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Applicability of Radar Level Gauges in Wave Monitoring

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Abstract

Besides traditional sensors for wave measurements, like pressure gauges, wave rider buoys or electric level gauges, radar altimeters are more and more applied in wave monitoring. Today various commercial radar altimeters are used as level-gauges, e.g. in the chemical industry. The applicability of two common, comparatively cheap, sensors in wave monitoring is experimentally investigated using wave-flume tests. A first analysis shows the need for an improvement of commercial radar altimeters with respect to spatial and temporal resolution. Common problems of today's sensors result from a high noise-level requiring a large averaging interval and from a large footprint of the sensor.

Introduction

Measurements of waves, both on site and in wave flumes, are carried out using different techniques. Common sensors deduce the water surface elevation by measuring:

- the pressure of the water column above the sensor (pressure gauge) [1]
- the acceleration of a floater swimming on the water surface (wave rider buoy)
- the electric resistance of the water column between two metal electrodes (electric level gauge)
- the traveling time of radio-wave pulse from the sensor to the water surface and back or the phase shift between two continuous radio-wave signals, one emitted from the sensor to the surface and the other reflected from the surface to the sensor (radar level gauge) [2]

In comparison to traditional sensors, i.e. the pressure gauge, the electric level gauge, and the wave rider buoy, the radar level gauge, being a remote measuring system, is advantageous because there is no direct contact to the water (no corrosion problems, no wave attack on the sensor) [3]. Nevertheless there are some problems in using standard radar level gauges in wave monitoring:

- mounting is needed (in contrast to the wave rider buoy).
- salinity of the water and sea-ice coverage influences the penetration of the radio-wave pulse into the water.
- the footprint of the radar has an averaging effect.
- reflection of the radio-wave pulse depends on the slope of the water surface.

Therefore the applicability of radar level gauges in wave monitoring was tested in the wave flumes "Schneiderberg" (WKS) and "Großer Wellenkanal" (GWK) of the Franzius-Institut in Hannover, Germany, comparing traditional electric level gauges (GHM wave height meter, WL Delft) with two different commercial radar level gauges (Vegaplus , Vega, and Kalesto, Ott) (Fig. 2).

Theoretical Background

Radar level gauges are based on one of the two different measuring principles mentioned above. Both principles are illustrated in Fig. 1.

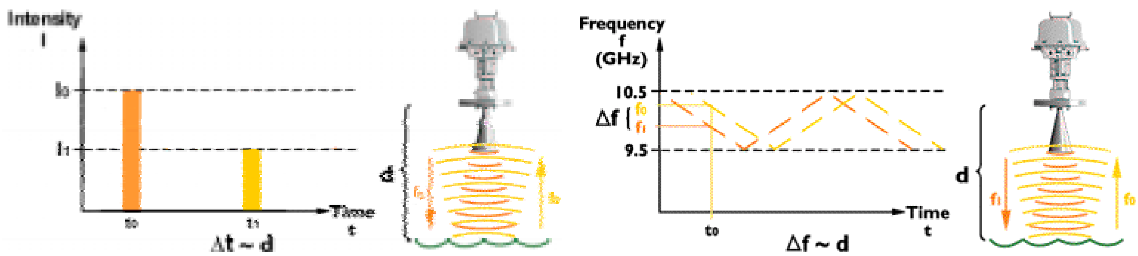

Fig.1 Measuring principles of radar level gauges based on the travel time of a radar pulse (left) or on the phase shift of a modulated continuous radar beam (right) [4]

The simplest approach to distance measurement by an optical method is to determine the transit time Δt of a short pulse of light reflected back from the remote target, i.e. the water surface (Fig. 1, left). The distance d of the water surface from the sensor is calculated by

$$d = 0.5 \cdot c \cdot \Delta t \qquad (1)$$

with the speed of light c. A high accuracy in measuring the time of $6.6{\cdot}10^{-12}$ s is required to yield a distance resolution of 10^{-3} m.

A more accurate method makes use of optical phase ranging. The frequency of the emitted continuous radio wave is modulated, as indicated in Fig. 1 (right). Therefore a phase shift Δf between the reflected wave received and the emitted wave occurs. Mixing the transmitted and reflected signals results in a low frequency signal (beat frequency) that can provide a measured value of the distance d with high accuracy [5]:

$$d = 4 \cdot c / F_m \cdot \Delta f / \Delta f_{max} \qquad (2)$$

where F_m is the modulation frequency and Δf_{max} is the deviation of the transmitter frequency.

The accuracy of level measurements with both types of radar level gauges is up to 1 mm in the range from 0 to 30 m in case of homogeneous reflecting surfaces [6]. For rough surfaces, e.g. water surface with irregular waves, the measurement error increases due to a modulation of the beam by inclinations of the relief of the surface roughness [7].

Experimental Set-Up

Figure 2 shows the different sensors mounted in the WKS and the GWK. Each radar sensor is located close to a traditional GHM sensor in order to allow an optimal comparison of the measuring systems.

Fig. 2 Experimental set-up in the wave-flume WKS (left) and GWK (right)

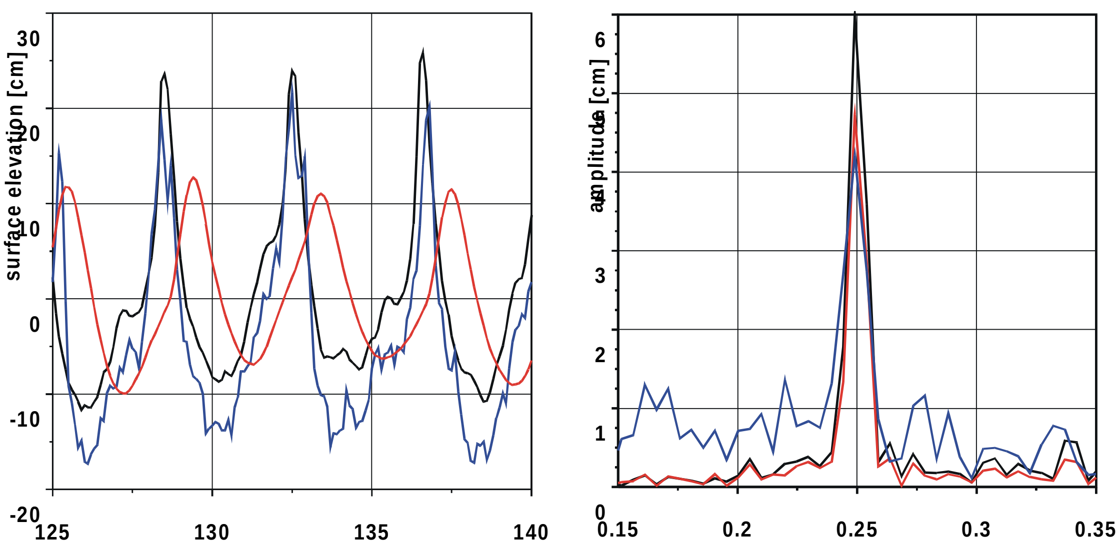

Fig. 3 Water-level elevation measured with GHM wave height meter (black), VEGAPLUS radar sensor (red) and KALESTO radar sensor (blue) in time domain (left) and frequency domain (right) in case of regular waves (d = 0.80 m, H = 0.30 m, T = 4 s)

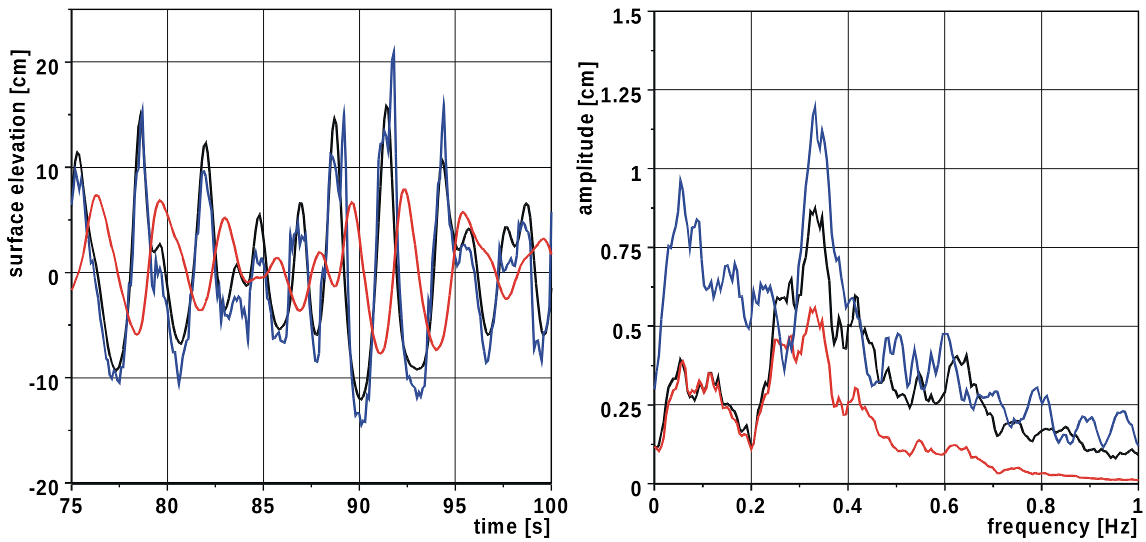

Fig. 4 Water-level elevation measured with GHM wave height meter (black), VEGAPLUS radar level-gauge (red) and KALESTO radar level gauge (blue) in time domain (left) and frequency domain (right) in case of irregular waves (d = 0.80 m, H_s = 0.25 m, T_p = 3 s)

The instruments were tested for different wave conditions (wave height, wave period, regular/irregular waves) and water-levels. In WKS the parameter set comprises water-levels from 0.80 m to 1.00 m, wave heights from 0.05 m to 0.40 m and wave periods from 1 s to 6 s. In GWK the behavior of the sensors was investigated at water-levels from 3.00 m to 5.00 m with wave heights of 0.60 m to 1.20 m and wave periods of 3.5 s to 9.5 s. Examples of data-sets gathered in the WKS are given for regular waves in Fig. 3 and irregular waves in Fig. 4. Both examples are given in time-domain (left) and frequency-domain (right).

Although the time plots of the surface elevation measured with different sensors are qualitatively the same there are large quantitative differences. Fig. 3 (left) gives a good first impression of the problems in applying radar level gauge, like spikes in the signal of the KALESTO radar, being a consequence of a poor signal-to-noise ratio, and a phase shift as well as a reduced amplitude of waves measured with VEGAPLUS. The latter results from internal filtering of VEGAPLUS to improve the signal-to-noise ratio. In frequency domain (Fig. 3 (right) and Fig. 4 (right)) the problems of KALESTO result in a white noise leading to an overestimation of spectral amplitudes of surface elevation while the problems of VEGAPLUS lead to an underestimation of spectral amplitudes. The wave period and the spectral peak respectively are measured correctly by the radar sensors.

The deviation of GHM sensor and radar sensors depends on the wave characteristics. A detailed analysis of some transfer functions is given below correlating the mean wave height of the different sensors or peak amplitude respectively. The mean wave height was determined in time-domain using the zero-down-crossing method. The threshold Δ was chosen to 4 % of the significant wave height H_s calculated from the amplitude spectrum S(f):

$$\Delta = 0.04 \cdot H_s \qquad H_s = 4.0 \cdot \sqrt{m_0} \qquad m_0 = \int S(f)\, df = \frac{1}{N} \cdot \sum_{i=1}^{N} \varsigma_i^2 \qquad (3)$$

with the discrete time-series of surface elevation ζ_i.

Results

The influence of the wave period on the ratio of the wave heights measured with GHM sensor and the radar sensors is given for regular waves in Fig. 2 and for irregular waves in Fig. 3.

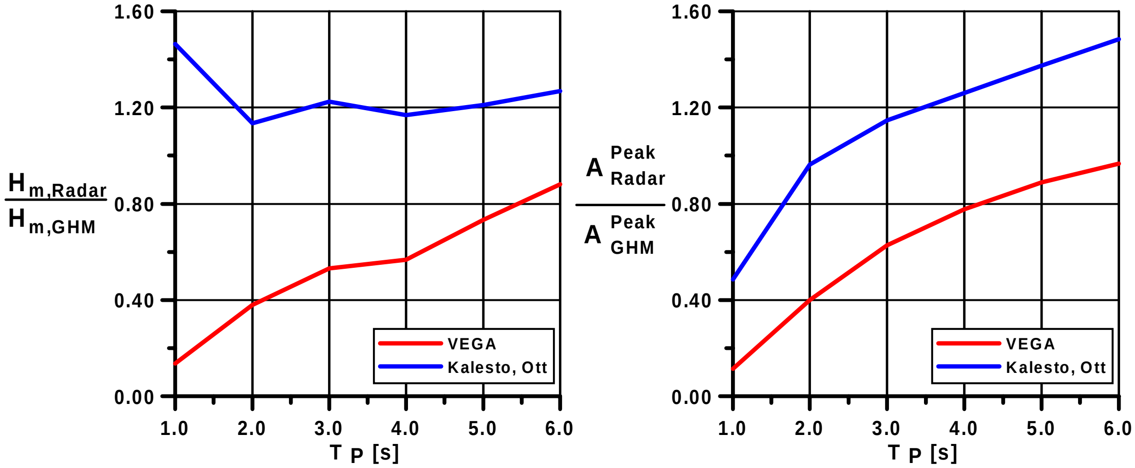

Fig. 5 Ratio of wave heights measured by radar level gauge and GHM wave height meter derived by analysis in time domain (left) and in frequency domain (right) in case of regular waves (H = 0.20 m)

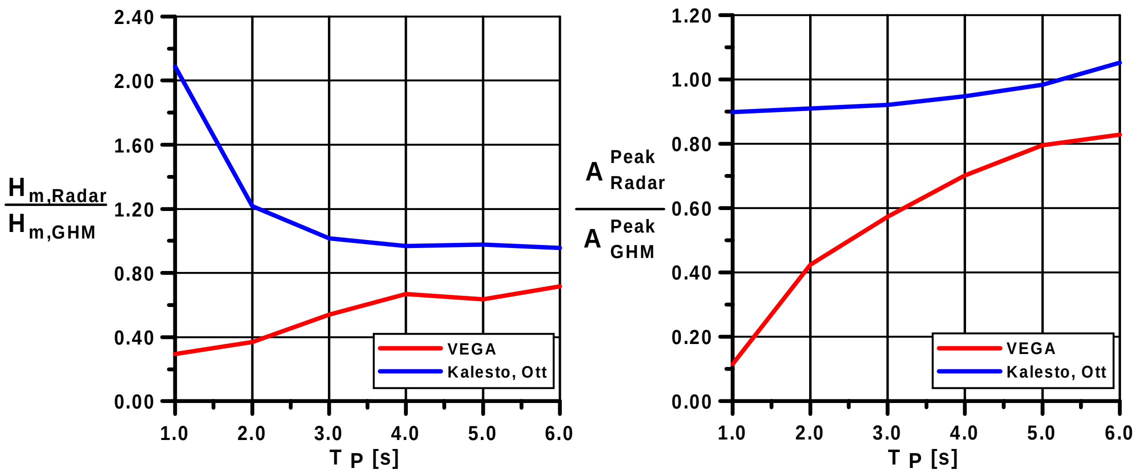

Fig. 6 Ratio of significant wave heights measured by radar level gauge and GHM wave height meter derived by analysis in time domain (left) and in frequency domain (right) in case of irregular waves (H_s = 0.15 m)

The KALESTO (blue) overestimates the mean wave height determined with the method of zero-down-crossing. The extent of overestimation decreases from $H_{m,Radar}/H_{m,GHM}$ = 1.3 to 1.2 in case of regular waves and from $H_{m,Radar}/H_{m,GHM}$ = 2.0 to 1.0 in case of irregular waves (JONSWAP spectrum) with increasing wave period T or T_p from 1 s to 6 s. Analysing the peak in the amplitude spectrum the KALESTO underestimates the spectral amplitude for low wave periods and overestimates it for higher wave periods. While the ratio of spectral amplitudes does not vary much for irregular waves the ratio varies from 0.5 to 1.5 for regular waves.

In contrast to the KALESTO the VEGAPLUS always underestimates the mean wave height and the spectral amplitude. The ratio of mean wave heights or of spectral amplitudes respectively increases from approx. 0.15 to 0.95 in case of regular waves and from approx. 0.10 to 0.80 with increasing wave period from 1 s to 6 s.

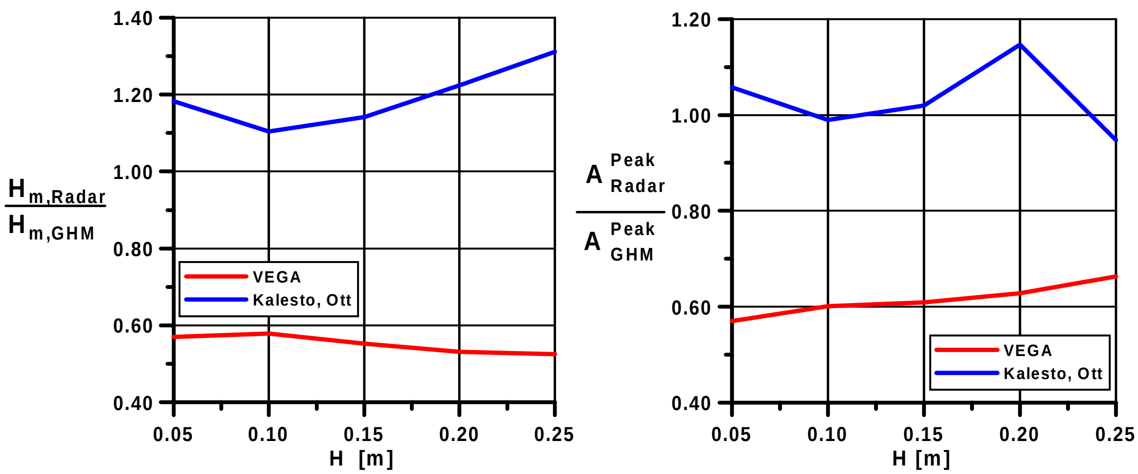

Fig. 7 Ratio of significant wave heights measured by radar level gauge and GHM wave height meter derived by analysis in time domain (left) and in frequency domain (right) in case of regular waves (T = 3 s)

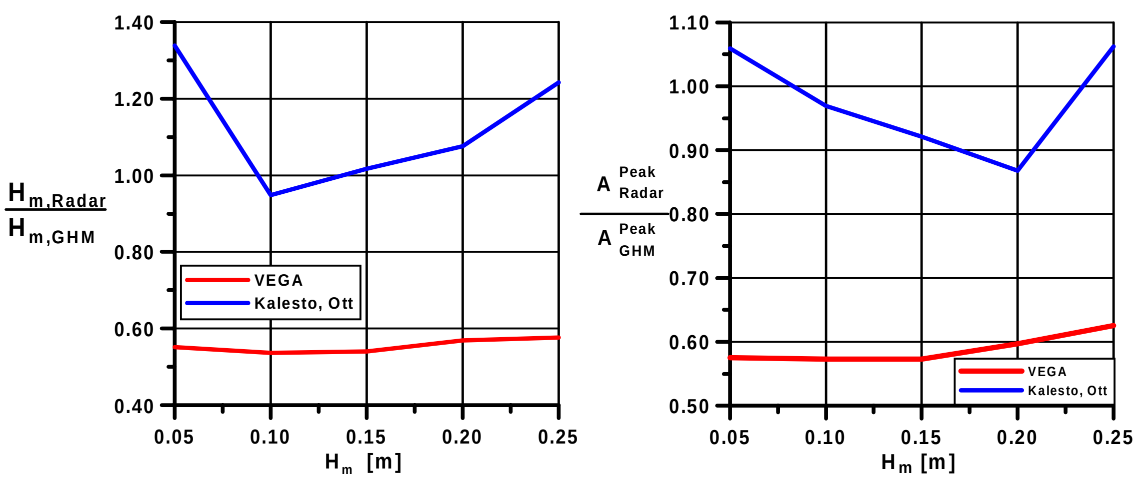

Fig. 8 Ratio of significant wave heights measured by radar level gauge and GHM wave height meter derived by analysis in time domain (left) and in frequency domain (right) in case of irregular waves (T_p = 3 s)

The influence of the wave height on the ratio of mean wave heights and of spectral amplitudes is less than the effect of wave period, as incidicated in Fig. 7 for regular waves and Fig. 8 for irregular waves. The ratio of wave height and amplitude of the spectral peak is approximately constant (≈0.55) for the VEGAPLUS. For the KALESTO it varies in the range from 0.9 to 1.3.

The mentioned effects are related to a poor signal-to-noise ratio of the KALESTO and the filtering of the VEGAPLUS, as stated above. The filter characteristics might be improved by a larger aperture of the antenna leading to a smaller footprint of the radar beam on the sea surface. The same improvement of the directivity are acchieved using higher radio frequencies, e.g. 24 GHz instead of 9 GHz [8].

Conclusion

The radars VEGAPLUS and KALESTO, being already applicable for the measurement of slow water–level changes (water-level gauges / tide gauges) [9], are not yet applicable in wave monitoring without using transfer functions. Future experiments planned in the wave flumes of the FRANZIUS-INSTITUT will help to overcome this inadequacy especially by improving the directivity of the antenna of the radar.

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