# GNSS Reflectometry Fundamentals

Prof. James L Garrison
Purdue University

*African Capacity Building Workshop*
*on Space Weather Effects on GNSS*
*ICTP, Trieste, Italy*
*11 October, 2022*

# Reflectometry: The Basic Concept

**Bistatic** radar with **passive** receiver.
Re-use of transmissions from **non-cooperative sources** operated for other purposes (e.g. **navigation** or communications)

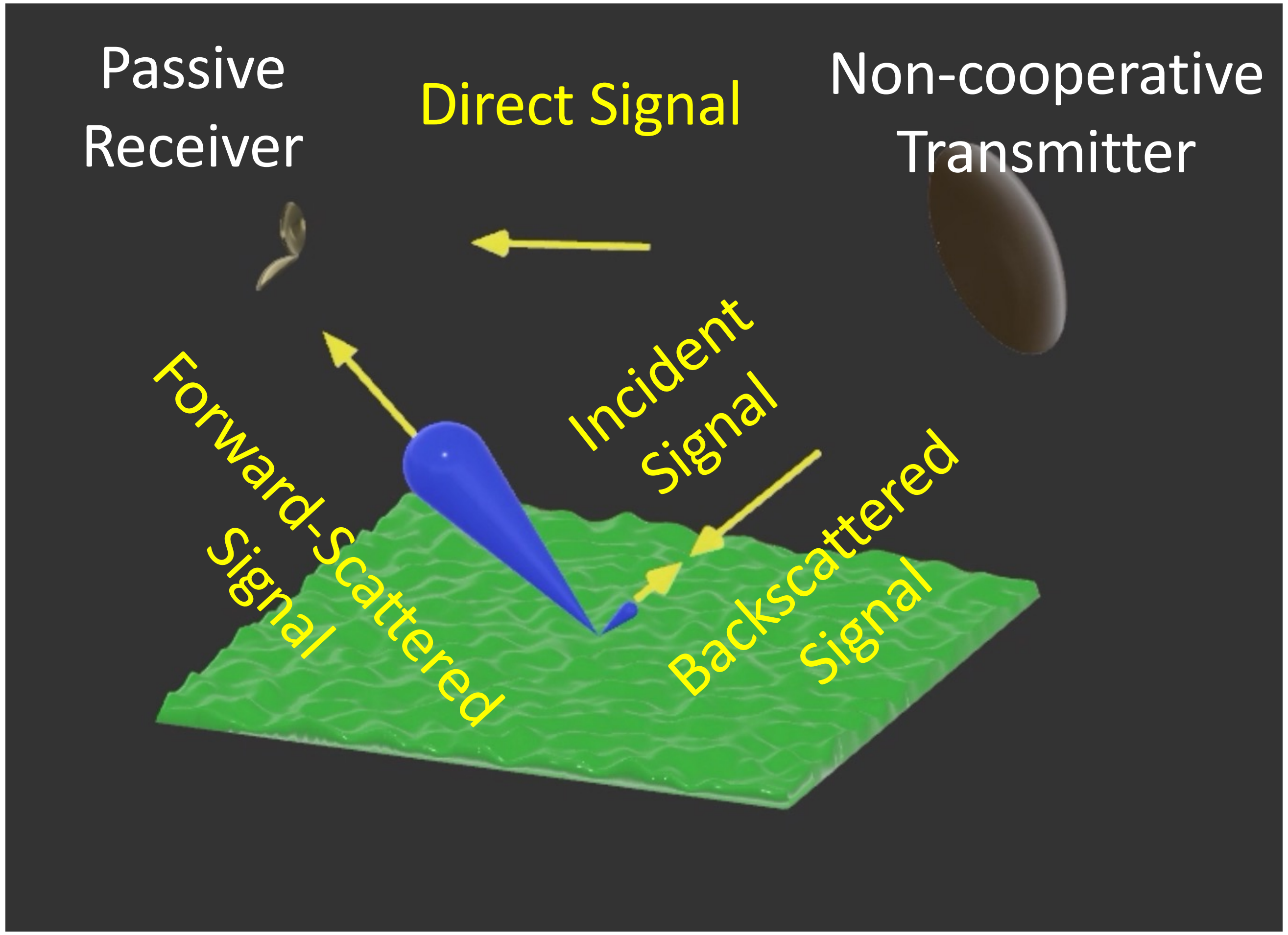
Definitions:

- GNSS-R = Global Navigation Satellite System Reflectometry
- SoOp-R = Signals of Opportunity Reflectometry

GNSS+R = {{GNSS-R} U {SoOp-R}}

# Reflectometry: The Basic Concept

- **Observables:**
  - **Reflectivity**
  - **Phase**
  - **Coherence**
  - **Delay-Doppler Map (DDM)**
- **Geophysical Retrievals:**
  - **Ocean winds**
  - **Altimetry (SSH)**
  - **Surface Soil Moisture**
  - **Wetlands extent**
  - **Sea Ice extent**
  - **Biomass (AGB), etc …**



# A brief history

# Pre-history of Reflectometry

[Tyler & Simpson (1970) Radio Science 10.1029/RS005i002p00263
Tyler (1968) JGR 10.1029/JB073i024p07609]
- Scatter of comm. link from Moon (Explorer-35) received at Earth.
- Estimate of Regolith thickness and large-scale surface roughness

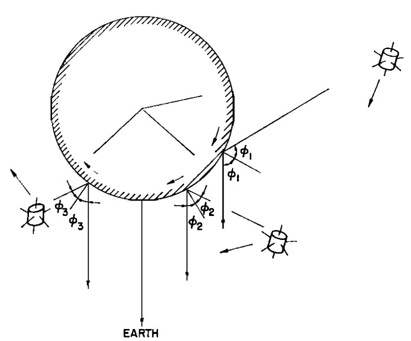



Fig. 1. Experimental geometry of moon and spacecraft.

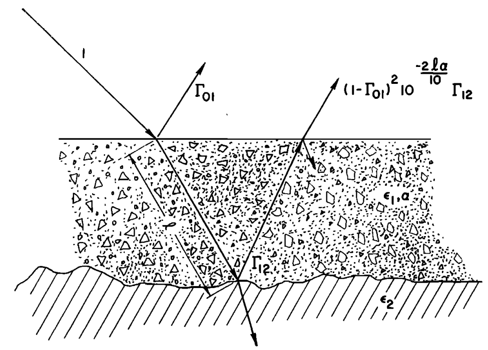


Fig. 8. Model for incoherently reflecting layers.

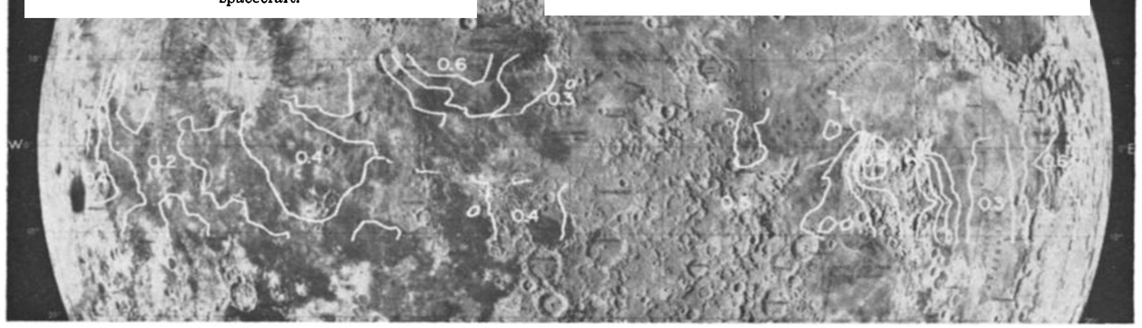



Fig. 4. Slope contours normalized to 0.1 radian. The 0.3 in Mare Fecunditatis indicates values of $h_0/d_0$ between 0.03 and 0.04 (1.7° to 2.2°) unidirectional rms slope. Only those contours within 0.1 lunar radius of data points (cf. Figure 1) are shown.

[Sutton, et al.,(1973) 10.1109/TCOM.1973.1091693]
- Satellite to Aircraft – study of ocean scatter multipath effects on communications
- Show relationship between bandwidth & roughness

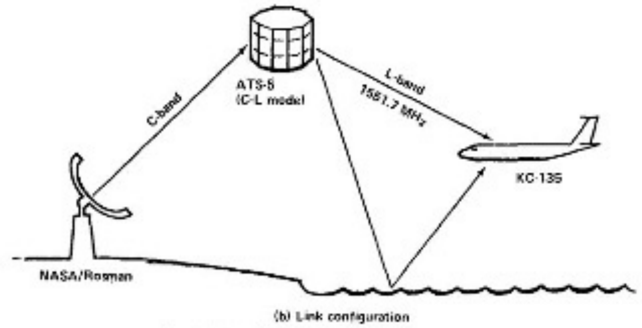



Fig. 1. Experiment implementation.

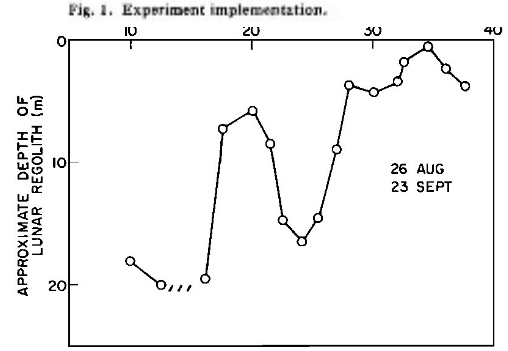
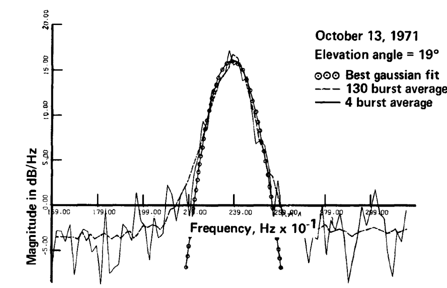
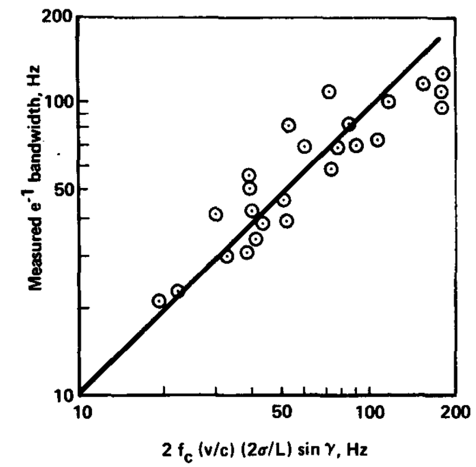



Fig. 9. Estimated depth of lunar debris for tracks of August 26 and September 23, 1967.



# Pre-history of Reflectometry(2)

[Hall & Cordey, (1988) 10.1109/IGARSS.1988.570200]

- Ocean scatterometry using GPS ***backscatte***r
- “incapable of giving useful performance”

| BACKSCATTER CROSSSECTION $\sigma^o_B$ (dB) | Kp (%) GPSS C/A code | POSSIBLE NEW SYSTEM C/A code | long code |
|---|---|---|---|
| 0 | 23 | 13 | 2 |
| -5 | 45 | 13 | 2 |
| -10 | 113 | 14 | 3 |
| -15 | 563 | 16 | 6 |
| -20 | 1011 | 23 | 13 |

| SYSTEM PARAMETERS name | symbol | unit | | | |
|---|---|---|---|---|---|
| Transmit Power | $P_{Tx}$ | (W) | 25 | 2500 | 2500 |
| Code Length | $M_{code}$ | (-) | 1023 | 1023 | long |
| No of Transmitters | $n_{Tx}$ | (-) | | 3 | |
| Losses (Tx) | $L_{Tx}$ | (dB) | | 1.5 | |
| Pulse Length | $\tau_p$ | (us) | | 1 | |
| Ground Resolution | $\rho_g$ | (m) | | 300 | |
| Incidence Angle | $i$ | (deg) | | 50 | |
| Wavelength | $\lambda$ | (m) | | 0.19 | |
| Range, Rx to ground | $R$ | (km) | | 1150 | |
| Integration Time | $\tau_i$ | (ms) | | 22 | |
| Losses (at) | $L_{at}$ | (dB) | | 0.5 | |
| Eff Signal Window | $\tau_{obs}$ | (us) | | 595 | |
| Eff Noise Window | $\tau_{noise}$ | (us) | | 595 | |
| Antenna Diameter | $D$ | (m) | | 4 | |
| Losses (Rx) | $L_{Rx}$ | (dB) | | 1.0 | |
| Noise Figure | $F_N$ | (dB) | | 2.0 | |

TABLE 1 PERFORMANCE OF CANDIDATE SCATTEROMETERS

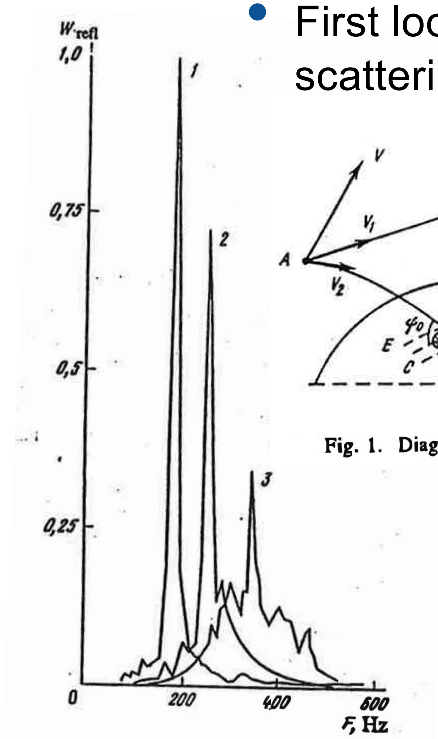
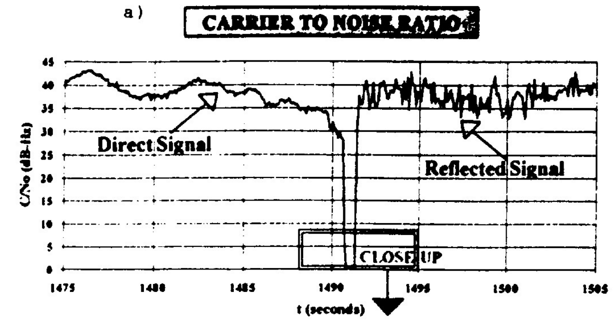



Fig. 2. Typical reflected signal spectra.

[Auber, et al., (1994) ION GPS]

- Observed ocean-reflected signals tracked by airborne receiver – leading to navigation solution errors
- First look at modeling rough surface scattering effect on PRN-coded signals



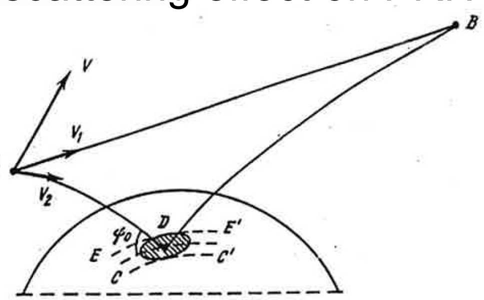




Fig. 1. Diagram of bistatic radar experiment.

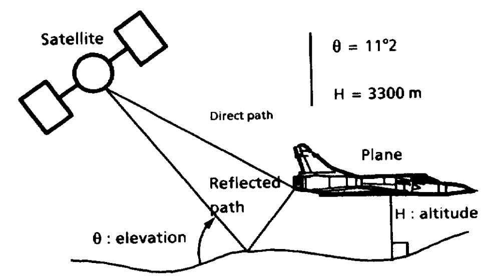
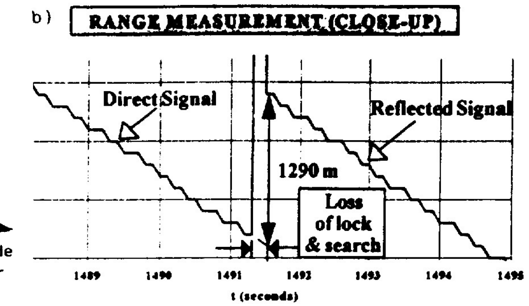
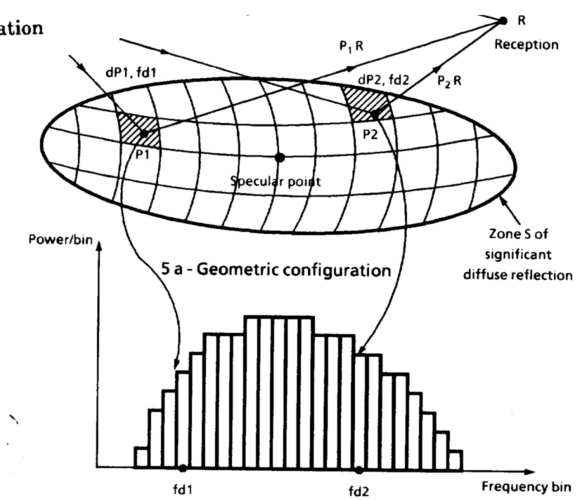



Figure 2 : Geometrical configuration




[Rubashkin, et al., J. Comm. Tech. & Elec. 1993]

- LEO transmitter, GEO receiver.
- Observed spectrum widening on ocean reflection

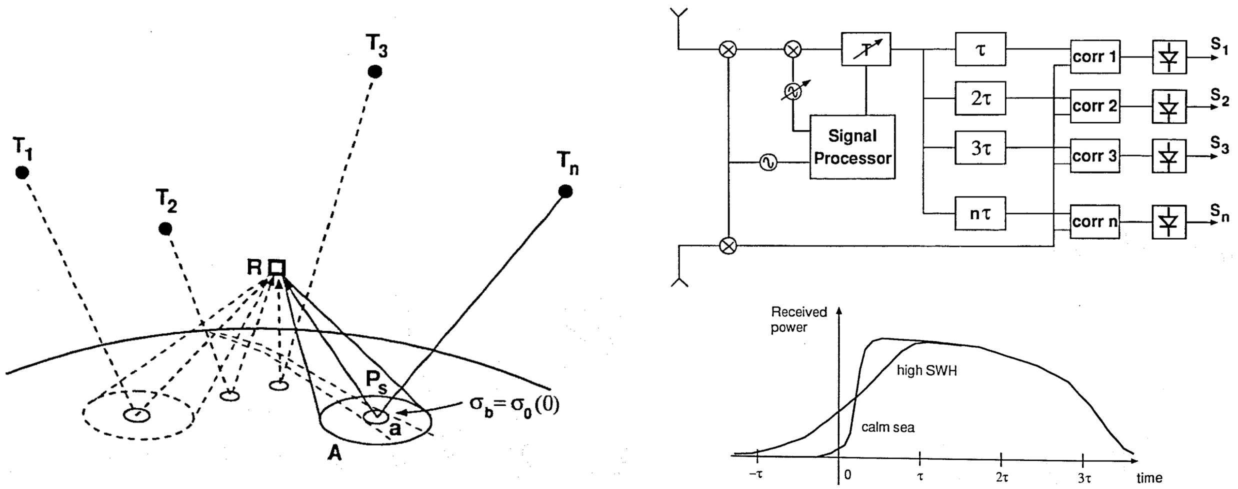



5 b - Corresponding spectra fd2

# First demonstrations of GNSS-R

## ...as presently used

- **Forward scatter**
- **Delay-Doppler correlation**



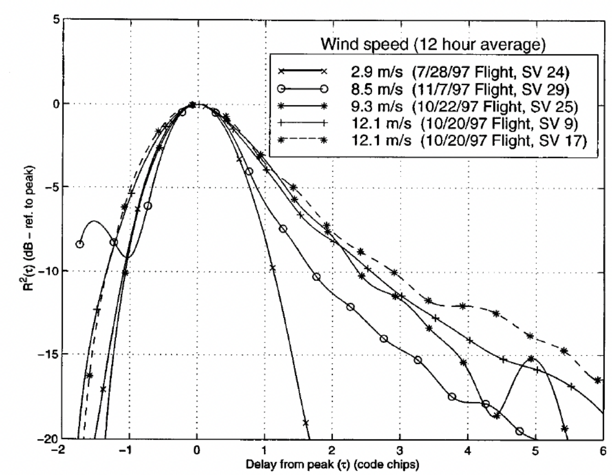

[Martin-Neira, M. (1993) ESA Journal]

- GNSS Altimetry
- Identified many of the key features developed later

NASA Technical Memorandum 4750

Utilizing GPS To Determine Ionospheric Delay Over the Ocean

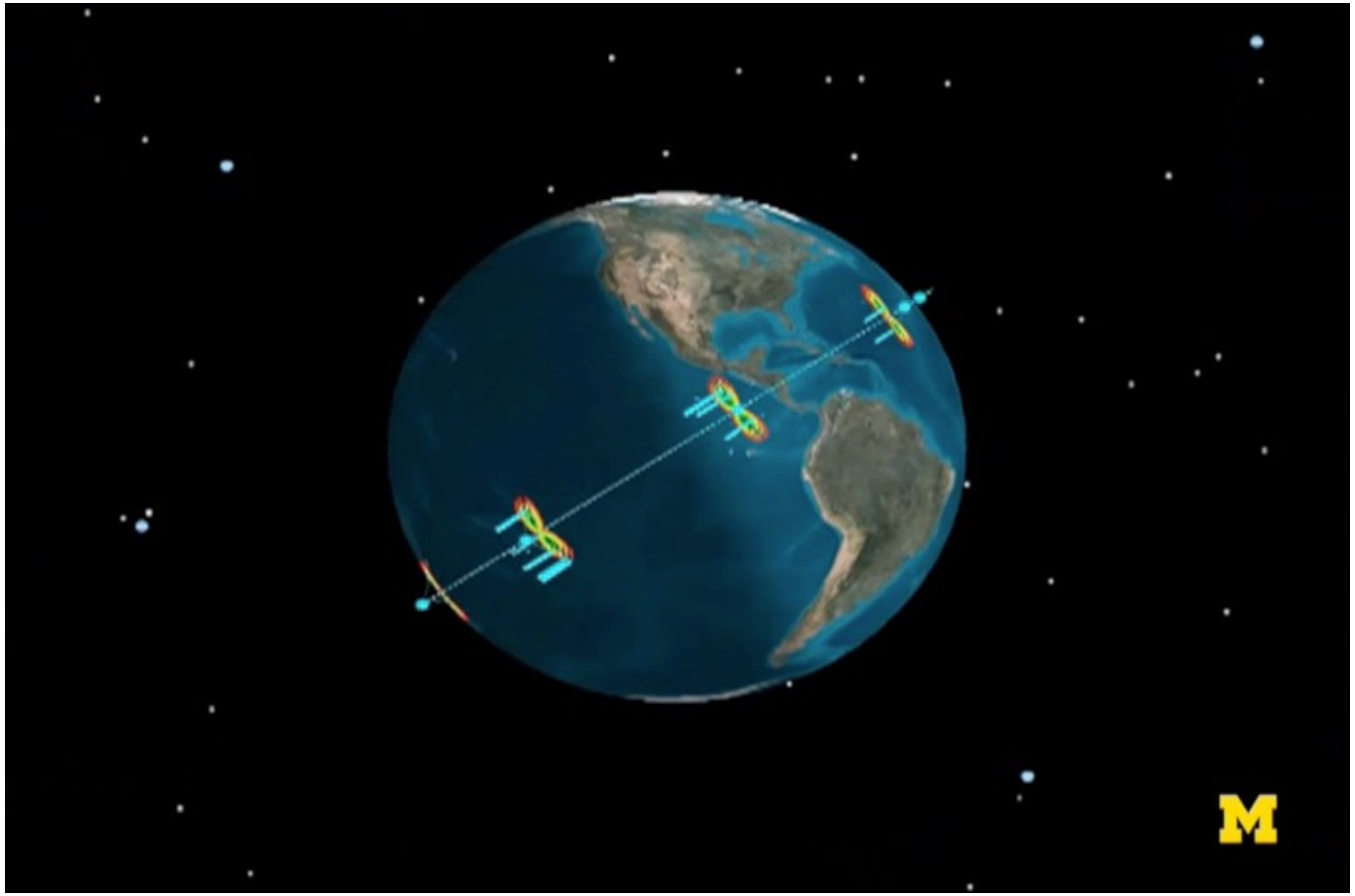
*Stephen J. Katzberg and James L. Garrison, Jr.*
*Langley Research Center • Hampton, Virginia*

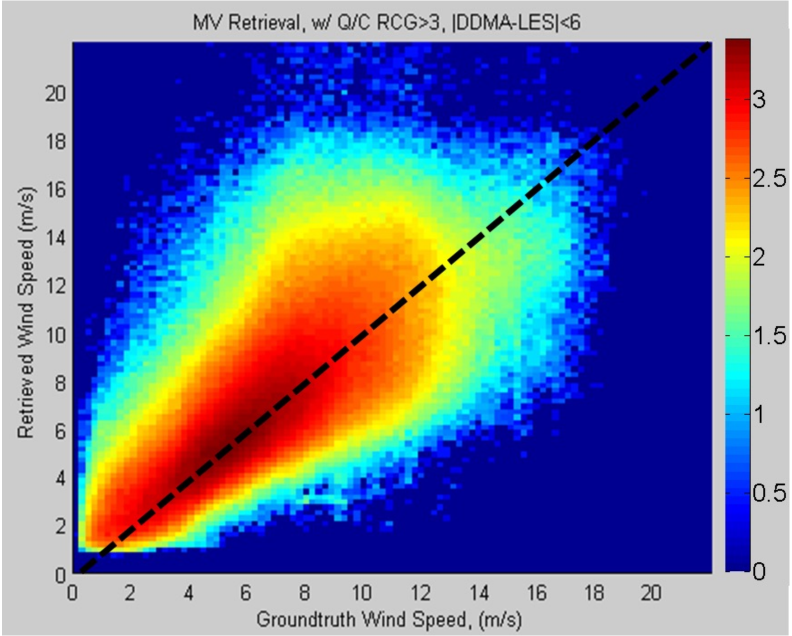



[Katzberg & Garrison NASA TM-4750 (1996)]
[Garrison, et al., GRL (1998), 10.1029/98GL51615]

- Prototype receiver
- First measurements of DDM “spreading” with roughness

# CYGNSS (Launch 2016)



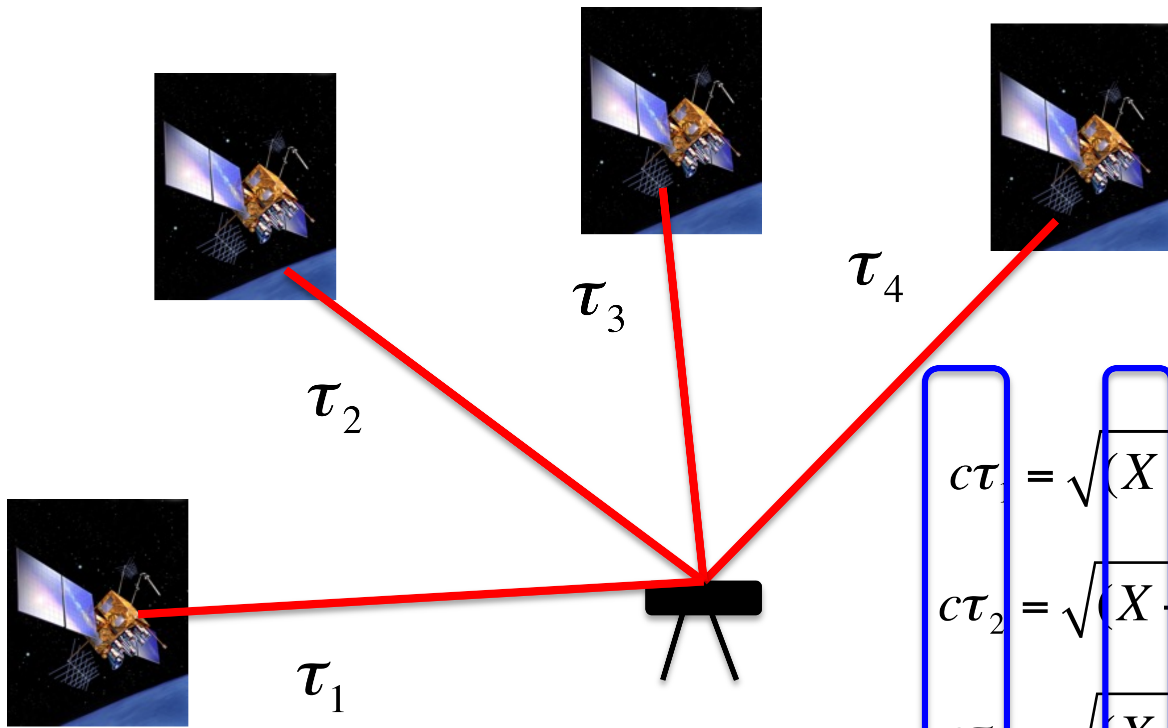




[JSTARS, 2018, DOI:10.1109/JSTARS.2018.2833075]

https://www.youtube.com/watch?time_continue=1&v=rRBqn6JPtv8

# Fundamentals of GNSS (review)

# Fundamentals of GNSS




4+ Observations

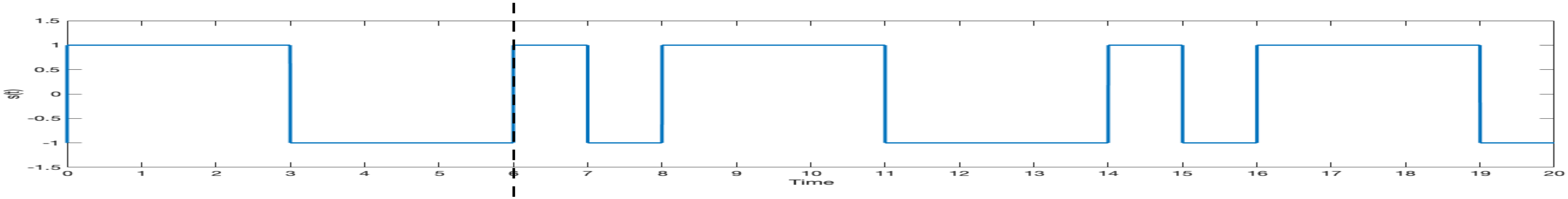
4 Unknowns

$$c\tau_1 = \sqrt{(X - X_1)^2 + (Y - Y_1)^2 + (Z - Z_1)^2} + ct_b$$
$$c\tau_2 = \sqrt{(X - X_2)^2 + (Y - Y_2)^2 + (Z - Z_2)^2} + ct_b$$
$$c\tau_3 = \sqrt{(X - X_3)^2 + (Y - Y_3)^2 + (Z - Z_3)^2} + ct_b$$
$$c\tau_4 = \sqrt{(X - X_4)^2 + (Y - Y_4)^2 + (Z - Z_4)^2} + ct_b$$

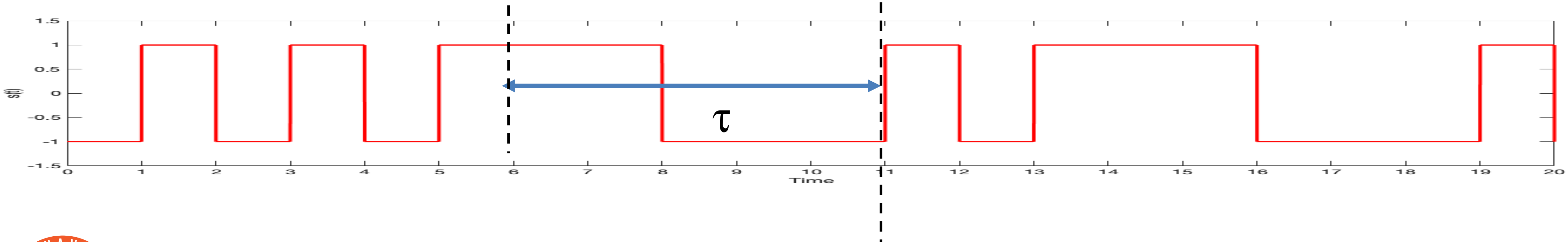
**How is delay measured ?**

# How is delay measured ?

Transmitter: Ideal ***infinitely-long***, ***random*** sequence of pulses
(P{-1}=P{+1}=0.5)

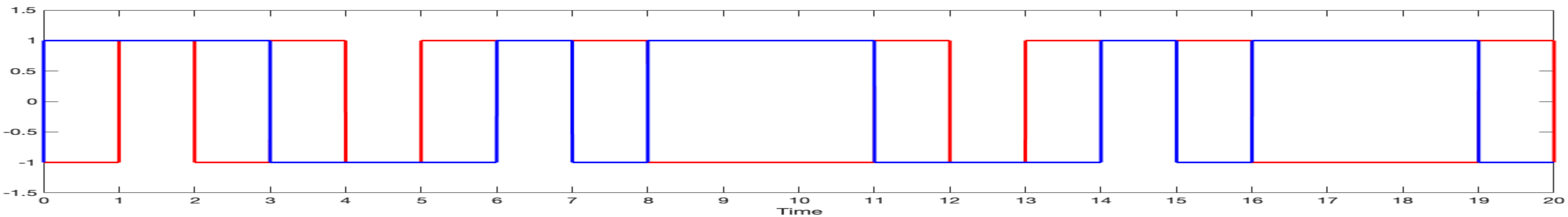



Delay (τ) in propagation to receiver:

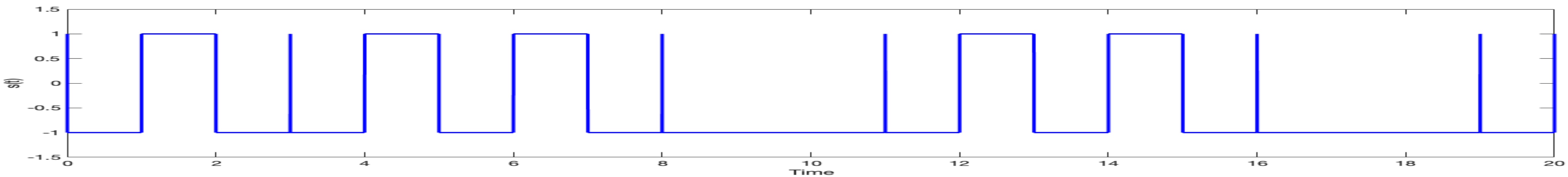


# How is delay measured ?

Receiver – generates ***identical local copy*** of signal (blue)




Multiples it with received signal (red)




For product: P{-1}=P{+1}=0.5, **Sum=0**

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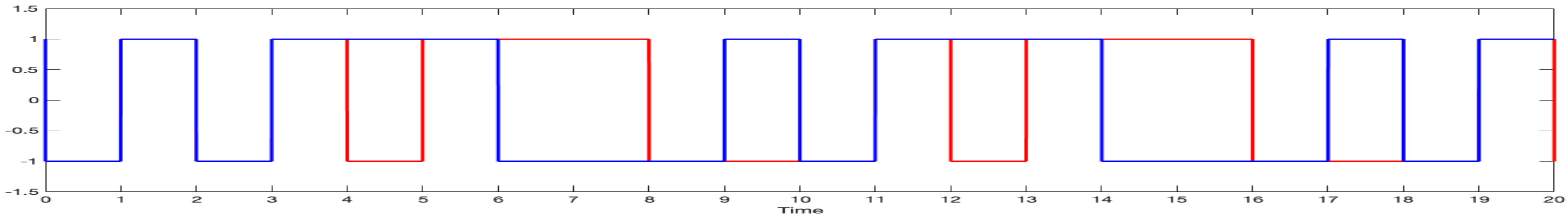
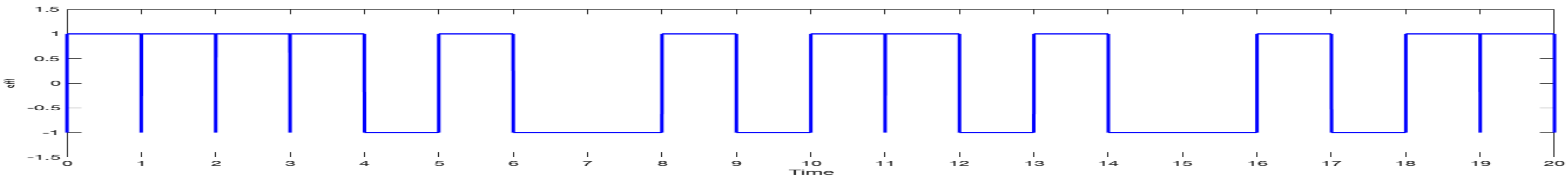
# How is delay measured ?

Receiver – varies delay of local copy (blue)




Multiples it with received signal (red)




$\tau$=1 $T_c$: P{-1}=P{+1}=0.5, **Sum=0**

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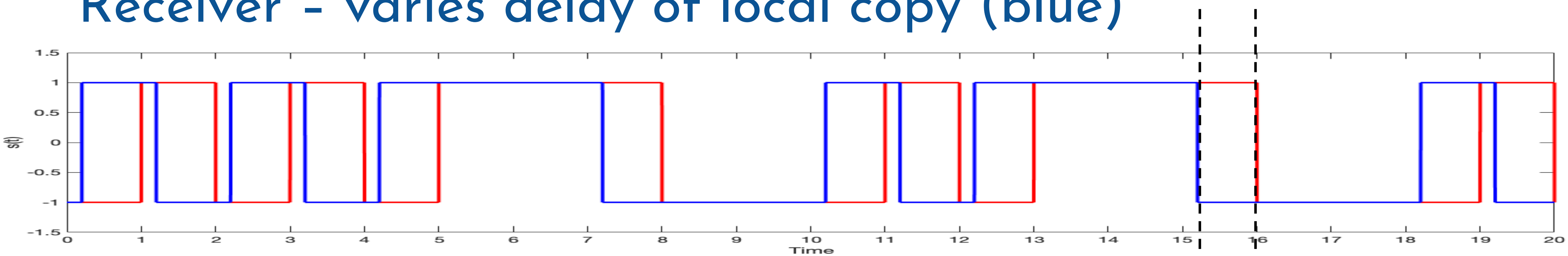
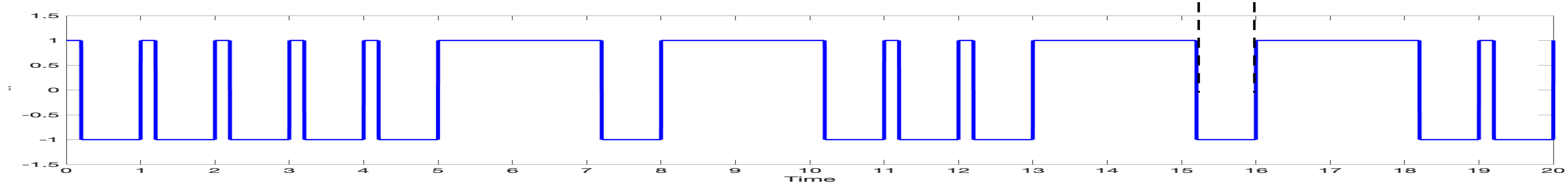
# How is delay measured ?

Receiver – varies delay of local copy (blue)



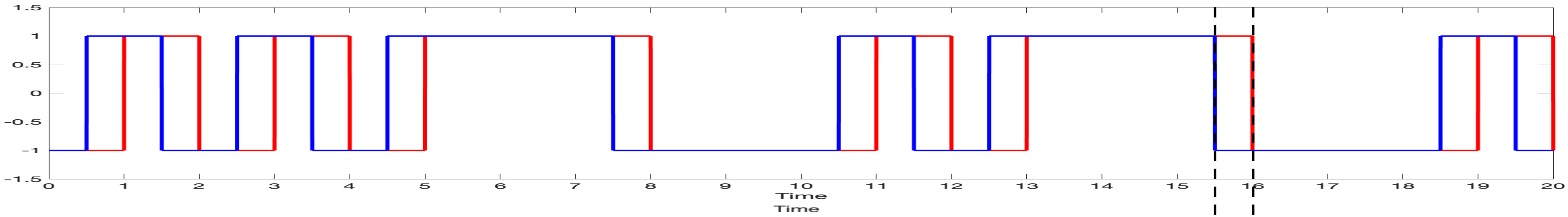

Multiples it with received signal (red)



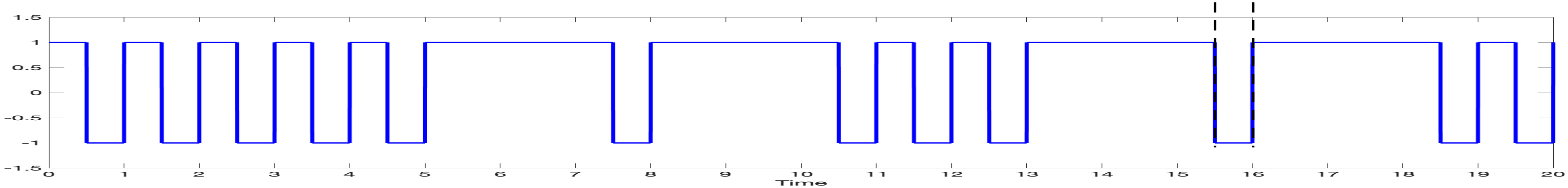

$\tau$=0.9 Tc: Sum=0.1(1) + 0.9(0) = **0.1**

# How is delay measured ?

## Receiver – varies delay of local copy (blue)




## Multiples it with received signal (red)




$\tau$=0.5 Tc:  Sum=0.5(1) + 0.5(0) = **0.5**

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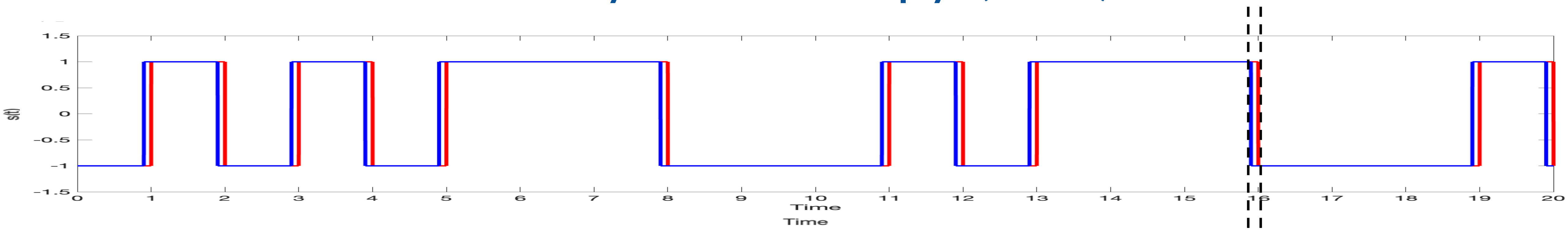
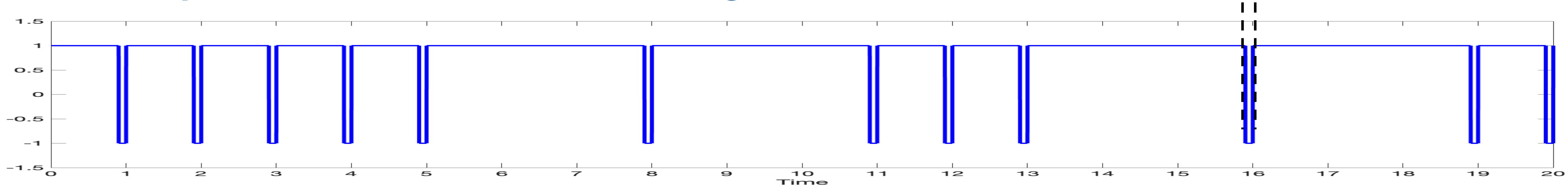
# How is delay measured ?

Receiver – varies delay of local copy (blue)




Multiples it with received signal (red)




$\tau=0.05\ T_c$: Sum=0.95(1) + 0.5(0) = **0.95**

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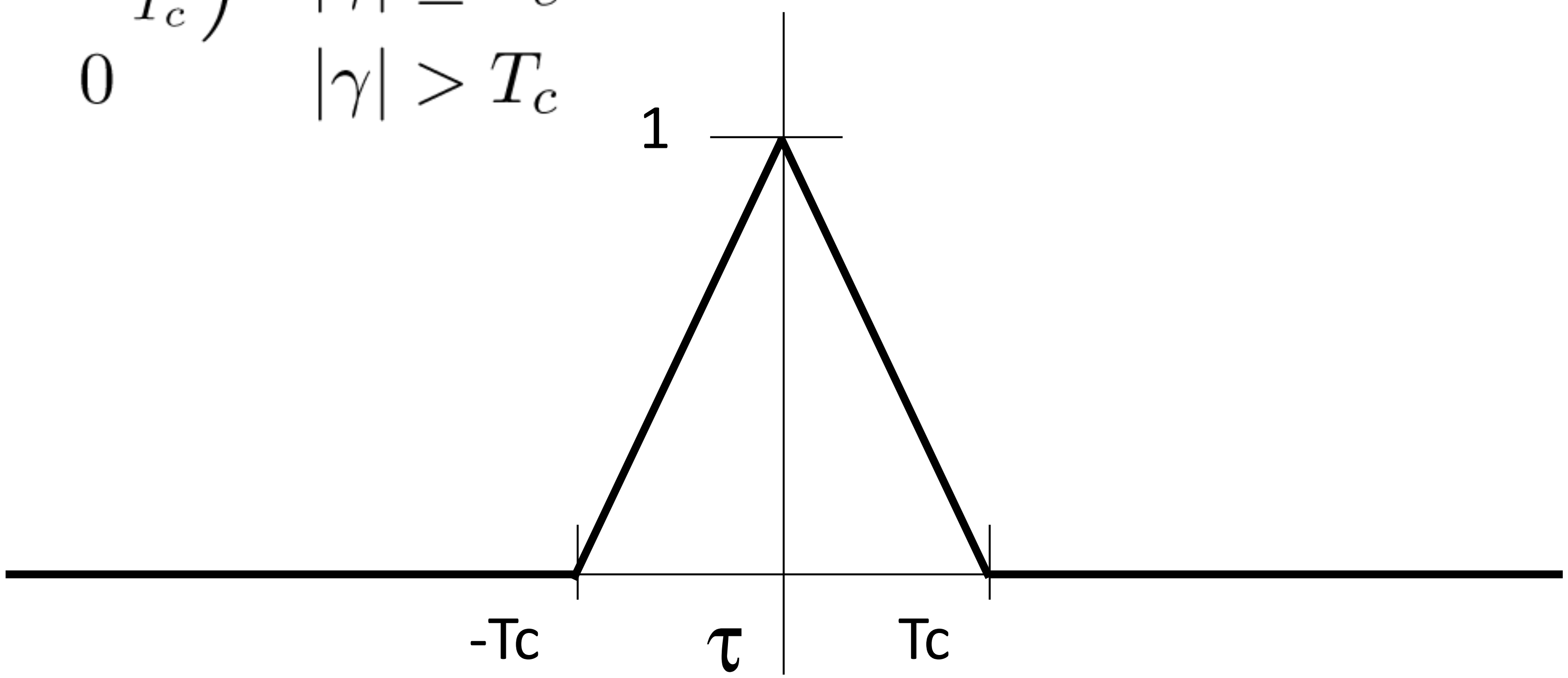
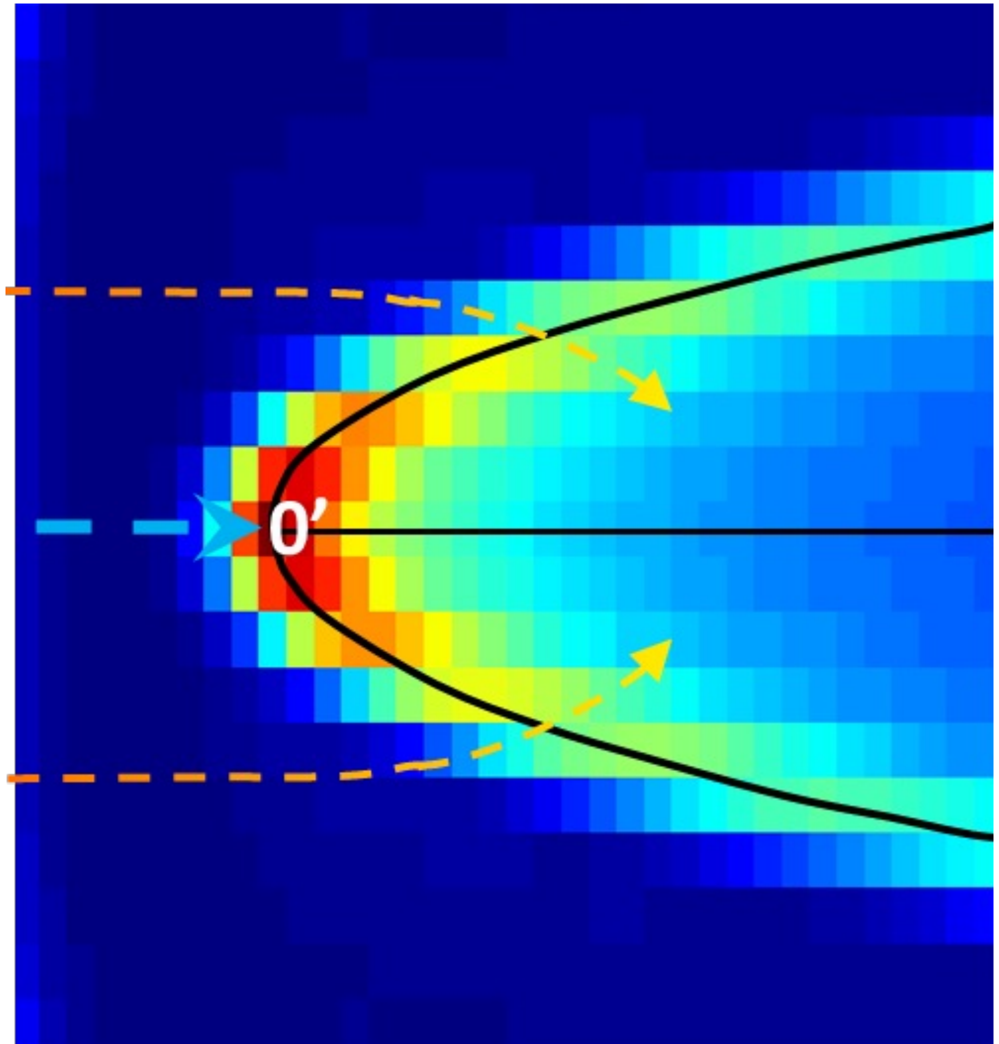
# Auto- and Cross-correlation

## This is the mathematical process of *correlation*

$$R_s(\gamma) = \begin{cases} \left(1 - \frac{|\gamma|}{T_c}\right) & |\gamma| \leq T_c \\ 0 & |\gamma| > T_c \end{cases}$$

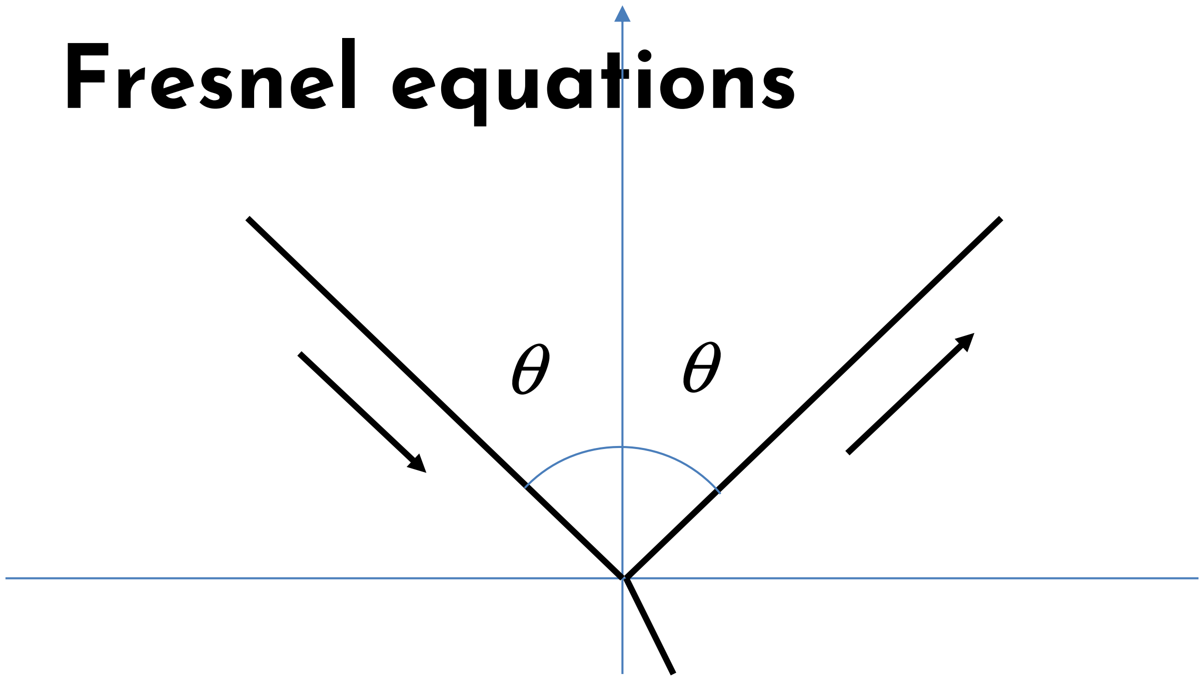





# From GNSS to GNSS+R

# Reflection from smooth surface

## Fresnel equations




$$\mathcal{R}_{HH} = \frac{\cos\theta - \sqrt{\varepsilon_r - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}}$$

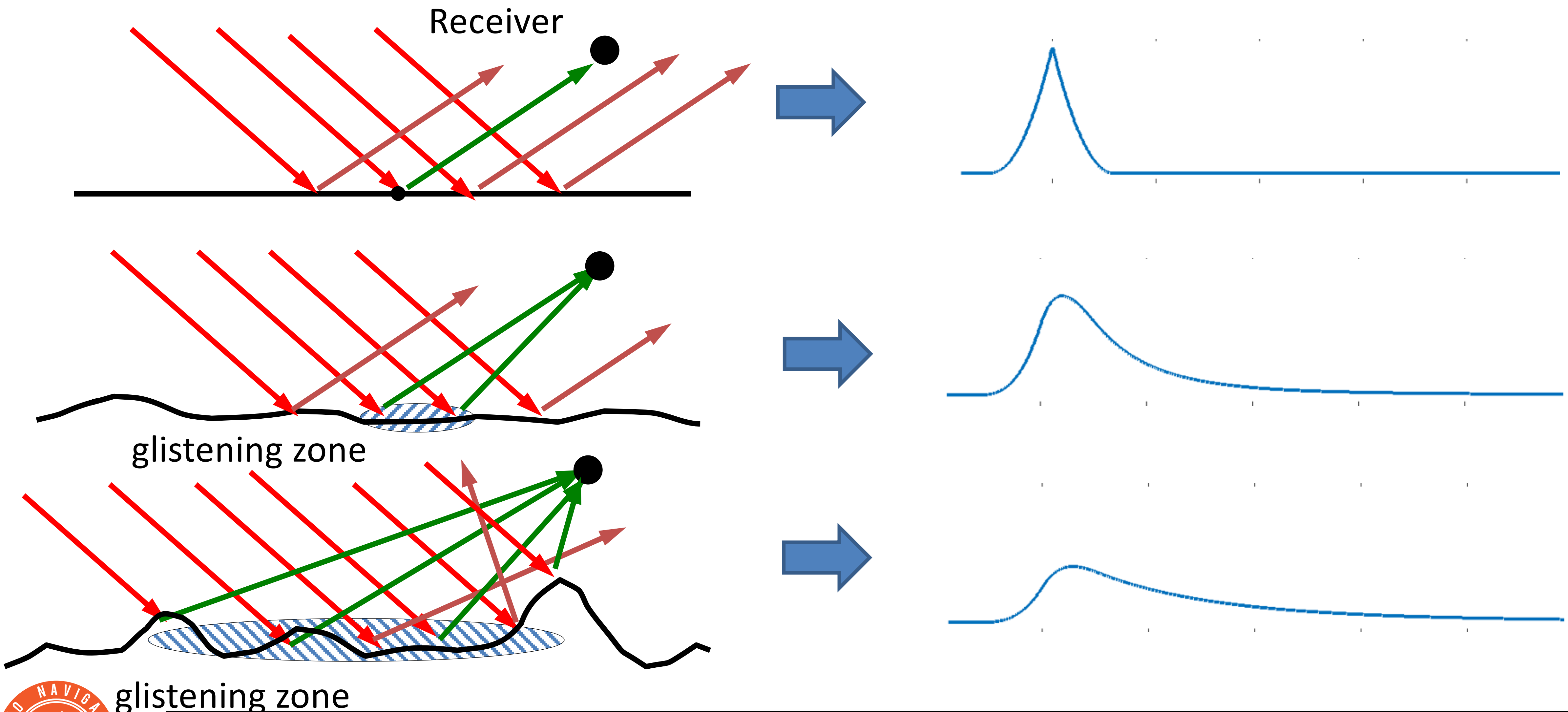
$$\mathcal{R}_{VV} = \frac{\varepsilon_r\cos\theta - \sqrt{\varepsilon_r - \sin^2\theta}}{\varepsilon_r\cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}},$$

$$\begin{bmatrix} \mathcal{R}_{LL} & \mathcal{R}_{LR} \\ \mathcal{R}_{RL} & \mathcal{R}_{RR} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} \mathcal{R}_{HH} + \mathcal{R}_{VV} & \mathcal{R}_{HH} - \mathcal{R}_{VV} \\ \mathcal{R}_{HH} - \mathcal{R}_{VV} & \mathcal{R}_{HH} + \mathcal{R}_{VV} \end{bmatrix}$$

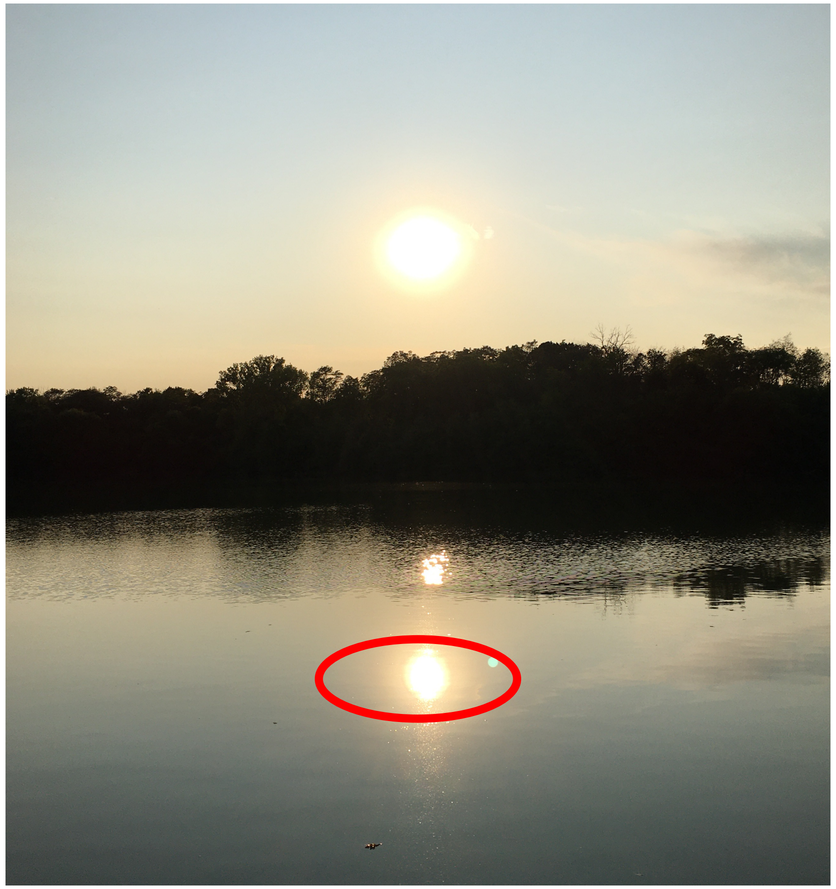
## Dielectric constant ($\varepsilon_r$) function of surface properties:

- Land: Surface soil moisture, VWC, roughness (small)
- Ocean: Salinity (SSS), temperature (SST)

# Reflection from a rough surface



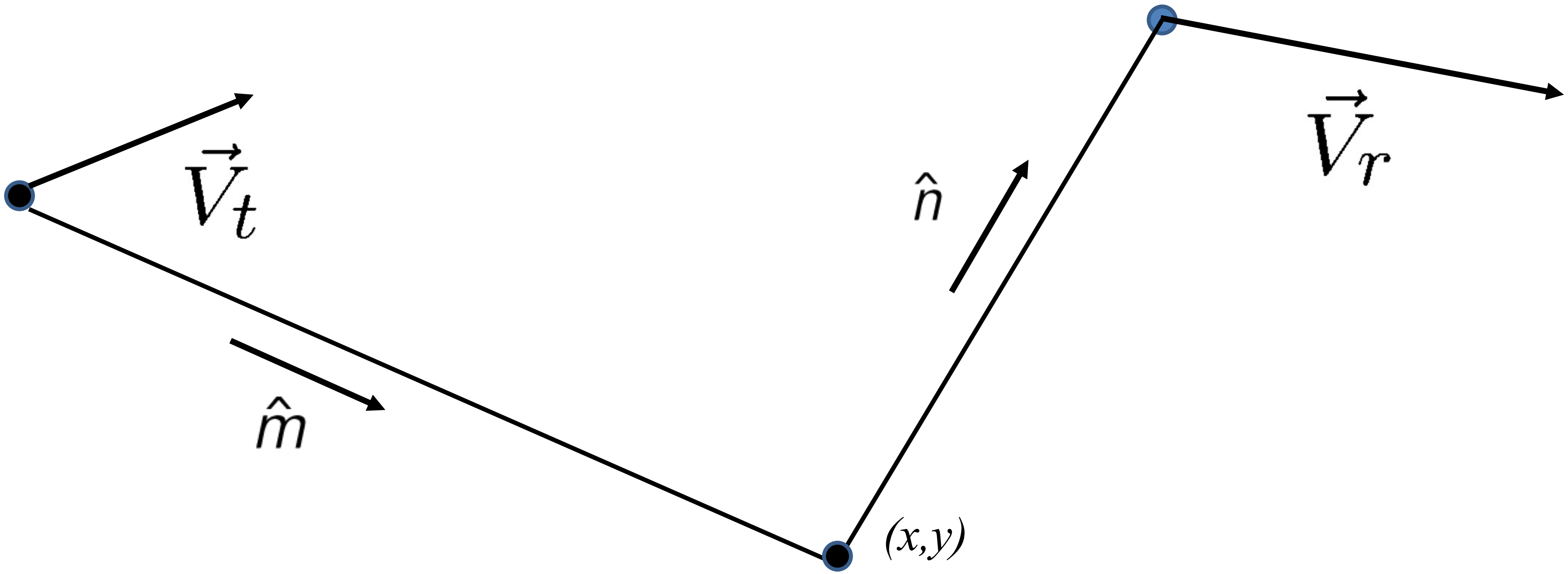
# Smooth (specular) vs rough (diffuse) scattering



(Photo taken 2020 Mays Lakes, Oak Brook, IL)

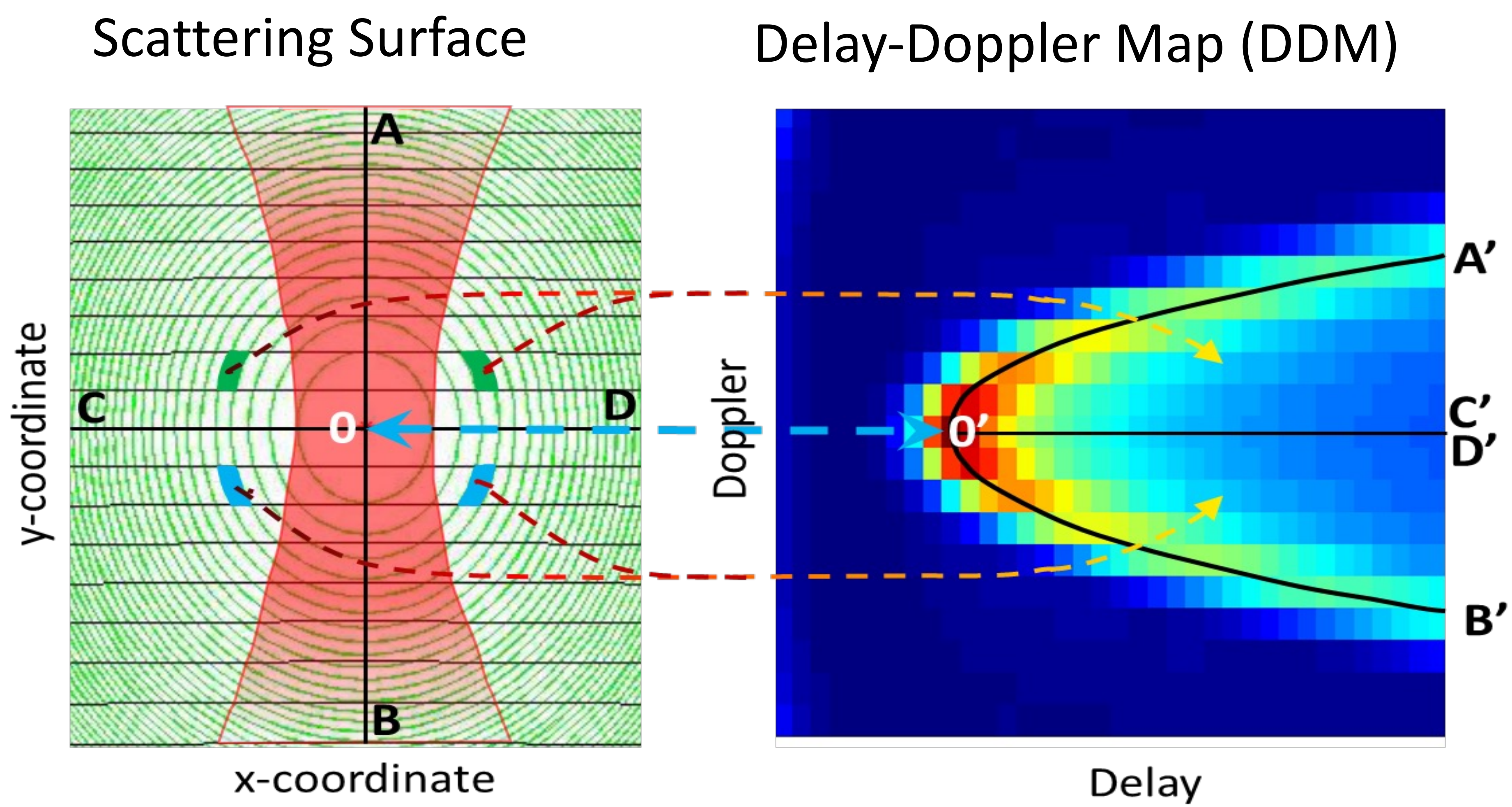
(Chapron and Ruffini, 2003 GNSS-R workshop, Barcelona. Photo taken at Le Conquet, Brittany)

# Doppler



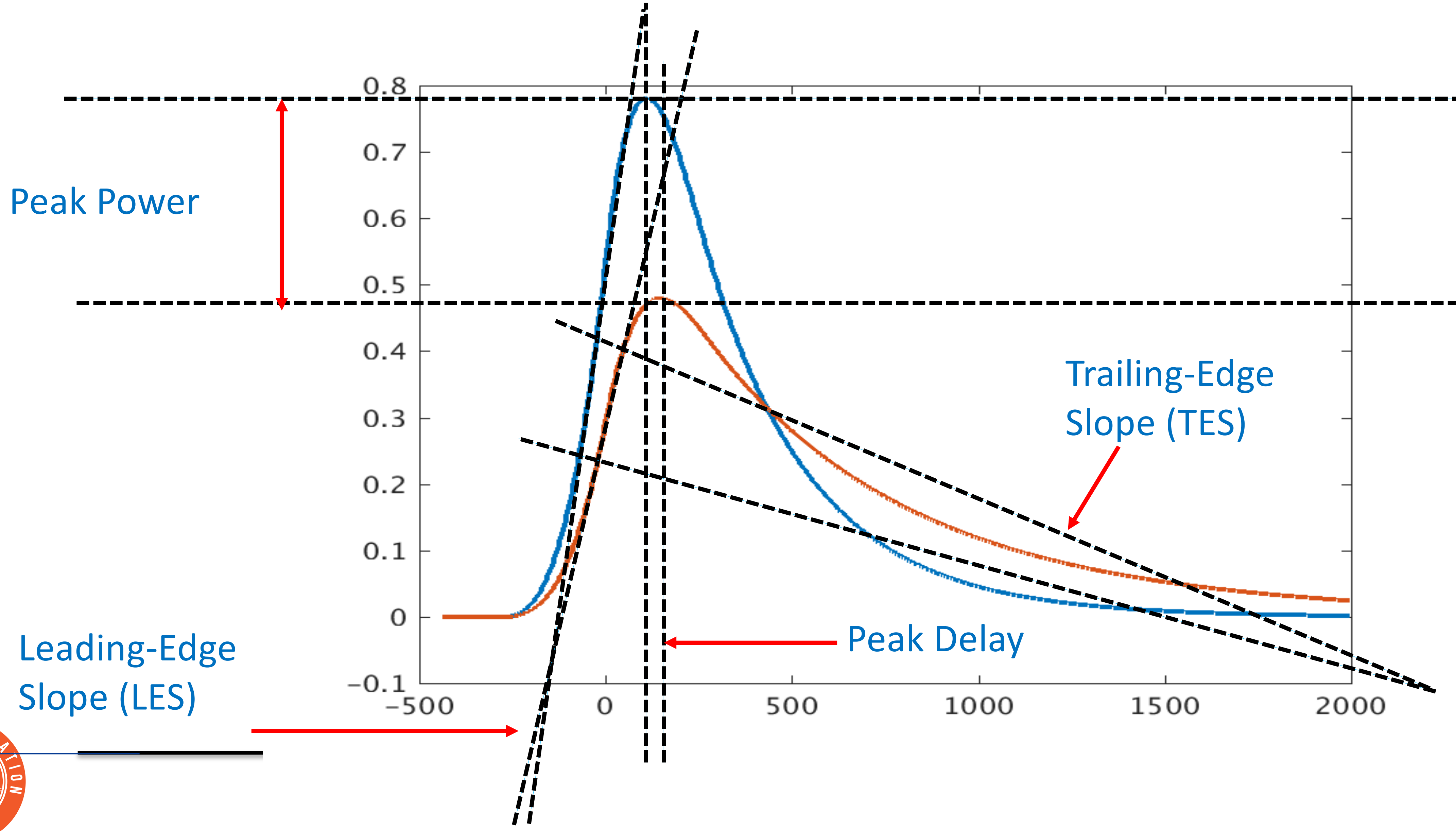

$$f_D(x,y) = \frac{1}{\lambda}\left[\vec{V}_t \cdot \hat{m}(x,y) - \vec{V}_r \cdot \hat{n}(x,y)\right]$$

# Delay-Doppler Map (DDM)

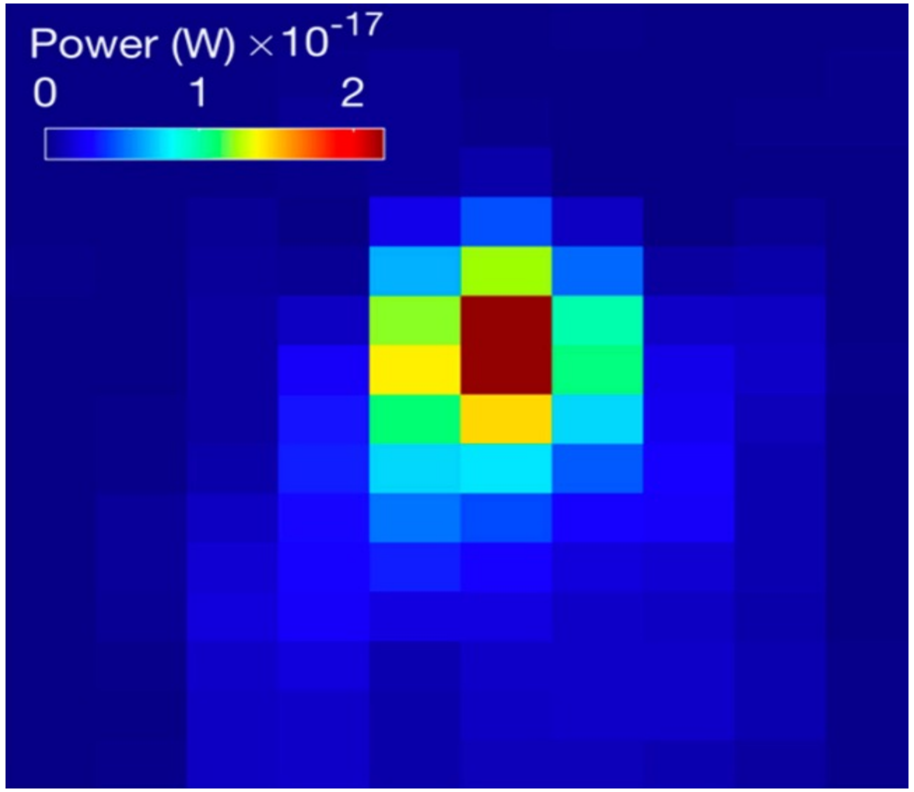



[Zavorotny, et al., IEEE GRSM DOI: 10.1109/MGRS.2014.2374220]

# Observables from the DDM



# Bistatic Radar Equation (BRE)



# Woodward Ambiguity Function (WAF)

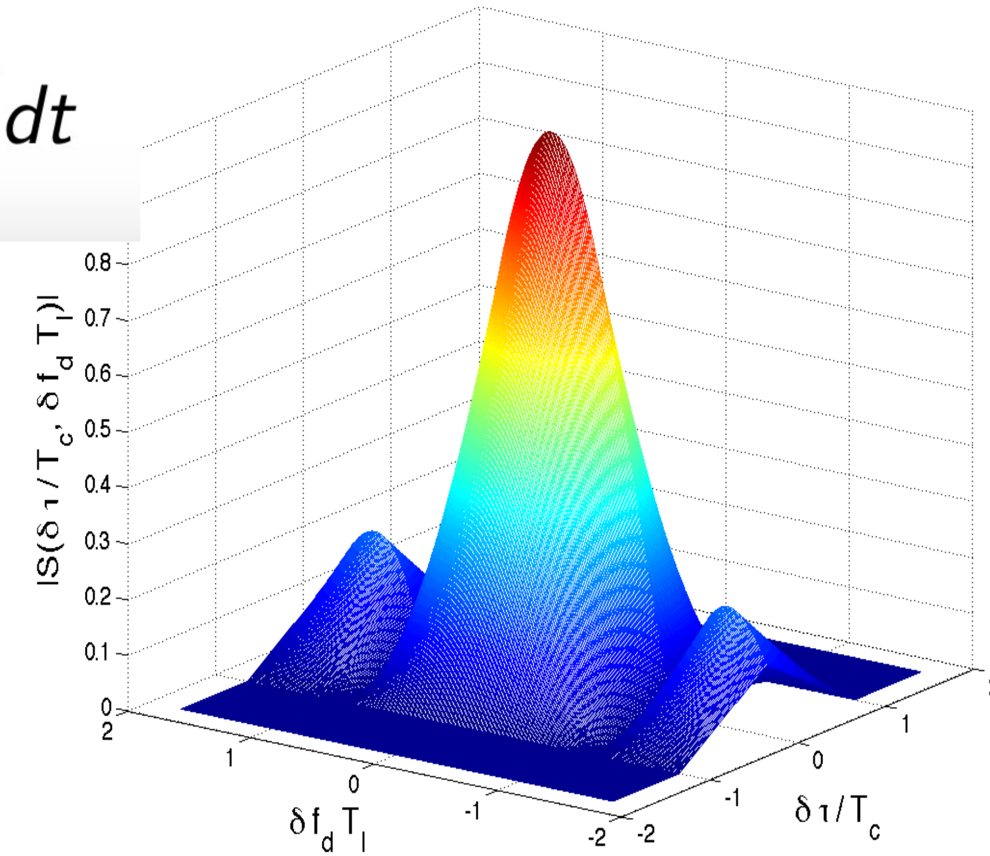
Key part of navigation signal design

$$\chi(\delta\tau, \delta f_D) = \frac{1}{T_I}\int s(t)s^*(t+\delta\tau)e^{-2\pi\delta f_D t j}dt$$

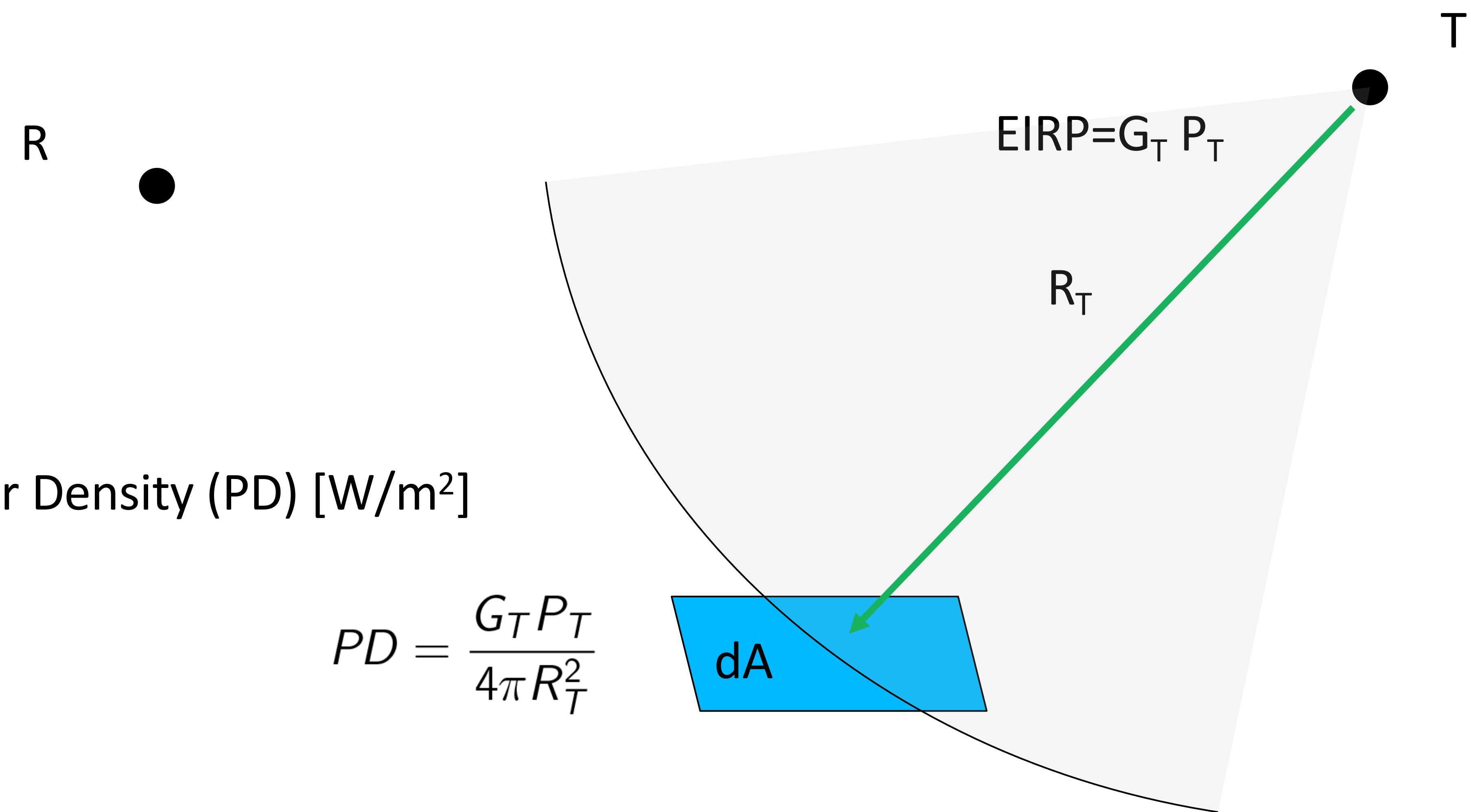
Response of correlation to delay & Doppler error

First nulls (for BPSK signal):

$$\delta\tau = \pm T_c \qquad \delta f_D = \pm\frac{1}{T_I}$$



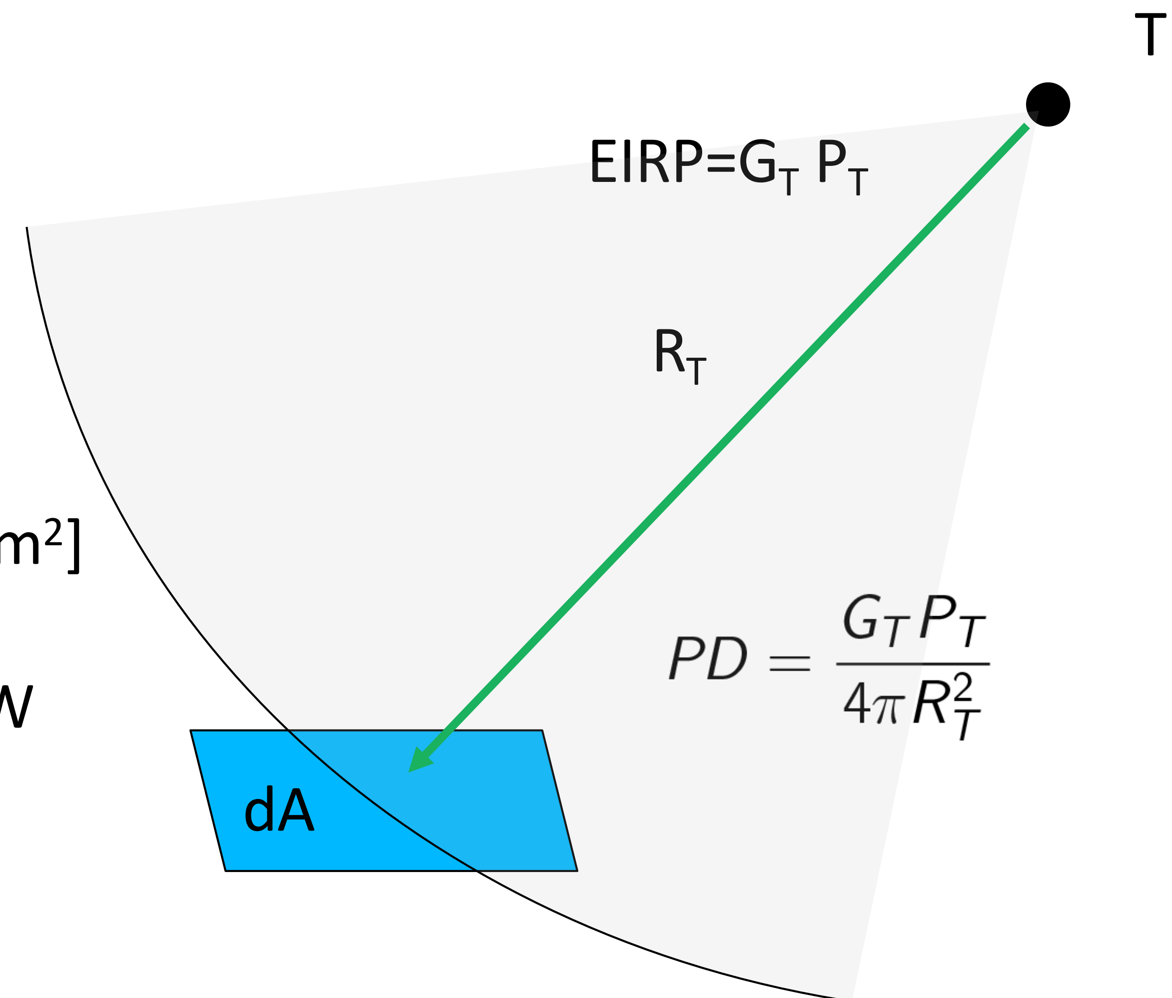
# Propagation for transmitter to surface




$$PD = \frac{G_T P_T}{4\pi R_T^2}$$

See [Zavorotny & Voronovich, TGARS, 2000,10.1109/36.841977] for more details

# Reflection from surface area dA



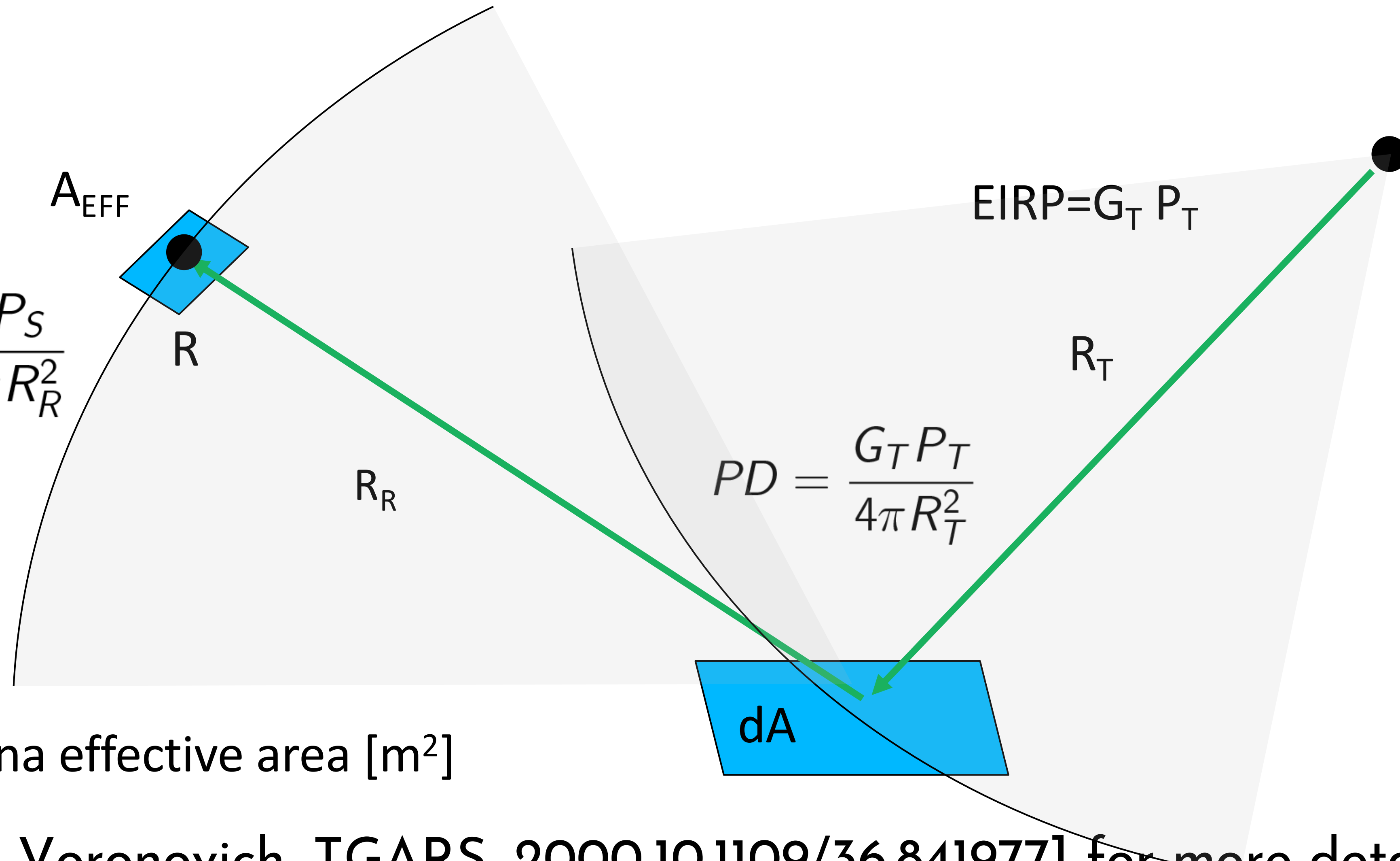

$\sigma^0$ = normalized bistatic cross-section [N.D.]

$\sigma^0 dA$ = Equivalent area of "perfect" reflector [$m^2$]

$$dP_S \propto \sigma^0 \, (PD) \, dA$$ [$W/m^2$] X [$m^2$]=W

See [Zavorotny & Voronovich, TGARS, 2000,10.1109/36.841977] for more details

# Propagation from Surface to Receiver




$$dP_R \propto \frac{dP_S}{4\pi R_R^2}$$

$$A_{EFF} = G_R \frac{\lambda^2}{4\pi}$$

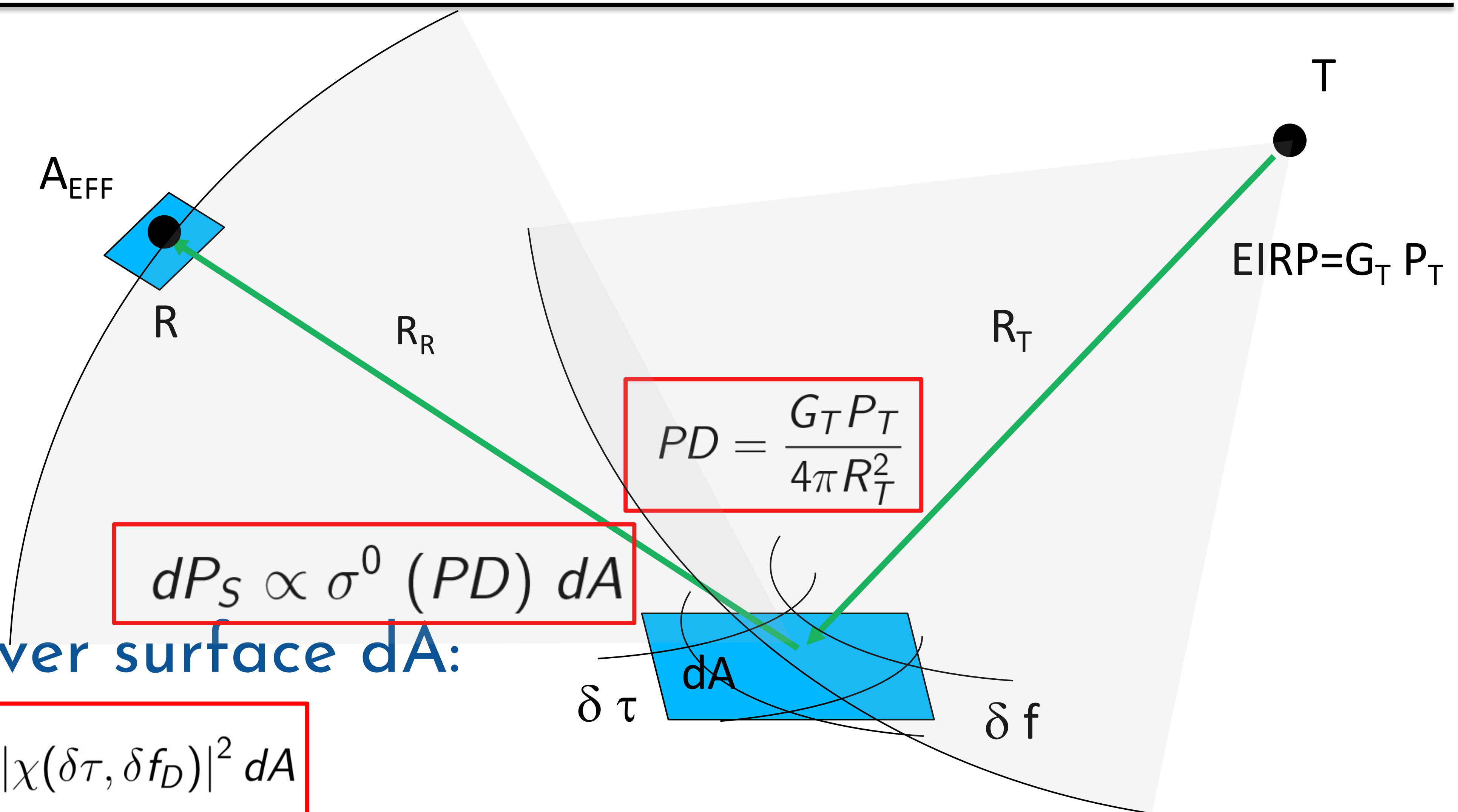
= Receiver antenna effective area [m²]

See [Zavorotny & Voronovich, TGARS, 2000,10.1109/36.841977] for more details

# Response of cross-correlation (WAF)

$$A_{EFF} = G_R \frac{\lambda^2}{4\pi}$$

$$dP_R \propto \frac{dP_S}{4\pi R_R^2}$$




$$PD = \frac{G_T P_T}{4\pi R_T^2}$$

$$dP_S \propto \sigma^0 \ (PD) \ dA$$

Integrate over surface dA:

$$P_R = \int\int |\chi(\delta\tau, \delta f_D)|^2 \, dA$$

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# Putting it all together …

Integral over surface

$$P_R \propto \int |\chi(\delta\tau, \delta f_D)|^2 \times G_R \times \frac{1}{R_R^2} \times \sigma^0 \times \frac{1}{R_T^2} dA$$

Masking of Surface by delay-Doppler mapping

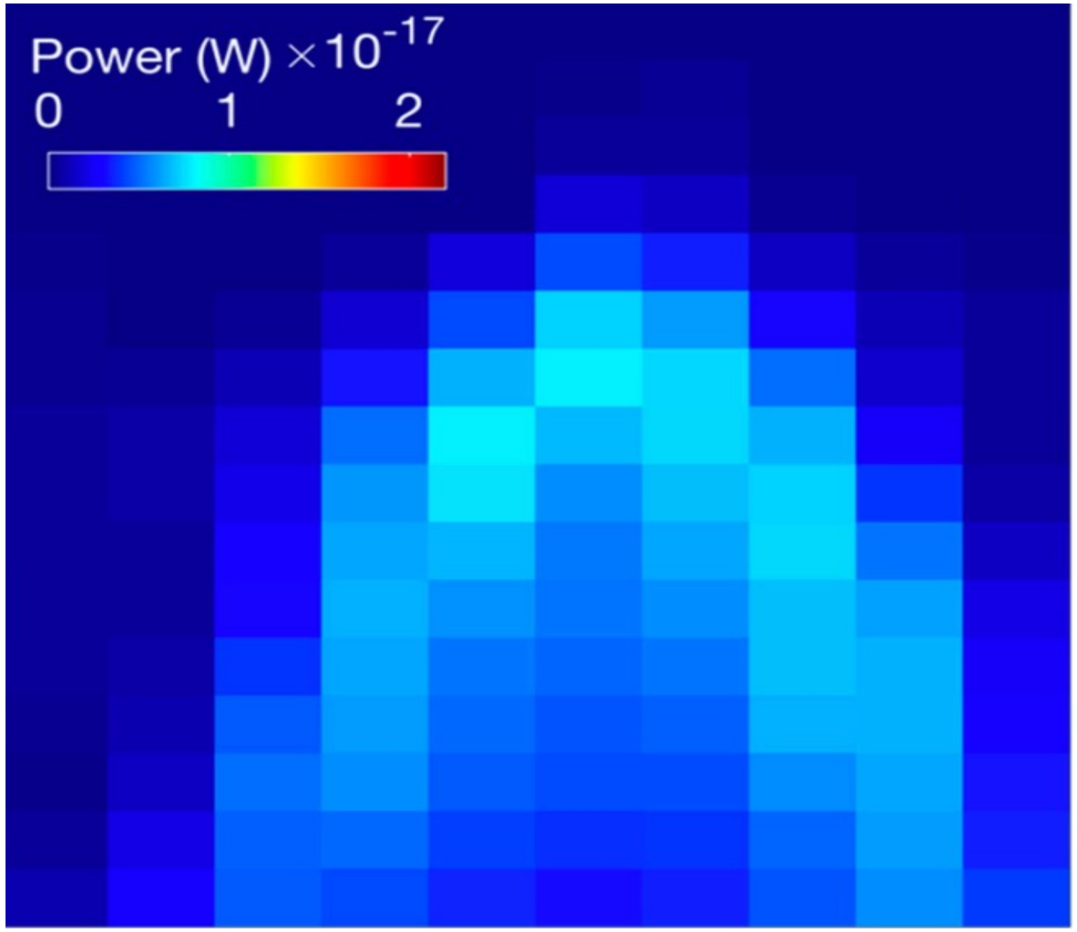
Masking of Surface by Receiver antenna

Path loss Surface-receiver

**Normalized Bistatic Radar Cross-section (NRBCS)**

Path loss Trans.-surface

RADIO NAVIGATION LAB




# Delay Doppler Maps (DDM)

# The complete result …

$$\langle |X(\tau,f)|^2 \rangle = \frac{\lambda^2 P_T G_T}{(4\pi)^3} \iint \frac{G_R |\chi(\Delta\tau, \Delta f)|^2}{R^2 R_0^2} \sigma_{pq}^0\left(\vec{\rho}\right) d^2\rho$$

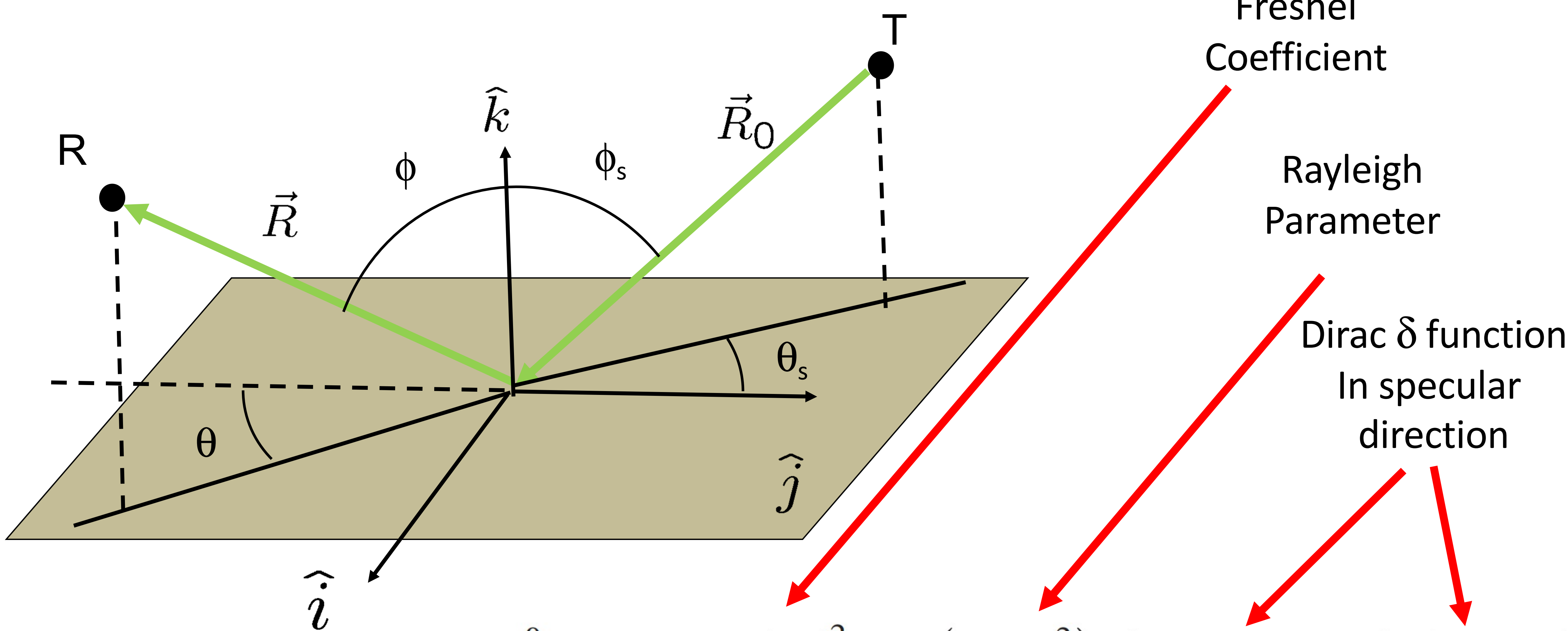
**Random rough surface - DDM will be a random variable**

- Speckle
- Thermal noise
- < > is ensemble average (Expected value)

**$\sigma_{pq}^0$= NBRCS function of:**

- Surface position ($\vec{\rho}$)
- Polarization (p,q)
- Surface roughness
- Reflectivity

# Specular (Coherent) Reflection

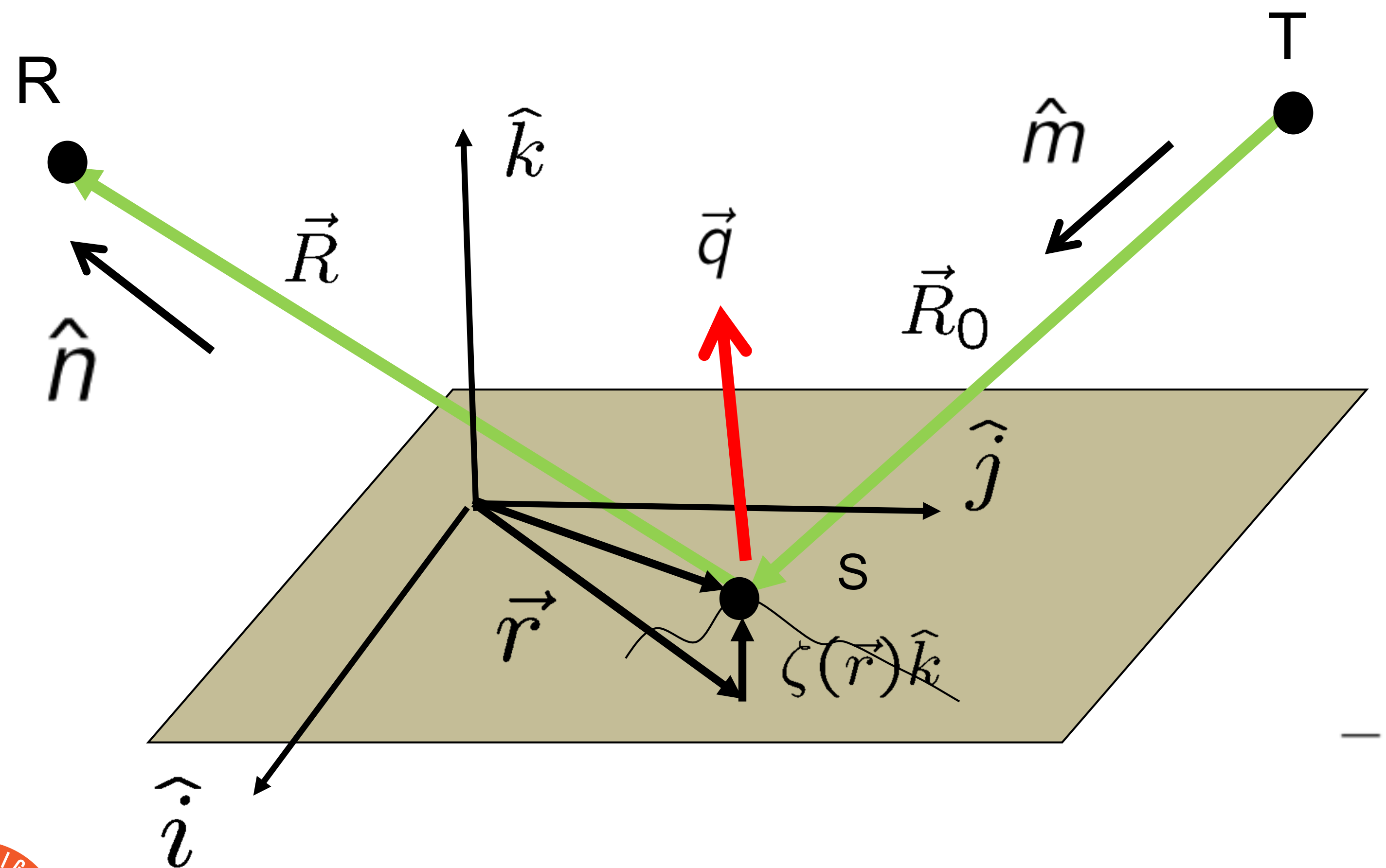



$$\sigma^0_{coh} = 4\pi cos\theta |\mathcal{R}|^2 \exp\left(-2R_a^2\right)\delta(cos\theta - \cos\theta_s)\delta(\phi - \phi_s)$$

Eq. (34.62) [PNT in the 21st Century, 10.1002/9781119458449.ch34]

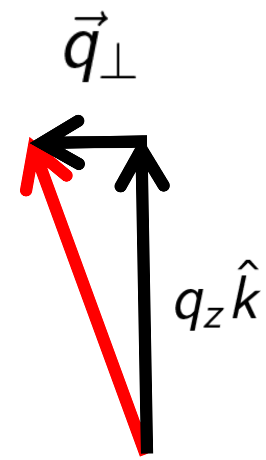
# Incoherent Reflection: Geometric Optics

## Definition of the q-vector




$$\vec{q} = \frac{2\pi}{\lambda}(\hat{m} - \hat{n})$$

$$\vec{q} = \vec{q}_\perp + q_z\hat{k}$$

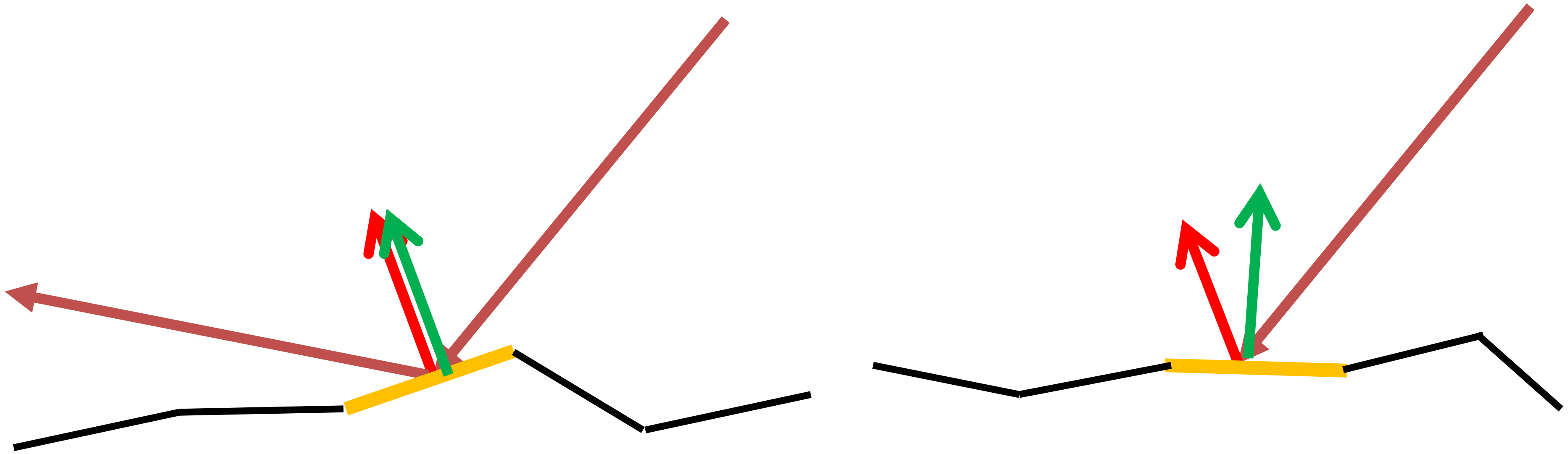



$-\frac{\vec{q}_\perp}{q}$ = bidirectional ***Slope*** of plane normal to q

# Incoherent Reflection: Geometric Optics

## NBRCS proportional to slope PDF
## Physical interpretation:

$$\sigma^0 = \pi |\mathfrak{R}|^2 \left(\frac{q}{q_z}\right)^4 P_{\vec{\nu}}\left(-\frac{\vec{q}_\perp}{q_z}\right),$$



Probability of surface slope
Giving "specular" reflection
In direction of receiver

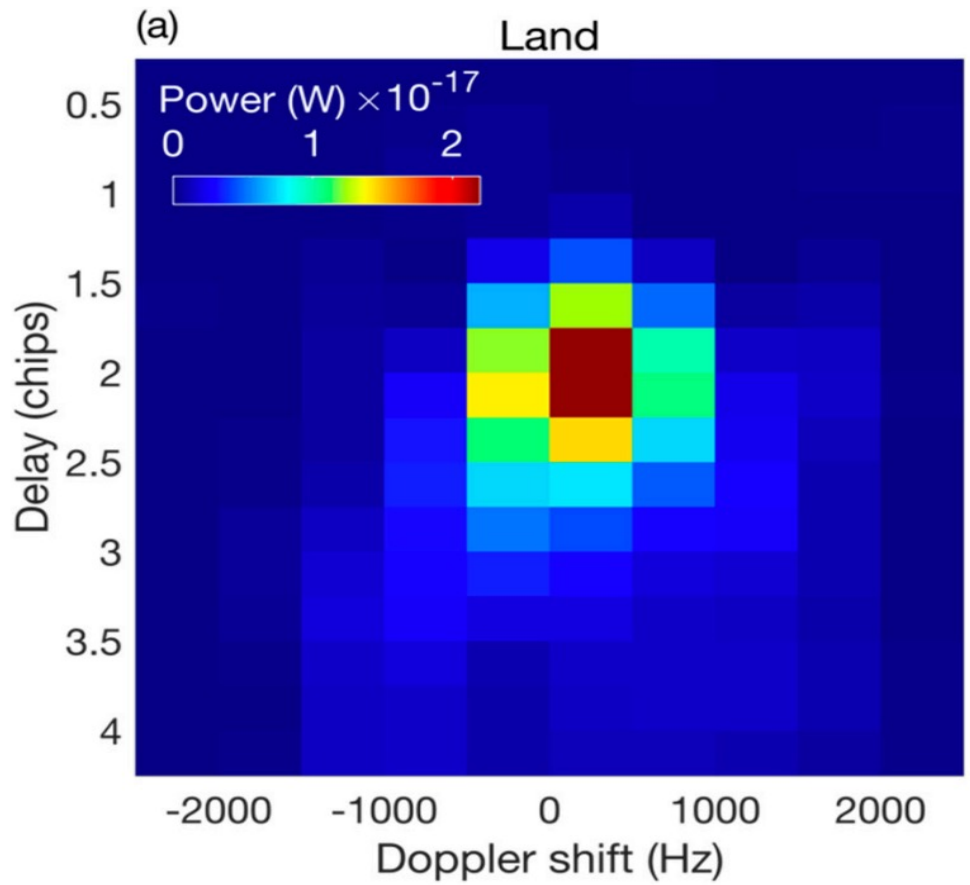
Green = normal to surface
Red = bisector (q) vector

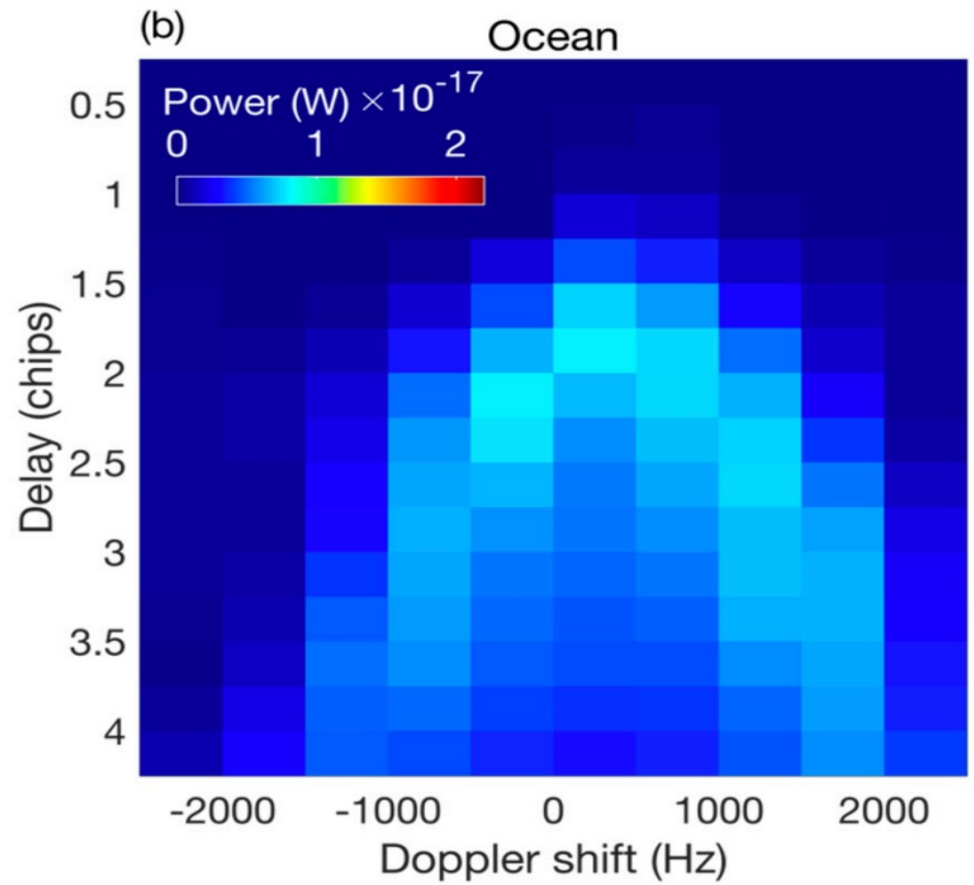
[Barrick, Proc. IEEE, 1968, 10.1109/PROC.1968.6718]

# Coherent / Incoherent

$$< |Y(\tau_s, f_s)|^2 >= \frac{\lambda^2 P_T G_T}{(4\pi)^2} \frac{G_R}{(R + R_0)^2}\Gamma$$

$$\langle |X(\tau,f)|^2 \rangle = \frac{\lambda^2 P_T G_T}{(4\pi)^3} \int\int \frac{G_R |\chi(\Delta\tau, \Delta f)|^2}{R^2 R_0^2} \sigma_{pq}^0 \left(\vec{\rho}\right) d^2\rho$$




[Chew & Small, Remote Sensing 2020, 10.3390/rs12101558]

# Model Limitations

**Kirchoff Approximation – Geometric Optics (KA-GO):**

- Local radius of curvature >> Wavelength
- Far field: k >> 1/R, 1/R0

**Limitations:**

- Depolarization
- Out of plane scattering

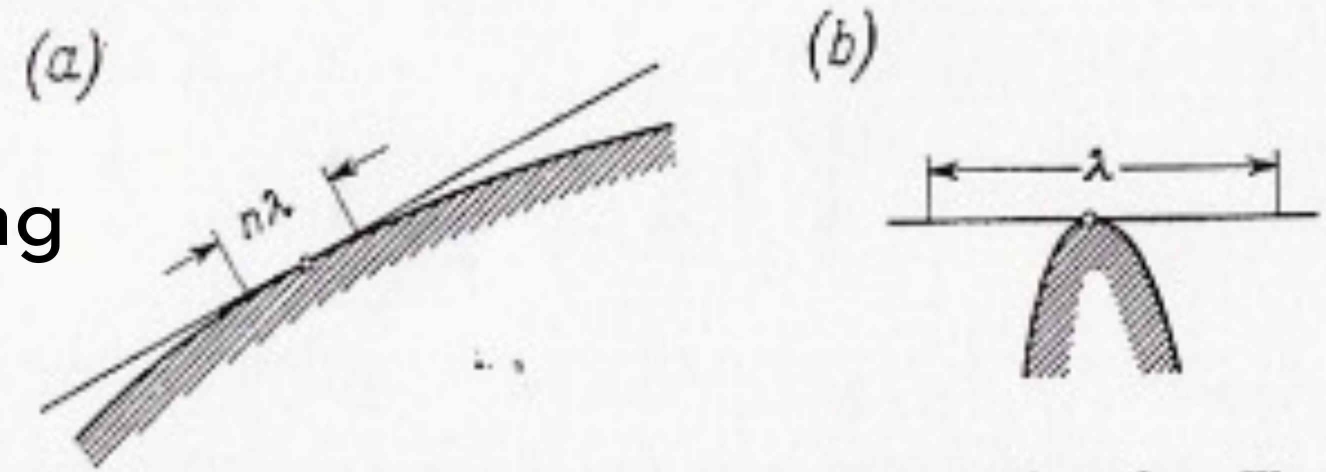



Fig. 3.4. The tangent plane at a general point of the rough surface. The radius of curvature is (a) large, (b) small in comparison with the wavelength.

[Beckmann & Spizzichino, 1987]

# Model Improvements

**Kirchhoff Approximation (Physical Optics)**

[Elfouhaily & Guérin (2004), 10.1088/0959 7174/14/4/R01]

[De Roo & Ulaby (1994) 10.1109/8.277216]

**Small Perturbation Method (SPM) - small surface variations & slopes**

**Two-Scale Model - early attempt to unify KA & SPM - arbitrary dividing wavenumber**

[Bass & Fuks (1979) Wave Scatt. from Stat. Rough Surfaces]

[Valenzuela (1978) 10.1007/BF00913863]

[Brown (1978) 10.1109/TAP.1978.1141854]

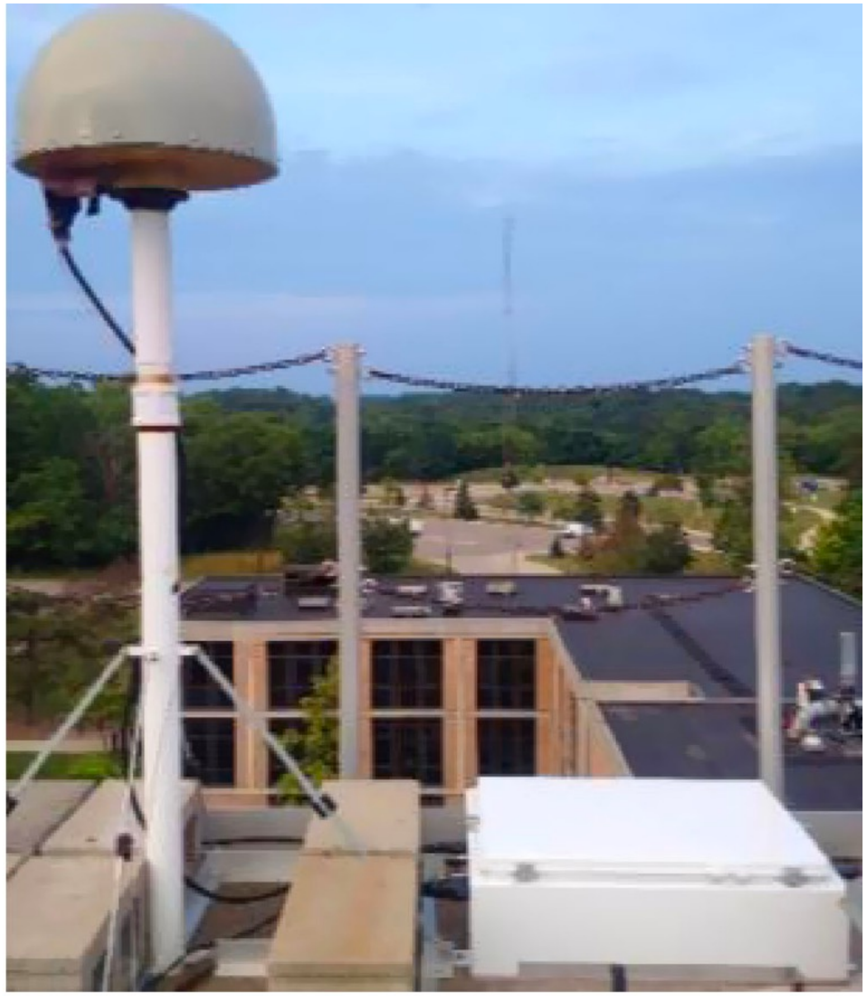
# Model Improvements (2)

**Integral Equation Models -** computationally expensive - reduces to GO for high frequency and SPM for low frequencies

**Small-Slope Approximation -** a "unifying method" - integrates entire spectrum without splitting into large & small scale - popular in GNSS-R

[Voronovich (2013) Wave Scattering from Rough Surfaces]

# Calibration



[Wang, et al.,10.1109/JSTARS.2018.2867773]

# Antenna Swapping

## Direct signal used to calibrate receiver gains

[Egido, et al. Remote Sensing (2012),10.3390/rs4082356]

- Correlator output in counts: C(τ,f)
- "Through" (T) configuration

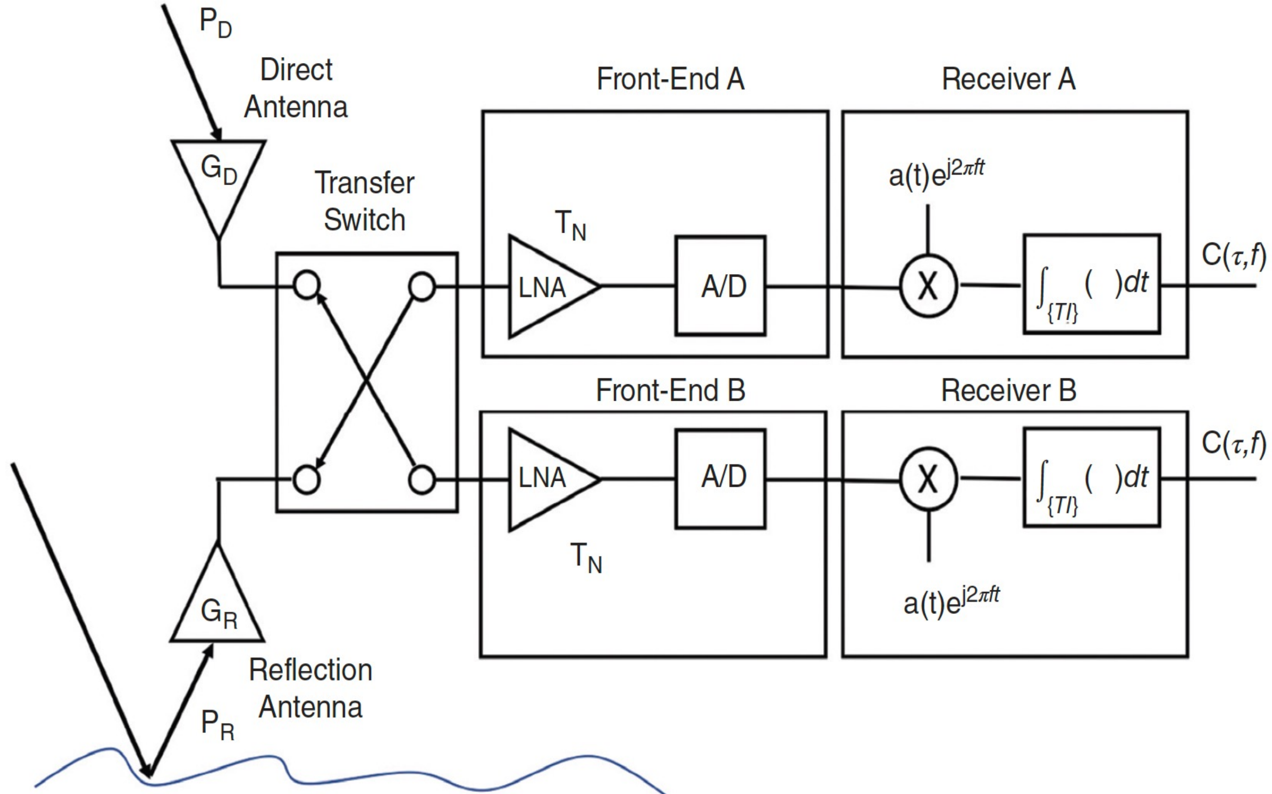
$$\frac{P_R}{P_D} = \left(\frac{G_A}{G_B}\right)\left(\frac{G_D}{G_R}\right)\frac{C_B^T - C_{N,B}^T}{C_A^T - C_{N,A}^T}$$

- "Swap (S) configuration

$$\frac{P_R}{P_D} = \left(\frac{G_B}{G_A}\right)\left(\frac{G_D}{G_R}\right)\frac{C_A^S - C_{N,A}^S}{C_B^S - C_{N,B}^S}$$

- These can be combined to cancel the receiver gain ratio

$$\frac{G_A}{G_B} = \frac{C_A^T - C_{N,A}^T}{C_B^S - C_{N,B}^S}.$$




[PNT in 21st Century (10.1002/9781119458449.ch34)]

# Reference Sources

## Level 1a: DDM in calibrated power (units of W)

- Method Follows the CYGNSS ATBD
- Uses calibration source in receiver @ $T_B$

$$C_B = G(P_B + P_{N,I})$$

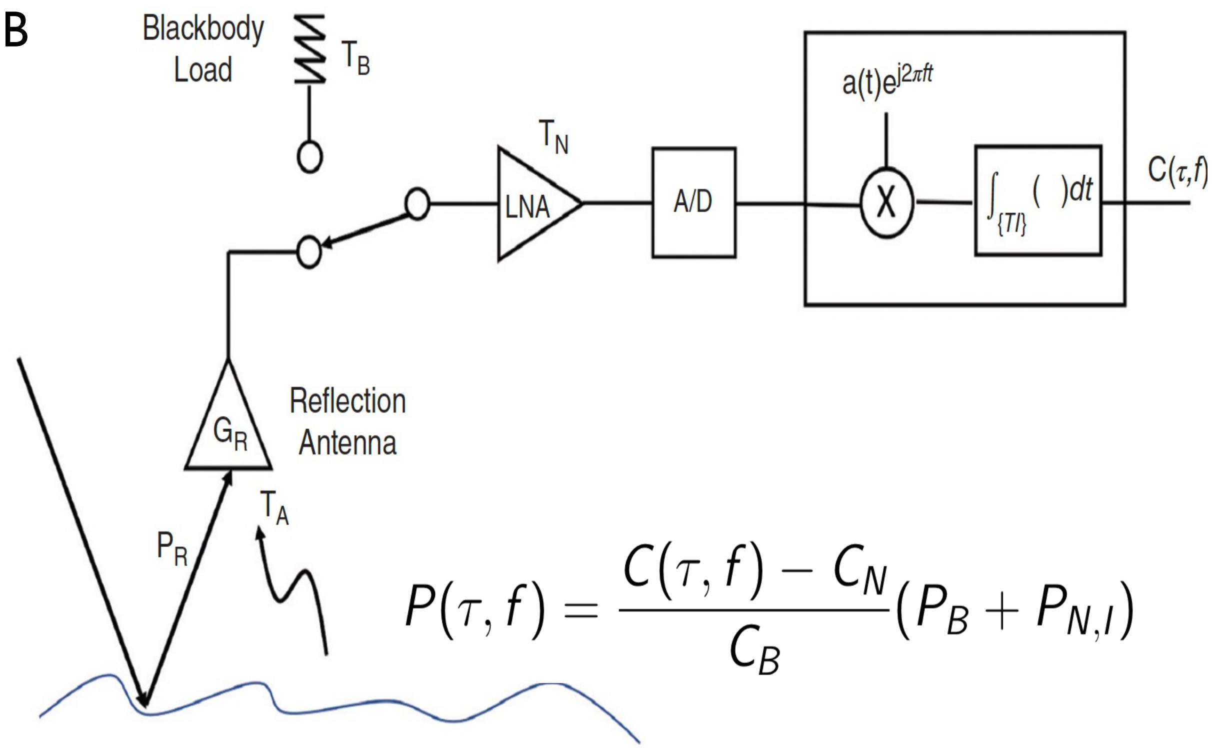
- G = Receiver gain (unknown)
- $P_{N,I}$ = Receiver noise power, calibrated with $T_R$

$$P_{N,I} = kB_I(290K)\left(NF(T_R) - 1\right)$$

- DDM in counts given by:

$$C(\tau, f) - C_N = GP(\tau, f)$$

$C_N$ = counts in noise-only "forbidden zone" of DDM

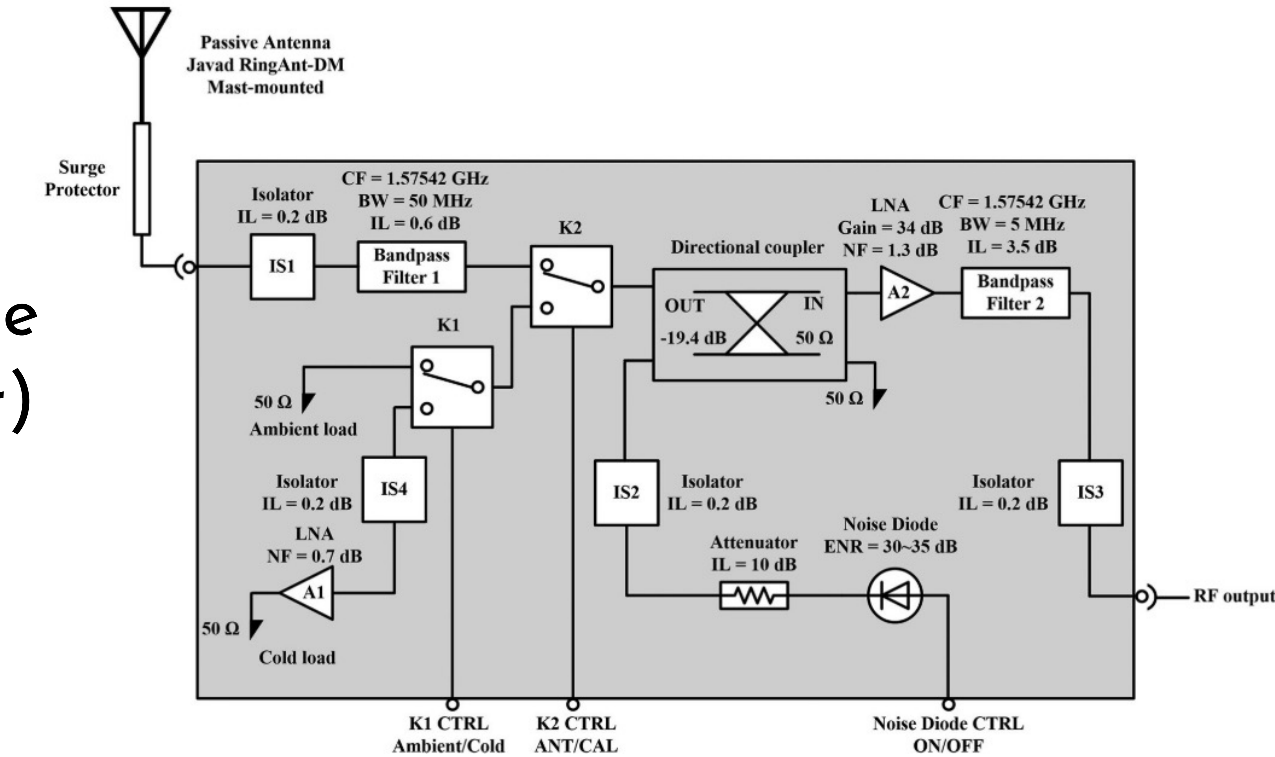



$$P(\tau, f) = \frac{C(\tau, f) - C_N}{C_B}(P_B + P_{N,I})$$

[PNT in 21st Century (10.1002/9781119458449.ch34)]

## Source power and antenna gain estimates

- DDM calibration of requires:
  - Transmitter power
  - Transmitter gain patterns
- GPS satellites can adaptively allocate power between channels (Flex power)
- Ground-based system designed at Michigan for support of CYGNSS
- Augmented by on-board power monitoring using direct antenna




[Wang, et al., 10.1109/JSTARS.2018.2867773]

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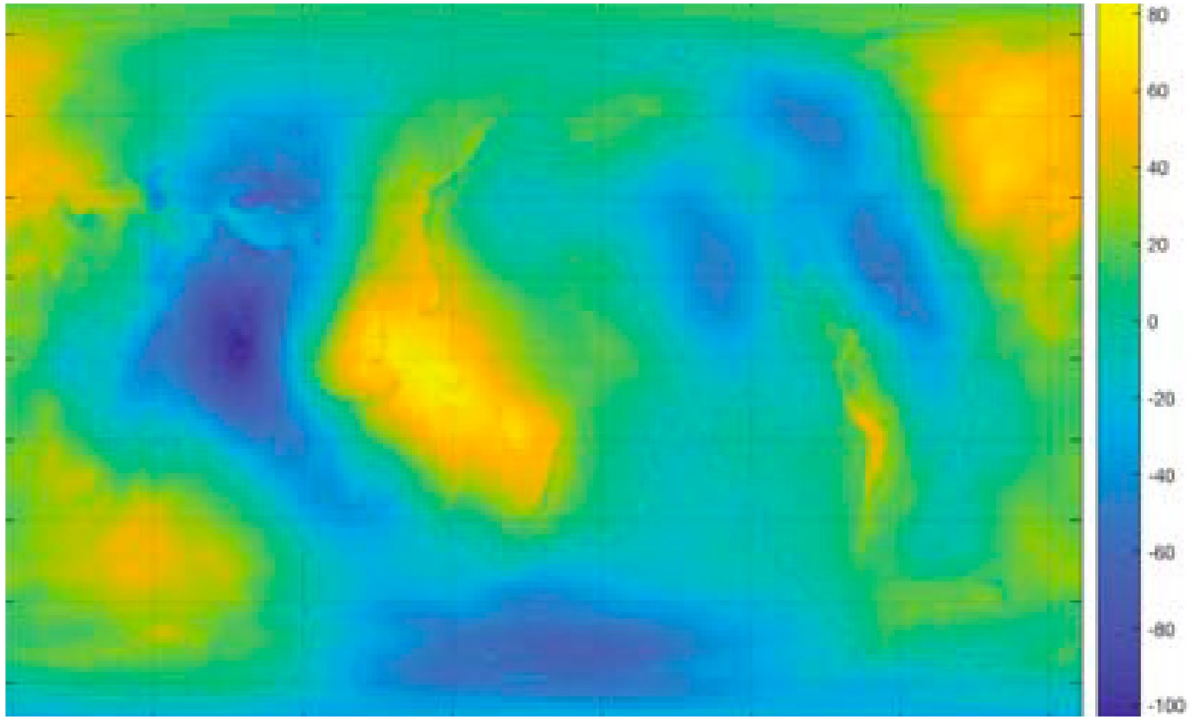
# Delay-Doppler Geometry



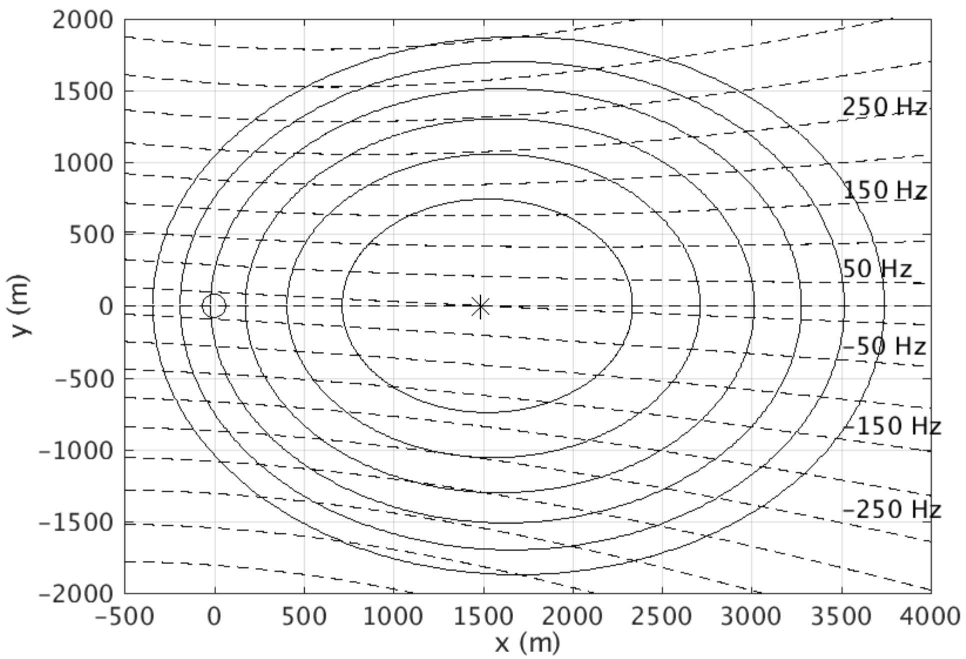
# Delay-Doppler Geometry

**Iso-range:** $\rho(x, y) = |\vec{R}_T - \vec{R}_S(x, y)| + |\vec{R}_R - \vec{R}_S(x, y)|$

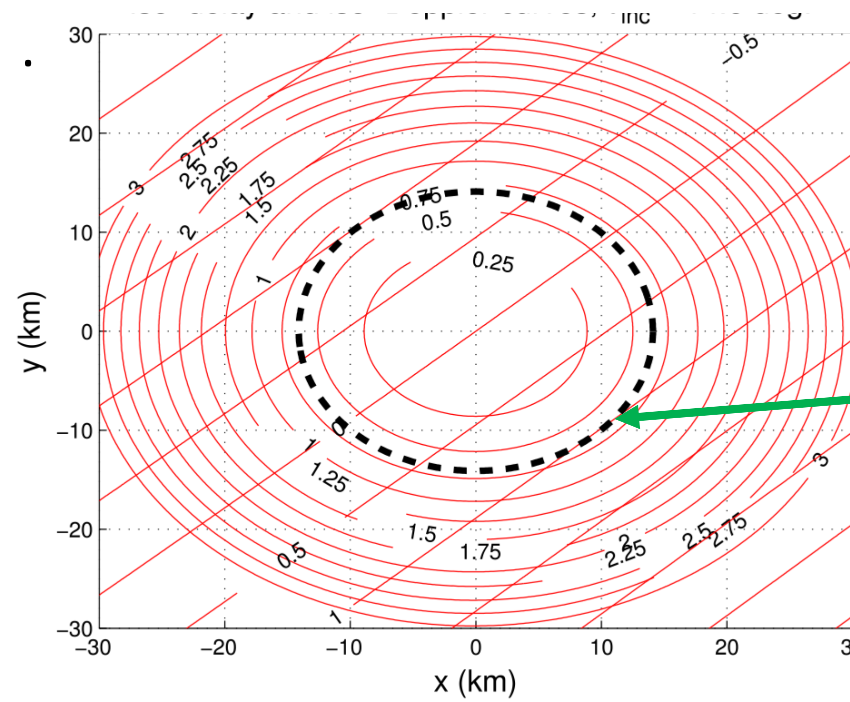
**Iso-Doppler:** $f_D(x, y) = \frac{1}{\lambda}\left[\vec{V}_t \cdot \hat{m}(x, y) - \vec{V}_r \cdot \hat{n}(x, y)\right]$

¼ chip delay increment

Airborne Receiver 4.6 km altitude




Satellite Receiver 500 km altitude




25 km Resolution

# Approximation: locally flat Earth cτ<<h

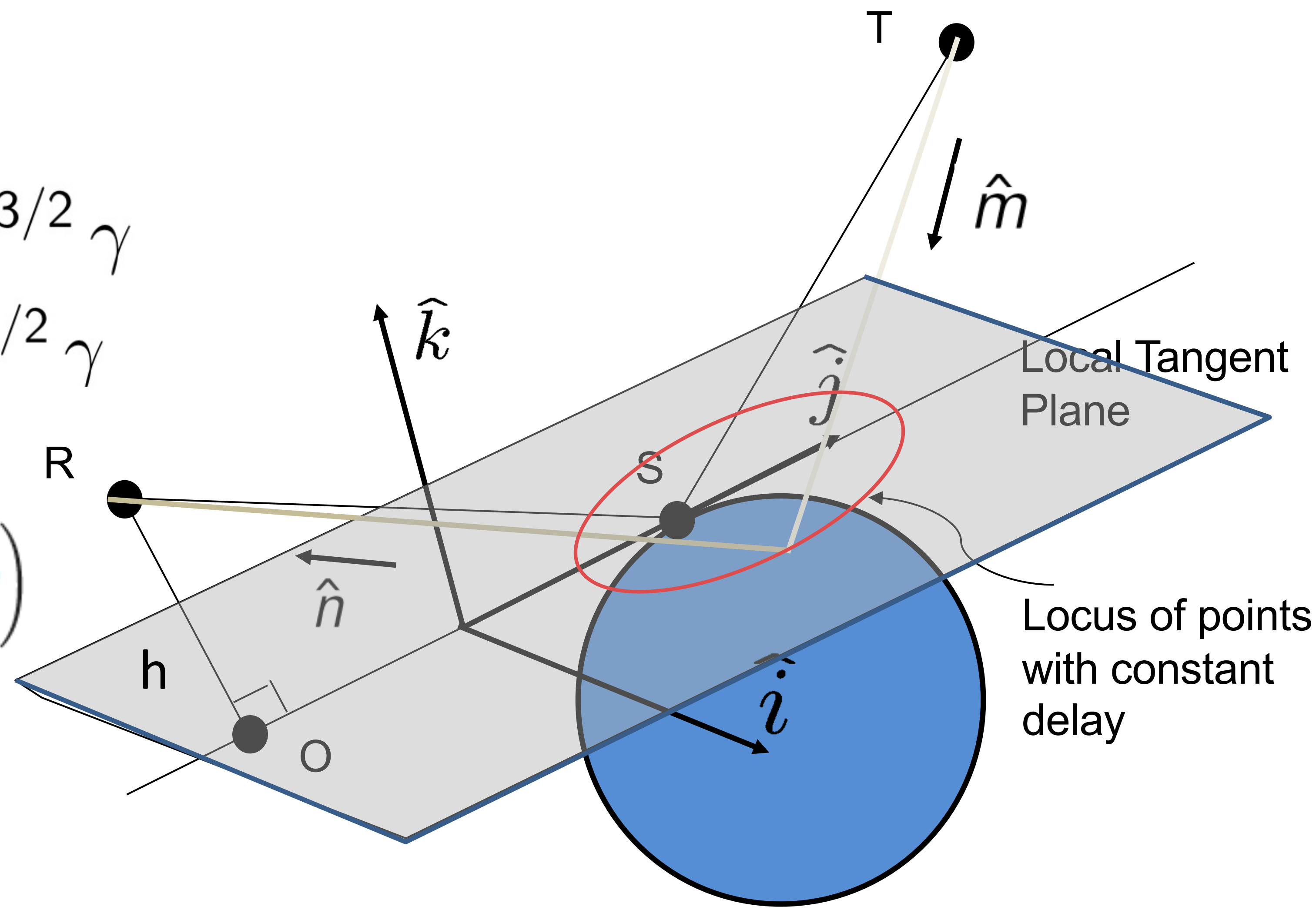
## Iso-range ellipse :

$$a \approx \sqrt{2ch\tau}\,\sin^{-3/2}\gamma$$

$$b \approx \sqrt{2ch\tau}\,\sin^{-1/2}\gamma$$

## Iso-Doppler hyperbola:

$$(x_0, y_0) = \left( \frac{hV_xV_z}{V_x^2 + V_y^2 - V_D^2}, \frac{hV_yV_z}{V_x^2 + V_y^2 - V_D^2} - h\tan\theta \right)$$

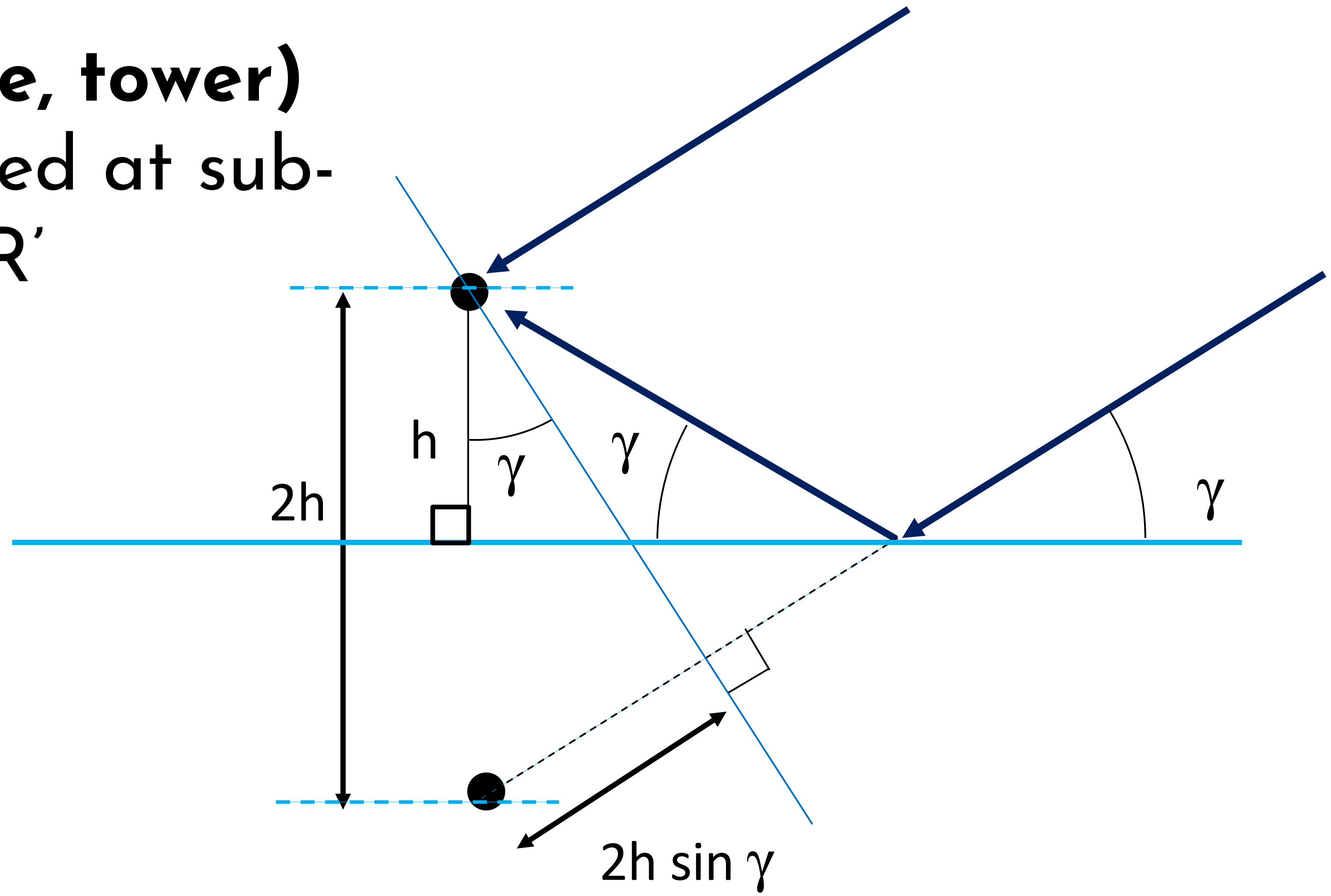


# Specular point: origin of the DDM

**Low-altitude (airborne, tower)**

Reflected signal received at sub-surface "virtual point" R'

$c\tau_s = 2h \sin \gamma$



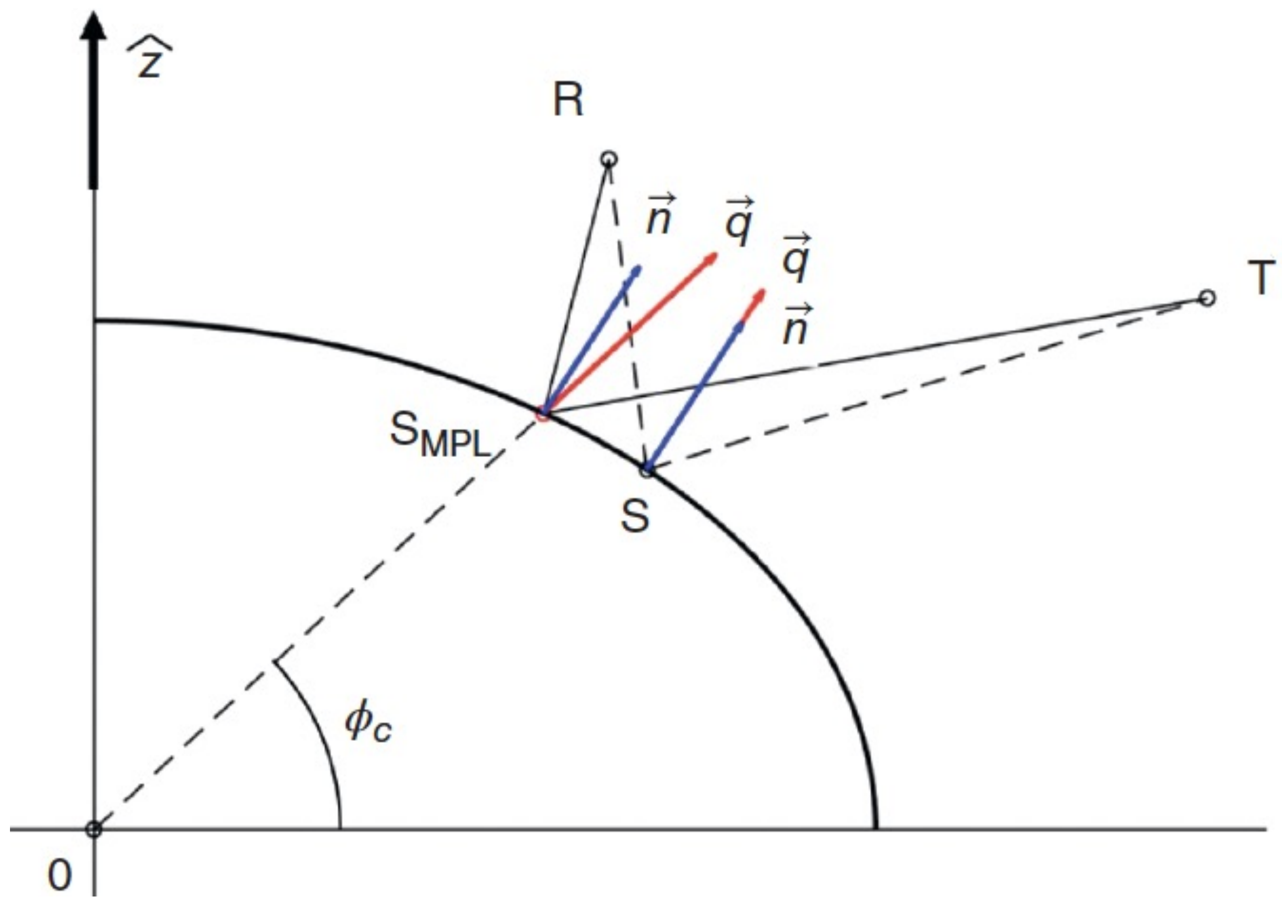
# Specular point on Ellipsoidal model

**Fermat's principle**
(Minimum path delay)

$$\rho\left(\vec{R}_S\right) = \left|\vec{R}_T - \vec{R}_S\right| + \left|\vec{R}_R - \vec{R}_S\right|$$

**Snell's Law ($\theta_I = \theta_R$)**
(bisector $\vec{q}$ aligned with surface normal $\vec{n}$ )

**Can be refined further in post-process**




[PNT in 21st Century (10.1002/9781119458449.ch34)]

# Specular point on Ellipsoidal model

## Unconstrained optimization ($\vec{R}_S(\phi,\lambda)$ is eqn. of ellipsoid)

Minimize: $$J_{unc}(\phi,\lambda) = \left|\vec{R}_T - \vec{R}_S(\phi,\lambda)\right| + \left|\vec{R}_R - \vec{R}_S(\phi,\lambda)\right|,$$

## Constrained optimization

Minimize: $J_{MPL}\left(\vec{R}_S\right) = \left|\vec{R}_T - \vec{R}_S\right| + \left|\vec{R}_R - \vec{R}_S\right|$ With constraint: $g\left(\vec{S}\right) = \frac{1}{2}\overrightarrow{R_S}^T \mathbf{M}\,\overrightarrow{R_S} = 1,$

## Can also use unit-difference (UD) gradient $\vec{\nabla} J_{UD}\left(\vec{R}_S\right) = \hat{q}\left(\vec{R}_S\right) - \hat{n}\left(\vec{R}_S\right)$ surface normal $\vec{n}$ )

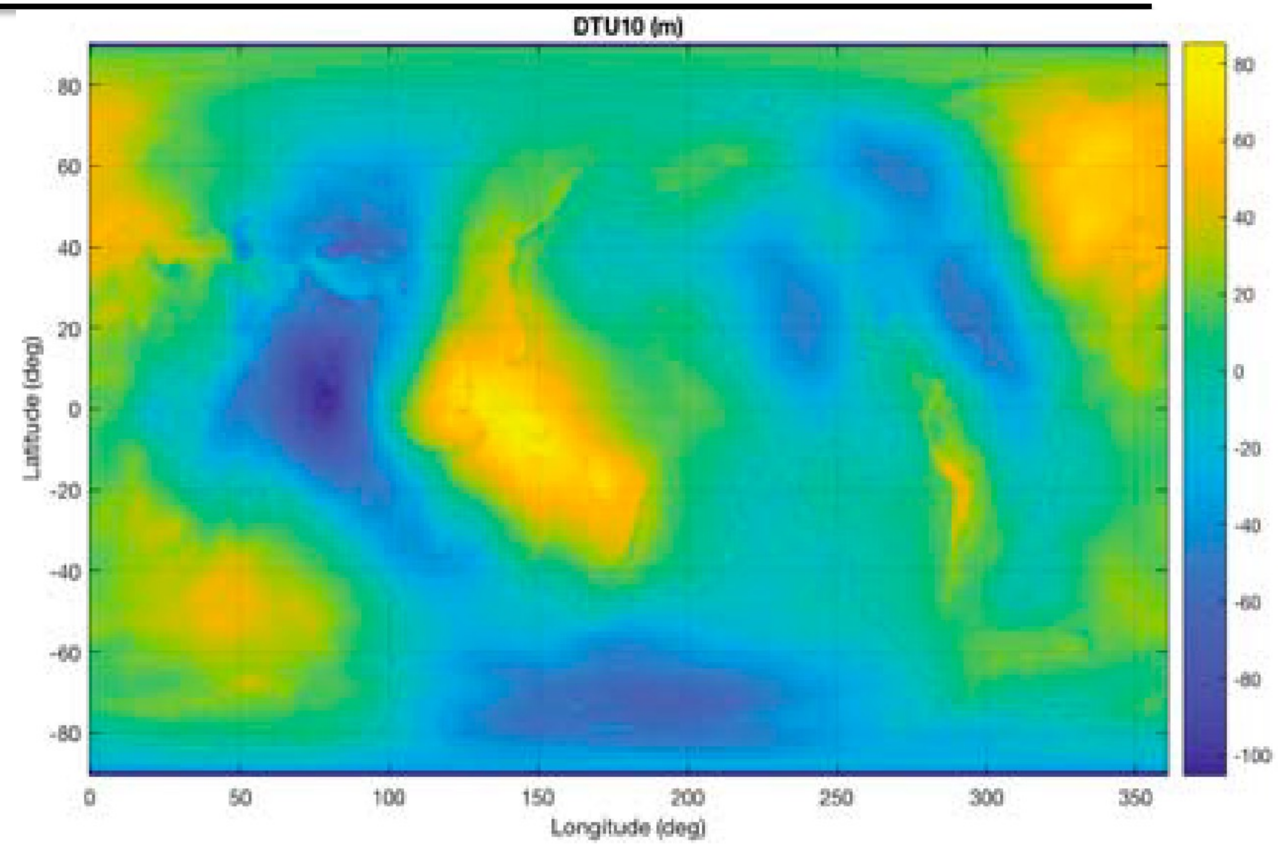

Jales, P. (2012) Ph.D Thesis University of Surrey.
Southwell & Dempster (2018) 0.1109/JSTARS.2017.2775647.
Garrison, et al.(2002) 10.1109/ 36.981349.
Gordon, W.B. (2014) 10.1109/TAP.2014.2299271

# Ocean Observations

MSL can vary up to +/- 100 m from WGS-84 ellipsoid

100m ht. error @ 30 deg. incidence = 170 m delay error (2.25 CYGNSS DDM pixels)

Grid search using interpolated DTU10* MSL around Ellipsoidal SP - find min. path delay




DTU10 MSL – WGS84 height adjustment
[Gleason, et al., S., (2019) 10.1109/JSTARS.2018.2832981]

*[National Space Institute (Denmark)]

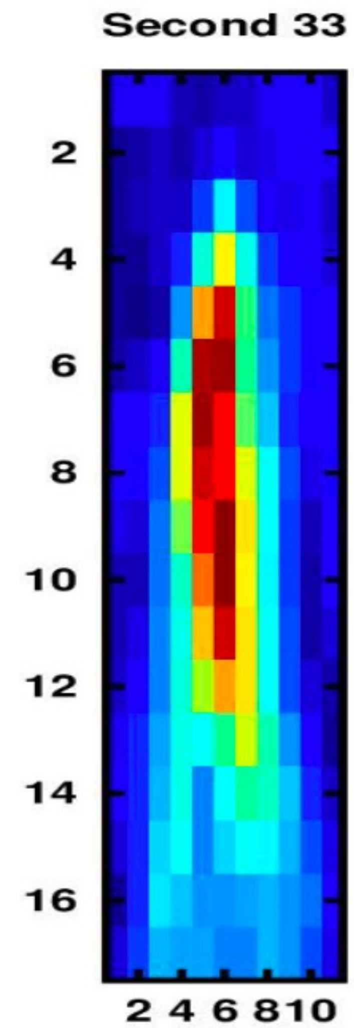
# Land Observations

**Terrain is more complex and variable**

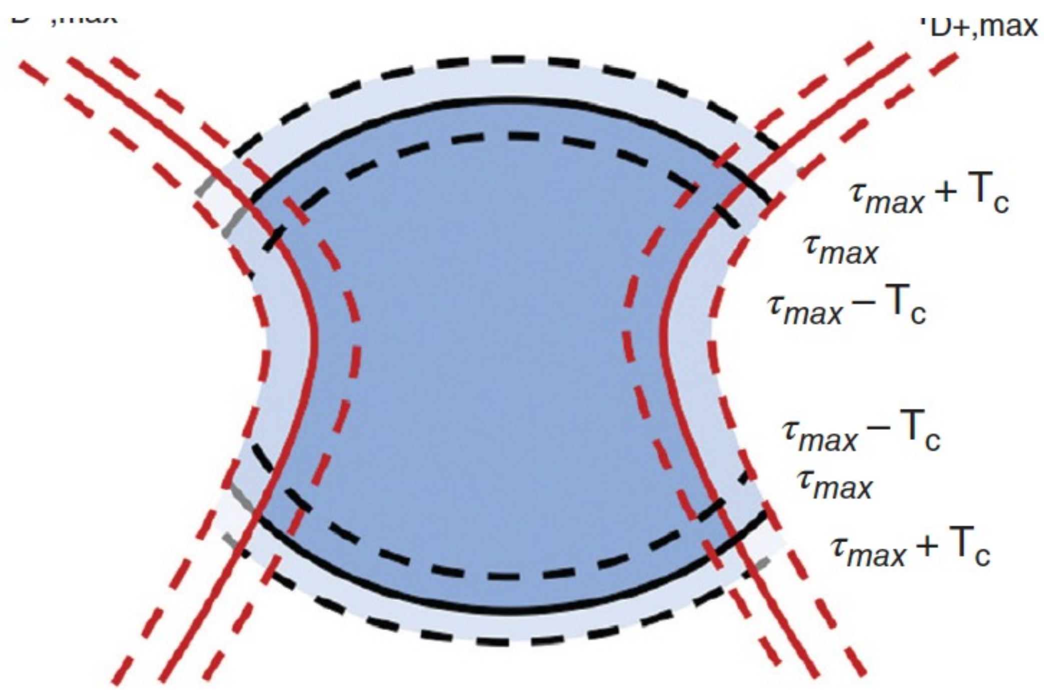
Multiple peaks possible

Gleason, et al. (2020) [10.3390/RS12081317] proposed consistency check:

- Delay/Doppler from SRTM DEM
- Snell's law ($\theta_I = \theta_R$)



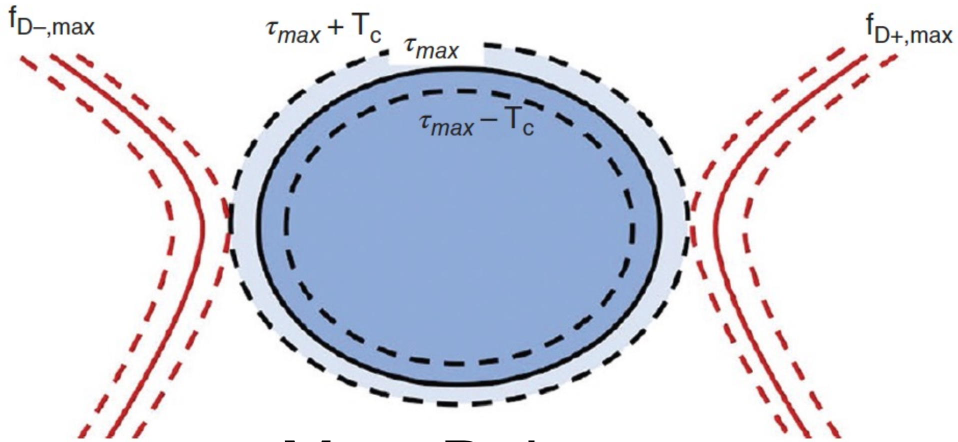

Example of multiple-peak DDM
[Gleason, et al. (2020) [10.3390/RS12081317]



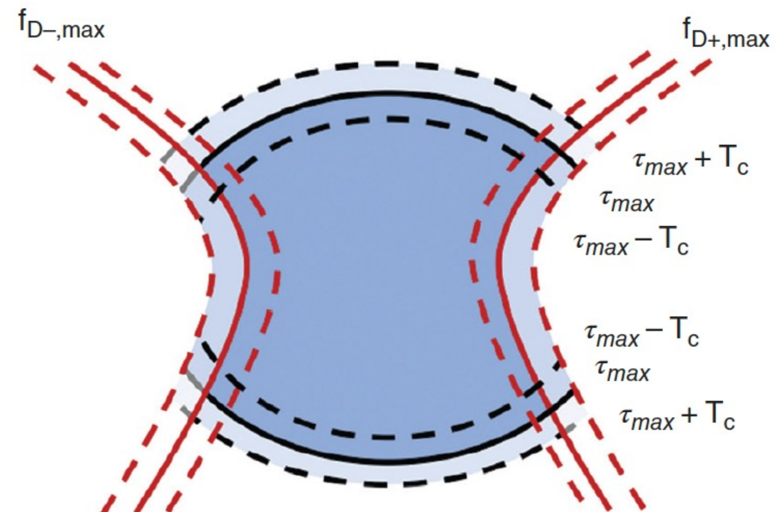

# Spatial resolution and coverage

# Resolution defined by the DDM

**Extent of DDM ($\tau_s$:$\tau_{max}$,+/- $f_{Dmax}$) used to produce single geophysical retrieval**




Max. Delay




Max. Doppler

[PNT in 21st Century (10.1002/9781119458449.ch34)]

**Complications:**

- Surface not uniformly weighted
- Time averaging will "spread" observation along flight path
- Specular reflection will not "fill" all delay-Doppler samples ("bins")

# Resolution defined by the DDM

Define as geometric average of semimajor & semiminor axes
First delay bin of DDM (assume diffuse scatter)

$$R = 2\sqrt{ab}$$

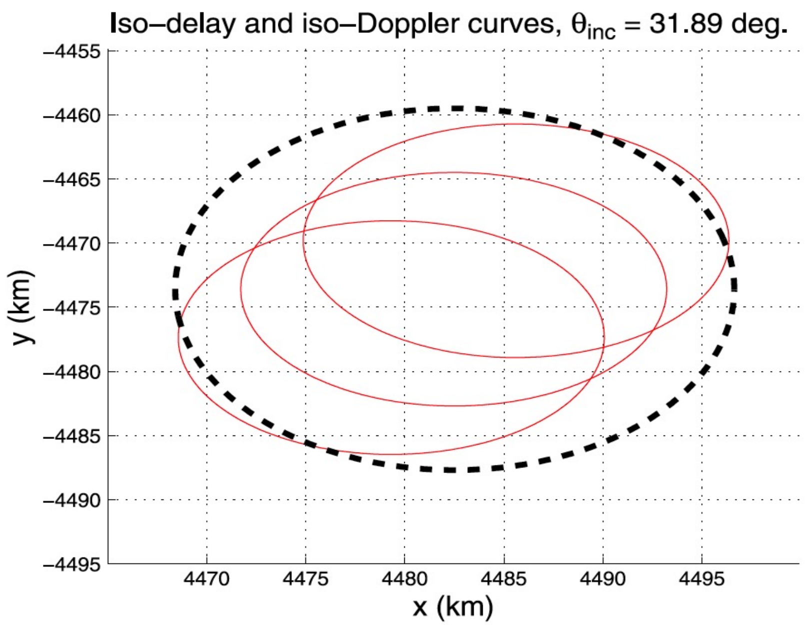
$$\approx 2\frac{\sqrt{ch(T_c/2)}}{\sin\gamma}$$

| Airborne: | B=1.023 MHz (GPS C/A) | B=10.23 MHz (GPS P(Y)) | B=400 MHz (DBS) |
|---|---|---|---|
| ($\gamma$=30°, h=10 km) | 4.8 km | 1.5 km | 219 m |
| ($\gamma$=60°, h=10 km) | 2.8 km | 880 m | 126 m |
| Satellite: | | | |
| ($\gamma$=30°, h=500 km) | 34.2 km | 10.8 km | 1.5 km |
| ($\gamma$=60°, h=500 km) | 19.8 km | 6.3 km | 894 m |

# Effect of Averaging

Often necessary to reduce error

``spreads" out resolution area in flight direction.




[Rodriguez-Alvarez & Garrison, 10.1109/TGRS.2015.2475317]

- Resolution requirement can set the max. averaging window

Surface area can be weighted with BRCS (stronger reflections contribute more to observable) [Clarizia & Ruf, 10.1109/LGRS.2016.2565380]

# Coherent Reflection

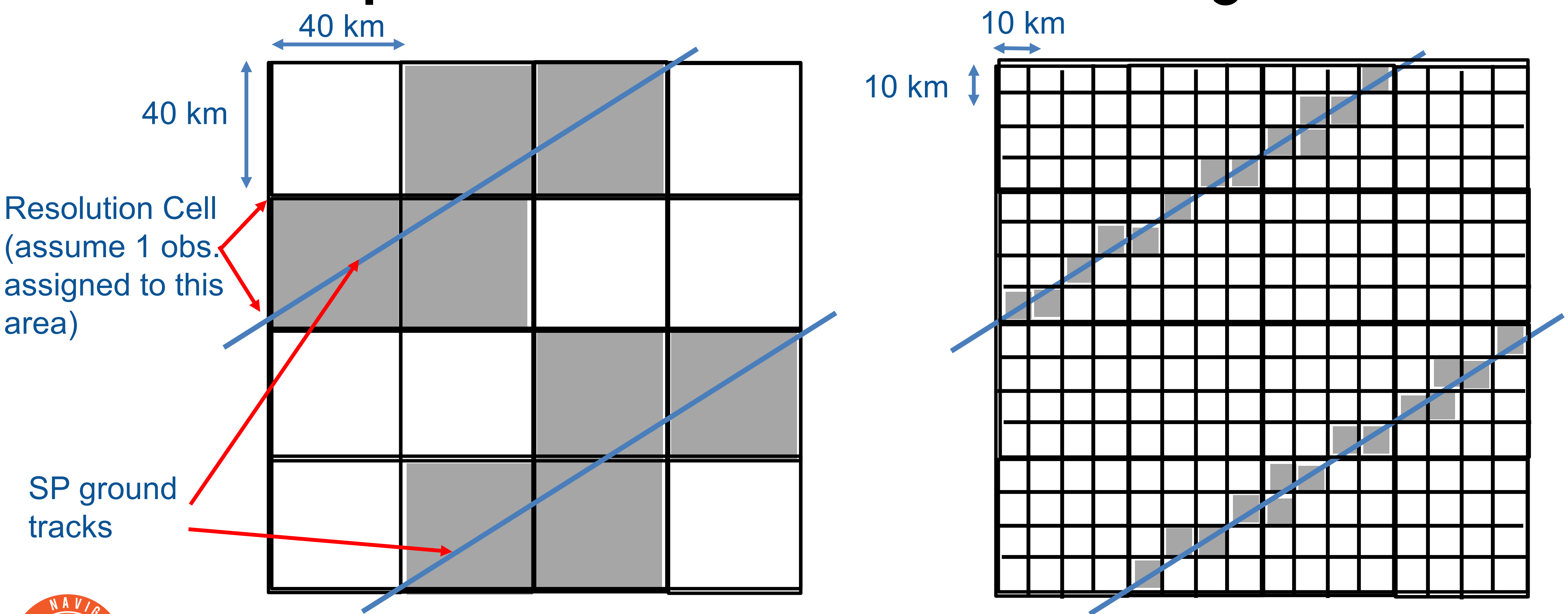
## Resolution approximated by first Fresnel Zone (FFZ)

$$R = 2\sqrt{ab} \approx 2\frac{\sqrt{h\lambda}}{\sin\gamma}$$

| Airborne: | L-band (1.575 GHz) | P-band (360 MHz) | I-band (137 MHz) |
|---|---|---|---|
| ($\gamma$=30º, h=10 km) | 174 m | 364 m | 592 m |
| ($\gamma$=60º, h=10 km) | 101 m | 210 m | 342 m |
| Satellite: | | | |
| ($\gamma$=30º, h=500 km) | 1.2 km | 2.5 km | 4.2 km |
| ($\gamma$=60º, h=500 km) | 712 m | 1.5 km | 2.4 km |

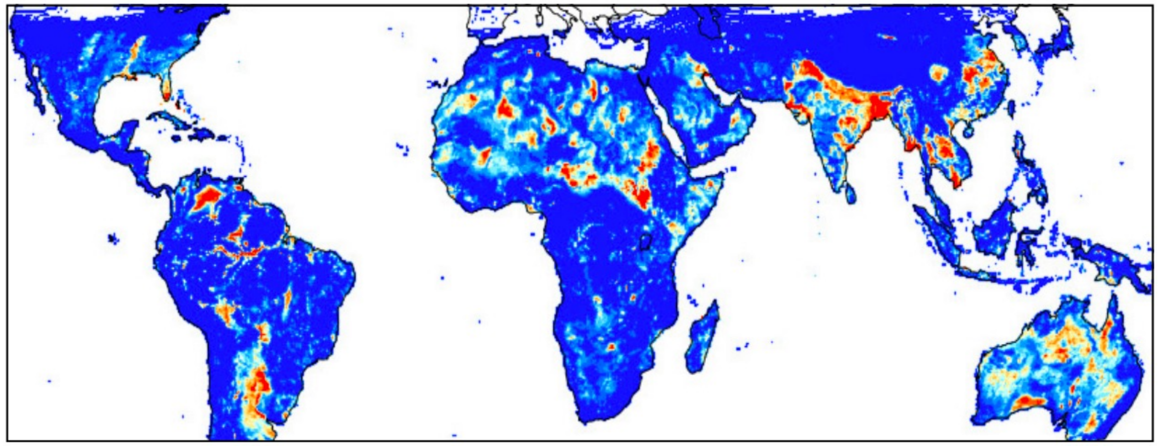
# Coverage and Revisit Time

## Relationship between resolution and coverage




Bussy-Virat, et al. [10.1109/JSTARS.2018.2833426]

# Coherence



[Al-Khaldi, et al. 10.1109/TGRS.2020.300978]

# Coherent vs. Incoherent Scattering

**Coherent- Power increase proportional to $T_I$**

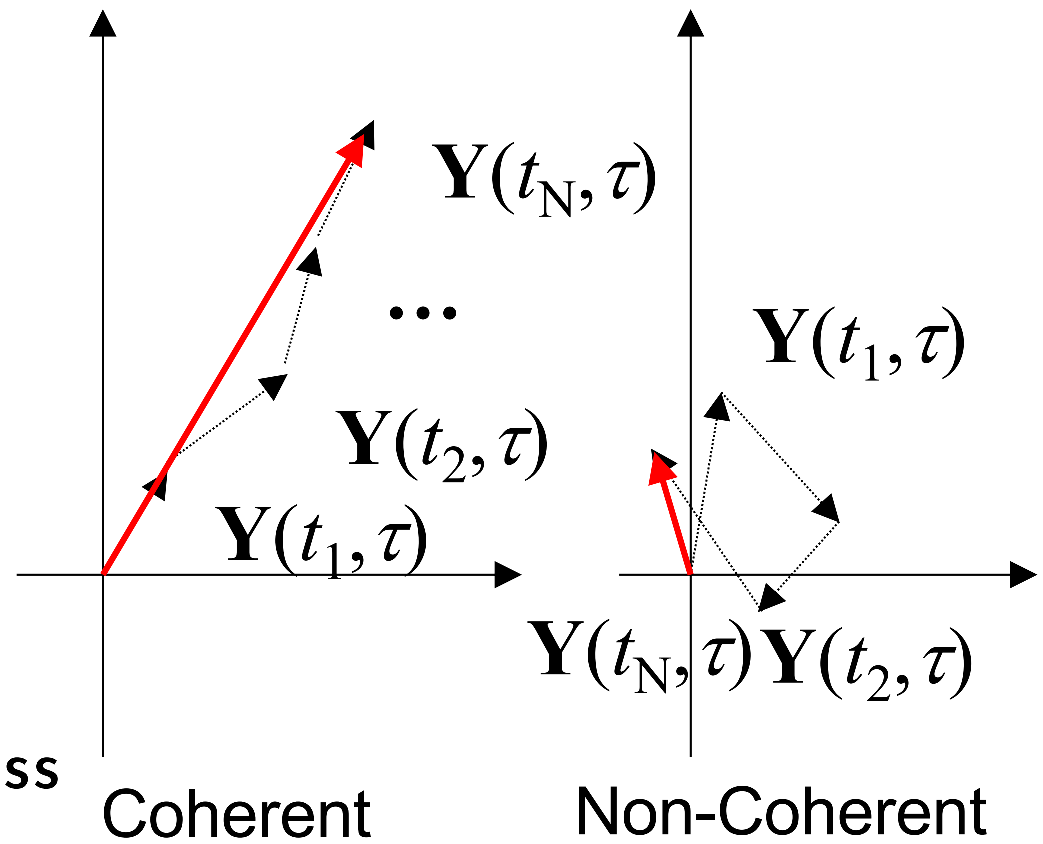
$$\frac{P_{coh,2}}{P_{coh,1}} = \frac{T_{I,2}}{T_{I,1}}$$

**"gold standard" test for coherence**

$$10\log_{10}\left(\frac{P_{T_I}}{P_{1ms}}\right) > \gamma_c$$

- Threshold $\gamma_c$
- Requires adjustment of $T_I$ (in practice, access to IF data – not operationally practical)

[Loria, et al., 10.1109/IGARSS.2018.8517441



# DDM Power Spread Detection (DPSD)

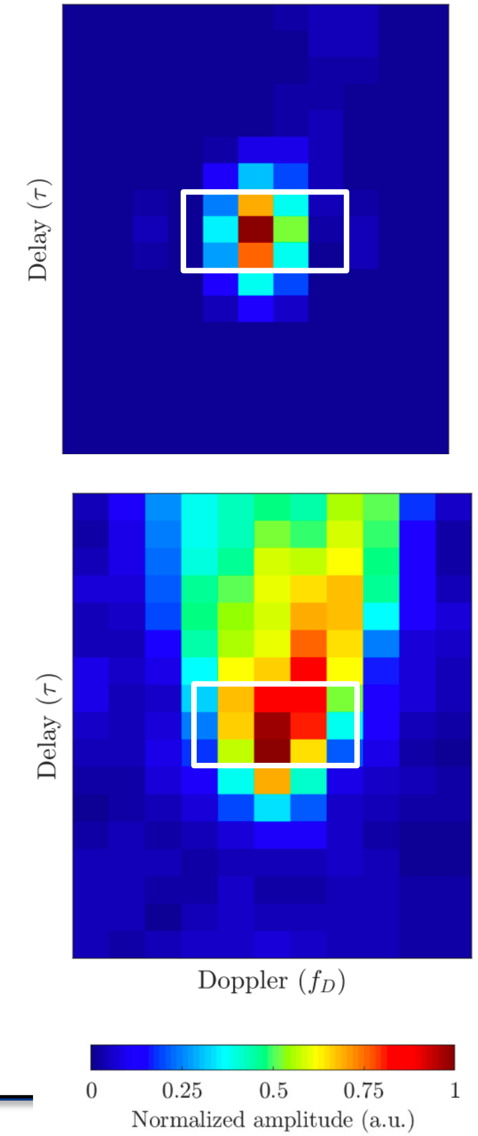
## Compares power ratio (PR) to threshold

$$PR = \frac{C_{\text{in}}}{C_{\text{out}}}$$

## Represents power "inside" specular pixels (3X5 for CYGNSS) and "outside" (Nt X Nf)

$$C_{\text{in}} = \sum_{i=-1}^{1} \sum_{j=-2}^{2} \text{DDM}(\tau_M + i, f_M + j) \qquad C_{\text{out}} = \sum_{i=1}^{N_\tau} \sum_{j=1}^{N_f} \text{DDM}(i, j) - C_{\text{in}}$$

- Can be applied to Level 0 "counts"
- Threshold "tuned" through comparison to "gold standard"
- "Outside" region adjusted to avoid noise pixels




[Al-Khaldi, et al. 10.1109/TGRS.2020.300978]

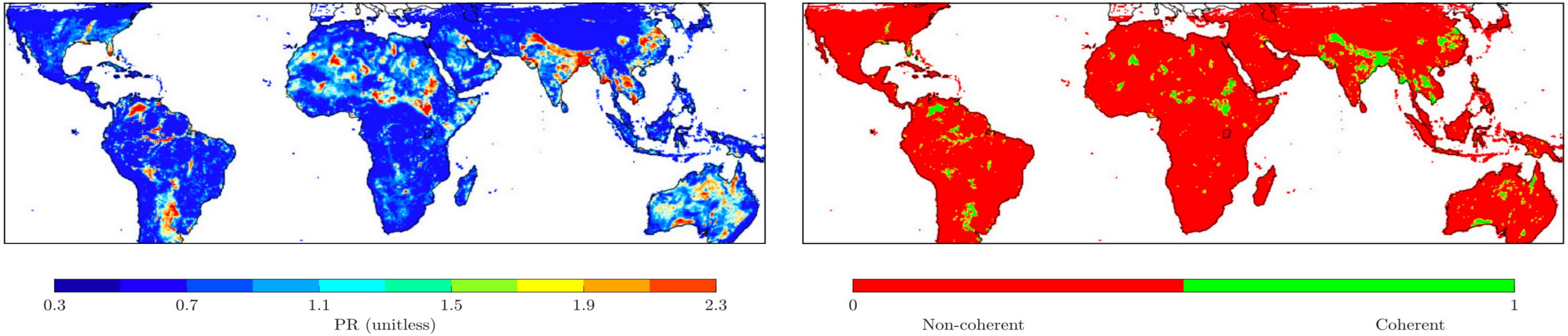
# Matched Filter Detection (MFD) test

Tests similarity of DDM to "pure" ambiguity function

$$R = \frac{|\langle Y(\tau, f_D)\chi(\tau, f_D)\rangle|^2}{\langle Y(\tau, f_D)Y(\tau, f_D)\rangle \langle \chi(\tau, f_D)\chi(\tau, f_D)\rangle}$$

Compares correlation (R) to threshold

MFD and DPSD give very similar results




[Al-Khaldi, et al. 10.1109/TGRS.2020.300978]

# Geophysical Conditions for Coherence

Coherence modeled using random rough surface

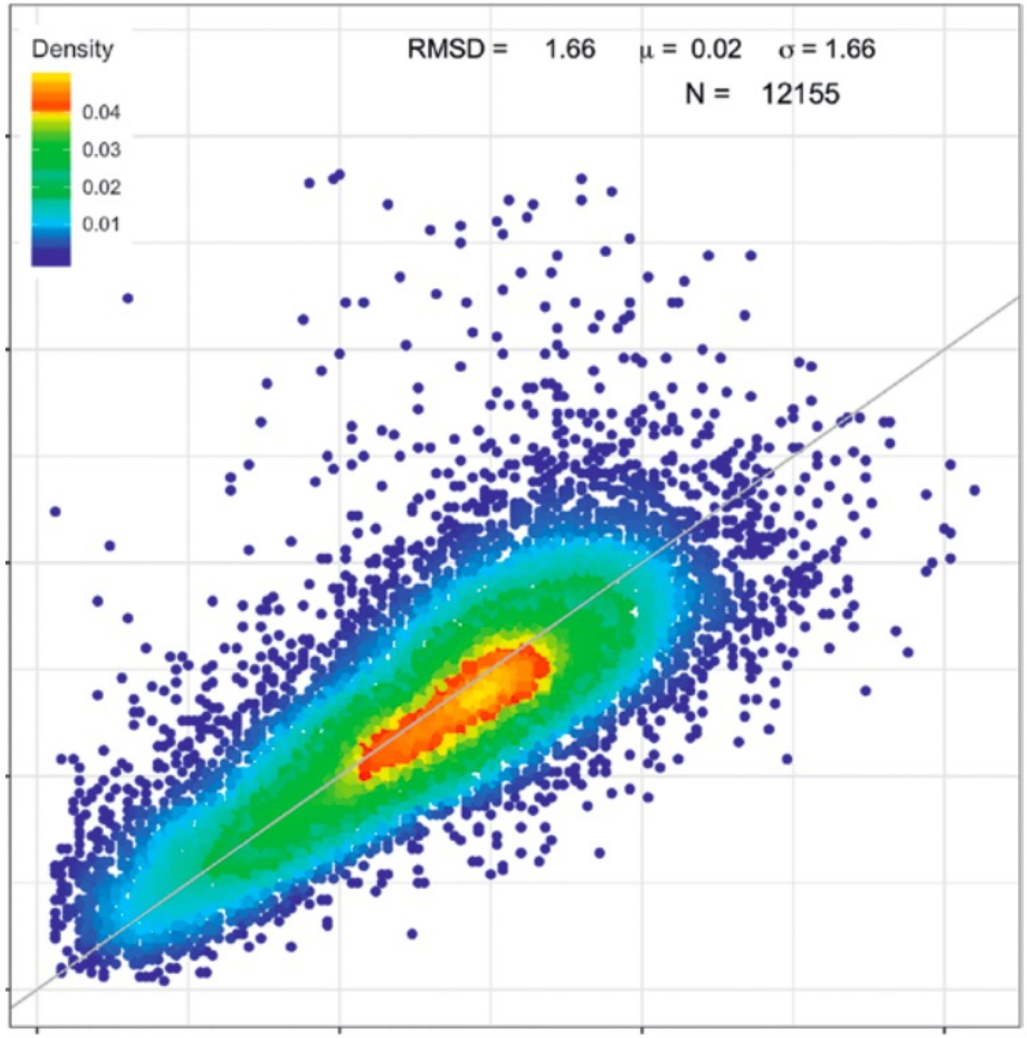
Altitude –size of FFZ in variance computation

Airborne or spaceborne Receiver:

| | L-band (1.575 GHz) | P-band (360 MHz) |
|---|---|---|
| Ocean Winds ($U_{10}$) | 2-3 m/s | 5-7 m/s |
| Land surface height RMS | 5-7 cm | 15-30 cm |

Tower (~10-50 m) receiver: Much more coherent

[Balakhder, et al., 10.1109/TGRS.2019.2935257]




# GNSS-R observables

# Level 1b retrievals: Incoherent case:

**Calibration produces Level 1a DDM's: P(τ,f) [W]**

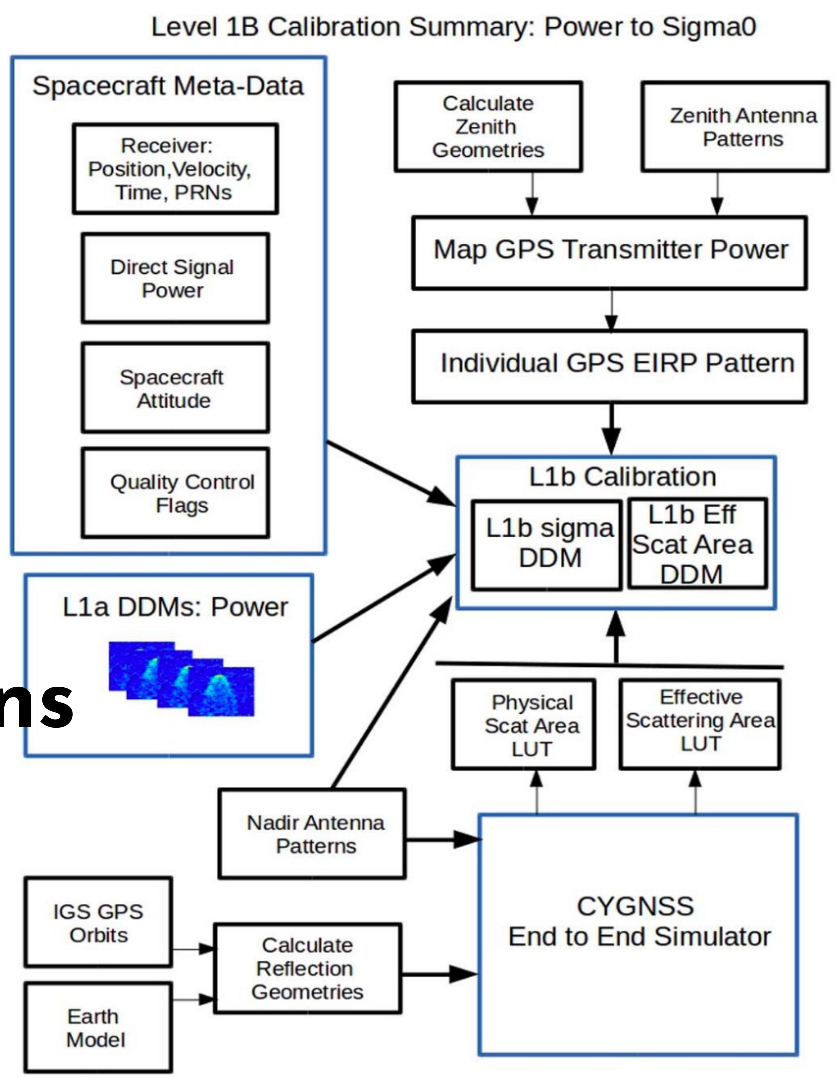
**"Unwrap" (Invert) radar equation to give BRCS for each (τ,f)**

$$\bar{\sigma}(\tau, f) = \frac{P(\tau, f)(4\pi)^3 L_{a1} L_{a2} L_{DDMI}(\tau, f) R_R^2 R_T^2}{\lambda^2 P_T, G_{T,S} G_{R,S}} \quad [m^2]$$

**NBRC observable formed from $N_\tau X N_f$ bins**

$$\sigma^0 = \frac{\sum_{i=1}^{N_\tau} \sum_{j=1}^{N_t} \bar{\sigma}(\tau_i, f_j)}{\sum_{i=1}^{N_\tau} \sum_{j=1}^{N_t} \bar{A}(\tau_i, f_j)} \quad [N.D.]$$

$\bar{A}(\tau_i, f_j)$ = Effective area at $(\tau_i, f_j)$




[Gleason, et al.,10.1109/TGRS.2015.2502245]

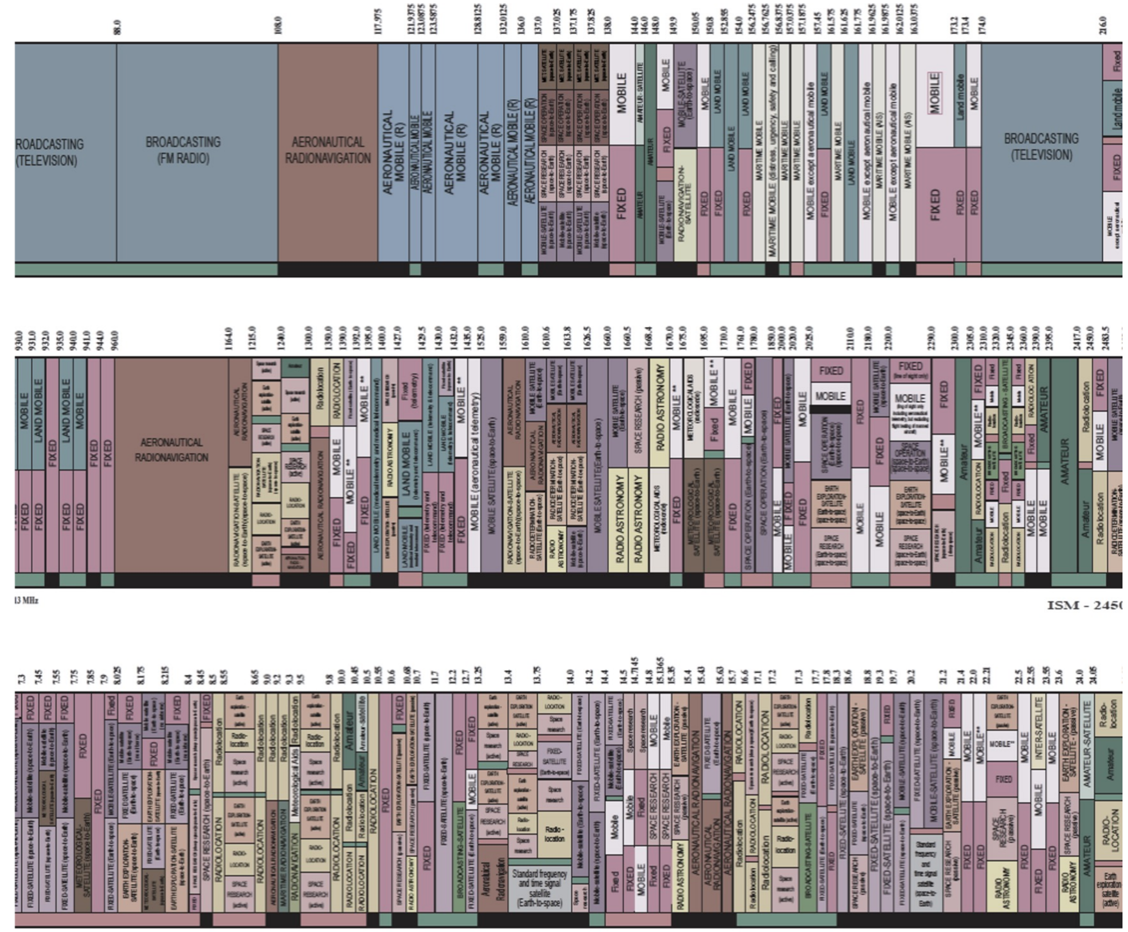
# Level 1b retrievals: Coherent case:

**Inversion of Friis' equation**

$$\Gamma(\tau, f) = \frac{P_{coh}(\tau, f)(4\pi)^2 L(R_R + R_T)^2}{\lambda^2 P_T, G_{T,S} G_{R,S}}$$

**Coherent reflection only from the specular point.**

# What can be used other than GNSS ?



# Why GNSS ?

**My career began with GNSS!**

(not radiometry, radar or communications)

GNSS orbits: **continuous global coverage**

**L-band**: good penetration of atmosphere, vegetation, rain, etc

… but:

- Only penetrates soil ~5cm
- Not sensitive to high frequency (>~$2\pi/(3\lambda)$) ocean waves

**Pseudorandom noise (PRN) code** – designed for ranging

# What about other signals ?

**Approximately 400 communication satellite Signals of Opportunity (SoOp) in GEO**

**High-powered (~30 dB above GNSS) signals**

**Allocations in most bands used for remote sensing:**

**P,L,S, C, Ku/Ka**

**Designed for data transmission - Not ranging!**

**Assumption: Compression& Encryption are very efficient at filling available spectrum, no periodic components**

- Data is nearly random
- Direct signal can be used as reference (e.g. iGNSS-R)

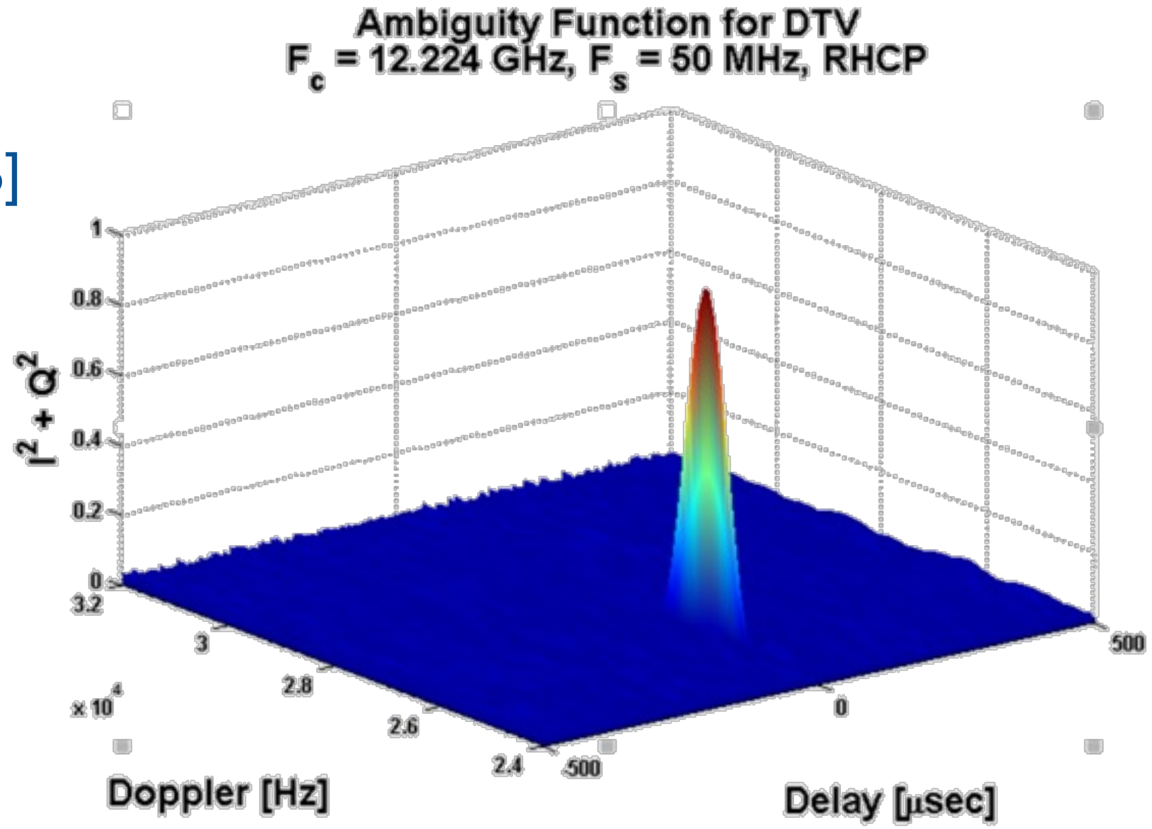
# Self-Ambiguity Function

## Defined by

$$|\chi(\tau, f_c)|^2 = \left| \frac{1}{T_I} \int_0^{T_I} s(t) s^*(t-\tau) e^{(-j2\pi f_c t)} dt \right|^2$$

*[Baker, et al., 2005, DOI: 10.1049/ip-rsn:20045083]

## Early DBS Experiment

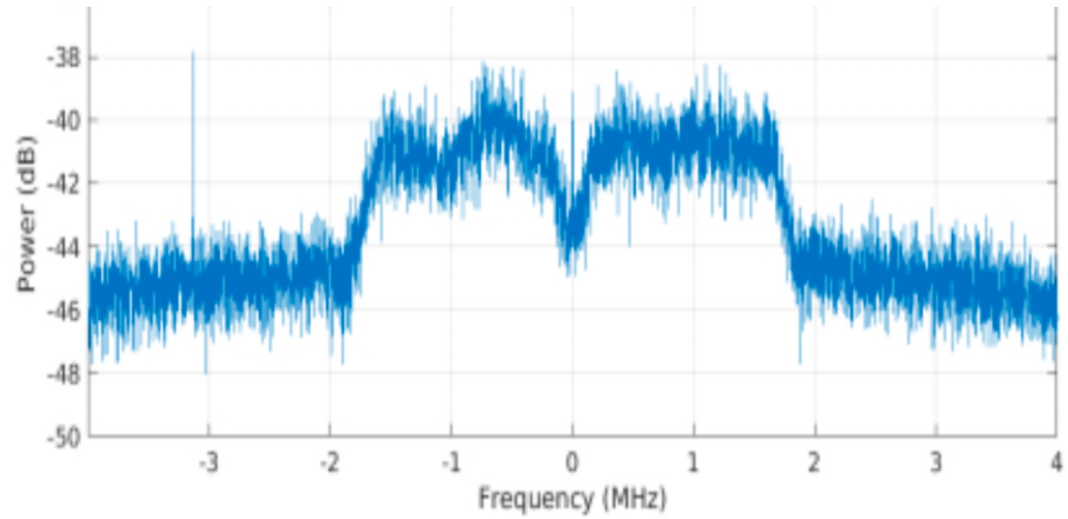



# What else is out there ?

## Link budget comparison ….

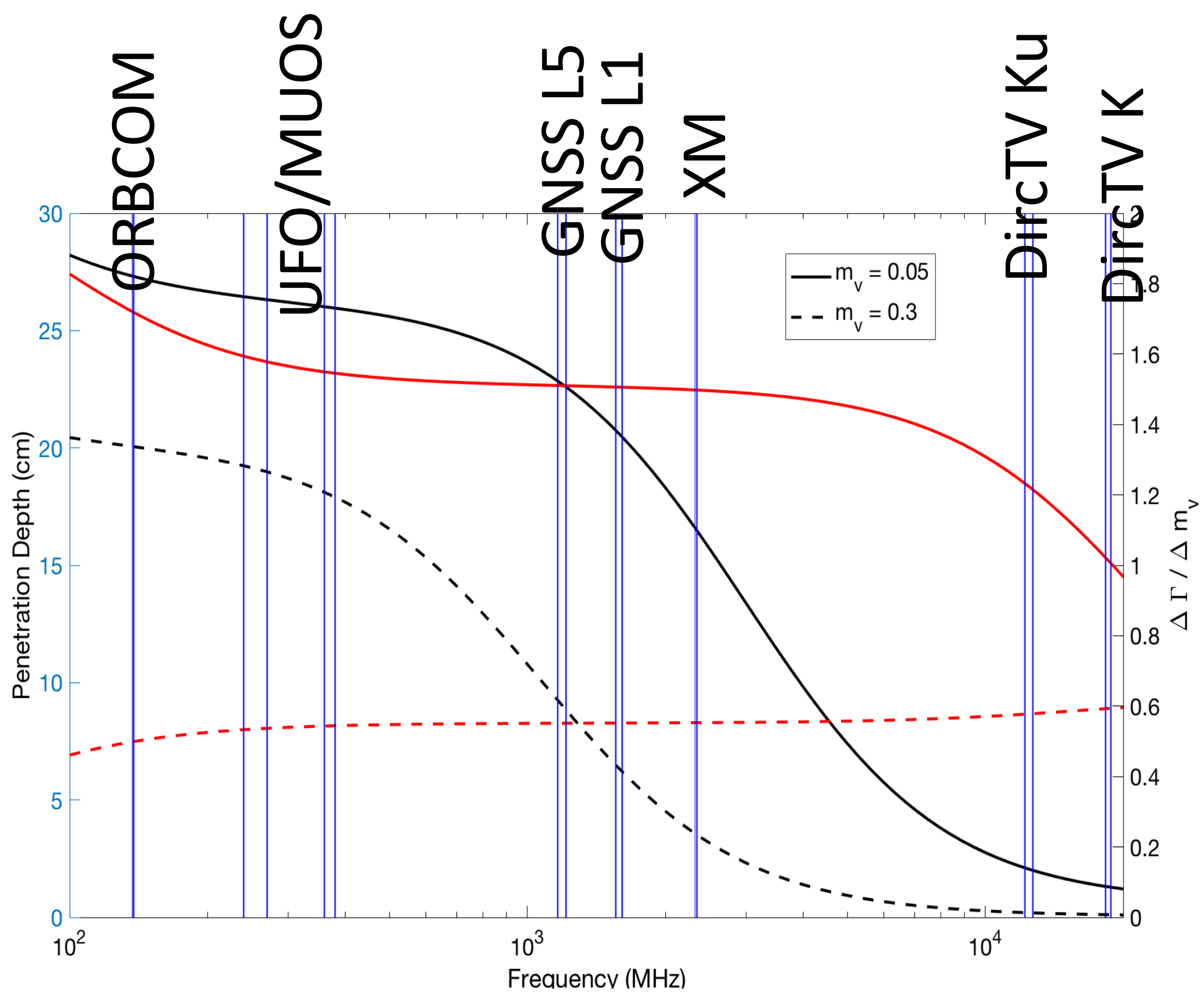
| | GPS | XM Radio |
|---|---|---|
| **EIRP (dBW)** | **24.5** | **68.5** |
| Frequency (MHz) | 1575.4 | 2342.2 |
| Atmos. Loss (dB) | -2.0 | -3.0 |
| Range (km) | 20200.0 | 35888.0 |
| Space Loss (dB) | -157.1 | -162.1 |
| Power Density (dB/m^2 | -134.6 | -96.6 |
| EAIA | -25.4 | -28.8 |
| Antenna Gain (dBm^2) | 3.0 | 3.0 |
| Received Power (dBW) | -157.0 | -122.4 |
| Noise Temp (K) | 290.0 | 290.0 |
| Bandwidth (MHz) | 2.0 | 2.0 |
| **SNR (dB)** | **-16.0** | **18.5** |

XM-Radio spectrum (@ receiver)

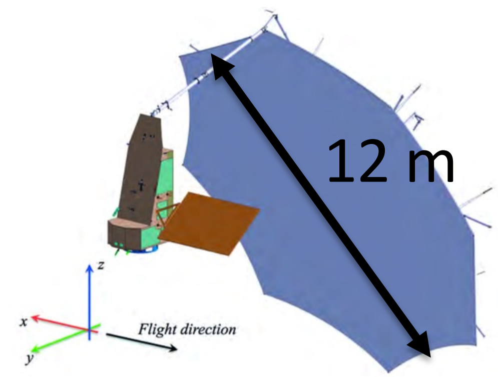



Very high SNR possible with communication signals!

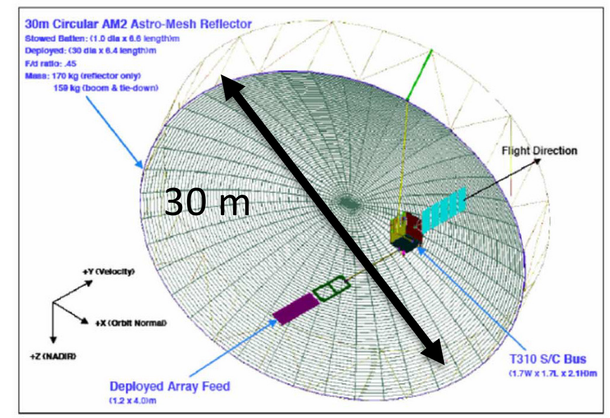
# Frequencies < 500 MHz (P-band)



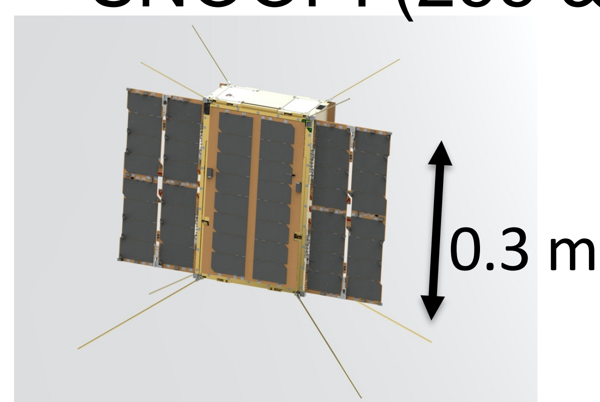

BIOMASS (435 MHz)

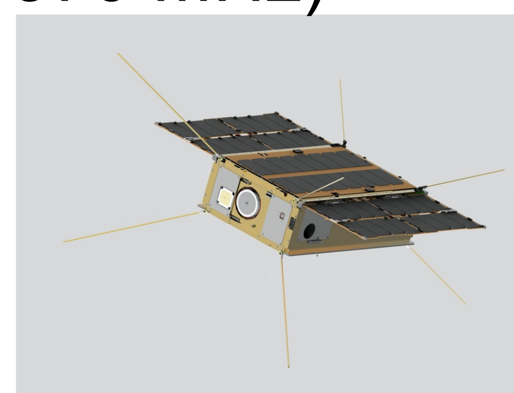



MOSS (137 MHz)



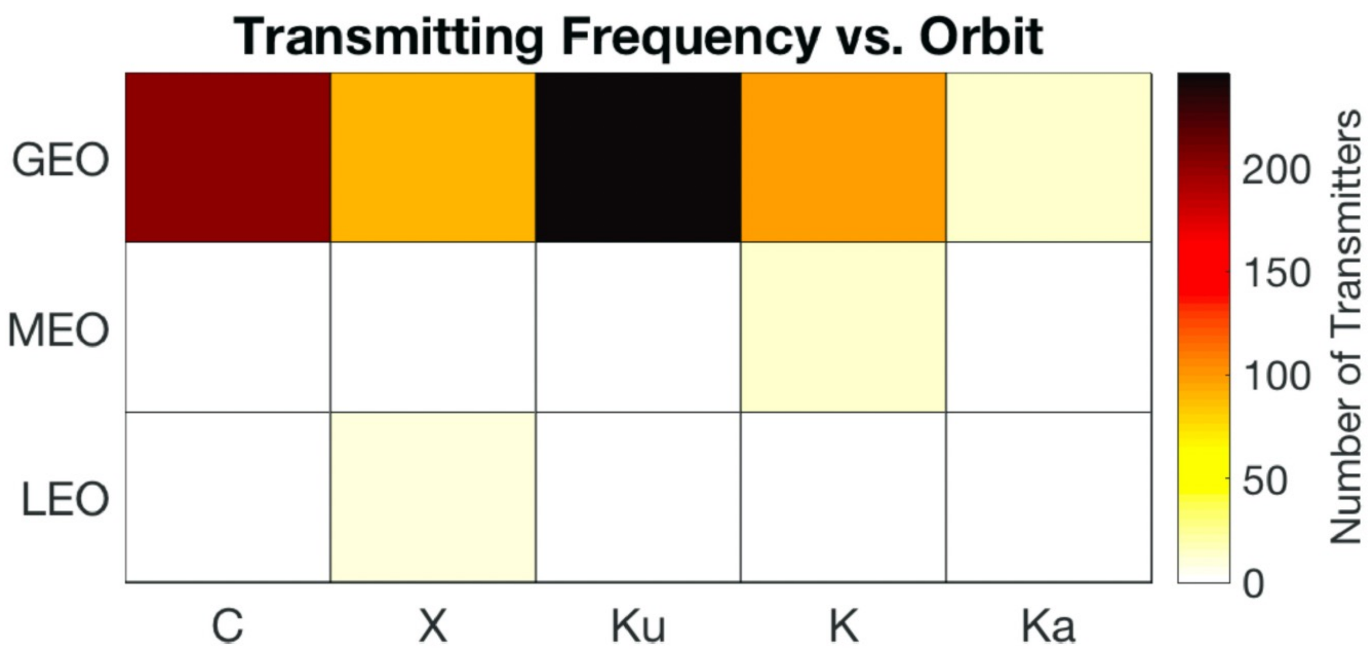

SNOOPI (255 & 370 MHz)



# Ku/K band

## Wide bandwidth, Good coastal coverage




[Benveniste et al., 10.3389/fmars.2019.00348]

| System | Frequency (GHz) | BW (MHz) |
|---|---|---|
| DirecTV | 12.5 (Ku)<br>18.6 (K) | 500<br>500 |
| Astra-4a | 12.2 (Ku)<br>20.3 (Ka) | 1050<br>200 |
| AEHF | 20.7 (Ka) | 1000 |

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# Ku/K band

## Altimetry error dependence on bandwidth