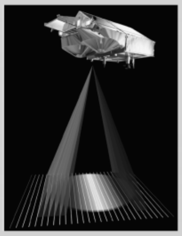
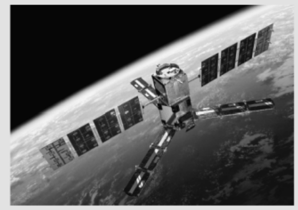
- **Ulaby**
- **Long**
- **Blackwell**
- **Elachi**
- **Fung**
- **Ruf**
- **Sarabandi**
- **Zebker**
- **Van Zyl**

Microwave Radar and Radiometric Remote Sensing



CHAPTER 7

Microwave Radiometric Systems



SMOS antenna array in orbit

Chapter 7 Contents

Radiometers

- Radiometers are **very sensitive receivers** that measure **thermal** electromagnetic **emission** (noise) from material media.
- The design of the radiometer allows **measurement of signals smaller than the noise** introduced by the radiometer (system's noise).

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Noise Voltage

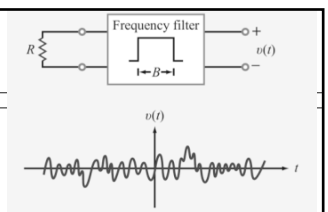


Figure 7-1: Random variation of noise voltage across a resistor.

$$V_n = \sqrt{\frac{4hfBR}{e^{hf/kT}-1}}\Bigg|_{\substack{Rayleigh\\Jeans}} \cong \sqrt{\frac{4hfBR}{hf/kT}} = \sqrt{4RkTB}$$

Noise Temperature

► Whereas the average (or mean) value of $\upsilon(t)$ is zero, its rms value, V_{rms}, is not. ◄

In 1928, Nyquist showed that at the output of a unity gain rectangular filter,

$$V_{rms}^2 = \langle \upsilon^2(t) \rangle = 4RkTB, \qquad (7.1)$$

where k is Boltzmann's constant, T is the physical temperature of the resistor, and B is the bandwidth of the filter.

Power received by matched load due to Emission by resistor R:

$$P_n = I_{rms}^2 R = \left(\frac{V_{rms}}{2R}\right)^2 R = \frac{V_{rms}^2}{4R} = kTB.$$

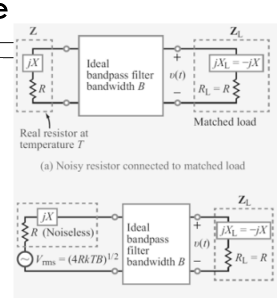


Figure 7-2: (a) Noisy resistor connected to a matched load, and (b) its equivalent circuit. The average power delivered to R_L is $P_n = kTB$.

Antenna Temperature

The Antenna Temperature T_A is the temperature that an antenna, when surrounded by a perfect blackbody at that physical temperature, would generate power kT_AB at the output of an ideal filter of bandwidth B.

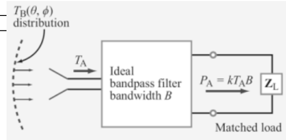
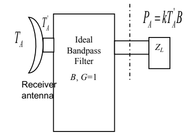


Figure 7-3: The average power delivered by an antenna with radiometric antenna temperature T_A to a matched load is $P_A = kT_AB$.

Equivalent Output Noise Temperature for any noise source

This property thermal-noise can be extended to define an equiv. output noise temperature ***TEº***



TEº is defined for any noise source when connected to a **matched load.** The total noise at the output is

$$P_{no} = kT_EB$$

Noise Figure

Noise generated by a device or system is characterized by its noise figure or its noise temperature.

$$F = \frac{P_s^i/P_n^i}{P_s^o/P_n^o} \qquad P_n^i = kT_0B.$$

If over the bandwidth B the average power gain of the device is G, then

$$P_s^o = GP_s^i, \quad (7.6a)$$

$$P_n^o = GP_n^i + \Delta P_n^o, \quad (7.6b)$$

where ΔP_n^o is the noise power generated by the device itself. Hence,

$$F = \frac{P_s^i}{P_s^o} \cdot \frac{P_n^o}{P_n^i} = \frac{1}{G} \cdot \frac{GkT_0B + \Delta P_n^o}{kT_0B} = 1 + \frac{\Delta P_n^o}{GkT_0B}. \quad (7.7)$$

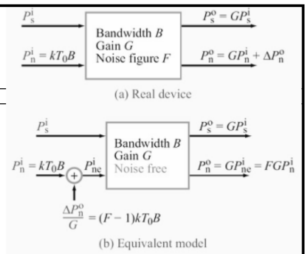


Figure 7-4: A noisy device can be replaced by a noise-free device if the input noise is increased by the noise figure of the device: (a) noisy device; (b) equivalent representation of (a) in terms of a noise-free device.

Traditionally, noise figure is defined for devices at room temperature: T_0 = 290 K. (62ºF)

Solving for the noise power generated Internally by the device:

Equivalent Input Noise Temperature

$$\Delta P_n^o = (F-1)GkT_0B,$$

and the total output noise power is

$$P_n^o = GP_n^i + \Delta P_n^o = GkT_0B + (F-1)GkT_0B$$
$$= FGkT_0B.$$

If the real device is replaced by an ideal, noise-free device and assigned an input temperature T_E^i such that the device generates the same output power, then

$$\Delta P_n^o = GkT_E^iB.$$

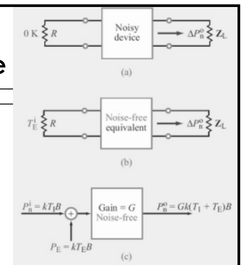
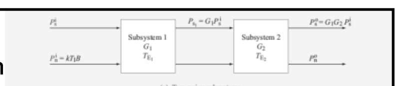


Figure 7-5: Definition and representation of equivalent input noise temperature T_E: (a) noisy device with input connected to a fictitious resistor at 0 K temperature; (b) equivalent noise-free device with input connected to a fictitious resistor at temperature T_E; (c) device-generated noise referred to its input terminals.

Hence:

$$T_E = (F-1)T_0.$$

Noise Temp of Cascaded System

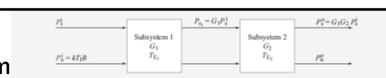


$$T_E = T_{E_1} + \frac{T_{E_2}}{G_1}.$$

By extension, the noise temperature of a system consisting of N cascaded subsystems is

$$T_E = T_{E_1} + \frac{T_{E_2}}{G_1} + \frac{T_{E_3}}{G_1G_2} + \cdots + \frac{T_{E_N}}{G_1G_2\ldots G_{N-1}},$$

Noise Temp of Cascaded System



$$\boxed{T_E = (F-1)T_0.}$$

$$T_E = T_{E1} + \frac{T_{E2}}{G_1} + \frac{T_{E3}}{G_1G_2} + \ldots + \frac{T_{EN}}{G_1G_2\ldots G_{N-1}}$$

T_E is referred to the input terminals, hence its name "Input Noise Temperature"

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \ldots + \frac{F_N - 1}{G_1G_2\ldots G_{N-1}}$$

For attenuator such as T.L.:

$$T_E = T_E^i = LT_E^o = (L-1)T_p.$$

Lossy Device

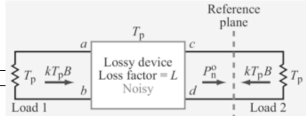


Figure 7-7: Noise generated in a lossy device of loss factor L and physical temperature T_p.

loss factor L, which is by definition the inverse of *power gain*:

$$L = \frac{1}{G} = \frac{P^i}{P^o}, \qquad (7.19)$$

P_n^o= Power moving from the left

KTpB=power moving from the right

Under thermodynamic equilibrium, the net power transfer is zero. Hence:

$$P_n^o = kT_pB.$$

$$P_n^o = \frac{1}{L} kT_pB + \Delta P_n^o.$$

Equating Eqs. (7.20) and (7.21) gives

$$\Delta P_n^o = \left(1 - \frac{1}{L}\right) kT_pB.$$

Equivalent output noise T:

$$T_E^o = \frac{\Delta P_n^o}{kB} = \left(1 - \frac{1}{L}\right) T_p.$$

Equivalent input noise T:

$$T_E = T_E^i = LT_E^o = (L-1)T_p.$$

Microwave Radar and Radiometric Remote Sensing, by Ulaby and Long

Noise Temperature

$$T_E^o = \frac{\Delta P_n^o}{kB} = \left(1 - \frac{1}{L}\right) T_p.$$

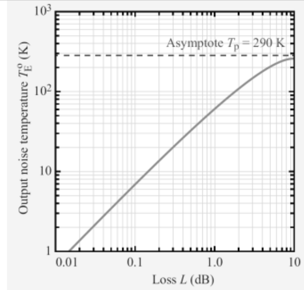


Figure 7-8: Output noise generated by a lossy device with a physical temperature T_p = 290 K.

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Antenna and Receiver

For an antenna, its radiation efficiency is

$$\xi = \frac{1}{L} \quad \text{(antenna)}, \qquad (7.25)$$

and the amount of noise power it generates by self-emission is

$$\Delta P_n^o = \left(1 - \frac{1}{L}\right) kT_pB = (1-\xi)kT_pB. \qquad (7.26)$$

noise temperature T'_{REC} referred to the antenna terminals, thereby treating the transmission line and receiver as noise-free. For the two-stage system,

$$T'_{REC} = T_{E_1} + \frac{T_{E_2}}{G_1}. \qquad (7.27)$$

In the present case, T_{E_1} is the input noise temperature of the transmission line and is given by Eq. (7.24), $T_{E_2} = T_{REC}$, and $G_1 = 1/L$. Hence,

$$T'_{REC} = (L-1)T_p + LT_{REC}. \qquad (7.28)$$

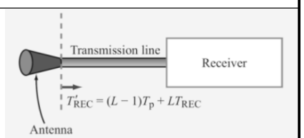

Figure 7-9: T'_{REC} is the input noise temperature of an equivalent noise-free transmission line and receiver combination. T_{REC} is the receiver input noise temperature alone, T_p is the physical temperature of the transmission line and L is its loss factor.

$$T_{REC} = T_{RF} + \frac{T_M}{G_{RF}} + \frac{T_{IF}}{G_{RF}G_M} + \cdots,$$

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Importance of RF Amp

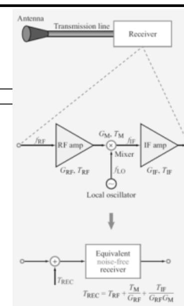

Figure 7-10: Front-end segment of superheterodyne receiver.

Case 1: With RF Amp

$$T_{REC} = T_{RF} + \frac{T_M}{G_{RF}} + \frac{T_{IF}}{G_{RF}G_M} + \cdots,$$

$$\begin{aligned} T_{RF} &= 200\ \text{K}, & G_{RF} &= 1000\ (30\ \text{dB}), \\ T_M &= 1200\ \text{K}, & G_M &= 200\ (23\ \text{dB}), \\ T_{IF} &= 100\ \text{K}, & G_{IF} &= 1000\ (30\ \text{dB}). \end{aligned}$$

$$\begin{aligned} T_{REC} &= 200 + \frac{1200}{1000} + \frac{100}{1000 \times 200} + \cdots \\ &= 200 + 1.2 + 5 \times 10^{-4} \\ &\approx 201.2\ \text{K} \quad \textbf{(with RF amplifier).} \end{aligned}$$

Case 2: Without RF Amp

$$\begin{aligned} T_{REC} &= T_M + \frac{T_{IF}}{G_M} \\ &= 1200 + \frac{100}{200} \\ &\approx 1200\ \text{K} \quad \textbf{(without RF amplifier).} \end{aligned}$$

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System Temperature

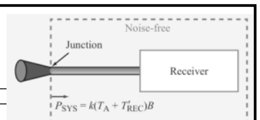

Figure 7-11: Equivalent input system noise power incorporates noise generated by the receiver, transmission line, antenna self-emission, and emission by the scene observed by the antenna.

Total Power Received, referred to Antenna Terminals:

$$\begin{aligned} P_{SYS} &= P_A + P'_{REC} \\ &= k(T_A + T'_{REC})B \\ &= kT_{SYS}B, \end{aligned} \qquad (7.30)$$

with T_{SYS} defined as the *system noise temperature*,

$$\begin{aligned} T_{SYS} &= T_A + T'_{REC} \\ &= \xi T'_A + (1-\xi)T_0 + (L-1)T_{tl} + LT_{REC}. \end{aligned} \qquad (7.31)$$

ξ Antenna radiation efficiency

L Transmission line loss factor

T_{tl} Transm. Line Physical T

T_{REC} Receiver Noise T, at its output

T'_A Antenna temperature (representing incident energy) for lossless antenna

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Measurement Accuracy and Precision

- Accuracy ("certeza") – how well are the values of calibration noise temperature known in the calibration curve of output corresponding to T_A . (absolute cal.)
- Precision ("precisión")– smallest change in T_A that can be detected by the radiometer output.(sensitivity) ΔT

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Measurement Accuracy

For a square-law receiver, output voltage is directly proportional to input power, which in turn is directly proportional to equivalent temperature.

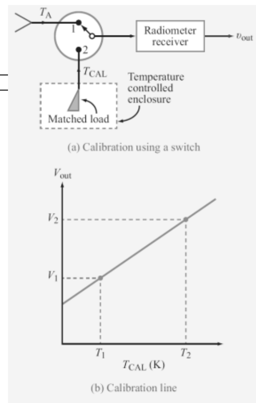


Figure 7-12: Calibration of a microwave radiometer.

Total-Power Radiometer

Double-sideband vs. single-sideband

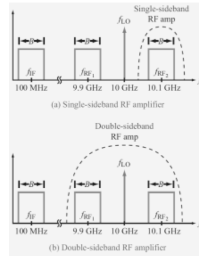


Figure 7-14: A local oscillator can mix with RF spectra centered at either f_{RF_1}, f_{RF_2}, or both, to generate the same bandwidth(s) at f_{IF}. The determination is made by the spectrum of the RF amplifier.

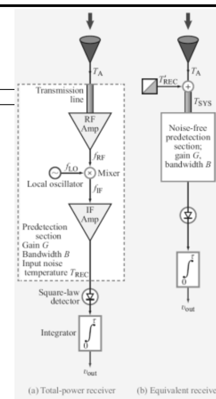


Figure 7-13: The representation in (b) replaces the predetection section with a noise-free equivalent and refers the receiver noise to the antenna terminals.

Receiver Operation

The figure illustrates the signal vs time and its spectrum at various stages, ignoring receiver noise. For a real receiver, we replace T_A with T_{SYS}.

$$P_{SYS} = P_A + P'_{REC} = kT_{SYS}B$$

with

$$T_{SYS} = T_A + T'_{REC}.$$

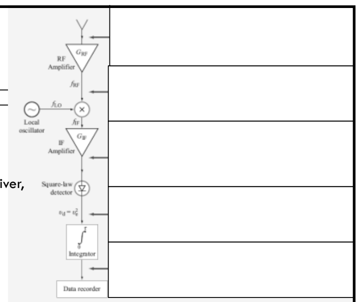


Figure 7-15: Total-power radiometer with a superheterodyne receiver. The signal voltage and corresponding spectrum are shown at various stages. Quantity I_f is the spectral density and B_{LF} is the bandwidth of the low-pass filter (integrator).

Remember that T_{SYS} is referred to the antenna terminals with everything after that treated as ideal, lossless components.

Receiver Operation

IF Voltage:

$$\upsilon_{IF}(t) = \upsilon_e(t)\cos[2\pi f_{IF}t + \phi(t)], \quad (7.35)$$

where $\phi(t)$ is a random phase angle. For noise, the envelope $\upsilon_e(t)$ and phase angle $\phi(t)$ are statistically independent random variables. Hence, the mean value of $\upsilon_{IF}(t)$ is

$$\overline{V}_{IF} = \langle \upsilon_{IF}(t)\rangle = \langle \upsilon_e(t)\rangle\,\langle\cos[2\pi f_{IF}t + \phi(t)]\rangle = 0.$$

IF Power:

$$\begin{aligned} p_{IF}(t) &= \upsilon^2_{IF}(t) \\ &= \upsilon^2_e(t)\cos^2[2\pi f_{IF}t + \phi(t)] \\ &= \upsilon^2_e(t)\left\{\frac{1}{2} + \frac{1}{2}\cos[4\pi f_{IF}t + 2\phi(t)]\right\}. \quad (7.37) \end{aligned}$$

The time-average value of $p_{IF}(t)$ is

$$\begin{aligned} \overline{P}_{IF} &= \langle p_{IF}(t)\rangle \\ &= \frac{1}{2}\langle \upsilon^2_e(t)\rangle + \frac{1}{2}\langle \upsilon^2_e(t)\rangle\,\langle\cos[4\pi f_{IF}t + 2\phi(t)]\rangle \\ &= \frac{1}{2}\overline{V^2_e}. \quad (7.38) \end{aligned}$$

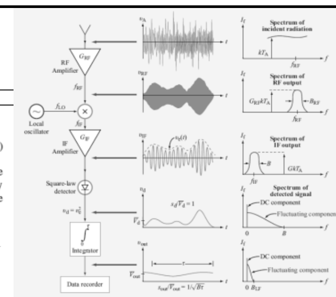


Figure 7-15: Total-power radiometer with a superheterodyne receiver. The signal voltage and corresponding spectrum are shown at various stages. Quantity I_f is the spectral density and B_{LF} is the bandwidth of the low-pass filter (integrator).

But: $\overline{P}_{IF} = GkT_{SYS}B$

Square-law Detector output:

$$\upsilon_d(t) = \upsilon^2_e(t),$$

$$\boxed{\overline{V}_d = \overline{V^2_e} = 2GkT_{SYS}B}$$

Receiver Operation

$$\boxed{\overline{V}_d = \overline{V^2_e} = 2GkT_{SYS}B}$$

For averaging the radiometer uses an Integrator (low pass filter). It averages the signal over an **interval of time** τ with voltage gain g_I.

Integrator Output:

$$\upsilon_{out}(t) = \frac{g_I}{\tau}\int_{t-\tau}^{t} \upsilon_d(t')\,dt'. \quad (7.41)$$

As we show in the next subsection, if $B\tau \gg 1$,

$$\upsilon_{out}(t) \approx \overline{V}_{out} = g_I\overline{V}_d = G_sT_{SYS} \quad (B\tau \gg 1), \quad (7.42)$$

where G_s is an overall system gain factor given by

$$G_s = 2g_IGkB. \quad (7.43)$$

Combining Eqs. (7.33) and (7.42) leads to

$$T_A = \frac{\overline{V}_{out}}{G_s} - T'_{REC}, \quad (7.44)$$

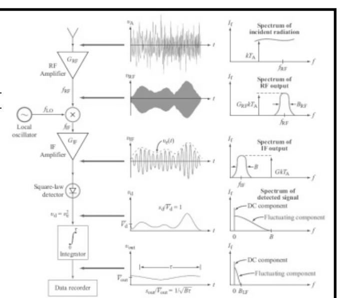


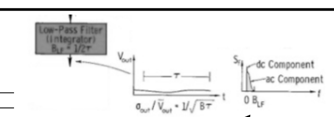
Figure 7-15: Total-power radiometer with a superheterodyne receiver. The signal voltage and corresponding spectrum are shown at various stages. Quantity I_f is the spectral density and B_{LF} is the bandwidth of the low-pass filter (integrator).

$$\frac{s_{out}}{\overline{V}_{out}} = \frac{1}{\sqrt{B\tau}} \quad \text{(after integration).}$$

Since $\overline{V}_{out} = G_sT_{SYS}$, Eq. (7.52) is equivalent to

$$\frac{\Delta T_{SYS}}{T_{SYS}} = \frac{1}{\sqrt{B\tau}},$$

Integration



- Averaging over a *B* bandwidth and during τ time, reduces the variance by a factor $N=B\tau$

$$\boxed{\frac{s^2_{out}}{\overline{V}^2_{out}} = \frac{s^2_d}{\overline{V}^2_d} = \frac{1}{B\tau}}$$

Still have fluctuations after LPF but are smaller

- Total *rms* uncertainty

$$\boxed{\frac{s_{out}}{\overline{V}_{out}} = \frac{1}{\sqrt{B\tau}}}$$

Noise averaging

- By averaging a large number N of independent noise samples, an ideal radiometer can determine the average noise power and detect a faint source that increases the antenna temperature by a tiny fraction of the total noise power.

$$N = B\tau \qquad \Delta T_{\mathrm{N}} = \frac{T_{\mathrm{SYS}}}{\sqrt{B\tau}}$$

$$\text{Radiometer resolution } \Delta T \to 0 \text{ as } \tau \to \infty$$

http://www.cv.nrao.edu/course/astr534/Radiometers.html

http://www.millitech.com/pdfs/Radiometer.pdf

Ideal Receiver

- An ideal receiver is totally stable, experiencing no gain variations.

$$\Delta T_{\mathrm{IDEAL}} = \frac{T_{\mathrm{SYS}}}{\sqrt{B\tau}} \quad \left(\begin{array}{c}\text{ideal total-power}\\ \text{radiometer}\end{array}\right)$$

A real Receiver exhibits two sources of variation, one due to noise And another due to gain variations:

$$\Delta T_{\mathrm{N}} = \frac{T_{\mathrm{SYS}}}{\sqrt{B\tau}} \qquad \Delta T_{\mathrm{G}} = T_{\mathrm{SYS}}\left(\frac{\Delta G_{\mathrm{S}}}{\overline{G}_{\mathrm{S}}}\right)$$

Total variation due to two statistically independent processes:

$$\Delta T = \sqrt{(\Delta T_N)^2 + (\Delta T_G)^2}$$

$$= T_{\mathrm{SYS}}\left[\frac{1}{B\tau} + \left(\frac{\Delta G_{\mathrm{S}}}{\overline{G}_{\mathrm{S}}}\right)^2\right]^{1/2}.$$

(total-power radiometer)

Example

$$\Delta T = \sqrt{(\Delta T_N)^2 + (\Delta T_G)^2}$$

$$= T_{\mathrm{SYS}}\left[\frac{1}{B\tau} + \left(\frac{\Delta G_{\mathrm{S}}}{\overline{G}_{\mathrm{S}}}\right)^2\right]^{1/2}.$$

(total-power radiometer)

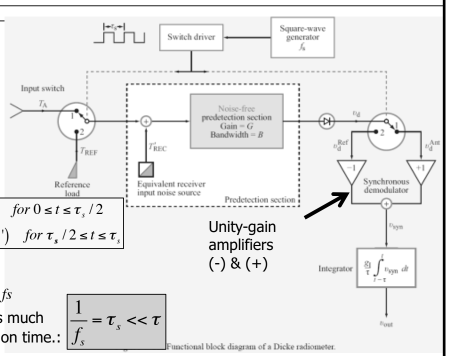
$T'_{\mathrm{REC}} = 600$ K, $B = 100$ MHz, $\tau = 0.01$ s, and a *normalized gain variation* $\Delta G_{\mathrm{S}}/\overline{G}_{\mathrm{S}} = 10^{-2}$. For an antenna temperature T_{A} in the neighborhood of 300 K, the above values lead to the following results:

Also, Try with 10^{-5} gain variation and no RF amp (T_{REC}'=3000K)

Gain Variations and the Dicke radiometer

- As you can see, gain variations in practical radiometers, fluctuations in atmospheric emission, and confusion by unresolved radio sources may significantly degrade the actual sensitivity compared with the sensitivity predicted by the ideal radiometer equation.
- One way to minimize the effects of fluctuations in both receiver gain and atmospheric emission is to make a *differential* measurement by comparing signals from two adjacent feeds. The method of switching rapidly between beams or loads is called ***Dicke switching*** after Robert Dicke, its inventor. [Using a double throw switch.]

Minimizing Gain Variation Effects: The Dicke Radiometer



Functional block diagram of a Dicke radiometer.

$$V_d^{Ant} = 2GkB(T_A + T_{REC}') \quad for\ 0 \le t \le \tau_s/2$$
$$V_d^{Ref} = 2GkB(T_{REF}' + T_{REC}') \quad for\ \tau_s/2 \le t \le \tau_s$$

The switching rate is fs switching period τ_S is much shorter than integration time.: $\frac{1}{f_s} = \tau_s << \tau$

The Dicke Radiometer

$$\overline{V}_{\mathrm{d}}^{\mathrm{Ant}} = 2GkB(T_{\mathrm{A}} + T'_{\mathrm{REC}}) \qquad \text{for } 0 \le t \le \tau_{\mathrm{s}}/2,$$
$$\overline{V}_{\mathrm{d}}^{\mathrm{Ref}} = 2GkB(T_{\mathrm{REF}} + T'_{\mathrm{REC}}) \qquad \text{for } \tau_{\mathrm{s}}/2 \le t \le \tau_{\mathrm{s}},$$

$$\upsilon_{\mathrm{out}}(t) = \frac{g_1}{\tau}\left[\int_{t-\tau}^{t-\tau/2} \upsilon_{\mathrm{d}}^{\mathrm{Ant}}(t)\,dt - \int_{t-\tau/2}^{t} \upsilon_{\mathrm{d}}^{\mathrm{Ref}}(t)\,dt\right]$$

$$\overline{V}_{\mathrm{out}} = \tfrac{1}{2} g_1(\overline{V}_{\mathrm{d}}^{\mathrm{Ant}} - \overline{V}_{\mathrm{d}}^{\mathrm{Ref}})$$
$$= g_1 GkB(T_{\mathrm{A}} - T_{\mathrm{REF}}) =$$

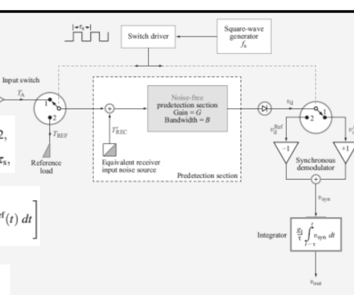


Figure 7-16: Functional block diagram of a Dicke radiometer.

Dicke radiometer resolution

- The uncertainty in T **due to noise** when looking at the **antenna** or **reference** (half the integration time)

$$\Delta T_{N\,ant} = \frac{(T_A' + T_{REC}')}{\sqrt{B\tau/2}} = \frac{\sqrt{2}(T_A' + T_{REC}')}{\sqrt{B\tau}} \qquad \Delta T_{N\,ref} = \frac{\sqrt{2}(T_{ref} + T_{REC}')}{\sqrt{B\tau}}$$

- Unbalanced Dicke radiometer resolution

$$\Delta T = \sqrt{\left[(\Delta T_G)^2 + (\Delta T_{N\,ant})^2 + (\Delta T_{N\,ref})^2\right]} = \sqrt{\left[\frac{2(T_A' + T_{REC}')^2 + 2(T_{ref} + T_{REC}')^2}{B\tau} + \left(\frac{\Delta G_S}{G_S}\right)^2 (T_A' - T_{ref})^2\right]}$$

Example

$$\Delta T = [(\Delta T_N)^2 + (\Delta T_G)^2]^{1/2} = T_{SYS}\left[\frac{1}{B\tau} + \left(\frac{\Delta G_S}{\overline{G_S}}\right)^2\right]^{1/2}.$$

(total-power radiometer)

$$\Delta T = \left[\frac{2(T_A + T'_{REC})^2 + 2(T_{REF} + T'_{REC})^2}{B\tau} + \left(\frac{\Delta G_S}{\overline{G_S}}\right)^2 (T_A - T_{REF})^2\right]^{1/2}.$$

(unbalanced Dicke radiometer)

Example: Observing Earth temperatures from 0 K to 300 K. With gain variations and Trec'=700K, and Tref=300K

For $B = 100$ MHz, $\tau = 1$ s,

$T'_{REC} = 700$ K, and $\Delta G_S/G_S = 10^{-2}$, Eq. (7.58) gives

$$\Delta T(\text{Total Power}) \approx \begin{cases} 7\text{ K} & \text{for } T_A = 0\text{ K}, \\ 10\text{ K} & \text{for } T_A = 300\text{ K}. \end{cases}$$

If we choose a reference noise source with temperature $T_{REF} = 300$ K, Eq. (7.68) gives

$$\Delta T(\text{unbalanced Dicke}) \approx \begin{cases} 3\text{ K} & \text{for } T_A = 0\text{ K}, \\ 0.2\text{ K} & \text{for } T_A = 300\text{ K}. \end{cases}$$

Balanced Dicke Radiometer

$$\Delta T = \left[\frac{2(T_A + T'_{REC})^2 + 2(T_{REF} + T'_{REC})^2}{B\tau} + \left(\frac{\Delta G_S}{\overline{G_S}}\right)^2 (T_A - T_{REF})^2\right]^{1/2}.$$

(unbalanced Dicke radiometer)

When $T_A = T_{REF}$ the radiometer is said to be balanced, in which case Eq. (7.68) reduces to

$$\Delta T = \frac{2(T_A + T'_{REC})}{\sqrt{B\tau}} = 2\,\Delta T_{IDEAL}, \qquad (7.69)$$

(balanced Dicke radiometer)

Balancing Technique 1: Control T_{REF}

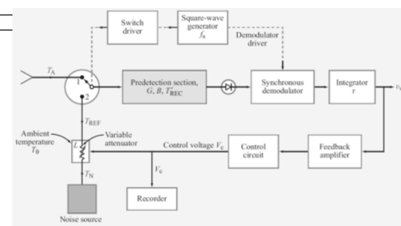
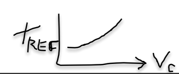


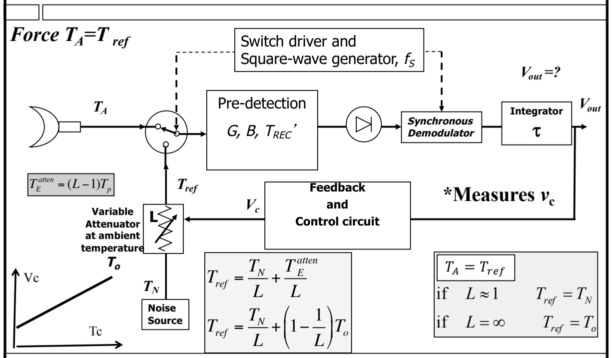
Figure 7-17: Dicke radiometer using feedback to control the reference noise temperature T_{REF}.

Use feedback to vary L so that output voltage is always zero.

$$T_{REF} = \frac{T_N}{L} + \left(1 - \frac{1}{L}\right) T_0$$



Reference Channel Control



Reference Channel Control

T_N and T_o have to cover the range of values that are expected to be measured, T_A

- If 50k< T_A < 300K

$$T_N < T_A \le T_o$$

- Use T_o= 300K and need cryogenic cooling to achieve T_N =50K.
- But L cannot be really unity, so need T_N < 50K. To have this cold reference load, one can use
  - cryogenic cooled loads (liquid nitrogen submerged passive matched load)
  - active "cold" sources (COLDFET); backward terminated LNA can provide active cold source.

Balancing Technique 2: Control T_A

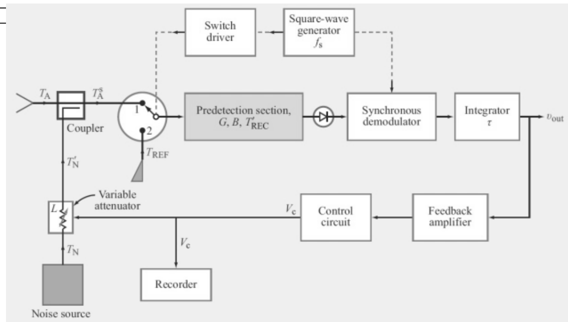
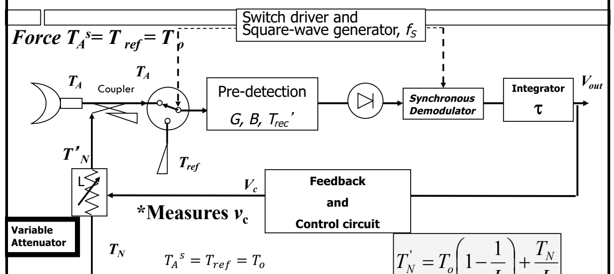


Figure 7-18: Balanced Dicke radiometer using feedback to control the level of the injected noise temperature T'_N to maintain the condition $T^s_A = T_{REF}$.

Microwave Radar and Radiometric Remote Sensing, by Ulaby and Long

Antenna Noise Injection



$T_A^s = T_{ref} = T_o$

$$T_A^s = \frac{T'_N}{F_c} + T_A\left(1 - \frac{1}{F_c}\right)$$

$$T'_N = T_o\left(1 - \frac{1}{L}\right) + \frac{T_N}{L}$$

F_c = Coupling factor of the directional coupler

Antenna Noise Injection

- Combining the equations and solving for L

$$L = \frac{T_N - T_O}{(F_c - 1)(T_O - T_A)}$$

from this equation, we see that T_o *should be* $>T_A$

- If the control voltage is scaled so that $V_c = 1/L$, *then* V_c will be proportional to the measured temperature, T_A

$$V_C = \frac{(F_c - 1)}{T_N - T_O}(T_O - T_A)$$

Example: Antenna Noise Injection

Find the necessary values of the Attenuator L, to measure this range of Temperatures and the resolution for this balanced Dicke radiometer given: $T_{REC} = 700K, B = 100\text{MHz}, \quad \tau = .01\text{sec}$

$$50K \le T'_A \le 300K$$
$$\text{20dB directional Coupler } (F_c = 100)$$
$$T_N = 50{,}000K \text{ (22dB ENR)}$$

Choose T_o=310K

$$L = \frac{T_N - T_O}{(F_c - 1)(T_O - T_A)}$$

Example: Antenna Noise Injection

- If 50K< T_A' < 300K, need to choose T_o>300K, say T_o=310K
- If F_c=100(20dB) and T_n=50,000K
- Find L variation needed:

$$L = \frac{T_N - T_o}{(F_C - 1)(T_o - T'_A)}$$

$$L = 1.93 \text{ (2.9 dB) } for \quad T'_A = 50K$$
$$L = 50.2 \text{ (17 dB) } for \quad T'_A = 300K$$

Antenna Noise Injection Resolution

$T_{REC} = 700K, B = 100\text{MHz}, \quad \tau = .01\text{sec}$

- For expected measured values between 50K and 300K, T_{ref} is chosen to be T_o=310K, so $L \ne \infty$
- Since the noise temperature seen by the input switch is always T_o, the resolution is

$$\Delta T = \frac{2(T_o + T_{REC}')}{\sqrt{B\tau}}$$ =2.02K

Pulse Noise Injection Method

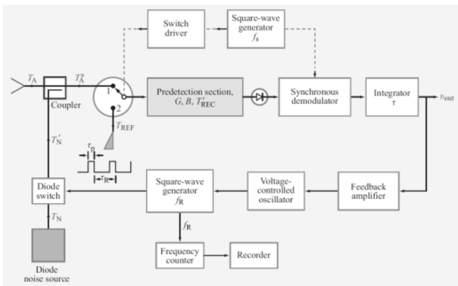
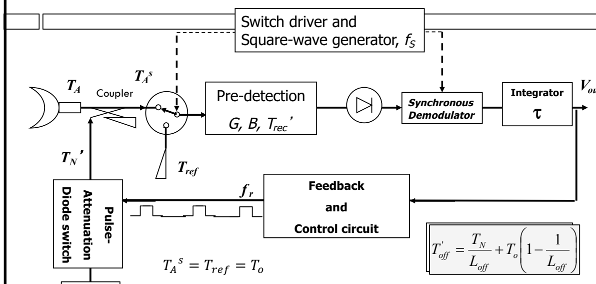


Figure 7-19: Balanced Dicke radiometer, using pulsed noise-injection to maintain $T_A^s = T_{REF}$. The output indicator of T_A is the pulse repetition frequency f_R.

Pulse Noise Injection

***Measures f_r**



$$T_{off}' = \frac{T_N}{L_{off}} + T_o\left(1 - \frac{1}{L_{off}}\right)$$

$$T_A{}^s = T_{ref} = T_o$$

$$T_A{}^s = \frac{T'_N}{F_c} + T_A\left(1 - \frac{1}{F_c}\right)$$

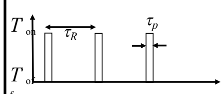
f_R=proportional to TA

Pulse Noise Injection

$$T_A{}^s = T_o = T_A\left(1 - \frac{1}{F_c}\right) + \frac{T'_N}{F_c}$$

- Reference T is controlled by the frequency of a pulse

$$T_{off}' = \frac{T_N}{L_{off}} + T_o\left(1 - \frac{1}{L_{off}}\right)$$



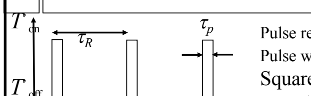
$$\overline{T_N'} = T_{ON}'\tau_p f_R + (1 - \tau_p f_R)T_{OFF}'$$

- The repetition frequency is given by

$$f_R = \frac{(F_C T_o - T_{OFF}') - (F_C - 1)T_A'}{(T_{ON}' - T_{OFF}')\tau_p} = \frac{(F_c - 1)(T_o - T_A')}{(T_{ON}' - T_o)\tau_p}$$

For L_{off} high, $T_{off} = T_o$, is proportional to T_A

Pulse Noise Injection



Pulse repetition frequency = $f_R = 1/\tau_R$

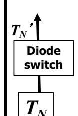
Pulse width is constant = τ_p

Square-wave modulator frequency $f_S < f_R/2$

$$\overline{T_N'} = \begin{cases} T_{ON}' & \text{for } 0 \le t \le \tau_p \\ T_{OFF}' & \text{for } \tau_p \le t \le \tau_R \end{cases}$$

Switch ON – minimum attenuation

Switch Off – Maximum attenuation



$$T_{OFF}' = T_o\left(1 - \frac{1}{L_{off}}\right) + \frac{T_N}{L_{off}}$$

$$\Delta T = \frac{2(T_o + T_{REC}')}{\sqrt{B\tau}}$$

Example: *For* $L_{on} = 2$, $L_{off} = 100$, $\tau_p = 40$ μs, $T_o = 300$K *and* $T_N = 1000$K, F=20dB

We obtain T_{on}= 650K, T_{off}= 307K

$$f_R \cong \frac{(F_C - 1)(T_o - T_A')}{(T_{ON} - T_o)\tau_p}$$

Example; Pulse Noise-Injection

With:

$\tau_p = 20\mu\text{sec}$

$F_c = 10dB$

$T_o = 315K$

$ENR = 20dB$

$L_{on} = 1.5dB$

$L_{off} = 50dB$

$60K \le T_A' \le 300K$

$$f_R = \frac{(F_c - 1)(T_o - T_A')}{(T_{ON}' - T_o)\tau_p}$$

$$T_{OFF}' = T_o\left(1 - \frac{1}{L_{off}}\right) + \frac{T_N}{L_{off}}$$

$$T_{on}' = \frac{T_N}{L_{on}} + T_o\left(1 - \frac{1}{L_{on}}\right)$$

Answers:

$F_c = 10$

$T_N = 31{,}815K$

$T_{OFF} = 315K$

$T_{ON} = 22615K$

$T_A' = 60K, f_r = 5kHz$

$T_A' = 300K, f_r = 302Hz$

Find frequency range needed

$$ENR = \frac{T_N}{T_o} - 1$$

$$ENR_{(dB)} = 10\log ENR$$

$\tau_s >> \tau_R$

$f_s << f_R$

f_s = switching freq

f_R = pulse repetition frequen

Table 7-3: Summary of system transfer functions and sensitivities of different types of radiometers. The radiometer output indication I_{out} is related to the input antenna temperature T_A by $I_{out} = a(T_A + b)$, and the sensitivity ΔT is defined relative to ΔT_{IDEAL} of the ideal radiometer given by Eq. (7.55).

Radiometer type	*Output indicator* I_{out}	a	b	$\Delta T/\Delta T_{IDEAL}$ *for* $T_A = 0$ K	$\Delta T/\Delta T_{IDEAL}$ *for* $T_A = T_0$
Ideal (Fig. 7-15)	V_{out}	G_S	T'_{REC}	1	1
Total power (Fig. 7-15)	V_{out}	G_S	T'_{REC}	$\left[1 + B\tau\left(\frac{\Delta G_S}{G_S}\right)^2\right]^{1/2}$	$\left[1 + B\tau\left(\frac{\Delta G_S}{G_S}\right)^2\right]^{1/2}$
Dicke (unbalanced) (Fig. 7-16)	V_{out}	$\frac{G_S}{2}$	$-T_0$	$\sqrt{2}\left[\left(\frac{T_0 + T'_{REC}}{T'_{REC}}\right)^2 + 1 + \frac{B\tau}{2}\left(\frac{\Delta G_S}{G_S}\right)^2\left(\frac{T_0}{T'_{REC}}\right)^2\right]^{1/2}$	2
Balanced Dicke* with noise injection (Fig. 7-18)	V_c	$-\left(\frac{F_c - 1}{T_N - T_0}\right)$	$-T_0$	$2\left(\frac{T_0}{T'_{REC}} + 1\right)$	2
Balanced Dicke* with pulsed noise injection (Fig. 7-19)	f_R	$-\left[\frac{F_c - 1}{\tau_p(T'_{ON} - T_0)}\right]$	$-T_0$	$2\left(\frac{T_0}{T'_{REC}} + 1\right)$	2
Noise adding* (Fig. 7-22)	V_{out}	$\frac{1}{T''_N}$	T'_{REC}	$2\left(\frac{2T'_{REC}}{T''_N} + 1\right)$	$2\left(\frac{T_0 + 2T'_{REC}}{T''_N} + 1\right)$

$^*T_{REF} = T_0$

Summary

Table 1. Main types of radiometers: block diagram, basic equations and radiometric resolution.

Radiometer schematics	Radiometer basic equations	Radiometric resolution
a) Total power radiometer	$V_0 = k_B \cdot (T_A^{'} + T_R) \cdot B \cdot G \cdot C_d + Z$	$\Delta T = (T_A^{'} + T_R) \cdot \sqrt{\frac{1}{B \cdot \tau} + \left(\frac{\Delta G}{G}\right)^2}$
b) Dicke radiometer (unbalanced)	$V_0 = \frac{1}{2} \cdot k_B \cdot (T_A^{'} - T_{REF}) \cdot B \cdot G \cdot C_d$	$\Delta T = \sqrt{\frac{2 \cdot (T_A^{'} + T_R)^2}{B \cdot \tau} + \frac{2 \cdot (T_{REF} + T_R)^2}{B \cdot \tau} + (T_A^{'} - T_{REF})^2 \cdot \left(\frac{\Delta G}{G}\right)^2}$
c) Balanced Dicke radiometer by duty cycle modulation	$V_0 = 0$ $\eta = (T_{REF} + T_R)/(T_A^{'} + T_{REF} + 2 \cdot T_R)$	$\Delta T = \sqrt{\frac{(T_A^{'} + T_R)^2}{B \cdot \tau \cdot \eta} + \frac{(T_{REF} + T_R)^2}{B \cdot \tau \cdot (1-\eta)}}$
d) Balanced Dicke radiometer by gain modulation	$V_0 = 0$ $\alpha = (T_A^{'} + T_R)/(T_{REF} + T_R)$	$\Delta T = \sqrt{\frac{2 \cdot (T_A^{'} + T_R)^2}{B \cdot \tau} + \frac{2 \cdot (T_{REF} + T_R)^2}{B \cdot \tau}}$
e) Balanced Dicke radiometer by reference channel	$V_0 = 0$ $T_A^{'} = T_{REF}^{'}$	$\Delta T = \frac{2 \cdot (T_A^{'} + T_R)}{\sqrt{B \cdot \tau}}$

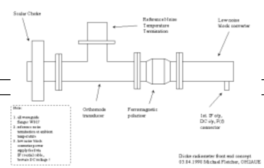
Cont… Source: "Microwave Radiometer Resolution Optimization Using Variable Observation Times, " by Adriano Camps and Jose Miguel Tarongí

Table 1. Main types of radiometers: block diagram, basic equations and radiometric resolution.

Radiometer schematics	Radiometer basic equations	Radiometric resolution
a) Total power radiometer	$V_0 = k_B \cdot (T_A^{'} + T_R) \cdot B \cdot G \cdot C_d + Z$	$\Delta T = (T_A^{'} + T_R) \cdot \sqrt{\frac{1}{B \cdot \tau} + \left(\frac{\Delta G}{G}\right)^2}$
b) Dicke radiometer (unbalanced)	$V_0 = \frac{1}{2} \cdot k_B \cdot (T_A^{'} - T_{REF}) \cdot B \cdot G \cdot C_d$	$\Delta T = \sqrt{\frac{2 \cdot (T_A^{'} + T_R)^2}{B \cdot \tau} + \frac{2 \cdot (T_{REF} + T_R)^2}{B \cdot \tau} + (T_A^{'} - T_{REF})^2 \cdot \left(\frac{\Delta G}{G}\right)^2}$
c) Balanced Dicke radiometer by duty cycle modulation	$V_0 = 0$ $\eta = (T_{REF} + T_R)/(T_A^{'} + T_{REF} + 2 \cdot T_R)$	$\Delta T = \sqrt{\frac{(T_A^{'} + T_R)^2}{B \cdot \tau \cdot \eta} + \frac{(T_{REF} + T_R)^2}{B \cdot \tau \cdot (1-\eta)}}$
d) Balanced Dicke radiometer by gain modulation	$V_0 = 0$ $\alpha = (T_A^{'} + T_R)/(T_{REF} + T_R)$	$\Delta T = \sqrt{\frac{2 \cdot (T_A^{'} + T_R)^2}{B \cdot \tau} + \frac{2 \cdot (T_{REF} + T_R)^2}{B \cdot \tau}}$
e) Balanced Dicke radiometer by reference channel	$V_0 = 0$ $T_A^{'} = T_{REF}^{'}$	$\Delta T = \frac{2 \cdot (T_A^{'} + T_R)}{\sqrt{B \cdot \tau}}$

UPR, Mayagüez Campus

Dicke Switch



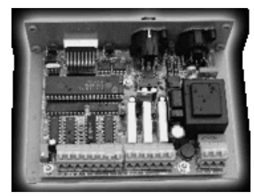
- Two types
  - Semiconductor diode switch, PIN
  - Ferrite circulator
- Switching rate, f_S,
  - High enough so that G_S remains constant over one cycle.
  - To satisfy **sampling theorem**, $f_S > 2B_{LF}$

http://envisat.esa.int/instruments/mwr/descr/charact.html

Dicke Input Switch

Important properties to consider

- Insertion loss
- Isolation
- Switching time
- Temperature stability



http://www.erac.wegalink.com/members/DaleHughes/MyEracSite.htm

Receiver Calibration

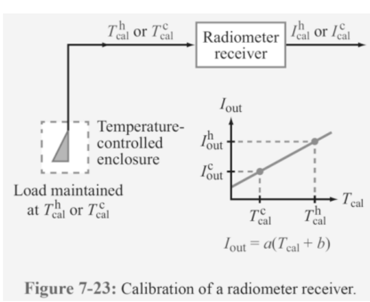
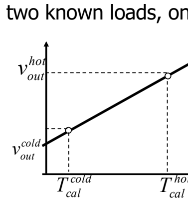


Figure 7-23: Calibration of a radiometer receiver.

Radiometer Receiver Calibration

- Most are **linear** systems $\boxed{i_{out} = a(T_A^{'} + b) \quad \text{or} = v_c \quad \text{or} = f_r}$
- Hach-radiometer is connected to two known loads, one *cold* (usually liquid N_2), one *hot*.

$$i_{out}^{hot} = a(T_{cal}^{hot} + b)$$
$$i_{out}^{cold} = a(T_{cal}^{cold} + b)$$



- Solve for a and b.
- Cold load on satellites
  - use outer space ~2.7K

http://ipnpr.jpl.nasa.gov/progress_report/42-154/154G.pdf

Antenna Properties

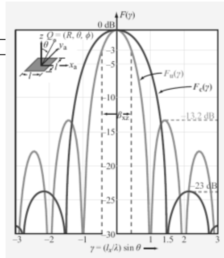


Figure 3-20: Comparison of the antenna pattern $F_a(\gamma)$ of a uniformly illuminated aperture with $F_c(\gamma)$ for a cosine-tapered illuminated aperture.

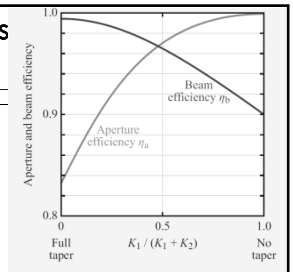


Figure 7-26: Beam and aperture efficiencies for a one-dimensional aperture as a function of taper [after Nash (1964)]. The aperture distribution is $E_a(x_a) = K_1 + K_2(1 - x_l^2)$, where $x_l = 2x_a/l$ and l is the aperture length.

For a given size antenna, uniform illumination generates the narrowest main beam possible, but the pattern contains sidelobes. The corresponding aperture efficiency is 1.0.

A tapered illumination reduces the sidelobes, but broadens the beam, leading to higher beam efficiency.

Measurement Retrieval

$$T_A = \xi \eta_b T_{ML} + \xi(1-\eta_b)T_{SL} + (1-\xi)T_0,$$

Measured by a calibrated receiver

T_{ML} The quantity of interest, the mainlobe radiometric temperature

ξ Antenna radiation efficiency

η_b Beam efficiency

T_0 Physical T of antenna(measured by thermistor)

T_{SL} Sidelobe radiometric T (estimated)

For an ideal antenna with unity beam and radiation efficiencies:

$T_A = T_{ML}$

Antenna Calibration

We need to measure the antenna's beam and radiation efficiencies

$$\eta_b = \frac{\iint_{\text{mainlobe}} F(\theta,\phi)\, d\Omega}{\iint_{4\pi} F(\theta,\phi)\, d\Omega},$$

$$\eta_b = \frac{\xi}{4\pi G} \iint_{\text{mainlobe}} F(\theta,\phi)\, d\Omega.$$

$$\xi = \frac{G}{D} = \frac{4\pi G}{\iint_{4\pi} F(\theta,\phi)\, d\Omega},$$

G is an easy parameter to measure (substitution method relative to a Standard antenna with known gain)

$F(\theta,\phi)$ Can be measured accurately over the main lobe

ξ can be measured by special technique (next slide)

Cryoload Technique for ξ

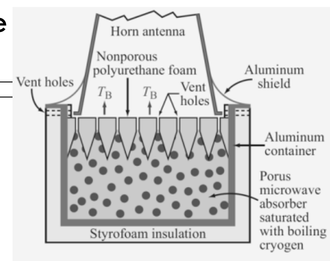


Figure 7-27: Construction of cryoload for calibration of radiometer antenna [after Hardy et al., 1974].

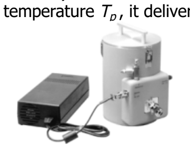
$$T_A = \xi T_B + (1-\xi)T_0$$

$$\xi = \frac{T_0 - T_A}{T_0 - T_B}$$

where in this case $T_B = 77.36$ K (the boiling temperature of liquid nitrogen at sea level).

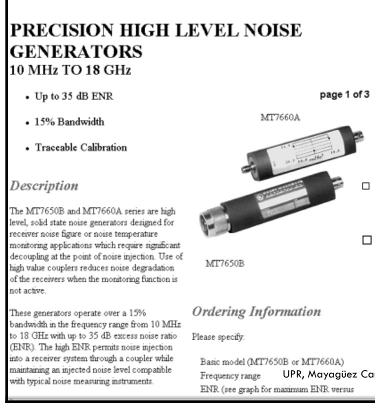
Cryogenic-cooled Noise Source

- When a passive (doesn't require power to work) noise source such as a matched load, is kept at a physical temperature T_p, it delivers an average noise power equal to kT_pB
- Liquid N_2 boiling point = 77.36°K



- Used on ground based radiometers, but not convenient for satellites and airborne systems.

Active "cold or hot" sources



PRECISION HIGH LEVEL NOISE GENERATORS
10 MHz TO 18 GHz

- Up to 35 dB ENR
- 15% Bandwidth
- Traceable Calibration

page 1 of 3

MT7660A

Description

The MT7650B and MT7660A series are high level, solid state noise generators designed for receiver noise figure or noise temperature monitoring applications which require significant decoupling at the point of noise injection. Use of high value couplers reduces noise degradation of the receivers when the monitoring function is not active.

These generators operate over a 15% bandwidth in the frequency range from 10 MHz to 18 GHz with up to 35 dB excess noise ratio (ENR). The high ENR permits noise injection into a receiver system through a coupler while maintaining an injected noise level compatible with typical noise measuring instruments.

MT7650B

Ordering Information

Please specify:

Basic model (MT7650B or MT7660A)
Frequency range
ENR (see graph for maximum ENR versus

- http://www.maurymw.com/
- http://sbir.gsfc.nasa.gov/SBIR/successes/ss/5-049text.html

Active noise source: FET

- The power delivered by a noise source is characterized using the *ENR=excess noise ratio*

$$ENR = \frac{P_n - P_o}{P_o} = \frac{kB(T_N - T_o)}{kBT_o} = \frac{T_N}{T_o} - 1$$

$$ENR_{(dB)} = 10 \log ENR$$

where T_N is the noise temperature of the source and T_o is its physical temperature.

Example for 9,460K:
ENR= 15 dB

Bucket Technique

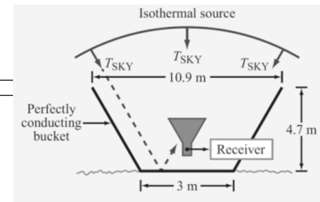


Figure 7-29: The bucket method for measuring the radiation efficiency of an antenna [after Carver, 1975].

$$T_A = \xi T'_A + (1-\xi)T_0, \qquad (7.101)$$

where T'_A is the antenna temperature for a lossless antenna and is equal to the integrated brightness temperature of the sky:

$$T'_A = \frac{\iint_{4\pi} T_{SKY}(\theta,\phi)\, F(\theta,\phi)\, d\Omega}{\iint_{4\pi} F(\theta,\phi)\, d\Omega}. \qquad (7.102)$$

T_{SKY} is calculated based on radiosonde data

Spatial Resolution

$$\Delta x = \beta_x h,$$
$$\Delta y = \beta_y h,$$

$$\beta = k\,\frac{\lambda}{l} \quad \text{radians},$$

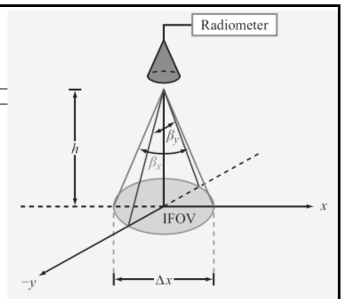


Figure 7-30: The Instantaneous Field of View (IFOV) for a nadir-pointing antenna with beamwidths β_x and β_y. The antenna platform is at a height h above the ground.

Scanning

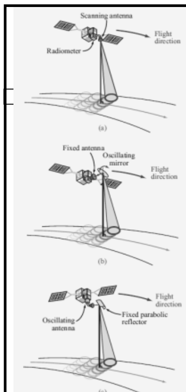


Figure 7-31: Mechanical scanning configurations: (a) scanning antenna; (b) fixed antenna and oscillating reflector; (c) fixed parabolic reflector and oscillating antenna feed.

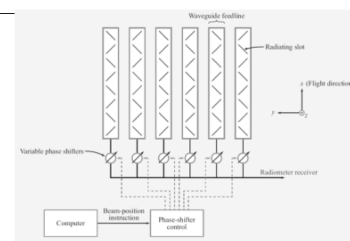


Figure 7-32: Phased-array antenna configuration for electronic scanning of the main beam in the y-z plane.

Electronic scanning

Mechanical scanning

Cross-Track and Conical Scanning

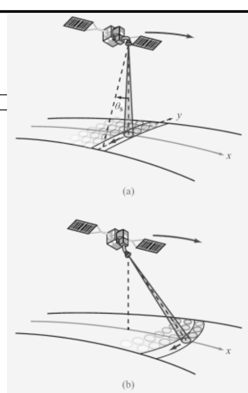


Figure 7-33: Radiometric imaging by (a) cross-track scanning in the plane normal to the direction of flight, and (b) conical scanning.

Radiometric Uncertainty Principle

$$\Delta T = \frac{M}{\sqrt{B\tau}}$$ M=figure of merit (radiometer-type specific)

$$t_l = \frac{\Delta x}{u} = \frac{\beta h}{u}$$ Time to travel one beam

$$\omega = \frac{2\theta_s}{t_l} \text{ rad/s}$$ Angular scanning speed

$$\tau_d = \frac{\beta}{\omega} = \frac{t_l \beta}{2\theta_s}. \qquad (7.108)$$

This time τ_d is called the ***dwell time*** because it is equal to the time that a point on the ground is observed by the antenna beam. Using Eq. (7.106), τ_d can be expressed in terms of the spatial resolution Δx:

$$\tau_d = \frac{(\Delta x)^2}{2u\theta_s h}, \qquad (7.109)$$

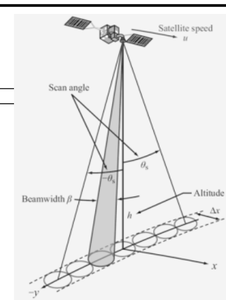


Figure 7-34: Geometry of airborne scanning microwave radiometer [after McGillem and Seling (1963)].

For $\tau = \tau_d$ inserting Eq. (7.109) into Eq. (7.105) leads to

$$\Delta T \cdot \Delta x \cdot B^{1/2} = M(2u\theta_s h)^{1/2}. \qquad (7.111)$$