Mathematical Model of Radio Altimeter LFM Signal Operating Over the Sea Surface

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Abstract

The article examines the features of the radar altimeter reflected signal modeling over the sea surface. The model operates at different wave heights, pitch and roll angels, speeds of the aircraft and widths of the antenna pattern. A brief description of the radio altimeter influencing factors is made. Modeling results are analyzed. The complex of hardware-in-the-loop (HIL) simulation with the implementation of the resulting mathematical model is considered.

1 Introduction

When designing radars it is important to carry out multiple experiments for debugging device algorithms. This step requires random signal realizations that characterise the object under study. There are various methods of making such realizations: conducting field tests, experiments and the use of HIL simulation systems, mathematical modeling.

Currently, modern computational power allows implementing quite plausible ways to simulate signals reflected from different objects. Besides the fact that modeling a random process is economically much more profitable than full-scale trials, it also allows to save time by modifying the test conditions almost instantly since all the simulation parameters are set by means of equations and constants that can be changed depending on the task. Mathematical modeling allows taking into account the features and characteristics of the radar objects under specified conditions of observation and provides the necessary accuracy of the physical processes description.

The aim of the study is the radar altimeter modeling above the sea surface.

The relevance of this topic lies in the fact that the development of low-altitude aircraft navigation systems arise the need to measure the sea state parameters in order to avoid emergencies at an altitude of up to 50 meters

The object of the study is the radio altimeter operation using a chirp signal over the sea surface.

Method of work – mathematical modeling in MatLAB that is computing environment using the phenomenological approach. This approach eliminates the mechanism of electromagnetic field scattering and reflection by surface. It replaces the spatial electrical characteristics with the relevant characteristics of the reflected signal [1].

2 Sea Waves Modeling

The principle of radio altimeter operation with frequency modulation is the following: a high-frequency signal with a symmetrical linear frequency modulation is radiated by the transmitting antenna and reflects from complex radar scene that consists of reflecting facets of the sea surface roughness [1, 5].

When studying sea surface it is necessary to consider the factors that influence wave generation, such as: speed and wind direction, waves fetch length, ocean motion, etc. [2].

The sea state modeling algorithm is as follows [3]:

– The energy spectrum of sea waves is calculated (capillary model for ripples and TMA model for wind waves):

$$E_{TMA}(f) = E_{JONSWAP}(f) \cdot \Phi(f^*, h) \quad (1)$$

$$E_{JONSWAP}(f) = \frac{\alpha \cdot g^2}{(2\pi)^4 \cdot f^5} e^{-\frac{5}{4}\left(\frac{fp}{f}\right)^4} \cdot \gamma^{e^{-\frac{\frac{f}{fp}-1}{2\cdot\sigma^2}}} \quad (2)$$

where α is the scaling parameter;
γ is the peak enhancement factor;
σ is evaluated as 0,07 for f ≤ fp and 0,09 otherwise;
F is fetch length;
fp is the frequency at the spectral peak;
Φ*(f*,h)* is the Kitaigorodoskii depth function.

– According to this spectrum, the parameters for each elementary wave of sea surface are defined (height and wavelength, direction of propagation, wave phase, etc.).

– These data, together with the aircraft speed vector, current time and antenna direction are inserted into the analytical formula:

$$\xi(x, y, t) = \sum_{n=0}^{N_{f-1}} \sigma_n \cdot sin\left(K_{0n} \cdot \left[(x + (V_x - U_{nx}) \cdot t) \cdot cos\beta_n + (y + (V_y - U_{ny}) \cdot t) \cdot sin\beta_n\right] - \Omega_n \cdot t + \alpha_n\right) \quad (3)$$

where x, y is the actual location at time t;
n is the number of wave trains;
V_x,V_y is aircraft speed projection;
U_{nx}, U_{ny} is waves speed projection;
z + (V_x – U_{nx})t, y + (V_y – U_{ny}) is offset in the Oxy plane;
α_n is the wave phase;
β_n is the direction of wave propagation;
Ω_n is the pulsation;
K_0 is the wave number;
N_f >> 1 is the number of waves;
σ is the standard deviation of sea wave heights;
C is the normalization constant.

– The resulting surface is converted into an unordered set of triangles by Delaunay triangulation (every three samples are grouped into facet) (Figure 1).

– Further, there is a calculation of each triangular facet parameters (facet area, center and normal vector).

– As the result there is a finite region of formed facets that represents sea waves (Figure 2).

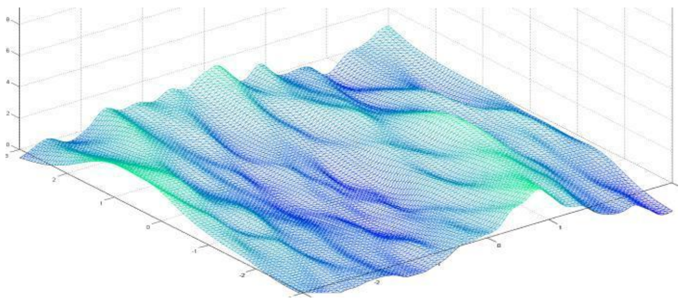

Figure 1: Discrete facets surface

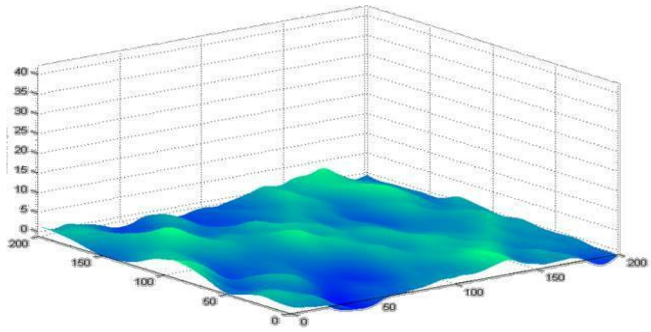

Figure 2: An example of sea surface

3 Radio Altimeter Modeling

In the mathematical model development of the radio altimeter beat-frequency waveform following assumptions were made:

– scan region is a square centered at the normal fall from the aircraft to the surface;
– antenna radiation pattern does not include side lobes (perfect antenna pattern);
– depending on the aircraft values of non-zero roll and pitch angles scan region extends to one or two sides.

The underlying surface is constructed as follows: taking into account the antenna pattern it is possible to construct a conical surface with a small number of faces. Further, this surface is determined by the intersection of the horizontal plane at a suitable distance. The rectangle is constructed from the resulting set by the extreme points. It includes all facets of sea surface.

The modeling algorithm of a signal reflected from the sea is as follows [3]:

– the scan area (area(j)) is determined by the formed sea wave facets;
– further the power of the signal reflected from each of the facets in the area (P_j), its time delay (τ_j) and Doppler frequency shift (ω_{dj}) are calculated;
– feedthrough signal (P_{ft}), its time delay (τ_{ft}) and white Gaussian noise (P_n) are measured;
– we can obtain a beat signal using previous data:

$$U_b = \sum_k \sqrt{P_k(t)} \cdot \sin\big(g_k(t)\big) + P_n(t) \qquad (4)$$

– spectrum of the beat signal is defined using fast Fourier transform FFT (Ub);
– the spectrum is assessed in three different ways: at the maximum spectral range, the leading spectral edge and the center of spectrum gravity [5].

4 Factors Affecting Radio Altimeter Operation Model

The radiation nature of FM radio altimeter leads to feedthrough signal effect at the input of the receiving antenna. This signal is generated by the parasitic electromagnetic coupling between transmitting and receiving antennas. The amplitude-modulated components of the signal have the greatest impact causing the voltage at the balanced mixer output. The main part of the noise voltage energy spectrum falls on the low-frequency portion in the area corresponding to the measured heights of flight.

The noise power at the balanced mixer output caused by the feedthrough signal does not depend on the height of the aircraft flight but the desired signal power decreases with the height increase. Thus there exists a certain height at which the powers become comparable which leads to deterioration of the radar altimeter accuracy.

The principle means of decreasing such a noise is improving the generator noise characteristics and increasing isolation which is expressed by the rational placement of antennas on the aircraft [5].

In this paper the energy proportion of the voltage noise spectrum falls on the frequencies of tens hertz at a distance of one meter between the transmitting and the receiving antennas. It slightly affects the radio altimeter accuracy in the measured heights range.

The influence of the Doppler effect in this model was also taken into account. The Doppler frequency is determined by the radial velocity (V_{rad}) of each element relative to aircraft. V_{rad} is the projection of the aircraft velocity vector in the radar direction that is a sea surface facet.

The Doppler effect results in a large number of the reflected signal frequencies corresponding to each spectral line of the probing signal, i.e. these lines are blurred upon the reflection and spectrum extends (figure 3,4).

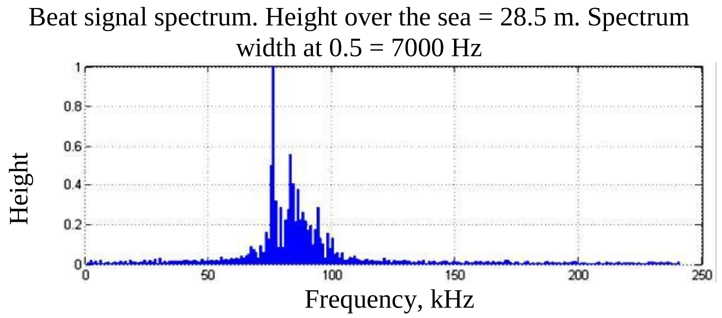

Figure 3: Beat signal spectrum at the aircraft speed = 0; height above the sea = 30 m; wind speed = 10 m/s; no pitch and roll angles

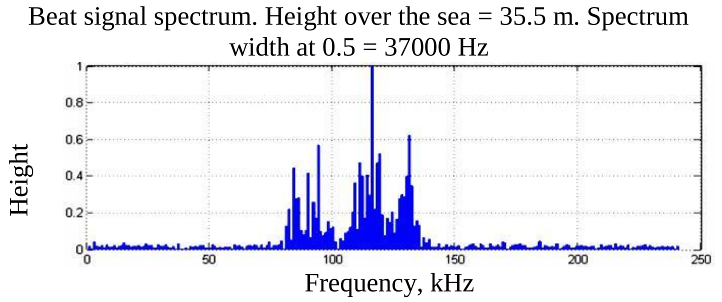

Figure 4: Beat signal spectrum at the aircraft speed = 100 m/s; height above the sea = 30 m; wind speed = 10 m/s; no pitch and roll angles

5 Modeling Results

Modeling results with different input parameters were obtained:

- wind speed variation, which leads to waves speed and height change in the sea surface;
- aircraft speed, pitch and roll angles, the height above the sea level;
- increasing (decreasing) antenna pattern.

The results are presented in Figures 5, 6, 7, 8, 9.

Each figure contains three graphs: 3-dimensional moving sea image, beat-frequency spectrum and beat-frequency signal.

Wind speed has a direct impact on the sea surface commotion. The faster wind speed, the faster wave formation and as a consequence the waves become higher. Heights variation determined by altimeter becomes larger than in perfectly flat surface. The spectrum amplitude is increased because of wave heights increasing. The maximum spectral range is more uncertain due to the spread of wave heights. Figure 5 shows plots at the wind speed of 1 m/s, Figure 6 shows the plots at the wind speed of 10 m/s.

In response to a weak deviation of the antenna pattern, the spectrum shifts to higher frequencies. This is due to the fact that in case of the aircraft deviation antenna pattern will scan long-distant facets and their frequencies will appear in the spectrum. If there is a strong deviation of antenna pattern (more than half of the antenna axis), the spectral maximum shifts in the region of high frequencies. Roll and pitch are 10 degrees in Figure 7.

The radio altimeter antenna pattern is one of the most important parameter. The wider it is, the higher should be the stability of the altimeter at large angles of pitch and roll. The width of the presented model antenna pattern is 40 degrees, which corresponds to the antenna pattern width of A-053 and A-052 altimeters [4].

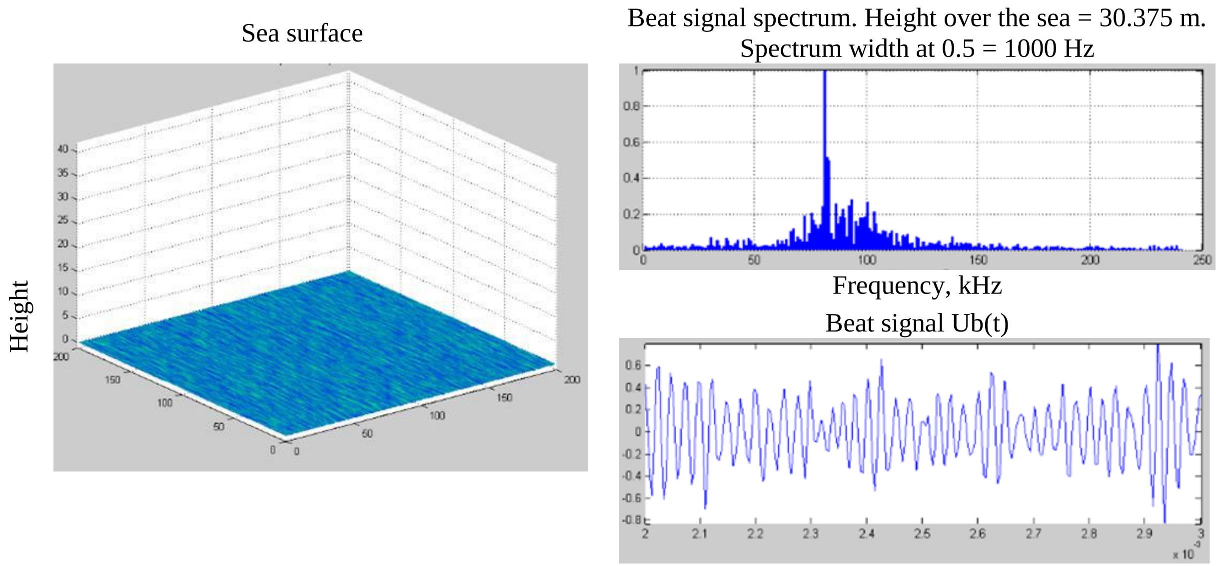

Figure 5: Output modeling data at aircraft speed = 0; height above the sea = 30 m; wind speed = 0 m/s; no pitch and roll angles; antenna pattern width = 40^0

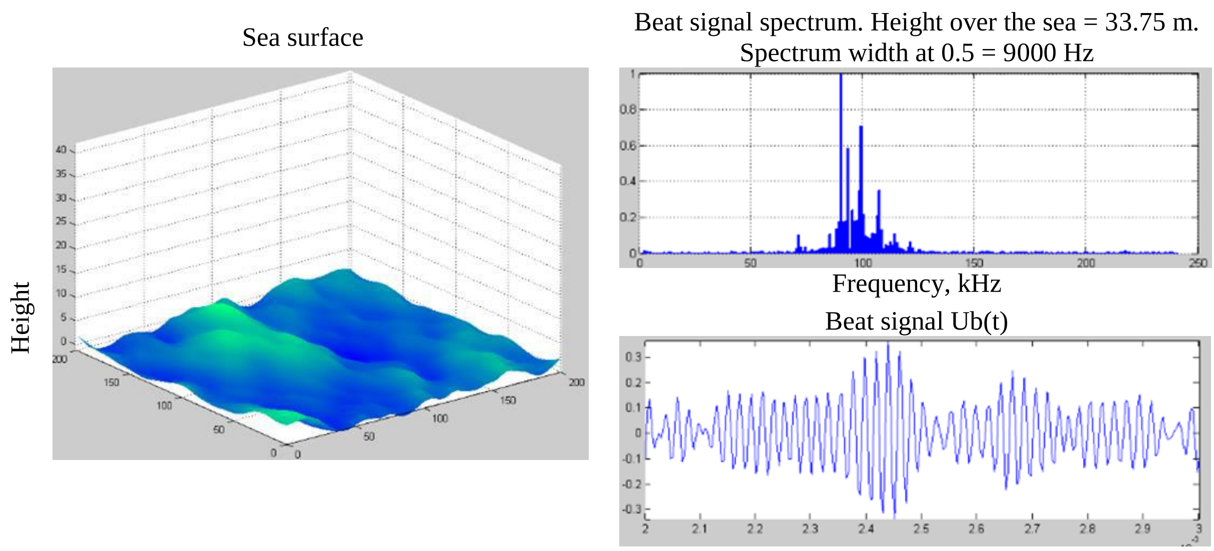

Figure 6: Output modeling data at aircraft speed = 0; height above the sea = 30 m; wind speed = 10 m/s; no pitch and roll angles; antenna pattern width = 40^0

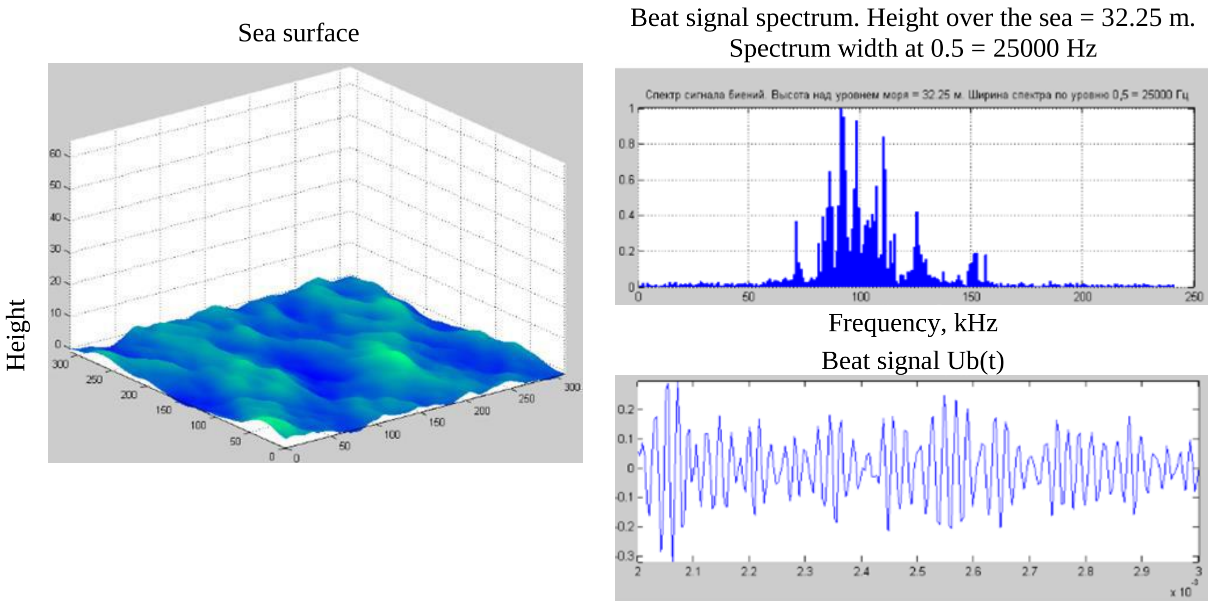

Figure 7: Output modeling data at aircraft speed = 0; height above the sea = 30 m; wind speed = 10 m/s; pitch and roll angles = 10^0; antenna pattern width = 40^0

One can observe a slight enlargement of the spectrum in the high frequency region when increasing the beam from 40 degrees to 60 degrees. It can be explained by the fact that with the beam width increase, the same and additional facets that are on the longer range with greater “amplitude” are also considered (Figure 8).

When decreasing antenna pattern, scanning area also decreases, and consequently the spectrum narrows (Figure 9).

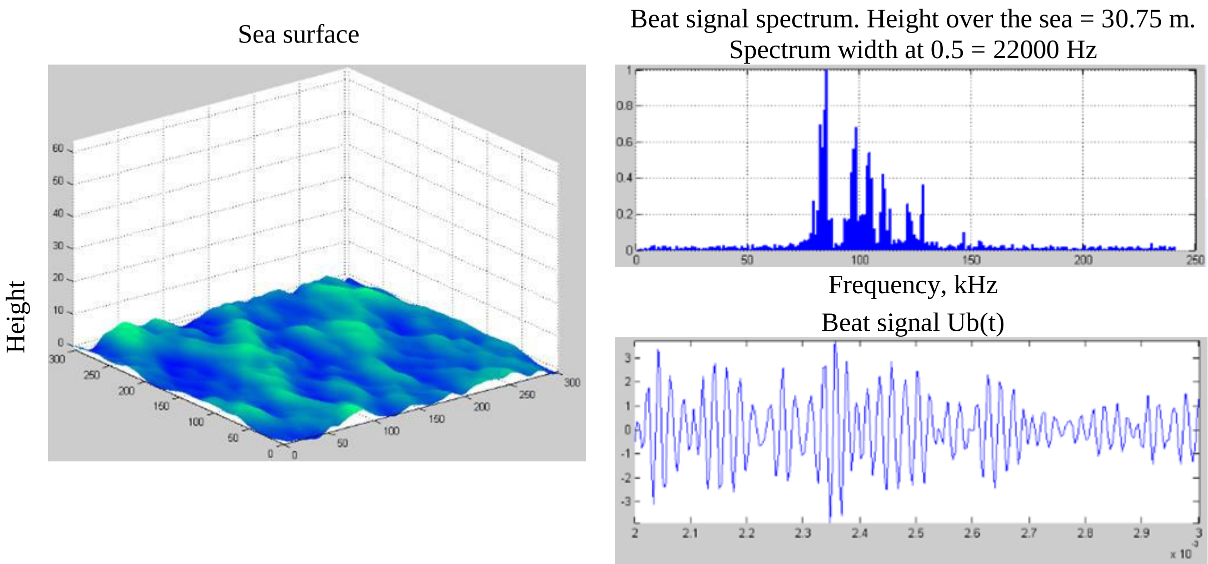

Figure 8: Output modeling data at aircraft speed = 0; height above the sea = 30 m; wind speed = 10 m/s; no pitch and roll angles; antenna pattern width = 60^0

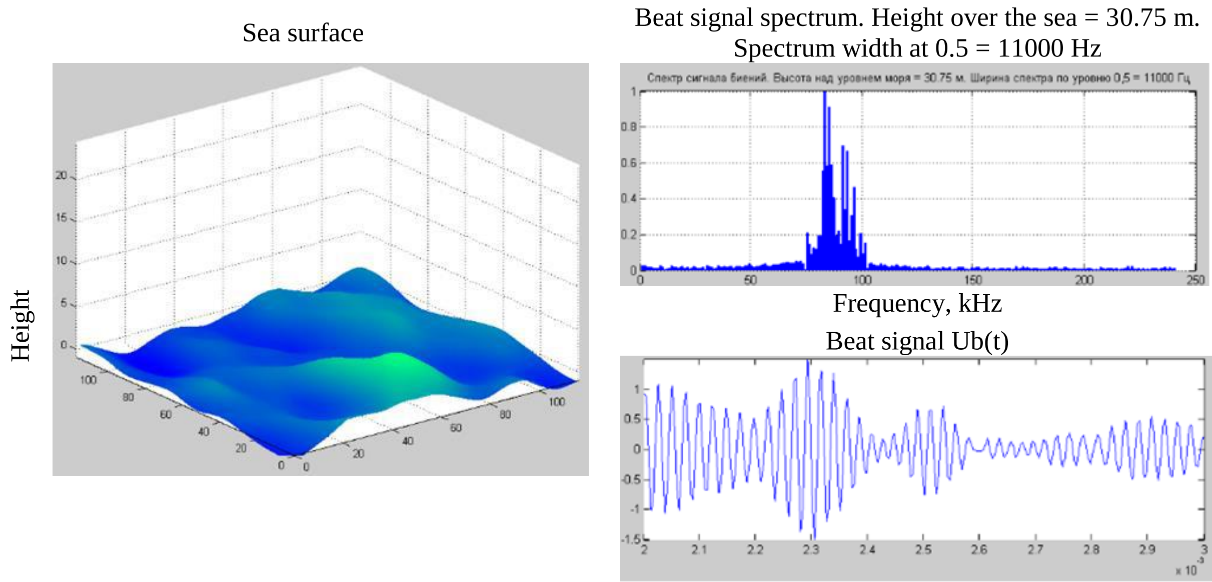

Figure 9: Output modeling data at aircraft speed = 0; height above the sea = 30 m; wind speed = 10 m/s; no pitch and roll angles; antenna pattern width = 20^0

We can determine the errors for each of the following spectrum assessment while calculating the heights above sea level.

The height measurement estimation errors above the sea in the absence disturbances at the sea surface and in the presence of waves up to 4 meters high (wind speed is 10 m/s) are shown in figures 10 and 11. The measurements are performed at attitudes up to 50 meters and typical conditions for radio altimeters operation [5].

Relative measurement error is defined by the following formula [2]:

$$\delta_x = \Delta x / X_{true} \tag{5}$$

where x is relative measurement error; $\Delta x = |X_{true} - X_{meas}|$ is absolute error; X_{true} is true value and X_{meas} is measured value.

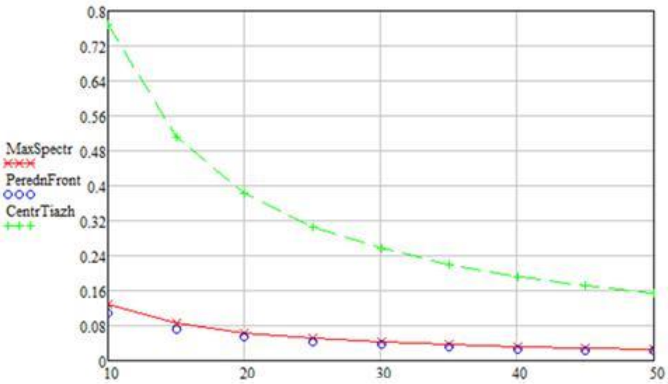

Figure 10: The relative error of the aircraft height determination that depends on the height of the flight in zero wind speed: MaxSpectr is the maximum range spectrum estimate; PerednFront is the leading spectrum edge estimate; CentrTiazh is the center of spectrum gravity estimate

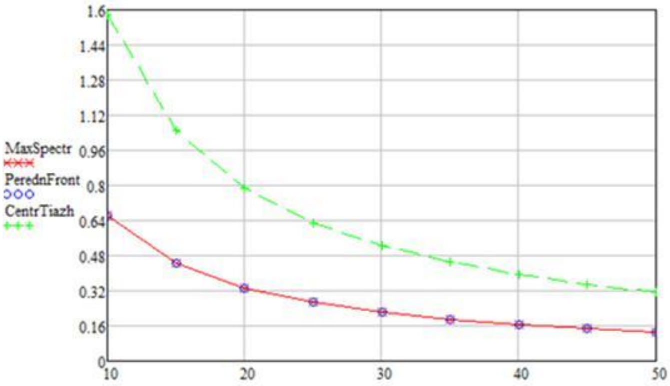

Figure 11: The relative error of the aircraft height determination that depends on the height of the flight in 10 m/s wind speed: MaxSpectr is the maximum range spectrum estimate; PerednFront is the leading spectrum edge estimate; CentrTiazh is the center of spectrum gravity estimate

The results are obtained by using the known measuring methods [5] (the maximum spectral range, the leading spectral edge and the center of spectrum gravity) in two states of the sea surface.

As we can see from the figures above, the center of spectrum gravity has the greatest error. The indication of height over the sea surface along the leading spectrum edge is the most accurate.

6 The Opportunities for HIL Simulation Using Altimeter Reflected Signal Complex IOS-RV

The radio altimeter model that has been obtained in MatLab software product can be further transferred to reflected signal simulator IOS-RV for development, debugging and experimentation to establish radio navigation equipment that works on the sea surface.

IOS-RV allows simulating the time delay and attenuation of the microwave signal emitted by the radio altimeter in accordance with the specified parameters of flight altitude, pitch and roll angles, the type of the underlying surface, the speed of the aircraft and the antenna system.

IOS-RV is used for HIL simulation of the radio altimeter. It helps developers to more thoroughly examine the behavior of the radio altimeter in conditions close to real, and obtain all the necessary information about it.

Using HIL simulation the under study system operates in its normal mode but the real signal propagation and reflection channel are simulated by a special device in accordance with the given system conditions and its dynamical changes.

A mathematical model of the channel "radio altimeter - surface" provides the calculation of the current signal settings on the receiving device input in accordance with the program by the certain algorithm. Physical model reproduces the signals in the receive path input of the side-looking airborne radar. Signal parameters vary according to the mathematical model. The antenna direction is set by the aircraft position. It is also predetermined by mathematical model. The signals that were created this way are fed to the input of the side-looking airborne radar receiving device [6].

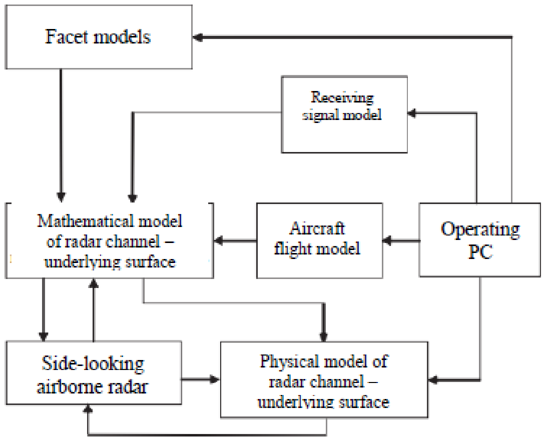

Figure 12: General block diagram of the side-looking airborne radar HIL simulation complex that operates on the earth and sea surface

Thus, the information is converted from a mathematical model to the physical signal waveform. Therefore, the most important element of the simulator work quality is mathematical model operation algorithm.

7 Conclusion

As a result of the work done, mathematical model of the radio altimeter beat signal is developed. It allows exploring the faceted surface. The sea waves dynamics is implemented at different wind speeds. The analysis of the modeling results is made.

The developed model adequacy is analyzed by changing the following input parameters: flight height variation above sea surface, the addition of the aircraft pitch and roll angles, establishment of the wind and aircraft speeds and changing the width of the antenna pattern.

According to the results obtained, the radio altimeter mathematical model is adequate enough and confirms the theoretical data.

The area of the application includes aircraft radar navigation systems. This work provides the opportunity to carry out mathematical and HIL modeling of radio altimeter systems under various external influences without expensive field tests.

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