Michael Perryman

Cavendish Laboratory, Cambridge (1977–79)
European Space Agency, NL (1980–2009)
[Leiden University, NL, 1993–2009]
Max-Planck Institute for Astronomy & Heidelberg University (2010)

Visiting Professor:
University of Bristol (2011–12)
University College Dublin (2012–13)
Lecture program

1. Space Astrometry 1/3: History, rationale, and Hipparcos
2. Space Astrometry 2/3: Hipparcos science results (Tue 5 Nov)
3. Space Astrometry 3/3: Gaia (Thu 7 Nov)
4. Exoplanets: prospects for Gaia (Thu 14 Nov)
5. Some aspects of optical photon detection (Tue 19 Nov)
M83

(David Malin)

Our Sun

Hipparchos

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
The first star distances...

After a 250 year marathon journey, Friedrich Bessel, Thomas Henderson, and Wilhelm Struve measured the first star distances around 1838–39

John Herschel:
“the sounding line in the Universe of stars has at last touched bottom”

Bessel was awarded the Royal Astronomical Society’s Gold Medal, for “the greatest and most glorious triumph which practical astronomy has ever witnessed”
Accuracy over time

Errors of best:
- positions
- parallaxes
- surveys
- all

Hipparchus - 1000 stars
Landgrave of Hessen - 1000
Tycho Brahe - 1000
Flamsteed - 4000
Argelander - 26000
CPD/CD
PPM - 400 000
FK5 - 1500
UCAC2 - 58 million
Tycho2 - 2.5 million
Hipparcos - 120 000
Bessel - 1
Jenkins - 6000
USNO - 100
Gaia - 1000 million
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 = 3x10^{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
Accuracy of positions from the ground (1/4)

Comment: accuracies are not limited by diffraction (Rayleigh criterion):

\[
\sin \theta = 1.22 \frac{\lambda}{D} \text{ for } D=0.3 \text{ m}, \lambda = 600 \text{ nm} \Rightarrow 0.5 \text{ arcsec}
\]

The theoretical photon-noise limited positional error for a monolithic telescope is:

\[
\sigma_{ph} = \frac{\lambda}{4\pi D} \frac{1}{S/N}
\]

... Lindegren (1978)

... for \( V = 15 \text{ mag}, \lambda = 600 \text{ nm}, D = 10 \text{ m}, \varepsilon = 0.4, t = 1 \text{ hr} \Rightarrow \sigma \sim 30 \mu \text{as}
\]

Even the best astrometric accuracies from ground fall far short of this due to atmospheric turbulence, usually further degraded by differential chromatic refraction.

Understanding the fundamental accuracy limits has evolved greatly over past 30–40 years:

• 1970s: long-focus telescopes + photographic plates gave \( \sim 20–30 \text{ mas} \) (Harrington & Dahn 1980)
• 1980s: CCDs eliminated the plate-specific error sources (but not atmospheric turbulence)

For small separations near the zenith (\( \approx 1 \text{ arcmin} \)) errors on the time-averaged separation between stars (\( \theta \)) are consistent with atmospheric (Kolmogorov-like) turbulence models:

\[
\sigma_{\delta} \approx 540 D^{-\frac{2}{3}} \theta t^{-\frac{1}{2}} \text{ arcsec}
\]

... Lindegren (1980)

... values of \( \theta = 1 \text{ arcmin}, D = 1 \text{ m}, t = 1 \text{ hr} \Rightarrow \sigma_{\delta} \sim 3 \text{ mas} \) (Gatewood 1987, Han 1989, Monet et al 1992)
Accuracy of positions from the ground (2/4)

With several reference stars, theoretical estimates give a further improvement, e.g.:

$$\sigma_\delta \propto D^{-1} \theta^\frac{4}{3} t^{-\frac{1}{2}}$$  \quad \text{Lindegren (1980)}$$

$$\sigma_\delta \propto D^{-\frac{3}{2}} \theta^\frac{11}{6} t^{-\frac{1}{2}}$$  \quad \text{Lazorenko (2002)}$$

Aperture apodisation + improved treatment of reference star symmetry gives:

$$\sigma_\delta \propto D^{-\frac{k}{2} + \frac{1}{3}} \theta^\frac{k}{2} t^{-\frac{1}{2}}$$  \quad \text{Lazorenko & Lazorenko (2004)}$$

where \((k, \mu)\) depend on the number of reference stars and their magnitudes.

... for 10-m telescopes, very good seeing, and \(t \sim 600\) s \(\Rightarrow \lesssim 100\) μas

Observational results:

- narrow-field AO on Palomar and VLT \(\Rightarrow 100-300\) μas (Neuhauser 2007, Roll 2008, Cameron 2009)
- VLT-FORS2 (\(R=16\) mag, \(t=17\)s, seeing=0.55 arcsec) \(\Rightarrow 300\) μas (Lazorenko 2006)

Note: these promising positional results refer to narrow-angle measurements, typically at zenith, and not to an all-sky reference system.
Accuracy of positions from the ground (3/4)

Interferometers:

For larger separations, $\theta \sim 0.5^\circ$, theory and data had suggested a turbulent-limited accuracy $\propto \theta^{1/3}$, and (to first-order) independent of $D$ (Lindegren 1980). Therefore interferometers were not immediately considered as particularly advantageous for relative positional measurements. But: when baselines exceed the beam separation at the top of the (turbulent) atmosphere, a qualitative change in atmospheric behaviour occurs, and:

$$\sigma_\delta^2 \approx 5.25 B^{-4/3} \theta^2 \int h^2 C_n^2(h)(Vt)^{-1} \, dh$$

Shao & Colavita (1992), eqn 2

... baseline $B$, star separation $\theta$ (arcmin), wind speed versus height $V(h)$, and integration time $t$. $C_n(h)$ is complicated function describing the atmospheric refractivity power spectrum with height, which determines the seeing.

For Mauna Kea, Shao & Colavita (1992, eqn 4) found:

$$\sigma_\delta \approx 300 B^{-2/3} \theta^{-1/2} \text{arcsec}$$

... equivalent to the single aperture form, with $B$ replacing $D$ (and a smaller numerical factor).

Accordingly, interferometric accuracy depends linearly on star separation, and improves with increasing baseline. For $\theta = 20$ arcsec, $B = 200$ m, $t = 1$ hr $\Rightarrow \sigma \approx 10$ μas

... as targeted (but still to be demonstrated) by VLTI–PRIMA (Phase-Referenced Imaging and Microarcsec Astrometry) and VLTI–Gravity (stellar motions in the Galactic centre).
Antarctic:

• the integrated amplitude of $C_n^2(h)$ determines the ‘seeing’, usually quantified through the Fried parameter $r_0$. At optical wavelengths, Antarctic seeing is not exceptional, at $\sim 1–3$ arcsec

• but the determining factor for interferometric astrometry is ‘tilt isoplanatism’, the second moment of the $C_n^2(h)$ profile in the previous equation. The $h^2$ factor means that the accuracy is dominated by high-altitude turbulence

• at the south pole, this high-altitude profile is less affected by the jet streams, trade winds, and high-altitude wind shear that govern the behaviour at mid-latitude

• measurements from Dome C confirm long atmospheric coherent times, and large isoplanatic angles ($\sim 30$ arcsec) over which the paths are temporally coherent... Lloyd et al (2002) even reported seeing Jupiter scintillate (angular diameter 30–50 arcsec)

• their studies suggest that a 100m interferometer at Dome C could reach 100 $\mu$as differential astrometry 300 times faster than a comparable interferometer at a good mid-latitude site
This is the problem...

These are the angles...

Viewed from Earth...

Neil

Golf ball

Star light

Plane waves above atmosphere

Turbulent atmosphere

Twinkling star light on ground
...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).

[Graph showing difference in declination (milli-arcsec) vs. Declination (degrees) for Hipparcos – FK5 systematic errors (Schwan 2002)]
• the original science case was to calibrate the upper part of the main sequence

• numerous political hurdles in getting the mission accepted by ESA (1978-1981)

• the work of 100 scientists, and 1000 engineers in 20 European industries

• two data analysis teams

• all conducted in an era when correspondence was by mail (telex if urgent) and data transferred on magnetic tape by post
Measurement principle

small angle measurements: ⇒ relative parallax: 
\[ \pi_1 - \pi_0 = (A-B)/2 \]

large angle measurements: ⇒ absolute parallax: 
\[ \pi_1 = (A-B)/2 \]

Earth’s orbit

ground, or HST–FGS etc

Hipparcos, Gaia
The basic angle follows from the great-circle rigidity...

\[ \log V(n, m, \gamma) \]

\[ n = 780 \text{ stars per scan} \]
\[ m = 4 \text{ stars per field of view} \]

(Hoyer et al 1981 A&A 101, 228)
• 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 $V_{\text{rad}}$)

• 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 **absolute** (rather than relative)

• Justification for making these measurements from space:
  – measurements **above** the atmosphere
  – the consequent ability to make **large-angle** measurements
  – the resulting provision of **absolute** parallaxes
Early discussions, Bordeaux 1965
The 30 cm diameter beam combining mirror (now in National Maritime Museum, London)
Hipparcos optical design

- Beam combining mirror
- Spherical primary mirror
- Field 1
- Field 2
- Baffle aperture
- 29°
- Modulating grid
- Flat-folding mirror
- Field 1
- Field 2
Hipparcos: measurements at the focal plane

- 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 $\gamma$)
- star positions established to ~1 arcsec \textit{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

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

- Signal amplitude ⇒ star magnitude
- Star image passes across modulating grid
- Phase difference ⇒ along-scan separation, modulo grid period (~1.2 arcsec) and basic angle (γ ~58°)
- Second harmonic (A, φ) ⇒ binary star (Δm, Δθ)

* Requires star positions a priori
* Dwell period ∝ star magnitude
* Switching frequency = f(structural modes)
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

Sky scans (highest accuracy along scan)

Scan width = 0.7°
• 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 \((\mu_x, \mu_y)\), parallax \((\pi)\)
Some Complications...

Background stars are moving

Background stars at finite distance

Star is moving

Star may be multiple (photocentric motion)

Binary may be variable

Curved space-time

Microlensing

Sun is moving

Sun moves in curved orbit

Earth moving around Sun

Earth rotating (or satellite)

Radial motion (Doppler shift)

Transverse ‘proper’ motion

...everything is moving!
Hipparcos: many detailed technical issues

- uplink of star catalogue to be observed over next hours
- gas jet thrusters to:
  - keep satellite spinning uniformly
  - follow the pre-determined sky-scanning law
- rigorous thermal control, including fixed angle of solar illumination (defined by the scanning law)
- on-board data handling
- downlink: telemetry stream with star identification
- 3-year observation lifetime to give separability positions, parallaxes, and proper motions
Satellite in ESA’s Large Solar Simulator
February 1988
Launch - transfer orbit - geostationary orbit

1. Launch into orbit
2. Motor firing at apogee
3. Unfold solar panels
4. Operations in geostationary orbit
Scientists losing hope for satellite trapped in orbit

By Mary Fagan
Technology Correspondent

Independent, 15 August 1989

Hi-Shear Part Blamed For Hipparcos Failure

By PETER B. de SELDING
Space News Staff Writer

PARIS — A faulty component supplied by a California company was the principal

Space News, 16 July 1990

Bad day for astronomers

Kourou, French Guiana

After a perfect launch in French Guiana on 8 August, the European astronomy
satellite Hipparcos ran into trouble when the apogee motor failed three times to
respond to commands to fire. The motor is responsible for lifting the satellite into
a stationary orbit around the Earth. As a result, Hipparcos can no longer transmit
carrying a West German direct broadcasting television satellite, TV-SAT2, as well
as Hipparcos. The first launch attempt was stopped seven seconds short of igni-
tion by an overzealous computer. But then the mission got off to a good start with
the perfect positioning of Hipparcos and TV-SAT2 in their transfer orbits. Just

Nature, 17 August 1989

Scientists battle to revive star satellite

By Steve Connor, Technology Correspondent

Scientifically, the Hipparcos satellite is the most important astronomical satellite
being launched to date. It is aimed at finding the precise positions and move-
ments of stars in the Messier and NGC catalogues, as well as a million fainter
stars. But before that can happen, it must be in the correct orbit around the Earth.

Daily Telegraph, 12 August 1989

Space partners fall out over British cuts to star map project

Robin McKie and Nicholas Booth

A BITTER conflict has broken out between Britain and its
European space partners over plans to halve UK funding for a
unique star-mapping probe that is circling the Earth.

The Observer, 24 March 1991
Retrospective of major milestones

• 1968: first proposals for space astrometry
• 1980: acceptance by ESA’s Science Programme Committee
• 1981: start of Phase B
• 1989: launch by Ariane 4, flight 33 (Kourou)
• 1993: end of satellite operations
• 1996: completion of data analysis (NDAC/FAST, TDAC)
• 1997: release of the Hipparcos Catalogue (118,000 stars)
  release of the Tycho Catalogue (1 million stars)
• 2000: release of Tycho 2 Catalogue (2.5 million stars)
Numerical results

A catalogue of 118,000 stars (published 1997):
each of the 5 parameters determined to $\sim 1$ milliarcsec
The printed catalogue...
What’s in the catalogue

• position (2) at mid-epoch (~1990)
• proper motion (2)
• parallax (1)
• covariance matrix (5x5)
  • formulae for propagation
• flags indicating fits
• photometry (B,V)
• variability indicators
• multiplicity
  • 7-parameter fits (acceleration)
  • full orbital solutions (235)
• intermediate astrometry
Internal (formal) standard error versus external (or true) error

- estimating true parallax accuracies is a classical problem in fundamental positional astronomy with, typically, $\sigma_{\text{int}} << \sigma_{\text{ext}}$
- true uncertainties have historically been assessed by:
  - analysis/modelling of all identified error sources
  - comparison with independent measurements of the same stars
  - use of spectrophotometric, kinematic, or dynamical data
  - statistical interpretation of the distribution of observed parallaxes
- Lindegren (1995) analysed the negative parallax distribution, assuming:
  - parallaxes are non-negative
  - observation error and true parallax are statistically independent
- result: $\sigma_{\text{ext}} / \sigma_{\text{int}} \sim 0.99 \pm 0.02$
- combined with other assessments, the final catalogue claims:
  - $\sigma_{\text{ext}} / \sigma_{\text{int}} < 1.2$
- difficult to consider this not applying to positions and proper motions
Degradation of the reference frame with time

<table>
<thead>
<tr>
<th>Year</th>
<th>Accuracy (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900</td>
<td>0</td>
</tr>
<tr>
<td>1950</td>
<td>100</td>
</tr>
<tr>
<td>2000</td>
<td>200</td>
</tr>
<tr>
<td>2050</td>
<td>300</td>
</tr>
</tbody>
</table>

- Hipparcos
- FK5
- Tycho 2 (best)
- Tycho 2 (all)
- Tycho 1 (V = 10.5)
- Tycho 1 (V < 9)
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
A retrospective...

Looking back, you might ask ‘what was the big deal?’ but Hipparcos pushed many simultaneous technology limits; it provided the biggest improvement factor in history; no other experiments have bettered it in 25 years; and perhaps... Bohdan Paczynski would have admired its small size!

“Hipparcos is the first time since Sputnik in 1957 that a major new development in space science has come from outside the United States”

Freeman Dyson (Infinite in All Directions) 1988