Study of the Science Capabilities of PRIMA in the Galactic Center

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ABSTRACT

The Phase-Referenced Imaging and Micro-arcsecond Astrometry (PRIMA) facility is scheduled for installation in the Very Large Telescope Interferometer observatory in Paranal, Chile, in the second half of 2008. Its goal is to provide an astrometric accuracy in the micro-arcsecond range. High precision astrometry can be applied to explore the dynamics of the dense stellar cluster. Especially models for the formation of stars near super massive black holes or the fast transfer of short-lived massive stars into the innermost parsec of our galaxy can be tested. By measuring the orbits of stars close the the massive black hole one can probe deviations from a Keplerian motion. Such deviations could be due to a swarm of dark, stellar mass objects that perturb the point mass solution. At the same time the orbits are affected by relativistic corrections which thus can be tested. The ultimate goal is to test the effects of general relativity in the strong gravitational field. The latter can be probed with the near infrared flares of SgrA* which are most likely due to accretion phenomena onto the black hole. We study the expected performance of PRIMA for astrometric measurements in the Galactic Center based on laboratory measurements and discuss possible observing strategies.

Keywords: Astrometry, Black hole, Galactic Center, General Relativity, Interferometry, PRIMA, VLTI

1. INTRODUCTION

During the past three to four decades sub-milliarcsecond radio astrometry with intercontinental long baseline interferometry (VLBI) led to the discoveries of super-luminal motions in relativistic radio jets of distant quasars and of molecular gas outflows in star forming regions. VLBI also yielded precision measurements of the dynamics of a warped accretion disk around the supermassive black hole (SMBH) in the external galaxy NGC 4258 and provided primary distance measurements throughout the Milky Way and reaching several external galaxies. Hipparcos astrometry of stars in the solar neighborhood revolutionized our knowledge of the dynamics of the Milky Way. Speckle and adaptive optics, near-infrared (NIR) astrometry of stars with the European Southern Observatory (ESO) New Technology Telescope (NTT) and Very Large Telescope (VLT) demonstrated that SgrA*, the compact radio source at the center of the Milky Way, must be a SMBH of about 4 million solar masses, beyond any reasonable doubt. NIR and optical interferometry with the Very Large Telescope Interferometer (VLTI) will open a new era of high resolution, narrow angle precision astrometry. It will allow phase-referenced imaging of faint sources at milliarcsecond (mas) resolution, and $10 - 100$ microarcsecond (μas) precision astrometry, all at the exquisite sensitivity provided by the large collecting area of the VLT (2 m diameter Auxiliary Telescopes, ATs, and 8 m diameter Unit telescopes, UTs).

In this paper we will discuss some of the exciting possibilities for dynamical measurements that PRIMA will offer in the Galactic Center research. Studies of stars and gas in the immediate vicinity of the event horizon of the massive SMBH in the Galactic Center (GC), with the ultimate goal of testing General Relativity (GR) in its strong field limit will be viable in only a few years time.

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2. THE PRIMA INSTRUMENT FOR THE VLTI

The PRIMA Instrument will allow simultaneous interferometric observations of two objects in the telescope field of view separated by max 1' on one baseline. It will be optimized for phase-referenced imaging on faint objects, from 1 to 10 μm, and for micro-arcsecond astrometry at wavelengths between 1.9 and 2.5 μm (Delplacke[1] et al. 2000). By tracking the fringes (the interference pattern) on a bright reference object one can actively stabilize the fringes of a second object. This allows long integration times of the fringes of the second object, which can therefore be much fainter than the reference object.

PRIMA consists of a star separator for each of the UTs and ATs, which allows to feed two arbitrary objects from the Coudé field of view into the Delay Lines of the VLTI. The difference of the white light fringe position of the primary and of the secondary star is adjusted by differential Delay Lines. In the astrometric mode, two identical interferometers, the Fringe Sensor Units (FSUs) measure the fringe position of the primary star and of the secondary star. A metrology system measures the internal differential delay, between both stars in both interferometer arms with a 5 nm accuracy requirement over typically 30 min. In addition to the astrometric mode, the second star can also be observed with other VLTI Instruments like MIDI and AMBER. For a more detailed technical description of PRIMA see Delplancke[1] et al. (2000) and Derie[2] et al. (2002).

The application of the PRIMA facility is threefold:

- The fringe tracking on a bright object ($m_K \approx 10$ on UTs and $m_K \approx 8$ on ATs) allows to stabilize the fringes of a faint object allowing for longer integration times. This pushes the limiting magnitude of visibility measurements with MIDI and AMBER to fainter objects ($m_K \approx 18$ on UTs and $m_K \approx 15$ on ATs).
- The phase-referenced imaging will allow for an unmatched resolution of up to 1 mas. The current VLTI instruments (MIDI, AMBER) are just giving the visibility modulus while PRIMA enables one to measure the phase, given by the relative position of the white fringe of the two stars.
- In the micro-arcsecond astrometry mode the differential delay between two stars is measured with a very high accuracy (5 nm RMS). Observing two objects separated by 10" with a 200 m baseline known to ~ 50 μm, and an integration time of 30 min (to null the differential effect of the atmosphere) this would yield a precession on sky of 10 μas (Delplancke[1,3] et al. (2000)).

The main observable of the astrometry mode is the differential delay or optical path difference (dOPD) of two stars. This means that PRIMA is only capable of measuring the relative distance along the baseline of one star with respect to a reference star. As the position of the reference object is usually not known to a μas precession this leaves only the relative velocity or the relative acceleration as a viable measurement.

3. THE GALACTIC CENTER

The GC harbors a SMBH of roughly 4 million solar masses at a distance of 8 kpc to our sun, see e.g. Eisenhauer[4] et al. (2005), Ghez[5] et al. (2005), Gillessen[6] et al (2008). Note, that an angular distance of 1" corresponds at a distance of 8 kpc to a projected distance of about 40 mpc ($8 \cdot 10^3$ AU). Figure 1 shows a K-band picture of the Galactic Center (Trippe[7] et al. 2008) indicating the position and distribution of the brightest stars.

The SMBH is extremely faint in all wavebands except the radio. The more remarkable was the detection of a flaring activity of SgrA* (Genzel[8] et al. (2003)). During a 'flare' the IR emission (K or L band) rises typically by a factor of three above the quiescent level. A flare lasts roughly 60 minutes and shows substructure in the light curve with a characteristic time scale of 20 minutes, see e.g. Trippe[9] et al. (2007). Several flares occur during a day. The nature of the flare and the interpretation of its substructure is still under discussion.

Observations of the GC with PRIMA aim at detecting the effects of Special and General Relativity (SR/GR) on the dynamics of test particles (e.g. stars). In addition, the measurements will give unique insights into the three dimensional structure, dynamics and evolution of the unique nuclear star cluster (Genzel[10] et al. (2003), Schoedel[11] et al.(2007), Trippe[7] et al.(2008)). The nuclear star cluster of our Galaxy is a laboratory for processes

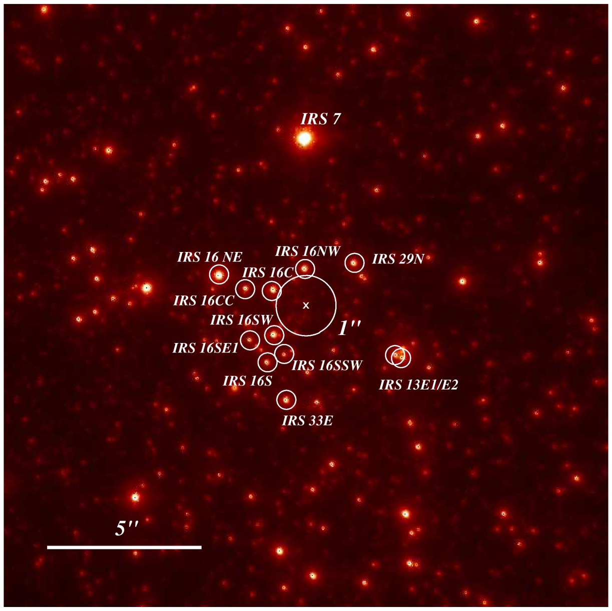

Figure 1. A K-band picture of the Galactic Center indicating the position and distribution of the brightest stars.

in galactic nuclei in general. Depending on the brightness of the source which determines the use of UTs or ATs and the projected distance from SgrA* which determines the years of continuous observation needed, there are three science goals foreseen with PRIMA:

- **$1'' - 20''$** The central parsec contains more than 100 early type stars, ranging from main sequence B stars to evolved Wolf-Rayet stars. They orbit the SMBH on one or two disks (this is still a matter of debate; e.g. Genzel[10] et al.(2003), Paumard[12] et al. (2006), Bartko[13] et al. (2008)) and were formed in a burst only a few million years ago. It is very difficult to understand how these short-lived stars can be observed so close to a SMBH, as standard in situ star formation would seem difficult or even impossible because of the strong tidal forces. These stars would also have had very little time to migrate from another, more favorable birth location outside the Galactic Center. With the current instrumentation it is possible to measure the proper motions and radial velocities of stars at a projected distance of less than 20 arcseconds. But to determine the orbit it is required to measure accelerations as well. Currently, full orbital solutions can only be determined for stars closer than one arcsecond to the Galactic Center on a realistic timescale of a few years. Therefore the disk properties can only be constrained by statistical means (Bartko[13] et al.(2008)). With PRIMA it will be possible to measure accelerations for stars up to projected distances of several arcseconds. This will greatly increase the significance with which one can constrain the scenarios of one or two disks of early type stars. Some of the brightest objects in the disks which are observable with the ATs are the IRS 16 stars ($m_K \approx 10$). Given their close distance to the SMBH they are expected to have the highest accelerations of the disk stars and are therefore the most promising objects. At a projected distance from SgrA* of roughly 3" one of the densest stellar clusters in the Milky Way (IRS 13) is located. The formation and evolution of such a dense cluster in the tidal field of a SMBH is still a puzzle to theory. One possible explanation is the existence of an intermediate mass black hole (IMBH) in the center of the cluster. To support or exclude this explanation the determination of the orbits of individual stars is necessary.

- **$\leq 1''$** Precision measurements of the peri-passages of the relatively bright known orbiting stars in the central $\approx 0.5''$ (S-stars: $m_K \approx 14 - 17$), which have been monitored by the current NACO/SINFONI program at the VLT. Typically once every 5 - 10 years one of these stars passes through peri-bothron where the post-Newtonian corrections due to SR and GR to the orbital parameters to order $\beta^2 = (v/c)^2$ are most pronounced. Observations with PRIMA may allow for the first time the determination of the astrometric terms due to a 30 times greater precision than the current AO imaging studies. Moreover, PRIMA observations are less affected by source confusion (from SgrA* flares and other, fainter stars) that strongly limit the precision of present adaptive optics (AO) data. The S-stars will be accessible as soon as PRIMA goes online on the UTs.

- **$\leq 100\,\mu$as** Time resolved, $10\,\mu$as astrometry of the NIR flares from SgrA A* itself. Given the growing evidence that these flares originate in the innermost accretion zone on scales of a few to ten times the event horizon (Genzel[8] et al. (2003)), where orbital velocities are a significant fraction of the speed of light and dynamical time scales are $\approx$ 10 min, astrometry of these flare events offer the unique opportunity of exploring the dynamics at $(R/R_s) \leq 10$, in the regime of strong gravity (R_s is the Schwarzschild radius of the event horizon). With $m_K \approx 16$ the observation of the flares will be the most challenging task and only viable with the large collecting area of the UTs. With PRIMA the interferometric observations can only be done with one baseline at a time. The needed integration time of 30 min to null the differential effect of the atmosphere, severely complicates the observation of dynamical processes of shorter timescales.

The PRIMA instrument will first be available for astrometric observations with the ATs. The limiting magnitude for the science object of $mK \approx 15$ (on ATs) basically excludes the observation of the S-stars and in particular the flares. Therefore, the luminous stars in the central stellar cluster, especially the stars belonging to the IRS 16 and IRS 13 groups, may well be the first observing targets with PRIMA in the Galactic Center. The bright ($m_K \sim 6.4$) star IRS 7, which is located only about 6" north of SgrA*, may serve as a phase reference star for these observations. In the following, the individual properties of these stars will be discussed in more detail.

3.1 IRS 7 as Phase Reference Star

The brightest NIR object within several arcseconds around SgrA* is IRS 7 with $m_K \sim 6.4$ (Paumard[12] et al.(2006)), locted 5.5" N and 0.4" E of SgrA*. It is classified as a red supergiant on the asymptotic giant branch (AGB) (Ott[14] et al.(1999)). Blum[15] et al.(1996) classified IRS 7 to be a M1I star and estimated an effective temperature of 3600 K. This leads to an angular size of the stellar radius of 0.5 mas at the distance of the GC (Pott[16] et al. 2008), less than the maximum angular resolution of PRIMA.

Being the most luminous source, IRS 7 is foreseen as the phase reference for the fringe tracking with PRIMA. The astrometry mode of PRIMA only measures distances (or distance changes) between the reference and the target source. Therefore, the scientific results are only relative velocities and accelerations. As IRS 7 has a non negligible velocity, which is not known with a μas accuracy, the acceleration becomes the most interesting feature. The gravitational potential of the innermost parsec is dominated by the SMBH. This means that existing accelerations only depend on the distance to the black hole ($a \sim R^{-2}$). The projected distance of IRS 7 of $\sim 6''$ yields a negligible contribution to the relative acceleration if measuring stars at projected distances of $\sim 2-3''$.

3.2 IRS 16 stars

In seeing-limited near-infrared images, the IRS 16 cluster is a bright source of broad He I 2.058 μm Brγ line emission very near to the dynamical center of our Galaxy. Since then IRS 16 has been resolved into a cluster of about a half-dozen stars, see e.g. Ott[14] et al.(1999), Paumard[17, 18] et al.(2001,2004) and references therein. These appear to be postmain sequence OB stars in a transitional phase of high mass loss, between extreme O supergiants and Wolf-Rayet stars. IRS 16SW needs some special attention as it is a contact binary with an orbital period of $\sim$ 20 d (Martins[19] et al. (2006)). Both companions have similar masses $M_1 \sim M_2 \sim 50 M_\odot$ and K magnitudes. IRS 16SW may therefore not be a point-source in interferometric observations with the VLTI. Paumard[12] et al.(2006) identify IRS 16C and IRS 16SW as part of the clockwise disk (CWS) and IRS 16NE as part of the counter-clockwise system (CCWS). IRS 16NW was assumed to be part of the CCWS disk but recent orbital fits have excluded this possibility (Gillessen[6] et al.(2008)).

3.3 The Star Cluster IRS 13E

The IRS13E cluster is the densest stellar association after the stellar cusp centered on SgrA* (Maillard[20] et al. (2004), Schödel[21] et al.(2005), Muzic[22] et al.(2008)). It contains several Wolf-Rayet and O-type stars of which at least four out of seven show a common velocity. The cluster is believed to be part of the CCWS. Muzic[22] et al. (2008) classify IRS 13E2 as part of the cluster but IRS 13E1 shows a significant deviation from the common velocity and is probably not bound to the cluster. Still under dispute is the existence of an Intermediate Mass Black Hole (IMBH) in the cluster. Some authors argue that the strong tidal disruptions in the vicinity of SgrA* raise the need for an IMBH in the core of a stable cluster (Hansen[23] et al.(2003), Maillard[24] et al.(2004)).

4. EXPECTED ASTROMETRIC PRECISION WITH PRIMA

The design goal of PRIMA is a 200 m baseline with a 5 nm error on the known differential optical path difference (dOPD) between the two telescopes and two stars located within a 1' field of view. Measuring the dOPD over 30 min the atmospherical disturbance averages to a residual dOPD of 5 nm. On a 200 m baseline this residual dOPD propagates as an uncertainty on sky of $\approx 10\,\mu$as. To compute the measurement accuracy, four observation periods per year with an individual astrometric precision of 10 μas for PRIMA and 300 μas for the infrared imager NACO at the VLT (see e.g. Clénet[25] et al.(2004)) were assumed. Fig. 2 shows the sensitivity (5σ detection limit for proper motion velocities and accelerations) as a function of time. Note, however, that the very first observations with PRIMA may be expected in late 2008, while the GC has already been continously monitored with NACO since 2002 (Gillessen[6] et al. 2008).

Table 1 shows the computed accelerations for the brightest stars with $m_K \leq 11$ and projected distance $d \leq 4''$ to the Galactic Center. The stars were assumed to be either part of the CWS or CCWS disk (disk inclinations were taken from Bartko[13] et al. (2008)). The mass of the SMBH was assumed to be $4 \cdot 10^6 M_\odot$ at a distance of 8 kpc. This fully determines the 3D position of the stars and yields the Kepler orbits plus accelerations. Possible uncertainties are mainly due to a finite thickness of the disk. Two of the most promising candidate stars for the IRS 13 and IRS 16 stellar clusters (IRS 13E2 and IRS 16C) are denoted in fig.2 as dashed lines. Note, that the star IRS 16NE is also a candidate member of the counter-clockwise disk with a smaller projected distance than IRS 13E2.

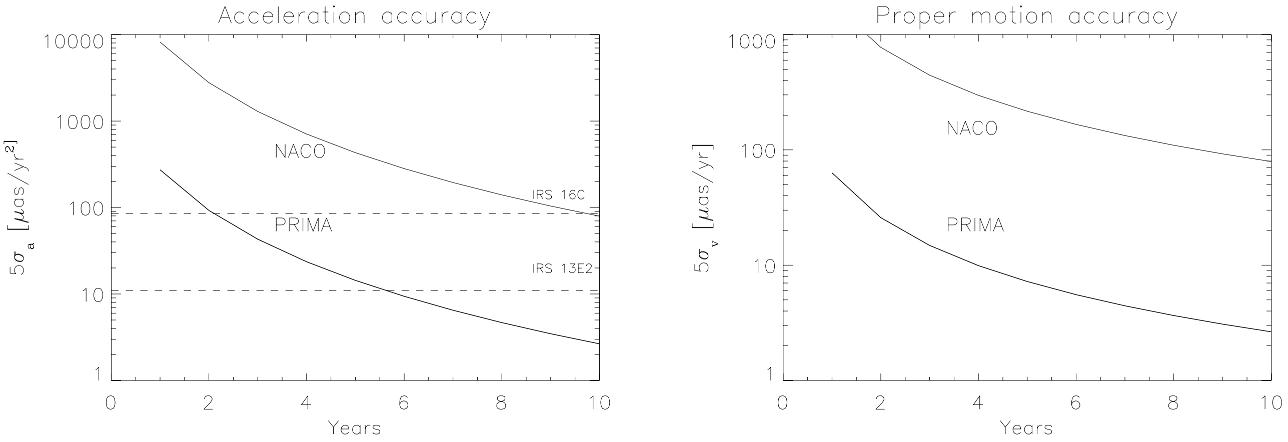

Figure 2. Acceleration and proper motion accuracies (5σ) that will be achieved with PRIMA, as a function of the length of the observing period, and compared to the accuracies that can be obtained with NACO/VLT AO imaging. An intrinsic 1σ astrometric uncertainty of 10 μas is assumed, with 4 measurement periods per year. The dashed lines show the calculated proper motion acceleration for the most promising star of the IRS 16 complex and for one star of the IRS 13 complex. For the calculation IRS 16C was assumed to be a member of the clockwise disk and IRS 13E2 to be a member of the counter-clockwise disk.

Name	d	$a_{\rm p}$	System	Years
IRS 16C	1.2	87 ± 21	CWS	2
IRS 16SW	1.4	66 ± 15	CWS	2.5
IRS 16CC	2.1	36 ± 7	CWS	3
MPE+1.6-6.8(16SE1)	2.2	37 ± 6	CWS	3
IRS 29N	2.1	32 ± 5	CWS	3.5
IRS 16SSW	1.8	26 ± 8	CWS	4
MPE+1.0-7.4(16S)	2.3	19 ± 5	CWS	4
IRS 16NE	3.0	17 ± 3	CCWS	5
IRS 13E1	3.4	13 ± 2	CCWS	6
IRS 13E2	3.6	13 ± 2	CCWS	6
IRS 33E	3.2	7 ± 2	CWS	7

Table 1. Computed accelerations for the brightest stars with $m_K \leq 11$ and projected distance $d \leq 4''$ to the Galactic Center are shown. They were either assumed to be part of the CWS or of the CCWS. The number of years to reach the 5σ detection limit of PRIMA is stated (see fig. 2). The projected distance d is given in arcsec (taken from Paumard[12] et al.2006) and the proper motion acceleration $a_{\rm p}$ in μas/yr^2

The first acceleration detections with PRIMA after 2 years of observation will be IRS 16C. The second most promising candidate is the binary star IRS 16SW. For both stars orbital solutions have already been obtained using the large SHARP/NACO data set extending over a time base-line of more than 15 years by Gillessen[6] et al. (2008). Within 3 years of PRIMA observations most of the IRS 16 orbits should be resolved and their disk membership determined. A longer observation run would be required for the IRS 13 cluster. To determine orbits and to conclude on the existence of a IMBH in the core it would take approximately 6 - 7 years. Within a period of 8 years the orbits of the bright stars ($m_K \leq 11$) at a distance of $\leq 4''$ should be fully determined.

5. CONCLUSIONS AND OUTLOOK

The Phase-Referenced Imaging and Micro-arcsecond Astrometry (PRIMA) facility at the VLTI will allow astrometric observations with a precision of up to 10 μas. It will first be available for observations with the ATs (aimed for limiting magnitudes of m_K of 8/15 for the reference/science object) and somewhat later for the UTs with limiting magnitude aims of $m_K = 10/18$. The Galactic Center star cluster contains a bright star, IRS 7, which will allow to use PRIMA already with the ATs.

With PRIMA one can determine stellar orbits of many of the early-type stars with time baselines of only a few years, much faster than with existing instrumentation like NACO. This will help to better understand the dynamics of the central star cluster of our Galaxy and to constrain models about star formation near supermassive black holes.

Using PRIMA together with the UTs, influence of General Relativity on the orbits of the S-stars in the central arcsecond may be observed. However, the needed integration time of 30 minutes may be too large to time-resolve the infrared flare events, which originate in the immediate vicinity of the supermassive black hole. This observation may first be done with the planned GRAVITY interferometer (Eisenhauer[26] et al.(2005)), which will use all four UTs.

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