Although the terminology of optical path differences in the VLTI nomenclature is concealed by an almost arbitrary reference to some beam enumeration in the VLTI laboratory, the FITS tables produced by the VLTI/MIDI interferometer contain all the information to interpret the motions of the internal and main delay line mirrors unambiguously. The text is arranged in a “Q&A” fashion.

Updates of this text are placed on http://www.strw.leidenuniv.nl/~mathar/public/matharMIDI20051110.pdf.

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*URL: http://www.strw.leidenuniv.nl/~mathar
I. OPD INFORMATION ENCODED IN MIDI FITS FILES

A. Which of the two piezos (internal delay lines) moved?

1. The motions of the two piezo-driven internal delay lines are recorded in the LOCALOPD column of the IMAGING_DATA table. Simple inspection on a case by case reveals whether the numbers in LOCALOPD[1] associated with beam A, or the numbers in LOCALOPD[2] associated with beam B changed with time. See again [18, 1.5.6] to disentangle the definition of beam A and beam B. Throughout this text here, I use the definition introduced by the consortium [12, 30, 32], where beam A is the western of the two beams that enter the optical table, the one that passes by the DLMT — which is the opposite of the nomenclature introduced later by ESO. The figure caption of [12, Fig. 1] is correct, but the description of the beam combiner reflection/transmission on page 2 of [12] should have the nomenclature swapped.

The 1-based indexing follows FITS rules; showing the data with a variety of programming languages may display them 0-based. One can actually create schedules which move both piezos at the same time as described in [18, 3.4], but the simplified interface offered through the templates to the standard observer ensures that only one of the two piezos is moving during the exposure.

If fv is installed, one can have an immediate look at this information with

```
fv your_file_name.fits
```

click on the button under the column All which selects the extension IMAGING_DATA. This opens a window with a table with columns FRAME, TIME, EXPTIME and so on up to INS_TRAIN. Now there are two ways to move on

- Click on the Tools button in the header of this new window and select Plot..., which opens another window. (This could also be reached by clicking Plot in the earlier window.) Enter either FRAME or TIME in the field Column name to the right of the X. Enter LOCALOPD[1] in the field Column name to the right of the Y. Click on Go, which shows the zig-zag pattern of the motions of piezo A. For comparison, close this POW window with File and-close POW, and use again Tools and Plot..., this time with LOCALOPD[2] in the Y field. This will open a window with a graph that effectively appears blank because these values are zero and fall right on top of the axis of the plot. To get an impression of the combined OPD of the MDL and internal delay line, you may enter OPD[2]+LOCALOPD[2]-OPD[1]-LOCALOPD[1] into the Y field, which displays the arithmetic sum-difference between the corresponding columns.

- Left-right scroll the table with the columns until one can click on the Modify underneath the LOCALOPD column. Select Expand which opens a new window with two columns. (With older fv versions, this is not needed and the two columns are already displayed both side by side.) If the left column shows negative numbers in the range of $-1 \times 10^{-5}$ (to be interpreted as meters) and the right column shows zeros, piezo A is moving; if the left column shows zeros and the right one negative numbers, piezo A was standing and piezo B was moving.

2. In addition, the same information is in the SCAN_SET UP1 binary table in each first of the split FITS files of an exposure (see App. B): only one of the LOC_OPL columns changes as a function of time, ie, along the table rows. A command like

```
```

would reveal this information if the eclipse software has been installed on your computer. A faster way is running my Fits2Ascii available from

http://www.strw.leidenuniv.nl/~mathar/progs/Ascii2Fits.C, or interactive inspection with fv.
3. There is a statistical bias toward moving beam A to scan fringes. This is a mere result of having defaults in some templates which the ordinary P2PP user would hardly bother to change or would not even being offered to change; it does not guarantee that this will always be the case. In particular, to enhance the internal delay from the 150 $\mu$m of a single piezo to the combined total stroke of 300 $\mu$m if both are moved at the same time, the interface to the schedule builder within the OS [18] allows synchronized motions of both. The combination

<table>
<thead>
<tr>
<th>“short FITS” SETUP keyword</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>INS PIEZ1 BASE1</td>
<td>0.</td>
</tr>
<tr>
<td>INS PIEZ1 STROKE1</td>
<td>$-150.e-6$</td>
</tr>
<tr>
<td>INS PIEZ2 BASE1</td>
<td>$-150.e-6$</td>
</tr>
<tr>
<td>INS PIEZ2 STROKE1</td>
<td>$+150.e-6$</td>
</tr>
<tr>
<td>INS PIEZ POSNUM1</td>
<td>5</td>
</tr>
</tbody>
</table>

for example would start at positions with piezo(Beam A) adding maximum delay to Beam A and piezo(Beam B) adding minimum delay to Beam B, and both ending up after each scan (in 5 steps of $\pm 30$ $\mu$m change in OPL per step per beam, combined 60 $\mu$m change in OPD per step) at the opposite extreme position. Of course one could start at an internal OPD which is different by 300 $\mu$m and flip the sign of the time-derivative of the OPD along the scan altogether by swapping the values between PIEZ1 and PIEZ2. The interface does not allow asynchronous motion, which means there is only one POSNUM value—without index at the PIEZ part of the keyword—that is used to create the motion schedules. (Detailed descriptions are in the CMM module dicMIDI which is accessible on the IWS and—not necessarily up-to-date—in http://archive.eso.org/DICB in the dictionary database link as ESO-VLT-DIC.MIDI.ICS.)

The pieces of information obtained from the first two items listed above ought be consistent.

B. What is the MIDI OPD sign convention?

1. The FITS files of the instrument do not obey an OPD sign convention, because only optical path lengths (between the instrument and the star) are provided, but no differences between these. The OPLs are encoded with the correct sign convention and an arbitrary offset (which means the common distance from a tangential plane that contains the projected baseline near the Earth to the star is discarded): Moving reflecting optical surfaces (the MDL mirrors, or the internal delay line mirrors) towards the star produces smaller numbers in the associated FITS binary table—consistent with [1, 3.5.3] which says that these columns ought contain the delays applied. (Here, smaller means arithmetically smaller, not smaller in absolute value.) Details are found in [18, 1.5.6], available in http://www.strw.leidenuniv.nl/~mathar/public/VLT-TRE-MID-15824-0264.pdf.

2. If, however, an application wants to apply the sign convention used in the ISS [31, 3.2.6.4], [18, 1.5.6] should be consulted to calculate a number which is consistent. According to this particular definition based on which beam is closer to some wall on Paranal, the contribution of the piezo motion plus the tracking commands sent to the MDL is

$$D = \text{OPD}[2] + \text{LOCALOPD}[2] - (\text{OPD}[1] + \text{LOCALOPD}[1] + \text{DLMT}),$$

(1)

where the (signed) value of the DLMT is found in the INS DLMT POS keyword in the primary header. This must be superimposed with the contribution by the blind tracking of the MDL to get a full picture of the total OPD (see Sec. 1G). The value in Eq. (1) is positive if the combined action of the internal and main delay line made the OPL from the star shining through beam B to the detector longer (synonymous to: from the star shining through beam A shorter) than following from the ISS blind tracking model geometry alone.

The reason of this fixed association of FITS indices with this particular OPD sign convention is the simplicity of the feeding optics, see Sect. 1D.

3. Astronomers should be aware that the OPDs applied carry some “intrinsic” sign which is opposite to the external OPDs of astronomical relevance, simply because the principal mode of operating delay lines keeps the total OPD close to the white light fringe such that the “total” OPD seen by the detector is close to zero: the OPD applied by one arm of the interferometer needs to be smaller if the OPL to the star is larger. In total, there are four different ways of defining this OPD (internal versus external plus an arbitrary choice of the “first” telescope) which results in two different sign conventions. Phase sign conventions add another ambiguity well known from Fourier transforms, which does not matter here.
C. Which of the two telescopes was closer to the star?

Some approaches to the answer are:

1. If one draws a line on the ground perpendicular to the baseline which cuts the baseline vector in half (an azimuth), this defines two opposite star directions along the line for which the answer is undecided, and defines two hemispheres of directions (of star azimuths) closer to the one or to the other telescope. Consider the position angles $\tau$ for the baseline directions as listed in [http://www.eso.org/observing/etc/doc/vlti/baseline/baselinedata.txt](http://www.eso.org/observing/etc/doc/vlti/baseline/baselinedata.txt), where $\tau$ is counted North through East seen from the first one. (All the links at the bottom of this ESO web page are broken (App. G1). One must add a subdirectory level `baseline` into these URLs to get links to information.) A bird’s view for the case of a star declination that places it South is Fig. 1.

![Fig. 1](image)

FIG. 1: In a topocentric coordinate system, the baseline direction is characterized by azimuth angles $\tau$ and $A_b \equiv \tau + 180^\circ$. In the case shown, $0 < A < \tau < 90^\circ$.

Further consider the azimuths $A$ as taken from the ESO ISS AZ keyword in the primary header with the convention $A = 0$ for pointing to the south and $A = +90^\circ$ for pointing to the West (see [http://archive.eso.org/Tools/DidRep/DidRepWebQuery?did=ESO-VLT-DIC.ISS](http://archive.eso.org/Tools/DidRep/DidRepWebQuery?did=ESO-VLT-DIC.ISS) and [39, §5.1.3]. This is the standard definition on the northern hemisphere, but not the one used in [40, 3.2.1] and [11]). $T_1$ sees $T_2$ under the azimuth angle $180^\circ + \tau$. A simple way to extract this number $A$ is

```
dfits MIDI*.fits | egrep '(AZ|ARCFILE)'`
```

with the `eclipse` software, or

```
fitshead MIDI*.fits | egrep '(AZ|ARCFILE)'`
```

where available. A combined conclusion is: the star is closer to the first (left) telescope in the table if

$$|180^\circ + \tau - A| > 90^\circ,$$

(2)

else closer to the second telescope. The formula is valid for the normalizations $0 \leq A \leq 360^\circ$ and $-180^\circ \leq \tau \leq 180^\circ$. With a definition

$$A_b \equiv 180^\circ + \tau$$

(3)

for the baseline azimuth, it could also be written

$$|A_b - A| > 90^\circ, \quad 0 \leq A, A_b \leq 360^\circ.$$  

(4)

2. The small numbers spread in the four `issgui` PostScript files of [http://www.strw.leidenuniv.nl/~mathar/vlti/](http://www.strw.leidenuniv.nl/~mathar/vlti/) show the signed external delay in meters as a function of azimuth and elevation for all station pairs where the finite range of the delay lines may render some portion of the sky not reachable (in the sense of placing the ZOPD near a common point in the interferometric lab).
3. The Java applet shown on page 17 in [http://www.strw.leidenuniv.nl/~mathar/vlti/prErrWeb.html](http://www.strw.leidenuniv.nl/~mathar/vlti/prErrWeb.html) has a well defined (but again arbitrary) sign convention as documented. It can be fed with the FITS keywords RA, DEC and LST of an existing primary header plus a pair of Paranal stations and emits a signed number. (Well, it does this in parallel for two stars and emits two numbers.) This number is larger than zero if the external path length from the star to what is called T1 in the applet is larger than the (external) path length to T2.

4. The interactive GUI by the Astrometric Preparation Software [http://obswww.unige.ch/~segransa/apes/](http://obswww.unige.ch/~segransa/apes/) can probably be used as well.

5. One can compute the product of equations (13) and (14) as formulated in (15). The variable $D$ used there is larger than zero and the angle $\theta$ smaller than 90° if the star is closer to T2.

The results of any of these approaches ought be consistent. All but one are redundant.

**D. Which of the two telescopes collected beam A, which beam B?**

By following the right angle turns of the 18 mm beams back we find:

1. Moving from the ARAL feeding optics [40, 4.5.4] [31, Fig 3.8.2-1] to the MIDI warm bench, beam A was the Western one.

2. Before hitting the ARAL feeding optics, beam A was the Northern one, beam B the Southern one.

Translation into the language of the “lab input beams” of [39, 3.2], the input beam number of beam A is larger than the input beam number of beam B, both ranging between 1 and 8 (once all DLs have been installed). By reverse lookup of the numbers of the two primary header keywords ESO ISS CONF INPUT1 and ESO ISS CONF INPUT2, one can get the information which of the two input beam numbers was coupled to the “first” and which to the “second” telescope. Then forward lookup with the keywords ESO ISS CONF STATION1 and ESO ISS CONF STATION2 gives the (station) names in the familiar nomenclature [40, Table 3-2]. Example:

```
HIERARCH ESO ISS CONF INPUT1 = 1 / Input channel in lab
HIERARCH ESO ISS CONF INPUT2 = 3 / Input channel in lab
HIERARCH ESO ISS CONF STATION1= 'U3 ' / Station of telescope 1
HIERARCH ESO ISS CONF STATION2= 'U1 ' / Station of telescope 2
```

Here $3 > 1$, therefore INPUT2 belongs to beam A. Therefore we have to follow the entry for STATION2 which tells us that U1 fed beam A.

**E. Was the OPL of beam A longer than the OPL of beam B?**

To the precision available from variables in the primary header, this question cannot be answered, since (see above) the external additional OPL to the telescope further away from the star is almost equally added to the other beam by the MDL while tracking the fringe. “Almost equally” means that dispersion effects in the air-filled delay lines, lensing by the Earth’s atmosphere etc [38] cause this to be true only for one “effective” point in the star spectrum.

If the question was in the sense of “Did beam A or beam B come from the telescope further away from the star?” the answer given by first answering the question in Section ID and moving with this answer on to Section IC.

**F. Did the MDL passed by beam A or the one passed by beam B move?**

As discussed in Section IA, LOCALOPD[1] or LOCALOPD[2] in equation (1) may change with time, LOCALOPD[1] always associated with beam A and LOCALOPD[2] always with beam B. The equivalent statement in not correct for OPD[1] and OPD[2], which means if for example OPD[1] does not change in time but OPD[2] does, nevertheless the MDL passed by beam A may be the one that moves, whereas the MDL passed by beam B may be standing (then baptized the “reference” DL). The MIDI software ensures that equation (1) remains correct, although the time-dependent numbers may have been swapped from OPD[1] to OPD[2] or the other way round, including a change in sign.
If the two telescopes are on different East-West sides of the tunnel, the two MDL are also on different sides \cite{40, 3.2.3.2.4}; see \cite{40, Fig 3-2} or \cite{40, Fig 3-6} to figure out whether this is currently the case: UT1, UT2 and ATs on rails A–G are West-side, whereas UT3, UT4 and ATs on rails H–M are East-side. By looking at the keyword DEL REF NAME and with the enumeration of \cite{40, Fig 3-6} one can quickly explore which of the two MDLs moved for this case. Example: if DEL REF NAME = ‘DL3’, the MDL associated with one of the East-side stations was not moving, neither for blind tracking nor for the commanded offsets stored in the OPD[].

However, if the current telescope pair was UT3+UT4 (both with larger \( U \) coordinates than the VLTI complex and both “East-side” telescopes), this information would still not tell whether DL3 was associated with UT3 or UT4 for a full answer, even though both delay line names are provided in ESO ISS CONF DL1 and ESO ISS CONF DL2. In this case one may get the information needed from a model of the change of the external OPD with time; from there, the change of the OPL reported by DEL DLT1 OPL END, DEL DLT1 OPL START, DEL DLT2 OPL END, and DEL DLT2 OPL START—one pair constant the other one the relevant one— may be either showing an increase or decrease. This sign of the time derivative of the DEL DLTi OPL that moved encodes explicitly whether the MDL moved that was associated with the telescope closer to the star, or the one associated with the telescope further away from the star.

**Fig. 2:**

Fig. 2 shows two situations with a star moving closer to \( T_1 \) as a function of time, indicated by the curved arrows above the telescopes. On the left, the lower main delay line (the “reference”) does not move and the upper one needs to move to the left to “stay on the fringe.” On the right, the role of the active and reference delay lines was swapped, and the lower delay line must move to the right as a function of time. We may assume that both delay line positions refer to coordinate systems that provide a (positive) relative distance to the facing/opposite wall, which means that the sign of the time derivative of the MDL positions differs in the two cases.

The GUI prErrWeb.html shown on page 17 shows the external OPD in units of meter and also its time derivative in units of mm/s. In the graph above and with the sign convention used in the GUI, the OPD of the graph is positive and its time derivative negative: it is eventually the quotient of \( dD/dt \) by the time derivative off the moving MDL position (both of approximately the same absolute value) which matters: if close to \(-1\), the MDL of \( T_1 \) moves, if close to \(+1\), the MDL of \( T_2 \).

**G. What was the actual external OPD?**

The quickest way to compute the unsigned \( \text{OPD} |D| \) is to use the vector equation

\[
D = b - P
\]

in the form

\[
D^2 = b^2 - P^2.
\]

The baseline length \( b \) could be obtained

- according to \( b^2 = (T1X - T2X)^2 + (T1Y - T2Y)^2 + (T1Z - T2Z)^2 \) with values extracted from the primary header keywords ESO ISS CONF T1X etc or from the column STAXYZ in the table ARRAY GEOMETRY.
- from the web page \url{http://www.eso.org/observing/etc/doc/vlti/baseline/baslinedata.txt}.
via the geographic coordinates \( \Phi \) (ESO ISS GEOLAT) and \( \lambda \) (ESO ISS GEOLON, including sign) of App. E 1, which are equivalent to the angle of separation \( Z \) between the two telescopes subtended at the center of the Earth, using [19]:

\[
b = (\rho + H)\sqrt{2(1 - \cos Z)} = 2(\rho + H)\sin \frac{Z}{2} \approx (\rho + H) \left( Z - \frac{Z^3}{24} + \frac{Z^5}{1920} - \cdots \right), \\
\cos Z = \sin \Phi_1 \sin \Phi_2 + \cos \Phi_1 \cos \Phi_2 \cos(\Delta \lambda).
\]

A numerically stable evaluation would insert the Taylor expansion

\[
2(1 - \cos Z) \approx (\Delta \Phi)^2 + \cos^2 \Phi_2(\Delta \lambda)^2 - \frac{\sin(2\Phi_2)}{2} \Delta \Phi(\Delta \lambda)^2 - \frac{\cos^2(\Phi_2)}{2}(\Delta \Phi \Delta \lambda)^2 - \frac{1}{12} (\Delta \Phi)^4 - \frac{\cos^2 \Phi_2}{12}(\Delta \lambda)^4
\]

into the first equation, where \( \Delta \lambda = \lambda_1 - \lambda_2 \). The effective Earth sphere radius \( \rho + H \) includes the mountain altitude ESO ISS GEOLEV. The major problem with this calculation is that the actual meaning of the GEOLAT keyword remains obscure: supposed it refers to a geodetic latitude, one would use the intermediate Cartesian coordinates [22] and the Pythagorean formula from the first bullet to calculate \( b \).

The projected baseline length \( P \) at the start and end of the exposure is listed under ESO ISS PBL12 START and ESO ISS PBL12 END in the primary header.

### H. How do piezo movements relocate the point of ZOPD on the sky?

#### 1. Qualitative: Sign

Sky positions of equal OPD are concentric circles on the celestial sphere centered at the baseline vanishing point, see [38, §29]. On an imaging detector, they are lines. Which of the two baseline directions points to the circle’s center depends on the sign of the OPD. Change of the internal OPD augments or shrinks the radius of this circle of ZOPD, as if one would select coherent light from a different position on the sky. This changes the star azimuth \( A \) (the point where this circle touches the observer’s horizon), and with equation (4) one may say that this change moves the star closer to \( T_1 \) if \( |A_b - A| \) increases, or else moves the star closer to \( T_2 \) if this absolute value decreases.

Normal interferometric VLTI operation tracks the star with the MDL such that the path length \( L_1 \) from the star through \( T_1 \) to the beam combiner equals the path length \( L_2 \) through \( T_2 \) to the beam combiner. Path lengths stretch over “external” plus “internal” parts,

\[
L_1 = L_2, \quad L_1 = L_1^{\text{ext}} + L_1^{\text{int}}, \quad L_2 = L_2^{\text{ext}} + L_2^{\text{int}}.
\]

Coherent with the rest of this script we adopt the sign convention

\[
D \equiv L_1^{\text{ext}} - L_2^{\text{ext}}
\]

for the external OPD. [There are four possible combinations of being closer to either telescope before the change and changing this closeness, equivalent to the “Kronecker product” of a sign in \( D \) and a sign in \( \Delta D \) caused by a change in one of the \( L_i \), and also equivalent to a sign of \( |A_b - A| - 90^\circ \) and a change of this value.] The previous two equations yield

\[
\Delta D = (L_1^{\text{ext}} - L_2^{\text{ext}}) = \Delta(L_1 - L_2 - L_1^{\text{int}} + L_2^{\text{int}}) = \Delta(L_1 - L_2) + \Delta(L_2^{\text{int}} - L_1^{\text{int}}).
\]

If we define the MIDI piezo motion relative to its rest position, we have \( \Delta L_i^{\text{int}} < 0 \) since it pushes the roof top mirror towards the beam during the standard “ramp” as the voltage is applied and the piezo expands. If furthermore we have a motion driven by the standard templates, this moves the beam with index \( i = A \), which is to be checked as described in Section IA. Furthermore \( \Delta L_A^{\text{int}} < 0 \) is equivalent to \( \Delta L_B^{\text{int}} > 0 \) with respect to \( \Delta D \), or equivalent to \( \Delta L_A^{\text{ext}} < 0 \), deduced from the equations above as the total path length is kept balanced between the two arms of the interferometer. In the nomenclature introduced above, this reduction in the external path length \( L_B^{\text{ext}} \) means the point on the sky moves towards the telescope of beam B: Figure 3.
FIG. 3: If the internal path difference $L_{\text{int}}^A$ for beam A is shortened by stepping the piezo such that it moves from the solid position to the dashed position, the effective pointing direction on the sky enlarges $L_{\text{ext}}^A$ to “register” with a new direction of zero, coherent total OPD. This effectively choses a pointing direction that moves closer towards the telescope of beam B.

2. Quantitative

We can work this out more quantitatively: We define the two geographic latitudes $\Phi_i$ and longitudes $\lambda_i$ of $T_1$ and $T_2$ and from there the Cartesian coordinates of the baseline vector $b_{12}$ from $T_1$ to $T_2$ [17, 19]:

$$b_{12} = (\rho + H) \cdot \begin{pmatrix} -\sin \Phi_1 \cos \Phi_2 \cos(\Delta \lambda) + \cos \Phi_1 \sin \Phi_2 \\ \cos \Phi_2 \sin(\Delta \lambda) \\ \cos \Phi_1 \cos \Phi_2 \cos(\Delta \lambda) + \sin \Phi_1 \sin \Phi_2 - 1 \end{pmatrix}$$

(13)

where $\Delta \lambda \equiv \lambda_1 - \lambda_2$, $|b_{12}| = b$, where $x$ points to the North, $y$ to the West and $z$ to the zenith at the location of $T_1$, and where $\rho + H \approx 6380$ km is the effective Earth radius at the platform. Alternatively, one may generate the first two components of this vector by subtracting two of the $e$ and $n$ numbers from http://www.eso.org/observing/etc/doc/vlti/baseline/vltistations.html and setting the third to zero, or using the table in [32, §6.2.1].

The star direction is

$$s = \begin{pmatrix} -\cos A \sin z \\ \sin A \sin z \\ \cos z \end{pmatrix}$$

in the same coordinates, with the Azimuth convention of Section IC. The external delay $D$ is the dot product

$$D = s \cdot b_{12} = b \cos \theta; \quad 0 \leq \theta \leq \pi$$

(15)

with the sign convention that $D > 0$ and $\cos \theta > 0$ if the star is closer to $T_2$ than to $T_1$. The cone angle $\theta$ of the circle of constant external OPD seen from the platform is

$$\cos \theta = s \cdot \hat{b}_{12}; \quad \hat{b}_{12} \equiv b_{12}/b; \quad P = b \sin \theta.$$  

(16)

$s$ is $P$, the value of the header keyword ESO ISS PBL12 START, divided by the value of $b$ taken from baseline-data.txt.

The (signed) change in OPD is related to the angular change $\Delta \theta$ of the ZOPD via the differential of (15)

$$\Delta D \approx -b \Delta \theta \sin \theta;$$

(17)

$$\Delta \theta \approx -\frac{\Delta D}{b \sin \theta} = -\frac{\Delta D}{P},$$

(18)

where $b > 0$, $\sin \theta > 0$, $P > 0$. The recipe to calculate the signed $\Delta \theta$ is
• take $P$ from the header as described in Section 1G.

• Check as in Section 1A whether the piezo of beam A or beam B moved, and obtain the local change $\Delta L$ ($L$ is the total path length from the star to the detector. Up to some arbitrary constant, $-150 \, \mu m < L^\text{int} < 0$, but $\Delta L^\text{int}$ may have both signs depending on what one defines as the reference. If the reference is the rest position, $\Delta L^\text{int} < 0$.)

• (Note that the next step associates $L$ with one of the telescopes and an “internal” delay, and that there are various equivalent ways of doing this as discussed above, only one of which is picked here.) Select one of the telescopes to be $T_1$, the other $T_2$, in accordance to the choice that defines the signs of Eq. (13) and (15). Figure out as in Sect. 1D whether the piezo handled the beam through $T_1$ or the beam through $T_2$. If the piezo modified the beam through $T_1$, flip the sign of $\Delta L^\text{int}$ (as to relate $L$ to the internal delay imposed by $T_2$).

• Define the ZOPD as given by (12),

$$\Delta D = \Delta L^\text{int}$$

(19)

and obtain the signed $\Delta \theta$ via (18).

The limitations for the piezo range ($|\Delta L| < 150 \times 10^{-6} \, m$), the baseline ($b \geq 46.6 \, m$ for UTs), and the zenith distance ($\theta \geq 30^\circ$) result in the limit $\Delta \theta \leq 6.4 \times 10^{-6} \, \text{rad} = 1.3''$ obtained from (18). Larger ZOPD shifts must be relayed to the MDL.

The orthogonal projection of the change $\Delta \theta$ along the perimeter of the circle is only resolved through the PSF of the single telescope ($1.2\lambda/d = 0.31''$ for $d = 8 \, m$ at $\lambda = 10 \, \mu m$, $1.2\lambda/d = 1.38''$ for $d = 1.8 \, m$ at $\lambda = 10 \, \mu m$), the radial direction resolved proportional to $\lambda/P$ of the interferometer. One may chose to associate $\Delta \theta$ not only with a change in the distance to the baseline’s line of sight, but also with a specific direction ($\Delta A, \Delta z$) in the tangential plane to the celestial sphere attached to $A$ and $z$. Then from [38, §28.3.4]

$$(\Delta \theta)^2 = (\Delta z)^2 + \sin^2 z(\Delta A)^2 - \frac{1 + 2\cos^2 z}{12} (\Delta z)^2 (\Delta A)^2 - \frac{1}{12} \cos^2 z \sin^2 z(\Delta A)^4 \pm \cdots$$

(20)

The two components of the gradient are

$$\frac{\partial D}{\partial A} = \frac{\partial s}{\partial A} \cdot b_{12} = \begin{pmatrix} \sin A \sin z \\ \cos A \sin z \\ 0 \end{pmatrix} \cdot b_{12},$$

(21)

$$\frac{\partial D}{\partial z} = \frac{\partial s}{\partial z} \cdot b_{12} = \begin{pmatrix} -\cos A \cos z \\ \sin A \cos z \\ -\sin z \end{pmatrix} \cdot b_{12}$$

(22)

by differentiation of (15). If one wants to calculate the direction ($\Delta A, \Delta z$) of radial (steepest) change of the circle of ZOPD, for example, one would chose $\Delta A/\Delta z = (\partial D/\partial A)/(\partial D/\partial z)$, calculate the partial derivatives from the dot products in the previous two equations, divide (20) through $(\Delta z)^2$, and obtain $\Delta z$ from (20). This approach works as well for the declination $\delta$ and right ascension $\alpha$ (or hour angle $h = \text{LST} - \alpha$, increasing with time, computed by subtracting the values of the FITS keywords LST and RA after scaling to common angular units) substituted for $A$ and $z$ in (14):

$$s = \begin{pmatrix} \cos \Phi \sin \delta - \sin \Phi \cos \delta \cos h_1 \\ \cos \delta \sin h_1 \\ \sin \Phi \sin \delta + \cos \Phi \cos \delta \cos h_1 \end{pmatrix}; \quad h_1 - h_2 = \lambda_1 - \lambda_2.$$  

(23)

A star at hour angle $h = 0$ is on the Meridian,

$$s = \begin{pmatrix} \sin(\delta - \Phi) \\ 0 \\ \cos(\delta - \Phi) \end{pmatrix}, \quad (h = 0),$$

(24)

north of the zenith at $A = 180^\circ$ if $\delta - \Phi > 0$, south at $A = 0$ if $\delta - \Phi < 0$. 


The dot product $s \cdot b_{12}$ between (23) and (13) is

$$D = (\rho + H) \cos(\delta \cos \varphi_2 \cos h_2 + \sin \delta \sin \varphi_2 - \sin \varphi_1 \sin \delta - \cos \varphi_1 \cos \delta \cos h_1).$$

(25)

$\Delta \Phi \equiv \Phi_1 - \Phi_2$ and $\Delta \lambda$ are small, measured in radian; from App. E1 we have $|\Delta \Phi| < 2.4 \times 10^{-5}$ rad and $|\Delta \lambda| < 3.1 \times 10^{-5}$ rad, the maximum North-South distance realized by the station pair B5–J6, and the maximum East-West distance by A1–M0. To avoid the massive cancellation of digits in (25), one would use the bivariate Taylor expansion

$$D/(\rho + H) \approx (\sin \Phi_2 \cos \delta \cos h_2 - \cos \Phi_2 \sin \delta) \Delta \Phi + \cos \delta \sin h_2 \Phi_2 \Delta \lambda$$

$$+ \frac{1}{2}(\sin \delta \sin \Phi_2 + \cos \delta \cos h_2 \Phi_2)(\Delta \Phi)^2 - \sin \Phi_2 \cos \delta \sin h_2 \Delta \lambda \Delta \Phi + \frac{1}{2} \cos \delta \cos h_2 \cos \Phi_2(\Delta \lambda)^2$$

The $\partial D/\partial \delta$ and $\partial D/\partial \alpha$ follow from there. For the details one must split the hour angle into a change in sky coordinate and a time difference $\Delta t = \Delta h + \Delta \alpha$, ie, judge to which degree the change in the piezo position has been instantaneous.

I. Phase measurements with MIDI

The basic equations: Consider an object $P_\lambda(\alpha)$, where $\alpha$ is an angle on the sky. We write its one-dimensional Fourier transform i.e. its complex visibility, as $P_\lambda(\alpha) = \int_{-\infty}^{\infty} P_\lambda(\alpha)e^{2\pi \text{imu} \alpha} \text{d} \alpha = |P_\lambda(\alpha)| \cdot e^{i \phi_\lambda(\alpha)}$ with visibility amplitude $A_\lambda(\alpha)$ and phase $\phi_\lambda(\alpha)$ . Reversing the direction in which $\alpha$ is increasing is equivalent to going from $P_\lambda(\alpha)$ to $P_\lambda(-\alpha)$ and would change the sign of $\phi_\lambda(\alpha)$ . Observing this object interferometrically with a baseline of projected length $B_{\text{proj}}$ and a corresponding spatial frequency $u = B_{\text{proj}}/\lambda$ on the sky leads for multiaxial beam combination to a visualisation of the visibility component $P_\lambda(u)$ as an instantaneous fringe pattern in the image plane with the modulating part

$$I_\lambda(x) \propto 2 |P_\lambda(u)| \cos(2\pi f_m x + \phi_\lambda(u)),$$

(27)

where $1/f_m$ is the spatial fringe spacing and the sign of the phase is positive for proper choice of the sign of $x$. Alternatively, in coaxial beam combination this visibility component shows as an OPD-scanned timewise fringe pattern of

$$I_\lambda(\text{OPD}) \propto 2 |P_\lambda| \sin(2\pi \text{OPD}/\lambda + \phi_\lambda),$$

(28)

where obviously $\Delta \text{OPD} = \lambda$ is the fringe spacing during an OPD scan. The latter method is used in the MIDI instrument on the VLTI. The presence of the sine function in relation (28) instead of the cosine function results from the well known $\pi/2$ phase shift in the symmetrically used beam splitter which brings about the coaxial recombination: the factor of two here results from taking the difference of the two beamsplitter output signals of opposite sign. As we will see, the $\pi/2$ phase shift is of no consequence for the phase determination of $\phi_\lambda$. The positive directions of $x$ in Equation (27) and OPD in Equation (28) need to correspond to the positive scan direction $\alpha$ over the source on the sky. Otherwise the phase $\phi_\lambda$ would change sign. In other words, defining the signs of $x$, resp. OPD and keeping Equations (27) resp. (28) also would define a positive direction $\alpha$ on the sky.

For later use we note that by the formulation of Equations (27) and (28), when $\phi_\lambda$ is going positive from the value 0 (which a point source at the origin would have), then the maximum, respectively the zero crossing of the fringe pattern (28) at the origin will move to negative values of $x$, respectively OPD.

Derivation from more general principles: Equations (27) and (28), though plausible, deserve some justification in detail, in particular to verify the sign of the angle $\alpha$, of the OPD and of the phases. We start from Boden’s presentation [2, p. 9]. A plane wave propagating from the object in direction $k$ towards the observer is written as $e^{ik \cdot x - \omega t}$ with $|k| = k = 2\pi/\lambda$. Using telescopes $A$ and $B$ we define the baseline vector $B$ as $\lambda \rightarrow B$. Pointing the telescopes to the object, we are viewing in direction $s = -k$. The total optical path difference counted in the sense $B$ minus $A$ then is $\text{OPD} = -s \cdot B + d_B - d_A$, where $d$ are the pathlengths from the telescopes to the locus of beam combination and $sB$ constitutes the external part of the OPD which decreases for viewing directions towards telescope $B$. From the superposition of the waves travelling through telescopes $A$, $e^{(sB + d_A - i\omega t)}$, and telescope $B$, $e^{(d_B - i\omega t)}$, the fringe pattern results as

$$F_\lambda(\text{OPD}) \propto \cos(k(s \cdot B + d_A - d_B)).$$

(29)
To relate positions on the sky to the instrumentally available internal OPD \( d_A - d_B \), we consider the viewing direction \( s \) as origin on the sky. We take as zero point of OPD that value of \( d_A - d_B \) where a point source at this origin would produce the white light fringe, i.e. where the argument of the cosine in Equation (29) is zero. We also note that with the accepted sign convention for the OPD (OPD = path length “MIDI beam B” minus path length “MIDI beam A”), an interferometric scan with MIDI moves the internal OPD \( d_B - d_A \) stepwise towards more positive values, since the piezo motion is shortening \( d_A \). In the actually used mechanical-geometrical setup, during such an OPD scan of the MIDI instrument the corresponding position of the white light fringe on the sky moves towards that one of the two used telescopes that sends its light beam into the right entrance window of the MIDI dewar, when seen with the incoming light (“MIDI beam B”). The fits headers of the stored data files carry the information which allows to transpose this somewhat convolved definition into a defined direction on the sky such that the phases will give defined information on the object. It is natural to count \( \alpha \) positive on the sky in the direction where the corresponding white light fringe moves during an internal OPD scan. According to Equation (29) this means that, because of \( d_A \) decreasing during the scan, \( \alpha \) as \( s \cdot B \) goes positive towards telescope B.

For an extended source we have to add the independent fringe patterns (Eqn. 29) contributed from all its parts, which means integrating over \( \alpha \), which is in the plane of the sky and perpendicular to \( s \). The integrand then reads \( P_\lambda(\alpha) \cdot \cos[k(s + \alpha)B - (d_B - d_A + \Delta\text{OPD}_{\text{int}})] \). Here, \( d_B - d_A \) is the value of the internal OPD corresponding to the white light fringe at \( \alpha = 0 \), and \( \Delta\text{OPD}_{\text{int}} \) is an intended instrumental offset from the white light position (describing, e.g. the piezo scan). Since \( s \cdot B + d_A - d_B = 0 \), the integrand simplifies to \( P_\lambda(\alpha) \cdot \cos[k(s \cdot B) - \Delta\text{OPD}_{\text{int}}] \) \( = P_\lambda(\alpha) \cos(2\pi \alpha B_{\text{proj}}/\lambda) \cos(\Delta\text{OPD}_{\text{int}}) + P_\lambda(\alpha) \sin(2\pi \alpha B_{\text{proj}}/\lambda) \sin(\Delta\text{OPD}_{\text{int}}) \). Keeping in mind the above definition of visibility \( P_\lambda(\alpha) \), and respecting \( k(s \cdot B) = 2\pi B_{\text{proj}}/\lambda \), the integral over \( \alpha \) refers to the integrand \( |P_\lambda(\alpha)| \cos(\phi_\lambda) \cos(\Delta\text{OPD}_{\text{int}}) - |P_\lambda(\alpha)| \sin(\phi_\lambda) \sin(\Delta\text{OPD}_{\text{int}}) \) which directly leads to the form

\[
F_\lambda(\Delta\text{OPD}_{\text{int}}) = |P_\lambda(\alpha)| \cos(2\pi \Delta\text{OPD}_{\text{int}}/\lambda + \phi_\lambda),
\]

from which Equation (28) follows simply by applying the \( \pi/2 \) phase shift. This verifies the formulation of Equation (28), including the sign of the phase.

A Gedankenexperiment: We now consider a binary with the center of light in the origin to confirm by a detailed look at the expected temporal fringe pattern that the phases determined by MIDI will have the correct sign. On the sky we are on save grounds: The phase would show the form of a staircase with width of the individual steps in spatial frequency \( u \) of \( \Delta u = 1/\text{separation} \) and the height of the steps depending on the brightness ratio. The phase will decrease with \( u \) if the companion is located at more negative \( \alpha \) with respect to the primary. On the other hand, the binary’s phase with removed linear trend – as it is determined in the instrument MIDI – corresponds to a different position, namely with the primary at the origin. The binary phase now oscillates around zero. For a companion at more negative position \( \alpha \) than the primary, the phase will increase with \( u \) (decrease with \( \lambda \)) at those spatial frequency values where the maxima of the visibility amplitude are found, a simple and useful criterion. In the instrument it looks like this: If we have a companion at slightly negative \( \alpha \) with respect to the primary, its contribution to the temporal fringe would have a maximum slightly earlier in the OPD scan, at \( \Delta\text{OPD}_{\text{comp}} = -\alpha \cdot B \). The maximum of the combined fringe pattern (primary plus companion) then will also be shifted to more negative values, by

\[
\Delta\text{OPD}_{\text{binary}} = -\alpha \cdot B \cdot \frac{F_{\text{comp}}}{F_{\text{prim}} + F_{\text{comp}}}. \tag{31}
\]

Measured in units of \( \lambda \), this shift will decrease in absolute value, i.e. get more positive, rise with increasing \( \lambda \). The phase \( \phi_\lambda \), corresponding to this shift of maximum, therefore will get more negative, decrease with \( \lambda \). This has the correct sign, and so the phases determined from MIDI should be correct with the sign as defined by the Fourier transform and as used in equations (28) and (30).

The treatment of phases in MIDI: In MIDI, OPD in Equation (28) is the actual optical path difference for a given individual exposure. One such exposure with the MIDI instrument gives \( F_\lambda(\text{OPD}) \) as function of \( \lambda \) for the range \( 8-13 \mu\text{m} \). Many of these exposures at a repeated sawtooth pattern of OPD steps scanning the fringe constitute an interferometric measurement. In each scan, the position of fringe maximum depends on the phase \( \phi_\lambda \).

For the determination of phases from MIDI measurements we have to recall that the total optical path difference consists of two parts of different behaviour: \( \text{OPD}_{\text{total}} = \text{OPD}_{\text{int}} + \text{OPD}_a \), where the “instrumental” \( \text{OPD}_{\text{int}} \) is quickly stepped through a few times the wavelength of \( \approx 10 \mu\text{m} \) during an interferometric measurement and is known including its sign, while \( \text{OPD}_a \) is mostly determined by the atmosphere and is more slowly varying with a few \( \mu\text{m}/\text{s} \), but in an unpredictable way.

The EWS (expert workbench system) part of the MIDI data reduction package determines the phase by mathematically shifting each exposure as given by Equation (28) to OPD zero and then averaging to obtain the complex
visibility - modulus and phase \[13\][37, 3.2.4]. Remembering that a shift in image space (and here also in OPD) corresponds to a phase factor in Fourier space of the kind \(e^{2\pi i u \text{OPD}}\), we multiply (28) by the factor \(e^{-2\pi i u \text{OPD}}\) to “shift” each exposure \(F_\lambda\) back to position \(\text{OPD}_{\text{int}} = 0\). Equation (28) now reads - expressing the sine function by exponentials, and apart from factors which do not matter here -
\[
F'_\lambda(\text{OPD}) = \frac{A_\lambda}{i} e^{2\pi i u \text{OPD} + i \phi_\lambda} - \frac{A_\lambda}{i} e^{-4\pi i u \text{OPD} - 2\pi i u \text{OPD}_{\text{int}} - i \phi_\lambda}.
\]

To determine the unknown atmospheric optical path difference \(\text{OPD}_{\text{a}}\), we Fourier transform (32) with respect to \(u\) and obtain peaks at \(+\text{OPD}_{\text{a}}\) and \((-\text{OPD}_{\text{a}} - 2\text{OPD}_{\text{int}})\). Of these, the second term, rapidly changing with \(\text{OPD}_{\text{int}}\) during a scan quickly smears out by averaging over different exposures, so the only remaining peak gives the wanted value of \(\text{OPD}_{\text{a}}\) with correct sign. We now can perform the “shifting back” correction also for the atmospheric part of the OPD by multiplying equation (32) with \(e^{-2\pi i u \text{OPD}_{\text{a}}}\). This leads to
\[
F''_\lambda(\text{OPD} - \text{corrected}) = A_\lambda e^{i(\phi_\lambda \pm \pi/2)},
\]
where we have omitted the strongly jittering part with the factor \(e^{-4\pi i \text{OPD}_{\text{a}} - 4\pi i \text{OPD}_{\text{int}} - i \phi_\lambda}\). The constant \(\pi/2\) results from the factor \(1/i\), its sign depends on which of the two complementary interferometric signals after the beam splitter is subtracted from the other one. Averaging equation (33) over the typically several thousand exposures of an interferometric measurement thus will reliably determine —apart from a constant known in principle— the wanted phase \(\phi_\lambda(u = B_{\text{proj}}/\lambda)\) over the wavelength range 8–13 \(\mu\)m. (At the same time, it will also give the visibility amplitude \(A_\lambda\)). We remove any linear trend with \(u\) from this phase, since it simply would correspond to a position offset of the source from the origin. As well we remove any remaining constant term \(\neq 0\). Again apart from our constant, this term could be and appears to be mostly due to differential longitudinal dispersion over the unequally long air paths of the interfering light beams and it thus mostly carries information not related to the object. Of course, subtraction of the constant term also takes care of the added \(\pm \pi/2\). This ends the determination of phase. We note that the data reduction procedure described here preserves the sign of phase as defined by the Fourier transform and given in Equation (28).

The phases determined with MIDI on the VLTI thus are not fully complete, with the constant and linear terms set to zero. But they allow e.g. to break the ambiguity of where the companion in a binary is located with respect to its primary. This property of the MIDI data is needed and used in the discussion of the close binary T Tau S above.

A check by a known binary: We wanted to check the signs of phase derived above from “first principles” with an object where we assume we know the position of the companion. The close binary Z CMa, with separation of 0.1″, consists of an infrared companion and an FU Ori component. At 4 \(\mu\)m the infrared companion is brighter by a factor of 6, this ratio rising with wavelength. The ratio of correlated fluxes at 10 \(\mu\)m, determined is in the range 5–10. We conclude that with these clear inequalities the component much brighter at 4 of 6, this ratio rising with wavelength. The ratio of correlated fluxes at 10 \(\mu\)m consists of an infrared companion and an FU Ori component. At 4 \(\mu\)m the constant term also takes care of the added \(\pm \pi/2\). The constant and linear terms set to zero. But they allow e.g. to break the ambiguity of where the companion in a binary is located with respect to its primary. This property of the MIDI data is needed and used in the discussion of the close binary T Tau S above.

II. IMAGING INFORMATION ENCODED IN MIDI FITS FILES

A. Where is North in the VLTI beams?

1. Without DDL or STS

The calculation of the field rotation angles \(\phi\) in the beams that propagate into the Western direction in the VLTI laboratory according to formulas found in [11] or [31, §3.2.5.1] can be done with the shell script \texttt{mioFieldAng} which is available from \url{http://www.strw.leidenuniv.nl/~mathar/progs/mioFieldAng}. For the case of UTs used—as usual—with beam compressor, this results in
\[
\phi = p - a - A + 167.02^\circ
\]
where \(p\) is the parallactic angle [21] \(A\) the azimuth as given in the MIDI FITS header, and \(a\) the elevation of the object. (This equation is adapted from [31, (Tab 3-3)]; the sign of \(A\) is flipped to transform the azimuth conventions [10].) \texttt{mioFieldAng} computes \(\phi\) for the ATs as well. Note that the results may be incorrect if
• The ATs field rotator angle is non-zero,
• ATs are equipped with the star separator (year 2008 or perhaps later),
• beams are passing by the PRIMA differential delay lines (year 2008 or perhaps later)

2. With DDL and/or STS

![Diagram showing beam paths](image)

FIG. 4: Change of the beam path in the VLTI laboratory [26] when switching from the AT SF (left) or the AT DF or UT (middle) to the AT/UT DF mode (right). Numbers are beam diameters in mm. The rightmost case is probably irrelevant since the windows of the “vacuum” option of the DDLs have not been designed for N-band transmission [20].

Introducing the DDL into the beam changes the paths from one of the two layouts at the left of Fig. 4 to the one at the right. All three cases include one flat mirror of the SWY which therefore yields no net difference with respect to field rotation. The BC or the DDL (Figs. 9, 10) each have the same individual effect on the field rotation: building a mirror inversion upside-down (always looking into the direction of beam propagation); cascading both as in the right part of Fig. 4 eliminates their net effect. In total, the effect of incorporating the DDL adds to [11] the following rotations/inversions in the laboratory:

• an additional inversion upside-down for UTs, which flips the sign of $\phi$ (since this has been defined relative to a horizontal coordinate) and changes the formula $\phi - 90^\circ$ for the East angle to $\phi + 90^\circ$ [31, Tab. 3-3],
• no effect for ATs compared to the case without STS and without DDL.

(We neglect the case of using the ATs with STS, with BC but without DDL.) In addition, there is predictable contribution within the STS relative to the case of a straight two-mirror layout. Since I have no immediate information on the optics of the STS of the UTs (this is one mirror less than the STS of the ATs), only the case of adding the STS to the AT is summarized here. We replace the three-mirror arrangement M9–M10–M11 of the AT SF layout as shown in Fig. 8 by the layout of derotator and STS shown in Fig. 30 in [38] and Fig. 5 here.

• For the derotator in its nominal position, the image rotation of both cases of the AT Coudé train is the same.

Summarizing with the description of the effect in the VLTI lab, adding derotator in its nominal position, STS, BC and DDL have the same beam rotation effect for ATs as leaving all these components out. For general positions of the derotator, one needs to add (or subtract, pending a sign definition of the corresponding angle which—one would hope—will be made by ESO at some time in the future corresponding to the position angles) its field rotation angle (which is twice the angle of the mechanical rotation around the vertical axis).

This information is presumably correct for all VLTI instruments with the exception of anything parked on the Visitor’s Instrument Table (for example GENIE).
FIG. 5: Tracing the effect of the derotator and STS on the beam rotation.

B. Where is North on the MIDI detector?

The result of an image tracing of the coordinates mentioned in the previous section through the MIDI feeding mirrors and cold optics looks as in Fig. 6 [14] (images are not to scale).

In the two graphs above for the photometric channel of beam B, the green line approaches the MIDI feeding optics on the optical axis, the blue line is shifted a little into the +V direction (displaced to the North) and the purple line is shifted a little into the +W direction (displaced to the ceiling). These are reflected by the feeding optics and pass by the internal delay line of the warm optics, here labeled W1 to W4, with no net rotational effect. (W2 and W3 are driven by a single piezo, the equivalent optics of the other beam is not shown and driven by the other piezo.) They move on to M1 to M3 in the cold optics with the intermediate focus between M1 and M2. The second graph shows one arm of the photometric beams coupled out with the mirror named P, reflected by M4 and M5, and approaching the camera CAM, equivalent to the $P_B$ channel in [12, Fig. 10]. Removing P and M4 as to represent the interferometric channels would have no net rotational effect, as comparison of the footprints of the beams that leave M3 and of the beams that leave M4 shows. After the switchyard, before the feeding optics, the blue ray was to the right and the purple ray above the green one—always as seen into the direction of light propagation. Before the camera, the blue line is below and the purple ray to the left of the green one. The camera lens inverts this when it creates the image, which leads to summary in Fig. 7 for both interferometric beams $I_1$, $I_2$, and both photometric beams $P_A$ and $P_B$:

In the left diagram, we show the field angle $\phi$ in a coordinate system as if one was looking from the switchyard to the instruments and feeding optics in the VLTI lab, into the $-U$ direction, as defined in [11]. Note

- this diagram shows an image of the sky directions as if one had inserted a virtual single lens at some $U$ coordinate which created the image on a sheet of paper in the $(V,W)$ plane [9].
- The angle is not the same as values for the ROTATION column of the IMAGING_DATA tables defined in [1]. A C++ program mioFitsPost is available from the author’s web page http://www.strw.leidenuniv.nl/~mathar/progs/ which fills the ROTATION column with the time-dependent angles $\phi + 180^\circ$ for UTs and $180^\circ - \phi$ for ATs, wrapped into the interval 0–360°.

This $\phi$ would be obtained from the procedure of Section II A. On the right, the equivalent angle is shown on the MIDI infrared detector from the point of view of the incoming light, looking towards the detector with the beam combiner behind the back. The summary is that the detector watched from the front side (not from the mounting side) or one of the FITS images in the DATAi columns of the IMAGING_DATA table shows a true image for UTs as one would display a field on the sky, although rotated. The Java applet of the http://www.strw.leidenuniv.nl/~mathar/vlti/prErrWeb.html shown on page 17 also provides this information in the circular grid area, where North and East are in the directions marked N and E.
FIG. 6: Evaluation of the field rotation across the MIDI feeding optics, the warm optical bench up to the camera lens.
FIG. 7: At the left, the image rotation angle $\phi$ in the VLTI tunnel coordinates $(V, W)$. At the right, the same field after transmission through the feeding optics, MIDI warm and cold bench and MIDI camera, in the $320 \times 240$ pixels in $(x, y)$ FITS coordinates.
C. How does the baseline project onto the sky?

The projection of the baseline onto the celestial sphere is summerized in [21, 23] and section 11A of [24]. The azimuths \( A_{T,1} \) and \( A_{T,2} \) of the telescopes that define the baseline can be obtained from the file \texttt{baselinedata.txt} where for each allowed telescope pair one finds the baseline length \( b \), and a quantity called Pos.Angle \( \tau \), which actually is an azimuth counted north over east. Seen from the mid-point of the baseline, telescope 1 then is at azimuth \( A \) is an azimuth counted north over east. Subsequent inspection of 

Our convention implies 

The angles 

The projection of the baseline onto the celestial sphere is summerized in [21, 23] and section IIA of [24]. The 

The resulting position angle for the projected baseline may be compared with the output of the routine 

Quick interactive ways to obtain 

• to start the Java applet \texttt{http://www.strw.leidenuniv.nl/~mathar/vlti/prErrWeb.html} shown on page II B, select the two stations, insert the star coordinates at PS: RA and PS: DEC, the sidereal time labeled LST, click on Update below! and read the value of proj. basel. orient. angle.
• or to start the Java applet \texttt{http://obswww.unige.ch/~segransa/apes/}, select baselines and star coordinates, and read off the value of Theta.
• The values of \( A_b \) and \( p_b \) are also reported by recent versions of \texttt{http://www.strw.leidenuniv.nl/~mathar/progs/mioFieldAng}, which scans the FITS files of an entire UNIX directory.

The resulting position angle for the projected baseline may be compared with the output of the routine \texttt{baseline.pro} under MIA+EWS (which may have been calculated for a different time than the start of the measurement, however). The angles \( p_b \) or \( \psi \) are not given in the primary header of the MIDI data *.fits files prior to July 2006. 

Programmers would probably use the \texttt{SLA_DBEAR} function of the SLALIB. Remarks:

• Since approximately June 2005, ISS adds two keywords \texttt{ESO ISS PBLA12 START and END} to the primary FITS headers, which are not directly related to \( \theta \) or \( p_b \). These header keywords are derived from the projected baseline vector \( \mathbf{P} \). If \( \mathbf{P} \) is projected onto the \( (U, V) \) plane of the Paranal platform, the azimuth angle of this horizontal, doubly projected vector angle is reported in \texttt{ESO ISS PBLA12}, modulo 180°. At small delay \( D \), the direction of \( \mathbf{P} \) becomes parallel to \( \mathbf{b} \) and the value of this keyword approaches \( \tau \) or \( \pm 180^\circ \). The major difference between this implementation and the one formulated above is that the formulation of this script here is compatible with the 

The time dependence of \( p_b \) is known from the \( u-v \) plots and more complicated than the sinusoidal motion of the delay \( D \). Illustrative plots of \( p, p_b \) and \( \psi \) as a function of time are shown in [20] which is available from 

Appendix A: Baseline Azimuth Angles

The baseline orientation \( \tau \) from \( T_1 \) to \( T_2 \) in the notation of \texttt{http://www.eso.org/observing/etc/doc/vlti/baseline/baselinedata.txt} is zero if \( T_2 \) is north of \( T_1 \), and +90° if it is East of \( T_1 \): Fig. 1. (Note that the tables
in [7] use a different definition.) In the limit of zero eccentricity of the Earth ellipsoid, the angle can be computed by plugging [22, (A19)] into [22, (78)],
\[ c_3 \equiv (\rho + H) \frac{\cos \Phi_1 \cos \Phi_2 \sin(\lambda_2 - \lambda_1)}{\sin Z}; \tag{A1} \]
\[ \tan \tau = \frac{c_3}{\sqrt{(\rho + H)^2 \cos^2 \Phi_1 - c_3^2}}, \tag{A2} \]
where \( Z \) is defined with (8), and where
\[ \mathbf{T}_i \equiv (\rho + H) \begin{pmatrix} \cos \lambda_i \cos \Phi_i \\ \sin \lambda_i \cos \Phi_i \\ \sin \Phi_i \end{pmatrix} \tag{A3} \]
are the Cartesian telescope coordinates in the geocentric rest frame, compatible with OIFITS [28, 29]. For higher accuracy with non-zero eccentricity, my program http://www.strw.leidenuniv.nl/~mathar/progs/Geod.java can be compiled and run.

Note that, strictly speaking, \( \tau \) does not transform into \( \tau \pm 180^\circ \) if the roles of \( \mathbf{T}_1 \) and \( \mathbf{T}_2 \) are swapped, because the great circles that fixate the \( \tau \) in the two tangent planes at either telescope are not loxodromes.

The transition from the position coordinates of the ARRAY GEOMETRY table defined in [1]—apparently a left-handed Cartesian coordinate system with the Y axis along the Greenwich meridian—to the OI ARRAY table of [28, 29]—a right-handed coordinate system with the X axis along the Greenwich meridian—works as follows: The OIFITS header value ARRAYX is set to the VLTI header value ARRAY. The OIFITS header value ARRAYY is set to the VLTI header value ARRAYZ. The OIFITS values in the tabular column STAXYZ are constructed from the VLTI values in the tabular column STAXYZ by transformation of the VLTI local Alt-Az system to the OIFITS coordinate system, which is (again) geocentric. The VLTI table values STAXYZ[1,2,3] are the coordinates \( v_{1,2,3} \) in a system with the first coordinate to the West, the second to the South, and the third to the zenith, or in terms of the unit vectors defined earlier in this section, the vector \( -v_1 \mathbf{E} - v_2 \mathbf{N} + v_3/(\rho + H) \mathbf{T} \). (The 19°-rotation from the Paranal \((U, V)\) to a compass system has already been done within the ISS.) We assume that the origin in this coordinate system, \( v_1 = v_2 = v_3 = 0 \), equals the tail of the vector described by ARRAY[XYZ]. Let us call the three values in the OIFITS STAXYZ \( o_{1,2,3} \): they are found by equalizing both representations in the same geocentric (earth-fixed) coordinate system:
\[ -v_1 \mathbf{E} - v_2 \mathbf{N} + v_3/(\rho + H) \mathbf{T} = o_1 \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} + o_2 \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} + o_3 \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}. \tag{A4} \]

This is solved by
\[ o_1 = v_1 \sin \lambda + v_2 \cos \lambda \sin \Phi + v_3 \cos \lambda \cos \Phi; \tag{A5} \]
\[ o_2 = -v_1 \cos \lambda + v_2 \sin \lambda \sin \Phi + v_3 \sin \lambda \cos \Phi; \tag{A6} \]
\[ o_3 = -v_2 \cos \Phi + v_3 \sin \Phi, \tag{A7} \]
where the coefficients form an orthogonal rotation matrix. The value of \( \lambda \) is the negative of the primary header’s ESO ISS GEOLON multiplied by \( \pi/180 \), and the value of \( \Phi \) the value of the ESO ISS GEOLAT multiplied by \( \pi/180 \). The numbers ought be compatible with those shown in the two lines with Geocen numbers in the GUI of page II.B.

This calculation is inaccurate if the representation with the VLTI keywords \( \Phi \) and \( v_i \) is of mixed type (\( \Phi \) in geodetic and \( v_i \) in geocentric coordinates or the other way round), on which I have no information (see App. E2). If this mixed representation occurs, correction of \( \Phi \) into the same system as \( v_i \) according to the standard formulas [34, §9][35] is needed as a preparatory step before the rotation matrix can be applied. The basic maths of this is summarized in App. F.

Appendix B: Head files of split exposures

Some hints on figuring out which of the files in a directory might be such “head” files of an exposure:
• Exposures are scheduled by the instrument software to start on straight seconds (w/o chopping) or on times commensurable with the chopping period. Since the chopping frequency is often 2 Hz, files with “straight” millisecond identifiers like MIDI.*.000.fits and MIDI.*.250.fits are usually the first ones of an exposure, whereas those with some random milliseconds like MIDI.*.376.fits are the followup files.

• If the keyword value of ORIGFILE in the FITS header ends on _01.fits, it is such a head file, whereas a higher index like _02.fits of the keyword value characterizes followup files.

• If the keyword value of ESO OCS EXPO FILENO in the FITS header is 1, it is such a head file. The other files show higher integers 2, 3... with this keyword.

For UNIX directories with the raw MIDI FITS files, the head files can simply be listed by

```bash
ls -l MIDI.????-??-??T??:??:??_01.fits
```

For directories assembled by the ESO pipeline, one might use

```bash
fitshead MIDI*.fits | egrep '(ORIGFILE|ARCFILE)' \ awk '{if (NR%2 ==1) n=strtonum(); else if (n==1) print $3}'
```

to list them. A C program mioFitsFNames.c that re-links a directory with files named according to the original instrument convention into another directory with the pipeline naming convention is available on the mididata account on the MPIA server sun47.

Appendix C: Pupil rotation in the VLTI train

In a color encoding consistent with the one above, the transversal of the beam for a UT pointing to the zenith looks as follows in the overview:

![FIG. 8: Overview of the VLTI mirror train.](image)

The uppermost mirror is M2, the one below M3; M1 is not shown. A detail of the three mirrors of the beam compressor looks as follows:

One more horizontal turn by the SWY mirror moves the beam leaving BC3 onto the feeding optics shown in Section II A. Zooming into the M13–M15 of the MDL it looks as follows:

Because the positions of the mirrors of the UT Coudé train are unavailable to the author, and a model of the foci higher up could not be made, we do not follow the rays further back through the optics.
FIG. 9: Field rotation by the three reflections within a beam compressor.

FIG. 10: Field rotation by the five reflections within a cat’s eye of the MDL or DDL.
Appendix D: Atmospheric N band transmission

A detailed transmission spectrum of the Earth atmosphere is reproduced in Fig. 11. The N band is limited at short wavelengths by H\(_2\)O and CH\(_4\) absorption, at longer wavelengths by CO\(_2\) absorption [4, Fig. 11.6]. Correlated line list of transitions found in the HITRAN database [33] is given in Figs. 12–13.
FIG. 12: HITRAN line locations and line strengths in units of cm$^{-1}$/molecule cm$^{-2}$ for CH$_4$, N$_2$O, CO$_2$ and H$_2$O.
FIG. 13: HITRAN line locations and line strengths in units of cm$^{-1}$/molecule cm$^{-2}$ for O$_3$, OH, SO$_2$, NH$_3$ and O$_2$. 

wavelength $\mu$m
Appendix E: Software Problem Reports

1. VLTSW20050024

<table>
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<th>Field Label</th>
<th>Field Value</th>
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<tr>
<td>Originator</td>
<td>ssandroc</td>
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<td>Location</td>
<td>ESO Paranal</td>
</tr>
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<td>Type</td>
<td>change request</td>
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<td>Responsible</td>
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<tr>
<td>Package</td>
<td>TCS Telescope Control System (kwirenst gchiozzi avalland rkarban)</td>
</tr>
<tr>
<td>Priority</td>
<td></td>
</tr>
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<td>Status</td>
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<tr>
<td>Module Version</td>
<td>1.147</td>
</tr>
<tr>
<td>Synopsis</td>
<td>GPS + geographical positions</td>
</tr>
<tr>
<td>cc</td>
<td>rkarban jargomed jspyromi</td>
</tr>
<tr>
<td>cc filter</td>
<td>rkarban jargomed jspyromi</td>
</tr>
<tr>
<td>Description</td>
<td>The geographical positions used by TCS should be updated. Based on the GPS timeserver values as input, the following table can be calculated. Compared to the previous values (taken from the VLT whitebook) the difference is about +6.5 arcsec (or 200 m) in both directions.</td>
</tr>
</tbody>
</table>

GPS-Timeserver:

<table>
<thead>
<tr>
<th>Longitude</th>
<th>Latitude</th>
</tr>
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<tbody>
<tr>
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<td>d m s rad</td>
</tr>
<tr>
<td>TS 70 24 18.948</td>
<td>1.228803656</td>
</tr>
<tr>
<td>-24 37 41.634</td>
<td>-0.429843732</td>
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Unit Telescopes:

<table>
<thead>
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<td>d m s rad</td>
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<td>UT1 70 24 18.27 1.228800386</td>
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<tr>
<td>UT2 70 24 17.39 1.228796107</td>
<td>-24 37 37.80 -0.429825122</td>
</tr>
<tr>
<td>UT3 70 24 16.32 1.228790929</td>
<td>-24 37 36.64 -0.429819523</td>
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<tr>
<td>UT4 70 24 14.26 1.228780856</td>
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Auxiliary Telescope Stations:

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</thead>
<tbody>
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<tr>
<td>A1 70 24 18.26 1.228800303</td>
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<tr>
<td>B0 70 24 18.17 1.228799886</td>
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<tr>
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<tr>
<td>B2 70 24 17.89 1.228795849</td>
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<tr>
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</tr>
<tr>
<td>B4 70 24 17.71 1.228796651</td>
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<tr>
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<tr>
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<td>M0 70 24 13.60 1.228777714</td>
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</tr>
</tbody>
</table>

Worklog

Last-modified-by

Modified-date
Status History
Status Modified-Time Modified-By
closed 2005/01/25 16:50:54 ssandroc

tcs 1.148 contains the new positions for UT1-4 and an average for ATs; the exact AT station positions must still be updated in the ATCS SW.

3/8/2005 5:15:56 PM vltsccm
assigned to SSA for JAN2006

(i) I propose to change the sign of the longitudes to become compatible with the sign convention of ESO ISS GEOLOX in the primary headers.

(ii) the nominal accuracy of 1.e-9 rad would be about 6.38 mm (with an earth radius of about 6380 km). Since the daily tidal motion on Paranal is up to 1.5 cm in all three directions, it makes sense to record *when* these data have been taken for later reduction of the tidal effects.
(I am not sure whether the actual accuracy, given finite sizes of any GPS antenna and the weather dependence of the GPS signal delays would warrant such a precaution.)

(iii) If this accuracy is maintained, I propose to define this as the mean center position in the middle of the M3 fron surface, since this seems to be the best definition of the baseline "anchor" point.

5/14/2006 12:37:03 AM ssandroc
Positions have meanwhile been implemented for UTs and ATs.

Note that λ used here has the opposite sign to what has been used in the SPR reproduced above.

2. VLTSW20050104

Problem Number VLTSW20050104
Create-date 3/2/05 11:03:41 AM
Module Name atcsmon
Module Version
Description update the position table according to measurements provided in VLTSW20050024
Worklog rkarban 7/27/05 11:04:58 AM
done in atcsmon 1.32

mathar 6/15/05 3:05:49 PM
Are the latitudes meant to be geodetic or geocentric?
I see that tcs/src/tcsVcc.c uses slaAoppa() in tcsCoord2AltAz(), which is defined to be fed with geodetic angles; it does the parallax calculation internally with some mean 1/298 prolate earth. From there I'd deduce that the tcs/dbl values are geodetic, but I cannot find any specific documentation, neither in the white book nor in the tcs module, nor in VLTSW20000166.
For Paranal, the difference between the two angles is about 695'' * sin(2*phi), or 530 arcsec at phi=-0.4298 rad.

vltsccm 4/1/05 6:38:45 PM
assigned to RKA for OCT2005

Status closed
Closed Status solved

3. VLTSW20060050

Problem Number VLTSW20060050
Create-date 2/14/06 6:28:32 PM
Module Name issarray, dicISS
Module Version
Description The reference longitude/latitude defined in ISS database shall refer to UVW=0 (between UT1 and UT2).
SPR VLTSW20050024 defines new values for all stations.
From these data the correct longitude and latitude can be computed as 1.228798831 -0.429829904 (radians)
The issarray class file shall be updated accordingly

The ISS dictionary shall be updated to give 8 decimal resolution (degrees). The comment shall clarify the reference point.
Worklog vltsccm 2/24/06 2:21:29 PM
assigned to AWA - closed as solved

awalland 2/15/06 5:39:37 PM
Updated in issarray v 4.11.
Tested OK in CM.
Can be closed after assignment.

Status closed
Closed Status solved

4. VLTSW20060066

From ARSystem@eso.org Wed Jul 26 16:09:49 2006
Date: Wed, 26 Jul 2006 16:03:00 +0200 (MEST)
From: ARSystem <ARSystem@eso.org>
Reply-To: ARSystem <ARSystem@eso.org>
To: mathar@strw.leidenuniv.nl
Subject: VLTSW20060066 closed

The problem VLTSW20060066 has been closed

Problem Number : VLTSW20060066
Originator : mathar
Responsible : awalland
Status : closed
Package : VLTI-ISS (awalland nhousen )
Module Name : isstrkws
Module Version : 3.4
Type : sw error
Location : Leiden Observatory
Closed Status : solved
cc : pgitton,ott@four-d.de,isperchar,Gilles.Duvert@obs.ujf-grenoble.fr
Synopsis : unexpected values of ISS PBLAij
Description : The calculation of PBLAij in the isstrkws seems to be either in error or poorly documented. The actual calculation projects the straight projected baseline vector (difference between the baseline vector and the delay vector into the star direction) onto the UV coordinate system and calculates some sort of azimuth angle (w.r.t. the horizontal West-South coordinate system). Most people in the interferometric community would expect to get the position angle discussed in section IIC of http://www.strw.leidenuniv.nl/~mathar/public/matharMIDI20051110.pdf
Worklog :
02/27/06 18:35:51 awalland
The PBLAij has been implemented according to SPR VLTSW20040333. This SPR has been triggered by AMBER consortia and no complains have been raised after this implementation. Please consult AMBER consortia and agree on a different algorithm if that is required.
The algorithm is given by Philippe Gitton and reproduced below.

Calculation of the angle between the projected baseline vector wrt North direction
==================================================================================================
GIP - May 10, 2006

The reference frame used is defined as
* -> X along East
* -> Y along North
* -> Z along Zenith

Let’s define two vectors:
Unit vector star defining the direction in which the telescopes point at using VLT convention:
AZ = 0 when pointing south
AZ = 90 when pointing east

start[0] = sin(AZ)*cos(alt);
start[1] = -cos(AZ) *cos(alt);
start[2] = sin(alt);

/* Baseline vector from TEL 1 to TEL 2 in units of meters */
baseline[0] = coordTEL2[0] - coordTEL1[0];
baseline[1] = coordTEL2[1] - coordTEL1[1];

/* The sidereal OPD (sign being either positive or negative) is computed via: */
sidOPD = star[0]*baseline[0]+star[1]*baseline[1]+star[2]*baseline[2];

/* The projected baseline vector ProjBaseline in meters is: */
ProjBaseline[0] = baseline[0] - sidOPD x star[0];
ProjBaseline[1] = baseline[1] - sidOPD x star[1];

/* Angle theta from North to the projection in the North-East plane of the projected baseline
angle = 0 if projection along North
angle = 90 deg if angle along East */
theta = arctan(ProjBaseline[0]/ProjBaseline[1]);

03/03/06 15:54:16 mathar
The OIFITS data format explicitly specifies the direction of the (x,y) plane--
and therefore the (u,v) plane--that catches the wavefront: this plane is
orthogonal to the direction of propagation, *not* orthogonal
to the topocentric zenith direction. To get a correct representation of the
coordinates as x=cos(angle)*PBL, y=sin(angle)*PBL in OI_VIS tables
(or angle replaced by angle+180 or angle+90 which is not explicitly defined by
OIFITS), the software must absolutely *avoids* to set angle=PBLA as currently
provided.
Note also that the angle is not defined modulo 180 [as currently implemented
with the arctan()] but modulo 360 degrees, as implemented with an arctan2().
This is because the first and the second telescope
define a baseline vector, and the projected baseline vector switches
direction if these are swapped. This adds 180 degrees to the angle
that ought be computed, and is equivalent to a sign convention for OPD's.
[This is independent of the obscure "wall-based" sign convention used within
the VLTI software.]
Note in passing that the ARRAY[XYZ] values in the ARRAY_GEOMETRY table
produced by ISS are also not compatible with the OIFITS standard: according
to OI_VIS the x component would beodel projected to the Greenwich
meridian, and the y component form a right-handed coordinate system with
the z component where z points to the North. So for Paranal at -70 deg
of longitude as in ISS IBS GEOLOC [although some astronomers would wrongly
argue this is +70 deg] we would need ARRAYX>0 and ARRAYY<0 and
|ARRAYX|<|ARRAYY| to be compatible with OIFITS.

03/30/06 22:41:48 mathar
Dear Richard,
I have forwarded your request to our software team. Can you tell us a
little bit more about the conventions you are using? I am in vacation
right now and I cannot check but we try to comply with usual
conventions of optical and radio interferometry. Hopefully, Gilles
Duvert will be able to reply to you on this subject.

Cheers,
fabien.

From Gerard.Zins@obs.ujf-grenoble.fr Tue Feb 28 08:54:18 2006
Date: Tue, 28 Feb 2006 08:53:18 +0100
From: Gerard Zins <Gerard.Zins@obs.ujf-grenoble.fr>
To: Richard Mathar <mathar@strw.leidenuniv.nl>
CC: Gilles Duvert <Gilles.Duvert@obs.ujf-grenoble.fr>,
Gilles Duvert <Gilles.Duvert@obs.ujf-grenoble.fr>
Subject: Re: [Fwd: Fwd: Remarks added to VLTSW20060066]

Dear Richard,
Gilles is in vacation this week. I will discuss this point with him next
week, and we will keep you informed.

Best regards,
Gerard.

04/05/06 18:44:59 mathar
The computational steps towards the baseline orientation angle are,
following the first proposal of Section IIC of my reference given before :
1) Compute A, the star azimuth, which is zero if the star is geographically
South, -90 deg if the star is West of the observatory. This is equivalent
to ISS AZ.
2) Compute $A_b$, the baseline azimuth on the platform. This is the
time-independent azimuth of $T_j$ in coordinates centered at $T_i$. It is zero
if $T_j$ is south of $T_i$, $+90$ deg if $T_j$ is west of $T_i$. This angle is
approximately $180$ degrees plus what is tabulated in
[We use only the difference between $A_b$ and $A$ below, so both
angles may be redefined with a different origin, for example a North=0
convention. The common sense of orientation is mandatory, though.]
Depending on the local programming conventions, this is some atan2() of
the telescope coordinate differences North/South and East/West.

3) Compute/Get the star elevation above the horizon, $a=90$ deg minus $z$, where
$z$ is the star azimuth. This is equivalent to ISS ALT.

4) Compute the auxiliary angle $\psi$, in C notation $\psi=$atan2(sin$\psi$,cos$\psi$),
from the 2 intermediate variables $\sin\psi=$sin($A_b-A$) and $\cos\psi=$cos($A_b-A$)$\times\sin(a)$ ... of course using radians instead of degrees.
This implements Eqs. (35) and (36) of the current version of the reference.

5) Compute the parallactic angle $p$ in the standard convention (that is
zenith angle North-over-East): Imagine the star, the zenith $Z$ and the
north celestial pole (NCP) marked on the celestial sphere. Define the line
from the observer to the star as an axis of rotation. Rotation of
the NCP by the angle $p$ around the axis moves the NCP onto the great circle
defined by $Z$ and the star. Since this angle is defined "North-over-East",
one needs a left-handed sign convention with the aforementioned axis.
[We avoid a clockwise or counter-clockwise terminology here because this
depends on whether one looks at the celestial sphere from the inside or
from the outside. It is impossible to tell from the current definition
within DIC.ISS whether this is ISS PARANG as currently implemented.]

6) Compute the final angle $p_i=p+\psi+180$ deg and normalize to the
range $0..360$ deg, $p_i=$ slaDranrm($p+\psi+\pi$)$\times$DRAD2DEG
Use this as the header keyword.

There has been no statement on this subject by the AMBER team so far. The
update of the keyword description on PLBAij in the DIC.ISS would simply be

cmt: projected baseline orientation angle
desc: Let the projected baseline be the great semicircle on the
celestial sphere that starts at $T_1$, passes by the star, and ends
at $T_2$. Let a rotation axis point from the observer at the sphere
center to the star. The keyword value is the angle that
actively rotates the North Celestial Pole around this axis until
it meets the semicircle. The sign of the angle is "North-over-East"
as if one would impose a "left-handed" rule on this directed axis
of rotation.

If, however, for historical reasons, anybody wants to keep the old
computation of the keyword, the DIC.ISS needs a much more precise definition
of the current implementation for the current PBLAij. Keep in mind that this
information will be used by people who have neither access to the ESO SPR
system to look up the Gitton proposal nor access to the source code of the
isstrkws CMM module:

cmt: topocentric doubly projected baseline angle
desc: Define a projected baseline vector vec($P$) from the delay
vector vec($D$), which points into the star direction, and the
baseline vector vec($T_i$-$T_j$): vec($D$)+vec($P$)=vec($T_i$-$T_j$).
Project vec($P$) on the topocentric plane defined by the
observatory's horizon (ie, subtract its zenith component).
The keyword value is some compass rose (geographical)
orientation, confined to the range $[-90,90]$ degrees which
means dropping this doubly projected baseline vector's
sense of orientation.

Then, a new keyword for the standard projected baseline angle, like PBAij,
(short for projected baseline orientation angle from i to j)
needs to be defined that is computed according to 1)-6), and gets the
ESO-VLT-DIC.ISS description mentioned first.

04/10/06 17:54:07 vltsccm
SPR assigned to AWA for JULY 2006
07/13/06 14:57:15 awalland
The new algorithm has been implemented in test program isstemPBLA.c available
in isstest v 1.49. Test cases have been defined, documented and verified (isstemPBLA.doc)
DMD has confirmed they have no objections to this change (no side effect on official
MIDI and AMBER pipeline).

Next steps
- change the algorithms in isstrkws (Juergen)
double pblaRMA (double alt, double az, double prltic, double T1[3], double T2[3])
{
    vltDOUBLE a, A, A_b, p;
    vltDOUBLE sinpsi, cospsi, psi;
    double rma;
    
    /* 1. Compute A, star azimuth, with FITS convention; 0=south, +90 west
     * VLT convention is 0=south, +90 east
     */
    A = (360 - az) * DDEG2RAD;
    
    /* 2. Compute baseline azimuth on the platform
     * This is zero if T2 is south of T1 and +90 deg if T2 is west of T1.
     * It seems that DLCS applies the convention X pos to west and Y pos to south
     * for station coordinates (T vectors).
     * In a south-over-west convention for 'A_b' and 'a', the y-component
     * of the atan2(y,x) must represent +West and the x-component +South.
     * The vector from T1[.] to T2[.] is obtained as T2[.]-T1[.].
     */
    A_b = atan2( (T2[0] - T1[0]), (T2[1] - T1[1]) );
    
    /* 3. Get a, star elevation
     * This is directly given by VLT altitude
     */
    a = alt * DDEG2RAD;
    
    /* 4. Compute auxiliary angle psi
    */
    sinpsi = sin(A_b - A);
    cospsi = cos(A_b - A) * sin(a);
    psi = atan2(sinpsi,cospsi);
    
    /* 5. Get parallactic angle.
    * This value is computed by ISS using standard slaPa
    */
    p = prltic * DDEG2RAD;
    
    /* 6. Compute final angle
    */
    rma = slaDranrm(p + psi + DPI) * DRAD2DEG;
    return rma;
}

07/17/06 10:38:19 jott
The modifications are implemented and archived in isstrkws v. 3.7. The tat test is extended to verify values given in isstest/src/isstestPBLA.doc, isstest v. 1.45.
07/25/06 15:10:13 awalland
Description of keyword is updated in dicISS v 1.41.
07/26/06 16:02:48 awalland
Tested OK in control model.
Data in FITS header and isstest program consistent.

Configuration UT1 and UT4. DOUBLE value is azimuth expressed in VLT convention

<table>
<thead>
<tr>
<th>HIERARCH ESO ISS ALT</th>
<th>65.190 / Altitude angles at start</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIERARCH ESO ISS PARANG START=</td>
<td>123.159 / Parallactic angle at start</td>
</tr>
<tr>
<td>HIERARCH ESO ISS PBLA12 START=</td>
<td>245.2 / Projected baseline orientation ang</td>
</tr>
<tr>
<td>HIERARCH ESO ISS PARANG END =</td>
<td>123.159 / Parallactic angle at end</td>
</tr>
<tr>
<td>HIERARCH ESO ISS PBLA12 END =</td>
<td>245.2 / Projected baseline orientation ang</td>
</tr>
<tr>
<td>DOUBLE = 244.157236</td>
<td></td>
</tr>
</tbody>
</table>

isstestPBLA 65.19 244.157 123.159 -130.3058260 -43.9989351911 0 9.924885621 20.334616923 0
alt=65.19, az=244.16, prltic=123.16 T1: -103.306 -43.999 0.00, T2: 9.925 20.335 0.00
A 2.022, A_b 1.054, a 1.138, psi -0.82 0.51 -1.012, p 2.150
GIP pbla = 55.4 deg
RMA pbla = 245.2 deg

HIERARCH ESO ISS ALT  = 58.385 / Altitude angles at start
SPR is closed as solved.

Create-date : 02/25/06 00:33:51

5. VLTSW20060227

Problem Number VLTSW20060227
Synopsis Use switchyard and not telescope type when determine scales
Originator awalland
Responsible awalland
Status progress
Package VLTI-ISS (awalland nhousen )
Module Name ISS
Type change request
Closed Status
cc ott@four-d.de,rollfinke@four-d.de

Description In many places ISS performs different coordinate transformations depending if the beam passes through beam compressor or not. The current standard configurations are UT with BC, AT without. With PRIMA STS AT will also passes through BC. Sometimes exotic configurations breaking this rule are used.

It would be safer always to use the position of the switchyard to determine which coordinate transformation to do, and not rely on the telescope type.

Worklog mathar 9/19/06 11:00:41 AM
The field rotation also depends on whether the beams pass by the DDL or are moved on immediately to the instruments via the switchyard. Actually, the effects of DDL and beam compressor on the field rotation are expected to cancel. Also, since the STS on the UT's is (currently) designed with one mirror less than the STS for the AT's, there will still be an effect from the telescope type (beyond the well known effects depending on the position of the telescopes North or South of the DL etc, VLT-TRE-ESO-15000-3092).

The field rotation will also depend on the positions of the derotators of the AT's; to make things more exciting, there are two of them, one per AT, and they will be positioned differently, either by intention or mistake.

See section IIA in the report public/matharMIDI20051110.pdf in my home page.

vltsccm 9/18/06 6:23:30 PM
Appendix F: Spheroidal Coordinates

The Earth ellipsoid defines a geocentric latitude \( \phi' \) and geodetic latitude \( \phi \), the latter measured by intersection of the normal to the tangential plane with the equatorial plane \([22]\).

The files \( \text{http://www.strw.leidenuniv.nl/~mathar/vlti/oiArray.fits} \), \( \text{http://www.strw.leidenuniv.nl/~mathar/vlti/oiArray2.fits} \) and \( \text{http://www.strw.leidenuniv.nl/~mathar/vlti/oiArray3.fits} \) contain OIFITS implementations of the different interpretations of the angles of latitude listed in Sect. E1: \( \text{oiArray.fits} \) interprets them as geocentric \( \phi' \), \( \text{oiArray2.fits} \) and \( \text{oiArray3.fits} \) interpret them as geodetic \( \phi \). Each case, the construction finds the pair \((x, z)\) on the geoid using the flattening and equatorial radius. Depending on which interpretation is taken, these two places are some kilometers apart measured in the Cartesian coordinate system. (This is already expected from multiplying the directional difference of \( v = 524'' = 0.00254 \text{ rad given in Sect. E2} \) by the Earth radius \( \rho_e \) which yields 16 km.) We then follow the direction given by either \( \phi \) or \( \phi' \) further outwards by \( H = 2681 \text{ m} \) for each station as to include the mountain altitude and use this as the sum of the ARRAYI and STAXYZ coordinates. These station coordinates are necessarily distributed on a slightly curved surface, because no attempt has been made to re-arrange the heights above the geoid to obtain a flat plane that includes all the points. The difference between \( \text{oiArray2.fits} \) and \( \text{oiArray3.fits} \) is that \( \text{oiArray2.fits} \) uses the the IERS values of geoid flattening and equatorial radius \([25]\), whereas \( \text{oiArray3.fits} \) uses the WGS84 values \([27]\), causing a relative shift of the telescope array by \( \approx 40 \text{ cm} \).

If one inserts the angular coordinates \(-24.6274394, -70.4049869\) of Sec. E3 into \( \text{http://maps.google.com} \), using the Satellite option, one hits the Paranal platform with a precision of better than \( \approx 30 \text{ m} \) \([6]\). This means the two ways of interpreting the coordinates are consistent. Most likely, the google maps are using a WGS84 system, although it is difficult to find any documentation on this issue.

Another hint on that the geodetic interpretation is correct is given by reverse astrometry with IPHASE run over the file \( \text{d14UT4U4IP3-d13UT3U3IP1}_20060412.\text{dat} \) of the vltipom module, which contains delay data obtained with MIDI+FINTO for the U4–U3 baseline. (This pair of telescopes stretches best from North to South and is presumably most sensitive to relocation along the geographic latitude.) If one assumes the angle is of geodetic origin, the \( \text{iphase} \) input file is fed with \(-24 37 33.12\) in the SITE configuration and produces a zenith component (tilt) of the baseline of 15 mm; if one assumes the angle is of geocentric origin and converts it to \(-24 46 24.76\) before using it as a SITE parameter, the zenith component of the fit becomes 72 mm. (The difference of 57 mm is expected because the North-South component of the U3–U4 baseline is 22.1 m, which multiplied by \( v = 0.0025 \text{ rad} \) induces a tilt of 56 mm.) If one assumes that the better fit is the one with the smaller inclination of the baseline vector in the topocentric horizontal system, the fit with 15 mm and therefore the geodetic interpretation are preferred.

No response has been received from ESO on the question which of the two interpretations is correct.

Appendix G: Web Page Change Requests

1. WWW-31864

Your support request number WWW-31864 has now been closed. You will find the resolution at the END of this message.

Please contact us again quoting the above number should you find the resolution unsatisfactory.

Rgds,
ESO Web Team

Entry-Id: WWW-31864
First Name: Email
Last Name: User
Category: Web Pages
Short-Description: broken links
Problem Description:
09/04/06 13:47:26 mathar

The links to
http://www.eso.org/observing/etc/doc/vlti/lengthdata.txt
and to
http://www.eso.org/observing/etc/doc/vlti/baselinedata.txt
and to
http://www.eso.org/observing/etc/doc/vlti/posangledata.txt
at the bottom of
http://www.eso.org/observing/etc/doc/vlti/vltistations.html
are broken.
Dear Richard,

many thanks for reporting these broken links. I’ve forwarded your report to the ETC webteam and they will contact you as soon as possible.

Kind regards,
Michael

Michael Naumann • ESO, Karl Schwarzschild Str.2 85748 Garching
Michael.Naumann@eso.org • http://www.eso.org/mnaumann
ESO Webmaster • Tel/Fax +49 89 3200 6430, Germany

Appendix H: Acronyms

ARAL Artificial Source and Alignment Toolkit
AT Auxiliary Telescope (of the VLTI) http://www.eso.org/projects/vlti/AT/index_at.html
BC Beam Combiner
BC Beam Compressor
DDL Differential Delay Line http://www.mpia-hd.mpg.de/PRIMA-DDL/
DF Dual Feed
DL Delay Line
DLMT Delay Line Mirror Translation Stage (of the MIDI warm optics)
ESO European Southern Observatory http://www.eso.org
FINITO Fringe-Tracking Facility of Nice and Torino
FITS Flexible Image Transport System http://fits.gsfc.nasa.gov
fv fits viewer http://heasarc.gsfc.nasa.gov/docs/software/ftools/fv/
GENIE Ground based European Nulling Interferometry Experiment http://www.strw.leidenuniv.nl/~nevec/GENIE/
GUI Graphical User Interface
IR Infrared
ISAAC Infrared Spectrometer and Array Camera http://www.eso.org/instruments/isaac/
ISS Interferometric Supervisor-Software
IWS Instrument Workstation
LST Local sidereal time
MIA MIDI Interactive Analysis http://www.strw.leidenuniv.nl/~koehler/MIDI/
MIDI Mid-Infrared Interferometric Instrument http://www.mpia.de/MIDI
MPIA Max-Planck Institut für Astronomie, Heidelberg http://www.mpia.de
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPD</td>
<td>optical path difference</td>
<td></td>
</tr>
<tr>
<td>OPL</td>
<td>optical path length</td>
<td></td>
</tr>
<tr>
<td>OS</td>
<td>Observation Software</td>
<td></td>
</tr>
<tr>
<td>P2PP</td>
<td>Phase 2 Proposal Preparation</td>
<td><a href="http://www.eso.org/observing/p2pp">http://www.eso.org/observing/p2pp</a></td>
</tr>
<tr>
<td>PRIMA</td>
<td>Phase-Reference Imaging and Microarcsecond Astrometry</td>
<td><a href="http://obswww.unige.ch/Instruments/PRIMA">http://obswww.unige.ch/Instruments/PRIMA</a></td>
</tr>
<tr>
<td>PSF</td>
<td>point spread function</td>
<td></td>
</tr>
<tr>
<td>SF</td>
<td>Single Feed</td>
<td></td>
</tr>
<tr>
<td>STS</td>
<td>star separator</td>
<td></td>
</tr>
<tr>
<td>SWY</td>
<td>switchyard (table in the VLTI lab)</td>
<td></td>
</tr>
<tr>
<td>TAD</td>
<td>transverse atmospheric dispersion</td>
<td></td>
</tr>
<tr>
<td>URL</td>
<td>Universal Resource Locator</td>
<td></td>
</tr>
<tr>
<td>UT</td>
<td>Unit Telescope (of the VLTI)</td>
<td><a href="http://www.eso.org/projects/vlt/unit-tel/">http://www.eso.org/projects/vlt/unit-tel/</a></td>
</tr>
<tr>
<td>VINCI</td>
<td>VLT Interferometer Comissioning Instrument</td>
<td></td>
</tr>
<tr>
<td>VLTI</td>
<td>Very Large Telescope Interferometer</td>
<td><a href="http://www.eso.org/vlti">http://www.eso.org/vlti</a></td>
</tr>
<tr>
<td>ZOPD</td>
<td>zero OPD</td>
<td></td>
</tr>
</tbody>
</table>
Appendix I: Notations

\( \alpha \) right ascension
\( a, a' \) star elevation; inclination of projected baseline plane towards horizontal
\( A, \Delta A; A_6; A_3 \) star azimuth angle, and its change; baseline azimuth; visibility amplitude
\( b, b_{12} \) baseline length and vector
\( d \) aperture diameter
\( \delta \) declination
\( D, D_a, D_i \) OPD
\( e \) eccentricity of the Earth geoid
\( f \) Earth flattening factor
\( \phi, \phi' \) field rotation angle, geographic latitudes
\( \Phi \) geographic latitude
\( \varphi \) angular phase shift
\( h \) hour angle, see page 9
\( H \) observatory sea level altitude
\( L \) path length
\( \lambda \) wavelength; geographic longitude
\( p \) parallactic angle
\( \rho_b \) positional angle of the projected baseline circle
\( P \) projected baseline
\( R \) angular difference between true and apparent azimuth by TAD
\( \rho, \rho_e, \rho_p \) Earth radius (equatorial and polar)
\( s \) unit vector into star direction
\( \sigma \) wave-number \( 1/\lambda \)
\( \theta \) angular separation between pointing and baseline vector
\( t \) time
\( \tau \) baseline position angle
\( v \) angle between geodetic and geocentric angles of latitude
\( U, V, W \) Paranal Cartesian coordinates
\( \psi \) intersection angle between projected baseline circle and star meridian
\( x, y \) Cartesian components in a cut through the Earth geoid
\( z, \Delta z \) zenith angle, differential zenith angle
\( Z \) baseline angle seen from the Earth center

Leinert, C., 2003, Transfer of V, W-“field” onto MIDI, priv. commun.


On page 110, \( f^{-2} \) should read \( f^{-8/3} \), \( f < f \) should read \( f < f_e \), and \( 1.38 \times 10^{-3} \) should be squared.


Soler, T., 1998, J. Geod. 72, 482.


