Analysis of Resolution in Aerial Earth Surface Photography

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Abstract. *The paper deals with a simplified analysis of subjective resolution of an aerial sensing system for Earth surface photography in the visible light spectrum. The proposed simplified linear method allows approximate estimation of the minimal target size in the image scanned using a camera with CCD sensor.*

Keywords

Aerial photography, resolution, target size, modulation transfer function, CCD sensor.

1. Introduction

Aerial Earth's photography has an important role not only in various military applications, but in management of natural environment, built infrastructure and in many other areas of human activities. The minimal distinguishable size of an Earth surface target for aerial sensing depends on the quality of the scanned picture – especially the spatial resolution of the used sensor and on the video signal-to-noise ratio S_t/N. CCD read noise (On-Chip) and dark signal with its variance have the main impact in this case.

The following basic simplifying premises are considered in the following analysis:

- Monochromatic picture scanned in the visible spectrum is assumed,
- the size of the target projection into the sensor plane is greater than the sensor's resolution (pixel distance),
- sensor axis (objective axis) is perpendicular to the Earth surface – so-called vertical aerial photography,
- on-line picture visual observation is available (observer is on the airplane board). This premise does not have to be satisfied provided a quality data down link, for example while using pilot-less reconnaissance,
- the scanned picture data are transmitted from the airplane to the ground station using a radio-frequency down link,
- the display system has an adequate resolution.

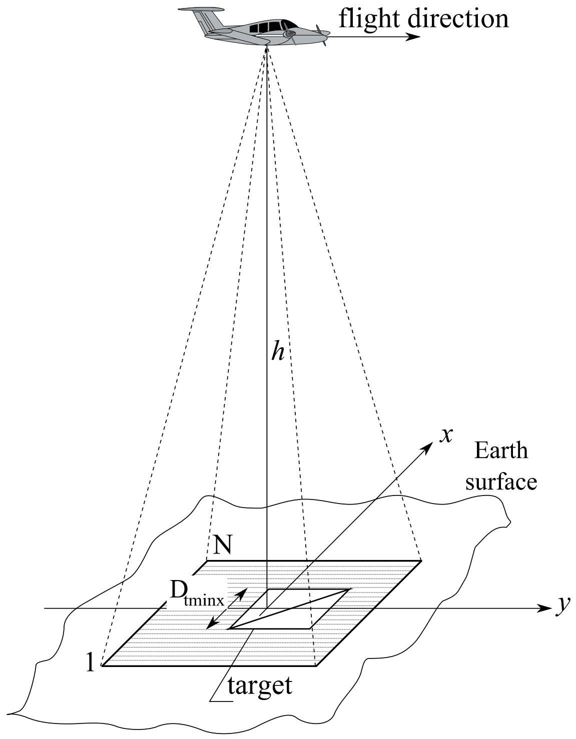

Fig. 1 Principle of the vertical aerial sensing of the Earth surface.

A simplified analysis of the aerial scanning system resolution and an approximate estimation of the minimum size of an object (searched target) in the picture represent the basic aims of this paper. The resolution can be increased by various computer methods of pattern recognition [5], [15], [16]. However, these methods fall beyond the scope of this paper. The impact of particular electronic and optical factors of the camera and the environment between the Earth surface and the sensor can be described by the MTF (Modulation Transfer Function). A simplified linear analysis is based on the premise that the target in the picture can be located provided that

- the spatial Nyquist frequency of the used CCD sensor is superior to the spatial frequency corresponding to the target size in the picture,
- the ratio of the video target signal power S_t to the complex of noise signals N in the scanned picture

achieves at least a minimal defined value. Experiments reflect that the minimal required value is (S_t/N) > 3 [18]. This value holds for pictures observed by a trained observer in daylight. The value was verified experimentally by analyzing a series of pictures taken in frame of the research project "Raster Scanning of Earth Surface from Pilotless Aircraft using Line CCD Sensors", done by the main author in the 90's for the Czechoslovak Ministry of National Defense (a part of public outputs of this project was published in [15]). Therefore the dependence S_t/N on all relevant factors that shall be taken into account in the aerial photography will be derived below.

2. Expression of the Scanning System Equivalent Transmission

Equivalent total transmission of all factors which influence the output signal of the scanning optoelectronic sensor and corresponding image quality can be expressed as a product of partial MTFs (Modulation Transfer Functions) or more precisely OTFs (Optical Transfer Functions) [3], [4], [19]. OTF is a function of the spatial frequency f_{sp} [cycles/mm or line pairs/mm] and is used for a precise analysis of transmission properties of optical systems. It is defined as

$$\mathrm{OTF} = \mathrm{MTF} \cdot \mathrm{PTF} = \mathrm{MTF} \cdot e^{\mathrm{j}\varphi} \tag{1}$$

where MTF is the modulus and $e^{\mathrm{j}\varphi}$ is the Phase Transfer Function.

The phase component PTF has no fundamental importance for the following simplified analysis, because it is not captured by the sensor. Therefore, only the magnitudes of the modulation transfer functions MTF are used.

$$\mathrm{MTF_{tot}} = \mathrm{MTF_{sen}} \cdot \mathrm{MTF_{obj}} \cdot \mathrm{MTF_{def}} \cdot \mathrm{MTF_{sm}} \cdot \mathrm{MTF_{atm}} = \mathrm{F}(f_{sp}) \tag{2}$$

where $\mathrm{MTF_{sen}}$ is the modulation transfer function of the used CCD sensor, $\mathrm{MTF_{obj}}$ is the modulation transfer function of the used objective, $\mathrm{MTF_{def}}$ is the modulation transfer function corresponding to the camera defocus – e.g. caused by the change of airplane altitude, $\mathrm{MTF_{sm}}$ is the modulation transfer function corresponding to the image smear caused by airplane motion, $\mathrm{MTF_{atm}}$ is the equivalent modulation transfer function corresponding to the contrast decrease depending on diffusion of the reflected light through the atmosphere.

These factors influence and degrade the scanned image in its optical and electronic form.

The total relative brightness modulation $\mathrm{BM_{tot}}$ of the scanned scene projected in the sensor image plane can be expressed by the formula

$$\mathrm{BM_{tot}} = \mathrm{BM_{br}} \cdot \mathrm{MTF_{tot}} = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}} \cdot \mathrm{MTF_{tot}} = \frac{\mathrm{CR} - 1}{\mathrm{CR} + 1} \cdot \mathrm{MTF_{tot}} \tag{3}$$

where $\mathrm{BM_{br}}$ is the relative brightness modulation of the scanned scene on the Earth surface, CR denotes the contrast ratio that is defined as

$$\mathrm{CR} = \frac{E_{\max}}{E_{\min}} \approx \frac{R_{\max}}{R_{\min}}$$

provided a constant external illuminance (usually sunlight) of the scanned Earth's surface. $R_{\max}$ and $R_{\min}$ are the maximal and the minimal reflectivity factors of the scanned Earth´s surface, respectively. The reflectivity factor depends on the light wavelength λ. $E_{\max}$ and $E_{\min}$ are the maximal and minimal illuminances (reflected irradiance) of the scanned surface, respectively. Illuminance is defined as the radiant flux φ per unit area S leaving a surface

$$E = \frac{\delta\varphi}{\delta S} \quad [\mathrm{W/m^2}]. \tag{4}$$

2.1 Partial Modulation Transfer Functions

a) *Modulation transfer function of the used objective* $\mathrm{MTF_{obj}}$.

$\mathrm{MTF_{obj}}$ can be expressed by the approximate formula [3]

$$\mathrm{MTF_{obj}} = 1 - \frac{4}{\pi}\left(\frac{f_{\mathrm{sp}} \cdot \lambda}{D_{\mathrm{obj}}}\right) \tag{5}$$

where f_{sp} is the spatial frequency [cycles/m], λ is the radiation wavelength [m] and D_{obj} is the objective aperture diameter [m]. In this formula the diffraction influence is not assumed and it is valid providing that $h/\mathrm{F_o} \gg 1$ (ratio of the scanned scene distance and the focal length of the objective).

b) *Modulation transfer function of the smear* $\mathrm{MTF_{sm}}$ *due to airplane motion.*

The exposure time for one picture is usually very short and plane motion induces only small smear in the picture. This effect causes the smear of scanned image only in the flight direction. It can be expressed by the formula [15]

$$\mathrm{MTF_{sm}} = \left[\frac{\sin\left(\pi \cdot d_y \cdot f_{\mathrm{sp}}\right)}{\pi \cdot d_y \cdot f_{\mathrm{sp}}}\right]^{\frac{1}{2}}. \tag{6}$$

For perpendicular Earth surface sensing, it holds

$$d_y = v_y \cdot t_{\mathrm{int}} \cdot \frac{\mathrm{F_o}}{h}. \tag{7}$$

In the relations (6), and (7), the symbols have the following meanings: f_{sp} is the spatial frequency of the scanned scene brightness distribution in the sensor image plane [cycles/m], v_y is the velocity of the sensor (airplane) [m/s], h is the flight height (altitude of the airplane above the ground) [m], t_{int} is the time of charge integration (exposure time) [s], F_o is the focal length of used objective lens [m].

c) *Modulation transfer function* MTF_{sen} *of the image CCD sensor*.

Exact expression of the area CCD sensor modulation transfer function is very complicated. This parameter is different in the direction x (across to the flight course) and in the flight course y, where the influence of smear, expressed by (7), is dominant. MTF of an ideal CCD sensor depends on pixel size and can be expressed (owing to the sampling character of the scanning) in the form sinc($k f_{sp}$) – see Fig. 2. The MTF in real conditions depends on the charge crosstalk among adjacent pixels and on the value of CTE (Charge Transfer Efficiency). MTF_{sen} also significantly depends on the spectral structure of incident luminous radiation. Therefore, dependences MTF_{sen}, given by the manufacturers, are most often used (see Fig.3 where the well known fact is evident, that the sensor resolution falls with increasing wavelength).

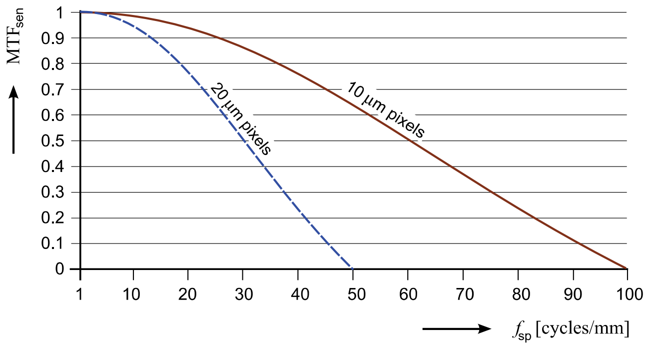

Fig. 2 MTF_{sen} for CCD sensor depending on the pixel size.

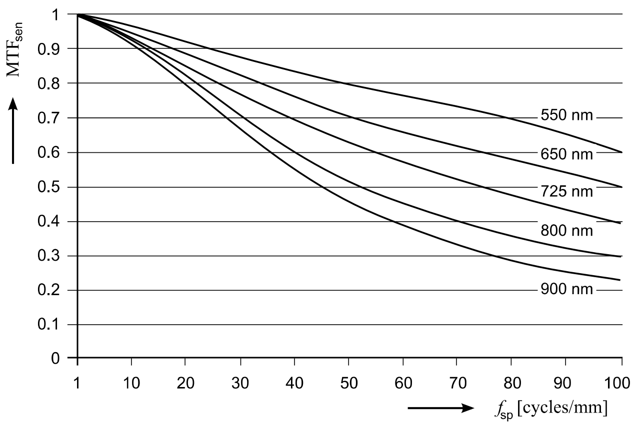

Fig. 3 Example of MTF_{sen} of the image sensor CCD 3041 (Fairchild).

d) *Modulation transfer function* MTF_{atm} *of the atmosphere*. Atmosphere influences the resulting contrast ratio in the sensor image plane, but the influence on the resulting system resolution is relatively small – therefore it can be supposed that $MTF_{atm} \approx 1$ [15]. We shall consider the atmosphere influence only by means of the optical decrement coefficient $\tau_{atm} < 1$. Because optical decrement depends on the radiation wavelength, this coefficient presents the mean value of integral across the range of operational wavelengths of the used sensor (for CCD about 400 – 1100 nm).

3. Simplified Analysis of the Resolution of an Earth Surface Sensing System

The principle of the further described analysis is based on the presumption that the definite detail (target) in the scanned scene with the defined contrast can be resolved if the video signal-to-noise ratio $S_v/N > 3$ [15], [17]. The expression S_v/N will be derived in the following part. This ratio is influenced by a number of different factors. Thus, some simplifying premises will be used, e.g. constant ambient temperature $\theta_a = \text{const.}$

3.1 Expression of Illuminance E_{sen} in the Sensor Image Plane

Illumination E_{sen} in the sensor image plane can be expressed by the formula [17]

$$E_{sen} = \frac{\mathrm{R} \cdot E_{ss} \cdot \cos^4 \alpha}{8K_{obj}^2 \left(1+\delta\right)^2}. \tag{8}$$

After substitution

$$\delta = \frac{\mathrm{F_o}}{h} \ll 1, \tag{9a}$$

$$\alpha = \arctan \frac{\mathrm{d_{sen}}}{\mathrm{F_o}}, \tag{9b}$$

$$K_{obj} = \frac{\mathrm{F_o}}{\mathrm{D_{obj}} \cdot \sqrt{\tau_{obj}}}. \tag{9c}$$

In the equations (9) – (9c), E_{ss} is the illuminance (irradiance) of a scanned scene in the distance h in front of the object lens [lx], R is the reflectivity factor of the scanned scene [-], F_o is the focal length of the used objective [m], h is the distance of the scanned scene in front of the camera objective [m], d_{sen} is the size of the photo-site array of the used CCD sensor [m], D_{obj} is the diameter of the input lens of the used objective [m], τ_{obj} is the optical transfer factor of the used objective [-] – ($\tau_{obj} < 1$).

For $h \geq 200$ m, it holds $\delta \ll 1$ and for $d_{sen} \ll F_o$, we can write $\cos^4 \alpha \approx 1$. Then

$$E_{sen} \cong \frac{E_{ss}}{8\mathrm{K}_{obj}^2}. \tag{10}$$

3.2 Expression of the Required Video Signal-to-Noise Ratio

The basic condition that must be satisfied for target localization in the scanned picture can be expressed by [12]

$$\frac{S_t}{N} = n_t \left(\frac{S}{N}\right)_{avr} \cdot \frac{|R_t - R_b|}{R_t + R_b} \cdot \mathrm{MTF}_{tot} \geq \left(\frac{S_t}{N}\right)_{req} \tag{11}$$

where $(S/N)_{avr}$ is the average value of the signal to noise ratio related to **one pixel** of the scene with brightness distribution containing the lowest spatial frequencies f_{spx} in direction x only (1 cycle/d_{sen}). For this scene it can be assumed that MTF $\cong$ 1. n_t denotes the number of the pixels corresponding to the target projected to **one line** of the used CCD sensor photo-site array [-].

The average value of the signal to noise ratio of the scene with brightness distribution containing only the lowest frequencies can be expressed as [15]

$$\left(\frac{S}{N}\right)_{avr} \approx \frac{\sum p_s}{\sum p_n} =$$
$$= \frac{1}{\mathrm{N} \cdot p_{n1}} \left[\frac{\mathrm{N}}{2} \cdot \frac{E_E \cdot \mathrm{T}_{atm} \cdot \mathrm{S}_{sen} \cdot \mathrm{P}_{sen} \cdot t_{int} \cdot \mathrm{d}_1^2}{8 q_{el} \cdot \mathrm{K}_{obj}^2} (\mathrm{R}_t + \mathrm{R}_b) \right] = \tag{12}$$
$$= E_E \cdot \mathrm{B} \cdot (\mathrm{R}_t + \mathrm{R}_b).$$

substituting the constant B

$$\mathrm{B} = \frac{\mathrm{T}_{atm} \cdot \mathrm{S}_{sen} \cdot \mathrm{P}_{sen} \cdot t_{int} \cdot \mathrm{d}_1^2}{16 q_{el} \cdot \mathrm{K}_{obj}^2 \cdot p_{n1}}. \tag{13}$$

The meaning of symbols in equations (11) – (13) is the following: E_E is the illuminance (irradiance) of the scanned Earth's surface [lx], R_t is the target reflectivity factor [-], R_b is the background reflectivity factor [-], S_{sen} is the the photo-electric responsivity of the used sensor [$A \cdot W^{-1}$], P_{sen} is the photo-radiometric conversion coefficient for incident radiation [$W \cdot m^{-2} \cdot lx^{-1}$], T_{atm} is the luminous radiation decrement in the atmosphere [-], q_e is the electric charge - $q_e = 1{,}6 \cdot 10^{-19}$ C, N is the total number of pixels in one line of the used CCD sensor, p_s is the number of light generated electrons in one line of the CCD sensor [-], p_n is the total number of thermally ejected noise electrons in one line of the CCD sensor [-], p_{n1} is the number of thermally ejected noise electrons in one pixel for a period of charge integration t_{int} and for an ambient temperature Θ_a [-], d_1 is the side length of one square sensor pixel [m].

The side length d_1 can be expressed by the Nyquist spatial frequency f_{spN} of the used CCD sensor [cycles/mm] as

$$\mathrm{d}_1 = \frac{\mathrm{d}_{sen}}{\mathrm{N}} = \frac{1}{2 \cdot f_{spN}}. \tag{14}$$

Note:

Values of $S_{sen}(\lambda)$, $P_{sen}(\lambda)$, $T_{atm}(\lambda)$ depend on the radiation wavelength. Therefore their **mean values** are calculated acquired by integration over the operational wavelength spectrum λ_{min} = 400 nm to λ_{max} = 1100 nm.

Substituting in the equation (11) yields

$$n_t \cdot E_E \cdot \mathrm{B} \cdot (\mathrm{R}_t + \mathrm{R}_b) \cdot \frac{|\mathrm{R}_t - \mathrm{R}_b|}{(\mathrm{R}_t + \mathrm{R}_b)} \cdot \mathrm{MTF}_{tot} =$$
$$= n_t \cdot E_E \cdot \mathrm{B}.|\mathrm{R}_t - \mathrm{R}_b| \cdot \mathrm{MTF}_{tot} \geq \left(\frac{S_t}{N}\right)_{req}. \tag{15}$$

The size d_{tx} of the target projected to **one line** (in the direction x) of the CCD sensor photo-site array $d_{tx} = n_t.\mathrm{d}_1$ can be expressed by target spatial frequency $f_{sp} = f_{sptx}$:

$$n_t \cdot \mathrm{d}_1 = \frac{1}{2 \cdot f_{sptx}}. \tag{16}$$

Then after substitution into (15) and formal rearrangement

$$|\mathrm{R}_t - \mathrm{R}_b| \cdot \mathrm{MTF}_{tot} = \left(\frac{S_t}{N}\right)_{req} \frac{2\mathrm{d}_1}{\mathrm{B} \cdot E_E} \cdot f_{sptx}. \tag{17}$$

The right-hand side of (17) represents the so-called threshold function. It is a linear function of unknown spatial frequency f_{sp}. The total modulation transfer function $\mathrm{MTF}_{tot}(f_{sp})$ also depends on the spatial frequency f_{sp}, but this quantity is not expressed explicitly. Mostly, functions $\mathrm{MTF}_{tot}(f_{sp})$ can be expressed in their graphic forms only as results of measurements. Therefore, the graphic calculus of the searched maximum target spatial frequency $f_{sp} = f_{sptx}$ is optimal in this case, see Fig. 4. In Fig. 4, the Nyquist spatial frequency f_{spN} of the used CCD sensor is also marked. The maximum searched spatial frequency must be $f_{sptx} < f_{spN}$. If it is the contrary, an unsuitable sensor is used, whose resolution is insufficient for the given conditions.

3.3 Calculation of the Minimum Target Size in the Scanned Scene

The maximum spatial frequency f_{sptx} in the direction x, corresponding to the smallest distinguishable target size on the Earth surface, can be found using the mentioned graphic method – see paragraph 3.4. The smallest size D_{tminx} of a distinguishable target on the Earth surface in direction x can be computed for the **perpendicular sensing** (photography) by the formula (see Fig. 1)

$$\mathrm{D}_{tminx} = d_{tx} \cdot \frac{h}{\mathrm{F}_o} = \mathrm{d}_1 \cdot n_t \frac{h}{\mathrm{F}_o} = \frac{1}{2 f_{sptx}} \cdot \frac{h}{\mathrm{F}_o} \tag{18}$$

In the perpendicular photography, the smallest target size D_{tminy} in direction y is practically comparable to the smallest target size D_{tminx} if the used CCD sensor has a symmetric structure of pixels in the photo-site array.

3.4 Numerical Example – Graphic Solution

Consider the following scanning system parameters:

- flight height above the ground h = 2000 m,
- angle of scanning (perpendicular scanning) β = 0º,
- minimal required signal-to-noise ratio for the target resolution $(S_t/N)_{req}$= 5,
- illumination of the Earth surface E_E = 1000 lx, eventually 500 lx,
- reflectivity factor of the searched target R_t = 0.6,
- reflectivity factor of the surroundings R_b = 0.2,
- mean value of the CCD sensor photo-electric responsivity S_{sen} = 0.21 A·W^{-1},
- mean value of photo-radiometric conversion coefficient for incident luminous radiation $P_{sen} = 3\cdot10^{-2}$ W·m^{-2}·lx^{-1},
- mean value of the luminous radiation decrement in atmosphere T_{atm} = 0.7,
- pixel dimensions of the used CCD sensor 7 x 7 μm ($d_l = 7\cdot10^{-6}$ m),
- number of pixels of the used CCD sensor 2048 x 2048,
- integration (exposure) time t_{int} = 2 ms,
- focal length of the used objective F_o = 200 mm,
- input lens diameter of the used objective D_{obj} = 25 mm,
- optical transfer factor of the used objective τ_{obj} = 0.95,
- number of thermally ejected noise electron in one sensor pixel in a period of charge integration t_{int} = 2 ms at an ambient temperature Θ_a =20ºC p_{nl} = 250 electrons.

After substitution into (9c) and (13)

$$K_{obj} = \frac{F_o}{D_{obj}\cdot\sqrt{\tau_{obj}}} = \frac{200\cdot10^{-3}}{25\cdot10^{-3}\cdot\sqrt{0,95}} = 8.2$$

and

$$B = \frac{T_{atm}\cdot S_{sen}\cdot P_{sen}\cdot t_{int}\cdot d_l^2}{16 q_{el}\cdot K_{obj}^2\cdot p_{nl}} =$$

$$= \frac{0.7\cdot0.21\cdot3\cdot10^{-2}\cdot2\cdot10^{-3}\cdot(7\cdot10^{-6})^2}{16\cdot1.6\cdot10^{-19}\cdot8.2^2\cdot250} = 0.01\text{lx}^{-1}.$$

Linear threshold function for e.g. E_E = 1000 lx and spatial frequency f_{sp} = 50 cycles/mm gets

$$\left(\frac{S_t}{N}\right)_{req}\frac{2d_l}{B\cdot E_E}\cdot f_{sptx} = 5\cdot\frac{2\cdot7\cdot10^{-6}}{0.01\cdot10^3}\cdot50\cdot10^3 = 0.35$$

(0.7 for E_E = 500 lx).

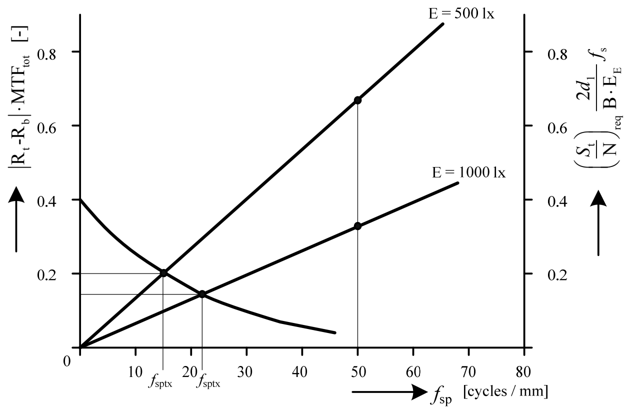

Fig. 4 Graphic solution of (17).

Graphic solution of the equation (17) in Fig. 4 shows that

f_{sptx} = 22 cycles /mm for E_E = 1000 lx,

f_{sptx} = 15 cycles /mm for E_E = 500 lx.

Then the smallest distinguishable target size on the Earth surface for perpendicular photography is, from equation (18),

$$D_{tminx} = \frac{1}{2f_{sptx}}\cdot\frac{h}{F_o} = \frac{2\cdot10^3}{2\cdot22\cdot10^3\cdot0.2} = 0,227 \text{ m}$$

for E_E = 1000 lx and

D_{tminx} = 0,33 m for E_E = 500 lx.

4. Conclusion

The described simplified analysis is focused on the limitations and quantitative formulation of the smallest distinguishable target size on the Earth surface at the subjective survey and assessment of aerial photographs without digital data pre-processing. The achieved results were verified by means of many aerial photographs realized in various light conditions and scanned by various photo-cameras (CCD sensors). These confrontations confirm very good agreement of the derived theoretical terms and experimental results. A major part of the experiments was done in frame of an unpublished research project "Raster Scanning of Earth Surface from Pilotless Aircraft using Line CCD Sensors", solved in the 90's for the Czechoslovak Ministry of National Defense. Some findings and results were now used for flight exploration of the Earth surface using cameras with CCD or CMOS sensors.

However, these research reports are still classified as confidential. As we presently have no possibility to verify the results in practice using airplane scanning, the method and the correlation of theory and practice was verified using static digital images, shot from relatively low heights (observation tower). In 2007, such pictures were taken from the CN Tower in Toronto (height cca. 345 m). To achieve variable signal-to-noise ratio, white noise was added afterwards.

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