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On-orbit Performance of the ETRSS-1 Attitude and Orbit Control Subsystem

Research Article

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Abstract

The Ethiopian remote sensing microsatellite, weighing 65 kilograms, was successfully launched into space in December 2019 from the Taiyuan launch facility, with the mission of collecting earth imagery data to assist Ethiopia in combating climate change. The satellite is controlled from a sun-synchronous orbit at an altitude of 628 kilometers by a ground control station on Mount Entoto. The purpose of this paper is to provide an overview of the ETRSS-1 satellite system, including its development and integration with AOCS subsystems, as well as its performance in orbit. Furthermore, the hardware used in the development of the satellite's AOCS will be discussed, and onboard telemetry data from the system will be analyzed to determine its current status.

Keywords: Attitude; Microsatellite; Multispectral; Workmode.

Introduction

The 65 kg multi spectral Ethiopian remote sensing satellite was made up of two distinct modules: the satellite bus module (platform) and the payload (instrument module), as shown in Figure 1. The platform module of the ETRSS-1 includes attitude and orbit control, onboard data handling, power supply, telemetry and telecommand, thermal control, and a structural subsystem, while the payload includes a multispectral camera and a data transmission system that provides imagery data. The key technical parameters required for the ETRSS-1 system design and development are listed in Table 1. The satellite was launched into a sun-synchronous orbit at an altitude of 628.61 kilometers, and it collects imagery data at a ground sampling distance of 13.45 meters over a four-day period. Furthermore, the collected data are used to address Ethiopian climate change in agriculture, forestry, water conservation, disaster prevention and mitigation, and weather-related phenomena.

Review of the ETRSS-1 satellite's orbital mission

The vast majority of remote sensing satellite platforms are in near-polar orbits, which means they travel north on one side of the Earth and then south on the other, a process known as ascending and descending, in order to record reflected or emitted (e.g., thermal) radiation from the surface using on-board sensors. Furthermore, Earth observation satellite missions frequently require constant solar illumination, the same ground resolution, and short repeat cycles, leading to the design of a repeat Sun-Synchronous Orbit (SSO) as the most appropriate, allowing observation of a given region of the Earth at the same local time after a time interval [1]. In this regard, ETRSS-1 is launched into a sun-synchronous orbit with a local time of the descending node of 10:30 AM and revising period of 4 days, and a ground sampling distance of greater than 15 meters. The satellite's mission is to provide earth imagery to address Ethiopian climate change and earth-related issues such as water resources, desertification, vegetation, and other periodic observations, as well as the detection and assessment of natural disasters caused by climate change. At the time of writing, Table 2, describes ETRSS-1'sKeplerian orbital parameters, which are derived from the satellite's real-time orbital tracking and are used to describe the shape and orientation of the satellite's orbit and position. As an ETRSS-1 orbits the Earth, its payload sensor footprint covers a portion of the planet's ground surface, focusing on East African countries (Figure 1) in an 87.309-kilometer-wide equatorial swath with each successive pass, the apparent movement allowing the satellite swath to cover a new area, and its camera coverage reaches 1153.780km with

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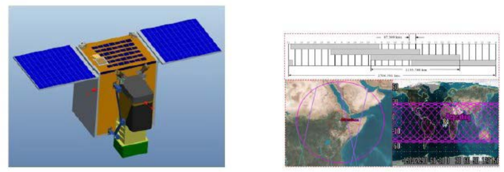
Table 1 Key technical parameters of ETRSS-1

Item name	Designed technical# parameters
Mass	total mass 65kg
Sun-synchronous orbit	Altitude 628.610 km
Attitude and orbit control system	3-axis stabilized, zero-momentum control;
	pointing accuracy: 0.1°/s (3σ, 3axis in normal mode);
	pointing stability: 0.01°/s (3σ, 3-axis);
	attitude determination accuracy: 0.05° (3σ, 3-axis);
	attitude maneuver: ± 35° (along roll axis);
	maneuver capability: 30°/70s
Telemetry and telecommand	USB + GPS
Power supply system	output poser of solar array be more than 150 W (EOL)
	Li-ion batter capacity: 20Ah
Multi-spectral camera	type: push broom imaging
	B1/blue: 0.45μm ~ 0.52μm, B2/green: 0.52μm ~ 0.59μm,
	B3/re: 0.63μm ~ 0.69μm, B4/NIR: 0.77μm ~ 0.89μm,
	ground sampling distance: $\leq$ 15m at 645km,
	swath: $\geq$ 60km at 645km
Data transmission system	frequency band: X-band,
	storage capacity: 128 Gbits,
	downlink data rate: 100 Mbps
Life/reliability	more than 2 years /$\geq$ 0.6

Figure 1: ETRSS-1 satellite and its coverage (Credit: DFH SATELLITE Co., Ltd).



(a) ETRSS-1 satellite (b) ETRSS-1 coverage

Table 2 Orbital parameters of ETRSS-1

Orbit element representation	Elemental name	# Parameter
a	Semi-major axis	6999.614 km
e	Eccentricity	.0016456
i	Inclination	97.8963°
Ω	Right Ascension of Ascending Node (RAAN)	289.4525°
ω	Argument of Perigee	67.9288°
f	True anomaly	292.3649°
-	Altitude	628.610 km
-	Local Time of Descending Node	13:30 PM
-	Flight Circles per Day	14.806
-	Revisiting periods	4 days
τ	orbital period (min)	97.134

38° rolling maneuvering and 4 days revisiting periods. The access times between ETRSS-1 and the ground control station during one day are 2 ~ 4; the maximum time is 10.59 min for accessing; and the maximum time is 33.33 min for all accessing in one day.

Material and Methods

ETRSS-1 AOCS Hardware System Configuration

The AOCS of a satellite is a critical subsystem in the microsatellite design and it is in charge of determining and controlling the satellite's orientation in relation to a given inertial reference frame. A satellite typically employs several sensors that operate in a closed loop with actuators or torquers, avionics, algorithms, software, and ground support equipment to correct the satellite's attitude orientation [5]. The ETRSS-1 AOCS subsystem (Figure 2) is primarily made up of central control units, actuators, and sensors. ETRSS-1 AOCS subsystems are used to automatically adjust the satellite's attitude and provide the attitude required by the satellite'swork modes in either sun-pointing mode (coarse) or Earth pointing mode, primarily attitude sustaining towards the target (mainly roll-maneuvering) during real-time imaging tasks. The momentum wheels of the satellite are installed on the pitch axis and provide gyroscopic stiffness for roll and yaw axis stabilization. They are designed to spin at a fixed rate without rate control. The measurement sensors include a fiber-optical gyroscope, dual-axis micro-analog sun sensor, digital magnetometer, Nano-star sensor, and SoC digital sun sensor.

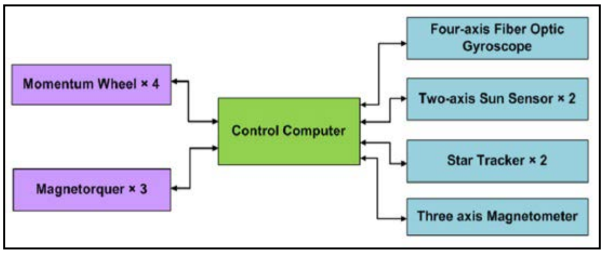
AOCS hardware sensors and actuators:

1.1) Fiber-optical gyroscope The ETRSS-1 FOG sensor measures the angular velocity around a single axis and has a dynamic measurement range of -50°/s ~ +50°/s. Furthermore, the sensor is intended to provide angular information for all control modes, as well as a long-term attitude reference for the satellite, as well as a coarse precision attitude measurement system linked to a sun sensor, a star track sensor, and a magnetic moment sensor. The sensor is installed on the satellite along the +X-axis at (90°, 90°, 180°), +Y-axis at (90°, 0°, 90°), and +Z-axis at (0°, 90°, 90°) with an assembly error requirement of less than 2'. Table 3 details the FOG specifications.

1.2) Nano-star sensor (STS). The ETRSS-1 uses two star sensors, which are basically cameras that detect and locate stars in the sky while also determining the satellite's orientation. By detecting star patterns in its 21° × 18° field of view (FOV), an autonomous star sensor detects and calculates its position in relation to the celestial sphere. Both sensor is installed on the satellite along the +X-axis at (48.439237°), +Y-axis at (67.478988°), and +Z-axis at (130°) with an assembly error requirement of less than 2' The ETRSS-1 AOCS Nano-star sensors are detailed in Table 4.

1.3) Digital and analog sun sensor. The sun sensor can measure the angle between the normal direction of the solar array and the

Figure 2: ETRSS-1 satellite AOCS composition.



object	index
weight	≤1.4kg
power consumption	steady state 8.2W initialization 13W
measurement range	-50°/s ~ +50°/s
size	157mm X 130mm X106mm
interface	4 X RS422
Power supply	-12V, 5V, independently for 4 gyro head

Table 3 FOG of AOCS

object	index
measurement accuracy	around optic axis ≤10" (3σ) perpendicular to the optic axis ≤50"
field of view	21° X 18°
work temperature	-20°C ~ +40°C
size	96mm X 40mm X 40mm
interface	4 X RS422 + 2 differential signa
power consumption	≤ 1.5W
Weight	≤ 200g

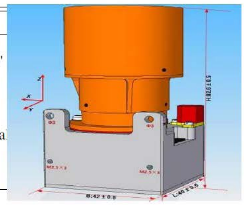


Table 4 Nano-star sensor of AOCS

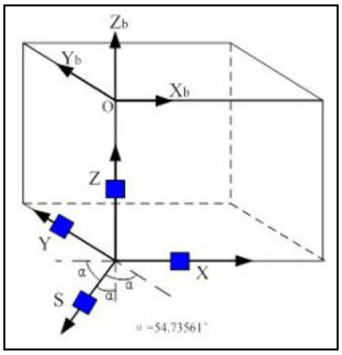
sun vector. ETRSS-1 AOCS employs two types of sun sensors: a dual-axis microanalog sun sensor that is primarily used during the injection period but can also be used for sun acquisition in an emergency situation, and a SOC Digital Sun Sensor, which is an experimental unit on board that uses an APS image sensor and an optical mask to create a sun sensor weighing no more than 40g and with an accuracy of 0.03°. Digital sun sensors (DSS) outperform analog sun sensors (ASS) in accuracy and stability due to the use of a charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) image detector [7]. The ETRSS-1 digital sun sensor has a field of view (FOV) of ± 64° × ± 64°, measurement accuracy of ≤ 0.03° (3σ), a data updating rate of ≥ 10Hz, the weight of less than 40g, and power consumption less than 0.5W, whereas that of analog sun sensor a measurement accuracy ≤ 0.5° (3σ), weighs less than 30g and has a working temperature range of -70°C to +70°C at the similar field of view with digital sun sensor. Both digital and analog sun sensor is installed on the satellite along the +X-axis at (0°, 90°, 90°), +Y-axis at (90°, 180°, 90°), and +Z-axis at (90°, 90°, 180°) with an assembly error requirement of less than 5'.

1.4) Digital magneto meter. The magnetic field is another useful vector for determining attitude, and it serves as the primary reference vector for attitude control during eclipses. Magnetic sensors are useful in space technology development for a variety of applications, the most prominent of which is in-orbit magnetic field measurement; other applications include magnetic encoders, angular and position sensors, and magnetometers or gradiometers for planetary magnetometry [9]. ETRSS-1's attitude and orbital control subsystem is equipped with two HMR 2300 3-axis Gadisa Dinaol et al. magnetometers for attitude reference, compassing, and navigation, one of which serves as a backup for the other. ETRSS-1 AOCS subsystem digital magnetometer dimensions are 83mm × 25mm × 22mm with measurement accuracy of 0.01% ~ 0.52%, measurement range of ± 1Gauss with resolution 0.000067Gauss, and an average measurement error of 0.0013 Gauss (1σ), power supply 6.5V ~ 15V at current 27mA ~ 45mA.

1.5) Momentum wheel. Momentum wheels are nominally treated as a black box for missions that do not require precise pointing [10] and are regarded as an ideal unit capable of producing the required control torque accurately, regardless of jitter or other disturbances. Magnetic actuators can be used to reduce the torque required by the reaction wheel, allowing satellites to run their momentum wheels at a slower rotation speed in order to reduce jitter. ETRSS-1 AOCS subsystem employs FWSR. 090.0.1-1C momentum wheel as the primary maneuvering actuators and core devices for implementing a zero-momentum control strategy. Furthermore, the actuators provide external torque to the ETRSS-1 satellite in order to achieve high attitude control performance and angular rate, as well as to construct the total angular momentum of the entire satellite in order to achieve zero angular momentum with four wheels. Earth satellite attitude control systems frequently use magnetic actuation, in which the mechanical torque required for attitude control is generated by the magnetic interaction between the geomagnetic field and onboard electromagnets or magnetic torquers [11]. ETRSS-1 momentum wheels X, Y, and Z are mounted orthogonally within their angular momentum vectors paralleled with respect to the +X, +Y, +Z axis of the satellite coordinates, while the momentum wheel S is mounted equi-angularly with the -X, -Y, -Z axis of the satellite coordinates as shown in Figure 3. The wheel weighs 1kg, has a working speed of 6000rpm, a maximum moment output of 15 Nm, an angular momentum of 0.36 Nm/s, and a steady state power consumption of about 9W.

1.6) Magnetic torquer. The magnetic torquer on the ETRSS-1AOCS can provide controllable magnetic momentum change of the satellite by using the effect of the Earth's magnetic field. It is primarily used for unloading angular momentum and magnetic damping, and it can provide torque to reduce the speed of the momentum wheels from real-time to nominal speed. The AOCS magnetic torquer specifications used in ETRSS-1 are detailed in Table 5.

Figure 3: Angle between momentum wheel I_{hh} and satellite axis.



object	index
Maximum output	$1Am^2 \pm 5\%$
Remnant magnetic moment	less than 0.01 Am^2
Control signal	5V pulse
Power consumption	$\leq$ 1.35W
Weight	less than 200g
Working temperature	-15° ~ +45°C
Size	115mm X Φ 14mm

Table 5 AOCS of ETRSS-1 magnetic torquer

ETRSS-1 AOCS control algorithm

Satellite attitude dynamics. The attitude dynamics of a spacecraft modeled as a rigid body rotating in space with flywheels and an inertial matrix J whose origin is at the center of mass and whose reference frame is fixed to the satellite body could be described using Euler's equation of motion.

$$J\dot{\omega}(t) = -\omega(t) \times J\omega(t) + T_c(t) + T_d(t) \text{ ---- (1)}$$

where $\omega(t)$ is the angular velocity vector expressed in a body reference frame and J is the inertia matrix, such that $J = J^T$, and T_c, T_d are, respectively, the control and disturbance torques acting on a satellite (caused by the space environment: light pressure, aerodynamic torque). The satellite's angular momentum is composed of the body angular momentum H and angular momentum h generated by momentum devices installed on the satellite, yielding

$$\dot{H} = -\dot{h} + T_c + T_d \text{ -----(2)}$$

and because the external torque affects the satellite's angular momentum, we have:

$$H(t) = H(0) + h(0) - h(t) + \int_0^t T_c dt + \int_0^t T_d dt \text{ ----- (3)}$$

where $H(0)$ is the initial value of body angular momentum, $h(0)$ is the initial value of angular momentum caused by momentum device, $\int_0^t T_c dt$ and $\int_0^t T_d dt$ are the external control angular momentum and external disturbing angular momentum respectively. As a result, solving attitude control problems becomes a matter of determining the values of $H(0)$ and (0) while handling the external disturbing angular momentum, $H_d(t)$. Normally, we keep h(0) = 0 which is called zero angular momentum control. Thus, in this case, $h(t)$ by momentum wheel and external control angular momentum, $H_c(t)$ by thruster and magnetic torquer have to deal with $H_d(t)$.

Results and Discussion

AOCS's Safe Control Mode of Operation

To complete the imaging mission, ETRSS-1's AOCS collaborates with other subsystems and will use several command sequences to implement the cooperation by providing a satisfied attitude condition. The AOCS on the ETRSS-1 satellite operates in six modes: global attitude acquisition mode, sun pointing mode, maneuver mode, earth pointing mode, attitude maintaining mode, and stop control mode. Global attitude acquisition mode employs a fiber optical gyroscope, a sun sensor, a magnetometer, a star sensor, and actuators such as a momentum wheel to reduce the satellite's angular velocity to the required range, as well as magnetic torques to stabilize the satellite after separation and drive the attitude close to nominal. Sun pointing mode is the satellite's normal operation mode, and the attitude determination scheme is "FOG with STS" or "FOG with the magnetometer," in which the attitude is controlled by a momentum wheel, and the redundant angular momentum is unloaded by magnetic torque. Maneuver mode is an interim mode that uses the estimation of FOG to implement attitude determination and momentum wheel to complete the attitude maneuver. The satellite operates in a three-axis zero-attitude earth-orientation mode, with attitude determination schemes comprised of a fiber optical gyro coupled with a star sensor or a fiber optical sensor coupled with a magnetometer. Attitude maintaining mode is followed by maneuver mode to maintain the required attitude, roll angle for imaging, or yaw 90° for calibration. The satellite can enter the stop control mode autonomously or via ground station control. In this mode, the central control unit no longer works on attitude control and only performs measurement and orbit calculation, and the output of the actuators is ZERO. Figure 4 depicts the conditions for the ETRSS-1's attitude control and mode of operation, while Figure 5 depicts the attitude angle and its corresponding angular velocity from January 2020 to 2023. When the satellite is in Earth pointing mode and attitude maintaining mode, its roll, pitch, and yaw angle vary between -0.1° and +0.1°. However, when in the earth pointing mode and attitude maintaining mode, the corresponding attitude angular velocity of

Figure 4: The control and operation modes of AOCS.

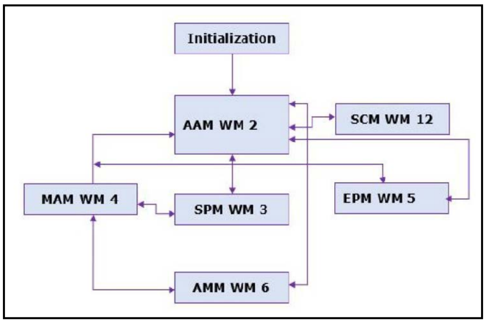
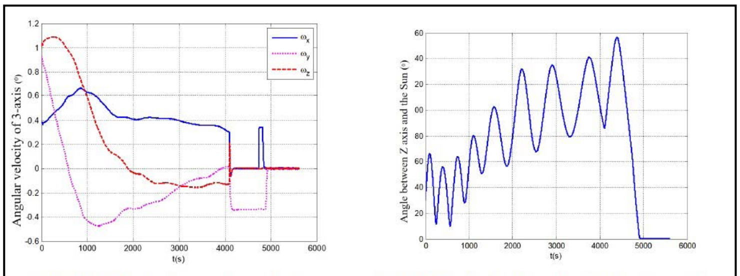
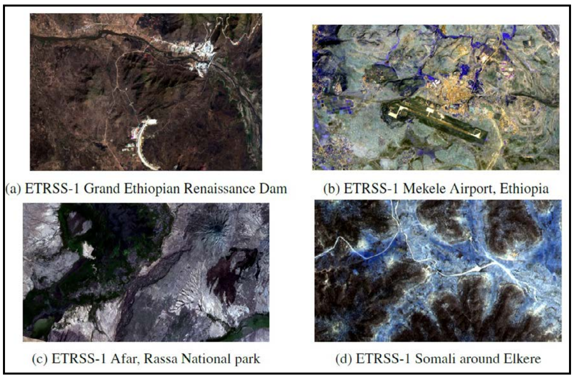


Figure 5: On-orbit result of ETRSS-1 damping moment.



(a) ETRSS-1 attitude angular velocity (b) ETRSS-1 attitude angle b/n Z axis and Sun

Figure 6: ETRSS-1 multi-spectral optical image.



(a) ETRSS-1 Grand Ethiopian Renaissance Dam (b) ETRSS-1 Mekele Airport, Ethiopia (c) ETRSS-1 Afar, Rassa National park (d) ETRSS-1 Somali around Elkere

the satellite, including the roll and pitch angular velocity, varies between -0.01°/s and +0.01°/s, while the yaw angular velocity varies between -0.1°/s and +0.1°/s. Figure 6 shows the satellite's magnetic damping moment's angular velocity during the initial separation.

Optical multispectral image

Optical imaging has been one of the most on-orbit missions of the ETRSS-1 microsatellite, due mainly to the satellite's good attitude performance. ETRSS-1 is equipped with a reinforced multispectral camera module for optical imaging, with a Ground Sampling Distance (GSD) of 13.4m at an orbit altitude of 628km and a swath of 80km. Figure 6 depicts the optical imagery captured by ETRSS-1 at various points in time and locations, including the Grand Ethiopian Renaissance Dam construction image. The image shows that the multispectral camera can capture the Earth, proving that the AOCS for ETRSS-1 is suitable and effective.

Conclusion

The ETRSS-1 satellite has been in orbit for more than three years, operating from a sun-synchronous orbit at an altitude of 628 kilometers, and has completed all missions successfully by providing imagery data via a ground control station facility located at Entoto. The ETRSS-1 attitude and orbital control subsystem is described in detail in this paper, and its on-orbit performance is evaluated. According to the satellite's original telemetry data, the attitude angle of the satellite varies between -180° and +180° when in working modes other than Attitude Acquisition Mode and Earth Pointing Mode.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could appear to have influenced the work described in this paper.

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