Performance Characteristics of Time Delay and Integration(TDI) Satellite Imager for Altitude Change and Line-Of-Sight Tilt over Spherical Earth Surface

Young-Min Cho
Korean Aerospace Research Institute
P.O. Box 113 Yuseong, Taejon, 305-600, Republic of Korea
TEL:82-42-860-2218, FAX:82-42-860-2007, E-mail:ymcho@kari.re.kr

ABSTRACT

A spherical Earth surface is used for realistic analysis of the geometrical performance characteristics about the variation of satellite altitude and 2-dimensional line-of-sight(LOS) tilt angle in a satellite imager using Time Delay and Integration(TDI) technique with fixed integration time. In the spherical Earth surface model TDI synchronization using LOS tilt is investigated as a solution to compensate geometric performance degradation due to altitude decrease. This result can be used for a TDI CCD imager with variable integration time in a certain as well.

1. INTRODUCTION

Recently many high resolution satellite electro-optical imaging instruments use Time Delay and Integration (TDI) technique in order to improve signal to noise ratio (SNR).

TDI technique is carried out by detecting a signal from one ground spot several times using a series of Charge Coupled Device (CCD) pixels and integrating all the signals of the pixels with time delay (Larson and Wertz, 1991). It is important in the TDI technique that each pixel used in the TDI detects one ground spot signal exactly with a certain time interval. It can be called TDI mismatch that each pixel does not detect one ground signal exactly. Usually the number of TDI means the number of all the CCD pixels used in the TDI. As the TDI number increases, the SNR is improved while the side effect of TDI mismatch can increases. The TDI mismatch can be caused by several reasons such as misalignment of the CCD pixels and give rise to blurred image. The performance of imaging instrument related to image contrast is usually expressed by Modulation Transfer Function (MTF). In general the MTF expression due to TDI mismatch is well known (ELOP, 2000).

It is natural that satellite has the capability to change the line of sight (LOS) and alters it often for its mission. The altitude of satellite decreases naturally from its initial orbit altitude after launch if it is not maintained by force (Kim, Kim, and Choi, 2002). It can also happen that satellite altitude changes from the designed value due to unexpected reason. The change of satellite altitude and LOS causes the variation of Ground Sample Distance (GSD) and TDI mismatch for the case that the change is out of the instrument limit. In other words the change of satellite altitude and LOS affects instrument performance which controls image quality mainly.

A recently report showed conceptual investigation about the variation of satellite altitude and LOS tilt in a

TDI satellite imager by approximating the Earth surface

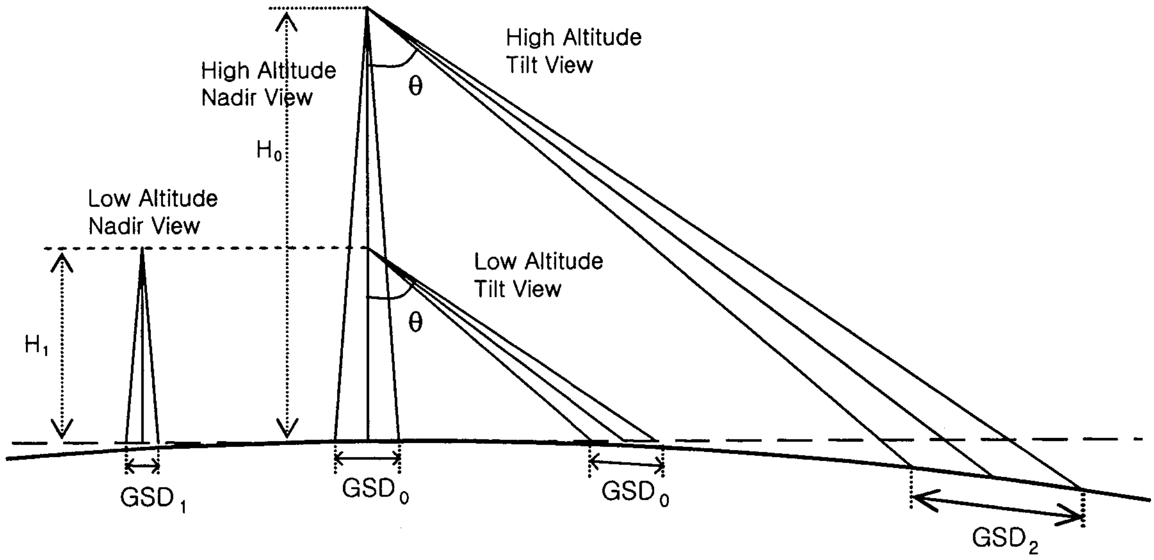

Fig. 1 The geometry of Ground Sample Distance (GSD) for variation of altitude(H) and LOS tilt angle(θ)

to a plane (Cho, 2002). In order to improve the investigation from conceptual level to realistic application level, a spherical Earth surface is introduced and any 2-dimensional LOS tilt direction is considered for geometric performance analysis of TDI satellite imager with fixed integration time.

2. ALTITUDE VARIATION

In the nadir view of a satellite imaging instrument, GSD is linearly proportional to the altitude of the satellite as shown in the geometry of the Fig. 1. Altitude change gives rise to the variation of ground scan velocity in the push-broom scanning satellite as well as the GSD variation. As the altitude decreases, the ground scan velocity increases while GSD decreases. This is why each TDI pixel can not detect the same ground position exactly in case that the altitude alters from the optimally designed altitude where TDI match is already achieved in case of the nadir view. It means that TDI mismatch occurs when altitude alters from the optimal value.

The Fig. 2 and the Fig. 3 show the main geometrical performance related to altitude variation in the high

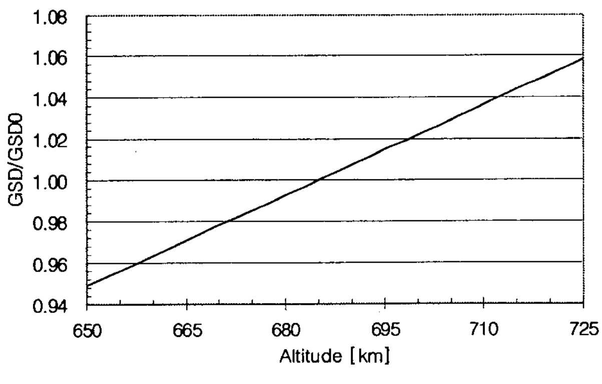

Fig. 2 GSD v.s. Altitude (GSD0: GSD at 685km)

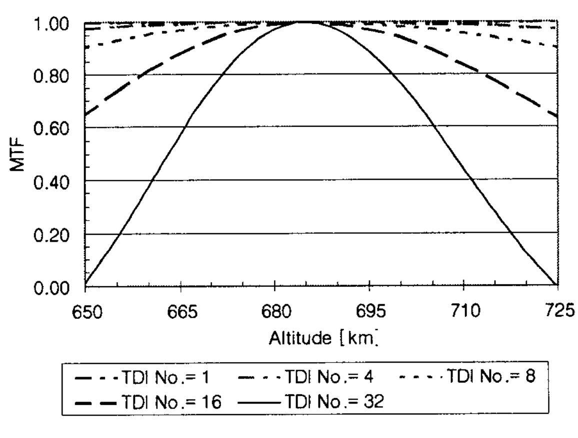

Fig. 3 TDI mismatch MTF v.s. Altitude

resolution satellite imaging instrument with the optimal design altitude of 685km. It is shown in the Fig. 2 that about 5% variation of GSD is caused by the altitude change of 30km from the altitude of 685km. The TDI mismatch MTF at the Nyquist frequency of each altitude is calculated in the altitude range of the Fig. 2 using its well known expression and the results are shown in the Fig. 3. The altitude change of 30km from the altitude of 685km gives considerable degradation of instrument performance, about 20~30% decrease of MTF for the TDI number of 16 and 70~80% decrease of MTF for the TDI number of 32. Since most high resolution satellite instruments use the TDI number of 32, the altitude change can not bring to the desired image quality with high possibility.

3. LINE-OF-SIGHT(LOS) TILT

Satellite often tilts its LOS toward the along track direction or the cross track in order to observe interesting ground area which is not located at the nadir view

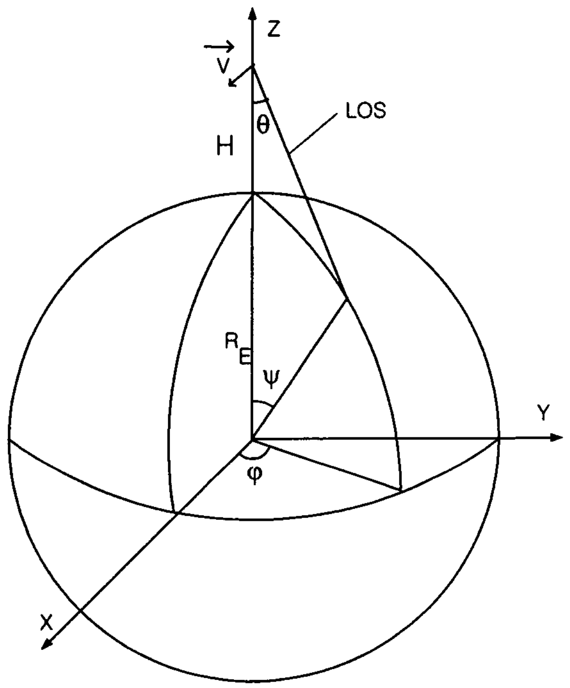

Fig. 4 Line-Of-Sight(LOS) tilt angles θ and φ

position. The tilt of LOS can be done by scan mirror rotation or satellite spin. In order to analyze the geometric performance degradation due to LOS tilt accurately to the extent of the accuracy almost applicable in the real operation of satellite, a spherical surface is used for Earth surface modeling in stead of a plane which is often used for conceptual investigation. The spherical Earth model gives more realistic results regarding the TDI mismatch than the plane as well.

Any 2-dimensional tilt direction over the spherical Earth surface is considered for realistic satellite operation. The direction of LOS from satellite to a ground observation position on the Earth surface can be expressed by two angles θ and φ which are defined as the angle between LOS and Z axis and the angle between the projection of LOS on XY plane and X axis respectively in the Cartesian coordinate, which has its origin at the center of the spherical Earth, X axis to the satellite velocity direction (in the along track direction), and Z axis from the origin to the satellite (opposite to the nadir direction) as shown in the Fig. 4. So, the angle θ is 0 deg. in the nadir view, the angle φ is 0 deg. with LOS in the along track direction, and the angle φ is 90 deg. with LOS in the cross track direction. From the symmetry of the geometry in the Fig. 4 it is clear that the tilt results for each of four φ divisions with the interval of 90 deg. in the total range of 360 deg. should be equal, so it is enough to consider the range of the angle φ as 0~90 deg. only.

From the geometry for the LOS tilt in the Fig. 1 it is easy to understand that the bigger tilt angle θ is the bigger GSD is. The variation of GSD in the altitude of 685km due to the change of both tilt angles is shown in the Fig. 5 and 6 with the contour plot of the Fig. 7 on the top plot surface. While the increase of the tilt angle θ gives the increase of GSD in the both direction, the along track direction (the X-axis direction) and the cross track direction (the Y-axis direction), the increase of the

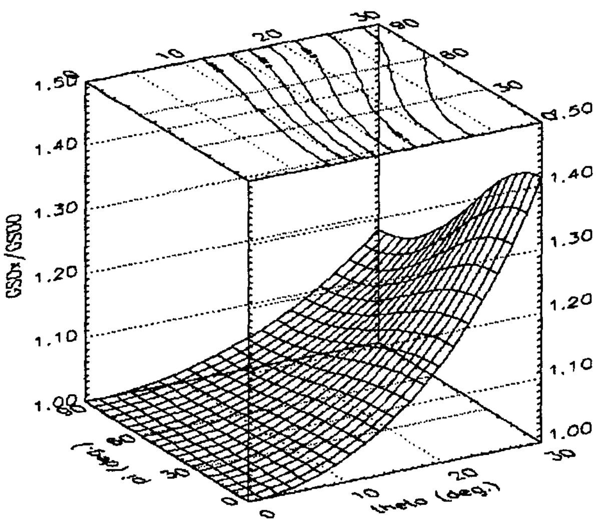

Fig. 5 Along track GSD (GSDx) v.s. LOS tilt angles θ and φ (GSD0: GSD at the nadir view)

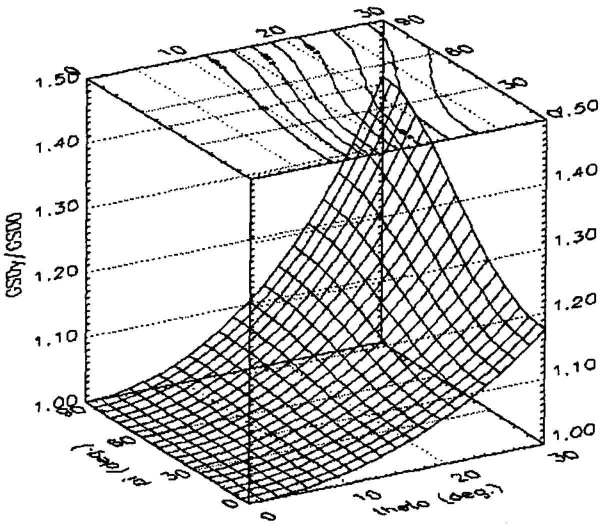

Fig. 6 Cross track GSD (GSDy) v.s. LOS tilt angles θ and φ (GSD0: GSD at the nadir view)

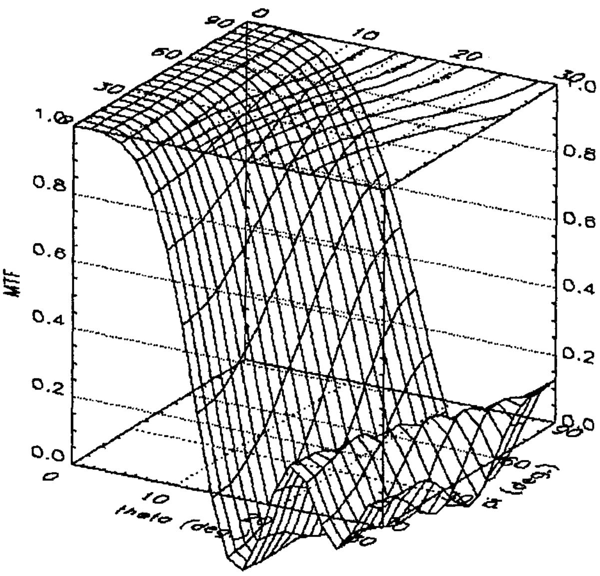

Fig. 7 TDI mismatch MTF v.s. LOS tilt angles θ and φ

tilt angle φ shows the opposite behavior in the along track GSD (GSDx) and in the cross track GSD (GSDy) each other. This GSD behavior to the tilt angle φ can be understood easily from the symmetry related to the GSD direction and the LOS tilt direction. For example the along track GSD (GSDx) at the along track tilt(φ = 0 deg.) has the same value as the cross track GSD (GSDy) at the cross track tilt(φ = 90 deg.). The tilt angle θ of 30 deg. brings to about 40% increase of the along track GSD from the GSD of the nadir view at the along track tilt and about 18% increase of the along track GSD at the cross track tilt. The tilt angle θ of 30 deg. brings to about 40% increase of the cross track GSD at the cross track tilt and about 18% increase of the cross track GSD at the along track tilt.

The TDI mismatch MTF of each LOS tilt is calculated at the Nyquist frequency for the TDI number of 32 in the altitude of 685km as shown in the Fig. 7. The 3-dimensional plot of the Fig. 7 has its contour map on the top plot surface. As the tilt angle θ increases, the MTF decreases significantly for bigger angles than about 5 deg.. The MTF is almost zero in the along track tilt with the tilt angle θ of about 13 deg. and in the cross track tilt with the tilt angle θ of almost 20 deg..

4. TDI RE-MATCH USING LOS TILT AT DECREASED ALTITUDE

The above paragraphs have shown that both the altitude change and the LOS tilt bring to not much GSD variation but result in significant image blur. Especially it is noted that GSD decreases as altitude decreases while GSD increases as LOS tilt angle from the nadir direction

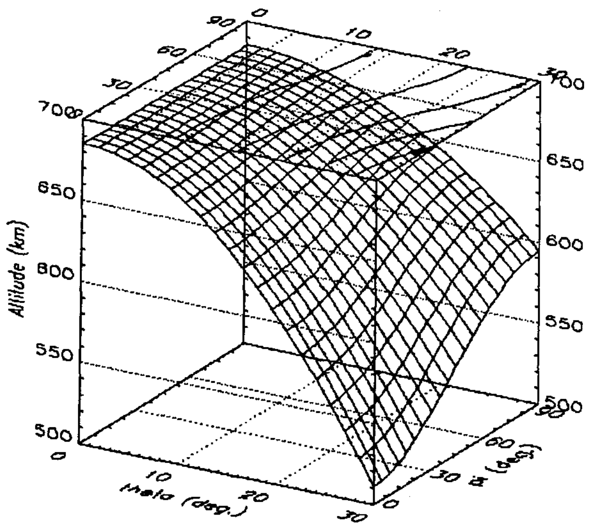

Fig. 8 LOS tilt angles for TDI re-match at altitudes decreased from 685km.

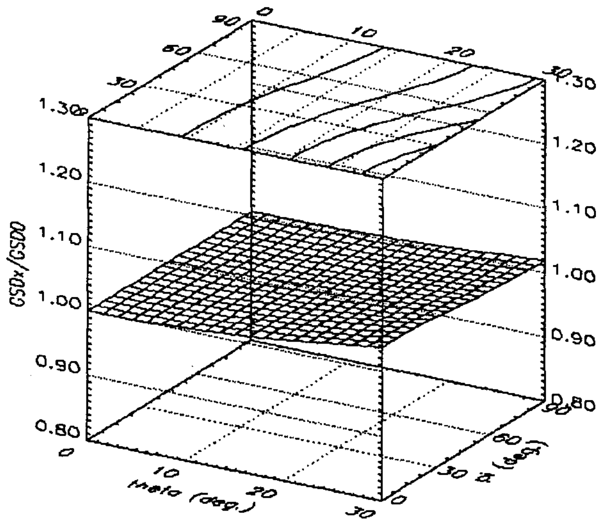

Fig. 9 Along track GSD (GSDx) v.s. LOS tilt angles θ and φ for TDI re-match (GSD0: GSD at the nadir view from the altitude 685km)

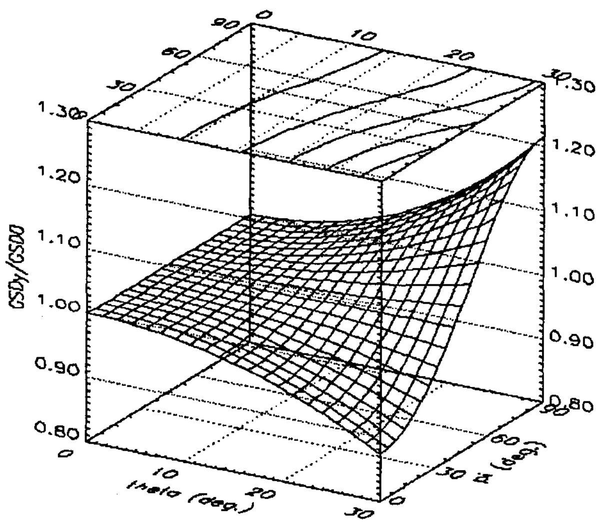

Fig. 10 Cross track GSD (GSDy) v.s. LOS tilt angles θ and φ for TDI re-match (GSD0: GSD at the nadir view from the altitude 685km)

increases. This gives rise to the idea that LOS tilt can cancel the GSD decrease due to altitude decrease and prevent significant geometric performance degradation in the case of altitude decrease. In other words the TDI mismatch produced from altitude decrease can be removed by an optimal LOS tilt at the decreased altitude to maintain the TDI MTF value of 1.0 (no TDI MTF degradation) and to prevent image blur due to altitude decrease. This is the case of the low altitude tilt view in the Fig. 1.

The optimal LOS tilt for the TDI re-match (the removal of TDI mismatch) can be expressed in terms of the angles θ and φ and is plotted in the Fig. 8 at decreased altitudes from the optimal design altitude 685km where TDI match is already achieved in case of the nadir view. The 3-dimensional plot of the Fig. 8 has its contour map on the top plot surface. The TDI re-match can be achieved by the along track tilt (φ = 0 deg.) with the angle θ of 30 deg. at the decreased altitude to about 510km from the 685km and the cross track tilt (φ = 90 deg.) with the angle θ of 30 deg. at the decreased altitude to about 590km from the 685km. At the altitude of 600km the TDI re-match can be achieved with the angle θ of about 20 deg. in case of the along track tilt or with the angle θ of almost 30 deg. in case of the cross track tilt. Since the along track tilt (φ = 0 deg.) can realize TDI re-match with the minimum angle θ at a given decreased altitude, the along track tilt can be most effective tilt.

The GSD in case of the TDI re-match by LOS tilt at decreased altitude is plotted with the parameters of the angles θ and φ in the Fig. 9 and 10. The 3-dimensional plots of the Fig. 9 and 10 have the contour map of the Fig. 8 on the top plot surfaces. The angles θ and φ in the Fig. 9 and 10 are equivalent to the LOS tilt angles for the TDI re-match in the Fig.8, i.e. the GSD in the Fig. 9 and 10 is the value obtained at the altitude of the Fig. 8 for the corresponding LOS tilt angles θ and φ. There is not much variation of the along track GSD (GSDx) versus LOS tilt in the Fig. 9 while significant variation of the cross track GSD (GSDy) is shown in the Fig. 10. It is important to note that the TDI re-match can achieved by small along track GSD increase (e.g. about 4% increase at the altitude of 510km in case of the along track tilt with the angle θ of 30 deg.) and by reduced cross track GSD in case of the tilt with angle φ less than about 40 deg. (e.g. 13% off at the altitude of 510km in case of the along track tilt with the angle θ of 30 deg.).

Another important note is that any 2-dimensional direction of LOS tilt given by the angles θ and φ can be used for the TDI re-match in case of altitude decrease as shown in the Fig. 8. This gives considerable mission operation flexibility that any ground point can be observed without image blur due to GSD variation and TDI mismatch although altitude decreases as long as the LOS is controlled in proper way as shown in the Fig. 8, 9, and 10. Since the along track tilt gives the minimum GSD increase as well as the minimum tilt angle for the TDI re-match, it is most effective and most desirable to use the along track tilt with the optimal angles θ at decreased altitude. It is recommended to use the tilt with angle φ less than about 40 deg. in order to maintain almost no increase of GSD in case of the observation of the ground area out of the nadir view position.

5. CONCLUSIONS

A spherical Earth surface is used for realistic analysis of GSD and MTF about the variation of satellite altitude and 2-dimensional LOS tilt angle in a TDI satellite imager with fixed integration time. LOS tilt is used as a solution to compensate geometric performance degradation due to altitude decrease. The compensation (TDI re-match) can achieved with no TDI MTF degradation and small GSD increase (e.g. less than about 4% increase at the altitude decreased to 510km from 685km in case of the along track tilt with the tilt angle θ of 30 deg.). The most effective TDI re-match can be obtained by the along track tilt. The tilt with angle φ less than about 40 deg is recommended for the observation of the ground area out of the nadir view position. This result can be used for a TDI CCD imager with variable integration time in a certain range as well.

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