

Cover Page

Title: Is There a Need for an Improved Celestial Reference Frame ?

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Is There a Need for an Improved Celestial Reference Frame ?

Abstract

The fundamental properties of the spacetime fabric of the local Universe cannot be determined without an observable, ultra-accurate standard of inertiality, which can be applied to any celestial object from high-*z* quasars to an exoplanet orbiting a nearby star. The only currently plausible method of setting such a standard is the establishment of an inertial reference frame based on grid stars anchored by extragalactic sources. An astronomical reference frame at 1 μas accuracy covering the entire sky will make it possible to observe and measure (rather than speculate) a wide range of physical and cosmological phenomena, essentially promoting new observational science. To name a few, **it will allow for the first time the direct detection of the acceleration of the Solar System within the Milky Way and the Local Group toward the Virgo cluster. Meaningful experimental constraints will be put on the broadband power of the relic gravitational waves, to constrain the mass function of free-floating planets and comets, to resolve the puzzles of the origin of radiation from radio-loud quasars and the coronal activity in tight RS CVn binaries, and obtain more accurate tests of alternative gravitation theories.** All of this will be accomplished by observing the motion and relative position of a large number of stars and distant "fixed" quasars.

1. Introduction

An optical astrometric space mission capable of defining a global grid of stars with positions at the μas , along with extragalactic sources to similar precision, will establish a new reference frame that will be applicable to many astrophysical studies. Here we discuss the resulting improvements in the reference frame, the science that can be accomplished on the objects comprising the frame, namely the quasars and the science enabled by a more precise grid and by an accurate tie to the celestial reference frames at other wavelengths. The future space missions of sub-milliarcsecond astrometry (SIM Lite and Gaia) will mutually complement and strengthen each other in establishing a new reference grid for the Universe. SIM Lite, a pointed

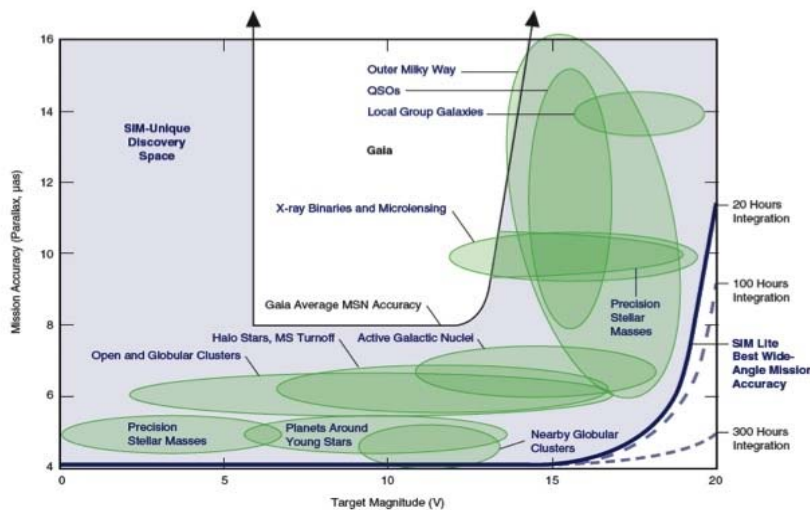


Figure 1. Estimated end of mission global astrometric accuracy of SIM Lite and Gaia for sources in the visual magnitude range 0-20. As a pointed mission, SIM Lite can achieve $<1 \mu\text{as}$ accuracy over small angles.

mission, has by far the highest astrometric precision of the proposed missions, and can be used

for pre-planned, localized experiments where the highest accuracy is essential. Gaia, a survey mission, will provide an orders-of-magnitude denser reference grid, promoting astronomical studies, which require large numbers of objects. Having two completely independent reference frames is the only way of assessing the systematic errors. Figure 1 illustrates the relative performance of these two missions with regards to various science goals.

2. SIM Lite–Gaia Complementarity

SIM Lite will greatly complement the Gaia mission due to its launch early in the next decade, as is illustrated in Table 1. While SIM Lite will observe fewer objects than Gaia, these objects will have better single-measurement errors (SMEs) and end-of-mission accuracies, and will be observed more times. In particular, Table 1 shows that, for a given magnitude, SIM Lite has a factor of 10 better SMEs, an advantage that will be leveraged to the maximum extent in all the astrophysics it will undertake, and in particular in the quasar and grid astrophysics. This complementarity is primarily due to the fact that SIM Lite is a pointed instrument where variable integration times are used based on object magnitude, whereas Gaia is a scanning instrument with constant integration time independent of magnitude. SIM Lite, like Gaia, uses quasars as fiducial markers to determine the parallax zero point, the frame spin, and the International Celestial Reference Frame (ICRF) frame tie.

Systematic and zonal errors prove to be the most intractable kind of imperfections in the global astrometry because it is often difficult or impossible to find out their origin and predict their character. At the same time, these imperfections become the main concern for astrophysical research involving large sets of objects, for example, determination of the distance to the Large Magellanic Cloud (LMC) or detection of tidal streams and Galactic merger remnants. We do not know enough about the propagation of zonal errors in Gaia to make a detailed comparison, but one fact is evident: these errors will be very different for Gaia and SIM Lite because of the mission architectures and the astrometric methods that have little in common. SIM Lite will have relatively large imperfections at the largest scales on the sky comparable to 4π whereas Gaia will probably suffer from zonal errors on the intermediate scale (15 to 50 degrees) where SIM Lite achieves the highest accuracy. Therefore, a comparison of the two reference systems will not only reveal these imperfections, but will probably allow us to correct them by combining the results.

| Spacecraft | End-of-Mission Accuracy, μ as | Single-Measurement Error, μ as | V mag | No. of AGN and Quasars Observed | No. of Obs. | Radio-Loud Fraction |
|--------------------------|-----------------------------------|------------------------------------|-------|---------------------------------|-------------|---------------------|
| SIM Lite: Science | 4 | 11 | 13–18 | 50 ^b | 150 | 80% |
| SIM Lite: Grid | 4 | 16 | 16 | 50 ^a | 150 | 40% |
| Gaia | 25 | 150 | <16 | 200 ^c | 80–100 | 10% |
| | 70 | 400 | <18 | 20,000 ^c | 80–100 | 10% |
| | 200 | 1200 | <20 | 500,000 ^c | 80–100 | 10% |

^a Measurement cadence matches grid star measurement cadence

^b Measurement cadence determined by science

^c Measurement cadence determined by mission design

Table 1. Estimated errors for SIM Lite and Gaia quasar observations.

3. Quasars and the Astrometric Grid

Aside from their astrophysical properties which can be studied with an astrometric mission, quasars are critical objects for the formation of a robust astrometric frame. Frame simulations using a grid of only stars have shown that the resulting astrometric grid has two undesirable properties. First, there is a relatively large offset in the parallax common to all grid stars from mission realization to mission realization, known in astrometry as parallax zero-point error. Second, the entire frame formed by the grid can spin about some arbitrary axis at an arbitrary rate and thus be non-inertial. Quasars, in particular radio-quiet quasars (RQQs) with little or no optical jet emission, are ideal additions to the grid that can correct these defects. Quasars are typically so far away (of order 1 Gpc) that on the μs scale they have no parallax and probably no peculiar proper motion. Extensive analysis and simulations have shown that quasars are ideal objects to remove both the grid frame parallax bias and other large-scale distortions (zonal errors), and the residual spin. For example, the overall accuracy of parallax with only 23 quasars in the grid of stars improves significantly, as seen in Figure 2.

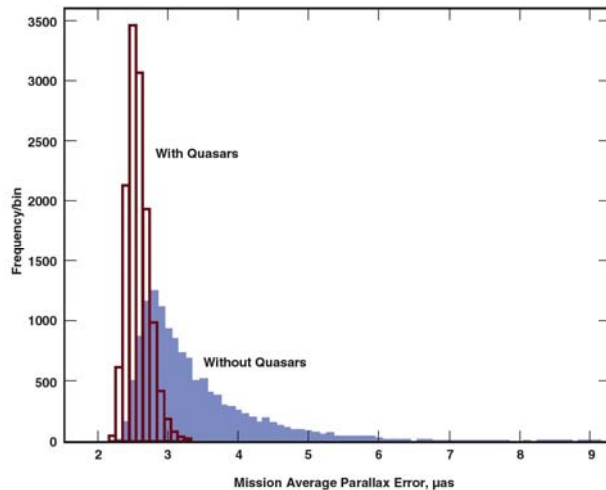


Figure 2. Comparison of the simulated SIM Lite astrometric grid accuracy with and without quasars. Monte Carlo simulations show that without quasars in the grid (blue histogram), the possibility of poor mission performance, while small, cannot be precluded. But when only 23 quasars are included in the grid (red histogram), the probability distribution becomes narrow and the most probable accuracy is greatly improved.

4. Frame Science

There are many scientific areas that benefit from a precise astrometric reference frame. For example, the parameterized post-Newtonian (PPN, Will 2006) prediction for small bending of light in gravitational fields [correction factor, $(1 - g)$] can be tested to a few parts in 10^{-6} . The reference frame will make a significant contribution to the verification of the principles of General Relativity and in testing the causal nature of the gravitational field by making ultra precise measurements of star positions close to the major planets of the Solar System, in particular, Jupiter and Saturn. When a planet happens to pass near a background star, the light rays from the latter become deflected by the gravitation of the planet. The deflection angles can be measured as a function of time for predicted limb-grazing passages of major planets near brighter stars. Several scheduled differential observations with SIM Lite will make it possible to determine not only the main monopole component of this deflection, but also, for the first time, the quadrupole component caused by the oblateness of the planet (Kopeikin and Makarov 2007). Furthermore, the gravitomagnetic term in this deflection, caused by the radial Doppler correction to the planet mass, will amount to a few μs in some instances. Taking several measurements at different relative orbital velocities will enable us to differentiate this exotic effect (not yet observed) from the possible contribution of the scalar gravitational field represented by the g parameter.

The proper motions of extragalactic sources will display secular aberration drift due to the Sun's orbit around the center of the galaxy. The Sun's own motion in the Galaxy shifts the apparent positions of all stars and quasars in a dipole pattern on the sky (Kopeikin and Makarov 2006). The pattern of secular aberration is in fact not static, but will slowly change with time because of the Sun's galactocentric motion and other components of acceleration. The presently proposed missions, at their unprecedented level of precision of order μas , will be quite sensitive to this gradual change, which manifests itself as a predictable pattern of apparent angular motions (proper motions) of all objects on the sky. Therefore, quasars will also exhibit this gradual motion on the sky with amplitude of approximately $4.2 \mu\text{as yr}^{-1}$ (Figure 3). Global astrometry will allow us to detect and directly determine the solar acceleration in the Galaxy.

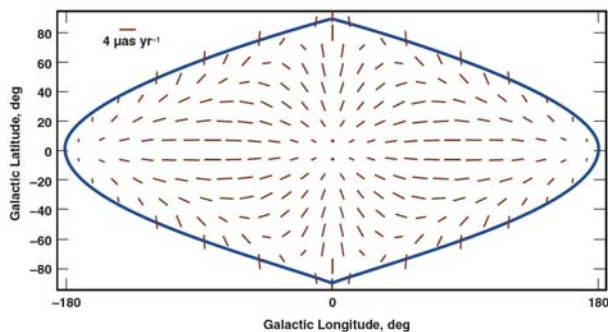


Figure 3. Simulated secular aberration effect over the celestial sphere showing the effect of the Sun's galactocentric motion, measurable by an astrometric mission. This must be fit to the frame quasars used to calibrate the astrometry. Deviations from this pattern will result from changes in the Sun's galactocentric motion and Galactic Latitude and from gravitational deflections due to massive bodies in our vicinity, including Jupiter and Saturn. This will also probe whether the Sun has a dim companion, long a subject of speculation.

Astronomers have been discussing the intriguing possibility that the Sun has a dim companion (Nemesis) on an eccentric orbit. An astrometric mission will be able to detect any invisible gravitating body in our vicinity in an elegant way if this body is close and massive enough. Any acceleration of the Sun caused by the gravitational pull from the companion will be observable as a systematic pattern of apparent proper motions of distant quasars. The axis of this pattern will indicate the direction in which such a companion should be visible. At the level of $4\mu\text{as}$, a body more massive than $0.33 M_J$ (mass of Jupiter) will be safely detected within 100 AU, and anything more massive than $330 M_J$ within 3160 AU.

Cosmological models of the early Universe imply the existence of relic gravitational waves (GW), including inflation and anisotropic phases. The present-day energy density of these long-period waves is expected to be of order $\approx 10^{-9}$ and comprise different modes of polarization and power spectrum. A plane monochromatic, linear-polarized GW propagating through the local part of the Universe bends light rays from distant sources in the transverse directions. The latter effect is observable with SIM Lite as apparent motion of quasars on the sky. Because of the quadrupole nature of GW radiation, ~ 80 percent of the power spectrum is carried by second-order vector harmonics of the proper motion field (Gwinn et al. 1997). Most theorists estimate the energy of relic GW to be too small to be actually detected. However, detection of GW from anisotropic phases in the early Universe may be possible in coherent spectral lines because of the "broadband" nature of astrometric measurements, in that the apparent motion of an object would integrate the wave power over a certain interval of frequency. A nondetection would put upper limits on the energy carried in such coherent spectral lines, with significant implications for cosmology.

5. Multi-Wavelength Frame-Tie Science

The current realization of the ICRF is based on very long baseline interferometry (VLBI) positions of sources with accuracies on the order of 300 μas . This accuracy is expected to improve to order 50 to 100 μas with the release of ICRF-2 in the near future. Optical astrometric observations of ICRF sources need to be made to this accuracy to align the optical astrometric frame with the ICRF.

An accurate tie between the optical astrometric frame and the ICRF will provide valuable insights into the physics of quasars and their jets. By directly linking the frames through quasar astrometry, one will be able to investigate the relationship between the radio core and optical photocenter at unprecedented accuracies. Scientific studies related to the linking of the frames will investigate correlations between the variability, separation, motion, and direction of radio/optical jet components close to the point of origin. In addition, an accurate tie between the frames will enable a variety of multi-wavelength scientific studies of both galactic and extragalactic sources.

Given the ability of future missions to directly observe quasars, future ties between the optical and radio frames will naturally be accomplished through observations of such compact extragalactic objects. To enable a high-precision tie between the optical and ICRF frames, candidate quasars must necessarily exhibit a high degree of astrometric stability at both radio and optical wavelengths. It is well known that the structure of the emission at cm wavelengths has a significant impact on astrometric stability (Fey and Charlot 1997, 2000). This impact is reduced as the observations move toward the mm regime (Charlot et al. 2009). However, the effects of optical source structure and photo-center wander on the μas -level astrometric precision expected for future missions is a completely unexplored region of phase space.

5.1 Extragalactic Sources

Quasar optical emission may originate from three potential sources: thermal emission from the accretion disk surrounding the black hole, nonthermal coronal disk emission, and for a subset of the extreme radio-loud quasars (i.e., blazars), nonthermal emission from knots in the relativistic jet. Recent results by Marscher et al. (2008), involving simultaneous VLBI and optical polarimetric monitoring, suggest that these knots of optical emission move outward through an acceleration and collimation zone toward a standing conical shock region thought to be the “core” at millimeter wavelengths. Studies involving the tie between the optical and radio reference frames have the potential to greatly improve our understanding of this phenomenon by registering and tracking the wander of the optical photocenter relative to the radio core and by correlating changes in the radio and optical flux. Concurrent multi-epoch radio VLBI and optical frame-tie investigations will almost certainly improve both the frame link and the quasar science (see Figure 4).

5.2 Galactic Sources

There are a variety of galactic sources (e.g., microquasars, RS CVn binaries, Algol binaries, late-type stars, X-ray binaries, etc.) for which an accurate frame tie would enable multi-wavelength science. For SIM Lite, observations will be limited to systems with either a large difference in

magnitude between the primary and secondary stars or orbital separations of order of the fringe spacing of the interferometer. Figure 5 provides

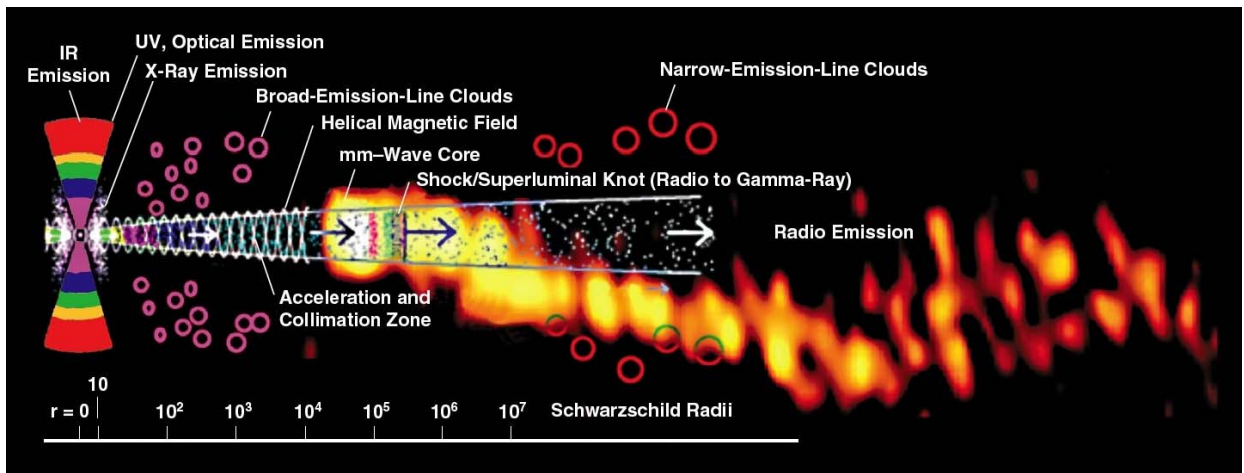


Figure 4. Overlay of 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999) on a diagram of a quasar from Marscher et al. (2008), not to scale. The figure shows the potential frame-tie quasar science that could be accomplished with SIM Lite. Knots of optical emission move outward from the black hole's accretion disk (left) through an acceleration zone toward the millimeter and radio "cores" and radio jet (right). Concurrent SIM Lite and VLBI observations will register and track the wander of the optical photocenter relative to the radio core.

an example of an RS CVn binary system, σ Geminorum, for which the radio emission could be tied to the optically astrometric determined positions of the stars in the binary. The system consists of a K1 III giant primary with $M_V = 4.15$ and a companion that is unseen in both photometric and spectroscopic observations. The radio emission as measured with VLBI shows a double-lobed structure with the lobes separated by ~ 3.4 mas. Interestingly, the major axis of the spectroscopically determined orbit is $2a \sin(i) = 0.13$ AU (~ 3.4 mas at the assumed distance to σ Gem of 37.5 pc). However, without precise astrometric data, it is impossible to determine whether the radio emission is coincident with one or both of the stars at the time of the observations. Possible models for the generation of radio emission in chromospherically active stars include phenomena such as gyro-synchrotron radiation from polar-cap regions of the active K-giant-type star, emission at the tops and/or feet of one or more coronal loops originating on the K-giant, and emission from active regions or hot spots near the surface of both stars in the binary, with possible channeling of energetic electrons from the K-giant to the surface of the smaller companion star along interconnecting magnetic field lines.

For systems such as σ Gem, SIM Lite and Gaia will provide positional information on the 10 μ s level and the three-dimensional orbit for the binary. Coordinated observations with other instruments such as the Very Large Baseline Array (VLBA) will allow the registration of the radio emission relative to the system components for orbital periods of order days. This more complete picture will help to distinguish between the various energy mechanisms for the radio emission.

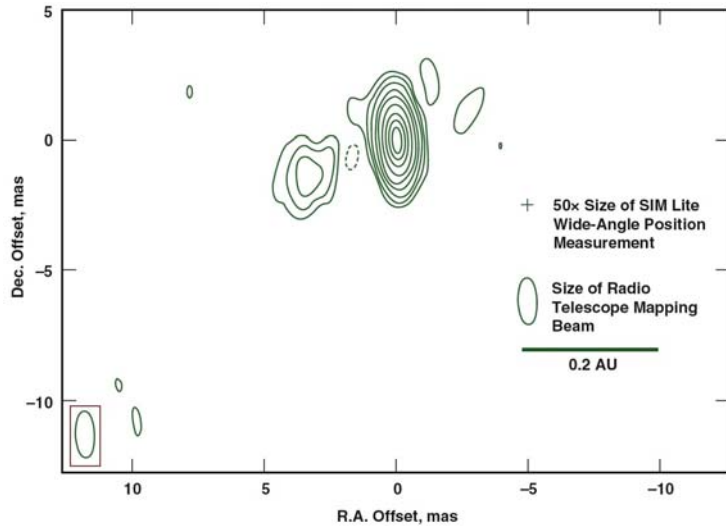


Figure 5. A total intensity contour map of the radio emission from the RS CVn binary system σ Geminorum. The peak flux density is ~ 55 mJy. The system is composed of a K-giant primary and an unseen companion. The spectroscopically determined major axis of the orbit is $2 a \sin(i) = 0.13$ AU (~ 3.4 mas at 37.5 pc). The relative separation between the two radio components is ~ 3.4 mas. SIM Lite angle measurement accuracy has to be magnified 50 times to be presented on the scale of this map.

6. Conclusion

The astrometric missions will accomplish significant science in the next decade. The Gaia mission will perform a full sky survey while the SIM Lite mission will be a pointed mission with an order of magnitude more precision than Gaia. At the level of $4 \mu\text{as}$ in global astrometry, and better than $1 \mu\text{as}$ in differential astrometry, and the ability to be pointed at the right object at the right time, a number of fundamental experiments can be set up with SIM Lite, such as detection of gravitomagnetic component in gravitational light deflection and detection of free-floating planetoids through weak gravitational microlensing.

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