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Condor-E Spacecraft with a Synthetic Aperture Antenna and Its Capabilities

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Abstract—The main parameters of a small spacecraft (SSC) (Condor-E) and its onboard radar with a synthetic aperture antenna (SAR) are presented in the paper. Two such SSCs were launched in Russia into a 500-km orbit in June 2013 and in December 2014. The structure of the radar with synthetic aperture antenna and the basic parameters of three standard imaging modes: detailed Spotlight (DSL), detailed Stripmap (DSM), and ScanSAR are also presented. All three modes are accompanied by radar images generated during flight tests. In this paper it is examined whether it is possible to introduce new modes (an interferometric assessment of terrain relief in the case of an "oblique" survey and the selection of moving targets) and the relevant pictures are provided. Condor-E SAR and TerraSAR are compared as typical space radars in their design and experimental modes. We conclude that the SARs perform similarly and give hope for the further augmentation of both SAR capabilities, including new modes without serious hardware modifications.

Keywords: small spacecraft, synthetic aperture radar, basic performance, high resolution, Condor-E, interferometric survey

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INTRODUCTION

The Condor-E small spacecraft (SSC) carrying an onboard radar with a synthetic aperture antenna (SAR) was launched in December, 2014, in Russia (*Aviatsionnye sistemy...*, 2015; Kondratenkov and Frolov, 2005; *Radiolokatsionnye sistemy zemleobzora...*, 2010; *Radiolokatsionnye sistemy vozdushnoi...*, 2008). The Condor-E was launched from the Baikonur spaceport for the benefit of a foreign customer. The launch was performed by Strela carrier rocket. The parameters of the initial orbit of Condor-E are as follows (according to information presented in the catalogue of the US Strategic Command): inclination is 74.75°, perigee altitude is 501.1 km, apogee altitude is 525.8 km, and rotation period is 94.66 min (Afanas'ev, 2015).

The prime developer of the spacecraft is AO VPK NPO Mashinostroyenia, and the prime developer of the radar with the synthetic aperture antenna is AO Vega Radio Engineering Corporation. A year and a half earlier, Mashinostroyenia launched the first spacecraft for radiolocation observation with high resolution (Afanas'ev, 2013). For a year and a half, two spacecrafts with onboard radar with a synthetic aperture antenna were launched in Russia. Certainly, the fate and performances of these spacecrafts and of the radar with the synthetic aperture antenna are interesting for specialists on radiolocation and space science and for the consumer of radio-location information, first and foremost for specialists on Earth remote probing (ERP). The possibilities of Condor-E are also of interest, since Mashinostroyenia has won a tender for "Creating a spacecraft complex for radiolocation operative all-weather round-the-clock monitoring of the Earth on the basis of the Condor-E spacecraft with an S-band radio locator" for the benefit of the Russian Federal Space Agency.

The Condor-E is intended for collecting, saving, and transferring high-detailed information obtained with the help of Earth remote probing in the microwave spectra band to the on-ground point of information receiving and processing. The radar with a synthetic aperture antenna secures all-weather and round-the-clock monitoring of the Earth surface. The radio location and service information transferring from the Condor-E to the on-ground points makes it possible to form a radio-location image (RLI) of the Earth surface and extract additional information contained in radio holograms.

In designing a radar with a synthetic aperture antenna for the Condor-E, the scientific team solved the problem of creating universal multimode equipment for solving user problems, including the problem

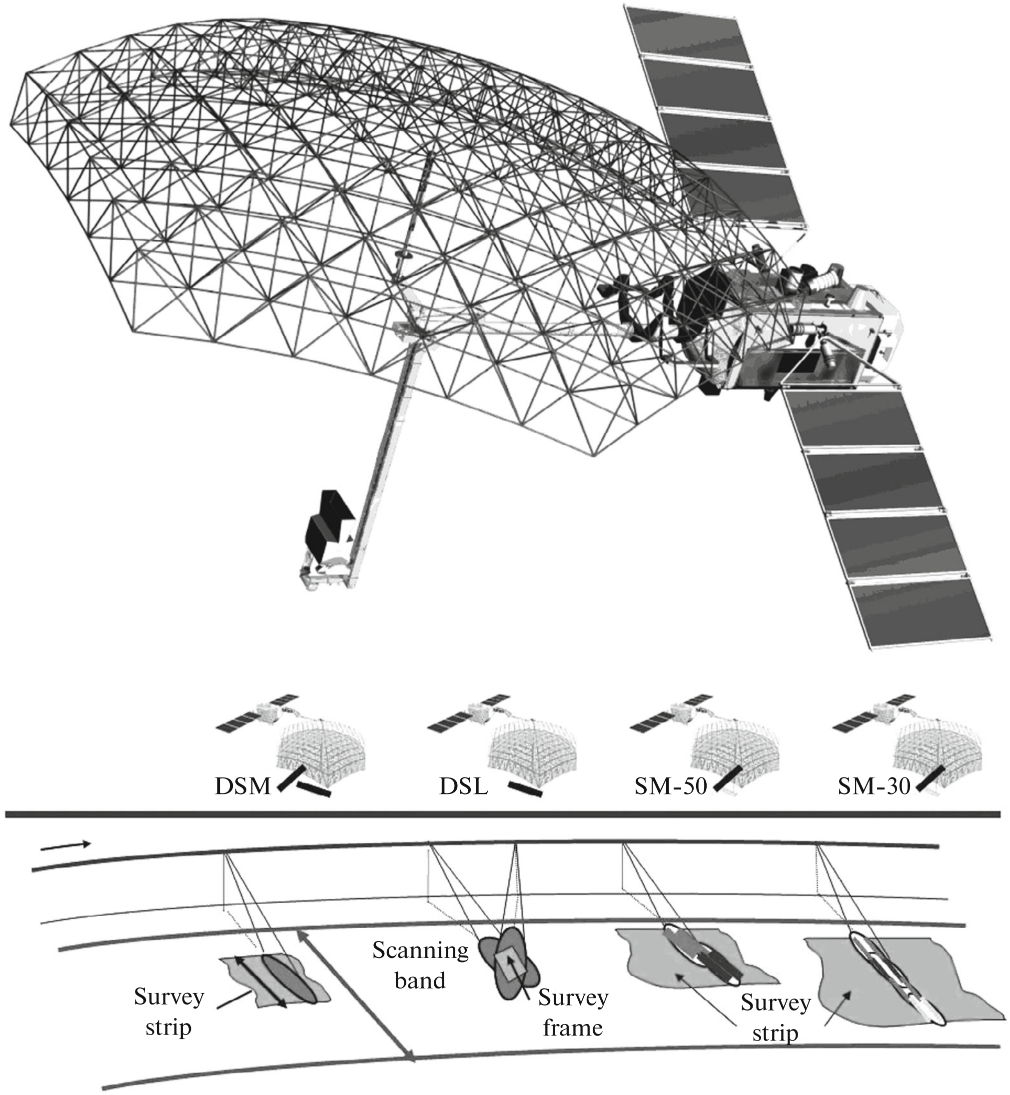


Fig. 1. External view of Condor-E spacecraft with open antenna clarifying SAR operation.

of monitoring the Earth surface, the navigation problem, and the problem of monitoring emergency situations. To place equipment aboard the SSC, its mass should be no more than 250 kg under the total mass of the SSC of 1000 kg (*Radiolokatsionnye sistemy zemleobzora*..., 2010; Neronskii, 2011; Osipov, et al., 2004a, 2006b).

The external view of the Condor-E is presented in Fig. 1. Several technical solutions for flexibly digitally controlling the survey band and the signal parameters and for optimizing power consumption as a function of survey cyclogram are accepted when designing the Condor-E. The light hybrid mirror antenna (HMA) with a reflector diameter of 6 m and with an efficient area of 28 m^2 is used in the SAR. It is placed on a rotating device that makes it possible to choose the survey direction and retarget according to terrain angle. The rotating feed in the form of a multihorn linear antenna grid in the horizontal position makes it possible to operate with HH polarizations and with electron-beam scanning within $\pm 2°$ over the azimuth for telescopic (spotlight) survey. If the feed is moved into the vertical position, it becomes possible to operate with VV-polarizations and to scan along the angle of the spot for the operative retargeting of survey strip, and also for operating under the ScanSAR mode (*Radiolokatsionnye sistemy zemleobzora*..., 2010; Zakharov et al., 2011).

STANDARD MODES OF SYNTHETIC APERTURE RADAR OPERATION

For solving several user problems, the following modes of operation are implemented in the SAR: (1) detailed Spotlight (DSL) with maximal resolution with RLI in the form of terrain image, (2) detailed

Table 1. Performances of Condor-E and its SAR

Performances of Condor-E	
Parameters of operating orbit: (i) altitude, km (ii) inclination, degree	 500 74
Mass, kg	1000
Information rate, Mbit/s	250
Frequency range	X
Lifetime, years	5
Performances of SAR placed onboard the Condor-E	
Frequency range	S
Mass, kg	300
Width of scanning band, km	2 × 500
Capture range, km: (i) spotlight (ii) stripmap (iii) scanSAR	 10 × 10 10–15 20–120
Resolution, m: (i) detailed Spotlight (ii) detailed Stripmap (iii) scanSAR	 1–2 1–3 6–12
Roll viewing angle range, degree	±20°–55°

Stripmap (DSM) with a high resolution for surveying the route with RLI in the map strip, and (3) ScanSAR with mean resolution on the base of wide-capture survey of map strip. The main performances of the SAR are presented in Table 1 (*Radiolokatsionnye sistemy zemleobzora*..., 2010; *Radiolokatsionnye sistemy vozdushnoi*..., 2008; Afanas'ev, 2013, 2015). Figure 1 presents schemes of SAR operation under all modes of survey.

Figures 2–4 depicts examples of radio-location images formed in all three modes of survey. All radiolocation images are presented in "incline diagonal (over horizontal)–azimuth (over vertical)" coordinates without geometrical and radiometrical corrections.

Figure 2a depicts the radio-location image of a naval base. The enlarged radiolocation and optical-electron images (OEI) of several objects are shown for comparison. Figure 3 depicts a fragment of a radiolocation image with a coastline and with an airdrome. The radio-location image is formed in the detailed Spotlight (DSL) mode of operation with a resolution of 2–3 m over both coordinates.

Figure 4 depicts SAR operation under the ScanSAR mode. Here the RLI consists of 20 partial frames (5 over azimuth and 4 over distance). Partial frame joints over azimuth are practically invisible. In the left top there is a note in larger scale.

Capabilities of SAR of X- and S-Ranges of Spacecrafts TerraSAR and Condor-E

It is interesting to compare the capabilities of the SAR placed onboard the Condor-E with a typical variant of modern space-based SARs in orbits now. The most promising sample of such a SAR is TerraSAR-X, which, jointly with SAR TanDEM, forms a bistatic pair and, in nearest future, the TerraSAR-L SAR can be added to them (*Radiolokatsionnye sistemy zemleobzora*..., 2010).

The TerraSAR-X SAR (Germany) was launched on June 10, 2007, onto a solar-synchronized 514-km orbit (limits 505–533 km) with an inclination of 95.7° by the Dnepr carrier rocket (Russia). The period of orbit repetition is 11 days, and the resurvey interval is 2.5 days for 95% of the Earth surface. The concept of SAR generation is based on SSCs with a mass of 250 kg launched by Dnepr and Rokot. Solar arrays generate 800 W per turn. An active-phased antenna (APA) is used as an antenna system in TerraSAR-X. The APA consists of 12 sections including 384 send–receive modules. Signal digital converting with the help of a one-of-eight analog-to-digital converter by using block adaptive quantization (BAQ) at the output of four, three, and two digit is used in SAR. The main performances of the spacecraft and TerraSAR-X are presented in Table 2.

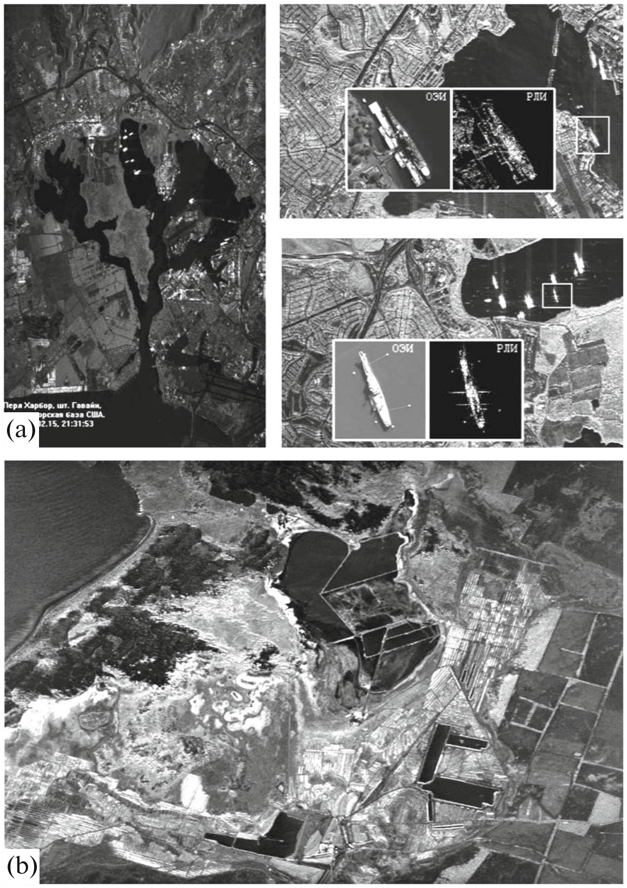


Fig. 2. (a) DSL, Pearl Harbor, United States, on the left from a radio-location image of separate objects, their optical-electron images are presented; (b) DSL, Penang, South Australia, initial resolution is 1 m.

It is seen that Condor-E and TerraSAR-X SARs are similar. In particular, both SARs were placed on SSCs and launched at approximately same (500 km) orbits. Both SARs are characterized by the same collections of modes with close space resolutions. But there are many differences between Condor-E and TerraSAR-X SARs. Among the principle differences, the main ones are as follows: different radiowave bands (TerraSAR has an X band and Condor-E has an S band) and different antenna-system generation (TerraSAR has an APA and Condor-E uses a hybrid scheme) (Osipov, et al., 2004, 2006; Neronskii, 2011).

The field of application of remote-sensing information collected by TerraSAR-X is declared as follows:

(1) generate and renew topographic and special maps up to M 1 : 1000;

(2) generate digital models for terrain relief with high accuracy (2–4 m over altitude);

(3) high-accurate monitoring of transport infrastructure (pipelines, railways, etc.), different buildings, and engineering constructions, etc.;

(4) estimate seismic danger and predict earthquakes and eruptions;

(5) all-weather monitoring natural and anthropogenic aftermaths (high water, earthquakes, anthropogenic emergencies, etc.);

(6) inspect shores and monitor ships;

(7) map crops and determine crop states;

(8) highly accurate agriculture;

(9) map forests, determine tree types in forests without on-ground examination, deforestation, and forest-state monitoring;

(10) control urban environments;

(11) secure defense and safety.

If we compare only the standard modes of radiolocation mapping, we can say that SAR performances of Condor-E and TerraSAR-X are similar. The Condor-E SAR meets all mentioned fields of application. Figure 5 depicts radio-location images orientated directly to this list.

Table 2. Generalized parameters of TerraSAR-X mode of operation

Mode/Parameter	Experiment $\Delta f = 300$ MHz	High Res. Spotlight	Sliding Spotlight	StripMap1	StripMap2	ScanSAR
Resolution, m (i) distance (ii) azimuth	 0.6–1.5 1	 1.2–3 1	 1.2–3 2	 3 3	 3 6	 16 16
Noise equivalent (NE), σ_{0NE}, dB		–19	–19	–19	–19	–19
Radiometric resolution, dB		1.5–2.7	1.5–2.7	1.5–3.1	1.5–3.1	1.5
Incident angle range, degree, $\Theta_1 \ldots \Theta_2$		20–55	20–55	20–45	20–45	20 – 45
Capture range (frame size), km	10 × 5	10 × 5	10 × 10	30 × up to 1650	30 × up to 1650	Four bands 100 × up to 1650

Fig. 3. DSM, Auckland, New Zealand, airport. Initial resolution is about of 2–3 m.

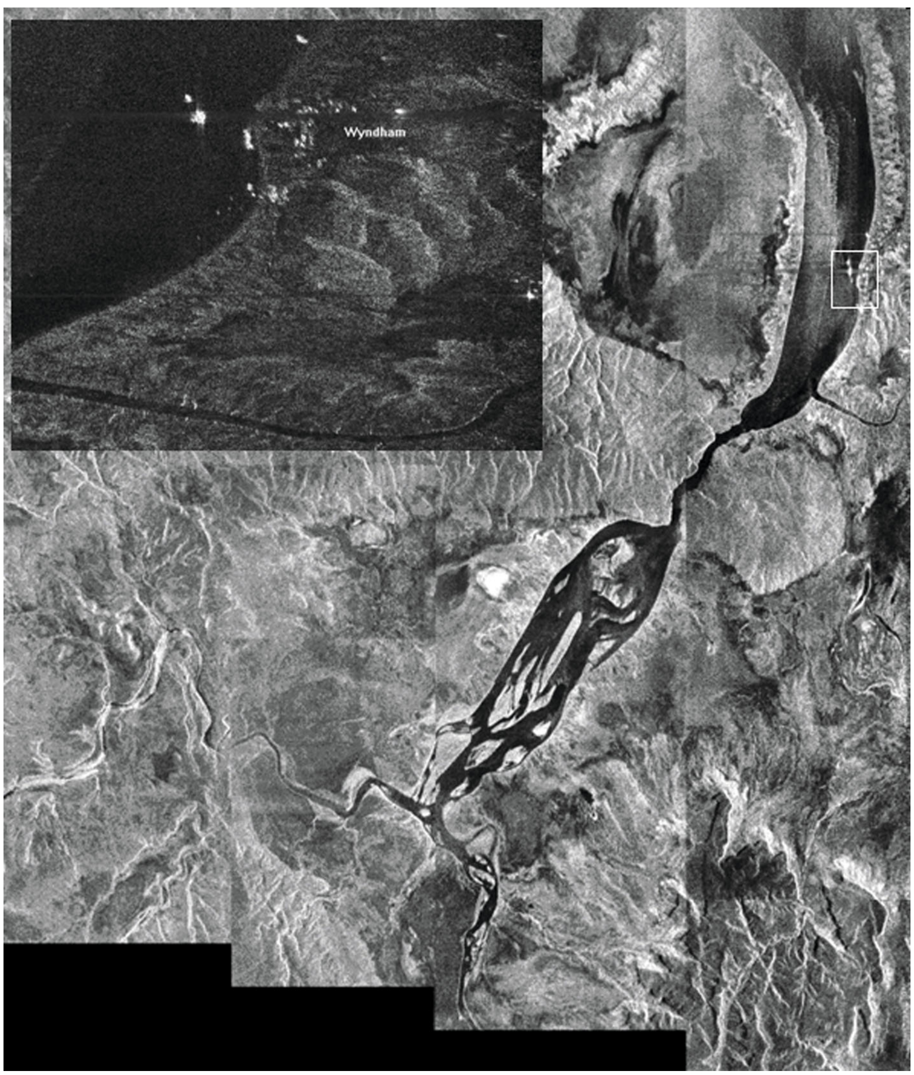


Fig. 4. SM, terrain near Wyndham, Western Australia. Initial resolution is higher than 3 m over distance and of about 10 m over azimuth.

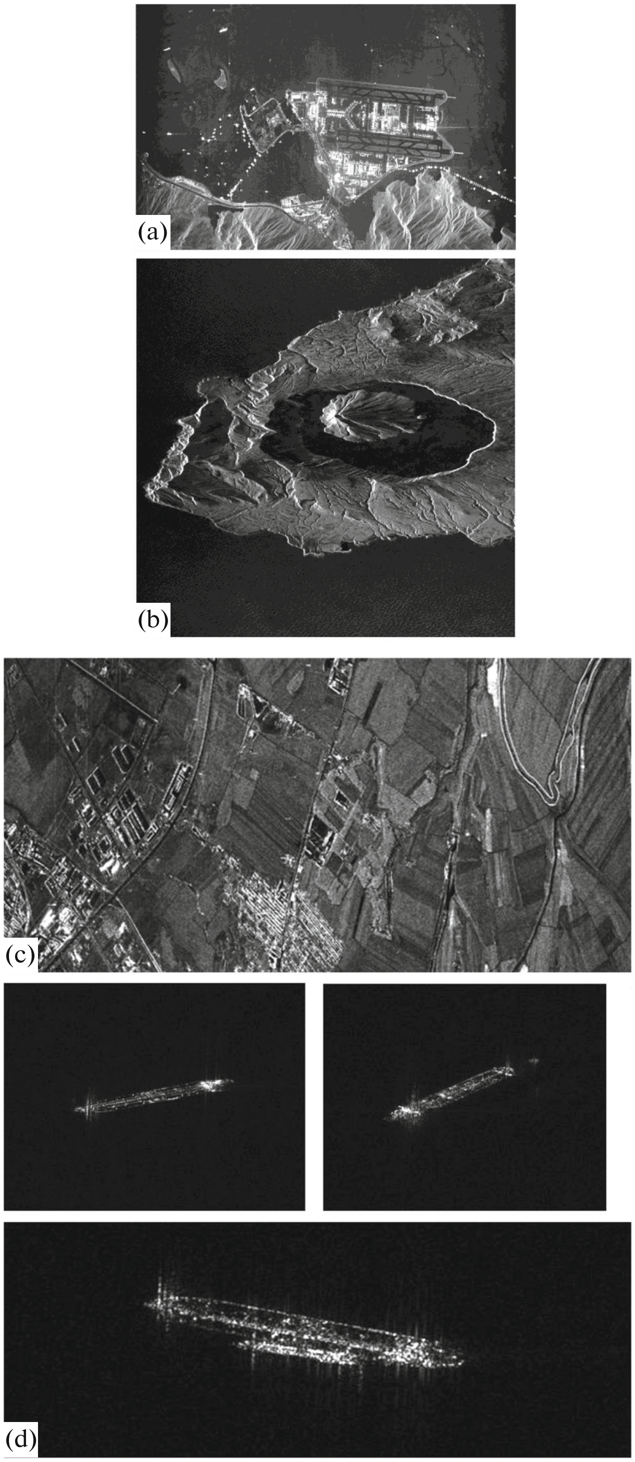


Fig. 5. Examples of radio-location images: (a) airport, Hong Kong; (b) volcano, Kurile Islands (lake Kol'tsevoe); (c) infrastructure fragment, Brisbane, Australia; (d) cargo ship in the sea.

The main performances of the Condor-E SAR are verified by flight tests and presented in Table 3.

It is necessary to point out that the SAR range of action is close to 1000 km, the coverage width is approximately 600 km, and the width of capture band of one scanning mode is 100 km.

Under DSL mode, the resolution over the incline distance is 0.75 m; on the Earth, by considering noncoherent accumulation, it ranges approximately from 2 down to 1 m. SAR performances under DSM mode are close to performances under DSL mode (see differences in Table 3).

Under the ScanSAR mode, three bands of probing signal can be used: 30, 50, and 200 MHz (respectively, modes SM30, SM50, and SM200). It is also possible to set the required spatial resolution or the capture band width (the number of bands over distance). Naturally, in this case a certain combination of these values is implemented. For example, the SM50 scanning mode is characterized by an initial resolution of 3 m over the azimuth and over distance. After resolution noncoherent accumulation, it becomes close to 12 m over both coordinates; the efficient noise equivalent (ENE), i.e., the noise equivalent by considering noncoherent accumulation (Zakharov, et al., 2011; Denisov, et al., 2014), ranges from –31 dB up to –26 dB and the radiometric resolution decreases down to 2 dB. The capture bandwidth in scanning mode runs up to 100 km. Detailed information is presented in Table 3.

One position in the list of applications, in particular, to generate digital models for terrain relief, in Condor-E and TerraSAR-X SARs is initially supported only by a two-pass variant of interferometry (which is difficult for implementation). At this point the situation has changed drastically.

Experimental Modes

The TerraSAR-X was launched into orbit in 2007, and this should be taken into consideration in the comparison. In 2010 the TanDEM radio-location station was added to the TerraSAR-X SAR, forming a bistatic pair that makes it possible to implement a highly accurate bistatic interfometric estimation of terrain relief.

Recently, specialists have noted that new modes of TerraSAR have appeared: the Staring Spotlight (ST) Mode, in which it is possible to form a radio-location image with an azimuth resolution of 24 cm, and the Wide ScanSAR Mode, supporting a capture band of about 200 m a under spatial resolution of 6–8 m over distance and 40 m over azimuth (Moreira, 2013), (Breit, et al., 2014).

At the same time, the theory of synthetic aperture has developed quickly. Currently, problems of interferometric and polarimetric processing, selection of moving target (SMT) and surfaces, and bistatic synthetic aperture can be looked at completely differently. In particular, in the Condor-E SAR, it was possible to test (Babokin, et al., 2014) the modes of single-passing inerferometric estimation of terrain relief (Fig. 6) and of

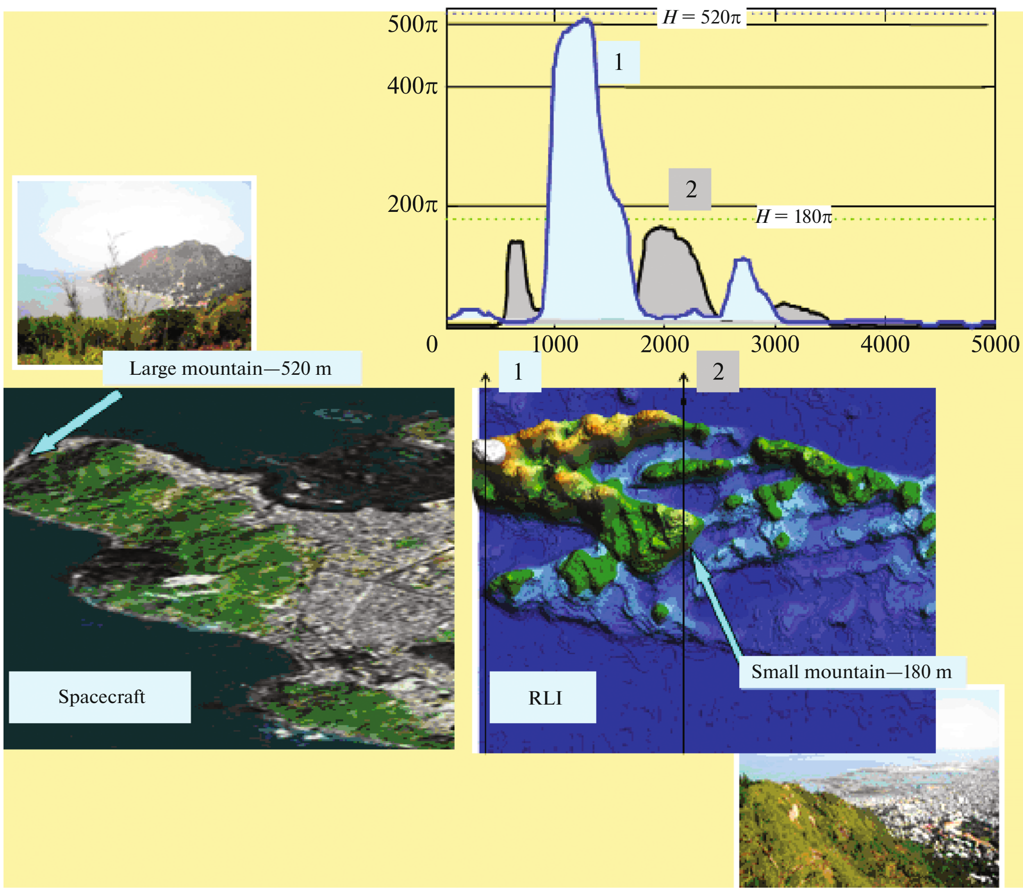


Fig. 6. Spacecraft optical image and the restored relief of a mountainous terrain near Ho Chi Minh City (Vietnam).

moving target selection (Babokin and Tsvetkov, 2012; Karpov and Tolsov, 2009).

Figure 6 presents optical-electron images of the terrain surface near Ho Chi Minh City (Vietnam) obtain by the spacecraft and pictures of a radio-location model (Digital Elevation Model) of the terrain relief with two cross sections. Radio holograms of the Condor-E SAR are formed under single-passing anterior lateral scanning and, after that, subjected to interferometric processing (Babokin, et al., 2014).

Figures 7a and 7b depict SMT capabilities (over tangential velocity) (Babokin and Tsvetkov, 2012). In principle, we prefer speaking about moving-object identification to speaking about selection since, during selection, the problems of detecting object motion and problems of determining radial and tangential veloci-

Table 3. Generalized parameters of operation for Condor-E SAR

Mode/Parameter	DSL	DSM	SM30	SM50	SM200	SM200 5 bands
Resolution, m (i) distance (ii) azimuth	 2...1 1	 2...1 3	 14...12...5.5 12	 8...12 12	 10...12 12	 12 18
NE ENE	−25...−20...−14 −30...−22	−25...−21...−14 −27...−20	−33...−25	−31...−25...−20 −33...−26	−25...−14 −35...−28	−25...−14 −35...−28
Radiometric resolution, dB	2.5	2.2...3	3.0...1.4	3...2	1.8...1.6	1.8...1.6
Inclination angle range, degree	20...38...55	20...37...55	20...55	20...40...55	20...55	20...55
Capture band (frame size), km	frame 10 × 10...15 × 30	band 10...15...30	band 30...100	band 30...100	band 30...100	band 50...150

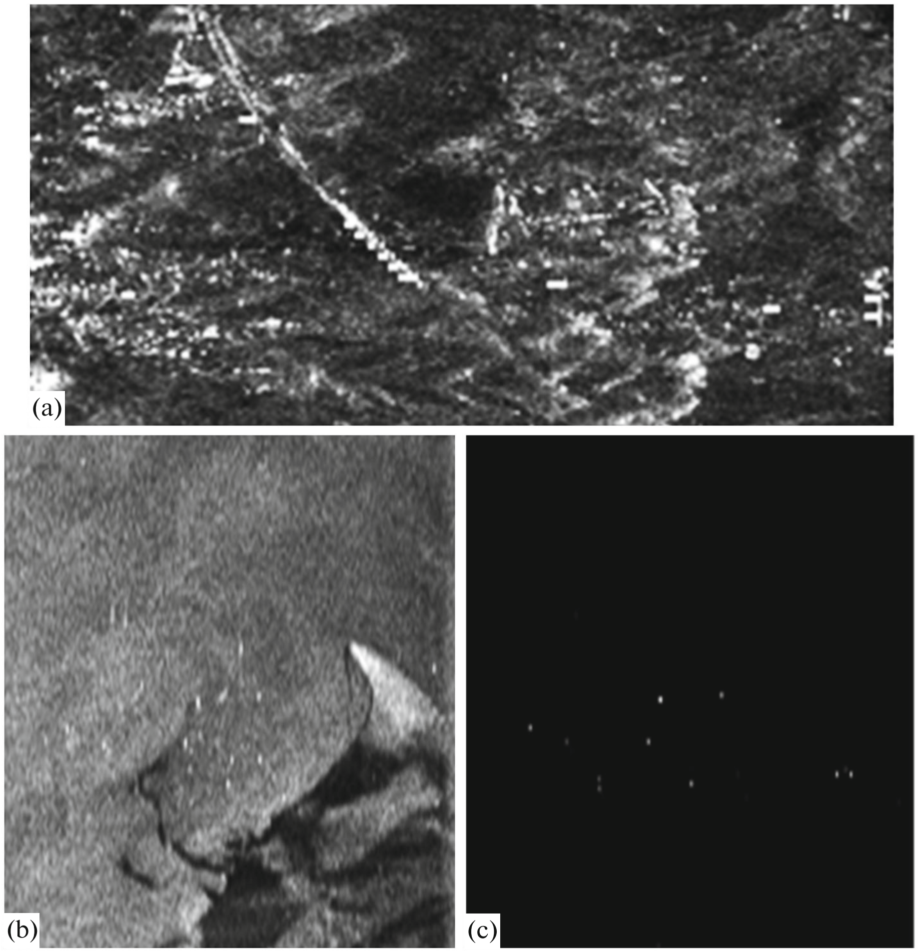


Fig. 7. Results from detecting moving objects on the background of a radio-location image: (a) land and (b) sea.

ties of a moving object and of setting the object mark into a true position over azimuth in SAR are solved.

Many characteristics are required for completely describing SAR capabilities under mapping. The main characteristic is the coverage range, size, and quality of the radio-location image. The most capacitive characteristics of radio-location image, speaking about the design level of SAR under a sufficient dynamic range, are as follows: (1) spatial resolution, (2) radiometric sensitivity (noise equivalent (NE)), and (3) the radiometric resolution (RR). Let us recall that the noise equivalent is such a specific EPR (SEPR) of statically uniform reflected terrain under which the signal power at SAR output is equal to the power of internal noise. The radiometric resolution (dB) is the difference in the SEPR of terrain segments, which is required for their recognition in radio-location images. We compare information presented in Table 2 and Table 3, and we can conclude that performances of Condor-E and TerraSAR-X SARs are similar.

All characteristics of SAR modes presented in Table 3, including radiometric resolution, are common and transparent. Maybe it is necessary to clarify how radiometric resolution influences the radio-location image, in particular, because there are many approaches for calculating radiometric resolution (Zakharov, 2011; Karpov and Tolsov, 2009; Ulaby et al., 1982, 1986; Frost, 1984; Yongtan, 1999; Ge et al., 2004; Neronskii et al., 1999). Radiometric resolution calculations presented in Fig. 10 are based on the traditional variant (Ge et al., 2004; Neronskii et al., 1999).

The role of radiometric resolution can be illustrated using the example of the ST SAR TerraSAR mode. The theoretically determined relationship between radiometric resolution and the number of incoherent accumulations is presented in Fig. 8. It can be seen that the radiometric resolution depends on which level of SEPR with respect to the noise equivalent the measurement is performed at. That is why, for determinacy, the SEPR level with respect to which the radiometric resolution is calculated is set. Figure 8 depicts three curves: for a SEPR equal to noise equivalent and for a SEPR 10 and 100 times higher than the noise equivalent. Usually radiometric resolution is counted from the bottom curve (Ge, et al., 2004).

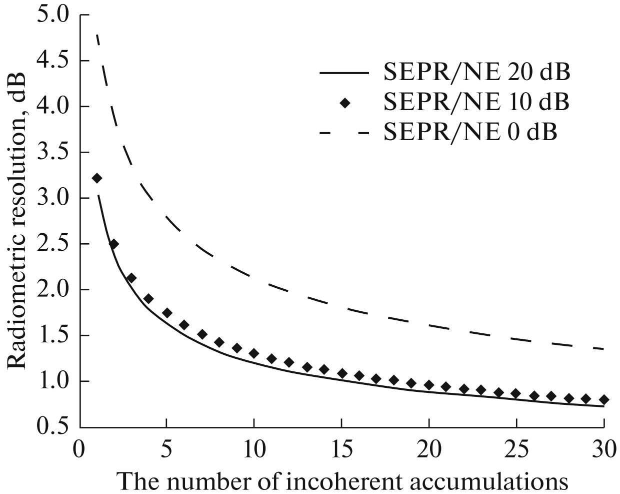


Fig. 8. Relationship between radiometric resolution and the number of incoherent accumulations.

Figure 9 depicts two radiometric resolutions (Breit, et al., 2014) formed in the frames of High Res. Spotlight SAR TerraSAR corresponding (over spatial resolution) to the DSL SAR of Condor-E. However, these two radio-location images are of different quality. One of them (on the left) is formed under the standard mode without incoherent accumulation. The other (on the right) is formed in the frames of experimental mode ST with spatial resolution over azimuth approximately 5 times higher than it is under the standard mode. Such a procedure makes it possible to perform five incoherent accumulations. The quality of radio-location image increases because the radiometric resolution increases (see conditions above) approximately from 3 up to 1.7 dB. This improvement can be seen in Fig. 9 (on the right). The improvement is so high that the terrain fragments and objects that were invisible earlier become visible, and the clear shadows of the objects, in particular, of the aircrafts, to which in the left picture we see only references, become clear. It is a result of incoherent accumulations and radiometric resolution improvement by approximately 1.3 dB. It is absolutely evident that the same procedures can be used also in the Condor-E SAR. Moreover, if we use interperiodical spectrum spreading in the SAR (Karpov, 2005), it becomes possible to improve the resolution over azimuth and increase the resolution over the incline distance by at least two times.

We analyze the main performance of Condor-E and TerraSAR-X SAR and we reveal that they are commensurable. If we examine the problem in detail, including the experimental modes, it becomes possible to see that, under standard modes, the resolution over distance in the SAR of Condor-E is better due to the wide spectrum of signal probing, and in the SAR of TerraSAR-X the capture band is wider in StripMap Mode (DSM mode in SAR of Condor-E), since the antenna size over vertical is lower. The Sliding Spotlight mode in the SAR of TerraSAR is introduced for spreading the frame of radio-location image up to 10 × 10 km which, due to the narrowness of the directional pattern over azimuth in High Res. Spotlight mode is difficult. In the SAR of Condor-E, this is not necessary, since the directional pattern over azimuth is sufficiently wide. And, finally, the experimental modes of both SARs are promising for both.

Returning from experimental modes to standard ones as the most important for practice, it is necessary to mention that radio-location images obtained with the help of the SAR of TerraSAR in X range and radio-location images of the same objects formed in the

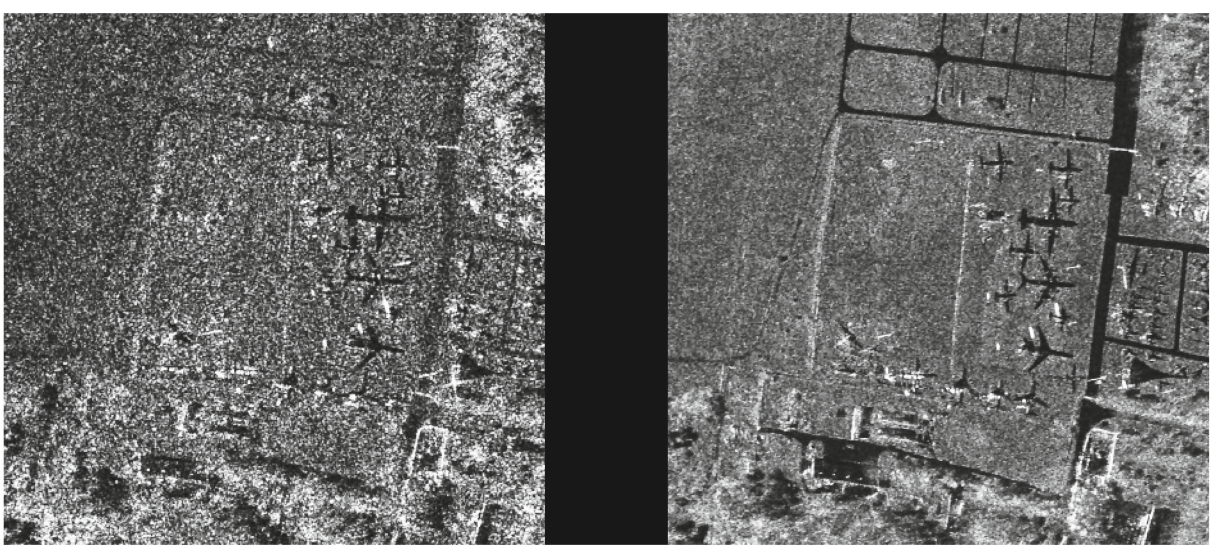
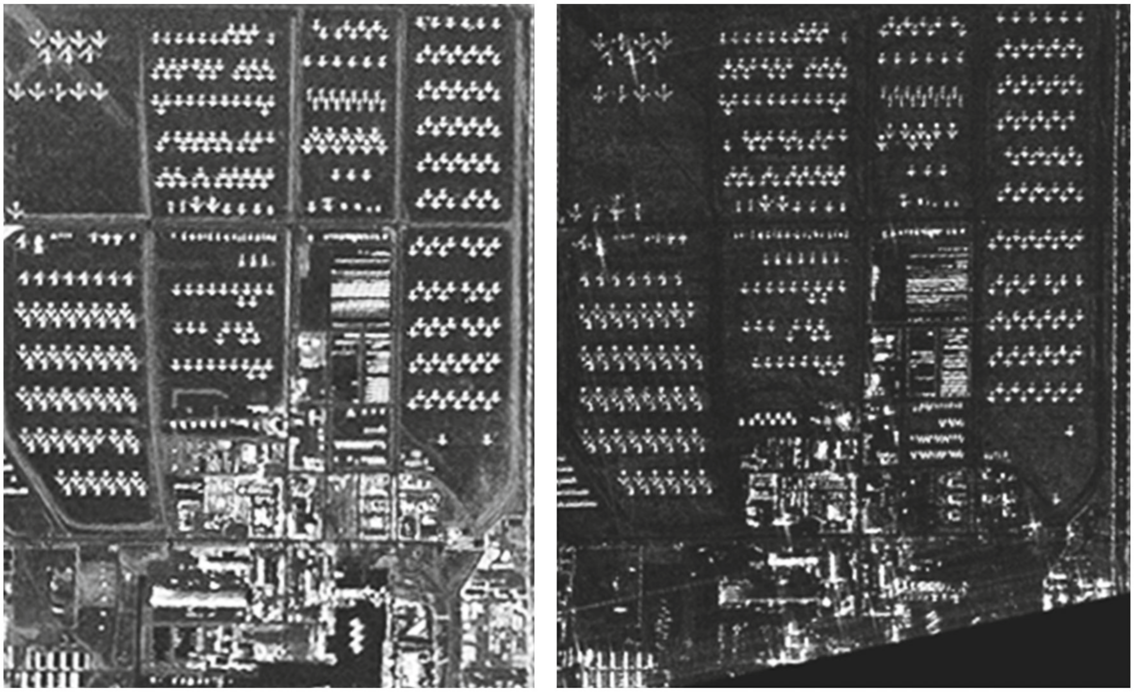


Fig. 9. Radiometric resolution improvement from 3.0 up to 1.7 dB after five-time incoherent accumulations.



SAR of spacecraft TerraSAR-X, SL PSAR of Condor-E, DSL

Fig. 10. Image of Davis–Monthan Air Force Base (Tucson, United States) obtained by TerraSAR-X and Condor-E, initial resolution is about of 1 m.

frames of Condor-E SAR in S range are similar. Figure 10 depicts radio-location images of the Davis-Monthan Air Force Base. It is necessary to point out that, under S-range, the terrain background is weakened and propagation in dense mediums is seen.

CONCLUSIONS

Summarizing all the above, we can say that a space SAR with performances corresponding to foreign ones have been designed and launched in Russia. In addition, it is possible to improve these SARs without hardware improvements not only to improve the standard-mode parameters, but to introduce new modes of operation, including interferometric ones.

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