

Fresnel reflection by wavy sea surface

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Abstract — In studying light and image transfer in sea waters, the influence of Fresnel surface reflection is as significant as scattering and absorption phenomena. In these cases knowledge of the reflective properties of sea surface at different wind speeds is very important. At present, little is published about these properties. We present here results of numerical modeling of angular reflection coefficients of sea water as a function of zenith angle of illumination and wind speed.

INTRODUCTION

The ray-tracing computer model was developed and implemented as slopes and elevations. The model used the Pierson-Moskowitz (PM) [1] and Paul Hwang (PH) [2] wave height spectrums in order to generate a realistic sea surface {see Fig. 1 and Eqs. (1) and (2)}. The Fresnel reflection coefficients were averaged over 10000 pixels of sea surface areas and 80 time realizations to produce resulting angular distributions of Fresnel reflection coefficient.

The Pierson-Moskowitz [1] wave energy spectrum is

defined as:

$$\chi_{PM}(k) = \frac{0.00405}{k^3} \exp\left(-\frac{0.74 g^2}{u^4 k^2}\right) \quad (1)$$

here $g = 9.8 \text{ m/s}$ is a gravitational acceleration, u is a windspeed in m/s , $k = g/u$ is a wavenumber in m^{-1} .

The Paul Hwang [2] wave energy spectrum is defined as:

$$\chi_{PH}(k) = \frac{1 \cdot 10^{-4}}{k^2} \begin{cases} 5.45, & k < g u^2, \\ 1.74 u / \sqrt{k}, & g u^2 \leq k < 16.0, \\ 6.96 u / k, & 16.0 \leq k < 100.0, \\ 0.682 u / (g + 0.00007 k^2), & 100 \leq k \leq 900, \\ 7.48 \cdot 10^6 u / k^3, & 900 < k. \end{cases} \quad (2)$$

This spectrum is specifically tailored to produce correct values of mean square slopes of ocean waves.

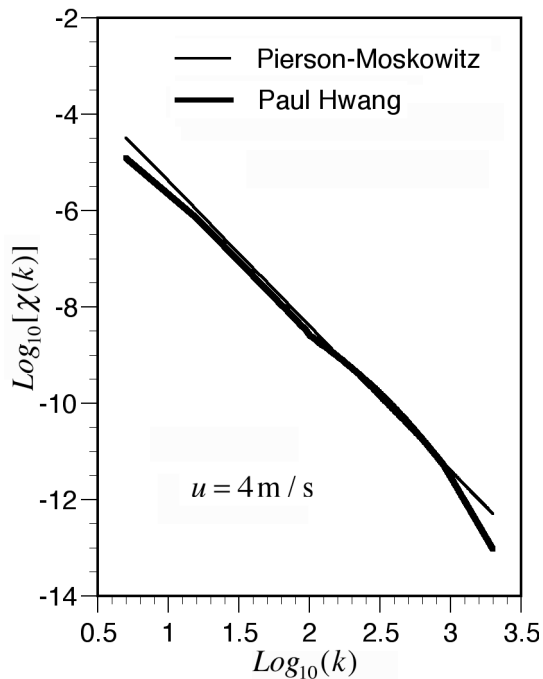


Figure 1. Comparison of Pierson-Moskowitz and Paul Hwang spectrums at windspeed of 4 m/s.

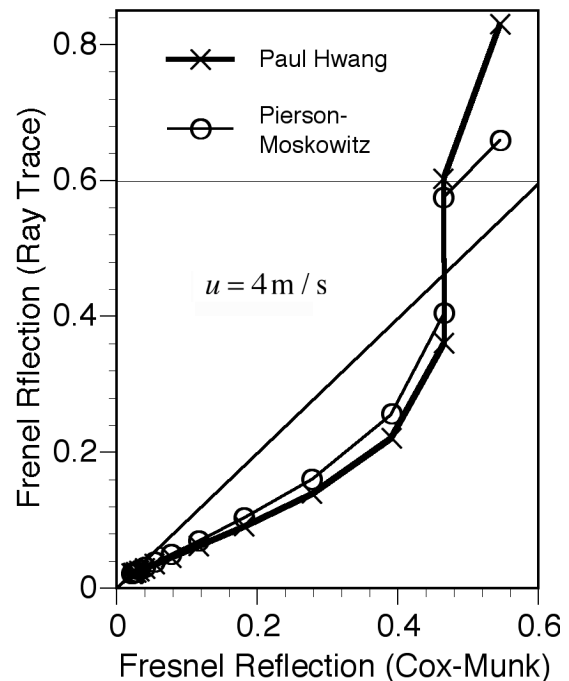


Figure 2. Comparison of Fresnel reflection coefficients of wavy surface calculated with energy spectrums and Cox and Munk distribution of slopes.

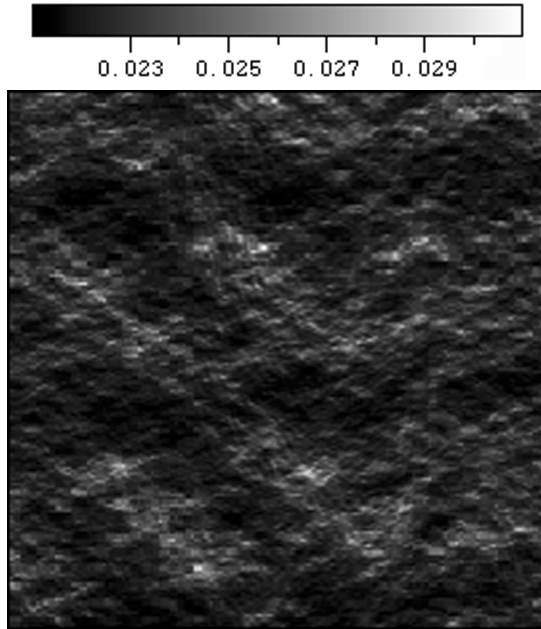


Figure 3a. Fresnel reflection coefficient generated using Pierson-Moskowitz energy spectrum [Eq. (1)] ($u = 4 \text{ m/s}$, $Z_s = 30^\circ$), view area: $2 \times 2 \text{ m}$.

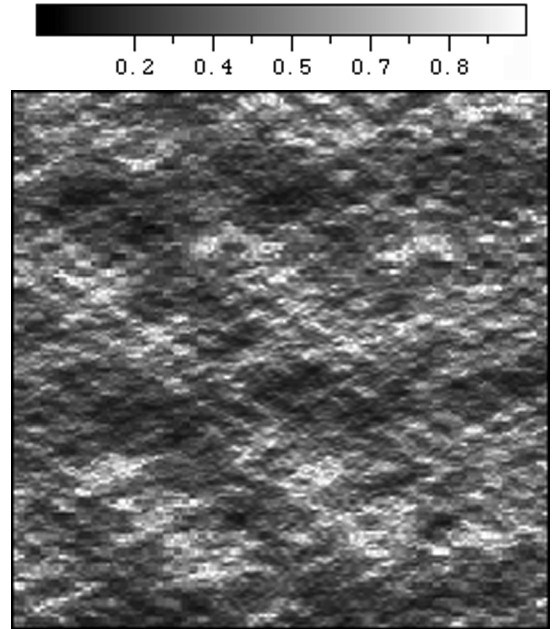


Figure 4a. Fresnel reflection coefficient generated using Pierson-Moskowitz energy spectrum [Eq. (1)] ($u = 4 \text{ m/s}$, $Z_s = 80^\circ$), view area: $2 \times 2 \text{ m}$.

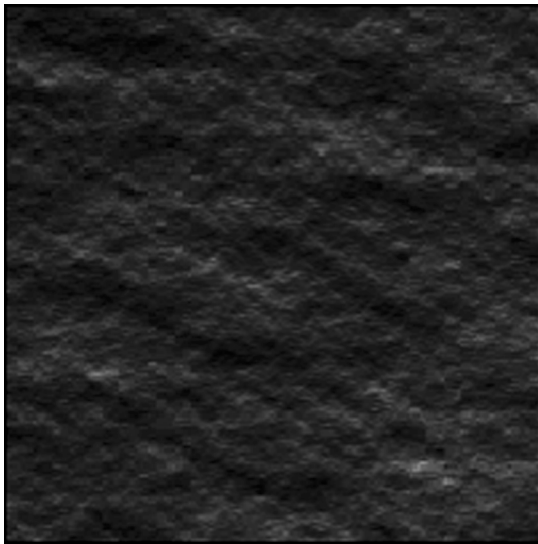


Figure 3b. The same as Fig.3a but generated with Paul Hwang [Eq. (2)] distribution.

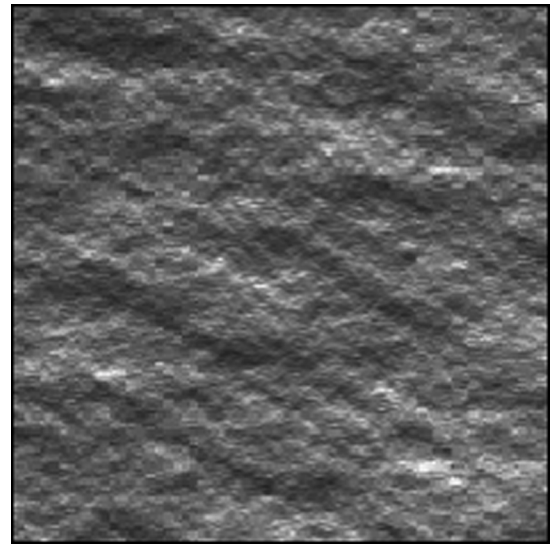


Figure 4b. The same as Fig.3a but generated with Paul Hwang [Eq. (2)] distribution.

Figure 2 shows comparison of Fresnel reflection coefficients (FRC) of wavy surface calculated with PM and PH energy spectrums and Cox and Munk (CM) [3] distribution of slopes for windspeed of 4 m/s. The general picture for other wind speeds is similar to the presented one with the differences between Cox and Munk and PM and PH energy spectrum approaches increasing with higher wind speeds.

Figs 3 and 4 show actual realizations of sea surface ($2 \times 2 \text{ meter}$) used to produce resulting Fresnel reflection

coefficients (Tabs 1 and 2). For smaller solar zenith angles ($Z_s \approx 65^\circ$) the values of FRC computed using energy spectrums are smaller than FRC values computed with CM distribution (compare values of FRC in Tabs 1 and 2 with values of FRC in Tab. 3, or compare corresponding values shown in Fig. 2). At larger solar angles spectrally derived values of FRC exceed Cox and Munk-derived values. The PM-derived values in this domain lie between PH- and CM-derived Fresnel reflection coefficients.

Table 1. Fresnel reflection coefficient of a wavy sea surface computed using Pierson-Moskowitz distribution [2].

$Z_s \setminus u$	2 m/s	4 m/s	6 m/s	8 m/s	10 m/s	12 m/s
0°	0.0212	0.0212	0.0212	0.0212	0.0212	0.0212
5°	0.0212	0.0212	0.0212	0.0212	0.0212	0.0212
10°	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213
15°	0.0213	0.0214	0.0214	0.0214	0.0214	0.0214
20°	0.0215	0.0216	0.0216	0.0216	0.0216	0.0216
25°	0.0219	0.0220	0.0220	0.0220	0.0220	0.0220
30°	0.0227	0.0228	0.0228	0.0227	0.0228	0.0228
35°	0.0240	0.0242	0.0242	0.0242	0.0242	0.0243
40°	0.0264	0.0267	0.0267	0.0266	0.0266	0.0268
45°	0.0305	0.0309	0.0310	0.0308	0.0308	0.0312
50°	0.0373	0.0380	0.0382	0.0379	0.0379	0.0385
55°	0.0488	0.0500	0.0502	0.0497	0.0497	0.0507
60°	0.0680	0.0700	0.0704	0.0694	0.0695	0.0711
65°	0.1002	0.1037	0.1042	0.1026	0.1028	0.1056
70°	0.1547	0.1606	0.1614	0.1587	0.1589	0.1638
75°	0.2471	0.2564	0.2581	0.2538	0.2544	0.2622
80°	0.3945	0.4048	0.4117	0.4057	0.4061	0.4078
85°	0.5724	0.5746	0.5890	0.5882	0.5908	0.5613
89.°9	0.6643	0.6592	0.6628	0.6684	0.6786	0.6195

Table 2. Fresnel reflection coefficient of a wavy sea surface computed using Paul Hwang energy distribution [3].

$Z_s \setminus u$	2 m/s	4 m/s	6 m/s	8 m/s	10 m/s	12 m/s
0°	0.0212	0.0212	0.0212	0.0212	0.0212	0.0212
5°	0.0212	0.0212	0.0212	0.0212	0.0212	0.0212
10°	0.0212	0.0212	0.0212	0.0212	0.0212	0.0212
15°	0.0213	0.0213	0.0213	0.0213	0.0213	0.0213
20°	0.0214	0.0214	0.0214	0.0214	0.0214	0.0214
25°	0.0217	0.0217	0.0218	0.0218	0.0217	0.0218
30°	0.0224	0.0224	0.0224	0.0224	0.0224	0.0224
35°	0.0235	0.0235	0.0236	0.0236	0.0236	0.0236
40°	0.0256	0.0256	0.0257	0.0258	0.0256	0.0257
45°	0.0291	0.0292	0.0293	0.0294	0.0292	0.0293
50°	0.0352	0.0353	0.0353	0.0356	0.0352	0.0353
55°	0.0453	0.0454	0.0456	0.0460	0.0454	0.0456
60°	0.0622	0.0625	0.0627	0.0635	0.0623	0.0627
65°	0.0906	0.0910	0.0914	0.0928	0.0908	0.0913
70°	0.1384	0.1392	0.1398	0.1422	0.1387	0.1396
75°	0.2195	0.2209	0.2220	0.2261	0.2199	0.2216
80°	0.3586	0.3609	0.3629	0.3701	0.3591	0.3621
85°	0.5992	0.6021	0.6041	0.6070	0.6001	0.6042
89.°9	0.8472	0.8295	0.8139	0.7797	0.8389	0.8243

The new values of Fresnel reflection coefficient presented in Tabs 1 and 2 differ considerably from the results generated with the Cox and Munk wave slope distribution (Tab. 3). The approach to calculate FRC based on ray tracing generation of wind waves is preferable to the approach that uses Cox and Munk wave slope distribution because it allows computation of realistic simulations of the sea surface. In addition it is open to improvement based on recent development in wind wave energy spectrums.

The values of FRC shown in Tab. 2 should be regarded as preferable to the values presented in Tab. 1 because the underlying energy spectrum is more precise in description of

Table 3. Fresnel reflection coefficient of a wavy sea surface calculated using Cox and Munk distribution [4].

$Z_s \setminus u$	2 m/s	4 m/s	6 m/s	8 m/s	10 m/s	12 m/s
0°	0.0212	0.0212	0.0213	0.0213	0.0213	0.0213
5°	0.0212	0.0213	0.0213	0.0214	0.0214	0.0215
10°	0.0213	0.0214	0.0215	0.0216	0.0216	0.0218
15°	0.0215	0.0216	0.0218	0.0219	0.0221	0.0223
20°	0.0218	0.0221	0.0224	0.0227	0.0230	0.0234
25°	0.0225	0.0230	0.0235	0.0241	0.0246	0.0252
30°	0.0238	0.0247	0.0256	0.0265	0.0274	0.0284
35°	0.0260	0.0275	0.0290	0.0306	0.0322	0.0338
40°	0.0299	0.0324	0.0350	0.0376	0.0402	0.0430
45°	0.0364	0.0407	0.0449	0.0493	0.0538	0.0585
50°	0.0474	0.0545	0.0617	0.0690	0.0765	0.0840
55°	0.0658	0.0778	0.0898	0.1018	0.1134	0.1241
60°	0.0967	0.1169	0.1363	0.1537	0.1684	0.1804
65°	0.1489	0.1815	0.2076	0.2264	0.2394	0.2481
70°	0.2365	0.2783	0.3002	0.3100	0.3133	0.3131
75°	0.3692	0.3913	0.3885	0.3786	0.3671	0.3557
80°	0.5043	0.4661	0.4310	0.4028	0.3802	0.3617
85°	0.5389	0.4655	0.4208	0.3896	0.3661	0.3475
89.°9	0.6153	0.5457	0.5011	0.4687	0.4437	0.4235

shorter wind waves that give maximum input in the mean square slopes of waves that are responsible for the major part in Fresnel reflection coefficient. Tables of FRC with greater windspeed and angular resolution will be published later.

The enhanced values of Fresnel reflection coefficient by wavy sea surface given in Tab. 2 may be used to improve remote sensing algorithms and radiative transfer models [4].

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