GaiaNIR – Solar System

Toward µas astrometry on small solar system bodies

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Science and technology roadmap for µas studies of the Milky Way
Lund, 18-20 July 2023

Gaia SSO main characteristics

- Gaia provides high precision astrometry, and photometry
  and colour/spectro-photometry
    - astrometry at *sub-mas* level (per CCD) approx 0.3—20mas for mag G 7—21
- Large number of bodies
    - largest set from a single instrument
    - from inner near-Earth objects NEOs to trans-Neptunian TNOs
      ++ comets and planetary satellites
- Some constrains from design - scanning law
    - no pointing but scanning, no visit planning/optimisation
    - no tracking at acquisition (motion in window, trail in CCD)
    - limiting magnitude modest (vs. new object)
    - visibility vs. orbit (cadence)
    - motion (fast), and size (large), and proximity to planet/bright object
    - solar elongation and solar phase angle
    - no specific target of interest (outreach)
        - e.g. no Gaia data of 2/I Borissov, barely for Didymos, so far none for Apophis, etc.

Gaia SSO main characteristics

Gaia astrometry of asteroids (per CCD) approx 0.3—20mas
more *sub-mas* than *µas*

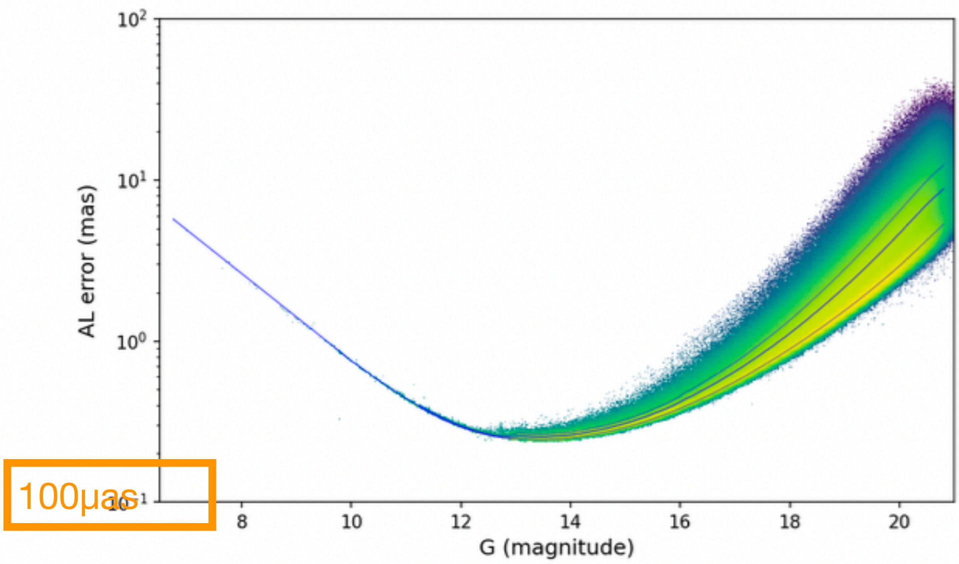

Fig. 3: Error model in the AL direction for the SSO astrometry in *Gaia* DR3, as a function of the G magnitude. The total error is represented, as given by the squared sum of the random and the systematic component. The colour represents the data density (yellow/light: higher density). The thick line and the two thin lines on each side are the quantiles corresponding to the mean and the 1-sigma level.

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    - astrometry at *sub-mas* level (per CCD) approx 0.3—20mas for mag G 7—21
- Large number of bodies <— all sky scanning
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Gaia SSO main characteristics

- Indirect outcome for SSOs
  - i.e. from astrometric stellar catalogue only
    - no direct observation of an SSO at all
  - reduction of observations, no systematics zonal error, better calibration
    - limited by photon noise and pixel resolution centroing
    - starting with DR2 with proper motions Gaia is the reference catalogue for any ground-based astrometry
    - no big further improvement expected – except old plates
  - stellar occultation/appulse
    - as new paradigm of astrometric observation?

- And/Or direct observations of SSOs
  - include/adapt data acquisition and data reduction pipeline
    to our ‘beloved’ moving objects
    at early stage

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Star catalog position and proper motion corrections in asteroid astrometry II: The Gaia era

(Eggl et al. 2020)

Siegfried Eggl[a,b,*], Davide Farnocchia[a], Alan B. Chamberlin[a], Steven R. Chesley[a]

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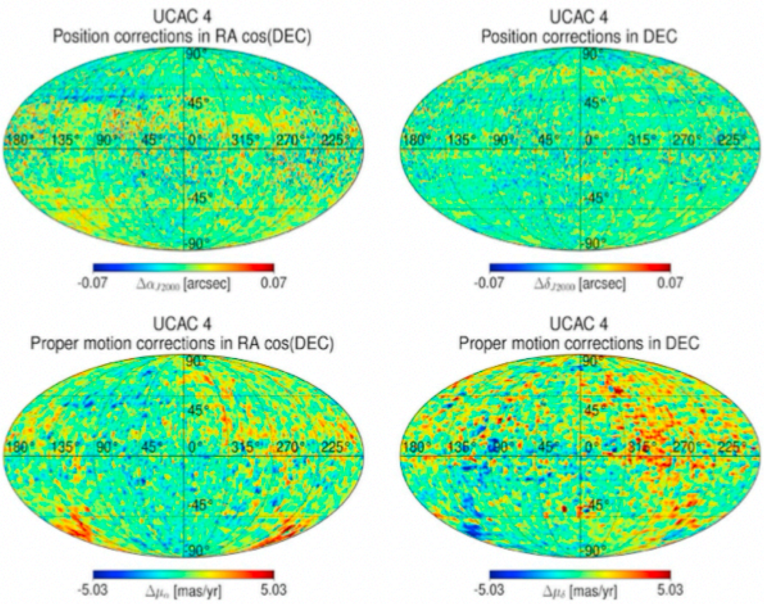
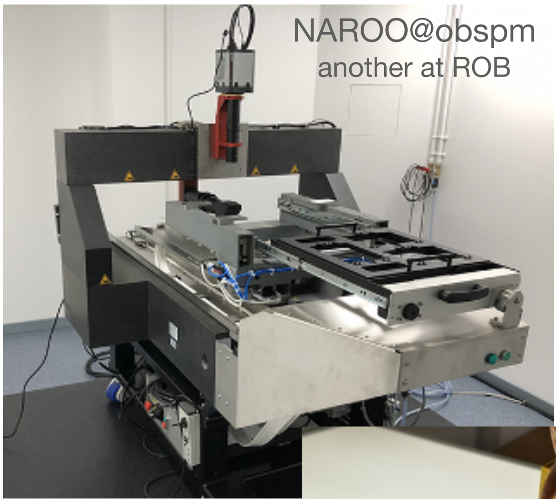


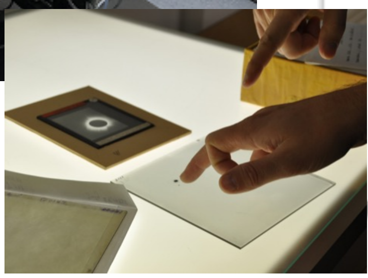
Fig. 5. Same as Fig. 3 but for the UCAC 4 catalog. Systematics are small in positions, but traces of stellar proper motion errors in the galactic plane are visible.

astrometry from stars

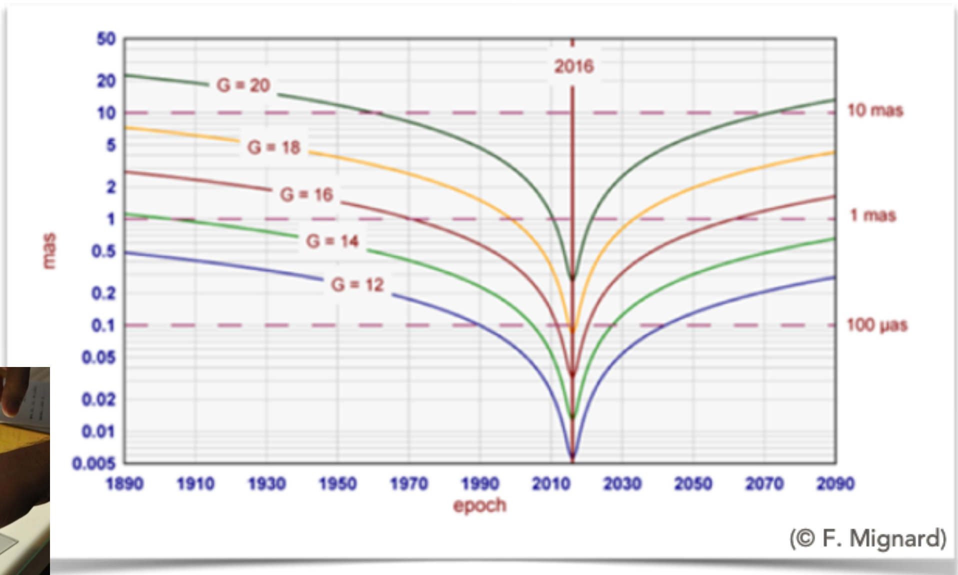


NAROO@obspm
another at ROB

‘prehistoric PNG’
even E. Høg didn’t used them:)



proper motion for photographic plates



scanning old photographic plates — re-reducing old observations with improved proper motions

=> high precision back a Century in the past

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astrometry from stars

- Stellar occultation as astrometric observation

- With high precision on the star's position+parallax+proper motion+RV
  error is dominated by angular size of the object, which can be ±arbitrarily small (vs. apparent size of star)
  approx 100x more precise than classical g-b astrom.

- => Interest for specific targets

- Direct astrometry from a stellar occultation of an NEO
  is as valuable as Arecibo/Goldstone radar tracking!
  and mostly complementary
  -> Desmars et al. 2023

astrometry from stars

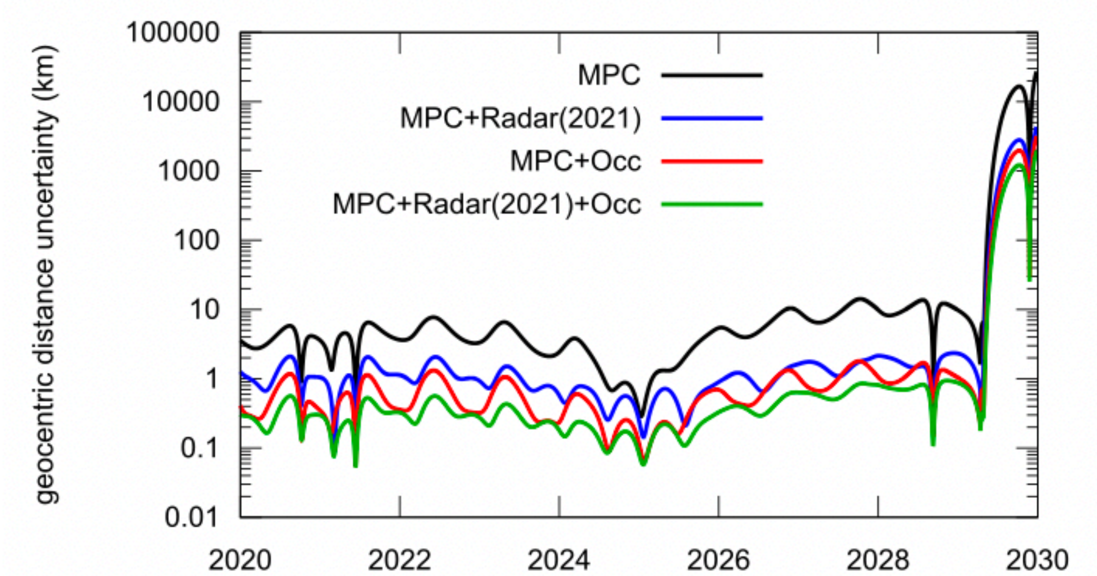

Fig.1 Uncertainty in geocentric distance over 2020-2030 using 4 datasets

Orbit of NEO/PHA asteroid Apophis with/wo stellar occultation astrometry:
add a few (6) occultation astrometry
=> stellar occultation as valuable as radar, and complementary
=> determination Yarko. param A_2

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Gaia and context

- Hipparcos/Tycho 1989—1993 : 48 aster (+satellites+planets) ≈10mas astrometry
- Gaia 2014—2025? : 350k asteroids ; sub-mas precision
- other surveys of SSOs
  - IR and visible ; mostly detection of NEOs (Planetary Defense) ; some serendipity (Euclid)
  - largest survey to come VRT/LSST
    - faint objects NEOs, MBAs, far TNOs, ISOs
  - none with µas, nor sub-mas!
- Most objects will be known (down to to V≈24)

Toward µas astrometry

NB:only a few ‘out of the blue’ thoughts

Some challenges — depending on actual epoch and final astrom. accuracy

- **Need of improved dynamical modelling (computed position)**
  - planetary and asteroids perturbations
  - mutual random perturbations
  - non-grav forces
  - relativistic acceleration
  - from computed CoM (t)_TCB to observed centroid ‘position’ at time t
    - if not point source, need photometry for shape/spin model
- **Which effects? to what order?**
  - deflection of light depends on true distance
  - relativistic perturbation of Sun and planets and cross-term
  - relativistic aberration; effect of ref frames, time scales; transformations, …
- **Numerical integration of equations of motions**
  - no more simple perturbed 2-body problem
  - more variational equations
  - iterations (and convergence)

Toward µas astrometry

simplified GR from Sun (Gaia DPAC)

perturbed 2BP (heliocentric)

all perturbations add linearly

$$\ddot{\mathbf{r}}_i = -G.(M_\odot + m_i)\frac{\mathbf{r}_i}{r_i^3} + \sum_p \mathbf{f}_p$$

planets/asteroids perturbations

relativistic from Sun (simpl.)

$$\mathbf{f}_{p|Grav} = -\sum_{j\neq i, j\geq 1}^{n_p} Gm_j \left\{ \frac{\mathbf{r}_i - \mathbf{r}_j}{r_{ij}^3} + \frac{\mathbf{r}_j}{r_j^3} \right\}$$

$$\mathbf{f}_{p|relat} \simeq \frac{GM_\odot}{c^2 r_i^3} \left\{ \left[\frac{GM_\odot}{r_i} \dot{\mathbf{r}}_i^2 \right] \mathbf{r}_i + 4(\mathbf{r}_i \cdot \dot{\mathbf{r}}_i)\dot{\mathbf{r}}_i \right\}$$

IEH equations (wikipédia)

N-body(barycentric)
Sun & planets
PN approx

$$\begin{aligned}\vec{a}_A = &-\sum_{B\neq A} \frac{GM_B}{r_{AB}^2}\vec{n}_{AB} \\ &+ \frac{1}{c^2}\left\{ -\sum_{B\neq A} \frac{GM_B}{r_{AB}^2}\left[v_A^2 - 4(\vec{v}_A \cdot \vec{v}_B) + 2v_B^2 - \frac{3}{2}(\vec{n}_{AB}\cdot\vec{v}_B)^2 - \frac{5GM_A}{r_{AB}} - \frac{4GM_B}{r_{AB}} \right]\vec{n}_{AB} \right. \\ &+ \sum_{B\neq A}\frac{GM_B}{r_{AB}}\left[\vec{n}_{AB}\cdot(4\vec{v}_A - 3\vec{v}_B)\right](\vec{v}_A - \vec{v}_B) \\ &+ \sum_{B\neq A}\sum_{C\neq A,B}\frac{G^2 M_B M_C}{r_{AB}^2}\left[\frac{4}{r_{AC}} + \frac{1}{r_{BC}} - \frac{r_{AB}}{2r_{BC}^2}(\vec{n}_{AB}\cdot\vec{n}_{BC})\right]\vec{n}_{AB} \\ &\left. -\frac{7}{2}\sum_{B\neq A}\sum_{C\neq A,B}\frac{G^2 M_B M_C}{r_{AB} r_{BC}^2}\vec{n}_{BC} \right\} + O(c^{-4})\end{aligned}$$

Toward µas astrometry

- and… all other perturbations (J2, non-grav, …)
- and… all partial derivatives in numerical integration
- and… to what order and cross-terms in developments

For what objectives?

- ¿ Scanning or Pointing ? what observation? what strategy? how many/what objects?
  - by pointing I mean pointing a specific SSO !
  - anyway, our SSO objects are mostly near the ecliptic… cf. LSST Northern spur
  - what integration time ? pixel size ?
  - nIR => more distant - redder objects
  - Photometry, spectro-photometry (nota near IR interesting for SSO)
- 1. High precision astrometry
  - 'individual' and global' effects : per object / \ all objects
  - detect subtle effects (spin/shape, Yarkovsky, binaries), compute IP risk assessment of PHA, …
  - grav (aster mass) and non grav (active aster vs comets) effects ; test gravitation in Solar System, …
- 2. Number/variety of targets, spread through Solar System
  - avoid systematic effects – averaging errors
    => less precision *but* less biases
- 3. Long-term astrometry and sparse photometry
  - extend baseline to Gaia data
  - good for outer orbit objects (with larger orbital period)
  - secular, quadratic, and long-period effects
  - long-term dynamics of planetary satellites (dissipation, formation)
  - realisation of a dynamically non-rotating frame
  - dG/dt, ref. frames, relativistic effects, …
  - local test of GR, gravitation to higher precision
- Testing gravity – Local test of GR i.e. in Solar System (small v/c ; GM/c^2)
  - in contrast to a hypothetic/potential dedicated space probe for GR test
  - maybe not better than other *local* tests, but independent, with different hypothesis/modelling
    (better to have multiple independent tests if you want to contradict Einstein GR)

For what objectives?

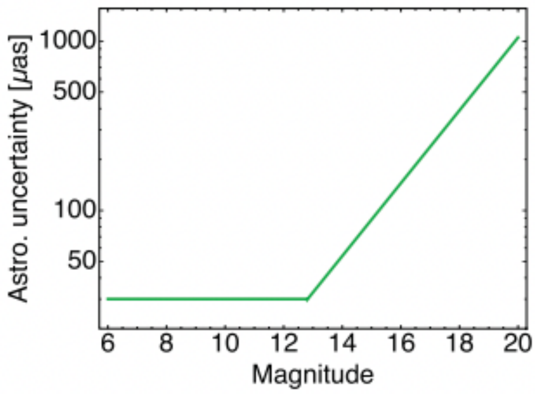
- Gaia type simulation - Variance analysis (Hees et al.):
  - 10k asteroids; 2D precision 0.2 mas; over 5years
  - De-correlated Solar J2 and PPN parameter β;
  - Variation dGM/dt
  - Strong Equivalence Principle through the η parameter.
  - Test Standard Model Extension "constrain Lorentz violation through the SME formalism" de-correlate parameters

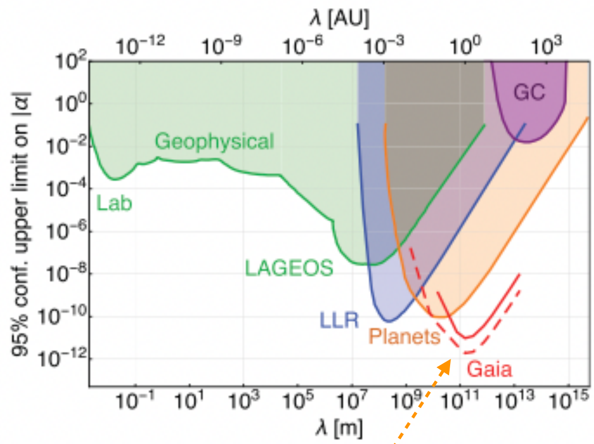
Table 1. Sensitivity on the SME gravity parameters.

SME parameters	Sensitivity (σ)
$\bar{s}^{XX} - \bar{s}^{YY}$	9×10^{-12}
$\bar{s}^{XX} + \bar{s}^{YY} - 2\bar{s}^{ZZ}$	2×10^{-11}
$\bar{s}^{XY}$	4×10^{-12}
$\bar{s}^{XZ}$	2×10^{-12}
$\bar{s}^{YZ}$	4×10^{-12}
$\bar{s}^{TX}$	1×10^{-8}
$\bar{s}^{TY}$	2×10^{-8}
$\bar{s}^{TZ}$	4×10^{-8}

(Hees et al. 2015)

For what objectives?





5th force

- now with 390k asteroids; 2D precision down to 200 µas;
- over 5years then over 10 years (dashed line)

Table 2. Statistical uncertainties reachable using Gaia observations to determine the SME $\bar{s}^{\mu\nu}$ coefficients considering a 5 years nominal mission and an extended mission of 10 years.

	$\bar{s}^{XX} - \bar{s}^{YY}$ $[10^{-12}]$	$\bar{s}^{XX} + \bar{s}^{YY} - 2\bar{s}^{ZZ}$ $[10^{-12}]$	$\bar{s}^{XY}$ $[10^{-12}]$	$\bar{s}^{XZ}$ $[10^{-12}]$	$\bar{s}^{YZ}$ $[10^{-12}]$	$\bar{s}^{TX}$ $[10^{-9}]$	$\bar{s}^{TY}$ $[10^{-9}]$	$\bar{s}^{TZ}$ $[10^{-9}]$
5 years mission	3.8	6.5	1.7	0.93	1.7	5.7	8.9	16.7
10 years mission	1.5	2.1	0.71	0.38	0.59	1.1	2.1	4.1

(Hees et al. 2018   IAUs)

a ‘final’ note

- Tatiana Muraveva (Bologna) asked Chat GPT
  What is Gaia NIR impact on… ?
  - it’s important to note that the specific advantages and impacts of a Gai NIR missions on the study of
    ~~…..RR Lyrae stars ……..~~
    …..Solar System Objects and Small Bodies……
    would depend on the mission’s design, capabilities, and scientific objectives
  - Indeed! and a sometime complicated figure of merit to achieve all scientific objectives together
  - can Gaia NIR rely on Gaia for a more relaxed scanning law / cadence procedure?

PS : can ESA, Horizon Europe, COST, etc. provide us with a chat GPT.4 licence?

- we were expecting:
- more (≈1500) NEOs
- more discover of Atira

Table 2: Object types in DR3.

NEOs (Atira, Aten, Apollo, Amor)

Object type	number of objects
Atira	1
Aten	43
Apollo	230
Amor	173
Mars Crossers	1550
Inner Main Belt	3305
Main Belt	144 975
Outer Main Belt	4940
Jupiter Trojans	1550
Centaurs	8
TNOs	24
Others	2
Total asteroids	156 801
Unmatched moving objects	1 320
Planetary satellites	31
Total	158 152