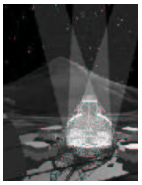
Venice 2001
Beyond Conventional Adaptive Optics



The FINITO fringe sensor for VLTI

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ABSTRACT

The FINITO project is a collaboration between ESO and the Osservatorio Astronomico di Torino for implementation of a two and three beam fringe sensor for VLTI. We present the instrument concept and the development status of the project. FINITO will provide the VLTI instruments the capability for closure phase measurement and significant improvements on accuracy and sensitivity, by the increase of exposure time from few milliseconds to several minutes. The instrument will also provide characterization of the atmospheric turbulence correlation over distances up to 200 m, by combination of the information on the piston disturbance from FINITO and on the local wavefront characteristics from the VLT adaptive optics system. Such data will be useful for a better understanding of the atmospheric behavior over the scale relevant for the future Extremely Large Telescopes.

1. INTRODUCTION

The European Southern Observatory (ESO) and the Osservatorio Astronomico di Torino (OATo) are engaged in the development of a fringe sensor unit (FSU) to be installed at the Very Large Telescope Interferometer (VLTI), Cerro Paranal, Chile (Glindemann et al. 2000). The instrument concept was previously implemented in a laboratory prototype (Prototype Fringe Sensor Unit, PFSU) by the Observatoire de la Côte d'Azur (Nice), hence the current name: Fringe-tracking Instrument of NIce and TOrino (FINITO). The new instrument adopts the present optical prescriptions for the VLTI beams, standard VLT electronics, and an high sensitivity array Detector.

FINITO is an interferometer based on afocal combination of collimated beams from two or three telescopes at a time, operating in H band ($\lambda\lambda = 1.5 - 1.8\,\mu m$), using fiber optics for spatial filtering and optical path modulation, endowed with an optical system allowing coverage of a small field and compensation of the chromatic mismatch with respect to other instruments. The two-three telescopes feeding FINITO are either the 40 cm siderostats, the 1.8 m auxiliary telescopes (AT), or the 8.2 m Unit Telescopes (UT). During the first phases, operations are based primarily on the siderostats and ATs, since UTs will require a complete adaptive optics (AO) system to achieve an acceptable performance in the near IR. The targeted limiting magnitude is of order of $H = 12\,mag$ on UT.

The purpose of a FSU, in the VLTI operating scheme, is the measurement over short periods of the optical path difference (OPD) among telescope beams, in order to identify the piston disturbance induced by atmospheric turbulence. The OPD information is fed to the Delay Line control loop, which acts to compensate them by means of a fast actuator in the delay lines (DL). The scientific instruments (SI) take advantage of the stabilized optical path, increasing the coherent exposure time from fractions of seconds to hundreds of seconds, with a significant sensitivity improvement in the faint limiting magnitudes, or with higher visibility accuracy on bright targets. Thus, the FSU function corresponds, in the interferometric framework, to that of a guiding camera for a conventional telescope, since it is the sensor of the *fringe tracking* loop.

The FINITO capability of operating with small separation on the sky between the primary and secondary source allows sampling of the structure of complex sources, whereas the simultaneous three beam operation (with independent measurement of two pair-wise combinations) provides the possibility of closure phase measurements.

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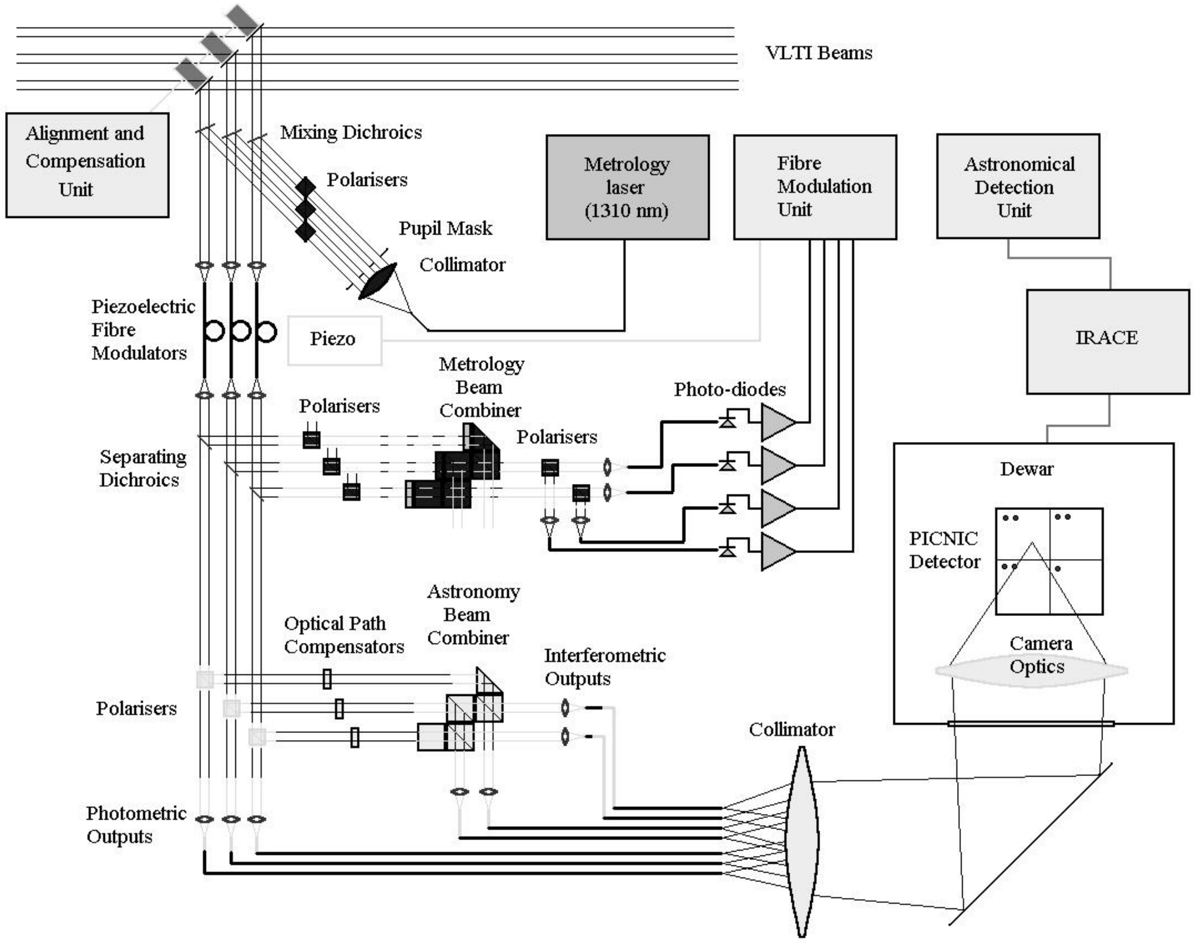

Figure 1. Conceptual schematic of FINITO

2. INSTRUMENT DESCRIPTION

The FINITO conceptual schematic is shown in Figure 1. The telescope beams reach the VLTI combination laboratory through the DL tunnel, and are distributed among the instruments by a switchyard. The Alignment and Compensation Unit (ACU) operates the longitudinal and transversal correction required for compensation of the differential atmospheric refraction. The FSU and SI operate at different wavelengths, over a field at a given zenith distance, so that a mismatch arises not only on the apparent target position, as in conventional telescopes, but also on the OPD of each interferometer. During observations, the angular and longitudinal offsets change progressively. The ACU gives the possibility of setting an arbitrary angular separation between FSU and SI, matched by the appropriate OPD, within the 2" field of the VLTI beams; therefore, complex sources can be scanned by the SI, with the interferometer locked by the FSU pointed on a reference bright spot.

The beams from the ACU are superposed to the laser beam of the internal metrology system, and sent to the Fiber Modulation Unit (FMU). The FMU fibers act as spatial filters, selecting the coherent part of the incoming wavefront; moreover, they are used for controlled variation of the optical path, in order to perform the interferogram scan required for cophasing and coherencing. The fiber modulators are manufactured by the Institut de Recherche en Communications Optiques et Microondes (IRCOM - CNRS, Limoges), based on the PFSU concept. Since the fibers are mono-mode, the output beam is quasi-Gaussian, providing at the output a nearly ideal flat wavefront. Residual error from adaptive optics is translated into beam intensity fluctuations by spatial filtering, as the current Strehl ratio defines the instantaneous beam power.

The fibers are wound around piezoelectric cylinders, and stretched under electric command; the OPD is modulated over an interval of a few fringe periods, in order to identify external path variations due to atmospheric turbulence and other instrumental noise sources. After the FMU, the metrology and astronomical beams are combined separately, using in both cases an assembly based on semi-reflective beam splitters. The metrology outputs are used to close the internal metrology loop, in order to preserve the nominal modulation law, whereas the residual phase fluctuations observed on the astronomical interferometric outputs are considered as atmospheric turbulence, to be controlled by the DL loop. The astronomical beams are sent to an asymmetric beam combiner, based on beam splitting cubes, in which the reference beam is split in two equal amplitude parts for independent pair-wise combination with the each other beam. One of the polarization components of the astronomical beams is extracted before combination, since the two polarization have different optical path in the birefringent material of the FMU fibers and are mutually incoherent; the three rejected beams are used as photometric outputs, for normalization of the four interferometric outputs from the beam combiner.

The seven light spots are injected in mono-mode optical fibers and sent to an integrating array detector, served by the upgraded version of the ESO IRACE electronics, by means of a refractive transfer optics. The interferometric outputs are normalized with respect to the photometric outputs, and filtered accordingly to the modulation law in order to deduce the phase, visibility and coherence signals to be sent to the OPD control loop for DL adjustment.

The control system of FINITO requires dedicated electronic boxes and three logical control units (LCU), with the proximity electronics (units close to the optical bench, e.g. the amplifiers to the piezoelectric actuators and from the metrology sensors) in a cooled electronics rack, and the main digital system placed in a room next to the combination lab. The LCUs take care, respectively, of the ACU, the FMU and the demodulation of the detector data. They are connected to the standard ESO communication network; in addition, the detector and demodulation LCU is connected to the VLT Fast Link in order to provide timely data to the OPD control loop. The processes running on the three LCUs are pre-programmed and synchronized on a common time base, deduced from the standard VLT Time Bus. Operations are selected by users through appropriate control panels on the workstation side of the standard ESO environment.

2.1. Optical path modulation

The ideal OPD scan law is a triangular wave, as shown in Figure 2. The left part shows the nominal OPD evolution during the scan, with time in milliseconds referred to the center of the rising ramp; the right part shows the corresponding variation of the differential interferometric output, normalized to its maximum value. The central operating wavelength is $\lambda_0 = 1.65\ \mu m$, with an ideal (rectangular, symmetric) passband, $\Delta\lambda = 0.3\ \mu m$; the polychromatic spectrum induces the progressive reduction of visibility at increasing distance from the central (“white") fringe.

The FSU function is to detect the current phase relation between the beams feeding the interferometer, which is due to perturbations of the optical path induced either by the atmosphere or by instrumental factors: in a small perturbation case, and without internal modulation, the output level is affected by small variations with respect to a constant value. In such a case, the modulation can be avoided, deducing directly the OPD error from the output variation in a fixed point of the fringe pattern; for convenience, it is possible to use either the two complementary outputs of a beam combiner (AC scheme), placed in opposition on the ideal interferograms, or four points in quadrature (ABCD scheme). The placement

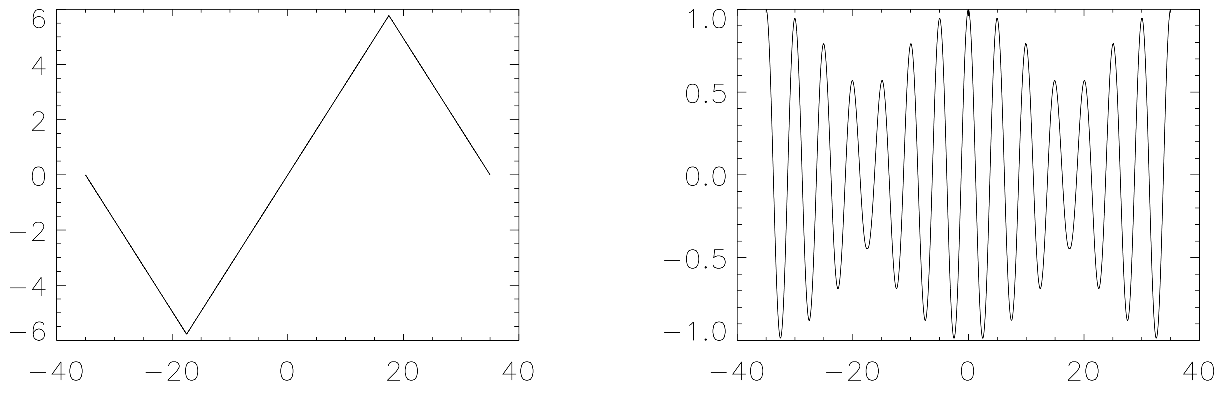

Figure 2. Example of the temporal OPD scan scheme, 200 Hz fringe rate, OPD range $= \pm 3.5$ fringes. Left: triangular modulation of the optical path (in μm) vs. time (ms); right: the corresponding interferometer output, in arbitrary units, vs. time (ms).

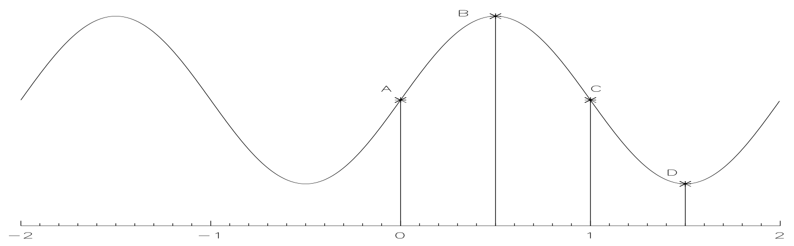

Figure 3. Conventional sampling points for cophasing on a monochromatic interferograms. The points A, B, C and D are in quadrature; A and C are in phase opposition.

of the A, B, C and D points is shown schematically in Figure 3. This operating mode is usually referred to as *cophasing*. The AC or ABCD algorithms have a dynamic range of ± 0.5 and ± 1 fringe periods, respectively.

Unfortunately, the interferometric experience currently shows that in general the small perturbation hypothesis does not hold; occasional large OPD variations occur, either because of atmospheric turbulence or due to instrumental limitations. In such cases, the simple AC and ABCD algorithms fail, due to their limited dynamic range, and the fringe tracking loop suffers a *fringe jump*, locking the interferometer on the nominal points closer to the current interferograms position, as in Figure 4. The SI measurement is degraded, because of the uncontrolled OPD variation and resulting interferograms blurring. To counteract fringe jumps, alternative approaches must be considered; this operating mode is called *coherencing*, and it is usually based on a multi-wavelength analysis (also defined *group delay tracking*, see e.g. Lawson et. al., 2000), in some cases based on dispersed fringes or simultaneous use of interferograms in different bandwidths. The algebra of beam combination, with an analysis of the cophasing schemes, has been described in Cassaing et al., 2000, and references therein.

For FINITO, the spectral content of the interferometric beams is used by scanning a portion of the polychromatic interferograms, accordingly to the scheme described above and shown in Figure 2. After a fringe jump, the section of interferograms scanned is no longer symmetric, and it can be easily identified by direct comparison with the nominal case (Figure 4). The cophasing and coherencing algorithms are operated in parallel, but the response time is slower for the latter, since the data of a significant OPD scan fraction must be evaluated. The former algorithms, analyzing a shorter data segment, corresponding to a significant fraction of one fringe, has larger bandwidth. The DL adjustment is performed on the phase, coherence and visibility data provided by both algorithms.

In the PFSU, the OPD scan is performed by a triangular modulation with amplitude 10 fringes and frequency 10 Hz; the corresponding fringe rate is 200 Hz. For FINITO, the fringe rate can be selected between 200 Hz and 500 Hz; the total OPD variation is smaller than in the PFSU, since full H band is used: the coherence length is $L_C = \lambda^2/\Delta\lambda = 9.1\ \mu m$, corresponding to 5.5 fringe periods at the central wavelength λ_0. The central lobe of the monochromatic interferogram, between the first two nodes, where the modulation vanishes, is $2L_C = 18.2\ \mu m$. The OPD scan range must be smaller, to retain a significant fringe amplitude, but sufficiently large to preserve the fringe jump signature; moreover, it is convenient

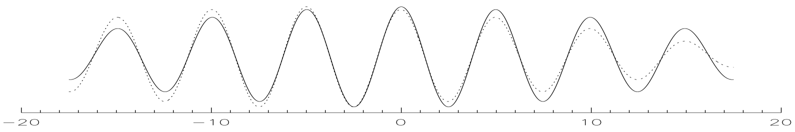

Figure 4. Effect of a fringe jump in the FINITO signal, plotted vs. time, in ms, centered on the nominal zero OPD point. The solid line is the normal OPD scan result, the dotted line is affected by a single fringe displacement to the left. The signal discrepancy increases with the distance to the actual zero OPD point.

to use a multiple integer of the fringe period, to achieve a smooth interferometric signal. In Figure 2, a modulation range of ±3.5 fringes, at 200 Hz rate, is considered, with a resulting triangle frequency of about 14 Hz. Using a 5 fringe amplitude, at a rate of 500 Hz, the triangle frequency reaches 50 Hz. If the full OPD ramp is used for the coherencing algorithm, the detection bandwidth ranges from zero to the triangle frequency. The fringe sampling frequency is up to 4 kHz, so that the piston detection bandwidth is limited to 2 kHz, consistent with the limiting operation frequency of the DL actuator; the piston estimate is then filtered in order to improve the performance.

The performance of both cophasing and coherencing algorithms depends upon the signal to noise ratio (SNR) of the star used as a reference, i.e. on the observing conditions, instrumental factors and on the reference source brightness and structure. At increasing magnitude, the residual error increases until exceeding the dynamic range of the cophasing algorithm. FINITO retains both methods, since for bright targets the fringe tracking loop benefits of faster sampling and better OPD correction; the performance degrades gracefully, for fainter stars, as the control is taken by the coherencing algorithm.

The time scale required for fringe tracking is comparable with that of adaptive optics, since both techniques arise from the need to correct the atmospheric turbulence. In particular, the VLT adaptive optics specification of 40 Hz bandwidth is directly transferred to the VLTI instruments, above all to the fringe tracking loop.

3. MEASUREMENTS

The VLTI array at Paranal can use either the 8.2 m UT (VLT Interferometer Main Array, VIMA) or the 1.8 m AT (VLT Interferometer Sub-Array, VISA). Although operations are quite similar, the interferometer geometry is quite different. A schematic of the telescope positions and of the achievable *u*-*v* plane coverage is shown in Figure 5. The *u*-*v* plane coverage by VISA has higher density because of the large number of baselines, distributed over large intervals of range and orientation. Conversely, the VIMA sensitivity is higher because of the large apertures.

One of the main factor limiting the design and operation of long-baseline optical and infrared interferometers has been identified in the OPD fluctuations due to the atmospheric turbulence. From a theoretical standpoint, the spatial and temporal perturbations are reasonably well understood, and adequate equations are available. Besides, it is not yet definitely clear to which spatial extent the theoretical functions can be retained as a good approximation, i.e. the outer scale length of the atmosphere, and its dependence from the environmental conditions.

The key question is how the OPD fluctuations, introduced between the wavefront parts reaching the separate interferometer aperture, increase with the baseline. The most relevant quantity for interferometry, the RMS OPD value, is expected to vary as 5/6 power of the length of the baseline, with the assumption of an ideal turbulence obeying Kolmogorov statistic, valid in the inertial sub-range confined between the outer scale length L_0 and the inner scale l_0.

An infinite outer scale length, as assumed in the original Kolmogorov approach, results in an indefinitely increasing RMS OPD with the baseline, jeopardizing the high angular resolution potential of VLTI because of the dramatic visibility

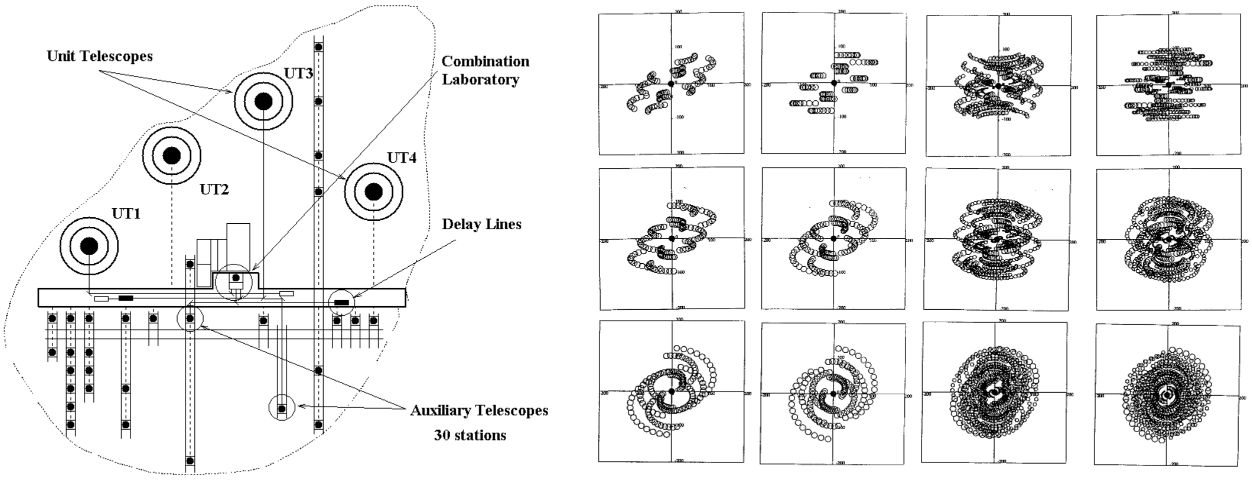

Figure 5. Left: schematic of the telescope placement at Paranal. Center: VIMA *u*-*v* plane coverage in several conditions. Right: VISA *u*-*v* plane coverage in several conditions.

reduction. Also, the dynamic range requirements of a fringe tracking system become much more stringent, and the high frequency components induce frequent fringe jumps, reducing the SI integration time. The potential performance of long baseline and large apertures interferometer is then critically conditioned by the actual behavior of the atmosphere.

An unambiguous value of L_0 is not yet available, but several works in the literature (Davis et al. 1995 and references therein) provide strong support to the range of few tens of meters. There is also observational evidence of departure of the OPD fluctuations from the 5/6 power law when the baseline size approaches the outer scale length. Piston measurements, performed with current interferometers (specifically, with SUSI: see Davis et al. 1995), show that the RMS OPD tends to saturate to few tens of micrometers when the baseline length approaches or exceeds the outer scale length.

Besides, accurate knowledge of the local properties of the atmosphere has an impact on the operations of the new generation of large aperture interferometers, in which the field of view potentially available depend on the correlation between the sub-apertures containing the scientific star and the reference target when the interferometer operates in dual feed mode (or with a large field of view, in general). Femenia et al. 2000, introducing the concept of isopistonic angle, demonstrate the strict relation between sky coverage and the outer scale length.

4. CONCLUSIONS

Direct measurements with several long baselines are definitely a suitable testbench for a good understanding of the atmospheric aspects directly affecting the piston properties. The fringe tracking system of VLTI offers a dense bi-dimensional coverage of the whole range of scales up to 200 m, and in particular FINITO has the capability for simultaneous measurement over two baselines at a time. The full-time VISA operation, using FINITO or the future fringe sensors, will therefore provide a large set of experimental data to be compared with the atmospheric models for the Paranal site.

ACKNOWLEDGMENTS

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REFERENCES

Cassaing, F., Fleury, B., Coudrain, C., Madec, P.-Y., Di Folco, E., Glindemann, A., Lévêque, S.A., “An optimized fringe tracker for the VLTI/PRIMA instrument", *SPIE Proc.* **4006**, pp. 152–163, 2000.

Davis, J., Lawson, P.R., Booth, A.J., Tango, W.J., Thorvaldson, E.D., “Atmospheric path variations for baselines up to 80 m measured with the Sidney University Stellar Interferometer", *Mon. Not. R. Astron. Soc.* **273**, pp. L53–L58, 1995.

Femenia, B., Carbillet, M., Esposito, S., Riccardi, A., “Considerations about the differential piston for adaptive optics interferometry", *SPIE Proc.* **4006**, pp. 1116–1127, 2000.

Glindemann, A., Abuter, R., Carbognani, F., Delplancke, F., Derie, F., Gennai, A., Gitton, P.B., Kervella, P., Koehler, B., Lévêque, S.A., Menardi, S., Michel, A., Paresce, F., Duc, T.P., Richichi, A., Schöller, M., Tarenghi, M., Wallander, A., Wilhelm, R., “The VLT Interferometer: a unique instrument for high-resolution astronomy", *SPIE Proc.* **4006**, pp. 2–12, 2000.

Lawson, P.R., Colavita, M.M., Dumont, P.J., Lane, B.F., “Least-squares estimation and group delay in astrometric interferometers", *SPIE Proc.* **4006**, pp. 397–406, 2000.