Preliminary Draft

A Data Exchange Standard for Optical (Visible/IR) Interferometry

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1 Introduction

Considering the number of optical interferometers in operation or under construction it seems imperative that a standard be established which will allow the exchange of data among various groups. As a first step, we should try to agree on a standard for exchanging *calibrated* data. By first concentrating on calibrated data we only need those instrumental parameters which are required to characterize the data for subsequent analysis.

It has been agreed that the Flexible Image Transport System (FITS), in particular FITS “binary tables”, will be used as the basis for the data exchange standard. This document forms the specification for the FITS-based data-file format.

This release of the format specification is designed to standardize the exchange of imaging data, but does not preclude the possibility of including other types of data in future releases (e.g. astrometry data).

Document Conventions

In what follows we use the FITS binary table nomenclature of keywords and column headings. The values associated with the keywords can be considered as scalars, while each column can be simply an array, or an array of pointers to other arrays. Allowed data types are: **I** = integer (16-bit), **A** = character, **E** = real (32-bit), **D** = double (64-bit), **L** = logical, **M** = complex (2 64-bit). In the tables below, the number in parentheses is the dimensionality of the entry.

The table names given below correspond to the values of the EXTNAME keyword. Other mandatory keywords describing the structure of the FITS binary tables have been omitted (see “Definition of The Flexible Image Transport System”). The reference also describes various extensions to binary tables that are not part of the FITS standard. None of these are currently used in this format.

The revision numbers of all tables are currently zero. After a suitable amount of discussion and consequent changes, the table definitions will be “frozen”, and assigned revision numbers of one. Further changes will require increments in the appropriate revision numbers.

We suggest that the common data format be referred to as the “OI Exchange Format”, or the “Exchange Format” when the context is clear. This document is the “Format Specification”. It uses US English spellings.

2 Definitions and Assumptions

Baseline vector

The baseline vector between two interferometric stations A and B whose position vectors are $\mathbf{x_A}$ and $\mathbf{x_B}$ is defined as $\vec{AB} = x_B - x_A$.

UV coordinates

u is the East component and v is the North component of the projection of the baseline vector onto the plane normal to the direction of the phase center, which is assumed to be the pointing center.

Complex Visibility

The basic observable of an interferometer is the complex visibility, which is related to the sky brightness distribution $I(x,y)$ by a Fourier Transform:

$$V(u,v) = \iint dx\,dy\,I(x,y)\,e^{-2pi(ux+vy)}$$

x and y are displacements (in radians) in the plane of the sky (which is assumed to be flat). The origin of this coordinate system is the phase center. x is in the direction of increasing right ascension (i.e. the x axis points East), and y is in the direction of increasing declination (the y axis points North).

With x and y defined, the above equation defines the sign convention for complex visibilities that should be used in the data format.

The visibility is normalized by the total flux from the target, which is assumed to remain constant over the time spanned by the measurements in the file. Neither the field of view over which the “total” flux is collected, or the field of view over which fringes are detected (i.e. the limits of the above integral), can be inferred from the data file.

Squared Visibility

The squared visibility is simply the modulus squared of the complex visibility:

$$S(u,v) = |V(u,v)|^2$$

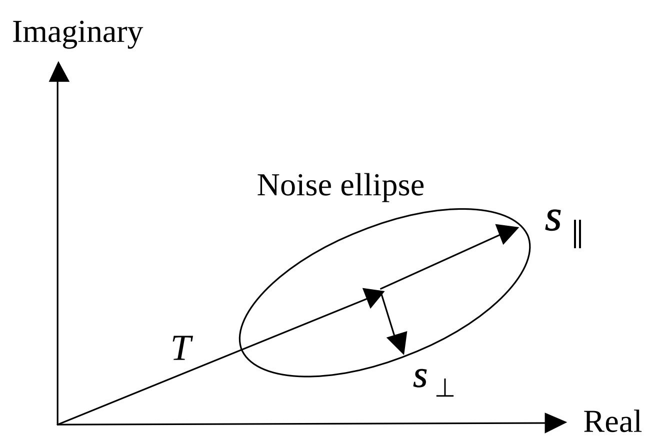
Triple Product

The triple product, strictly the *bispectrum*, is the product of the complex visibilities on the baselines forming a closed loop joining three stations A, B and C. In the following expression, (u_1, v_1) is the projection of **AB** and (u_2, v_2) is the projection of **BC** (and hence (u_1+u_2, v_1+v_2) is the projection of **AC**):

$$T(u_1, v_1, u_2, v_2) = V(u_1, v_1)V(u_2, v_2)V^*(u_1+u_2, v_1+v_2)$$

Noise model for triple product

The data are assumed to be complex triple products averaged over a large number of “exposures”. In such a case, the noise can be fully described in terms of a Gaussian noise ellipse in the complex plane. Photon, detector and background noise tend to lead to noise ellipses that are close to circular. On the other hand, fluctuating atmospheric phase errors across telescope apertures typically cause fluctuations in the amplitude of the triple product which are much larger than the fluctuations in the phase. Thus the “atmospheric” contribution to the noise ellipse is elongated along the direction of the mean triple product vector in the Argand diagram, as shown in the figure. Such noise needs to be characterised in terms of the variance $\sigma_\perp^2$ perpendicular to the mean triple product vector T and the variance $\sigma_\parallel^2$ parallel to T. We can parameterize the perpendicular variance in terms of a “phase error” $\sigma_\theta = (180/\pi)(\sigma_\perp/|T|)$. The phase error gives an approximate value for the rms error in the closure phase in degrees. We denote $\sigma_\parallel$ as the “amplitude error”.



In many cases, the observer may be interested primarily in the closure phase and not the triple product amplitude, and therefore may choose not to calibrate the amplitude. Such a case can be indicated in the above notation as an infinite amplitude error and a finite phase error. The data format specifies that such a case should be indicated by a NULL value for the amplitude (the amplitude error value is then ignored).

Noise model for complex visibility

There has been much discussion of the representation to use for complex visibilities in the standard. The interested reader is referred to the oi-data email list: `oi-data@rsd.nrl.navy.mil`

A number of different classes of data can be represented as complex visibilities, including several varieties of differential phase data. In all cases the standard should only be used to store averaged data. Thus, as with triple products, we must consider the shape of the noise ellipse in the complex plane.

It has been demonstrated (see `http://www.mrao.cam.ac.uk/~jsy1001/exchange/complex/complex.html`) that both circularly-symmetric noise, and noise ellipses elongated parallel to or perpendicular to the mean vector can occur in practice. Thus far there has been no evidence for noise ellipses elongated parallel to the real or imaginary axes, although examples of some classes of data have yet to be presented.

Hence an amplitude/phase representation of complex visibilities, mirroring that used for triple products, has been adopted in the current version of the standard.

3 FITS File Structure

A valid exchange-format FITS file must contain one (and only one) OI_TARGET table, plus one or more of the data tables: OI_VIS, OI_VIS2, or OI_T3. Each data table must refer to an OI_WAVELENGTH table that is present in the file. There may be more than one of each type of data table (e.g. OI_VIS2). One or more OI_ARRAY tables (or equivalent e.g. for aperture masking, in future releases of the Standard) may optionally be present. Where multiple tables of the same EXTNAME are present, each should have a unique value of EXTVER (this according to the FITS standard – however the example C code and John Monnier's IDL software do not require EXTVER to be present).

The tables can appear in any order. Other header-data units may appear in the file, provided their EXTNAMEs do not begin with "OI_".

Reading software should not assume that either the keywords or the columns in a table appear in a particular order. This is straightforward to implement using software libraries such as cfitsio.

Any of the tables may have extra keywords or columns beyond those defined in the Standard. It would facilitate the addition of new keywords and columns in future releases of the Standard if the non-standard keywords and column names were given a particular prefix e.g. "NS_", to avoid conflicts.

4 Tables Defined by the Standard

OI_ARRAY *revision 0*

As defined, this table is aimed at ground-based interferometry with separated telescopes. Alternative tables could be used for other cases. These must have at least an ARRNAME keyword, for cross-referencing purposes. Each OI_ARRAY-equivalent table in a file must have a unique value for ARRNAME.

Keywords

OI_REVN	**I**	Revision number of the table definition
ARRNAME	**A**	Array name, for cross-referencing
FRAME	**A**	Coordinate frame
ARRAYX		
ARRAYY	**D**	Array center coordinates (meters)
ARRAYZ		

Column Headings (one row for each telescope)

TEL_NAME	**A** (16)	Telescope name
STA_NAME	**A** (16)	Station name
STA_INDEX	**I** (1)	Station number
DIAMETER	**E** (1)	Element diameter (meters)
STAXYZ	**D** (3)	Station coordinates relative to array center (meters)

Number of elements

There is no keyword giving the number of elements (NELEMENT in a previous revision of this document), as this is equal to the number of rows in the FITS binary table, which is given by the standard NAXIS2 keyword. For the same reason, there are no format-specific keywords giving the number of rows in any of the other tables.

Coordinate frame

If the FRAME keyword has the value “GEOCENTRIC”, then the coordinates are given in an earth-centered, earth-fixed, Cartesian reference frame. The origin of the coordinates is the earth’s centre of mass. The z axis is parallel to the direction of the conventional origin for polar motion. The x axis is parallel to the direction of the intersection of the Greenwich meridian with the mean astronomical equator. The y axis completes the right-handed, orthogonal coordinate system.

Currently, no other values for the FRAME keyword may be used. This will change if the need arises.

Array coordinates

The ARRAYX, ARRAYY, and ARRAYZ keywords shall give the coordinates of the array center in the coordinate frame specified by the FRAME keyword. Element coordinates in the main part of the table are given relative to the array center, in the same coordinate frame. Coordinates are given in meters.

Station number

Each row in the table shall be assigned a unique station number, which shall be used in other tables as an index into this one.

The table structure is the simplest possible i.e. there is no explicit concept of different "configurations" within the table. Each row in the table shall correspond to a distinct set of station coordinates used in taking the data stored in the file.

Element diameter

This is the effective aperture size, e.g. if the telescope is stopped down.

OI_TARGET revision 0

Keywords

OI_REVN	**I**	Revision number of the table definition

Column Headings (one row for each source)

TARGET_ID	**I** (1)	Index number
TARGET	**A** (16)	Target name
RAEP0	**D** (1)	RA at mean equinox (degrees)
DECEP0	**D** (1)	DEC at mean equinox (degrees)
EQUINOX	**E** (1)	Equinox
RA_ERR	**D** (1)	Error in RA at mean equinox (degrees)
DEC_ERR	**D** (1)	Error in DEC at mean equinox (degrees)
SYSVEL	**D** (1)	Systemic radial velocity (meters per second)
VELTYP	**A** (8)	Reference for radial velocity ('LSR', 'GEOCENTR', etc.)
VELDEF	**A** (8)	Definition of radial velocity ('OPTICAL', 'RADIO')
PMRA	**D** (1)	Proper motion in RA (degrees per year)
PMDEC	**D** (1)	Proper motion in DEC (degrees per year)
PMRA_ERR	**D** (1)	Error of proper motion in RA (degrees per year)
PMDEC_ERR	**D** (1)	Error of proper motion in DEC (degrees per year)
PARALLAX	**E** (1)	Parallax (degrees)

PARA_ERR	**E** (1)	Error in parallax (degrees)
SPECTYP	**A** (16)	Spectral type

Target position

The RAEP0 and DECEP0 columns shall contain the right ascension and declination respectively of the phase center at the standard mean epoch, in degrees. RA_ERR and DEC_ERR shall contain the one-sigma uncertainties in these quantities.

The phase center is assumed to be the pointing center. The EQUINOX field shall contain a (floating point) Julian year giving both the epoch of the position (RAEP0, DECEP0) and the equinox for the celestial coordinate system in which the position is expressed.

The PMRA and PMDEC columns should contain the proper motions of the source in right ascension and declination respectively, in degrees per Julian year. If the proper motion is unknown then both fields should be set to zero. PMRA_ERR and PMDEC_ERR shall contain the one-sigma uncertainties in these quantities.

If an apparent position at the time of an observation is required, it should be obtained by applying the appropriate transformations to the catalogue position given by RAEP0 and DECEP0, making use of PMRA, PMDEC, and PARALLAX.

Velocity Information

The SYSVEL column shall give the systemic radial velocity of the target (positive if receding).

The VELTYP column shall contain a string that specifies the frame of reference for the systemic velocities. The string shall be one of the following:

LSR	Local Standard of Rest
HELIOCEN	Relative to the SUN
BARYCENT	Solar system barycenter
GEOCENTR	Center of mass of the earth
TOPOCENT	Uncorrected

The VELDEF column shall contain a string indicating the convention used for the (relativistic) systemic velocities. It shall be either “RADIO” or “OPTICAL” (the distinction is not important for velocities much less than the speed of light).

OI_WAVELENGTH revision 0

Keywords

OI_REVN	**I**	Revision number of the table definition
INSNAME	**A**	Name of detector, for cross-referencing

Column Headings (one row for each wavelength channel)

EFF_WAVE	**E**	Effective wavelength of channel (meters)
EFF_BAND	**E**	Effective bandpass of channel (meters)

Name of detector

Each OI_WAVELENGTH table in a file must have a unique value for INSNAME.

Wavelengths

Each OI_WAVELENGTH table describes the spectral response of detector(s) with a number of spectral channels. Each table gives the wavelengths for one or more of the data tables (OI_VIS, OI_VIS2, OI_T3), and will often correspond to a single physical detector.

The EFF_WAVE column shall contain the best available estimate of the effective wavelength of each spectral channel, and the EFF_BAND column shall contain the best available estimate of the effective half-power bandwidth. These estimates should include the effect of the earth's atmosphere, but not the spectrum of the target (the effect of the target spectrum should be taken into account as part of any model-fitting/mapping process, i.e. the target spectrum is part of the model).

OI_VIS *revision 0*

Keywords

OI_REVN	**I**	Revision number of the table definition
DATE-OBS	**A**	UTC start date of observations
ARRNAME	**A**	(optional) Identifies corresponding OI_ARRAY
INSNAME	**A**	Identifies corresponding OI_WAVELENGTH table

Column Headings (one row for each measurement)

TARGET_ID	**I** (1)	Target number as index into OI_TARGET table
TIME	**D** (1)	UTC time of observation (seconds)
MJD	**D** (1)	Modified Julian Day
INT_TIME	**D** (1)	Integration time (seconds)
VISAMP	**D** (NWAVE)	Visibility amplitude
VISAMPERR	**D** (NWAVE)	Error in visibility amplitude
VISPHI	**D** (NWAVE)	Visibility phase in degrees
VISPHIERR	**D** (NWAVE)	Error in visibility phase in degrees
UCOORD	**D** (1)	U coordinate of the data (meters)
VCOORD	**D** (1)	V coordinate of the data (meters)

STA_INDEX	**I** (2)	Station numbers contributing to the data
FLAG	**L** (NWAVE)	Flag

OI_VIS2 ***revision 0***

<u>Keywords</u>

OI_REVN	**I**	Revision number of the table definition
DATE-OBS	**A**	UTC start date of observations
ARRNAME	**A**	(optional) Identifies corresponding OI_ARRAY
INSNAME	**A**	Identifies corresponding OI_WAVELENGTH table

<u>Column Headings</u> (one row for each measurement)

TARGET_ID	**I** (1)	Target number as index into OI_TARGET table
TIME	**D** (1)	UTC time of observation (seconds)
MJD	**D** (1)	Modified Julian Day
INT_TIME	**D** (1)	Integration time (seconds)
VIS2DATA	**D** (NWAVE)	Squared Visibility
VIS2ERR	**D** (NWAVE)	Error in Squared Visibility
UCOORD	**D** (1)	U coordinate of the data (meters)
VCOORD	**D** (1)	V coordinate of the data (meters)
STA_INDEX	**I** (2)	Station numbers contributing to the data
FLAG	**L** (NWAVE)	Flag

OI_T3

<u>Keywords</u>

OI_REVN	**I**	Revision number of the table definition
DATE-OBS	**A**	UTC start date of observations
ARRNAME	**A**	(optional) Identifies corresponding OI_ARRAY
INSNAME	**A**	Identifies corresponding OI_WAVELENGTH table

<u>Column Headings</u> (one row for each measurement)

TARGET_ID	**I** (1)	Target number as index into OI_TARGET table
TIME	**D** (1)	UTC time of observation (seconds)
MJD	**D** (1)	Modified Julian Day
INT_TIME	**D** (1)	Integration time (seconds)

T3AMP	**D** (NWAVE)	Triple Product Amplitude
T3AMPERR	**D** (NWAVE)	Error in Triple Product Amplitude
T3PHI	**D** (NWAVE)	Triple Product Phase in degrees
T3PHIERR	**D** (NWAVE)	Error in Triple Product Phase in degrees
U1COORD	**D** (1)	U coordinate of baseline AB of the triangle (meters)
V1COORD	**D** (1)	V coordinate of baseline AB of the triangle (meters)
U2COORD	**D** (1)	U coordinate of baseline BC of the triangle (meters)
V2COORD	**D** (1)	V coordinate of baseline BC of the triangle (meters)
STA_INDEX	**I** (3)	Station numbers contributing to the data
FLAG	**L** (NWAVE)	Flag

The following comments apply to one or more of the OI_VIS, OI_VIS2, and OI_T3 tables.

Cross-referencing

Each data table must refer (via the INSNAME keyword) to a particular OI_WAVELENGTH table describing the wavelength channels for the measurements. Each data table may optionally refer, via the ARRNAME keyword, to an OI_ARRAY table.

Start date of observations

This shall be a UTC date in the format YYYY-MM-DD, e.g. "1997-07-28".

Time of observation

The value in the TIME column shall be the mean UTC time of the measurement in seconds since 0h on DATE-OBS. Note this may take negative values, or values > 86400 seconds, and hence the epoch of observation for the particular table is not restricted to DATE-OBS.

The value in the MJD column shall be the mean UTC time of the measurement expressed as a modified Julian Day. It might be appropriate to use the MJD values instead of the TIME values when dealing with long time-spans, but the Standard makes no stipulation in this regard.

Integration time

The exchange format will normally be used for interchange of time-averaged data. The "integration time" is therefore the length of time over which the data were averaged to yield the given data point.

Data arrays

If the triple product amplitudes are meaningless, as is the case for COAST data, NULL values for T3AMP may be used. The closure phases should still be treated as valid.

NWAVE is the number of distinct spectral channels recorded by the single (possibly "virtual") detector, as given by the NAXIS2 keyword of the relevant OI_WAVELENGTH table.

Complex visibility and visibility-squared UV coordinates

UCOORD, VCOORD give the coordinates in meters of the point in the UV plane associated with the vector of visibilities. The data points may be averages over some region of the UV plane, but the current version of the Standard says nothing about the averaging process. This may change in future versions of the Standard.

Triple product UV coordinates

The U1COORD, V1COORD, U2COORD, and V2COORD columns contain the coordinates of the bispectrum point – see page 2 for details. Note that U3COORD and V3COORD are implicit.

The corresponding data points may be averages in (bi-) spatial frequency space, but this version of the Standard does not attempt to describe the averaging process.

Flag

If a value in this vector is true, the corresponding datum should be ignored in all analysis.

4 Optional Tables

It may be useful to allow for some optional tables. For example, there might be one that contains instrument specific information, such as the backend configuration. Another optional table could contain information relevant to astrometry.

The EXTNAMEs of additional tables should not begin with "OI_".

References

Definition of the Flexible Image Transport System, NOST, 1999.