Technologies for a GW astrometric antenna

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Contents

✓ The operational principles of a GWAA

A GWAA is capable of estimating the strength of and pin-point the direction to GWs by utilizing suitable natural star-like close pairs as antenna "arms".

$$\cos\left(\psi_{ij}^{SS} + \delta\psi_{ij}^{GW}\right) = \cos\psi_{ij}^{SS} + F_{ij}^{GW}$$

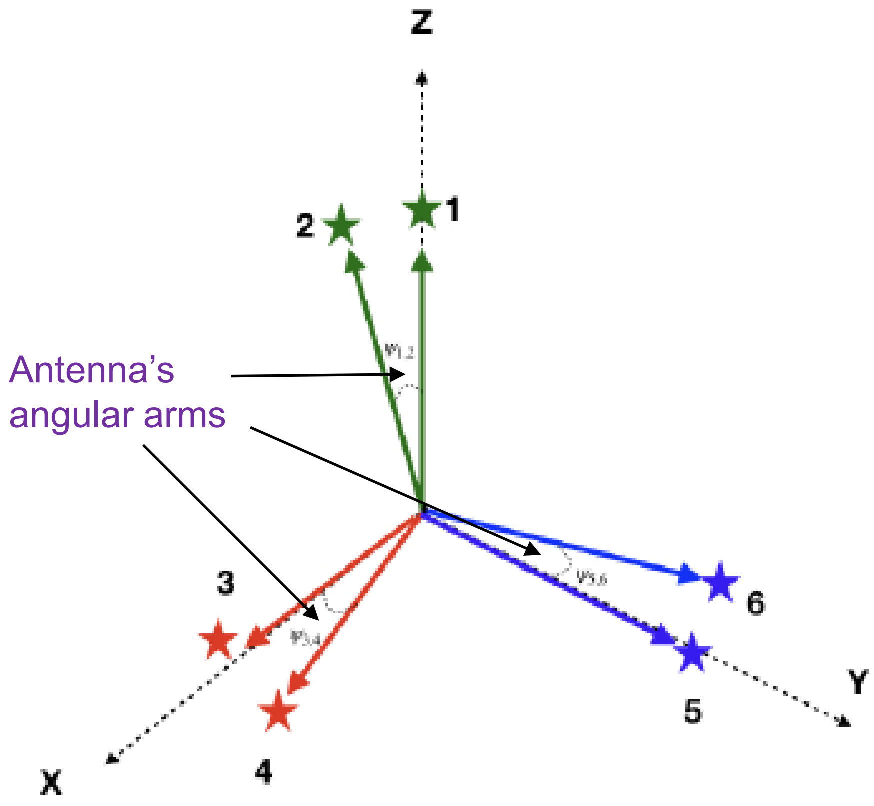
Observation equation of the GWAA

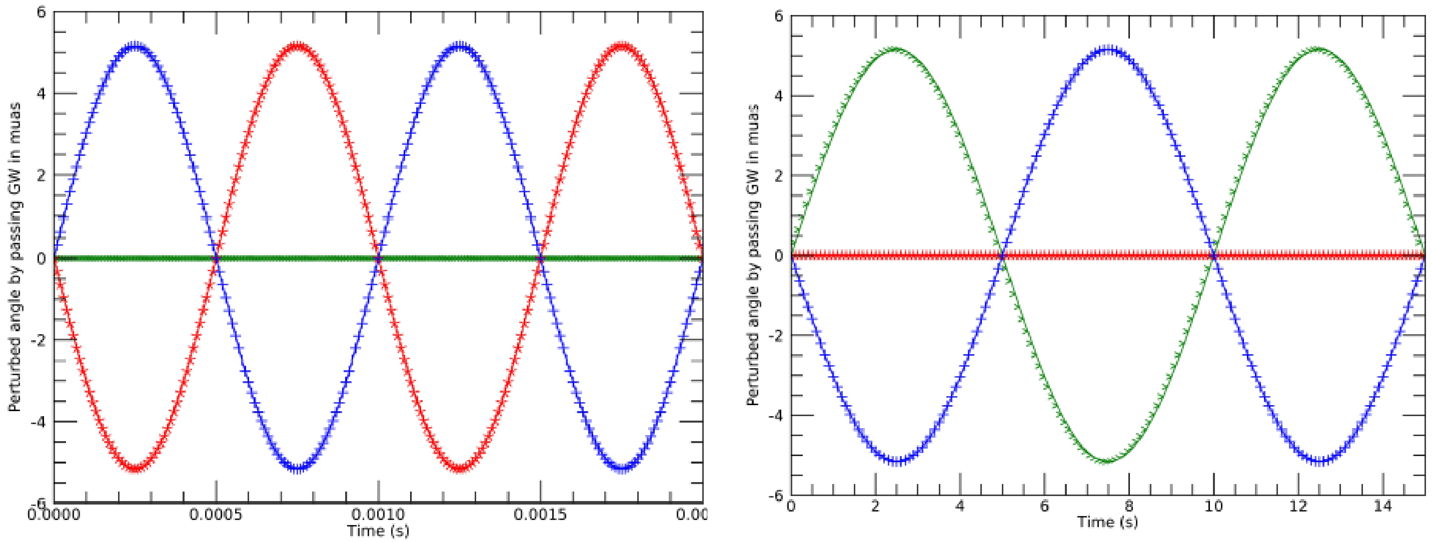
$$F_{ij}^{GW} \equiv F_{ij}^{GW}\left(h_{ij}^{GW};\, \cos(\psi_{iop});\, \cos(\psi_{jop})\right)$$

Strain ***amplitude*** and phase (***direction***) terms

$$\delta\psi_{ij}^{GW} \simeq -\frac{F_{ij}^{GW}\left(h^{GW};\, \cos(\psi_{iop});\, \cos(\psi_{jop})\right)}{\sin\psi_{ij}^{SS}}$$

GW astrometric signature generator





$$\delta\psi_{ij}^{GW}(t)$$ Two examples of GW astrometric perturbations

What is the actual OBSERVABLE?

$$\boxed{\psi_{ij}(t) = (\psi_{ij}^{SS} + \delta\psi_{ij}^{GW})\,(t)}$$

✓ The technological Challenges

The challenges (including computational) facing the actual realization of a compact antenna in space that, complementary to current or future facilities, utilizes (sub)-micro-arcsecond astrometry as fundamental measurements.

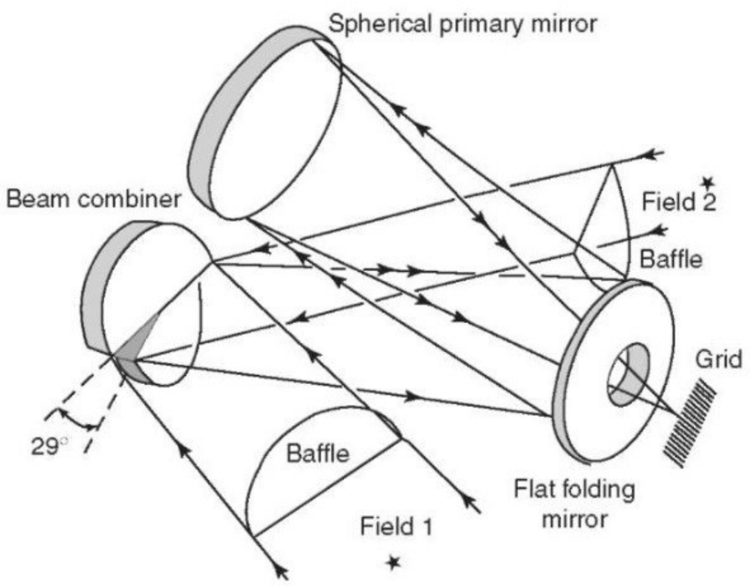
I. The very possibility to build a 3-LOS multiplexing telescope -> 2-LOS: **Hipparcos, POINTS** (Reasenberg et al. 1988, AJ, 96, 1731), **Gaia** (see next slides)

II. the limit of centering accuracies of star-like images on digital detectors,

III. Actual (beyond Rayleigh's) resolution limits for the antenna arms (depending not only on the optics and detection system, but also on magnitude and color of the stellar pairs),
→ ***from 0.1" (Rayleigh) to 0.01", i.e., 10 mas*** (*on, e.g., HST,* see Bernacca, MGL et al. 1993 &1995; MGL et al. 1997; Steffen, Mathieu, MGL et al. 2001)

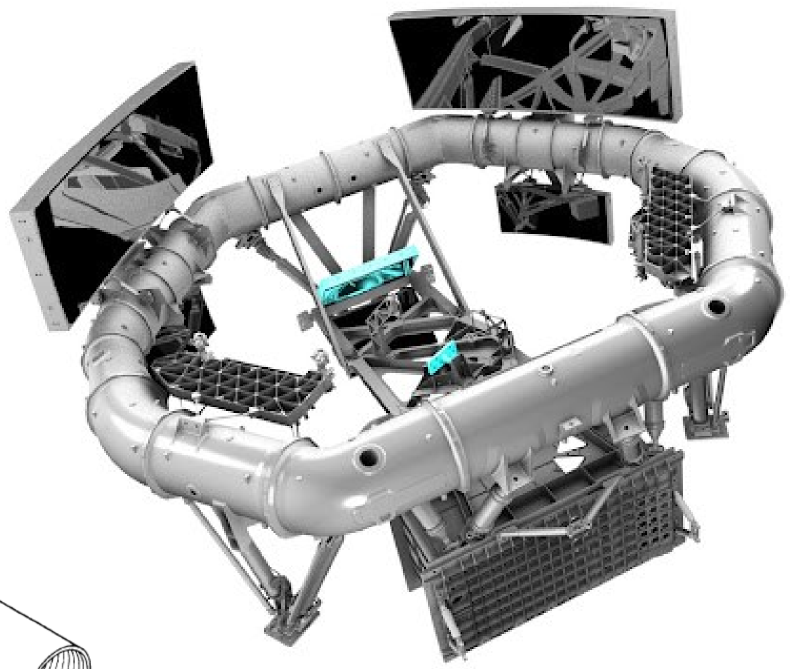
IV. other natural (intrinsic or cosmic) causes of astrometric noise as stellar variability (both astrometric and photometric),

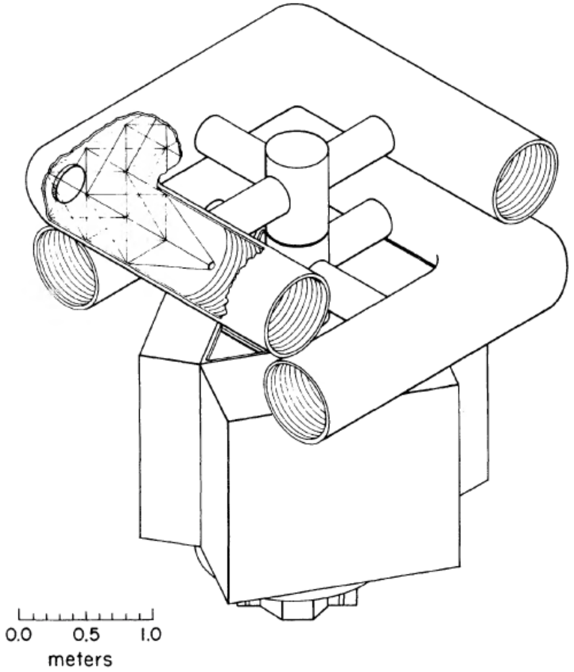
V. identify (via spatial laser metrology of critical degrees-of-freedom) and deal with instrumental noise mimicking unwanted variations of the antenna arms ψ_{ij}



Hipparcos 2-LOS Telescope (launched, 1989)

Gaia 2-LOS Telescope (launched, 2013)





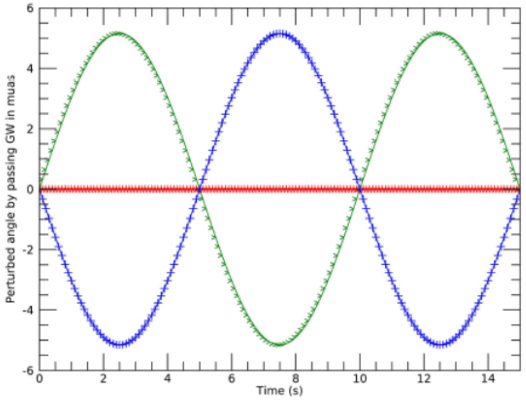
POINTS, concept (1988)

✓ The technological Challenges (Cont.)

In addition, we will have to simulate much more realistic scenarios (i.e., more general forms of GW's and use real-sky pairs) and conditions (realistic noise levels) to investigate viable strategies for the actual retrieval of amplitude and phase (carrying the direction information). However, for these particular aspects we can certainly draw from the great amount of work done, and proven on real data by the LIGO and VIRGO collaborations.

To simulate a library of GW related astrometric perturbations

$$\boxed{\delta\psi_{ij}^{GW} \simeq - \frac{F_{ij}^{GW}\left(h^{GW}; \cos(\psi_{iop}); \cos(\psi_{jop})\right)}{\sin\psi_{ij}^{SS}}}$$

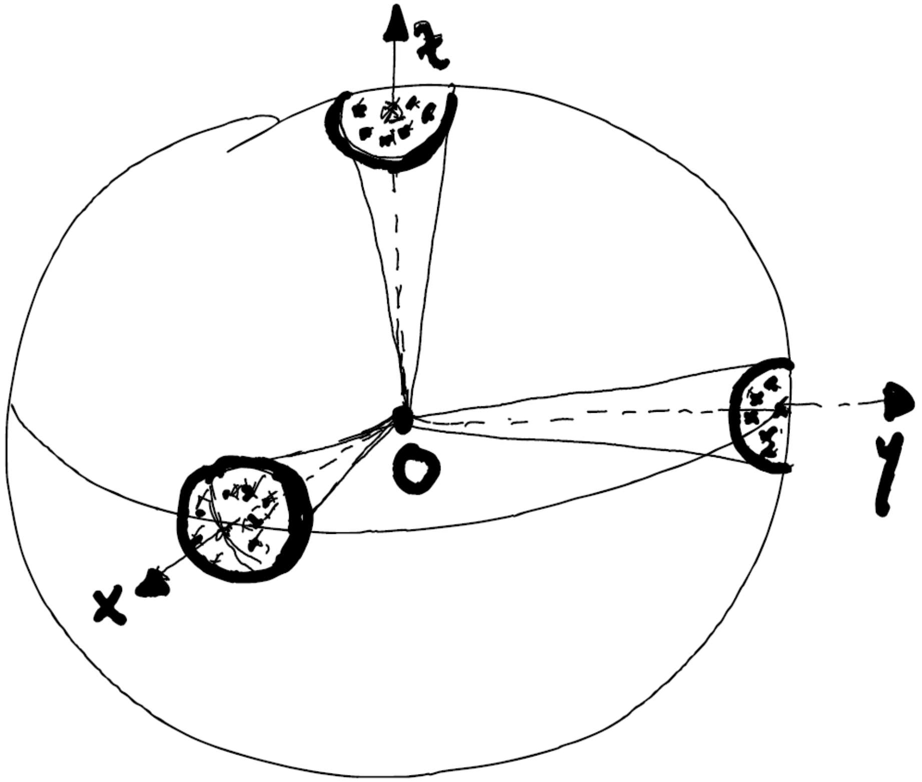


✓ Designs, reduction strategies, and lab activities

Some of the designs, reduction strategies, and lab activities being carried out by the ASTRA Team are presented.

A possible strategy to cope with natural (intrinsic or cosmic) causes of astrometric noise.

Fiind suitable fields and start characterization and calibration campaign



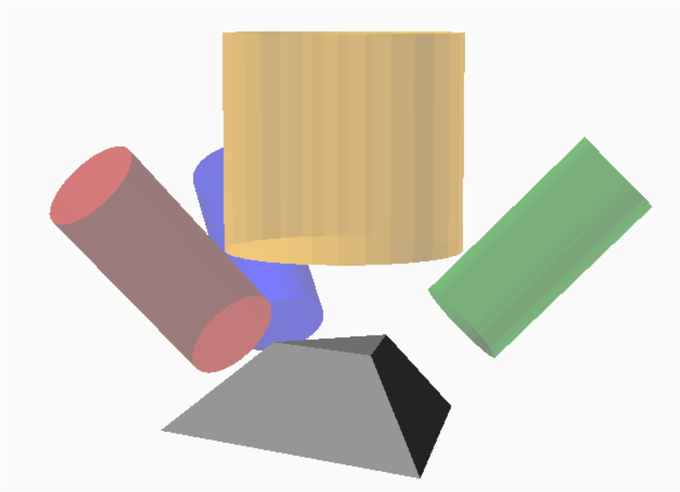
Actual mission profiles that can prove this is a must!

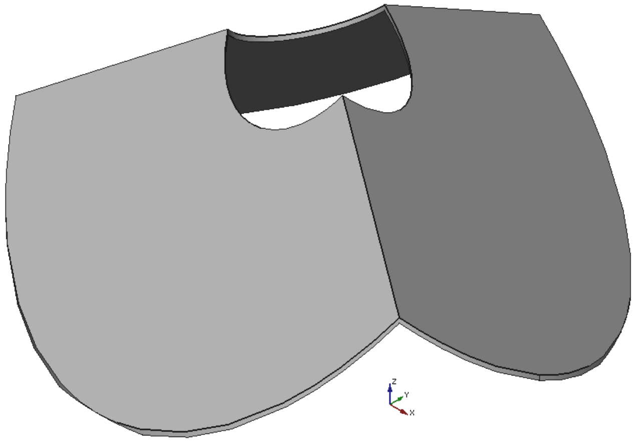
✓ Designs, reduction strategies, and lab activities (cont.)

Multiple Line Of Sight Telescope

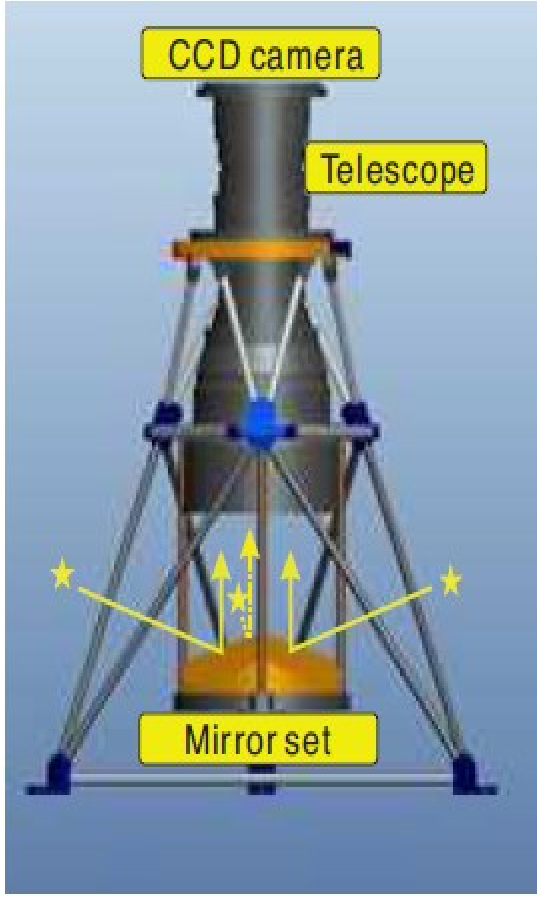
The beam combiner concept implemented by Hipparcos was based on two half-mirrors cemented together. This defines a large angle on a plane, i.e. a one-dimensional angle. Simultaneous observation along three, non-planar LOSs can similarly be based on three, non-redundant angles, providing an operational definition of a bidimensional angular measurement on the celestial sphere.
The telescope is **<u>common mode</u>**, and performs simultaneous measurements over the three directions.

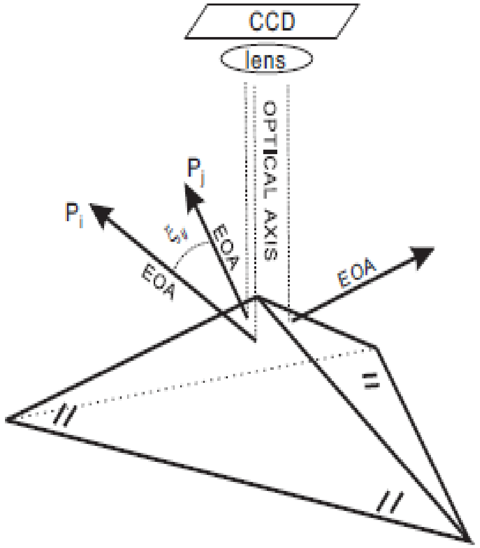
Pyramidal beam combiner principle (left), and a possible lightweight implementation by means of a three mirror assembly.





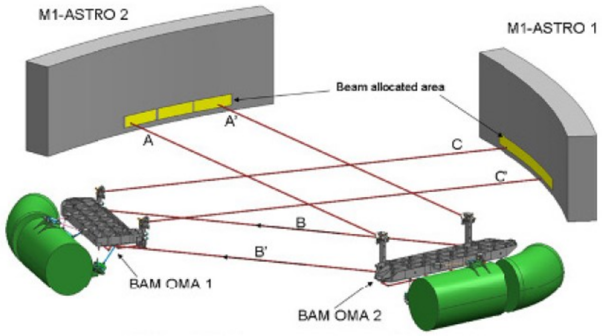
✓ Designs, reduction strategies, and lab activities (Cont.)

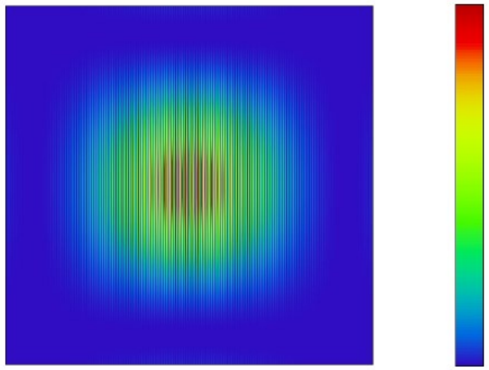




(courtesy of Qi's team)

Metrology Embedded in Telescope
Metrology is being used in the Gaia Basic Angle Monitoring (BAM) device (Riva et al. 2014) to keep track of instrument perturbations, small with respect to the scale of conventional imaging quality, but relevant to the astrometric error
budget. The BAM noise performance was specified at the level of **a few μas over the timescale of a few minutes**. In the case of Gaia, the conceptual requirement is to measure the angle (or its variation) between the LOS of two telescopes. The three-way telescope will have to monitor three angles among the three LOS.





The metrology device aboard Gaia: interferometric (diluted) system

✓ **Designs, reduction strategies, and lab activities (cont.)**

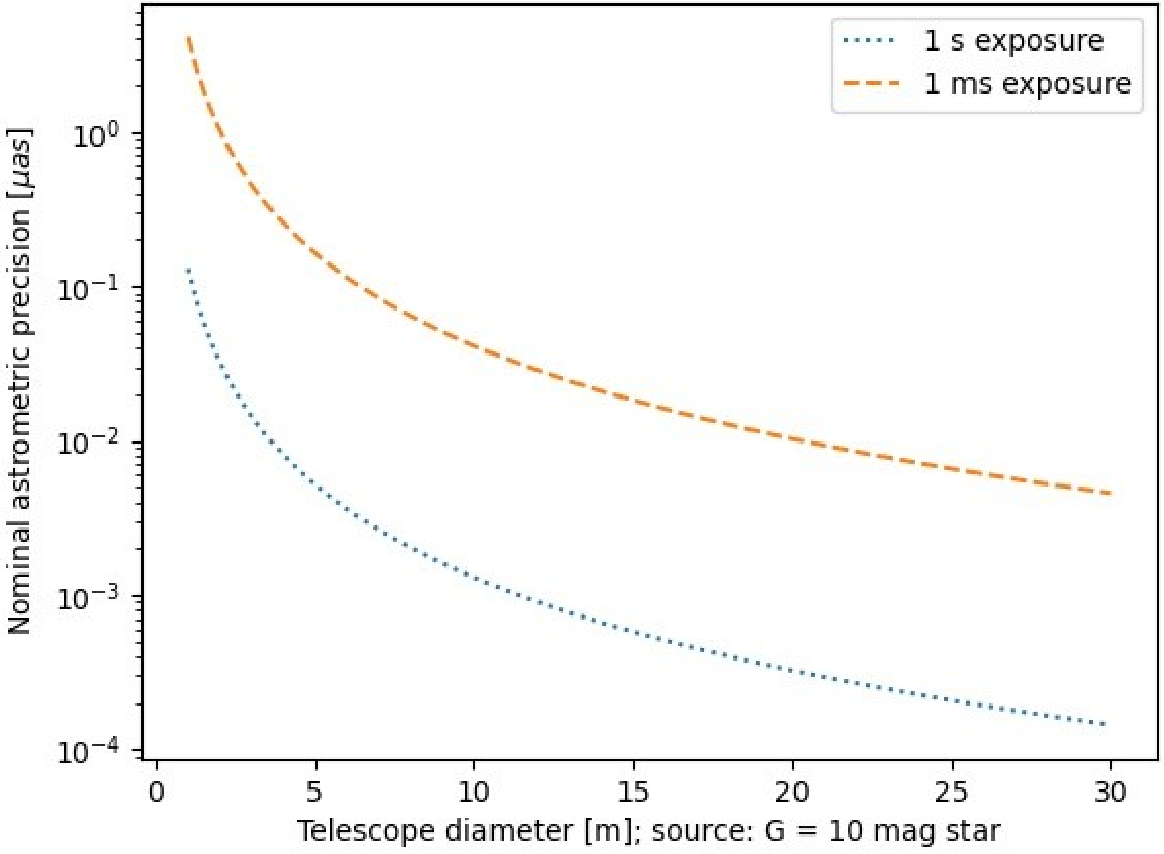
$$\frac{\delta\psi_{ij}^{GW}}{\psi_{ij}^{SS}} \Rightarrow \left(\text{for } \psi_{ij}^{SS} \sim 10\,\text{mas}\right) \begin{cases} \sim 10^{-4} \\ \sim 10^{-3} \\ \sim 10^{-2} \end{cases}$$

Requires PSF centering accuracies ~ 1/2000 pixel (on 5 μm pixels of digital detectors) (current scales on focal planes ~ 20 mas/pixel)

✓ **Designs, reduction strategies, and lab activities (cont.)**

Any theoretical limitations we must face?

~ diffraction / SNR



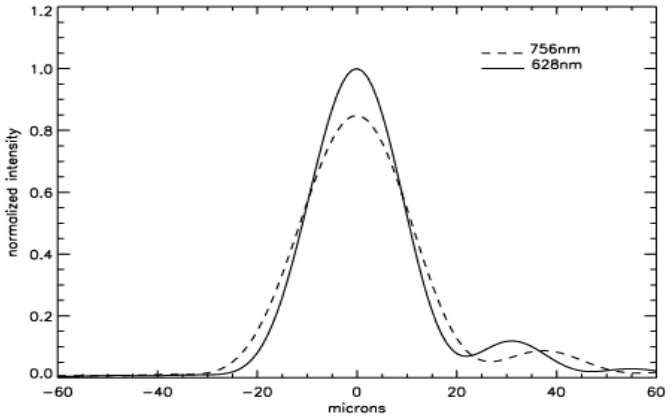
Note. Actual curves depend on, e.g., geometrical factors that can be used to improve over classical shapes.

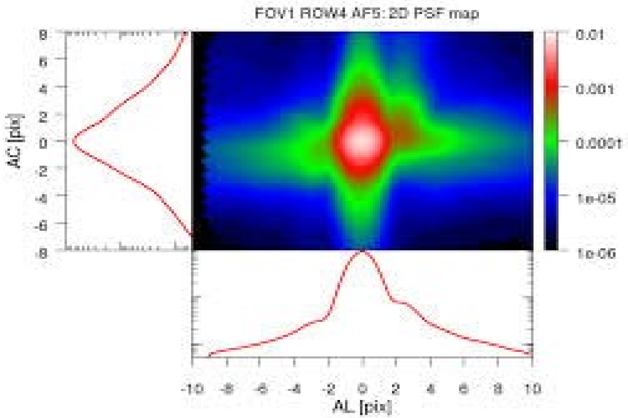
✓ Designs, reduction strategies, and lab activities (cont.)

Chromaticy: the "chromatic aberration" of all-reflective optics

(First introduced at the time of the Hipparcos mission)

Reasons: Imperfect psf (odd aberrations like, e.g., third order coma), truncated images, finite sampling





Asymmetry factor

$$\langle y \rangle = \sim \frac{\lambda 4\epsilon}{\sqrt{2\pi}}$$

$$\Delta = \delta\langle y \rangle = \frac{4\epsilon}{\sqrt{2\pi}} \cdot \delta\lambda_{\mathrm{eff}}$$

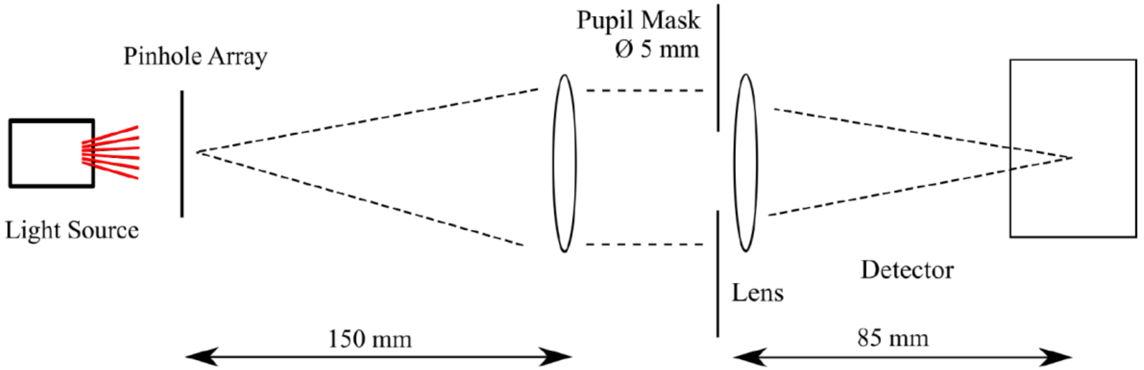
(Busonero et al., 2006)

✓ Designs, reduction strategies, and lab activities (cont.)

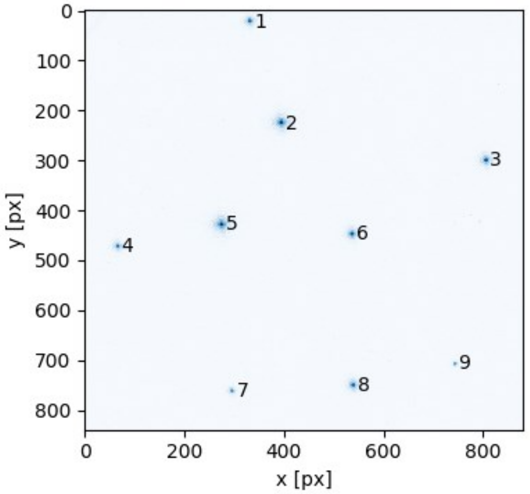
Image Centering Experiment (at the Electro-optical Lab of INAF-OATo)

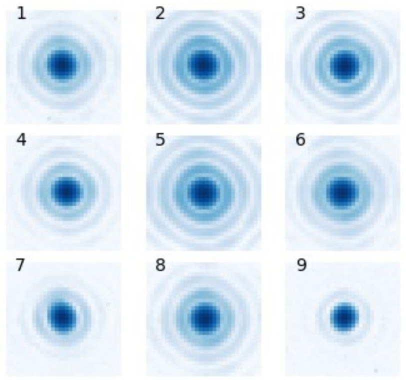
The principle is similar to that implemented in Gai et al. (2001),25 and consists in the simplest representation of an imaging instrument, i.e. a camera fed by a doublet, observing a simulated stellar field. The location uncertainty is:

$$\sigma_c \geq \frac{\sigma}{SNR}$$



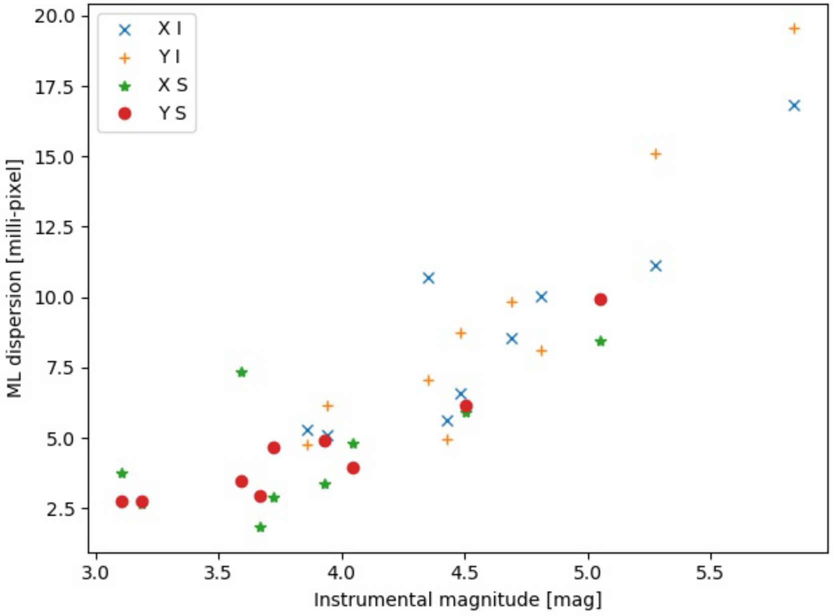
Simulated stellar field image (left) and diffraction limited images (right)





✓ Designs, reduction strategies, and lab activities (cont.)

Location dispersion vs. instrumental magnitude



Current results:
$\sigma \approx 1/600$ pixel
(using low quality CMOS)

✓ Designs, reduction strategies, and lab activities (cont.)

Ather challenges considered for (sub-)μas astrometry, relevant **sources of systematic errors** are:

1. the field variation of telescope optical response;
2. the variation of electro-optical response over detectors;

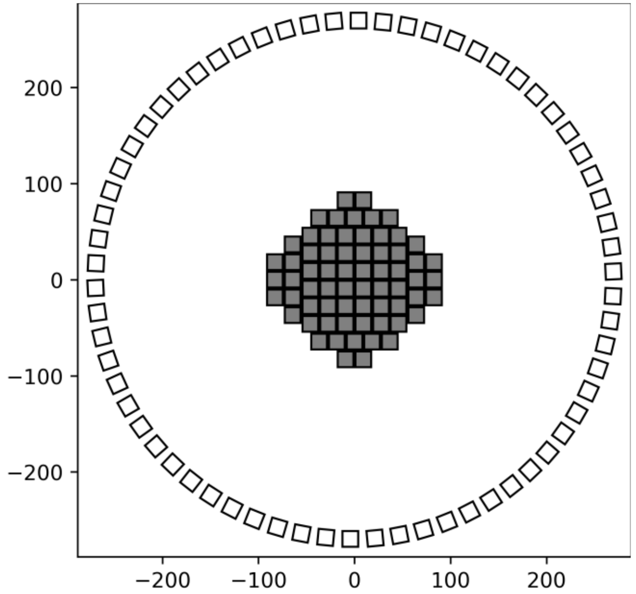
As a possible mitigation strategy with respect to the above challenges (and the choice of suitable stellar fields), we investigated the concept of an annular field telescope (**RAFTER: Ring Astrometric Field Telescope for Exo-planets and Relativity, Riva et al.19**). It features highly uniform optical response over a large focal plane area, thus providing favorable characteristics with resect to the possibility of averaging out detector and source variability over a set of observations.

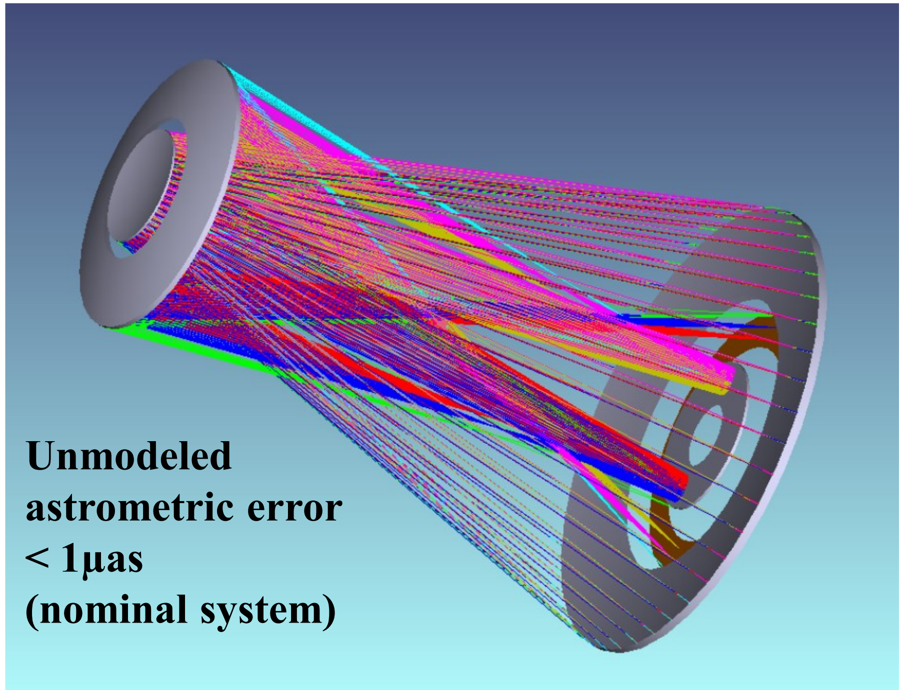
✓ Designs, reduction strategies, and lab activities (cont.)

Ring Astrometric Field Telescope: uniform response over large field

Design exercise: minimization of systematic errors by enforcing circular symmetry at all stages, including focal plane.
Benefit: simultaneous observation of targets within 2° separation

Ring focal plane with radius 1°, composed of 66 detectors, and the same devices (dark gray) arranged around the optical axis. Plot axes are in mm.





✓ Conclusions

- Space (environmental stability: noise suppression and control/monitoring) can be the key for the detection and characterizaion of the largest possible range of GWs and associated sources.

- This is certainly the case for optical astrometry (vs, e.g., radio-astrometry)

- GWAA can be accomodated in relatively compact configurations (meters scale)

- Actual experiments can be already done with data already available (Gaia) and using telescopes that are or are going into orbit in the near future (Euclid, CSST;…) -> «piggy-bag» precursors

- Laboratory experiments probably suitable to prove the key technologies to full scale

- Low-cost technological demonstrators in space

- Highly complementary to current and future efforts with linear-arm antennas

Members of the ASTRA Team

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