1 Overview - Project milestones

The ASTRA project aims at upgrading the KI with the technology needed to alleviate the limitations of ground-based interferometry imposed by the turbulent atmosphere. Due to the fact that the project upgrades an existing instrument used for scientific observations by the community both the hardware testing and implementation has to occur with the least possible impact on the operating system. At the same time specifications for instrumental performance and stability are different for individual goals of ASTRA. To cope with this situation we designed a modular approach which develops the ASTRA functionality gradually and offers step-by-step integration into the existing system. Lessons learned from each previous step feed back into the next, and leave some flexibility for the final design and implementation. The latter is necessary to efficiently realize such a complex project in which every part of the infrastructure affects the final instrument performance. In the following the three major project phases are outlined.

1.1 Phase 1: Self-phase-referencing

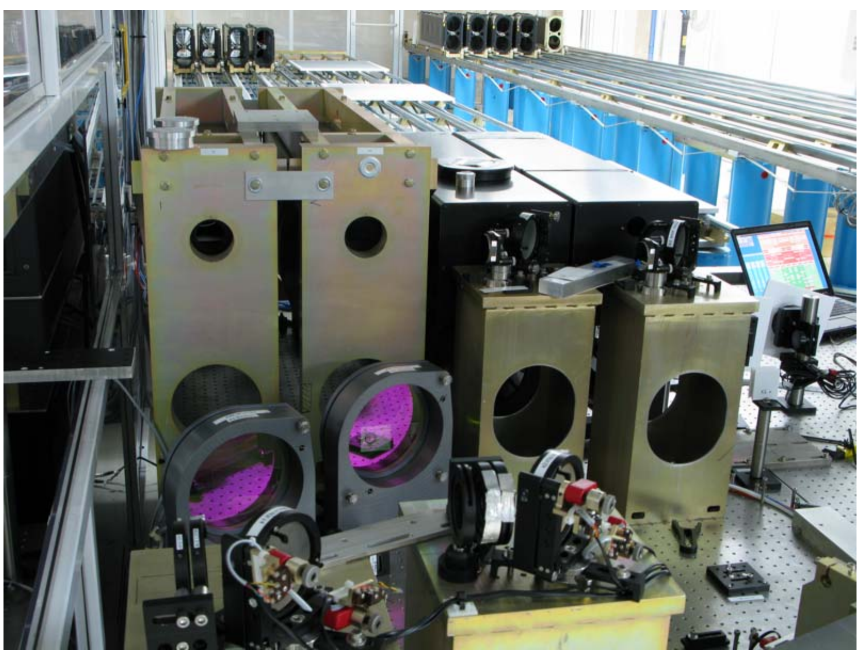

Fig. 1. The fast delay lines are shown in the back of the picture. They add delay to the quasi-static long delay lines (LDL) to complete the correction for the geometric delay. In addition they correct for atmospheric turbulence at high bandwidth (a few hundred Hz) and create the controlled fringe pattern in delay space by introducing a saw-tooth delay. In the foreground the beam splitting optics are visible which are used in the ASTRA-SPR mode to split the light before the beam combination.

A lot of physical insights derive from spectroscopy, emission lines reveal their excitation conditions, absorption lines trace the chemistry of transmitted matter etc. A similar line of reasoning holds for the spectroscopically resolved visibility measurement: spectro-interferometry. The obvious advantage of spectro-interferometry is to be able to compare the size scales of one spectral region with another, e.g. to estimate how far the line-emitting region is from the stellar photosphere. In addition, also the differential phase can be retrieved when the spectral resolution is high enough to reveal non-linear phase changes over the spectrum. Such phase shifts indicate translations of the photo-center over the respective spectral channels on the sky. For example an emission line can show a differential phase signature when emitted from an outflow. Recently Weigelt et al. (2007) studied such differential phase signals of the LBV η Carinae with VLTI/AMBER demonstrating the astrophysical potential of such measurements.

Due to the light dispersion and less flux per spectral channel, spectro-interferometry hits sensitivity limits even sooner than quasi-continuum measurements (see the argumentation in the previous section). In the K-band the KI reaches its sensitivity limit at $K \sim 10$ (7) with a spectral resolution of $R \sim 30$ (230). The ASTRA self-phase-referencing (SPR) mode breaks that limit for high dispersion spectroscopy, currently enabling $R \sim 1800$ at $K \sim 7$. Right before the beam combination the light is split and sent in parallel to two fringe cameras. While the first beam is dispersed only over 5 pixels to enable phase and group delay estimation for a fast fringe stabilization, the second beam passes a grism to achieve the maximum dispersion of $R \sim 1800$ provided by the KI fringe cameras FATCAT (see Vasisht et al., 2003). The first or primary fringe camera, acting as a *fringe tracker*, commands the delay lines to continuously take out the piston and keep the phase rms within about a radian. Now the necessary SNR for a solid fringe detection of about 100 can be achieved at the second fringe camera in each spectral channel simply by increasing the detector integration times (DIT). DITs as long as 1 sec and longer can be achieved in SPR as recently demonstrated in an ASTRA-commissioning run, longer by a factor of 100 or more than the usual limits imposed by the atmospheric piston noise.

1.2 Phase 2: Dual-field operation

The dual-field operation is a natural extension of the SPR mode. Again two fringe cameras run in parallel. The first one tracks the fringes typically at 250 Hz for good piston and vibration correction, enabling much longer DITs at the second camera to increase the SNR. But in contrast to SPR, the dual-field phase-referencing mode (DFPR) focuses on increasing the limiting magnitude of the low-dispersion mode by about 5 magnitudes by pointing the second fringe camera on a faint star within the isopistonic patch around a bright star. The new limiting magnitudes achieved by dual-field operation will open a whole new ensemble of observable targets and science cases. The key difference in the implementation between these first two phases is that for the dual-field operation the light has to be split already in the image plane at the Nasmyth foci of the telescopes.

After this field separation (see Sect. 2.4) the light travels along two separated beam trains down to the beam combining laboratory, thus a doubled delay line infrastructure is needed. The additional delay lines are already in place and in regular use for the operation of the KI-Nuller instrument, a 10 μm nulling interferometer build to detect and study the exo-zodiacal dust around nearby stars (Colavita et al., 2008). The atmospheric piston, as measured on the bright star in the primary field, can be applied to both fields to stabilize the fringe motion. This correction is effective as long as the star separation is smaller than the isopistonic angle (see the theory section). But monitoring helper systems are needed to ensure that the non-common path after the beam separation does not suffer from vibration induced decorrelation and differential tip-tilt. Colavita (2008) discusses adverse effects in dual-feed interferometry.

First on-sky tests with the dual-field operation are planned for the summer of 2009. The advantage of the dual field operation is two-fold. It will enable visibility amplitude measurements on fainter stars reaching limits well beyond $K \sim 10$, a brightness range which yet has not been explored at all, and which will open the door to systematic interferometric studies of faint binary companions, YSO's and AGN. But dual field operation will also allow to use the one (unresolved) star as phase reference against the other. An unresolved star has no intrinsic visibility phase, so the measured phase derives entirely from the atmosphere and the instrument. This knowledge can be used to calibrate and retrieve the intrinsic phase information from the (fainter) companion in the second field. As mentioned before, this will help to disentangle imaging information about the object in the second field, e.g. asymmetric dust around an AGN would produce such an intrinsic phase.

1.3 Phase 3: Interferometric astrometry

Once stable dual field operation is available, an *astrometric* measurement between both targets can be conducted. Such an astrometric measurement is complementary to the dual-field visibility experiment described in the previous section because the interferometric astrometry focuses on measuring the differential fringe location or phase between the two fringe packets, rather than the fringe contrast in the individual packets. For the phase-referenced visibility measurement the absolute fringe location does not matter, as long as the geometrical delay is corrected for well enough to ensure that the fringe pattern stably ends up on the detector. The visibility information is encoded in the *contrast* of the interference signal. But also the differential fringe *location* contains astronomical information, as shown by the following equation

$$OPD_\mathrm{i} = \vec{s_\mathrm{i}} \cdot \vec{B}, \quad \text{and} \quad \Delta OPD = \Delta\vec{s} \cdot \vec{B} \tag{1}$$

where atmospheric and instrumental contributions and intrinsic source phases are neglected. $\vec{B}$ is the three-dimensional baseline vector, connecting the pivot points of the telescopes, also called the wide-angle baseline for it predicts via Eq. 1 the fringe location due to the geometric delay over the entire accessible sky or over wide angles between individually observed stars. $\vec{s_\mathrm{i}}$ denotes the direction toward each of the stars.

The product of both is the geometrical optical path difference OPD_i or the fringe position in the laboratory. It relates to the amount of optical path which the delay lines have to correct for. In reality, the location and vibration of the mirrors and the current index of refraction of the atmosphere additionally affect the exact location of the fringes. But if those effects are stable and comparable for both stars they cancel out in the differential measurement, and only the true geometric difference survives as written down in the second part of Eq. 1. This is the core of an astrometric measurement (see also Sect. 2 in Delplancke, 2008).

The absolute separation between two stars is encoded in the differential fringe location. And the third phase of ASTRA provides the KI with a laser metrology system precise enough to measure ΔOPD at the 20 nm level, which transforms into a precision better than 100 μas for stars separated closely enough that the differential atmospheric phase distortions do (nearly) cancel out, i.e. for two stars from within the isopistonic angle.

2 Details - The ASTRA technology

In this section we want to present in some more detail the individual systems needed to implement the three phases of ASTRA as described above. This article does not aim at describing the complete design and functionality of each system at an engineering-level. But we want to demonstrate the conceptual design of each subsystem to develop a general understanding of the functioning of a modern large aperture dual-field interferometer. Such an understanding is required to appreciate the control and calibration work mostly done by black boxes like software pipelines and control systems, invisible to the general user. But understanding the details of a running system qualitatively also enables the reader to estimate the current technical limits and to foresee which of these limitations might be pushed further in the future by respective developments.

The following sections are arranged with respect to their relation to the three ASTRA phases, which were introduced in Sect. 1. Angle tracking (2.1), vibration control of the optical path (2.2) and LGS operation of the interferometer (2.3) will serve all phases, while the field separation (2.4) is only required for the off-axis phase referencing (1.2) and the astrometry (1.3). The interferometric narrow-angle astrometry further requires special systems to monitor the internal differential optical path in dual-field operation (2.5) and the astrometric baseline (2.6).

2.1 Sensitive angle tracking

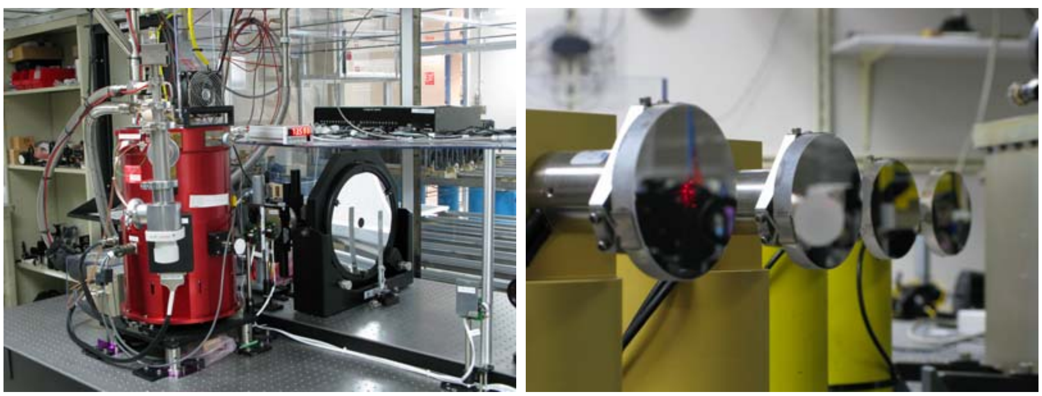

Fig. 2. The Keck Angle-Tracking camera (KAT) in the dewar (left). It commands the fast tip-tilt mirrors which can tilt the collimated beams at a bandwidth of about 100 Hz. This angle-tracking system is essential to continuously achieve high injection ratios in the fringe tracker single mode fiber guaranteeing high fringe SNR.

The flux-efficient operation of an interferometric beam-combiner requires a tip-tilt stabilized wavefront. The operation of the KI has shown that turbulence in the long air-filled beam-trains introduce such a tip-tilt variation which is not corrected for by the AO-system since it is mainly introduced by air motion along the optical path between the Nasmyth deck and the basement, i.e. after the AO-system. An infrared camera called KAT is in place to monitor this residual tip-tilt and feed back to actuated mirrors to correct for it and stabilize the beam combiner input (Fig. 2). This control loop is currently run typically at 80 Hz.

A large part of this tip-tilt originates from vibrations of the optics of the interferometer. Currently KAT is monitoring this internal tip-tilt by using the J- or H-band light of the star which requires stellar magnitudes smaller than ~ 10. Since the dual-field operation foresees observing fainter stars in the phase-referencing mode, an internal light source will be implemented at the telescope to simulate the star light on KAT. This tip-tilt monitor will run at high bandwidths while in addition in a hybrid operation mode the classical on-star tip-tilt correction can work at reduced bandwidth (~ 1 Hz) to increase the detector sensitivity by the required amount to measure fainter stars, and track the residual drifts.

2.2 Internal OPD stabilization

Longitudinal vibrations will add artificial piston to the star light and reduce the fringe contrast. The required vibration control of ASTRA is closely following the concept of the classic KI operation. It is based on a modular design. The primary telescope mirrors are monitored by accelerometers. The additional piston introduced by vibrations along the beam-train are telemetered by a HeNe-laser metrology system. In addition the mount of every single optical element along the optical path is optimized to minimize vibrations. This primary OPD stabilization does not fulfill the task of the *differential* dual-field metrology, which is introduced in Sect. 2.5 and necessary for the high precision astrometry of ASTRA.

2.3 Two laser guide stars for the interferometer

AO-correction of the incoming wavefronts is crucial for the KI to enable high fringe SNR in particular when the correlated flux is low due to a source extension resolved by the interferometer. An adaptive optics system is needed to ensure that as much light as possible is coupled into the fiber by flattening the wavefront and correcting for atmospheric tip-tilt (see also Sect. 2.1). The KI is only operated with closed AO-loops at both telescopes. The Keck AO-system (as most others) is equipped with a visible wave-front sensor whereas the interferometric measurement is done in the near-infrared. Most stellar sources are bright enough to fulfill both sensitivity constraints: in the visible for the AO wavefront sensor, and in the near-infrared (NIR) for the fringe measurement. But the AO-limit of $R \sim 12$ prevents on-axis AO-corrected KI-observation of red objects which would be bright enough in the NIR: dust enshrouded YSO's and evolved stars, sources in the Galactic center due to the high amount of interstellar extinction, and some active galactic nuclei (AGN).

To enable KI-observation of such red targets, and to make the broadest use of the ASTRA upgrade, a second laser guide star system (LGS) system is currently implemented to work in parallel to the original LGS at the other telescope. Once available, interferometric observations with both telescopes' AO-loops locked on an artificial laser beacon are possible. Such LGS-IF operation of the KI is expected to stabilize the performance of the interferometric

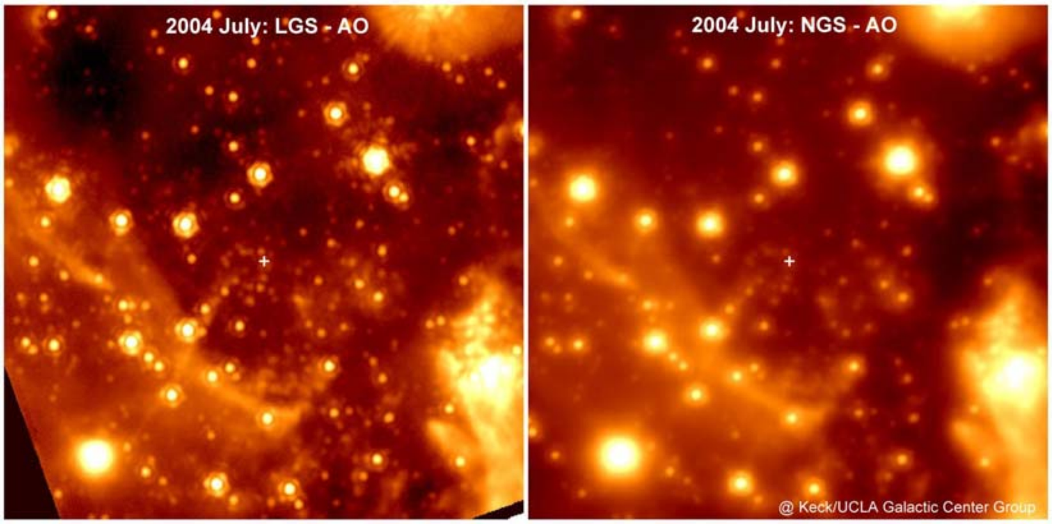

Fig. 3. The UCLA Galactic center group demonstrated the increased efficiency of LGS-AO assisted Keck observations on stars in the Galactic center which appear very red due to the high interstellar extinction. The closest natural guide star (NGS) is a foreground star about 20 arcsec away from the very center. The location of the central massive black hole is marked with a white cross in these L'-band images, which are $7.5''$ across. The Strehl ratio is increased by a factor of 2 by the LGS (see Ghez et al., 2005, for further details on the NGS vs. LGS comparison of Galactic center observations).

measurement of intrinsically faint objects similar to the gains achieved with single telescope LGS-assisted observations (Bouchez et al., 2004, and Fig. 3). First on-sky tests of LGS-IF operation are foreseen for early 2010.

2.4 Field separation

The field separation in the Nasmyth foci of the telescopes is a crucial process at the heart of the ASTRA project (Fig. 4). The ASTRA design concept includes the use of an annular mirror which reflects an *off-axis* field of 60 arcsec diameter, centered on the *on-axis* phase-reference star. The size of the usable off-axis field is given by the isopistonic angle. After field separation the re-collimated light enters the underground beam trains and delay lines. The annular mirror will be actuated to select the right off-axis star for the second beam train. For this blind step to work, good differential coordinates of sub-arcsec precision are required. These are typically provided by an AO-assisted K-band image of a large telescope.

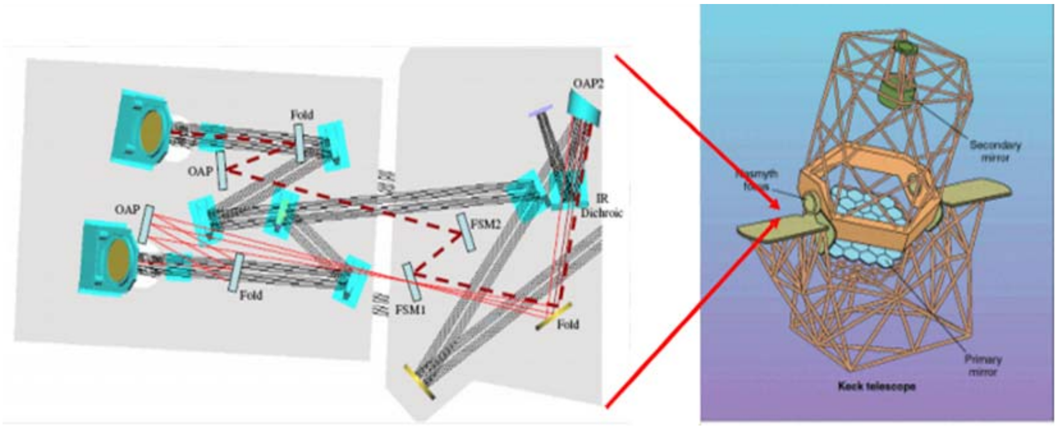

Fig. 4. Conceptual design of the ASTRA dual-field facility. It is locate in the Nasmyth focus of each telescope (right panel). The red lines (solid and dashed) are representing the optical path of the primary and secondary star, respectively. A central uncoated area in the optic called FSM1 transmit the primary star light, and reflects the surrounding light. FSM1&2 are movable to select the location of the secondary star to be relayed to the beam train after collimation in an off-axis parabola (OAP).

2.5 Internal differential dual-field metrology

Following Eq. 1, the astrometry requires to measure precisely the *differential* optical path difference ΔOPD, created by the differential phase of the two stars. One of the technical challenges is that the light of the two objects will travel along different optical paths after the field separation. A static difference in the optical paths could be measured once and calibrated out. But to guarantee that this difference is continuously known down to an accuracy of a few nm, an internal laser metrology system will be implemented. The task is to track the differential internal optical path differences which will vary with time due to changing conditions in the transmitted air and mirror position. To minimize dispersion induced misinterpretation of the metrological signal the wavelength of the metrology laser will be in the infrared, close to the science wavelengths.

2.6 Monitoring the astrometric baseline

Having a goal of sub-100 μas precision for the astrometry not only requires a very precise knowledge of the differential OPD. Also the baseline vector $\vec{B}$ is required to be known at the 100 μm precision level. A careful investigation of the instrumentation concept, namely the internal differential dual-field metrology, reveals a particularity of ASTRA-like interferometric astrometry. The *astrometric* baseline, needed to derive the angle between the two stars

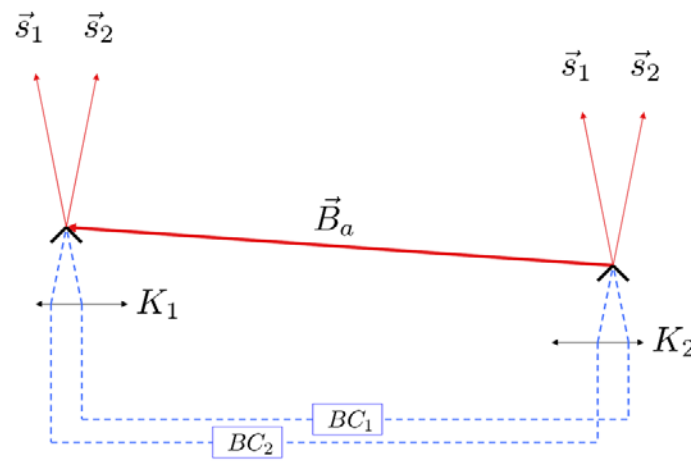

Fig. 5. A sketch showing a typical astrometric baseline. K1 and K2 denote the primary apertures of the Keck telescopes, they shall include the pivot point of the telescopes. The black corners represent the reflection corner cubes of the internal differential metrology system, projected in the primary space of the telescopes. The astrometric baseline $\vec{B}_{\mathrm{a}}$ can always be defined as the connection between these conjugated locations of the corner cubes if the corner cubes cannot be positioned exactly at the pivot points.

from the differential phase (or OPD) measurement (Eq. 1), is not simply the separation vector between the two telescopes. Since the differential phase measurement relies on the internal differential dual-field metrology, the astrometric baseline is given by the difference vector of the end-points of this metrology, calculated in the primary space of the telescope (Fig. 5, [1]). The astrometric baseline is equivalent to the plate scale in imaging astrometry.

For opto-mechanical reasons these endpoints are not exactly coincident with the pivot points of the telescopes, which are usually used to define the interferometric (or so-called wide-angle) baseline vector. The ASTRA internal metrology will end at the telescope focus and not at the pivot points which are close to the tertiary mirrors. In the three-dimensional telescope primary space the astrometric baseline is only identical with the wide-angle baseline if the non-monitored paths between pivot point and the endpoints of the metrology system are identical for both telescopes. Otherwise the non-monitored path difference has to be accounted for (see Fig. 5).

Experimental data show that the 10 m Keck primaries and their mounts are moving on the order of the required precision when slewed significantly. As part of the ASTRA upgrade we plan to monitor this mostly random telescope

[1] The metrology endpoints are physically located in the beam-compressed space after the primary mirrors. This requires to conjugate the endpoints back into the 10 m primary space to understand or predict the ΔOPD in relation to the star separation angle.

runout with an imaging system to understand the effective change of the baseline when slewing between calibrator and science targets. It is further planned to investigate if it will be necessary to monitor the actual distance between the pivot point and the endpoints of the metrology. A change of this distance can originate from telescope flexure over the night.

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