Interferometric Astrometry

Gerard T. van Belle*,[a]

[a]*European Southern Observatory, Karl-Schwarzschild-Str. 2,*
85478 Garching bei München, Germany

Abstract

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1. Introduction

Since this presentation was delivered in the context of a preliminary talk in a summer school, I decided to include (as with the talk) some initial highlights from the underlying history of astrometry, which should deliver the reader unto the modern era of astrometry, particularly as it is manifested in dual-star interferometry. The title provided to me for my presentation (and still gracing the top of this article) was fairly broad, but I tried to keep with the overall spirit of the school and concentrate upon that emphasis of astrometric interferometry, in both its theoretical and practical forms. This appears to compliment the other articles in the volume well (eg. see the discussion by Mark Colavita).

2. A (very) Brief History of Astrometry

The origin of astrometry in classical antiquity is often ascribed to Hipparchus (ca. 190-120 BC) (Toomer, 1978), who was a working astronomer from at least 147 BC to 127 BC. Hipparchus produced a star catalog of at least 850 stars, original of which did not survive - however, the catalog appears to have been copied by Ptolemy in Books VII and VIII of his *Almagest*

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*Corresponding author
Email address: `gvanbell@eso.org` (Gerard T. van Belle)
URL: `http://eso.org/~gvanbelle` (Gerard T. van Belle)

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(Ptolemy and Toomer, 1984; Rawlins, 1982) Among the inventions ascribed to Hipparchus were the astrolabe, the armillary sphere, and the stellar magnitude scale, which ranked the 20 brightest stars as magnitude one, down to the dimmest stars still detected by the human eye at magnitude six.

Earlier examples of star catalogs include the catalog of Chinese astronomers Shi Shen and Gan De (Du Shiran, 1992) which dates to the 4th century BC, and that of Timocharis of Alexandria and Aristillus in the 3rd century BC (Heath, 1991). It was Hipparchus' comparison of his own star position measurements to that of Timocharis' that led Hipparchus to discover that the longitude of the stars had changed over time, thereby leading to his discovery of the precession of the equinoxes.

During medieval times, Muslim astronomers published a large number of catalogs. In 850 AD, Alfraganus published a corrected compendium of Ptolemy's *Almagest* (Corbin, 1998); Azophi's *Book of Fixed Stars* illustrates the constellations with descriptions of the stars, including their positions, color, and magnitudes (Al Sufi, 964). Azophi's book also includes mentions of the Andromeda Galaxy, the Large Magellanic Cloud, and other notable astronomical objects. Over 200 Islamic *Zîj*[1] books for calculating astronomical positions of the Sun, moon, stars, and planets were produced between the 8th and 15th centuries (Kennedy, 1956); due to this widespread and persistent activity in astronomy during this era, many stars are still known by their Arabic names.

In Western Europe, the science and art of astrometry languished along with the other disciplines during those medieval times, reappearing during the middle Renaissance most notably with the work of the 'unlikely pair' of Tÿcho Brahe (1546-1601)[2] and Johannes Kepler (1571-1630) (Ferguson, 2002). Brahe, who is considered by many to be the last, greatest naked-eye astronomer, collected stellar astrometric measurements of unprecedented precision (between roughly 30" and 50") (Wesley, 1978) and repeated his measurements, allowing for quantification of measurement repeatability and temporal effects. After Brahe passed away[3], Kepler's use of Brahe's astrometric observations of the motions of the planet Mars that allowed him to work out his 3 laws of planetary motion. Contemporaneous with these two

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[1] From the Middle Persian term *zih* or *zig*, meaning 'cord'.

[2] Who is super-cool just because he has an umlaut over the 'y' in his name.

[3] A passage that has been noted to be suspiciously convenient for releasing Brahe's close-held data sets to Kepler (Gilder and Gilder, 2005).

figures, Johann Bayer published his *Uranometria* star atlas, incorporating Brahe's stellar positions, and the first to cover the entire celestial sphere. The Bayer star designations (eg. α Orionis, λ Boötis, etc.) originating with this atlas are still in use today.

The individual who is widely honored as the founder of modern astrometry is Friedrich Wilhelm Bessel (1784-1846). Early in his career he published *Fundamenta Astronomiæ* (Bessel, 1818), which contained accurate positions *and many proper motions* of over 3,200 stars, remarkable not only in its content but in light of the fact that Bessel was wholly self-educated from textbooks. Later in his career, Bessel was the first to measure stellar parallax, determining the value for 61 Cyg to be $\pi = 0.3136 \pm 0.0202$" (Bessel, 1838)[4], winning a close competition with Friedrich Georg Wilhelm Struve and Thomas Henderson, who measured the parallaxes of Vega and Alpha Centauri in the same year, respectively. Bessel's work has been noted as "signaling the official end to the dispute over Copernicanism". The article by Fricke (1985) is very informative of the meticulous work of Bessel in these notable achievements.

In order to enforce the brevity of this section (and the accuracy of its title), our final stop in this whirlwind tour will be the ESA space mission Hipparcos. Hipparcos overcame a flawed launch and incorrect orbit (Kovalevsky and Froeschle, 1993) to achieve full recovery of mission objectives, including the Hipparcos catalog, containing ~120,000 stars with 2-4 mas accuracy (Perryman et al., 1997), and the Tycho catalog, with ~1 million stars with 20-30mas accuracy (Høg et al., 1997).

3. Science with Astrometry

Of the data products that enable science with astrometry, the most basic and intuitively accessible in terms of everyday experience is distance. It is a fundamentally enabling parameter, one of paramount importance in limiting the understanding the astrophysical objects we view, and one that is *directly* determined for an exceedingly small cadre of targets.

Before we explore the implications of knowing distance in further detail, let us briefly examine the most straightforward technique for obtaining

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[4] In agreement with the modern value reported by Hipparcos of $\pi = 0.28718 \pm 0.00151$" (Perryman et al., 1997).

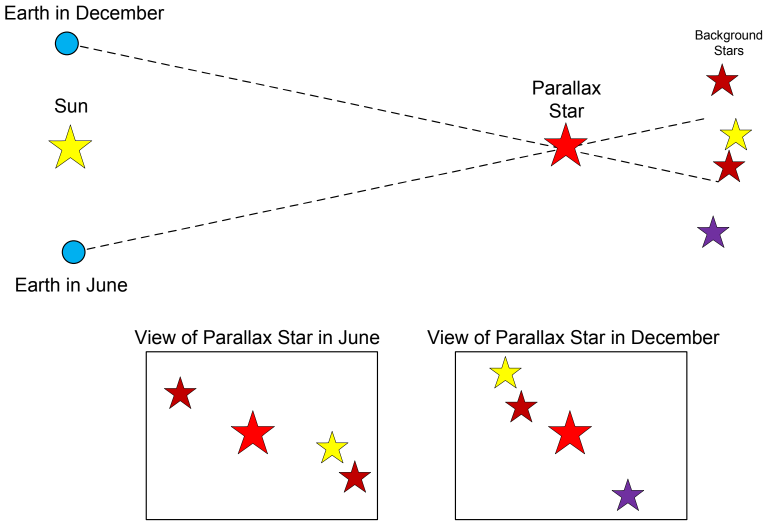

Figure 1: An illustration of the parallactic effect: as the Earth orbits the sun, the nearby star ("parallax star") appears to shift its position relative to more distant background star(s).

distance to an object - the determination of astronomical parallax. The parallactic effect, simply put, is the apparent shift in position of a nearby object relative to a distant background, due to the actual shift in position of the observer. The geometry of this situation as it applies to astronomy is see in Figure 1.

As the Earth orbits the Sun, it shifts in position by 2 astronomical units (AUs). Since the AU is thought to be well-determined[5], precise measurement of the size of the parallactic motion that the target star appears to sweep through as the Earth orbits should in principle allow determination of the distance through simple geometry. The shape of this motion will be related to the star's position relative to the plane of the earth's motion (more circular at more extreme declinations; more ellipsoidal at lower declinations and finally linear at a declination of zero). This is, of course, complicated in practice by a number of considerations.

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[5] Currently defined as $149,597,870,691 \pm 6$ meters; the limitations on this value in fact trace back to imprecise knowledge of the value of the gravitational constant G (International Bureau of Weights and Measures, 2006).

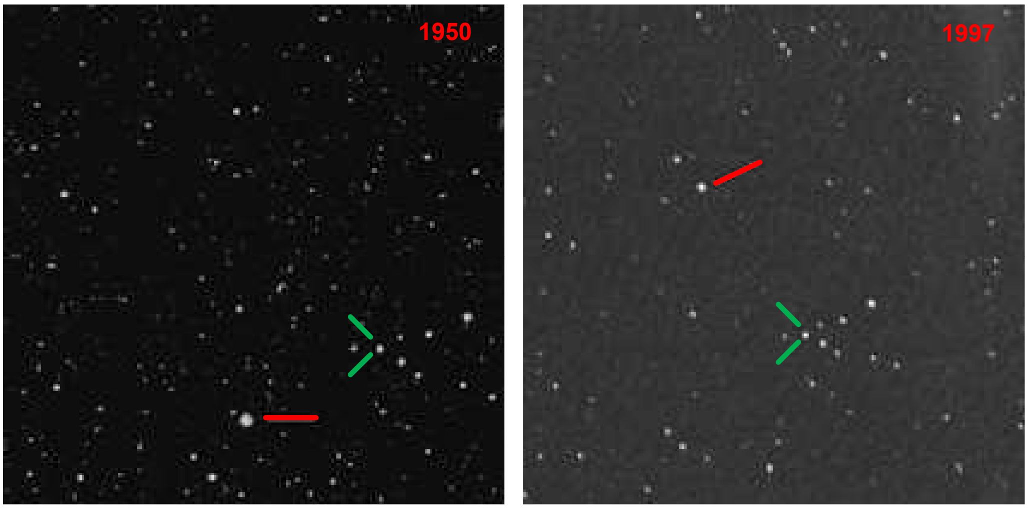

Figure 2: Proper motion of Barnard's Star (marked in red) relative to background stars (a prominent asterism is marked in green; each of the two image frames is roughly $10' \times 10'$ in size). Barnard's star is notable for having the largest known proper motion ($\mu_{\rm RA} = -798.71$mas/yr, $\mu_{\rm DE} = 10337.77$mas/yr) of any star.

First of all, the measurement of the parallactic angle must be done relative to some reference point. A common approach obtaining angular fiducials is to use background reference stars. If these stars are infinitely distant, the parallactic angle as it would be obtained from the two sub-frames of Figure 1 readily provide the desired angular measure. However, since the background stars are in fact not infinitely distant, they themselves march through some (albeit smaller) parallactic motion, for which the target parallax measurement must be corrected.

If the stars (target or background) being observed are moving through space, this will add constant term offsets to the angles being measured as well. The apparent motion of objects on the plane of the sky ('proper motion') can be measured but is frequently of a magnitude to require multi-year measurements to do so accurately. An extreme example is seen in Figure 2. Insufficient time baselines can increase the measurement error on the proper motion values, which in turn propagate into the derived parallax values. Certain kinds of proper motion, if inadequately measured, can bias the parallax measurements. Proper motion is itself an astrophysically interesting observable from the standpoint of topics such as galactic dynamics and star formation.

Stars can also have unseen companions that affect their apparent position upon the sky. In 1844 Bessel deduced from changes in the proper motion of Sirius that it had an unseen companion, which was confirmed by direct detection in 1862 by telescope-maker Alvan Clark. In the case of planetary companions about target stars, this can lead to desired detections of such objects; when the unknown secondaries are about background reference stars, this can lead to unexpected errors in parallax measurements.

As one digs deeper into astrometric accuracy, from errors measured in arcseconds to milliarcseconds to microarcseonds, additional terms need to be considered in cleanly determining the astrometric observables of position, distance, and proper motion. These include (but are not limited to):

- Aberration of starlight - Due to the changing velocity vector of the Earth as it orbits the sun, coupled with the fact that light travels with a finite speed, shifts the apparent positions of stars that are in a direction perpendicular to that velocity vector. For example, for Polaris, the star travels in a circular displacement of radius 20.6"; stars closer to the celestial equator see more of an elliptical displacement traced out over the course of a year. This effect was detected by Bradley (1727) while attempting to detect parallax.

- Parallax - Both annual *and* diurnal: for stars sufficiently near to the sun, the parallax caused by the daily change in a telescope's position due to Earth rotation is a non-negligible term.

- Epoch transformations - Astrometric coordinates given on the sky are based upon the projection of the Earth's equator outwards onto the sky, and the intersection of that great circle with the plane of the ecliptic being the starting point for measurements of right ascension. Since precession and nutation of the Earth's rotational axis cause this point to vary over time, coordinates called out in such a system are valid at only a moment in time - that is, at a given epoch. Observations that occur at times other than the epoch in which the coordinates are defined need to be adjusted accordingly.

- Gravitational deflection of light - As noted by Einstein (1915), light passing by an object of any mass will bend around that object - the more massive the object, the greater the effect. Astrometry at the microarcsecond level generally requires that the locations of the planets

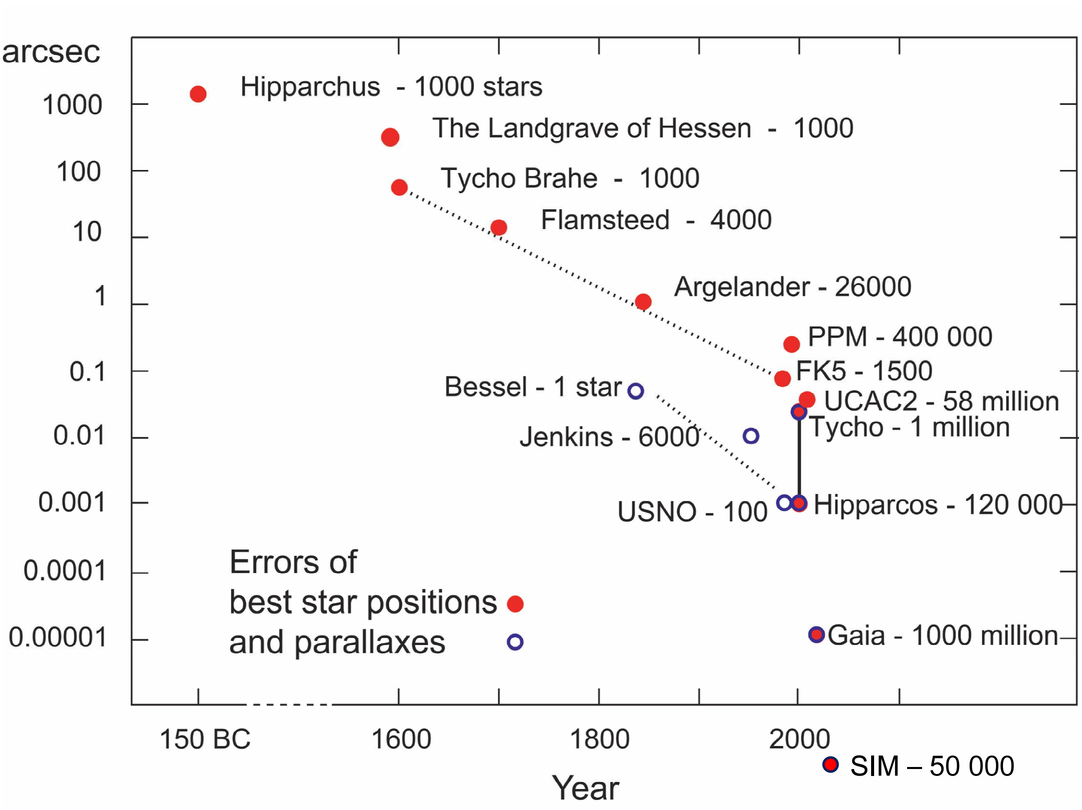

Figure 3: Progress in astrometry through the ages, beginning with Hipparchus and ending (currently) with Hipparcos. Performance from the developmental Gaia and proposed SIM missions (off the bottom of the chart) are also shown.

and even more massive minor solar system bodies be known and their contributions to this effect be accounted for.

The overall difficulty in distilling high precision astrometry from observations can be illustrated by the current state of the art: from new (& presumably improved) reduction of data for the Hipparcos catalog (van Leeuwen, 2007), less than 18,600 objects have their distances determined to better than 10%, and only 722 of those have distances at the $<$ 1% level. The overall progress in this field can be seen in Figure 3.

3.1. Why Astrometry?

Of all the astrophysical parameters, distance to objects is arguably one of the most fundamental; it is also one of the most difficult to ascertain. How-

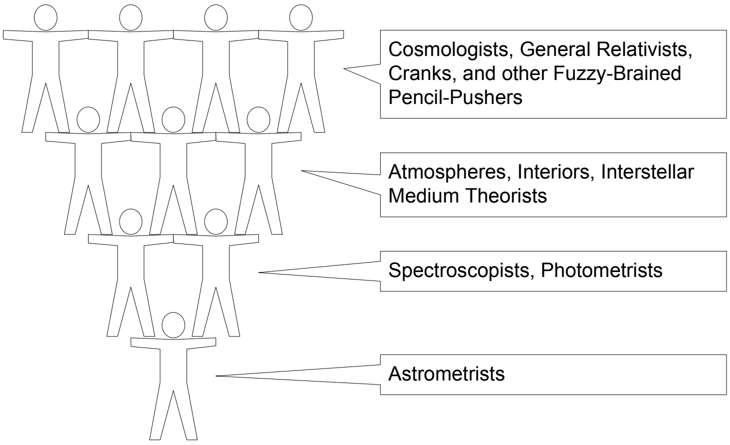

Figure 4: 'The Astronomical Pyramid' - a somewhat tongue-in-cheek illustration of the interdependence of the various areas of study; adopted from an earlier illustration by Ron Probst (ca. 1974).

ever, in spite of that fact, many astrophysical deductions rest upon that thin, tenuous thread of distance information that has been painstakingly gleaned over the years from astrometrists. In turn, further deductions rest upon those initial derivations, making the overall edifice of astronomy one that is rather precariously perched upon a small number of initial measurements, as illustrated in Figure 4.

There are distinct regimes of interest where levels of accuracy (or, depending on the situation, precision) come into play with astrometry. At the arcsecond level, the proper motions of the "fastest" stars can be seen annually (as illustrated in Figure 2); also (surprisingly enough), one of the most obvious effects of general relativity turns up in the precession of Mercury's orbit - approximately 43" of the 5,600" per century orbital precession is due to GR. At the milliarcsecond (mas) level, the parallaxes of the nearest stars turn up (α Cen, at 700mas); micro- and nanoarcsecond (μas and nas) astrometry is needed to detect planets about nearby stars (500μas for a Jupiter orbiting a 1 $M_\odot$ star at 10pc, 300nas for Earth).

Importantly, calibration of the cosmic distance scale is a core activity for astrometric science. As noted in the previous section, current parallax measurements with $< 1\%$ errors reach only to about 100 pc. Since distance determination in astronomy is effectively a 'ladder of staggered rungs' (Figure 5), errors - and biases - in the determinations propagate throughout as greater and greater distances are probed. Ideally, distances would be directly determined via geometric parallax for all objects, but this is simply not possible at present.

4. Description of Various Approaches

With an emphasis on interferometric approaches, we will now examine the means by which astrometric detections of extrasolar planets may be achieved. It worth noting that, for any astrometric orbital solution, a substantial number of parameters need to be specified: at least five positional terms associated with the system, namely coordinates (α,δ), parallax (π), and proper motion ($\Delta\alpha$,$\Delta\delta$); and then, the description of the orbit itself, the Keplerian orbital terms[6]. Keeping in mind that a unique solution requires at least $N > 11$ independent data points needed to solve for orbits - and that adequate SNR is often achieved only through repeated measurements for each term - and one may readily see that astrometry is generally a game of patience and control of systematics over the long stretches of time that go into observing programs.

4.1. Single-Aperture Astrometry

Many past experiments have explored the limits of single-aperture astrometry (Gatewood, 1987; Monet et al., 1992), which are expected from theoretical limits of atmospheric noise to be at the ∼1 mas level (Lindegren, 1980). These limitations appear to be somewhat permeable with the judicious use of adaptive optics and appropriate data reduction techniques (Lazorenko and Lazorenko, 2004); recent results from VLT (Lazorenko et al., 2007) indicate, over times scales of a few days, achievement of 200-300μas per measurement for stars B=18-19. The authors go on to argue that a limit of 30-40μas per hour is expected in certain operational cases, although this has not been demonstrated operationally. Cameron et al. (2009) demonstrate astrometric imaging behind the AO system of the Palomar 200" telescope with $\lesssim$ 100μas results that repeat on time scales of 2 months. However, it

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[6] Semi-major axis a, eccentricity e, inclination i, longitude of the ascending node Ω, argument of periapsis ω, and epoch T_0. See, as an example, the relevant discussion in Boden et al. (1999).

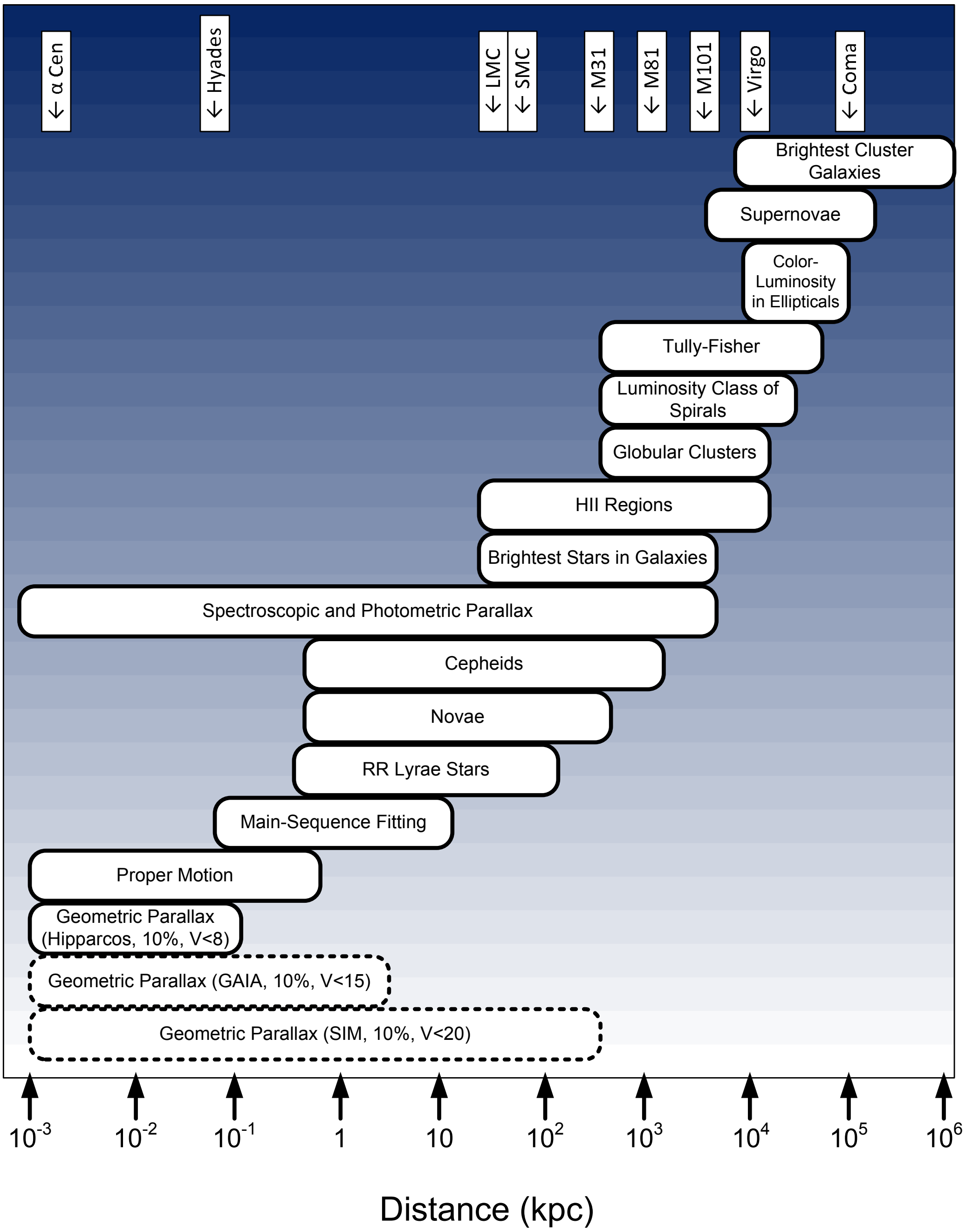

Figure 5: Cosmic distance ladder. At the bottom are the only directly geometric measures of distance - the Hipparcos space mission, and the developmental Gaia and proposed SIM missions.

is worth noting that these results are limited to relatively dense fields with objects of similar brightness.

4.2. Long Baseline Astrometry

In order to overcome the spatial resolution limitations of single-aperture observatories, long-baseline interferometry was proposed by Shao and Colavita (1992) as a solution to achieve significantly higher relative measurement accuracy than possible with single aperture instruments. In the traditional regime of "narrow-angle" (eg. with fields ~30' in size) astrometry is where the product of the stellar angular separation θ and the atmospheric height h is significantly greater than the aperture size D: $\theta h \gg D$. In this regime, the astrometric error is effectively independent of D and only weakly dependent on θ. However, in the case of long-baseline interferometer operating in a "very-narrow-angle" regime (eg. with objects separated by ~30"), the two atmospheric paths traveled by the target star and any astrometric reference objects have highly correlated errors, and a relative measure of the angle separating them can be made to significantly higher levels of precision. In this regime, for an interferometer of baseline B, $\theta h \ll B$; the astrometric error decreases with increasing B and is linearly dependent upon θ.

Since long-baseline interferometers are typically constructed as single-object instruments, astrometric interferometers that take advantage of this aspect of atmospheric noise statistics have been constructed as pairs of such instruments for the technique of 'dual-star astrometry'. Operationally, a dual-star instrument operates as follows: a bright primary star is fed into both apertures of one of the two interferometers[7]. Since it is bright, light from the object is used to phase the individual apertures of that interferometer, and then further utilized to cophase the interferometer through tracking of the bright object's interference fringes. Meanwhile, a dimmer secondary star, near the primary star on the sky (typically within one isoplanatic patch, roughly ~10-20"), is fed into the second interferometer. Corrections from the bright star for both individual aperture and interferometer cophasing can be utilized for high-frequency corrections of that second interferometer. These corrections are isolated from mechanical imperfections of the whole system by tying together the two interferometers via laser metrology that

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[7] Fortunately, in the case of hunting for planets about nearby stars, the target of interest tends to actually be quite bright.

follows the dual starlight paths and monitors pathlength differences. Each of the two interferometers incorporate delay lines whose positions d_1 and d_2 are monitored by separate, subsystem-specific laser metrology systems. As such, for two objects at sky locations indicated by pointing vectors $\hat{s}_1$ and $\hat{s}_2$, observed with a dual-star interferometer with baseline vector $\vec{B}$:

$$\begin{aligned} d_2 - d_1 &= (\hat{s}_2 \cdot \vec{B} + C_2) - (\hat{s}_1 \cdot \vec{B} + C_1) && (1) \\ &= (\hat{s}_2 - (\hat{s}_1) \cdot \vec{B} + (C_2 - C_1) && (2) \\ \Delta d &= \vec{\Delta s} \cdot \vec{B} + \Delta C && (3) \end{aligned}$$

As such, with the instrumental signature (ΔC) calibrated in part by the system-wide laser metrology, the delay difference Δd directly relates back to the sky separation $\vec{\Delta s}$. Since laser metrology systems currently can routinely produce (time-averaged) distance measurements at the 1-10nm level, $\vec{\Delta s}$ should in principle be measurable at the 10μas level with a ~100m baseline.

However, in practice, this level of precision is rather difficult to realize, both in part due to the obvious problems inherent in realizing a system capable of what is described above, and also due to some subtle breakdowns in the simple mathematics above. Specifically, propagating out the interferometric tolerances for measurement of the separation vector with differential astrometry

$$\Delta s \approx \frac{\Delta d}{B} \tag{4}$$

leads to

$$\begin{aligned} \delta\Delta s &\approx \frac{\delta\Delta d}{B} + \frac{\Delta d}{B^2}\delta B && (5) \\ &= \frac{\delta\Delta d}{B} + \Delta s\frac{\delta B}{B} && (6) \end{aligned}$$

Thus $\sigma_d \sim \sigma_s \times B$ and $\sigma_B/B \sim \sigma_s/s$; so, for $B \sim$ 100m and $\Delta s \sim$ 20", to make a 10 μas measurement, there are two requirements: first, we must measure Δd to $\sim 2.5 \times 10^{-9}$m (2.5 nm), although making this measurement in a time-averaged sense is sufficient. However, while that measurement is being made, we must know B to 2.5 parts in 10^7 - about 25 μm.

What makes this knowledge of B particularly difficult is as follows: mechanical imperfections in large telescope optics make it difficult to have stabilize the mirrors that define the interferometer baseline at a level better than

$\sim$ 100um; and the baseline ‘seen’ by each starlight path is slightly different that the other, since the optical paths are slightly different, a challenge referred to as the ‘narrow-angle baseline problem’.

For telescopes purpose-built for the task (Hrynevych et al., 2004), limitations of the $\sim$ 100um mechanical instabilities were accounted for by designing in baseline monitoring systems that reduced the error in B to $\sim$ 35um, along with additional systems to monitor the primary and secondary starlight paths and characterize the narrow-angle baseline errors at a similar level. Overall, due to these limitations in properly characterizing B, achievement of high accuracy relative astrometry over scientifically meaningful fields (Δs <20”) will probably be limited in the near term to accuracies of 20-30 μas.

4.3. An Engineering Demonstration: The Palomar Testbed Interferometer

It is useful to examine in some greater detail the Palomar Testbed Interferometer (PTI, Colavita et al., 1999), an instrument built to demonstrate the basic operating principles and possibilities of an astrometric dual-star interferometer. As described in the last section, PTI effectively consisted to two independent interferometer subsystems, each fed by a common pair of siderostat telescopes. As seen in Figure 6, starlight collected by each of the siderostats was split at the telescope foci with a field separator that sent the primary and secondary starlight into separate but parallel beam paths, into the beam combining laboratory.

These primary and secondary beams were then sent to a common delay line cart that applied pathlength compensation appropriate for the secondary star; a second cart did the same for the pair of starlight beams from the second siderostat (see Figure 7). The secondary starlight beams from both siderostats were then routed to a beam combiner table for detection of the fringes for that secondary star; similarly, the primary beams went to their own combiner table, but by way of a secondary delay line, to add static pathlength commensurate with the on-sky angular separation of the primary and secondary stars. Laser metrology launched from the two beam combiner tables traveled out to the siderostats and retroreflected back to the tables at the common corner cube noted in Figure 6 (to calibrate the time-variable portion of the ΔC term above); separate laser metrology systems monitored the delay line positions for characterization of the Δd term. Also at the beam combiner tables, visible light was split off to feed a quadrant of avalanche photo diodes, to drive the tip-tilt correction mirror M4. The field separator for PTI was originally envisioned as a pinhole mirror, but ultimately was

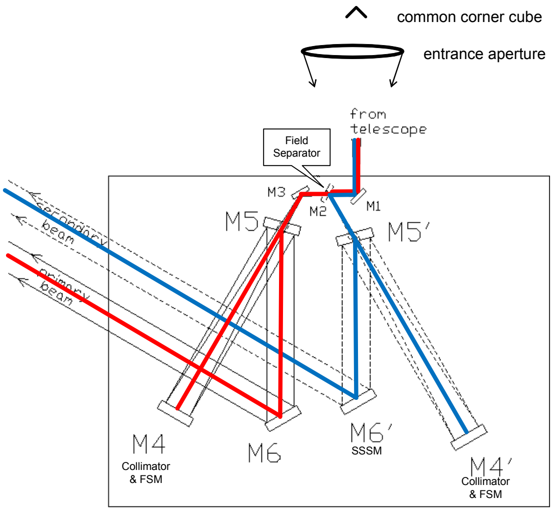

Figure 6: Schematic of the PTI Dual-Star Feed (DSF). One DSF is located at each siderostat and provides collimated starlight beams from each of two stars from a small (20”) field. A focused beam of starlight from the siderostat telescope enters the DSF at M1 and the two fields are separated at M2 (which can be a mirror with a pinhole or, as was the case with PTI, simply a 50/50 beamsplitter). The M4 mirrors collimate each beam, and also act as a fast steering mirror (FSM) for tip-tilt tracking of the beams. M6 on the secondary beam also acts as the secondary star selector mirror (SSSM), which can be steered to feed a desired secondary star down the secondary beam path.

simply a 50/50 beam splitter: this enabled feeding the primary star simultaneously into both interferometer paths to determine a zero point the ΔC term for the astrometric solution.

PTI was able to demonstrate the technique of dual-star astrometry by observing the nearby binary star 61 Cyg A & B, a pair of K-type main sequence stars only 3.5pc distant, separated on sky at present by roughly 24” locked in an orbit with roughly a 650 year period[8]. As reported in Lane et al. (2000), PTI was able to detect night-to-night variations in the relative positions of the two stars; for the 7 consecutive nights of highest quality data, the residual RMS in declination was 97 μas (the corresponding errors in right ascension were larger, since the PTI baseline used for these observations was primarily north-south). Unfortunately, the sensitivity limitations of this pathfinder instrument precluded observations of dimmer stellar pairs.

4.4. Hubble FGS: The Existing Astrometric Space Interferometer

The benefits of ground-based long-baseline interferometry are vastly surpassed by a space-based facility, although to date no optical/near-infrared missions have been launched. However, aboard the Hubble Space Telescope,

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[8] Additionally, PTI was utilized to perform a wide range of general-purpose ‘classic visibility science’, such as observations of close binaries and determinations of stellar diameters and shapes.

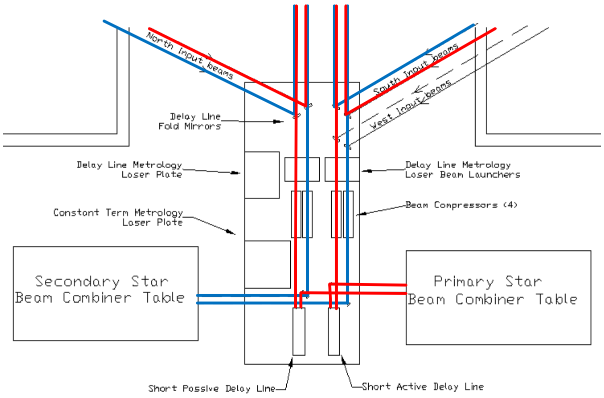

Figure 7: Schematic of the PTI delay laboratory. Starlight from each siderostat is routed through a delay line (unseen, off the top of the figure), with the primary and secondary beams following parallel but vertically separated paths out and back from the delay line cat's eye optics. After $\sim 4:1$ beam compression, the secondary starlight is passed along to a beam combiner table. Each of the two primary starlight beams passes through a secondary delay line, to (a) provide a fringe tracking pathlength dither, and (b) provide a static delay line offset to account for the slight difference in sky position between the primary and secondary star. The primary beams are then also passed along to a beam combiner table.

the Fine Guidance Sensors (FGS) which are nominally used for astrometric stabilization of telescope pointing are astronomical instruments in their own right - and interferometric as well. As such, they can provide astrometric information on faint targets with errors at the ∼0.20mas level. Recently this capability was demonstrated in the impressive writeup by Benedict et al. (2007), who used HST FGS data to determine the distances to 9 galactic Cepheid variables. As noted in §3.1, precise calibration of the lower rungs of the cosmic distance ladder is exceedingly important for building confidence in the further-reaching upper rungs.

Errors from the Benedict et al. (2007) study ranged from 0.16mas to 0.29mas for objects with parallaxes of 1.9 to 3.0 mas, and V-band brightnesses ranging from 3.7 to 5.7 (although ∼10 background reference stars per target were in the range of V∼10-15). Their results allowed them to calibrate the galactic Cepheid period-luminosity relationship (PLR), finding it consistent with the Freedman value for H_0, although implying a slight increase needed in the Sandage H_0 value. This study with HST was one of the key reasons the mission was initially funded over two decades ago.

5. Future Prospects for Astrometric Interferometry

For the VLTI (Very Large Telescope Interferometer) the PRIMA (Phased Referenced Imaging and Micro-arcsecond Astrometry) facility is designed to enable dual star astrometry at the ∼30-40μas level for a reasonably sized program of astrometric detection of planetary companions using the VLTI's 1.8m Auxiliary Telescopes (van Belle et al., 2008). Similarly, the Keck ASTRA (ASTrometric and phase-Referenced Astronomy) upgrade to the Keck Interferometer will enable the twin 10m telescopes to carry out dual-star astrometry at the $\sim 100\mu$as level (Pott et al., 2008). The SIM (Space Interferometer Mission) spacecraft, if flown, will calibrate the rungs of the distance ladder throughout the Galaxy (to 10% at 25,000 pc, 1% out to distances of 2,500 pc) (Unwin et al., 2008). It will be by pushing astrometry to the sub-μas level that we will be able to peer into the cosmic veil and probe the machinery underneath (Figure 8).

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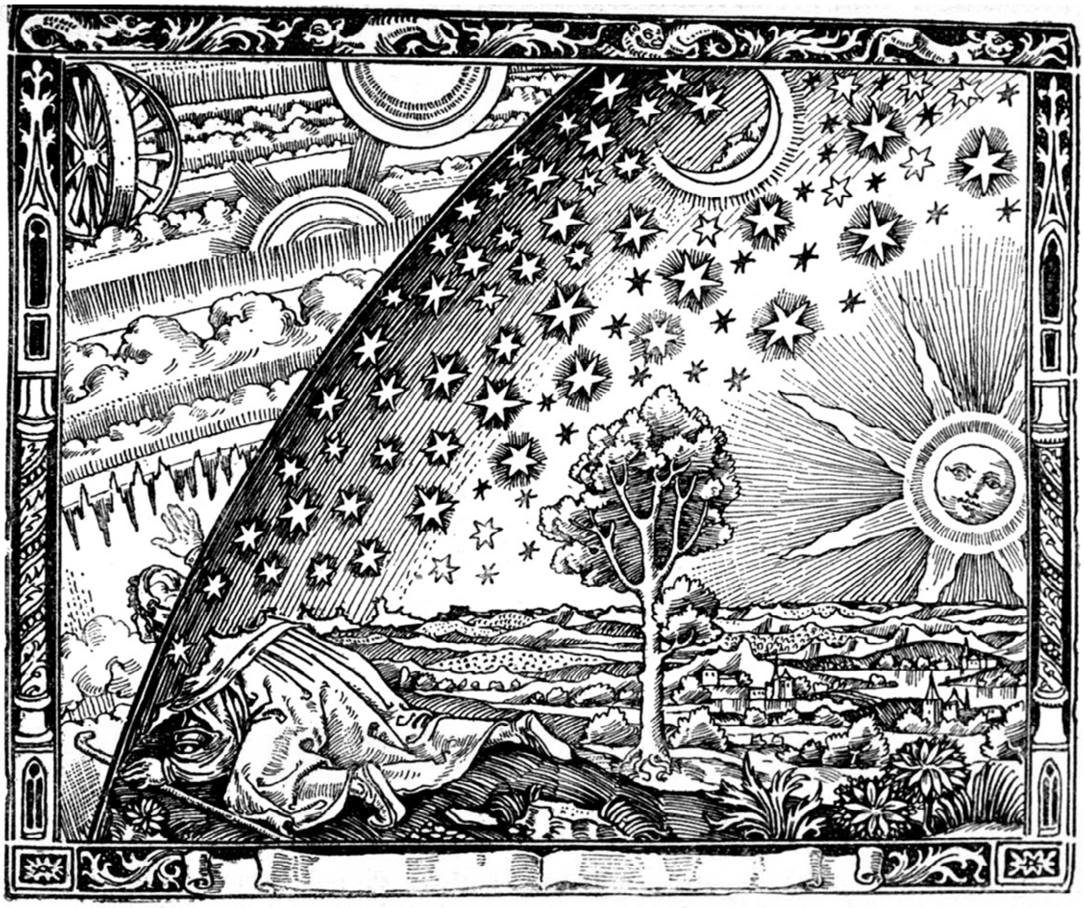

Un missionnaire du moyen âge raconte qu'il avait trouvé le point où le ciel et la Terre se touchent...

Figure 8: The "Flammarion Woodcut", anonymous, first seen in *L'atmosphère: météorologie populaire* by Camille Flammarion, 1888. The captions translates to "A medieval missionary tells that he has found the point where heaven and Earth meet..."

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