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E4230
Microwave EO Instrumetation

(5 cr)
Jaan Praks
Aalto University

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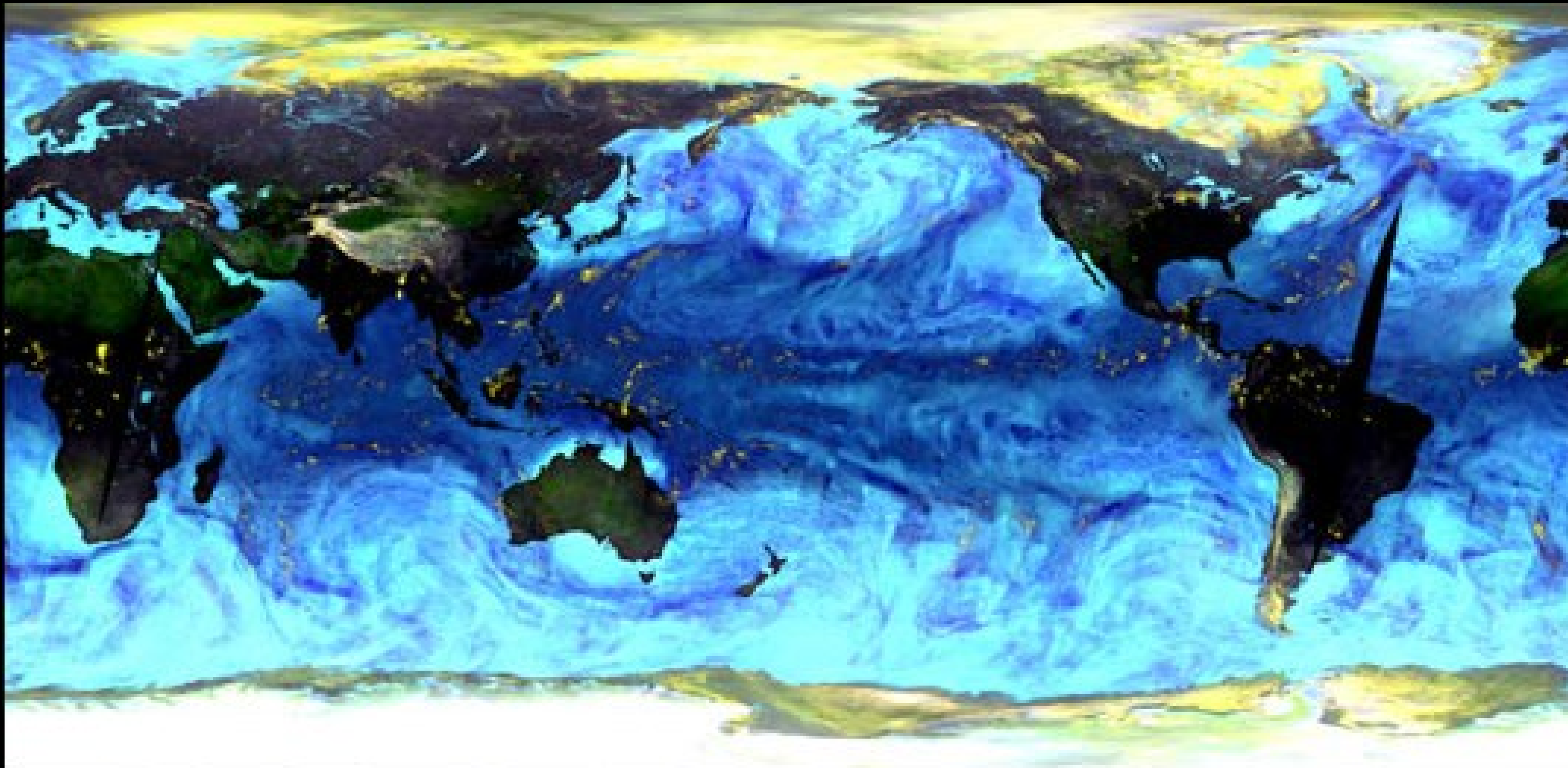
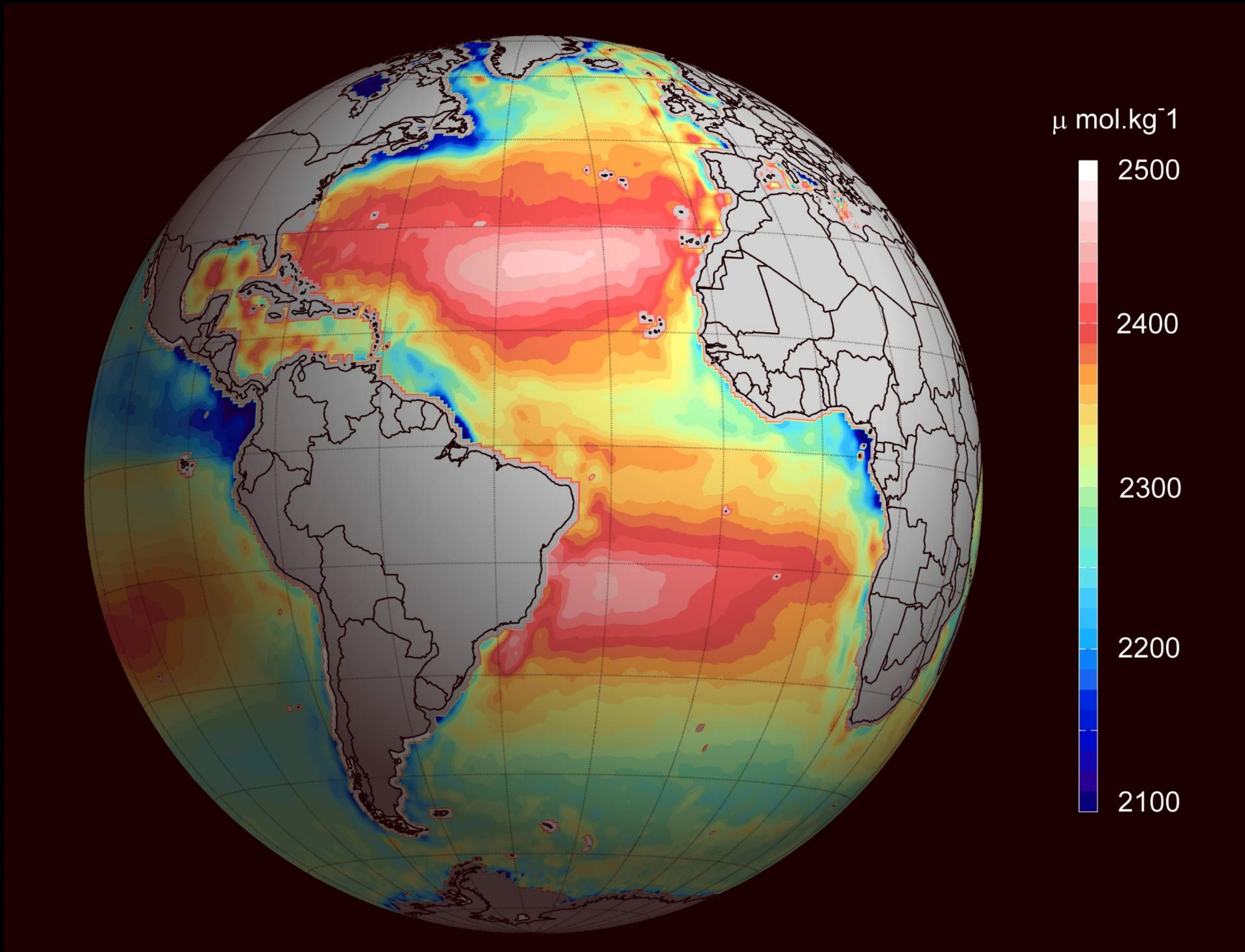
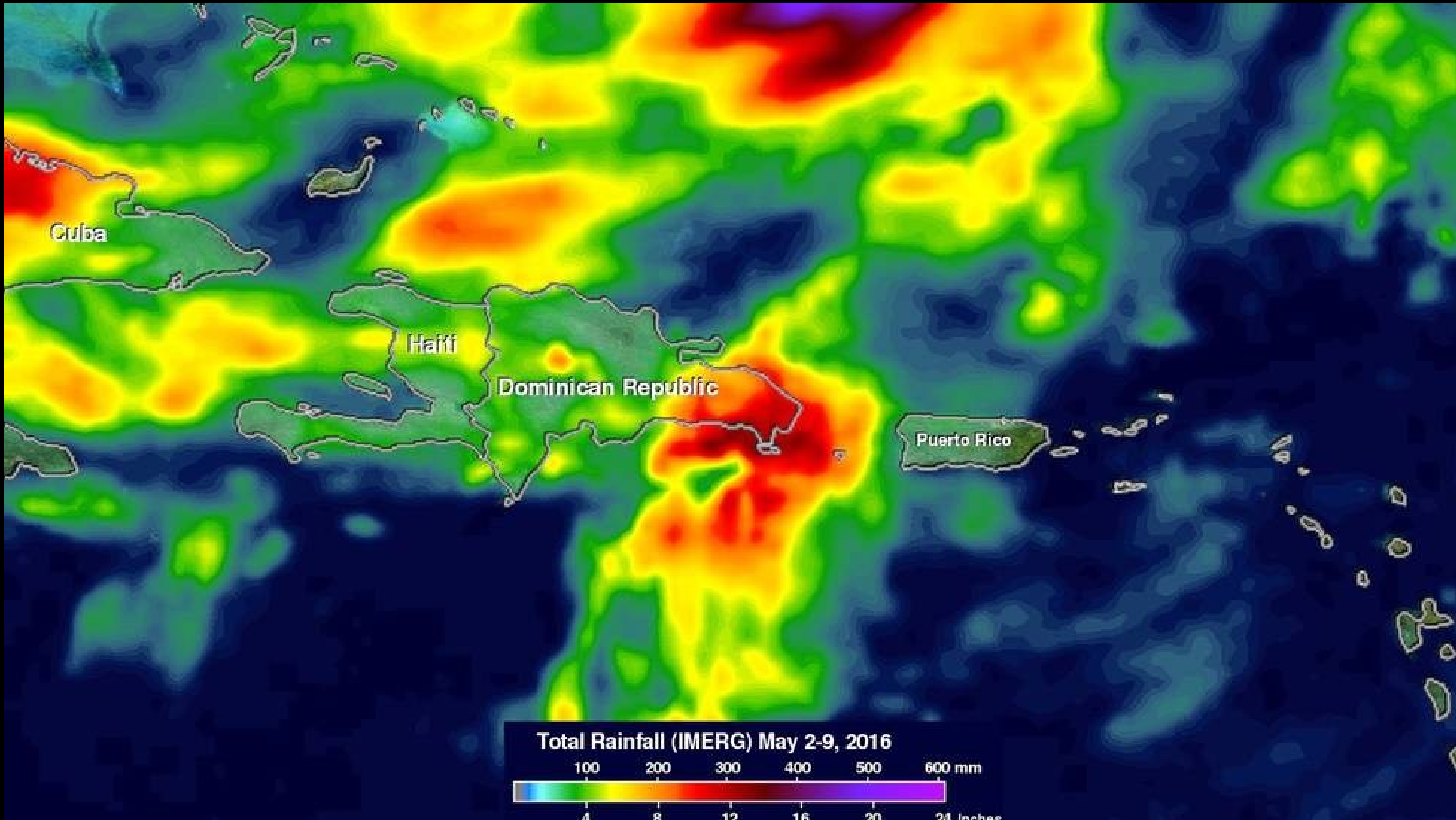
What is common for next images?

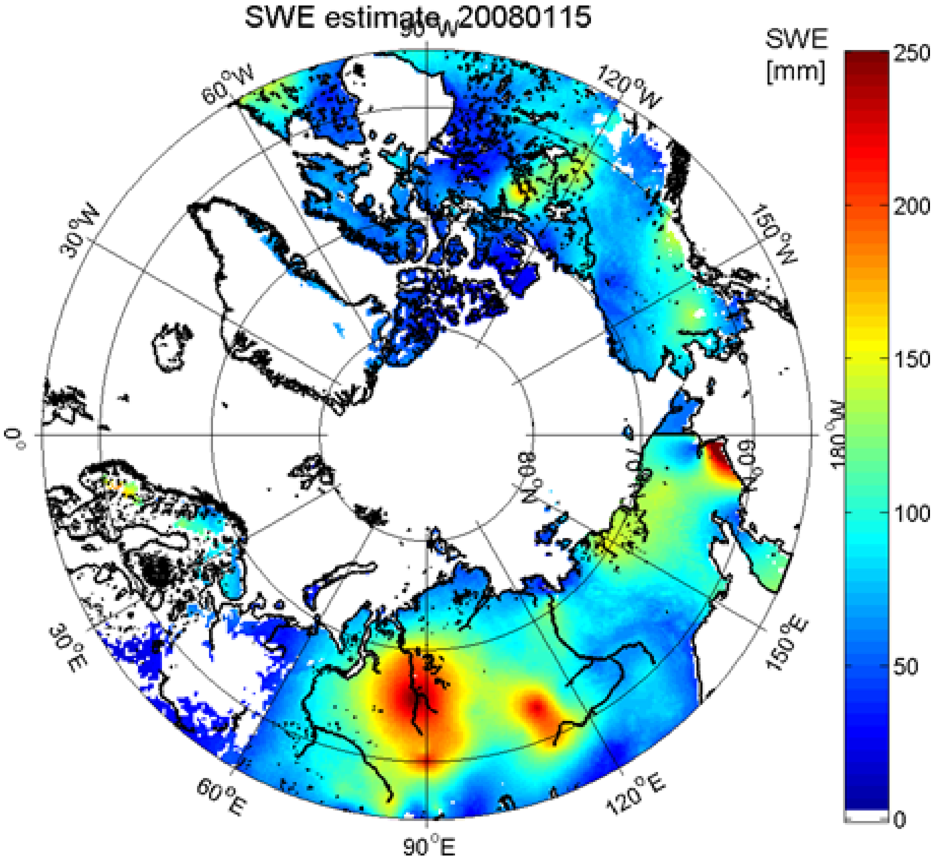


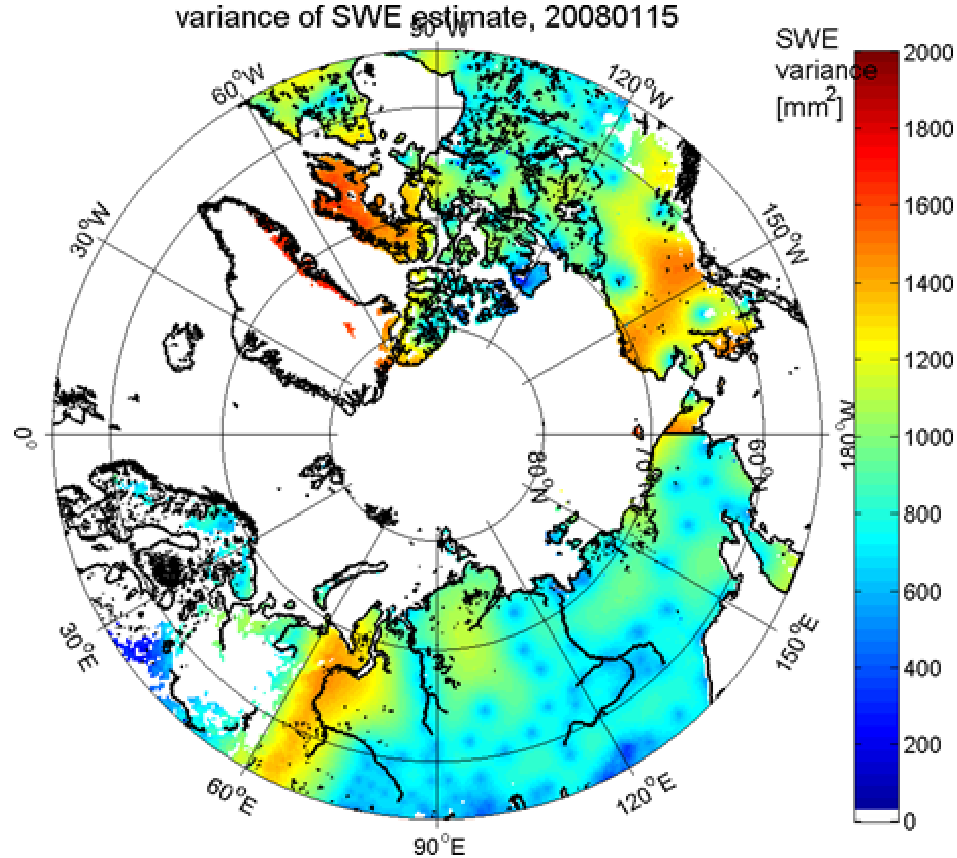
Brightness Temperature


μ mol.kg⁻1
2500
2400
2300
2200
2100

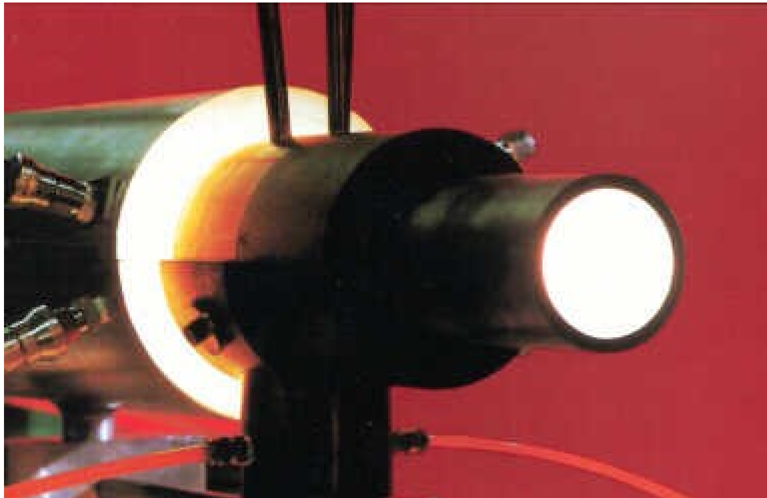

Cuba
Haiti
Dominican Republic
Puerto Rico
Total Rainfall (IMERG) May 2-9, 2016
100 200 300 400 500 600 mm
4 8 12 16 20 24 Inches

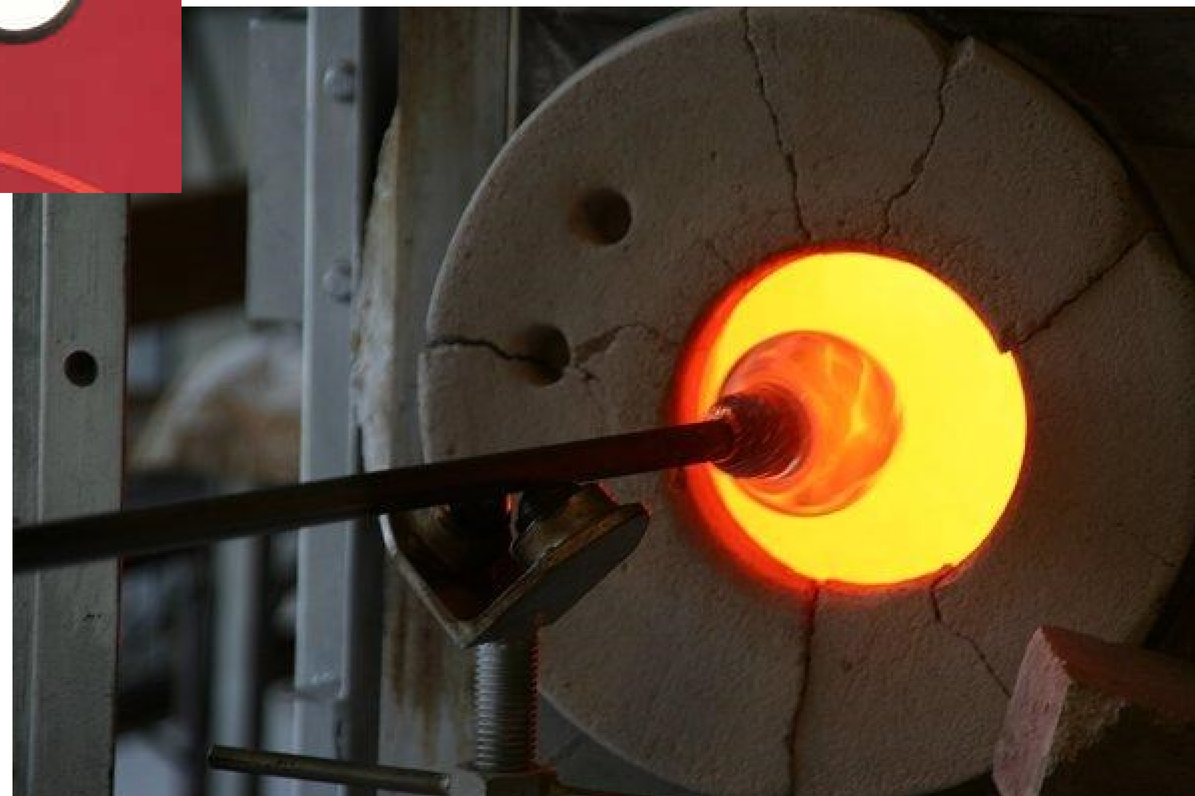
Snow water equivalent and the estimation uncertainty for 15 January 2008





Blackbody





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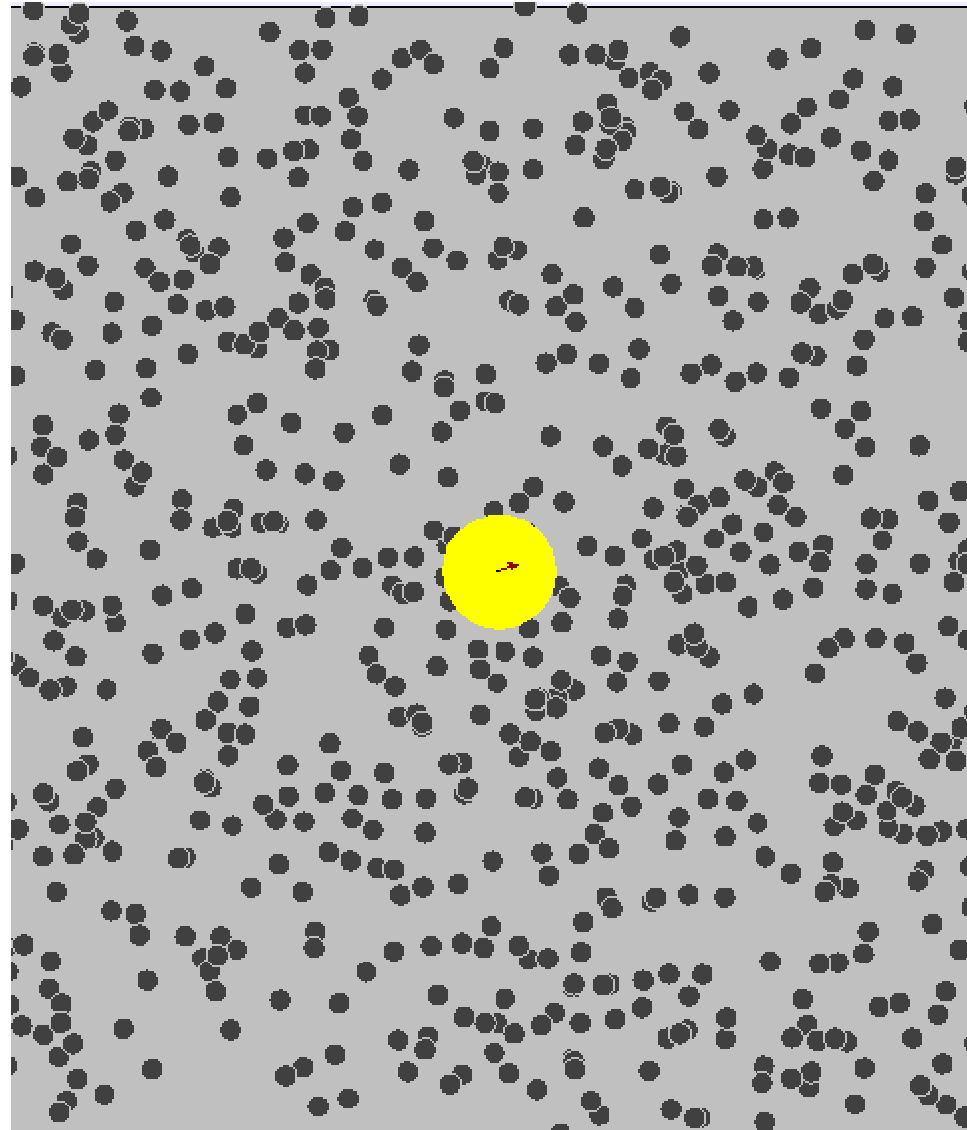
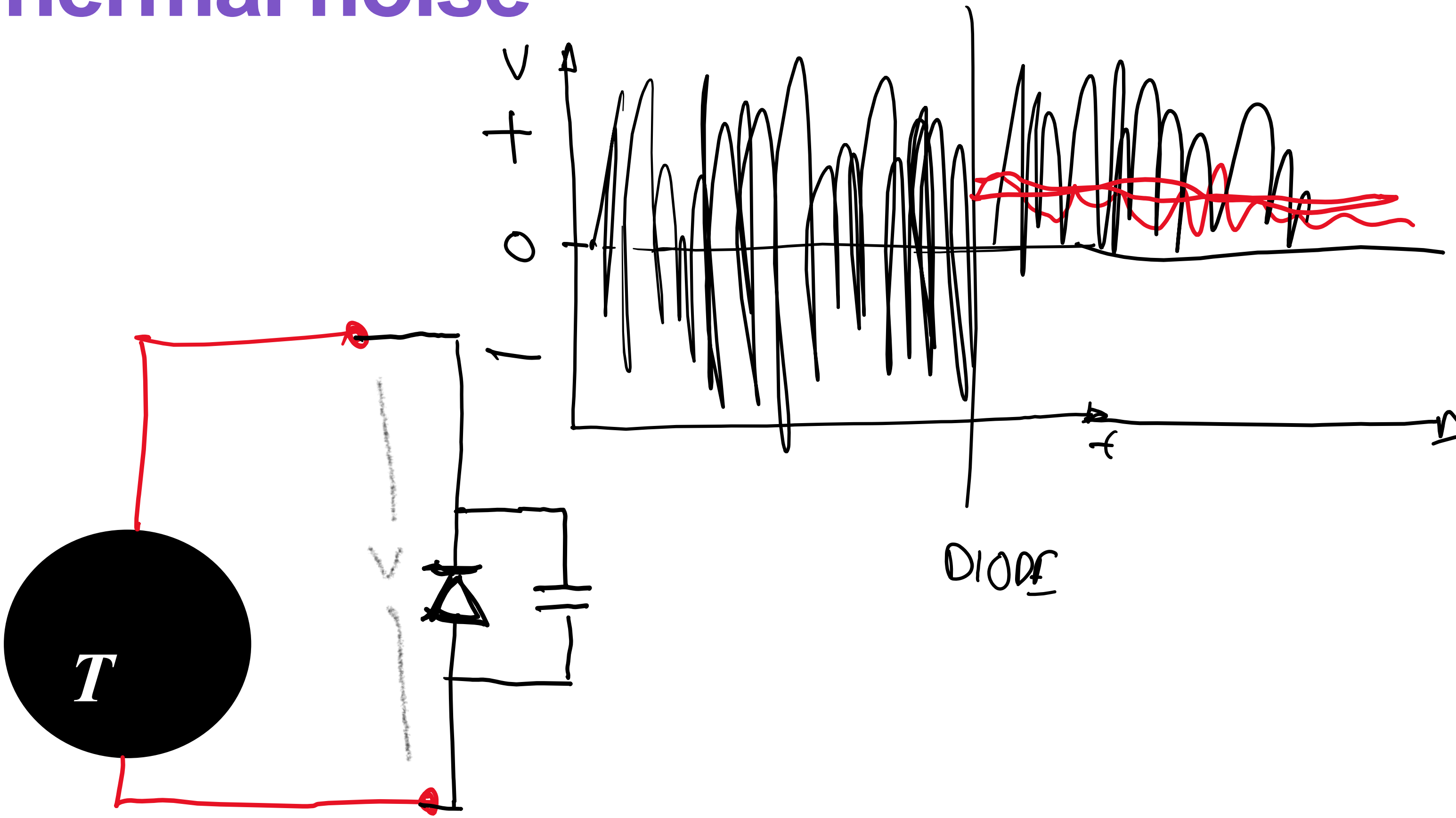
Measuring thermal noise



Thermal noise



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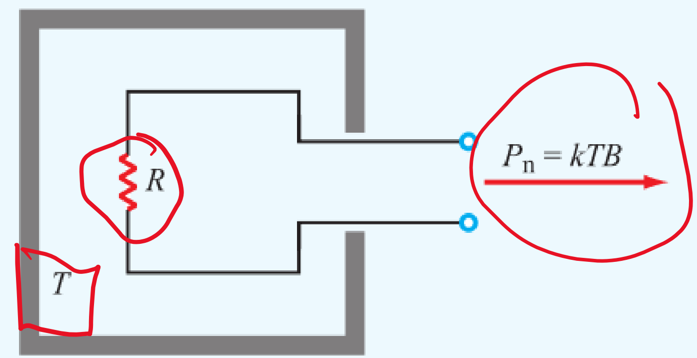
Power and temperature equivalence



(b) Resistor at temperature T

Power and temperature equivalence -- also for system with an antenna

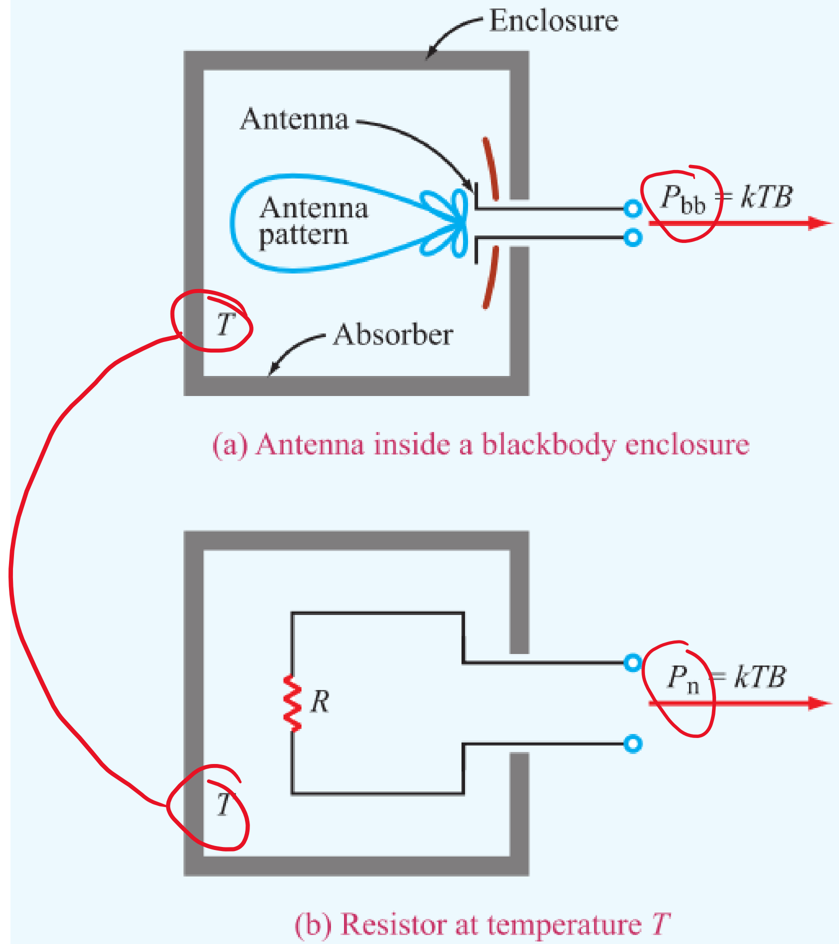
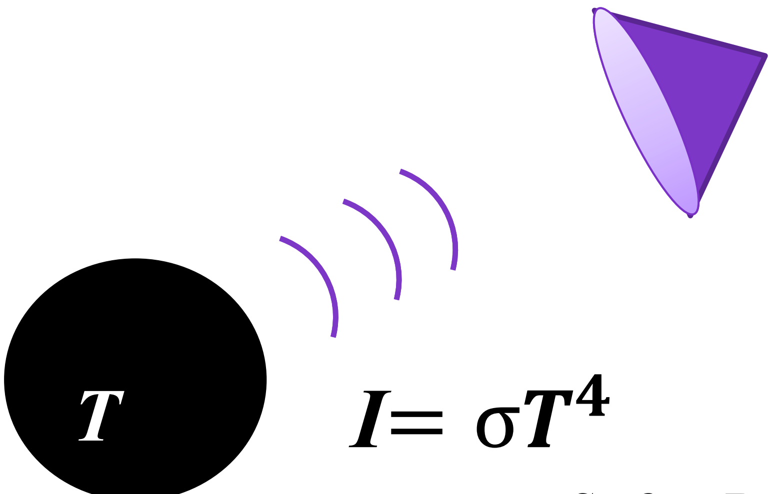


Figure 6-5: The power delivered by (a) an antenna placed inside a blackbody enclosure of temperature T is equal to the power delivered by (b) a resistor maintained at the same temperature.

Measuring the radiation



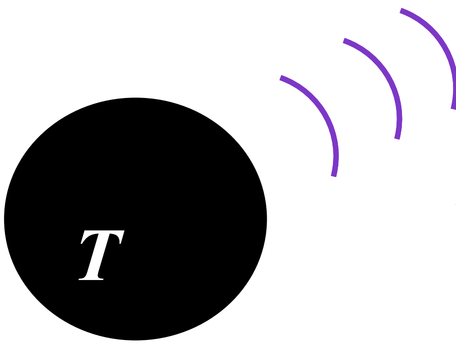
$$I = \sigma T^4$$

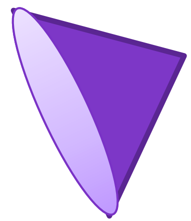
Stefan–Boltzmann law

$$\sigma = \frac{2\pi^5 k_B^4}{15 h^3 c^2}$$

We add an antenna:

Radiated energy is directly related to temperature T^4





$$I_f = \frac{2hf^3}{c^2}\frac{1}{e^{\frac{hf}{kT}}-1}$$

Planck's law

However, we can only measure a certain frequency with antenna.

Radiated energy as a function of frequency.

h - Planck constant
k - Boltzmann constant

Planck's law

$$I_f = \frac{2hf^3}{c^2} \frac{1}{e^{\frac{hf}{kT}} - 1}$$

A blackbody is defined as an idealized, perfectly opaque material that absorbs all the incident radiation at all frequencies, reflecting none.

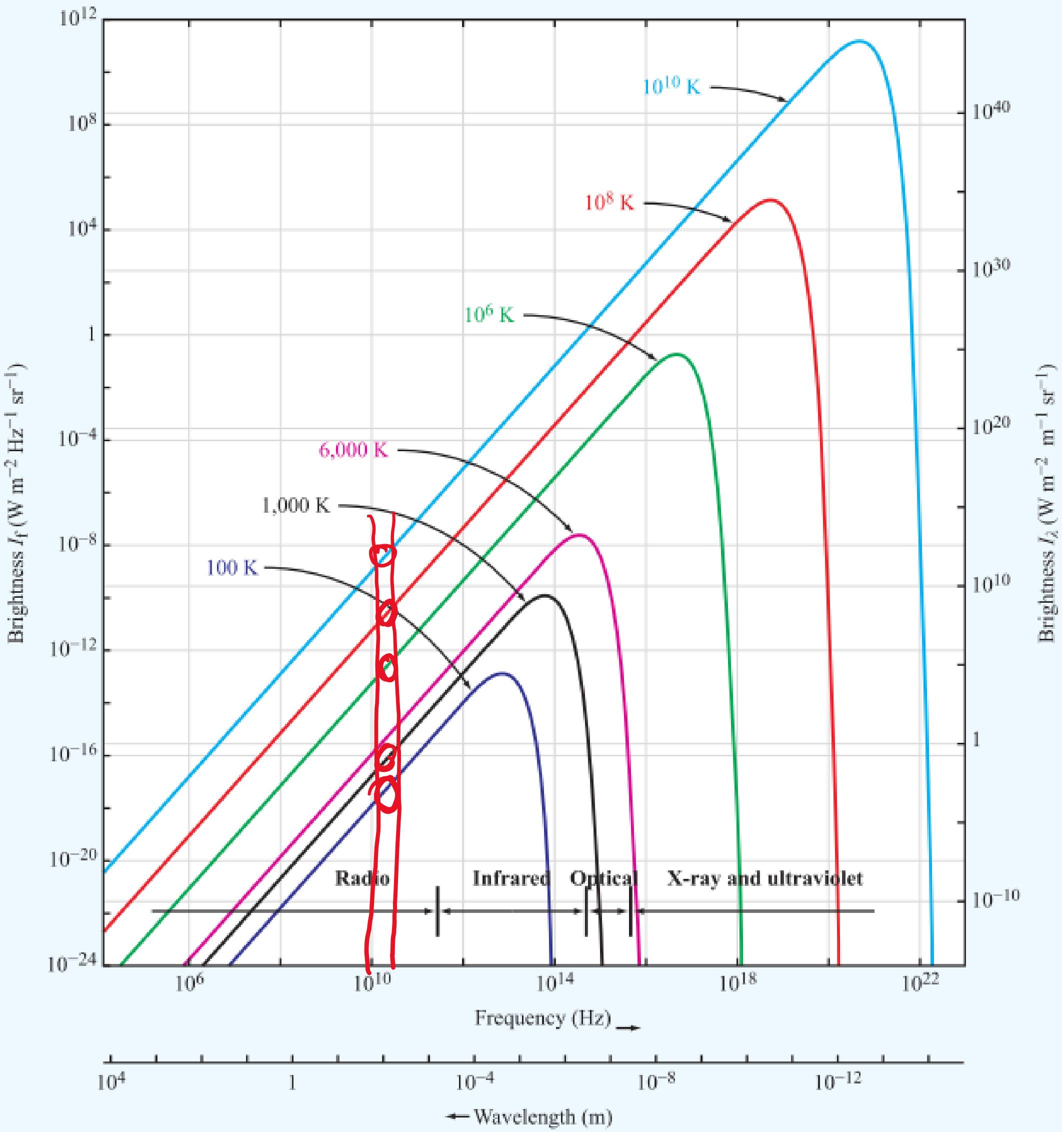


Figure 6-1: Planck's radiation law [adapted from Kraus, 1966].

Rayleigh–Jeans's law

The Rayleigh–Jeans approximation is very useful in the microwave region: it is mathematically simpler than Planck's law and yet its fractional deviation from Planck's exact expression is less than 1% if $\lambda T > 0.77$ m K,

or equivalently,

$f/T < 3.9 \times 10^8$ Hz K^{-1}.

$$I_f \approx \frac{2kT}{\lambda^2}$$

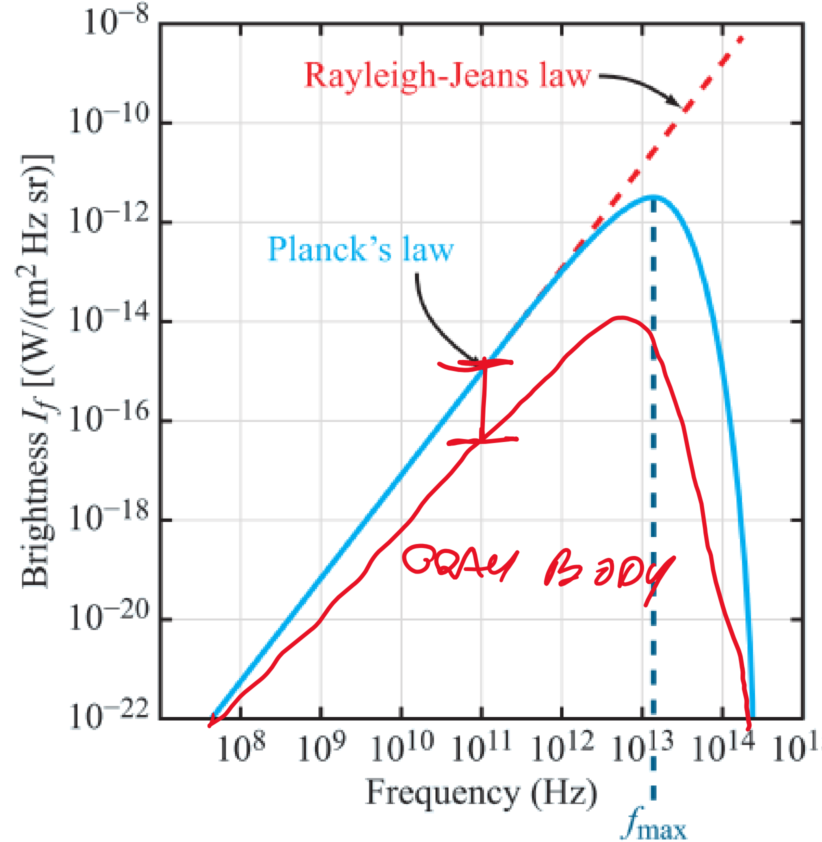


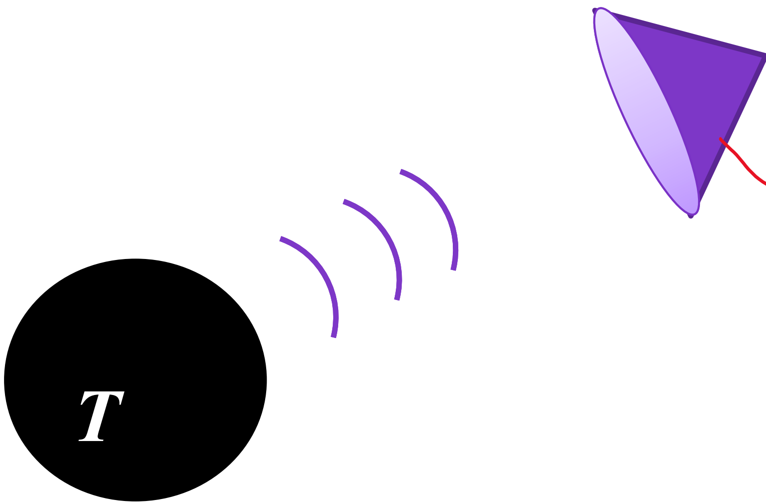
Figure 6-3: Comparison of Planck's law with its low-frequency approximation (Rayleigh–Jeans law) at 300 K.

Blackbody concept

A blackbody is defined as an idealized, perfectly opaque material that absorbs all the incident radiation at all frequencies, reflecting none.

A body in thermodynamic equilibrium emits to its environment the same amount of energy it absorbs from its environment. Hence, in addition to being a perfect absorber, a blackbody also is a perfect emitter.

Measuring Blackbody temperature

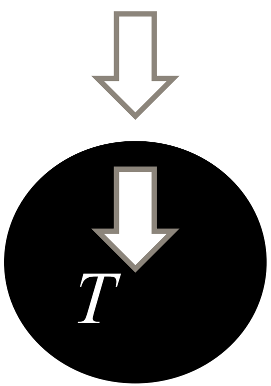


$$I_f = \frac{2kT}{\lambda^2}$$

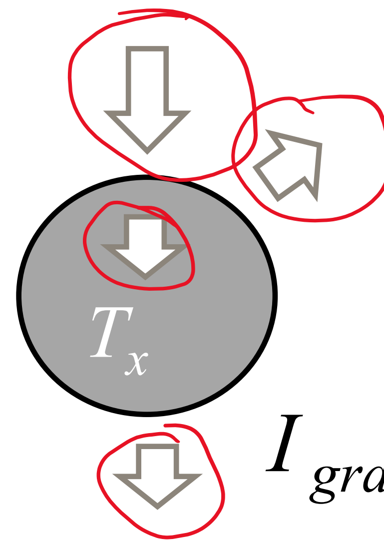
With ideal radiometer and ideal backbody we can measure temperature of the body.

Gray body, perfect absorber is not realistic

Real body cannot absorb <u>everything</u>, because they also reflect and transmit something! If absorbing is not 100%, also emitting cannot be 100%.



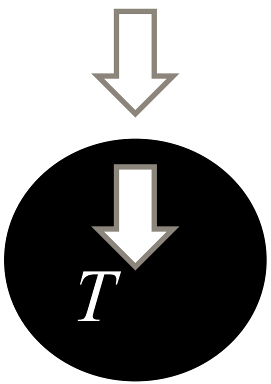
$$I_{black} = \sigma T^4$$



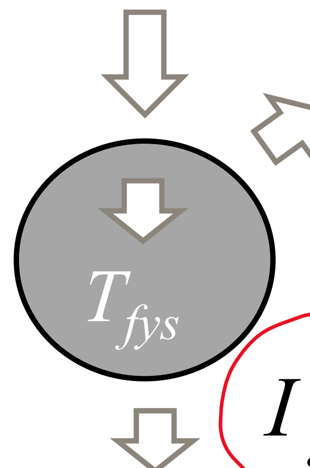
$$I_{gray} = e\sigma T_{real}^{4}$$

Gray body

Simplest approximation for real body is gray body, a body which emits and absorbs less than black body, scaled by a simple parameter ε emittance. This allows reflectance and transmittance!



$$I_{black} = \sigma T^4$$

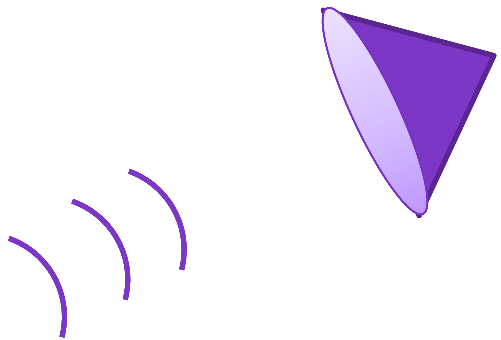


$$I_{gray} = e\sigma T_{real}^4$$

Graybody brightness temperure

$$I_f = \frac{2kT_B}{\lambda^2} = \frac{2keT_{real}}{\lambda^2}$$

Appears like a blackbody with temperature T_B



$$T_{blackbody} = eT_{real}$$

$$e = \frac{T_{black}}{T_{real}}$$

With ideal radiometer we can measure apparent temperature of the body and emissivity, if we know the real temperature!

Brightness temperature – the temperature of an imagined black body would emit to match the measurement.

Often noted as $\mathbf{T_B}$ or **TB**. Sometimes also pronounced TB.

It is easier to use temperature than brightness. Therefore, radiometer community talks about brightness temperature while they are meaning irradiance.

How emissivity is connetced to electromagnetic properties??

Because emissivity is dependent on reflectivity and transmissivity, it depends on dielectric properties of the medium, as well as on many other parameters

$$\eta = \sqrt{(\mu/\varepsilon)}$$

$$T_B(\theta) = e(\theta, \varepsilon, \mu, \lambda, T)T_{real}$$

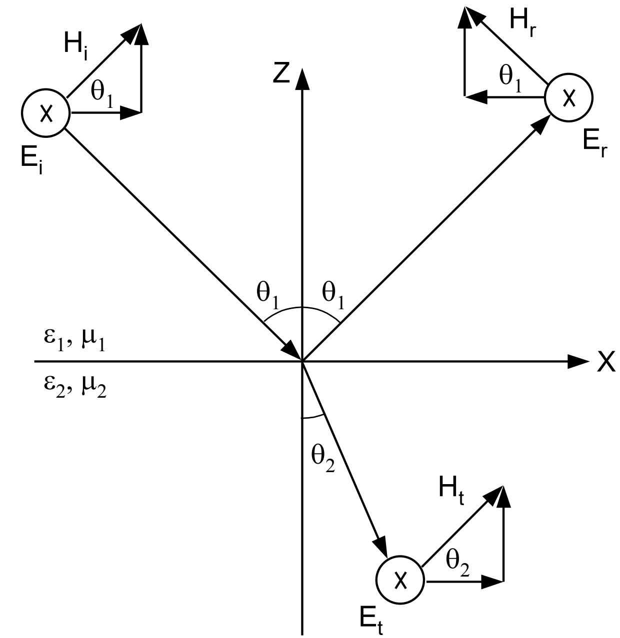
Reminder, reflectivity depends on dielectric properties

Reflection coefficient for H and V polarizations:

$$\rho_h = \frac{\eta_2 \cos\theta_1 - \eta_1 \cos\theta_2}{\eta_2 \cos\theta_1 + \eta_1 \cos\theta_2}$$

$$\rho_v = \frac{\eta_1 \cos\theta_1 - \eta_2 \cos\theta_2}{\eta_1 \cos\theta_1 + \eta_2 \cos\theta_2}$$

For power quantities: $R_v = |\rho_v|^2$

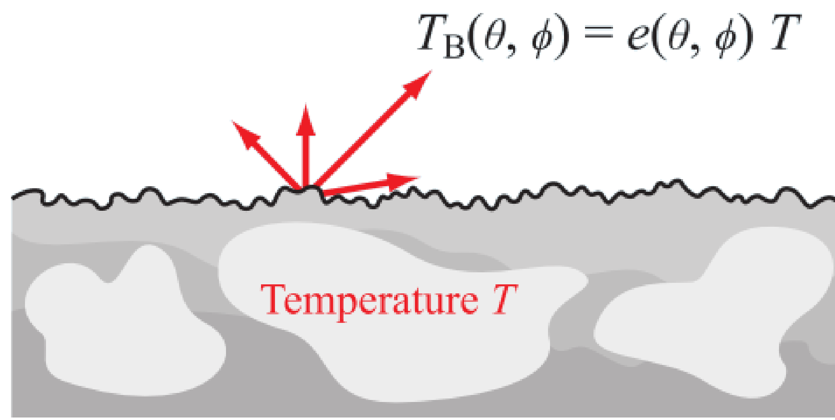


Emissivity

The ratio of the brightness intensity $I(\theta,\varphi)$ of the material to that of a blackbody at the same temperature is defined as the emissivity $e(\theta,\varphi)$:

$$e(\theta,\phi) = \frac{I(\theta,\phi)}{I_{bb}} = \frac{T_B(\theta,\phi)}{T}.$$

$0<e<1$



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Radiometric Quantities

Chaper 6 in course book

Table 6-1: Standard units, symbols, and defining equations for fundamental radiometric quantities.

Microwave terminology	Optical terminology	Symbol	Defining equation	Unit	Abbreviation
Energy	Radiant energy	$\mathcal{E}$		joule	J
Power	Radiant flux	P	$P = \partial\mathcal{E}/\partial t$	watt	W
Power (or flux) density	Radiant flux	$\mathbb{S}$	$\mathbb{S} = \partial P/\partial A$	watt per square meter	$\mathrm{Wm^{-2}}$
Brightness intensity	Radiance	I	$I = \partial^2 P/\partial\Omega\,\partial A$	watt per steradian per square meter	$\mathrm{W\,sr^{-1}m^{-2}}$
Emissivity	Emissivity	e	$e = I/I_{\text{blackbody}}$	(unitless)	
Reflectivity	Reflectance	Γ	$\Gamma = P^{\mathrm{r}}/P^{\mathrm{i}}$	(unitless)	
Absorptivity	Absorptance	a	$a = P^{\mathrm{a}}/P^{\mathrm{i}}$	(unitless)	
Transmissivity	Transmittance	$\mathbb{T}$	$\mathbb{T} = P^{\mathrm{t}}/P^{\mathrm{i}}$	(unitless)	

Superscripts: i = incident, r = reflected, a = absorbed, and t = transmitted.

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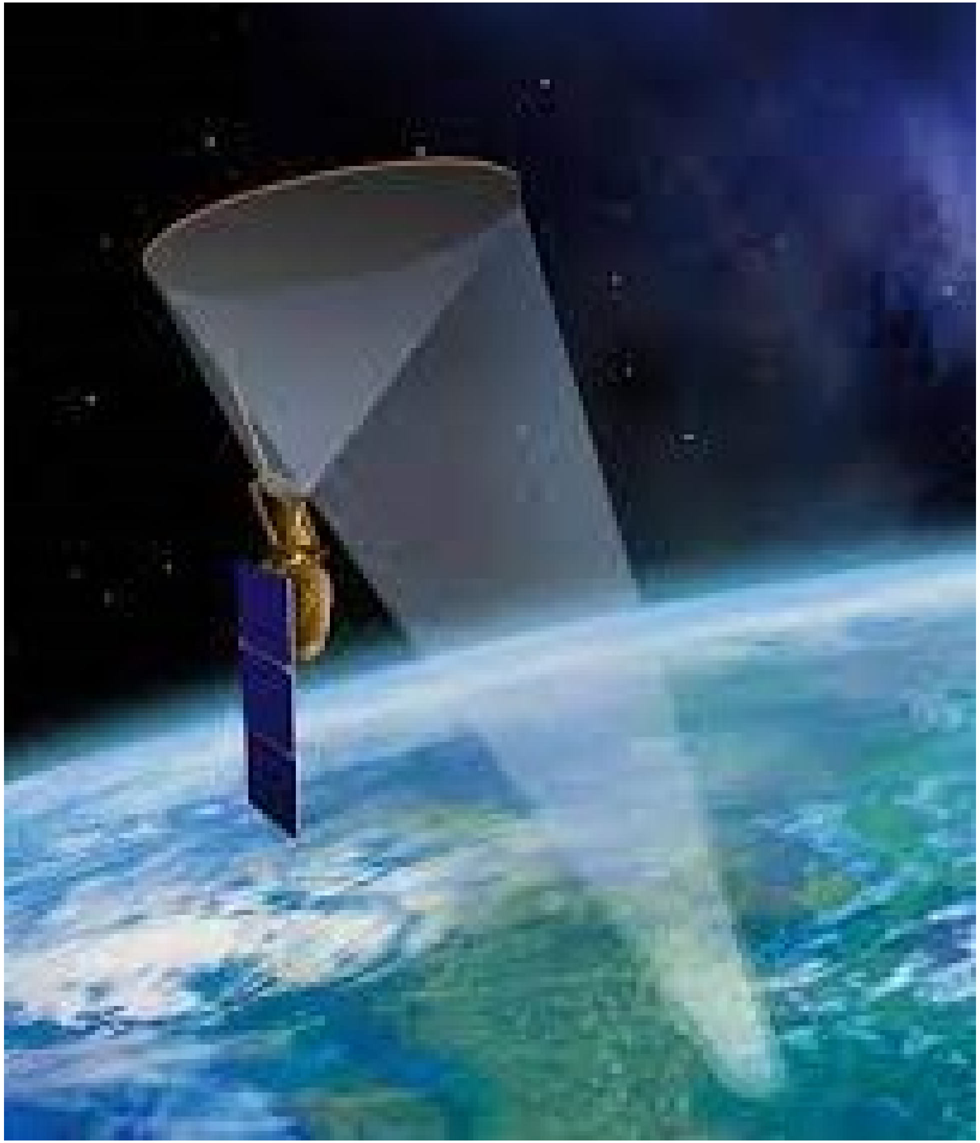
Antennas and dependence on direction

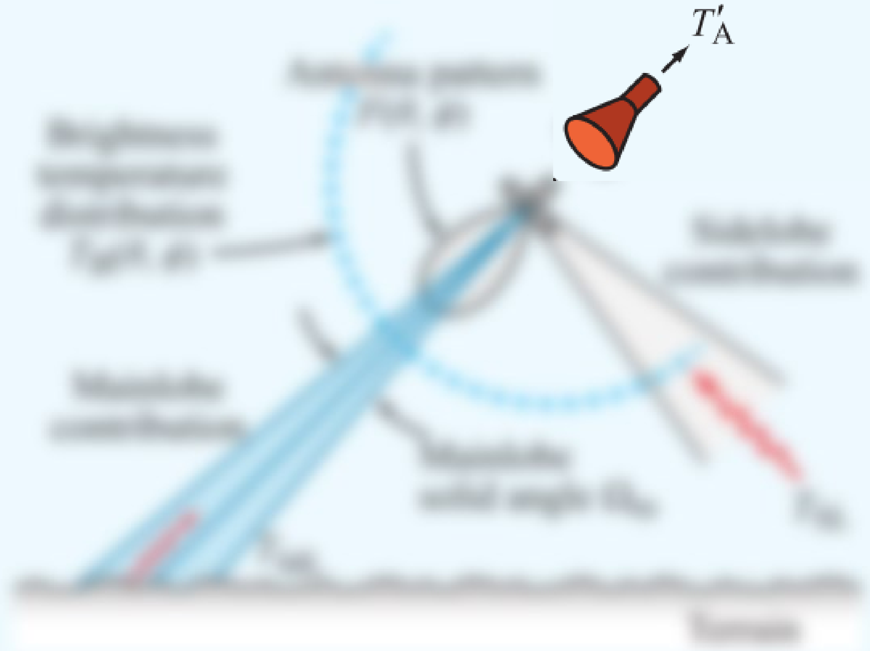
Chaper 6 in course book



Antenna temp

The antenna temperature T′ is the brightness temperature reduced to the antenna location.

An ideal and lossless antenna would deliver this temperature to receiver.



Generic Radiometer system

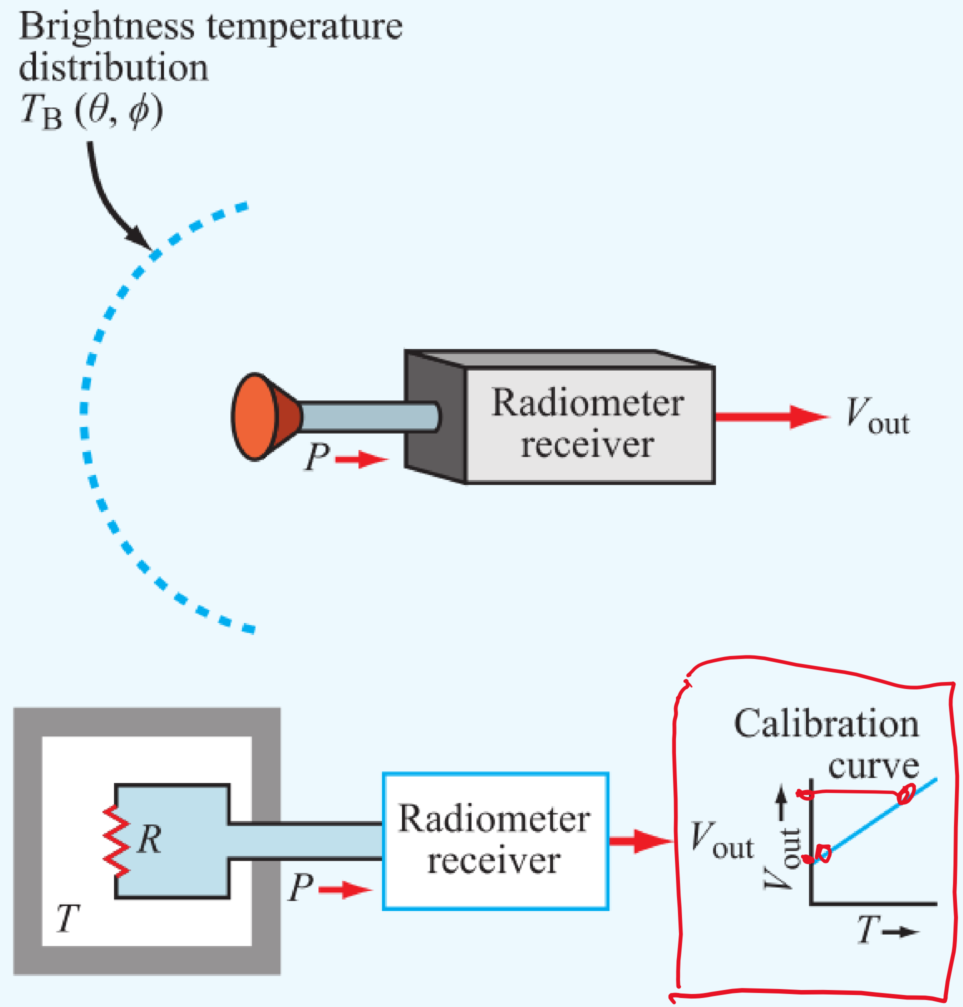


Figure 6-8: The power received by an antenna is equivalent to the noise power delivered by a matched resistor.

Antenna temperature: the brightness temperature a lossless antenna would deliver to receiver.

Beam efficiency and sidelobes

$$\eta_b = \frac{\Omega_m}{\Omega_p} \,. \qquad (6.36)$$

$$T'_A = \eta_b T_{ML} + (1 - \eta_b) T_{SL} \,. \qquad (6.37)$$

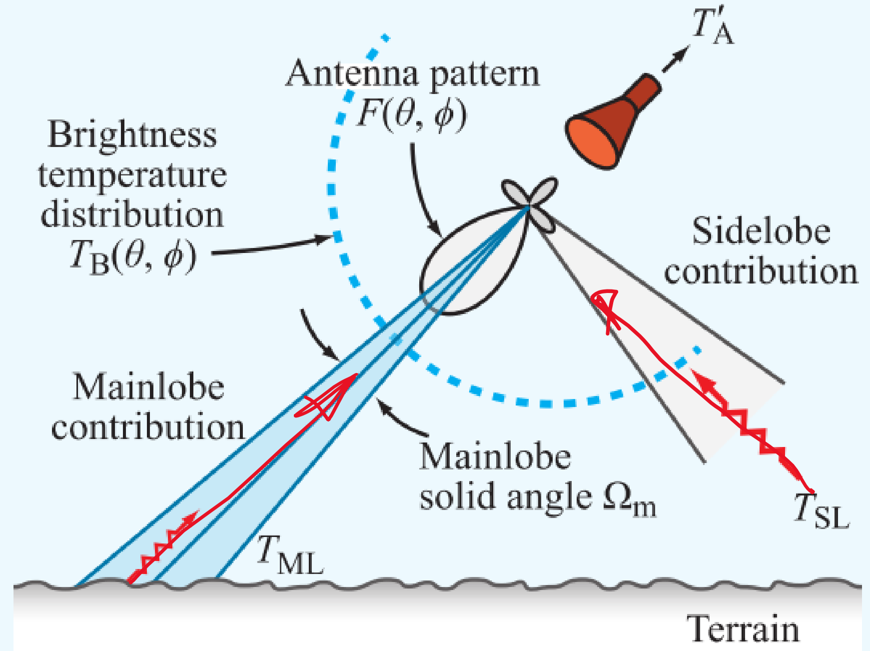


Figure 6-9: T_{ML} and T_{SL} are the mainlobe and sidelobe contributions to antenna temperature T'_A.

$$P = \int_{f_1}^{f_2} P_f \, df = A_r \Omega_s \int_{f_1}^{f_2} I_f \, df. \qquad (6.11)$$

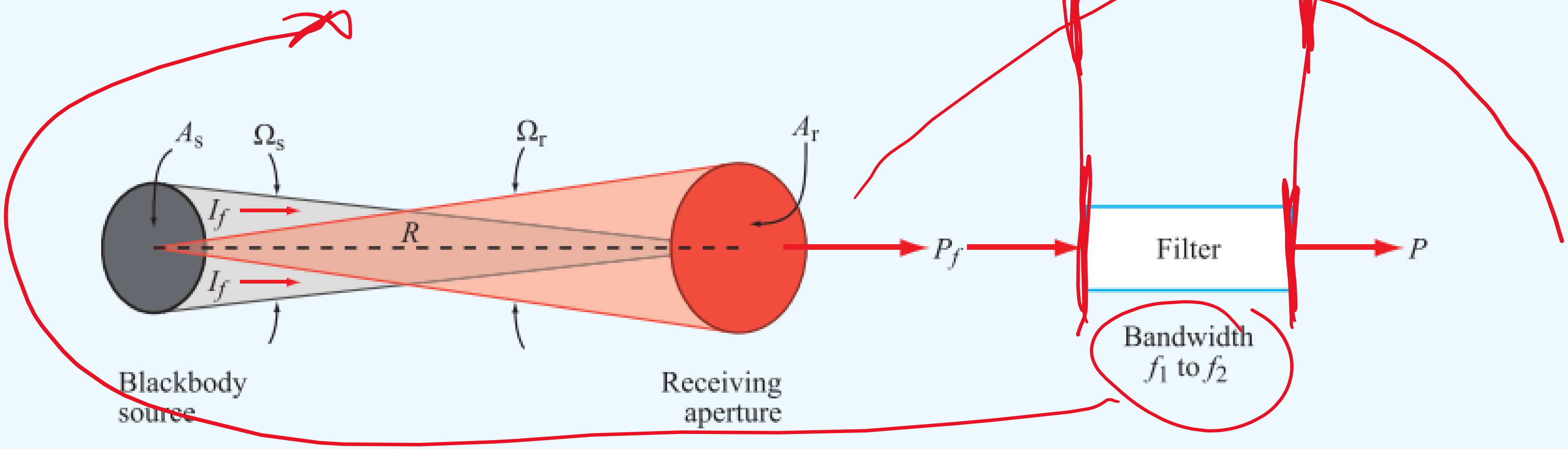


Figure 6-2: Geometry for power received from a blackbody source.

From: Microwave Radar and Radiometric Remote Sensing, by Ulaby and Long, 2014, with permission.

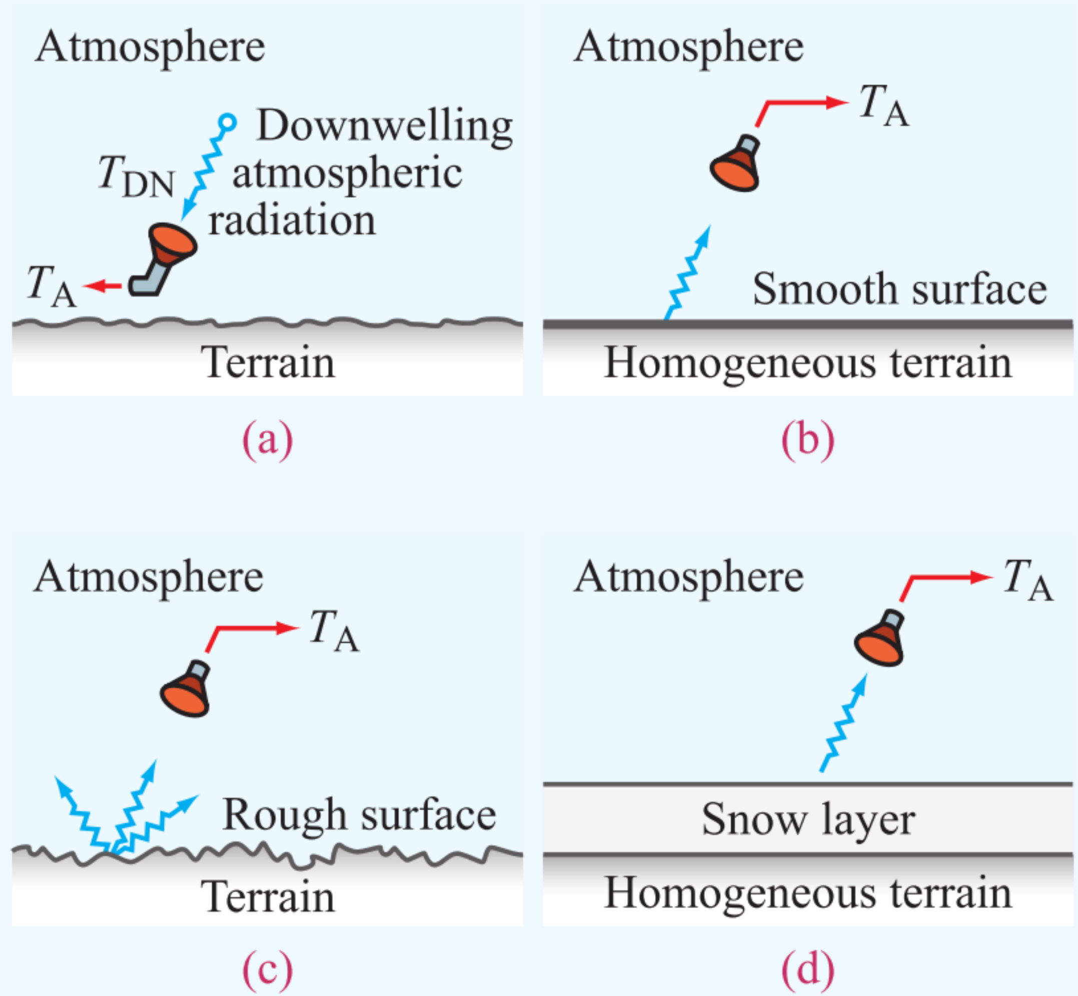
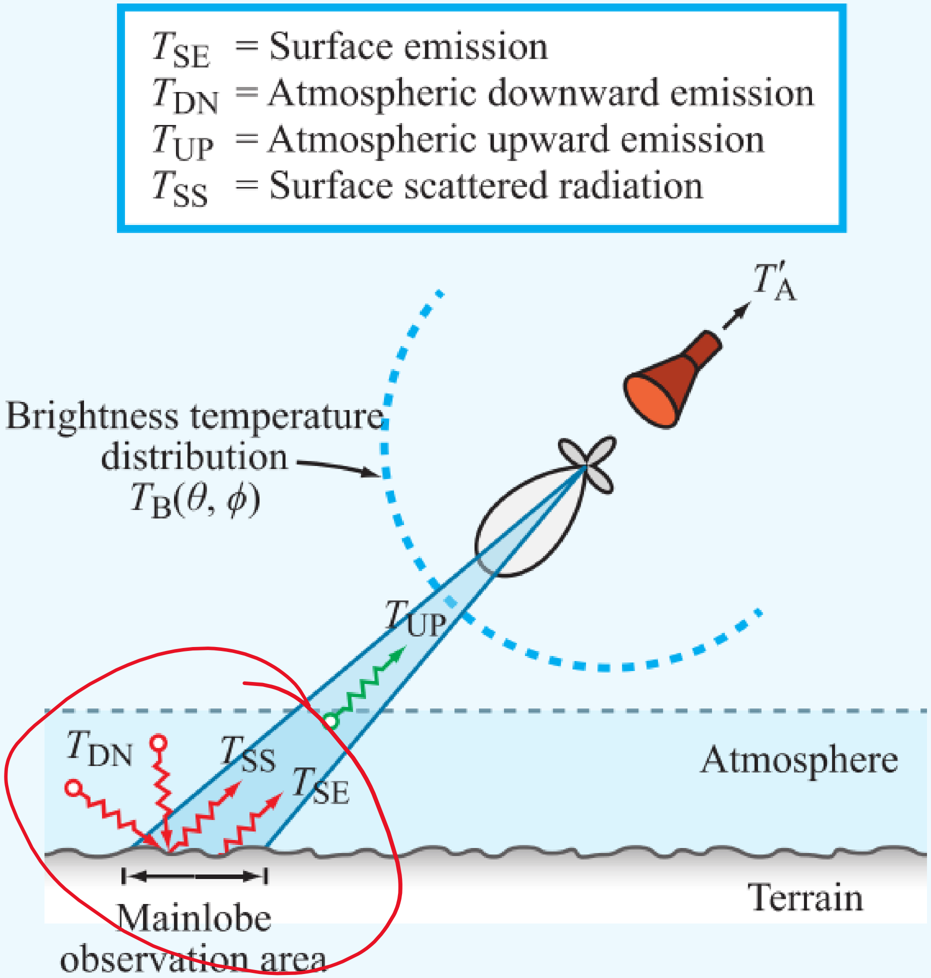
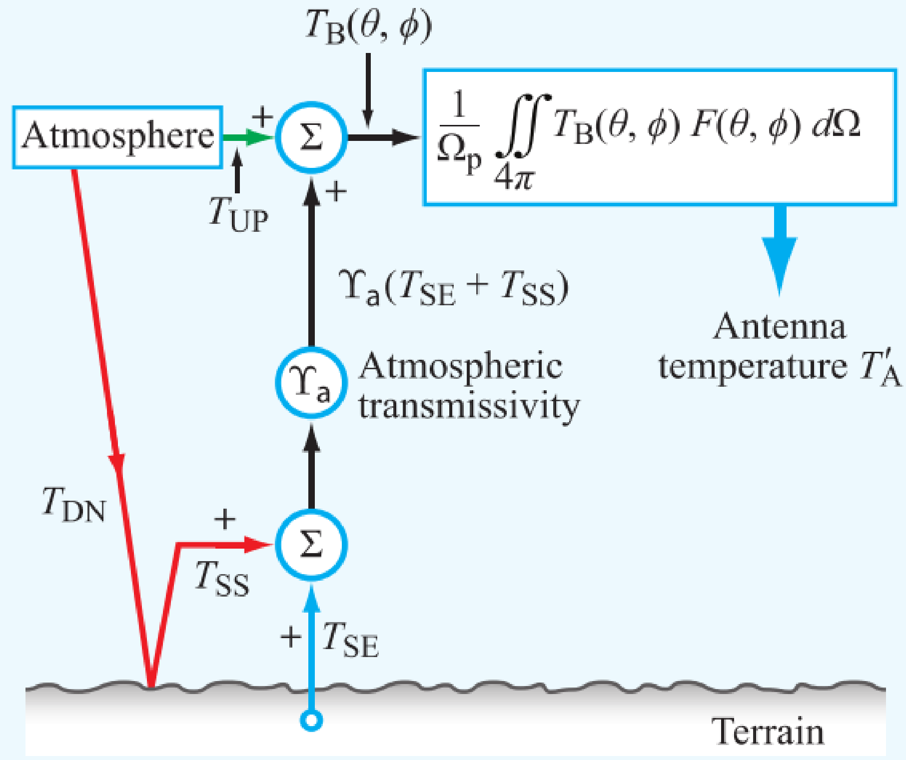


Figure 6-11: Examples of configurations of interest in radiometric remote sensing: (a) upward-looking radiometer, and downward-looking radiometer with (b) smooth-surface boundary, (c) rough-surface boundary, and (d) two-layer terrain.



(a) Emission by surface and atmosphere



(b) Block diagram

TB brightness temperature distribution

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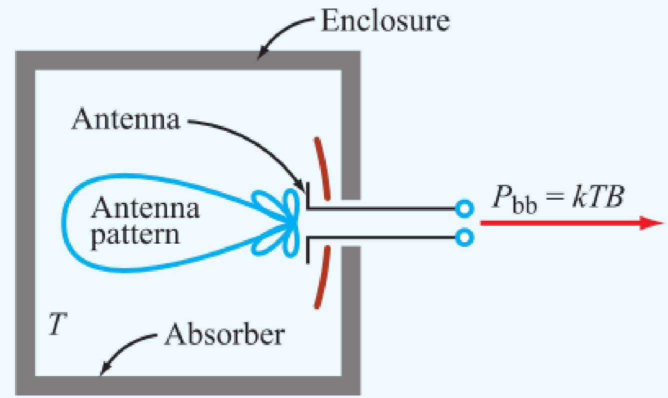
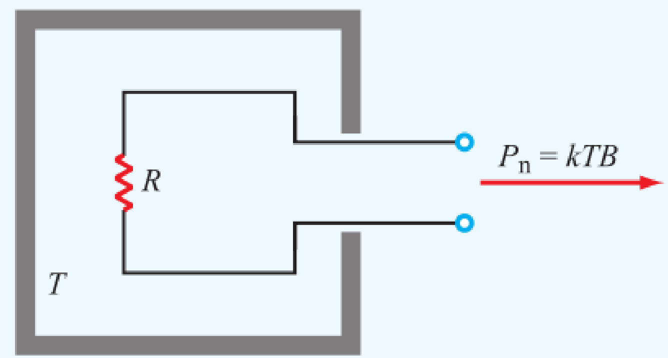
Radiometer system

Power and temperature equivalence

From the standpoint of an ideal receiver of bandwidth B, the antenna connected to its input terminals is equivalent to a resistance R_{rad}, called the antenna **radiation resistance**.



(a) Antenna inside a blackbody enclosure



(b) Resistor at temperature T

Figure 6-5: The power delivered by (a) an antenna placed inside a blackbody enclosure of temperature T is equal to the power delivered by (b) a resistor maintained at the same temperature.

Power received by an antenna

effective aperture — antenna pattern

$$dP_f = I_f A_r F(\theta,\phi)\, d\Omega. \qquad (6.15)$$

$$P = A_r \int_{f_1}^{f_2} \iint I_f\, F(\theta,\phi)\, d\Omega\, df, \qquad (6.16)$$

$$P = \frac{1}{2} A_r \int_{f_1}^{f_2} \iint_{4\pi} I_f\, F(\theta,\phi)\, d\Omega\, df. \qquad (6.17)$$

$$B = (f_2 - f_1)$$

(polarized antenna)

$$P_{bb} = kTB\, \frac{A_r}{\lambda^2} \iint_{4\pi} F(\theta,\phi)\, d\Omega. \qquad (6.19)$$

$$\Omega_p = \frac{\lambda^2}{A_r}$$

$$P_{bb} = kTB. \qquad (6.22)$$

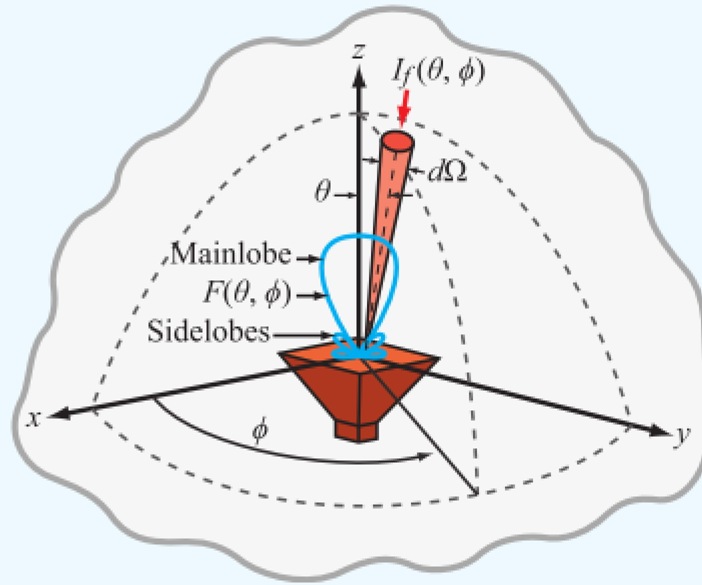


Figure 6-4: Blackbody spectral brightness I_f incident on an antenna with effective aperture A_r and radiation pattern $F(\theta,\phi)$.

Brightness temp and brightness intensity

Because of the one-to-one correspondence between the brightness temperature

$T_B(\theta,\varphi) \sim I(\theta,\varphi)$ *often* T_B *is used instead of intensity* I.

T_B means usually intensity!

$T_B(\theta,\varphi)$ *is called brightness temperature distribution.*

Simple Radiometer system

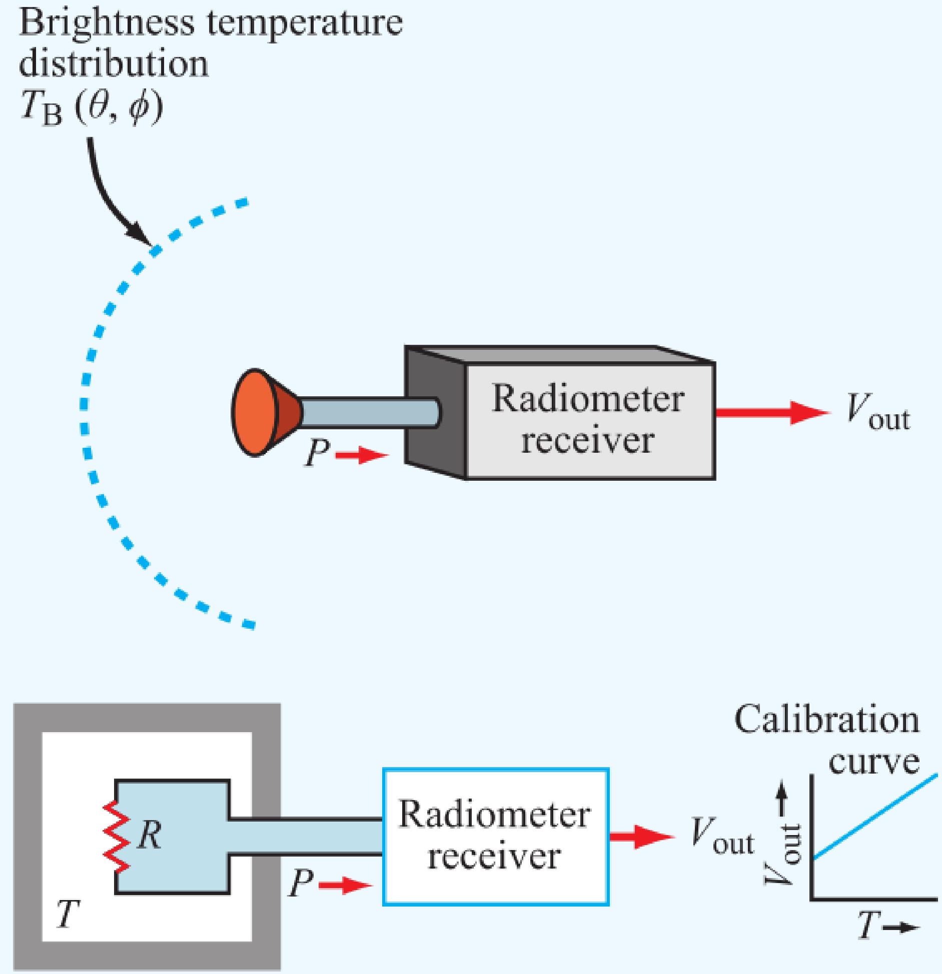
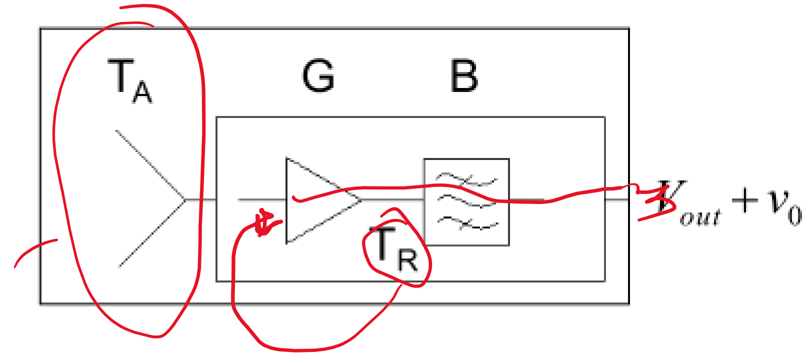


Figure 6-8: The power received by an antenna is equivalent to the noise power delivered by a matched resistor.

Generic radiometer system

The radiometer -

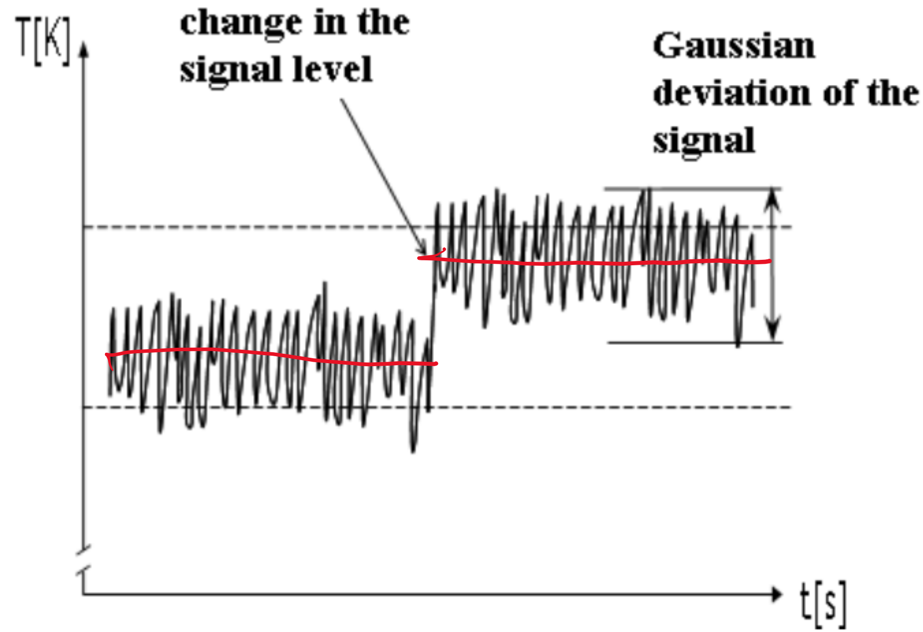
- antenna collects radiation from the target
- amplifies (*G*=gain) and filters (*B*=bandwidth) the collected signal
- detects the signal intensity, i.e. the noise power coming from the antenna.



$$V_{out} = k \cdot G \cdot T_{SYS} \cdot B + v_0 = k \cdot G \cdot (T_A + T_R) \cdot B + v_0$$

Measured signal is thermal noise

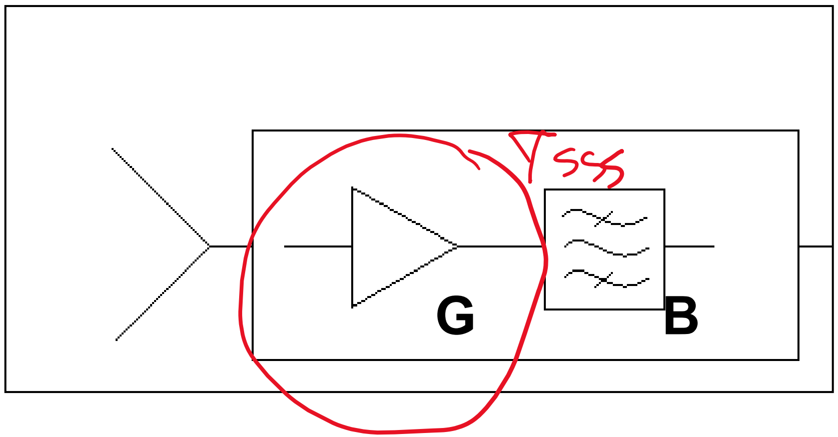
- ✓ The measured signal is electromagnetic noise, i.e. it's a composition of all the possible polarizations and phase states.
- ✓ Measurement of a noisy signal is noisy, i.e. inaccurate. Averaging of the result helps.



Signal is weak

- As predicted by Planck's law, level of the measured signal is **LOW** (10^{-13} – 10^{-14} Watts. Also, bandwidths reserved for passive use are reasonably narrow.
- In order to detect the incoming power high gain is required.
- High gain causes problems like crosstalk, coupling, thermal instability etc..

$$V_{out} = k \cdot G \cdot T_{SYS} \cdot B$$

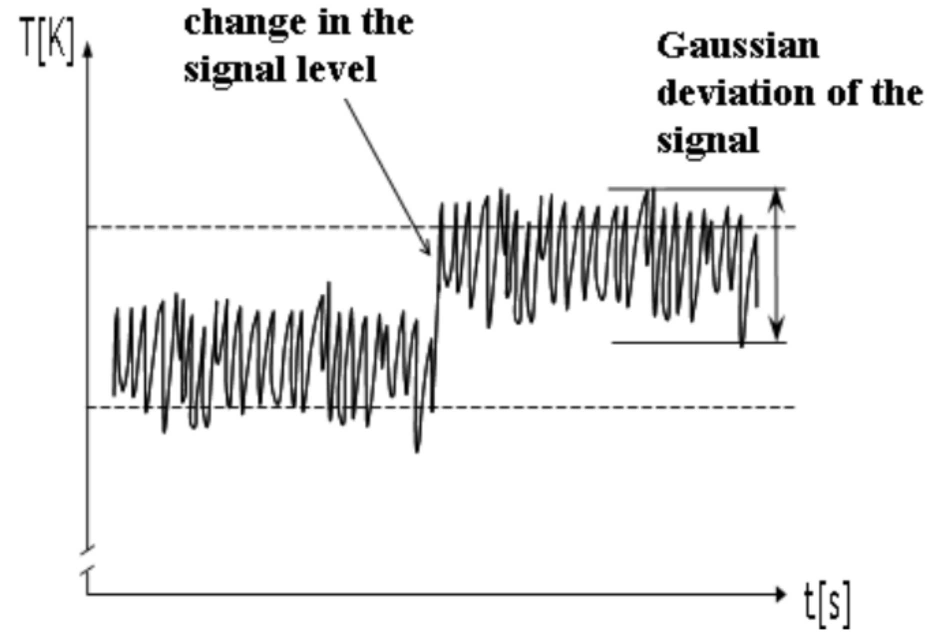


Measurement accuracy

✓ **The best accuracy which can be achieved by a measurement of a radiometer is called Radiometric Resolution:**

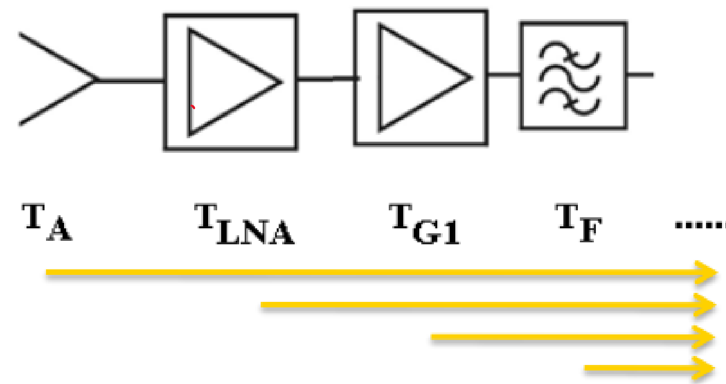
$$\Delta T = C \frac{T_{SYS}}{\sqrt{B\tau}}$$

T_{SYS}	system temperature
B	bandwidth
τ	integration time
C	Constant depending on receiver type



Receiver generates and amplifies it's own noise as well!

- ✓ As predicted by Planck's law, also all electrical components create noise.
- ✓ This noise mixes with the noise from the antenna. In order to solve the noise from antenna, receiver's own noise needs to be characterized.
- ✓ Receivers equivalent noise temperature TR reduces all the noise components to the input of the receiver.



$$T_R = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \ldots$$

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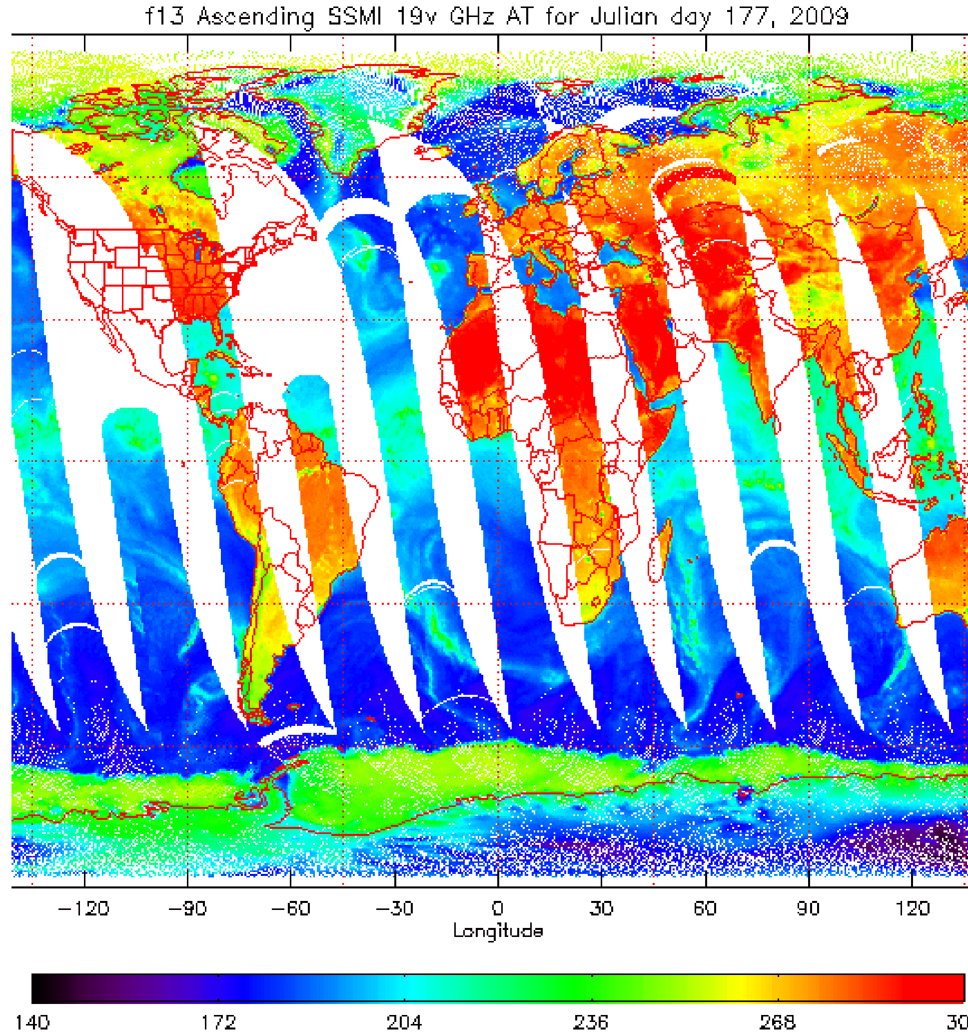
Radiometer systems types

Chapter 7 in the course book

Image by SSMI radiometer



Radiometers

Noise-injection radiometer

Dicke-type radiometer

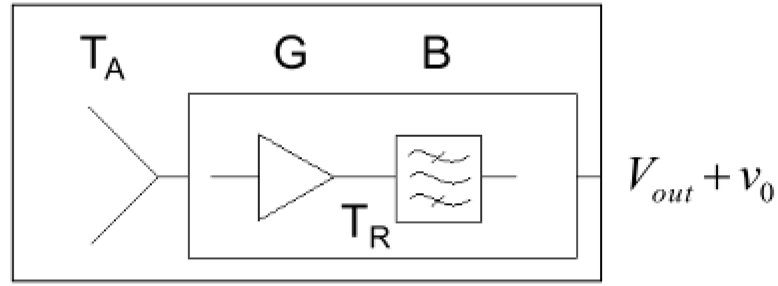
Total power radiometer

Complexity, performance, price, etc. increases

Simple radiometer

The radiometer -

- antenna collects radiation from the target
- amplifies (G=gain) and filters (B=bandwidth) the collected signal
- detects the signal intensity, i.e. the noise power coming from the antenna.



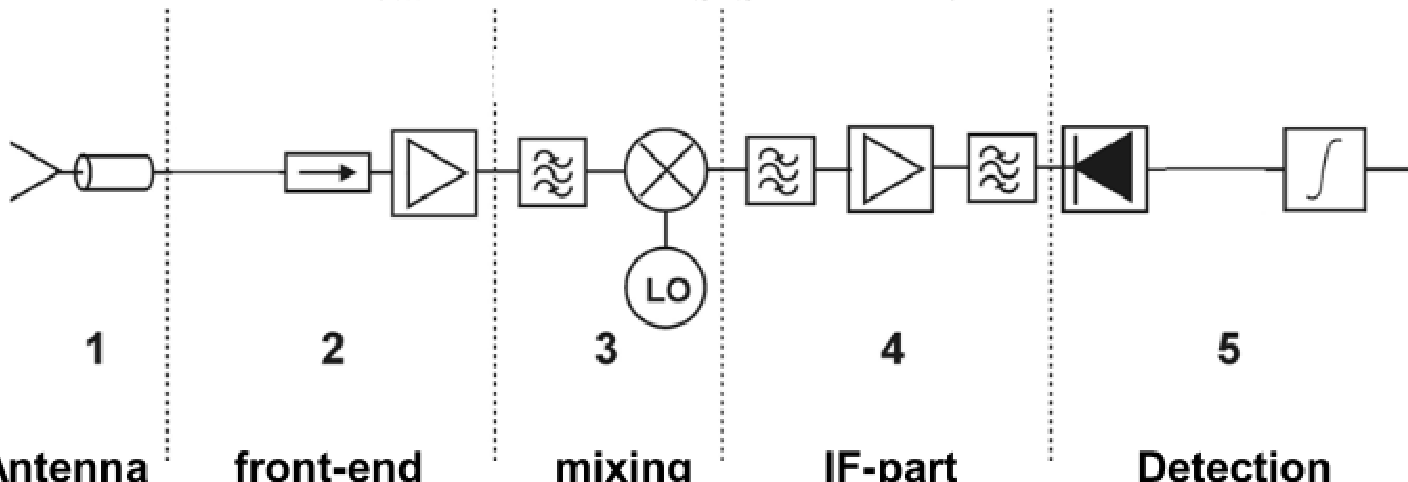
$T_{RECEIVER} = T_{SYS}$

$$V_{out} = k \cdot G \cdot T_{SYS} \cdot B + v_0 = k \cdot G \cdot (T_A + T_R) \cdot B + v_0$$

Total power radiometer

The name emerges from the fact that the receiver simply detects the total power that is propagated through the receiver chain.

$$V_{out} = k \cdot G \cdot T_{SYS} \cdot B + v_0$$



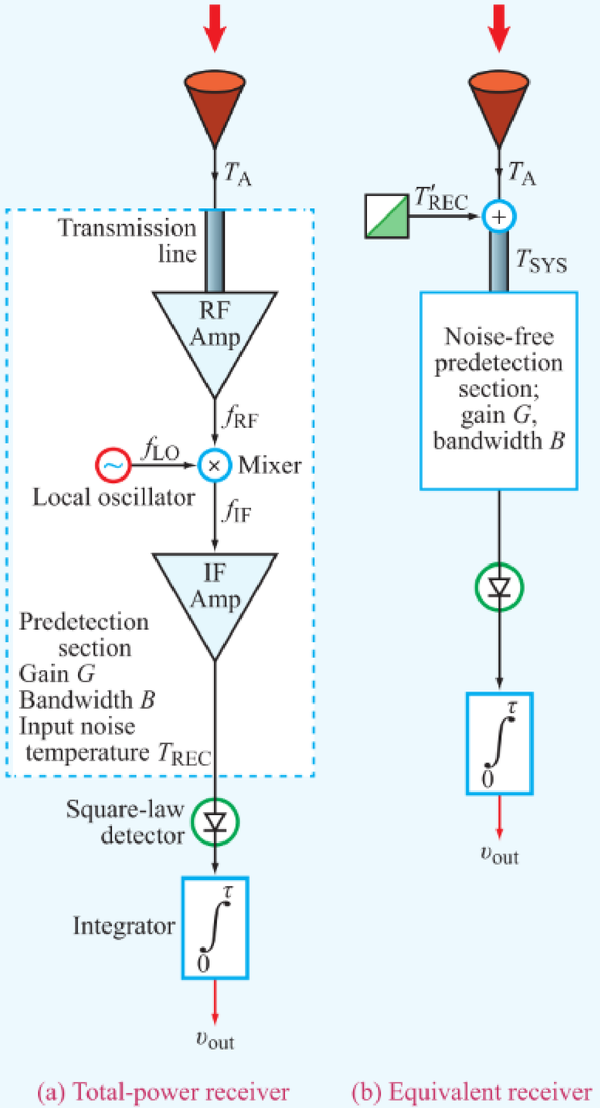


Figure 7-13: The representation in (b) replaces the predetection section with a noise-free equivalent and refers the receiver noise to the antenna terminals.

From: Microwave Radar and Radiometric Remote Sensing, by Ulaby and Long, 2014, with permission.

Total power radiometer

$$V_{out} = k \cdot G \cdot (T_R + T_A) \cdot B + v_0 \quad \Leftrightarrow \quad T_A = \frac{V_{out} - v_0}{kGB} - T_R$$

- In order to calculate T_A from the detected output voltage V_{out}, one needs to know G, B, v_0, and T_R.
- Solving of these by some means is called **RADIOMETER CALIBRATION**, and accuracy of it determines the accuracy of the radiometer. This, because error in any of the parameters propagetes directly to the error of T_A.
- Radiometric resolution of the total power radiometer is (C=1):

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

Typically e.g.:

T_{SYS}=600 K;
B = 20 MHz;
τ = 1s

$$\Delta T \approx 0.13K$$

Total power radiometer

$$V_{out} = k \cdot G \cdot (T_R + T_A) \cdot B + v_0 \quad \Leftrightarrow \quad T_A = \frac{V_{out} - v_0}{kGB} - T_R$$

- In practice, the gain (and T_R) is the most unstable parameter in radiometers. Changes in gain propagate to errors in T_A. In the case of a total power radiometer this influences T_{SYS}:

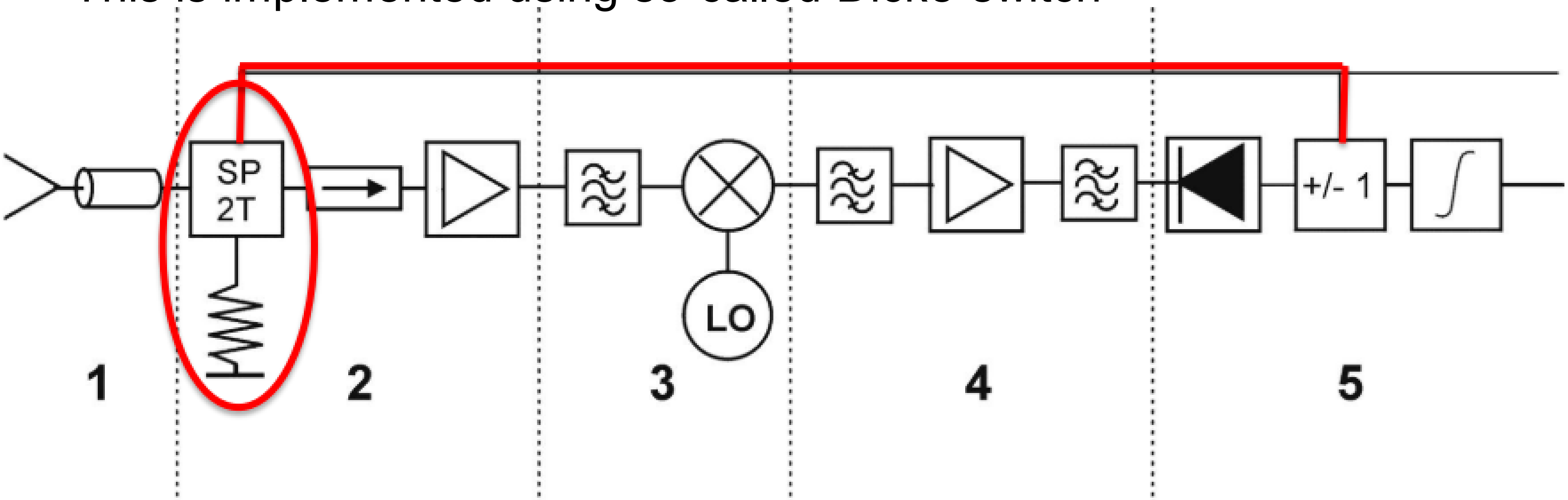
$$\Delta T_A = -\frac{V_{out} - v_0}{kG^2 B} \Delta G = -\frac{V_{out} - v_0}{kGB} \frac{\Delta G}{G} = T_{SYS} \frac{\Delta G}{G}$$

e.g. 600 K

- Typically $\Delta G/G \approx 10^{-2}..10^{-3}$, so, $\Delta T_A \approx <10$K.. This dominates the radiometric resolution. This is the weakness of total power radiometers.

Dicke Radiometer

- Dicke Radiometer measures the antenna the first half of the integration period, and a reference load for the second half.
- This is implemented using so-called Dicke-switch

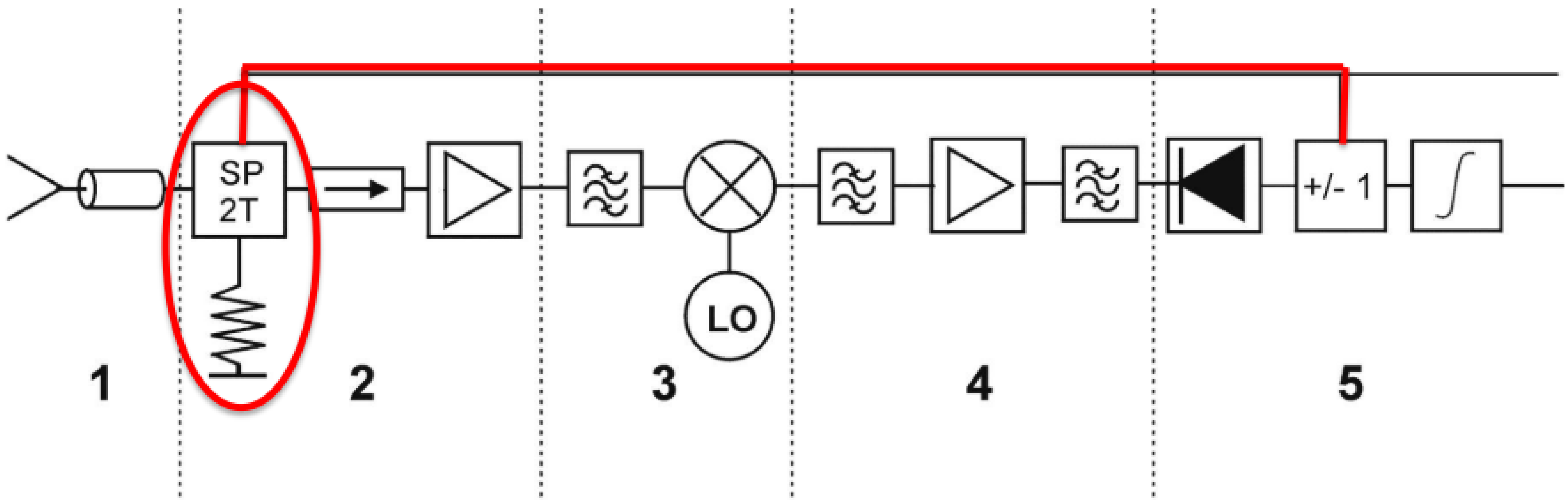


Dicke Radiometer

$$V_{out} = V_{out\_T_D} - V_{out\_T_A}$$

$$V_{out\_T_A} = kBG(T_R + T_A) + v_0$$

$$V_{out\_T_D} = kBG(T_R + T_D) + v_0$$



Dicke Radiometer

$$V_{out} = kBG(T_D - T_A) \quad \Leftrightarrow \quad T_A = T_D - \frac{V_{out}}{kGB}$$

- Solving the antenna temperature from this doesn't require calibration of receiver noise temperature TR or voltage offset v0.
- Radiometric resolution of Dicke radiometer is decreased, since the antenna is measured only half of the integration period (C=2):

$$\Delta T = \frac{2 \cdot T_{SYS}}{\sqrt{B\tau}}$$

$$\Delta T_A = \frac{V_{out}}{kG^2 B}\Delta G = -\frac{V_{out}}{kGB}\frac{\Delta G}{G} = (T_A - T_D)\frac{\Delta G}{G}$$

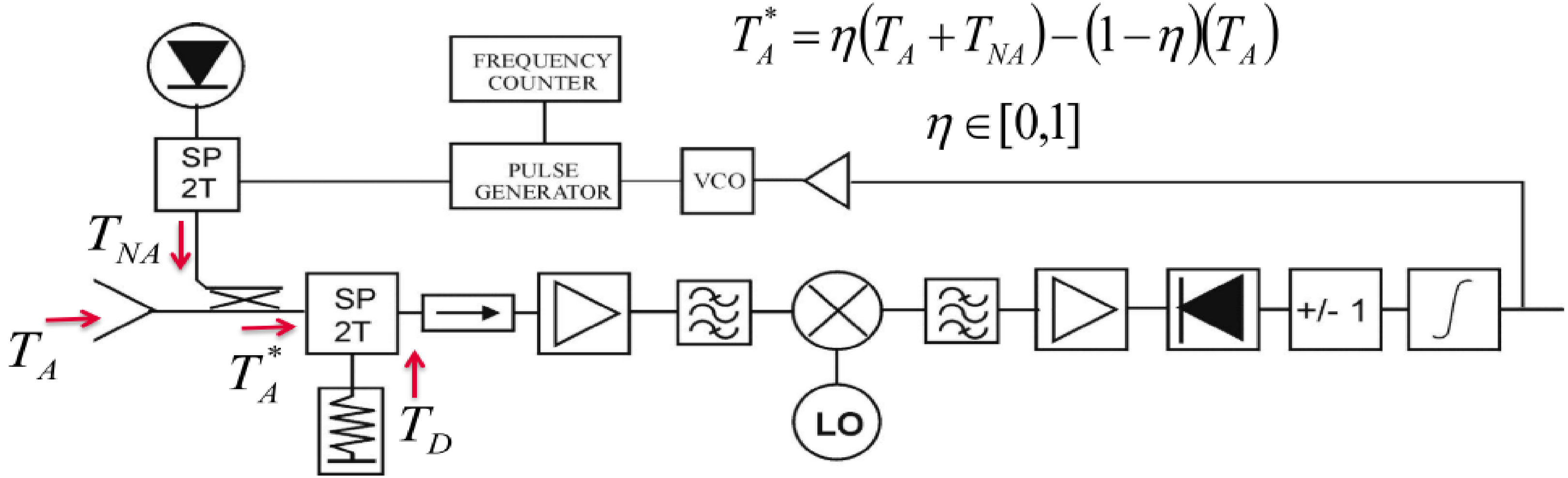
Balanced Dicke Radiometer (noise injection radiometer)

- A Dicke radiometer with additional noise diode circuitry, from which an additional noise pulse is coupled into the antenna branch at each integration period
- The length *η* of the injected noise pulse is controlled by a feedback loop so, that the power from antenna branch equals to the noise power from the reference load.

$$V_{out} = V_{out\_T_D} - V_{out\_T_A} = kBG(T_D - T_A^*) = 0$$

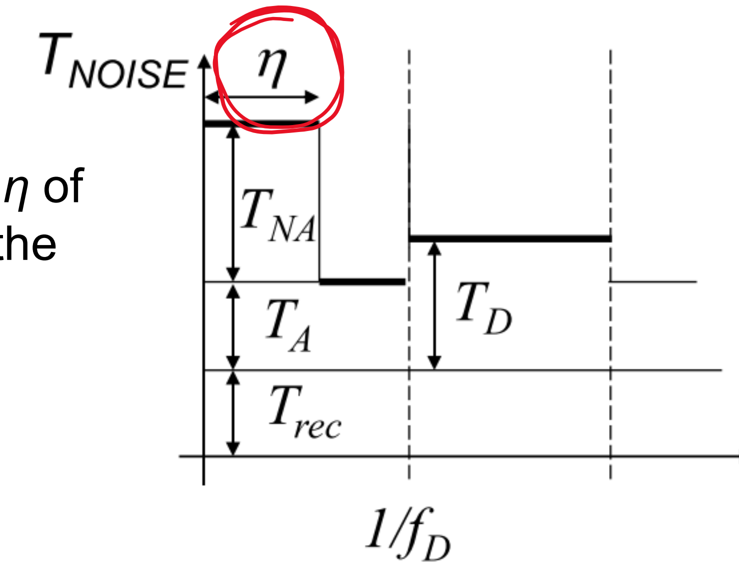
$$T_A^* = \eta(T_A + T_{NA}) - (1-\eta)(T_A)$$

$$\eta \in [0,1]$$



Balanced Dicke Radiometer (noise injection radiometer)

- One integration period of a noise injection radiometer:
- $V_{out}=0$ by definition
- The actual measurement result is the length η of the injected pulse that is needed to balance the powers.



$$T_D = \eta(T_{NA} + T_A) + (1-\eta)T_A$$

$$T_A = T_D - \eta T_{NA}$$

Balanced Dicke Radiometer (noise injection radiometer)

$$T_A = T_D - \eta T_{NA}$$

- Measurement of noise injection radiometer is not depending on Gain, bandwidth, of receiver noise temperature calibration.
- The only variable that needs calibration is the noise power of the noise injection circuitry, T_{NA}.
- Radiometric resolution is constant, (i.e. Independent on target):

$$\Delta T_A \approx \frac{2 \cdot \left(T_{ref} + T_{rec}\right)}{\sqrt{B\tau}}$$

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Calibration of a radiometer

Radiometer calibration

- Calibration means determination of instrument's parameters so that the calculation of the main observable becomes possible:

TOTAL POWER RADIOMETER:

$$T_A = \frac{V_{out} - v_0}{kGB} - T_R$$

$$G; B; T_R; v_0$$

DICKE RADIOMETER

$$T_A = T_D - \frac{V_{out}}{kGB}$$

$$G; B$$

NOISE INJECTION RADIOMETER

$$T_A = T_D - \eta T_{NA}$$

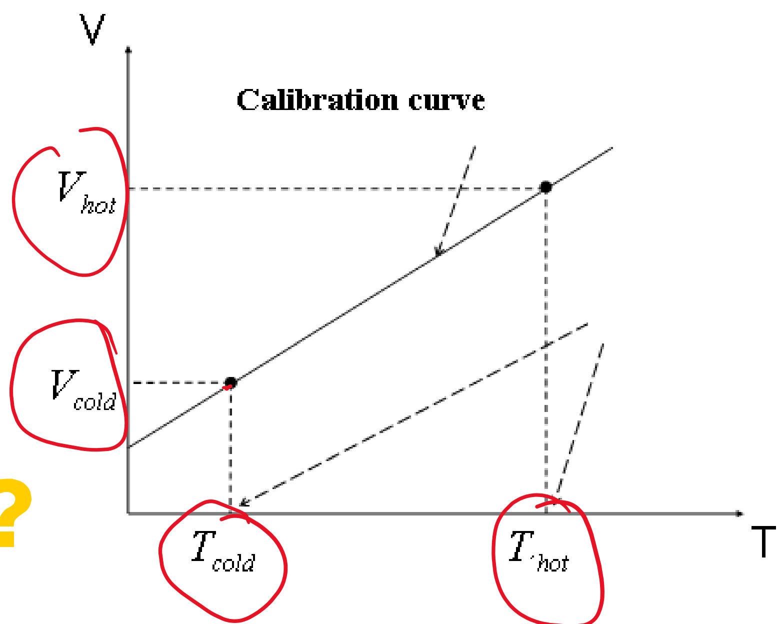
$$T_{NA}$$

Calibrating with two known temperatures

- Total power and Dicke radiometers require calibration of receiver's G and B.
- Linear model with A and B
- Requires measurements of two known targets.
- Neglects the voltage offset

$$T_A = \frac{Vout}{kGB} - T_R$$

$$T_A = AV + B$$



$$\begin{cases} T_{hot} = \dfrac{V_{hot}}{kGB} - T_R \\ T_{cold} = \dfrac{V_{cold}}{kGB} - T_R \end{cases}$$

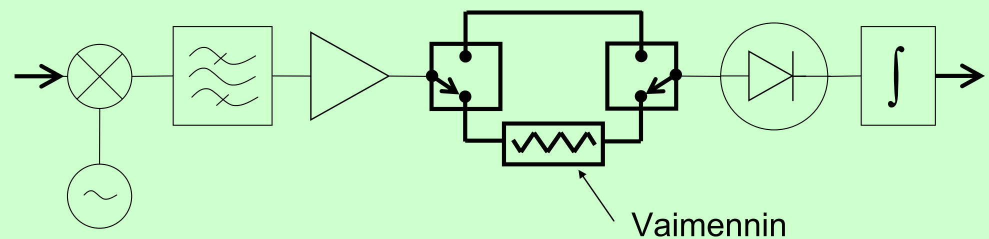
$$A = \frac{T_{hot} - T_{cold}}{V_{hot} - V_{cold}}$$

$$B = \frac{T_{cold}V_{hot} - T_{hot}V_{cold}}{V_{hot} - V_{cold}}$$

A?

Four point calibration

- Utilizes a tunable attenuator at IF
- Compensates for voltage offset v_0



- Four measurements altogether: Two known sources with two IF attenuator values

→ Gain and offset are retrieved without the knowledge of the absolute values of the known temperatures (only the difference matters)!

$$V_1 = V_{off} + G(T_{cold} + T_{rec})$$

$$V_2 = V_{off} + G(T_{hot} + T_{rec})$$

$$V_3 = V_{off} + \frac{G}{L}(T_{cold} + T_{rec})$$

$$V_4 = V_{off} + \frac{G}{L}(T_{hot} + T_{rec})$$

$$V_{off} = \frac{V_2V_3 - V_1V_4}{(V_2 - V_4) - (V_1 - V_3)}$$

$$G = \frac{V_2 - V_1}{T_{hot} - T_{cold}}$$

$$T_{rec} = \frac{aT_{cold} - T_{hot}}{1 - a}, \quad a = \frac{V_2 - V_{off}}{V_1 - V_{off}}$$

$$T'_{rec} = \frac{YT_{cold} - T_{hot}}{1 - Y}, \quad Y = \frac{V_2}{V_1}$$

Calibration of noise injection radiometer

$$T_A = T_D - \eta T_{NA} \qquad\qquad T_{NA}$$

➢Only one unknown: only one calibration target ($T_{A,KNOWN}$) required

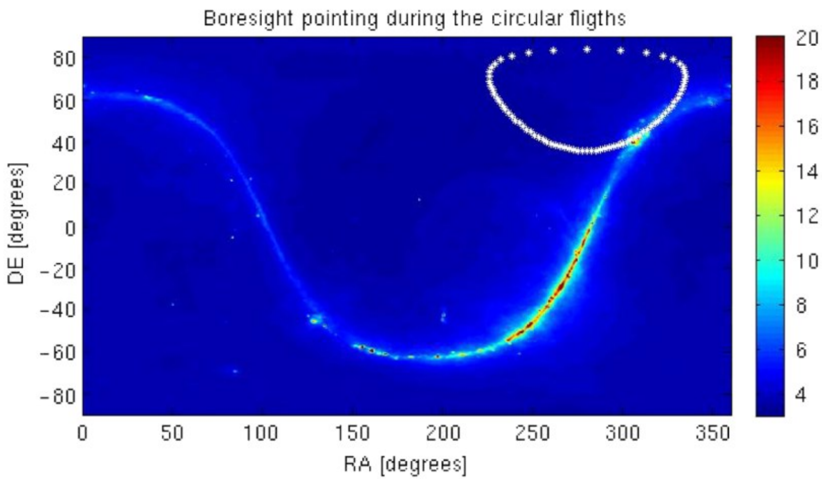
→
$$T_{NA} = \frac{T_D - T_{A,KNOWN}}{\eta}$$

➢In practice, the stability of T_{NA} (with respect to time/temperature/linearity) becomes a dominant factor.

Radiometer calibration
Calibration sources

Through the antenna:

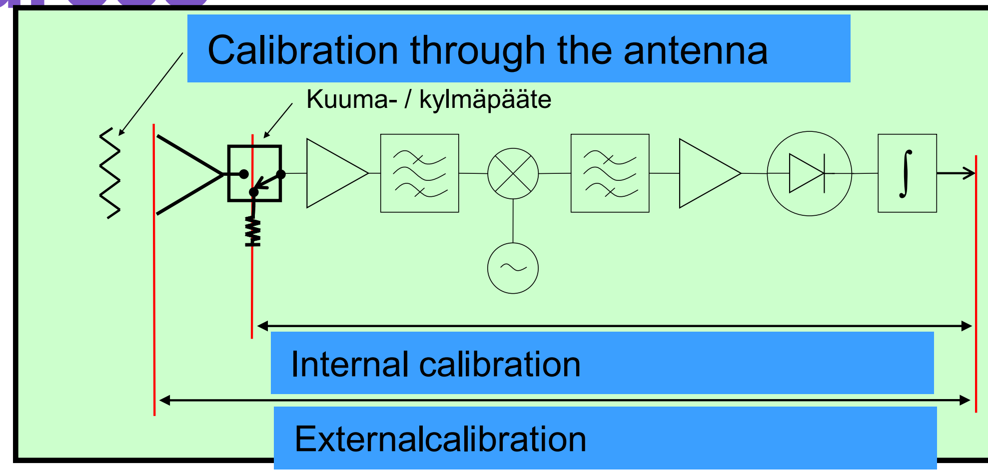
- ➢**High absorption materials (e~1)**
- ➢**Liquid Nitrogen cooling**
- ➢**Cky (CMB+atmoshphere)**
- ➢**Water**

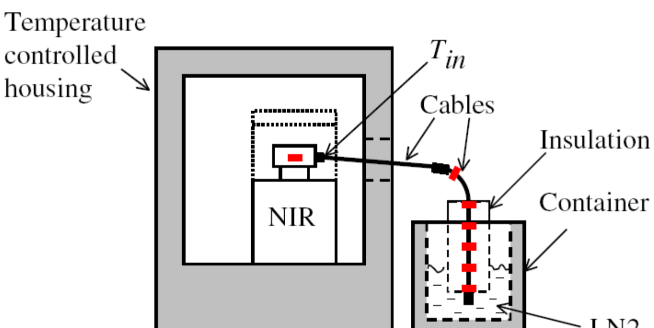


Radiometer calibration
Calibration sources

Without the antenna:

- ➢ **Terminated loads**
- ➢ **Active loads (cool or hot)**
- ➢ **Liquid nitrogen cooling**





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Radiometer measurement

$$T_B(\theta) = e(\theta, \varepsilon, \mu, \lambda) T_{fys}$$

For homogeneous target brightness temperature

$e(\theta)$ = emissivity, $0 \le e \le 1$
T_{fys} = target physical temperature (K)
θ = incidence angle off nadir

Radiometer measured temp called antenna temperatutre T_A

$$T_A = \frac{\iint_{4\pi} T_B(\theta,\phi) F_n(\theta,\phi) d\Omega}{\iint_{4\pi} F_n(\theta,\phi) d\Omega}$$

F_n = normalized antenna power pattern (value between 0 and 1)

Calibration the entire system

Measure a target with radiometer => antenna effects are included in calibration

Method 1: Measure with radiometer so called calibration targets

- Absorbing material, whose emissivity = 1 ("blackbody")
  - *Then brightness temperature = physical temperature*
- Use two calibration targets
  - *Hot load: high brightness temperature (T_B ~ 290 K)*
  - *Cold load: low brightness temperature (T_B < 100 K)*

  =>If radiometer is linear, region 100...290 K is calibrated

Method 2: Measure with radiometer natural targets, whose T_B at desired frequencies, polarizations and incidence angles is known

- Calm water surface: T_B can be calculated accurately
- Sky (no clouds, normal humidity, avoiding known radio emitters)
- This approach is only used as an additional method to make sure that calibration based on Method 1 is OK

Fundamental restrictions

Reveiver

- The amount of radiation collected by the antenna is **VERY small in powers** (typically in the order of 10^{-13} – 10^{-14} Watts). In order to detect the signal level amplification is needed.
- Typically, square-law detectors are used. (Output voltage is linear with input noise power)
- The bandwidth under measurement must be well known for the sake of

  1) Power control

  2) Frequency regulations

  3) Interference control

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Antennas and scanning

Chapter 6 in the course book

SMOS antenna

Antenna properties

Beam Efficiency – main lobe related to side lobe

$$\eta_b = \frac{\Omega_m}{\Omega_p} \, .$$

Radiation Efficiency – how much losses are in antenna

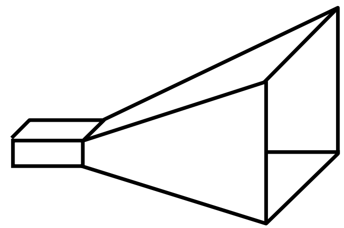
$$T_A = \xi \eta_b T_{ML} + \xi (1 - \eta_b) T_{SL} + (1 - \xi) T_0 .$$

Used antenna types

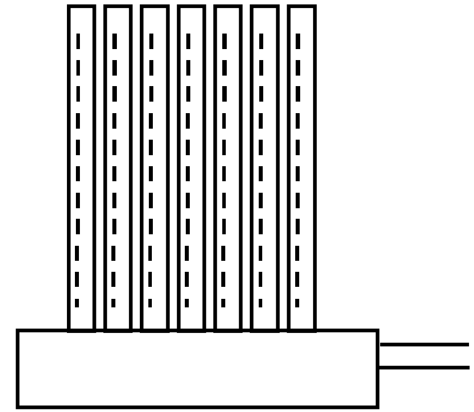
Horn antenna: Often used onboard satellite as feed antenna for a paraboloid antenna

Phased array: Many elements, each equipped with a phase shifter => narrow beam, scanning antenna

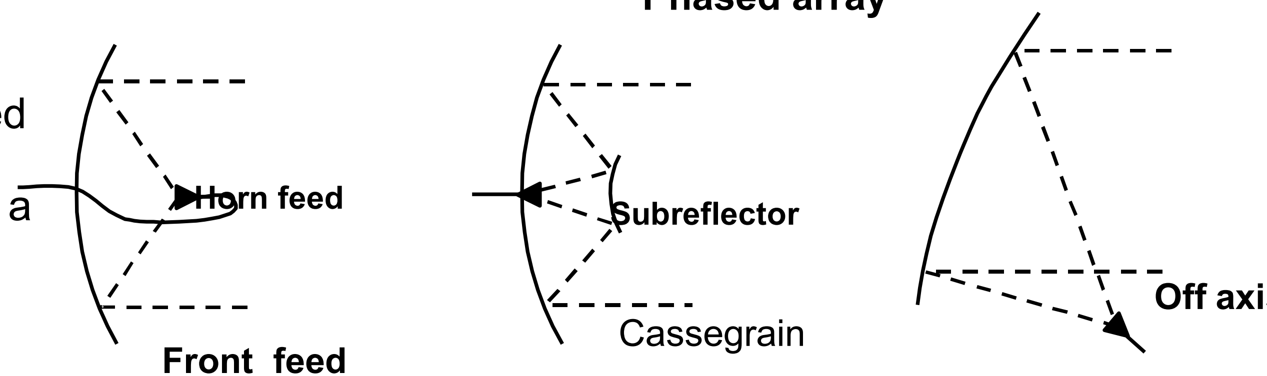
Paraboloid: Cassegrain feed mostly used (good cross-polarization properties with a corrugated horn)



Horn antenna

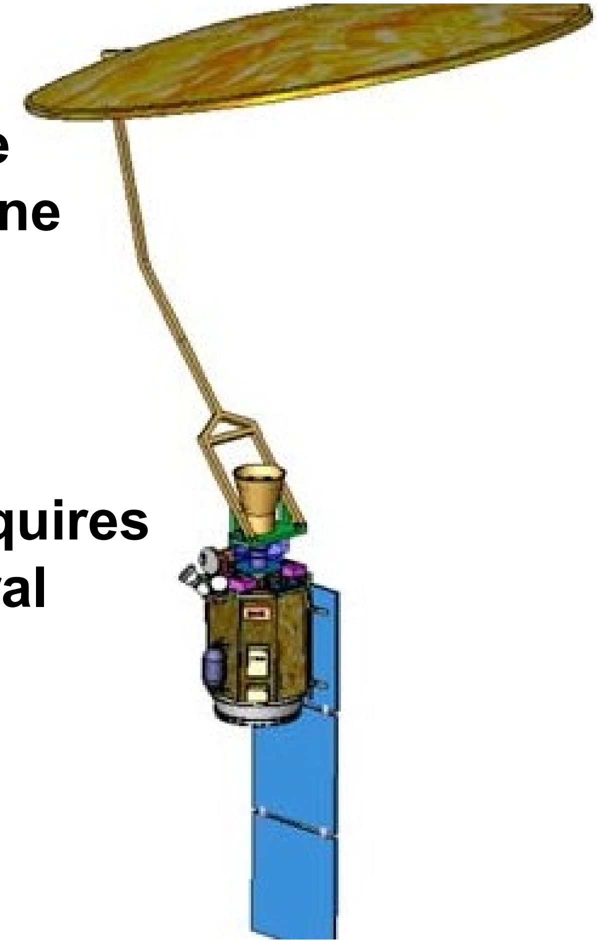


Phased array



Paraboloid antennas with various feed systems

Antenna opening angle and resolution



Opening angle of the antenna determines the angular resolution. For parabolic antennas one can estimate:

$$\theta_{3dB} \approx 1.4 \frac{\lambda}{D}$$

At microwaves, even mediocre resolution requires antennas in size of tens centimeters to several meters!

How to form an image?

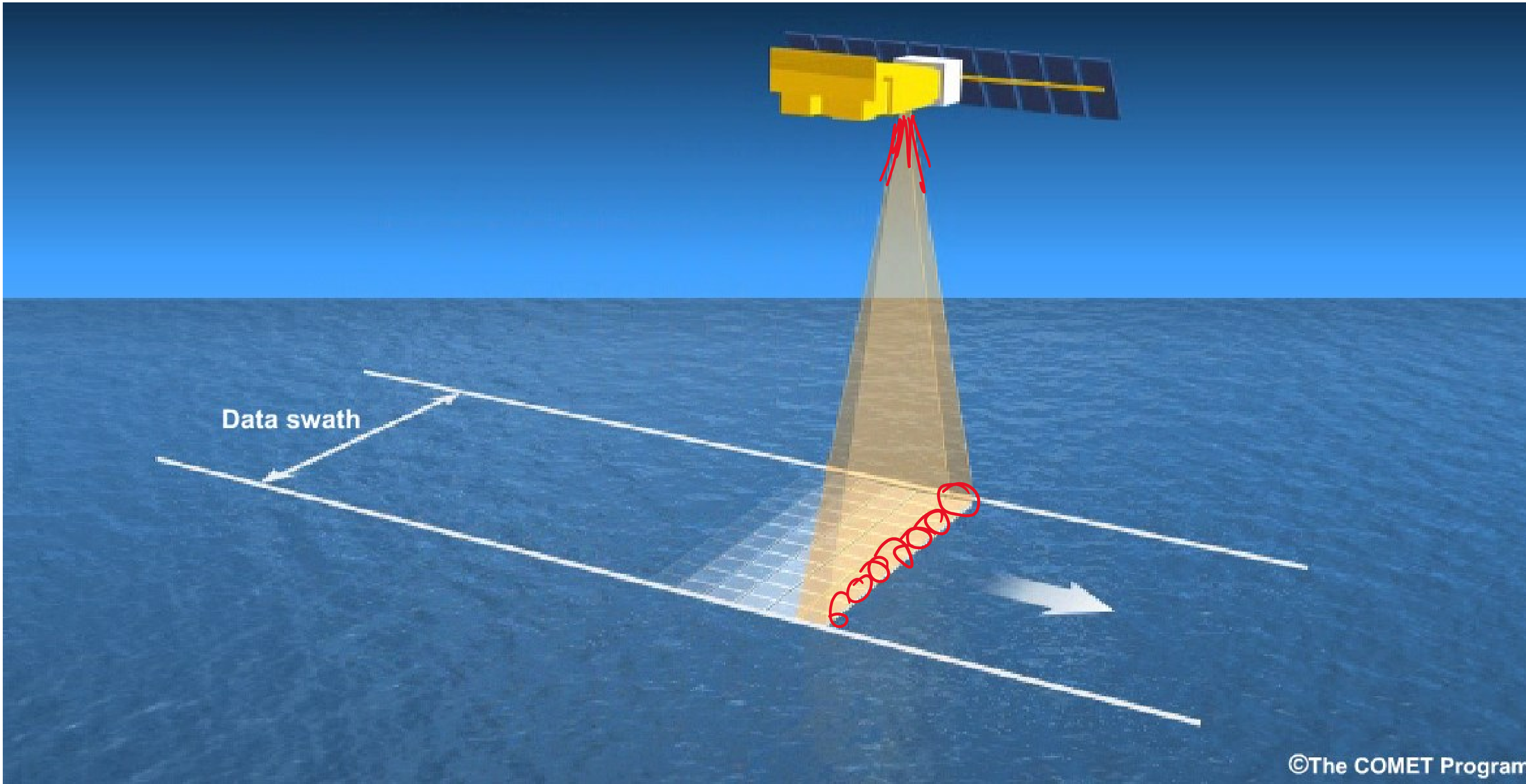
Scanning methods in satellite radiometry

- **Conical scanning**: antenna moves as along the surface of a cone, eg. at 50° incidence angle off nadir

- **Pushbroom techniques**: several antennas producing beams next to each other either along flight direction or perpendicular to it
  - *Several receivers*

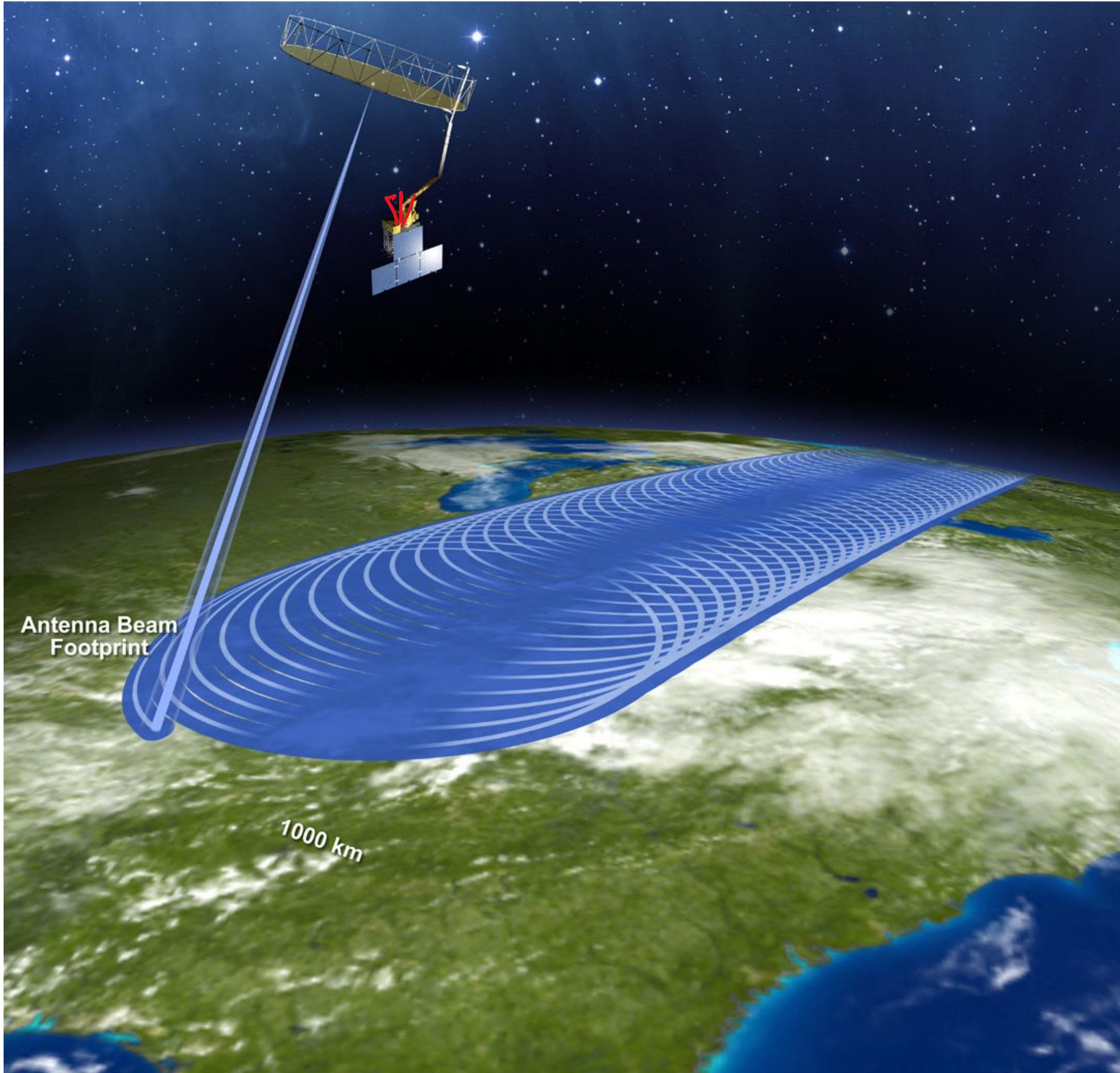
- **Interferometry**: Image formation without mechanical/electrical scanning by correlating outputs from all antenna pairs
  - *Several antennas with individual receivers (several receivers)*

Pushbroom scanning



Conical scanning

SMAP



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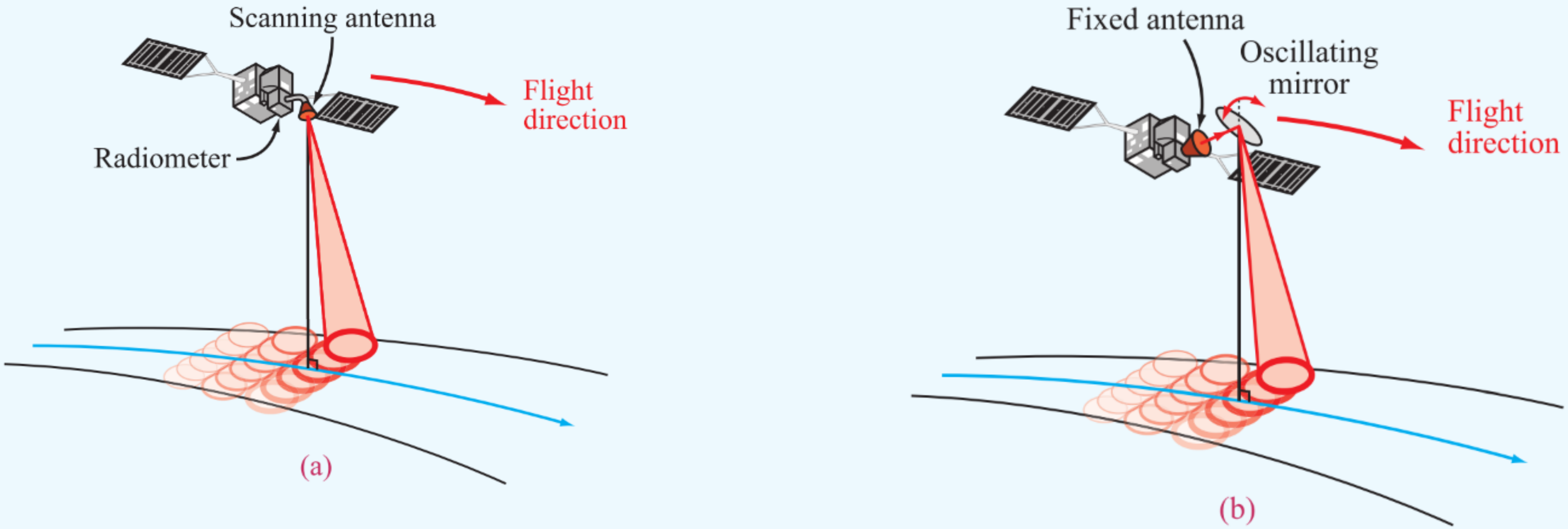


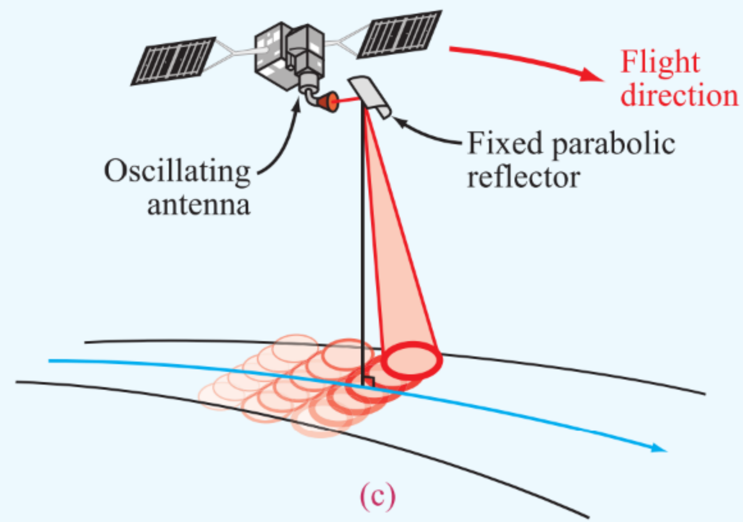


Figure 7-31: Mechanical scanning configurations: (a) scanning antenna; (b) fixed antenna and oscillating reflector; (c) fixed parabolic reflector and oscillating antenna feed.

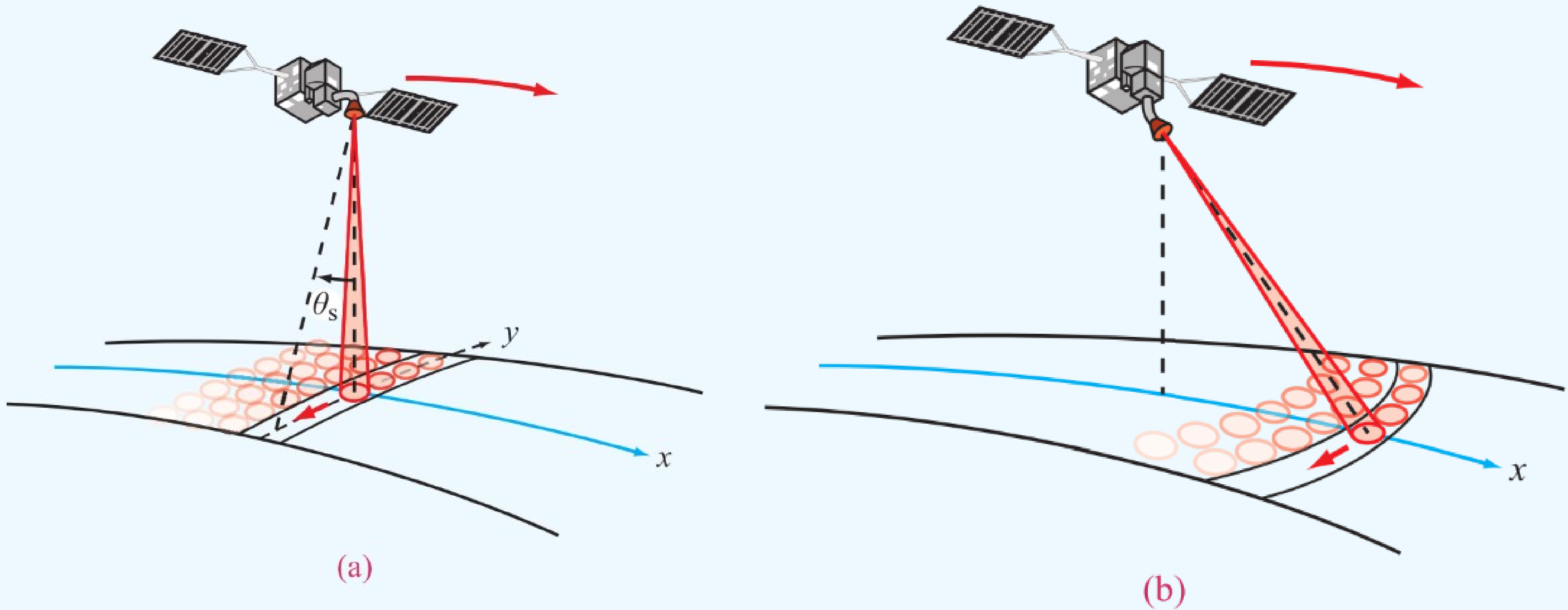
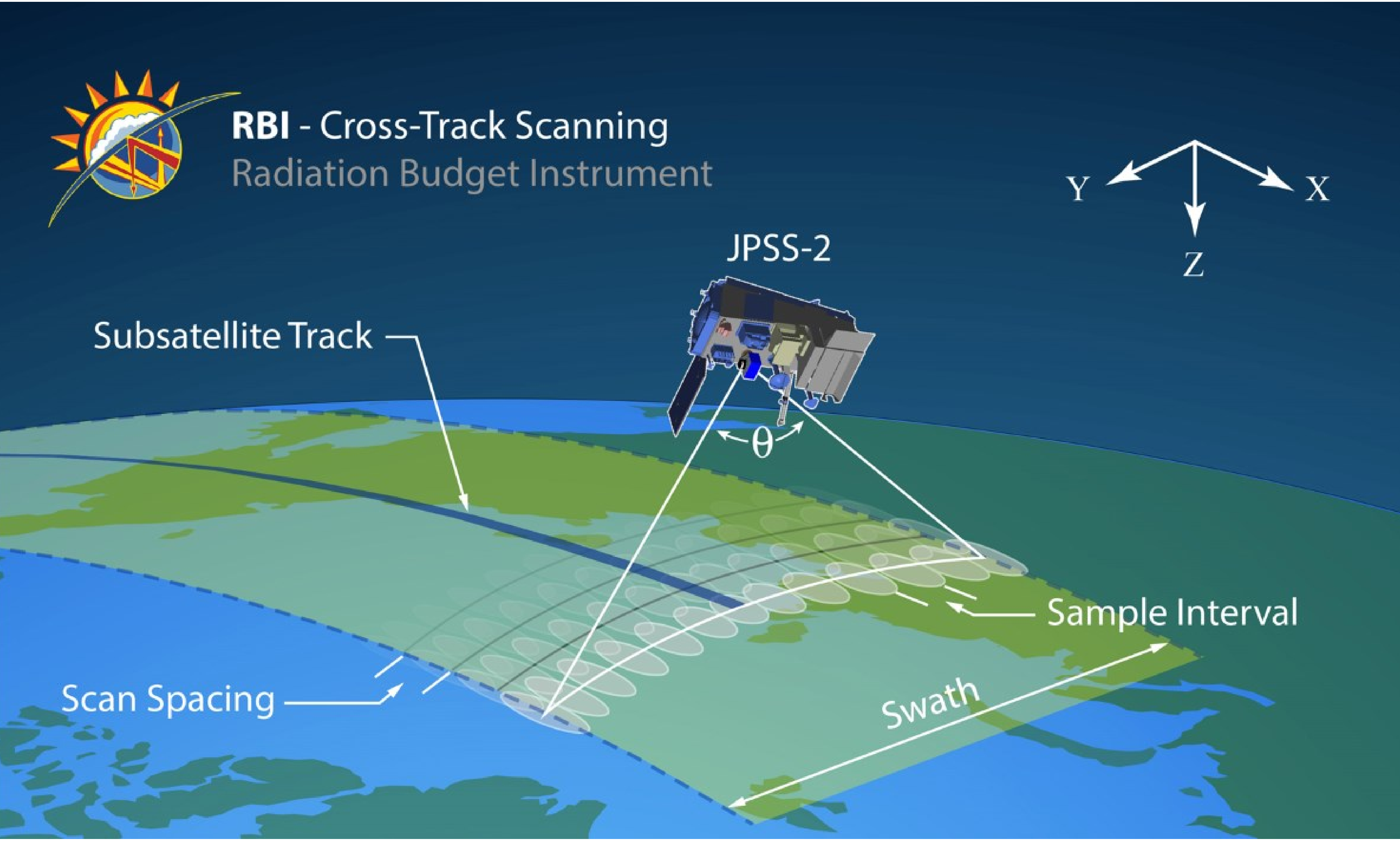
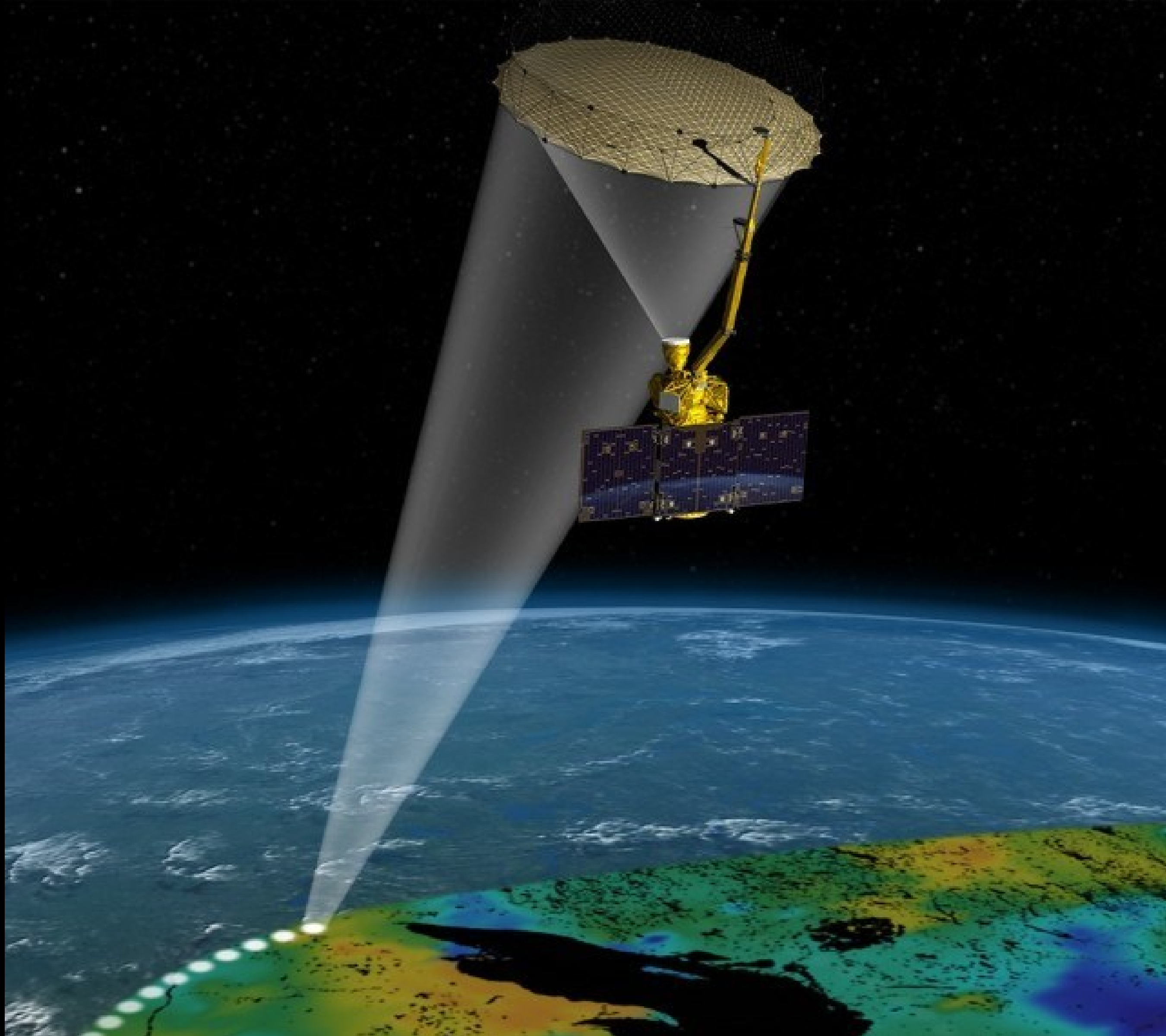
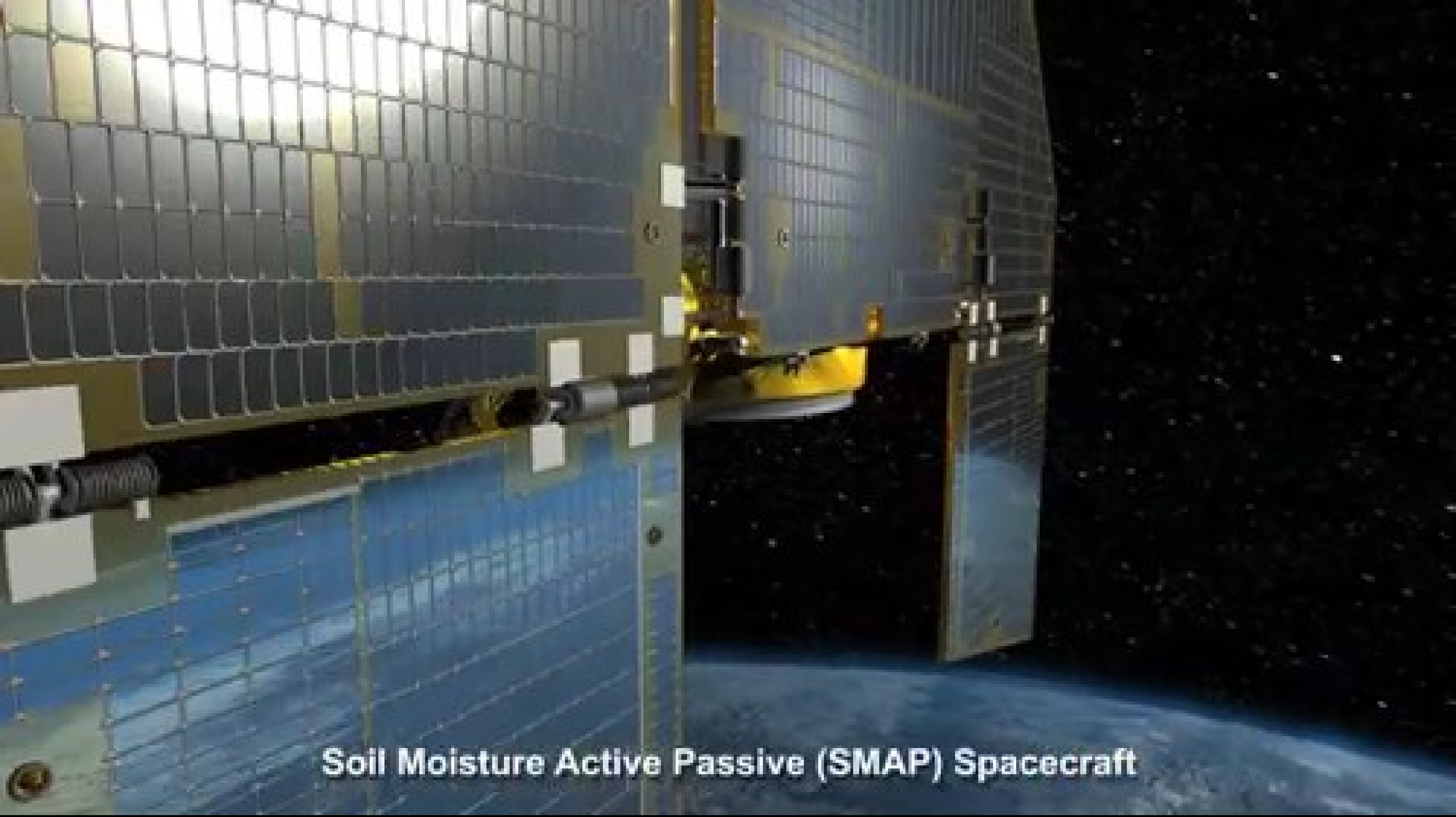
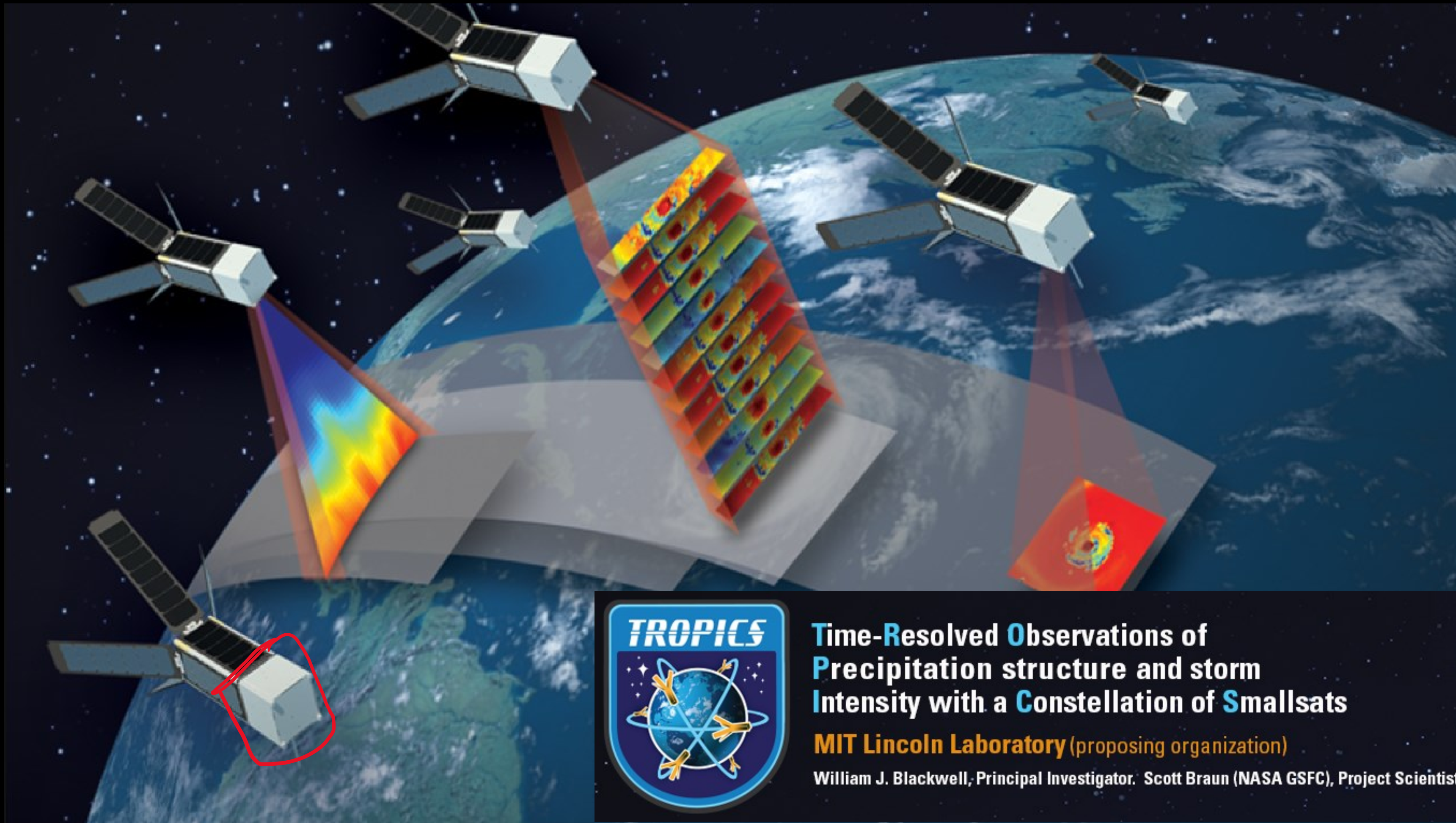


Figure 7-33: Radiometric imaging by (a) cross-track scanning in the plane normal to the direction of flight, and (b) conical scanning.


RBI - Cross-Track Scanning
Radiation Budget Instrument
Y
X
Z
JPSS-2
Subsatellite Track
θ
Sample Interval
Scan Spacing
Swath



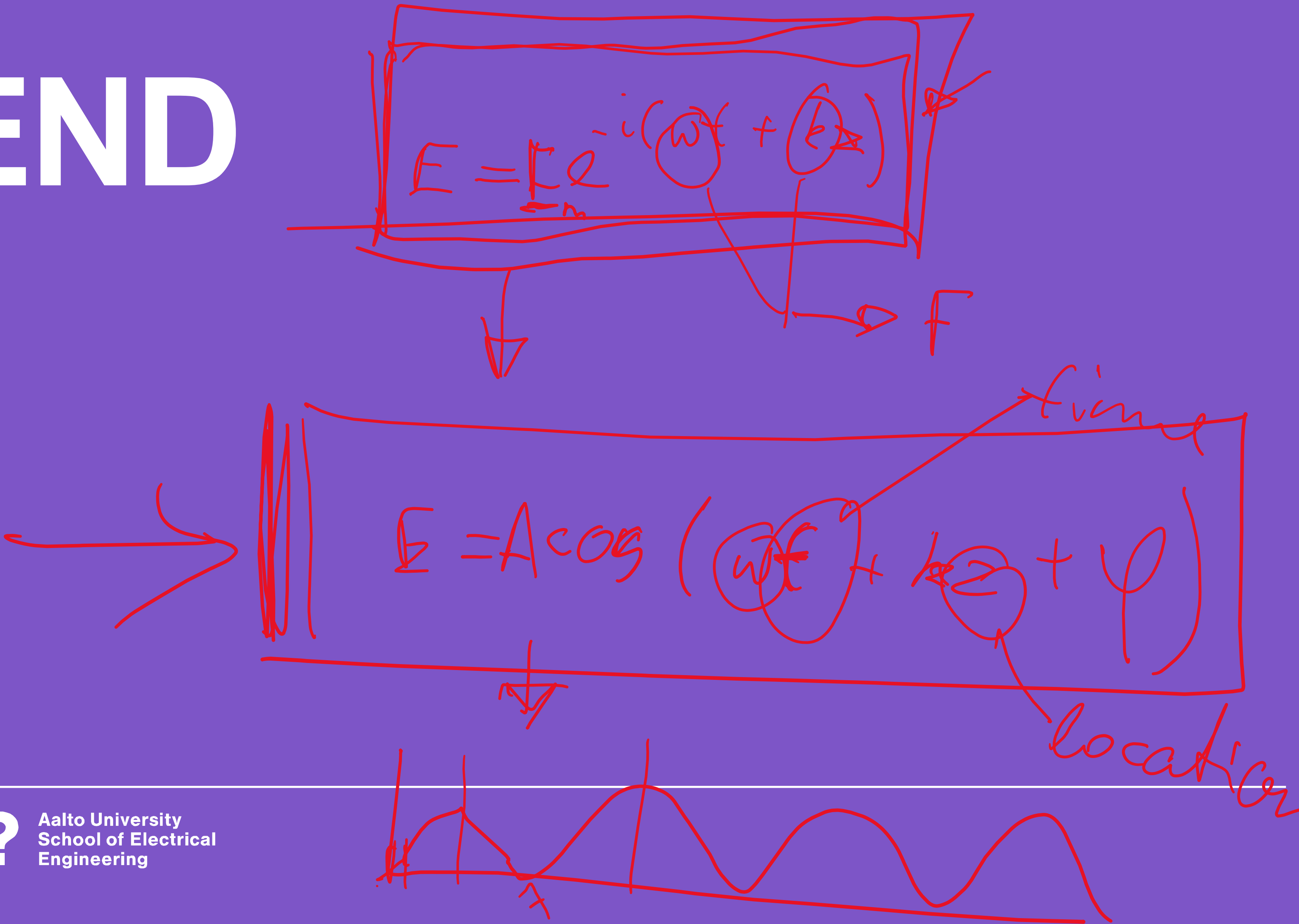

Soil Moisture Active Passive (SMAP) Spacecraft



A constellation of identical 3U CubeSats provide sounding (left CubeSat has a temperature profile of a simulated Tropical Cyclone (TC) from a numerical weather prediction (NWP) model) and 12-channel radiometric imagery (center CubeSat has simulated radiances from NWP model and radiative transfer model and the near right CubeSat has a single-channel radiance image of a TC) with a median revisit rate approaching 30 minutes to meet most PATH requirements.

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

END



Effect of Antenna in Radiometry

Definition of antenna (radiometric) temperature

- Atmosphere ignored

$$T_A = \frac{\iint_{4\pi} T_B(\theta,\phi) F_n(\theta,\phi)\, d\Omega}{\iint_{4\pi} F_n(\theta,\phi)\, d\Omega}$$

Effect of main lobe and side lobes*

T_A = term 1 + term 2

$$T_A = \frac{\iint_{\text{main lobe}} T_B(\theta,\phi) F_n(\theta,\phi)\, d\Omega}{\iint_{4\pi} F_n(\theta,\phi)\, d\Omega} + \frac{\iint_{\text{side lobes}} T_B(\theta,\phi) F_n(\theta,\phi)\, d\Omega}{\iint_{4\pi} F_n(\theta,\phi)\, d\Omega}$$

We define:

Main-lobe antenna temperature T_{ML}:
(actually: effective apparent temperature of the main lobe contribution)

$$T_{ML} = \frac{\iint_{\text{main lobe}} T_B(\theta,\phi) F_n(\theta,\phi)\, d\Omega}{\iint_{\text{main lobe}} F_n(\theta,\phi)\, d\Omega}$$

Side-lobe antenna temperature T_{SL}:
(actually: effective apparent temperature of the side-lobe contribution

$$T_{SL} = \frac{\iint_{\text{side lobes}} T_B(\theta,\phi) F_n(\theta,\phi)\, d\Omega}{\iint_{\text{side lobes}} F_n(\theta,\phi)\, d\Omega}$$

Effect of Antenna in Radiometry

We recall: $\eta_b = \frac{\Omega_m}{\Omega_p}$ => *$Term\ 1 = \eta_b\, T_{ML}$ and $Term\ 2 = \eta_m\, T_{SL}$*

Antenna temperature:

- Brightness temperature modified by lossless antenna

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

LOSSY ANTENNA:

Radiation emitted by passive component (antenna)

- L = antenna attenuation
- ξ = antenna radiation efficiency
- T_o = antenna physical temperature

$$T_N = \left(1 - \frac{1}{L}\right) T_0 = (1-\xi) T_0$$

Noise power arriving at the receiver (attenuated T_A + antenna emission)

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

Final antenna temperature (by employing T_A from above)

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

Radiometer Measurement Ambiguity

Introduced mainly by sidelobes

$$T_{ML} = \left(\frac{1}{\xi \eta_b}\right) T_A - \left(\frac{1-\eta_b}{\eta_b}\right) T_{SL} - \left(\frac{1-\xi}{\xi \eta_b}\right) T_0. \quad (6.42)$$

Sidelobe factor

$$T_{ML} = aT_A + b, \quad (6.43)$$

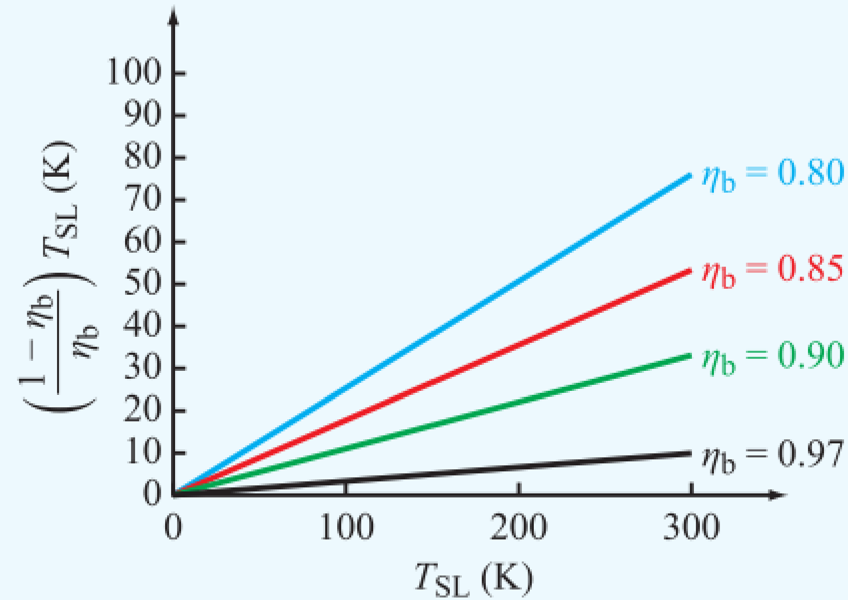


Figure 6-10: Sidelobe factor as a function of the incident sidelobe brightness temperature T_{SL} for each of several values of the beam efficiency η_b.

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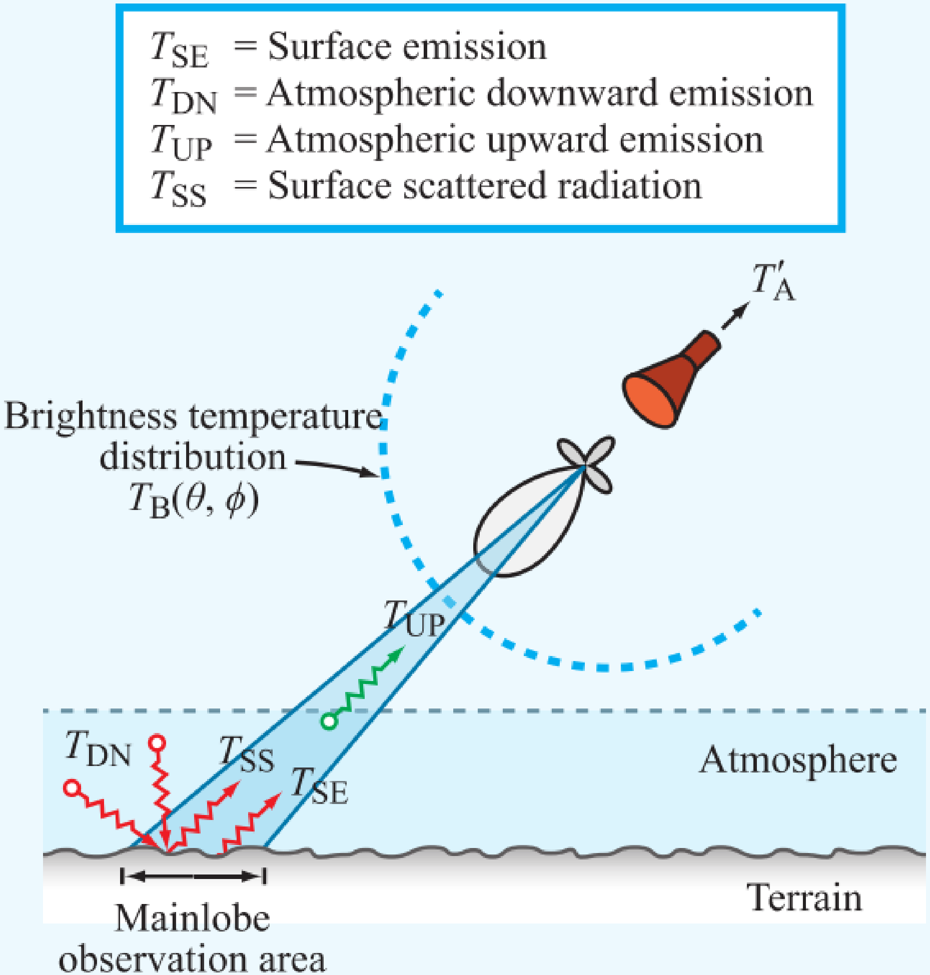
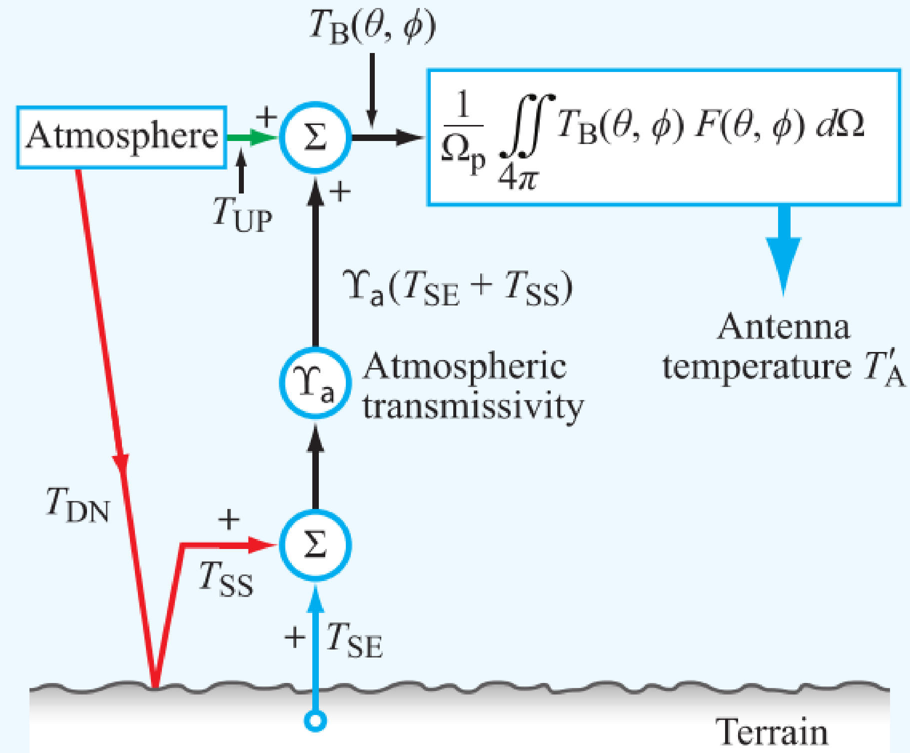


(a) Emission by surface and atmosphere

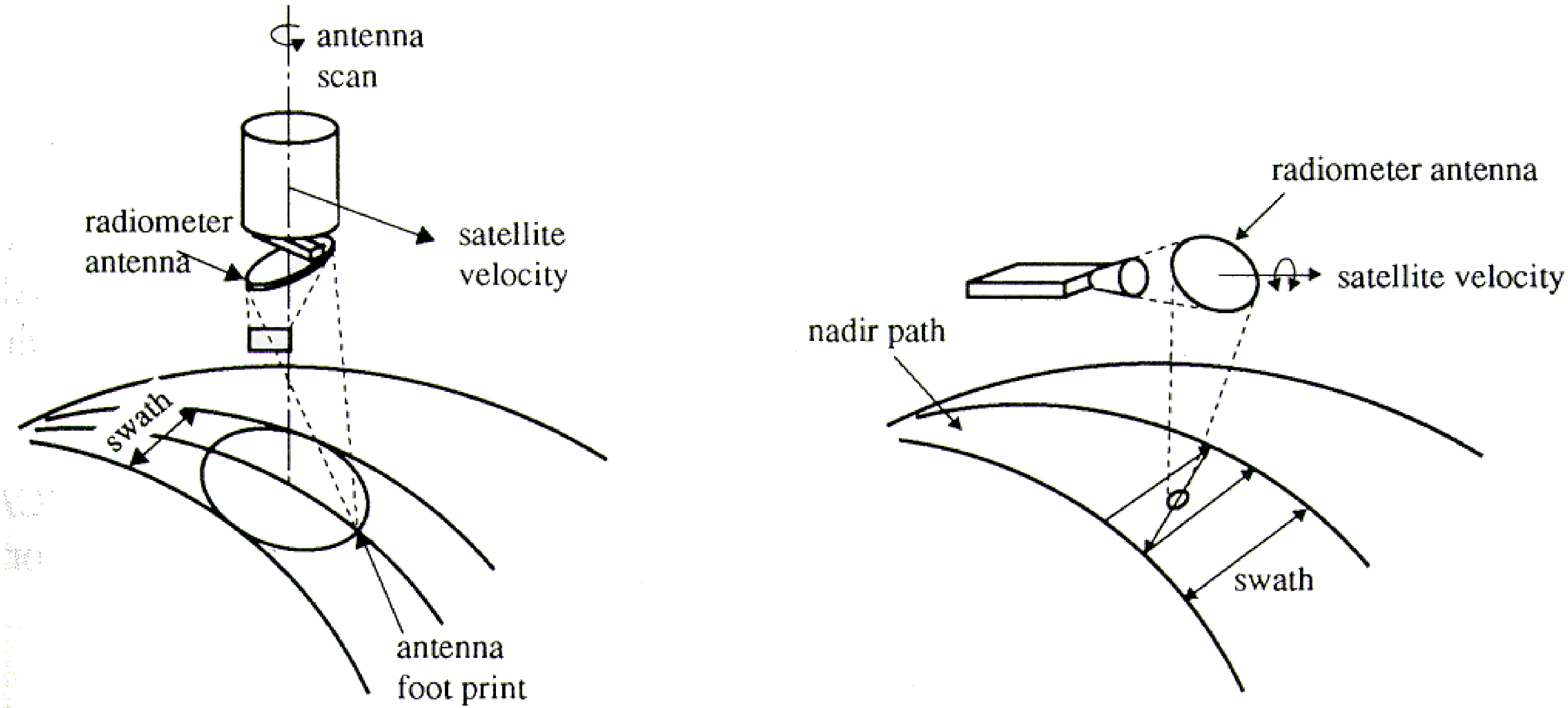


(b) Block diagram

TB brightness temperature distribution

From: Microwave Radar and Radiometric Remote Sensing, by Ulaby and Long, 2014, with permission.

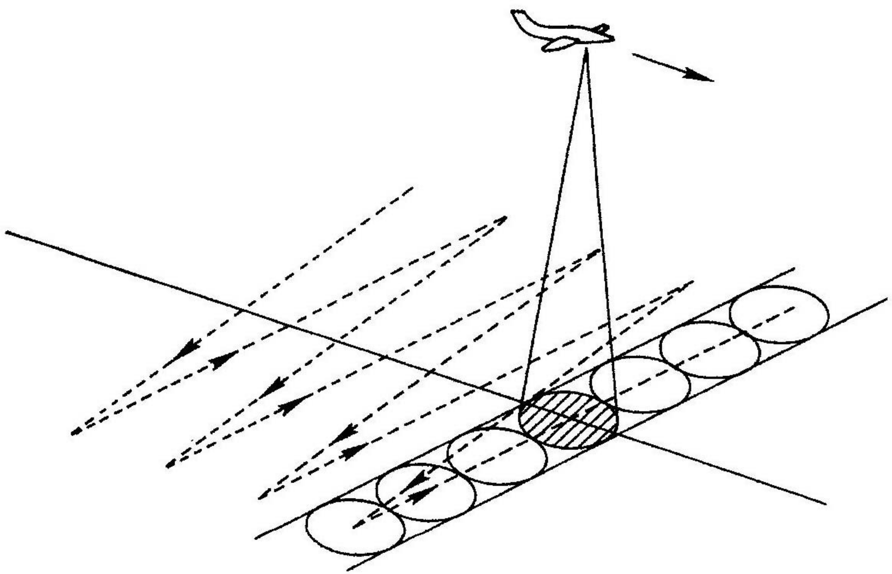
Scanning

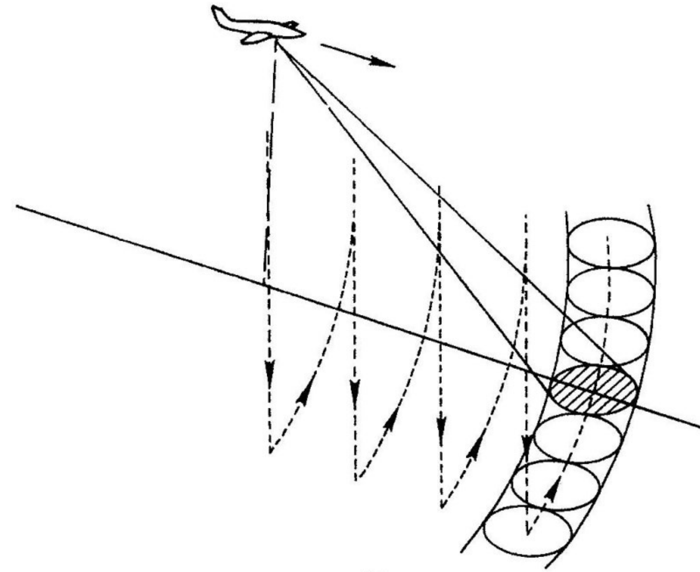


(a) conical scanning type

(b) cross-track scanning type

Scanning





(b)

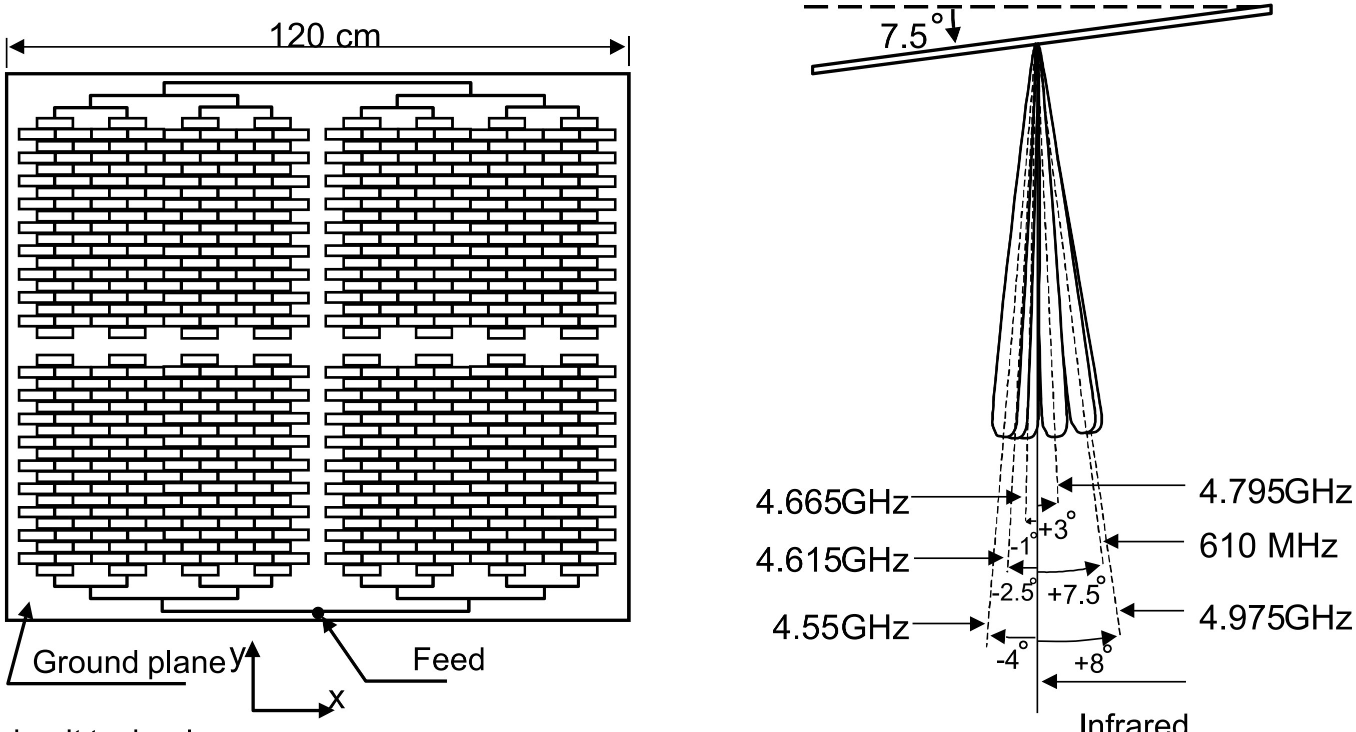
Optical scanner (looking down)

Polarization and incidence angle vary

Conical scanning (looking forward)

Polarization and incidence angle preserved from pixel to pixel

Example: airborne 5 GHz antenna



- Printed circuit technology
- By choosing antenna dimensions vs. frequency properly the main beam direction depends on frequency as shown, swath at 610 MHz is equal to that at 4.5 to 5 GHz

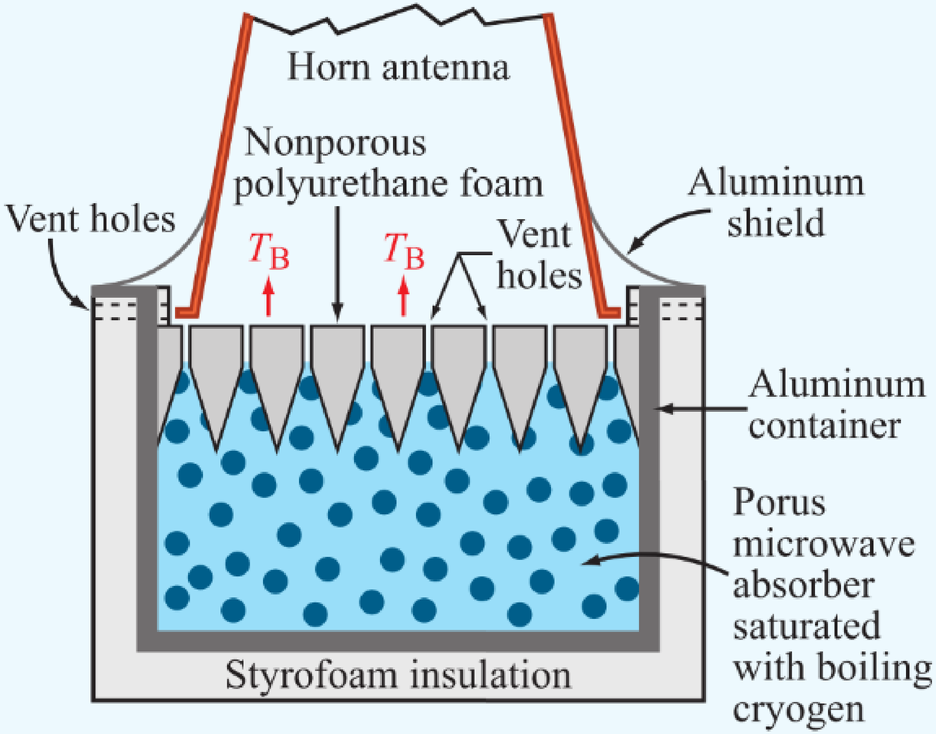


Figure 7-27: Construction of cryoload for calibration of radiometer antenna [after Hardy et al., 1974].

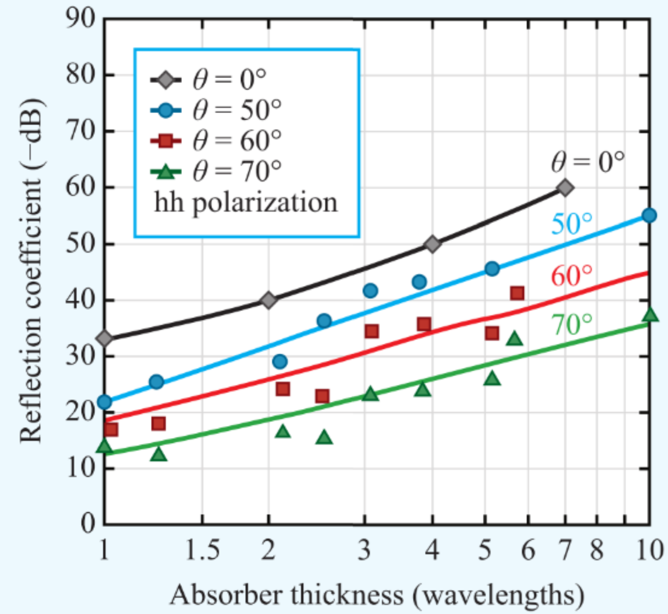


Figure 7-28: Characteristics of RF absorbers [after Emerson, 1973].

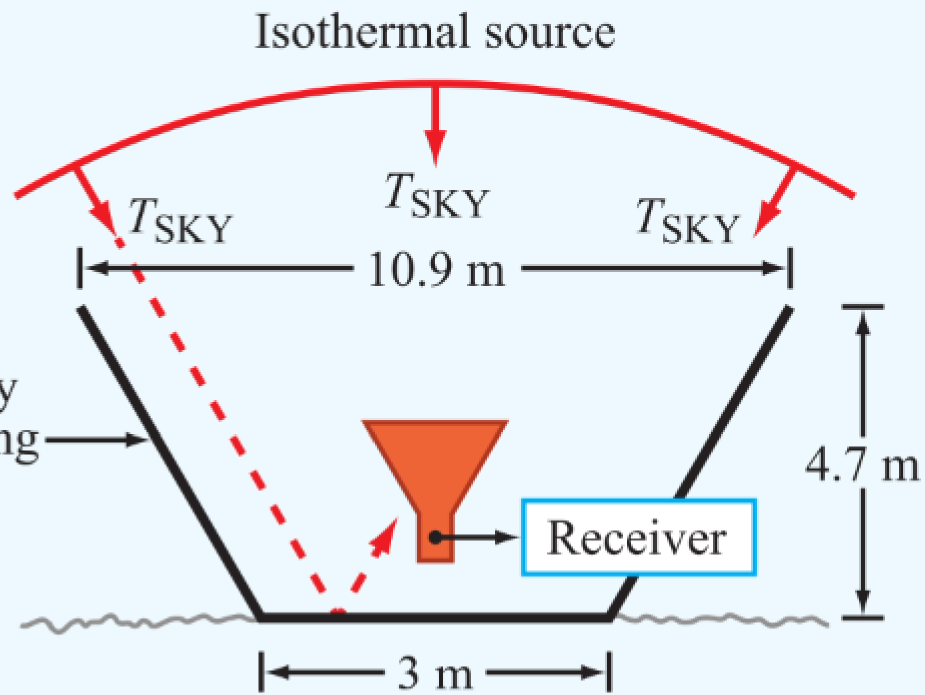


Figure 7-29: The bucket method for measuring the radiation efficiency of an antenna [after Carver, 1975].

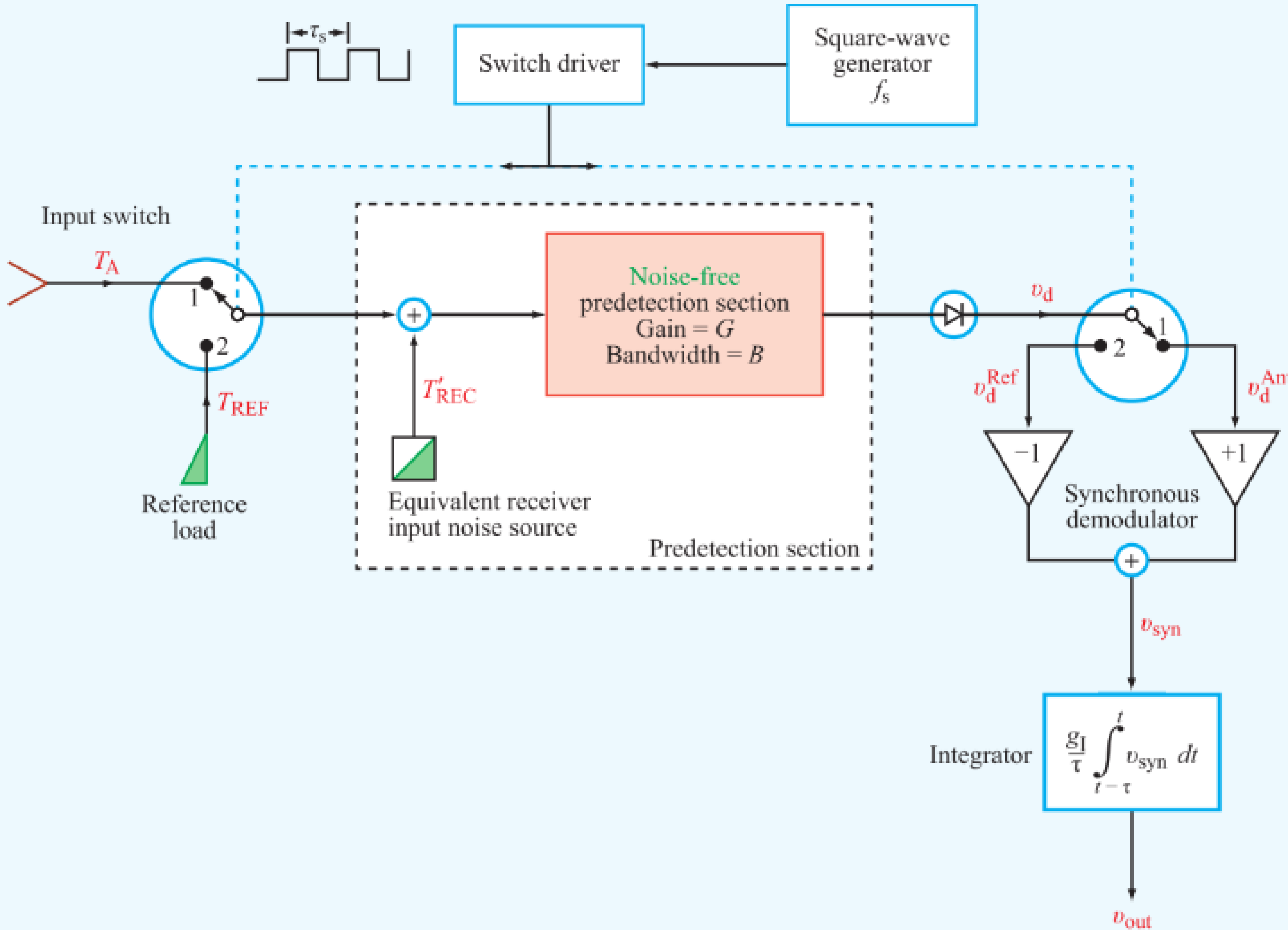


Figure 7-16: Functional block diagram of a Dicke radiometer.

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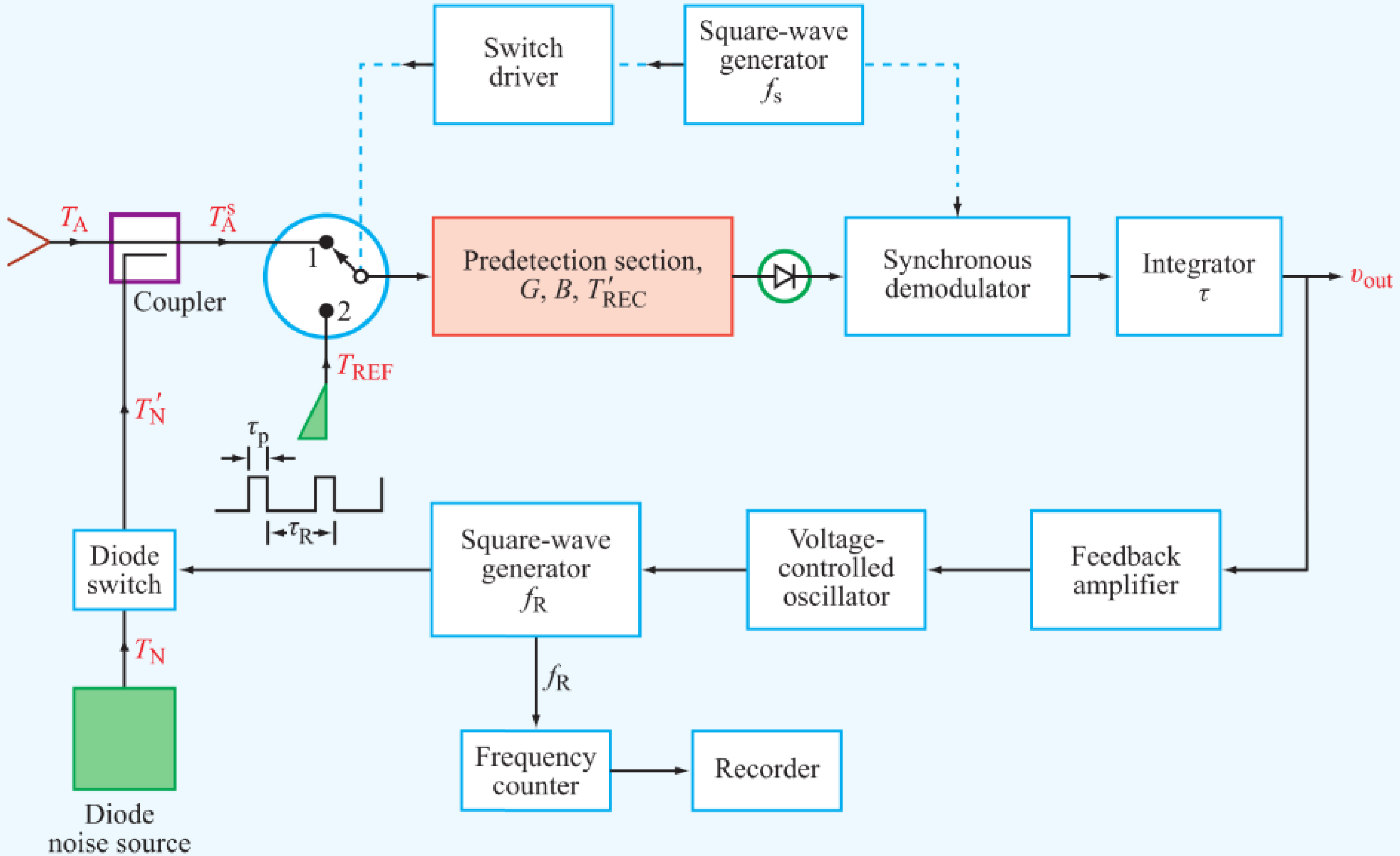

Figure 7-19: Balanced Dicke radiometer, using pulsed noise-injection to maintain $T_A^s = T_{REF}$. The output indicator of T_A is the pulse repetition frequency f_R.

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