Information characteristics of an orbital side-scan synthetic aperture radar

Oleg Chernoyarov1*, Vladimir Ivanov1, Elena Chernoiarova1, and Yuliya Litvinenko2

1National Research University “MPEI” Department of Electronics and Nanoelectronics, 111250 Moscow, Russia
2Voronezh State Technical University Department of Computer Aided Design and Information Systems, 394026 Voronezh, Russia

Abstract. Ratios are given for estimating the amount of information in the channels of sensing and data transmission of the orbital synthetic aperture radars (SAR) based on information-theoretic and statistical methods. They are presented in terms of the indicators characterizing the amount of information received about the state of the object of observation. It is shown that the sensing channel should use significantly redundant information in relation to the final result of radar observation. On the example of the SAR of the "Venera-15" and "Venera-16" spacecrafts, the specific conditions of an orbital radar imaging are illustrated, and its informational characteristics are given for both methods of transmitting observation data. The qualitative consideration carried out in the paper makes it possible to estimate the potentially achievable reduction in the amount of information in the data transmission channel when using onboard SAR signal processing under specific radar imaging conditions.

1 Introduction

The orbital synthetic aperture radar (SAR) is a powerful remote sensing tool. The initial product formed by a SAR is constituted by complex digital samples of a radio hologram (the signals reflected from the surface), which are transmitted via a radio data transmission link to a ground reception station for digital processing and obtaining a radar image in the form of a radio-brightness “mosaic” [1, 2].

A distinctive feature of orbital SARs is the large extent of the imaging area. Combined with a wide capture area and high resolution over the observed surface, it results in a huge amount of data that must be transmitted to a ground receiving station via a digital radio link. The task of transferring such data arrays to the Earth is complicated for orbital SARs used for radio mapping of other planets in the Solar system due to the low bandwidth of deep space radio links [3].

To overcome the limitations in the bandwidth capability of the radio link for data transmission to the Earth, the onboard equipment of orbital SARs uses radio hologram compression (for example, by the BAQ method, which is block adaptive quantization) [4]. In particular, in the radar system for probing the surface of Venus, due to the lack of...
bandwidth capability of the radio link of the “Magellan” spacecraft, the orbital SAR data acquisition scheme is used in batch mode and the data is passed through a digital filter, which reduces the data transfer rate, but does not degrade the image quality [5].

Another approach to reducing the amount of information in the data transmission channel is the processing of a radio hologram by means of the SAR onboard equipment. This technique was first used in radar imaging of the surface of Venus with the help of automatic interplanetary stations “Venera-15” and “Venera-16”. In the equipment of these stations, when extracting the components of the reflected SAR signal, delay compression and unfocused aperture synthesis were performed. The transmission of the obtained radar image to the Earth made it possible to reduce the flow of scientific information in the data transmission channel by several times [6, 7]. Embedded processing, which will reduce the amount of images and data transmitted over the radio link to the Earth, is provided in the orbital interferometric synthetic aperture radar VISAR (Venus Interferometric Synthetic Aperture Radar), whose mission to Venus is planned by NASA in 2027 [8].

The amount of SAR scientific data transmitted over the radio link depends on its informational content. In the present study, its comparative estimation in a radar image in the channels of sensing and data transmission of orbital SARs is carried out based on statistical [9, 10] and information-theoretic [11, 12] methods that characterize the amount of information obtained about the state of the object of observation, which is mapped surfaces in our case.

2 Basic relationships in surface scan by synthetic aperture radar

The informational content of the radar image obtained by scanning the surface with a SAR is determined by the following main parameters: linear resolution on the surface $\delta_s$, the area of the simultaneously synthesized image $S$, the dynamic resolution $\delta_d$, the dynamic range of radio brightness of the resolution elements $L_d$ and the energy signal-to-noise ratio for a single element $q$.

The required linear resolution $\delta_s$ determines the choice of the effective spectrum width $\Delta F_s$ of the probing signal and the synthesis time $T_s$ in accordance with the ratios [1]:

$$\Delta F_s \approx c/\delta_{sz} \quad \psi \quad \lambda D/\delta_{sy} \quad T_s \approx \lambda D/\delta_{sy}$$

where $c$ is the speed of propagation of radio waves; $\delta_{sz}$ is the resolution in the plane sight; $\delta_{sy}$ is the resolution along the flight path (the azimuthal resolution); $\psi$ is the average angle of sliding of the probing beam relative to the surface; $\lambda$ is the operating wavelength; $D$ is the average radial range to the surface elements; $\nu$ is the linear velocity of the SAR carrier.

The limiting area of a simultaneously synthesized radar image is determined by objective time-frequency ratios for a coherent radio signal. With a periodic probing signal having a repetition period $T_r$, the condition must be satisfied:

$$T_r \Delta F_r \leq$$
where $\Delta f_d \approx v \Delta \theta / \lambda$ is the spectrum width of the Doppler frequencies in the reflected signal, and $\Delta \theta$ is the width of the directional pattern of the actual antenna in a azimuthal plane. At that

$$S \leq c \lambda D / \sqrt{\delta x \delta y \psi}$$

and the number of the resolution elements in the image (when $\delta_{sz} = \delta_{xy} = \delta_z$) is

$$m = \delta_x / \delta_z \leq c \lambda D / \sqrt{\delta_x \delta_y \psi}$$

Dynamic resolution (the contrast or radio brightness sensitivity) $\delta_d$ is determined by fluctuations in the signal level caused by random interference conditions during reflection, and is understood as an increment of the average intensity of the signal reflected by the resolved element. It is in fact an increment of the specific effective scattering area, and it can be observed with the necessary reliability. Its value is limited by the residual level of fluctuations in the processed signal and is often assumed to be equal to the relative effective value of these fluctuations, expressed in decibels. In turn, residual fluctuations are caused by the random nature of the reflections from the element as an extended target (the so-called “speckle noise”) as well as by an uncorrelated noise at the output of the receiving device. The required value $\delta_d$ is achieved by repeated probing of the captured surface area, allowing averaging to smooth out the “speckle noise” by superimposing several independent images. In most cases, these independent images are obtained by interperiod processing of the received signal. For the total time of observation of the signal $T$, it is customary to use an approximate formula to estimate the value of $\delta_d$ [13, 14]:

$$\delta_d \approx \sqrt{\delta_x \delta_y \psi} / \sqrt{N} \approx \sqrt{\delta_x \delta_y \psi} / \sqrt{N}$$

where $N$ is the number of images synthesized over the time $T$, while $q$ is the ratio of the average signal power to the noise power.

Formula (5) shows in particular that the energy characteristics of the radio channel during radio observation through the SAR specifically affect the effectiveness of radio observation. An increase in the signal-to-noise ratio from above $q$ practically does not affect the value of contrast sensitivity, which in this case is approximated equal to

$$\delta_d \approx \sqrt{\delta_x \delta_y \psi} / \sqrt{N}$$

The dynamic range of radio brightness $L_d$ is determined by the mutual influence of the signals reflected by various resolution elements, thus characterizing the effect of masking weak reflections with stronger ones. The numerical expression of $L_d$ depends on the tasks of radio observation. In radio mapping, the ratio of the statistically average intensity of the useful signal at the output of the corresponding processing channel to the intensity of the interfering signal with the same scattering cross-section (SCS) can be taken as a measure of the dynamic range of radio brightness.

The signal-to-noise ratio in the resolution element $q$ is determined by the energy characteristics of the SAR radio channel and is further considered to be given.
The main feature of a radar imaging from the orbit of a spacecraft is the need to limit the use of the area $S$ of the synthesized image, since thus the maximum value of one of the most important indicators of the effectiveness of radio observation of the surface – the width of the imaging area – is achieved. Such a scan mode can be considered as matched with the sensing radio channel. Matching is achieved by the appropriate choice of the directional pattern of the actual antenna, the sliding angle $\psi$ and the parameters of the probing signal.

3 Estimation of the amount of information in the SAR sensing and data transmission channels

The SAR radio line includes a sensing channel and a data transmission channel for radar observation. The information of the sensing channel is contained in a radio signal reflected from the surface, which can be represented at the synthesis interval $T_s$ by the independent two-dimensional normal samples $\xi_j = \{c_j | s_j\}$ taken with the time step $\Delta t = \Delta F_s$. In the matched scan mode, the number of signal samples $K = \Delta F_s T_s$, in accordance with (1), (4), coincides with the number of resolution elements $m$ on the surface. Accordingly, the average energy signal-to-noise ratio with respect to the reproduced SAR samples $\xi_j$ coincides with $q^2$. The amount of information $I(\xi_j | \xi_i)$ in $\xi_j$ should be determined from the ratio [15]:

$$
I(\xi_j | \xi_i) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{w(\xi_j | \xi_i)}{w(\xi_j)} \xi_j \xi_i \, d\xi_j \, d\xi_i
$$

where $w(\xi_j | \xi_i)$, $w(\xi_j)$, $w(\xi_i)$ are the joint and proper distributions of $\xi_j$ and $\xi_i$, and the logarithm to the base 2.

With a sufficiently large number of resolution elements in the observation area, it is permissible to consider the distribution of signal samples as normal. For the normal distributions of $w(\xi_j | \xi_i)$, $w(\xi_j)$, $w(\xi_i)$ and the specified $q^2$, one can obtain [16]:

$$
I(\xi_j | \xi_i) = \log \left(1 + q^2\right)
$$

The total amount of information about the reflected signal in the case of $n$-multiple probing of the same section $S$ can be found as:

$$
I_s = mn \log \left(1 + q^2\right)
$$

The information of the data transmission channel received during radar observation and with the on-board processing involved is contained in the radar image. The construction of a radar image consists in the selection of the signals reflected by individual resolution elements by means of the matched filtering with a consequent estimation of their intensity. Such filtering carried on each of the $j$-th $T_s$ interval results in $m$ pairs of independent quadrature normal samples.
In this case, the likelihood function of the intensity \( \zeta_l \) takes the form

\[
w(z_i | \zeta_l) = \frac{1}{(\pi)^{n/2} \zeta_l^n} \exp \left[ -\frac{1}{\zeta_l} \sum_{j=1}^{n} (x_{ij} + y_{ij}) \right].
\]

The maximum likelihood estimate \( \hat{\zeta}_l \) for \( \zeta_l \) is equal to

\[
\hat{w}(z_i | \zeta_l) = \frac{n^n}{(n-1)\zeta_l} \hat{\zeta}_l^{n-1} \left( -\frac{\hat{\zeta}_l}{\zeta_l} \right).
\]

Introducing the new variables \( u_l = \log \zeta_l \) and \( \hat{u}_l = \log \hat{\zeta}_l \), one gets the following for the conditional distribution \( w(\hat{u}_l| u_l) \):

\[
w(\hat{u}_l| u_l) = n^n \left[ n(\hat{u}_l - u_l) \right] \left[ -n \left( n(\hat{u}_l - u_l) \right) \right] / (n-1).
\]

Quadratic approximation of \( w(\hat{u}_l| u_l) \) near \( \hat{u}_l = u_l \) results in:

\[
w(\hat{u}_l| u_l) \approx \sqrt{n} \left[ -n(\hat{u}_l - u_l) \right] \sqrt{n} / \sqrt{\pi}.
\]

Thus, the conditional distribution appears to be normal with the mathematical expectation \( \bar{u}_l = u_l \) and the dispersion \( \sigma^2 = \sqrt{n} \), which is a measure of the dynamic resolution \( \delta_d \).

On the assumption of the normal distribution of \( u_l \) one gets

\[
w(u_l) = \frac{u_l}{\sqrt{n}} / \sigma_u \sqrt{\pi},
\]

where \( \sigma_u \) characterizes the dynamic range of radio brightness of the surface elements \( L_d \), and then the amount of information in \( \hat{u}_l \) relative to \( u_l \) is equal to [15]

\[
I(\hat{u}_l| u_l) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} w(\hat{u}_l| u_l) w(u_l) \frac{\hat{w}(\hat{u}_l| u_l)}{w(u_l)} d\hat{u}_l du_l = \frac{1}{\sigma_u \sqrt{\pi}} \left( 1 + n\sigma_u^2 \right).
\]
The total amount of information in the radar image frame relative to the plane $S_i$ constitutes

$$I_p = m \log_2 (1 + n \sigma_u)$$

and it is sufficiently less than the amount of information in the signal $I_s$ in common conditions of the orbital observation.

Based on these ratios, one can find out quantitative estimates of the gain obtained when transmitting or registering the processed signals of radar observation results in comparison with the direct transmission (registration) of the received radio signal samples that remains the standard method of maintaining the data transmitting radio channel at the modern orbital SARs:

$$I_s / I_p = n \log_2 (1 + q^2) / \log_2 (1 + n \sigma_u)$$

### 4 Numerical results

In Fig. 1a, the dependence (9) of the total amount of information $I_s$ about the reflected signal upon the signal-to-noise ratio $q^2$ in the case of $n$-multiple probing of the same sector $S$ is shown.

![Graphs](image)

**Fig. 1.** The dependences of the total amount of information about the reflected signal (a) and the total amount of information in the frame after on-board processing (b).

It follows from Fig 1a that the amount of information in the sensing channel increases with the signal-to-noise ratio $q^2$ and the number of independent synthesized images $n$, which hereafter takes values from 2 to 8. The total amount of information in the frame $I_p$...
(17) after on-board processing increases with the dynamic range of radio brightness of the resolution elements $L_d$ and the number of independent synthesized images $n$ (Fig. 1b). The dependencies of $I_s/I_p$ in Fig. 1a and Fig. 1b are normalized in the terms of the number of $m$ resolution elements in the radar image.

Fig. 2 demonstrates the gain (18) in the amount of transmitted information $I_s/I_p$ when using on-board processing, depending on the dynamic range of radio brightness of the resolution elements $L_d$ and the number of independent synthesized images $n$ for two values of the ratio of the average signal power to the noise power. These values are $q^1 = q$ (Fig. 2a) and $q^2 = q$ (Fig. 2b).

The dependences in Fig. 2a and Fig. 2b show that the use of on-board processing makes it possible to reduce the amount of transmitted information by $I_s/I_p$ times. As for the gain from the use of on-board processing, it increases with both the signal-to-noise ratio $q$ and the number $n$ of independent images synthesized during the time the element stay in the irradiation zone. The decrease in the dynamic range of radio brightness of the elements of the resolution $L_d$ also improves the gain.

Fig. 2. The dependences of the gain in the amount of transmitted information when using on-board processing: a) $q^1 = q$; b) $q^2 = q$.

Based on the results obtained, the information characteristics for both methods of generating radio observation data can be compared on the example of the SARs mounted on the spacecrafts “Venera-15” and “Venera-16” [2, 17]. They performed mapping of the northern part of the surface of the planet Venus in 1984-1985. A feature of these orbital SARs was the presence of on-board processing equipment capable of generating real-time samples of the radio brightness of the illuminated zone elements. That zone had a width of
about 130 km and a length of up to 8000 km with a surface resolution of no worse than 2.7×2.7 km. At the end of the 16-minute radar scan session, the radio brightness samples, together with the initial radio hologram and the results of the radio altimeter sensing, were transmitted to the ground station via a radio link at a speed of 100 kbit/s. The results of on-board processing received on Earth during the communication session were displayed on a video monitor for operational quality control of the radio hologram produced.

The conditions of the orbital radar scan carried out by the SARs of spacecrafts “Venera-15”, “Venera-16”: the ratio of the average signal power to noise power for a single element was $q^{-1} \geq 10^2$; the number of images synthesized during the time the element stay in the irradiation zone was $n = 8$; the dynamic range of radio brightness of the resolution elements according to the results of experimental studies of the reflectivity of the Venus surface for the field of view of 10°... 20° and at the wavelength of 8 cm was $L_d \leq 64$. According to Fig. 2, one can conclude that, under the specified conditions of radar imaging, the amount of transmitted information after on-board processing is reduced by 6 or more times.

5 Conclusion

A comparative estimate of the amount of information in the sensing and data transmission channels of orbital SARs in various conditions of radio observation can be performed based on the information-theoretic methods and using the indicators characterizing the amount of information received about the state of the object of observation. The obtained ratios show that significantly redundant information is used in the sensing channel in relation to the final result of radar observation. Although, as a rule, such indicators are not used as absolute characteristics due to the complexity of their practical interpretation, a qualitative examination of the information characteristics makes it possible to identify the relationship of the potential efficiency of on-board processing with such indicators as linear resolution on the surface, the area of the simultaneously synthesized image, dynamic resolution, dynamic range of radio brightness of resolution elements and energy signal-to-noise ratio for a single element. The amount of information as such a measure has the advantage that it is a generally accepted characteristic of the effectiveness of many radio communication systems.

The estimates of information characteristics for both methods of transmitting observation data carried out with the help of the SARs mounted on the “Venera-15” and "Venera-16" space crafts are confirmed by the results practically obtained in the conditions of orbital radar scan.

The qualitative review carried out in the present study makes it possible to estimate the potentially achievable reduction in the amount of information in the data transmission channel when using on-board processing of SAR signals in specific radar scan conditions.

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