Guidelines for observing time estimates with the NIKA2 continuum camera at the IRAM-30m Telescope

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Abstract

The present document explains how the total integration time t_{total} for a given map size to be observed with the NIKA2 camera is calculated. The formula for t_{total} is derived step-by-step and the python script used to calculate t_{total} is described using two examples, for point-like and extended sources. This document has been updated for the upcoming semesters accounting for the numbers of NEFD and fraction of valid pixels as described in [1]. The python script used to calculate t_{total} is described using two examples, for point-like and extended sources. This manuscript is partially based on the previous document for GISMO and NIKA observations [2], calculations done by F.-X. Désert.

1 The NIKA2 Camera

The *New IRAM KID Array 2* (NIKA2) camera is the kilo-pixel expansion of the NIKA prototype camera. It is a dual-band imaging camera built for the 30m telescope [3, 4, 5] by an international consortium lead by Alain Benoit and Alessandro Monfardini from the *Institut Néel* in Grenoble, France. The camera is equipped with a novel type of superconducting detectors called KIDs (Kinetic Inductance Detectors). The focal plane consists of three filled arrays: a 2 mm array, and two 1.2 mm arrays for horizontal and vertical polarization measurements. They operate at 100 mK, delivered by a continuous closed-cycle dilution fridge, and optimized for observations in the atmospheric windows at 2 mm and 1.2 mm. A dichroic is used to split the long/short wavelengths such that both channels observe the sky simultaneously with a common instantaneous field-of-view (FoV) of 6.5' in diameter. The 2 mm (1.2 mm) array is made up of 616[1] (2×1140 for Horizontal and Vertical polarizations) square pixels. Currently, the observing mode for **extended and point sources** with NIKA2 is the OTF observing mode, in which while the telescopes drives continuously in a certain direction, data and positional information are recorded for later map reconstruction (See Appendix in the previous document given for the summer semester 2017 (Garcia et. al) for a schematic view of the OTF scanning pattern).

2 Observing Time Estimate

The expected noise flux density per beam of a map is given by:

$$\sigma = \frac{\text{NEFD}}{\sqrt{t_{beam}}}, \tag{1}$$

where σ is expressed in [mJy/beam], NEFD is the Noise Equivalent Flux Density in [mJy$\cdot\sqrt{s}$], and t_{beam} is the integration time per beam in seconds. The NEFD can further be expressed as:

$$\text{NEFD} = \text{NEFD}_0 \cdot e^{\tau/\sin(el)} \cdot h_{filter}, \tag{2}$$

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[1] This number corresponds to the array installed in Sept. 2016.

where NEFD$_0$ is the instrumental NEFD without the atmosphere, τ is the zenith opacity at the reference frequency, el is the source elevation in radian, and h_{filter} is a dimensionless factor that accounts for post-processing noise filtering. The sensitivity penalty for retrieving extended emission in NIKA2 observations leads to values $1.0 \leqslant h_{filter} \leqslant 2.0$, depending on the source extent.

The **integration time per beam** is derived from the total integration time of the observation t_{int} (excluding overheads), the FoV of the camera, and the area covered by the observations. If the scanning pattern covers a rectangular area A$_{map}$ of sides Δ_x and Δ_y, then the integration time per beam is expressed as:

$$t_{beam} = \frac{A_{FoV}}{A_{map}} \cdot t_{int}, \tag{3}$$

where $A_{map} \sim \Delta_x \cdot \Delta_y + A_{FoV}$, and the ratio A_{FoV}/A_{map} represents the average fractional coverage[2] of the map. Notice that the $\Delta_x \cdot \Delta_y$ area is the area covered by the central pixel of the array. Due to differences in performance, a small fraction of the pixels covering the camera FoV will not be available for the measurements (bad pixels), reducing the nominal FoV area to an *effective* FoV area. If the fraction of good pixels in the array is f_{pix}, then the effective FoV area of the camera can be expressed as $f_{pix} \cdot A_{FoV}$.

Putting the above information together, the following general formula that describes the total observing time t$_{total}$ required to reach a given flux uncertainty of σ is obtained:

$$\boxed{t_{total} = \left(\frac{\mathrm{NEFD}_0 \cdot e^{\tau/\sin(el)}}{\sigma} \cdot h_{filter}\right)^2 \times \left(1 + \frac{\Delta_x \cdot \Delta_y}{f_{pix} A_{FoV}}\right) \times h_{overhead}} \tag{4}$$

The $h_{overhead}$ factor accounts for telescope overheads (slewing, pointing, focusing, calibration), i.e. all telescope time which is not spend integrating on-source. This overhead factor depends strongly on the observing project. For instance, deep integrations on a single source lead to small overheads while short integrations on multiple sources spread over the sky lead to significantly larger overheads due to the increased telescope slew time. We recommend to use $1.5 \leqslant h_{overhead} \leqslant 2.0$, depending on the project. The right term within brackets accounts for small maps where a point source is always within the FoV (so there is always time ON-source in the OTF scans), and larger maps, where the FoV goes OFF-source a fraction of the time. In order to achieve an homogeneous RMS distribution within the $\Delta_x \cdot \Delta_y$ area, we recommend to carry out maps with lengths $\geqslant 2$ [arcmin]. In Equation 4, is it assumed that for 1.2 mm observations, both horizontal and vertical polarizations are combined for the estimation of t$_{total}$. Table 1 summarizes the NIKA2 instrument's specifications while in Table 2 the parameters used in the time estimator are listed. For deep integrations ($< 0.5 - 1$ [mJy/beam]) we remind proposers to consider estimating confusion noise levels as it might prevent reaching such low rms values. Also useful for large scale mapping is to estimate the mapping speed of the array in units of [arcmin^2 hour^{-1} mJy^{-2}]. This can be derived by noticing that the total integration time in Equation 4 can be expressed as:

$$t_{total} = \left(\frac{A_{map}}{S_{map}}\right) \times \frac{1}{\sigma^2}, \tag{5}$$

where S_{map} is the mapping speed of the array. Using Equations 2 and 4, solving for S_{map} we obtain:

$$S_{map} = \left(\frac{f_{pix} A_{FoV}}{NEFD^2}\right) \times \frac{1}{h_{overhead}}. \tag{6}$$

The values of the mapping speed for the example cases in Section 4 are listed in Table 4. In Appendix of the previous document given for the summer semester (Garcia et al.), the predictions from Equation 4 are

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[2] Note that the approximation $A_{map} \sim \Delta_x \cdot \Delta_y + A_{FoV}$ overestimates the covered area if the source stays on-array during the observation, in which case $t_{beam} \sim t_{int}$. For a detailed derivation of this approximation see appendix in the previous document given for the summer semester

compared with simulations of the NIKA2 OTF observing mode.

Table 1: NIKA2 instrument's specifications [6].

Definition	Symbol	NIKA2	
Band		1	2
Central Wavelength	λ [mm]	1.2	2.0
Central Frequency	ν [GHz]	260	150
Frequency Bandwidth	$\Delta\nu$ [GHz]	240 – 280	125 – 170
Number of pixels	N_{pix}	2×1140	616
Pixel Spacing	[Fλ]	0.9	
Half-Power Beam Width (HPBW)	Θ_{res} [arcsec]	12	18

Table 2: Parameters used in the time estimator.

Definition	Symbol	NIKA2	
Band		1	2
Noise equivalent flux density	$\mathrm{NEFD}_\circ$ [mJy$\cdot\sqrt{s}$]	33[1]	8
Field-of-View diameter	D_{FoV} [arcmin]	6.5	
Field-of-View area	A_{FoV} [arcmin^2]	33.2	
Fraction of good pixels	f_{pix}	0.75	
Post-processing overhead	h_{filter}	$1.0 \lesssim h_{filter} \lesssim 2.0$	
Telescope overheads	$h_{overhead}$	$1.5 \lesssim h_{overhead} \lesssim 2.0$	
Noise goal	σ [mJy]	user defined	
x-length of A_{map}	Δ_x [arcmin]	user defined	
y-length of A_{map}	Δ_y [arcmin]	user defined	

[1] The sensitivity at 1.2 mm is obtained after combining the measurements of the two 1.2 mm arrays. The values of $\mathrm{NEFD}_\circ$ and fraction of valid pixels refer to [1]. No polarization measurement is provided for the time being.

3 Recommanded scan sizes for science projects

To optimize the correction of data instabilities, the length of NIKA2 sub-scans, i.e. the size of scans along the scan direction should be at least:

NIKA2 FOV (6.5') + NIKA2 beam width (12" at 1mm, 18" at 2mm) +
source size above the noise + 2s × scan speed

The third term makes sure that KIDs instabilities are properly corrected by data reduction. The fourth term is added because known tracking deviations of the 30m telescope can hinder the quality of data records, up to 2s after the beginning of each sub-scan. Perpendicularly to the scan direction, there is no minimum size limit, but too long scans can expose to a risk of loosing tuning over time. Note that the size computed in this way is the Delta(x) described in the exposure time calculator documentation, and not the size of the final map. The latter is larger by one FOV size.

4 Time Estimator Test Cases

A *python* script performs the calculations to obtain the total integration time for a given project. A help menu describing each script's option is displayed by running the following instruction in a terminal:

```
> python NIKA2_Time_Estimator.py --help
```

In the following, some illustrative examples of the time estimator results for OTF mapping are presented. These are summarized in Table 3 and typical weather conditions at the 30m telescope's site are compiled in Table 4.

- **Point Source:** to observe a single point source of flux 1 [mJy/beam] at 2 mm and 1.5 [mJy/beam] at 1.2 mm with NIKA2, we would use the OTF observing mode with $\Delta_x = \Delta_y = 2'$, and the most aggressive filtering scheme for with $h_{filter} = 1.0$, which is optimized for point source photometry. For a 5-σ detection of this source, one requires a flux uncertainty $\sigma = 0.2$ [mJy/beam] at 2 mm and at 0.3 [mJy/beam] at 1.2 mm. Assuming 4 mm of precipitable water vapor (pwv), i.e. an opacity $\tau \sim 0.10$ at 2 mm and $\tau \sim 0.30$ at 1.2 mm, and a typical source elevation of 50 degrees, Equation 4 gives a total observing time of 1.0 hours for the 2.0 mm band, and 12.6 hours for the 1.2 mm band, including overheads ($h_{overhead} \sim 1.5$). Note that in practice we would split this long observation into smaller observing blocks.

- **Nearby Galaxy:** to observe a nearby galaxy of size $\Delta_x = \Delta_y = 15'$, where extended emission at a level of 2.22 [mJy/beam] at 1.2 mm and 1.26 [mJy/beam] at 2 mm shall be detected, we would use the OTF observing mode with the least aggressive filtering scheme with $h_{filter} = 2.0$, which is optimized for extended emission. For a 3-σ detection of this source, one requires a flux uncertainty $\sigma = 0.74$ [mJy/beam] and 0.42 [mJy/beam] for the 1.2 mm and 2 mm bands, respectively. Assuming 2 mm of precipitable water vapor (pwv), i.e. an opacity $\tau \sim 0.15$ at 1.2 mm and $\tau \sim 0.05$ at 2 mm, and a typical source elevation of 45 degrees, Equation 4 gives a total observing time of 7.9 hours for the 2.0 mm band and an observing time of 61.5 hours for the 1.2 mm band, including overheads ($h_{overhead} \sim 2.0$). Note that in practice we would split this long observation into smaller observing blocks.

Table 3: Summary of time estimates in Section 4 and average pwv values in Summer/Winter conditions

source	**Point Source**		**Nearby Galaxy**	
band	1.2 mm	2.0 mm	1.2 mm	2.0 mm
Δ_x [arcmin]	2	2	15	15
Δ_y [arcmin]	2	2	15	15
pwv [mm]	4	4	2	2
τ	0.30	0.10	0.15	0.05
El [deg]	50	50	45	45
h_{filter}	1.0	1.0	2.0	2.0
$h_{overhead}$	1.5	1.5	2.0	2.0
rms [mJy/beam]	0.30	0.20	0.74	0.42
	Total Integration Time Results			
$\mathbf{t}_{spec}$ [hours]	12.7	1.0	61.5	7.9
	Mapping Speed			
$\mathbf{S}_{map}$ [arcmin^2 hour^{-1} mJy^{-2}]	28.0	860.3	7.5	181.8

Table 4: Typical Summer/Winter weather conditions at the 30m telescope's site

	Winter Conditions			**Summer Conditions**		
	excellent	**good**	**average**	**excellent**	**good**	**average**
pwv [mm]	1	2	4	2	4	7
τ (1.2 mm band)	0.08	0.15	0.30	0.15	0.30	0.53
τ (2.0 mm band)	0.03	0.05	0.10	0.05	0.10	0.18

References

[1] Adam, R., Adane, A., Ade, P. A. R., et al. 2018, A&A, 609, A115

[2] Guidelines for observing time estimates with IRAM-30m continuum cameras. N. Billot, C. Kramer, S. Leclercq, I. Hermelo, X. Desert & A. Kovács, August 4, 2014

[3] Improved mm-wave photometry for kinetic inductance detectors. Calvo, M., Roesch, M., Désert, F.-X., et al. 2013, A&A, 551, L12

[4] Performance and calibration of the NIKA camera at the IRAM 30 m telescope. Catalano, A., Calvo, M., Ponthieu, N., et al. 2014, A&A, 569, A9

[5] The NIKA2 Instrument, A Dual-Band Kilopixel KID Array for Millimetric Astronomy. Calvo, M., Benoit, A., Catalano, A., et al. 2016, arXiv:1601.02774

[6] The NIKA2 commissioning campaign: performance and first results. Catalano, A., Adam, R., Ade, P., et al. 2016, arXiv:1605.08628