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Very Large Telescope

Paranal Science Operations

PIONIER User Manual

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1 Introduction

PIONIER (Precision Integrated Optics Near Infrared ExpeRiment) is a four telescope interferometric combiner at the VLTI operating in the H band. It has a limited spectral capability of one spectral channel (band width $\sim 0.3\mu$m) or six spectral channels (spectral resolution $\sim$40). It measures simultaneously six squared visibilities (V^2) and four closure phase values (CP) in order to characterize the spatial structure of a source at an angular scale as small as one milli-arcsecond (1 mas, 0.001") at the longest baselines available. Its main characteristics are a high efficiency making it suitable for interferometric imaging and a high accuracy of the measured quantities making it suitable for high contrast observations.

PIONIER was originally a VLTI visitor instrument (`http://www.eso.org/sci/facilities/paranal/instruments/vlti-visitor.html`) built by IPAG Grenoble (PI: J.-B. Le Bouquin) which is now offered to the ESO community in an analogous way to standard ESO instruments. This manual is based on the information provided by the original PIONIER user manual (author: J.-B. Le Bouquin) and additional information on the instrument operation by ESO and updated instrument performance.

1.1 Scope of this document

The scope of this document is to introduce the user to the instrument. The instrument modes offered in service mode and visitor mode as well as the capabilities and limitations of the instrument are discussed. Information useful for the user for proposal preparation such as execution time of standard observations are given. This instrument manual should be used in conjunction with the VLTI user manual available from the manual web pages (`http://www.eso.org/sci/facilities/paranal/instruments/pionier/manuals.html`).

1.2 Contact information and useful links

Please address any questions or comments to the ESO User Support Department (email: usd-help@eso.org, web page: `http://www.eso.org/sci/observing/phase2/USD.html`). Questions concerning scheduled visitor mode observations should be addressed to Paranal science operations (email: paranal@eso.org, web page: `http://www.eso.org/sci/facilities/paranal/sciops.html`). For updated information on instrument modes and performance, see the PIONIER instrument web page (`http://www.eso.org/sci/facilities/paranal/instruments/pionier.html`).

2 Context

2.1 Basics of optical interferometry

The contrast and phase of monochromatic fringes obtained on a celestial source with a telescope baseline B (projected on the sky) and light wavelength λ yield the amplitude and phase of a Fourier transform (FT) component of the source angular brightness distribution at the spatial frequency $f = B/\lambda$ in the Fourier plane (or u-v-plane). If the full FT is sufficiently sampled, i.e. the spatial power spectrum of the source's brightness distribution is sampled at many different spatial frequencies, then an inverse FT yields a model independent reconstruction of the source brightness distribution at the wavelength λ and an angular resolution of λ/B_{max}. There are three ways to collect and sample the FT of spatial information in order to assess the geometry of the source: 1) to obtain data on different station quadruplets, 2) to rely on the natural earth rotation to sample different projected baselines, and 3) to record data simultaneously in several spectral channels, i.e., at different wavelengths.

PIONIER is the first VLTI instrument specifically designed for high efficiency observations suitable for interferometric imaging. The limited spectral resolution available (in GRISM mode, 6 spectral channels) allows one to obtain only limited spectral information. It rather ensures that each data point is measured over a narrow spectral band width. This reduces the range of wavelengths (transformed into spatial frequencies) contributing to a single measurement, thereby improving the accuracy of the obtained data. In addition, the different spectral bins sample different spatial frequencies simultaneously, thereby improving the coverage of the u-v-plane with a given set of observations.

2.2 PIONIER overview

2.2.1 Optical bench and feeding optics

PIONIER is a four telescope interferometric combiner operating in the *H* band. It has limited spectral capabilities: one spectral channel ($\lambda/\Delta\lambda \approx 5$) or six spectral channels ($\lambda/\Delta\lambda \approx 30$) across the *H* band. A sketch of the optical bench of PIONIER is shown in Fig. 1. An integrated optics beam combiner (IOBC) is used for the beam combination (see details below). It is fed by single mode, polarization maintaining fibers. The light paths from the four VLTI beams are modulated and injected into the fibers by the four strictly identical arms of the input and optical path delay unit (IOPDU). Each arm of the IOPDU consists of (in that order, following the direction of the incoming light): (1) a dichroic which collects the *H* band, while the *K* band is transmitted to the Infrared Image Sensor (IRIS) which is used for the lab guiding of the telescope beams, (2) a periscope changing the vertical position of the beams, as PIONIER is physically located on top of FINITO, (3) an optical path delay (OPD) scanning unit which consists of a mirror mounted on a piezo translation stage, (4) a tip-tilt mirror which controls the injection into the fiber, (5) a shutter, (6) a lithium-niobate plate of 2 mm thickness used to compensate for the polarization phase shift, and (7) an off-axis parabola focusing the light into the fiber. The interferograms are temporally encoded by modulating the OPDs in the scanning units.

2.2.2 Integrated optics beam combiner

For a detailed description of the IOBC, see Benisty et al. (2009, A&A 498, 601). The four VLTI beams are each separated in three portions for pairwise combination. For each of the six resulting baselines four phase states are created (static ABCD mode, phase shifts of 0 for channel A, $\pi/2$ for channel B, π for channel C, and $3\pi/2$ for channel D). This results in six baselines $\times$ four phase stages = 24 outputs of the IOBC. After the IOBC, a dispersive element (prism) can be inserted into the optical paths of the 24 outputs. The spectrally dispersed or undispersed light from the outputs of the beam combiner are then focussed and imaged by a detector. The scanning speed of the piezos is adjusted to the frequency frame of the detector in order to sample the fringe contrast as a function of OPD by 512 points. The frequency frame of the detector is set by the detector integration time (DIT) which accepts values between 0.5 ms and 3.0 ms, according to the target brightness and atmospheric conditions. A DIT of

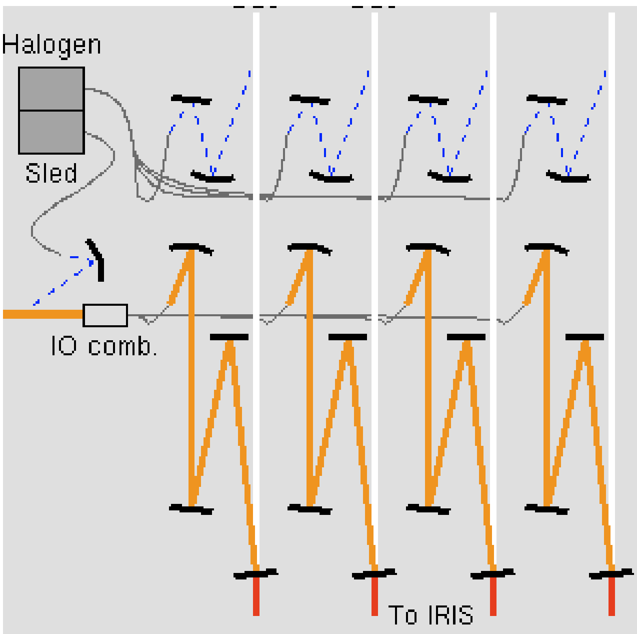

Figure 1: Sketch of the PIONIER optical bench. The four beams from the telescopes enters the optics from the top of the image (white lines). The beam combiner is located at the left. Figure from the original IPAG PIONIER user manual.

0.5 ms yields a full scan time of ∼300 ms.

Different combinations of the four outputs for each baseline allow to extract the fringes (A-C+B-D) and photometry (A+B+C+D). A dark level is measured by integrating with all shutters in, while a kappa matrix (flux splitting ratios of the IOBC) is measured by integrating four times on source with only one of the four shutters open at a time.

2.2.3 Detector

The 24 (dispersed or undispersed) outputs of the IOBC are imaged on a fast infrared detector called RAPID. This innovative camera uses Avalanche Photo Diode amplification up to 20 times and fast intra-pixel electronic. The amplification can be adjusted to provide a gain of 0.1 e/adu (HIGH sensitivity) or 0.4 e/adu (MEDIUM sensitivity). The noise RMS is about 25 adu per pixel (including background photon noise and detector noise) at the typical frame rate of ∼1 kHz. The camera is linear up to flux of 4000 adu. The small dynamic range of the detector (1:100) poses sever difficulties when observing very resolved targets (small visibilities).

2.2.4 PIONIER and the UTs

Due to significant vibration, the use of the 8 m Unit Telescopes (UTs) is currently not expected to result in a significant improvement in sensitivity compared to the 1.8 m Auxiliary Telescopes (ATs). Thus, the use of PIONIER in combination with the UTs is discouraged unless specific necessity is demonstrated in a proposal (such as the lack of sufficiently bright guide stars for the ATs). However, test data will be obtained and these limits will be updated for P97.

2.3 PIONIER observables

In the following, we briefly describe the observables measured with PIONIER. For a more rigorous mathematical treatment, see Lachaume et al. (2003, A&A 400, 795). For a detailed description of methods and effects in optical interferometry, see Monnier (2003, RPPh 66 789).

- **The squared visibility (V^2)** in each baseline and spectral channel: This quantity measures to first order the spatial extent of a target along the direction of the projected baseline. Mathematically, it measures the even terms of the Fourier transform (FT) of the spatial flux distribution. This quantity ranges from zero to one and is large if the source extent is small compared to the resolution λ/B of the measurement and decreases with increasing extent of the object (unity if the object is fully unresolved, zero if the object is fully resolved). Measurements at different spatial frequencies constrain models of the angular brightness distribution of a resolved target. The V^2 are not sensitive to non centro-symmetric brightness distributions.

- **The closure phase (CP)** in each baseline triplet and spectral channel: Deviation from point symmetry in the spatial flux distribution introduces a phase shift in its FT (i.e., odd terms in the FT). This phase shift cannot be measured directly, because it is heavily corrupted by atmospheric phase delays. A way to circumvent this problem is to measure the closure phase (phase of the bispectrum) instead. The bispectrum is the complex product of three visibilities along a closed triangle. The CP is therefore equal to the sum of the three phases along the three baselines:

$$\begin{aligned}
\Phi(1,2) &= \Phi_0(1,2) + [\Phi(1) - \Phi(2)] \\
\Phi(2,3) &= \Phi_0(2,3) + [\Phi(2) - \Phi(3)] \\
\Phi(3,1) &= \Phi_0(3,1) + [\Phi(3) - \Phi(1)] \\
\Phi(1,2,3) &= \Phi(1,2) + \Phi(2,3) + \Phi(3,1) \\
&= \Phi_0(1,2) + \Phi_0(2,3) + \Phi_0(3,1)
\end{aligned}$$

  In these equations, $\Phi(1,2)$, $\Phi(2,3)$, and $\Phi(3,1)$ are the simultaneously measured phases on the pairs of telescopes 1, 2, and 3, $\Phi_0(1,2)$, $\Phi_0(2,3)$, and $\Phi_0(3,1)$ are the contributions intrinsic to the target, and the terms in brackets are the phase shifts introduced by the atmospheres. The CP is, to a great extent, independent from atmospheric perturbations and instrumental phase offsets. It is therefore a robust quantity in terms of calibration stability. The CP is a powerful tool to investigate asymmetry in the source geometry and to detect high contrast companions.

3 Observation

3.1 Data acquisition

A typical PIONIER observation of a calibrator or science target is composed of:

- Recording of five times 100 interferograms (scans)
- One dark exposure

- One recording of a kappa matrix (flux splitting ratios of the IOBC)

The last item is usually only executed once per observing block concatenation – usually on the brightest target – and are skipped in the other observations of the concatenation (see below).

3.2 Calibration plan

Calibration for PIONIER observations – as for any VLTI instrument – is executed by observing calibration stars (CAL) prior and after the observation of the science target (SCI). The time for these observations is charged to the scientific program and needs to be taken into account by the PI for the time estimate. The observations are carried out in concatenations of SCI and corresponding CAL observations. In Service mode, two options are offered, CAL–SCI–CAL and CAL–SCI–CAL–SCI–CAL, where CAL can be observations of different calibrators but only one science target is allowed per concatenation. In visitor mode the calibration sequence is left to the visiting astronomer.

3.3 Time estimate

The time estimated for the execution of the two sequences offered in service mode are the following:
CAL–SCI–CAL: 30 min
CAL–SCI–CAL–SCI–CAL: 45 min.
The average time per observation for the sequence of three observations is slightly longer than for the sequence of five, because overheads for long telescope preset, pupil alignment, instrument setup, and fringe search typically apply only once per sequence. These times assume a DIT of 0.5 ms and efficient execution of the observations. The numbers are used to estimate service mode execution times. In practice, the DIT needs to be adjusted according to target brightness and atmospheric conditions. This is done by the operations staff in service mode, and additional execution time is covered by the observatory, i.e., not charged to the time allocated to the observing program. In visitor mode, where a fixed time slot is allocated to the program, the visitor should plan for additional 10% to 20% of execution time in case of faint targets and/or complex acquisition (e.g., if the target brightness in V and/or H band is different from that of the calibrators by more than 1 mag).

4 Calibrator selection and planning of observations

PIONIER calibrators should have a similar brightness as the science target (roughly ± 1 mag in H band) so that they can be observed with the same setup. In particular for faint science targets it is recommended to select slightly brighter calibrators than the science target in order not to be limited in accuracy by the faintness of the calibrator. In addition, calibrators should be as close as possible to a point source at the baselines used or to a uniform disk with a well known diameter (i.e., no binaries or extended, asymmetric objects). The constraint on binarity is particularly problematic because little information on the multiplicity of suitable calibration stars at relevant separation and contrast is available in the literature. An option is to use late type giant stars, because the probability that these stars have companions bright enough to be detected with PIONIER is low ($\sim$1%). A list of bright, suitable K giants with accurate diameters can be found in Mérand et al. (2005, A&A 433, 1155). Fainter

K giants are usually distant enough to have sufficiently small angular diameters. Useful tools to search for calibrators are `SearchCal` from the JMMC group (http://www.jmmc.fr/searchcal_page.htm) and CalVin provided by ESO in collaboration with the JMMC group (http://www.eso.org/observing/etc/bin/gen/form?INS.NAME=CALVIN+INS.MODE=CFP).

Observations with PIONIER are affected by a differential polarization effect in the VLTI optical path. In PIONIER, the internal polarization phase shift created in the fibers and the IOBC are corrected using niobate plates to cophase the two linear polarizations directions. An (external) change of the alignment of the polarizations due to changing polarization in the optical path will reduce the fringe contrast and thus affect the calibration. The polarization effect in the VLTI is found to depend on the pupil rotation (altitude + azimuth) in the VLTI optical train, in other words on the position on sky. As a consequence, it is critical to select calibrators very close in sky to the science target (ideally within 3°). This will limit this systematic effect to a few percent.

The high efficiency of PIONIER allows to observe a large number of targets within a reasonable amount of time. A handy tool to handle the potentially long lists of science targets and calibrators, to plan the observations, and to keep an overview in particular in visitor mode is `Aspro2` from the JMMC group (http://www.jmmc.fr/aspro_page.htm). [1]

5 Instrument performance

The main characteristics of a fiber based optical interferometer are the limiting magnitudes, accuracy on the measured observables, and lowest fringe contrast detectable. For PIONIER, the limiting magnitude is constrained toward bright targets by the limited dynamic range of the detector and the usually low fringe contrast of bright sources. Toward faint targets, it is limited because PIONIER is tracking the fringes internally on the science data and the scan speed needs to be large enough compared to the coherence time in order to minimize the degrading effects of atmospheric turbulence during a scan. In order to track the fringes, at such short integration times the (correlated) flux must be high enough to reach a good signal-to-noise ratio (SNR) in each single scan.

The accuracy on the measured observables predominantly depends on the scan speed relative to the speed of the atmospheric turbulence (coherence time). In the following, the effects of the relevant atmospheric conditions on the instrument performance are summarized. Observing parameters that can be adjusted to the atmospheric conditions and their effects are described. For a detailed and updated list of limiting magnitudes and instrument setups depending on atmospheric conditions, see the instrument web page (http://www.eso.org/sci/facilities/paranal/instruments/pionier.html). The statistical uncertainty of the PIONIER visibilities in good conditions is of the order of 1%. Using the standard calibration sequence described in Sect. 3.2 and calibrators with similar correlated flux within ~3° from the target, the additional systematic calibration uncertainty is ~3% on the V^2 and ~2° on the CP. The accuracy on the wavelength calibration of the spectral channels is 2%.

The lowest fringe contrast detectable is limited by the dynamic range of the detector. The limits can be found on the instrument web page (http://www.eso.org/sci/facilities/paranal/instruments/pionier.html).

[1]Note that OBs created using Aspro2 still need to be imported to ESO observing tools, see http://www.eso.org/sci/observing/phase2.html

5.1 Relevant atmospheric parameters and effects of observing parameters

The main atmospheric characteristics affecting PIONIER observations are seeing, coherence time, and sky transparency. In the following, the sky transparency is assumed to be CLEAR, while other conditions predominantly affect the flux from the target reaching the telescopes and can be treated like a different target magnitude. The seeing and coherence time are coupled, but the effects of the two parameters can be treated separately.

A degraded seeing reduces the stability of the positioning of the telescope beams on the fibers and thus results in flux loss and instability. The main effect is a reduction of the total flux and thus a decrease of the SNR in the single points of the scans. In good seeing conditions a fainter limiting magnitude can be reached, while bad conditions limit the observations to brighter targets.

The coherence time mostly affects the quality of the scanned fringes, because in the case of short coherence time the position of the fringe will vary significantly during a single scan, which corrupts the signal. As a consequence, a high scan speed needs to be used in case of short coherence time, limiting observations again to brighter targets if the same accuracy is intended.

The main parameter of the PIONIER observing setup is the detector integration time (DIT) of a single exposure (i.e., of a single point in a scan). It ranges from 0.5 ms to 3 ms. A short DIT results in a fast scan (each scan is sampled by a fixed number of 512 points and is 40 um long). The minimum DIT of 0.5 ms can be used at average seeing of 0.8 arcsec for targets with a correlated magnitude down to $H \sim 6$. The DIT will be set by the operator during the observations according to the observing conditions and correlated magnitude of the targets (SCI and CAL) in an observing block concatenation and remains unchanged within a concatenation as otherwise the calibration would be broken.

PIONIER is offered in two spectral setups, FREE (one spectral channel), and GRISM (six spectral channels). The standard mode used is GRISM, while FREE should only be chosen on very faint targets to increase the SNR.

5.2 Highest accuracy observations

The statistical uncertainty of the PIONIER visibilities in good conditions is of the order of 1%. In order to reduce the polarization effect (in the VLTI optical train, external to PIONIER) to this level, one would have to select calibrators at least within 2°. Unfortunately, the density of suitable calibrators in the sky is typically not high enough. Thus, to make full use of PIONIER's accuracy, one has to apply an additional calibration. Therefore, on has to sample well the dependence of the polarization effect in the sky by observing several CAL-SCI-CAL sequences using different calibrators and science targets at a range of sky positions within one night and correcting for the well defined polarization behavior (see Ertel et al. 2014, A&A 570, 128 for details). This is not offered in service mode and is only recommended for expert users.

6 Comments on visitor mode

Only a total of ∼20% of the VLTI time, including PIONIER, is foreseen to be allocated in visitor mode. Thus, PIs requesting visitor mode should very well justify this. One example of a case where visitor mode can be justified is the requirement of special calibrations such as the calibration for the polarization effect if an accuracy better than few percent is needed (Sect. 5.2).