Radar: Active Microwave Remote Sensing

RADAR (acronym) = Radio Detection And Ranging.
It is now a commonly-used term no longer identified as an acronym.
Recall the basic differences between radiometry and radar.

- **Radiometry:**
  - Natural emission from the atmosphere, potential for volume scattering from hydrometeors
  - Emitted depth

- **Radar:**
  - Signal from radar scattered by the surface
  - Penetration depth

Radiative transfer equation for radar

**Radiometry:**\[ \frac{dE(r,s)}{ds} = -k_e E(r,s) + k_T T(r) + \int P(r,s') E(r,s') d\Omega' \]

**Radar:**\[ \frac{dI(r,s)}{ds} = -k_e I(r,s) + \int P(r,s') I(r,s') d\Omega' \]

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

\((I(r,s)) = (E(r,s)) \quad \text{just another name for the same quantity)}

Note: No thermal emission in radar version since it is not a significant source of radiation. We use \( I(r,s) \) instead of \( E(r,s) \) to emphasize the radiation is generated by the radar.
Radar Equation

transmitter = Tx

\( \text{Gain} = G_t \)

\( \text{Scatterer} = \text{S} \)

\( \text{Receiver} = \text{Rx} \)

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

Recall definitions: directivity, gain, and effective aperture:

\[ D_p(\theta, \phi) = \text{radiation intensity at } (\theta, \phi) \]

\[ = \frac{F_p(\theta, \phi)}{\pi \int_0^{2\pi} F_p(\theta, \phi) d\Omega} \]

where \( p \)-polarization

\[ F_p(\theta, \phi) = R^2 S_p \]

\[ [F_p] = \text{W sr}^{-1} \]

\( S_p(\theta, \phi) = p\text{-pol power density} \)

\( P_{rad} = \text{power radiated} = \int_0^{2\pi} F_p(\theta, \phi) d\Omega \)

\( G_p(\theta, \phi) = \xi_p D_p(\theta, \phi) \)

\( \xi_p = \text{efficiency factor that accounts for losses} \)

\[ A_{\text{eff}, p}(\theta, \phi) = \text{effective aperture or capture area of antenna} = \frac{\lambda^2}{4\pi} G_p(\theta, \phi) \]

Now relate power transmitted to power received.

\[ G_t(\theta, \phi) = \frac{F_p(\theta, \phi)}{\pi \int_0^{2\pi} F_p(\theta, \phi) d\Omega} \]

\[ = \frac{R^2 S_{tp}(\theta, \phi)}{4\pi} \]

\[ S_{tp}(\theta, \phi) = \frac{P_{tx}}{4\pi R^2} G_{tp}(\theta, \phi) \]

\[ = \text{power density @ polarization } p \text{ of transmitted radiation at the scatterer} \]
\[ P_{r,ip} = \text{power intercepted by the scatterer} = S_{r,ip}(\theta_t, \phi_t) A_{r,ip}(\theta_s, \phi_s) \]  \hspace{1cm} (2)

\[ P_{t,ip} = \text{power radiated by scatterer} = P_{t,ip} (1 - f_{a,ip}) \]  \hspace{1cm} (3)

\[ f_{a,ip} = \text{fraction of energy absorbed by the scatterer at polarization } p \]

incident radiation excites currents
in the scatterer and some energy is lost (heating of the scatterer) and the currents radiate, producing the scattered field

\[ S_{r,ip}(\theta_s, \phi_s) = \text{power density at the receiver} = \frac{P_{t,ip}}{4\pi R_r^2} G_{r,ip}(\theta_s, \phi_s) \]  \hspace{1cm} (4)

scattering treated like an antenna!

\[ P_{r,ip} = \text{power intercepted by the receiver} = S_{r,ip}(\theta_s, \phi_s) \frac{\lambda^2}{4\pi} G_{r,ip}(\theta_t, \phi_t) \]

effective capture area of receiving antenna

Now combine (1) through (5) (will now drop the p subscript since we got the idea that everything is polarization dependent!)

\[ P_r = \frac{\lambda^2}{4\pi} G_r(\theta_r, \phi_r) \frac{P_{t,ip}}{4\pi R_r^2} G_s(\theta_s, \phi_s) \]

\[ = \frac{\lambda^2}{4\pi} G_r(\theta_r, \phi_r) \frac{(1 - f_{a}) S_t(\theta_t, \phi_t) A_{r}(\theta_s, \phi_s)}{4\pi R_r^2} \frac{P_{t,ip}}{4\pi R_r^2} G_s(\theta_s, \phi_s) \]

\[ = \frac{\lambda^2}{4\pi} G_r(\theta_r, \phi_r) \frac{G_s(\theta_s, \phi_s)}{4\pi R_r^2} (1 - f_{a}) A_{r}(\theta_s, \phi_s) \frac{P_{t,ip}}{4\pi R_r^2} G_s(\theta_s, \phi_s) \]

group together, call this
\[ \sigma = \text{radar scattering cross section} \]

\[ [\sigma] = \text{m}^2 \]

\[ \text{radar equation} \]

Use this to design a radar!
For the backscatter case (when the transmitter and receiver are the same instrument): \( R_t = R_r = R \) \( G_t = G_r = G \)

and assuming \( \kappa = 1 \) for simplicity,

\[
Pr = P_t \frac{G_t^2(\theta, \phi)}{(4\pi)^2} \frac{\lambda^2}{R^4} \sigma^0
\]

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

For large \( R \):

\[
\frac{Pr}{Pt} = \frac{\text{ratio of received}}{\text{transmitted power}} = \frac{\lambda^2}{(4\pi)^3} \frac{G_t^2(\theta, \phi)}{R^4} \int_{0}^{2\pi} \sigma^0 \, d\phi
\]

**The point:** In radar remote sensing, \( \frac{Pr}{Pt} \) is related to the \( \sigma^0 \) of a surface/scatterer

and \( \sigma^0 = f(\text{roughness}, \text{surface/scatterer dielectric constant}, \text{physical size}, \text{individual scatterers}, \text{polarization orientation}, \text{scatters}, \ldots) \);

So the challenge is to relate \( \sigma^0 \) to the geophysical parameter of interest!

**Pulse Radar**

- Microwave frequency
- Pulse
  - Time for pulse
  - \( T = \text{time for pulse} \)
  - \( T = \text{travel to target} \)
  - \( b = \frac{2R}{c} \)

- This microwave frequency "interacts" with the target

- \( T_p = \frac{1}{f_p} \)
- \( T_p = \text{period of pulses} \)
- \( f_p = \text{pulse repetition frequency}, \text{Hz} \)
- \( T_p = \text{time for pulse} \)
To must be long enough so that the transmitted and received pulses do not overlap! \[ R_n = \text{range} = \frac{c T_p}{2} = \frac{c}{2 T_p} \]

The two targets will be "resolvable" as separate targets as long as \( t_2 > t_1 + T \) \[ \frac{2R_2}{c} \geq \frac{2R_1}{c} + T \]

\[ \frac{XR_2}{c} \geq \frac{XR_1}{c} + T \Rightarrow R_2 \geq R_1 + \frac{c T}{2} \]

Hence the range resolution of a radar is \( \Delta R = R_2 - R_1 = \frac{c T}{2} \)

This range resolution is one reason why radars have a better spatial resolution than radiometers! (the other is SAR)

Doppler Radar detects a shift in the frequency \( f_r \) of the received signal:

\[ f_r = f_s + f_d \]

\[ E(R_s) = \text{electric field} = E_0 e^{-j (\omega s t - k R_s)} = E_0 e^{-j \frac{2 \pi}{\lambda_s} u_s t} \]

\[ f_s = \omega_s t - k R_s = 2 \pi f_s + \frac{2 \pi}{\lambda_s} u_s t = \text{phase of wave at } R_s \text{ relative to } P_s=0 \text{ and } t=0. \]

If the scatterer is moving towards the receiver, then \( R_s = R_0 - u_s t \)

where \( u_s \) = velocity of scatterer towards receiver

The phase at \( R_s \) is: \( f_s = 2 \pi f_s + \frac{2 \pi}{\lambda_s} (R_0 - u_s t) \) and since \( c_s = \frac{df_s}{dt} \) and \( c_s = 2 \pi \)

\( f = \text{received frequency} = f_s - \frac{u_s}{\lambda_s} \).

Since \( \lambda_s \) is Doppler shifted relative to \( \lambda_t = \text{transmitted wavelength}, \ f_d = \frac{2 u_s}{\lambda_t} \) and considering direction of motion

\[ f_d = -\frac{2 u_s}{\lambda_t} \cos \Theta \]  
(See Fig. 10.14 for definition \( \Theta \))
Radar missions
- Topex-Posidon (altimeter)
- TRMM
- Aquarius
- SMAP
- GPM

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
- Soil moisture sensitivity decreased (must travel through canopy twice)
- Expensive (complexity and power)
Figure 10-10: A pulse radar transmits a continuous train of RF pulses at a repetition frequency $f_p$.

Figure 10-11: Radar beam viewing two targets at ranges $R_1$ and $R_2$.

Figure 10-15: A wave radiated from a point source when (a) stationary and (b) moving. The wave is compressed in the direction of motion, spread out in the opposite direction, and unaffected in the direction normal to motion.

Figure 10-17: The Doppler frequency shift is negative for a receding target ($0 \leq \theta \leq 90^\circ$), as in (a), and positive for an approaching target ($90^\circ \leq \theta \leq 180^\circ$), as in (b).