Cosmology with the Very Large Telescope
Interferometer using a space based astrometric
reference frame *

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Abstract. Cosmology with large interferometric telescopes is a rich and largely unexplored subject, involving three types of measurement: astrometric measurement of absolute distances and proper motions, dispersions of relative proper motions, and images. The ground based interferometers can have huge apertures, which are necessary for faint cosmological targets. But, alone, they are limited to astrometry within the isoplanatic patch, and hence to relative positions, which are of little use for parallaxes and proper motions because reference stars have unknown parallaxes and huge (500 µarcsec) unknown motions. We propose that space missions should measure global astrometric parallaxes and proper motions for (V > 16) reference stars within the isoplanatic patches of important cosmological and Galactic targets. Ground based interferometers can then measure absolute distances (parallaxes) and proper motions to 10 µarcsec, tied to these reference stars. In combination, space and ground based interferometers can make a wide variety of measurements, some of which were believed to be restricted to space missions, and others where not considered possible because space missions lack light gathering power: absolute distances accurate to <10% for most globular clusters and about ten near by galaxies; proper motions of stars in near by dwarf galaxies and stars near to giant black holes; the masses and distances to individual MACHOS which cause microlensing events in the halo and bulge of our galaxy; proper motions of 1000 galaxies out to Virgo; and images of giant black holes, AGN and distant galaxies.

But cosmological observations stretch the VLTI technically. To observe the few best targets, we need to be able to measure positions to <10µarcsec over a large portion of the sky. Since natural guide stars are too far apart, or too faint, laser guide stars are needed to correct the wavefronts of the individual 8-m unit telescopes, and the fringe tracking system must have an extremely high throughput to work on the brightest stars (V > 16) near to important targets. Most of the science is at 1 – 2 microns, where excellent adaptive optics will be needed on the 8-m telescopes.

1 VLTI Characteristics

I preview cosmological observations which could be made with ground based interferometers which use large aperture telescopes, with specific reference to the VLTI. I have borrowed heavily from Peterson et al (1996) who reviewed science with a space interferometer, because I show that the ground based telescopes can undertake some projects which were considered for space alone. Science with

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interferometric images with $1 - 10 \mu$-arcsecond ($\mu$as) resolution was discussed by Begelman & Krolik (1991). I take an optimistic view, skip over the many technical and observational difficulties, such as integration times and confusion in complex fields, and omit many relevant references. Let us begin with an introduction to the technical issues, which require close attention if the VLTI is to do cosmology.

Following the Palomar Testbed Interferometer (Shao & Colavita 1992), the VLTI will have a dual feed, which allows high precision narrow angle (or differential) astrometry (Kovalevsky 1995). One feed looks at a relatively bright reference star, while the other looks at the target, which can be very faint. The two can be separated by up to 60 arcsec, but astrometric accuracy improves linearly with the inverse separation (Shao & Colavita 1992), as the paths through the atmosphere to the target and reference become nearly identical. Each feed covers about 2 arcsec diameter, the potential imaging area.

To correct the wavefront of the light gathered by the individual 8-m unit telescopes, we need a bright star $V,K < 13$ within 10 arcsec of the target to sense the wavefront. This restriction rules out all but a tiny fraction of the sky, and must be overcome using laser guide stars, one for each unit telescope. Lasers allow us to correct the wavefront anywhere in the sky.

To provide stable interference fringes (fringe tracking), we can use slightly fainter reference stars ($V,K < 16$ assuming the wavefront is already corrected to near the diffraction limit of the unit telescopes). Sky coverage as a function of angle to the reference star is reasonable at the Galactic plane: 15% at 10 arcsec, 45% at 20 arcsec and 75% at 30 arcsec, but unacceptably small at the pole: 0.8% at 10 arcsec, 3% at 20 arcsec and 7% at 30 arcsec. The ideal fringe tracking system would work on fainter stars, with higher throughput, wider bandwidth or perhaps better open loop stability.

The key advantage of the VLTI over most other interferometers is its sensitivity: $V = 25$ and $K = 23$ in 600 sec with signal to noise ratio 10 in 0.7 arcsec seeing. This is why it can play an important role in cosmology.

Tip/tilt correction is sufficient to make the auxiliary 1.8 m telescopes diffraction limited at $> 1$ micron, and the unit 8-m telescopes at $> 5$ microns. But adaptive optics is essential for cosmology, which will use the 8-m unit telescopes (UTs) at $< 1$ microns.

Baselines are $B < 200$ m for the 1.8 m telescopes (0.001 arcsecond = 1 mas point spread function at 1 micron) and $B < 130$ m for the UTs ($< 1.6$ mas).

2 Ground Based Astrometry using stars on a Global Reference Frame from Space

In an extremely important paper which opened up a whole new astronomical technique, Shao & Colavita (1992) pointed out that ground based telescopes can make extremely high precision relative astrometric measurements whenever references stars are a few arcsec from targets: 10 $\mu$as with the VLTI for reference
stars within < 10 arcsec, when the signal to noise in the fringe visibility is about >55 at 2.2 microns. The smaller then angle to the reference, the more similar the light paths through the atmosphere, and the better the relative astrometric accuracy. There are many uses for relative astrometry: binary stars, orbits of unseen brown dwarfs and planets, masses and distances to microlenses, dispersions of the proper motions of stars in clusters and galaxies.

However distances require absolute parallaxes. Parallaxes relative to a reference star with an unknown parallax are of little use because we do not know how to proportion the motion between the two stars, and if both are at the same distance, no relative parallax motion is seen. Similarly, absolute proper motions are much more useful than those measured relative to stars with unknown motions. All faint reference stars move, by about 500 $\mu$as /yr (24 km/s at 10 kpc, which is much more than the 150 $\mu$as relative astrometric accuracy of a single 8-m aperture). There are far too few within an isoplanatic patch to give a reference frame stable to 10 $\mu$as, so ground based observations give relative not absolute parallaxes and proper motions.

We propose that ground based telescopes should use reference stars which are observed from space. Space observations can give even higher astrometric accuracy over both narrow and wide angles, and hence they can construct a global astrometric reference frame, with absolute parallaxes and motions. This synergy between the global reference frame from space, and the fainter targets from the ground based, allows large ground based telescopes to measure distances (absolute parallaxes) and absolute proper motions, tied to the space frame. This greatly increases the range of cosmological observations for the VLTI.

Of the various space astrometry missions, Hipparchos lacks accuracy: 1000 $\mu$as. The proposed ESA mission GAIA is close to what is needed: 10 $\mu$as to $V = 15$, but it covers the whole sky, where as the VLTI would prefer fainter reference stars ($V = 16$ or 17, as faint as fringe tracking allows), selected because they are in the isoplanatic patches of important Galactic and cosmological targets. This is a task better suited to NASA’s SIM mission, which should obtain 5 $\mu$as on pre-selected targets ($V=16$ in 2,000 sec, or $V=18$ in 10,000 seconds, with a baseline of B=7 m).

The use of a space based absolute reference frame is a natural way to use the VLTI, since there must be a relatively bright reference star within the isoplanatic patch for fringe tracking. We are proposing that this same star should also provide absolute position, motion and distance.

3 Comparison with other Instruments

The VLTI has unique advantages, but only if it is fully equipped with laser guide stars, adaptive optics, and high throughput fringe tracking, and even then only for a few years, as many other instrument and missions are competitive.

HIPPARCHOS: 1000 $\mu$as (VLTI 100 times better), survey of $10^5$ stars (VLTI gives 100 times better relative astrometry, but points at selected targets).
HST: point spread function of 100 mas at 1 micron (VLTI 50 times better), arcmin field of view (VLTI 1000 times smaller).

DIVA: A proposed small German interferometric satellite, which would survey $10^6$ stars with $V < 10$ giving parallaxes to 800 $\mu$as (Bastian et al 1996).

SIM: NASA’s Space Interferometer Mission (2003) (Peterson et al. 1996). $V < 20$ (VLTI readily goes 5 magnitudes fainter, but SIM may reach $V = 26$ in 20 hours), 5 yr life (for proper motion – not parallax – the VLTI can compensate for its lower annual accuracy with more years of observation) 0.3 arcsec field (VLTI is 40 times larger), 4 $\mu$as with a $B=10$ m (VLTI is 2 times worse, and needs a space reference grid for parallax), good UV plane coverage (VLTI is not as good for complex fields), dynamic range $< 2000$ and can null out bright sources to $10^4$ at 70 $\mu$as or $10^5$ at 7 $\mu$as (VLTI worse).

GAIA: ESO proposed sky survey to $V < 16$ (VLTI 9 magnitudes better), $5 \times 10^7$ star sky survey (VLTI points), 10 $\mu$as at $V=15$ (VLTI similar, but needs space reference frame for parallax).

NGST: An 8-m version of NASA’s Next Generation Space Telescope (www://ngst.gsfc.nasa.gov/) gives 5 $\mu$as astrometry (VLTI 2 times worse), over 4 arcmin field (VLTI $10^4$ times smaller area), with much higher sensitivity and dynamic range. The NGST is dramatic! It will compete strongly with all large ground based optical/IR telescopes and planned interferometers.

Keck Interferometer: Two 10-m telescopes and four 2-m outriggers, 2003. (VLTI much better UV coverage).

There are also many interferometers with smaller apertures including the Palomar Testbed Interferometer, I2I, ISI, OCAST, SUSI, IOTA, NPOI and CHARA, which will not compete on fainter cosmology targets.

4 Assumptions

For the remainder we will assume a cosmology friendly VLTI. 1) Laser guide stars on at least two 8-m UTs. 2) Adaptive optics on at least two UTs (movable to others), allowing fringe tracking on $V > 16$ to get good sky coverage, and science at 1 – 2 microns. 3) Parallax and proper motion from space and on a global reference frame for at least one reference star ($V \approx 16$) in the isoplanatic patch of all interesting targets. The VLTI then gives positions to about 14 $\mu$as when the reference star is 10 arcsec away, and 30 $\mu$as at 30 arcsec.

5 Extragalactic Distance Scale

The VLTI can be used to provide improved distances to standards. However space missions such as GAIA or SIM are needed to provide reference stars in the global reference frame, and those same missions can and will also observe the luminosity standards themselves, because they are bright. Indeed they are brighter than the reference stars. There are three main types of object:
Cepheids distances come from main sequence fits to open clusters. The VLTI could get >1% distances to < 20 stars with parallaxes of 200 – 1000 μas and V < 10. An excellent next step after the huge ground based studies from microlensing (Beaulieu & Sasselov 1997).

RR-Lyrae distances come from statistical parallax. The VLTI could get 1 – 10% distances to < 20 stars at < 5 kpc with V = 8 – 11.

Planetary Nebulae do not have good distances. The VLTI could obtain 1 – 10% distances for < 40 with parallax 100 – 1000 μas and V = 12 – 16.

5.1 Galaxy Distances from Rotation

Absolute distances to a few near by Galaxies can be obtained by comparing Galactic angular and radial velocity rotation rates (van Maanen, Reasenberg et al., 1988; Peterson et al. 1996). Measure both the angular and radial velocities at two places where the rotation velocity (relative to that galaxies center) is expected to be the same, then solve for the rotation velocity, inclination and distance. A transverse velocity of 100 km s\(^{-1}\) at 1 Mpc is 210 μas /10 years, which gives a distance to 5% per star, and 1% for 25 stars. The target A – F supergiant stars are bright, with M\(_v\) ≃ −8.5 and V = 21.5 by 10 Mpc, but few stars in the galaxy will be near to V < 16 reference stars.

6 Globular Cluster Distances and Ages

The next satellite measurements of the cosmic microwave background should determine the age of the universe to about 1%. VLTI could improve globular cluster ages from 10% today to a few percent. Improving distances improves the turnoff luminosity, which improves the mass and thence the age. A 12% distance error is a 22% age error (Renzini et al. 1996). The VLTI can give 1% distances at 1 kpc, and 3% distances with 10 stars at 10 kpc. Stars with M\(_v\) ≃ −1 are V ≃ 14 at 10 kpc, providing excellent reference stars.

Meylan (this meeting) discusses relative proper motions inside clusters. If we assume globular clusters are isotropic, then a comparison of radial and angular velocities gives distances. No global reference frame is needed for this since we are measuring the dispersion in proper motions, not the absolute values. Consider a cluster like 47 Tuc with σ\(_v\) = 11.5 km s\(^{-1}\), but at 10 times the distance: 46 kpc. The dispersion of proper motions will be σ\(_μ\) = 53 μas /yr. Since stars are close together in the clusters, we can take advantage of the gains in relative astrometry with close pairs, perhaps obtaining 2 μas on pairs separated by 1.6 arcsec (V ≃ 14). If we then measure 100 stars we get a 10% error on the σ\(_μ\). But gains are slow, since σ\(_μ\) ≫ measurement error, and crowding and changing blends may spoil the accuracy. Astrometric images might be competitive, because they capture many stars at once. A single 8-m should give errors of 150 μas /yr, or ≃ 3.5σ detections of proper motion per star in 10 years, which would be difficult for distant clusters, because the physical dispersion is only 3.5 times the expected
measurement error, which we need to measure accurately and subtract from the observed dispersion.

7 Dark Matter in the Galaxy

The VLTI is well suited to the measurement of the masses and distances to individual MACHOS in the galactic halo and bulge when they cause microlensing events. Microlensing events are seen where the density of stars is unusually high: the galactic bulge (detect 50/yr), the Magellanic clouds (6 – 8 events in 3 years), and in the near future, the inner regions of M31.

The bulge events have typical masses of 0.3 M⊙, and may be caused by ordinary stars in the bar of our Galaxy. If we knew individual masses and distances we could identify the lens objects, and later measure masses for planets which we expect will be found orbiting the lenses (Rhie & Bennett 1996; Peale 1996).

Events towards the LMC are of unknown origin. Their masses are around 0.2 M⊙, depending on the halo kinematics, and hence they might be old, cold white dwarfs.

Several possible measurements could be attempted (Miralda-Escudé 1996). The maximum image splitting seen in the sky (Miyamoto & Yoshii 1996) is

$$2\theta_E = \frac{4}{c} \sqrt{GM} \left( \frac{1}{D_L} - \frac{1}{D_S} \right)^{1/2} \leq 2 \left( \frac{M}{M\odot} \frac{8 \text{ kpc}}{D_S} \right)^{1/2} \text{mas},$$

where M is the lens mass, D_L and D_S are the distances to the lens and source star. The event lasts about 40 days (typically 5-100 days, depending on the relative velocities and M), and will be hard to observe because the point spread function is about 1 mas at 1 micron with a 200 m baseline.

The centroid shift is 1 – 2% of the splitting, or < 20 – 40 µas for a 1 M⊙ lens at D_L = 4 kpc towards a source at D_S = 8 kpc, which will also be hard to measure.

The proper motions of the lens and source are huge: ≃ 4 mas/yr, but measurements will be hard because of the blending of the lens, source and many other stars in these crowded fields.

Proper motion will separate the lens and source in the sky, to about 18 mas in 5 yr (transverse velocity 100 km s^{-1}, D_L = 6 kpc), so that they could be resolved. The lens might be faint, V=24 for M_v = +10, and we would like to measure colors to determine a spectroscopic distance. Hardware and techniques intended to observe planets near to stars may help with this observation, although it may be built to handle much larger separations (about 1 arcsec) and higher contrast ratios (10^9).

The lens and source parallax are large: 170 µas at 6 kpc, but again the field is crowded, and the lens is very faint.
8 Structure of Other Galaxies

The mass to light ratio in dwarf galaxies increases up to 100 as luminosity drops. The VLTI could measure the proper motions of many stars to check the isotropy of the velocities which might change M/L determinations by a factor of two (e.g. Eckart & Genzel 1996). The individual stars in a galaxy at 80 kpc (parallax 12 μas) with internal motions of 10 – 100 km s$^{-1}$ would have proper motions of 25 – 250 μas. The distribution of the dispersion in proper motions across the galaxy can be used to map out the distribution of dark matter relative to light, while unusually large motions can indicate mass concentrations (black holes). Alternatively, if we assume the velocities are isotropic, the comparison of proper motions with radial velocities gives a distance. Proper motions of stars in large galaxies are hard, but just possible out to Virgo: 41 μas in 10 yrs for 300 km s$^{-1}$ velocities at 16 Mpc.

9 Proper Motions of Whole Galaxies

The proper motions of many whole galaxies are just within the range of the VLTI. A 500 km s$^{-1}$ velocity at Virgo (16 Mpc) gives 6 μas/yr, or a 25% error in 7 years. The target stars are faint: V=22.5 for $M_V = -8.5$ A – F Population I supergiants in spirals and irregulars, and many should be measured per galaxy to map out and correct for the internal motions in the galaxies. A large project could be launched to map the motions of 1000 galaxies, to reconstruct orbits, identify groups, and map out the mass distribution. This project requires fringe tracking on very faint stars, since an 8 kpc galaxy at 16 Mpc covers 1.7 arcmin, and includes on 0.9 foreground stars brighter than V=16 near the Galactic poles, or 16 in the plane.

10 Search for Black Holes in Galaxies

The presence of a massive black hole in a galaxy can be deduced indirectly from the AGN activity (radio, IR, UV, X-ray and broad emission lines), and more directly by sensing the distribution and motions of stars and gas (e.g. Miyoshi et al 1995).

Images can be used to look for light cusps in the centers of distant galaxies. If an HST images can reveal a $10^9$ M$\odot$ black hole at 16 Mpc in images with 100 mas resolution, then the VLTI might see the same at 400 Mpc with 4 mas images, far enough to sample $10^6$ galaxies.

The VLTI has the astrometric sensitivity to measure the proper motions of individual stars near black holes out to Virgo, but this would be hard because of crowding. Low resolution spectra of the integrated light from within a few mas of a massive black hole would show huge velocities, allowing their detection to great distances (500 km s$^{-1}$ at 4 mas for a $2 \times 10^9$ M$\odot$ hole at 1000 Mpc – where I scaled distance against angular resolution from the M87 observations.
of Ford et al. 1994), or the detection of lower mass holes in Virgo galaxies (500 km s\(^{-1}\) at 16 Mpc for a \(3 \times 10^7\) M\(\odot\) hole, where \(v^2 \propto M/\text{[angular resolution]}\)).

11 AGN and QSOs

Beyond Virgo, proper motions are too small for the VLTI, and images and spectra become the main cosmological measurements. At cosmological distances, 2 mas resolution at 1 micron corresponds to \(24 \ h_{\text{50}}^{-1}\) pc at \(z = 3\) for \(q_0 = 0.5\). Narrow emission line regions of massive black holes (QSOs) are 100 pc in size and resolved at all redshifts. Broad line regions are only 0.1 pc across (2 mas at 10 Mpc) and hard to resolve, but important because their shape and homogeneity is unknown. Ward (this volume) discusses IR observations of molecular torii. Knots in the jets of superluminal sources are probably <pc in size, and move 0.1 – 1 mas/yr. Their dynamical range is unknown on mas scales. Comparison of optical with radio data relate to the physics of the radiation mechanism and the magnetic fields. If the light from some AGN is dominated by starbursts (Melnick, this volume), then the star cluster may be resolved. It would be especially interesting to null out the QSO light to image the inner structure of high z active galaxies. High angular resolution images of gravitational lenses provides accurate astrometry which is the key to the construction of accurate mass models.

12 Young Galaxies

Galaxies with cool gas and young stars have a lot of structure; compare HST images of the near by M100 spiral before and after the refurbishment. There types of galaxies look fuzzy from the ground because of the Earth’s atmosphere, and we expect more substructure at high redshifts because there is more star formation, and lumps from which galaxies are made are not well mixed. Although the high galaxies are extremely faint, and they will have complex shapes, requiring many baselines, it would be exciting and presumably rewarding to attempt mas resolution images of even a few.

High redshift galaxies are common, so they can be chosen near to bright fringe tracking stars. Steidel et al (1996) find 0.4 galaxies at \(z \simeq 3\), so that 3% of random positions on the sky (e.g near bright stars) have one such high redshift object.

It would be very interesting to make high resolution images of galaxies causing absorption lines seen towards bright high redshift QSOs. Most such QSOs have \(V \geq 18\), but a few at \(z \simeq 2\) have \(V = 16\) for fringe tracking. We could determine what types of galaxies cause various types of absorption.

13 Conclusions and Requirements

Cosmological observations with ground based interferometers are technically challenging, but the equipment also would benefit most other studies. The sci-
ence is rich and largely unexplored.

There are two main types of measurement: differential astrometry, and images. The astrometry can give absolute parallaxes and proper motions when the reference star in the isoplanatic patch (of the target) has a known parallax and proper motion. Observations from space are needed to place these reference stars in a global (absolute) reference frame. Astrometry can also measure the dispersion in proper motion of stars in a globular cluster, dwarf galaxy, or near a massive black hole, without the need for a reference star in a global reference frame.

Adaptive optics is needed to work in the near-IR, while laser guide stars are needed on the unit 8-m telescopes to obtain useful sky coverage. We need two perpendicular baselines for astrometry and images, so three unit telescopes should be equipped, or only two if the hardware is moved between telescopes.

Every effort should be made to increase throughput and bandwidth so that stars fainter than $V=16$ can be used for fringe tracking. Otherwise sky coverage at the Galactic pole is unacceptably small (3% with a reference star within 20 arcsec) and most individual cosmological targets will not be observable.

Ability to record spectra with a resolution of 100 km s$^{-1}$ from light from areas of a few mas is important for the detection of massive black holes and the structure of AGN emission line regions.

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