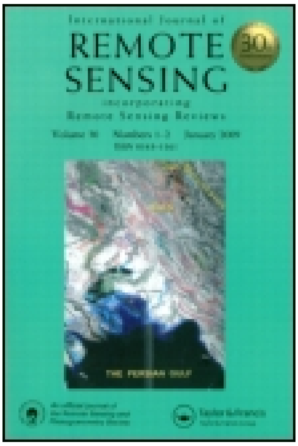

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A very compact imaging spectrometer for the micro-satellite STSAT3

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STSAT3, a ∼150-kg micro-satellite, is the third experimental micro-satellite of the STSAT (Science Technology Satellite) series designated for the Long-Term Plan for Korea's Space Development by the Ministry of Education, Science and Technology of Korea. A Compact Imaging Spectrometer (COMIS) for use in the STSAT3 micro-satellite is currently under construction. It is scheduled to be launched into a low sun-synchronous Earth orbit (∼700 km) by the end of 2012. COMIS was inspired by the success of Compact High Resolution Imaging Spectrometer (CHRIS), a small hyperspectral imager developed for the European Space Agency (ESA) micro-satellite Project for On Board Autonomy (PROBA). COMIS, as its name implies, is very compact in terms of volume, mass and power. The total mass including the optics, housing and electronics is approximately 4.3 kg, and the average operational power is less than 13 W. Its main operational goal will be the imaging of the Earth's surface and atmosphere with ground sampling distances of 27 m at the 18–62 spectral bands (0.4–1.05 μm). COMIS takes hyperspectral images in two different modes: strip imaging and stereo viewing observation. This imaging will be used for environmental monitoring, such as the inland water quality monitoring of Paldang Lake, which is located close to Seoul, South Korea.

1. Introduction

The Ministry of Education, Science and Technology of South Korea initiated the STSAT (Science Technology Satellite) series in 2000, as part of a Long-Term Plan for Korea's Space Development. The STSAT series was based on the successful technical development and demonstration of Korea's first micro-satellite KITSAT (Korea Institute of Technology Satellite) series (Park *et al.* 1996, Choi *et al.* 1997, Kim *et al.* 2000). The STSAT series consist of university-based micro-satellite programmes to achieve engineering objectives, by demonstrating core-satellite technologies, as well as scientific objectives, by providing in-space measurements to space/earth science communities (Lim *et al.* 2003, Hwang *et al.* 2005, Lee *et al.* 2005).

STSAT3, a ∼150-kg micro-satellite, is the third experimental micro-satellite of the STSAT series. It provides a testbed for five engineering technologies, including multi-functional composite structures and Hall thrusters, as well as a platform for two payloads, a Multi-purpose Infrared Imaging System (MIRIS) for infrared (IR) imaging of the Galaxy at 1–2 μm wavelengths and a Compact Imaging Spectrometer

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(COMIS) for hyperspectral imaging of the Earth's surface in the visible and near-IR bands at 0.4–1.05 μm wavelengths (Lee *et al.* 2007).

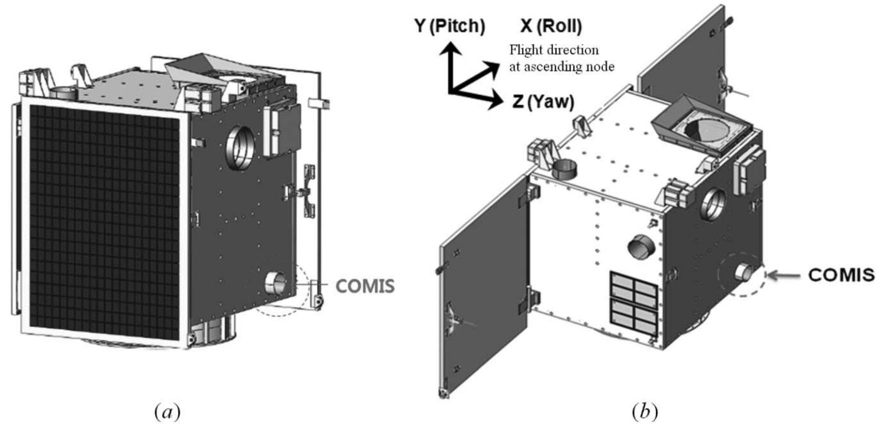
COMIS was inspired by the success of Compact High Resolution Imaging Spectrometer (CHRIS), a small hyperspectral imager developed for the European Space Agency (ESA) micro-satellite Project for On Board Autonomy (PROBA) (Cutter *et al.* 2000, Barnsley *et al.* 2004). COMIS is designed to achieve nearly equivalent imaging capabilities as CHRIS in a smaller (entrance pupil diameter of 65 mm and mass of 4.3 kg) and mechanically superior (in terms of alignment and robustness) package. COMIS is capable of hyperspectral imaging at approximately ground sampling distances of 27 m over a 28-km swath at an altitude of 700 km. The number of bands is adjustable (18–62). COMIS takes hyperspectral images in two different modes: push-broom and multi-directional observation. The major scientific applications of the COMIS are for environmental monitoring, such as inland water quality monitoring of Paldang Lake, located close to Seoul, the capital of South Korea.

2. STSAT3 platform

2.1 *Overview*

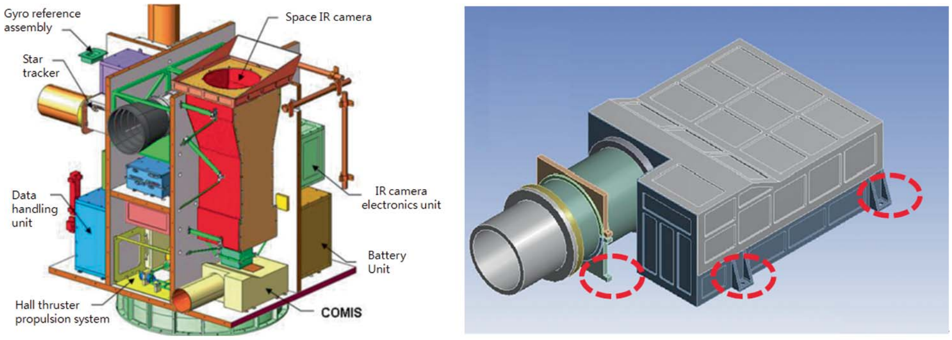
The main purpose of the STSAT3 platform is providing a small and low-cost platform for technical demonstrations and the two payloads. It consists of a structure and thermal subsystem, a communication subsystem, an attitude and orbit control subsystem, an electrical power subsystem and a command and data handling subsystem. It weighs approximately 150 kg, including its payloads, and measures approximately 85 cm × 82 cm × 100 cm in its stowed configuration, as shown in figure 1, where COMIS is indicated by the dotted circles.

The main structure is built using aluminium and composite honeycomb panels. The COMIS hyperspectral imager is located on the bottom panel of the bus platform, as shown in figure 2. The optical axis of COMIS is normal to the face panel so that it is pointed in the same direction as the orientation of the antennas. As the antennas are pointed towards the ground station located in Daejeon, South Korea, COMIS will



(*a*) (*b*)

Figure 1. STSAT3 models, with COMIS indicated by the dotted circles. (*a*) Stowed configuration; (*b*) deployed configuration.



(*a*) (*b*)

Figure 2. Mechanical interfaces between COMIS and the STSAT3 platform. (*a*) Internal view of the STSAT3, with COMIS located on the bottom panel; (*b*) COMIS is fixed onto the STSAT3 bottom panel by six M6 bolts.

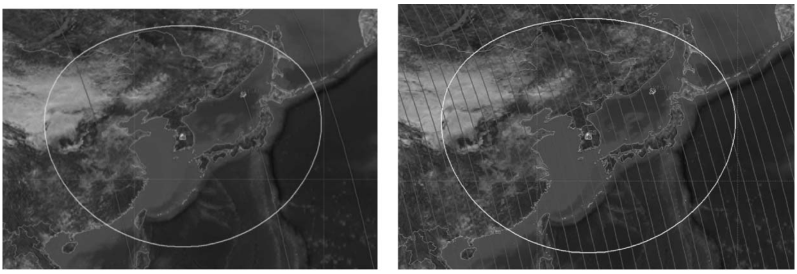
always be able to maintain line of sight over the Korean Peninsula when STSAT3 is passing overhead.

2.2 *Mission orbit*

The STSAT3 mission orbit is sun-synchronous, with an equatorial crossing time of 10.50. The orbital period is 98.88 min, the inclination 98.19° and ground speed 6.7 km s^{-1}. Figure 3 shows the orbital track on the ground over the Korean peninsula. The distance between successive orbits is nearly 2752 km and the distance between the adjacent orbits is 172 km. The repeat cycle of the orbit is 16 days.

2.3 *Attitude control and pointing*

STSAT3 is three-axis stabilized. Its position and attitude are acquired with the use of four coarse sun sensors, two global positioning system (GPS) receivers, a three-axis magnetometer and two star trackers. The spacecraft attitude is controlled by a set of four reaction wheels. These allow the satellite to manoeuvre in each of the three planes, that is, roll, pitch and yaw. Each axis is defined in figure 1. The roll axis is the flight direction. Consequently, the satellite can tilt in both the along-track and



(*a*) (*b*)

Figure 3. Proposed orbital tracks on the ground over the Korean peninsula. The ground station is located at Daejeon, South Korea (127.26° E, 36.20° N). (*a*) Successive orbits; (*b*) all possible orbits.

across-track directions with pointing accuracies of ±0.13° for the roll/yaw and ±0.22° for the pitch directions.

2.4 *Onboard data storage*

STSAT3 has 32 Gbit of onboard data storage located within the mass memory unit. COMIS can transfer mission data to the mass memory unit through two serial communication links at 100 Mbps. The memory unit can store the mission data of three days, as the maximum data generated by the two payloads are 10.9 Gbit day^{-1}.

2.5 *Communication*

STSAT3 communicates with a ground station located in Daejeon, South Korea. The spacecraft bus is capable of acquiring and transmitting mission data simultaneously and of transmitting the stored mission data. The downlink is though X-band communication. Its data transfer rate is 10 Mbps. The daily ground contact time of the X-band downlink varies from 1141 to 1926 seconds, which exceeds time required to download the content acquired in one day, that is, 1090 seconds.

3. COMIS instrument

3.1 *General description*

COMIS is a compact and small hyperspectral imager. It consists of an imaging telescope and an imaging spectrometer attached to a charge-coupled device (CCD)-array detector system. The imaging telescope forms an image (of the Earth's surface) on an intermediate image plane. The imaging spectrometer disperses the image and relays it to the detector image plane. As COMIS operates in the push-broom mode, the CCD rows are assigned to accommodate different wavelengths and the CCD columns change separately to different resolved areas of an image (the Earth's surface). COMIS, as its name implies, is very compact in terms of volume, mass and power. It weighs 4.3 kg, including its optics, housing and electronics, and occupies a volume of 35 (L) × 20 (W) × 12 (H) cm. The operational average power is less than 13 W. Details of the optics and opto-mechanical designs are available in the literature (Lee *et al.* 2008, 2009).

3.2 *Optics*

COMIS is comprised of a catadioptric telescope and an imaging spectrometer, as shown in figure 4. The catadioptric telescope images a 27.3 m × 28 km section of the Earth's surface onto a line slit of 11.8 μm × 12.1 mm, corresponding with a ground sampling distance of 27.3 m and a swath width of 28 km for nadir observation at an altitude of 700 km. The telescope has an entrance pupil diameter of 65 mm that operates at f/4.6. The telescope is a conventional two-mirror telescope with four weak lenses. The two front meniscuses are employed mainly to correct spherical aberrations and the two lenses located close to the slit plane offset the presence of residual aberrations. The secondary mirror surface is a central part of the rear surface of the second meniscus lens. The imaging telescope is designed to provide nearly diffraction-limited performance for all wavelengths and fields.

The imaging spectrometer disperses light from the slit and reimages it onto an area CCD. The imaging spectrometer is essentially a modified version of an Offner relay

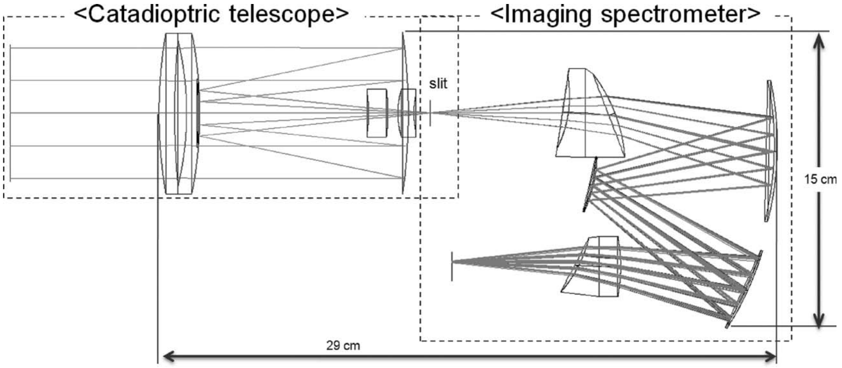


Figure 4. Optical layout of COMIS, comprising a catadioptric telescope and an imaging spectrometer.

with two dispersing prisms, as patented by Sira Electro-Optics (Kent, UK) (Lobb 2001). This design was modified from the patented design to make the optical axis of the entrance and exit beams parallel to that of the imaging telescope. This mitigates any alignment difficulties and makes the optics less sensitive to thermal contraction and expansion of the mechanical housing. As part of the modification, the magnification of the relay was changed slightly from 1 to 1.1 to optimize its optical performance with all spherical surfaces.

3.3 *Detector (CCD)*

The detector used is an area CCD. It is a frame-transfer device with 1024 rows and 1024 columns. A single pixel has dimensions of 13 × 13 μm. The CCD with a broad-band coating offers high quantum efficiency over the visible and near-IR ranges, therefore providing the ability to make radiometric measurements in the spectral range of 400–1050 nm. The quantum efficiency of the CCD is better than 75% at 400 nm and 13% at 1000 nm with a peak of 85% at 500 nm.

3.4 *Spectral resolution*

Given that prismatic dispersion power is used to disperse the spectral band, the spectral resolution varies depending on the refractive index of the prism and hence the wavelength. The spectral dispersion is nonlinear due to the nonlinearity of the refractive index dispersion of the prism. The 400–1050 nm spectrum positions 1.4 mm over the CCD row, that is, ~110 pixels. The corresponding spectral resolution over a single CCD pixel varies from 2 nm at 400 nm to 15 nm at 1050 nm across the spectrum (figure 5).

3.5 *Signal-to-noise ratio*

Each optical surface is coated with an anti-reflection coating or a high-reflection coating. COMIS, with coated optics and the CCD, offers high overall throughput over the spectrum. This throughput is better than 10% at 400 nm and 6% at 1000 nm with a peak of 44% at 580 nm (figure 6). The signal-to-noise ratios (SNRs) of COMIS are predicted by radiometric modelling for soil, healthy vegetation and turbid water.

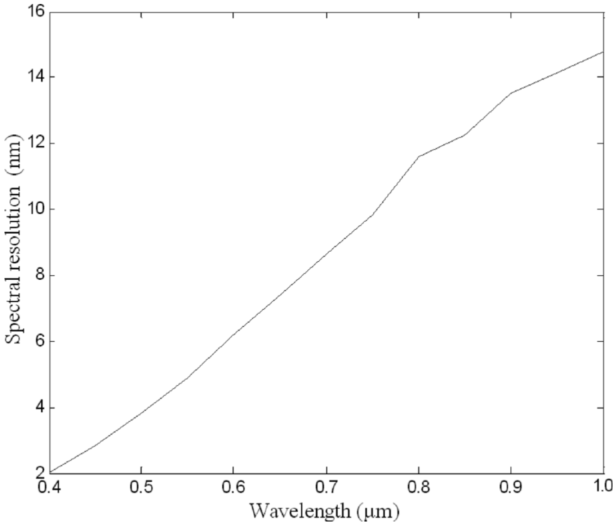
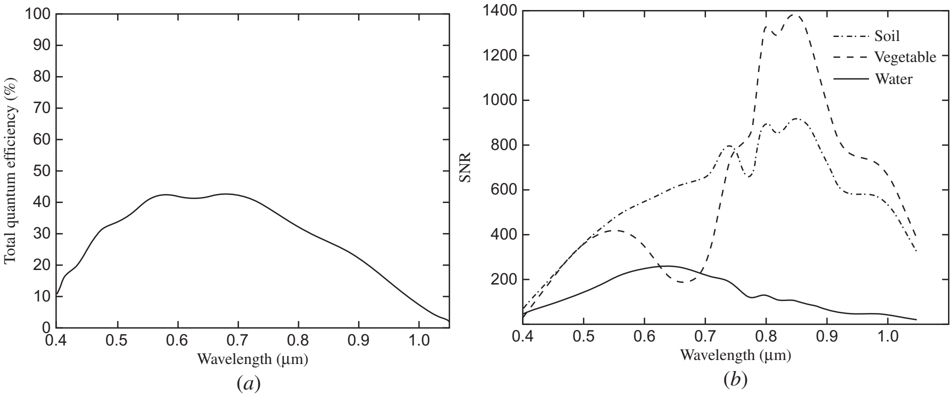


Figure 5. COMIS spectral resolution plotted against the central wavelength.



(*a*) (*b*)

Figure 6. (*a*) Effective quantum efficiency of COMIS and (*b*) SNR plotted against the central wavelength.

These are plotted in figure 6. The prediction was for irradiance collected by a single pixel without aggregation. As the spectral resolution can be altered by binning charges on the CCD detector array, the SNRs for the observation bands will be better than those plotted.

3.6 *Electronics*

COMIS electronics include focal plane electronics, video electronics, control electronics, and a low-voltage power supply. The focal plane electronics convert received irradiance/photons to 12-bit electrical signals with noise reduction capability. The COMIS electronics then sample and sum the sets of row signals for spectral band selection. The gain of the detector can be varied identically to all channels for

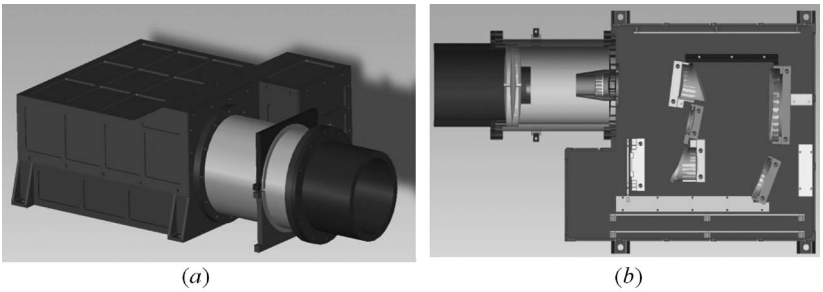

(a) (b)

Figure 7. (*a*) 3D model of the COMIS structure and (*b*) cross-sectional view of COMIS.

optimum usage of the analogue-to-digital converter resolution at different latitudes and observation targets. The sampled and line-integrated data are then communicated to the mass memory unit. The average power consumption for normal operation and in standby mode is 13 and 4.5 W, respectively.

3.7 *Structures*

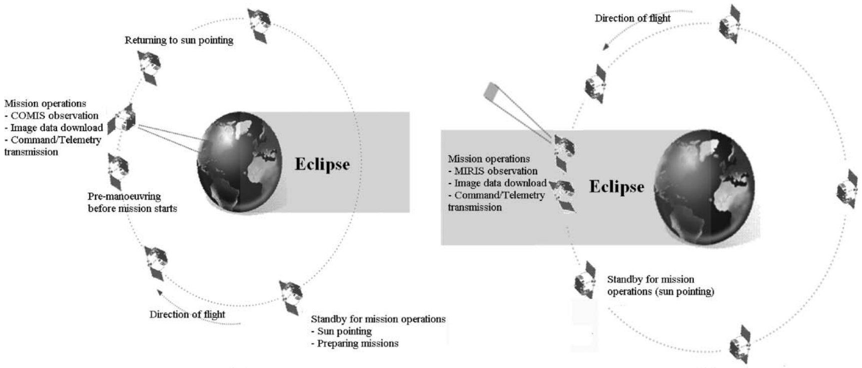
COMIS, as implied by its name, is very compactly designed to survive in launch and space environments and to maintain optical performance while in orbits. The opto-mechanical design was optimized to have a system modulation transfer function (MTF) in excess of 0.29 at the Nyquist frequency of the CCD detector (38.5 lines/mm) in orbit. A compact opto-mechanical design realizes the expected level of performance by adopting a single material approach for an imaging telescope and a quick thermal equilibrium approach for the spectrometer box (figure 7). The design was demonstrated through finite element analysis to be stiff and stable enough to survive and operate during the launch and while in orbit in space (Lee *et al*. 2009).

4. COMIS missions

4.1 *Operational concept*

STSAT3 has the two payloads: MIRIS and COMIS. The MIRIS IR imager surveys the Galaxy at 1–2 μm wavelengths when STSAT3 is in night or eclipse shadows, and the COMIS imaging spectrometer observes the solar flux reflected by the Earth's surface in the visible and near-IR bands during day periods. Figure 8 shows the operational concepts. As MIRIS is a passive thermal IR imager, its temperature rise should be minimized even before it starts to operate. The STSAT3 platform provides the passive thermal control by continuous attitude control of the platform. It is not recommended that COMIS and MIRIS operate simultaneously during a single orbital overpass. Therefore, four successive orbits per day are allocated to the COMIS operations. It is worth noting that operation life of the MIRIS IR imager is one year. For this reason, more orbital passes will be allocated to COMIS operations after the termination of the MIRIS operation.

The COMIS spectrometer on the STSAT3 platform offers some control of the view and azimuth angles of the imaging, allowing it to view any target of interest. Due to the narrow field of view of COMIS, STSAT3 must be tilted at some angle in the



(*a*) (*b*)

Figure 8. Operational concepts of STSAT3. (*a*) COMIS operation in the day; (*b*) MIRIS operation at night or during an eclipse.

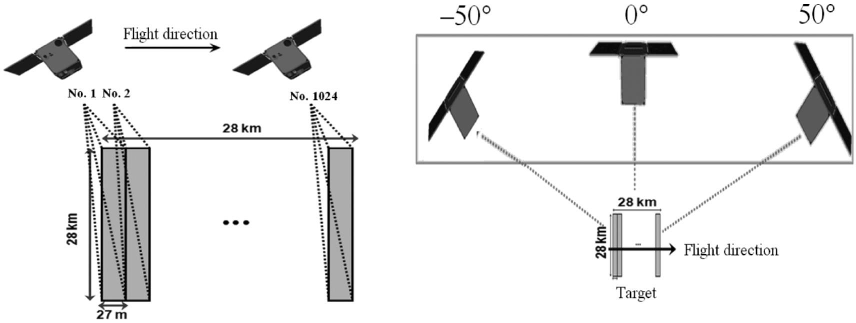
across-track direction so that the target area falls within the sensor's field of view. With this tilting capability, any target site can be imaged on any given day but with variation of the spatial sampling intervals.

4.2 *Imaging mode*

COMIS has two imaging modes: the strip imaging mode and the stereo imaging mode (figure 9). In the strip imaging mode, a target site is scanned with a constant across-track tilt angle as STSAT3 flies over the surface. Several target sites can be scanned successively or discretely with different across-track tilt angles. In the stereo imaging mode, three images of a given target area, each at a different zenith angle (–50°, 0°, 50°), can be acquired during a single orbital overpass. The scan direction is identical to the flight direction.

4.3 *Observation bands*

COMIS operates in the visible and near-IR band from 400 to 1050 nm. Spectral sampling varies from 2 nm at the blue end of the spectrum to nearly 15 nm at 1050 nm. Different sets of bands can be used for different applications. The number and spectral bandwidths of the wavebands can be controlled through commands from



(*a*) (*b*)

Figure 9. The two COMIS imaging modes. (*a*) Strip imaging; (*b*) stereo imaging.

the ground station. The number of the wavebands can vary from 18 (default) to 62. The principal wavebands are adapted from the CHRIS instrument (Cutter *et al.* 2000) and these will be updated before launch based on a wavelength calibration of COMIS.

As the data generation rate of COMIS is limited by the maximum communication rate between COMIS and the mass memory unit, that is, 100 Mbps, the spatial sampling is aggregated by pixel pinning down to the size of the image data when the number of the wavebands exceeds 25.

4.4 *Mission sciences*

COMIS operations are primarily focused on environmental monitoring over the Korean Peninsula, but the COMIS team is quite open to ideas for participation in projects of the international community. Currently, three applications are proposed as primary candidates. They involve water-quality control of Paldang Lake in Korea, rice plant growth modelling over the Yongin rice field, and an aerosol optical thickness study.

The first candidate involves monitoring the water quality of Paldang Lake, which is the main source of water for the city of Seoul. Figure 10(*a*) shows a picture of Seoul, near to which Paldang Lake lies. The boxed area is 30 × 15 km in size. The lake is a stratified lake with a buoyant incoming flow. Among several environmental factors degrading the water quality, algal blooms have been the focus of most effort to control the quality of water in this lake. To control algal blooms more effectively, hydrodynamic and water-quality modelling was studied for spatial and temporal patterns of phytoplankton growth (Na and Park 2006), and an early forecasting system of harmful algal blooms was developed (Kim *et al.* 2007). The COMIS spectrometer on the STSAT3 platform will take hyperspectral images of the lake once a day by tilting the platform with a high spatial sampling interval of 28 m at the nadir-looking angle. The high-temporal COMIS data will be used for updating the hydrodynamic and water-quality model and for developing an early forecasting system for distributed harmful algal blooms over the lake.

The second candidate is to model rice plant growth by multi-angular monitoring of crop canopies. The selected test site is the Yongin rice field located in the middle of Korea. The crop status can be remotely sensed by COMIS. In particular, structural features of rice plant such as gaps and the arrangement, orientation and spacing of surface-scattering elements can be studied from the bidirectional reflection

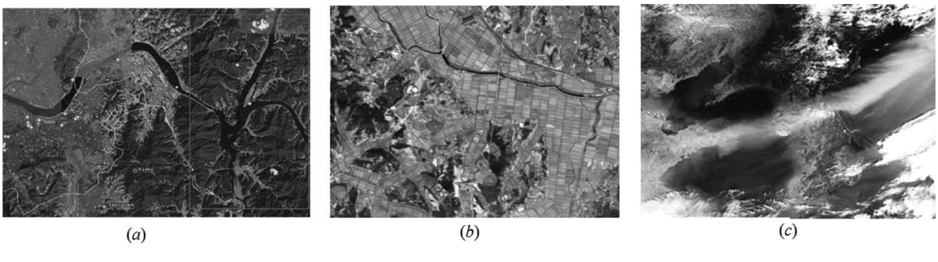

(*a*) (*b*) (*c*)

Figure 10. Three proposed applications of the COMIS spectrometer: (*a*) water-quality control of Paldang Lake (127.296° E, 37.504° N), in the boxed area; (*b*) rice plant growth modelling of Yongin rice field (127.188° E, 37.278° N) using multi-angular monitoring of the crop canopies; (*c*) prediction modelling of the Yellow Sand from Tongliao desert (43.619° E, 122.266° N).

distribution functions (BRDFs) of the vegetation canopies (Goel 1987). The COMIS spectrometer will take the hyperspectral images of the field every day during the farming period.

Every spring and autumn, the Korean Peninsula experiences a phenomenon known as Yellow Sand storms that originate in China. The third candidate is to create a prediction model of Yellow Sand storms using aerosol optical thickness estimation. In some senses the COMIS spectrometer is inappropriate for monitoring the Yellow Sand phenomenon due to its small field of view and its low temporal sampling frequency. However, the high spatial and spectral resolutions of the COMIS spectrometer allow an investigation into the variation of the aerosol concentration over smaller length scales. The COMIS spectrometer will monitor a test site, yet to be selected, on a daily basis. The COMIS data will be correlated with that of other spaceborne instruments such as Along Track Scanning Radiometer-2 (ATSR-2), Advanced Along-Track Scanning Radiometer (AATSR), Polarization and Directionality of the Earth's Reflectance (POLDER) and Multi-angle Imaging Spectroradiometer (MISR).

4.5 *Data formation and distribution policy*

Details of COMIS data distribution, including the data format, level, interval and accessibility, have not been finalized.

5. Conclusion

The STSAT3 programme is a government-funded university programme for studying space core technologies and providing in-space measurements to space/earth science communities. STSAT3 weighs approximately 150 kg, including its payloads, and measures approximately 85 × 82 × 100 cm in a stowed configuration. The STSAT3 programme began in 2006. Currently, an engineering model is under development. It is scheduled to be launched into a low sun-synchronous Earth orbit ($\sim$700 km) with an equatorial crossing time at launch of 10.50 by the end of 2012.

The STSAT3 platform is a small and low-cost platform for technical demonstrations that carries the two payloads of a MIRIS for IR imaging of the Galaxy at 1–2 μm wavelengths, and the COMIS for hyperspectral imaging of the Earth's surface in the visible and near-IR bands at 0.4–1.05 μm wavelengths. COMIS is a compact and small hyperspectral imager. It consists of an imaging telescope and an imaging spectrometer, which are attached to a CCD-array detector system. The imaging telescope forms an image (of the Earth's surface) on an intermediate image plane. The imaging spectrometer disperses the image and relays it to the detector image plane. COMIS, as its name implies, is very compact in terms of volume, mass and power. It weighs 4.3 kg, including its optics, housing and electronics, and occupies a volume of 35 (L) × 20 (W) × 12 (H) cm. The operational average power is less than 13 W. For an altitude of 700 km, the ground sampling distance is 27 m at the nadir-looking angle and the corresponding field of view is 28 km. The spectral resolution over a single CCD pixel varies from 2 nm at 400 nm to 15 nm at 1050 nm across the spectrum.

The COMIS spectrometer on the STSAT3 platform offers some control of the view and azimuth angles of the imaging so that it can view any target of interest. With this tilting capability, any target site can be imaged on any given day with multi-angular (–50°, 0°, 50°) monitoring over an area in a single orbital overpass. The COMIS spectrometer can generate as much as 10.9 Gbit of mission data per day without ground downloading, as allocated by the mass memory unit of the SATSAT3 platform. The number and spectral bandwidths of the wavebands are principally adapted from the PROBA/CHRIS instrument and will be tuned based on the calibration of COMIS.

Applications for the operation of COMIS have yet to be determined; however, several studies have been proposed in three different areas (inland water, land surface and atmospheric aerosol). The currently proposed applications are primarily focused on environmental monitoring over the Korean Peninsula. They include water quality control of Paldang Lake, rice plant growth modelling over the Yongin rice field, and prediction modelling for the Yellow Sand phenomenon. The COMIS team is quite open to ideas for participation in projects of the international community.

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