System considerations and potential for topographic mapping with small satellites

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ABSTRACT:

Small satellites are powerful tools to support many Earth observation tasks. Nowadays, the advances in various fields of technology allow to develop and operate even high resolution optical topographic mapping systems on the basis of small satellites. But there are physical constraints to be considered which may restrict the use of small satellites for topographic mapping. The paper gives a MTF based metrics to explain which features the camera and the spacecraft have to provide to support the anticipated GSD. In this context the paper deals with such important parameters for topographic mapping with small satellites like spatial resolution, radiometry, pointing accuracy, stability, and agility. Data rates and data volumes are also issues to be considered when talking about the mapping system. It is shown that the imagers as well as the spacecraft bus need to follow certain rules to allow high resolution topographic mapping using small satellites.

1. INTRODUCTION

High resolution mapping systems follow the trend to smaller ground sample distances (GSD). Figure 1 shows this trend for civil Earth surface imagers using passive optical approaches. The increasing number of spaceborne imaging systems in the last decade, (see Kramer, 2002, Jacobsen, 2005 for more) shows that an increasing number of countries is dealing with spaceborne technology and that there is an increasing need for mapping systems for different applications (Konecny, 2003). The trend to smaller GSDs was and is supported by the improvements in diverse fields of technology as for instance optics, mechanics and materials, electronics, signal processing, communication and navigation. In this paper we consider a GSD of 5 m or less as high resolution. The necessary high resolution optical systems have to overcome a couple of problems.

Smaller GSD needs larger focal lengths. The physics behind optical systems allows only a restricted number of tricks to overcome the problems of large focal length optics in terms of volume and mass. The size of the focal plane depends on the detector system size and is part of the equation concerning optics volume and mass. The pointing stability is another important issue. What are the requirements and restrictions? High resolution means also to deal with small amounts of energy coming from small ground pixels to be registered in small integration time periods according to the high satellite orbit velocities. Figure 2 gives an overview of the different space borne system components and their influences on the topographic mapping system performance

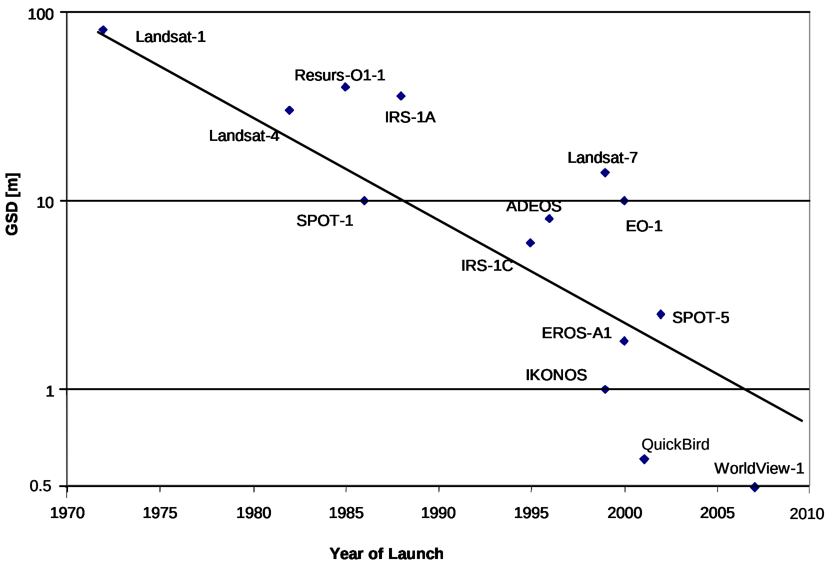

Figure 1. Some civil Earth surface imagers, trend of GSD

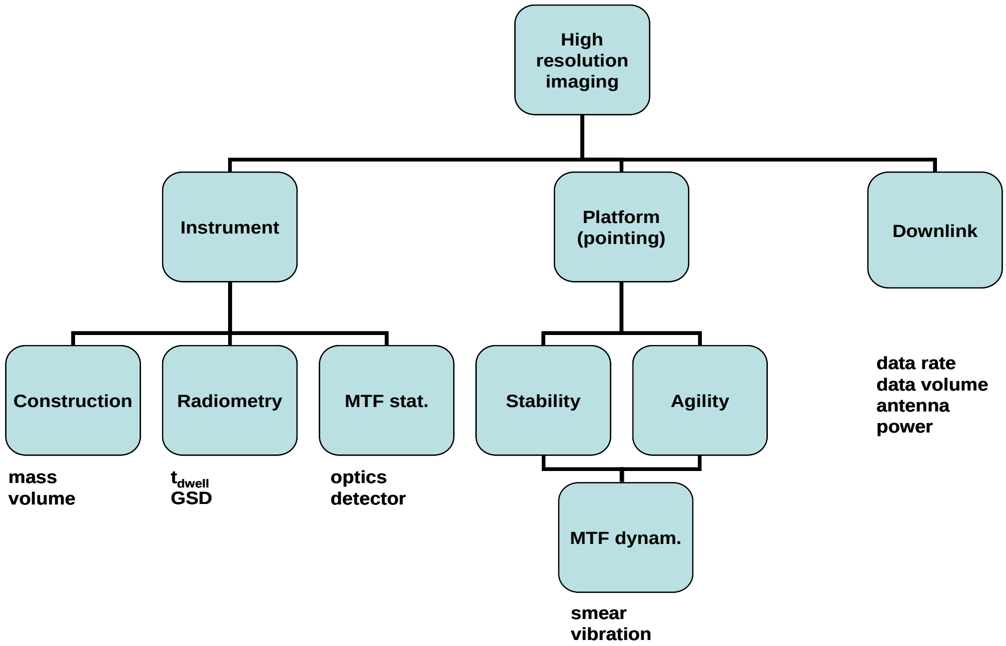

Figure 2. Components of a space borne mapping system and their influences on the system performance

2. IMPORTANT PARAMETERS FOR SPACEBORNE MAPPING SYSTEMS

2.1 Spatial Resolution

Some major features are considered which influence the image quality from the spatial resolution point of view. A very effective way to describe the image quality is to use the Modulation Transfer Function MTF. Using the MTF approach, you can multiply all the image quality influencing MTF components of a linear system (or quasi linear system) which may base on different physical effects (e. g. optics, CCD, electronics) in order to create the system MTF. The resulting point spread function PSF of the system is then computed applying the Inverse Fourier Transform (IFT). For simplicity we use here

$$MTF_{SR} = MTF_{Optics} \cdot MTF_{D} \cdot MTF_{PS} \tag{1}$$

(SR – spatial resolution, D – detector, PS – platform stability)

The MTF_{PS} of the platform stability is subject of chapter 2.3. MTF_{Optics} includes the diffraction part as well as the aberration part.

For most of the operating systems, the optical system may be considered near diffraction limited and in focus. The diffraction causes a diffraction disc or Airy disc in the focal plane (see Jahn and Reulke, 1995). It is one of the important parameters which can be related to the detector pixel size x

$$d = 2.44 \cdot \lambda \cdot \frac{f}{D} = 2.44 \cdot \lambda \cdot F \tag{2}$$

with f the focal length, D the aperture of the optics, and λ the average wavelength of the radiation. If x is larger than d the system is detector limited, the resolution is determined by the detector. Otherwise the optics determines the spatial resolution. Figure 2 shows the borderline for an average wavelength of $\lambda = 0.55\,\mu m$ (green). The optics designs should be near to the borderline on the optics limited side in order to get maximum energy for the detector avoiding too large aliasing effects. For state-of-the-art CCD detectors with a pitch of 7 µm, an f/5.2 optics would satisfy this approach.

Detector

The pixel size of the detector is projected via the focal length to the ground pixel size. The smaller the detector elements x the shorter the focal length f (see figure 4). As an example, the state-of-the-art CCD pixel size of 7µm results in a focal length of f = 4.2 m from an orbit altitude of 600 km and GSD = 1 m. Of course with smaller detector sizes less energy is integrated. If the sensitivity of the pixel element is not sufficient to obtain the necessary SNR, TDI needs to be applied or a so called slow-down mode allows to enlarge the dwell time to the sufficient extent (see chapter 2.2).

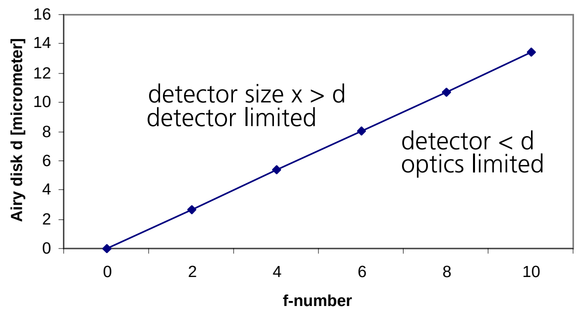

Figure 3. Airy disk parameter d as a function of the f-number F (λ=0.55 µm)

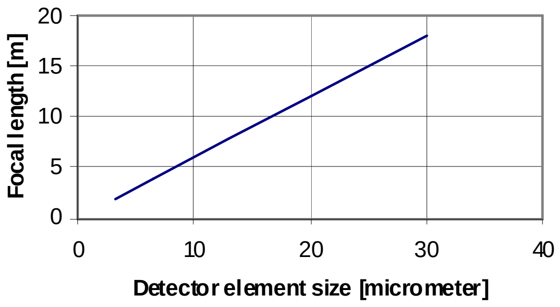

Figure 4. Dependence between detector element size x and necessary focal length f for a given ground pixel size of X = 1 m from an orbit altitude of 600 km MTF_D of the detector element with size d is described by the sinc function (in x-direction)

$$MTF_D(f_x) = \mathrm{sinc}(\pi \cdot d \cdot f_x) = \frac{\mathrm{sinc}(\pi \cdot d \cdot f_x)}{\pi \cdot d \cdot f_x} \tag{3}$$

MTF_D in y-direction has the same structure.

Fig. 5 gives an impression of the relations for a CCD pixel size of x = 10 µm behind an f/1.2 optics.

2.2 Radiometric Aspects

The number of photoelectrons generated in a solid state camera is

$$n_{pc} = \frac{A_D \cdot T_{Optics} \cdot t_{\mathrm{int}}}{4F^2} \int_{\lambda_1}^{\lambda_2} R_d(\lambda) L(\lambda) d\lambda \tag{4}$$

(A_D – detector area, T_{Optics} – transmission of the optics, t_{int} – integration time, F –f-number, R_d – detector responsivity, L – radiation flux) with $t_{int} < t_{dwell}$.

Once the detector is selected, A_D and R_d are given. L is also given as well as F and T_{Optics} when the optics is selected or designed taking into account the technological and/or the mission constraints. $\Delta\lambda$ is fixed in most cases, so that the only real variable part is the integration time t_{int}. For a satellite in LEO, the satellite ground track velocity is about 7 km/s. In other words, the dwell time is 1 ms for a ground sample distance GSD of 7 m. For high resolution imagers with GSD of about 1 m, t_{int} < 1/7 ms is too short for a sufficient good signal and SNR.

$$t_{dwell}(1m) / t_{dwell}(10m) = 1/10 \tag{5}$$

Even more severe is the influence of the pixel field of view (IFOV).

$$IFOV(1m) / IFOV(10m) \,\hat{=}\, 1/100 \tag{6}$$

Taking both aspects into account, reducing the GSD by a factor of 10^{-1} causes a time related and geometry related decrease of energy at the detector of about 10^{-3}.

There are two possibilities to overcome this obstacle:

- use TDI (Time Delay and Integration) technology with N stages in order to increase the signal N-fold and improve the SNR by the factor of $\sqrt{N}$ (this technique is used e. g. in the IKONOS and QuickBird missions)
- use the so-called slow-down mode in order to decrease the ground track velocity of the line projection on the surface (those technique is used for instance in the EROS-A1 mission) with respect to the satellite velocity in order to obtain the necessary dwell time t_{dwell}.

2.3 Pointing Stability

For mapping of the Earth's surface, deviations from the necessary pointing precisions can be corrected using precise ground control points. The pointing stability is of more importance in order to maintain the ground sample distance and the image quality. For high resolution, the MTF_{PS} of the platform has two major components

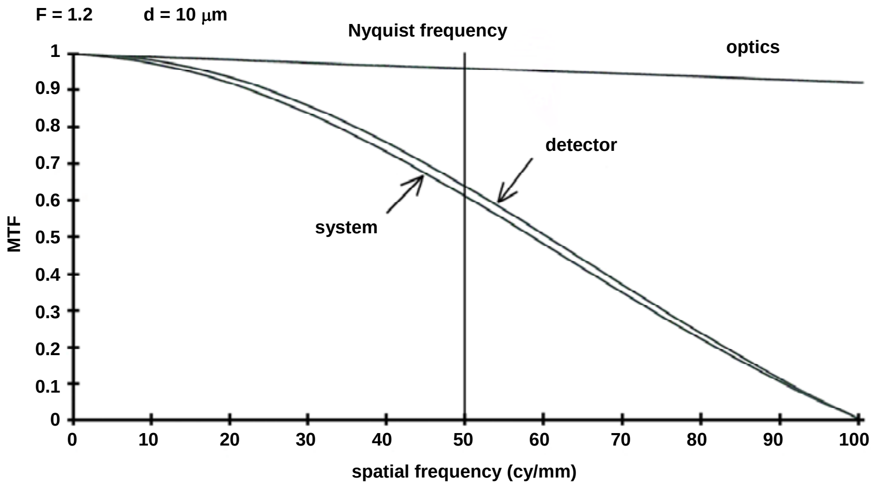

Figure 5 System MTF composed of MTFoptics and MTFD

$$MTF_{PS} = MTF_{LM} \cdot MTF_J \tag{7}$$

(PS – platform stability, J – jitter)

The MTF degradation due to linear motion of the satellite is

$$MTF_{LM}(f_x) = \mathrm{sinc}(\pi \cdot a_{LM} \cdot f_x) \tag{8}$$

where f_x is the spatial frequency, and a_{LM} the distance the target edge moves across the detector pixel. MTF_{LM} only affects the MTF in the direction of the motion. The distance a_{LM} is v · Δt. In many cases Δt is close to the dwell time and MTF_{LM} is approximately MTF_D. Fig. 6 shows the influence of a_{LM} on the MTF_{LM}. MTF_{LM} with a_{LM} = 1 equals the detector MTF_D. The abscissa shows the spatial frequency normalized to the system dependend maximum value $f = f_x / f_{x,\max}$. For instance, with a detector pitch of 6.5 µm the spatial frequency of 150 cyc/mm equals $f_{x,max}$ = 1. As a rule-of-the-thumb, when the linear motion causes an image shift less than about 20 % of the detector size, the effect on system performance is minimal.

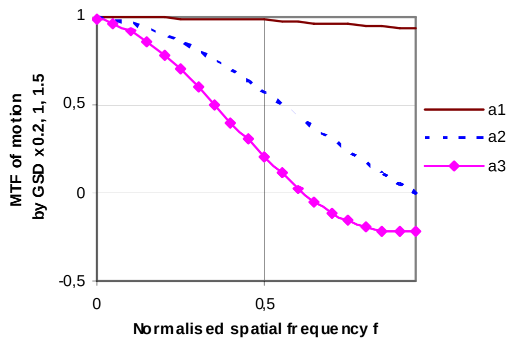

Figure 6 Influence of a_{LM} on MTF_{LM} with a_{LM} = 0.1, 1, 1.5 · GSD

2.4 Agility

Agility is an important feature of mapping systems when we apply certain stereo imaging concepts or strive to cover as much as possible area on as many as possible different ground sites according to customer request or the actual cloud coverage condition. To give a hint about the agility parameters like acceleration and retargeting rate, the stereo imaging mode may serve as an example. For stereo imaging with a one-sensor concept, the agility depends on the B/H-ratio (stereo-baseline/orbit-height).
For example: Assuming a 600 km orbit, a GSD = 1 m, a B/H = 1 and using a 10 k x 10 k matrix-camera, we plan to generate a stereo pair of about 10 km x 60 km ground area. The camera view angle needs to be retargeted by about 100 deg within 74 sec resulting in an average turning rate of about 1.4 deg/sec. If you want to cover other areas as well, you need to have a high retargeting capability including the acceleration capability at the start and before stop of retargeting.
WorldView-1 provides good numbers as for instance:

From an orbit altitude of 600 km, a GSD of 1 m equals an IFOV of 1.7 µrad or approximately 1/3 of an arcsec. During the dwell time, the drift shall be less than 20 % of the IFOV resulting in a drift rate of about 2.4 mrad/s or 8 arcmin/s in order to stay in the limit for minimal degradation of the MTF due to drift effects. When using the TDI principle to improve the SNR, for a 96 step TDI the tolerable drift rate becomes even 25 µrad/s or about 5 arcsec/s!

For MTF_J (jitter or random motion) is assumed that the jitter is a superposition of different high-frequency motions so that the central limit theorem can be applied. It says that many random movements can be described by a Gaussian distribution

$$MTF(f_J) = \exp(-2\pi^2 \sigma_J^2 f_J^2) \tag{9}$$

with σ_J the rms random displacement. Fig. 7 shows the influence of σ on the MTF_J for σ = 0.1 · x and σ=1·x (x – detector element size).
As a rule-of-the-thumb, when σ_J is less than about 10 % of the detector size x, system performance is only minimal effected.

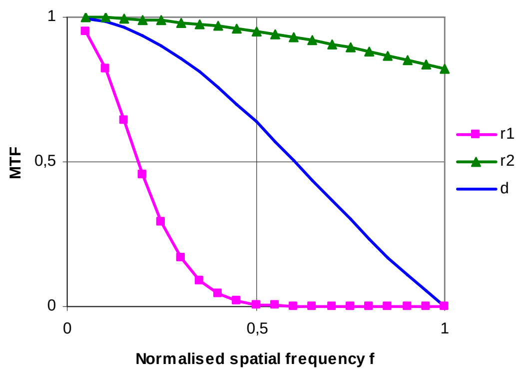

Figure 7 Influence of σ on the MTF_J with σ = 0.1, 1 · x. For comparison, MTF_D is also shown (MTF_d).

- Acceleration: 2.5 deg/s/s
- Rate: 4.5 deg/s

3. SENSOR DATA RATES AND DATA VOLUMES

Sensor data rates can be treaded in the same manner for both linear and matrix sensor technologies because both sensors have exactly the same pixel dwell time under the same circumstances (GSD, focal length, detector size, orbit height).
Sensor data rates depend on
- the number of pixels across flight direction N of a linear or matrix array
- radiometric resolution in number of bits per pixel (M)
- ground track velocity (depends on the orbit altitude)
- ground sample distance (GSD).

The ground track velocity and GSD determine the effective dwell time

$$t_{dwell} = \frac{GSD}{V_{ground}} \tag{10}$$

The sensor data rate DR is determined in bits per second (bps) by

$$DR = \frac{N \cdot M}{t_{dwell}} \tag{11}$$

The data volume DV in bits generated within the imaging time t_{image} is

$$DV = DR \cdot t_{image} \tag{12}$$

Example assumptions:
H_{orbit} = 600 km (V_{ground} ca. 7 km/s)
CCD line with N_y= 12 Kpixels
radiometric resolution M = 8 bit
quadratic image $N_x = N_y$ = 12 Kpixels
$t_{image} \approx 15 \cdot 2^{10} \cdot t_{dwell}$

These assumptions are equivalent to using a matrix with 12 K x 12 K pixels. The results for different GSD are given in table 1.

Table 1. Data rates and volumes for GSD = 10 m and GSD = 1 m from 600 km orbit, radiometric resolution 8 bit

GSD	DR	DV
10 m	70 Mbps	150 Mbyte
1 m	700 Mbps	150 Mbyte

4. SUMMARY

This paper showed the problems connected with high resolution topographic imaging. They can be solved, even by means of small satellites. So it is not surprising that there is already a good number of small satellites (total mass < 500 kg) with high-resolution instruments (≤ 5 m GSD) in orbit or planned (Table 2). This number and the number of nations joining the space community will soon increase. At the same time the trend to decrease the GSD will continue.

Table 2. Small satellite high resolution mapping missions

Mission	**Highest GSD [m]**	**Launch**
IKONOS 2/USA	0.82 m	1999
EROS-A1/ Israel	1.8 m	2000
PROBA/ESA	5 m	2001
HRG on SPOT-5/France	5 m	2002
OrbView 3/USA	1 m	2003
FORMOSAT-2/Taiwan	2 m	2004
PAN (BJ-1)/China	4 m	2005
EROS-B/ Israel	0.82 m	2005
TOPSAT/UK	2.5 m	2005
DMC/China	4 m	2005
PAN (Cartosat-1)/India	2.5 m	2005
Resurs DK 1/Russia	1 m	2006
CBERS-2B/China/Brazil	2.4 m	2007
WorldView-1/USA	0.45 m	2007
THEOS/Thailand	2 m	2008
GeoEye 1/USA	0.41 m	2008
MAC/ Korea, Malaysia	2.5 m	planned
MSMI/ South Africa	2.5 m	planned

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