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RADAR SENSING OF THE SEA SURFACE USING SMALL SPACECRAFT

ABSTRACT

The possibility of using a constellation of small spacecraft as receiving satellites, when "highlighting" the sea surface from existing (navigational, communication) or specially created spacecraft − to form a wide-area (about 1 000 km) radar survey zone at a given resolution (about 10 m) − is under consideration. Such a constellation could provide operational monitoring of fast-moving atmospheric cyclones, measuring directly the parameters of storm waves (altitude and orbital velocity) − which would replace the existing constellation of microwave scatterometers, providing operational monitoring of the World Ocean surface in the 3H (H − altitude of the satellite's orbit) field of view with a resolution of about 10 km − but with calibration of the received images by wind speed and direction, which leads to huge errors when trying to introduce altitude calibration in the Small spacecraft have many advantages over large satellites. For example, they are relatively inexpensive to build, take minimal time from design to launch, are easily modified to solve a specific problem, and create less radio interference. The approach under consideration consists in redistribution of tasks to be solved between the constellation of satellites in orbit. High orbiting navigation satellites, for example, can be used as transmitter carriers (of the illumination of the surface) that use the necessary broadband signal with acceptable periodicity. Receivers of reflected signals are placed on board small spacecraft, and at formation of wide-band radar image of sea surface with necessary resolution ~ 10 m (that only on order exceeds acceptable on small spacecraft size of receiving antennas) − in flight direction is necessary to use synthesized aperture of receiving antenna. This work has the character of "staged" research.

KEYWORDS: small spacecraft, radar aperture synthesis, searchlight mode of view, radar imaging, sea surface sounding

INTRODUCTION

Since the beginning of space exploration, many remote sensing satellites have been launched and a large number of experiments have been carried out to evaluate the potential of new methods for the global monitoring of land and ocean sites. The study of the world's oceans with more effective methods fits squarely within the implementation plan for the Decade of Ocean Science for Sustainable Development (2021−2030), and has been identified as a major science and technology challenge because of its increased importance in the life of humankind. However, despite the increasing intensity of ocean research, the current level of knowledge about the patterns of ocean processes is far from meeting the practical needs. For more detailed and operational monitoring of nonstationary processes in the World Ocean with diagnostics of their parameters, there is an increasing need for obtaining information about ongoing processes with minimal repetition time of the images being formed.

At present the term "small spacecraft" (SSA) defines not only mass and dimensions characteristics but also a fundamentally new constantly progressing architecture of construc-

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tion. The architecture of SSA construction defines proper mass-size, cost characteristics, personal (payload), user equipment, launch system (both during constellation creation and during its operative replenishment) and real-time operational control system [*Kartsan*, 2009; *Kartsan* et al., 2018; *Kartsan, Efremova*, 2019]. The category of SSA according to their weight dimensions also includes nano-satellites (weight from 1 kg to 10 kg), picosatellites (weight from 100 g to 1 kg), femtosatellites (weight up to 100 g); these kinds of SSA due to their minimal power parameters are not considered in this work.

The use of SSA will make it possible to move to a higher productive level of solving the assigned tasks of remote sensing due to the possibility of rapid deployment or replacement of the SSA constellation. As is known, the development of satellite systems for storm wave monitoring began with the installation on the SeaSat (1978) of the SeaWind broadband microwave scatterometer, which has a swath of ~1000 km with a resolution of ~10 km [*Stern*, 1983; *Klimenko, Zanin*, 2019]. Further development of broadband radar systems has led (in addition to various types of microwaves scatterometers) − to the study of the possibility of using the current constellation of navigation satellites (Glonass, GPS) to create a "global illumination" of the sea surface and receiving reflected signals inexpensive constellation of SSA [*Gutmann* et al., 1985; *Voronovich*, 1994; *Zavorotny, Voronovich*, 2000; *Lowe* et al., 2002; *Zavorotny* et al., 2010; *Voronovich, Zavorotny,* 2012]. These studies (initiated in the USA by former RAS collaborators A.G. Voronovich and V.I. Zavorotny) led to the creation of the current GNSS (Global Navigation Satellite System [*Zavorotny* et al., 2003; *Zavorotny* et al., 2014]), which uses a group of small satellites to receive "quasi-mirror" signals reflected by sea surface, while "highlighting" the surface by broadband periodical signal from the operating GPS constellation. Currently, the GNSS system continues to be updated with new receivers. The advantage of this method as compared with microwave scatterometry is that exactly the slopes of large waves are measured − while the scatterometer measures the intensity of small (resonant) waves, and large waves modulate the signal in such a way that rough calibration of radar images is possible only by wind speed and direction, and is impossible by wave height.

Currently on two low-altitude (but slightly different slightly elliptical orbits) are the German TerraSAR-X spacecraft launched from Baikonur [*Pitz, Miller,* 2010], which form the Tandem TerraSAR synthetic aperture interference radar (IRSA) [*Moreira* et al., 2004; *Krieger* et al., 2007; *Zink* et al., 2014]. The main task of this constellation is to form a three-dimensional image of the Earth land relief − including natural landscape (mountains, valleys, river estuaries, etc.) and man-made structures (roads, buildings, embankments, dams, etc.). Today we have already received digital "three-dimensional maps of relief" of a number of land areas with a resolution of about 1m on all three axes. It is necessary to note, that formation of such radar images demands enormous accuracy in measurement of ballistic parameters of IRSA, as a vertical component of antenna base of IRSA continuously changes. Both satellites are receiving and transmitting, and for precise pointing of antennas are equipped with special (controlled from the Earth) devices. The initiator and actual leader of the program, funded by the DLR (German Space Agency), is Alberto Moreira. It was this constellation that first carried out the formation of the field of gradient currents on the sea surface with a resolution of ~10m, including small-scale currents and orbital velocities of energy-carrying waves [*Romeiser*, 2013]. At the same time, the IRSA used not the vertical, but the horizontal component of the antenna base, the so-called "interferometer with a longitudinal antenna base". Recently, it was reported that DLR plans to dramatically strengthen this constellation by launching a large number of receiving ICs and leaving only one satellite as a radiating one [*Zonno* et al., 2018]. However, according to available data, the main task of the constellation remains the formation of a stationary relief of the land with high resolution, which, of course, allows ground processing of the initial radio holograms (RHG) with a long delay after their release to GRP (ground receiving point). If we set the task of monitoring of marine objects − then, of course, their non-stationarity requires not only processing in "almost real" time, but also ensuring the necessary (sufficiently small) "repeatability time" of formed radar images for a given object and a given water area of the World Ocean.

Processing of initial RHGs in the formation of RSA radar images is currently standard [*Neronsky* et al., 1999; *Ksendzuk* et al., 2009; *Kartsan* et al., 2016; *Tyapkin* et al., 2017]. At present, it is expected to put into operation several domestic RSA of new generation according to the "Condor-E" program, capable to form bright radar images of high resolution (about 1 m) in various modes of Earth surface survey [*Afanasyev,* 2013; *Turuk* et al., 2016; *Turuk* et al., 2017]. Processing of "paired" RHGs in IRSA is a little more complicated, especially at formation of a field of a relief of a surface of the Earth. Processing of "paired" RHGs in IRSA should be considered as a special group when forming velocity fields, which include sea objects: storm waves, currents and waves of seismic origin (including relatively short waves arising above the earthquake origin) [*Pereslegin, Sinitsyn,* 2011; *Pereslegin, Halikov,* 2014; *Pereslegin* et al., 2021]. Finally, two-position quasi-mirror radars, which allow generating bright radar images of sea surface with wide field of view (~1000 km) and average resolution (10−30) m, should be referred to a separate perspective group [*Pereslegin*, 2009; *Pereslegin, Halikov,* 2011; *Pereslegin* et al., 2017]. Radars forming "level" radars with the same view area and resolution of about 1 km should be referred to the same group − they could serve as an extremely necessary for many applications "panoramic radio altimeter" [*Pereslegin, Halikov,* 2010]. For example, such a constellation of several pairs of receiving-transmitting SSA could provide (in the given areas of the World Ocean) operational monitoring of gravitational seismic waves, forming tsunamis.

MATERIALS AND METHODS

The sea surface, unlike the land surface, allows for most hydro-meteorological conditions to use numerical-model methods of calculations, which allows, based on existing ideas about the processes on the surface (hydrophysics) − to proceed to the processes of interaction between the surface and the electromagnetic signal (radio physics), and then to the engineering calculations associated with the application of certain configurations of radar systems (radiolocation itself). The choice of optimal parameters of radar system is quite a complex engineering task.

A radar image contains many easily distinguishable and identifiable features and has a clear resemblance to images obtained by optical instruments, but this resemblance is deceptive. The resolution of optical systems used in remote sensing is rarely limited by diffraction at a given aperture, with radar this phenomenon is almost unavoidable. Radar irradiates the rotating curved surface of the Earth with radio waves with a spherical front. Airplane-based systems do not take these features into account due to the low flight altitude, but in high resolution space-based systems (RSA, IRSA) they must be taken into account.

Aspiration to provide high enough periodicity of observation of the given water area (small "repeatability time" of radar information), at acceptable cost can be reached at creation of orbital constellation of spacecraft. At the same time, achievement of wide imaging swath when using RSA as a receiver and a third-party source of periodic broadband signal − is limited by the maximum possible range of slant range: . Physically, this means that during the time the receiving antenna of its length (Dx) flies over the speed of the vehicle (Wx), it is necessary to receive at least two reflected signals with a repetition period Tr=ΔR/c (the "external coherence" mode). It is easy to see that with an acceptable horizontal antenna size Dx = 2m and an orbital altitude of 1500km (Wx = 7.5km/s), the maximum range of oblique ranges will be only 40 km. Nowadays two possibilities are used for obtaining larger lateral view zone: electronic scanning of antenna beam by location angle [*Neronsky* et al., 1999] (with preservation of external coherence mode) and stretching of view zone (by horizon) in relation to ΔR value − that is achievable in "quasi-mirror scattering" mode under condition that beams of emitting and receiving antennas are in the same vertical plane and "mirror point" viewing angle is not less than 600 [*Pereslegin, Halikov,* 2011].

One spacecraft with an orbital altitude of 1 500 km, over one point of the sea surface, can carry out radar sounding at least 6 times a day. For operational receiving of information about the sea surface condition from the SSA at the orbit altitude of 1 500 km, it is necessary to create a constellation with 4 orbits with 3 SSA on each, by analogy with the orbital constellation of multifunctional system of personal satellite communication "Gonets-D1M".

Fig. 1 [*Zavorotny* et al., 2014] shows the concept of functioning of the above mentioned American bistatic GNSS radar system, where with one low-orbit spacecraft it is possible to receive reflected "quasi-mirror" signal simultaneously from three high-orbit navigation satellites.

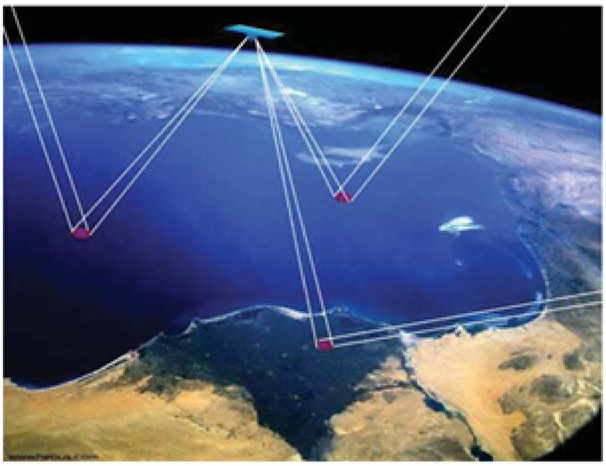

Fig. 1. Depiction of GNSS bistatic remote sensing concept

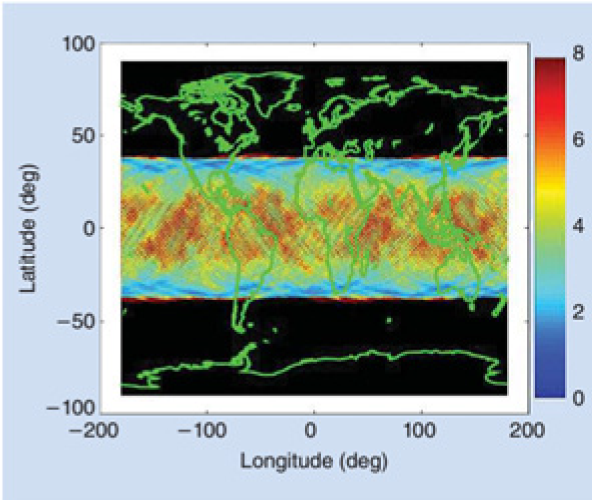

Fig. 2. Simulated coverage and revisit time map for the CYGNSS constellation. Mean revisit time over equatorial regions between approximately ± 38^0 latitude is approximately five hours

Fig. 2 [*Zavorotny* et al., 2014] shows the global picture of the most important parameter of this system − the revisit time for a given point of the Earth's surface. It is noted that the shortest revisit time (about five hours, i.e., 5 times a day) with one receiving spacecraft with a small orbit inclination is achieved at low latitudes (± 38°), when using ten transmitting spacecraft of GPS and Galileo systems.

In fig. 3 [*Zavorotny* et al., 2014] the same parameter (revisit time) is calculated for 24 simultaneously working low-orbit near-polar spacecraft with the same ten transmitting spacecraft. It can be seen that in this case almost-global coverage is achieved (except for circumpolar regions), but the repeatability of measurements drops sharply (up to half a day in the equatorial region).

Judging by the published materials [*Zavorotny, Voronovich*, 2000; *Lowe* et al., 2002; *Voronovich, Zavorotny,* 2012], the GNSS method does not allow to combine the large-scale radar information of wave slope with the necessary resolution, i.e., "stitching" of radar information from separate (reflecting mirror) sections of water areas, obtained by successive "flares", is hardly possible with the required accuracy − both on geographical coordinates and on the measured (averaged) slope of large waves.

Another direction of these studies [*Gutmann* et al., 1985] is an attempt to apply interference reception of the reflected quasi-mirror signal, using pairs of SSA with accurately measured antenna bases. Obviously, in this case it will be possible to measure the relief of the Earth's surface. However, the interference method requires appropriate power, i.e., the background/noise ratio must be high (at least 20 dB). This is possible for the sea surface in the quasi-mirror scattering mode − but interferometry imposes additional restrictions on the ballistics of the

SSA constellation and apparently requires an even greater increase in the number of receiving vehicles.

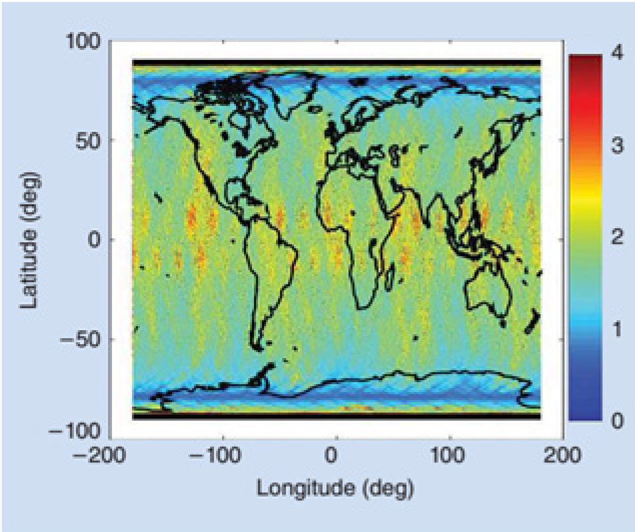

Fig. 3. Simulated coverage and revisit time map for a 24-satellite polar orbiting constellation, with each satellite tracking up to 10 GPS and Galileo measurements. Mean revisit time over entire globe is less than two hours

RESULTS AND DISCUSSION

The German Tandem TerraSAR constellation mentioned above consists of two transmitting and receiving satellites located on slightly elliptical (almost circular) low orbits of ~600 km altitude [*Moreira* et al., 2004; *Krieger* et al., 2007; *Zink* et al., 2014]. Eccentricities of orbits are shifted relative to the center of the Earth, so the base of interferometer, formed by receiving from two positions reflected by the surface signal, smoothly changes in its magnitude and slope relative to the vertical. Since the main goal of the radar complex is a consistent formation of the three-dimensional terrain of the Earth with high resolution (about 1m on all three axes), the most difficult task here is to measure the ballistic parameters of orbits with an accurate calculation of the size of the vertical component of the antenna base. The tasks of ensuring small repeatability time of radar images and processing of paired RHG in "almost real" time are not worth it here − due to the stationarity of the terrestrial objects. Recently there was a message [*Zonno* et al., 2018] about the planned DLR development of this system by a sharp increase in the number of receiving (passive) SSA with only one radiating satellites (fig. 4).

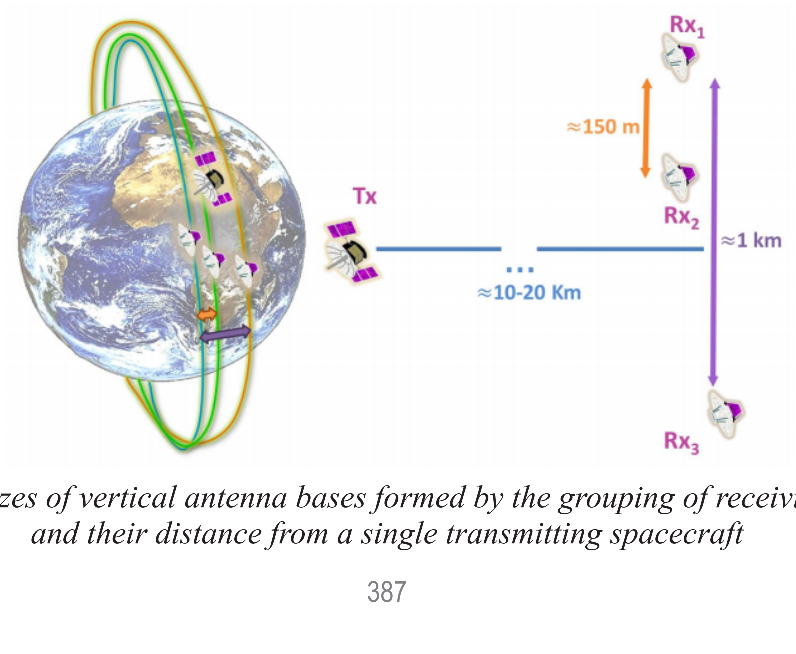

Fig. 4. Sizes of vertical antenna bases formed by the grouping of receiving spacecrafts and their distance from a single transmitting spacecraft

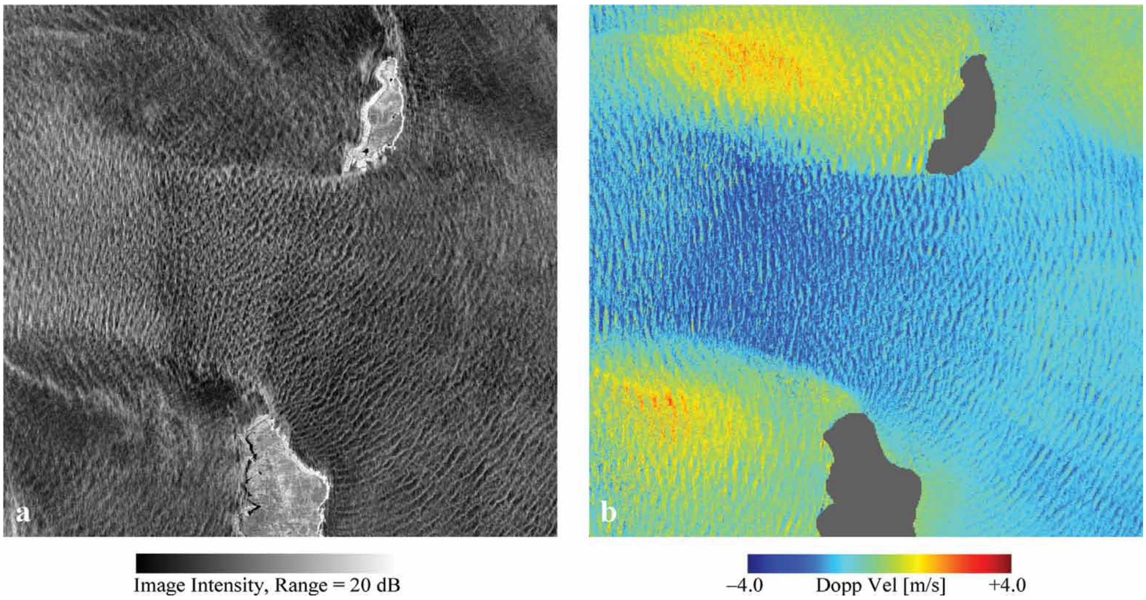

*Fig. 5. Sizes of vertical antenna Brightness (left) and velocity (right) radar images of gradient currents and orbital velocities of wind waves in the Strait near the Pentland-Firth Islands (Scotland), obtained by the Tandem TerraSAR-X system. Frame size (10*10) km, resolution ~10m, contrast-brightness fluctuation sensitivity ~3dB, velocity fluctuation sensitivity ~0.5m/s*

As for the sea (non-stationary) surface, the work [*Romeiser*, 2013], where the brightness and velocity radar images of the sea surface are formed using the Tandem TerraSAR-X system (fig. 5) was published. Here, in contrast to fig. 4, the horizontal component of the antenna base, which has a size of the order of 200 m, is used. At horizontal size of receiving antennas Dx = 4m and width of a spectrum of a signal ~100MHz the corresponding "focused" spatial resolution $r_x \sim r_y \sim 3$m at width of a review zone (on horizontal range) Ly~10km is received. Naturally, the processing of the primary RHG was carried out with a huge delay after their reset on the GRP − so that the problems of "stitching" of consecutive radar information in order to expand the viewing area, as well as the problems of ensuring small repeatability time of radar information and processing RHG in "almost real" time were not taken into account here at all.

It remains to cite the data of the proposed promising radar system, solving the problem of operational monitoring of the sea surface state in order to diagnose and forecast dangerous phenomena − storm waves and gravity seismic waves, forming tsunamis [*Pereslegin*, 2009; *Pereslegin, Halikov,* 2011; *Pereslegin* et al., 2017].

Fig. 6 shows the geometry of sea surface sounding in the "quasi-mirror" scattering mode: two low-orbit SSA, located at strictly the same height (about 1 000 km), have antennas with a wide (cosequential) form of the directional diagram in the vertical plane.

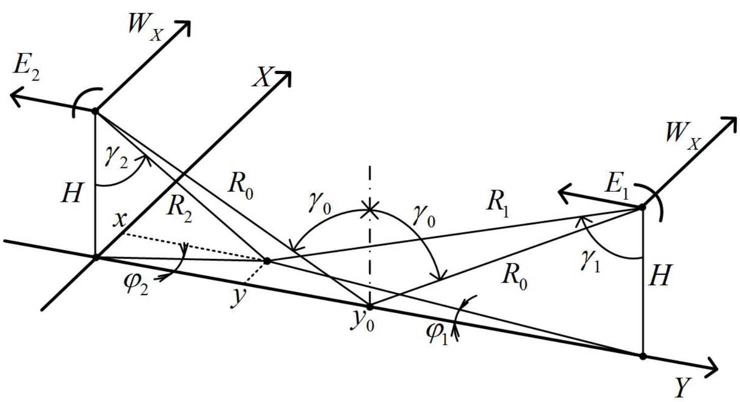

Fig. 6. Geometry of two-position quasi-mirror sea surface sounding

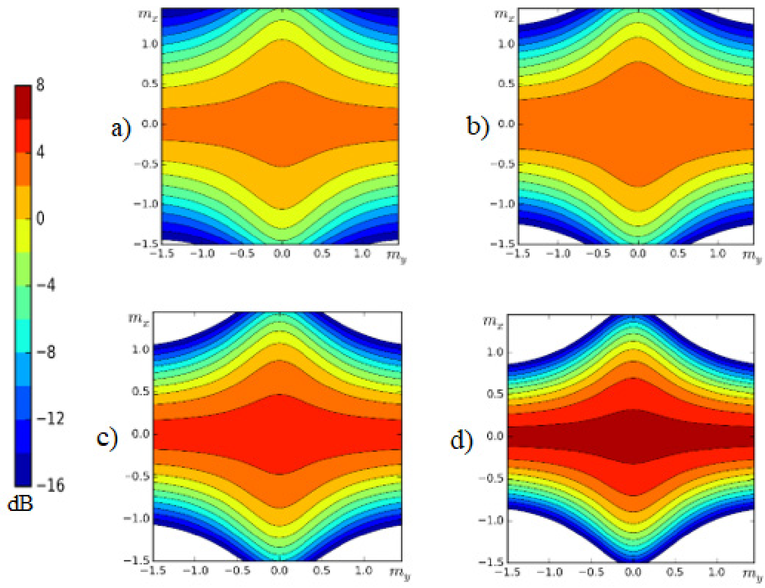

Fig. 7. Quasi-mirror scattering diagrams at wind speed W=4m/s:
a) λ=0.03m; b) λ=0.1m; c) λ=0.3m; d) λ=1m

When sighting the mirror point (angle γ_0) the worst horizontal range resolution is obtained, similar to the resolution of radioaltimeter − therefore the area near the mirror point at the receiving end is gated, as well as the "line of sight" area. In the region where the coefficient , the horizontal resolution $r_y \sim (10–30)\ m$ at a signal width of 300 MHz. Three-dimensional scattering diagrams are constructed for different values of wind speed (W), radio wavelength (λ), and for coaxial (HH) and crosstalk (HV) polarization components of the reflected signal [*Pereslegin* et al., 2017]. Fig. 7 shows an example of such diagrams plotted for the specific effective scattering surface $S_0(m_x, m_y)$ with coaxial-horizontal polarization of the antennas. It can be seen that the transverse width of the diagrams $S_0(m_y)$ is large compared to the longitudinal width $S_0(m_x)$, and that in the working region $m_x = \pm 0.5$, the specific effective scattering surface is close to 1. It is this fact that allows the use of small emitting spacecraft at an average radiation power of the order of 30W, and the small variations in the specific effective scattering surface reflect changes in the mean gradient of large waves.

Fig.8 shows the trajectory sweep of such tandems in Mercator projection (identical SSA are launched sequentially to the same orbit). It can be seen that when passing near-polar areas, the transmitting and receiving antennas of SSA change places, so to preserve the continuity of review at latitudes ~±75° − programmable switching of left and right-side antennas from transmitting to receiving and back is necessary.

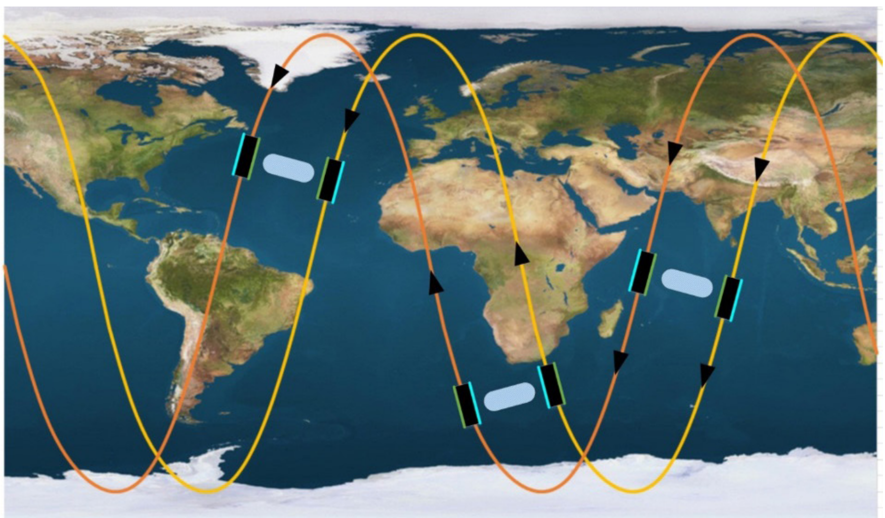

Fig. 8. Trajectory sweep of "tandem" SSA on the Earth's surface

Fig. 9 shows a variant of such tandem, where the vertical (relatively small, about 5m) interferometer antenna base is used, i.e., the number of receiving antennas on SSA is doubled. Calculations show that for a radio wave length of 0.8 cm (Z-band), such a tandem is able to replace a huge number of tracers radioaltimeters − i.e., to work as a badly needed "panoramic radioaltimeter" [*Pereslegin, Halikov,* 2010]. Since in this case (with such a small antenna base) only a narrow band of signal spectrum (only ~ 5 MHz) is allowed, the transverse horizontal resolution is of the order of 1 km, and there is no need to use a synthesized aperture, for the same order has the longitudinal resolution of the real aperture.

A generalized functional scheme of RSA considered above with one spacecraft-transmitter (high-orbit navigation satellites or low-orbit emitting satellites), one SSA-receiver and ground complex, is shown in fig. 10.

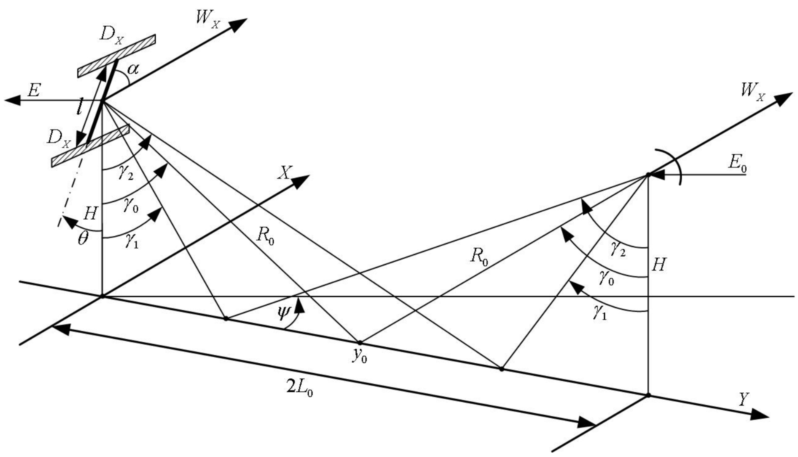

Fig. 9. Two-position "quasi-mirror" radar sighting of the sea surface: interferometer with transverse antenna base installed on the receiving SSA

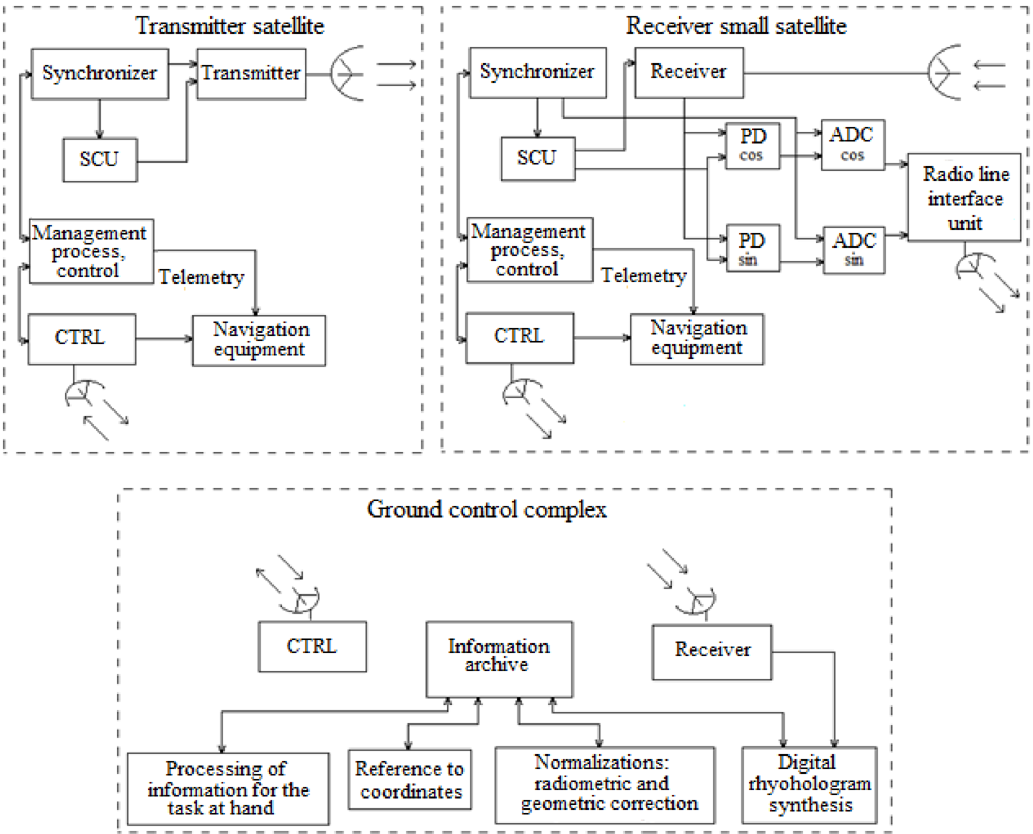

Fig. 10. Functional diagram of elements of a multi-position radar system including transmitting spacecraft, receiving spacecraft and ground control system

Space radar complex of the systems under consideration includes antennas − transmitting on the radiating spacecraft and receiving on the spacecraft with RSA; block of signal formation (SCU); synchronizer; receiver with outputs to the phase detector (PD) sine and cosine quadrature channels; analog-digital converter (ADC) of quadrature channels; interface block with radio data transmission line; control and monitoring processor; navigation equipment; command and telemetry radio line (CTRL) and radio data transmission line.

The ground complex includes a command and telemetry radio line; a receiver; an archive of the information component; a device for synthesis of a digital radio hologram; devices for normalization, radiometric and geometric correction of images, georeferencing, as well as a workplace for information processing for the assigned task.

When working over the oceans, dumping of information to GRP and further processing with obtaining brightness, velocity or level radar images of sea surface with specified spatial resolution and maximum (transverse) width of view area − takes much time, so such parameter as small time of radar repeatability when tracking hazardous phenomena in specified areas of the World Ocean is hardly achievable with the technologies available in Russia. Obviously, a radical solution of such problems requires formation of consecutive radar images directly onboard the receiving spacecraft.

CONCLUSION

The multi-position radar systems with the use of SSA considered above − should in the future provide operational monitoring of oceanic phenomena, including dangerous: storm waves in fast-moving atmospheric cyclones, forming tsunami of gravity large-scale seismic waves and vibration small-scale waves occurring directly over the sources of earthquakes.

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