Calibration & Performance of NIKA2

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on behalf of the NIKA2 Collaboration

ILLUSTRATION Clément C. Fabre

mm Universe @ NIKA2
Observing the millimeter Universe with the NIKA2 camera

3-7 June 2019 LPSC Grenoble

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

Objectives & Outline

Objectives

1. presentation of the *baseline* calibration method
2. report on the performance assessment

Perotto, Ponthieu, Macías-Pérez et al. 2019 [in internal reviewing]

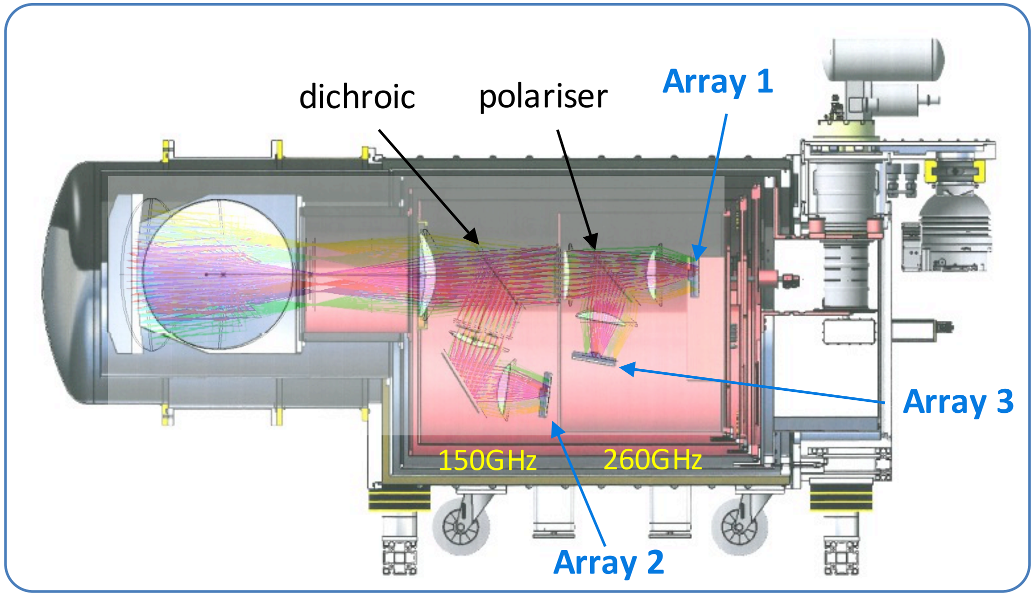
+ F.-X Désert, J.-F. Lestrade, H. Aussel, F. Mayet, F. Ruppin: a.k.a. the Commissioning Tiger Team

Outline

1. KID arrays and bandpass
2. Short summary of the commissioning phase
3. Data set
4. Field-of-view reconstruction
5. Beam
6. Atmospheric opacity estimation
7. Flux density calibration
8. Photometric stability & robustness assessment
9. Sensitivity
10. Summary

Arrays and bandpass

- **260 GHz frequency channel**
  - a.k.a. « 1 mm »
  - 2 arrays:
    - *Array 1* : 260-V
    - *Array 3* : 260-H
  - bandwidth = 50 GHz

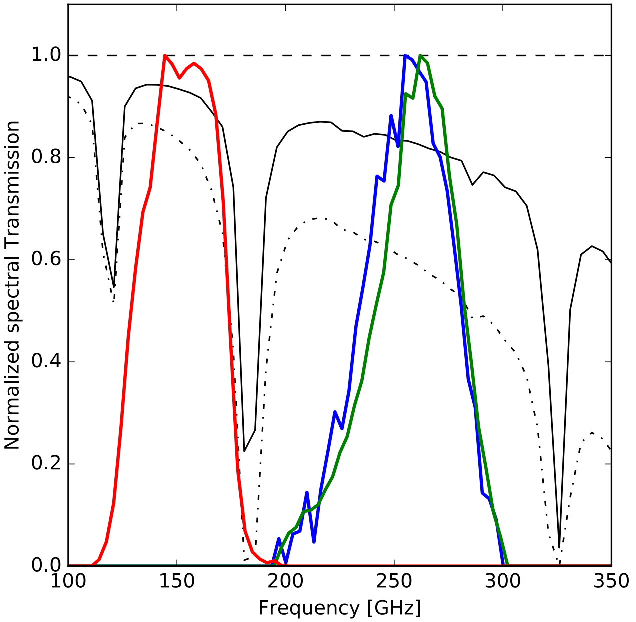


- **150 GHz frequency channel**
  - a.k.a. « 2 mm »
  - *Array 2*
  - bandwidth = 40 GHz

- In laboratory measurements
  - filters included / no dichroic
  - precision : 1%

- On-going in situ measurements using a dedicated interferometer **[see Alessandro's Talk]**

⇨ Minimal use of the bandpass for the *baseline* calibration (color correction only)



The commissioning timeline

Commissioning

- First light in October 2015
- First campaign with a complete readout electronic in January 2016
- 10 commissioning campaigns (about 60 days)
- Upgrade in September 2016
- February 2017: First campaign in the final instrumental set-up → **N2R9**
- April 2017: commissioning successively completed, Science Verification Phase
- September 2017: IRAM End-of-commissioning review

NIKA2 is now opened to the community for the next decade

- October 2017: First «Summer» scientific campaign → **N2R12**
- January 2018: First «Winter» scientific campaign → **N2R14**
- Already 18 scientific campaigns (about 4 per semester) **[see Bilal’s Talk]**
- ~ 2030: NIKA2 is a resident instrument at IRAM 30-m telescope

The reference campaigns for the performance assessment

Data set & baseline scan selection

Reference data set

- 3 observation campaigns (N2R9, N2R12, N2R14)
- > 1000 observation scans (150h) per campaigns

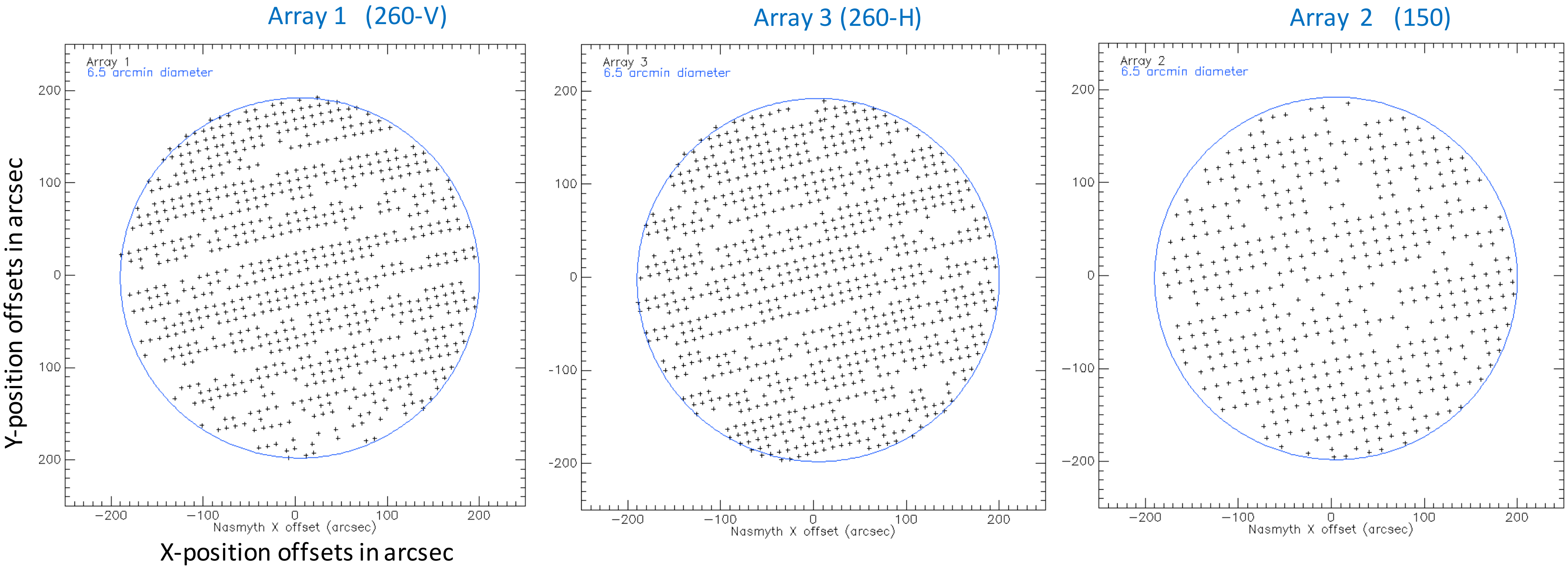
Baseline scan selection

- We perform a mild selection on the observing conditions
  - (tau x air mass) < 0.7 @ 1mm → a factor two atmospheric attenuation on the flux density
  - elevation > 20°
  - tau @ 1mm < 0.5

- Sunrise (from 9:00 UT to 10:00 UT) and late afternoon (from 15:00 to 22:00) periods are excluded

Field-of-view (FOV) Geometry

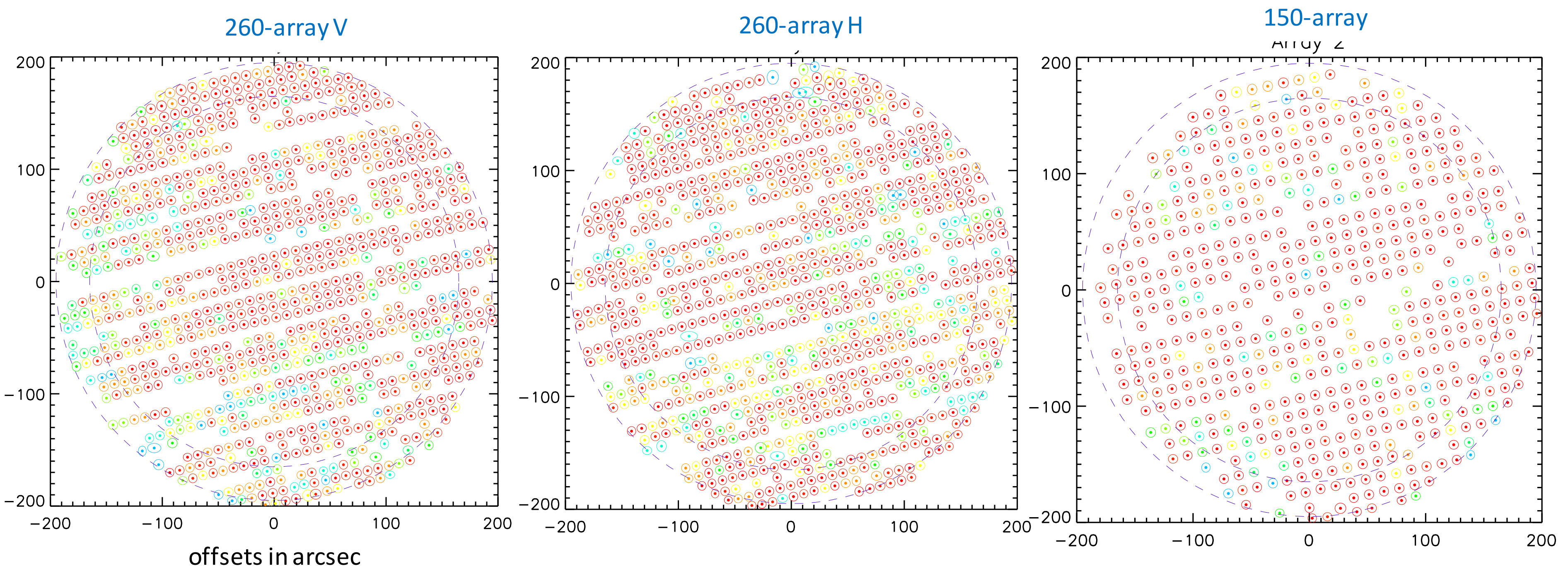
- Matching the KID frequency tones to positions on the sky is needed for each observation campaign
- We use **beammaps** = deep integration scans of about 20’ toward bright point sources to perform individual maps per KID
- From these maps, we derive i) KIDs positions on the FoV, ii) beam properties, iii) inter-calibration
- These info are gathered in the «KID database» for the campaign : the **reference kidpar**



The full 6.5 arcmin diameter FOV is covered

KID selection

- All the (2,900) design KIDs are responsive!
- Some of them are affected by cross-talk or their frequency tuning is lost during a scan
- we perform a KID selection from a series of quality criteria for several beam-map scans



KID position colour-coded as a function of the number of times they met the selection criteria (from red = valid for all selections to blue = valid in two selections)

- fraction of 'valid' (=stables in at least 2 scans) KIDs: 84% at 260 GHz and 90% at 150GHz

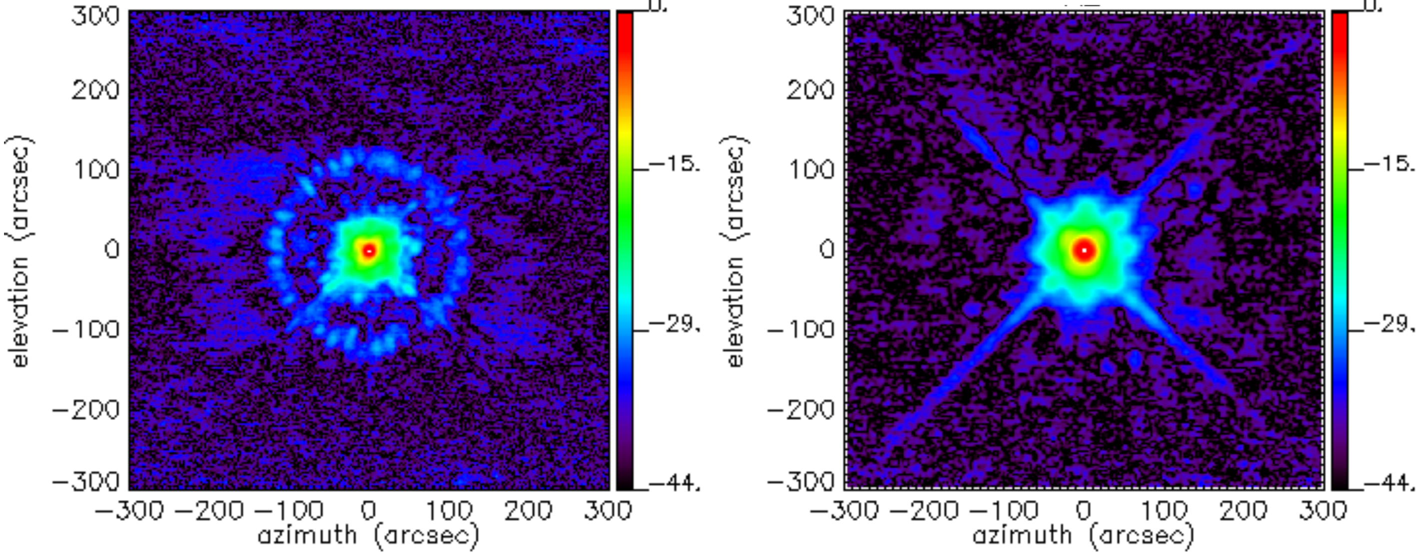
Beam Pattern

- Deep integration map using a combination of beammaps

Observed features:

- main beam
- error beams
- diffraction ring
- M2 quadrupod arms
- other spikes

Beam Pattern [dB]

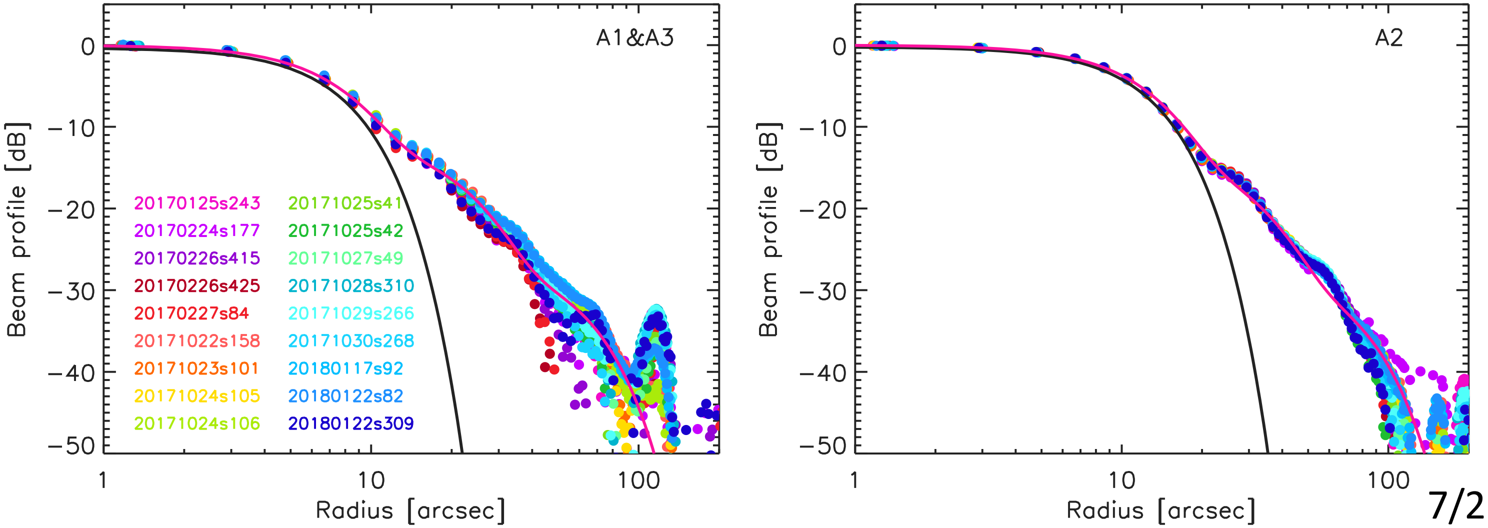


260-arrays

150-array

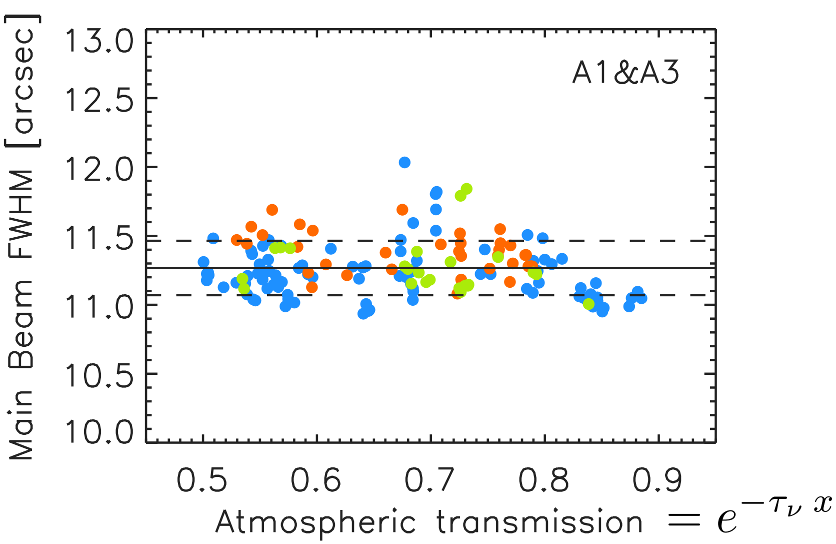
- Stability checks

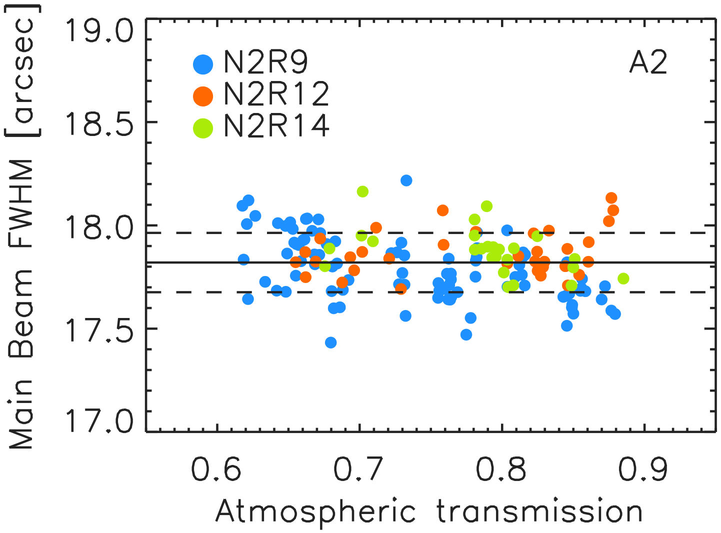
Beam radial profile [dB]



Main Beam

- Modeling the main beam with a Gaussian, we fit the main beam FWHM
- We developed 3 methods that mitigate the error beams and side lobes contribution in different ways, for methodological robustness test
- Stability checks against atmospheric conditions using a series of bright source scans





- Average FWHM

11.1” ± 0.2” at 260 GHz
17.6” ± 0.1” at 150 GHz

→ better than specifications (12”@260GHz, 18”@150GHz)

Main Beam Efficiency

- Definition: ratio between the solid angle of the main beam and the total solid angle

- We estimate the main beam efficiency up to a radius of 180'' : BE_180

55% ± 3% at 260 GHz
77% ± 2% at 150 GHz

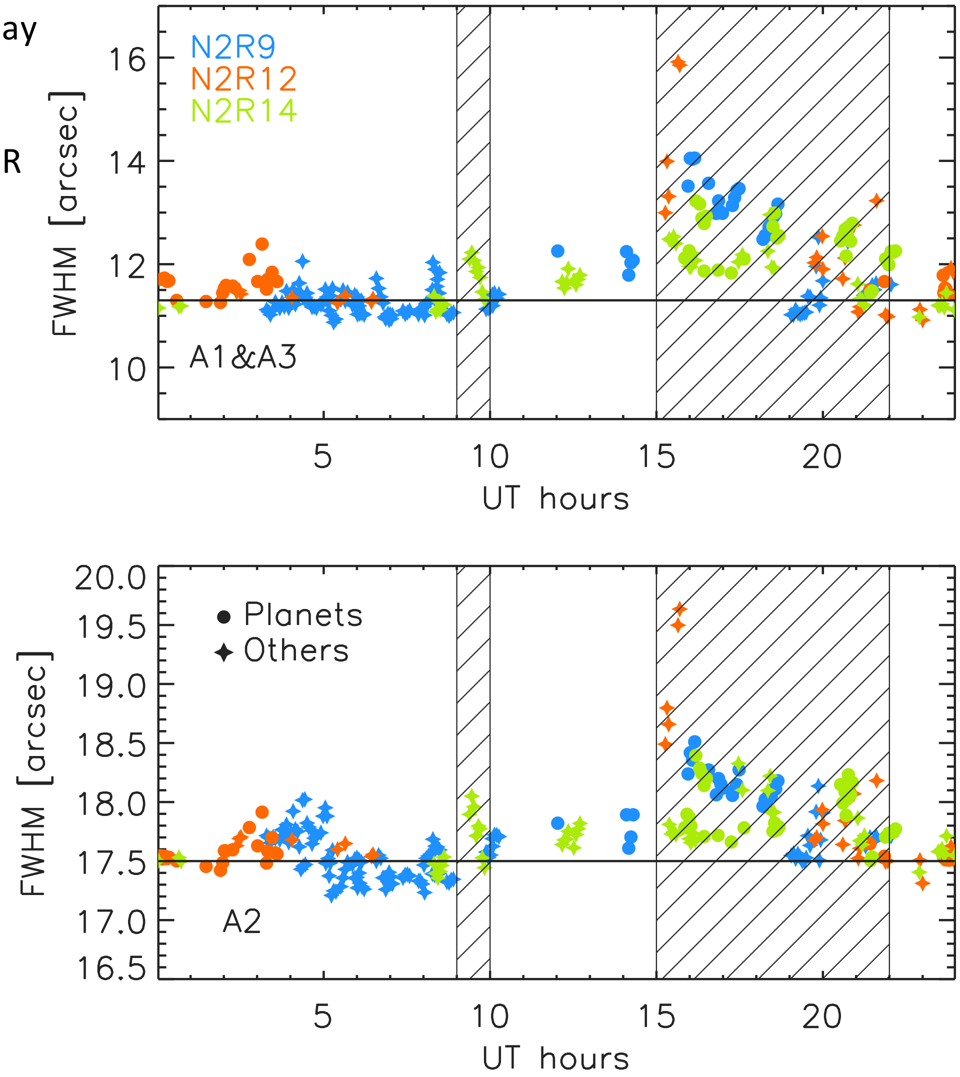
- We estimate some correction to the measured total solid angle (Omega_180) to account for the power at radii>180'' **[Kramer+2013]**

- The total solid angle is a key measurement for the aperture photometry and for the study diffuse source (more details later on)

FWHM daily variations

- The measured FWHM depends on the time of the day at which the observation was made
- Already observed with MAMBO-2, impact also EMIR
- Two main probable origines:
  - large-scale deformation of the 30m primary mirror subject to partial solar illumination
  - Anomalous refraction
- Hence the name:

  temperature-induced beam variations
- Two most impacted periods :
  - Sunrise **9:00 to 10:00 UT**
  - Late afternoon **15:00 to 22:00 UT**



Observation acquired during these periods are discarded for the calibration and performance assessment

Atmospheric opacity

- The uncorrected flux densities are exponentially attenuated by the atmospheric absorption
- $\tilde{S}_\nu = S_\nu \, e^{-\tau_\nu x}$, the airmass is estimated as $x = (\sin el)^{-1}$
- We compare 2 methods to estimate the atmospheric opacity in NIKA2 bandpass τ_ν

Using the 225 GHz resident taumeter

- time-stamped τ_{225} : 1 measure every 4 minutes at a fixed azymuth
- interpolated at the time of the scan
- interpolated at NIKA2 observing frequencies

Using NIKA2 as a taumeter for each scan

Catalano, Calvo, Ponthieu et al. 2014

1) We calibrate the relation between the KID resonance shift and the atmospheric opacity

$$f^k_{\mathrm{reso}} = \mathcal{F}_k(\tau_\nu)$$

for all the KIDs k

2) and invert it to compute the opacity for each scan

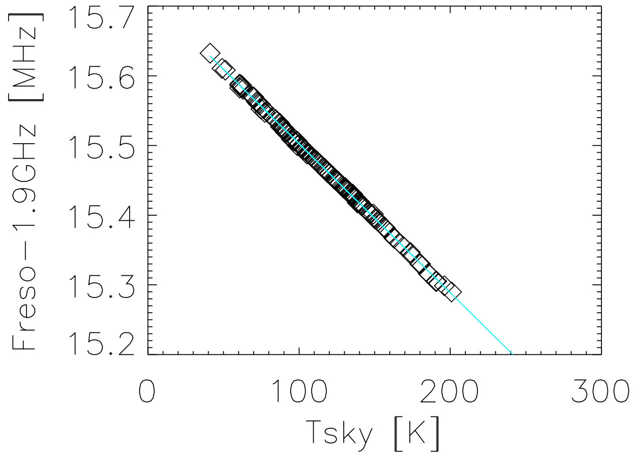
$$\tau_\nu = \mathrm{Med}\left(\mathcal{F}_{\mathrm{k}}^{-1}(\mathrm{f}^{\mathrm{k}}_{\mathrm{reso}})\right)$$

NIKA2 skydip-derived opacity

- Calibration of the relation between f^k_{reso} and τ_ν
  → the $c^k_0,\ c^k_1$ estimation

$$f^k_{\mathrm{reso}} = c^k_0 - c^k_1 T_{\mathrm{atm}}[1 - e^{-\tau_\nu x}]$$

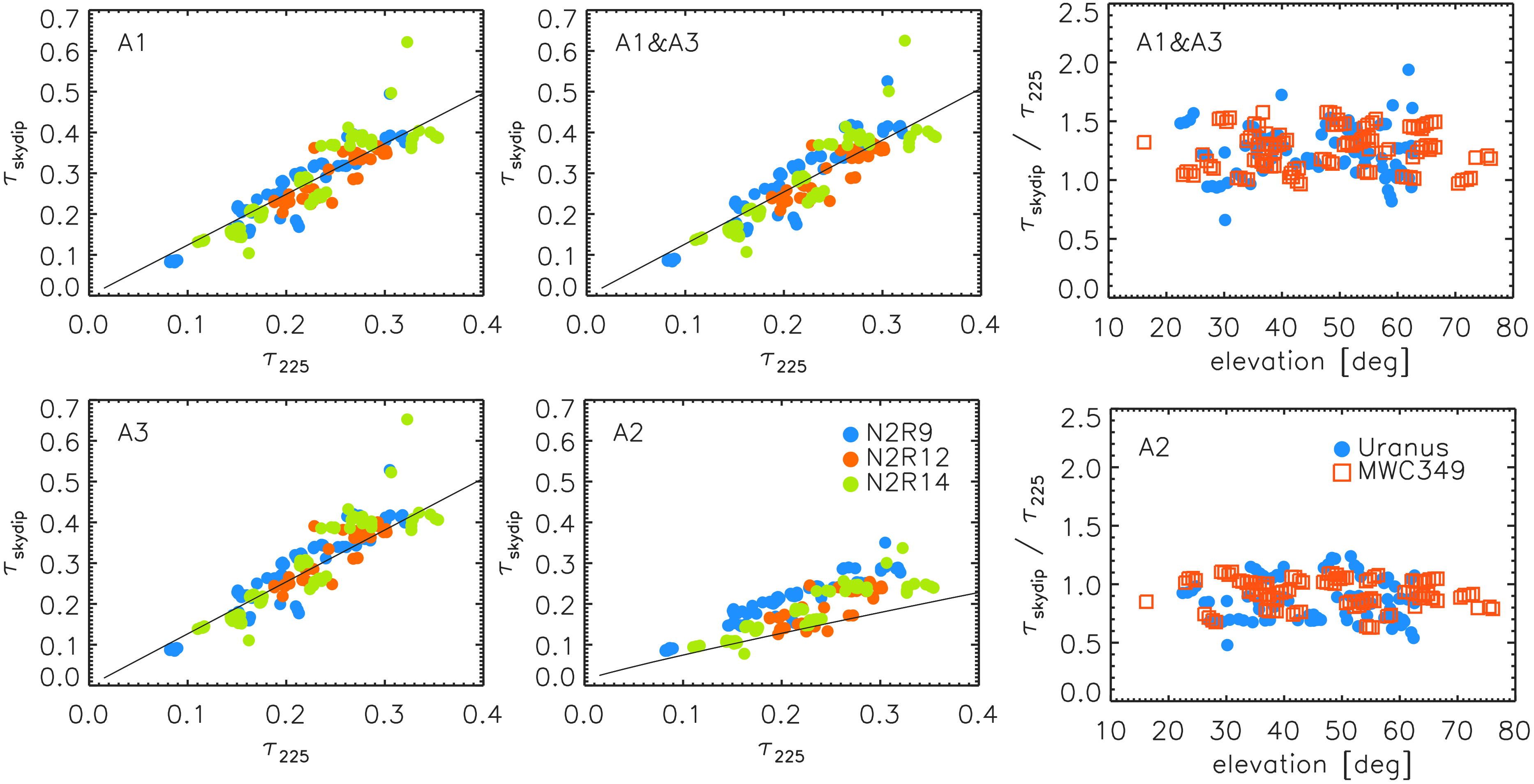
Example of C0, C1 fit for one KID



- We use **NIKA2 skydip scans**
  11 elevation steps between ~ 20 and 65°

- Joint fit of $c^k_0,\ c^k_1$ for all the KIDs using a series of skydip scans at varying opacity

Opacity measurements: consistency checks



- same correlation between the NIKA2 skydip-derived opacity and the 225GHz taumeter opacity for the 3 refence campaigns
- no dependence on the observing elevation

Photometric system & Calibration

Photometric system

	1 mm	2 mm
Reference frequency ν_0	260 GHz	150 GHz
Reference FWHM FWHM_0	12.5”	18.5”

- the maps are calibrated in Jy/FWHM_0 beam

$$M_{\mathrm{calibrated}} = \frac{S_{\mathrm{c}}(\nu_0)}{A_{\mathrm{c}}} M_{\mathrm{raw}}$$

Expected flux density of the calibrator at nu_0

Amplitude of a FWHM_0 Gaussian fitted on the calibrator map

- Uranus is the main primary calibrator
- Expected flux calculaled using the Moreno-Bendo model, model uncertainties = 5%

S_nu : the flux density of a point source is the amplitude of a FWHM_0 Gaussian (+ color correction)

Diffuse source calibration

- For diffuse source or aperture photometry, the maps in Jy/FWHM_0 must be converted in Jy/sr

$$M_{\mathrm{ap}} = \frac{\mathrm{BE}_0}{2\pi\sigma_0^2} M_{\mathrm{s}}$$

reference beam efficiency

solid angle of the FWHM_0 Gaussian

- We estimate the reference beam efficiency up to a radius of 180’’
- We give correcting factors to BE_0 to account for the power stemming from larger radii **[Kramer+2013]**

	A1	A3	A1&3	A2
FWHM_0 [arcsec]	12.5	12.5	12.5	18.5
$\mathrm{BE}_0{}^a$ [%]	70 ± 4	72 ± 4	70 ± 4	85 ± 3
η_{390}	0.95	0.95	0.95	0.96
η_{tot}	0.78	0.78	0.78	0.85

Practical calibration

KID gains

1) Estimation of a calibration coefficient per KID at zero opacity using a *beammap* scan toward Uranus

$$G_k = \frac{S_{\rm c}(\nu_0)\, e^{-\tau_\nu\, x}}{A_k}$$

⟶ relative calibration and absolute calibration on a single scan

Multi-scan recalibration

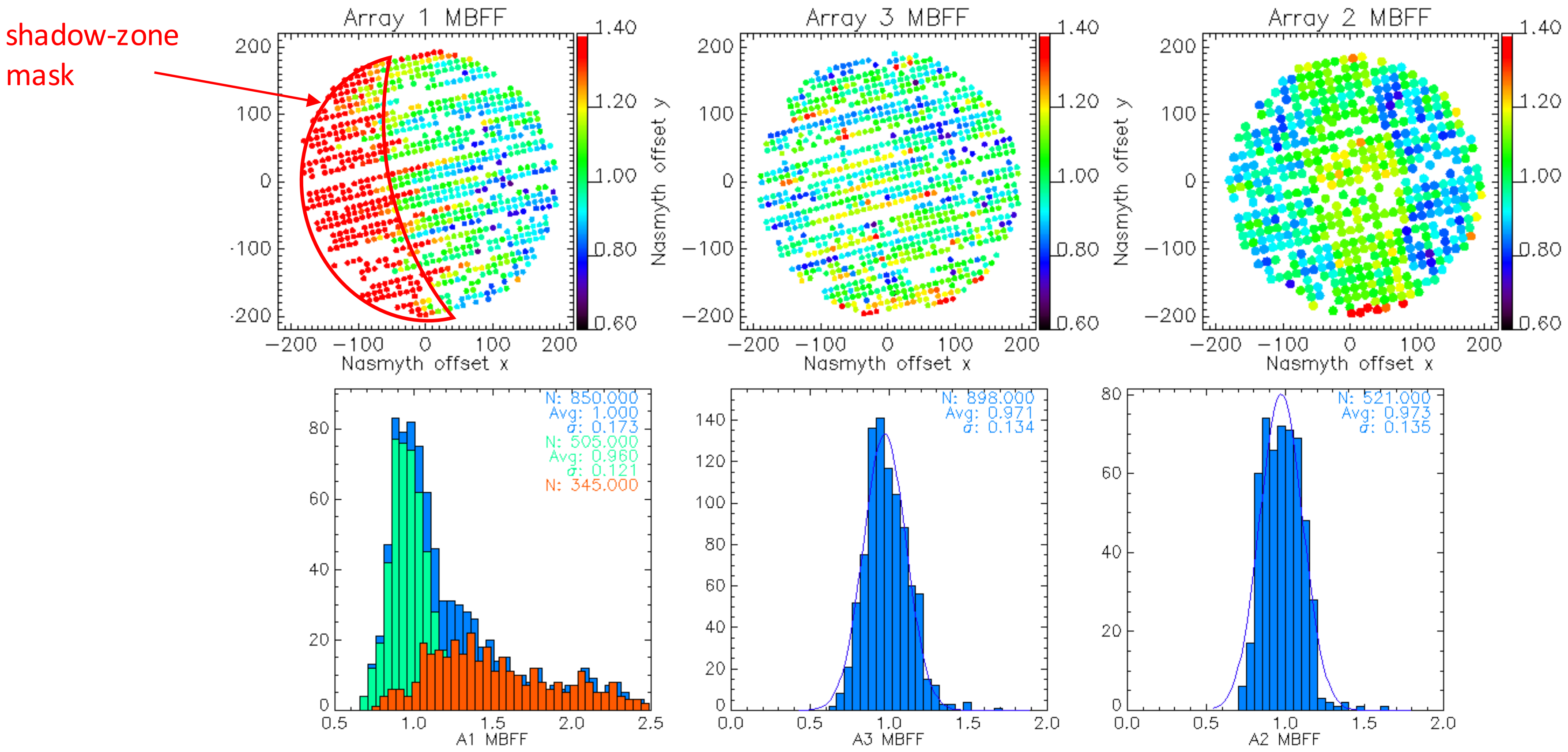
2) Improvement of the absolute calibration in monitoring Uranus all along the campaign
we compute the averaged expected-to-measured flux per array

$$< \frac{S^{\rm theo}(\nu_0)}{S_\nu^{\rm meas}} >$$

⟶ accurate absolute calibration on a series of scans

Flat fields

- FOV distribution of the KID gains G_k w. r. t. the average gain



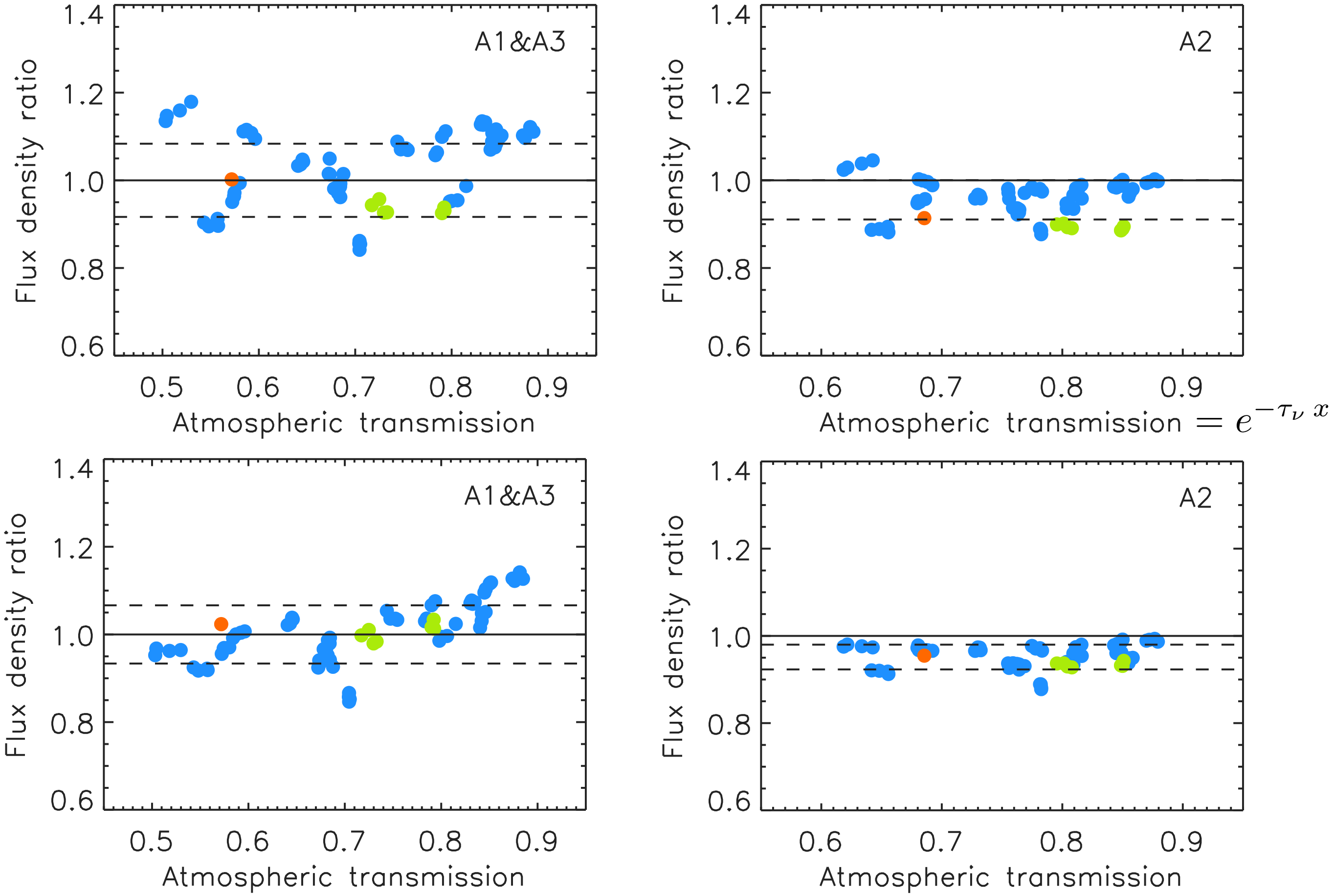
- We observe a large variation of the KID gains across Array 1: about 1/3 of A1-KIDs are shadowed
- This is due to a default in the transmission of the polarised light at 1mm by the dichroic
- September 2018 dichroic replacement test: the shadow-zone disappeared at 1mm at the price of huge distortion of the 2mm beam : the current dichroic has been re-installed.

Photometric check using secondary calibrators

- We use MWC349: routinely monitored using PdBI/NOEMA and VLA → the most reliable flux densities expectation at the NIKA2 frequencies

Atmospheric opacity correction using the 225GHz **taumeter**

using **NIKA2 skydip**



- less flux ratio dispersion using NIKA2 skydip than using taumeter

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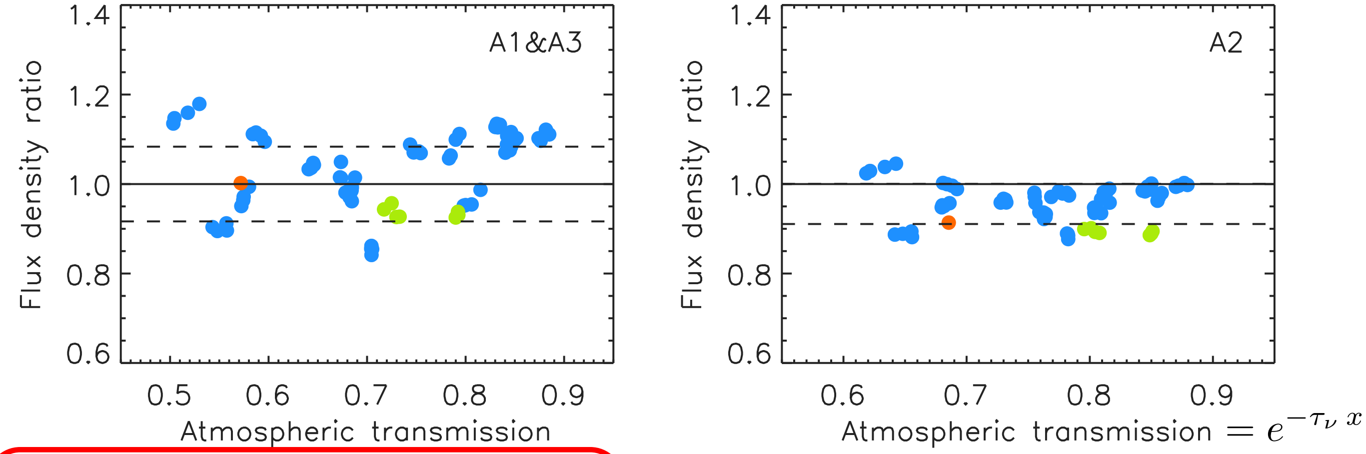
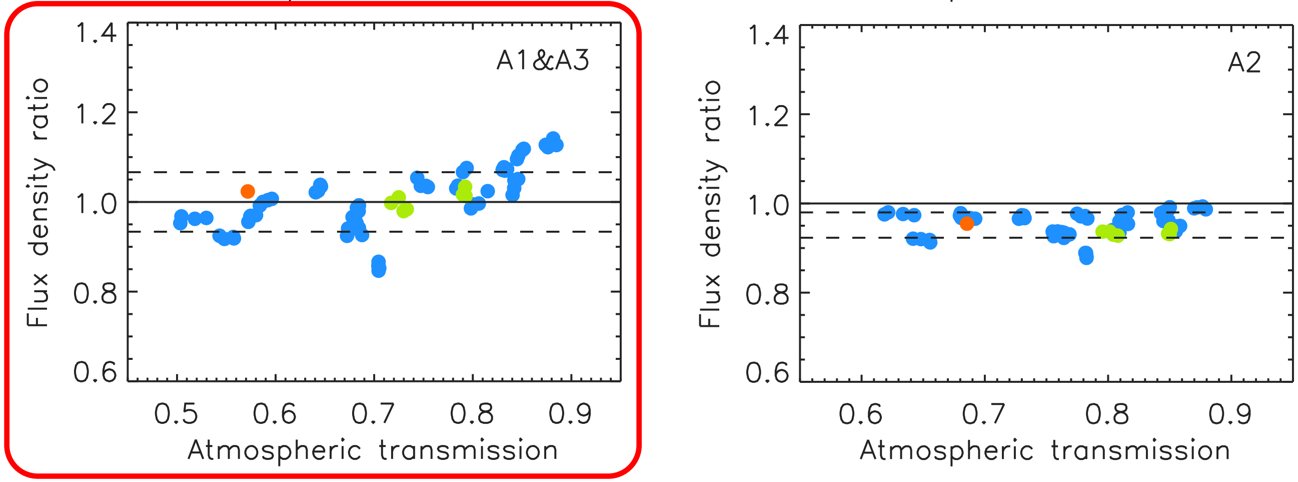


using **NIKA2 skydip**



- less flux ratio dispersion using NIKA2 skydip than using taumeter
- BUT small correlation with the atmospheric transmission at 1mm

Baseline calibration: the corrected skydip method

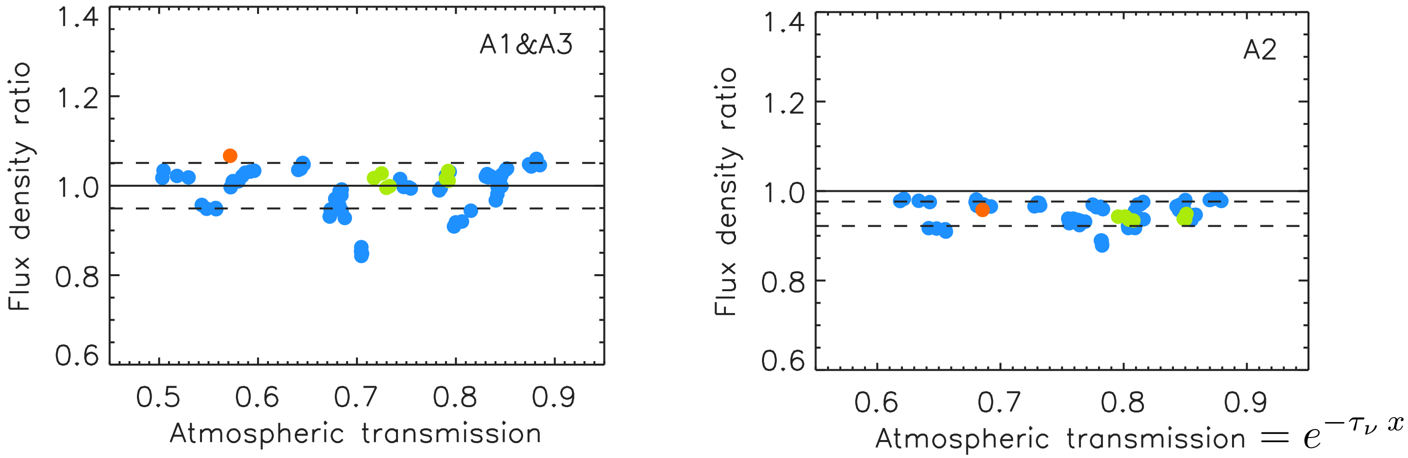
- for the *baseline* calibration, we use a corrected version of the NIKA2 skydip opacity estimates = aka **corrected skydip**
- we fit a correcting factor to τ_{skydip} so that the flux density is constant for all the scans of MWC349 taken at N2R9 (68 scans)

$$S_\nu = \tilde{S}_\nu \; e^{a_\nu \tau_{\mathrm{skydip}}\, x}$$

a_A1 = 1.36 ± 0.04; a_A3 = 1.23 ± 0.02; a_1mm = 1.27 ± 0.03; a_A2 = 1.03 ± 0.03

- stability checks using the 3 reference campaigns (N2R9 + N2R12 + N2R14)

using **corrected skydip**
= Baseline

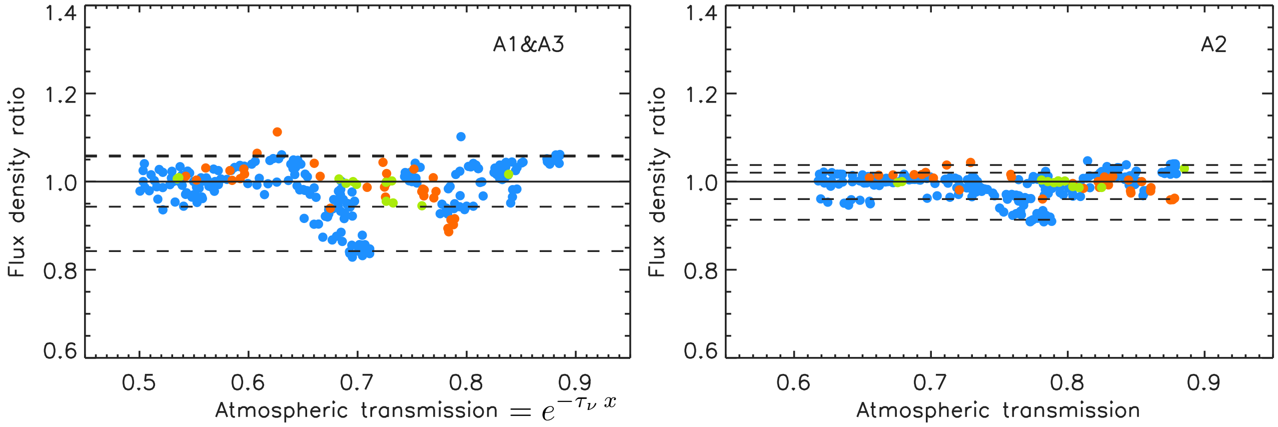


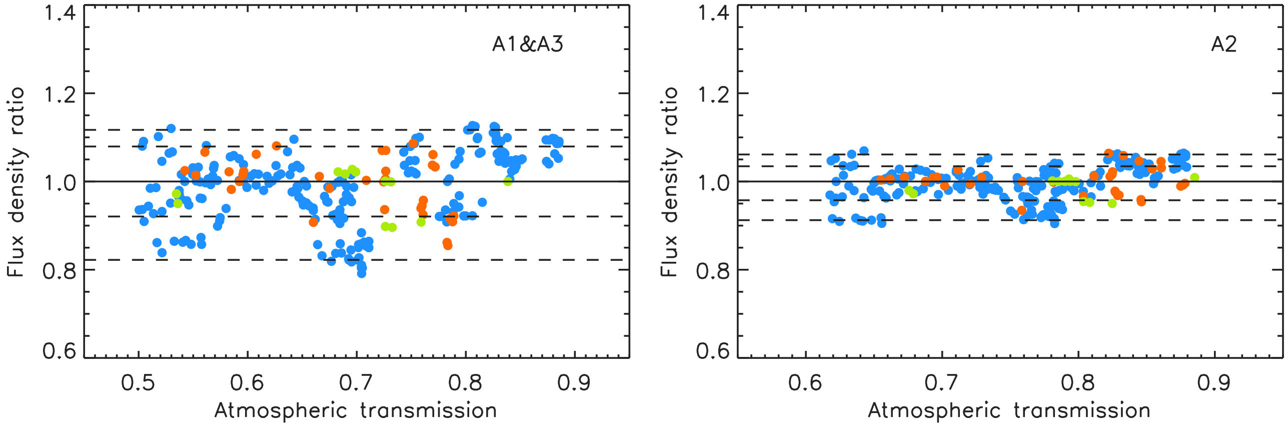
Using the corrected skydip opacity estimate, MWC349 flux density measurements are stable against the atmospheric opacity and consistent for 3 campaigns

Statistical calibration uncertainties

- we use all the scans of bright (> 1 Jy) sources to estimate the statistical calibration uncertainties
- we compute the rms of the median-to-measured flux densities

264 scans	1mm	2mm
Baseline	**5.7 %**	**3%**
Taumeter	7.9 %	3.8%





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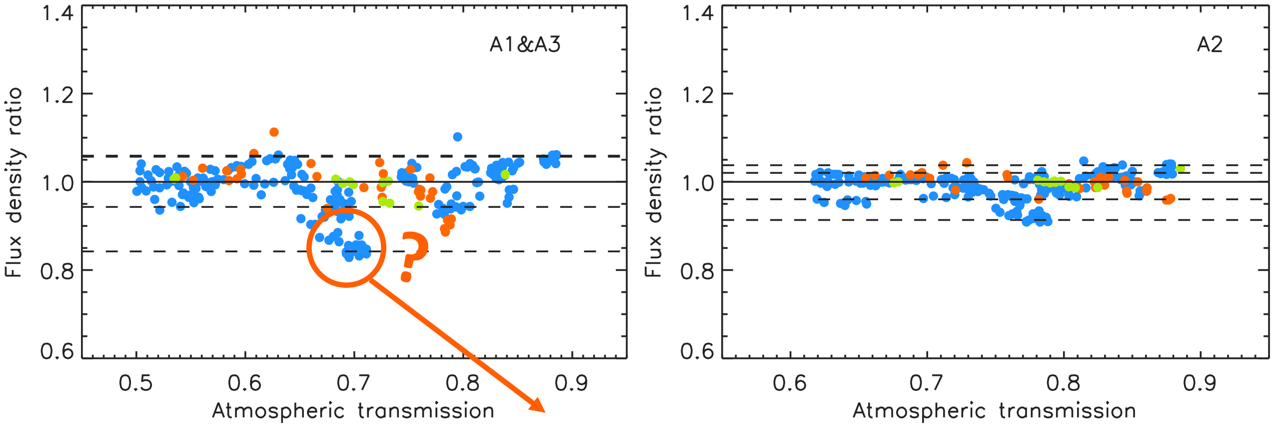
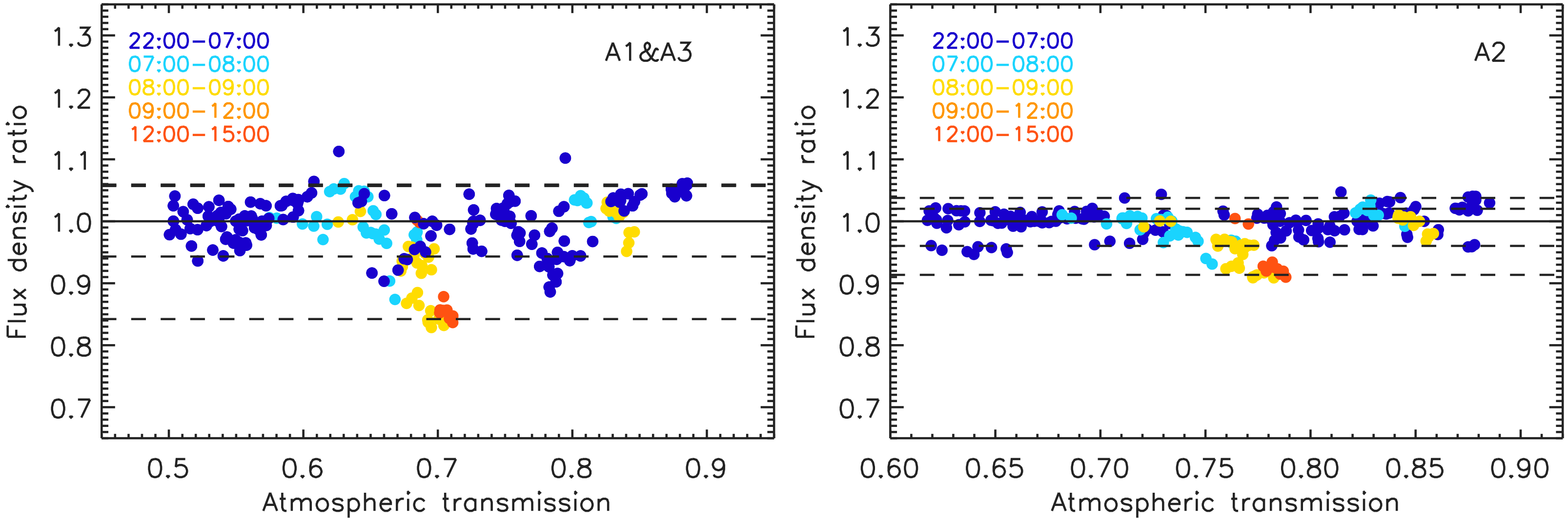




Systematic calibration uncertainties

All effects depending on the observing conditions or source properties are accounted for in the rms estimates

Other effects that are not accounted for include :

	1mm	2mm
▪ Uranus model uncertainties	5%	5%
▪ Uncertainties on the corrected skydip factor $\Delta a_{\nu}^{\mathrm{skydip}}$ = 0.03		
→ reference IRAM 30m winter conditions (pwv = 2mm, el = 60°)	0.6%	0.3%
→ mediocre observing conditions tau_nu x = 0.7 @ 1mm, 0.5 @ 2mm	2%	1.5%
▪ Precision of the bandpass measurement (used for color correction) 1%		
→ depends on the source SED, but neglectible in most of the cases	<0.1 %	

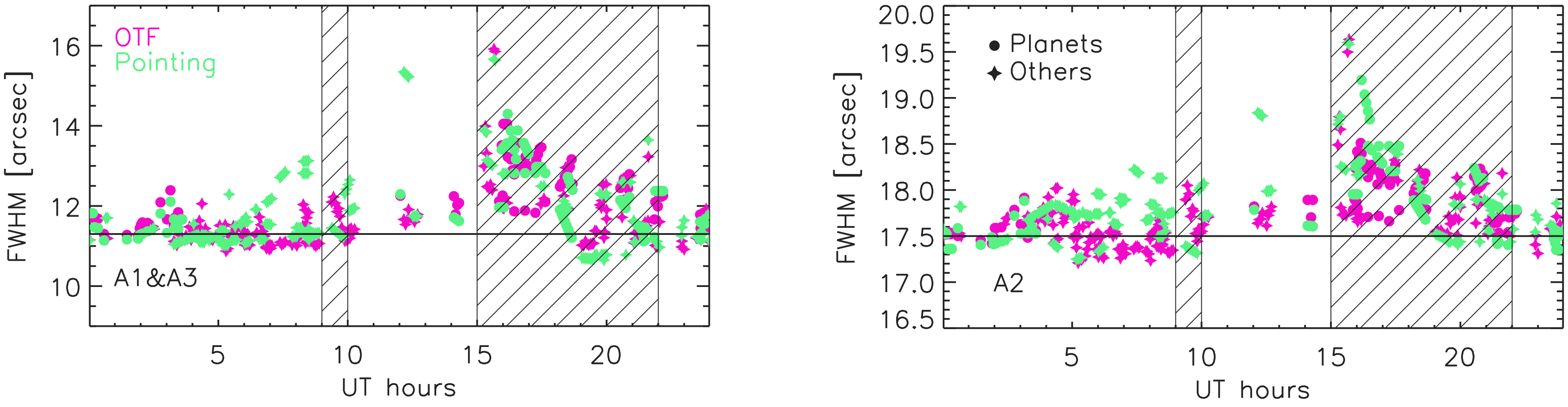
Calibrating during the afternoon I/II

- Temperature-induced variation of the beam size during sunrise and afternoon → Flux variation
- Basic idea: jointly monitor the beam size & the flux to correct for this effect

$$S_{\mathrm{pcorr}} = \boxed{f(\mathrm{FWHM})}\,\mathrm{S}$$

photometric correction

- We use pointing scans to monitor the FWHM
  - 4 subscans of 10 s : enough to project a map and fit the FWHM
  - one pointing per hour : enough to monitor the FWHM
  - interpolation of the FWHM at the time of the scan = $\mathrm{FWHM}_{\mathrm{pointing}}$
- Comparison of $\mathrm{FWHM}_{\mathrm{pointing}}$ for bright sources and the fitted FWHM on the map



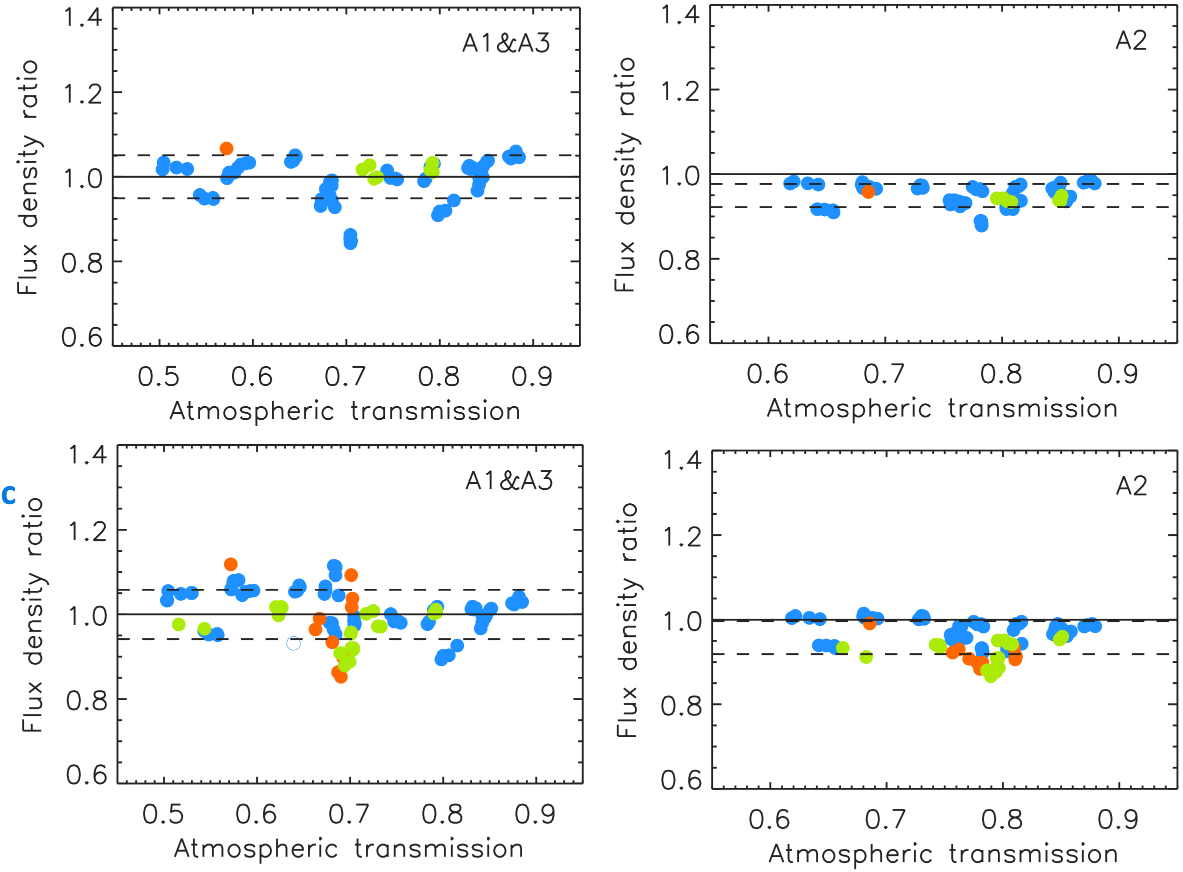
Calibrating during the afternoon II/II

We repeat the absolute calibration using the photometric correction and compare to the *baseline* results

MWC349 measured-to-expected flux ratio

Baseline

Pointing Photometric Correction



rms calibration uncertainties on bright (> 1Jy) sources

	1mm	2mm
264 scans	**5.7 %**	**3%**
264 +20 scans	4.9 %	2.4%

Encouraging results: alternative method if precise FWHM monitoring is made (using dedicated scans)

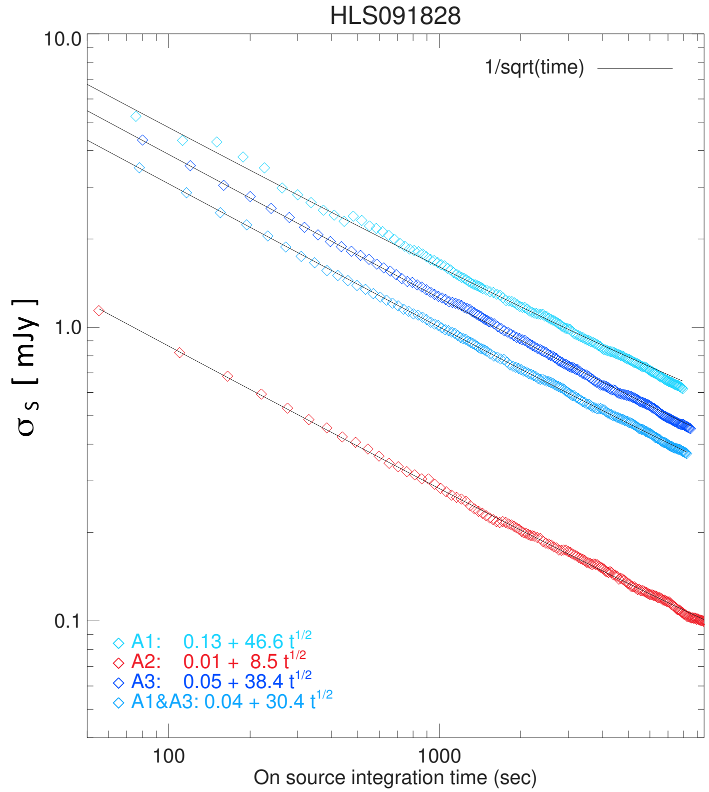
Sensitivity

Noise Equivalent Flux Density (NEFD): the 1σ error on the flux density in 1s of on-source integration time

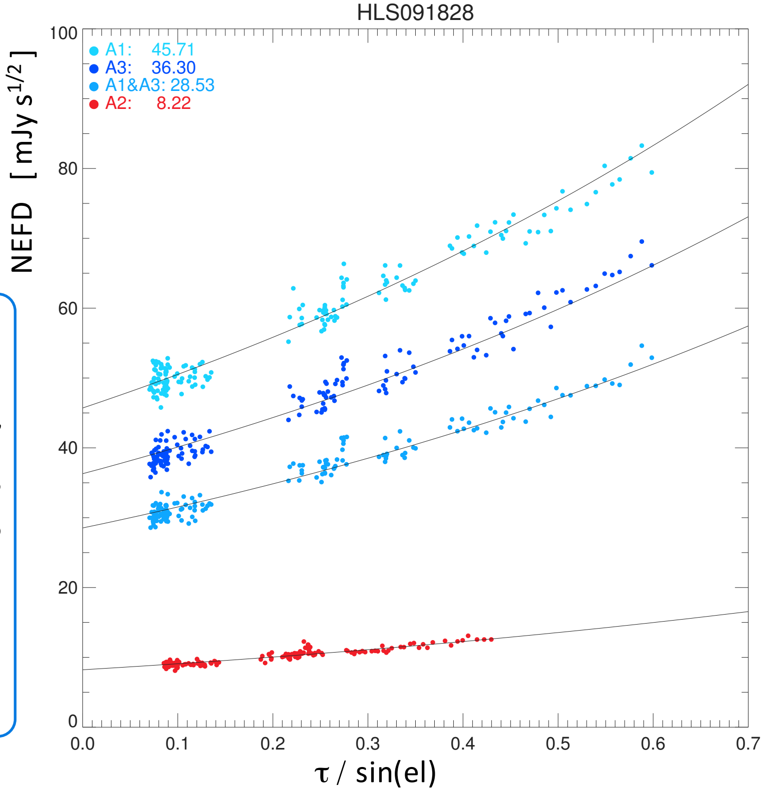
$$\sigma_S(t) = \mathrm{NEFD}\, \mathrm{e}^{\tau_\nu\, \mathrm{x}} / \sqrt{\mathrm{t_{det}}}$$

on-source time spent by a detector

Data set: we use deep integration (about 3hrs) on a moderately weak source (NIKA1 fluxes: 37mJy@1.2mm & 9mJy@2.1mm), HLS J0918+5142



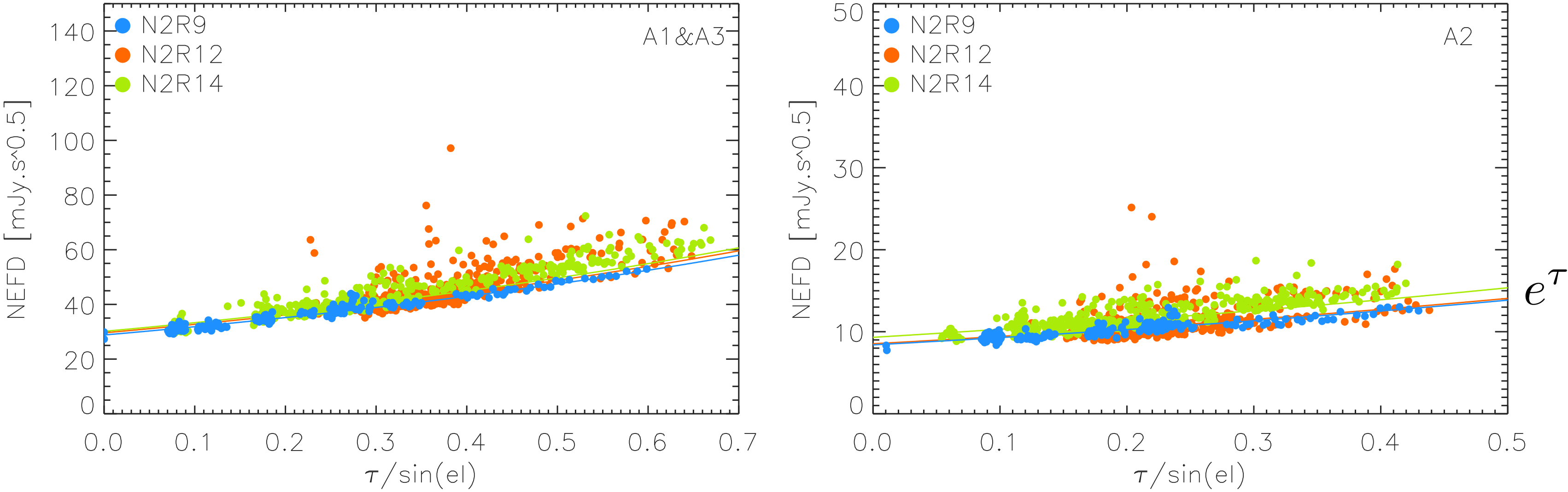
	NEFD [mJy $s^{1/2}$]	
A1	46.6	45.7
A3	38.4	36.3
A1&A3	30.4	28.5
A2	8.5	8.2



- the flux uncertainties scale down as 1/sqrt(time)
- both methods give consistent results

Sensitivity vs atmospheric conditions

- NEFD estimates using >1000 scans of sub-Jy sources acquired during 3 campaigns



$e^{\tau_\nu x}$

- Mapping speed: the sky area that can be mapped at a noise level of 1mJy in 1 hour $M_\mathrm{s} = \eta \, \frac{\pi}{4} d_\mathrm{FOV}^2 \, \frac{1}{\mathrm{NEFD}^2}$

	A1&A3	A2
NEFD [mJy $s^{1/2}$]	30 ± 3	9 ± 1
M_s [arcmin^2 / mJy^2 / h]	111 ± 11	1388 ± 174

- State-of-the-art mapping speed : mJy-scale source can be detected in less than 1 hour of integration!

Performance summary

The performance assessment relies on the *baseline calibration method* (FWHM_0 Gaussian amplitude)

We have used all scans of 3 observation campaigns taken during the 16h most stable hours of the day

		Array 1&3	Array 2
Bandpass	Reference Wavelength [mm]	1.15	2.00
	Reference Frequency [GHz]	260	150
	Frequency [GHz]	254.7-257.4	150.9
	Bandwidth [GHz]	49.2-48.0	40.7
FOV reconstruction	Number of designed detectors	1140	616
	Number of valid detectors[a]	952-961	553
	Fraction of valid detectors [%]	84	90
	Pixel size in beam sampling unit[b] $[F\lambda]$	1.1	0.87
Beam	FWHM[c] [arcsec]	11.1 ± 0.2	17.6 ± 0.1
	Beam efficiency[d] [%]	55 ± 3	77 ± 2
	Relative rms FWHM on the FOV [%]	6	3
	Reference FWHM[e] [arcsec]	12.5	18.5
	Reference Beam efficiency[f] [%]	70 ± 4	85 ± 3
Calibration uncertainty	Rms pointing error [arcsec]	< 3	
	Absolute calibration uncertainty [%]	5	
	Relative rms calibration error [%]	5.7	3.0
	α noise integration in time[g]	0.5	0.5
Sensitivity	NEFD[h] [mJy · $s^{1/2}$/beam]	30 ± 3	9 ± 1
	M_s[i] [arcmin^2/h/mJy^2]	111 ± 11	1388 ± 174

NIKA2 has state-of-the art performance and unique capabilities

Future improvements

Hardware-based improvements

- the sensitivity of Array 1 is mainly limited by a non-optimal transmission of the current dichroic
- the temperature-induced beam variation is worsened by the surface of the 30m primary mirror

[see Alessandro's Talk]

Software-based improvements

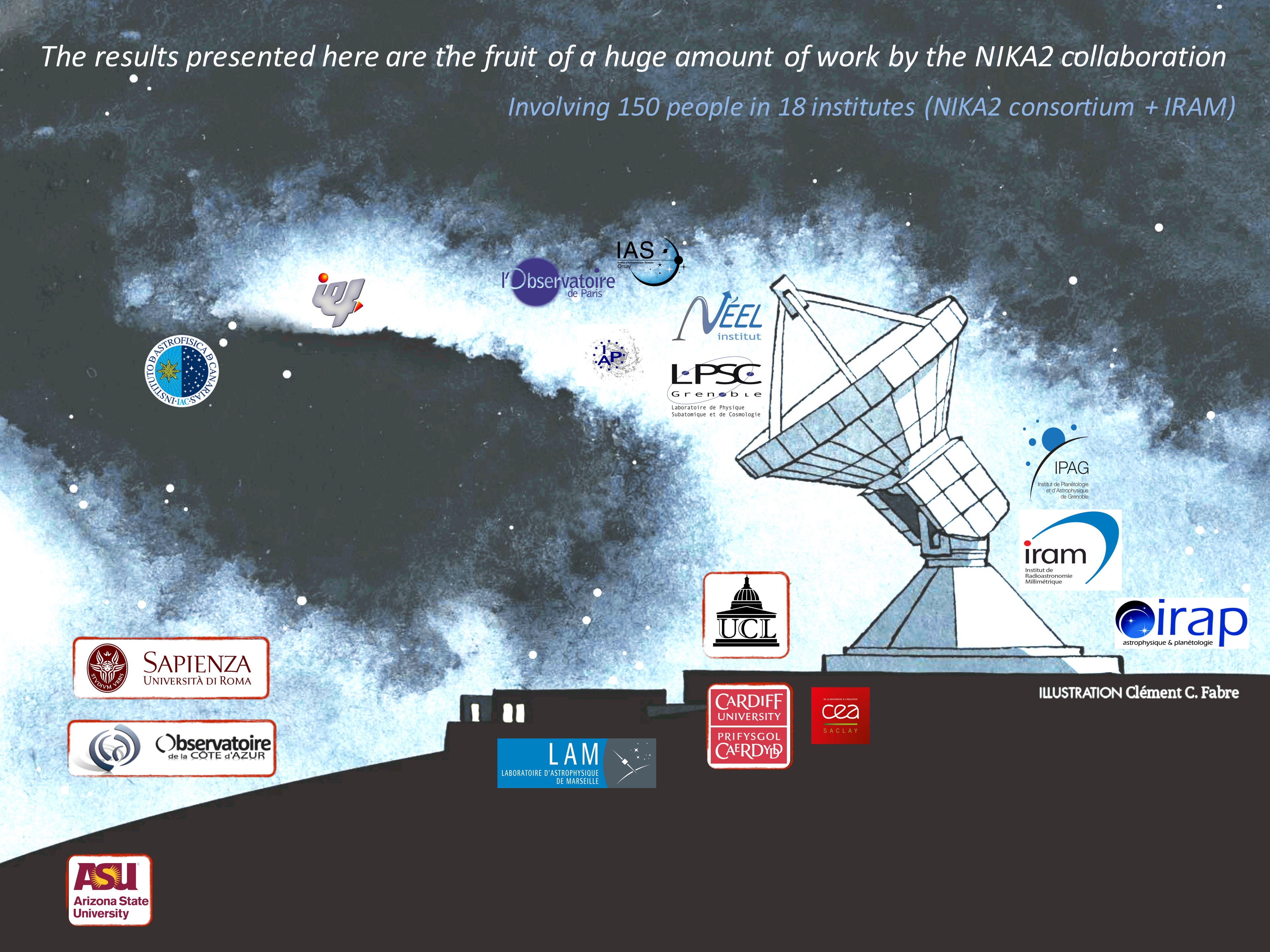
- The *baseline* calibration method relies on a « simple and robust » noise decorrelation, well-suited for point-source study. Other methods are currently developped to
  - improve the measure of the Beam Efficiency and measure at radius larger than 180''
  - improve the removal of the correlated noise **[see Nico's Talk]**

- Better treatment of the time of the day impacted by the temperature-induced beam variations
  - beam size monitoring using the pointing scans is promising but not sufficient : need dedicated scans for an accurate monitoring of the beam

A large amount of good-quality science data are available: a wealth of astrophysical and cosmological results are coming!

The results presented here are the fruit of a huge amount of work by the NIKA2 collaboration

Involving 150 people in 18 institutes (NIKA2 consortium + IRAM)



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NÉEL institut

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IPAG
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iram
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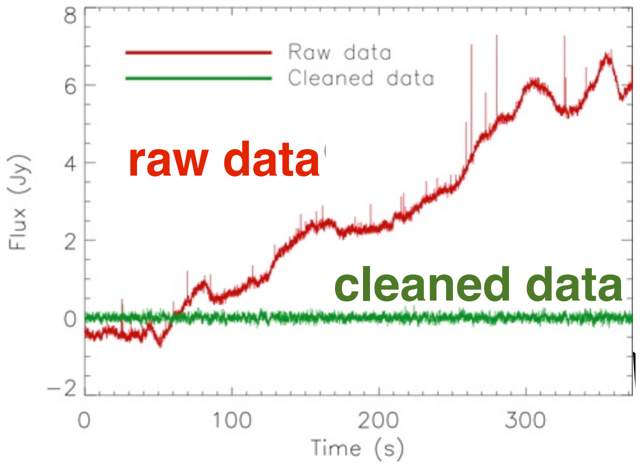
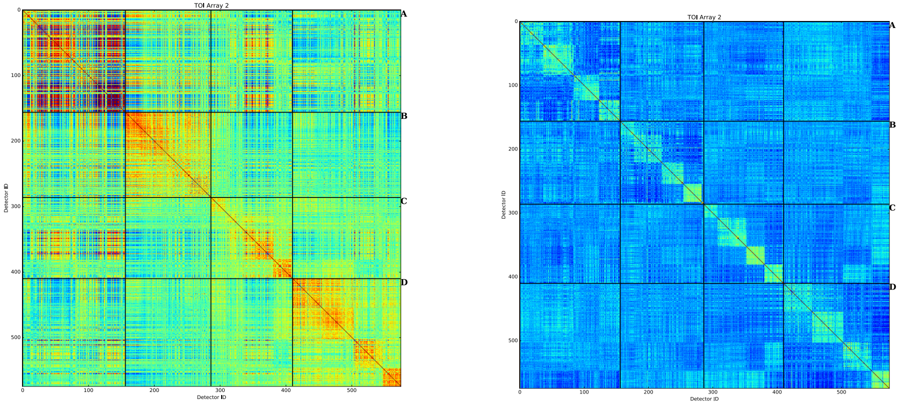
Noise properties

- Dominant noise is the atmospheric fluctuations:
    - inducing strong 1/f noise spectrun
    - As it is seen by all the detectors, it can be decorrelated



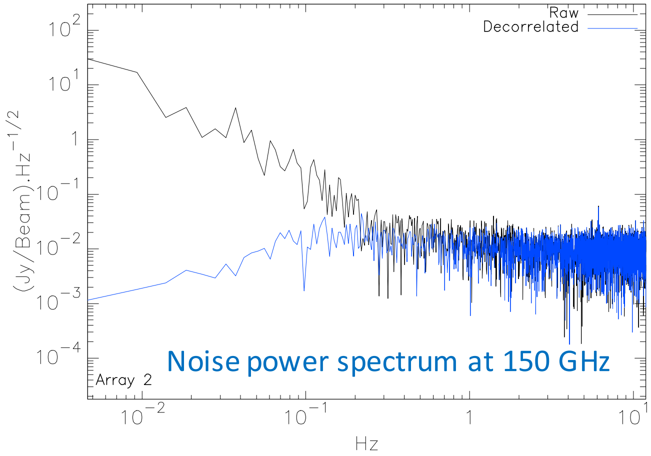
- After decorrelation, correlated noise residuals from the atmosphere and the electronics at sub-dominant level in the maps



Common mode subtraction

PCA decorrelation

Kid-Kid correlation matrix at 150 GHz



Noise power spectrum at 150 GHz

- …which do not affect the noise scaling down with integration time : we checked that the flux uncertainties reduce as 1/sqrt(t)

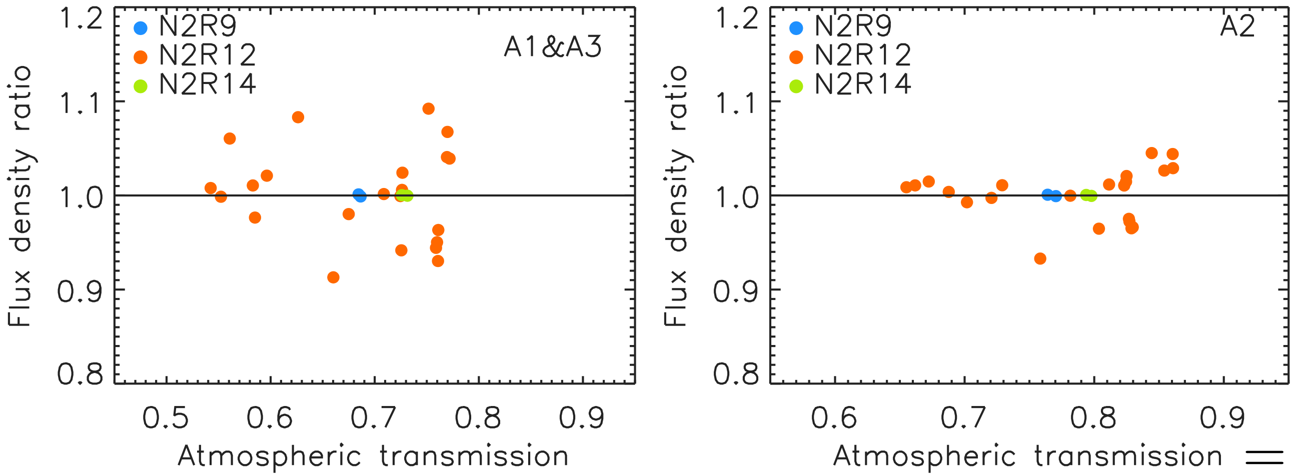
Calibration et performance

	150 GHz	260 GHz
Number of detectors	616 (553)	2x 1140 (960)
FoV diameter	6.5‘	6.5’
Angular resolution: FWHM	17.6’’ ± 0.2’’	11.1’’ ± 0.1’’
Calibration uncertainties (rms)	3%	6%
Sensitivity: NEFD	9 ± 1 mJy.s$^{1/2}$	30 ± 3 mJy.s$^{1/2}$

Multi-scan calibration

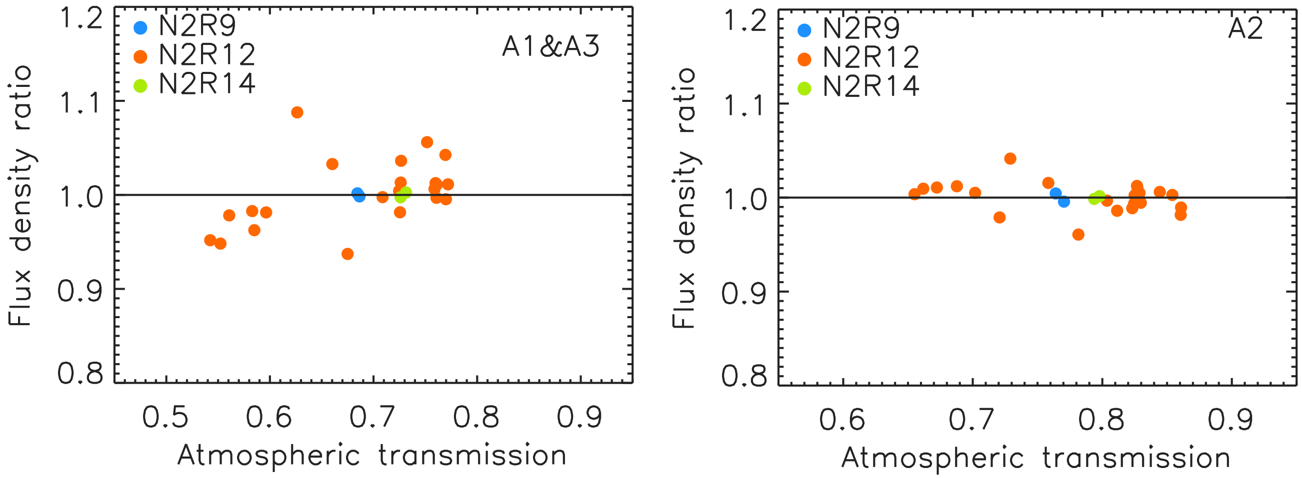
- We monitor **Uranus** flux during the campaign and estimate the expected-to-measured flux ratio

Atmospheric opacity correction
using the 225GHz
taumeter



$$= e^{-\tau_\nu\, x}$$

using **NIKA2 skydip**



- no significant correlation with the atmosperic transmission
- more rms dispersion using « taumeter » than « NIKA2 skydip »

Diffuse source calibration

- For diffuse source or aperture photometry, the maps in Jy/FWHM_0 must be converted in Jy/sr

$$M_{\mathrm{ap}} = \frac{\mathrm{BE}_0}{2\pi\sigma_0^2} M_{\mathrm{s}}$$

reference beam efficiency

solid angle of the FWHM_0 Gaussian

- We estimate the reference beam efficiency up to a radius of 180’’
- For aperture photometry on deep integration scan or for studying very extended source, we must account for the power stemming from 180’’ and r_cut
- We use the large-scale beam pattern characterisation using moon limb observations with EMIR

Kramer et al. (2013)

- … to calculate correcting factors to BE_0

$$\eta_{r_c} = \left(1 + \frac{\Omega_{180<r<r_c}}{\Omega_{180}}\right)^{-1}$$

	A1	A3	A1&3	A2
FWHM_0 [arcsec]	12.5	12.5	12.5	18.5
$\mathrm{BE}_0{}^a$ [%]	70 ± 4	72 ± 4	70 ± 4	85 ± 3
η_{390}	0.95	0.95	0.95	0.96
η_{tot}	0.78	0.78	0.78	0.85

account for the power up to 180’’

account for the 3 error beams up to 390’’

account for all beam contributions