ASPRO2: get ready for VLTI's instruments GRAVITY and MATISSE

Optical and Infrared Interferometry and Imaging V

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Introduction

- ASPRO2 = the 2nd version of the Astronomical Software to PRepare Observations
- Developped & maintained by the JMMC since 2010
- Software package + documentation available at: `http://www.jmmc.fr/aspro`
- Supports all optical interferometers in operation (VLTI, CHARA, SUSI, NPOI) and their instruments
- Regular releases imposed by ESO & CHARA Call for Proposals

- Your feeback is welcome at `jmmc-user-support@ujf-grenoble.fr`

Main features

To prepare VLTI observations:

- define science and calibrator targets (Simbad and SearchCal services).
  Every object can have either an analytical or user model,
- manage many targets for large programs,
- define the observation setup by selecting the interferometer & the ESO Period, the instrument, configuration (quadruplet), the observation date... ,
- display the observability of all targets and the UV coverage of the target along with its model,
- produce a simulated observation, including accurate noise modelling, that other tools can use to perform model-fitting or image reconstruction.

Main features

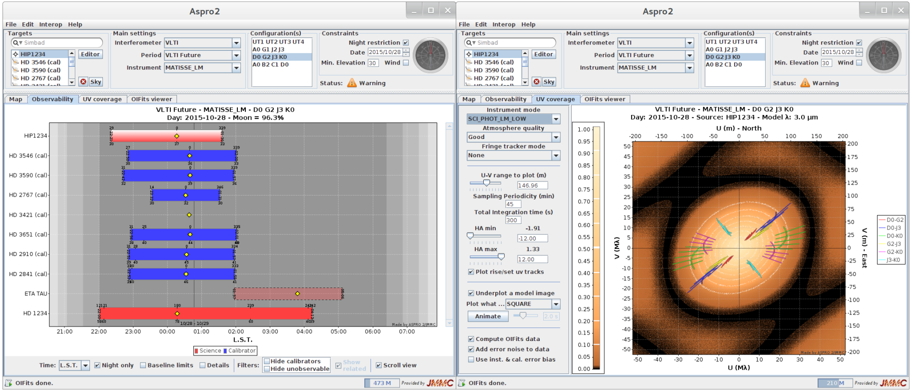


Figure : the observability and the UV Coverage plots for a MATISSE L+M observation

Main features

To determine the source observability, ASPRO2 takes into account:

- the night limits at the observation date,
- the chosen minimum elevation,
- telescope horizons (shadowing) i.e. new ESO profiles recently released,
- UV coverage restrictions due to the limited optical path compensation for the configuration,
- the moon avoidance rules,
- (telescope pointing restrictions due to the wind direction).

UV coverage:

- projected baselines on the Fourier plane sampled regularly within observability ranges,
- each UV segment represents the spectral range of the instrument mode,
- the target model is computed (complex visibility) and scaled (amplitude or phase).

VLTI GRAVITY configuration

Since 2014: GRAVITY and MATISSE instruments present in the VLTI "Future" period.

GRAVITY configuration:

- Period 98: official ESO quadruplets,
- "Future" period with more quadruplets (commissioning),
- 4-telescope instrument in the K band (1.9 to 2.5 μm),
- LOW, MEDIUM & HIGH resolutions ($=$ 50, 1100, 8000),
- internal fringe tracker in the H band.

TODO:

- effective MEDIUM & HIGH resolution modes (windowing),
- support the dual-field observation mode.

VLTI MATISSE configuration

MATISSE configuration:

- "Future" period only (testing phase),
- "polychromatic" 4-telescope instrument (3 to 13 μm) described by 2 different instruments:
  - MATISSE_LM: full L+M bands (2.8 to 5.0 μm) with LOW, MEDIUM, HIGH & VERY HIGH resolutions (= 30, 500, 950, 4000),
  - MATISSE_N: full N band (7.5 to 13.5 μm) with LOW & MEDIUM resolutions (= 30, 300).
- 2 observing modes:
  - SCI_PHOT mode: simultaneous Interferometry and Photometry measurements (2/3, 1/3 ratio)
  - HIGH_SENS mode: Interferometry measurement only (maybe plus some photometry measurements)

TODO:

- refine spectral ranges to match the detector windowing constraints (high resolutions)
- adjust observing modes (HIGH_SENS)
- support the GRA4MAT fringe tracker (H band)

User Models

The Target editor supports either Analytical (gray) or User models (FITS cubes):

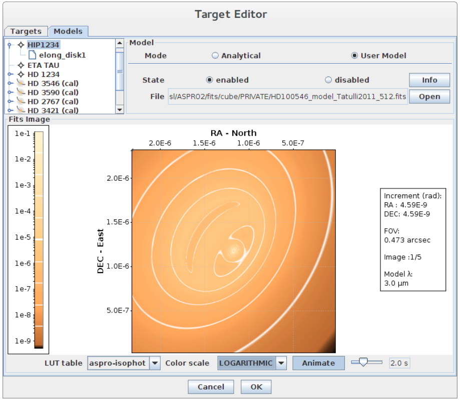


Figure : Target Editor for a MATISSE user model (5 images)

User Models

User models gives the object flux over the sky (spatial axes RA/DEC):

- FITS images (monochromatic models),
- FITS cubes (polychromatic models) where the 3rd axis is the spectral axis.
- ASPRO2 interprets FITS keywords:
  - extract spatial and spectral increments, their coordinate references and units.
  - e.g. spectral axis: initial wavelength and increment expressed in: meter, micron, nano-meter, hertz.

ASPRO2 computes complex visibilities for the spectral channels of the instrument mode:

- determine which image corresponds to every spectral channel by selecting the image whose wavelength is the closest (within the spectral bandwidth and increment),
- handle sub-sampling (less images than channels) or super-sampling (several images per channel).

Observing Blocks

- Export the observation setup for VLTI instruments (AMBER, PIONIER) to ESO P2PP tool:
  - 1 OB per target (science or calibrator),
  - 1 container OB aggregating the science object with its calibrators.

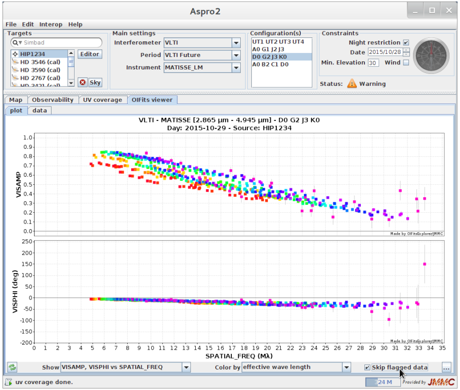
- 2016: Observing Blocks for GRAVITY observations (single field mode only),
- polarization mode set (COMBINED or SPLIT).

TODO:

- support the dual-field mode: manage the association and constraints between the two objects,
- generate Observing Blocks for the MATISSE instrument (once templates are defined).

OIFITS Simulator

- simulate observation data according to the OIFITS standard (version 1),
- provide the OIFITS viewer to plot observables quantities, as a function of many parameters: spatial frequency, hour angle, wavelength...



Principle

- observable target: sampled hour angles (HA) and its position (azimuth, elevation),
- selected interferometer and configuration: projected baseline vectors between each telescope pair then sampled UV points for sampled HA,
- selected instrument mode: spectral channels and their bandwidth

Observable quantities (OI_VIS, OI_VIS2, OI_T3) are computed at the spatial frequencies (u_{freq}, v_{freq}) corresponding to the sampled HA and baselines (UV points = rows) and per spectral channels λ:

- Target model: compute complex visibilities C_{vis} at (u_{freq}, v_{freq}) for each spectral channel (λ) organized as a 2D table [rows][channels],
- Noise modelling: compute the error on the complex visibilities σ_{vis} per row and spectral channel,
- derive observable quantities (VIS, VIS2, T3) and their errors from C_{vis} and σ_{vis} using a sampling approach.

Principle

- Calibrating an observation introduces new uncertainties as the transfer function evolves between calibrator observations (CAL–SCI–CAL sequence)
- but "calibration error" = bias and not an additional gaussian error term !

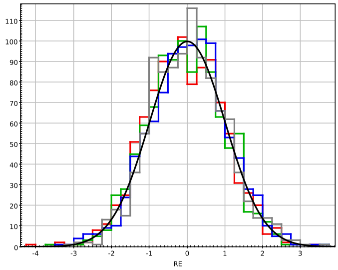
Future improvement but a complex task:

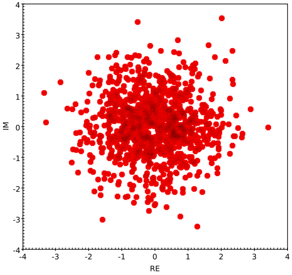
- simulate both science and calibration observations with their errors,
- add the transfer function variability (to be modelled),
- perform the calibration to obtain realistic square visibilities and (ultimately non-gaussian) errors.

Sampling approach

Complex visibility sampling with a circular-symmetric error distribution (1024 samples):

- $C_{sample} = C_{vis} + D(\sigma^2_{vis})$
  - $\Re_{sample} = \Re_{vis} + N(0, \sigma^2_{vis})$
  - $\Im_{sample} = \Im_{vis} + N(0, \sigma^2_{vis})$





Sampling approach

To compute correlated quantities VIS, VIS2 and T3 for the related UV points (baseline or triplets), ASPRO2 uses one distribution D per UV point but determine randomly a sampling index j for each hour angle and spectral channel to get consistently the jth sample of each observable quantity:

C_{vis} (Re, Im)	σ_{vis}	Baseline (stations)	D (distrib.)	sample index
C_{12}	σ_{12}	1-2	D_1	j
C_{23}	σ_{23}	2-3	D_2	j
C_{13}	σ_{13}	1-3	D_3	j

Sampling approach

Complex visibility sampling:

- numerically compute samples of the observable quantities,
- estimate the appropriate mean and variance of these sampled variables.

For angular variables (VISPHI, T3PHI), compute in two passes:

- the average angle,
- the variance as the sum of the squares of the distance [0..180 deg] to the average angle.

The *jth* sample is retained as the observable value (“correlated” quantities).

Observable quantities

- unbiased square visibility:
  - $VIS2DATA = |C_{sample}|^2 - bias = \Re^2_{sample} + \Im^2_{sample} - 2\sigma^2_{vis}$
- (theoretical) visibility, as it is strongly dependent on the data reduction algorithm:
  - $VISAMP = |C_{sample}| = \sqrt{\Re^2_{sample} + \Im^2_{sample}}$
  - $VISPHI = \arg(C_{sample}) = atan2(\Im_{sample}, \Re_{sample})$
- bi-spectrum $T3$: 3 different complex visibility distributions (C_{12}, C_{23}, C_{13}):
  - $T3_{sample} = C_{12} C_{23} \overline{C_{13}} = \Re_{T3\_sample} + i\Im_{T3\_sample}$
  - $\mathrm{T3AMP} = |T3_{sample}| = \sqrt{\Re^2_{T3\_sample} + \Im^2_{T3\_sample}}$
  - $\mathrm{T3PHI} = \arg(T3_{sample}) = atan2(\Im_{T3\_sample}, \Re_{T3\_sample})$

Noise Modelling improvements

- Approach described in the document "Noise Model for Interferometric combiners"[1] that models a generic interferometer and recombiner observing the science object:

Photons from the science object are affected by the atmosphere transmission, the adaptive optics system (Strehl ratio) to perform injection into the spatial filter of the recombiner, and finally by the interferometer and instrument transmission.

- Let $N(\lambda)$ define the photon count of the science object per second, per beam and per spectral channel and $N_{th}(\lambda)$ the photon count of the thermal background per spectral channel.
- Spectral channels depend on the instrument mode (wavelength range and spectral resolution) and their bandwidth may be non-linear.

[1] http://www.jmmc.fr/doc/index.php?search=JMMC-MEM-2800-0001

Noise Modelling improvements

- Instrument recombiner is modelled by:
  - one Interferometric channel
  - several Photometric channels
  - measured by a CCD detector (read-out noise σ_{det}) where photons are spectrally dispersed on interferometric and photometric pixels: per spectral channel n^{I}_{pix} and n^{P}_{pix} per photometric beam.
  - fractions f_I and f_P describe the proportions in the interferometric and photometric channels.

- Total integration time in ASPRO2 = total time spent on the science object that determines the number of frames that improves SNR by $\sqrt{n_{frame}}$.
- Frame duration t_{int} ? normally 1 *dit* (no saturation) but with FT: t_{int} can be increased.

- ASPRO2 does not work in terms of the duration of an observing block (OB) including overheads, chopping, etc... but could be done in the future.

Noise Modelling improvements

To convert the photon count per second to the number of photo-electrons per frame, ASPRO2 uses the following formula including the quantum efficiency of the detector ($\approx 50\%$ in mid. infrared):

$$N_I^{e^-}(\lambda) = f_I N(\lambda) Q_E t_{int}\,, \quad N_P^{e^-}(\lambda) = f_P N(\lambda) Q_E t_{int},$$

and for the thermal background:

$$N_{I\_th}^{e^-}(\lambda) = f_I N_{th}(\lambda) Q_E t_{int}\,, \quad N_{P\_th}^{e^-}(\lambda) = f_P N_{th}(\lambda) Q_E t_{int}.$$

Noise Modelling improvements

- Square visibility error $\sigma(|V|^2)$ computed from the interferometric and the photometric contributions to the square coherent flux error:

$$\sigma(|V|^2) = \frac{|V|^2}{\mathrm{SNR}(|V|^2)}, \quad \frac{1}{\mathrm{SNR}(|V|^2)^2} = \frac{1}{\mathrm{SNR}(|F_c|^2)^2} + \frac{2}{\mathrm{SNR}(F_p)^2},$$

- SNR of the square coherent flux is

$$\mathrm{SNR}(|F_c|^2) \approx \frac{N_I^{e^-} V_{inst}|V|}{\sqrt{2N_{tel}(N_I^{e^-} + N_{I\_th}^{e^-}) + 2n_{pix}^I \sigma_{det}^2}} \sqrt{n_{frame}},$$

  - V_{inst} = total instrumental visibility,

Noise Modelling improvements

- SNR of each photometry is

$$\mathrm{SNR}(F_p) = \frac{N_P^{e^-}}{\sqrt{N_P^{e^-} + n_{exp}^P (N_{P\_th}^{e^-} + n_{pix}^P \sigma_{det}^2)}} \sqrt{n_{frame}},$$

  - n_{exp}^P is the number of photometric exposures per photometric beam (chopping).

- Complex visibility error is derived from

$$\sigma(|V|) = \frac{\sigma(|V|^2)}{2V} = \frac{|V|}{2\mathrm{SNR}(|V|^2)}$$

and is equally distributed on real and imaginary parts (circular-symmetric distribution).

MATISSE setup in ASPRO2

MATISSE_LM and MATISSE_N instruments:

- Instrument setups SCI_PHOT and HIGH_SENS:
  - noise modelling parameters (typical *dit*, flux fractions f_I & f_P, detector's quantum efficiency Q_E and read-out noise σ_{det}, average pixel count per spectral channel n^I_{pix} and n^P_{pix}) that are not depending on the spectral resolution,
  - exposure sequences (SCIENCE, SKY, PHOTOMETRY...) to describe chopping ($n^P_{exp} = 2$), and optionally the interferometry / photometry successive exposures (HIGH_SENS).
- Instrument modes (= spectrally-dependent parameters) using data tables (computed theoretically by A. Matter):
  - spectral channels λ and $\Delta\lambda$
  - related noise modelling parameters per telescope (UT or AT):
    - thermal photon count $N_{th}(\lambda)$ per second
    - interferometer + instrument transmission $T_{ins}(\lambda)$
    - instrument visibility V_{inst}.

MATISSE thermal background noise

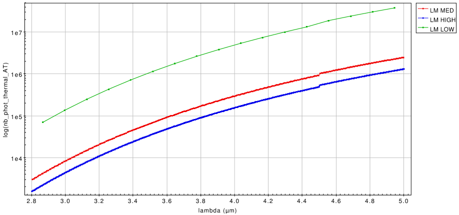


Figure : thermal photon count $N_{th}(\lambda)$ per second for the MATISSE L+M bands (2.8 to 5.0 μm) on AT telescopes at LOW, MEDIUM and HIGH resolutions

- Good description of the spectral channels (supporting variable bandwidths) and spectrally dependent parameters,
- Data tables to be updated during test or commissioning phases.

Object photon count

- Basic approach = magnitude to flux conversion:

$$flux(\lambda) = \phi_0(band)10^{-0.4m_{band}}$$

  where ϕ_0 is the zero-magnitude flux in the band.
- TODO: obtain the flux either from polychromatic user models or from user-given spectra.

- The total number of photons (per beam, per second) is given by

$$N(\lambda) = flux(\lambda).\Delta\lambda.S_{tel}.Strehl(\lambda, elevation).T(\lambda),$$

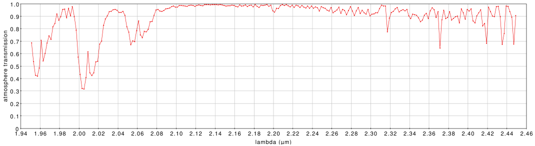
  where the global transmission combines the atmosphere transmission $T_{atm}(\lambda)$ and the interferometer and instrument transmissions $T_{ins}(\lambda)$, that gives

$$T(\lambda) = T_{atm}(\lambda)T_{ins}(\lambda)$$

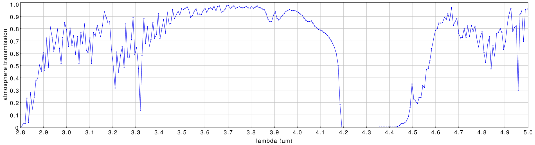
Atmosphere transmission

- ASPRO2 uses one atmosphere transmission spectra at high resolution, provided by the ESO SkyCalc tool, for average conditions:
  - yearly average,
  - airmass = 1 arcsec,
  - PWV = 2.5mm,
  - object at zenith,
- Resampling according to the instrument mode (resolution): $T_{atm}(\lambda)$.
- Important impact at the band boundaries, between L & M bands or at high resolutions.
- Other weather conditions (PWV, airmass) or the target elevation could be handled in the future.

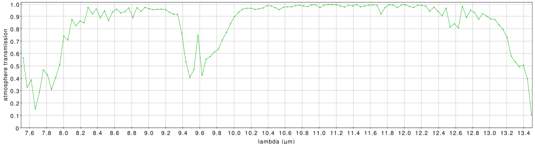
Atmosphere transmission



GRAVITY (K)



MATISSE (L+M)



MATISSE (N)

Figure : atmosphere transmission for GRAVITY & MATISSE instruments at medium resolution

Strehl ratio

- zenithal angle correction ($\gamma = 90 - elevation$) of the object on the sky to estimate the Fried parameter r_0 from the seeing θ (arcsec) at the observing wavelength λ:

$$r_0 = 0.251 \cos(\gamma)^{3/5} (\frac{\lambda_V}{\theta})(\frac{\lambda}{\lambda_V})^{6/5}$$

- Strehl ratio computed for each spectral channel (AO or tip-tilt):

$$S = \exp(-\sigma^2_\phi) + \frac{1 - \exp(-\sigma^2_\phi)}{1 + (\frac{D}{r_0})^2}$$

$$\sigma^2_\phi = \sigma^2_{\mathrm{alias+fit}} + \sigma^2_{\mathrm{photons}} + \sigma^2_{\mathrm{fixed}} \, , \, \sigma^2_{\mathrm{fixed}} = -\log S_{max}$$

$$\sigma^2_{\mathrm{alias+fit}} = 0.87 N_{\mathrm{act}}^{-5/6} (\frac{D}{r_0})^{5/3}$$

$$\sigma^2_{\mathrm{photons}} = 1.59 \times 10^{-8} (\frac{D}{r_0})^2 (\frac{\lambda}{\lambda_V})^{-2} N_{\mathrm{act}} 10^{0.4 m_V}$$

Conclusion

- ASPRO2 is now 6 years old !
- JMMC makes its best to maintain and improve it according to user feedbacks and support new instruments such as GRAVITY and MATISSE, thanks to the collaboration with instrument teams.
- This is an ongoing effort to refine the offered observing mode in ASPRO2 (and noise modelling parameters) to propose a "realistic" simulated instrument to the end-user (neither optimistic nor pessimistic) as these instruments are providing high resolution and polychromatic observations.

Perspectives

Here is a list of future improvements:

- Define new target associations (guiding star, dual field) as calibrator-like relationships and allow user-defined tags (priorities, programs...) to targets,
- Export Observing blocks for GRAVITY (dual-field mode) and MATISSE,
- OIFITS 2 support & OIFITS Explorer improvements,
- Target flux from FITS cube (polychromatic model) or from user-given spectrum ?
- Noise modelling improvements:
  - adjust parameters for GRAVITY / MATISSE,
  - chopping correction factor (MATISSE).

Thank you for your attention.
Questions ?