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Dynamic MTF estimate of the optical imager onboard Alsat-1B satellite

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ABSTRACT

Unwanted movements during image recording usually cause problems for optical imaging systems onboard Earth Observation satellites. The major effect of these movements is the degradation of image quality by smearing and distortion. The aim of this paper is to provide estimates of the blur-caused MTF of an isolated CCD detector element as a result of linear motion to evaluate the impact of such blur, that may be experienced operationally, on the whole system MTF of the Alsat-1B imager. The estimates are made on ground prior to launch and include effects caused by linear motion of the spacecraft relative to the earth and exclude effects of motion caused by mechanical vibration or platform drift. Those estimates are of great importance as part of system level analysis which can help restoring the degraded image.

Keywords: Optical Imaging Systems, Earth Observation Satellite, Motion Smear, Modulation Transfer Function

1. INTRODUCTION

Optical imaging systems onboard Earth Observation satellites are usually prone to angular movements during image recording that can result in severe degradation of image quality by smearing. These unwanted velocities are mainly caused by: (1) satellite orbital motion relative to the earth; (2) Line of sight (LOS) angular motion in inertial space due to spacecraft mechanical vibration. It is thus quite useful to estimate the expected image degradation caused by image motion as part of system level analysis which can help restoring the degraded image. Degradation of image quality as a result of image motion can be described by the modulation transfer function, MTF. The modulation transfer function has been recognized to be a convenient form to include such effect in system design. The MTF is an often used performance criterion for describing the resolving capability of optical imaging systems in particular those on board Earth Observation Satellites. An important property of the MTF of a system is that it is made up of the product of the separate MTFs of all the components within the system. This includes optics, imaging detector and imaging system electronics. The total system MTF is generally limited by the MTF of the weakest component. In systems involving image motion or vibration, this weakest component is often the blur caused by the image motion, rather than resulting from optical or electronic components [1].

A wide range of works have been proposed in the literature for on orbit MTF assessment [2-4]. However, few of works have been devoted to Dynamic MTF measurement and estimation on ground prior to launch [5], [6].

In this paper, we present a methodology with which to estimate the blur-caused MTF of an isolated CCD detector element as a result of linear motion to evaluate the impact of such blur, that may be experienced operationally, on the whole system MTF of the Alsat-1B imager. It should be noted that the MTF of an isolated detector element can be measured in the laboratory, but cannot easily be measured in orbit because the MTF of the whole system is affected by sampling considerations.The estimates include effects caused by linear motion of the spacecraft relative to the earth and exclude effects of motion caused by mechanical vibration. Estimation of the expected effect of mechanical vibration on the performance of Alsat-1B satellite imager has been the subject of another work [7]. Those estimates are of great importance for system design and system analysis purposes.

This paper is organized as follows. A brief description of Alsat-1B satellite is provided in Section 2. The adopted process for estimating the dynamic MTF is described in Section 3. In Section 4, the results obtained are discussed. Finally, Section 5 concludes this paper.

2. ALSAT-1B SATELLITE

Alsat-1B is a medium resolution Earth Observation satellite with a mass of 100 kg. It has been launched into a 670 km sun-synchronous orbit on board the PSLV launch vehicle on 26 September 2016. Alsat-1B image products will be used for agricultural and resource monitoring, disaster management, land use mapping and urban planning [8].

Alsat-1B is based on the SSTL-100 platform, and flies a 24 m multispectral (MS) imager and a 12 m panchromatic (PAN) imager delivering images with a swath width of 140 km. Alsat-1B imager is based on CCD linear array detectors. The multispectral (MS) channels (Red, Green, Blue and Near-Infrared) call for signals from adjacent pairs of detector elements to be binned (co-added) in order to achieve the effective 24 m nominal ground sampling distance (GSD) in the across-track direction (the direction orthogonal to the flight direction), whereas the extended exposure time applied to the spectral channels allows for the 24 m GSD in the along-track direction (flight direction).

3. METHODOLOGY

The task is to provide estimates of the blur-caused MTF as a result of linear motion to evaluate the impact of such blur on the whole system MTF of Alsat-1B imager. The calculation is based upon the following inputs:

- Detector MTF estimates (derived from a simulation model). Detector MTF estimates are made separately for each spectral band.
- Telescope MTF estimates drawn from an optical model. Telescope MTF estimates are made separately for each spectral band.
- Operational parameters including the operating mode, the exposure times, orbit inclination and ground speed at different latitudes.

3.1 Assumptions

The effects of motion smear are calculated based on the following assumptions:

- All image motions are assumed to result from a combination of the orbital motion and the Earth's rotation and do not take account of any effect caused by mechanical vibration.
- It has been assumed that the platform remains "steady" throughout image acquisition: this means that roll, pitch and yaw motions are assumed to impart minimal movements to the image.
- The estimates are provided for the nominal design orbit which has an altitude of 700 km, for which the velocity of the sub-satellite point has been calculated. This velocity is aligned according to the orbit inclination.
- The velocity of the earth's surface at selected latitude is computed assuming a spherical Earth. This is combined with the orbital velocity to give the effective ground velocity of the sub-satellite point (speed and direction over ground).
- The telescope's focal length is used to scale the image of the scene on the focal plane. All calculations are then carried out in terms of the image motion at the focal plane.

3.2 Motion Smear Calculation

This section is concerned with the calculation of the blur-caused MTF as a result of linear motion during image acquisition.

The MTF degradation due to linear motion is given by [1]:

$$MTF(f) = \left|\mathrm{sinc}\left(\pi\ f\ vT_e\right)\right| \tag{1}$$

where v is the uniform relative velocity of the satellite over the ground, T_e is the exposure time of the camera and f is the spatial frequency coordinate.

The effects of motion smear are calculated by reference to the following quantities:

- The exposure times for the PAN and multi-spectral channels (these are related by a factor of two).
- The velocity of the sub-satellite point over the ground is computed from the orbit parameters (inclination, altitude) and the velocity of the earth's rotation (which varies with latitude).
- Using the telescope geometry, the velocity of the image can be computed, allowing for a potential "yaw" of the imager with respect to the flight direction. This step gives image motions resolved along the detector axis and across the detector.

Assuming that the motion is a simple linear displacement at a constant and uniform speed, it is then possible to calculate the corresponding contribution to the MTF in the form of a one-dimensional "*sinc*" function (Equation 1) whose width is inversely proportional to the total motion that occurs during the exposure. Two different motion smear corrections are then calculated (PAN and multi-spectral, according to the exposure times). This MTF contribution is then applied (by multiplication) to the system static MTF.

3.3 Total system MTF calculation including motion smear

The total MTF including linear motion smear is then given by:

$$\text{System dynamic MTF} = \text{System static MTF} \times \text{Blur-caused MTF} \qquad (2)$$

where static MTF is the expected MTF without any motion smear and including detector and telescope (optics) MTFs contributions [9].

All estimates are made as ‘‘2-D" MTFs – MTFs which are calculated as a function of spatial frequency and direction. Special attention is given to the directions parallel to and orthogonal to the detector long axes.

4. RESULTS AND DISCUSSION

The modifications to the Alsat-1B MTF which are caused by linear motion smear are made available for inspection by generating plots. These plots represent the MTF of one isolated detector element at the focal plane of the telescope; no account is taken of sampling artefacts.

4.1 Linear Motion Smear

Figure 1 shows the two MTF contributions from motion blur calculated as described above for the PAN and Multispectral bands.

Each MTF contribution is a tilted 1-dimensional "*sinc"* function. The PAN motion blur contribution is relatively much wider because the shorter exposure time gives rise to a smaller image smear. The MS smear contribution is half as wide because the image smear is double that of the PAN channel. The rotation implies that, whilst the majority of the MTF degradation will be applied in the across-detector direction (flight direction), a small component will also be applied in the "along-detector" direction. The black bands in these figures indicate spatial frequencies at which the MTF contribution is zero.

The tilt shown in the figures (which has an angle of -3.9 degrees) is caused by the motion of the earth under the sub-satellite point: the effect is most severe at the equator, where the track over ground is deflected by 3.9 degrees compared to the orbital inclination of 8.5 degrees with respect to the polar direction. Image acquisition at higher or lower latitudes will incur a smaller yaw tilt. The calculation can be made at different latitudes.

The effects of motion smear will be to restrict the MTF somewhat in the vertical axis, but the MTF in the along-detector direction (horizontal axis) will remain largely un-changed.

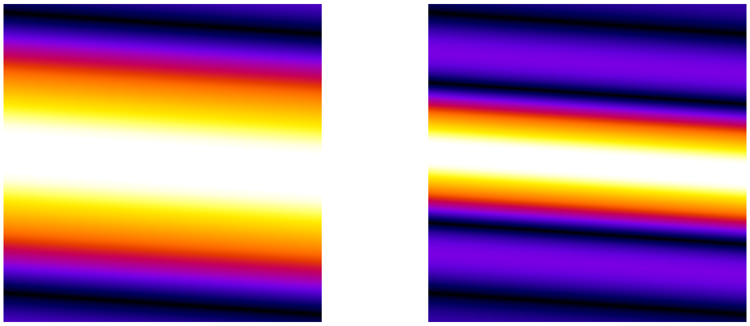

Figure 1. Motion blur MTF contributions for PAN band (left) and Multi-Spectral bands (right). The vertical axis represents the nominal flight direction. Scale is +/- 142 cycles / mm on each axis.

4.2 MTF of isolated detector elements including Motion Smear effect

To quantitatively characterize the effect of motion smear on MTF, the linear motion contributions described above are combined with the static MTF according to Equation (2) to calculate the total effective MTF of a single detector element for the PAN band or of an isolated, adjacent pair of detector elements whose signals have been co-added for the MS bands.

To illustrate the expected MTF performance before any motion smear is taken into account, static MTFs including telescope and detector contributions are presented for the PAN and selected multi-spectral (GREEN) channels (Figure 2(left) and Figure 3(left)). The Green band static MTF in the ‘‘along-detector” direction (horizontal axis) is significantly narrower than that of the PAN channel; this is the consequence of the binning. The effect of binning is, in fact, to apply a one-dimensional ‘‘sinc” function to the static MTF in the along-detector direction only with a width inversely proportional to two detector elements wide.

Figure 2(right) displays the expected dynamic MTF including motion smear for a single PAN detector element. It can be seen that the PAN MTF has been contracted in the across-detector direction (vertical axis) as expected with a smaller effect on the MTF in the along-detector direction. The MTF is very slightly “skewed” because of the yaw, but in practical terms this difference is very small.

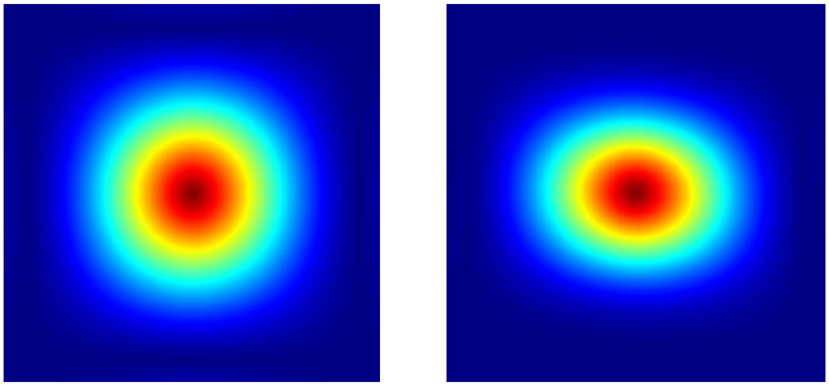

Figure 2. (Left) Static MTF for PAN band including telescope and detector contributions. (Right) PAN band dynamic MTF for an isolated detector element. The MTF range is +/- 142 cycles / mm on each axis and the vertical axis represents the nominal flight direction. The image motion is inclined with respect to the detector axes.

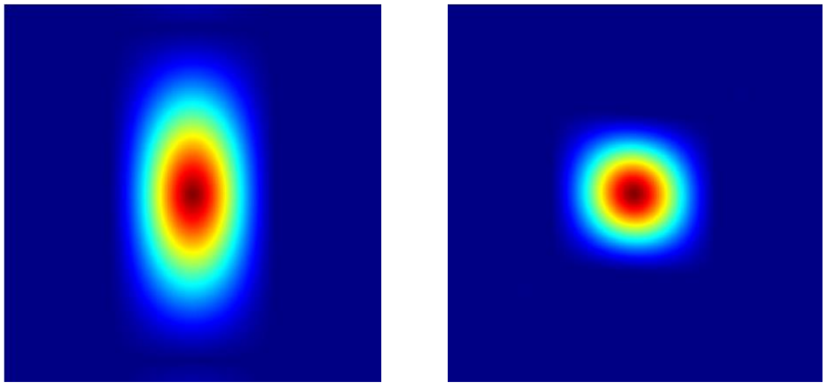

Figure 3. (Left) Static MTF for GREEN band, including telescope and detector contributions. (Right) GREEN band dynamic MTF for an isolated detector element. The MTF range is +/- 142 cycles / mm on each axis and the vertical axis represents the nominal flight direction. The image motion is inclined with respect to the detector axes.

Figure 3(right) illustrates the expected dynamic MTF including motion smear for an isolated pair of GREEN detector elements. The effect of motion smear for this case is more noticeable as expected. The green band dynamic MTF is significantly narrower than that of the PAN channel: this is controlled mainly by the binning in the x-axis and by the motion smear acting mostly in the vertical axis. The plot shows also the skew produced by the earth surface motion. This is true for all MS bands.

This statement is confirmed by the estimated values of the dynamic MTF at Nyquist frequency given in Table 1. It can be noticed that the Near Infra-Red (NIR) MTF is obviously lower compared to the other bands; this is the consequence of the light absorption depth and lateral charge diffusion.

Table 1. Estimated values of Static and Dynamic MTF @ Nyquist Frequency. For PAN band: Nyquist frequency is 62.5 cycles/mm at the detector. For MS bands: Nyquist frequency is 31.25 cycles/mm at the detector.

Band	**Along-Detector**		**Across-Detector**	
	Static MTF @ Nyquist	**Dynamic MTF @ Nyquist**	**Static MTF @ Nyquist**	**Dynamic MTF @ Nyquist**
PAN	0.42	0.42	0.43	0.26
Blue	0.47	0.47	0.77	0.45
Green	0.47	0.47	0.75	0.45
Red	0.46	0.46	0.74	0.44
NIR	0.35	0.35	0.71	0.42

5. CONCLUSION

This paper provided estimates of the Alsat-1B dynamic MTF that may be experienced operationally. Estimates of motion smear caused MTFs have been first calculated for the panchromatic and Multispectral channels. Then, the impact of motion smear has been evaluated by calculating the whole system MTF of Alsat-1B imager including the estimated motion-caused MTF. The simulation results demonstrated that the effects of motion smear will be to restrict the MTF somewhat in the vertical axis (the flight direction), but the MTF in the along-detector direction (horizontal axis) will remain largely un-changed. It has to be noticed that the estimated MTFs contribute to but do not completely represent the MTF of the entire camera system. These estimates include just the effects of linear motion of the payload/platform in orbit and do not take account of any effect caused by mechanical vibration or sampling process. Those effects are the subject of other works.

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