Recent Results with NIKA & GISMO at the 30-meter telescope

Samuel Leclercq
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1. Reminders

2. NIKA 2\textsuperscript{nd} run at the 30m telescope

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1. Atmosphere opacity & background limited NEFD at Pico Veleta

Simple model (1 pseudo-continuum + 11 H₂O & O₂ lines based on fits to ATM in the 50-400 GHz range)

⇒ 90 & 150 GHz always, 250 GHz often, 350 GHz few weeks/year.
1. Purpose of the continuum prototypes

Test new technologies to replace MAMBO-2 with a better instrument:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>MAMBO-2</th>
<th>Future instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bands</td>
<td>1.2 mm</td>
<td>1.2 mm &amp; 2.1 mm</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>35 mJy·s(^{1/2})</td>
<td>5..10 mJy·s(^{1/2})</td>
</tr>
<tr>
<td>FOV (diameter)</td>
<td>4 arcmin</td>
<td>~ 6 arcmin (each band)</td>
</tr>
<tr>
<td>Coverage of the FOV</td>
<td>25 % (horns)</td>
<td>&gt; 90 % (filled array)</td>
</tr>
<tr>
<td>Polarization</td>
<td>No</td>
<td>Possible</td>
</tr>
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</table>

⇒ More pixels: 117 → 2000..8000
⇒ Mapping speed more than ×100 faster* !
⇒ New observing window at the 30m MRT

* Mapping time: \( t \sim \text{NEFD}^2 \cdot (\Omega_{\text{map}}/\Omega_{\text{e array}}) \)
⇒ \( t_{\text{MAMBO-2}} / t_{5' \times 5', 0.5 F\lambda, \text{filled}} = (35^2/(117 \cdot 11/60^2)) / (8^2/6^2) \approx 150 \)
1. GISMO main features

- **Transition Edge Sensors** (bolometers)
- $\nu = 150 \text{ GHz} (\lambda = 2 \text{ mm}), \Delta \nu = 22 \text{ GHz}$
- $0.9 F\lambda$ bare-pixels ($15'' \times 15''$ in sky)
- Unpolarized, pixel absorption = 90% (~20% full optical chain)
- DC coupled $\Rightarrow$ total power
- $8 \times 16 = 128$ pixels filled array
- SQUID amplifiers & multiplexers ($4 \times 32$)
- 260 mK $^3$He sorption cooler
- Built by GSFC (Nasa), PI: Johannes Staguhn

Absorbed photons modify membrane temperature which modify TES resistance

\[ R [\Omega] \]
\[ T [K] \]
1. GISMO runs 1 to 3

1st run (11/07):
• 50% useable pixels (broken bias line + bad feedbacks)
• Problems: baffling, saturation load, EM pickup
⇒ Map* NEFD ~ 200 mJy·s^{1/2}  


Upgrades: Detector board, Baffle, EM shield, Shutter, Lissajou

2nd run (10/08):
• 60% useable pixels (short in 1 MUX + some bad SQUIDS)
• Problems: noisy pixels, shocks, cloudy weather
⇒ Map* NEFD ~ 45 mJy·s^{1/2}  

Articles: Staguhn et al., AIP conf. 2009; Arendt et al. in prep.

Upgrades: MUX, ND Filter box, software (control & processing)

3rd run (04/10):
• 90% useable pixels (some bad SQUIDS)
• Problems: stray lights in ND filter box, others (time losses)
⇒ Map* NEFD ~ 45 mJy·s^{1/2}  


* Time stream NEFD = Map NEFD/\sqrt{2}, background limit ~ 5..10 mJy ·s^{1/2}
1. NIKA main features

- **Kinetic Inductance Detectors**
  - $\nu = 150 \text{ GHz} (\lambda = 2 \text{ mm}), \ \Delta \nu = 40 \text{ GHz}$
  - $\sim 0.7 F\lambda$ bare-pixels ($\sim 9^\prime \times 9^\prime$ in sky)
- Total power
- Filled arrays
- Antenna KID
- Lumped Elements KID
- Multiplexing all pixels in one feed line
- 80 mK $^3\text{He}-^4\text{He}$ dilution fridge
- Built by CNRS-Néel / IRAM* / AIG/Cardiff / SRON, PI: Alain Benoit

Absorbed photons modify kinetic inductance, which modify resonance frequency

*Markus Rösch PhD. (LEKID)
1. NIKA run 1

1\textsuperscript{st} run (10/09):

- 42 A-KID array (SRON), then 32 LEKID array (Néel/IRAM/AIG-Cardiff)
- Polarized pixels, absorption \(~60%\) (~30% full optical chain)
- \(> 90\%\) useable pixels (some frequency shifts due to flux trapping)
- Problems: EM pickup, non-optimal pixel architecture

\(\Rightarrow\) Map \(*\) NEFD \(~120\) mJy\(\cdot\)s\(^{1/2}\)

Article: Monfardini et al, A&A 2010

* Background limit \(~5..10\) mJy \(\cdot\)s\(^{1/2}\)
2. NIKA 2\textsuperscript{nd} run: Upgrades & lab tests

\textbf{Sky simulator:} cold black body for optical tests in lab (T adjustable from 50 to 300 K)
~5mm "planet" on X-Y table

\textbf{New NIKA elements:}
- Optics (biconic mirror, 4 lenses, polarizer, filters)
- Cryostat: longer baffle, 2 array holders
- 2.1 mm: Néel-IRAM 144 pixels, $f_0 = 1.5$ GHz, $\Delta f_{\text{mux}} = 2$ MHz
- 1.3 mm: SRON 256 pixels, $f_0 = 5$ GHz, $\Delta f_{\text{mux}} = 4$ MHz
- Electronic: 2 Casper Roach Boards (230 MHz bandwidth), IRAM 1.5 GHz amplifier, Caltech 5 GHz amplifier
⇒ Sensitivity goal: $\sim \times 4$ better than 1\textsuperscript{st} run

NIKA 1 optics and cryostat, and main changes for NIKA 2
NIKA 2 cryostat optics

Total optical transmission $\approx 40\%$
2. NIKA 2\textsuperscript{nd} run: Upgrades & lab tests

- **1.3 mm band** (220 GHz) SRON
  - pixel size = 1.6mm
  - $= 0.8F\lambda = 11"$
  - FWHM on the sky; 62 used in run $\rightarrow$ 
  - $\sim 1.5’$ FOV

- **2.0 mm band** (150 GHz) Néel-IRAM: pixel size =
  - 2.25mm $= 0.75F\lambda$
  - $= 17”$ FWHM on the sky; 112 used in run $\rightarrow$ 
  - $\sim 2’$ FOV

50 mK/Hz$^{1/2}$ (1Hz) $\leftarrow$ NET with sky simulator (NET_{bkg}=1mK/Hz$^{1/2}$) $\rightarrow$ 6 mK/Hz$^{1/2}$ (1Hz)
2. NIKA 2\textsuperscript{nd} run: Calibration on sky at the the 30m

Mapping **planets**
⇒ relative positions of arrays in the sky (pointing)
⇒ relative pixel responses (gains)
⇒ beam sizes & height vs M2 shifts (focus)
⇒ known signal vs noise (sensitivity)
⇒ response to various fluxes (linearity)

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<tr>
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<th>1.3mm</th>
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<td><strong>Signal</strong>:</td>
<td>2-4 kHz</td>
<td>10 kHz</td>
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<td><strong>Noise</strong>:</td>
<td>2 Hz/Hz(^{1/2})</td>
<td>16-20 Hz/Hz(^{1/2})</td>
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<td><strong>Mars flux</strong>:</td>
<td>40 Jy</td>
<td>107 Jy</td>
</tr>
<tr>
<td><strong>S/N</strong>:</td>
<td>≈ 1000 Hz(^{1/2})</td>
<td>≈ 500 Hz(^{1/2})</td>
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<tr>
<td><strong>NEFD (1Hz)</strong>:</td>
<td>≈ 30 mJy/Hz(^{1/2})</td>
<td>≈ 150 mJy/Hz(^{1/2})</td>
</tr>
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<td><strong>NEP (1Hz)</strong>:</td>
<td>≈ 0.23 fW/Hz(^{1/2})</td>
<td>≈ 3 fW/Hz(^{1/2})</td>
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**NEP (1Hz) ≈ estimated by sky simulator!**

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**Average « raw » S/N on Mars:**

- **Signal**: 2-4 kHz
- **Noise**: 2 Hz/Hz\(^{1/2}\)
- **Mars flux**: 40 Jy
- **S/N**: ≈ 1000 Hz\(^{1/2}\)
- **NEFD (1Hz)**: ≈ 30 mJy/Hz\(^{1/2}\)
- **NEP (1Hz)**: ≈ 0.23 fW/Hz\(^{1/2}\)

**Flat and stable noise spectra**
⇒ Sensitivity still dominated by pixel, but much lower than 1st run AND large bandwidth
2. NIKA 2\textsuperscript{nd} run: Quick-Look to some sources

Radio sources, galaxies, clusters of galaxies, quasars

Example of Quick-Look sum maps with causal filter obtained with the 2 arrays

1.3 mm

2 mm

>1 Jy sources (DR21OH, MWC349, NGC7027...) in real time, few 100 mJy (NGC 1333...) seen quickly
2. NIKA 2\textsuperscript{nd} run: Data analysis and results

Pixels characteristics & pointing

- 62 at 1mm + 98 at 2mm = 172 valid pixels / 224 electronics outputs (52 double, blind, bad, off resonance, undefined)
- FWHM: 12.5” at 1mm, 16” at 2mm (focus from QL, not redone yet...)
- Simple pointing method: offset, rotation, scaling on EMIR pointing model
- Pointing accuracy: array optical axis < 1”, pixel < 2”, source to source ~1-2”
- Source Az/El offset corrections done offline from nearest planet/quasar data

Valid pixels on the 1mm and 2mm arrays: green = inside the bandwidth of the tones generators, orange = outside)
2. NIKA 2\textsuperscript{nd} run: Data analysis and results

**Photometry (current status, work in progress)**

- 10% reproducibility within a planet (same planet observed at different days)
- Neptune (19.5"., 7.4Jy) from Uranus (54.8", 20.7Jy) calibration: (16.9", 7.0Jy) = 15% precision
- MWC349 using Mars one day and Uranus another day: fluxes are off the official values (2.01 and 1.49 Jy) by 12% and 30%, but they are stable
- Atmosphere opacity correction: use $\tau$(225GHz), a $v^2$ law, and elevation
- To be done: intercalibration (flat-field), Skydips, OnOff (wobbler) data

**Map-Making**

- 1 map per kid per scan produced with interpolation to the 4 nearest grid points
- Pointing: use on-the-fly center coordinates and beam map offsets
- Noise evaluated at detector map level by histogram fitting. Pixel correlation corrected

**Filtering**

- Necessary to remove the zero level
- Bandpass for sky noise decorrelation is 10-110 arcsec
- Only strong sources are masked (no bias for the detection of weak sources)
2. NIKA 2\textsuperscript{nd} run: Some processed images

Radio sources, galaxies, clusters of galaxies, quasars

1.3 mm

MWC349 $T_{\text{int}} = 8$ min.

Cyg A $T_{\text{int}} = 36$ min.

IRC10420 $T_{\text{int}} = 33$ min.

2 mm
2. NIKA 2nd run: Conclusion

- Unpacking to 1st astronomical light in only 24 hours! (4 days for 1st run)
- ~<10% bad pixels, number of pixels limited by readout electronics
- Alignment and focus extremely quick and easy (M6 attached to cryostat)
- Control software improved since 1st run, real time quick look analysis very convenient
- Strong to moderately weak (few mJy) sources observed
- Non-optimal sky calibration, better than 30% accuracy on absolute photometry

Sensitivity: conservative **NEFD** (data reduction still in progress)

- $= 450 \text{ mJy} \cdot \text{s}^{1/2} @ 1\text{mm}$ → >10x MAMBO-2 (OK for a 1st time)
- $= 37 \text{ mJy} \cdot \text{s}^{1/2} @ 2\text{mm}$ (NET = 6 mK·s$^{1/2}$) → ~3x better than 1st run! Still ~4x to gain to reach the background limit

- Successful run: lot of progress done since 1st run (one year before), only minor problems at the telescope, sky simulator validated, improvements foreseen

1st time that

- KIDs achieve such a high sensitivity on a telescope (almost = state-of-art APEX SZ TES)
- so many KIDs are successfully installed on a telescope
- so many detectors observe the sky at the 30m MRT
- a dual band multi-pixel continuum instrument is used at the 30m

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3. Gismo 4th run: Upgrades

Upgraded Gismo elements:
- 2 motorized neutral density filters (NDF) with 65% and 40% transmissions respectively (compensate the restrained dynamic range of Gismo in case of poor weather conditions)
- One additional low-pass filter (total of 7 filters)
- New mm/THz/IR black-paints on the NDF box and baffles (suppression of residual stray lights)
- SQUID tuning algorithm
- Updated versions of the Gismo control software & CRUSH

⇒ Sensitivity goal: ~×2 better than 2nd & 3rd runs
3. GISMO 4th run: Calibration on sky

Mapping planets
⇒ relative positions of arrays in the sky (pointing)
⇒ relative pixel responses (gains)
⇒ beam sizes & height vs M2 shifts (focus)
⇒ known signal vs noise (sensitivity)
⇒ response to various fluxes (linearity)

S/N analysis: NEFD (1Hz) ≈ 16 mJy·s\(^{1/2}\) per beam
3. GISMO 4\textsuperscript{th} run: Quick-Look to some sources

Radio sources, galaxies, clusters of galaxies, quasars

Example of Quick-Look maps automatically posted on a log page after each scan

Remark 1: these individual scan images are "almost raw" (generated with CRUSH basic filter) and serve as real-time quick look control of the good behavior of the observations; the quality and information obtained with processed images are significantly better.

Remark 2: pointings on nearby strong point sources were done between each scan, focus several times a day (particularly at dawn and sunset), beam maps and gains and flux calibrations several times a week.
3. GISMO 4th run: Data analysis & preliminary results

**Pixels characteristics & pointing**
- 107 = valid pixels (all TESs OK, some dead SQUIDs in the MUX given by NIST)
- FWHM: ~17” (fluctuations depending on the time of the day & night)
- Simple pointing method*: offset, rotation, scaling on EMIR pointing model
- Pointing accuracy (current status): < 3” rms whole array
- Source Az/El offset corrections done offline from pointing references

* We did pointing cessions to implement a GISMO model to the telescope NCS, but this attempt failed due to problems understanding/matching GISMO and NCS coordinate parameters (solvable, need to be worked out)

**Photometry (current status, work in progress)**
- 7% rms blind calibration up to tau(225 GHz) ~ 1
- Calibration factor itself well determined to ~1.2% rms
- 0.1 rms on the radiometer values = 4% calibration noise @ 2mm
  ⇒ Skydips seem unnecessary (time consuming vs longer datasets)
- Flat distribution of the the main peak relative flux vs beam size
  ⇒ same calibration factor for extended and point sources
- NEFD ~ 15-17 mJy·s^{1/2} in all weather (τ)
  ⇒ background noise limit has to be ~5 mJy ·s^{1/2}
3. GISMO 4th run: Some processed images

Eyelash (z=2.326 submm galaxy)

T_{int} = 40 min.

IRDC G035.39-00.33 (see C.Kramer)

~6' x 30', T_{int} = 90 min,
RMS ~ 120 \mu Jy/beam

GDF (GISMO Deep Field in HDF / GOODS-N)

5' x 5', T_{int} = 20 h

"jack-knife"
(source extraction)

"GDF images are for IRAM internally
and the SAC only" J.Staguhn

S/N histogram of the GDF:
excess at the high-positive \sigma

10/05/2011
SAC meeting IRAM Grenoble
3. GISMO 4\textsuperscript{th} run: Conclusion

- ~30 hours needed from closing cryostat in workshop to 1\textsuperscript{st} astronomical light (quite fast)
- \(~<10\%\) bad pixels, number of pixels limited by bad SQUIDs (all TES OK)
- Alignment and focus faster than previous runs (\(~5\) hours, but doable in less than 2h)
- User friendly control software \& real time quick look analysis very convenient
- Strong to very weak (<0.2 mJy) sources observed
- Sky calibration looks good with accuracy <10\% on absolute photometry

Sensitivity: conservative \textbf{NEFD} (data reduction still in progress)
\[ = 17 \text{ mJy} \cdot \text{s}^{1/2} ! \] Still \(~3\)x to gain to reach the background limit

\textarrow{Successful run: lot of progress done compared to previous runs, except for an excess spill-over on M7 no problem with the instrument, the background limit seems reachable}

\textsuperscript{1}\textsuperscript{st} time that
- A bolometer instrument achieve such a high sensitivity at the 30m telescope
- So many TESs are successfully installed at the 30m MRT
- A map as deep as the GDF is obtained at the 30m?
4. Perspectives: NIKA

Data analysis:
• Reduce all scans homogeneously (v3 in progress)
• Improve on photometric accuracy (sky noise flat field, IQ circle calibration, next runs: modulate the frequency carrier)
• Improve on sky noise decorrelation (detector choice, map vs sky noise timeline)

Hardware for next run:
• Cryostat → Stronger magnetic field shielding. Pulse Tube Cooler ?
• Filters → from NIKA 2010
• Splitter → Dichroic ?
• Detectors 2mm → Same as NIKA2010 (best Al LEKID tested in laboratory reaches the target sensitivity !) ; dual-polar if dichroic
• Detectors 1mm → Antenna or LEKID (best sensitivity and number of pixels)
• Pixels → 224 per array over a 400 MHz band (see electronics). AR coating ?
• Electronics → «NIKEL» from LPSC (> 256 channels, > 400 MHz band) or ROACH board if LPSC not ready, 1 kHz frequency modulation for better photometry, automatic frequency lock on resonances
4. Perspectives: GISMO

Data analysis:
- Reduce all scans homogeneously (in progress)
- Data available to IRAM astronomer whose project have been observed

Ready to be proposed to the community:
- Only updates foreseen: larger M7 and cold snout to reduce stray lights
- Instrument and software in final state
- Sensitivity < 10 mJy·s^{1/2} seems reachable
- User friendly & documented
- However: issues of GISMO pointing model in NCS and limitation to 28° elevation must be solved

Dedicated position in receiver cabin?
- One proposition with a MAMBO-GISMO switch
- Need 2 flat mirrors, easily movable
- Need a new anti-vibration table?
- Need to move MAMBO 2 backend
4. Perspectives and conclusion: Beyond the prototypes

GIMSO and NIKA showed impressive sensitivity improvements. The goal of a background limited instrument seems reachable, the scaling to kilopixel arrays still needs to be proven. The preparation for the science grade instrument continues: Optics (GISMO-2, NIKA-x, cabin), Detectors (LEKIDs), GIMSO and NIKA teams works, call for tender imminent.

- **2 colors** (bands / channels): $\lambda = [2.05 ; 1.25]$ mm ($\nu = [240 ; 146]$ GHz)
- **Background limited** (NEP_{inst} $\sim [18 ; 38]$ aW/Hz$^{1/2}$ ; NET_{beam} $\sim 0.5$ mK$\cdot$s$^{1/2}$ & NEFD_{beam} $\sim 5$ mJy$\cdot$s$^{1/2}$ for both bands under good sky conditions in 1-100 Hz frequency domain)
- **Large dynamic range** (20-200 K_{RJ} background) $\Rightarrow \Delta T/(NET/2) = 10^6$ s$^{-1/2}$
- Nyquist sampling pixels (0.5F$\lambda$, best for mapping)
- Filled array (best against anomalous refraction)
- **Field Of View = 6.5’** maximum $\Rightarrow \sim 2000 + 6000$ pixels
- **Negligible sensitivity to stray-lights**
- Mapping speed improvement expected $> 150$
- **Cost = 1M€ cash + 1M€ dedicated time** from IRAM
- Delivery to community: 2014
- (polarization option)
END