Increasing the Scientific Return of Stellar Orbits at the Galactic Center

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Abstract. We report a factor of $\sim 3$ improvement in Keck Laser Guide Star Adaptive Optics (LGSAO) astrometric measurements of stars near the Galaxy’s supermassive black hole (SMBH). By carrying out a systematic study of M92, we have produced a more accurate model for the camera’s optical distortion. Updating our measurements with this model, and accounting for differential atmospheric refraction, we obtain estimates of the SMBH properties that are a factor of $\sim 2$ more precise, and most notably, increase the likelihood that the black hole is at rest with respect to the nuclear star cluster. These improvements have also allowed us to extend the radius to which stellar orbital parameter estimates are possible by a factor of 2.

1. Introduction

High angular resolution astrometry has been a very powerful technique for studies of the Galactic center (GC). Over the last decade, it has revealed a supermassive black hole (Eckart & Genzel 1997; Ghez et al. 1998), as well as a disk of young stars surrounding it (Levin & Beloborodov 2003; Genzel et al. 2003; Paumard et al. 2006; Lu et al. 2009). While the speckle imaging work carried out on the GC in the 1990’s had typical centroiding uncertainties of $\sim 1$ mas, recent deep, adaptive optics (AO) images have improved the precision of stellar centroiding by a factor of $\sim 6-7$, significantly increasing the scientific potential of astrometry at the GC (Ghez et al. 2008; Gillessen et al. 2009). Further gains in astrometric precision could lead to ultra-precise measurements of the distance to the Galactic center ($R_o$), measurements of individual stellar orbits at larger galacto-centric radii, and, more ambitiously, to measure post-Newtonian effects in the orbits of short-period stars (e.g., Jaroszyński 1998, 1999; Salim & Gould 1999; Fragile & Mathews 2000; Rubilar & Eckart 2001; Weinberg, Milosavljević & Ghez 2005; Zucker & Alexander 2007; Kraniotis 2007; Nucita et al. 2007; Will 2008).

Two factors that currently limit astrometric measurements of stars at the GC are (1) the level to which AO cameras’ geometric distortions are known and (2) differential atmospheric refraction (DAR), which has not yet been explicitly corrected for in any Galactic center proper motion study (Ghez et al. 2008; Gillessen et al. 2009). While optical distortion from an infrared camera is expected to be static, distortion from the AO system and the atmosphere not

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corrected by AO, is not. Initial estimates of the optical distortions for AO cameras are generally based on either the optical design or laboratory test, which do not perfectly match the actual optical distortion of the system. Both uncorrected camera distortions and DAR leave \( \sim 1-5 \) mas scale distortions over the spatial scales of the stars that are used to define the reference frame for proper motions of stars at the Galactic center. It is therefore critical to correct these effects.

In this contribution, we report our work to identify and correct for two systematic errors, optical distortion and DAR (Section 2). Using our updated astrometry, we obtain estimates of the central potential that are a factor of 2 more precise than earlier work (Section 3), and we extend the radius to which stellar orbital parameter estimates are possible (Section 4). A more detailed account of this work will be reported in Yelda et al. (in preparation).

2. Improving Keck/NIRC2 Distortion Models

Observations of the globular cluster M92 (NGC 6341; \( \alpha = 17 \; 17 \; 07.27, \; \delta = +43 \; 08 \; 11.5 \)) were made from 2007 June to 2009 May using the AO system on the W. M. Keck II 10 m telescope with the facility near-infrared camera NIRC2 (PI: K. Matthews). M92 was observed at 79 different combinations of position angles (PAs) and offsets, producing a final list of 2398 stellar positions. These were compared to measurements obtained with ACS Wide Field Channel (WFC; \( \delta_{\text{pos}} \sim 0.5 \) mas, Anderson 2005) to derive a new NIRC2 distortion model, which produces a factor of 4 times smaller positional residuals than the previously used distortion solution\(^1\).

In addition to the correction for optical distortion, we implement for the first time on Galactic center data a correction for differential atmospheric refraction. DAR causes the separation between a pair of stars viewed through the Earth’s atmosphere to differ depending on the zenith angle at which they are observed. This effect can be as large as \( \sim 5 \) mas across our 10” field of view for the elevations at which the Galactic center is observed at Keck. We therefore correct for this effect based on the prescriptions described in Gubler & Tytler (1998).

3. Improved Galactic Center Astrometry

With these changes, the Galactic center astrometry (absolute and relative) at Keck has significantly improved over previous work (e.g., Ghez et al. 2008; Lu et al. 2009). For the case of absolute astrometry, the position and velocity of Sgr A*-radio in the IR reference frame improved by a factor of \( \sim 2 \) when computed in the same way as in Ghez et al. (2008), who used the overly-conservative approach of a half-sample bootstrap. Using the more appropriate jack-knife analysis, the errors improved by an additional factor of \( \sim 3 \) to \( \sim 0.6 \) mas and \( \sim 0.2 \) mas/yr for the position and velocity errors, respectively. For the case of relative astrometry, our uncertainties in the position, velocity, and acceleration for stars brighter than \( K=15.5 \) are now 0.1 mas (\( \sim 1 \) AU), 0.04 mas/yr (\( \sim 1.5 \) km/s), and

\(^1\)http://www2.keck.hawaii.edu/inst/nirc2/preship\_testing.pdf
0.02 mas/yr² (∼0.8 km/s/yr), respectively. With acceleration errors that are a factor of 3 times better, we are now constraining orbital parameters for stars at distances of R∼2″ (two times further than our earlier work).

Figure 1. Left: Orbit from Ghez et al. (2008) showing their best fit to the astrometric data of S0-2 (solid). Right: Best fit orbit after implementing the new distortion solution and DAR correction (solid). The dotted (blue) and dashed (red) orbits show additional solutions which give the minimum and maximum velocity, respectively, for Sgr A* relative to the cluster for solutions with (χ²-χ²_{min}) < 1. Note that all orbits assume no priors on the black hole’s position or motion.

In recent orbital analyses, the need to introduce a term to account for possible relative motion between the black hole and the reference frame has been emphasized as a way to account for systematic errors that might arise from instabilities in the reference frame (Ghez et al. 2008; Gilessen et al. 2009). Using our improved astrometry from measurements reported in Ghez et al. (2008) as well as new measurements taken in 2008 and 2009, we obtain revised estimates for the orbit of S0-2, which are compared with that obtained in Ghez et al. (2008) in Figure 1. Two additional orbital solutions are plotted over the best fit solutions; these show solutions giving the smallest and largest velocities for Sgr A* for solutions with (χ²-χ²_{min}) < 1. The new orbital analysis allows for a smaller velocity for Sgr A*, increasing the likelihood that the black hole is at rest relative to the nuclear stellar cluster. We also find similar values for the black hole mass and the distance to the GC as in our earlier work, but with smaller errors. Figure 2 shows a comparison of the resulting fit parameters before and after this work. We find for the black hole mass \( M_{BH} = 4.1 \pm 0.3 \, M_{\odot} \) and for the distance to the Galactic center \( R_0 = 8.0 \pm 0.3 \, \text{kpc} \). This exercise was repeated using only the data sets used in Ghez et al. (2008) and we find similar values for the fit parameters, within the uncertainties.
4. Conclusions

We have improved upon existing geometric distortion solutions for the NIRC2 camera at the W. M. Keck II telescope and have, for the first time, implemented DAR corrections to our Galactic center astrometry. With our improved astrometric reference frame we find a nearly closed orbit for the short-period star, S0-2, with little motion allowed for the central black hole. Furthermore, we have detected accelerations in the plane of the sky out to a projected distance of $R \sim 2"$.

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