2024 Short Course on GNSS-IR for Water Level Measurements – Collaborative Research Center 1502 DETECT, University of Bonn

GNSS Interferometric Reflectometry: Basic Theory

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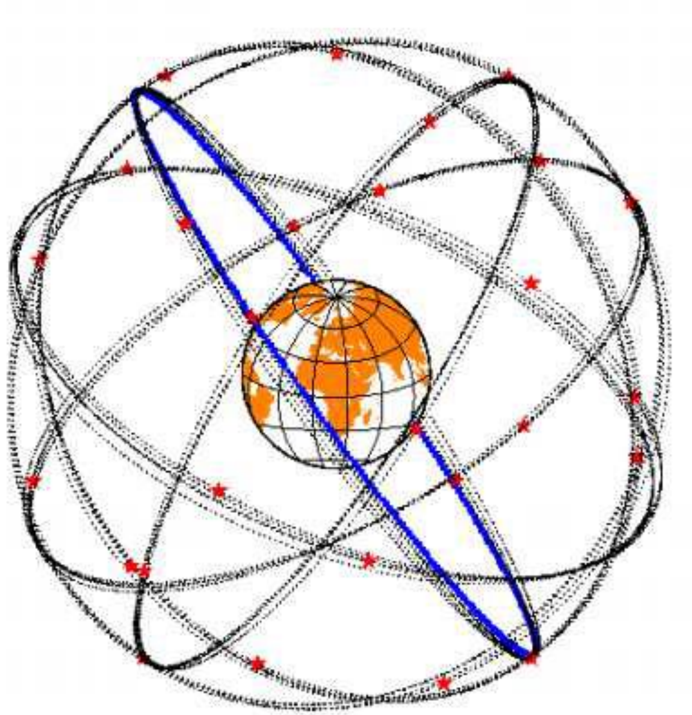
Summary

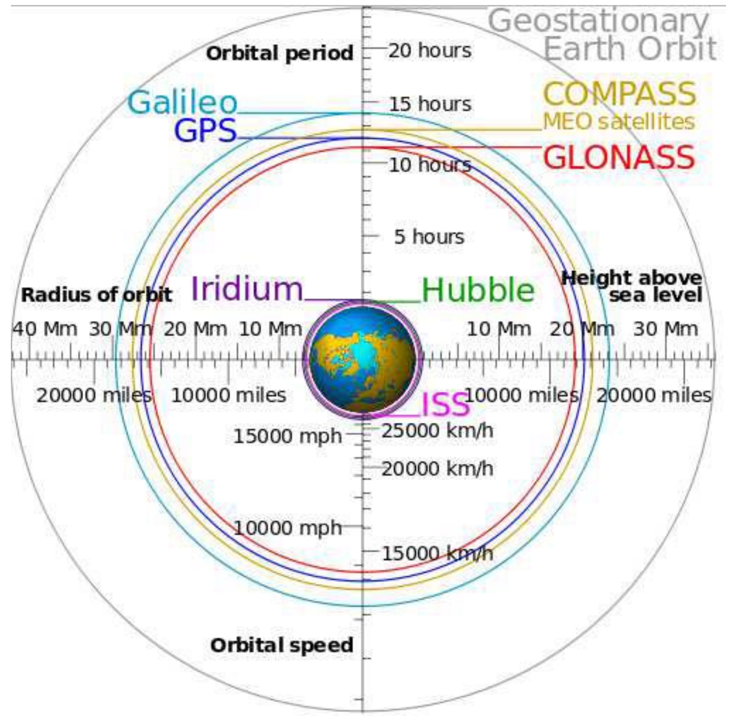
1) Context
2) Principles
3) Geometry
4) Physics
5) Analysis

Geremia-Nievinski (2023) "Low-Cost Ground-Based GNSS Reflectometry", In: Sideris (ed.) *Encyclopedia of Geodesy*, https://doi.org/10.1007/978-3-319-02370-0_175-1 Also at: https://researchgate.net/publication/365173903

GNSS orbital constellations



Inclination ~ 55 deg.

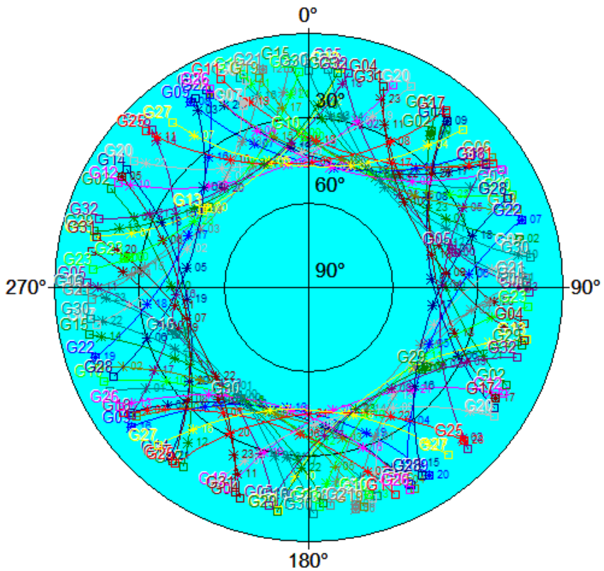


Altitude ~ 20,000 km

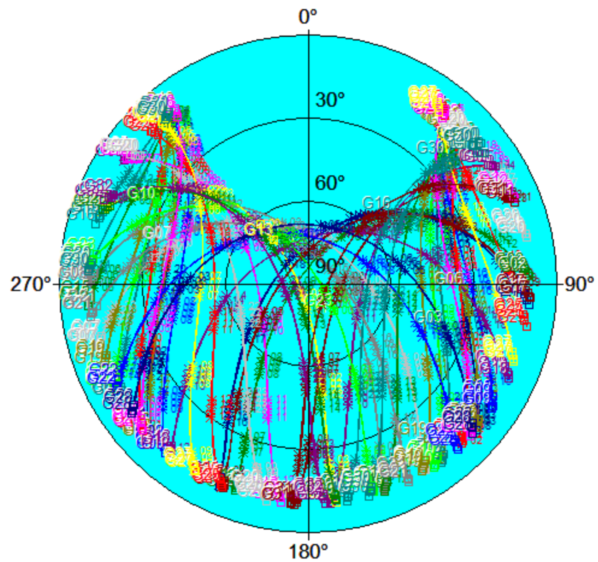
System	2002	2008	2020
GPS	24 satellites	31 satellites	~31 satellites
Galileo		2 satellites	~27 satellites
Compass		1 satellite	~35 satellites
GLONASS	8 satellites	16 satellites	~24 satellites
Total	32 satellites	50 satellites	~120 satellites

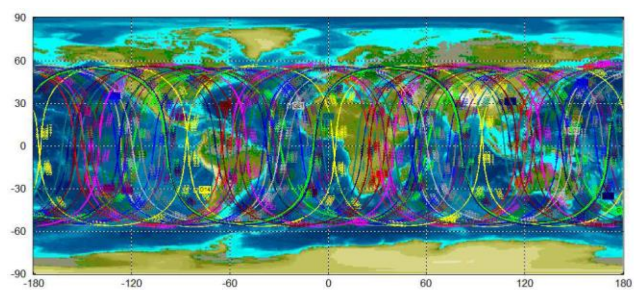
GNSS satellite sky tracks

polar

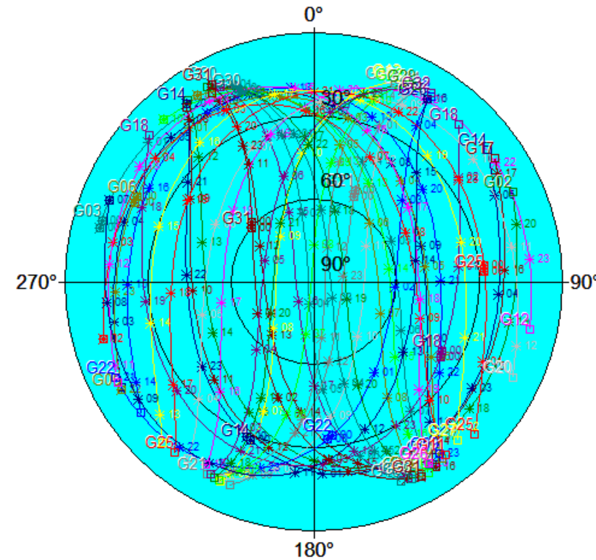


mid-latitude





equatorial

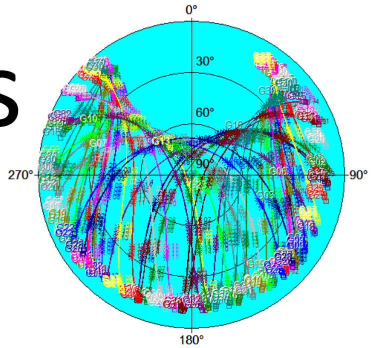


elevation angle (0-90 deg)
azimuth (0-360 deg.)

polar hole

rising/setting
satellites

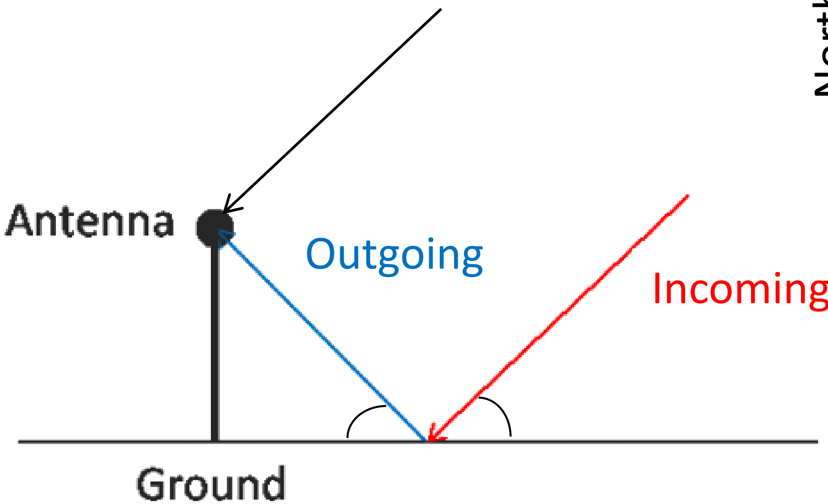
Specular reflection points

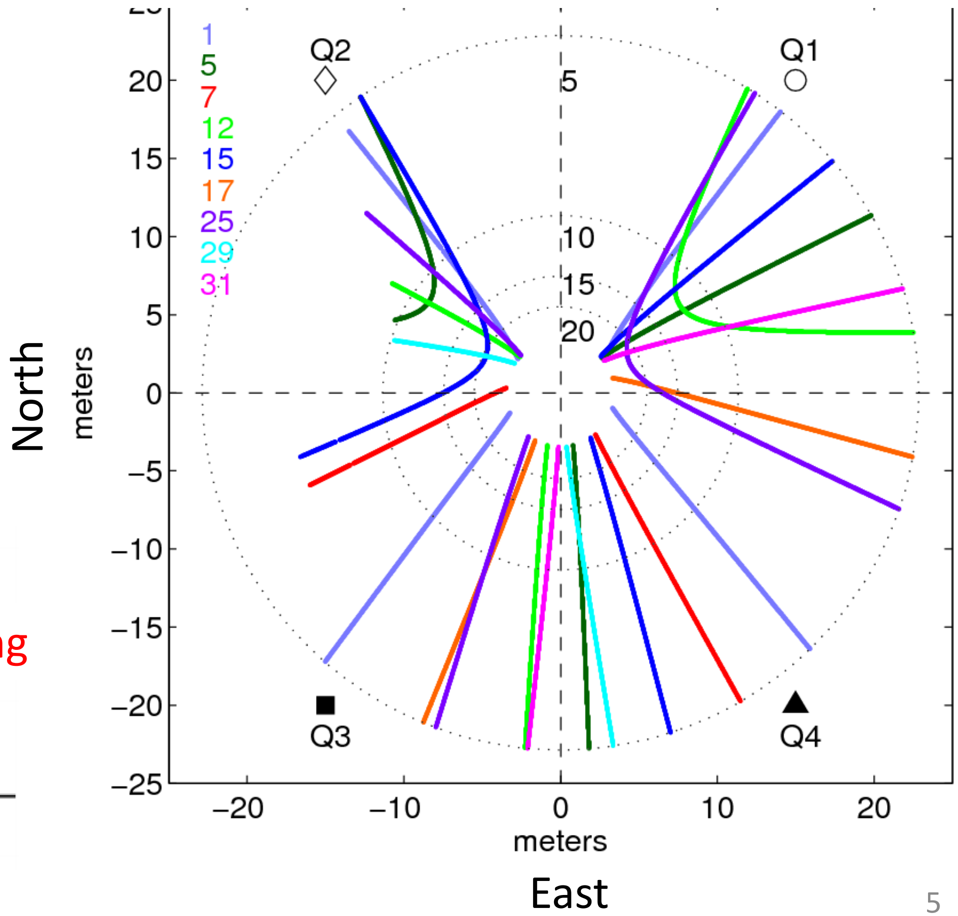


R = h/tan(e)

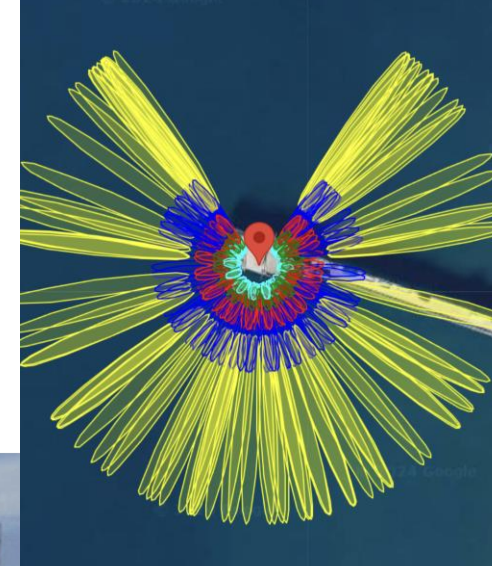
Geometric Optics

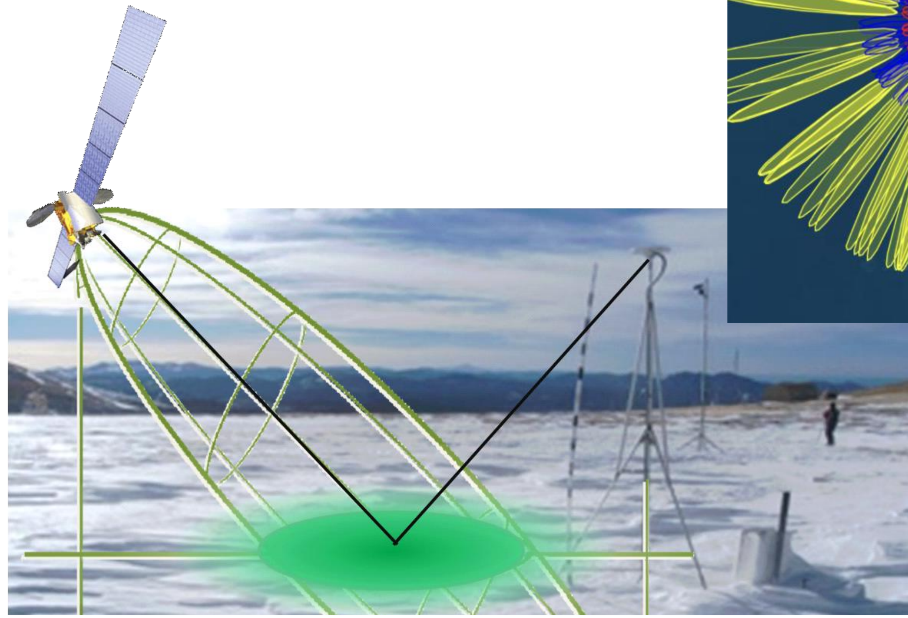
- Thin "rays"
- Direct and reflection
- Snell's law



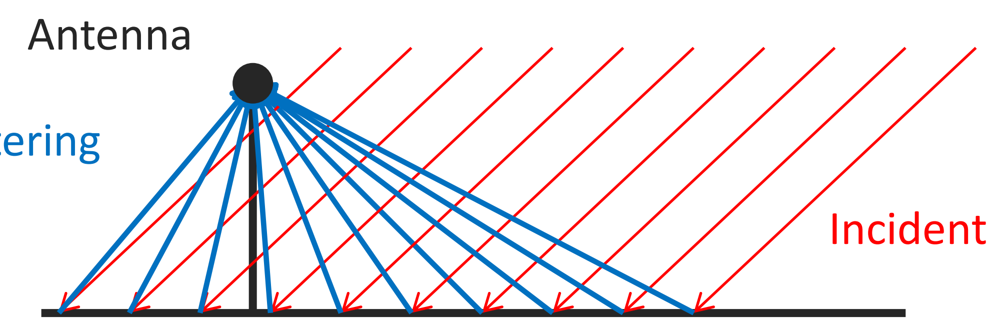


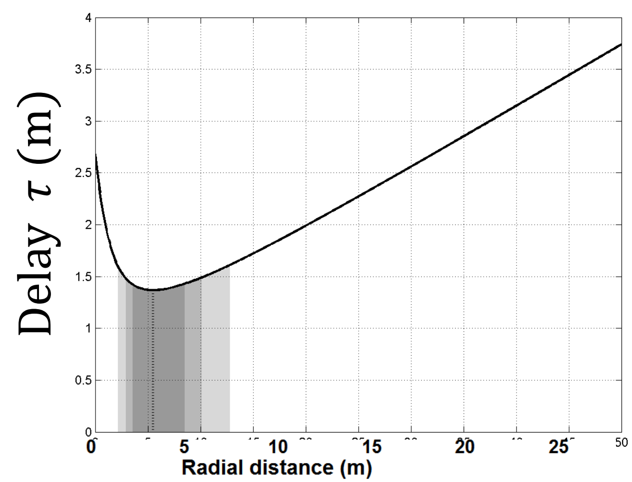
Fresnel zones



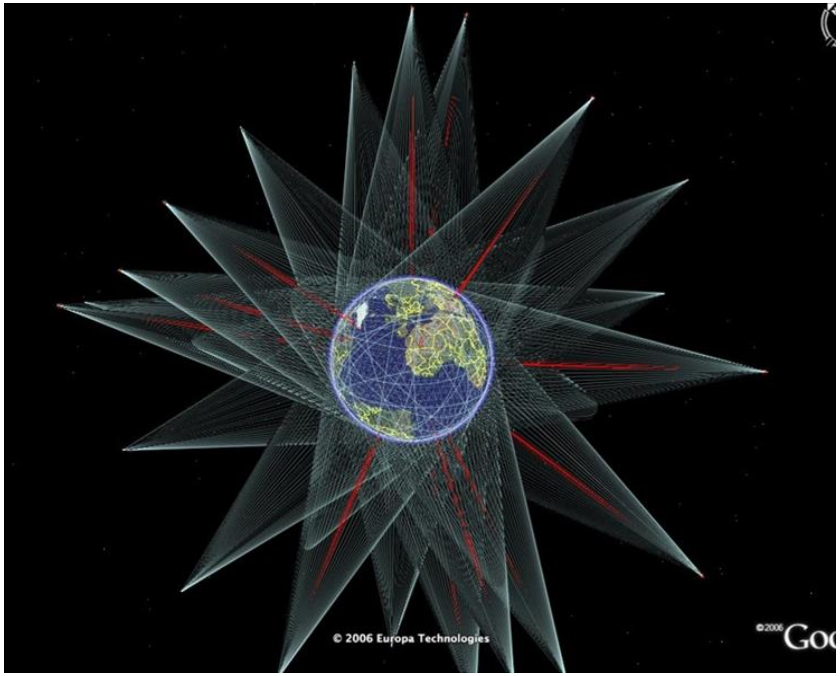


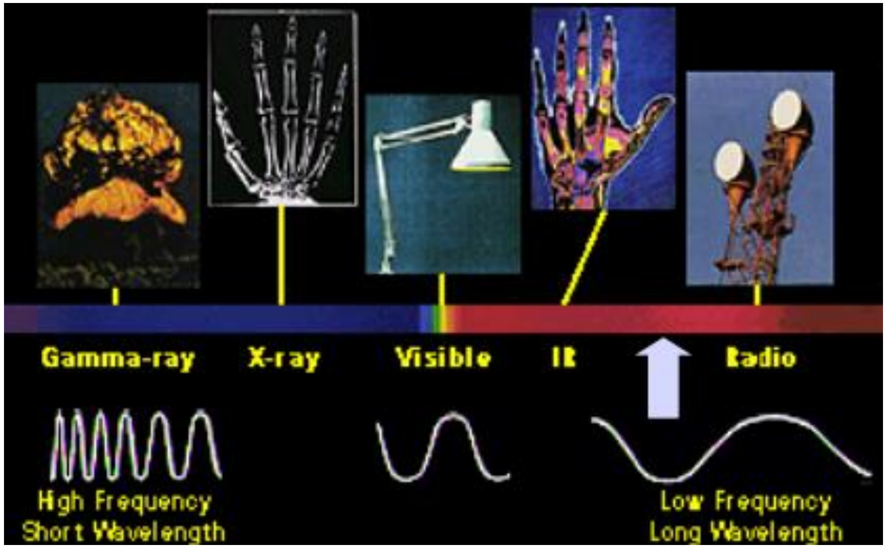
- Physical Optics
  - Elliptical footprint
    - Ray “thickness”
    - Lower → larger
  - Scattering wavelets
    - Stationary near SP
  - Gradual tapering
    - (Otherwise, diffraction)

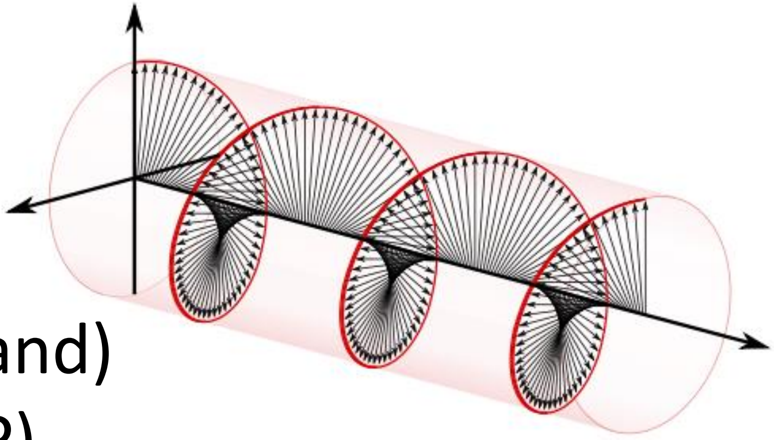




GNSS radio waves

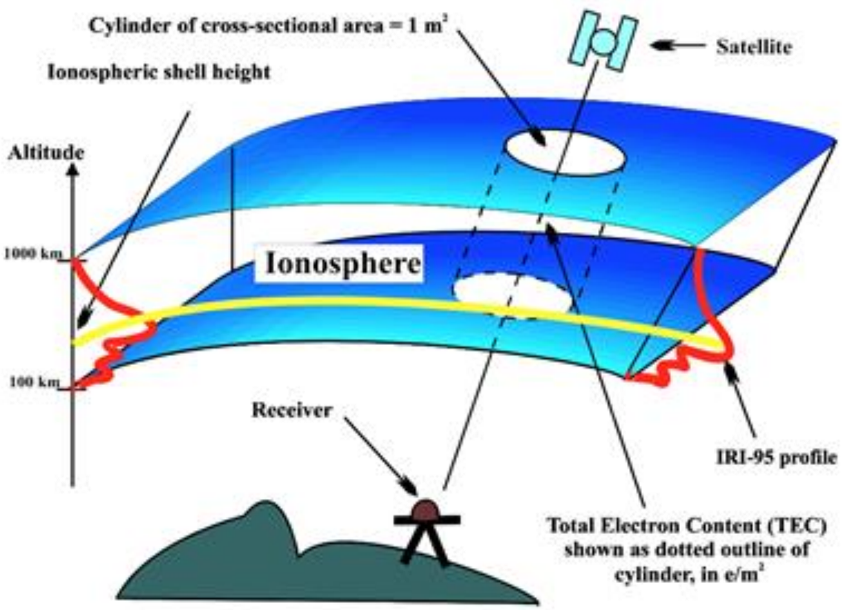




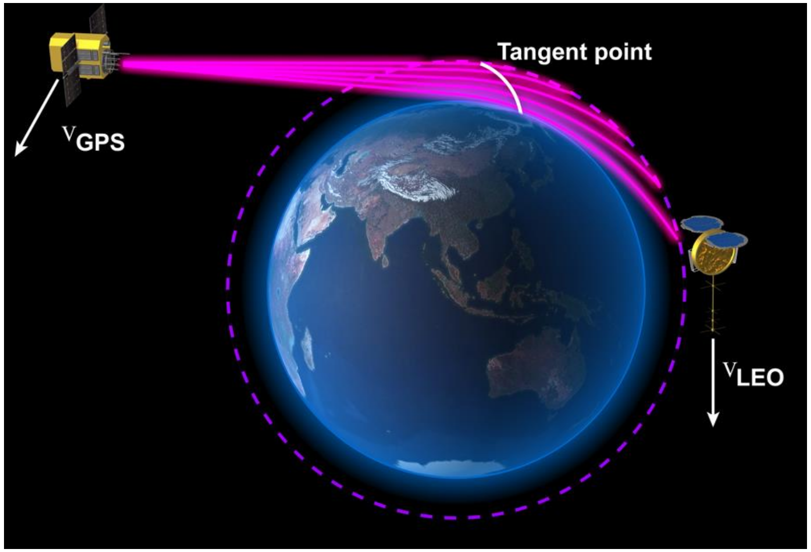


Multiple independent carriers
Carrier wavelength ~ 20 cm (L band)
Polarization: right-handed (RHCP)

GNSS atmospheric remote sensing



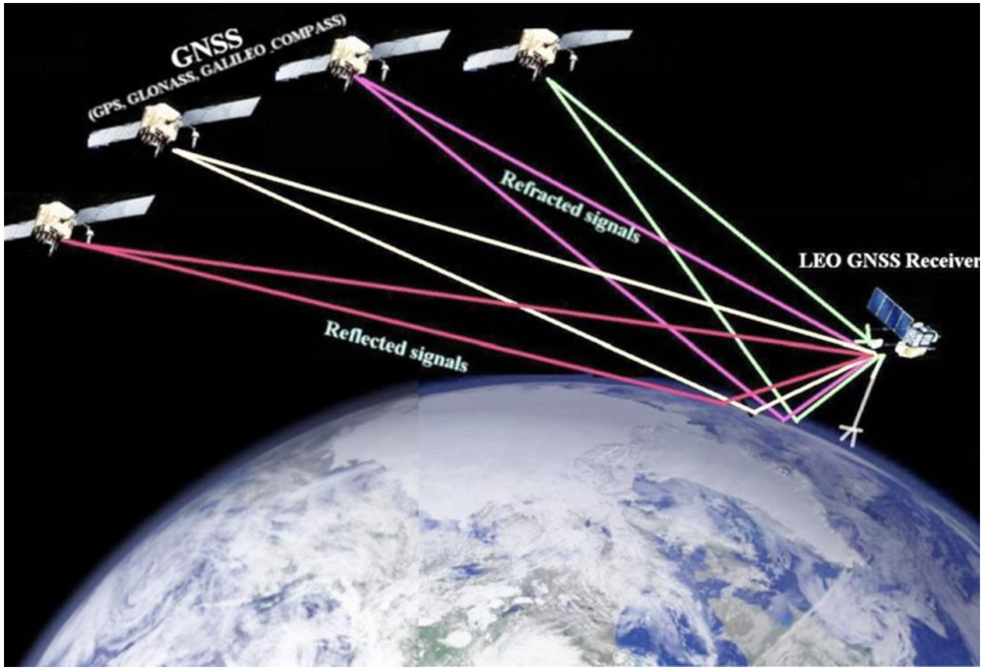
Ground-based (integrated GNSS met.)



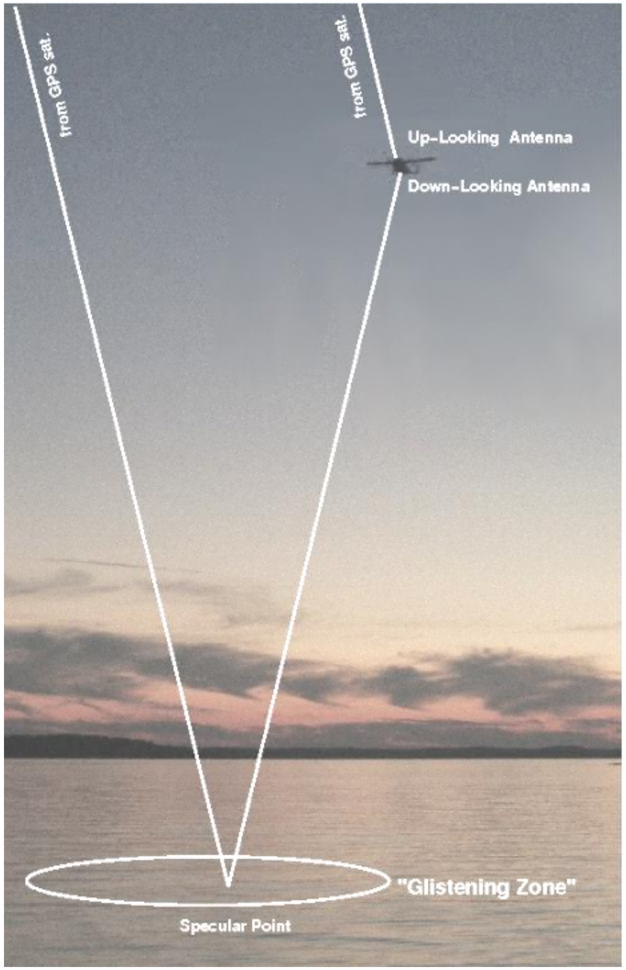
Space-based (radio occultation or limb sounding)

GNSS Reflectometry

Dual channel: up/down
(direct/reflection)



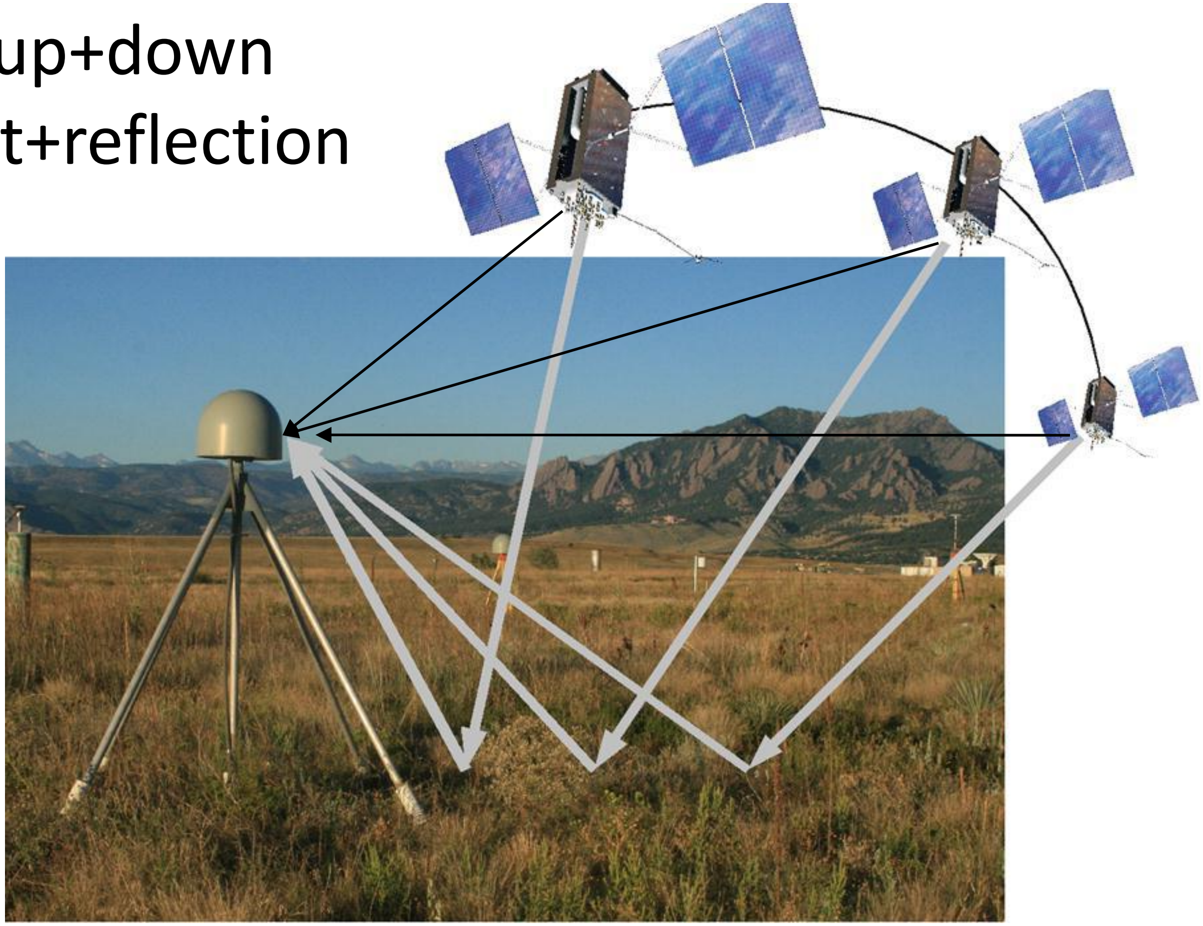
Space-borne



Airborne

GNSS Interferometric Reflectometry

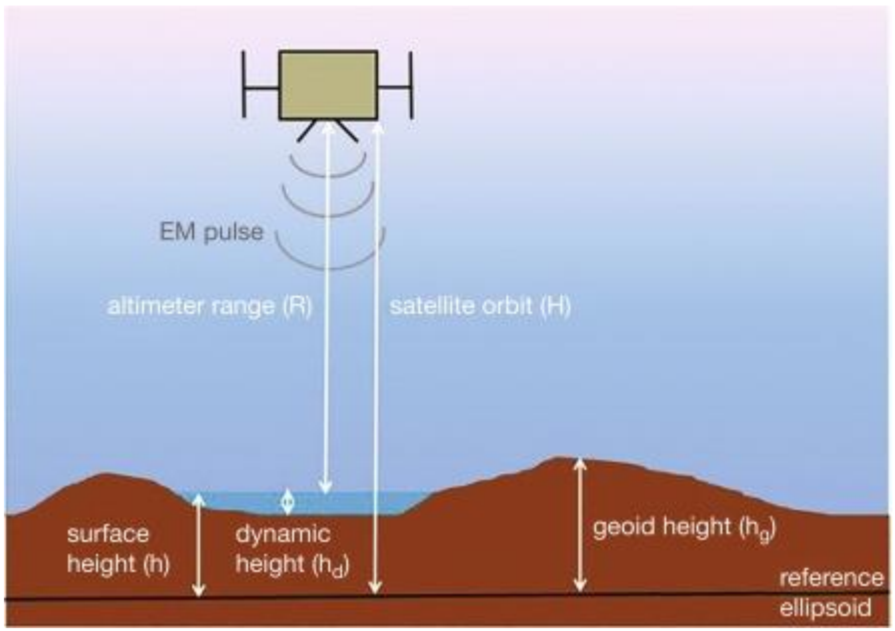
Single channel: up+down
multipath=direct+reflection



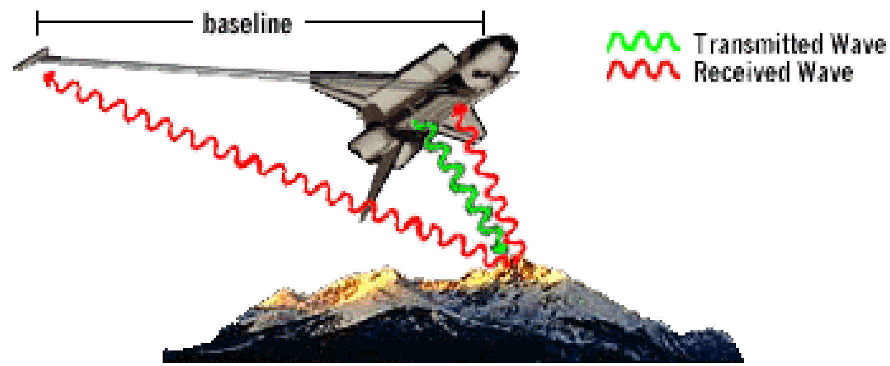
Ground-based

Related radar sensors

Radar altimetry
(monostatic, vertical)



Radar interferometry
(bistatic, imaging)

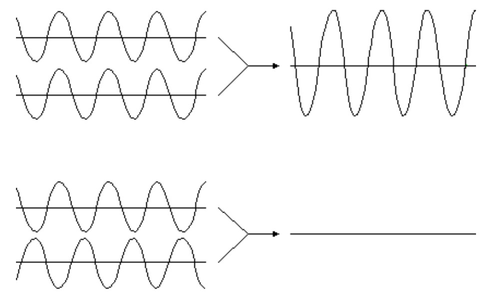


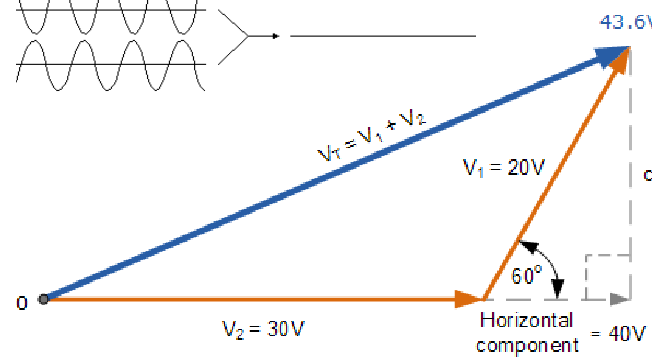
Radar signals being transmitted and recieved in the SRTM mission (image not to scale).

GNSS-R is a type of parasitic bistatic radar (non-imaging)

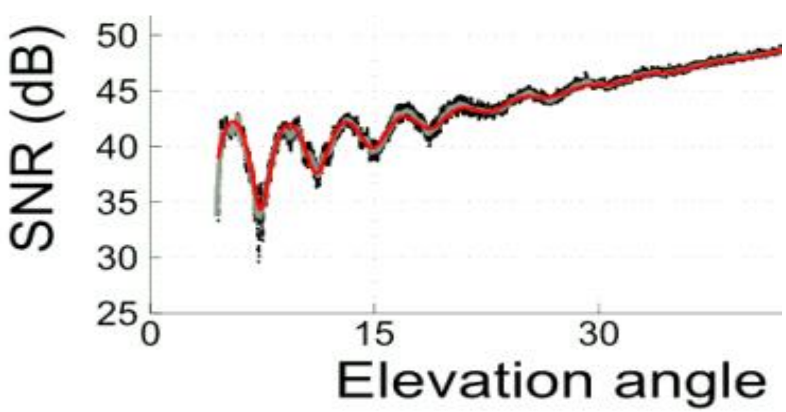
Signal-to-noise ratio (SNR)

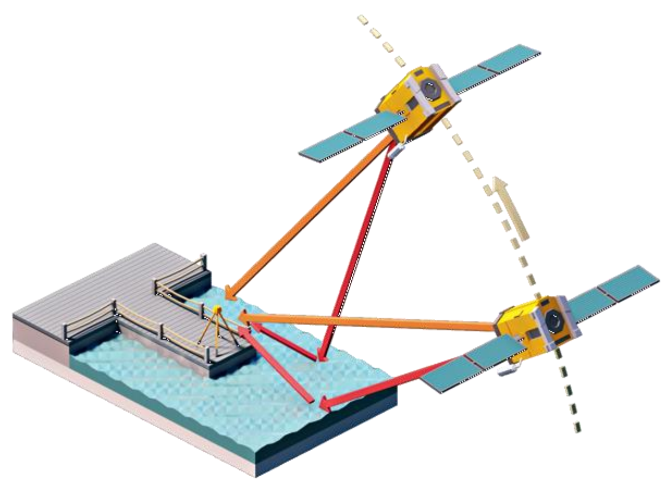
- Interference pattern
  - Constructive/destructive
  - Superposition of direct and reflected radio waves





$$SNR \propto P_c = P_d + P_r + 2P_d^{0.5}P_r^{0.5}\cos\phi_i$$
$$= P_d\left(1 + P_i + 2P_i^{0.5}\cos\phi_i\right)$$





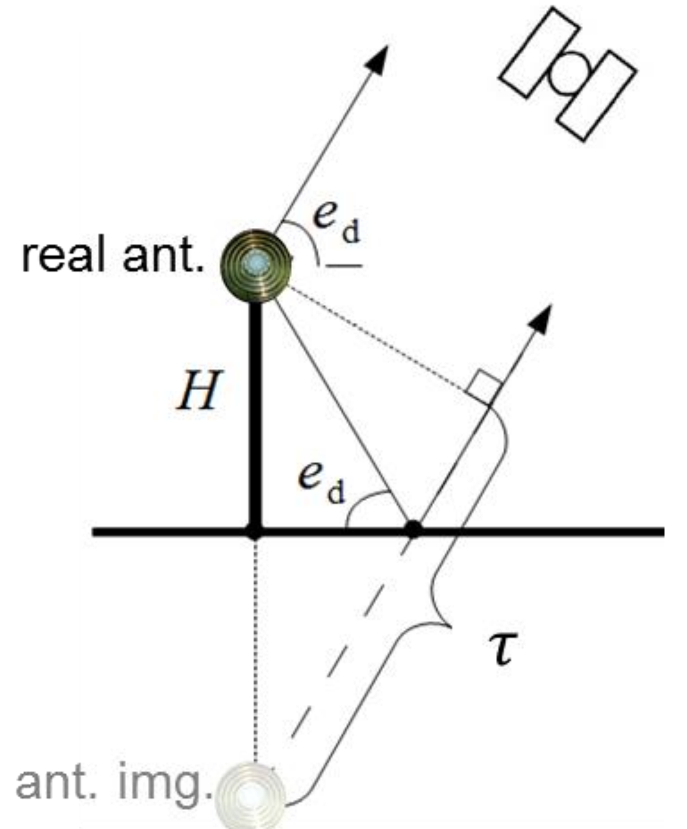
Interferometric delay and phase

- Reflection minus direct propagation distance

  $$D_i = \tau = 2H \sin e$$

  - Maximum: 2H @zenith
  - Minimum: zero @horz.
- Non-geometric phase ϕ_X
  - Surface + Antenna
- Total:

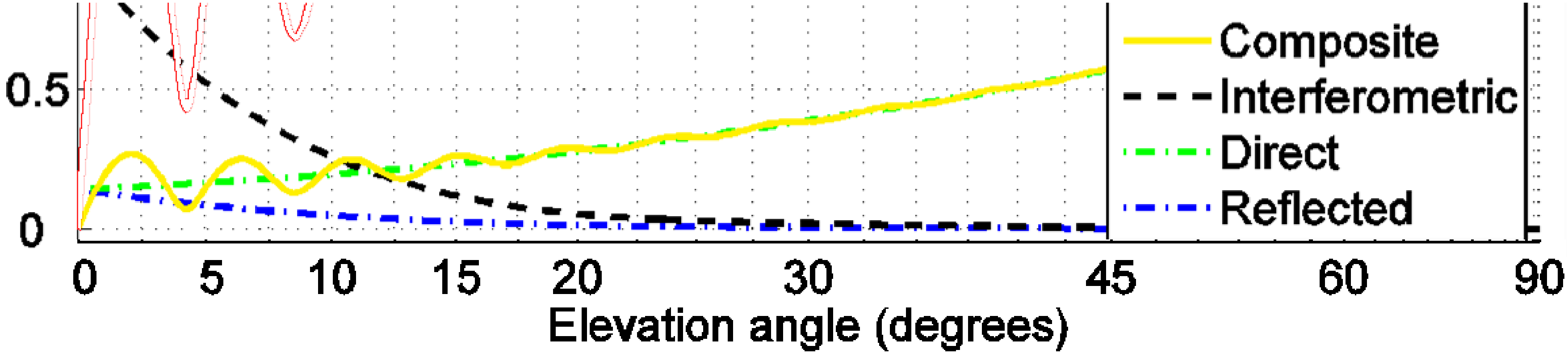
  $$\phi_i = kD_i + \phi_X + \cdots$$
  $$k = 2\pi/\lambda$$



Interferometric power

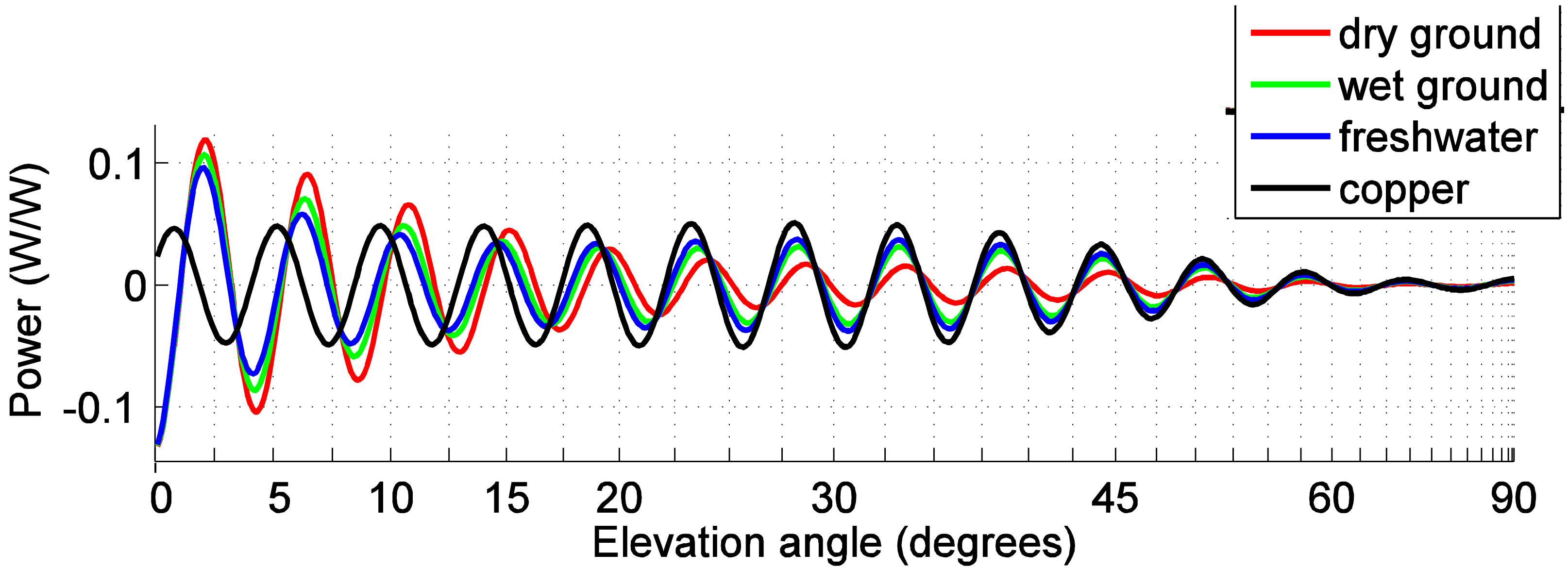
- Reflection power over direct power
- Maximum 1 @horz.
- Minimum zero @zen.

$$P_i = P_r / P_d$$



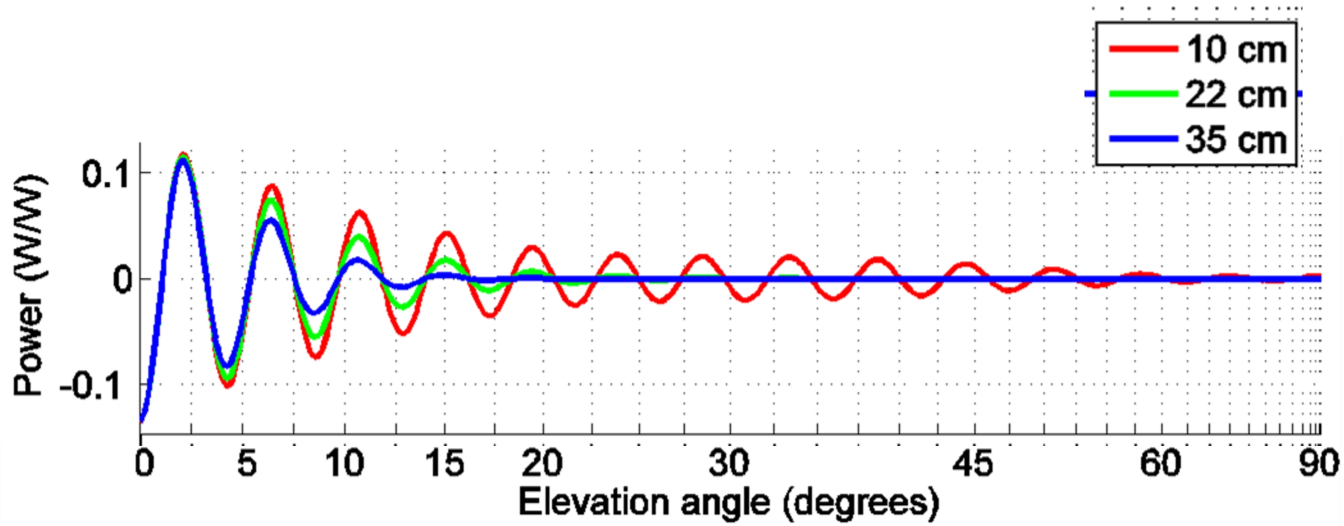
Driven by antenna gain & phase patterns.
Also by surface roughness & material.

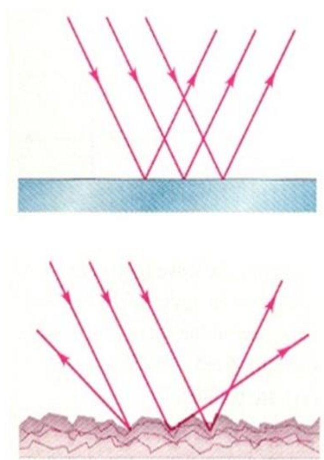
Surface material



Function of complex permittivity (real and imaginary).
Affects both amplitude and phase.

Random roughness

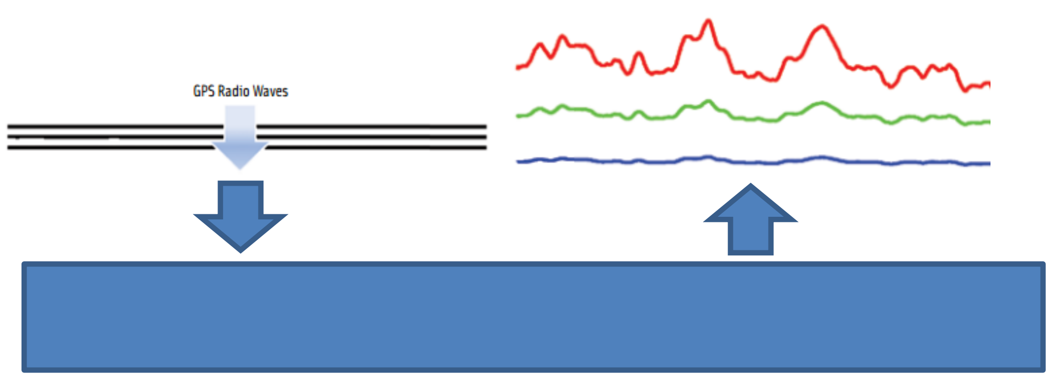




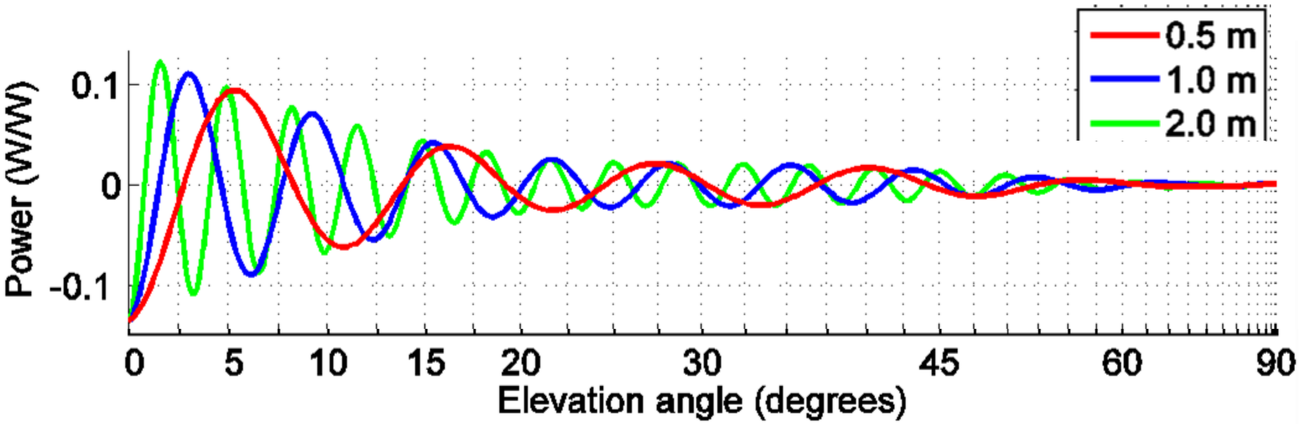
Loss of coherence due to height fluctuations

$$\sigma_{D_i} = 2\sigma_H \sin e$$

(re: wind waves)



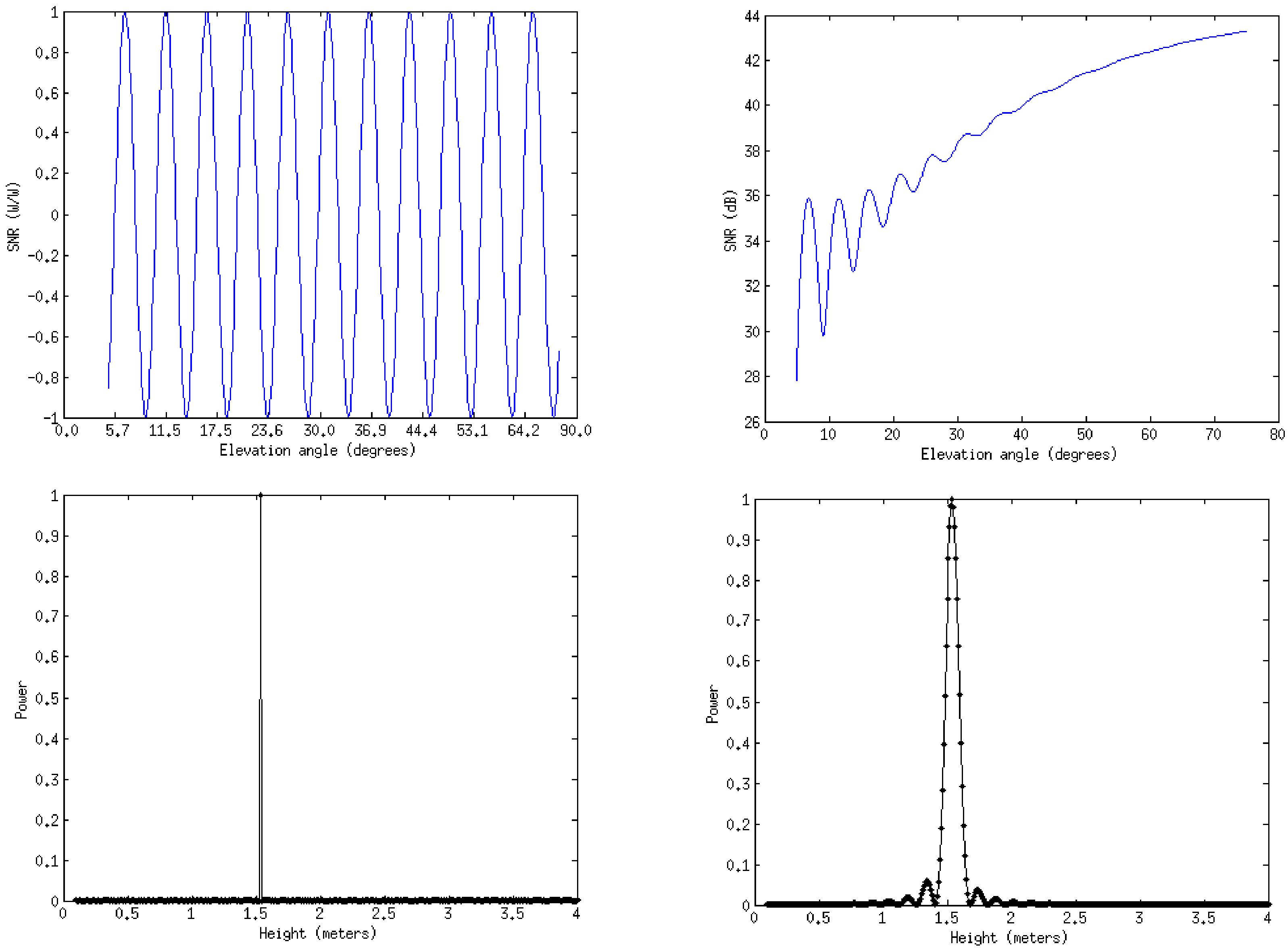
Antenna height



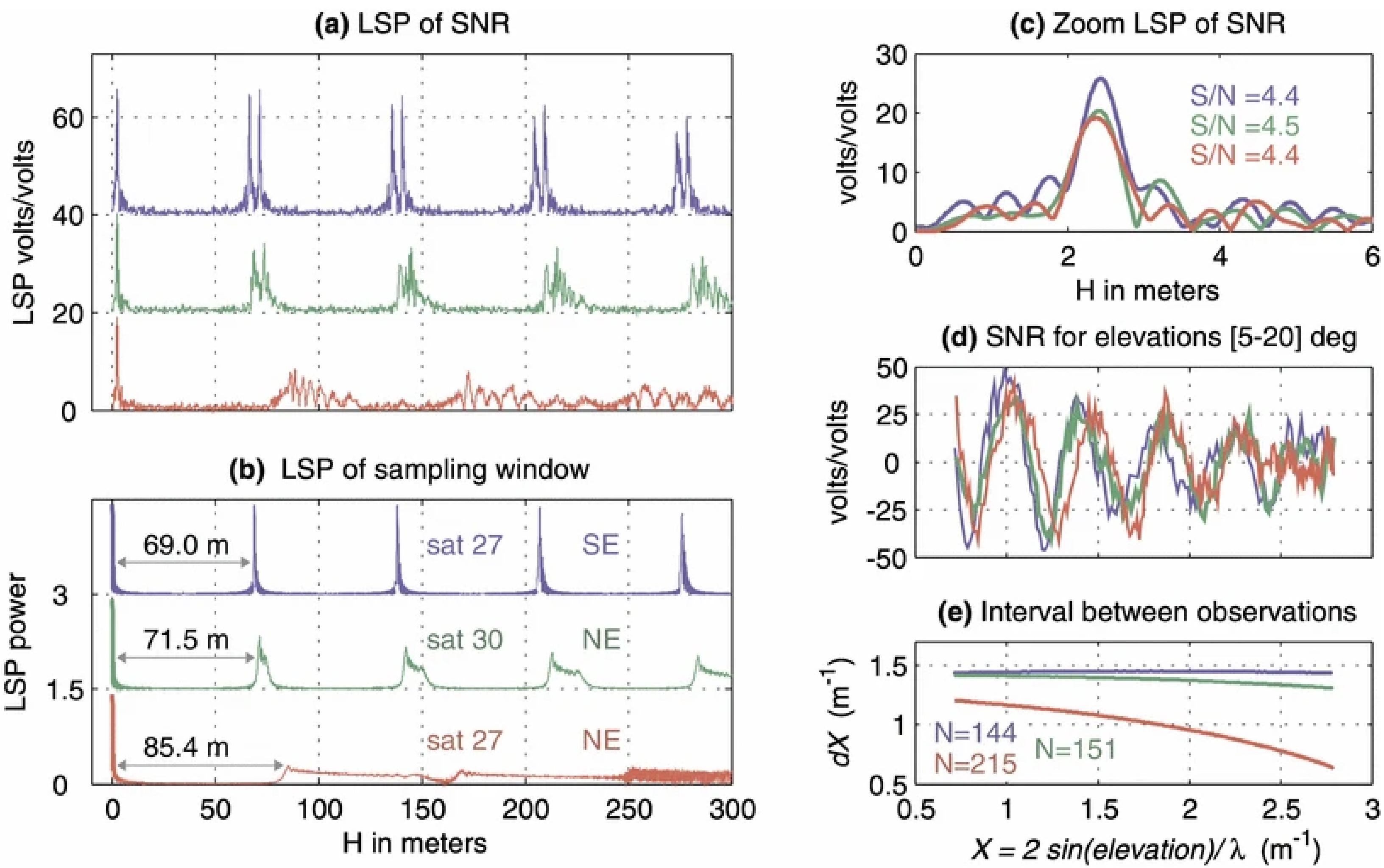
altimetry retrieval: $H = 0.5\lambda * N/(\sin(e_2)-\sin(e_1))$

water level: $L = -H + H_0$

Spectral analysis

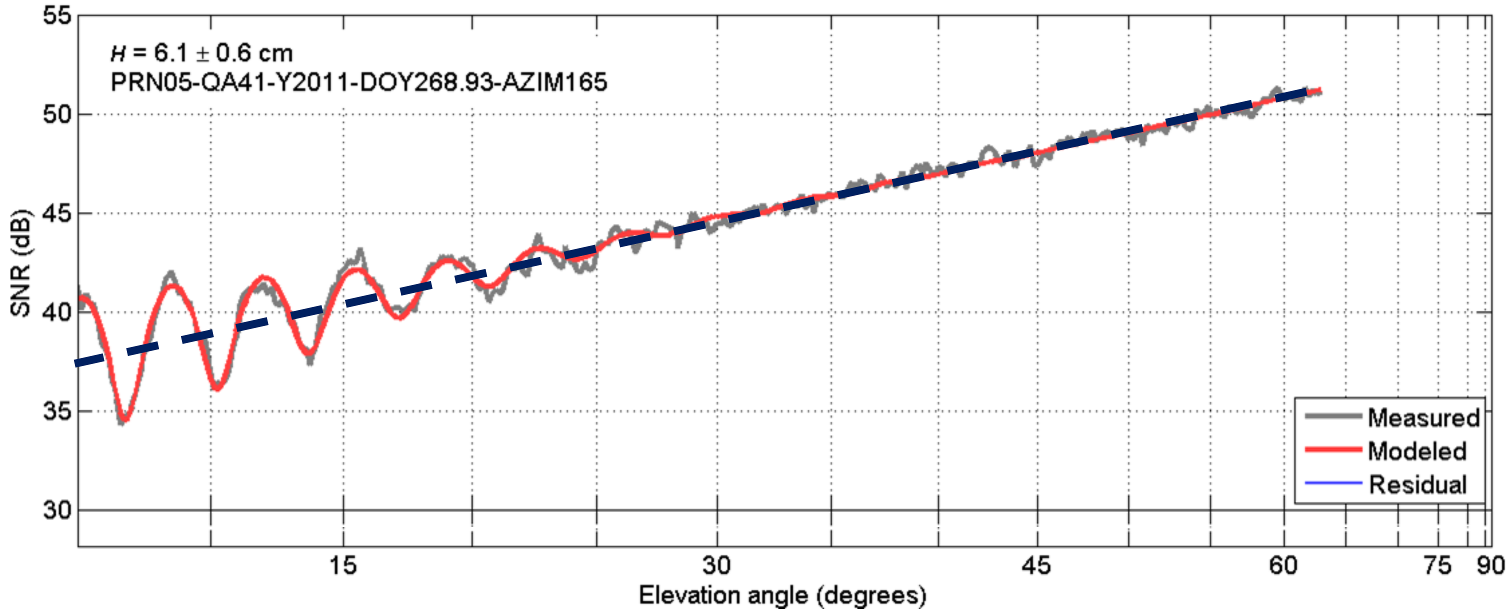


Maximum resolvable height
(~ Nyquist frequency)



(Roesler & Larson, 2018)
https://doi.org/10.1007/s10291-018-0744-8

SNR data fitting



total = trend + (damped) oscillations:

$S = \bar{S} + s$

$$\overline{S} = c_0 + c_1 k_z + c_2 k_z^2 + \cdots$$

$$s = A \cos\left(\widehat{H} k_z + \varphi\right)$$

$$k_z = 4\pi\lambda^{-1} \sin e = 2k \sin e$$

Empirical—physical model matching

trend ~ antenna gain pattern

$$\overline{S} \approx P_d(1+P_i)N_0^{-1},\ s \approx 2P_dP_i^{0.5}N_0^{-1}\cos\phi_i$$

oscillation ~ reflection

$$c_1 \approx \mathrm{E}\{S/k_z\},\ c_0 \approx \mathrm{E}\{S - c_1k_z\}$$

amplitude ~ roughness

$$A \approx (2\mathrm{Var}\{s-\overline{s}\})^{0.5} \approx \mathrm{E}\{2P_dP_i^{0.5}N_0^{-1}\}$$

Phase rate ~ reflector height

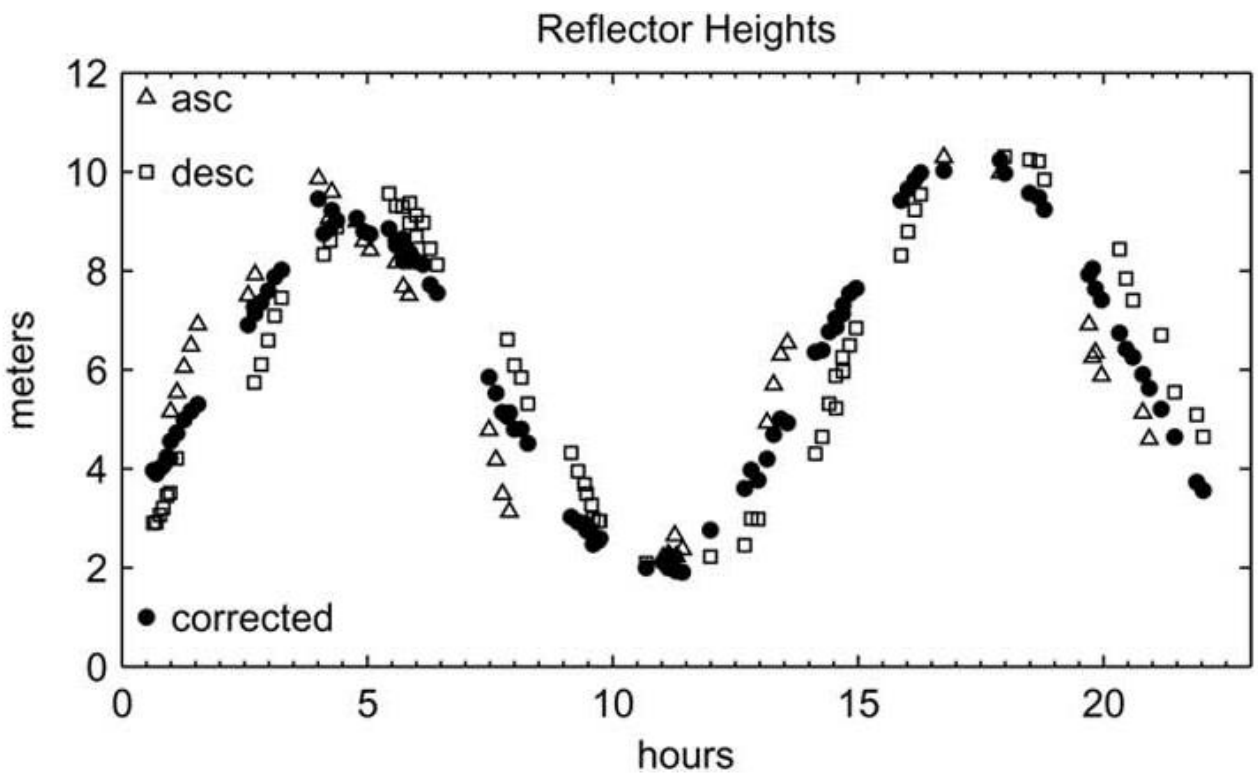
$$\widehat{H} \approx \mathrm{E}\{\partial\phi_i/\partial k_z\},\ \varphi \approx \mathrm{E}\left\{\phi_i - \widehat{H}k_z\right\}$$

$$\widehat{H} \approx H + \mathrm{E}\{\partial\phi_X/\partial k_z + \cdots\}$$

Altimetry retrieval will be primarily geometric height plus small non-geometric terms: vertical velocity, tropo. refraction, antenna radiation pattern, etc.

Vertical velocity or height rate bias

$$\widehat{H} = H + \dot{H}\tan(e)/\dot{e}$$



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