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ABSTRACT

PRIMA (Phase-Referenced Imaging and Microarcsecond Astrometry) is an ESO/VLTI instrument designed for phase-referenced imaging and narrow-angle astrometry, dedicated to exoplanet detection. The astrometric data-reduction software (ADRS) is a key component of the system, calculating very precise (∼10 µas) differential angular separations projected on the sky. For an interferometer with a baseline of 100 m, this separation corresponds to measuring the (differential) optical path difference with a precision of 5 – 15 nanometers. This precision can only be achieved with careful calibration of the instrument, including effects that are irrelevant for almost any other scientific application. PRIMA is currently being commissioned on Paranal, and we expect to obtain the first astrometric data in September 2010. These data will provide a new insight into the operation and calibration of the instrument.

Keywords: exoplanet detection, parallax, proper motion, PRIMA, VLTI, narrow-angle astrometry, optical interferometry, data-reduction software

1. INTRODUCTION

The PRIMA (Phase-Referenced Imaging and Microarcsecond Astrometry) facility at ESO/VLTI is currently being commissioned on Cerro Paranal, Chile.\textsuperscript{1} It will have two operational modes, phase-referenced imaging and dual-star narrow-angle astrometry.\textsuperscript{2,3} The Exoplanet Search with PRIMA consortium (ESPRI), which is constructing the instrument in collaboration with ESO, will use guaranteed time observations (GTO) to perform an astrometric exoplanet survey.

In the astrometric mode (called PACMAN\textsuperscript{4}), PRIMA measures the angular separation between two stars separated by less than ≈ 30 arcsec, the size of the isoplanatic patch at K band. The final results are the fully calibrated differential delays, narrow-angle baselines, and projected angular separations on the sky. These quantities can be used to fit for parallaxes, proper motions, exoplanet orbits, etc. According to the error budget,\textsuperscript{5} the projected angular separations must be accurate at the ≈ 10 – 30 µas level to detect Saturn-sized exoplanets. Calibration of systematic errors in the presence of random errors is key for the success of PRIMA and PACMAN.

PRIMA is used in conjunction with the existing VLTI infrastructure, in particular the auxiliary telescopes (ATs) and main delay lines (MDLs). PRIMA itself consists of the following subsystems: two star separators (STSs, one for each AT), a differential laser metrology system (PRIMET), two fringe sensor units (FSUs),\textsuperscript{6} and four differential delay lines (DDLs).\textsuperscript{2,3} One FSU is used for the bright star (normally the science target), while the other FSU is used for the fainter star (normally the astrometric reference).

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Proc. of SPIE Vol. 7734  77344B-1
PRIMET is comprised of two separate laser interferometers, PRIMETA and PRIMETB, operating at \( \approx 1.3 \mu m \). They correspond to FSU A and FSU B. Each interferometer measures the change in optical path length from telescope to beam combiner for each star light beam. PRIMET = PRIMETA - PRIMETB measures the differential delay between two stars. In single-star mode, PRIMETB records the delay for a single star, which is used to estimate the initial (wide-angle) baseline. It also acts as a constant-term metrology system, monitoring motions within VLTI.

The FSUs monitor stellar fringes in five narrow (\(<0.016\mu m^{-1}\)) filters spanning the Johnson K filter (\(\approx 0.4 - 0.5 \mu m^{-1}\)). Most interferometers track fringes by “dithering” across the central fringe. Each dither cycle is typically divided into four bins (labeled ABCD) that are separated by 90°. Visibilities and phases may be calculated directly from these bins. PRIMA is unique among interferometers because it employs a polarization modulation scheme that yields all ABCD bins simultaneously with no dithering.6–8

The astrometric data-reduction software (ADRS) is responsible for processing the raw data from these various subsystems, ultimately producing science-grade data products. The Landessternwarte (LSW) team is responsible for writing and testing the ADRS. The LSW team is also working with ESO on integrating the ADRS with the rest of the instrument. In addition, the ESPRI consortium will create the initial versions of semi-permanent calibration files.

2. SOFTWARE REQUIREMENTS

The ADRS is a data-reduction pipeline based on ESO’s common pipeline library (CPL). It will run on a workstation on Paranal during observations with PRIMA to reduce the data and allow a quick assessment of the data quality. The ADRS will also be used at the ESO headquarters in Garching, where the data is archived. In Garching, the data will be re-reduced regularly with improved calibration files. Furthermore, the ADRS will be made available publicly, to allow users of PRIMA to reduce their scientific data at their home institutions.

These different operational environments impose different requirements on the software: On Paranal, the pipeline must run fully automatically, without intervention by human operators. The first step in the data reduction must also be fast enough to keep up with the data coming from the instrument. As a rule of thumb, the reduction of a data set should not take longer than the observation time.

The reduction in Garching must also run mostly automatic (except for a few global settings). There is also a time-critical aspect, since we expect to collect hundreds of nights of data. It should be avoided to re-run reduction steps that do not depend on improved calibration files.

On the other hand, users at their home institutions will want to experiment with different parameters, different combinations of science and calibration data, etc.

Meeting these conflicting requirements is accomplished by different user-interfaces provided by ESO. There is a command-line-based tool called esorex. Its primary input is an ASCII file called a set of frames (SOF), which contains the path, name, and data organization (DO) category of each input file. The SOF files may be created manually, but it can easily be generated by automated tools.

Gasgano is a more user-friendly tool to run the data reduction pipeline. Via a graphical user interface (GUI) it automatically associates related files to each other and feeds them to the desired data reduction module (called a “recipe”). For example, a file containing both raw fringe and metrology data can be associated with sky background and star flat files, and then all of them can be sent to the on-line processing recipe that computes averages.

Observations at ESO telescopes are organized in so-called observation blocks (OBs). Each OB consists of a number of templates that comprise atomic steps in the observation. The templates are instrument-dependent, there are templates for target acquisition, calibration, and the recording of scientific data. For each template that records data, there is a corresponding recipe in the data reduction pipeline that reduces this kind of data.
3. RECIPES AND DATA FLOW

There are two types of ADRS recipes, on-line and off-line. Execution of on-line recipes is triggered in real time by the templates on Paranal, or by the users at their home institutions. In service mode, the off-line recipes are run by the day astronomer after a night of observations. In visitor mode, the user reduces the data himself/herself. Depending on the amount of effort, science-grade results are possible on Paranal, if desired. The full names of the recipes start with the first 5 characters of the instrument name (“pacma”) to avoid conflicts with other pipelines. This first part of the name is left out in the following for the sake of brevity.

The on-line recipes are:

**lab dark:** This recipe processes a raw laboratory dark calibration file and creates an averaged file with the average dark for each pixel and DIT.

**lab flat:** This recipe processes a raw laboratory flat calibration file and creates a file of relative pixel gains. It is not needed for the standard ADRS reduction, it is used for health checks only.

**fsu response:** This recipe processes FTS data of a laboratory source and creates a file of complex FSU bandpasses for each pixel. It also computes effective wavenumbers for each pixel and the phase differences between the $ABCD$ channels.

**vlti response:** This recipe processes FTS data of a star with a known spectrum and creates a file of complex VLTI bandpasses.

**star spectrum:** This recipe processes FTS data of a star and creates a stellar SED. Standard SED files are provided with the calibration files and can be used in place of this recipe.

**sky background:** This recipe processes a raw sky background calibration frame and creates a frame of averaged sky backgrounds.

**star flat:** This recipe processes a raw star flat calibration file and creates a file of relative pixel gains. Unlike the lab flat, it is part of the standard ADRS data reduction.

**sciave:** This recipe calculates “one-second” averages from raw laser metrology data (linear fitting) and FSU data (averaging). The main purpose of this recipe is to (literally) reduce the amount of data. The subsystems of PRIMA produce data with typical rates of 1000 to 8000 frames per second, which sciave reduces to about one frame per second. This is probably the most computationally intensive recipe of the entire ADRS. We want to avoid re-running it when improved calibration data are available (e.g. spectral responses or stellar spectra). Therefore, most corrections that require calibration data are applied later in the data flow by the recipes scired1 and scired2. The output of sciave is called Level 1 data.

The association map for the on-line processing may be found in Figure 1.

The off-line recipes are:

**environment:** This recipe processes raw environmental data from the ESO engineering database by low-pass filtering and interpolating them onto the average time grid created by sciave.

**scired1:** This recipe corrects for instrumental effects in the data. This involves calculating the effective wavenumber from the FSU bandpass, VLTI bandpass, and star SED; calculating offset corrections for the differential delays from the cross-visibility phases; calculating “dispersion” corrections using environmental data and a refractive index model; and calculating environmental corrections for both the differential delays and delays.

**baseline:** This recipe calculates the initial (wide-angle) baseline estimate from the corrected delays using the IPHASE library.
Figure 1. The association map for the on-line processing. The boxes in the top row contain the names of the observing templates. The second row of boxes gives the name of the recipe triggered when a template has finished. The data flow within a recipe is from top to bottom along the solid lines. The names in the ellipses at the end of the lines give the resulting data product. The data flow of the processed data progresses from left to right along the dashed lines. If a recipe requires a data product as input, then the intersection between the solid and the dashed line is marked by a thick dot.

Figure 2. The association map for the off-line processing. See Fig. 1 for an explanation of the data flow. Only pacma_environment has an associated template, pacma_scired1, pacma_baseline, and pacma_scired2 work on the output of other recipes (in particular, pacma_fsuresponse, pacma_vltiresponse, pacma_starspectrum, and pacma_sciave).
**scired2**: This recipe removes the arbitrary PRIMET zero point and slow drift of the differential constant term from the differential delays. This is accomplished by combining three level 1 files. In the first and third file, the faint star was observed by FSUA and the bright star by FSUB. In the second file, the FSUs are exchanged, thereby changing the sign of the astrometric path difference, but not the sign of the PRIMET zero point. The recipe also removes unwanted astrometric effects from the differential delays, and calculates the angular separations on the sky.

**scired3**: This recipe utilizes the angular separations computed by scired2 from data collected over a long period of time (at least one year). It solves for position, proper motion, and parallax, all differential between the target and the reference star. These differential quantities are used by scired2 in the calculation of corrections for the unwanted astrometric effects (proper motion, parallax, yearly and daily aberration, relativistic light deflection, and light time delay due to the radial motion of the stars). To compute and remove these astrometric effects, a good knowledge of the absolute positions, and a very good knowledge of the relative positions of the stars is required. Scired2 and scired3 have to be run iteratively, but only a few iterations will be necessary to reach convergence, depending on the precision of the previously known astrometric parameters.

The association map for the off-line processing may be found in Figure 2.

**4. FIRST RESULTS FROM PRIMA COMMISSIONING**

PRIMA is currently being commissioned on Paranal, only a subset of its subsystems could be used so far. In particular, the star separators are not yet fully operational, which means that no dual-mode observations were possible. Since the retro-reflectors for PRIMET are part of the star separators, this also means that no PRIMET data is available for observations on the sky, only in the lab.

Most of the commissioning data usable by the ADRS are calibrations in the lab. Test of the fringe tracking performance were carried out with a generic observing template, not the obs.astrometry template. Therefore, many header keywords important for the astrometric data reduction are not present in the FITS files.

However, the calibrations obtained in the lab were already useful to check whether the assumptions in the ADRS about the performance and behavior of the instrument were correct or not. One result is that the phase differences between the ABCD-channels are not as close to 90° as we had hoped. Figure 3 shows the phase differences computed from data collected during the commissioning in February 2010. Due to the limited amount of data, it is not clear how stable the phase differences are, and how often they have to be calibrated. Furthermore, the data were collected in the lab, the calibration light source and optical elements between the source and the FSU might introduce some phase shifts. We are working on the analysis of data collected on sky to determine the phase differences without the calibration source.

Results from the commissioning data will also be used to define the parameters used for quality control, i.e., what a health check considers “healthy” performance of PRIMA. For example, the pacma.labdark recipe will check whether the dark current is similar to values measured before. It will issue a warning if the dark is too high (which might indicate that stray light is falling onto the detector) or too low (which might indicate a malfunction in the detector or electronics). We are currently working on determining these parameters.

**5. OUTLOOK**

Commissioning of the remaining PRIMA subsystems will continue in Summer 2010. We expect the first dual-star fringe-tracking observations in July or September. Full astrometric commissioning will commence in Winter 2010/11. The data gathered then will be used to test, debug, and optimize the ADRS.
Figure 3. Phase differences between channel A and B (top panel), A and C (middle), and A and D (bottom). The symbols correspond to the five spectral channels. In an ideal instrument, the phase differences would be 90°, 180°, and 270°, resp.
REFERENCES


