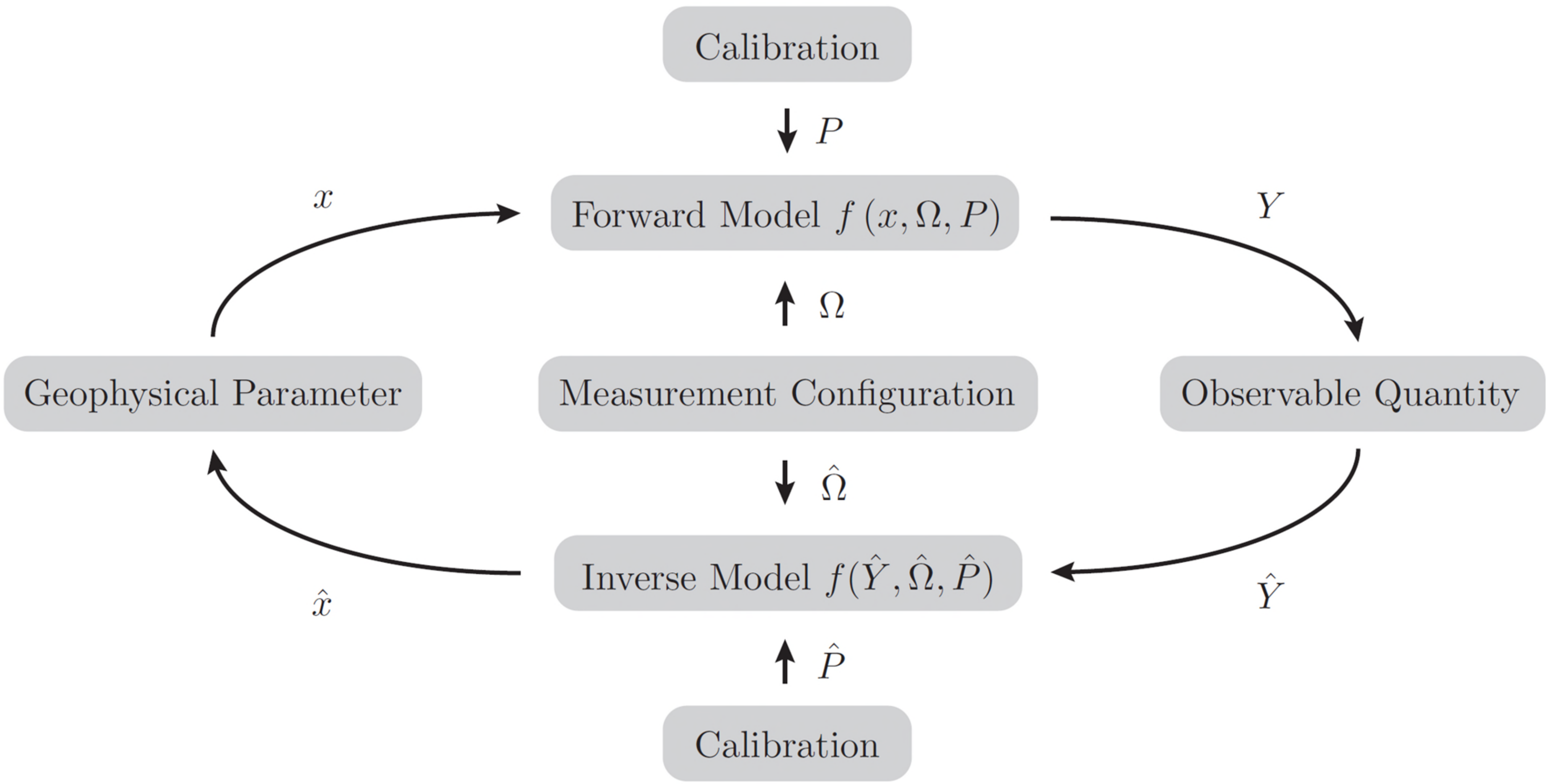
Chapter 4
Forward Modelling

4.1 Backscatter from Vegetation

4.2 Backscatter from Bare Soil

4.3 Parsimonious Land Surface Backscatter Models

1.4 Data Modelling



Approaches to Build Forward Models

- Theoretical models
  - Based upon electromagnetic theory → but simplifying assumptions (based upon empirical evidence) always needed
  - Based upon radiative transfer theory → but absorption, emission and scattering processes need to be "parameterized" (= empirical description of interaction processes)

- Empirical models
  - From simple linear regressions to advanced machine learning methods
  - Depend crucially on the quality of training data (in situ, remote sensing)
  - Model selection must be guided by an understanding of the data and processes

- Semi-empirical models
  - Combine both theoretical and empirical elements

Forward Modelling of Backscatter

- We illustrate the different approaches by discussing a concrete case, namely forward modelling of backscatter from vegetated soils
  - Thanks to the high transparency of the atmosphere at low microwave frequencies (1-10 GHz), atmospheric effects can be neglected

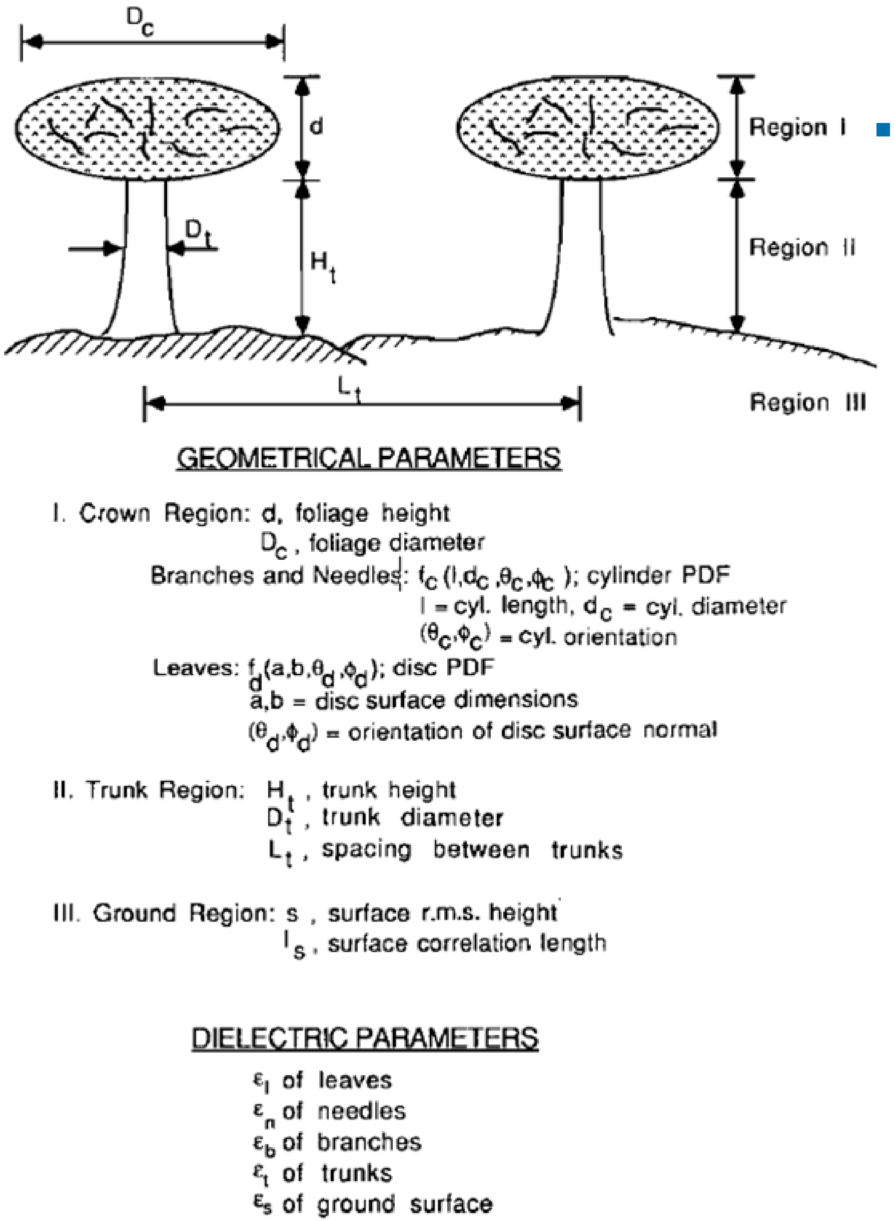
- This discussion shall illustrate following generic aspects:
  - Model complexity
    - Complex (= many model parameters) vs parsimonious (=few model parameters) models
  - Model adequacy
    - Which processes are described, which not?

4.1 Backscatter from Vegetation

- Usually modelled with radiative transfer theory
  - Only the net energy change of the radiation is considered even though in certain instances the phase may be important
  - Model parameters are effective quantities that describe interference effects indirectly

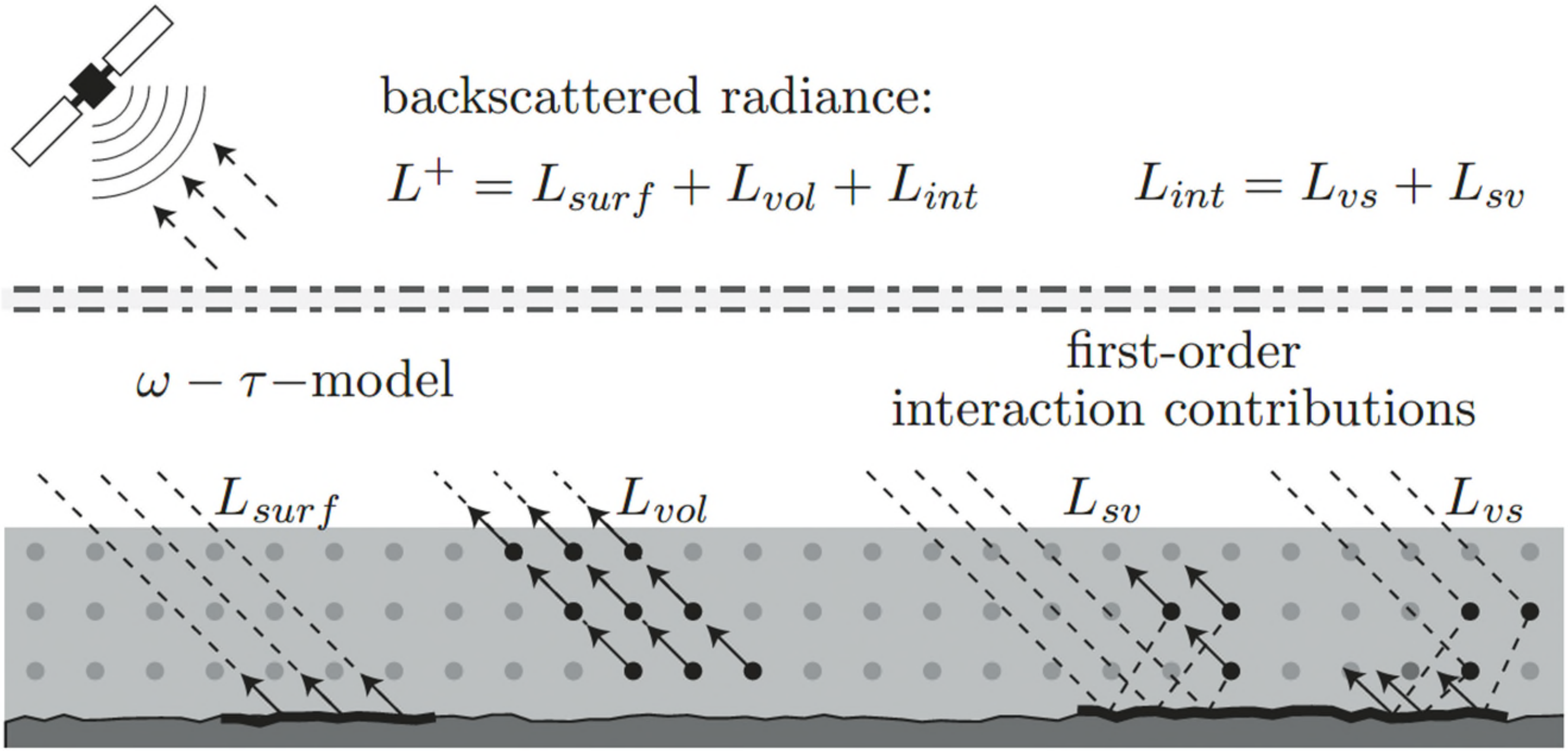
- Three main scattering components
  - Volume scattering
    - Direct backscatter from vegetation
  - Surface scattering
    - Backscatter from the soil attenuated by the vegetation (two-way)
  - Interaction term
    - Multiple scattering by vegetation and soil

Vegetation Modelled by its Structural Elements



- Michigan Microwave Canopy Scattering Model (MIMICS)
  - First-order radiative transfer model expansion
  - Three regions: Crown, trunk, ground
  - Input data
    - Statistical distributions for dimension, orientation and dielectric properties
    - Surface RMS-height and correlation-function
    - Relation between dielectric properties and water-content, frequency, temperature of individual constituents
    - Number of trees per unit area

Vegetation Modelled as a Homogeneous Medium



$$\sigma^0 = \sigma^0_v + \sigma^0_s + \sigma^0_{int} = 4\pi \frac{L_v + L_s + L_{int}}{L_i} cos(\theta)$$

Radiative Transfer Equation

Remember from last week....

dL=dL(emission)-dL(absorption)+dL(scattering)

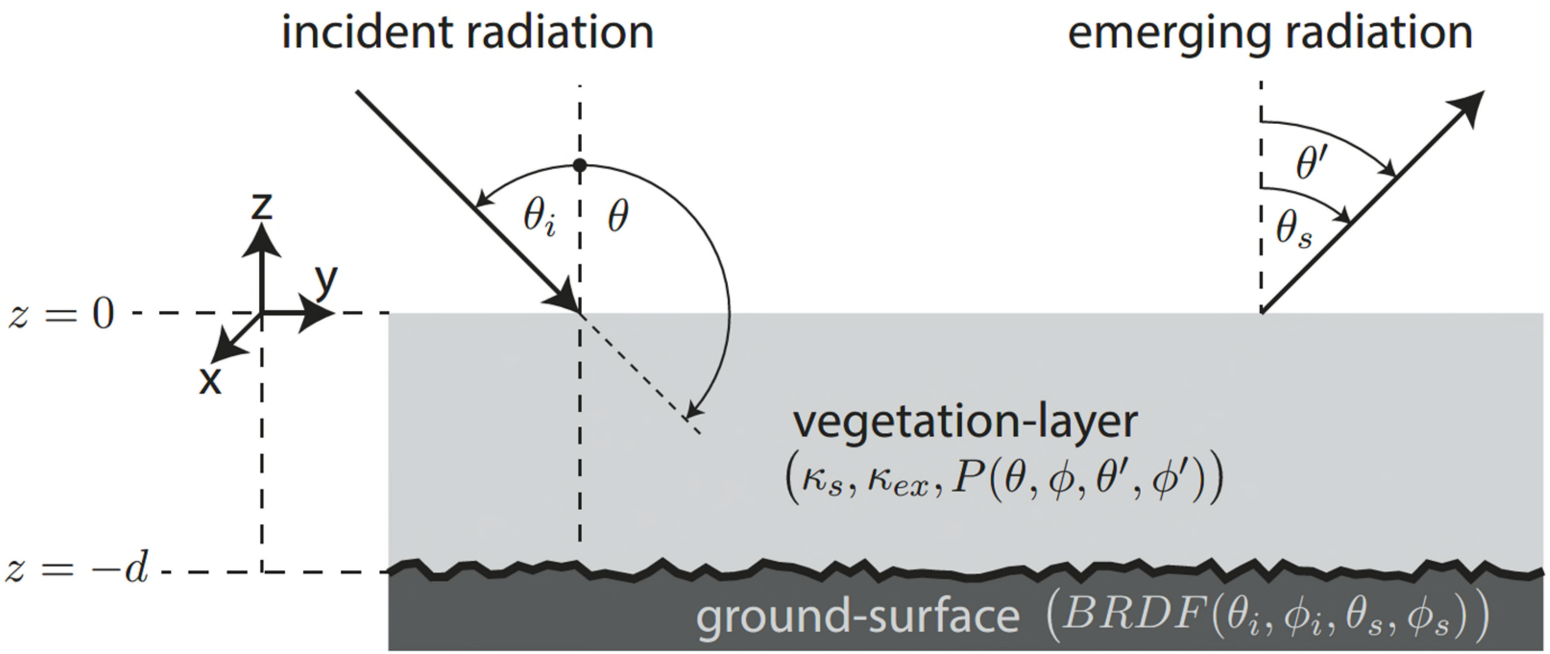
$$\frac{dL(\theta,\phi)}{dr} = -\kappa_e L(\theta,\phi) + \frac{\kappa_s}{4\pi}\int_0^{2\pi}\int_0^{\pi} P(\theta,\phi,\theta',\phi')L(\theta',\phi')\sin\theta' d\theta' d\phi'$$

Extinction and scattering coefficient

Scattering phase function (directionality)

Model Formulation

- Vegetation is treated as a homogeneous medium (air) embedded randomly with particles (vegetation elements)
  - Scattering coefficient κ_s
  - Extinction coefficient κ_e
  - Phase function $P(\theta, \phi, \theta', \phi')$



ω-τ Model

- Ignoring the interaction term, and assuming a certain volume scattering phase function (e.g. Rayleigh) gives

$$\sigma^0(\theta) = \cos(\theta)\frac{3\omega}{4}\left(1 - \gamma(\theta)^2\right) + \sigma^0_{soil}(\theta)\gamma^2(\theta)$$

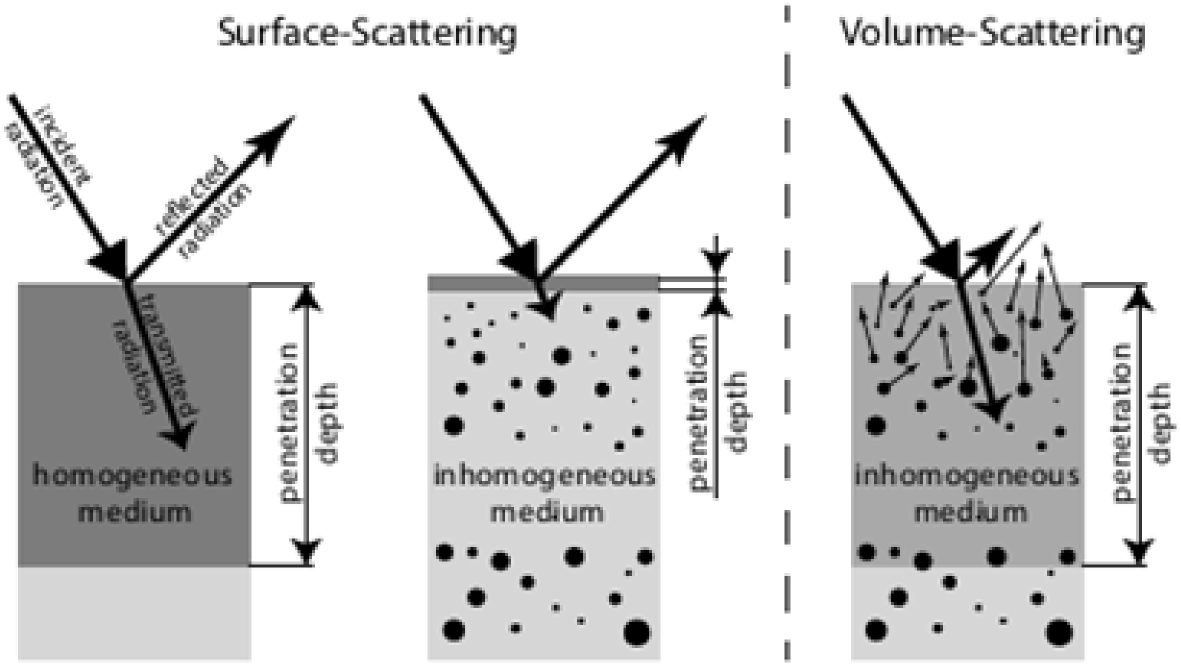
where γ^2 is the two-way attenuation factor

$$\gamma^2(\theta) = e^{-\frac{2\tau}{\cos\theta}}$$

- In essence identical to the Water Cloud Model (Section 4.3.1)

- Parsimonious model that uses only two parameters (ω and τ respectively γ^2) to describe the complex interactions of microwaves with vegetation

4.2 Backscatter from Bare Soil

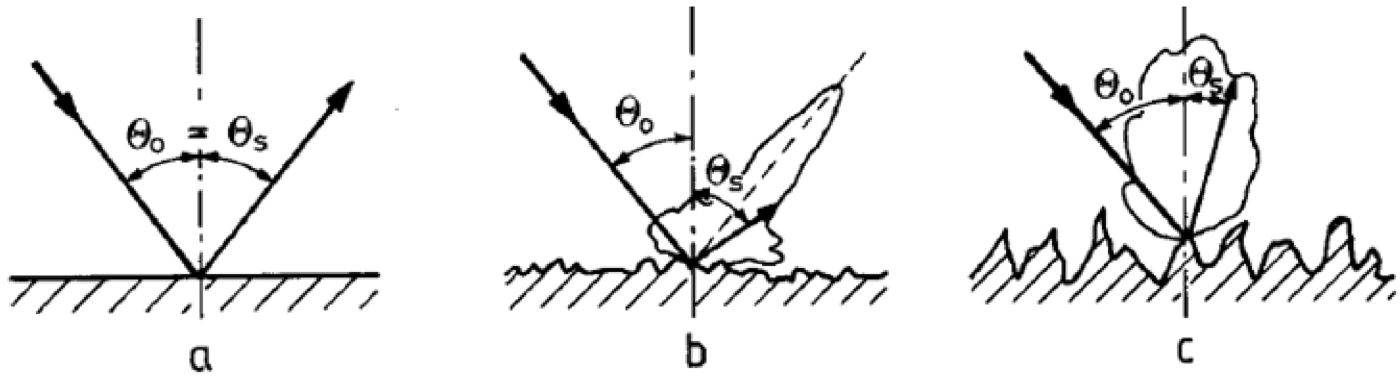


4.2 Backscatter from bare soils

- Soil scattering is principally driven by
  - Soil surface “roughness”
    - Relative to wavelength
    - Dependent on soil moisture
  - Soil dielectric constant
    - Soil moisture
    - Texture

4.2.1 Theoretical models

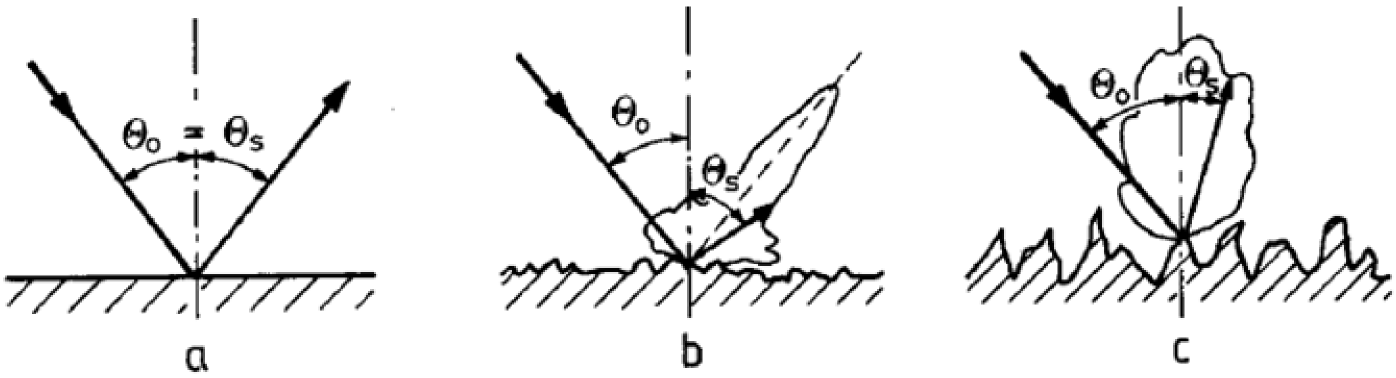
Depending on the roughness of a soil surface:



a. Specular reflection
b. Predominantly forward scattering
c. Uniform scattering in all directions

4.2.1 Theoretical models

Depending on the roughness of a soil surface:



a. Specular reflection
b. Predominantly forward scattering
c. Uniform scattering in all directions

Theoretical models - Soil dielectric constant

Fresnel reflectivity

$$\Gamma_{\parallel} = \frac{E^{s}_{0,\parallel}}{E^{i}_{0,\parallel}} = \frac{\cos\theta\ - \sqrt{\epsilon - sin^2\theta}}{\cos\theta + \sqrt{\epsilon - sin^2\theta}}$$

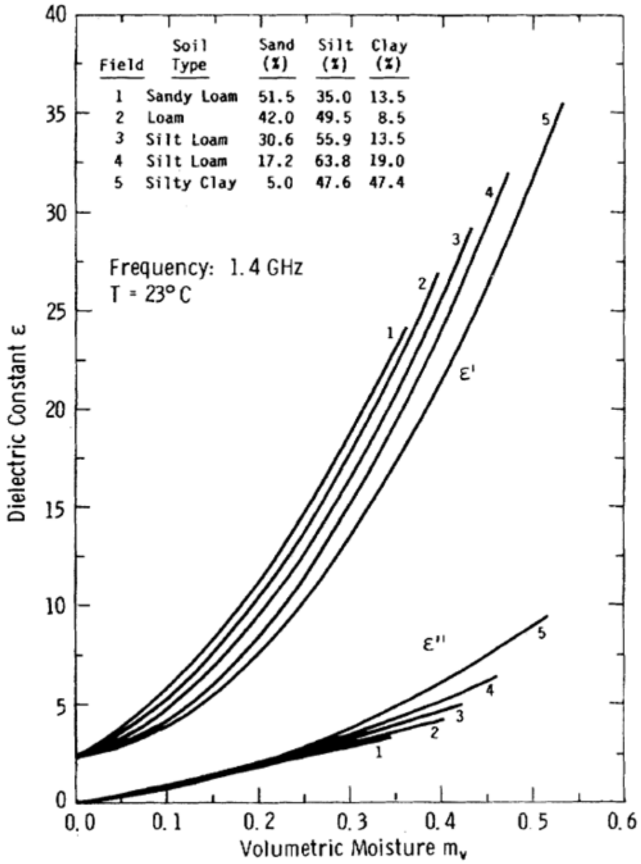
- Reflectivity is dependent on incidence angle and dielectric constant ε

Theoretical models - Soil dielectric constant

Fresnel reflectivity

$$\Gamma_{\parallel} = \frac{E^{s}_{0,\parallel}}{E^{i}_{0,\parallel}} = \frac{\cos\theta \; - \sqrt{\epsilon - sin^2\theta}}{\cos\theta + \sqrt{\epsilon - sin^2\theta}}$$

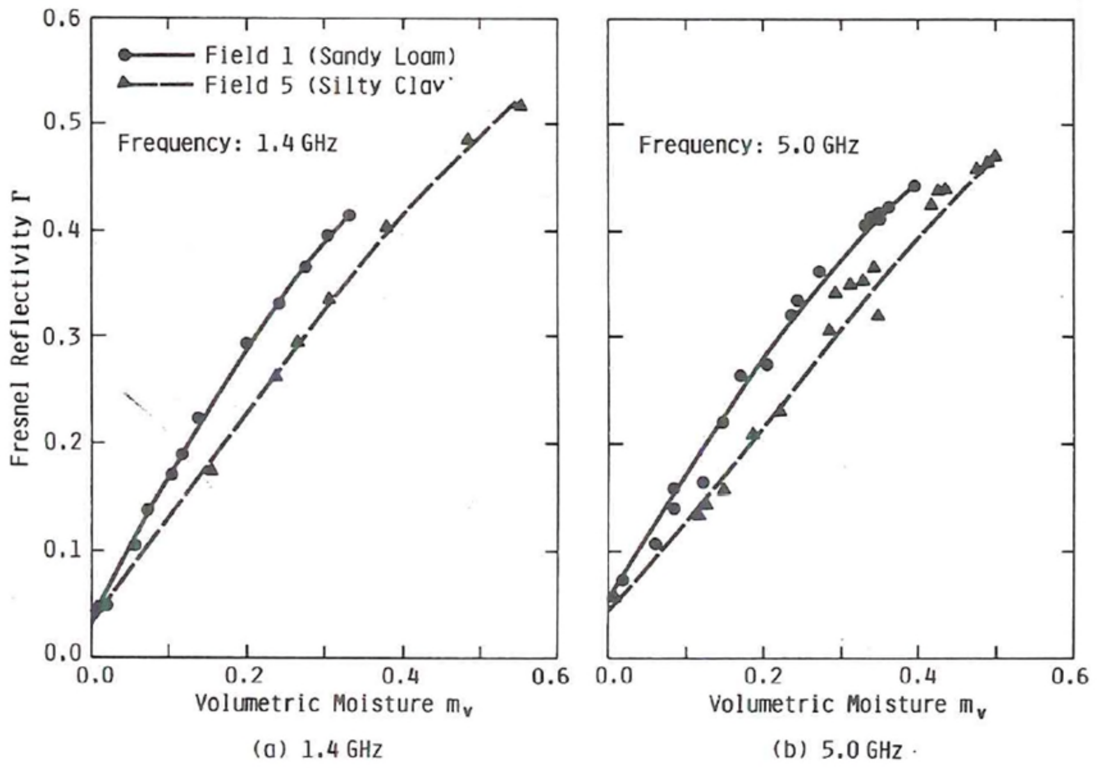
- Strong increase of ε with increasing soil moisture



Theoretical models - Soil dielectric constant

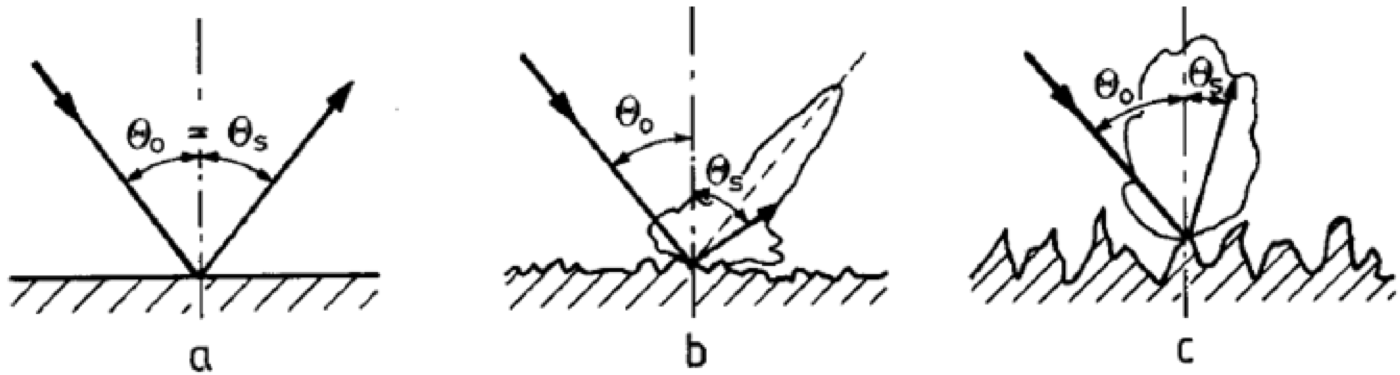
Fresnel reflectivity

- Γ increases with soil moisture



Theoretical models

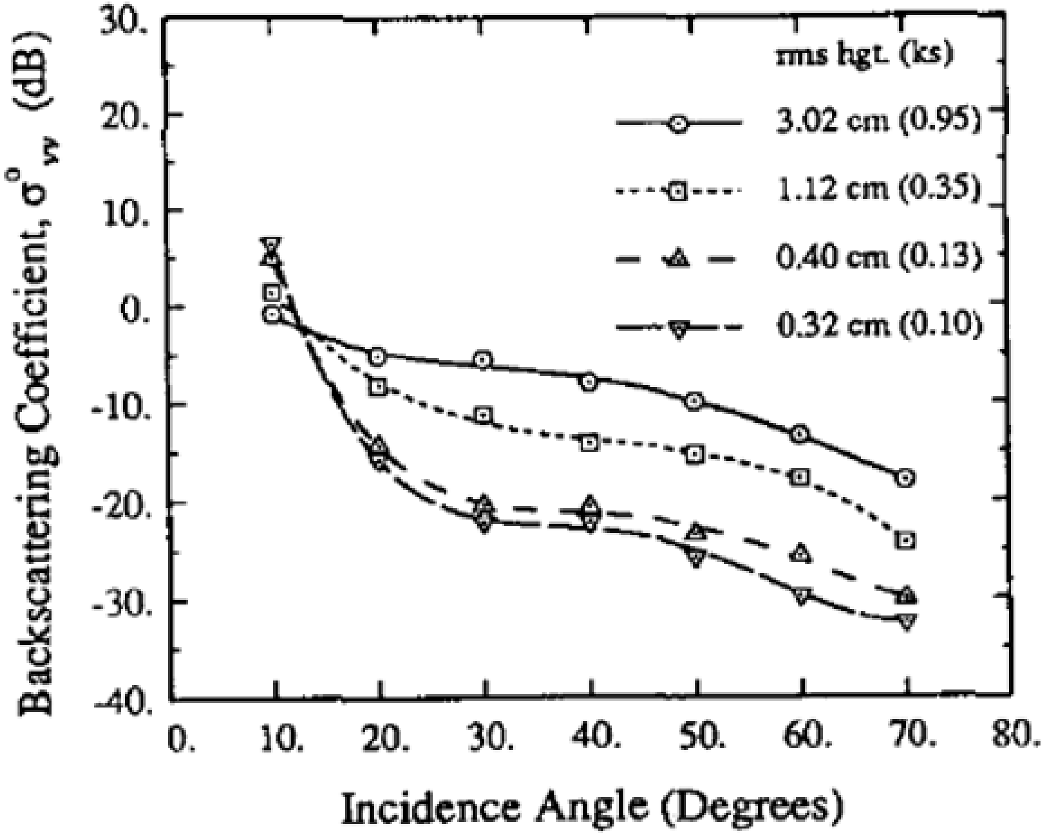
Depending on the roughness of a soil surface:



a. Specular reflection
b. Predominantly forward scattering
c. Uniform scattering in all directions

Theoretical models - Effect of roughness

Roughness affects the distribution of the scattered energy



Theoretical models - Effect of roughness

- Many models exist to describe surface roughness
  - Geometric Optics Model
  - Small Perturbations Model
  - Integral Equation Model

- Approximations must be made – How do you quantify roughness?

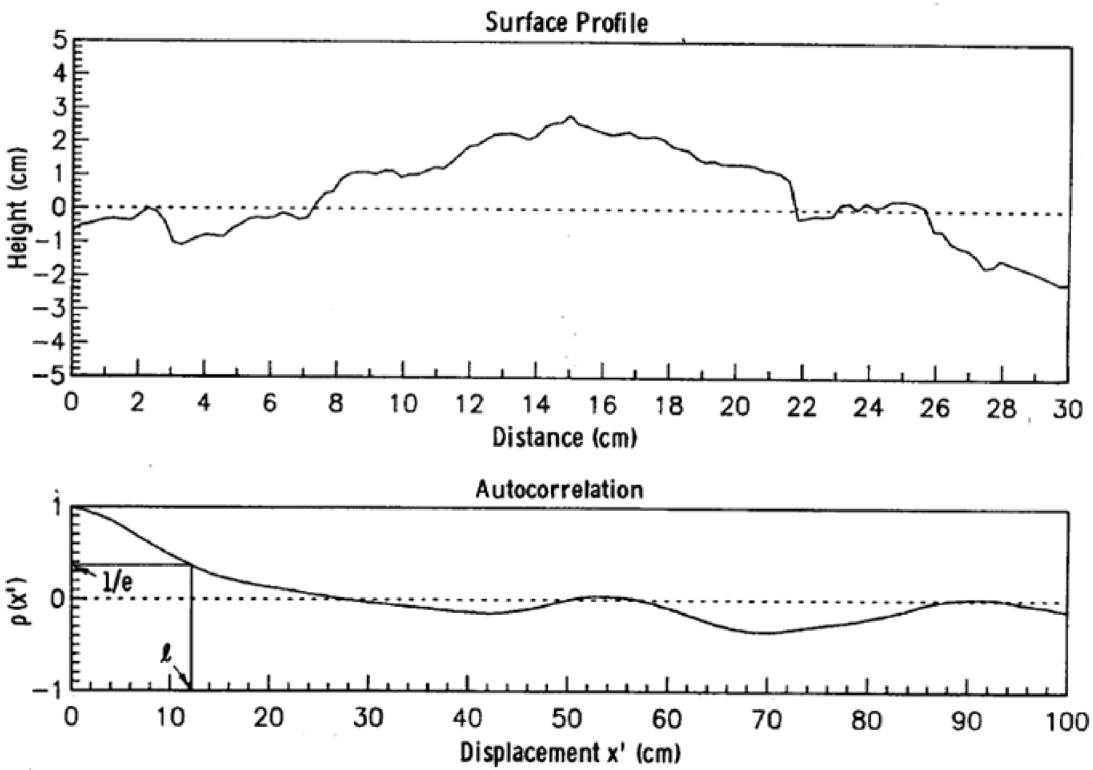
Theoretical models - Effect of roughness

Root mean square height (*s*):

$$p(z) = \frac{1}{\sqrt{2\pi s^2}} e^{-\frac{z^2}{2s^2}}$$

Correlation length:

$$\rho(x') = \frac{\int z(x)z(x+x')dx}{\int z^2(x)dx}$$



Purely geometric concept

4.2.2 Empirical models

- From experimental data.

- Take into account the validity range
  - Model parameters are usually valid only for the experimental data
  - Model structure can be valid for a wider range

Empirical models – Linear Model

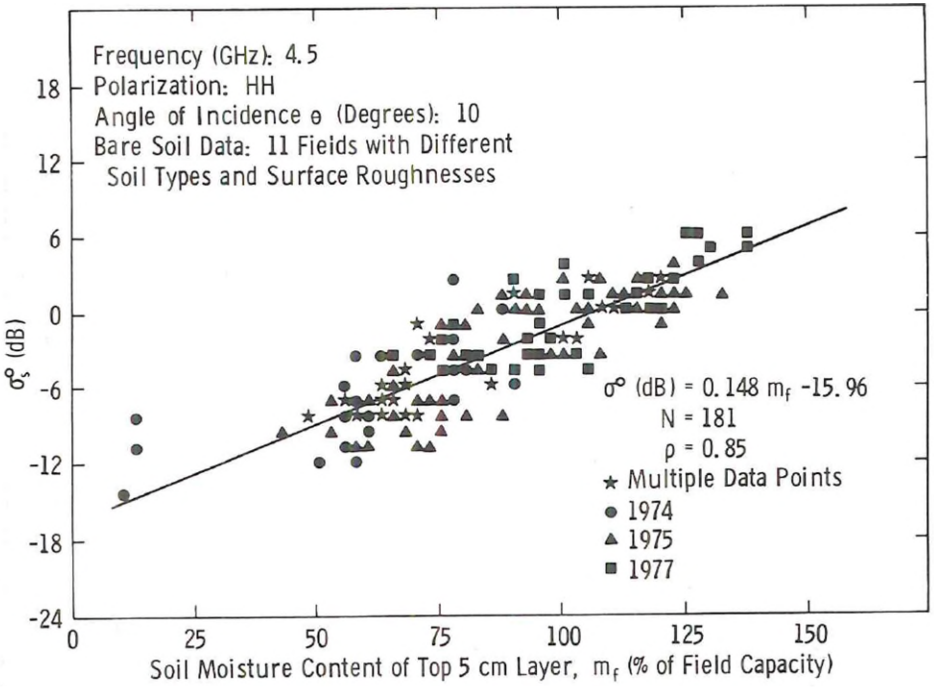
$$\sigma^0_{soil}[dB] = A + Bm_v$$

$$\sigma^0_{soil}[m^2m^{-2}] = 10^{\frac{A+Bm_v}{10}} = e^{\frac{ln10(A+Bm_v)}{10}} = ae^{bm_v}$$

m_v = soil moisture

A = dry soil backscatter

B = sensitivity

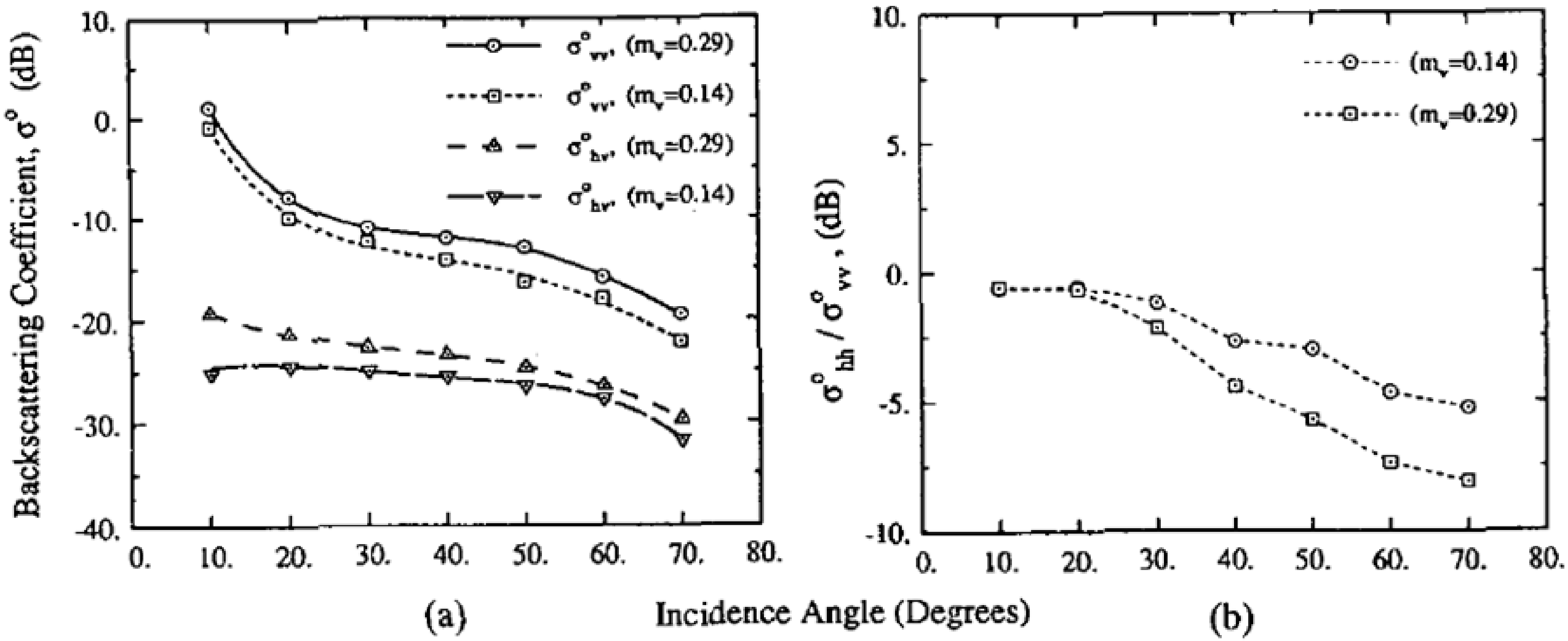


Empirical models – Oh Model

- Developed in 1992 because most models did not take into account surface roughness, or only limited range.
- For predicting the root mean square height and soil moisture from multi-polarized, multi-incidence radar observations.

  - VV, HH VH
  - 10-70 degrees incidence angle range
  - Different surface roughness
  - Different soil moisture

Empirical models – Oh Model



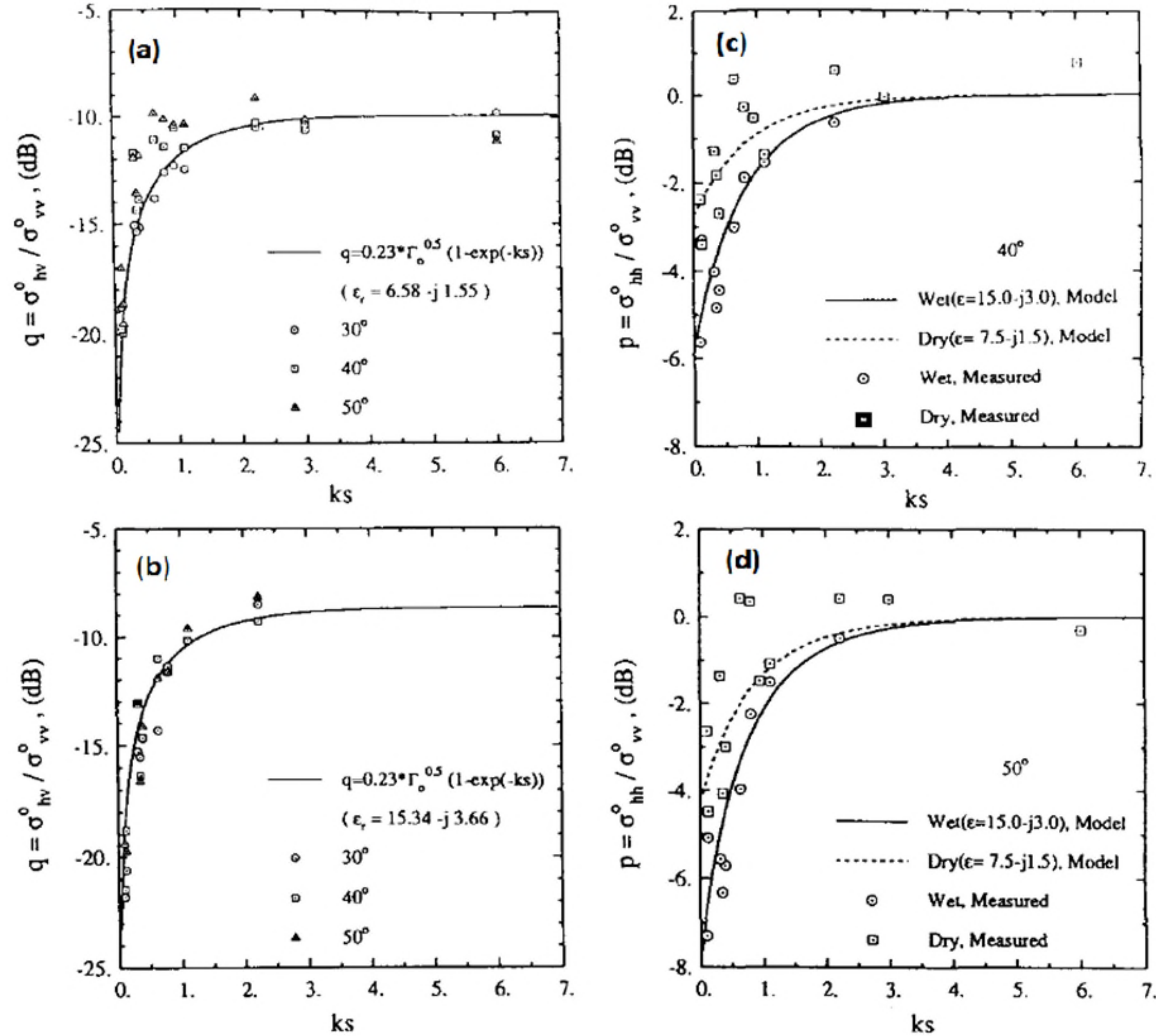
Angular responses of (a)σ°_{vv}, and σ°_{hv} and (b) the ratio σ°_{hh} / σ°_{vv} for different soil moisture conditions.

Empirical models – Oh Model

$$q = \frac{\sigma^0_{hv}}{\sigma^\circ_{vv}} = 0.23\sqrt{\Gamma_0}(1 - e^{-ks})$$

$$\sqrt{p} = \sqrt{\frac{\sigma^\circ_{hh}}{\sigma^0_{vv}}} = 1 - \left(\frac{2\theta}{\pi}\right)^{\frac{1}{3R_0}} e^{-ks}$$

- Γ_0 Fresnel reflection coefficient in nadir direction
- ks root mean square height multiplied with the wave number
- θ is the incidence angle.



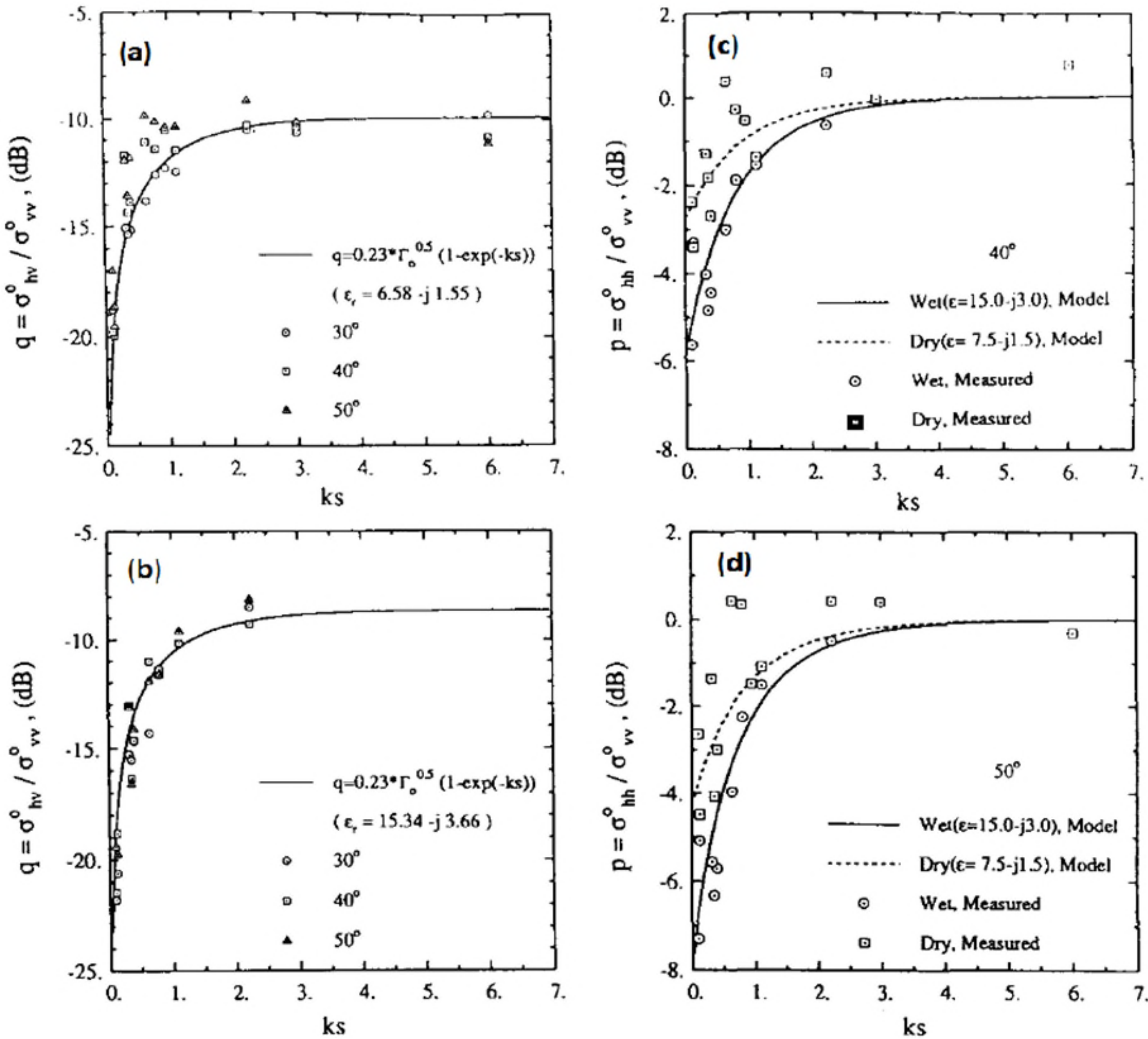
Roughness dependency of the cross-polarized ratio for (a) dry and (b) wet soils, and the co-polarized ratio at 40° (c) and 50° (d)

Empirical models – Oh Model

$$q = \frac{\sigma_{hv}^{0}}{\sigma_{vv}^{\circ}} = 0.23\sqrt{\Gamma_0}(1 - e^{-ks})$$

$$\sqrt{p} = \sqrt{\frac{\sigma_{hh}^{\circ}}{\sigma_{vv}^{0}}} = 1 - \left(\frac{2\theta}{\pi}\right)^{\frac{1}{3R_0}} e^{-ks}$$

- Difference between HV and VV and HH and VV becomes smaller with increasing roughness
- q does not depend on θ and soil moisture is a constant scaling factor
- p depends on both θ and soil moisture



Roughness dependency of the cross-polarized ratio for (a) dry and (b) wet soils, and the co-polarized ratio at 40° (c) and 50° (d)

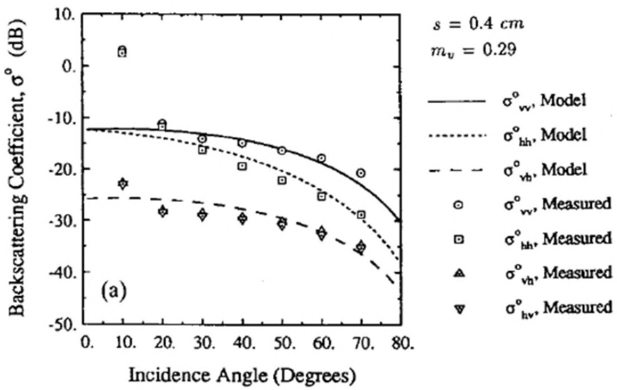
Empirical models – Oh Model

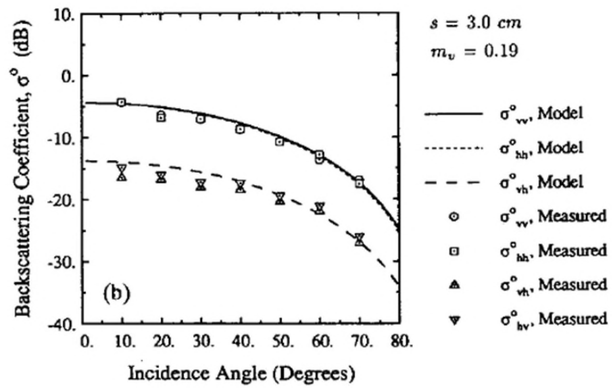
Empirically define $\sigma°_{vv}$:

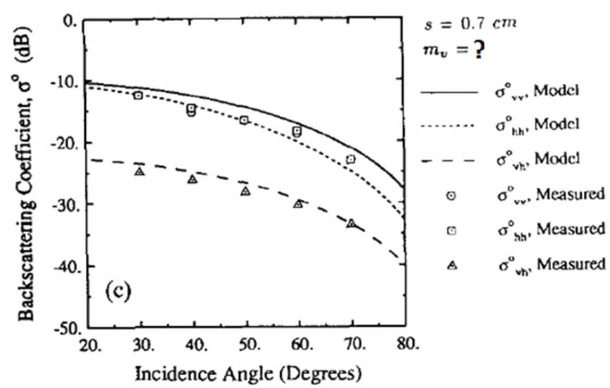
$$\sigma^\circ_{vv}(\theta,\varepsilon,ks) = \frac{g\cos^3\theta}{\sqrt{p}}[\Gamma_v(\theta)+\Gamma_h(\theta)]$$

$$\sigma^\circ_{hh}(\theta,\varepsilon,ks) = p\,\sigma^\circ_{vv}(\theta,\varepsilon,ks)$$

$$\sigma^\circ_{hv}(\theta,\varepsilon,ks) = q\,\sigma^\circ_{vv}(\theta,\varepsilon,ks)$$

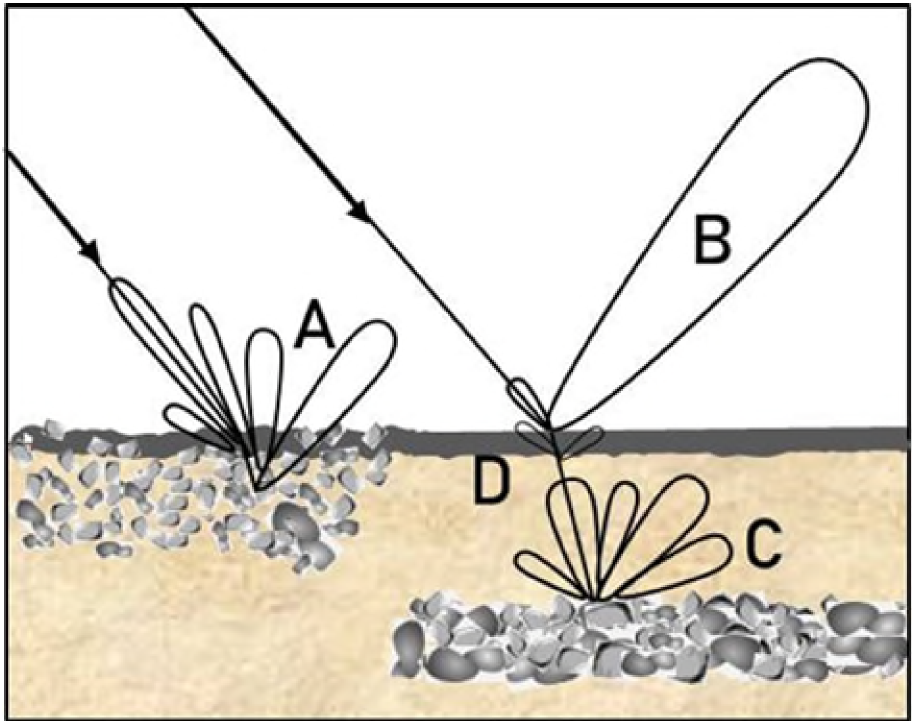




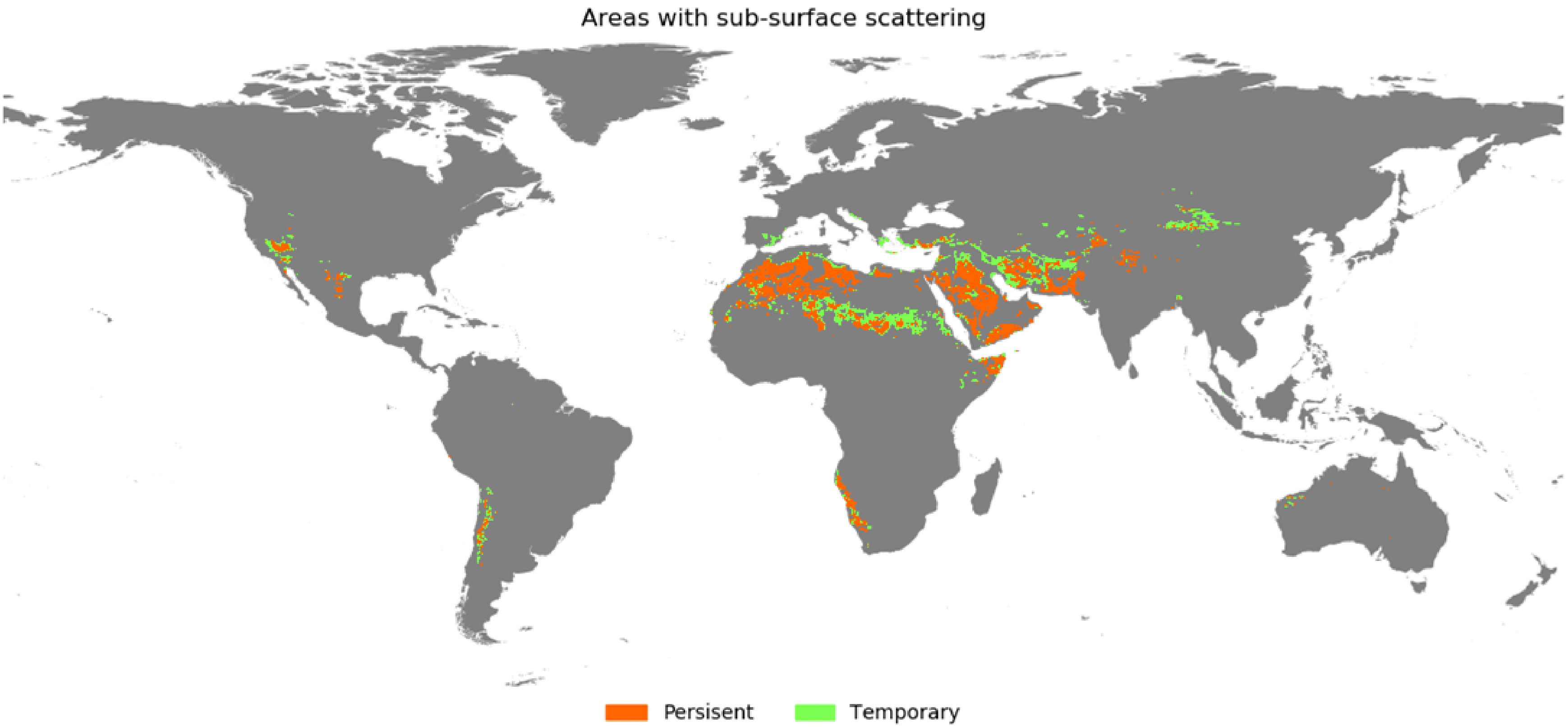


4.2.3 Subsurface Scattering – when models fail…

- The models cannot explain the physical phenomenon



4.2.3 Subsurface Scattering – when models fail…



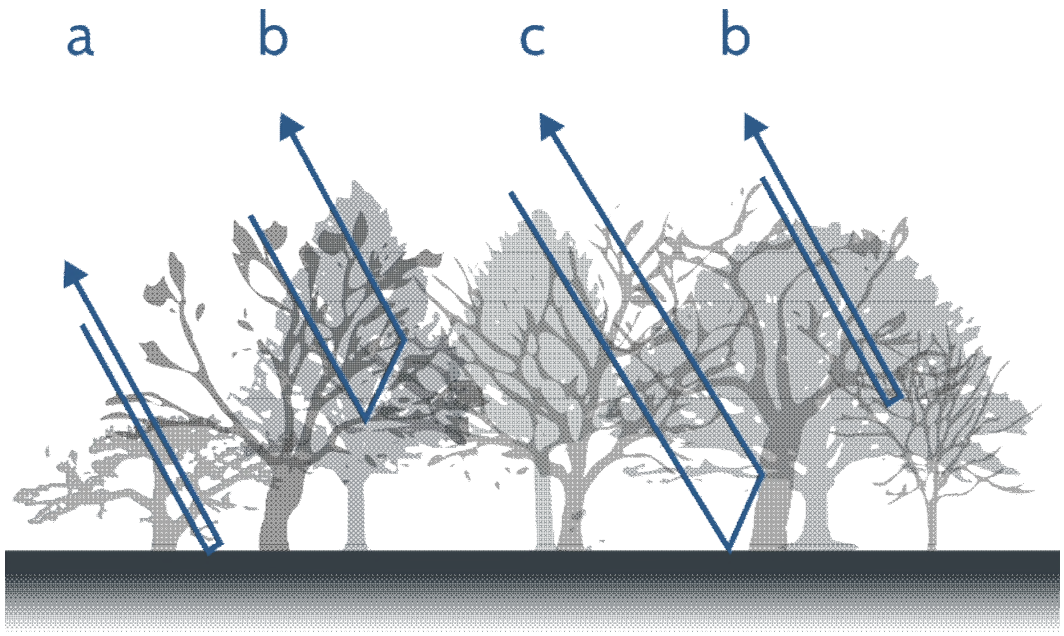
4.3 Parsimonious land surface backscatter models

$$\sigma°(\theta) = \sigma°_S(\theta) + \sigma°_V(\theta) + \sigma°_{INT}(\theta)$$

a b c

- Combining
  - Vegetation model
  - Bare soil model

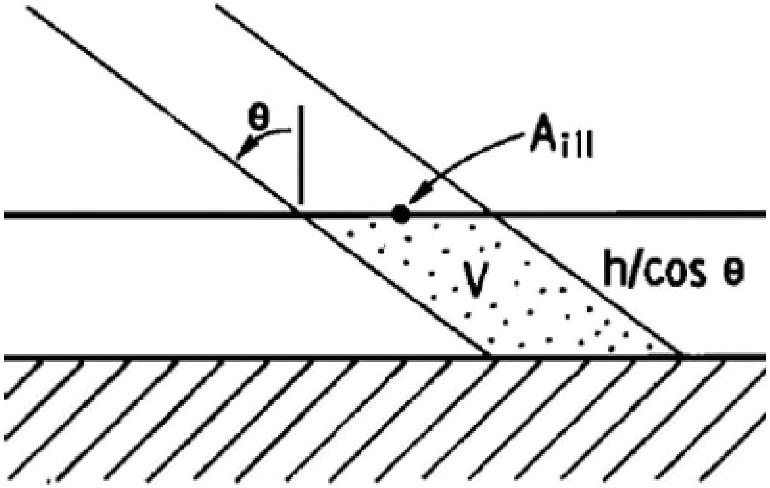
- Examples
  - Water cloud model
  - TU Wien model



4.3.1 Parsimonious models - water cloud model

$\omega - \tau$ model

$$\sigma°(\theta) = \sigma°_{veg}(\theta) + \sigma°_{s}(\theta)$$



Vegetation

$$\sigma°_{veg} = \frac{\overline{P_r}}{SA_{ill}} = \left(\frac{k_s}{2k_e}\right)\left[1 - e^{-\frac{2k_e h}{cos\theta}}\right]cos\theta$$

$k_s = N\sigma_s$ $\qquad$ $k_e = N\sigma_e$

Parsimonious models - water cloud model

Soil:

$$\sigma°_s = Ae^{Bm_v}$$

$\omega - \tau$ model

$$\sigma°(\theta) = \sigma°_{veg}(\theta) + \sigma°_s(\theta)$$

$$\sigma°(\theta) = \left(\frac{k_s}{2k_e}\right)\left[1 - e^{-\frac{2k_e h}{cos\theta}}\right]cos\theta + Acos\theta e^{Bm_v \frac{-2k_e h}{cos\theta}}$$

Parsimonious models - water cloud model

How to get the model parameters ks, ke?

C is related to the extinction and scattering of the particles

$$C = \frac{N\sigma_b}{2N\sigma_e} = \frac{k_s}{2k_e} = \frac{\omega}{2}$$

D is related to the extinction of the particles:

$$DW \cong 2N\sigma_e = 2k_e$$

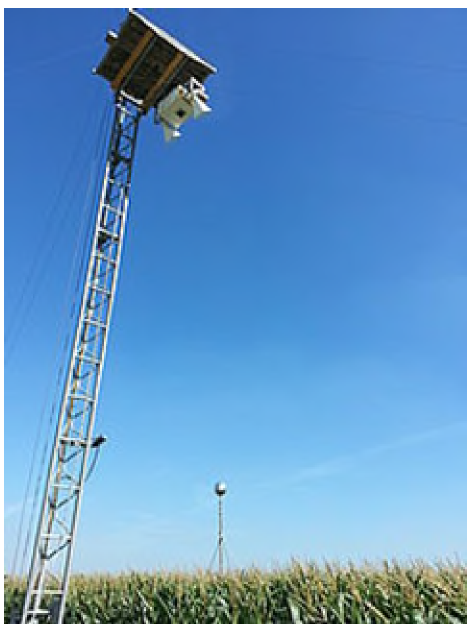
$$2k_e h = 2\tau$$

$$\sigma°(\theta) = C cos\theta \left(1 - e^{\frac{-DWh}{cos\theta}}\right) + A cos\theta e^{Bm_v \frac{-DWh}{cos\theta}}$$

Parsimonious models - water cloud model

$$\sigma^\circ(\theta) = C cos\theta \left(1 - e^{\frac{-DWh}{cos\theta}}\right) + A cos\theta e^{Bm_v \frac{-DWh}{cos\theta}}$$

- How do we calibrate, *A*, *B*, *C* and *D*?



Radar over corn field. Courtesy of S.C. Steele-Dunne, TU Delft

TABLE I. Summary of ground truth data for the 1974 radar cross section data. W is the volumetric water content of the canopy; h is the canopy height; m_s is the soil moisture content.

Date	W(kg/m³)	h (m)	m_s (kg/m³)
Alfalfa			
May 22	1.353	.17	280
June 14	3.488	.43	330
June 24	3.091	.55	230
June 28	2.000	.55	170
July 5	2.456	.55	300
July 10	4.000	.11	150
July 17	2.138	.29	20
July 23	3.111	.45	30
Aug. 12	2.671	.73	160
Corn			
May 20	.693	.30	240
May 24	1.503	.40	260
May 30	2.268	.58	120
June 5	2.358	.88	100
June 13	4.968	1.25	340
June 26	3.447	2.3	80
July 1	3.825	2.6	70
July 8	3.960	2.6	300
July 11	4.410	2.6	150
July 16	3.366	2.6	60
July 22	4.338	2.6	40
Aug. 5	2.124	2.6	70
Aug. 15	0.891	2.7	260
Sept. 5	1.359	2.7	290
Sept. 19	0.522	.33	100
Milo			
July 12	2.200	.30	60
July 18	4.200	.46	30
July 25	6.000	.71	30
Aug. 1	25.600	.77	30
Aug. 7	7.500	.92	260
Aug. 19	11.900	.92	120
Aug. 21	11.600	.92	70
Aug. 29	6.400	1.12	310
Sept. 17	5.300	1.17	170
Wheat			
May 21	5.760	.90	360
May 27	5.600	.96	400
May 31	5.520	.96	310
June 6	4.240	.96	350
June 10	4.160	.96	360
June 17	2.550	.96	20
June 21	1.040	.84	310
June 25	0.880	.32	210

Parsimonious models - water cloud model

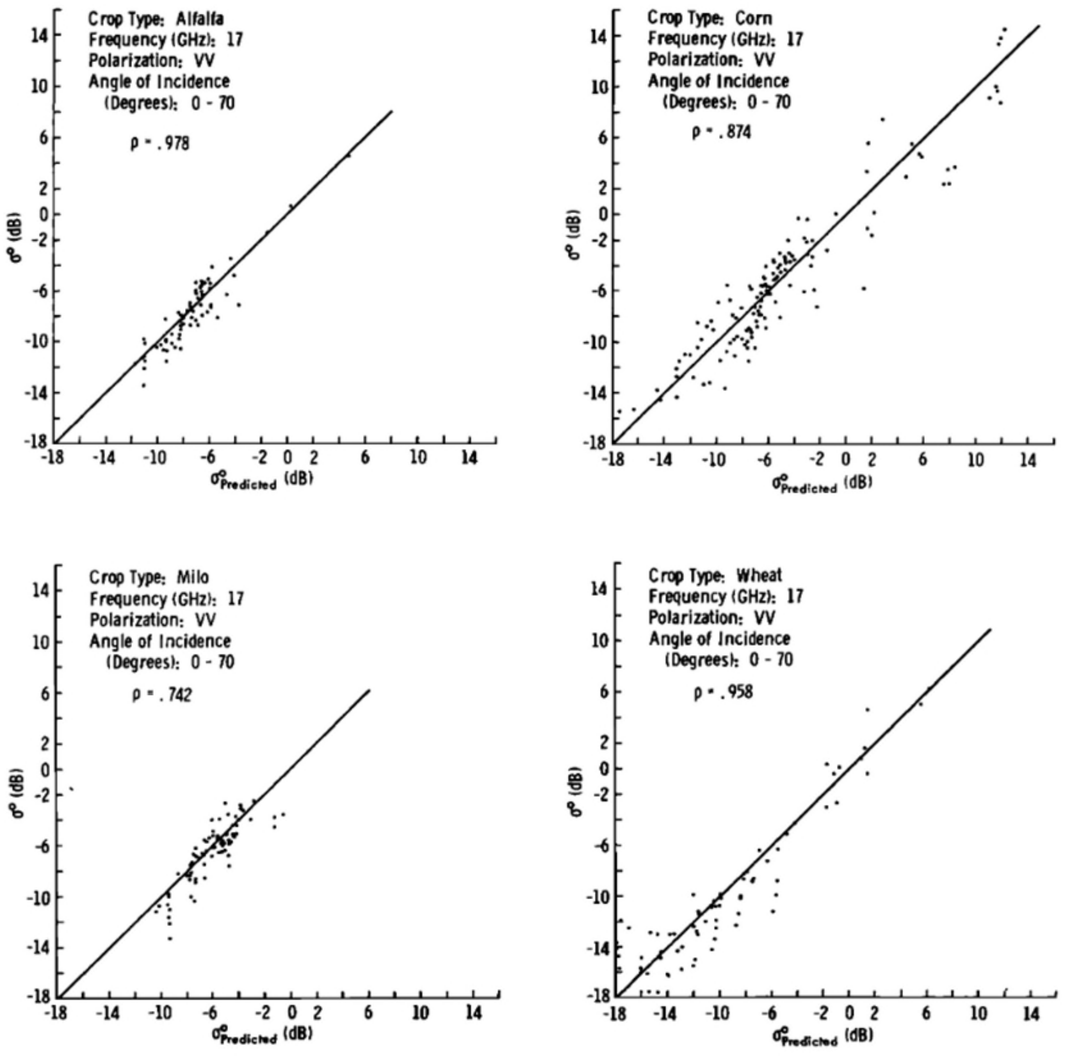


Fig. 2. Measurements versus model predictions of σ° for alfalfa, corn, milo, and wheat.

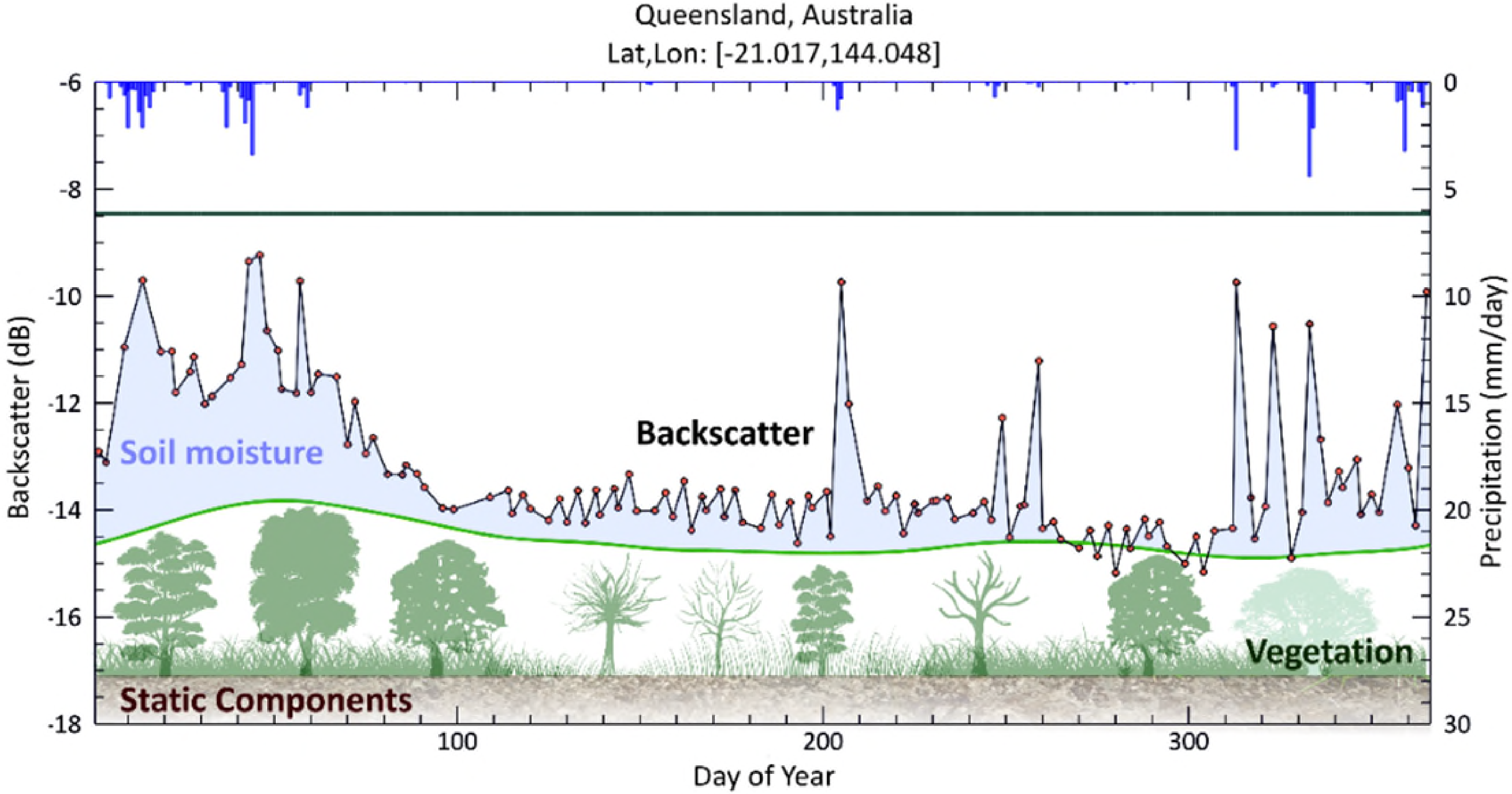
Parsimonious models - TU Wien method

- Change detection method: Linear soil backscatter model extended to a vegetated surface.
- define backscatter from the lowest observed backscatter related to driest soil conditions and a shift in backscatter

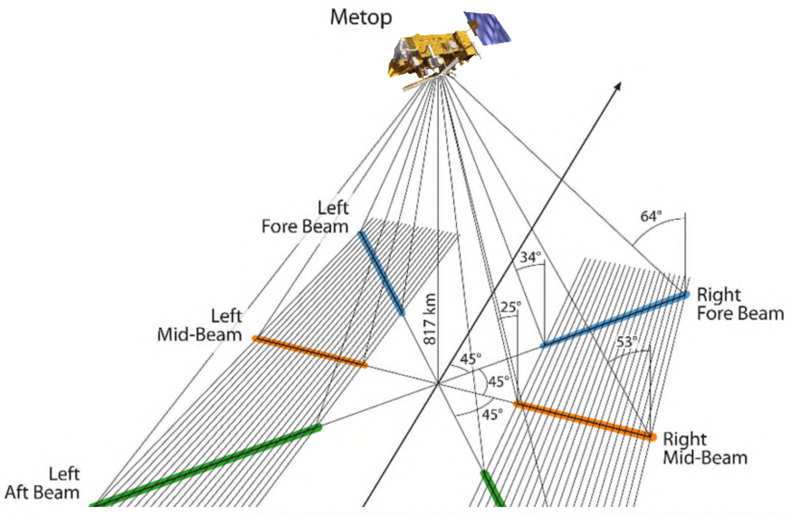
- Model assumptions:
  - backscatter, in decibels, is linearly related to soil moisture
  - backscatter is strongly dependent on incidence angle
    - Vegetation changes the slope and curvature
    - Soil moisture increases backscatter over all incidence angles equally
  - Soil roughness and land cover are stable over time

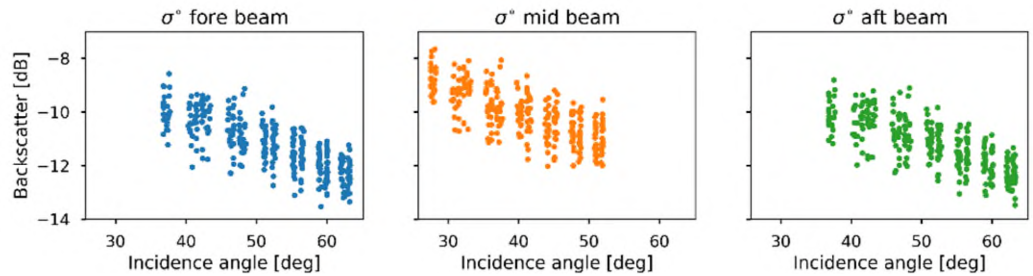
4.3.2 Parsimonious models - TU Wien method

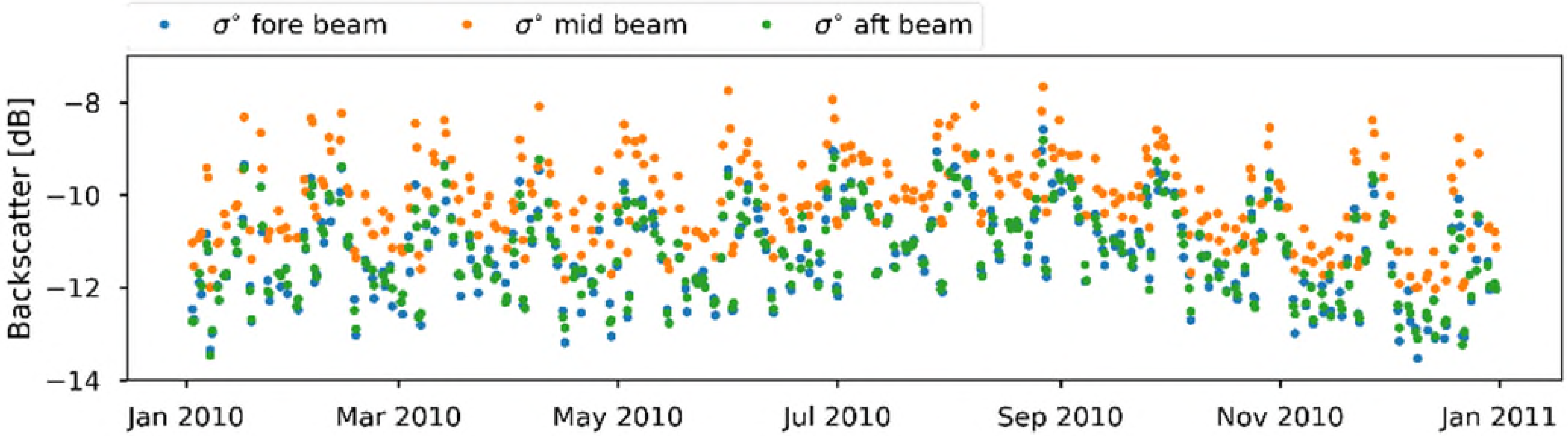
- define backscatter from the lowest observed backscatter related to driest soil conditions and a shift in backscatter



ASCAT geometry, backscatter vs incidence angle

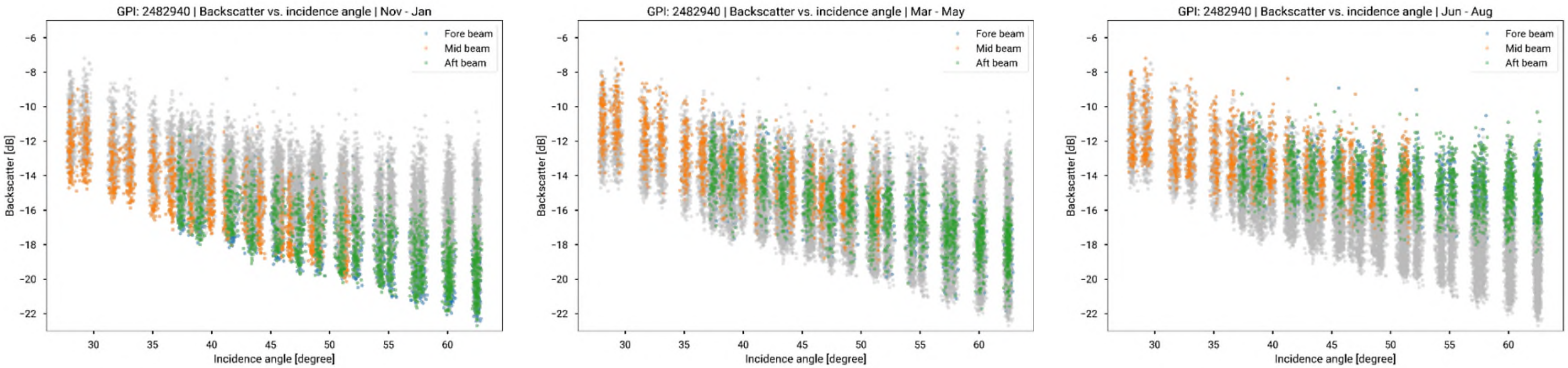




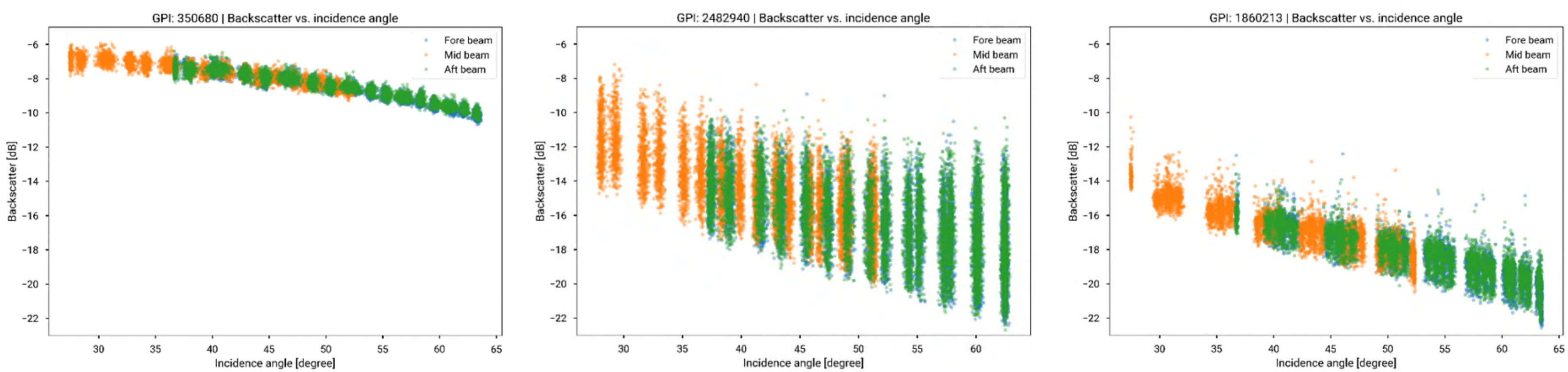


Incidence angle dependency of backscatter

- Incidence angle characteristics change over time



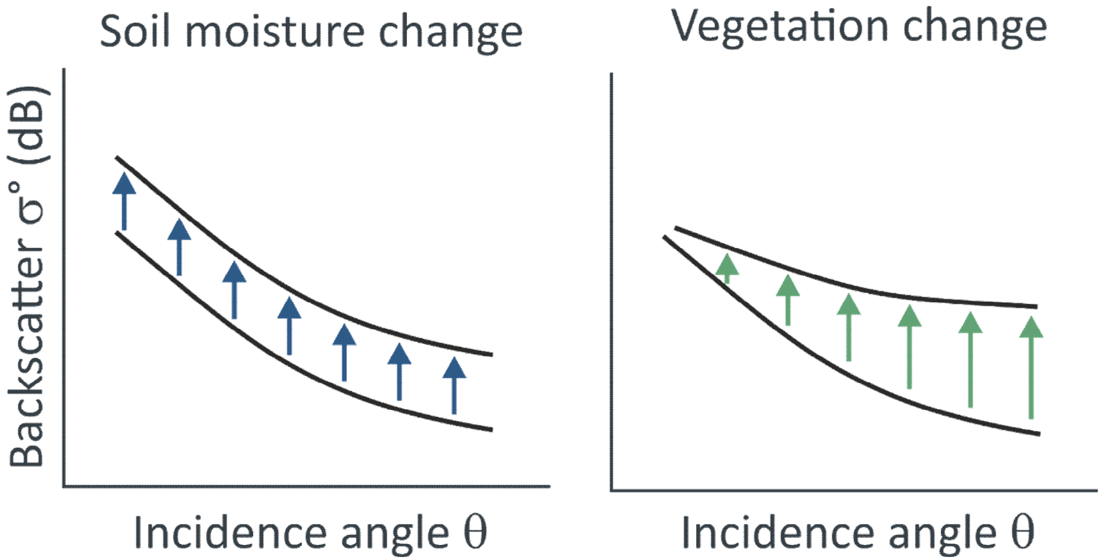
- And depend on location (land cover, vegetation , topography



Parsimonious models - TU Wien method

- TU Wien model uses the multi-incidence angle viewing geometry of ASCAT to describe vegetation:

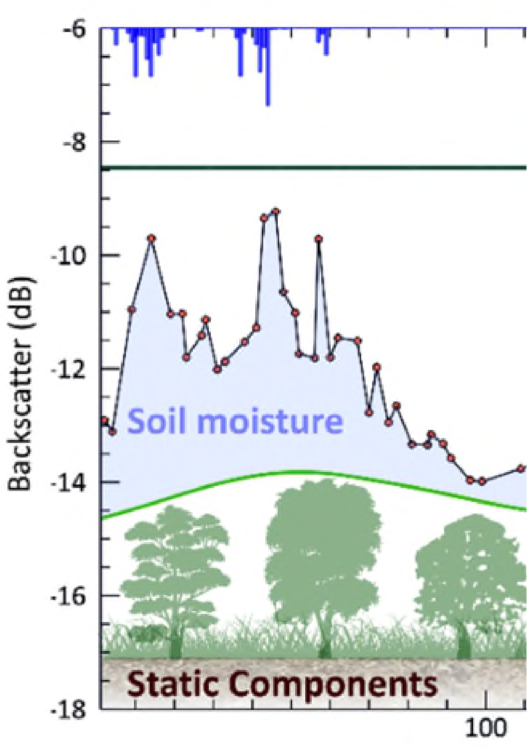
- Slope and curvature of σ°- θ relationship are sensitive to changes in vegetation.



Parsimonious models - TU Wien method

- Change detection method
- Total backscatter is dependent on θ, m_s s, and V

$$\sigma°(\theta, m_s, s, V) = \sigma°_{dry}(\theta, s, V) + \Delta\sigma°(\theta, m_s, s, V)$$



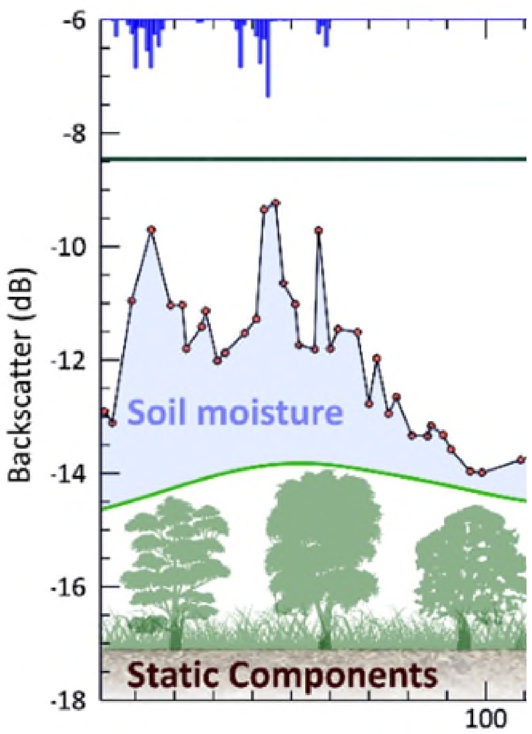
Parsimonious models - TU Wien method

- Total backscatter is dependent on θ, m_s s, and V

$$\sigma°(\theta, m_s, s, V) = \sigma°_{dry}(\theta, s, V) + \Delta\sigma°(\theta, m_s, s, V)$$

- $\sigma°_{dry}$ the driest ever recorded conditions
- Upper boundary as soil saturates $\sigma°_{wet}$

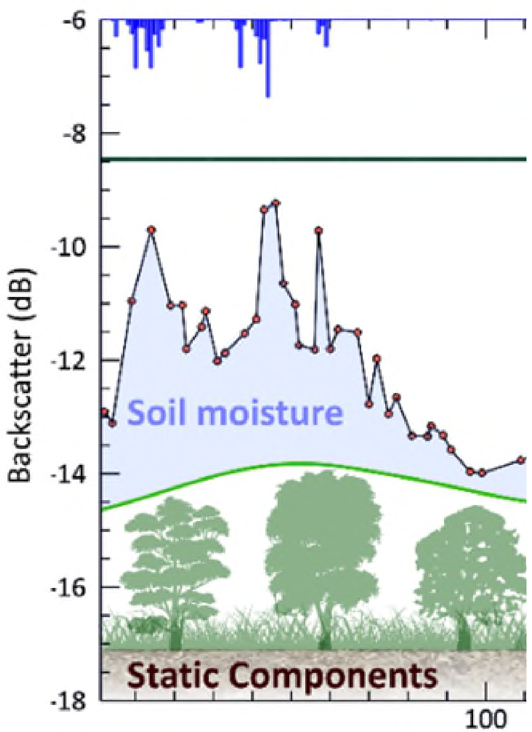
- $\Delta\sigma°$ the difference between the dry and wet reference at this angle, scaled with the degree of saturation m_s



Parsimonious models - TU Wien method

- Total backscatter is dependent on θ, m_s s, and V

$$\sigma°(\theta, m_s, s, V) = \sigma°_{dry}(\theta, s, V) + \Delta\sigma°(\theta, m_s, s, V)$$



- $\sigma°_{dry}$ the driest ever recorded conditions
- Upper boundary as soil saturates $\sigma°_{wet}$

- $\Delta\sigma°$ the difference between the dry and wet reference at this angle, scaled with the degree of saturation m_s

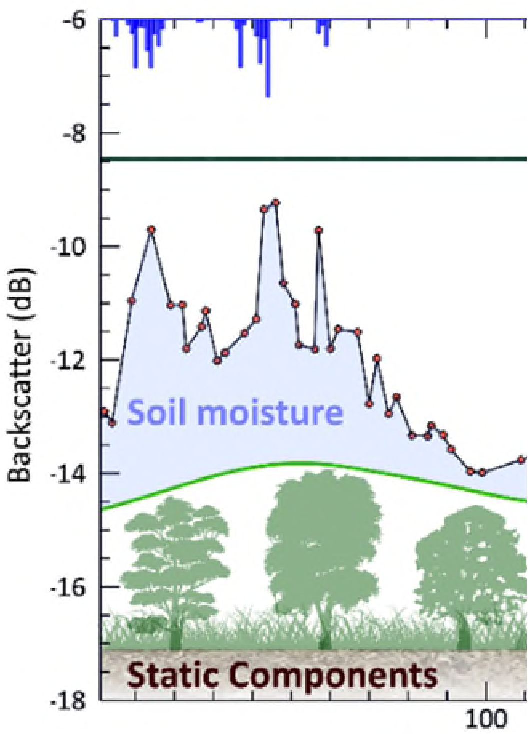
$$\Delta\sigma°(\theta, m_s, s, V) = m_s[\sigma°_{wet}(\theta, s, V) - \sigma°_{dry}(\theta, s, V)]$$

Parsimonious models - TU Wien method

$$\sigma°(\theta, m_s, s, V) = \sigma°_{dry}(\theta, s, V) + \Delta\sigma°(\theta, m_s, s, V)$$

$$\Delta\sigma°(\theta, m_s, s, V) = m_s[\sigma°_{wet}(\theta, s, V) - \sigma°_{dry}(\theta, s, V)]$$

$$\sigma°(\theta, m_s, s, V) \\ = \sigma°_{dry}(\theta, s, V) + m_s[\sigma°_{wet}(\theta, s, V) - \sigma°_{dry}(\theta, s, V)]$$



How to obtain incidence angle behavior, $\sigma°_{wet}(\theta, s, V)$ and $\sigma°_{dry}(\theta, s, V)$?

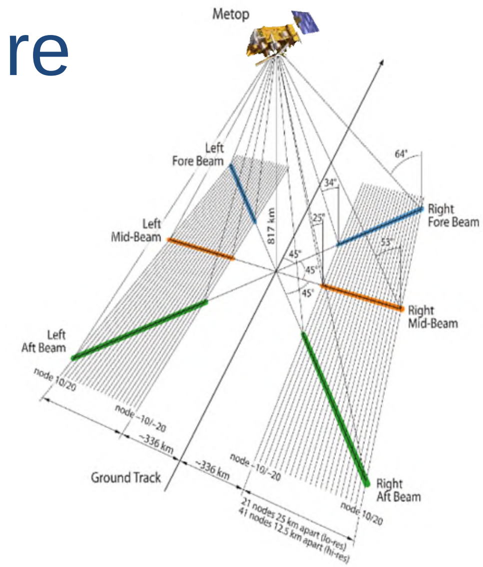
Parsimonious models - TU Wien method

- The incidence angle behavior of $\sigma°$ is usually modelled using a second-order Taylor series expansion based on known backscatter data

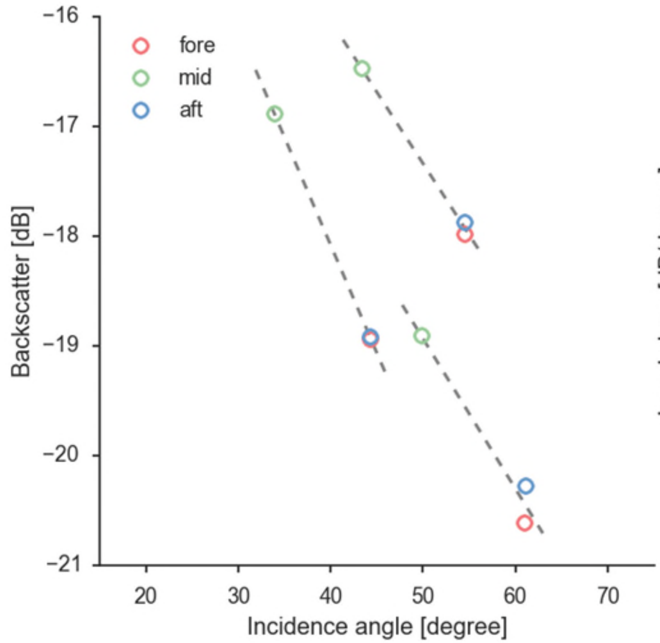
$$\underbrace{\sigma^0(\theta,t)}_{\text{measure}} = \sigma^0(\theta_{ref},t) + \underbrace{\sigma'(\theta_{ref},t)}_{\text{slope}}(\theta - \theta_{ref}) + \frac{1}{2}\underbrace{\sigma''(\theta_{ref},t)}_{\text{curvature}}(\theta - \theta_{ref})^2$$

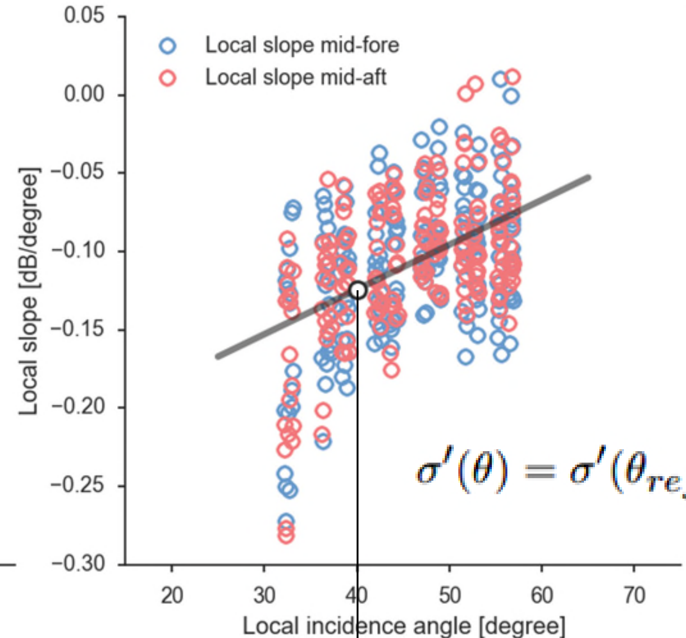
- θ_{ref} reference incidence angle
- σ' slope
- σ'' curvature

Estimating Slope and Curvature



- As ASCAT measures a backscatter triplet the local slope can be calculated, being quasi an – albeit noisy - observable





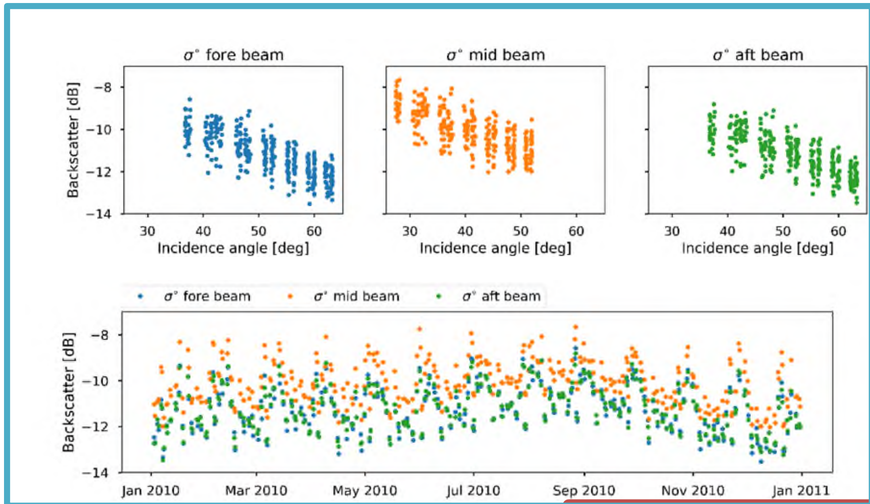
$$\sigma'(\theta) = \sigma'(\theta_{ref}) + \sigma''(\theta_{ref})(\theta - \theta_{ref})$$

Reference angle θ_{ref}

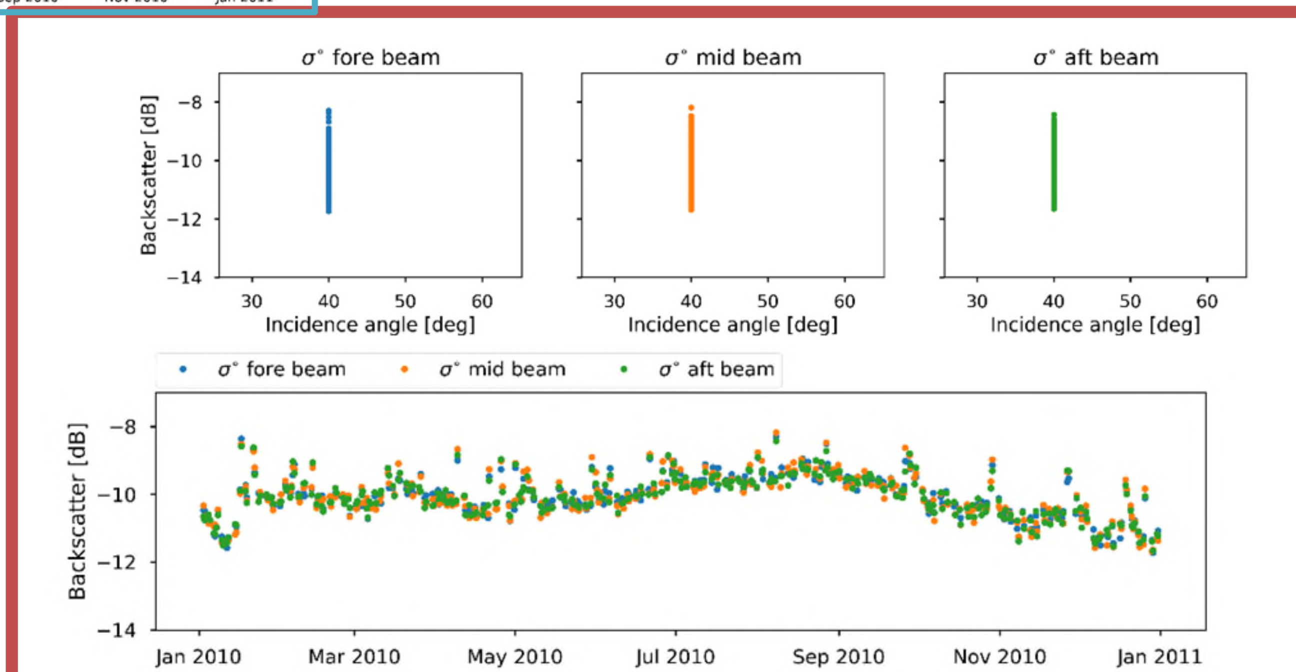
$$\sigma'\left(\frac{\theta_{mid} - \theta_{fore}}{2}\right) = \frac{\sigma^0_{mid}(\theta_{mid}) - \sigma^0_{fore}(\theta_{fore})}{\theta_{mid} - \theta_{fore}}$$

$$\sigma'\left(\frac{\theta_{mid} - \theta_{aft}}{2}\right) = \frac{\sigma^0_{mid}(\theta_{mid}) - \sigma^0_{aft}(\theta_{aft})}{\theta_{mid} - \theta_{aft}}$$

ASCAT geometry, backscatter vs incidence angle



No incidence angle correction



With incidence angle correction

Parsimonious models - TU Wien method

- 4 model parameters all depending on V and *s*:
  - $\sigma^{\circ}{}_{dry}$ dry reference
  - $\sigma^{\circ}{}_{wet}$ wet reference
  - σ' slope
  - σ'' curvature

- How do we estimate dry and wet reference?
  - Depend on incidence angle and vegetation state → Vegetation changes spatially and temporally
  - Need to be estimated without vegetation affecting backscatter signal