• Examples of cameras and new issues
• Extension to polarization
Mapping speed

- Mapping speed ($NEFD$ in mJy.s$^{1/2}$)

$$\frac{d\Omega}{dt} = N_{pix} \left( \frac{F_\nu(1\sigma)}{NEFD} \right)^2 \omega_{pix}$$

- Cameras have similar point-source sensitivities

The time to cover a given field is

$$t = \max(\text{Field}/\text{FOV},1) \ast (\text{NEFD}/F_{nu})^2$$

- FOV=$N_{pix}.\omega_{pix}$

- The field-of-view increases linearly with the number of pixels

- Increasing need for statistics: fight sample variance, find correlation functions, respect
The power of mapping

Figure 1. Left-hand panel: The galaxy density map from Scoville et al. (2007a), with the boundaries of the AzTEC, Bolocam and MAMBO millimetre surveys within the COSMOS field indicated. The location of the \( z = 0.73 \) cluster environment is identified by the dashed circle. Right-hand panel: The AzTEC/COSMOS map with \( > 3.5 \sigma \) source candidates identified by circles with diameters equal to twice the AzTEC FWHM on the JCMT. The map has been trimmed to the ‘75 per cent coverage region’ and has an average rms noise level of 1.3 mJy beam\(^{-1}\) and an area of 0.15 deg\(^2\). The signal map has been Wiener filtered for optimal identification of sources as described in Section 3.5. See the online journal for a colour version of this figure.
SCUBA2 programmes

Figure 13: Summary of the approved SCUBA-2 Legacy programmes for the JCMT in terms of total area to be covered to a certain depth.

Holland, et al arXiv0606.338
Mapping speed

From J. Staguhn
Angular scale coverage
Complementary between sensitivity and resolution

\[ \frac{l(l+1)C_l}{2\pi} \]

Sensitivity

Planck/HFI

30m, Apex Cameras

PdB++

Alma

180 deg

5 arcmin

20 arcsec

0.1 arcsec

1/Angular scales
Map making, in full

- Mapping equation
  \[ d = A m + n \]
  \[ N = \langle n n^t \rangle \]
  \[ \tilde{m} = W d \]
  \[ W \equiv [A^t N A]^{-1} A^t N \]
  \[ \Sigma \equiv W N W^t \simeq [A^t N^{-1} A]^{-1} \]

- (unbiased) solution

- Minimizing variance

- m: map, d: raw data, n: noise, A: pointing

- Tegmark, 1997, Phys Rev D55, 5895
Map making, simplified

- Simplified map-making: average with natural weight

\[
m = \frac{1}{\sum_i w_i} \sum_i w_i d_i
\]

\[
w_i = \frac{1}{\sigma_i^2}
\]

\[
\frac{1}{\sigma_m^2} = \sum_i \frac{1}{\sigma_i^2}
\]
Fig. 3. Mollweide projections of sky maps computed by Mirage algorithms from simulated timelines: a) the Signal (CMB anisotropy + Galaxy) map to be reconstructed; b) to f) difference maps: maps processed by Mirage algorithms running on simulated timelines with CMB + Galaxy signal only, with the Signal map subtracted. These maps show and sometimes enhance the systematics induced by algorithms processing the timelines with signals of large amplitude (Galaxy map brightest pixel’s value is 13000). We observe that SlopeKillerMask b) induces very little distortion, while MirageDC c) tends to minimise the Galaxy brightest pixels. d) shows the difference map computed by high-pass filtering and coaddition of the timeline. Large systematic shows in and around the galaxy area due to the high-pass filter and its side-effect ringing. e) and f) show the efficiency of MirageAC and the rough filtered map making algorithms to minimise distortion and ringing in maps. Still, large distortions do remain and MirageAC is of little use for mapping the Galaxy or other foreground, but turns out to be very useful for CMB $C_l$ estimation when data involve noise with high frequencies and strong $1/f$ features.
Sampling the focal plane

- $f$ gives the plate scaling $d = f \alpha$
- $F = \frac{f}{D}$ up to 2. A beam has a typical width of $\alpha = 1.2 \frac{\lambda}{D}$
- On the focal plane, the natural unit is thus $F.\lambda$. One beam projects as $1.2 F.\lambda$
- A horn samples at $2 F.\lambda$
- Plane arrays can go down to $0.5 F.\lambda$
- A telescope has no angular frequencies larger than $\frac{D}{\lambda}$
- Horn arrays have to fill in the holes with 16 positions.
- The mapping speed of a filled array can be up to 3 times the horn-array one
Horn vs. Filled arrays

- Griffin, Bock, Gear, Applied Optics, 2002, 41, 6546
- Griffin, 2000, Nuclear Instruments and Methods in Physics Research, 444, 397
- Benoit & Desert, astrophy/9901414

\[
\text{gamma} = \frac{\text{NEPdet}}{\text{NEPph}}
\]
Plane array

Figure II.4. The 204 pixels focal plane array. Left: mask design. The inner circle represents the FWHM of the over-sampled 150 GHz diffraction spot. Right: picture of one of the fabricated arrays. Credit: B. Beller.

Courtesy: DCMB collaboration
Kuo et al., Antenna coupled TES for polarimetry, astrophy/0606366

Figure 1. Left: The focal plane of the ESA CMB satellite mission Planck, to be launched in 2008. Right: A 150 GHz prototype antenna-coupled bolometer array with 8 x 8 spatial pixels and 256 bolometers. The new architecture is advantageous in weight, cost, and detector density.
Sky noise

Nearfield and farfield: advantage to big telescopes
Rayleigh range is the altitude $H$
Correlate $N$ pixel, take $H/N$

\[
\frac{D}{H} \approx \frac{\lambda}{D}
\]

\[
H = \frac{D^2}{\lambda} = 4 \text{ km} \left( \frac{D}{2 \text{ m}} \right)^2 \left( \frac{\lambda}{1 \text{ mm}} \right)^{-1}
\]
Sky noise
100m / 100s

Figure 2: Same simulation (as in Fig. 1) of the water vapour emission map at a given time but as seen on the 30 m telescope focal plane. Left figure is for $\alpha = 11/3$ and right figure is for $\alpha = 8/3$. The maps typically represents a 2500 m wide field. The size of the telescope smoothing imprint is shown as the red disk on the left. Three positions of the camera imprint on the atmosphere are shown as the three little dots within the bigger black rings.
Sky noise
25 faster than real, 8’x8’ focal plane

2nd order term is 1/40 1st term
- Mambo uses ring decorrelation
- Halverson et al (2008) arXiv/0807.4208: on Apex-SZ camera, removing a constant plus a tilted plane removes most of the sky noise
Sky noise

Figure 4: Evolution of the map pattern with time, as quantified by the average level, gradient and curvature across the camera field of view. Case of $\alpha = 11/3$ (see text). The last plot (lower right) shows a correlation between the level of gradient across an image and the derivative with time of the average image level.

Another advantage of large arrays: get access to larger angular scales
Figure 3. Top left-hand panel: The raw time-stream signals for a sample bolometer during a single scan. Bottom left-hand panel: The same time-stream signals after PCA cleaning. Note the factor of 20 reduction in the noise level post-cleaning. Right-hand panel: The PSD of the same scan, before (thick) and after (thin) PCA cleaning, demonstrating the reduction of low-frequency signal. The PSD before PCA cleaning has been multiplied by a factor of 100 to offset the two curves. The PSD of the post-cleaned data is truncated at 16 Hz due to a digital low-pass filter that is applied to the data before PCA cleaning.
The TES is a superconducting film biased in the middle of its transition. It is voltage biased, and in this mode it has high stability and linearity due to negative feedback that occurs between the thermal and electrical “circuits” of the bolometer. The signal from a TES is measured using a Superconducting QUantum Interference Device (SQUID) ammeter, which can operate at cryogenic temperature. Our team has experience building TES detectors over the last few years.

Lee et al. 1996
The high-impedance thermistor (e.g. Mambo) is replaced by a superconducting transition, very low resistance device. The multiplexing can be in the time domain (GISMO, MUSTANG, ACT) or in the frequency domain (SPT, Apex-SZ).
SPT array
Carlstrom et al arXiv/0907.4445

Fig. 9.— 161 element bolometer array (without feedhorns and filters). The spacing between bolometers is \( \sim \) 5 mm. Bias filters for the frequency multiplexed readout are on the circuit board at the bottom of the picture.
GISMO: a 2mm TES camera at the 30m telescope

8x16 pixel 0.9 Flambda
FWHM: 17” FOV: 2x4’
TDM: Time Domain Multiplexing
Study of the Crab nebula
Arendt et al, arXiv/1103.6225
Laboca
(v1 high-impedance v2 TES)
300 mK 345 GHz 295 horns on APEX
KID principles

- $h\nu_{\text{min}} = 2 \Delta = 3.53 \, kT_c$
- Al: $T_c = 1.2 \, \text{K}, \nu_{\text{min}} = 115 \, \text{GHz}$
- Ti: $T_c = 0.5 \, \text{K}, \nu_{\text{min}} = 48 \, \text{GHz}$
- TiN: $T_c = 0.7 - 4.5 \, \text{K}, \nu_{\text{min}} = 70 - 430 \, \text{GHz}$
Low cost and simplicity

- The Cooper pairs in the superconducting layer are insulated. No need for building structures.
- $T << T_c$: very small sensitivity to the bath temperature nor microphonics
**KID principles**

Detection and multiplexing are on the same substrate.

*Figure II. 7. First LEKID design for mm-wave detection. Bright areas are metal on the chip (20 ± 40 nm-thick Aluminium). The equivalent circuit is an inductively-coupled LRC resonator, as explained in the text.*

*Figure II. 8. Left: LEKID optical coupling for NIKA. The wafer is back-illuminated, and the thicknesses of the silicon substrate and back-short have to be optimised. Right: Impedance of the LEKID pixel as seen by the incoming mm-wave radiation.*
KIDs coupling to radiation

Figure II.14. Arrays and single-pixel images. (a) LEKID 30 pixel array and (b) antenna-coupled 42 pixel array with sapphire microlenses. The dimensions of the focal plane are in both cases ≈ 1 cm², corresponding to a 45 arc-sec field-of-view. (c) Single LEKID resonator design and (d) antenna-coupled resonator design. For both designs, a high quality metallic film is first deposited onto a dielectric wafer. A subsequent etching process is then used to remove metal in the black regions.
KID measurement: I,Q
KID multiplexing

**Figure II.9. Multiplexing measurement schematic. The component labels correspond to: A) 0.1 + 8 GHz High-frequency synthesizer, B) Splitter, C) Mixer, D) Attenuator, E) Amplifier, and F) Low-pass filter. Not shown is an acquisition computer connected to the FPGA via a communication link. From [1].**

NuRadiation = 150 GHz

IF: NuResonance = 1-4 GHz

RF: NuResonance = 0.5 GHz

Computer readout:
fAcquisition = 50 Hz
NIKA 2010

Figure II.17. Left: NIKA dual-band prototype optics. L1 coincides with the cryostat window. Band/polarisation splitting is achieved via a grid polarizer. Right: NIKA dual-band spectral response measured in laboratory (Martin-Puplett Interferometer).
NIKA 2010, Focal Planes

Figure 11.18. Left, top: Sky simulator allowing to fake, in laboratory, almost real observing conditions. Left, bottom: NIKA 2010 arrays. LEKID 144 pixels and antenna-coupled 256 pixels arrays. Right: contours of the beams as measured on Mars on the 2010-Oct-20. Top: 2 mm array (98 valid KID), Bottom: 1.4 mm array (62 valid KID).
Figure II.19. Left: SgrB2(FIR1) maps at both frequencies. The Galactic Center map is complex and shows at least three common sources and one North-South extended component. The very center has a flux of 76 ± 3 Jy and 17.7 ± 0.7 Jy at 1.4 and 2 mm, respectively; Center: maps at 2 and 1.4 mm of the radio source Cygnus A and its two radio lobes; Right: NIKA maps of NGC1068 Seyfert galaxy. From [1].
GM Aur
201+-19, 55.5+-1.2 mJy
500 s
IRC10420
106.0+-13, 24.0+-1.3 mJy
2000s
MWC349
No filtering but sky noise removal
NIKA in the 30m telescope receiver cabin since June 2012

Screenshot from Zemax simulation used to design the NIKA optics for this permanent position

Sketch up of the 30m receiver cabin with GISMO (blue) and NIKA (green)

NIKA installed in the 30m receiver cabin

08/07/2013

7/20

From Samuel Leclercq
NIKA (170, 130 pixels)

Scans quick looks

Geometry scan = all pixels on the source
⇒ FOV geometry (pixels map on sky)
⇒ PSF
⇒ Flat field

Pointing scan
⇒ Establish pointing model / check drift of the telescope pointing
3.3. Future cabin & NIKA2 2015

NIKA 2 cryostat main characteristics: 2.3 m long, ~900 kg, total consumption ~20 kW, 100mK cryogen-free dilution, 2 pulse tube coolers, possibility to open the cryostat on site for upgrades and maintenance. Technical drawings, mechanics study and full specification well advanced.
A comparison of continuum imagers

<table>
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<th>High impedance bolometers</th>
<th>TES</th>
<th>KID</th>
</tr>
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<td>Horn/FilledArray</td>
<td>Horn</td>
<td>Horn</td>
<td>FA</td>
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<tr>
<td>Example</td>
<td>Mambo, Scuba1</td>
<td>Apex SZ, Laboca2</td>
<td>Scuba2, NIKa</td>
</tr>
<tr>
<td>Technol. maturity</td>
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<tr>
<td>Complexity</td>
<td>Manageable</td>
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<td>Scaling</td>
<td>Difficult Limited to 300</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>1000 achieved</td>
<td>200 achieved</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5000 soon</td>
</tr>
<tr>
<td>Multiplexing</td>
<td>No</td>
<td>Freq or Time</td>
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</tr>
<tr>
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<td>Photometric Calibration</td>
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<td>Operational</td>
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<tr>
<td>Sensitivity</td>
<td>Near BLIP</td>
<td>Near BLIP</td>
<td>2 BLIP</td>
</tr>
<tr>
<td>Microphonics</td>
<td>Sensitive</td>
<td>Under control</td>
<td>Mostly immune</td>
</tr>
<tr>
<td>Temperature dependence</td>
<td>Strong</td>
<td>Important</td>
<td>None/Weak</td>
</tr>
<tr>
<td><strong>Cost...</strong></td>
<td></td>
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</tbody>
</table>
Polarization

- Malus’ Law

\[ I_{\text{out}} = I_{\text{in}} \cos^2(\theta_{\text{in}} - \theta_{\text{pol}}) \]

- Cross-Polarization leakage

\[ \eta = \frac{I_{\text{min}}}{I_{\text{max}}} \]

and polarization efficiency \( \rho \)

\[ \rho = \frac{1 - \eta}{1 + \eta} \]

Fig. 9. Signal of PSB 100-1b with respect to the angle in the horn aperture plane; each color represents one rotation of the polarizer (8 turns); the signal is fitted using a standard sine curve. The difference exhibits a systematic effect that can be explained by standing waves between the polarizer and the focal plane (see text).

Planck HFI Ground measurement
Rosset et al 2010 AA 520, A13

courtesy Wik
Stokes Parameters

Electromagnetic field

\[ E_x = A_x \cos(\omega t) \]
\[ E_y = A_y \sin(\omega t + \phi) \]

Linear/circular polarization

\[ \phi = 0 \]
\[ \phi = \frac{\pi}{2} \]

Stokes parameter

\[ I = \langle A_x^2 \rangle + \langle A_y^2 \rangle \]
\[ Q = \langle A_y^2 \rangle - \langle A_x^2 \rangle \]
\[ U = 2 A_x A_y \cos(\phi) \]
\[ V = 2 A_x A_y \sin(\phi) \]

Degree of polarization

\[ p = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} \]

Angle of polarization

\[ \theta = \frac{1}{2} \arctan \frac{U}{Q} \]

Link with axes of coordinates

\[ Q' = Q \cos(2\alpha) + U \sin(2\alpha) \]
\[ U' = -Q \sin(2\alpha) + U \cos(2\alpha) \]
Polarization : Stokes parameters

\[ Q = I_x - I_y \]

\[ U = I_x^{45} - I_y^{45} \]
Polarization fundamentals

- Stokes parameters
- Mueller matrix

\[
\begin{bmatrix}
I \\
Q \\
U
\end{bmatrix} = \begin{pmatrix}
k_{11} & k_{12} & k_{13}
k_{12} & k_{22} & k_{23}
k_{13} & k_{23} & k_{33}
\end{pmatrix}
\begin{bmatrix}
I_{in} \\
Q_{in} \\
U_{in}
\end{bmatrix}
\]

- Reformulation of Malus’ law

\[
m = I + \rho [Q \cos 2\alpha + U \sin 2\alpha]
\]
\[
\rho = \frac{1 - \eta}{1 + \eta}
\]

- General solution of polarized map-making
Polarization in practice

- Need at least three angles
- Need to calibrate the polarization efficiency and the orientation of each detector
- Need calibrated source: e.g. Crab,...
Calibration of polarization

Measurement of the Crab nebula polarization at 90 GHz as a calibrator for CMB experiments

J. Aumont¹, L. Conversi², C. Thum³, H. Wiesemeyer⁴, E. Falgarone⁵, J. F. Macías-Pérez ⁶, F. Piacentini⁷, E. Pointecouteau⁸, N. Ponthieu¹, J. L. Puget¹, C. Rosset⁹, J. A. Tauber¹⁰, and M. Tristram¹¹

arXiv/0912.1751
27”
89 GHz

Figure 2. Maps of the Crab nebula at 89.189 GHz in antenna temperature (K) for intensity I (top-left), Q polarization (top-right), U polarization (bottom-left) and polarized intensity P (bottom-right). The position of the Crab nebula pulsar is indicated by the black cross.
The Crab is the main polarimetric source for Planck

$I=195\pm11\text{Jy}$
$S(P)=14.5\pm3.2\text{Jy}$
$\alpha (5\text{ arcmin beam})=149.9\pm0.2\text{ deg.} \pm 0.5\text{deg (absolute accuracy)}$
$P=8.8\pm0.2\%$ (agrees with WMAP 94 GHz)

\textit{Figure 4.} Map of the Crab nebula polarized intensity $P$ at 89.189 GHz in antenna temperature on which polarization vectors have been overplotted. Intensity contours at 0.15, 0.30 and 0.45 K are also displayed.
Polarization Examples

- Starlight polarization
- Submillimetre measurements

  Synchrotron is polarized but anomalous and free-free emissions are not

- Scientific targets
Starlight Polarization

- $p$ increases with $AV$: link with the interstellar medium. Serkowski’s law $p(\lambda)/p_{max}$ as a function of $\lambda_{max}$ (e.g. 0.55um)
- $p/p_{max} = \exp(-1.15 \ln 2(\lambda_{max}/\lambda))$
- $p/AV$ typically few % per mag
Grain Alignment: the angular momentum will align with the magnetic field

- Davis-Greenstein mechanism (1951): paramagnetic (single electron spin lagging coupling to magnetic field) dissipation in rotating grains (counteracted by collisions)
- Gold mechanism (1952): collisions with beams of atoms
- Purcell 1979: Photoelectric effect, H2 on grain
- Dolginov Radiative torques (1972): anisotropic particle flows or photon fluxes (L or R polarized light)
Dust polarization: absorption vs. emission

\[ \tau = \frac{\tau_a + \tau_b}{2} \]

\[ P_{abs} = \frac{e^{-\tau_a} - e^{-\tau_b}}{e^{-\tau_a} + e^{-\tau_b}} = -\frac{\tau_a - \tau_b}{2} \]

\[ P_{em} = \frac{(1 - e^{-\tau_a}) - (1 - e^{-\tau_b})}{(1 - e^{-\tau_a}) + (1 - e^{-\tau_b})} = \frac{\tau_a - \tau_b}{\tau_a + \tau_b} = -\frac{P_{abs}}{\tau} \]

- Dust emission is polarized orthogonally to dust absorption
Big grains

- Selective visible absorption along the major axis
- Favored emission along the major axis

Dust emission is polarized orthogonally to the magnetic field rather insensitive to its intensity

The polarization degree should not depend on frequency for a given grain population

M51 magnetic field

Location

Polarization IR $\perp$ optical

Courtesy N. Ponthieu

Mihalas & Binney, 1981

Berkhuijsen et al 1997
Dust Polarization in absorption

![Starlight Polarization (5500 Stars)](image)

**FIGURE 2.** Starlight polarization vectors in Galactic coordinates for a sample of 5513 stars. The upper panel shows polarization vectors in local clouds, while the lower panel displays polarization averaged over many clouds in the Galactic plane. The length of the vectors is proportional to the polarization degree and the scale used is shown in the lower panel.

Dust polarized emission

I
Q
U

Archeops 353 GHz  Model

Fig. 10.12 – De bas en haut : Cartes en température et polarisation Q et U (en $\mu$K$^{-1}$) à 353 GHz construites à partir des données Archeops (gauche) du modèle d'émission thermique de poussière avec un champ magnétique MLS pour les valeurs optimales des paramètres (droite).
Synchrotron Polarization

- Relativistic electrons in a magnetic field
- Synchrotron angle of polarization is the same as for dust emission if they both align orthogonally to the magnetic field.

\[
\frac{dN}{dE} \propto E^{-u}
\]

Radiation power

\[
I_\nu \propto \nu^{-s} \\
\frac{dN}{dE} \propto E^{-u}
\]

Polarization degree

\[
p = \frac{u + 1}{u + 7/3}
\]

\[
\nu = 3, \ s = 1, \ T_{RJ} \propto \nu^{-3}, \ p = \frac{3}{4}
\]
Anomalous Emission

Fauvet's thesis 2010
Designing in-array polarimetric capabilities

Figure II.24. **Left:** polarization-sensitive hexagonal focal plane. The Stokes parameters can be determined in real time. **Right:** alternative rhombus design.

Monfardini, 2011, HDR
Conclusions

- Millimetre continuum measurements have used all modern technological developments
  - semiconductors (High impedance bolometers),
  - supraconductors (Transition edge supraconductors bolometers),
  - KID (supraconductor photon counting device)
- Still a point source is detected with a noise of 1/2 mJy after an hour of integration
- Mapping speed is improved by going from single detectors to 100 ones. Fully integrated arrays allow to reach the 1000 pixel size. 10000 coming.
- Biggest issues with new cameras: filtering due to sky noise, preserving photometry, integrating polarimetry
The race continues

Fig. 4.4. There has been a dramatic increase in the number of detectors employed by instruments since the invention of the TES and MKID bolometric detectors, which lend themselves to mass production using standard silicon microfabrication techniques. Blue points indicate arrays operating in instruments, green indicate planned instruments which have not yet realized operation. (Figure provided by J. Zmuidzinas).