Imaging System Design Performance of Multi-functional Transport Satellite

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Abstract

Multi-functional Transport Satellite (MTSAT) will be launched in geostationary orbit at 140 east longitude around August 1999. MTSAT has two functions; one is for meteorological services in Japan Meteorological Agency (JMA) and the other for air-traffic control services in the Civil Aviation Bereau, Ministry of Transport of Japan.

The Preliminary Design Review of MTSAT was held in December 1995 and the Critical Design Review was held in October 1996. This report describes the design performance of the imaging function of MTSAT.

1. MTSAT

Multi-functional Transport Satellite (MTSAT) will be launched in geostationary orbit at 140 east longitude around August 1999. MTSAT has two functions; one is for meteorological services in Japan Meteorological Agency (JMA) and the other for air-traffic control services in the Civil Aviation Bereau, Ministry of Transport of Japan.

MTSAT will be a successor to Geostationary Meteorological Satellite-5 (GMS-5). The major functions of MTSAT for the meteorological services are:

- Imaging function
  - Five-channel Imager (Visible and Infrared Radiometer)
- Telecommunication function
  - Transmission of raw Imager data
  - Relay of High Resolution Imager Data (HiRID: in place of Stretched-VISSR, processed data)
  - Relay of weather facsimile (WEFAX) and Low Rate Image Transmission (LRIT) signals
  - Relay of Data Collection Platform (DCP) signals

Figure 1 shows the communication links between MTSAT and ground systems for the meteorological services.

Space Systems/Loral of Palo Alto, CA, is the prime contractor for MTSAT. The Aerospace/Communication Division of ITT Industries is the subcontractor to SS/L for the Imager instrument. The Preliminary Design Review of MTSAT was held in December 1995 and the Critical Design Review was held in October 1996. This report describes the design performance of the imaging function of MTSAT.

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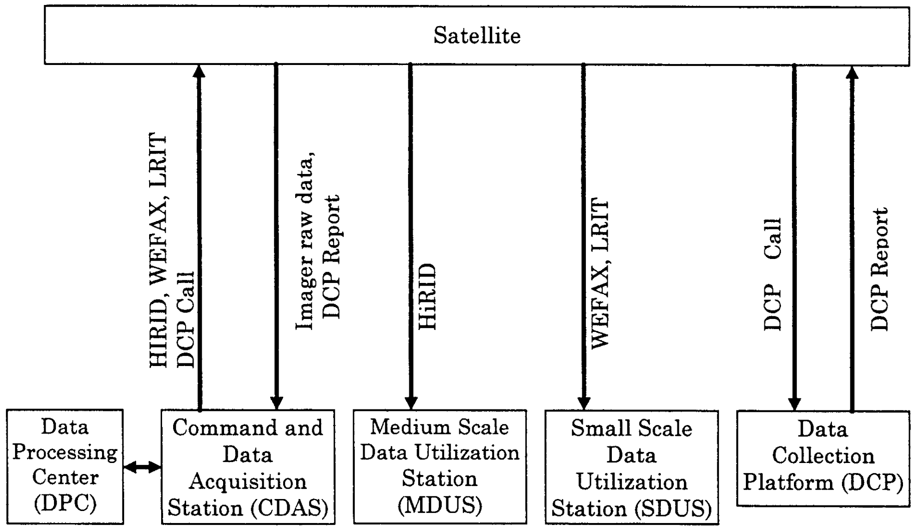


Figure 1 Communication links for meteorological services

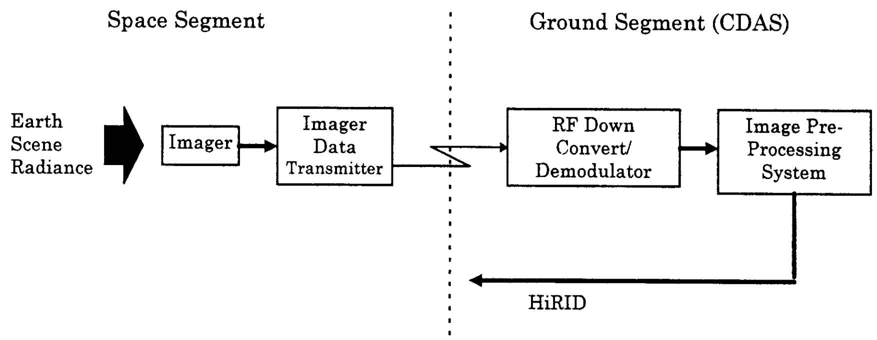


Figure 2 Image Signal Flow through Imaging System

2. Imaging System

Figure 2 shows the image signal flow through the MTSAT imaging system. The Imager collects scene radiance and converts it into a digital data stream. This data stream is transmitted to the Command and Data Acquisition Station (CDAS), then the stream is demodulated and provided to the Image Pre-Processing System. The Image Pre-Processing System generates the HiRID that is sent to users.

3. Spacecraft Configuration

The MTSAT spacecraft configuration, shown in Figure 3, is a three-axis, body-stabilized design capable of continuously pointing the optical line of sight of the Imager to the earth. A single-wing, three-panel solar array on the south-facing side rotates to track the sun. The use of a single-wing solar array allows the passive north-facing radiation cooler of the Imager to view cold space. A solar sail on the north side balances the torque caused by solar radiation pressure. A trim tab panel at the end of the solar array provides the fine balance control of the solar radiation pressure.

The MTSAT spacecraft configuration is based on the Geostationary Operational Environmental Satellite (GOES) I-M spacecraft configuration.

4. Imager

4.1 Modules

The MTSAT Imager is based on the GOES I-M Imager. The Imager consists of Electronics Module, Power Supply Module and Sensor Module. Figure 4 shows three modules of the Imager.

The Sensor Module contains the telescope, scan assembly, detectors, thermal louver, and passive radiant cooler. The passive radiant cooler maintains the infrared detectors below 100 K. Average power consumption of the Imager is approximately 100 W, total weight of three modules is approximately 125 kg.

The Electronics Module performs command, control, and signal processing functions. The Power Supply Module contains the converters, fuses, and power control interface with the spacecraft power subsystem.

4.2 Detectors

The Imager has one visible channel and four infrared channels. The visible channel uses photovoltaic silicon detectors. The infrared channels use photovoltaic InSb and photoconductive HgCdTe. Figure 5 is a drawing of the detector geometry.

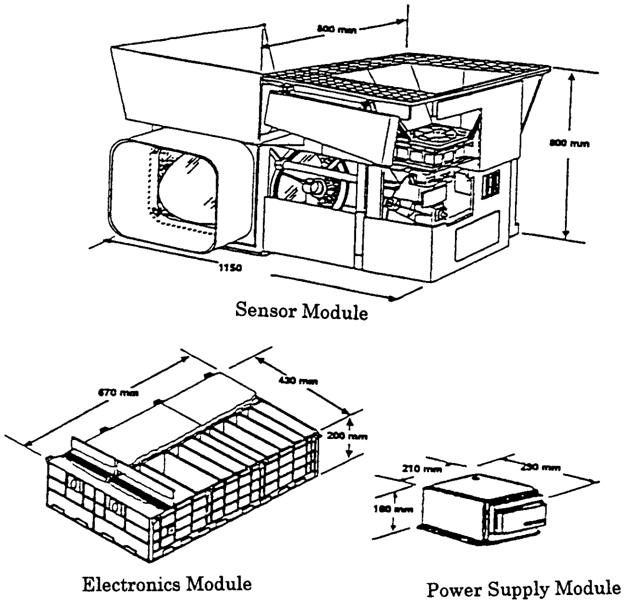


Figure 4 Imager Modules

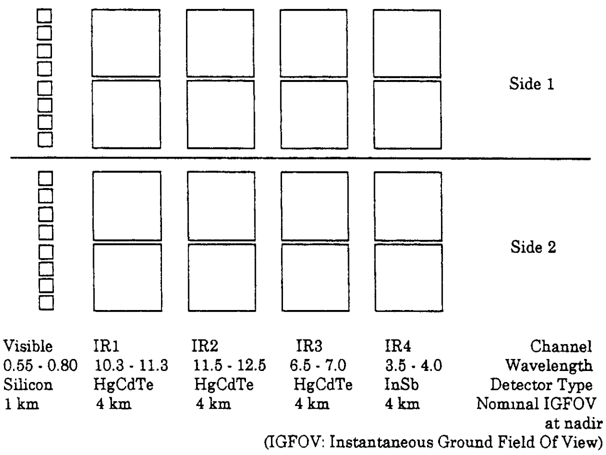


Figure 5 Detector Geometry

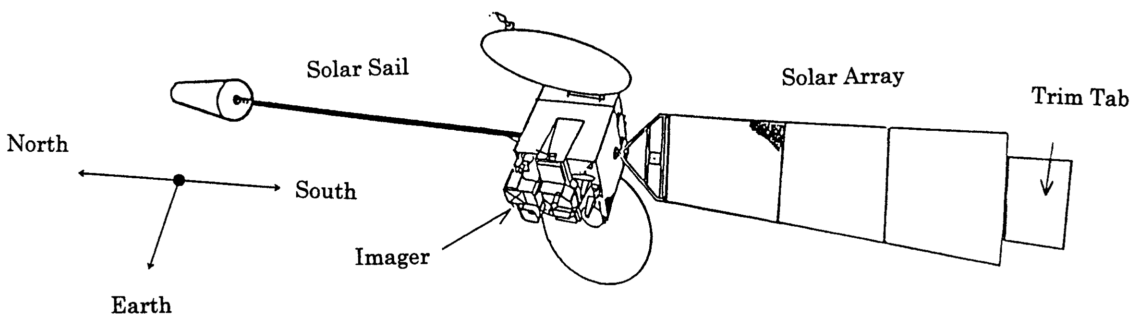


Figure 3 MTSAT On-Orbit Configuration

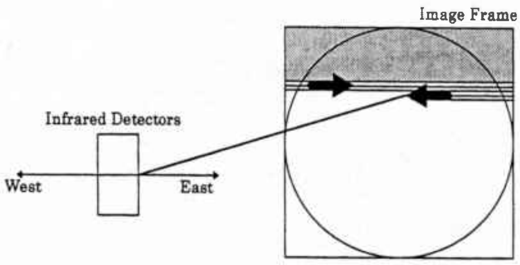


Figure 6 Scan Operation

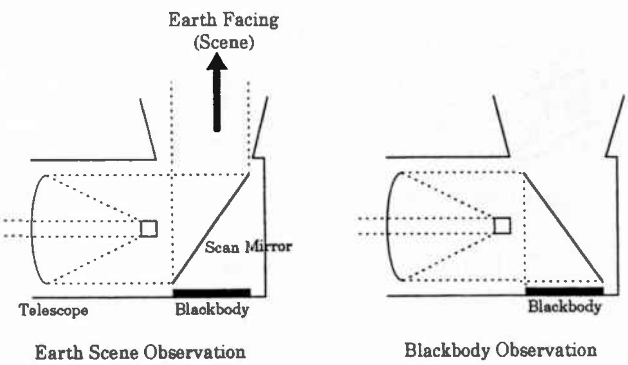


Figure 7 Blackbody Calibration

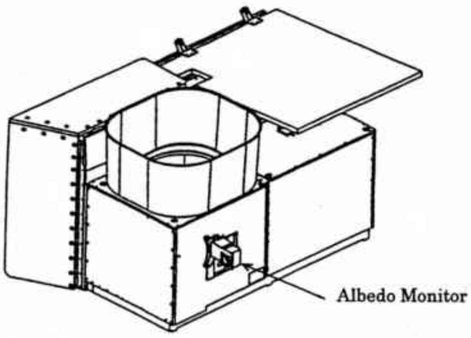


Figure 8 MTSAT Imager with Albedo Monitor

4.3 Operation

The Imager contains a servo-driven, two-axis gimballed scan mirror. During scan operation, a scan line is generated by rotating the scan mirror in east-west direction. The first scan line is acquired by rotating the scan mirror in the west-to-east direction. At the end of the line, the scan mirror elevation (north-to-south direction) is changed by a stepped rotation. The next scan line is acquired by rotating the scan mirror in the east-to-west direction. Figure 6 shows the concept of the Imager scan operation.

The full disk scan time of the Imager is 27.5 minutes and the half-disk scan time is 14.3 minutes. In other words, the Imager observes repeated full disk scans every 30 minutes with a 2.5 minutes margin, and observes repeated half-disk scans every 15 minutes with a 0.7 minutes margin.

Position and size of a scan area are controlled by command, so the Imager is capable of various scan area sizes. Scan area selection provides continuous, rapid viewing of local areas for monitoring mesoscale phenomena.

Motion of the Imager scan mirror causes a small disturbance of spacecraft attitude. The disturbance caused by scan motion is calculated by the Attitude and Orbit Control Subsystem (AOCS) of the spacecraft. Then, the AOCS provides the compensation signals of scan mirror positions to the Imager.

4.4 Infrared Channels Calibration

An internal blackbody of the Imager is used to calibrate the infrared channels. The blackbody is within the Imager, near the scan mirror. Figure 7 shows the concept of the infrared calibration using the blackbody source. The Imager views the blackbody source when the scan mirror rotates 180 degrees (to the opposite direction) from nadir. The blackbody calibration will be performed every 30 minutes.

4.5 Visible Channel Calibration

Calibration of the visible channel is performed using the albedo monitor. Figure 8 shows the albedo monitor installed on the Imager. The albedo monitor sends sunlight into the Imager optical path. The amount of sunlight passing through the

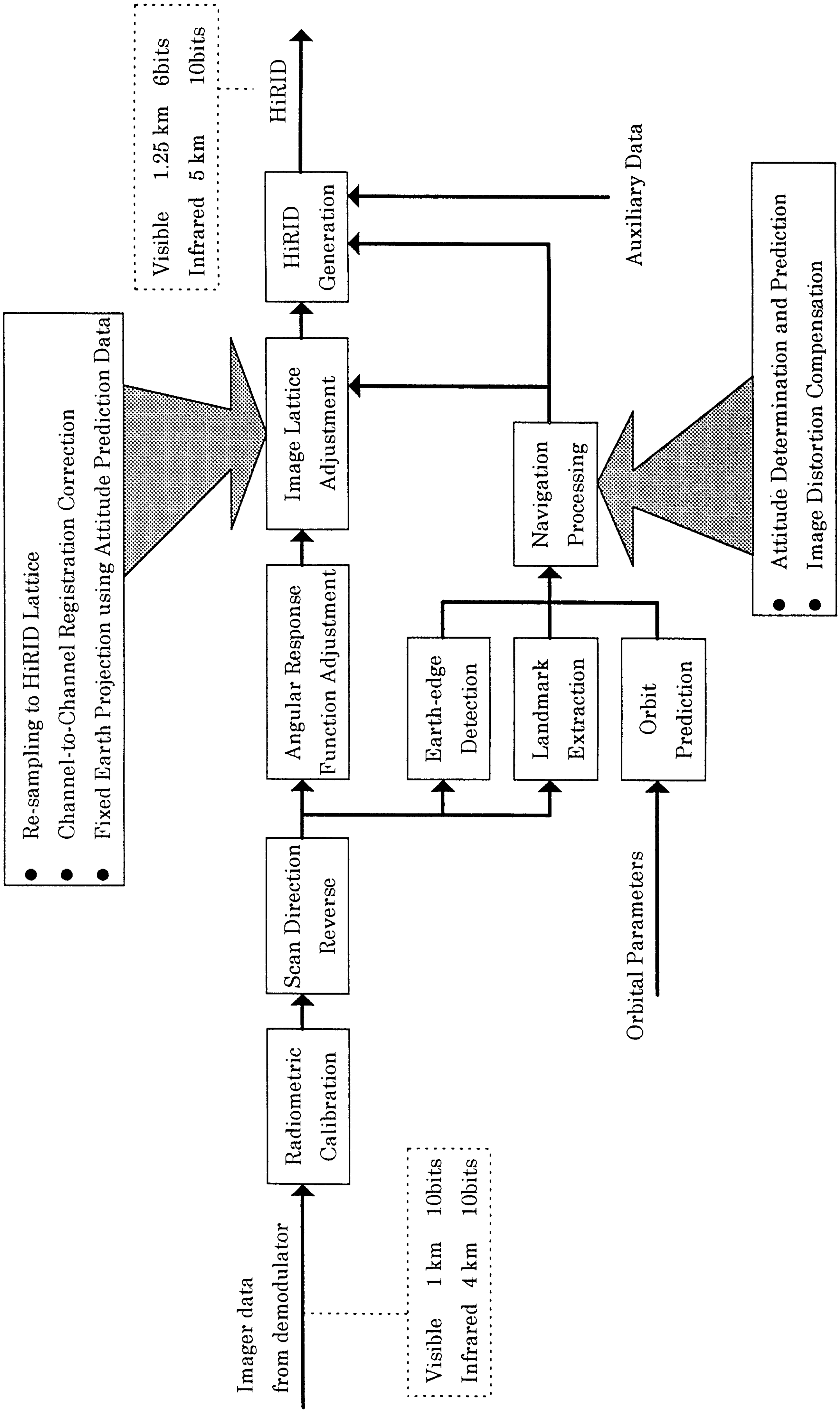


Figure 9 Image Pre-processing Flow

albedo monitor simulates an albedo radiance between 50 % to 115 %.

The visible channel calibration using the albedo monitor will be performed once a day.

5. Image Pre-Processing

5.1 Image Pre-Processing Flow

Figure 9 shows the flow of the image pre-processing. The input of the image pre-processing is the demodulated Imager raw data, and the output of the image pre-processing is the HiRID streams.

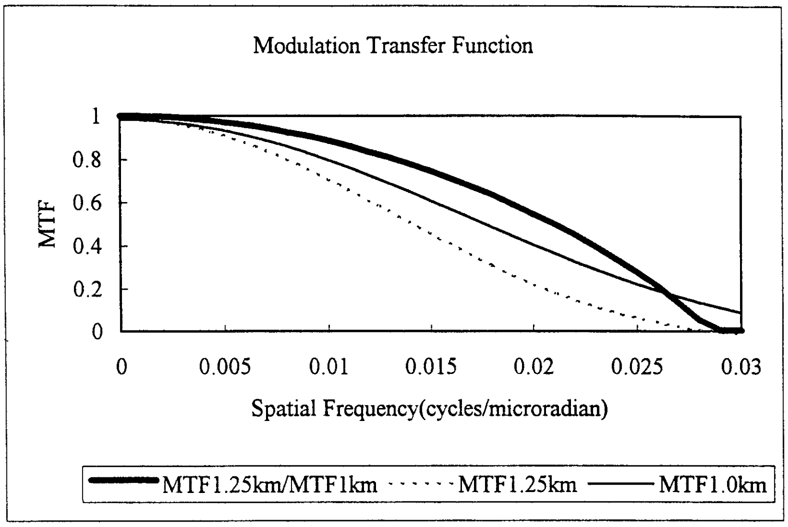
The HiRID format originated in Stretched-VISSR (Visible and Infrared Spin Scan Radiometer) of the spin-stabilized GMS spacecraft. Angular responses (i.e., IFOV) and ground sample distance (GSD) of the HiRID and Stretched-VISSR are 1.25 km for visible and 5 km for infrared. However, the downlinked Imager raw data has a 1 km IFOV and north-south GSD, and a 0.57 km east-west GSD for visible. It has a 4 km IFOV and north-south GSD, and a 2.3 km east-west GSD for infrared. Therefore, the image pre-processing performs the IFOV and GSD conversions of the Imager data.

There are six functions that the image pre-processing must perform:

1. Radiometric calibration
2. Angular response (IFOV) conversion
3. Image lattice (GSD) adjustment
4. Channel-to-channel registration correction
5. Navigation data generation using landmark and earth-edge data
6. HiRID generation

5.2 Radiometric Calibration

The data is radiometrically corrected using the onboard calibration data from the infrared blackbody source and the albedo monitor. The output of the radiometric calibration function is the calibrated data, and does not show raw digital counts from the Imager.



0.005	-0.011	0.025	-0.058	0.227	0.628	0.227	-0.058	0.025	-0.011	0.005

Spatial Domain Digital Filter generated by $MTF_{1.25km}/MTF_{1km}$

Figure 10 MTF and Spatial Domain Digital Filter

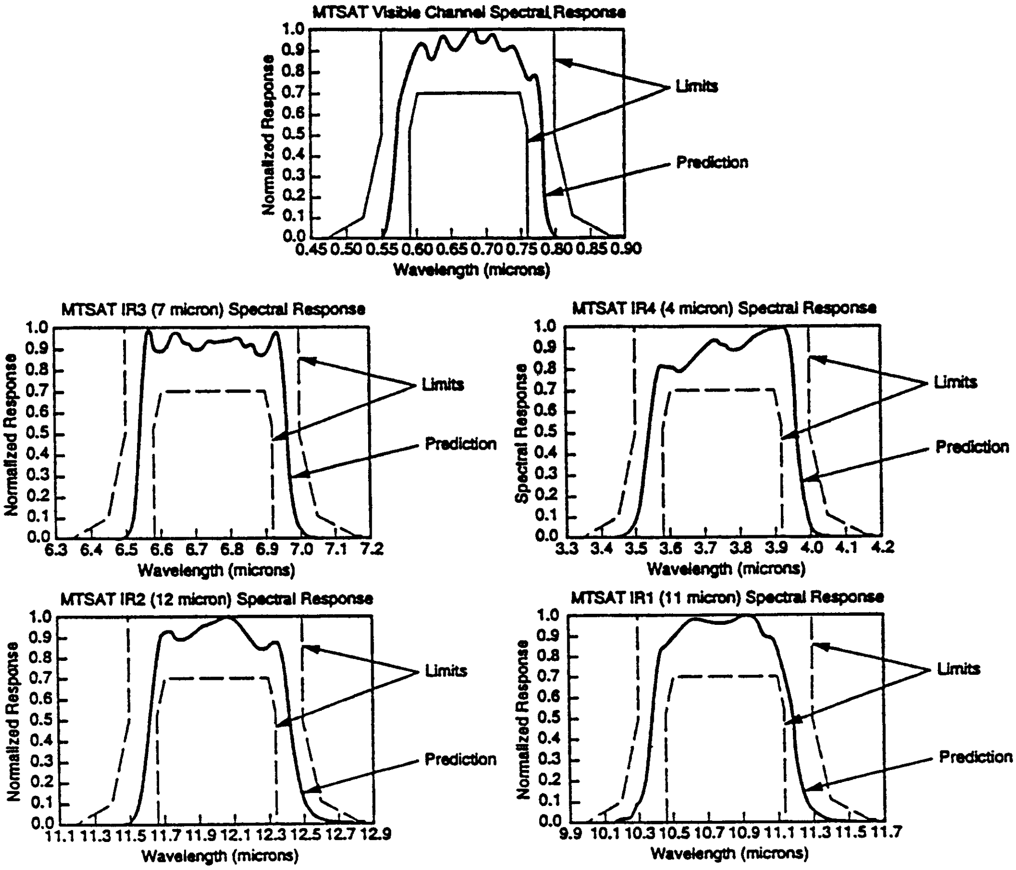


Figure 11 MTSAT Imager Spectral Response

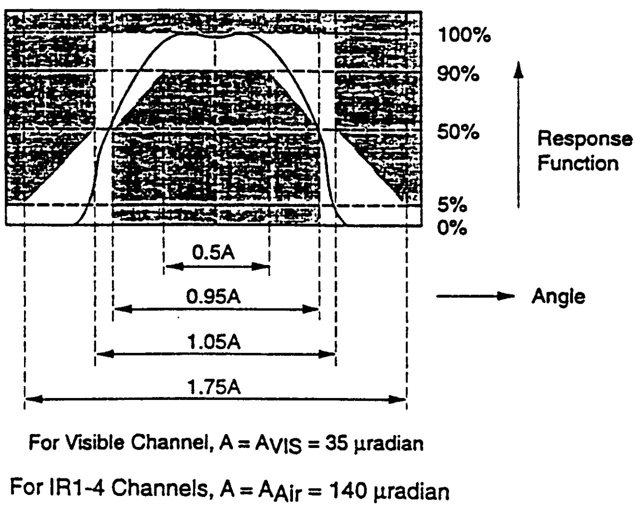


Figure 12 HiRID Angular Response

5.3 Angular Response Conversion

The calibrated Imager data is processed by spatial domain digital filters to convert the angular response (i.e., IFOV: instantaneous field-of-view). The filters are generated from the frequency domain transfer functions obtained from MTF_{HiRID}/MTF_{Imager}. Figure 10 shows the examples of MTF and the spatial domain filter.

5.4 Image Lattice Adjustment / Channel-to-channel Registration Correction

An interpolator is used to convert the Ground Sample Distance (GSD) of the IFOV-converted image data. In addition, channel-to-channel registration error is corrected in this process.

5.5 Navigation Data Generation

The earth-edge detection and landmark extraction of the calibrated image data are performed in the image pre-processing. The function of the earth-edge detection and image distortion compensation is based on the existing technique (Fine Tuning of Stretched-VISSR Image Mapping by Kigawa: 1993). The landmark extraction uses more than 300 reference areas and is performed automatically for both visible and infrared. The HiRID contains the image navigation parameters that are compensated by the earth-edge and landmark data. (Kigawa: 1996)

5.6 HiRID Generation

The visible data is converted a 10-bit intensity scale to a 6-bit intensity scale by a square-root function. The image data, navigation parameters and auxiliary data are combined together to the HiRID format.

6. Imaging System Performance

Table 1 shows the performance of the HiRID image data, that is the imaging system performance of MTSAT. The requirements of the Imager are explained by Kigawa (1995).

The Table should be updated by the ground test data of the Imager in 1999 and the on-orbit data in 2000.

Acknowledgments

The author wishes to acknowledge the cooperation and efforts of team members of Japan Meteorological Agency, Space Systems/Loral and ITT Industries.

Reference

Kigawa, S., 1993. Fine Tuning of Stretched-VISSR Image Mapping. Meteorological Satellite Center Technical Note, No.26, March 1993, p1-10.

Kigawa, S., 1995. Requirements of MTSAT/Imager. Meteorological Satellite Center Technical Note, No.30, March 1995, p33-39.

Kigawa, S., 1996. Image Navigation of Multi-functional Transport Satellite. Meteorological Satellite Center Technical Note, No.32, November 1996, p23-42.

Table 1 Imaging System Performance (1/4)

<table>
<tr><th>Item</th><th>Requirement</th><th>Design</th></tr>
<tr><td>1</td><td>Observataion and Operating Requirements
① Numbers of observations
Imager shall perform >93,000 observations.
② Simultaneous operation
House-keeping operations shall not effect the hourly imager observations and the wind measurement observations every 6 hours.</td><td>① Imager will perform >93,000 observations in full frame.
② Imager design meets to requirements.</td></tr>
<tr><td>2</td><td>Image Frame
The frame is defined as the maximum unit of observation area having the size of ≧17.6 degree to N/S and E/W direction respectively.</td><td>Designed Image Frame
● Frame : 19.2°(E/W)×17.6°(N/S)
● Imager will be able to observe the complete frame or any specified section.</td></tr>
<tr><td>3</td><td>Observation Frequency
Observation frequency :
● ≧ 1 full frame for 30 min.
● ≧ 2 full frames for 60 min.
● ≧ 48 full frames for 24 hours
● ≧ 1 half frame for 15 min.
● ≧ 2 half frames for 30 min.
● ≧ 4 half frames for 1 hour</td><td>Designed Observation Frequency
● 1 full frame for 30 min.
● 2 full frames for 60 min.
● 48 full frames for 24 hours
● 1 half frame for 15 min.
● 2 half frames for 30 min.
● 4 half frames for 1 hour
Note: Some images will be canceled to avoid the over-temperature of the Imager instrument.</td></tr>
<tr><td>4</td><td>Time Delay
The time delay from on-board digitizing to users of the image data shall be less than 3 minutes including CDAS processing.</td><td>Designed Time Delay
● Time delay: 13.1 sec. <3 min.</td></tr>
<tr><td>5</td><td>Channels
Imager shall be capable of simultaneous observation in 5 wave bands (channels).
<table>
<tr><th>Channel</th><th>Minimum</th><th>Maximum</th></tr>
<tr><td>VIS</td><td>0.55μ m</td><td>0.75～0.90μ m</td></tr>
<tr><td>IR1</td><td>10.3μ m</td><td>11.3μ m</td></tr>
<tr><td>IR2</td><td>11.5μ m</td><td>12.5μ m</td></tr>
<tr><td>IR3</td><td>6.5μ m</td><td>7.0μ m</td></tr>
<tr><td>IR4</td><td>3.5～3.8μ m</td><td>4.0μ m</td></tr>
</table>
Table 5-1 Wavelength Limits</td><td>Designed Channel Allocation
Imager will be capable of simultaneous observation in 5 channels. Response function meets Requirements (Fig. 11).
<table>
<tr><th>Channel</th><th>Minimum</th><th>Maximum</th></tr>
<tr><td>VIS</td><td>0.55μ m</td><td>0.80μ m</td></tr>
<tr><td>IR1</td><td>10.3μ m</td><td>11.3μ m</td></tr>
<tr><td>IR2</td><td>11.5μ m</td><td>12.5μ m</td></tr>
<tr><td>IR3</td><td>6.5μ m</td><td>7.0μ m</td></tr>
<tr><td>IR4</td><td>3.5μ m</td><td>4.0μ m</td></tr>
</table>
Table 5-2 Designed Wavelength Limits</td></tr>
<tr><td>6</td><td>Radiometric Resolution
<table>
<tr><th>Channel</th><th>Radiometric Resolution</th></tr>
<tr><td>VIS</td><td>≧84 at 100% albedo
≦6.5 at 2.5% albedo</td></tr>
<tr><td>IR1</td><td>≦0.20K at 300K
≦0.55K at 220K</td></tr>
<tr><td>IR2</td><td>≦0.22K at 300K
≦0.55K at 220K</td></tr>
<tr><td>IR3</td><td>≦0.15K at 300K
≦0.85K at 220K</td></tr>
<tr><td>IR4</td><td>≦0.35K at 300K</td></tr>
</table>
Table 6-1 Radiometric Resolution</td><td>Designed Radiometric Resolution (HiRID)
<table>
<tr><th>Channel</th><th>Radiometric Resolution (S/N or NEDT)</th></tr>
<tr><td>VIS</td><td>94 at 100% albedo
7.0 at 2.5% albedo</td></tr>
<tr><td>IR1</td><td>≦0.10K at 300K
≦0.28K at 220K</td></tr>
<tr><td>IR2</td><td>≦0.15K at 300K
≦0.36K at 220K</td></tr>
<tr><td>IR3</td><td>≦0.08K at 300K
≦0.54K at 220K</td></tr>
<tr><td>IR4</td><td>≦0.09K at 300K</td></tr>
</table>
Table 6-2 Designed Radiometric Resolution (HiRID)</td></tr>
</table>

Table 1 Imaging System Performance (2/4)

<table>
<tr><th>Item</th><th>Requirement</th><th>Design</th></tr>
<tr><td>7</td><td>Dynamic Range
<table>
<tr><th>Channel</th><th>Minimum</th><th>Maximum</th></tr>
<tr><td>VIS</td><td>≦1% albedo</td><td>≧115% albedo</td></tr>
<tr><td>IR1</td><td>≦130K</td><td>≧330K</td></tr>
<tr><td>IR2</td><td>≦130K</td><td>≧330K</td></tr>
<tr><td>IR3</td><td>≦130K</td><td>≧300K</td></tr>
<tr><td>IR4</td><td>≦130K</td><td>≧320K</td></tr>
</table>
Table 7-1 Dynamic Range</td><td>Designed Dynamic Range (HiRID)
<table>
<tr><th>Channel</th><th>Minimum</th><th>Maximum</th></tr>
<tr><td>VIS</td><td>≦1% albedo</td><td>≧115% albedo</td></tr>
<tr><td>IR1</td><td>4K</td><td>≧330K</td></tr>
<tr><td>IR2</td><td>4K</td><td>≧330K</td></tr>
<tr><td>IR3</td><td>4K</td><td>≧320K</td></tr>
<tr><td>IR4</td><td>4K</td><td>≧320K</td></tr>
</table>
Table 7-2 Designed Dynamic Range (HiRID)</td></tr>
<tr><td>8</td><td>Calibration Accuracy
<table>
<tr><th>Channel</th><th>Within one observation</th><th>Over any 10 day period</th></tr>
<tr><td>VIS</td><td>≦5% albedo (rms)</td><td>≦1% albedo (1δ)</td></tr>
<tr><td>IR at 300K
at 220K</td><td>≦0.50K(rms)
≦0.75K(rms)</td><td>≦0.25K(1δ)
≦0.40K(1δ)</td></tr>
</table>
Table 8-1 Calibration Accuracy</td><td>Designed Calibration Accuracy (HiRID)
<table>
<tr><th>Channel</th><th>Within one observation</th><th>Over any 10 day period</th></tr>
<tr><td>VIS</td><td>≦3.4% albedo (rms)</td><td>≦0.8% albedo (1δ)</td></tr>
<tr><td>IR at 300K
at 220K</td><td>≦0.21K(rms)
≦0.11K(rms)</td><td>≦0.21K(1δ)
≦0.11K(1δ)</td></tr>
</table>
Table 8-2 Designed Calibration Accuracy (HiRID)</td></tr>
<tr><td>9</td><td>On-Board Calibration
Imager shall be capable of performing following calibration functions.
① Equivalent black body temperature calibration
② Albedo calibration
③ Amplifier calibration
④ Calibration shall be required not more than once per observation to fulfill the calibration accuracy requirements. Albedo calibration shall be possible at least once per day over the entire year.</td><td>On-Board Calibration Functions
① Black body calibration using internal black body reference is possible.
② Albedo calibration using sunlight and mirrors is possible. (once per day over the entire year)
③ Amplifier calibration using reference electronic signal is possible.
④ Imager will fulfill the calibration accuracy requirements based on one calibration operation per obserbation for black body and amplifier. Albedo calibration performed once per day over the entire year.</td></tr>
<tr><td>10</td><td>Response to Radiation from Celestial Body
● No effect of sun and moon signals (removing offset)
● All requirements shall be satisfied after termination of solar rediation input.
● The change of equivalent black body temperature with scanning 300K black body for angle 17.6 degrees: ≦0.15K
● The change of albedo with scanning 100% albedo for 17.6 degrees: ≦1% albedo</td><td>Designed Imager Response
● No effect of sun and moon signals with automatic function.
● All requirements will be satisfied after termination of solar radiation input.
● Droop ≒ 0
● Droop ≒ 0</td></tr>
<tr><td>11</td><td>Quantization
VIS: 6 bits or more/pixel
IR : 10 bits or more/pixel</td><td>Designed Quantization (HiRID)
VIS: 6 bits/pixel (root approximation)
IR : 10 bits/pixel (linear approximation)</td></tr>
</table>

Table 1 Imaging System Performance (3/4)

<table>
<tr><th>Item</th><th>Requirement</th><th>Design</th></tr>
<tr><td>12</td><td>Ground Resolution
● VIS: ≦1.25km
● IR : ≦5.0km</td><td>Designed Ground Resolution (HiRID)
● VIS: 1.25km
● IR : 5.0km</td></tr>
<tr><td>13</td><td>Detctor Field of View
The field of view of all detector shall be square.</td><td>Designed Detector Field of View
● VIS: 28 μ rad (E-W) × 28 μ rad (N-S)
● IR : 112 μ rad (E-W) × 112 μ rad (N-S)</td></tr>
<tr><td>14</td><td>Instantaneous Field of View (IFOV)
① Angle of 50% response
● VIS: 35 μ rad ±5%
● IR: 140 μ rad ±5%
② Angular response function shape requirements</td><td>Designed IFOV (HiRID)
① Angle of 50% response
● VIS: 35 μ rad ±5% (E-W and N-S)
● IR: 140 μ rad ±5% (E-W and N-S)
② Angular response function meets to Requirements (Fig. 12).</td></tr>
<tr><td>15</td><td>Pixel Registration angular
The FOV center angular distance between IR1 and IR2～IR4:
● 140 μ rad multiplied by integer number ±14 μ rad</td><td>Designed Pixel Registration (HiRID)
The FOV center angular distance between IR1 and IR2～IR4:
● 140 μ rad multiplied by integer number ±14 μ rad</td></tr>
<tr><td>16</td><td>System MTF (Modulation Transfer Function)
<table>
<tr><th>Channel</th><th>Sine wave input (cycles/rad)</th><th>System MTF</th></tr>
<tr><td>VIS</td><td>4000
8000
12000
16000</td><td>≧0.79
≧0.57
≧0.30
≧0.00</td></tr>
<tr><td>IR</td><td>500
1500
2500
3500</td><td>≧0.85
≧0.62
≧0.33
≧0.00</td></tr>
</table>
Table 16-1 System MTF</td><td>Designed E-W and N-S MTF in worst case (HiRID)
<table>
<tr><th>Channel</th><th>Sine wave input (cycles/rad)</th><th>System MTF</th></tr>
<tr><td>VIS</td><td>4000
8000
12000
16000</td><td>0.86
0.71
0.53
0.35</td></tr>
<tr><td>IR</td><td>500
1500
2500
3500</td><td>0.85
0.69
0.54
0.36</td></tr>
</table>
Table 16-2 Designed System MTF</td></tr>
<tr><td>17</td><td>Navigation Accuracy
≦35 μ rad (rms) in sunlight
≦140 μ rad (rms) during solar eclipse + 10min.
<table>
<tr><th>Time interval</th><th>In sunlight</th><th>During solar eclipse + 10min</th></tr>
<tr><td>15min.</td><td>≦25 μ rad (rms)</td><td>≦100 μ rad (rms)</td></tr>
<tr><td>30min.</td><td>≦50 μ rad (rms)</td><td>≦100 μ rad (rms)</td></tr>
<tr><td>90min.</td><td>≦50 μ rad (rms)</td><td>No requirement</td></tr>
</table>
Table 17-1 Navigation</td><td>Designed Navigation Accuracy (HiRID)
≦18 μ rad (rms) in sunlight
≦60 μ rad (rms) during solar eclipse + 10min.
<table>
<tr><th>Time interval</th><th>In sunlight</th><th>During solar eclipse + 10min</th></tr>
<tr><td>15min.</td><td>≦24 μ rad (rms)</td><td>≦79 μ rad (rms)</td></tr>
<tr><td>30min.</td><td>≦25 μ rad (rms)</td><td>≦80 μ rad (rms)</td></tr>
<tr><td>90min.</td><td>≦25 μ rad (rms)</td><td>No requirement</td></tr>
</table>
Table 17-2 Designed Navigation Stability</td></tr>
</table>

Table 1 Imaging System Performance (4/4)

Item	Requirement	Design
18	Imager Line of Sight Stability ● ≦17.5 μ rad (3 σ) in N-S and E-W direction respectively in sunlight ● ≦70 μ rad (3 σ) in N-S and E-W direction respectively during solar eclipse + 10min.	Designed 1 to 10 sec. stability in N-S and E-W respectively ● ≦15.5 μ rad (3 σ) in E-W direction in sunlight ● ≦ 9.1 μ rad (3 σ) in N-S direction in sunlight ● ≦18.5 μ rad (3 σ) in E-W during solar eclipse + 10min ● ≦10.6 μ rad (3 σ) in N-S during solar eclipse + 10min
19	Imager Data Format ● Imager shall output its data along fixed data format including calibrataion and navigation information. ● The bit order of the pixel data shall be MSB (Most Significant Bit) first and LSB (Least Significant Bit) last. ● Pixel output order shall be from North to South, West to East.	Designed Imager Data Format ● Imager data format will be fixed data format and will include telemetry data necessary for Imager data calibration, the data necessary for Imager data nevigation and a code for satellite identification. ● Pixel data is MSB first and LSB last. ● Output order is North to South, West to East (HiRID).
20	Ground Processing of Imager Data ● Sampling, resampling, re-quantization and conversion of gradation for Imager data processing in CDAS should be assumed. ● To achieve the required navigation accuracy, landmark and earth limb detection is assumed.	Ground Processing Functions ● The assumption of Image pre-processomg in CDAS meets to Requirements. ● To achieve the required navigation accuracy, landmark and earth limb detection is assumed.
22	Data Transmission Rate ● ≦3.0Mbps	Designed Data Transmission Rate ● 2.62Mbps

運輸多目的衛星の画像取得機能の設計性能について

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運輸多目的衛星は、平成11年夏に東経140度の赤道上空に打上げられる予定である。運輸多目的衛星は、静止気象衛星５号の後継機として、画像取得、画像データの配信並びに各種データの中継を行う気象ミッションが搭載されている。

運輸多目的衛星の設計のベースラインを決定する基本設計審査が平成７年12月に、設計の詳細を決定する詳細設計審査が平成８年10月に開催された。ここでは、運輸多目的衛星の画像取得機能の概要と設計性能を示す。