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, for both total intensity and polarization (1.2 mm band only) observations. 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 2024 semesters according to the parameters given in the reference article [1], the summary of the NIKA2 polarization commissioning report [6], and the recent behavior of the instrument. 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 detector called KID (Kinetic Inductance Detector). 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 ∼160 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 (2×1140 for Horizontal and Vertical polarization) square pixels. Currently, the observing mode for **extended and point sources** with NIKA2 is the OTF (*zig-zag*) observing mode in which, while the telescope drives continuously in a certain direction, data and positional information are recorded for later map reconstruction. Following links provide further information about scripting and observing with NIKA2.

2 Observing Time Estimate

First of all, **it is essential that the NIKA2 users define the minimum scan size according to what is specified in Section 3, and adopt a value of precipitable water vapor (pwv [mm]) as less restrictive as possible, depending on the season of interest (cf. Table 4)**. Having said that, the equations and parameters that govern the operation of the NIKA2 observing time estimator are as follows.

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:

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

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 $1.0 \leqslant h_{\text{filter}} \leqslant 2.0$, depending on the source extent.

The **integration time per beam** on total and polarized intensity 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:

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

where $A_{\text{map}} \sim \Delta_{\text{x}} \cdot \Delta_{\text{y}} + A_{\text{FoV}}$, and the ratio $A_{\text{FoV}}/A_{\text{map}}$ represents the average fractional coverage[1]. Notice that the $\Delta_{\text{x}} \cdot \Delta_{\text{y}}$ area is the area covered by the central pixel of the array. Due to variations in the 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 $f_{\text{pix}} \cdot A_{\text{FoV}}$.

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:

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

The h_{overhead} factor accounts for telescope overheads (slewing, pointing, focusing, calibration), i.e. all telescope time that is not spent 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 using $1.5 \leqslant h_{\text{overhead}} \leqslant 2.0$, depending on the project; $h_{\text{overhead}} \sim 2$ if you wanted to be conservative in this regard**. 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 a homogeneous RMS distribution within the $\Delta_{\text{x}} \cdot \Delta_{\text{y}}$ area, we recommend carrying out maps with lengths $\geqslant 2$ [arcmin]. In Equation 4, is it assumed that for 1.2 mm observations in total power, 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:

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

[1]Note that the approximation $A_{\text{map}} \sim \Delta_{\text{x}} \cdot \Delta_{\text{y}} + A_{\text{FoV}}$ overestimates the covered area if the source stays on-array during the observation, in which case $t_{\text{beam}} \sim t_{\text{int}}$

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

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

The values of the mapping speed for the example cases in Section 4 are listed in Table 4.

2.1 NIKA2 polarization observations considerations

For polarization observations (1.2 mm band), the the key parameter driving the estimated time, aside from the total intensity, is the polarization degree or polarization fraction. The polarization degree can be as low as a few percent in molecular clouds (e.g. Fig.9 in [7]). Measurements of the linear polarization therefore require deep, time consuming integrations. For example, if the total intensity (Stokes I) is 100 mJy/beam and reached with a S/N of 3 (i.e. Stokes I rms of ∼33.3 mJy/beam), a 6% polarization degree requires a deep integration down to 0.06*100 = 6 mJy/beam to reach a S/N of 3 in polarized intensity (i.e. Stokes Q and U rms of 2 mJy/beam). As the integration time is proportional to the rms squared, the polarization degree is the dominant driver of the integration time.

In addition, for NIKA2 polarization projects it is recommended to use $h_{\rm overhead} = 2$, to account for project specific overheads like slewing, local pointing, and worse weather conditions than anticipated. The increased overhead time is also favorable for extra time needed for polarization-specific calibration observations, e.g. observations of strong, (un)polarized quasars, which can improve the instrumental polarization calibration of your project. Finally, note that the observing system design for polarimetric observations with NIKA2 poses an upper limit to the scanning speed of the observations, namely ∼35-40 arcsec/s, to minimize the contamination between Stokes parameters I, Q and U and to allow a Nyquist sampling of the beam in time per each phase of the rotating HWP. We point the reader to Chapter 6 of the PIIC manual for more details.

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

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 design pixels	$\rm N_{pix}$	2×1140	616
Pixel Spacing	$[\lambda_{\rm fraction}]$	1.1	0.9
Half-Power Beam Width (HPBW)	$\Theta_{\rm res}$ [arcsec]	11.1	17.6

3 Recommended 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 (Xsize) should be at least:

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

Table 2: Parameters used in the time estimator.

Definition	Symbol	NIKA2	
Band		1	2
Noise equivalent flux density	$\mathrm{NEFD}_\circ$ [mJy·$\sqrt{s}$]	30[1]	9
		(20 in Stokes Q and U)[2]	
Fraction of good pixels	f_{pix}	0.86	0.83
Field-of-View diameter	$\mathrm{D}_{\mathrm{FoV}}$ [arcmin]	6.5	
Field-of-View area	$\mathrm{A}_{\mathrm{FoV}}$ [arcmin^2]	33.2	
Post-processing overhead	h_{filter}	$1.0 \lesssim h_{\mathrm{filter}} \lesssim 2.0$	
Telescope overheads	h_{overhead}	$1.5 \lesssim h_{\mathrm{overhead}} \lesssim 2.0$	
Noise goal	σ [mJy]	user defined	
Xsize of A_{map}	Δ_{x} [arcmin]	user defined	
Ysize of A_{map}	Δ_{y} [arcmin]	user defined	

[1] The sensitivity on total intensity at 1.2 mm is obtained after combining the measurements of the two 1.2 mm arrays. The values of $\mathrm{NEFD}_\circ$ refer to [1]. The f_{pix} values are subject to statistics of the instrument gathered in 2022.
[2] According to [6].

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 single scans (i.e. $\gtrsim$ 20 min.) can expose the observer to a risk of losing tuning over time. Note that the size computed in this way is the Δ_{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 2.X 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_2024.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. In case of doubt, please contact a member of the NIKA2 Pool Managing Team (see the NIKA2 homepage).

- **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 (total intensity) with NIKA2, we would use the OTF observing mode at a scanning speed of 20 arcsec/sec with an estimated map size of $\Delta_{\mathrm{x}} = \Delta_{\mathrm{y}} = 8.5'$, and the most aggressive filtering scheme for with $h_{\mathrm{filter}} = 1.0$, 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 4.0 hours for the 2.0 mm band, and 32.3 hours for the 1.2 mm band (14.4 hours to reach such rms in Stokes Q & U for polarimetry mode), including overheads ($h_{\mathrm{overhead}} \sim 1.5$). Note that in practice we would split this long observation into smaller observing blocks.

- **Nearby Galaxy:** to observe a nearby galaxy of size 7′ at a scanning speed of 40 arcsec/sec, we estimate a map size of $\Delta_{\rm x} = 15.5$, $\Delta_{\rm y} = 11.0$, where extended emission at a level of 1.26 [mJy/beam] at 2 mm and 2.22 [mJy/beam] at 1.2 mm (total intensity) shall be detected, we would use the OTF observing mode with the least aggressive filtering scheme with $h_{\rm filter} = 2.0$, which is optimized for extended emission. For a 3-σ detection of this source, one requires a flux uncertainty $\sigma = 0.42$ [mJy/beam] and 0.74 [mJy/beam] for the 2 mm and 1.2 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 8.5 hours for the 2.0 mm band and an observing time of 39.0 hours for the 1.2 mm band (17.4 hours to reach such rms in Stokes Q & U for polarimetry mode), including overheads ($h_{\rm overhead} \sim 2.0$). Note that in practice we would split this long observation into smaller observing blocks.

- **Polarized point Source:** to observe a single point source with total intensity of 50 [mJy/beam] at 1.2 mm and a polarization degree of 5% with NIKA2, we would use the OTF observing mode at a scanning speed of 35 arcsec/sec with an estimated map size of $\Delta_{\rm x} = \Delta_{\rm y} = 8.5'$, and the most aggressive filtering scheme for with $h_{\rm filter} = 1.0$, which is optimized for point source photometry. For a 5-σ detection of the polarized intensity in this source, which is $5\% \cdot 50 = 2.5$ [mJy/beam], one requires a flux uncertainty $\sigma_{\rm pol} = 0.5$ [mJy/beam]. Assuming 4 mm of precipitable water vapor (pwv), i.e. an opacity $\tau \sim 0.30$ at 1.2 mm, and a typical source elevation of 50 degrees, Equation 4 gives a total observing time of 6.9 hours for the 1.2 mm band, including overheads ($h_{\rm overhead} \sim 2.$). This amount of observing time ensures that the polarized intensity of the source will be detected at a 5-σ level and the total intensity at a much higher significance level (67-σ, $\sigma_{\rm I} = 0.75$). Note that the maximum scanning speed in polarization observations is $\sim$ 35-40 arcsec/s, for the reasons described above. Note that in practice we would split this long observation into smaller observing blocks.

- **Polarized extended source:** to observe an extended source (e.g. a galactic cloud) of size 5′ at a scanning speed of 35 arcsec/sec, we estimate a map size of $\Delta_{\rm x} = 13.$, $\Delta_{\rm y} = 9.0$, where extended emission at a level of 18 [mJy/beam] at 1.2 mm in total intensity and 10% polarization shall be detected, we would use the OTF observing mode with the least aggressive filtering scheme with $h_{\rm filter} = 2.0$, which is optimized for extended emission. For a 3-σ detection of the polarized intensity in this source, which is $10\% \cdot 18 = 1.8$ [mJy/beam], one requires a flux uncertainty $\sigma_{\rm pol} = 0.6$ [mJy/beam]. Assuming 2 mm of precipitable water vapor (pwv), i.e. an opacity $\tau \sim 0.15$ at 1.2 mm and a typical source elevation of 60 degrees, Equation 4 gives a total observing time of 17.8 hours for the 1.2 mm band, including overheads ($h_{\rm overhead} \sim 2.0$). This amount of observing time ensures that the polarized intensity of the extended emission will be detected at a 3-σ level and the total intensity at a much higher significance level (20-σ, $\sigma_{\rm I} = 0.9$). Note that the maximum scanning speed in polarization observations is $\sim$ 35-40 arcsec/s, for the reasons described above. 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**		**Polarized point source**	**Polarized extended source**
band	1.2 mm	2.0 mm	1.2 mm	2.0 mm	1.2 mm	1.2 mm
Δ_x [arcmin]	8.5	8.5	15.5	15.5	8.5	13.0
Δ_y [arcmin]	8.5	8.5	11.0	11.0	8.5	9.0
pwv [mm]	4	4	2	2	4	2
τ	0.30	0.10	0.15	0.05	0.3	0.15
El [deg]	50	50	45	45	50	60
h_{filter}	1.0	1.0	2.0	2.0	1.0	2.0
h_{overhead}	1.5	1.5	2.0	2.0	2.0	2.0
total intensity [mJy/beam]	1.5	1.0	2.22	1.26	50.0	18.0
polarization degree [%]	–	–	–	–	5.0	10.0
rms [mJy/beam]	0.30	0.20	0.74	0.42	0.5	0.6
	Total Integration Time Results					
$\mathbf{t}_{\text{spec}}$ [hours]	32.3	4.0	39.0	8.5	6.9	17.8
	Mapping Speed					
$\mathbf{S}_{\text{map}}$ [arcmin^2 hour^{-1} mJy^{-2}]	34.7	626.9	9.3	132.5	58.5	22.7

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

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