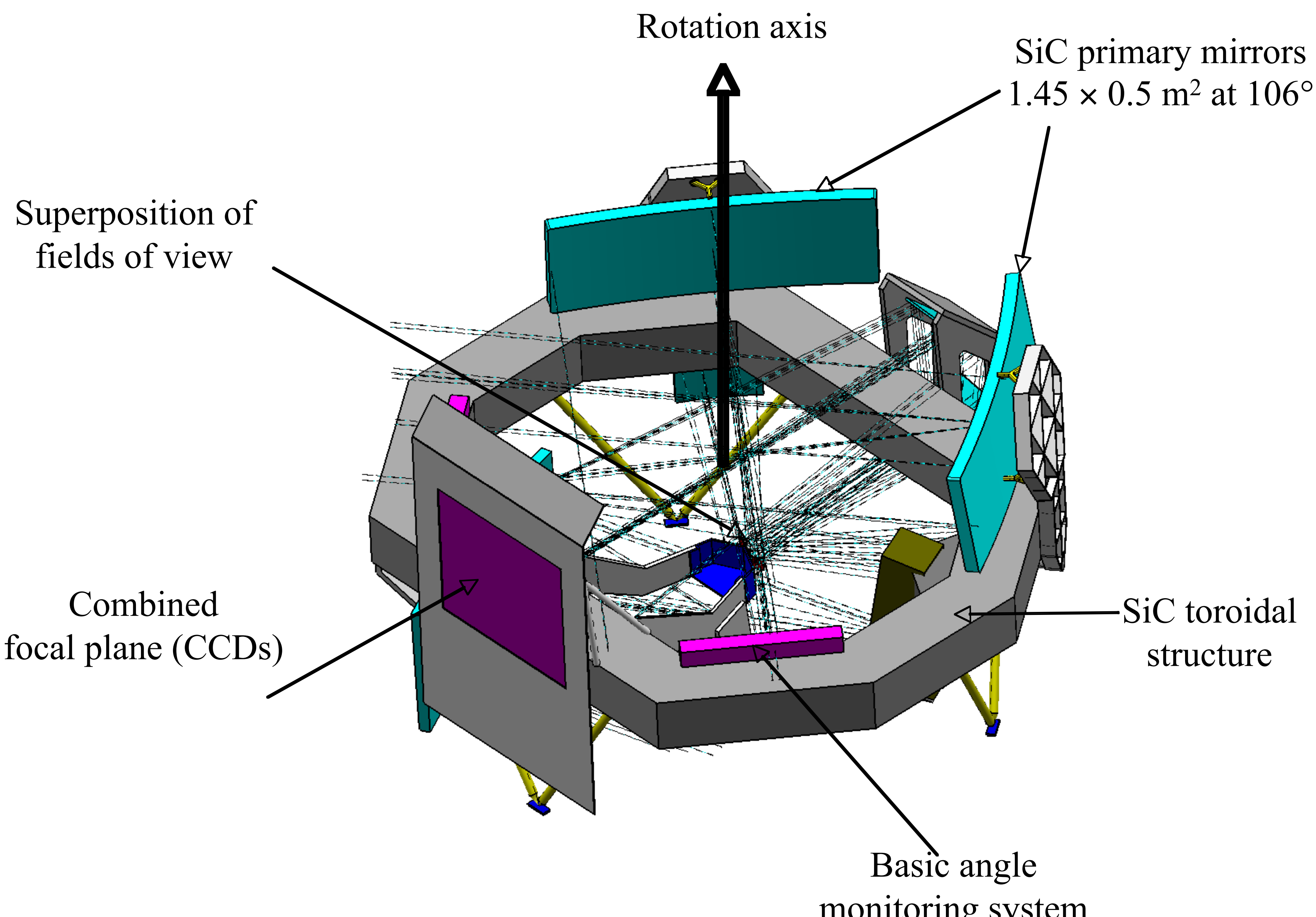
- a modest telescope aperture (30cm)
- modulating grid leading to ~30% light loss
- a low-efficiency photocathode detector (~10%)
- sequential (non-multiplexed) star observations

These shortcomings are addressed by Gaia,
which uses the same principles as Hipparcos
to improve accuracies by x50

Gaia

proposed (Lindegren & Perryman): 1993
accepted by ESA: 2000
launched: December 2013

Gaia: payload/telescope



Gaia: specifications

- astrometry:
  - 10^9 stars to 20 mag (complete: on-board detection)
  - represents ~1% of the Galaxy's stellar population
  - accuracy at 15 mag: 25 microarcsec
  - applies to positions, parallaxes, annual proper motions
- photometry:
  - multi-colour, in about 10 bands (cf 2 for Hip-Tycho)
- radial velocities for 5-150 million stars

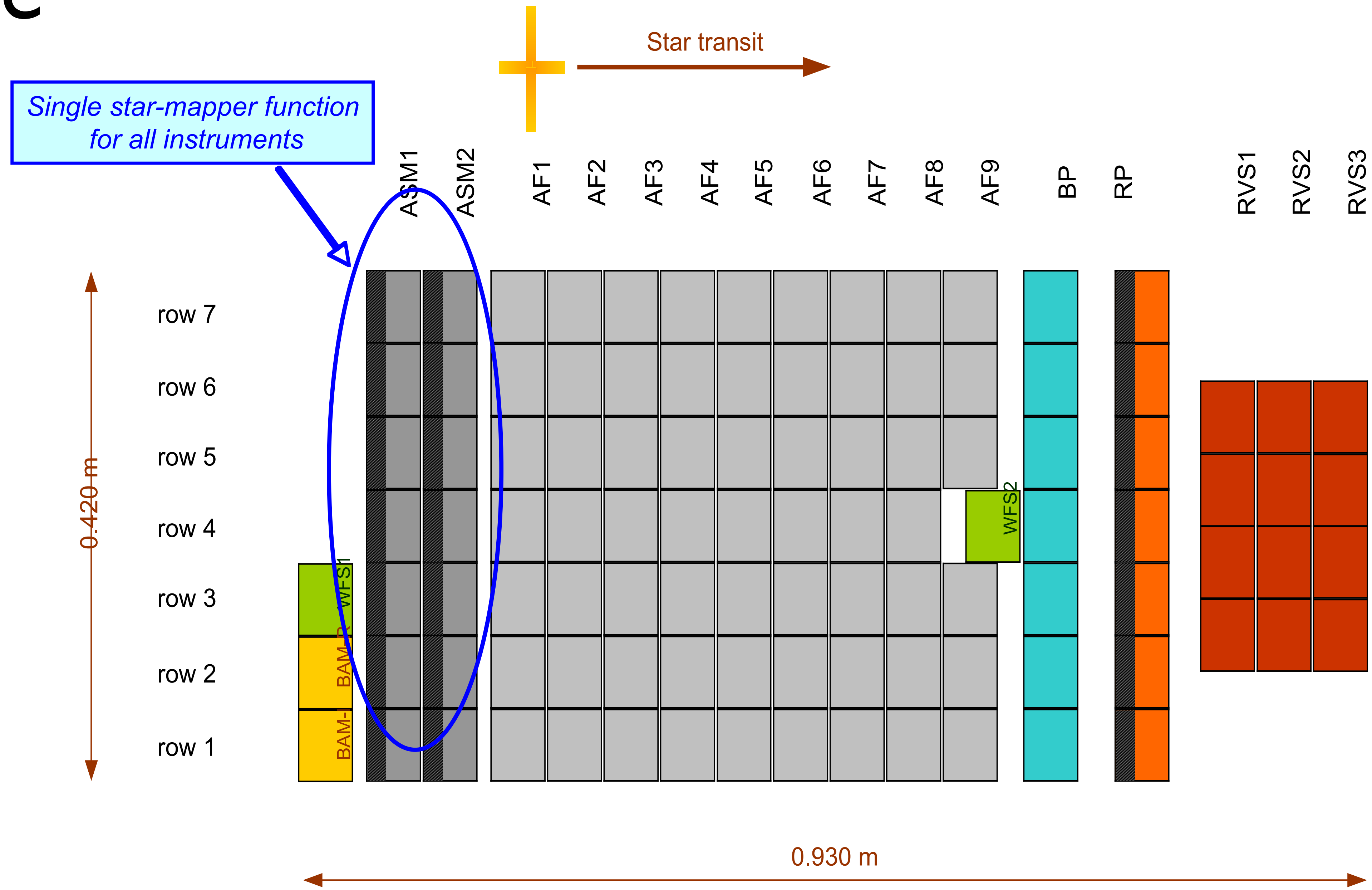
Gaia compared with Hipparcos

	Hipparcos	Gaia
Magnitude limit	12	20 mag
Completeness	7.3 – 9.0	~20 mag
Bright limit	~0	~3-7 mag
Number of objects	120 000	26 million to V = 15 250 million to V = 18 1000 million to V = 20
Effective distance limit	1 kpc	1 Mpc
Quasars	None	$\sim 5 \times 10^5$
Galaxies	None	10^6 - 10^7
Accuracy	~1 milliarcsec	7 μarcsec at V = 10 25 μarcsec at V = 15 300 μarcsec at V = 20
Photometry	2-colour (B and V)	Spectrum to V = 20
Radial velocity	None	1-10 km/s to V = 16 -17
Observing programme	Pre-selected	Complete and unbiased

Why a Survey to 20 mag?

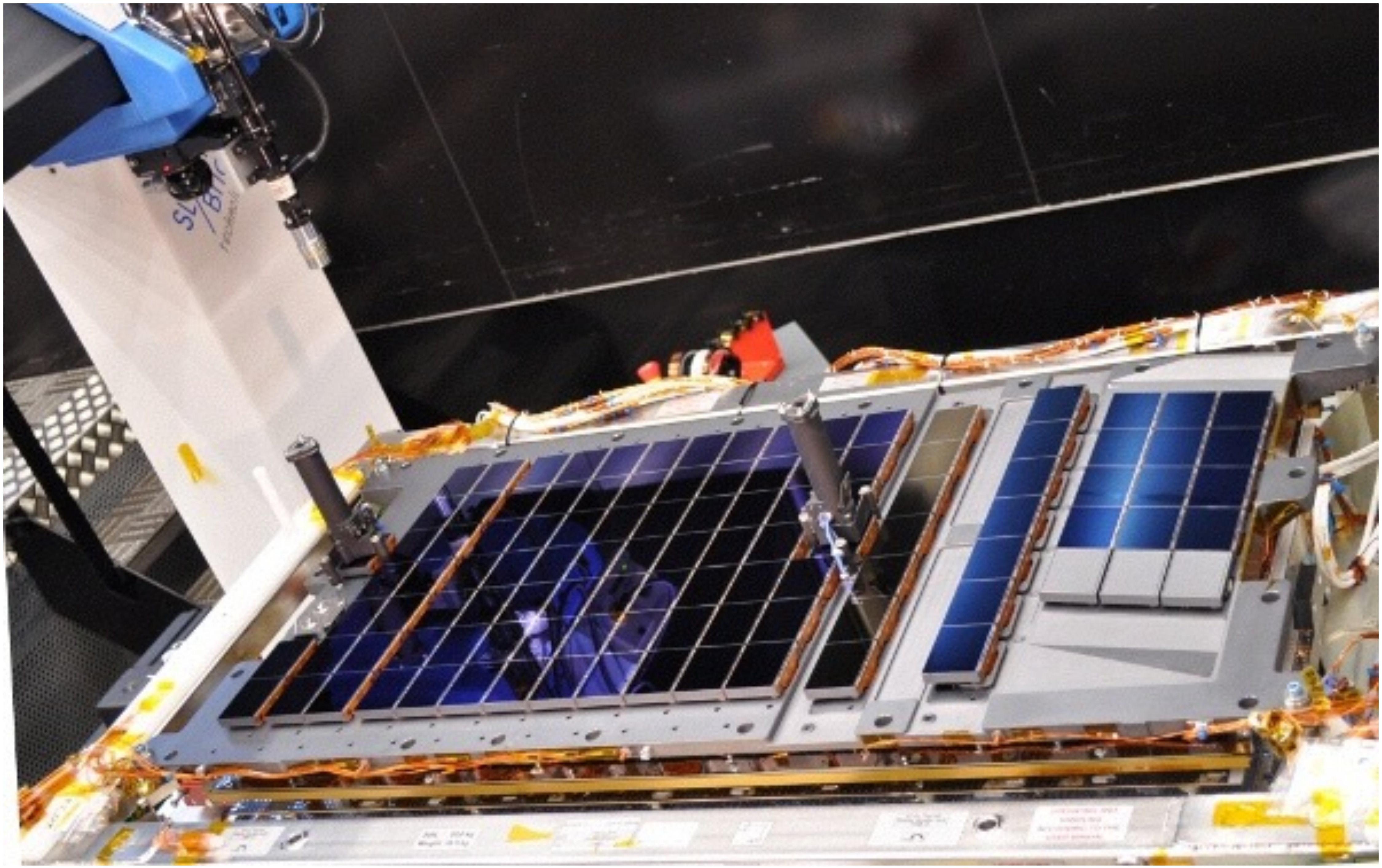
Population	Tracer	Mv	l	b	d	Av	V_1	V_2	ε_T	σ_{μ_1}	σ_{μ_1}	σ_{π_1}
		mag	deg	deg	kpc	mag	mag	mag	km/s	μas/yr	-	-
Bulge	gM	-1	0	<20	8	2-10	15	20	100	10	0.01	0.10
	HB	+0.5	0	<20	8	2-10	17	20	100	20	0.01	0.20
	MS	+4.5	1	-4	8	0-2	19	21	100	60	0.02	0.60
Spiral arms	Cepheids	-4	All	<10	10	3-7	14	18	7	5	0.03	0.06
	B-M supergiants	-5	All	<10	10	3-7	13	17	7	4	0.03	0.05
	Perseus Arm (B)	-2	140	<10	2	2-6	12	16	10	3	0.01	0.01
Thin disk	gK	-1	0	<15	8	1-5	14	18	40	6	0.01	0.06
	GK	-1	180	<15	10	1-5	15	19	10	8	0.04	0.10
Disk warp	gM	-1	All	<20	10	1-5	15	19	10	8	0.04	0.10
Thick disk	Miras, gK	-1	0	<30	8	2	15	19	50	10	0.01	0.10
	HB	+0.5	0	<30	8	2	15	19	50	20	0.02	0.20
	Miras, gK	-1	180	<30	20	2	15	21	30	25	0.08	0.65
	HB	+0.5	180	<30	20	2	15	19	30	60	0.20	1.50
Halo	gG	-1	All	<20	8	2-3	13	21	100	10	0.01	0.10
	HB	+0.5	All	>20	30	0	13	21	100	35	0.05	1.40
Gravity, K-z	dK	+7-8	All	All	2	0	12	20	20	60	0.01	0.16
	dF8-dG2	+5-6	All	All	2	0	12	20	20	20	0.01	0.05
Globular clusters	gK	+1	All	All	50	0	12	21	100	10	0.01	0.10
Satellite orbits	gM	-1	All	All	100	0	13	20	100	60	0.30	8.00

Focal Plane



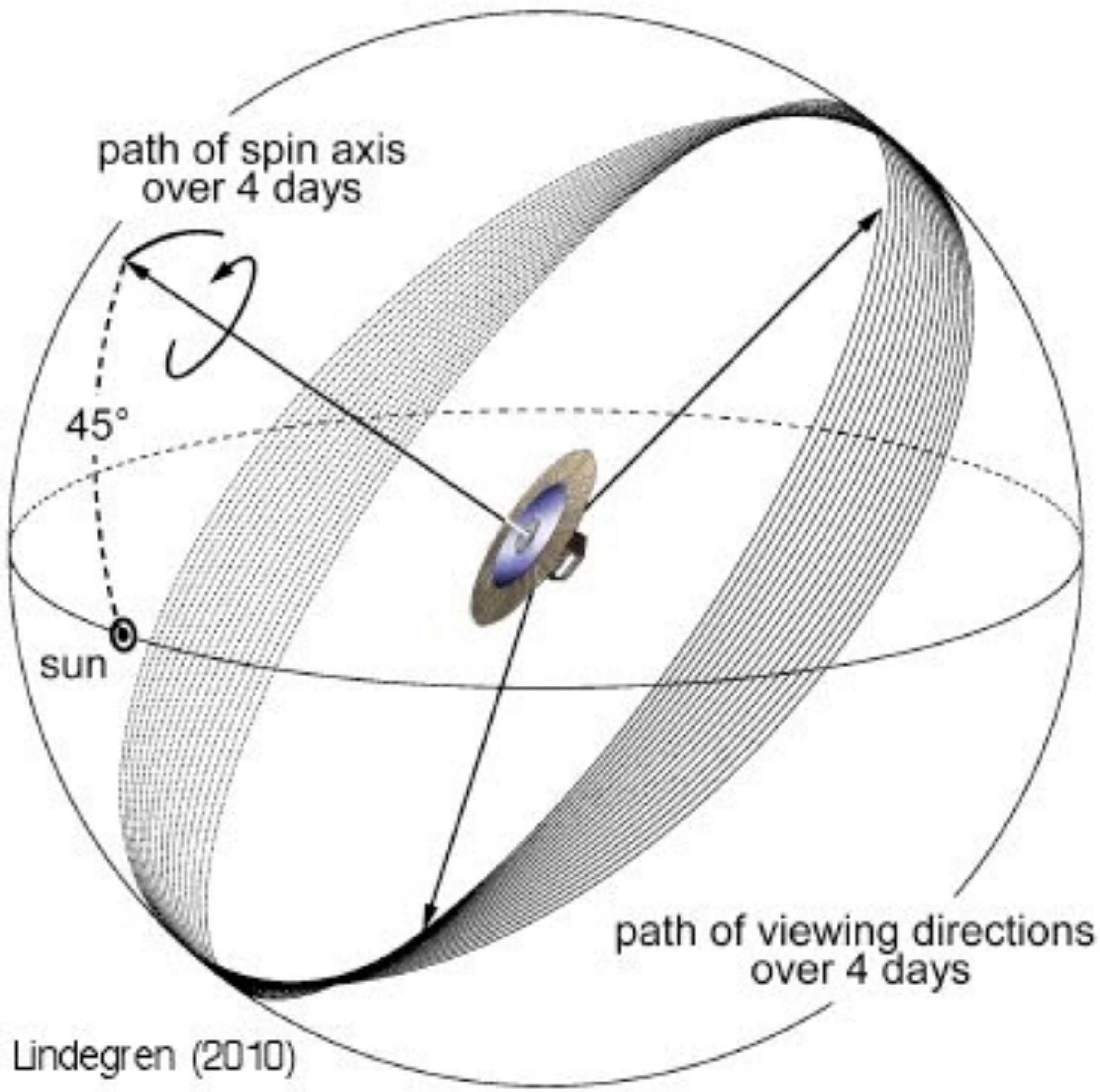
- stars detected (ASM1) and confirmed (ASM2) as they enter the field; no input catalogue
- this is crucial for variable stars, high proper motions stars, asteroids, etc
- measured using TDI as they cross the astrometric field (AF1 to AF9), centroiding on ground
- photometric measurements across blue and red photometers → classification, chromaticity
- radial velocity spectrometer: measurements (in Ca II) for bright stars across RVS1 to RVS3
- also: Basic Angle Monitoring (BAM) and Wave Front Sensors (WFS) for focusing

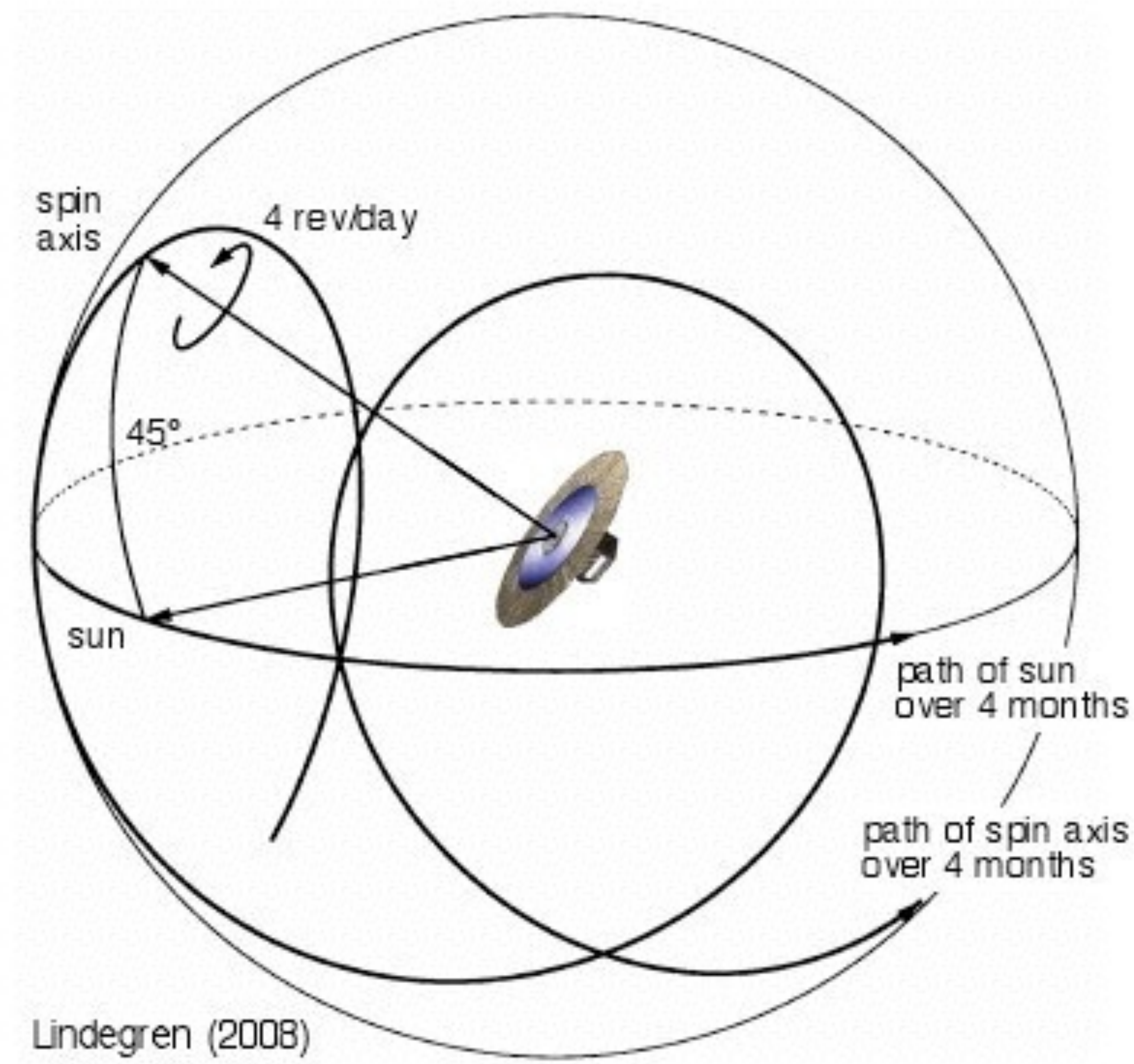
The complete package of CCDs, bolted to the SiC support structure, providing thermo-mechanical stability



Astrium, January 2012

Sky scanning





- scanning of celestial great circles by the two fields of view due to the six hour spin period
- the slow precession of the spin axis changes the orientation of the scanned great circles allowing coverage of different areas on the sky

- precession of the spin axis at 45° around the Sun with a period of 63 days
- this period gives the depicted overlap which ensures that each position on the sky is observed in at least three distinct epochs each half year

Gaia: a Global Iterative Solution

The Hipparcos and Gaia data are amenable to a more 'logical' and more rigorous solution:

- the satellite observations (star positions and motions), as well as instrument calibration parameters, the satellite attitude, and its orbit and velocity are self-consistent
- therefore a block iterative solution can be adopted. As implemented, it consists of four blocks which can be calculated independently, although each block depends on every other block; evaluated cyclicly until convergence
- the solution can be visualised as a successive iteration of:
    - S = A + G + C
    - A = S + G + C
    - G = S + A + C
    - C = S + A + G
    - S: the star update
    - A: the attitude update
    - C: the calibration update
    - G: the global parameters update
- details: mathematical formulation: Lindegren et al (2012, A&A); computational aspects : O'Mullane et al (2011, ExA)
- the data processing (currently 1.5 Tflops at ESAC), and data storage requirements (~10 PBytes), are very large
- the intention is to directly iterate some 100 million sources, and interpolate the remaining 90%
- the practical implementation has proven very difficult:
    - studies were already made (in Italy) in the context of the Hipparcos data processing ~1990
    - first experiments was based on a re-analysis of the Hipparcos data (100,000 stars) ~1997
    - groups in Madrid (GMV), Barcelona (UB) and Torino (OATo) have not been able to get a working solution
    - it has been the subject of a major effort at ESAC (Spain) since ~2005
    - the Gaia s/w will be used for the analysis of the Japanese nano-Jasmine satellite data (Gouda et al)

End