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SPACE REMOTE SENSING SYSTEMS TRANSMISSION CAPABILITIES MODELING

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Summary

Space information, or information obtained by means of space remote sensing, is widely and effectively used by many countries to solve a lot of scientific, technical and applied problems.
Most manufacturers of space remote sensing systems declared the high resolution values of their systems. However, these values are computed theoretically, without considering the various factors affected them. To determine the real resolution of the system, we have considered mathematical modeling which describes the influence of different factors on the satellite images resolution. Some of these factors are: atmosphere turbulence, image shift, residual defocusing, and diffraction. One of the most important characteristic of the images resolution is the modulation transfer function (MTF) which allows the estimation of different factors affected on the image resolution.
The modulation transfer function (MTF) is a fundamental tool for assessing the performance of imaging systems. Various authors [Zhang et al. 2012, Hwang et al. 2008, Ryan et al. 2003] investigate different MTF assessment methods of high resolution satellite images: a slant-edge method, a knife-edge method, a sine wave method and a grill pattern. We propose a generalized approach for MTF assessment based on theoretical assumptions which allows to determine the influence of different factors.
A comparative analysis of the modulation transfer function(s) for different space imaging systems shows that the image resolution depends mainly on the atmosphere turbulence and size of a sensor element. Additionally, we established that atmospheric turbulence significantly reduces the transmitting possibility of images. The parameters which describe the influence of turbulence required additional studies.
The main goal of our researches is to show that real spatial image(s) resolution is much "inferior" than the value provided by the manufacturers of space remote sensing systems.

Keywords

space image • modulation transfer function • resolution

1. Introduction

Five National Space Programs [Бурштинська 2010] were adopted in the Ukraine to ensure the space activity. The First State Space Program (1993–1996) allowed to preserve the scientific and production potential of the space industry. The Second

National Space Program (1998–2002) was intended to create the regained space infrastructure based on existing structures and to provide the modernization of the Space Control Center. The Third National Space Program (2003–2007) was aimed at the implementation of special target programs. The Fourth National targeted Scientific and Technical Program (2008–2012) was aimed to ensure the development and effective use of Ukrainian space capabilities. These were to be in different fields such as: State defense, land management, ecology, education. And lastly, the Fifth National Space Program (2013–2017) is aimed at the development of space technologies and their integration into the national economy, security and defense. These programs were to lead to the implementation of space remote sensing, the development of space systems for telecommunications and navigation and space activities in the interests of national defense and security, scientific space researches.

Most manufacturers of space remote sensing systems gave us high resolution values of their systems, computed as a projection of the CCD-matrix element on the Earth's surface. These values do not include the influence of different internal factors which depend on such system parameters as: CCD-matrix resolution, the quality of the optical system, focus length, defocus and some external factors. These depend on the contrast of the objects, atmospheric transparency and image shifts, etc.

The Modulation Transfer Function (MTF) is the function which takes into account all these factors. This is the reason why the determination of the influence of different factors to the quality of space images is very important.

2. Methodology

One of the most important characteristic of the image(s) resolution is the modulation transfer function (MTF) [Кашкин 2001, Савиных 1997]. MTF describes the dependence of changes between the source contrast that has passed through the optical system and the contrast of the object(s) at different frequencies. This function allows us to separately consider each of the influence factors.

The expression of the resulting modulation transfer function is as follows [Живичин 1980, Кучко 1988, Фризер 1978]:

$$T_{\Sigma}(N) = K \cdot T_{tur}(N) \cdot T_{op}(N) \cdot T_{sh}(N) \cdot T_{def}(N) \cdot T_{dif}(N) \cdot T_{ph}(N) \tag{1}$$

where:
K – the contrast of objects, N – frequency (lines per millimeter), $T_{tur}(N)$ – MTF of atmosphere turbulence, $T_{op}(N)$ – MTF of optical system, $T_{sh}(N)$ – MTF of image shift, $T_{def}(N)$ – MTF of defocusing, $T_{dif}(N)$ – MTF of diffraction, $T_{ph}(N)$ – MTF of discrete photodetector.

The atmospheric turbulence:

To take into account the influence of atmospheric turbulence on the MTF, we used the expression [Савиных 1997]:

$$T_{tur}(N) \cong \exp\left(-2 \cdot \pi^2 \cdot \sigma_T^2 \cdot f_K^2 \cdot N^2\right), \tag{2}$$

where: f_k – focal length [mm], σ_T – the atmospheric turbulence constant (for favorable conditions of observation $\sigma_T \approx 10^{-6}$).

Image shift:

The contribution of image shift on MTF we used following equation:

$$T_{sh}(N) = \frac{\sin(\pi \cdot \Delta_{sh} \cdot N)}{\pi \cdot \Delta_{sh} \cdot N}, \tag{3}$$

where: Δ_{sh} is about 10–20% of the pixel size.

Residual defocusing:

The influence of residual defocusing can be described by formulae:

$$T_{def}(N) \cong \exp\left(-2.5 \cdot A_{def}^2 \cdot \left(\frac{f_k}{d_0}\right)^{-2} \cdot N^2\right), \tag{4}$$

where: A_{def} – shift of the focal plane due to residual defocusing [mm], $\left(\frac{f_k}{d_0}\right)$ – the denominator of the relative aperture.

Diffraction:

The influence of diffraction of the optical system modeled by equality:

$$T_{dif}(N) \cong 1 - 7.5 \cdot 10^{-4} \cdot \frac{f_k}{d_0} \cdot N, \tag{5}$$

Discrete sensor:

The influence of one element of the discrete sensor can be computed via expression:

$$T_{ph}(N) = \frac{\sin(\pi \cdot \Delta \cdot N)}{\pi \cdot \Delta \cdot N}, \tag{6}$$

where: Δ – the CCD pixel size [mm].

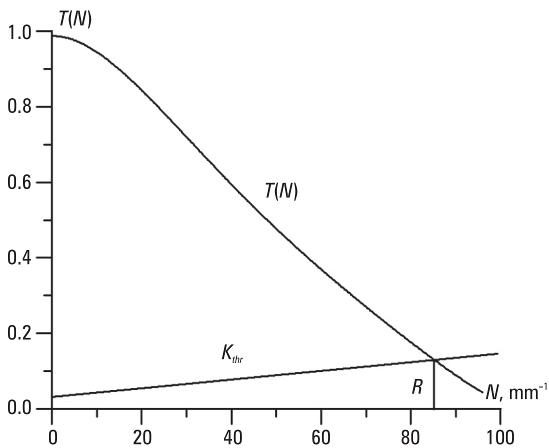
The total RMS (Root Mean Square) of noise in passed channel, expressed as optical density values has to be known to compute the threshold modulation curve $K_{thr}(N)$. For sensor of satellite IRS-1D, this information is given for panchromatic channel $\sigma_д^2 \approx 0{,}03 \div 0{,}05$. Noise for sensors of other satellite imaging systems is less compared to the system IRS-1D [Бурштинська, Долинська 2010].

The methodology described above was used to compute the spatial resolution and the modulation transfer functions for different imaging systems. For further computations, we used characteristics of satellite imaging systems, given in Table 1.

Table 1. Characteristics of Satellite Imaging Systems

No.	Satellite imaging system	Orbit height *H* [km]	Focus length *f* [m]	Relative aperture	CCD pixel size [μm]
1	Landsat-7	705	2.438	6.025	51.9
2	SPOT-4	832	1.082	3.500	13.0
3	SPOT-5	830	2.164	8.000	6.5
4	IRS-1D	817	0.975	5.600	7.0
5	Ikonos-2	681	10.000	14.285	12.0
6	OrbView-3	430	3.000	6.000	7.0
7	QuickBird-2	450	5.080	12.500	6.9
8	Eros-A1	480	3.500	10.000	13.0
9	Terra ASTER	705	0.685	6.000	14.6
10	Ресурс-01	650	0.500	5.600	34.6
11	Океан-О	668	0.350	5.600	26.2
12	GeoEye-1	684	13.300	12.000	8.0
13	WorldView-2	770	13.300	12.000	8.0

The resolution value can be derived as the intersection of the modulation transfer function with the threshold modulation function of contrast (Figure 1). The threshold modulation function of contrast depends on the noise of the system. For computations, we used the average value $K_{thr} = 0.18$ (assuming K_{thr} lies between 0.1 and 0.5).



Source: Фризер 1978

Fig. 1. Determination of imaging system resolution: $T(N)$ – modulation transfer function as a function of spatial frequency N, K_{thr} – threshold modulation function, R – image resolution

3. Results

As a result, we present plots of the different factors influencing on the modulation transfer function of satellite imaging systems (Figure 2).

Figure 3 shows resulting modulation transfer functions, which are defined by different values of contrast (C = 0.2, 0.4, 0.6, 0.8, 1.0) for systems of Ikonos-2 and WorldView-2 respectively.

The results of efficient resolution computations for different resolutions (R) and contrasts (C) are given in Table 2.

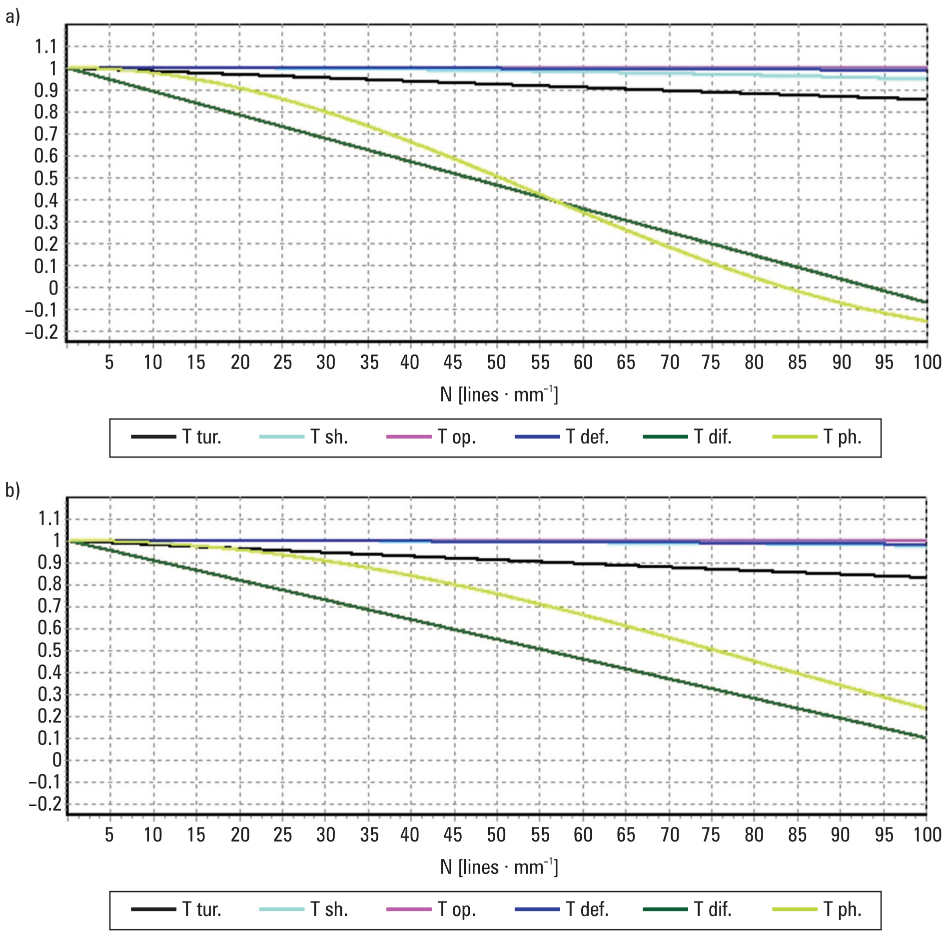
Table 2. Efficient Resolution Values of Satellite Imaging System

No.	**Satellite imaging system**	**Resolution values R [lines · mm^{-1}]**				
		C = **0.2**	C = **0.4**	C = **0.6**	C = **0.8**	C = **1.0**
1	Landsat-7	4.2	11.8	14.0	15.1	15.9
2	SPOT-4	14.3	43.2	52.1	57.0	60.2
3	SPOT-5	12.6	50.7	64.5	72.8	78.6
4	IRS-1D	17.0	64.6	81.0	90.5	96.9
5	Ikonos-2	4.8	16.5	20.7	23.3	25.1
6	OrbView-3	13.0	45.8	57.7	64.8	69.8
7	QuickBird-2	7.5	28.6	36.5	41.1	44.5
8	Eros-A1	8.6	31.3	39.2	43.9	47.1
9	Terra ASTER	11.6	38.1	46.3	50.8	53.7
10	Ресурс-01	6.2	17.6	20.9	22.6	23.7
11	Океан-О	7.8	22.8	27.3	29.6	31.1
12	GeoEye-1	8.5	43.3	56.5	64.2	69.4
13	WorldView-2	8.6	43.7	56.9	64.6	69.8

Finally, to estimate the spatial resolution R_t, we used the simple expression:

$$R_t = \frac{H}{f \cdot R}, \tag{7}$$

where: H – orbit height [km], f – focus length [m], R – resolution value [lines per mm].



Source: authors' study

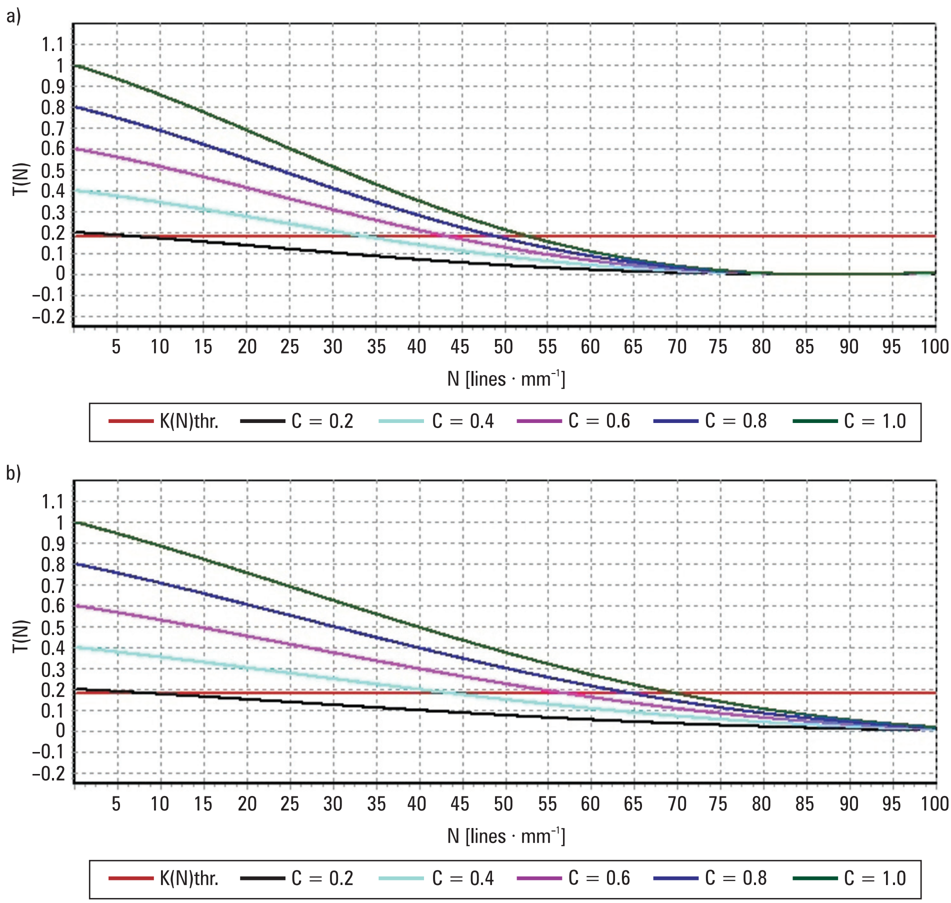
Fig. 2. Modulation transfer functions for different factors: a) for the Ikonos-2 system, b) for the WorldView-2 system

Table 3 shows the comparative resolution value computed as a projection of CCD pixel size on the Earth's surface and the resolution computed by taking into account, the influence of different factors.

Table 3. Comparative terrain resolution values

No.	Satellite imaging system	The pixel projection on the Earth surface [m]	Computed resolution value R_t [m]
1	Landsat-7	15.00	18.19
2	SPOT-4	10.00	12.56
3	SPOT-5	2.50	3.96

4	IRS-1D	5.80	8.24
5	Ikonos-2	0.82	1.29
6	OrbView-3	1.00	1.45
7	QuickBird-2	0.61	1.21
8	Eros-A1	1.80	2.45
9	Terra ASTER	15.00	19.06
10	Ресурс-01	45.00	54.85
11	Океан-О	50.00	61.37
12	GeoEye-1	0.41	0.74
13	WorldView-2	0.5	0.83



Source: authors' study

Fig. 3. The resulting modulation transfer functions: for the Ikonos-2 system, b) for the World-View-2 system

Evidently, the computed resolution value is much greater than the value submitted in the characteristics of the imaging systems.

4. Conclusions

Companies which produce satellite imaging equipment, compute spatial resolution as a projection of the CCD-matrix element onto the Earth's surface that overstates the real resolution values of these systems.

To determine the real spatial resolution, we considered a mathematical model which describes the influence of different factors: atmosphere turbulences, image shifts, defocusing, diffraction, discrete structure of the photodetector and the contrast of the objects.

A comparative analysis of the modulation transfer functions (MTF) for different satellite imaging systems has been completed and the preliminary results show that the image resolution is greatly dependant on the atmospheric turbulence and the size of a sensor element. The comparison of our results with results of other MTF assessment methods is a case of our further investigations.

Additionally, we have established that the atmospheric turbulence significantly reduces the transmitting possibility of images, but the integral coefficients that characterize the influence of turbulence, requires additional study.

The threshold modulation function which depends on the type of imaging system, including the size of the smallest sensor element also requires additional study.

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