2/15/05

Astro 731 - Bolometry

I Bolometers vs. Heterodyne Systems

Bolometers are <u>total</u> <u>power</u> detectors.

characteristic	Heterodyne System	Bolometric System
Processing of Radiation	Coherent Detection (Fields are summed then squared)	Incoherent Detection (fields are squared then summed)
Noise	noise terms add linearly $\Delta T_{sys} \sim \frac{\sum T_i}{\sqrt{\Delta\nu\, \tau}}$ (radiometer eq.)	noise terms add in quadrature $NEP_{sys} \sim \left[\sum_i NEP_i^2 \right]^{1/2}$
Bandwidth	10's of GHz (defined by wave guide)	THz
Throughput	$A\Omega = \lambda^2$	$A\Omega = n\lambda^2$ ← # of modes
Quantum Efficiency	$T_{sys} > \frac{h\nu}{k}$ (7.2 K at 150 GHz)	none
RAW ~~Typical~~ System Sensitivity (at 150 GHz)	$NET = \frac{T_{sys}}{\varepsilon\sqrt{\Delta\nu\,\tau}}$ $= 2.8\,mK\sqrt{s}$ for $\Delta\nu = 45\,GHz$, $T_{sys} = 60\,K$, $\varepsilon = 10\%$	$NET = \frac{NEP}{dP/dT}$ $= \frac{NEP}{\varepsilon \int d\nu\, A\Omega \frac{dB_\nu}{dT} d\nu\, f(\nu)}$ $= \frac{4\times10^{-17}}{4\times10^{-13}}$ $= 100\,\mu K\sqrt{s}$

For current bolometers typical NEP's from ground are $\sim 10^{-17}$ W/$\sqrt{Hz}$

CMBPol, SPECS, & SAFIR will require detectors with NEP $\sim 10^{-21}$ W/$\sqrt{Hz}$!

But there is no free lunch:

- detectors must be cooled below 300 mK
- detectors have relatively small dynamic range
- detectors are microphonically sensitive and very sensitive to RFI
- current bolometers remain complex, fragile, & tempermental

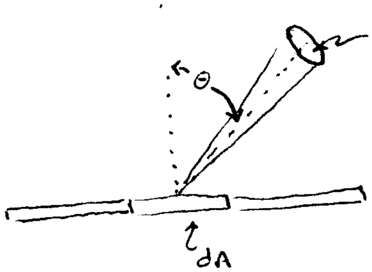
II The Physics of Bolometers

A) Optical Model of Simple Bolometer

in general: the infinitesimal power dW from a solid angle dΩ of the sky incident on a surface of area dA is

$$dW = B \underbrace{\cos\Theta}\, d\Omega\, dA\, d\nu$$

(true only for a flat plate)



B = sky brightness at dW in W/m² Hz sr

Θ = angle between dΩ and normal to dA

dν = infinitesimal bandwidth in Hz

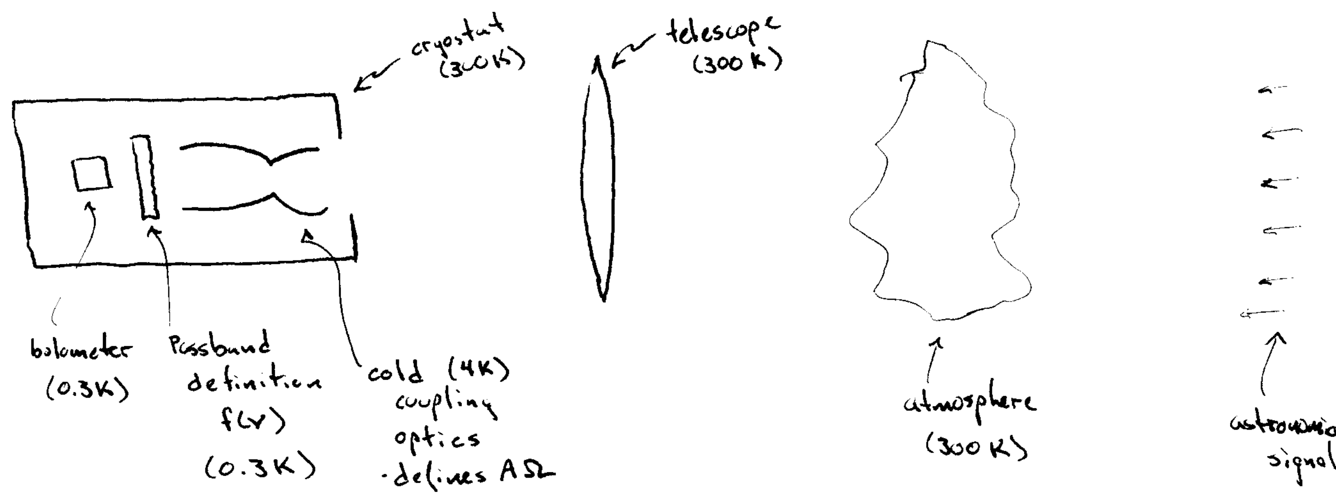
we design our system such that dW is uniform across bolometer area A.

then the power absorbed due to a blackbody with emissivity ε is

$$W = \epsilon A \int_0^\infty f(\nu)\, d\nu \int_{sky} d\Omega\; P(\Theta,\phi)\; B_\nu(T(\Theta,\phi))\; \mathcal{E}(\Theta,\phi)$$

- $f(\nu)$: spectral bandpass of system (normalized)
- $P(\Theta,\phi)$: beam response function (normalized)
- B_ν: Planck function
- $\mathcal{E}(\Theta,\phi)$: emissivity

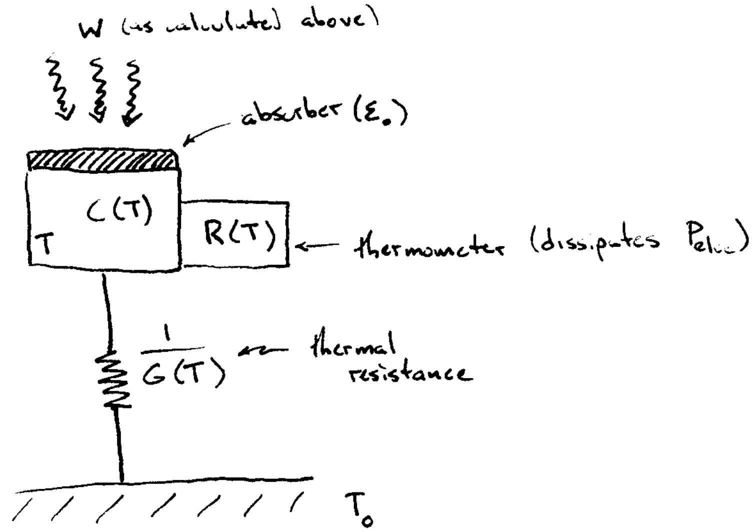
Of course, a realistic optical system has many sources to consider:



now

$$W = A \int_0^\infty d\nu \; f(\nu) \int_{sky} d\Omega \; P(\theta,\phi) \; \sum_i B_\nu\left(T_i(\theta,\phi)\right) \varepsilon_i(\theta,\phi)\, \epsilon_\circ$$

B) Thermal Model of Simple Bolometer



Power balance:

$$W + P_{elec}(T) = \int_{T_0}^{T} \left(G(T)\, dT\right) - C(T)\frac{dT}{dt}$$

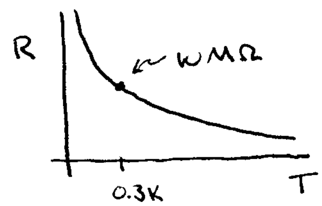
c) Electrical Model of Simple Bolometer

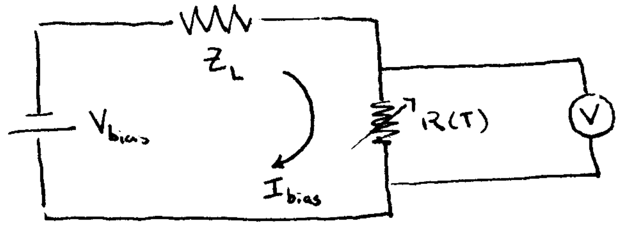
Bolometers typically use a temperature sensitive resistor as the thermometer. There are 2 dominant varieties right now

i) AzTEC Detectors

- thermometer is a doped semiconductor (nutron doped germanium)
- $R(T) = R_0 e^{\sqrt{T_0/T}}$

$R_0 \sim 1000\,\Omega$
$T_0 \sim 25\,K$





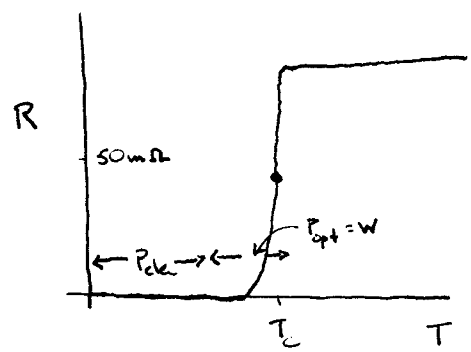
Readout circuit
(constant current through bolo)

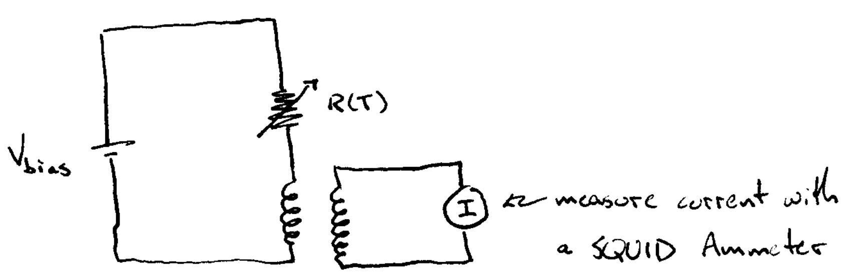
so $P_{elec} = I_{bias}^2 R(T)$

Note electrothermal feedback!

ii) SPEED Detectors

- thermometer is a superconductor biased onto its transition
- $R = $ cnst! (when working)
- $T = $ cnst! (when working) $= T_c$





now $P_{elec} = \frac{V_{bias}^2}{R}$

↑ strong electrothermal feedback

III Noise Sources

Three dominant noise sources in bolometers.
Noise is characterized by the Noise Equivalent Power (NEP).

A) Johnson Noise

- fluctuations in internal conductivity of a resistor

$$NEP_{Johnson} = \sqrt{4kTP_{bias}} \left| \frac{Z_L + R}{Z_L - R} \right| (1 + \omega^2 \tau^2)$$

↑ detector time constant $= \frac{C(T)}{G(T)}$

B) Phonon Noise (Thermal Noise)

- shot noise in # of energy carriers in weak thermal link

$$NEP_{phonon} = \sqrt{4k\bar{G}T^2}$$

↑ temperature weighted average conductivity

C) Photon (shot) Noise

- shot noise in # of photons absorbed

$$NEP_{photon} = \left[\frac{4A\Omega}{c^2} \frac{(kT_*)^5}{h^3} \int \frac{x^4 dx}{e^x - 1} \left(1 + \frac{\varepsilon_0 \varepsilon f(\nu)}{e^x - 1} \right) \varepsilon_0 \varepsilon f(\nu) \right]^{1/2}$$

where $x = \frac{h\nu}{kT_*}$

T_* = source temperature

ε = source emissivity

$$NEP_{sys}^2 = NEP_{Johnson}^2 + NEP_{thermal}^2 + NEP_{photon}^2 + NEP_{electronics}^2 + \dots$$

↑ should be the dominant term for ground-based observations if $NEP_{sys} \simeq NEP_{photon}$:

then signal $\propto$ # of modes (remember that $A\Omega = n\lambda^2$ for bolometers)

while noise $\propto$ [# of modes]$^{1/2}$

so $S/N \propto n^{1/2}$

also signal $\propto$ optical efficiency

noise $\propto$ [optical efficiency]$^{1/2}$ (over a range of efficiencies)

so $S/N \propto \varepsilon^{1/2}$

why is this important? Because for a $\sqrt{2}$ increase in S/N we get a factor of 2 reduction in observing time.

IV Map Making with Bolometers

The time-stream signal from a bolometer is composed of a true sky (astronomical + atmosphere) signal + noise. For a particular time i

$$d^i = s^i + n^i$$
$$= A^i_\alpha T^\alpha + n^i$$

where $A^i_\alpha = (N_{\text{time ordered data}} \times N_{\text{pixel}})$ matrix

with $A^i_\alpha = 1$ if bolometer sees pixel α in sample i and $= 0$ otherwise

T^α = temp of sky in pixel α

If the noise is gaussian then it is completely described by $N^{ij} = \langle n_i n_j \rangle$

and we can write

$$\chi^2 = (d^i - A^i_\alpha T^\alpha)\, W_{ij}\, (d^j - A^j_\alpha T^\alpha)$$

the best estimator of T^α occurs when $\frac{\delta \chi^2}{\delta T^\alpha} = 0$

this gives

$$T^\alpha = \underbrace{(A^k_\alpha W_{kl} A^l_\beta)^{-1}}_{C^{\alpha\beta}} A^i_\beta W_{ij} d^j$$

where $W_{ij} = N^{-1}$

↑ pixel-pixel covariance matrix

Note: while this is the minimum variance solution

1) Atmospheric fluctuations are included in T^α

2) N^{ij} is an $N_{tod} \times N_{tod}$ matrix and can not be inverted directly to get W

3) No guarantee that noise is gaussian!

The Solution Most Often USED (SCUBA, BOLOCAM)

- assume N^{ij} is diagonal - every sample is independent.

Note - this is patently untrue.

The solution We Will Use

- use quadrature channel to ensure gaussianity of noise
- use iterative fitting to find best fit T^α using all bolometers simultaneously.

But that's another lecture...