Optical and radar observations of steep and breaking waves of decimeter range („mesowaves”) on the sea surface: electrodynamical and hydrophysical interpretation

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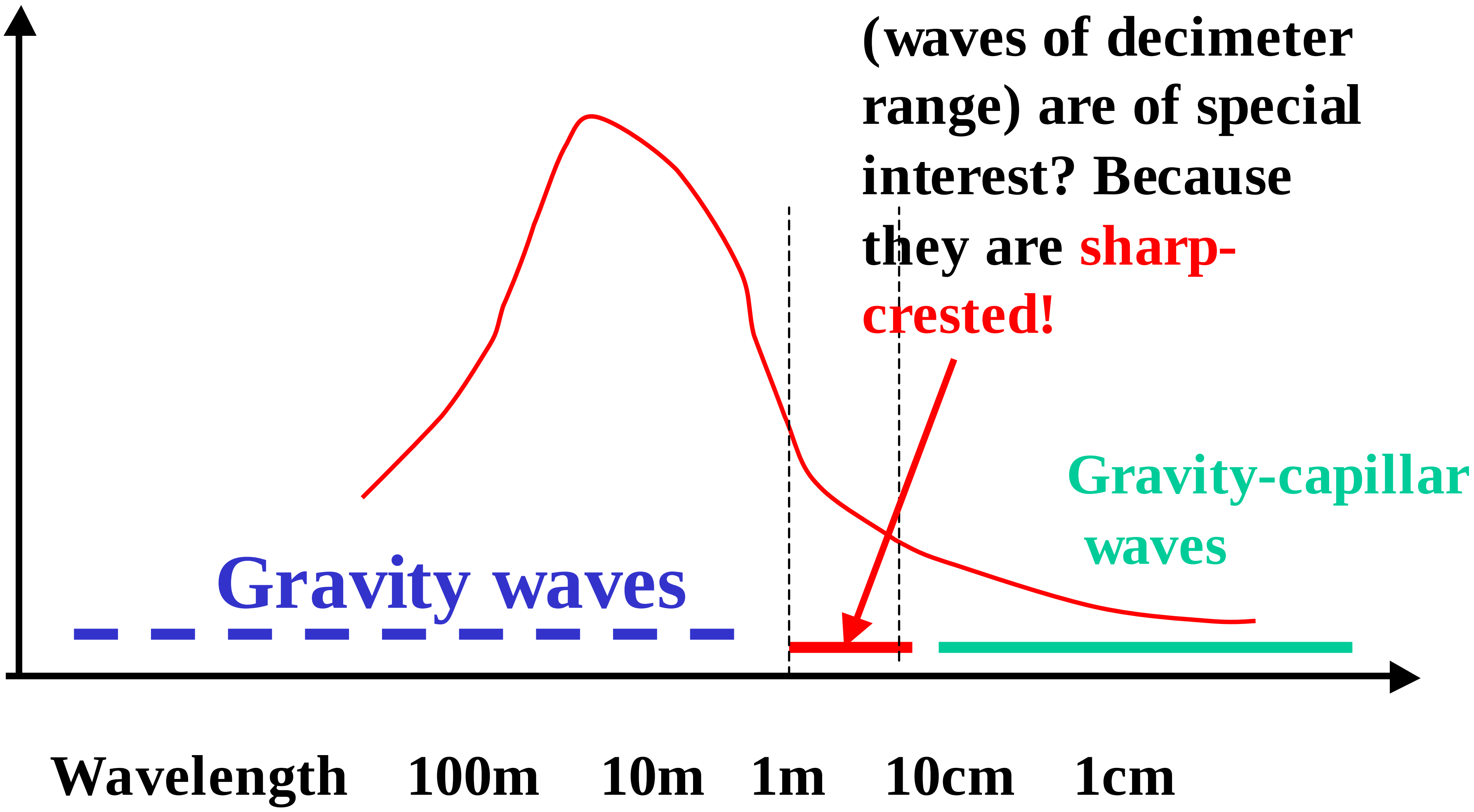
1. Introduction: what are mesowaves? why mesowaves?

- Wave spectrum

Why mesowaves (waves of decimeter range) are of special interest? Because they are sharp-crested!



Steep and sharp-crest waves of decimeter range are of special interest, because they have sharp crest and therefore might be responsible for:

- **Strong spikes on radar images of the Sea surface**
- **Enhanced energy and momentum transfer from the wind to water surface**
- **Manifestations of the internal waves on the SAR ocean images**

2.Optical observations

2.1. Gdansk Bay (IO PAN, Z.Klusek)

2.2. Pacific 1

2.3. Pacific 2

2.4 „Microbreaking” or „microscale breaking waves”

- Nature, 1993;
- Sharkov, 1996-1998: aircraft photo images, containing both „macro-breakings” (white caps) and „micro-breakings”, that is mesowaves breaking without foam and sprays
- Measurement Sci. Technol., 2006

- **2.5. Photo registration of „microbreakings” (breaking without foam and sprays) simultaneously with radar observations (Kwoh et al., 1980;**

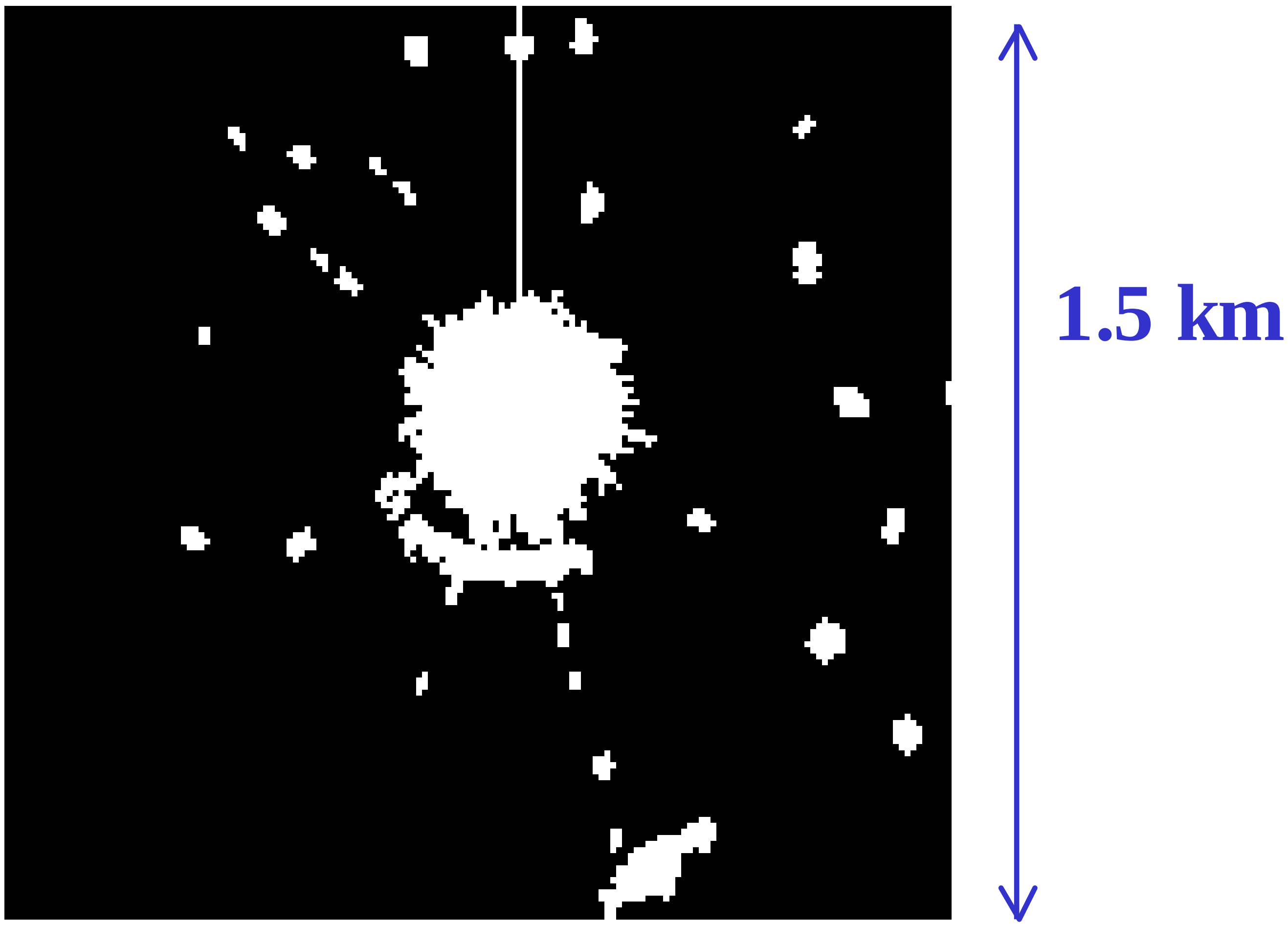
  Paper in Nature, 1993, and many other publications)

3. RADAR OBSERVATIONS

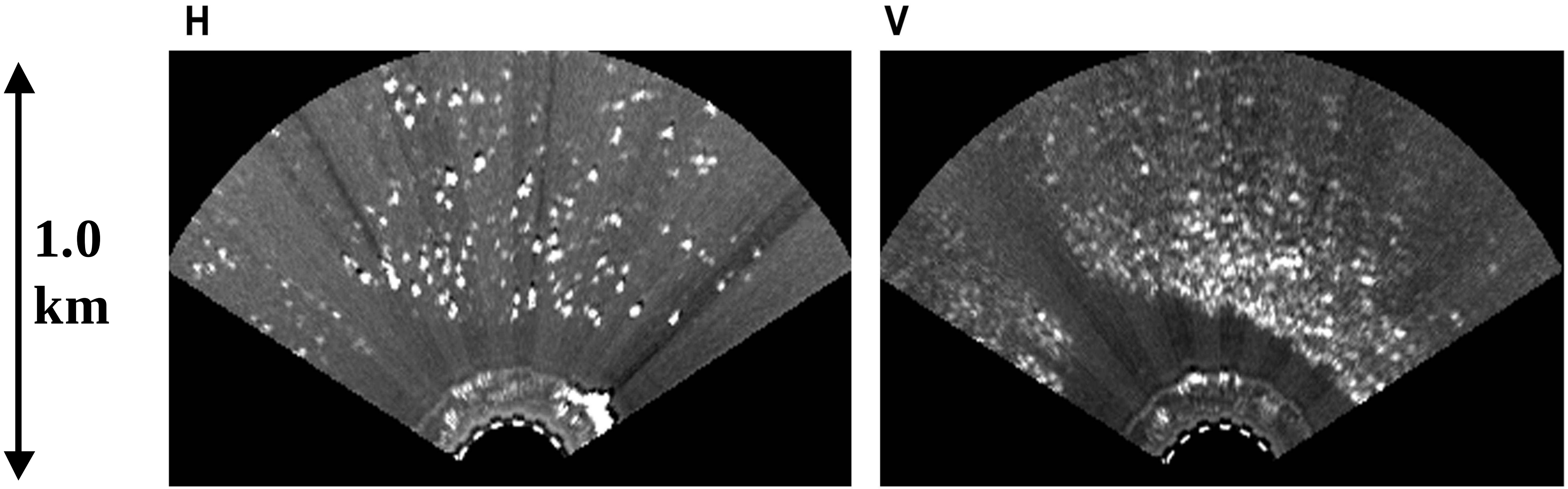
3.1. RADAR OBSERVATIONS ON THE BALTIC SEA (RADAR OF THE TRAINING SHIP „NAWIGATOR XXI", SZCZECIN MARITIME UNIVERSITY)

Szczecin Maritime University training ship "Nawigator XXI" is equipped in radar system by Kelvin Hughes Company (KHC) (**wavelenght about 3 cm**). KHC radar has sufficiently high resolution: about 1.5° in azimuthally direction and 10 m in radial direction.

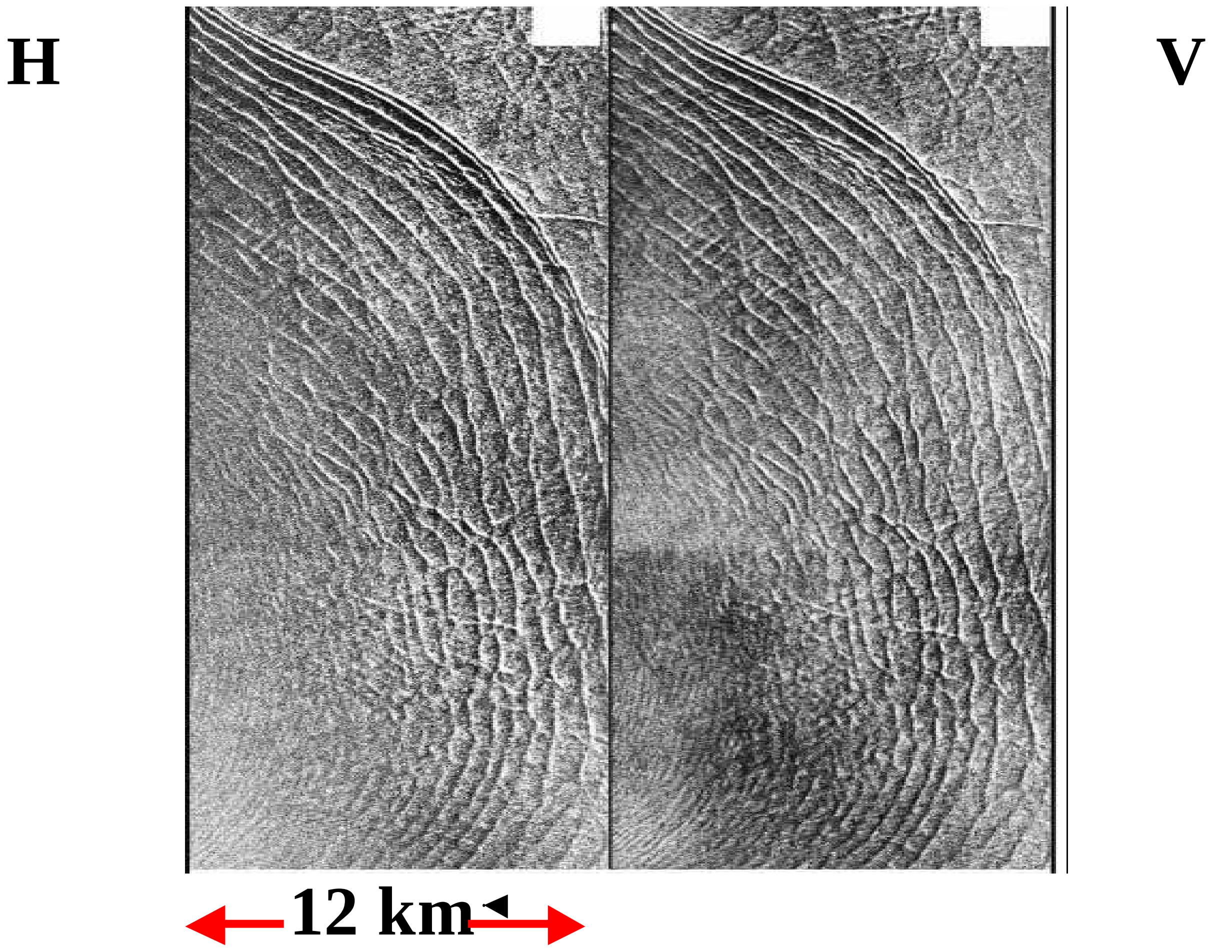
An example of the Baltic Sea image in conditions, when **the sea surface was free of white caps.** The image contains iscrete echoes, which **might be accepted for false targets.**



3.2. Radar observations on the Black Sea (Mobile radar by the Space Research Institute, Russ.Acad. Sci., Moscow)



3.3. Aircraft radar image of the internal waves manifestations on the Sea Surface (JUSREX'92: Joint US and Russia radar experiment 1992, Space Res. Inst. ,Rus.Acad.Sci.)



- **3.4. Satellite SAR (Synthetic Aperture Radar) images of the Ocean: visual manifestations of the oceanic internal waves**
- **Sabinin et al. Int. J. Remote Sensing, 2002; Physics Uspekhi, 2003;**
- **site of the Space Res. Institute:**

  www.asp.iki.rssi.ru)

4. RADAR MODELS OF THE SEA SURFACE

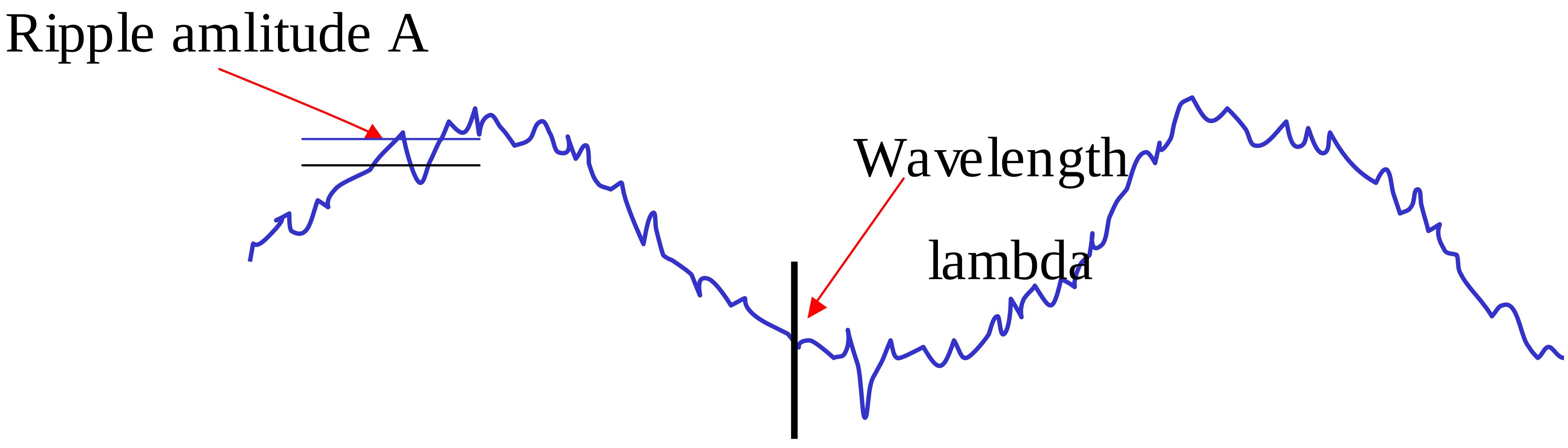
4.1. Two scale **composite model**

Two scale **composite model is commonly accepted for interpretation** of microwaves scattering by the rough water surface.

The two scale composite model deals with small scale gravity-capillary waves (“ripples”) by few cm of wavelength, lying on the large scale gravity waves of wavelength **longer than 3-5 m.**

TWO SCALE **COMPOSITE MODEL:**

"RIPPLES" ON THE LARGE GRAVITY WAVE



Resonant (Bragg) theory is valid only if the amplitude of ripples A is small as compared with the radar wavelength lambda: A<<lambda.

The two scale model satisfactory describes the main properties of the radar echo. However, at low grazing angles 10°-15° some phenomena have been observed, which principally could not be explained by the resonant theory of scattering. It concerns above all the abnormal polarization ratio: the observed ratio of the cross-section at horizontal polarization to that at vertical polarization often exceeds a unit, while Bragg theory predicts very low polarization ratio [Bass, Fuks 1979; Rytov, Kravtsov, Tatarskii 1989]:

$$\left(\frac{\sigma^{H}}{\sigma^{V}}\right)^{observed} > 1, \quad \left(\frac{\sigma^{H}}{\sigma^{V}}\right)^{Bragg} << 1,$$

.

At second, the radar echoes at low grazing angles demonstrate **large spikes** or **“superevents”**, which are not explainable by the Bragg theory

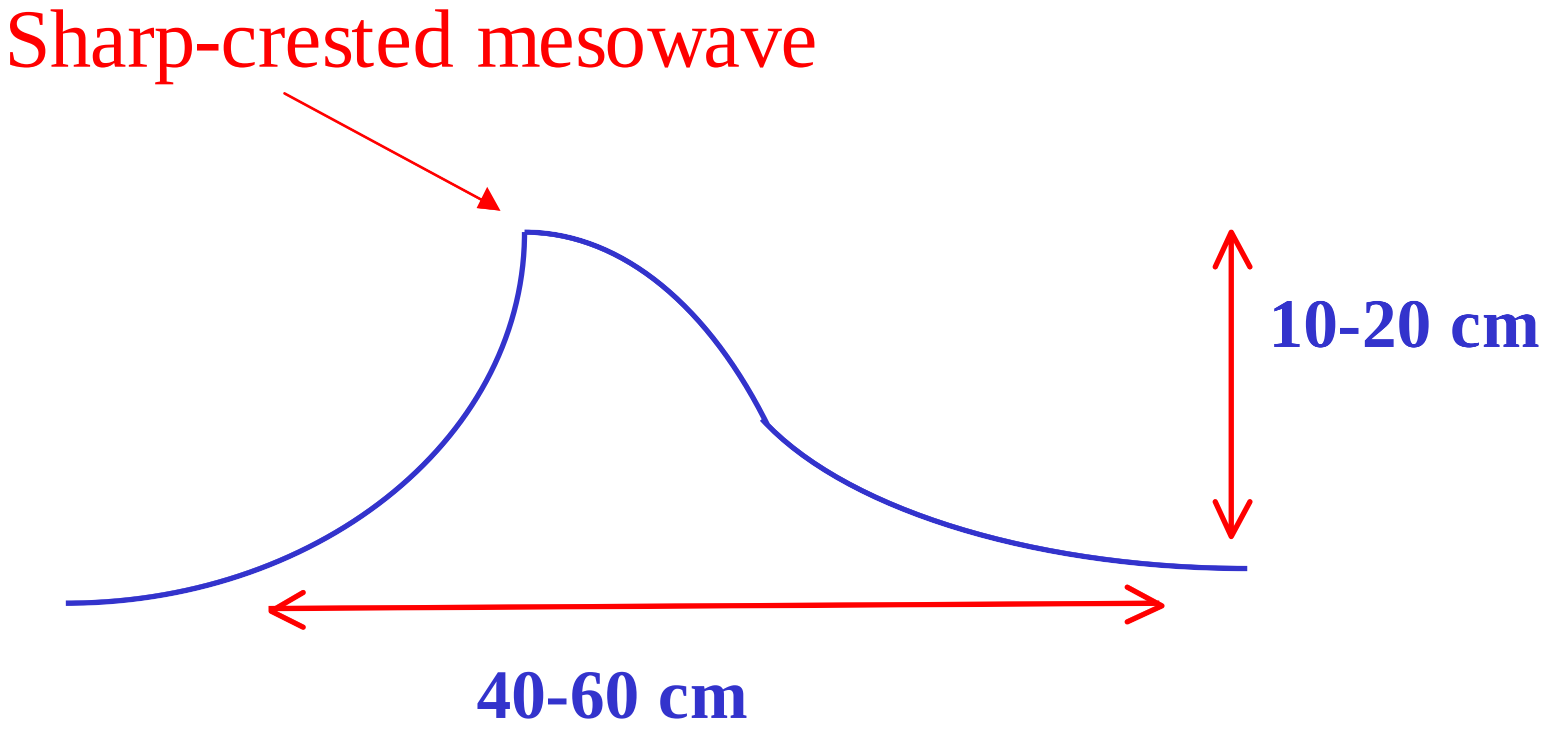
The same is true for the observed **asymmetry between upwind and downwind radar cross-sections .**

4.2. **EXTENDED COMPOSITE** MODEL OF THE SEA SURFACE, UNITING THE **BRAGG** AND NON- **BRAGG** MECHANISMS OF SCATTERING

- **Two main reasons for non-Bragg scattering**
- **1) Large scale breaking waves (white caps)**
- **2) Sharp-crested mesowaves**

of decimeter scale,

The characteristic lengths (40-60 cm) and heights (10-20 cm) of mesowaves are intermediate between those of small-scale (a few centimeters) and large-scale (meters and longer) components of the wave spectrum.



Fragment of the sea surface with sharp-crested mesowaves.

The **extended** compo**site** model of the sea surface incorporate**s** **macrobreaking waves and microbreaking** mesowaves into standard two scale model**:**

Two scale composite model (Bragg scattering) + breaking waves and mesowaves (non-Bragg scattering) => extended composite model of scattering

The **extended** model represents the total radar cross-section of the area S as a sum

$$\sigma_S = (1-q)\sigma_S^{Bragg} + q\sigma_S^{nonBragg} = (1-q)\int \sigma_1^{Bragg} ds + q\sum_k \sigma_k^{nonBragg}$$

The first term in this equation describes contribution of the ripples, dimensionless quantity σ_1^{res} is treated here as a resonant (Bragg) cross-section per a unit surface. The second term summarizes the contributions of mesowaves within the resolution element S,

$\sigma_k^{nonBragg}$ being a cross-section of the k-th mesowave.

Thus, the **extended** component model combines continuous resonant scattering from small scale ripples, like in standard two scale composite model, and discrete non-resonant reflections from the individual **breaking waves and** mesowaves.

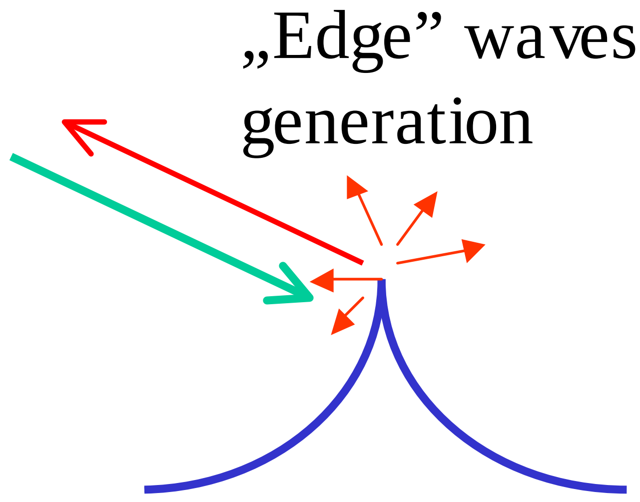
4.3. MICROWAVE DIFFRACTION AT SHARP-CRESTED MESOWAVES

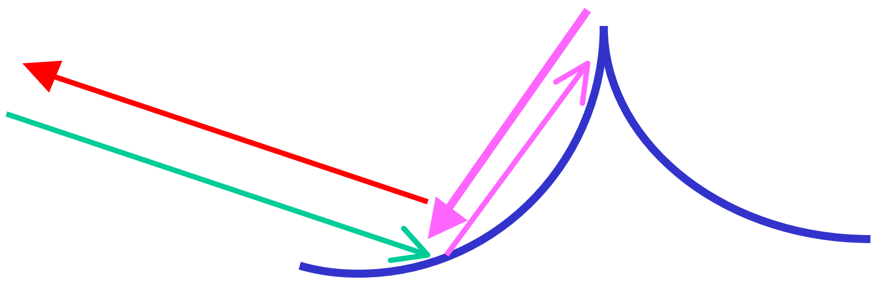
The most important features of multiple diffractions at curvilinear wedge are presented by the four/five channel model.

The four-channel model includes the following four terms:

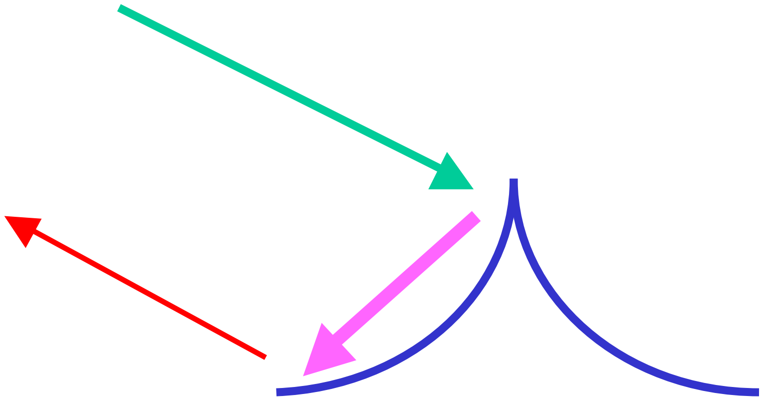
$$u_{four} = u_e + u_{es} + u_{se} + u_{ses}$$

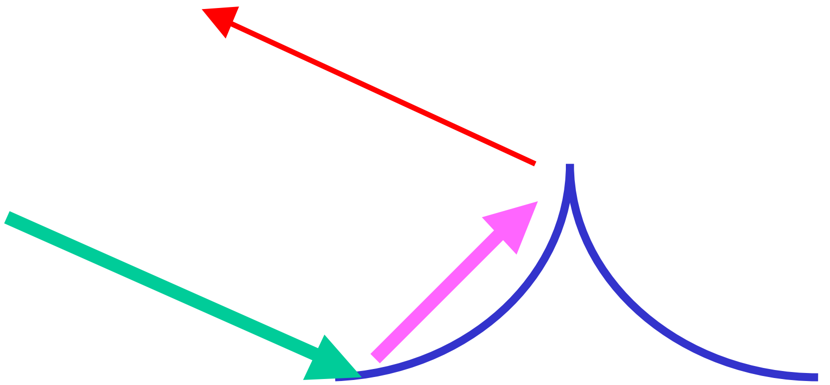
Single scattered edge wave u_e **Triple scattered wave u_{ses}**





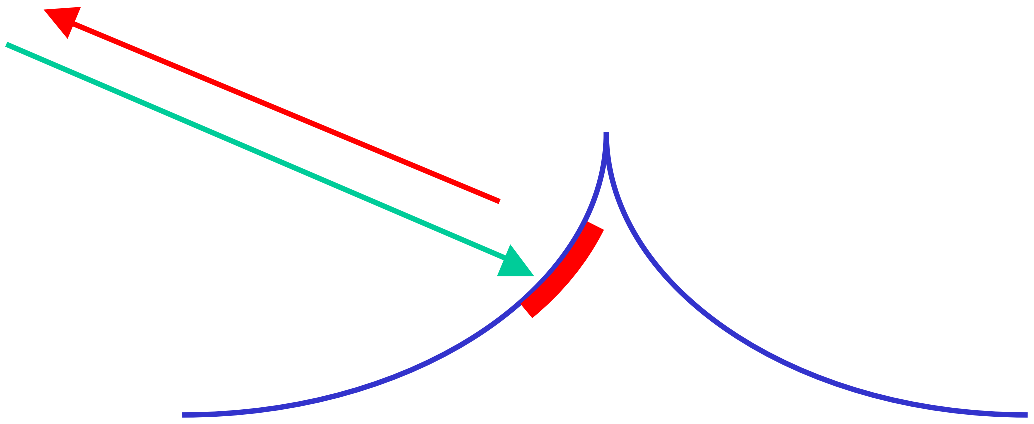
Coherent double scattered waves $u_{es} = u_{se}$





At last, when specular reflection comes into play, specular term u_s will appear in the total wave field. Then four channel model converts into five channel model

$$u_{five} = u_e + u_{es} + u_{se} + u_{ses} + u_s$$



Transition from four-channel to five-channel model might be performed on the basis of the UNIFORM THEORY OF DIFFRACTION, which generalizes GEOMETRICAL THEORY OF DIFFRACTION for light-shadow boundaries.

4.4. PHENOMENA, DESCRIBED BY THE EXTENDED COMPOSITE MODEL

A. Polarization ratio

Brewster phenomenon is well known in optics: for *vertical polarization* of electromagnetic wave at definite angle, which is named *Brewster angle*, all the energy completely passes through the interface of two dielectrics, and *reflection coefficient turns out to be zero*.

Brewster Phenomenon

Polarization-dependent reflection:

In microwave range Brewster phenomenon plays an important role. Strong influence of the Brewster phenomenon on polarization ratio was pointed by Trizna et al (1991). According to Trizna, at low grazing angles the Fresnel reflection coefficient from the sea water at vertical polarization is at 5-7 dB smaller as compared to that at horizontal polarization, what results in significant suppression of the radar echo at vertical polarization.

B. Superevents

Sea spikes **(superevents)** of backscattered **radar** signal are most prominent at horizontal polarization and only rarely are visible at vertical one. **The** amplitude of a sea spike at horizontal polarization can be much higher, sometimes by 10 dB, than its amplitude at vertical polarization. **Superevents in no way can be explained by the Bragg theory**.

It looks quite surprising that most of the sea spikes are not accompanied by visual breaking.

Echo signals at horizontal polarization might be of significant strength. On the basis of Geometric Theory of Diffraction (GTD) the radar cross-section of the wedge crest of L_c by length can be estimated as :

$$\sigma^{non-resonant\ H} \approx L_c^2$$

It means that coherently illuminated wedge crest of L_c =1 m by length provides unexpectedly high radar cross-section:

$$\sigma^H \approx 1m^2$$

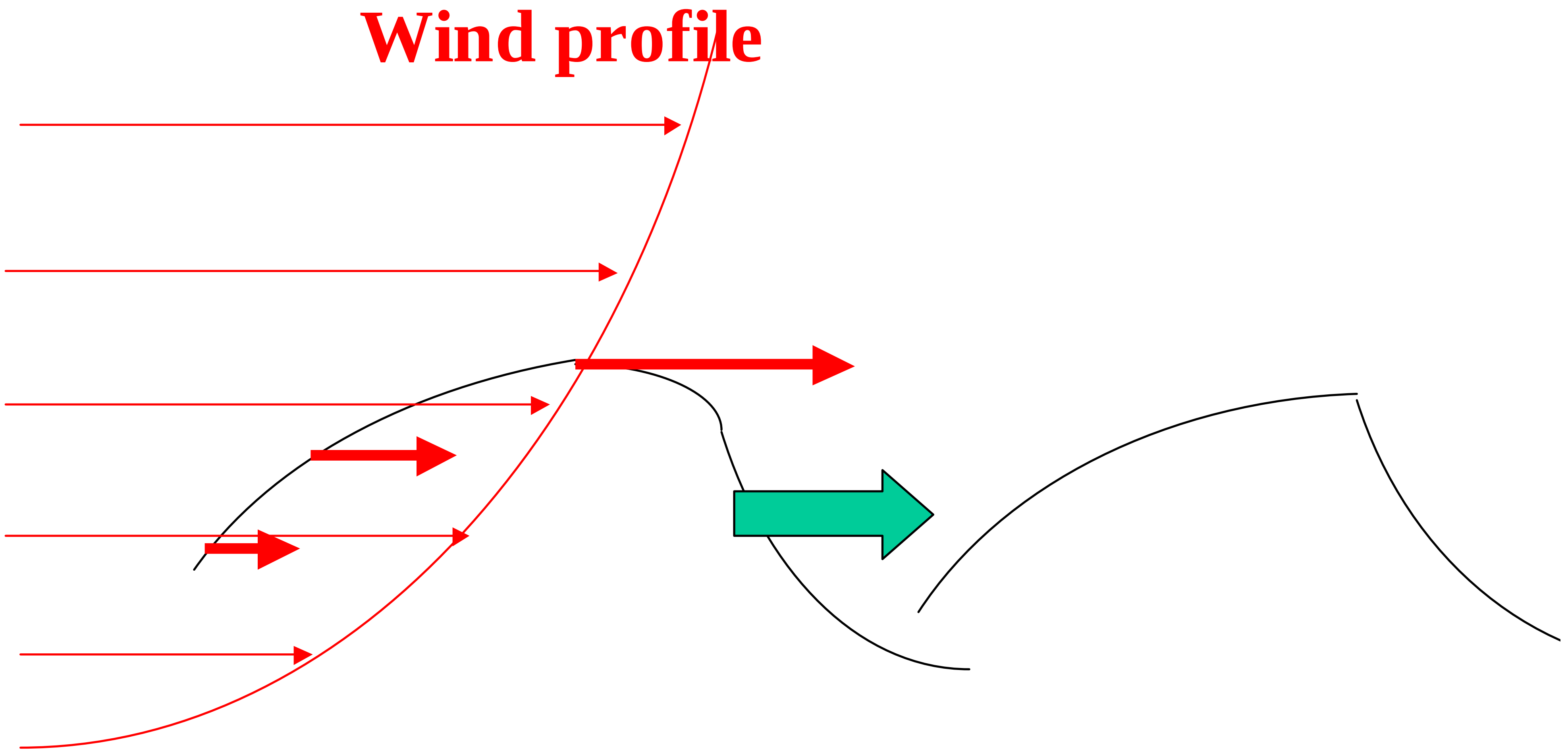
which is at least 100 times greater as compared with the resonant **(Bragg)** radar cross-section **and is comparable with cross-section of a boat or small yacht**. **The problem is to eliminate the radar reflections from mesowaves by digital methods, using algorithms of moving targets distinguishing.**

5. Hydrophysical aspects

- **5.1. Hypothetic mechanisms for sharp crested mesowaves forming**

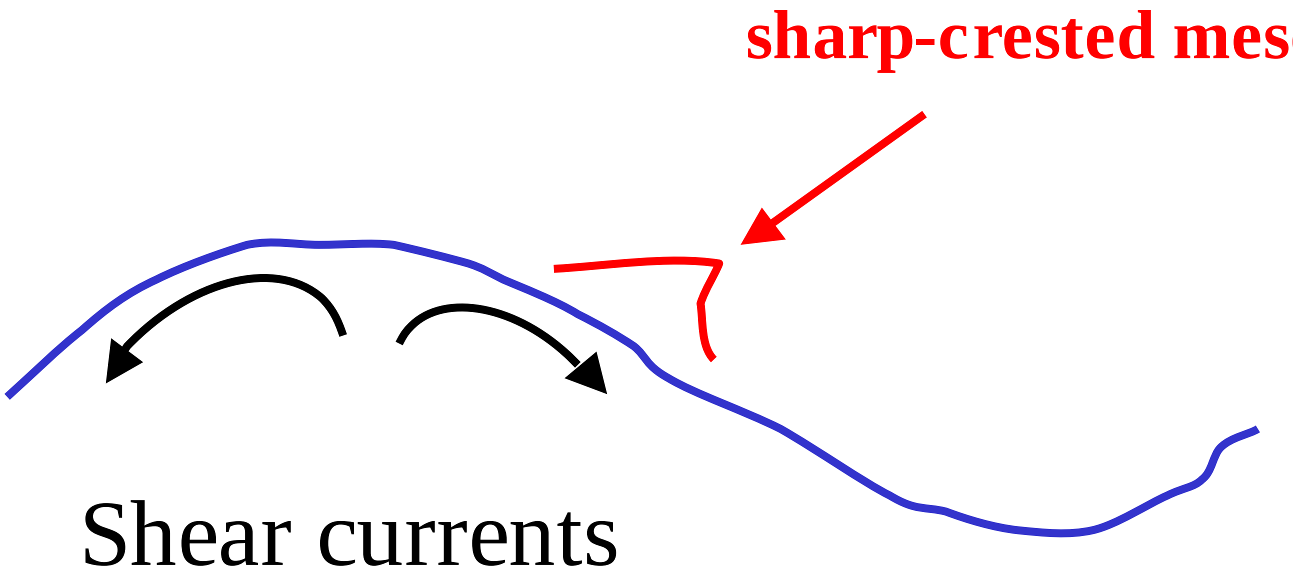
Sharp-crested mesowaves hypothetically might be soliton-like solution of the hydrodynamical equations in the presense of the shear wind and the shear water currents, induced by gravity wave.

Influence of the shear wind



Influence of the shear currents

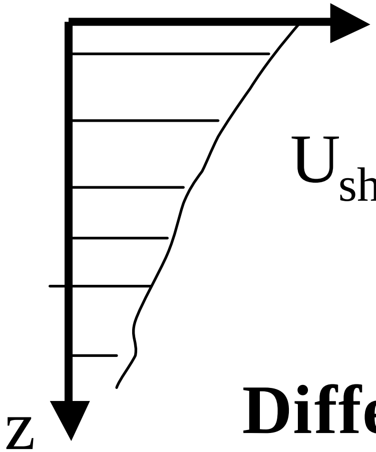
According to visual observations, sharp-crested mesowaves arise predominantely at the front side of a gravity wave:



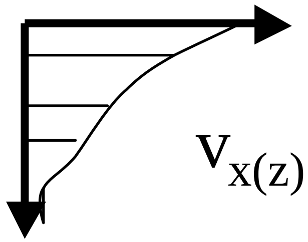
Hypothetic effect of differential surface wave transfer by shear current, which might be responsible for sharp peak forming

- Shear current profile

Sufface wave vertical profile



$U_{shear}=U_0\exp(-Kz)$



$v_{x(z)}= v_x(0)\exp(-kz)$

Differential shear transfer velosity

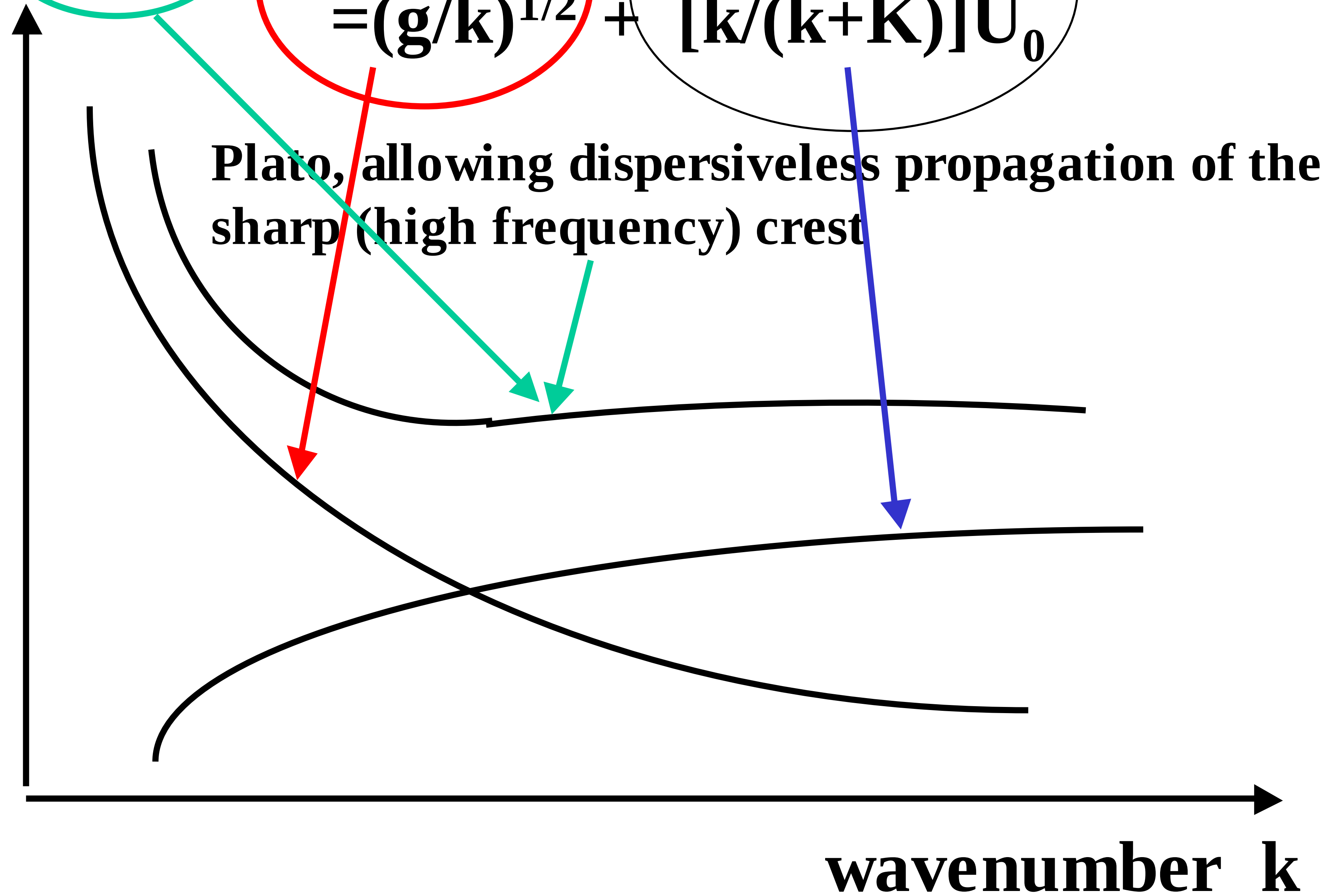
$\mathbf{V_{trans}==U_0[k/(k+K)]}$

$\mathbf{= U_0}$ **for short surface waves, k>>K**

$\mathbf{= U_0(k/K)<<U_0}$ **for longer waves, k<<K**

- **Total velocity**

$$V_{tot}(k) = V_{phase}(k) + V_{trans}(k) = (g/k)^{1/2} + [k/(k+K)]U_0$$



5.2. Possible role of sharp-crested mesowaves in the wind-sea interaction

- Sharp-crested mesowaves may act like a small sails and thereby may contribute into Jeffrey echanism of wind waves production. That is why sharp-crested mesowaves might be of great practical interest as a factor, determining dynamics of the wind waves. **Unfortunately , the authors did not find any mentioning of contribution of the sharp-crested waves into fetch phenomena.**

6. Conclusion

- 1) Optical and radar data are presented, evidencing the inportant role of sharp-crested mesowaves in forming discrete redar echoes from the sea surface.

- 2) Hydrophysical mechanisms for sharp-crested mesowaves forming as well as their role in wind-sea interaction are not clarified until now.