Tycho-Gaia and beyond

Combining data for precision astrometry

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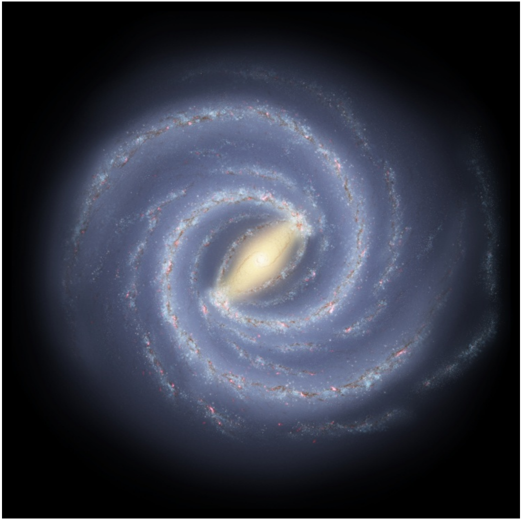
2010–2015: Ph.D. at Lund University, Sweden
2009–2010: Young Graduate Trainee, European Space Agency

Step 1

The motivation: Our Galaxy

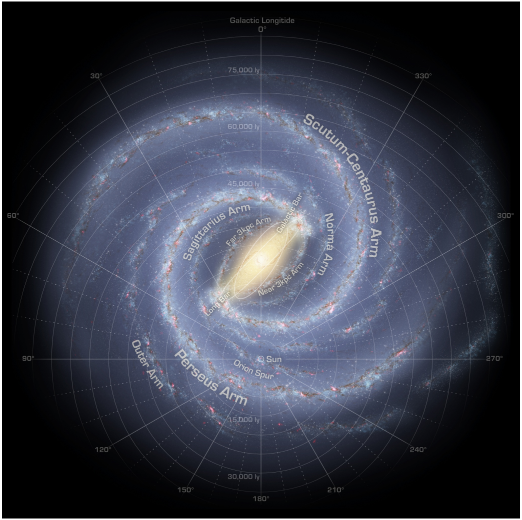
The Milky Way – a spiral galaxy



Artist impression

Illustration Credit: R. Hurt (SSC), JPL-Caltech, NASA
Survey Credit: GLIMPSE

The Milky Way – a spiral galaxy



Artist impression

Illustration Credit: R. Hurt (SSC), JPL-Caltech, NASA
Survey Credit: GLIMPSE

The Milky Way – a spiral galaxy

Structure hard to determine – we see it from within (real photograph)

⇒ Measuring direction of and distances to the stars

Photo: J. Westlake (Colorado Mountain College)

Step 2

The technique: Astrometry

Astrometry

(Four-dimensional) mapping of stars, planets, galaxies, etc

Astrometric parameters, single stars:

- Positions α, δ (since Antiquity)
- Parallaxes ϖ (since 1838)
- Proper motions $\mu_{\alpha*}, \mu_{\delta}$ (since 1718)

Large distances $\Rightarrow$ high accuracy required

ca 1600: Tycho Brahe's mural quadrant

Astrometry: scientific objectives

Astrometric data are fundamental for many purposes

- Orbits and position predictions of asteroids and comets
- Detection of invisible companions (binaries, exoplanets)
- Stellar evolution
- Structure and kinematics of the Milky Way
- Calibration of the cosmical distance ladder
- Determination of reference frame
- Test of fundamental physical assumptions

Proper motion illustration

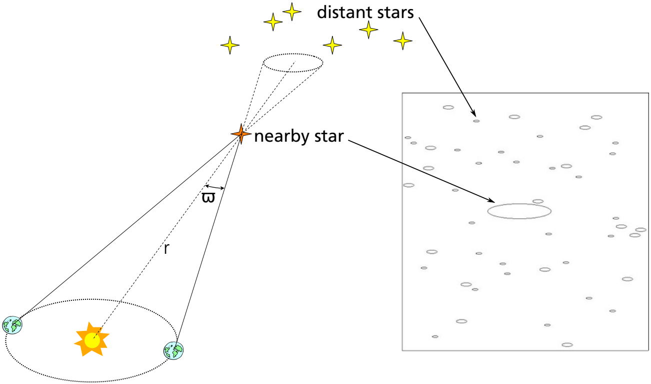
Proper motions of the stars of a well-known constellation
From 100 000 years ago to today to 100 000 in the future

Animation: D. Michalik & Stellarium

Parallax effect

Earth orbits Sun ⇒ displacement of a star dependent of its distance

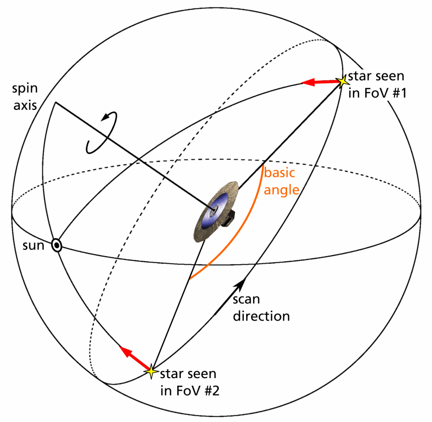
- Only direct method (model-independent)



Click for video: The Earth orbiting the Sun causes the parallax effect
Click for video: Simulations of the real effect, 150 000x exaggerated

Figure: L. Lindegren & D. Michalik
Videos: (1) ESA podcast (2) D. Michalik & Stellarium

Absolute parallaxes



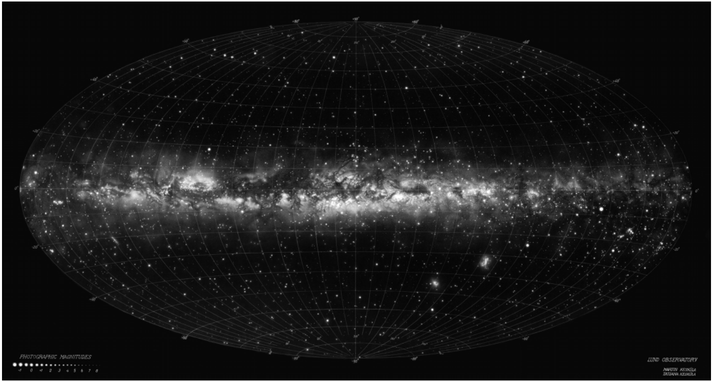
Requires global astrometry

- Scans along (many different) great circles
- Two simultaneous viewing directions, large basic angle
- From space to observe continuously in all directions
- Stable thermal environment

Figure: Lindegren & Michalik

Mapping the stars is not a new idea

- E.g., Hipparchus (ca 150 BC), Brahe (ca 1600), Flamsteed (ca 1700), Bonner Durchmusterung (ca 1850), Carte du Ciel & Astrographic Catalogue (ca 1900), Palomar Sky Survey (ca 1950)



Lund Panorama of the Milky Way (K. Lundmark/M. and T. Kesküla)

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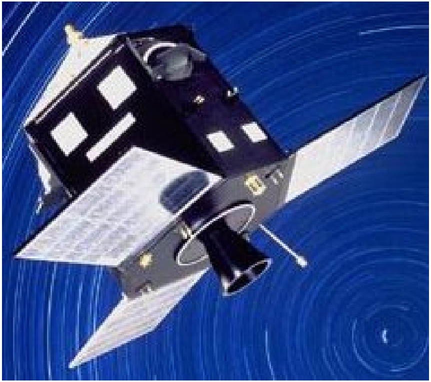
- ESA satellite Hipparcos (1989–1993)



Significant contribution by L. Lindegren/E. Høg/F. Mignard

Illustration: ESA

Mapping the stars is not a new idea

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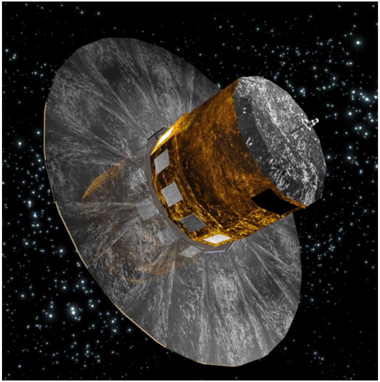
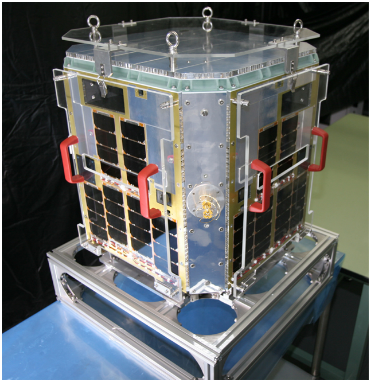
- ESA satellite Hipparcos (1989–1993)
- Gaia (2013–2022), Nano-JASMINE (earliest launch 2017)

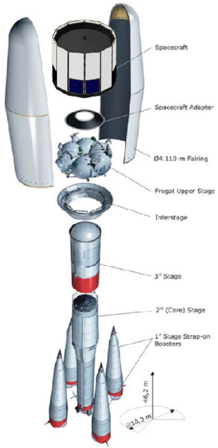



Left: Gaia (Artist illustration: ESA)
Right: Nano-JASMINE (Photo: Nano-JASMINE team)

Step 3

The mission: Gaia

Gaia overview



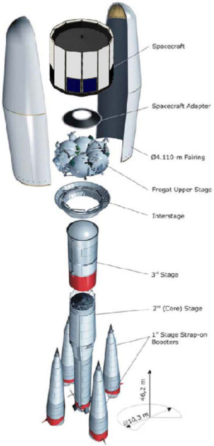
Soyuz-Fregat rocket

- European satellite
- Launched December 2013
- 500 million EUR (+ science staff)
- Five year mission time
- Proposed 25 years ago by L. Lindegren/E. Høg/M. Perryman

Illustration: Spacecraft during launch

Figure: Arianespace. Movie: ESA, C. Carreau

Gaia overview



Soyuz-Fregat rocket

- Astrometry, Photometry, Spectroscopy
- More than 1 billion stars in our Galaxy
- 100s of thousands of Solar System objects (asteroids and comets)
- Tens of thousands of exo-planets
- Half a million of extra-galactic quasars

Illustration: Unfolding of the solar shield

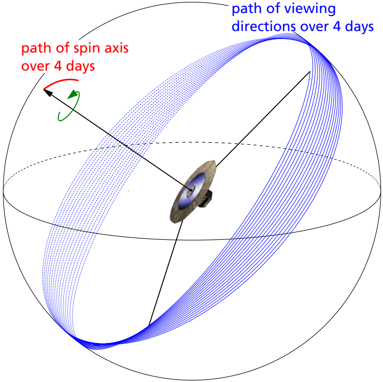
Figure: Arianespace. Movie: ESA, C. Carreau

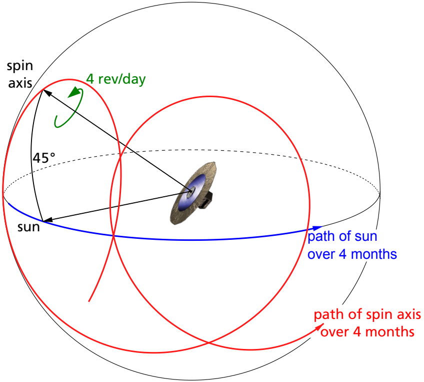
Gaia release schedule (old)

Tentative schedule, **status 15 Nov 2015**

- Science Alerts as soon as possible
- Summer 2016:
    - Positions & G-magnitudes for 100s of millions of stars
    - Ecliptic pole data
    - Proper motions to Hipparcos stars (HTPM)
- 2017: + first 5 parameter astrometry, bright star radial velocities, integrated BP/RP photometry, (astrophysical parameters)
- 2018: + BP/RP data, some RVS spectra, astrophysical parameters, orbital solutions for short period binaries
- 2019: + variability, solar system objects
- 2022: Final catalogue release

Gaia scanning the sky





Figures: L. Lindegren & D. Michalik

Gaia scanning the sky

Sky coverage over time (Nsl37 + Nsl_{GAREQ})

Animation: D. Michalik & B. Holl

Gaia data processing

Preprocessed observations ⇒ Individual source parameters

- Have: 10^{12} observations
- Want: ca $5x10^9$ unknowns:
  Astrometric source parameters, attitude, calibration
- How: **Globally**, self-consistent manner
- Strategy: **Iterative Solution**
- Tool: Astrometric Global Iterative Solution (AGIS)

⇒ A linear least-squares problem $\boldsymbol{Nx} = \boldsymbol{b}$ with iterative solution

Read more: Lindegren et al. (2012, A&A)

A software package for development and testing of AGIS algorithms and experiments with scientific exploitation

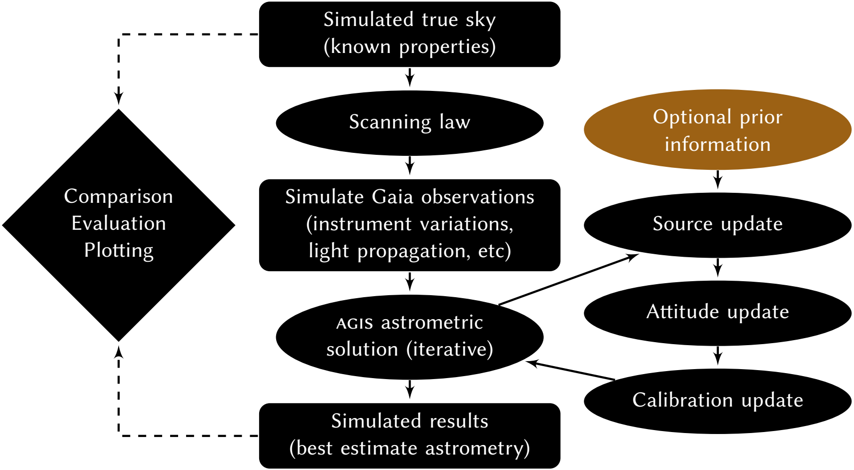
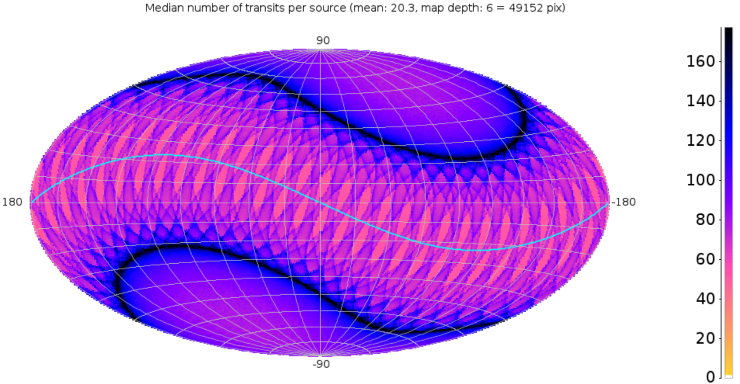


Figure: D. Michalik

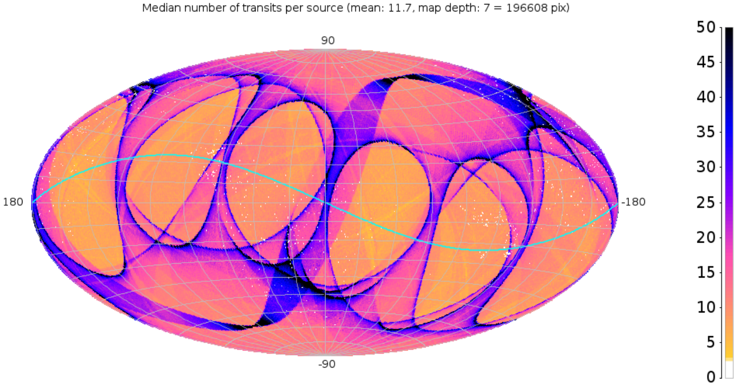
First release is special



Number of transits in a nominal 5 year interval: smooth coverage, 80 transits on average

Simulations: D. Michalik

First release is special



Number of transits during the 13 months for Gaia-DR1: some areas are poorly observed

Simulations: D. Michalik

Step 4

The problem: ambiguity in short datasets

Change in observed coordinate over 5 years

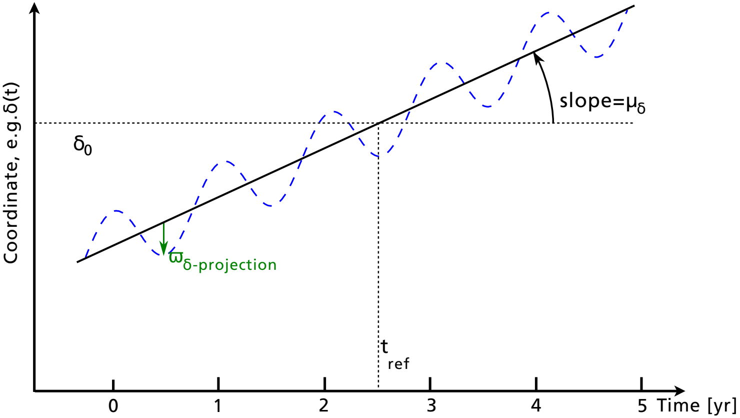


Figure: D. Michalik & L. Lindegren

Gaia observations over 5 years ⇒ pos, ϖ, μ

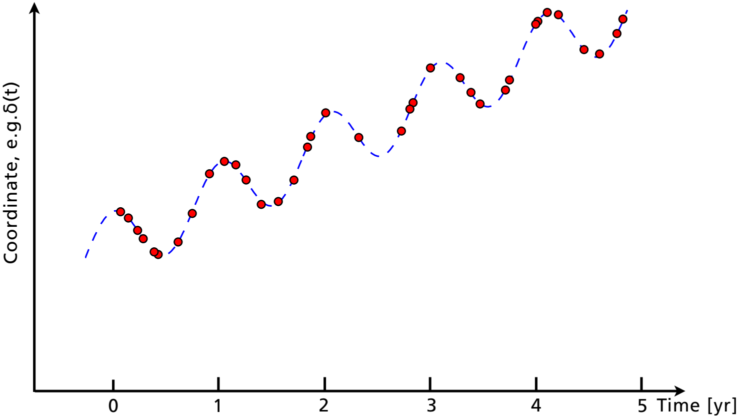


Figure: L. Lindegren & D. Michalik

Gaia observations over 1 year ⇒ marginal

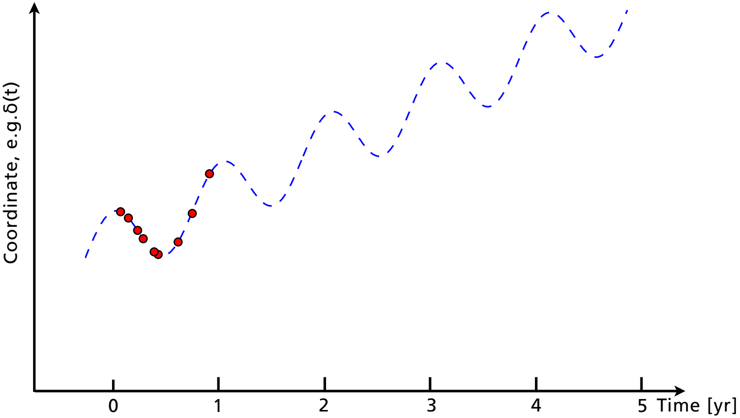


Figure: L. Lindegren & D. Michalik

$\mu - \varpi$ degeneracy for < 1 year observations

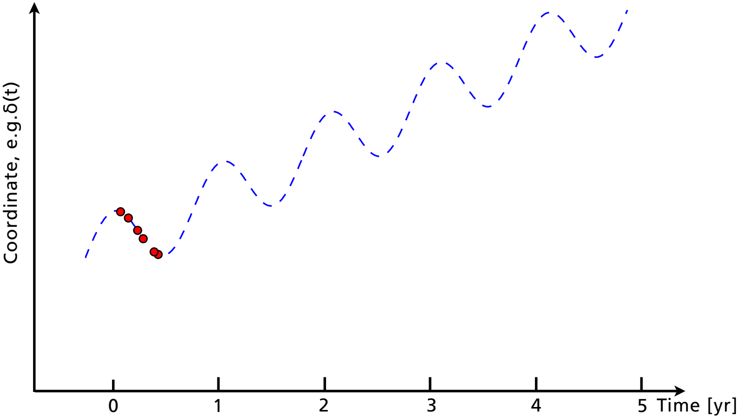


Figure: L. Lindegren & D. Michalik

$\mu - \varpi$ degeneracy for < 1 year observations

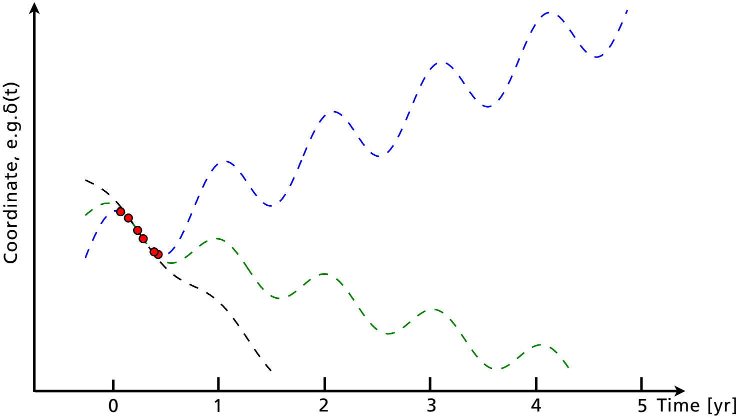


Figure: L. Lindegren & D. Michalik

Step 5

Prior information to the rescue

Integrating prior data in Gaia astrometry

Using Bayes' rule $f(\boldsymbol{x}|\boldsymbol{h}) \propto L(\boldsymbol{x}|\boldsymbol{h}) \times p(\boldsymbol{x})$

- Prior probability density function $p(\boldsymbol{x})$ from prior data
- Likelihood $L(\boldsymbol{x}|\boldsymbol{h})$ from Gaia
- Assuming Gaussian errors: posterior $f(\boldsymbol{x}|\boldsymbol{h})$ is given by joint solution of combined normal equations

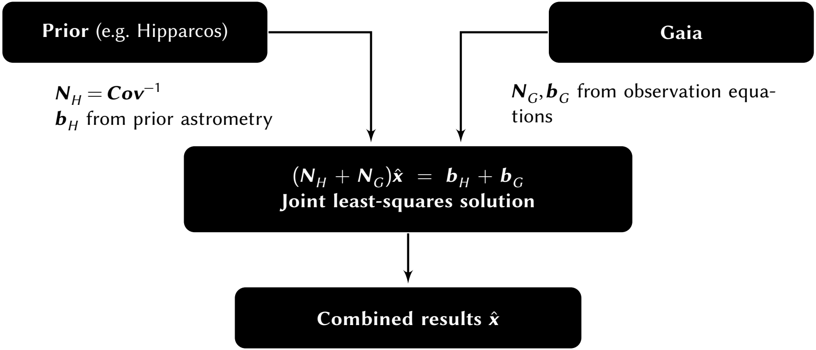
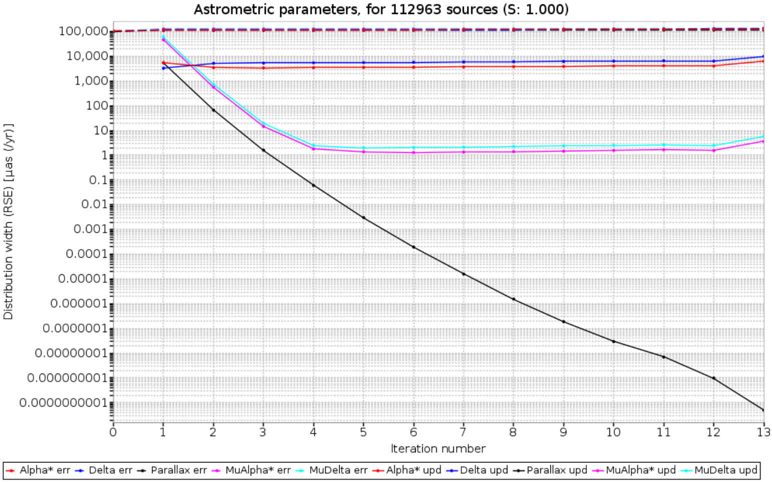


Figure: D. Michalik

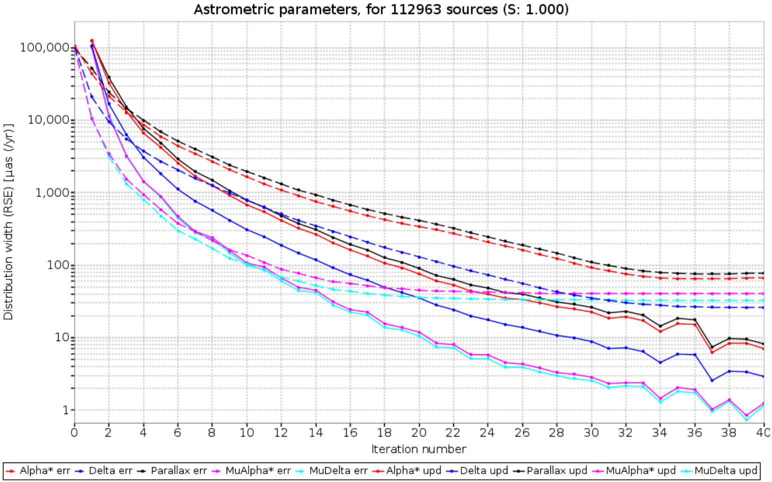
Prior information lifts the degeneracy



Gaia 0.5 yr, diverges

Simulations: D. Michalik

Prior information lifts the degeneracy



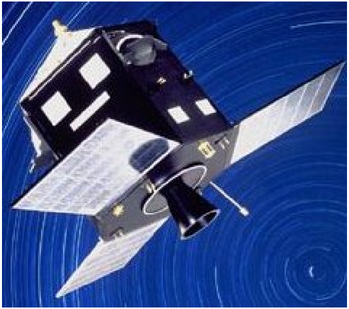
Gaia 0.5 yr with Hipparcos prior, converges nicely.

Simulations: D. Michalik

Step 6

The 1st example: Hundred Thousand Proper Motions (HTPM)

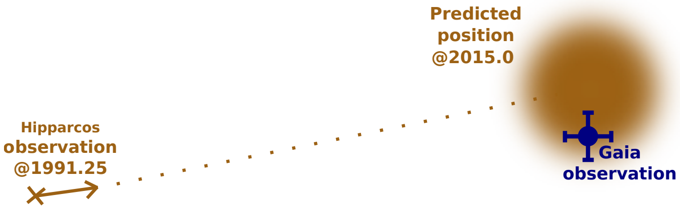
Source of prior information: Hipparcos



- Five parameters for 120 000 stars, < 1 mas
- Telescope: diameter 0.29 m
- Instrument: image-dissector tube and modulating grid

Illustration: ESA

Hundred-Thousand Proper Motions (HTPM)

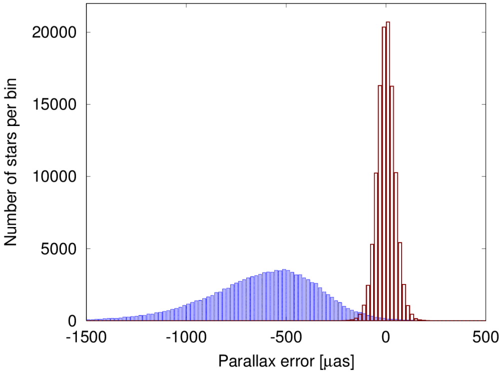


- Combine full Gaia and Hipparcos datasets (10^5 stars in common)
- Original plan for the first Gaia release (Gaia-DR1)
- Accurate and long-term proper motions (baseline 23.75 years)
  - ⇒ Many-fold improvement to Hipparcos
  - ⇒ Remains useful even after the final Gaia release
- We developed the joint solution originally for HTPM

Read more: Michalik et al. 2014

Hipparcos not dense enough for attitude solution

- About 10^6 auxiliary (non-HIP) stars must be added
- Needs >1 yr of Gaia observations for a good unbiased solution



Blue: 0.5 yr, median -591 µas
Red: 1 yr, centered on zero

Figure: Michalik et al. 2014, Fig. 2

Step 7

The improvement: Tycho-Gaia Astrometric Solution

Source of prior information: Tycho-2 catalogue

2.5 million positions at J1991.25, σ = 5–70 mas, 90% complete to V=11.5, obtained from Hipparcos starmapper (auxiliary photomultiplier and grid for attitude determination)

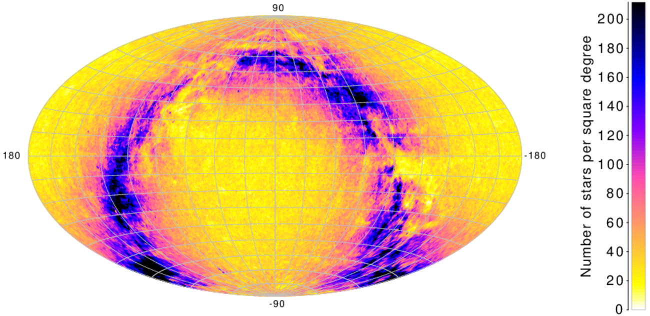


Figure: Tycho-2 sky coverage (Michalik et al. 2015a, Fig. 2, left)

Position alone sufficient to lift the degeneracy

⇒ **Independent** long-baseline proper motions, parallaxes

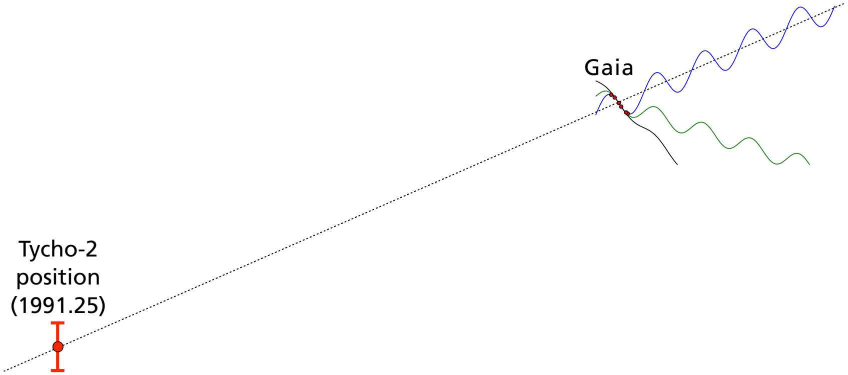
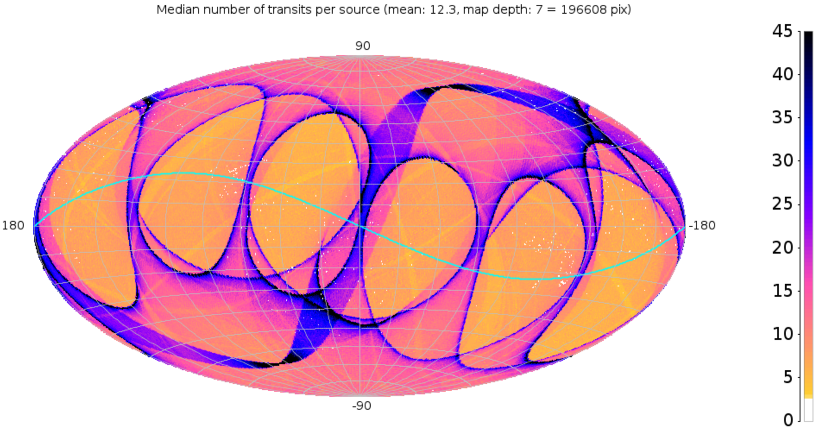


Figure: L. Lindegren & D. Michalik

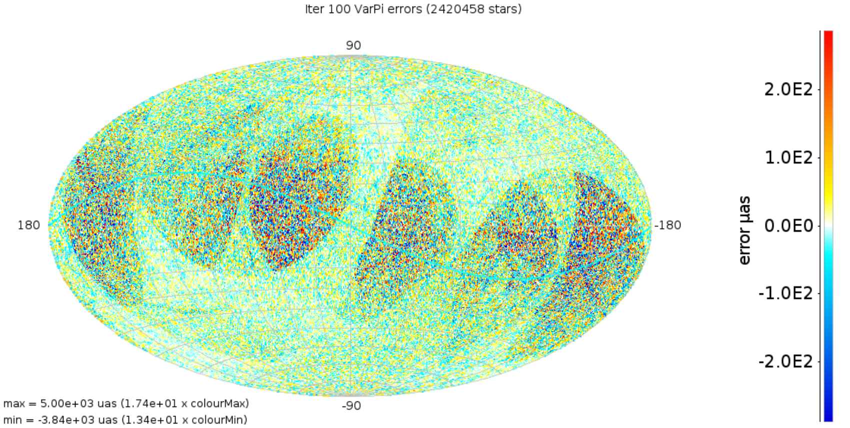
Simulated Gaia observations (July 2014–May 2015)



Number of focal plane transits
(simulated with AGISLab)

Figure: D. Michalik

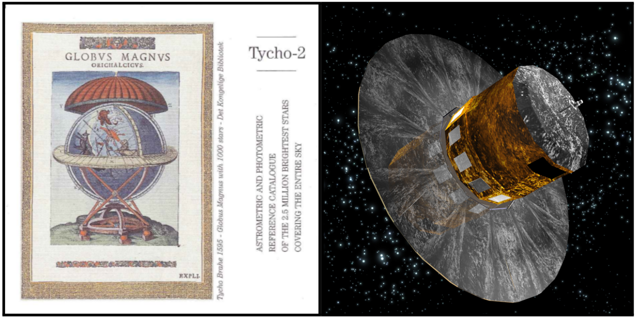
Simulated Gaia observations (July 2014–May 2015)



Unbiased parallax errors (average per pixel), small spread
⇒ **Success!** (...in a perfect world)

Figure: D. Michalik

Tycho-Gaia Astrometric Solution (TGAS)



- Use Tycho-2 stars instead of arbitrary auxiliary stars
- Prior: add their positions at J1991.25 as additional observations
- Full solution with much less Gaia data (approx. one year earlier)
- HTPM is an integral part of TGAS
- **Independent proper motions and parallaxes for 2.5 M stars**

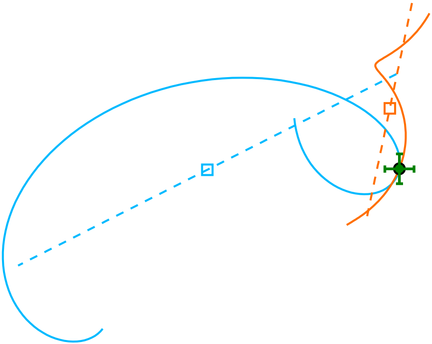
Left: Tycho-2 CD cover
Right: Illustration Gaia satellite (ESA)
Read more: Michalik et al. 2014, 2015a

Step 8

A prior to rule them all

Short/scarce datasets need a prior

- Gaia observes 1 billion of the Milky Way stars (a few 100 billion)
- Tycho prior for 2.5 M – what about the remaining 997.5 M?
- Actual parallax and proper motion cause (unknown!) bias



- Same partial solution for very different astrometric parameters
- Is the observation a nearby dwarf (blue) or a distant giant (orange)?
- Formal errors grossly underestimate the actual errors!

Figure: L. Lindegren & D. Michalik

A generic approach for incomplete data

Objective: Obtain positions and correct error estimates, even for:

- First release (too short a time interval)
- Stars at the detection limit (seen too seldom)
- Transient objects (too short a time interval)

What is ...

- the influence of a prior to an astrometric solution?
- the probability density function of the positional offset?
- a realistic distribution of true ϖ and μ?
- the optimal prior to pick, and what does it depend on?

Study based on Gaia Universe Model Snapshot (GUMS)

Read more: Michalik et al. 2015b

Behaviour of astrometric solution with prior

Left: Quasi two parameter solution

- Formal errors grossly underestimate actual errors

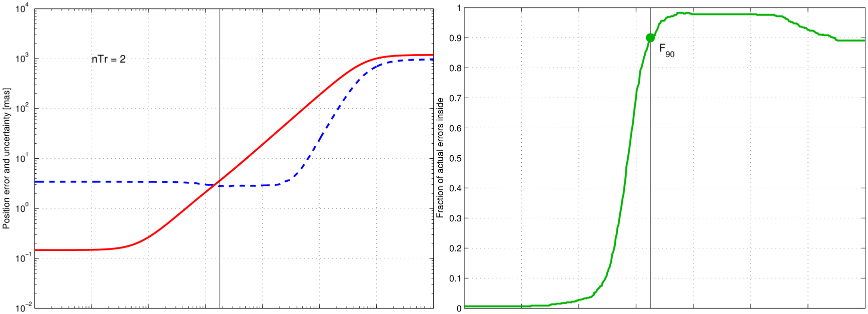
Middle: Use knowledge that parallaxes, proper motions are small

- 5 parameter solution, realistic formal errors

Right: Degenerate solution

Figures: Michalik et al. 2015b, Fig. 1+2

Generic prior properties

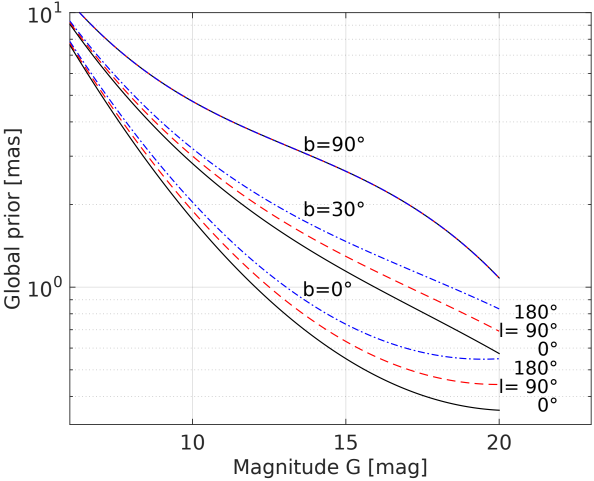


90% of the actual position errors contained in the 90% confidence formal uncertainty ellipse

Excerpt from Michalik et al. 2015b, Fig. 3

Generic prior properties

Prior uncertainty depends on magnitude and Galactic latitude



Generic prior results

Table: Actual errors and agreement factor with formal uncertainty.

Prior $\sigma_{\varpi,p}$	Fraction in 90% conf. ellipse			Actual position errors [mas]		
	$G \simeq 11$	$G \simeq 15$	$G \simeq 19$	$G \simeq 11$	$G \simeq 15$	$G \simeq 19$
none (2 parameters)	0.5%	1.8%	13.5%	33.0	16.3	15.2
Generic prior	90.1%	91.4%	91.2%	7.6	4.3	7.6

Benefits: always provides a non-singular solution

1. Reasonable error estimates and better actual errors
2. With insufficient amount of observations

Caveats: biases the solution

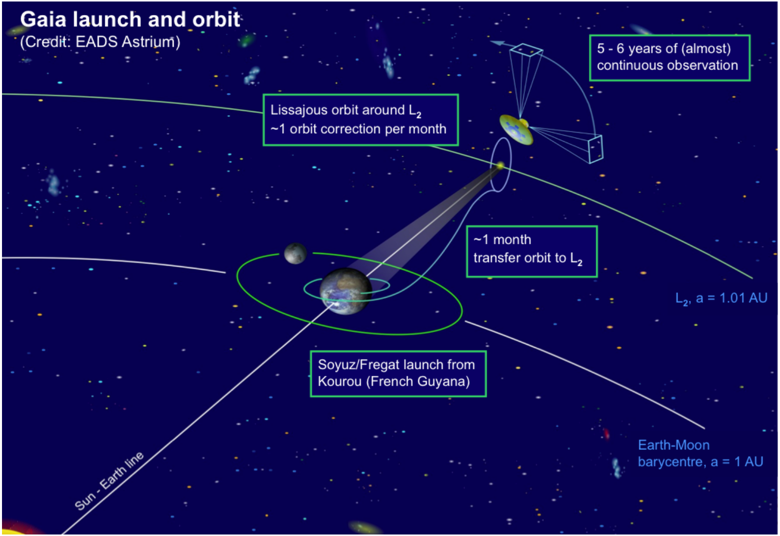
1. Serious for $\varpi, \mu \Rightarrow$ Not to be published
2. Must not be used as soon as enough information are available

Table: Excerpt from Michalik et al. 2015b, Table 2

Step 9

Intermission: Launch

Launch to L2



Launch and orbit

Launch to L2

Folded Gaia spacecraft

Launch to L2

Loading bay

Launch to L2

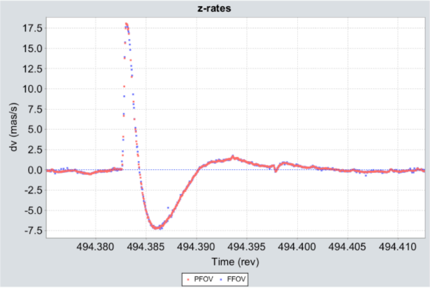
Rocket before launch

Launch to L2

Step 10

The complications: Basic Angle Variations

Real life ≠ simulations



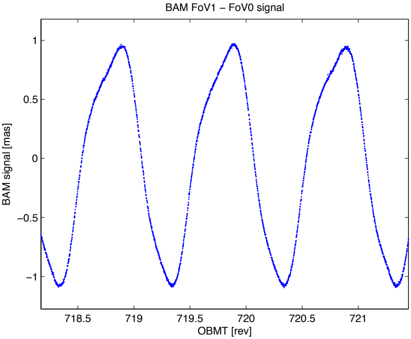
Some of the real life complications:

- Data gaps due to orbit maintenance, cosmic rays
- Transmission loss ⇒ Heating for decontamination
- Re-focussing
- Micro-meteoroid hits
- Thermal micro-clanks (material relaxation)

And the eternal nightmare of an astrometrist …

Figure: a real Gaia micro-meteoroid hit

Basic Angle Variations

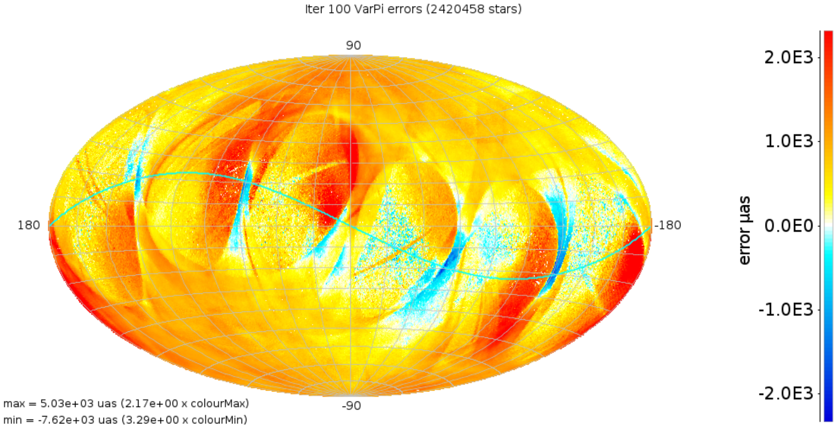


- Basic angle (BA), $\Gamma = 106.5\,\mathrm{deg}$
- Stability critical for absolute parallaxes
- Gaia has on-board metrology, the Basic Angle Monitor (BAM)
- **BAM data shows large variations (approx. 1 mas)**

Figure: L. Lindegren
Publicly available from A. Mora et al. (2014, SPIE)

Results with BA variations

- Simulating variations found by BAM
- Without corrections ⇒ large systematics in parallaxes

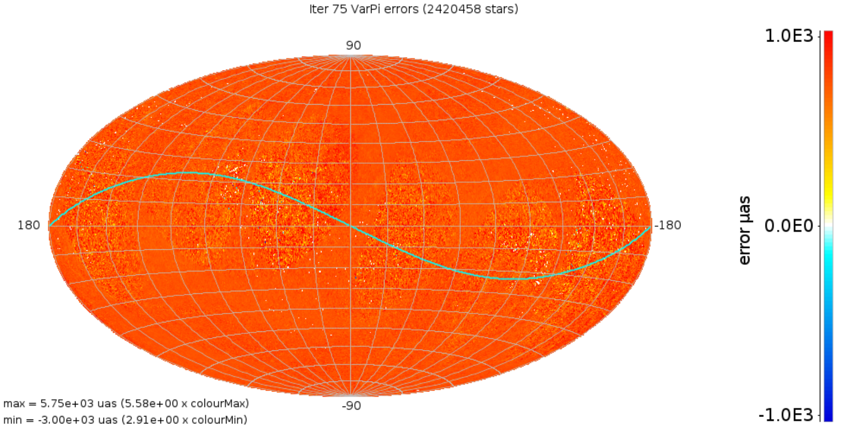


Parallax errors (average per pixel, overall median ∼ 0.8 mas)

Figure: D. Michalik. BAV implementation by L. Lindegren & A. Bombrun

Solving BA variations from observations

- Most harmonics can be entirely removed
- Homogeneous shift remains, must be verified through quasars



Parallax errors (average per pixel, overall median ∼ 0.8 mas)

Figure: D. Michalik. AGIS-GGU and VBAC by S. Klioner, H. Steidelmüller & A. Bombrun

Verification of TGAS parallaxes through quasars

Are BAM measurements real? (Michalik & Lindegren 2016)

But: Independent quasar solution in TGAS not possible

1. Add prior for quasars: Assuming zero proper motion
2. Compare resulting parallaxes to zero (BAM expectation: 871.9 µas)

Demonstrated in simulations

Subset	Median [µas]
with spurious proper motions	
Stars	**872.0** ± 0.2
Quasars	**877.7** ± 3.4
with 5% contamination	
Stars	**872.0** ± 0.2
Quasars	**872.0** ± 2.4

Table: excerpt from Michalik & Lindegren 2016, Table 1

Step II

Conclusions

Summary of thesis research

Study of how to handle stars with insufficient observations

- Scenarios: first release, transient sources, sources at detection limit
- Solution by incorporating prior information
- Demonstrated through detailed simulations

Generic prior for non-Hipparcos and non-Tycho stars

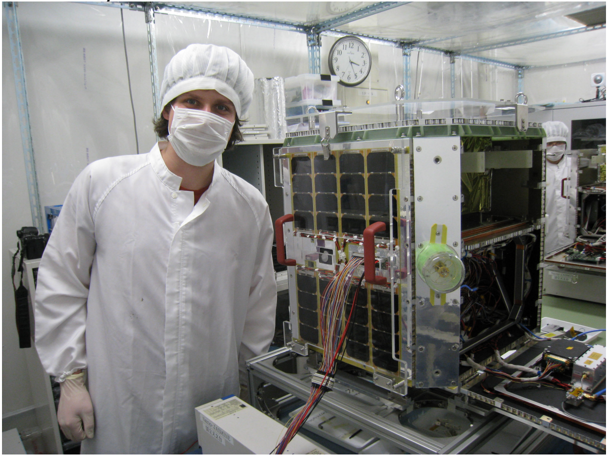
- Ensures sensible position estimates and uncertainties

Tycho-Gaia: long-baseline astrometry, full five parameter

- Preliminary results (real data!) very exciting and promising
  - 2.2 million parallaxes and proper motions, Hipparcos-like quality
  - 1 million of very high quality ($\sigma_\varpi < 0.32$ mas)
  - Independent parallaxes and proper motions
  - Includes Hipparcos stars
- Challenges: scientific validation, basic angle variations
- Quality of parallaxes to be verified through quasars

Versatile concepts

Applicable to scanning global astrometry satellites in general, e.g. the Japanese astrometry satellite Nano-JASMINE



…or a potential Gaia successor mission in a few decades time

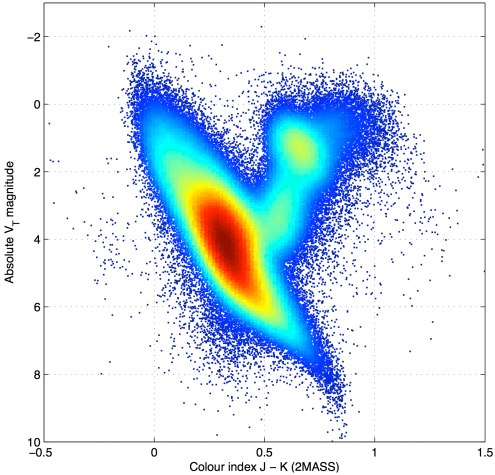
Photo: with the satellite in the clean room in Tokyo
Read more: Michalik et al. 2012, 2013

Long-lived results

- Mean long-baseline proper motion from joint solution (TGAS)
- Instantaneous proper motion from Gaia alone
- Difference reveals long-period exoplanets/binaries
- Similar principle to $\Delta\mu$-binaries in Hipparcos

HR-diagram from TGAS trial (real data)

Results are based on a trial run using just a few months of Gaia data



(approx. 480 000 Tycho-2 stars, with 2MASS colours, $\varpi > 0$, $\sigma < 1$ mas, $\varpi/\sigma > 10$)

Plot: L. Lindegren

Gaia release schedule (revised)

Updates to the schedule, **current prediction**

- Summer 2016:
  - **Improved positions, realistic uncertainties and G-magnitudes for 100s of millions of stars**
  - Ecliptic pole data (photometry calibration)
  - **5 parameter astrometry for approx. 2 million Tycho and Hipparcos stars (Tycho-Gaia Astrometric Solution; TGAS)**

Second release postponed to summer 2017, remaining schedule from 2018 onwards unchanged