Radar: Active Microwave Remote Sensing

RADAR (acronym) = R.A dio Detection And Ranging.

It is now a commonly-used term and no longer identified as an acronym.

Recall the basic differences between radiometry and radar.

Radiative transfer equation for radar

\[ \frac{dB(r, \beta)}{dr} = -keB(r, \beta) + \frac{k}{\alpha} T(r) + \int P(\beta, \beta') B(r, \beta') d\Omega' \]

\[ \frac{dI(r, \beta)}{dr} = -keI(r, \beta) + \int P(\beta, \beta') I(r, \beta') d\Omega' \]

where \( I(r, \beta) \) = specific intensity of radiation, \( W \cdot m^{-2} \cdot sr^{-1} \cdot Hz^{-1} \)

\[ [I(r, \beta)] = [B(r, \beta)] \] just another name for the same quantity, the difference is in where/how the radiation originates!

Note: No thermal emission included in the radar version since it is not a significant source of radiation as compared to the other terms. We use \( I(r, \beta) \) instead of \( B(r, \beta) \) to emphasize that the radiation is generated by the radar.
Radar Equation - used for discrete scatterer or surface

transmitter = \( Tx \)

\( G_t(\theta, \phi) \) is the gain of the transmitter

\( \text{Pr} = \text{power transmitted} \)

receiver = \( Rx \)

\( G_r(\theta, \phi) = \text{gain of receiver} \)

\( \text{Pr} = \text{power received} \)

Recall definitions for directivity, gain, and effective aperture:

\[
D_p(\theta, \phi) = \frac{\text{radiated intensity at } (\theta, \phi)}{\text{radiated intensity from an isotropic source radiating the same amount of power}} = \frac{F_p(\theta, \phi)}{\frac{1}{4\pi} \int F_p(\theta, \phi) \, d\Omega}
\]

where \( p \) = polarization

\[ F_p(\theta, \phi) = R^2 S_p(\theta, \phi) , \quad [F_p(\theta, \phi)] = \text{W sr}^{-1} , \quad [S_p(\theta, \phi)] = \text{W m}^{-2} \]

\[ \text{Pr} = \text{power radiated} = \int F_p(\theta, \phi) \, d\Omega \]

\[ G_p(\theta, \phi) = \frac{S_p D_p(\theta, \phi)}{} \]

\[ \text{Ae}\text{D}_{\text{p}}(\theta, \phi) = \text{effective aperture or capture area of antenna} = \frac{\chi^2}{4\pi} G_p(\theta, \phi) \]

Relative power transmitted to power received:

\[ G_{t\text{p}}(\theta, \phi) = \frac{\text{Pr}}{\frac{1}{4\pi} \int F_p(\theta, \phi) \, d\Omega} = \frac{\text{Pr}^2 S_{t\text{p}}(\theta, \phi)}{\frac{1}{4\pi} \text{Pr} S_{t\text{p}}} \]

\[ S_{t\text{p}}(\theta, \phi) = \frac{\text{Pr} S_{t\text{p}}}{\frac{1}{4\pi} R^2} G_{t\text{p}}(\theta, \phi) \]

\[ \text{(1)} \]

= power density at polarization \( p_j \) transmitted radiation at the scatterer from \( Tx \) point of view

So more power must be sent to \( Tx \) to make up for losses in order for \( Pr_{t\text{p}} \) to be radiated

\[ S_{t\text{p}}(\theta, \phi) = \frac{\text{Pr} S_{t\text{p}}}{\frac{1}{4\pi} R^2} G_{t\text{p}}(\theta, \phi) \]
\[ P_{r,p} = \text{power received (intercepted) by the scatterer} = S_{t,p} (\Theta_s, \phi_s) \text{ Ar}_s (\Theta_s, \phi_s) \quad (2) \]

\[ P_{t,s,p} = \text{power radiated by scatterer} = P_{r,p} (1 - f_{a,p}) \quad (3) \]

Where \( f_{a,p} = \text{fraction of energy absorbed by the scatterer at polarization } p \)

incident radiation excites currents in the scatterer and some of this incident energy is lost (due to heating of scatterer) and the rest of the energy is radiated by currents in the scatterer, and the radiation produces the scattered field

\[ S_{r,p} (\Theta_s, \phi_s) = \text{power density at the receiver} = \frac{P_{t,s,p} \text{ G}_{s,p} (\Theta_s, \phi_s)}{4 \pi R_r^2} \quad (4) \]

\[ P_{r,p} = \text{power intercepted by the receiver} = S_{r,p} (\Theta_s, \phi_s) \frac{\lambda^2}{4 \pi} \text{ G}_{r,p} (\Theta_r, \phi_r) \quad (5) \]

Now combine (1) through (5)

\[ P_r = \lambda^2 \frac{\text{ Gr}(\Theta_r, \phi_r) P_{t,s} \text{ G}_{s,p} (\Theta_s, \phi_s)}{4 \pi R_r^2} \]

\[ = \frac{\lambda^2}{4 \pi} \text{ Gr}(\Theta_r, \phi_r) \frac{1 - f_{a,s}}{4 \pi} \text{ St}(\Theta_s, \phi_s) \text{ Ar}_s (\Theta_s, \phi_s) \text{ G}_{s,p} (\Theta_s, \phi_s) \]

\[ = \frac{\lambda^2}{4 \pi} \text{ Gr}(\Theta_r, \phi_r) \frac{(1 - f_{a,s}) \text{ Ar}_s (\Theta_s, \phi_s) \text{ G}_{s,p} (\Theta_s, \phi_s)}{4 \pi R_r^2} \]

\[ = \frac{\lambda^2}{4 \pi} \text{ Gr}(\Theta_r, \phi_r) \frac{(1 - f_{a,s}) \text{ Ar}_s (\Theta_s, \phi_s) \text{ G}_{s,p} (\Theta_s, \phi_s)}{4 \pi R_r^2} \frac{P_t}{\delta_t} \frac{\text{ Gr}(\Theta_t, \phi_t)}{4 \pi R_t^2} \]

\[ P_r = \frac{P_t}{\delta_t} \frac{\text{ G}_{s,p} (\Theta_s, \phi_s) \text{ Gr}(\Theta_r, \phi_r) \lambda^2}{(4 \pi)^3 R_r^2 R_t^2} \]

\[ \delta_t = \text{radar scattering cross section, m}^2 \]

\[ \delta_t = \text{radar equation} \]

Use this to design a radar!
For the backscatter case (when the transmitter and receiver are the same instrument): \( R_t = R_r = R \) \((S_t = G_t = G)\)
and assuming \( S_t = S_r = 1 \) for simplicity,

\[
P_r = P_t \frac{G^2(G_t G_r)}{(4\pi)^3} \frac{\lambda^2}{R^4} \theta^0
\]

(bistatic radars (which are not common) have separate \( T_x \) and \( R_x \))

Definition: \( \theta^0 = \text{scattering coefficient} = \frac{\theta^0}{\text{area of scatterer}} \)

For large \( R \), \( \frac{P_r}{P_t} = \frac{\text{ratio of received power}}{\text{transmitted power}} = \frac{\text{radar power}}{\text{transmitted power}} = \frac{\lambda^2}{(4\pi)^3} \frac{G^2(G_t G_r)}{R^4} \int \theta^0 \, dA \)

so \( R \) can be taken out of the integral, since each point in area illuminated by radar is different \( R \)

So... in radar remote sensing,

\[
\frac{P_r}{P_t} \text{ is related to the } \theta^0 \text{ of a surface or scatterer}
\]

and \( \theta^0 = f(\text{roughness, dielectric constant of surface/scatterer, physical size, number of individual scatterers, polarization, orientation of scatterers, ...}) \)

The challenge is to relate \( \theta^0 \) to the geophysical parameter of interest!
Radar Missions

TOPEX - Poseidon (altimeter)
TRMM
GPM Core Observatory
Aquarius
SMAP
ALOS - L-band radar with high spatial resolution but poor temporal frequency so it is not useful for hydrometeorology!

Radar Challenges

- Highly sensitive to surface roughness
- Speckle (coherent interference)
- No good models for the effect of vegetation
  
  \"change detection\": assume change in soil caused by change in soil moisture
- Soil moisture sensitivity is decreased since the radiation must travel through the canopy twice
- Expendable (complexity and power)
Pulse Radar

- Pulse length, $T$
- Period of pulses, $T_p$
- Pulse repetition frequency, $f_p$

$T_p = \frac{1}{f_p}$

$T = \text{time for a pulse to travel to the target and back}$

$T = \frac{2R}{c}$

where $c = \text{speed of light}$

$R = \text{distance to target}$

$T_p$ must be long enough (backscatter case) so that the transmitted and received pulses do not overlap!

$R_u = \text{unambiguous range} = \frac{1}{2}cT_p = \frac{1}{2}cT_p$

The furthest radar can "see"

Range resolution

$pulse$ returns from $1$ at $t_1 = 2\frac{R_1}{c}$

$pulse$ returns from $2$ at $t_2 = 2\frac{R_2}{c}$

The two targets will be "resolvable" as separate targets as long as

$t_2 \geq t_1 + T$

$\frac{2R_2}{c} \geq \frac{2R_1}{c} + T$

$R_2 \geq R_1 + \frac{cT}{2}$

Hence, the range resolution of a radar is

$\Delta R = R_2 - R_1 = \frac{cT}{2}$

and so,

$T = \frac{2\Delta R}{c}$

Pulsed radars have a better spatial resolution than an "equivalent" radiometer because of this range resolution.