Introduction to Space

Astrometry

The Gaia Mission

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Summary

- Astrometry
- Reference frames & Parallaxes
- Hipparcos
- Gaia
Astrometry in a nutshell
What is Astrometry?

- Astrometry deals with the measurement of the positions and motions of astronomical objects on the celestial sphere.
  - Global or wide field astrometry
  - Local or small field astrometry
- Astrometry relies on specialized instrumentation and observational and analysis techniques.
- It is fundamental to all other fields of astronomy.
The astrometric revolution

- The two pillars of space astrometry

Reference frame

Absolute parallaxes
Astrometry Golden Age

2000 yrs - 4.5 dex

2000 yrs - 4.5 dex

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Reference Frames
Reference frame: standard view

• Pre-existing reference graticule
Reference frame: fundamental view

- Stellar sources as fiducial points
Classical Astronomical Reference Frames

- **Astronomical catalogues**
  - Large full sky astronomical catalogues widely available in 1970
    - BD (1860) & Cordoba (1890) with 700,000 stars
    - HD (Henry Draper) since 1920, 230,000 entries with spectral type
    - SAO (1966) with 270,000 stars with positions and PM
  - Positions and PM based on an existing reference frame

- **Fundamental catalogues**
  - Absolute observations with no reference to previous determinations
  - Historically tied to the equator and equinox at a particular epoch
    - assumed to provide absolute and inertial orientation
  - observations of the Sun or planets mandatory
**Fundamental Catalogues**

- Small catalogues, many years of tedious labour to get absolute positions

<table>
<thead>
<tr>
<th>Year</th>
<th>Catalogue</th>
<th>Stars</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1790</td>
<td>Maskelyne</td>
<td>36</td>
<td>zodiacal stars, one epoch</td>
</tr>
<tr>
<td>1818</td>
<td>Bradley/Bessel</td>
<td>3000</td>
<td>no PM, nearly fundamental</td>
</tr>
<tr>
<td>1830</td>
<td>Bessel</td>
<td>36</td>
<td>with PM, + precession</td>
</tr>
<tr>
<td>1878</td>
<td>FK1</td>
<td>539</td>
<td></td>
</tr>
<tr>
<td>1898</td>
<td>Newcomb</td>
<td>1297</td>
<td>Start of the GC series</td>
</tr>
<tr>
<td>1907</td>
<td>FK2</td>
<td>925</td>
<td></td>
</tr>
<tr>
<td>1937</td>
<td>FK3</td>
<td>873</td>
<td>1st IAU supported international RF</td>
</tr>
<tr>
<td>1963</td>
<td>FK4</td>
<td>1535</td>
<td>$\sigma_{1950} \sim 0^&quot; 07 - 0^&quot;15$, $\sigma_{2000} \sim 0^&quot;15-0^&quot;30$</td>
</tr>
<tr>
<td>1988</td>
<td>FK5</td>
<td>1535</td>
<td>$\sigma_{2000} \sim 0^&quot;.05 - 0^&quot;10$</td>
</tr>
<tr>
<td>1997</td>
<td>Hipparcos</td>
<td>100,000</td>
<td>(quasi fundamental)</td>
</tr>
<tr>
<td>1998</td>
<td>ICRF</td>
<td>212</td>
<td></td>
</tr>
</tbody>
</table>
Limitations of the classical approach

- System defined with equator and equinox
  - precession and nutation modelling
    - solution: fixed frame not linked to solar system \(\rightarrow\) ICRS

- Observations from the ground
  - many stations needed to cover the sky
  - disturbances from the atmosphere
    - solution: go to space for global astrometry \(\rightarrow\) Hipparcos

- System based on stars
  - problems with proper motions, multiplicity
    - solution: distant sources \(\rightarrow\) already considered by W. Herschel & Laplace
    - Adopted in \(\sim\) 1990 with ICRS and ICRF in 1998
ICRF-1 (1998)

Accuracy ~ 1 mas

- Definition sources (212)
- Candidate sources (294)
- Other sources (102)
ICRF-2 (2009)

- Accuracy ~ 0.2 to 2 mas
QSOs distribution with Gaia

- Based on the simulation used in the DPAC Universe model

Slezak & Mignard, 2007
Stellar Parallaxes
Parallactic effect

\[ \pi = \frac{\beta_1 + \beta_2}{2} \]

smaller than 1"

reference directions

what you see on the sky
**Absolute parallaxes**

Absolute positions
No reference to distant stars

what you see on the sky

these directions not really accessible

\[ \pi = \frac{\beta_1 + \beta_2}{2} \]

Methods applied:
- measurements of declinations
- zenith distances
- wide angle or global astrometry
- virtually impossible from the Earth to 0"001
# Parallaxes: Evolution 1840 - 1980

<table>
<thead>
<tr>
<th>Year</th>
<th>Value</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>1840</td>
<td>3</td>
<td>published parallaxes</td>
</tr>
<tr>
<td>1850</td>
<td>20</td>
<td>Catalogue of Peters</td>
</tr>
<tr>
<td>1888</td>
<td>40</td>
<td>Catalogue of Oudemans</td>
</tr>
<tr>
<td>1910</td>
<td>100</td>
<td>of which 52 photog. parall. from Kapteyn</td>
</tr>
<tr>
<td>1912</td>
<td>250</td>
<td>Catalogue of Bigourdan</td>
</tr>
<tr>
<td>1917</td>
<td>500</td>
<td>Catalogue of Walkey</td>
</tr>
<tr>
<td>1924</td>
<td>1870</td>
<td>Catalogue Schlesinger</td>
</tr>
<tr>
<td>1930</td>
<td>2000</td>
<td>From here it may include spectroscopic parallaxes</td>
</tr>
<tr>
<td>1950</td>
<td>5800</td>
<td>&quot;</td>
</tr>
<tr>
<td>1965</td>
<td>7000</td>
<td>&quot;</td>
</tr>
<tr>
<td>1980</td>
<td>10000</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

- Estimated error: 0''.016
  \[ \sigma(\pi)/\pi = 50\% \text{ at } 30 \text{ pc}! \]
- Mean value of the parallaxes: 0''.018

*Many of these parallaxes have no individual significance*
A route to absolute parallaxes: Two fields of view

- Overall principles set forth by P. Lacroute in 1967.
- Optical combination of two viewing directions
- The two FOVs are mapped onto a common focal plane
- Stars are combined by pairs
- Wide angle measurements are carried out
Space Astrometry Missions

From Hipparcos to Gaia
**Space astrometry**

- Astrometry is the main reason to go to space ...
  - global, accurate, absolute
  - not achievable from the ground

- but astrophysics is the main reason to pay for it
  - benefits almost everywhere
  - secures its foundations
Goals of Space Astrometry

• Primary Objectives not achievable from Earth
  - Ascertain the distances of the stars
    • stellar parallaxes for astronomers
  - Define and materialise the inertial frame
    • now based on extragalactic sources

• Secondary objectives
  - Astrophysics with astrometry, photometry, spectroscopy
    • stellar and galactic physics
    • detection of extrasolar planets
    • solar system dynamics
  - Tests of fundamental physics in space
    • based on light path geometry
Space astrometry: two complementary concepts

• Survey of a large number of stars
  - Continuous scanning of the sky
  - Input catalogue or on-board detection
  - Complete up to a limiting magnitude or selection of stars
  - The scanning law determines the integration time
  - Frozen observing program

• Pointing at individual sources
  - Pre-selected sources
  - Variable and adapted integration time
  - Longer operation dead time
  - Flexible program, can react to external demand
**Space Astrometry: Past & Present**

- **A successful forerunner: HIPPARCOS (ESA)**
  - accuracy of 1 mas ~ a coin @ 1000 km

- **The unfortunate followers**
  - accuracy of 0.1 mas ~ a nail @ 1000 km
  - Roemer, FAME-1, FAME-2, DIVA, Lomonossov, AMEX

<table>
<thead>
<tr>
<th>ESA</th>
<th>US</th>
<th>US</th>
<th>DE</th>
<th>RU</th>
<th>US</th>
</tr>
</thead>
</table>

- **Study phase**
  - JASMINE (Japan) in the IR

- **Cancelled (Dec 2010)**
  - SIM (US) with 1 μas accuracy

- **Funded - launch 2011 - 2014**
  - NanoJasmine [4 mas], J-MAPS (US) [1 mas]
  - Gaia (ESA): 25 μas (a hairwidth @ 1000 km)
Main Features of Hipparcos

- ESA mission launched in August 1989
- Continuous sky scanning over 3.5 years
- Results published in 1996-7
- One single telescope of 29 cm in diameter
- Two fields of view separated by 58°
- Detection with a photoelectric tube ($r = 0.003$)
- One source observed at a time
Basic astrometric model

- Absolute motion of Vega
  - non rotating reference frame

Motion of VEGA (2000-2005)

\[ \mu_a = 200 \, \text{mas/yr} \]
\[ \mu_\delta = 280 \, \text{mas/yr} \]
\[ \pi = 170 \, \text{mas} \]

parallactic ellipse
Main features

• **Simultaneous observations in two widely separated directions**
  - angular distance between pair of stars
  - angular scale determined by the angle of a complex mirror
  - self calibrating instrument

• **Regular scanning of the sky over 3 years**
  - scanning instrument with no pointing
  - every direction sampled about 110 times during the mission

• **Observation of selected sources: no on-board detection**
  - fixed observing program
Main Results of Hipparcos

• An astrometric catalogue of 118 000 stars
  - Hipparcos is a quasi-fundamental catalogue
  - $\sigma(\alpha) \sim \sigma(\delta) \sim \sigma(\pi) \sim 1\text{ mas at } V = 9 \text{ at } 1991.25$
  - $\sigma(\mu_\alpha) \sim \sigma(\mu_\delta) \sim 1\text{ mas/yr at } V = 9$

• Complete to $V = 7.3 - 9.2$ (depending on galactic latitude)

• Limiting magnitude 12.4

• Distances better than 10% for 21 000 stars, $D < 200\text{ pc}$

• Density: $3.0*/\deg^2$

• Linked to the ICRF with radio stars to within 0.6 mas and 0.25 mas/yr

• Supplemented by Tycho and later Tycho-2
Additional products

• A survey of binary stars
  - solution for 13000 systems
  - discovery of about 3000 new systems
  - astrometric detection of nearly 2000 pairs
  - masses for about 50 systems

• A photometric data base with 130 observations per star
  - $\sigma(H) \sim 0.001$ mag
  - $13 \times 10^6$ epoch observations
  - survey of variability for many types of stars to the $10^{-3}$ mag level
    • remains the best source of homogenous data today
  - 2500 periodic variables with periods and folded light-curves
Standard error in \( \pi \) - ecliptic coordinates
### PPN parameter $\gamma$ with Hipparcos

- **Relativistic effect of light bending introduced in the model**
- **Solution with Hipparcos data**
  - general parameter in the astrometric model
  - measurements a large angles from the Sun
    - from $47^\circ$ ($\delta \theta \sim 10$ mas) to $133^\circ$
  - serious problem with the correlation with parallaxes
- **Solution in absolute astrometry**
  - no comparison of position with or without the Sun
  - no use of small field astrometry
- **Numerous experiments designed to assess the accuracy**

<table>
<thead>
<tr>
<th>Result: $\gamma = 0.997 \pm 0.003$ (Froeschlé, Mignard &amp; Arenou, 1997)</th>
</tr>
</thead>
</table>

- **First determination of light deflection at large angle**
After Hipparcos?

- W. Fricke (Fundamental Catalogues: Past, Present & Future, 1985)
  - "one would wish that the Hipparcos mission should not be unique but be repeated after a period of 10 to 20 years".
- Hipparcos positions degrade quickly (1 mas/yr) $\sigma \sim 15$ mas today
- With no technological improvement, two absolute catalogues
  - $\uparrow \sigma \sim 1$ mas:
    - $\Delta t \sim 20$ yrs
      - $\Rightarrow$ PM to 50 muas/yr $\Rightarrow$ just one order of magnitude improvement.
- ESA Survey Committee in 1994:
  "Initiate a Cornerstone-level program in interferometry to perform astrometric observations at the 10 µas level"
• $10^9$ stars
• $10 \, \mu\text{as} \@ \, V < 13 \, \text{mag}$
• $25 \, \mu\text{as} \@ \, V = 15 \, \text{mag}$

• Photometry ($\sim 25$ bands)
• Radial velocity
• Low resolution spectroscopy

ESA mission
Launch: mid 2013
Mission: 5 years
Mission requirements summary

• **A Stereoscopic Census of Our Galaxy**

• **Astrometry (V < 20):**
  - completeness to 20 mag (on-board detection) $10^9$ stars
  - parallax accuracy: 7 μas at <10 mag; 12–25 μas at 15 mag; 100–300 μas at 20 mag

• **Photometry (V < 20):**
  - astrophysical diagnostics (low-dispersion photometry) + chromaticity
    - 8–20 mmag at 15 mag: $T_{\text{eff}} \sim 200$ K, log $g$, [Fe/H] to 0.2 dex, extinction

• **Radial velocity (V < 16.5–17):**
  - Third component of space motion, perspective acceleration
    - <1 km/s at 13–13.5 mag and <15 km/s at 16.5–17 mag
Assets of Gaia

- A single mission with three nearly synchronous data taking
  - Astrometric, photometric and spectroscopic data
- GAIA is a scanning mission
  - no pointing, no change in the schedule Uniform coverage of the sky
- Quasi regular time sampling over 5 years
  - ~ 80 observations \( \Rightarrow \) photometry, orbits of binaries, asteroids
- Survey mission sensitivity limited
- Internal and autonomous detection system to \( G = 20 \)
- Global astrometry of staggering precision
  - Internal metrology, thermal and mechanical stability
- Experienced and motivated community in Europe after Hipparcos
  - scientific and in industry
Global astrometry in space

- Wide angle measurements
- Two fields of view
- One common focal plane

Spin axis

\[ P = 6h \]

\[ \psi = \gamma - \Delta \]

Focal plane

FPOV

Scan direction

PFOV

image motion

106.5°
Scanning & Sky coverage

- Time average is a combination of the sky distribution and the scanning law
  - two different symmetries: galactic plane and ecliptic plane
10 µas: Incredibly small!

- 0.3 mm displacement on the Earth
- edge-on sheet of paper @ 2000 km
- 1 hair @ 1000 km
- displacement of a 100 mas/yr star in one hour
- motion of a fast minor planet in 100 µs.

10 µas = 50 prad
The Spacecraft in orbit

~10 m
Gaia: telescopes and detector

- 2 off-axis telescope
- 1.45 x 0.5 m²
- 35 m focal length

- single focal plane
- 106 CCDs
- 1 Gigapixel
- 0.93 x 0.42 m²
Detection and measurement systems

- Red & blue photometer detectors
- RVS detectors
- Photometer prisms
- RVS grating and afocal field corrector
- M5 & M6 fold mirrors
- M4/M’4 beam combiner
- BAM & WFS
- Sky mapper
- Astrometric field
Multiplexing observations

106 CCDs, 938 million pixels, $2800 \text{ cm}^2$

Sky Mapper CCDs

Astrometric Field CCDs

Blue Photometer CCDs

Red Photometer CCDs

Radial-Velocity Spectrometer CCDs

Star motion in 10 s

Image motion
**Number of sources per day**

- Number of sources detected per day (log scale) during the mission

![Graph showing the number of sources detected per day during the mission. The graph is on a log scale and displays a trend of daily detections over the course of the mission. There is a horizontal line indicating a constant value of ~45 x10^6.]
Number of stars in the FOVs

- # stars measured at any time in the combined FOVs
Astrometric accuracy: single transit

- Single observation accuracy → orbit, solar system
  - one field transit: integration over 9 AF CCDs
  - point source, 1D astrometry
Astrometric Accuracy : EOM

\[ \mu \text{as} \& \mu \text{as/yr} \]

- Parallax
  - \( \sim 25 \mu \text{as} \)
  - \( \sim 20 \mu \text{as} \)
  - \( \sim 13 \mu \text{as/yr} \)

- Position

- PM
  - \( \sim 80 \mu \text{as} \)
  - \( \sim 60 \mu \text{as/yr} \)
  - \( \sim 110 \mu \text{as} \)

G mag

Astrometric Accuracy (EoM)

Nice, 08 September 2011 - F. Mignard
Distances for stellar physics

- Accurate distances through the Galaxy

Recall: Hipparcos: 20,000 stars with $\sigma_\pi/\pi < 10\%$

$\sim 2.5 \text{ kpc}$
Cepheids with Gaia

- 15 \( d < 0.5 \text{ kpc} \), 65 \( d < 1 \text{ kpc} \), 165 \( d < 2 \text{ kpc} \)
  - bright enough \(( V < 14 \))

- In the plot: 400 galactic cepheids from David Dunlap DB
  - distance and magnitude \( \rightarrow \) Gaia predicted accuracy for parallax

![Histogram of \( \sigma_m / \sigma \) vs. number of cepheids](image)

F. Mignard 2002, 2009

Nice, 08 September 2011 - F. Mignard
Transverse velocity estimate with Gaia

![Graph showing accuracy in transverse velocity as a function of G (mag) and d (kpc) at G = 15, with a line at 1 km/s.](image)
Radial velocity accuracy (EOM, km/s)

- Performances strongly dependent on stellar type
- Average of 40 transits (i.e. 120 CCD crossings)

RAVE: $\langle V_r \rangle \sim 2\, \text{km/s, } 9<1<12$

data: P. Sartoretti et al., 2007; plot: J. de Bruijne
Sky coverage

• The Scanning law is optimized to explore the same area at more or less regular intervals ➔ parallax, proper motions, variability, orbits

• The scan direction must allow alpha and dec measurements

• The along-scan speed must be constant

• Mathematically: a set of two differential equations
Gaia: Scanning

Motion of the spin axis

Sky covered over 4 days

- Spin axis path over 4 months
- Sun path over 4 months
- Lines of sight over 4 days

Crédit: L. Lindegren
Sky coverage

• The Scanning law is optimized to explore the same area at more or less regular intervals \( \Rightarrow \) parallax, proper motions, variability, orbits

• The scan direction must allow \( \alpha \) and \( \delta \) measurements

• The along-scan speed must be constant

• Mathematically: a set of two differential equations
  - Three independent rotational motions
Sky coverage: Equatorial coordinates

# Transits during the mission
**S/C main characteristics**

- **S/C launch mass**: 2 t
- **Power available**: 2 kW
- **S/C height**: 3 m
- **Sunshield diameter**: $\varnothing = 10$ m

**Payload**
- **Entrance pupil**: $1.45 \times 0.5$ m$^2$
- **Focal length**: 30 m
- **Focal plane**: ~ 1 G pixels
Thermal Insulation

- 170 °C

Torus & mirrors
- 150 °C
+/- 5 µK

- 150 °C
+/- 15 µK

- 100 °C
+/- 0.1 K

Sunshield
Solar side
+ 70 °C

Credit: F. Chassat, Astrium
First full deployment test with new motor
Timeline of the mission

• Selection by ESA in 2000 (and confirmed in 2002)
• Prime contractor selected in February 2006
• Data analysis consortium formed in June 2006
  - selected by ESA SPC in March 2007
• Launch: summer 2013
  - from Kourou with a Soyouz rocket
• Orbit around L2
• Continuous observation to 2018
• End of data processing to 2020
  - data base of 1pB of volume
  - volume of computation $\sim 10^{21}$ FLOPS
• Results and data available in 2020
  - one or two intermediate releases foreseen
Thanks for your attention