1. Introduction

Thanks to its long history of affordable space technology development, the Intelligent Space Systems Laboratory (ISSL) of The University of Tokyo has been engaging in various international cooperation programs with developing countries willing to reap the benefits brought by the CubeSat revolution. Following this philosophy, the ISSL initiated the TRICOM project in order to provide developing countries around the world with solutions to two of their most pressing issues: 1) the lack of knowledge and local capabilities with regards to space technology development and utilization, and 2) the complexity to control their territory due to the lack of comprehensive ground infrastructure, in particular for cellular phone connectivity. This project relies on the design of a standardized 3U bus for store-and-forward communications, providing a very affordable solution for satellite-based ground-to-space communication, coupled with the development and large-scale deployment of very affordable ground transmitters capable of sending data to the TRICOM CubeSat using very low transmission power. Moreover, the simplicity and efficiency of the TRICOM standardized bus makes it a convenient tool for hands-on satellite development capacity building. From its inception, the TRICOM project was developed with a high level of international cooperation in mind. This includes testing technologies by establishing a global network of ground sensors and ground receiving stations, and establishing a jointly developed and operated global constellation of store-and-forward TRICOM CubeSats.

This paper is organized as follows. Section 2 presents the philosophy of the TRICOM project, which is inherited from the Hodoyoshi-class satellites developed at the ISSL. Section 3 explains the detailed design of the TRICOM family of satellites. Section 4 explains the reasons for redesigning the TRICOM satellites. Section 5 introduces the first international cooperation achieved in the TRICOM project: the Rwandan-Japanese JPRWASAT satellite, also known as RWASAT-1, deployed from the International Space Station’s (ISS) Japanese Kibo module on November 20, 2019. Finally, Section 6 outlines the long-term strategy of the TRICOM project in Africa and around the world.

2. Philosophy of the TRICOM Project

The TRICOM project builds upon the long experience of affordable small satellite development at the ISSL, in particular, the one acquired through the Hodoyoshi project. The goal is to develop a low-cost satellite communications system to be used both for development and educational purposes.

2.1. Succeeding the Hodoyoshi project

The Japanese word hodoyoshi can be translated into English as “reasonably reliable.” Drawing from this unique Japanese expression, Professor Nakasuka of The University of Tokyo established the eponymous project, envisioning to find the appropriate balance between the development cost...
and reliability of small satellites. Beyond producing innovative small satellite designs for remote sensing and store-and-forward (S&F) communications (Fig. 1), the Hodoyoshi project established the basis of a domestic network of small satellite parts manufacturing and procurement (i.e., off-the-shelf). This new environment allowed the apparition of various micro- and nanosatellite projects for different purposes. The TRICOM project is one of them. It consists in developing a low-cost 3U CubeSat bus with a very sensitive S&F receiver inherited from one of the Hodoyoshi-class microsatellites, which is funded by the Ministry of Economy, Trade and Industry of Japan (METI).

2.2. Providing affordable S&F communication

The main mission of TRICOM-class satellites is to provide very affordable data relay services using a high-sensitivity receiver that is capable of receiving small data packets from sensors spread around the world while using a very weak signal (i.e., approximately 20 mW). Using a very weak signal for data transmission from the ground sensors to the satellites allows the cost of sensor development and manufacturing to be reduced as broadcasting would only require a very-low-power energy source and a compact patch antenna.

2.3. Useful educational tool

Beyond its actual utilization for data gathering, TRICOM satellites can be used as educational tools thanks to the simplicity of their design. The short development cycle and easily purchasable parts for building TRICOM satellites makes it an excellent choice for a country that desires to establish a space program. Within less than six months, engineers from “non-space” countries can witness the full assembly, integration, and testing of a satellite. Therefore, after only a few years of research and producing a few TRICOM-class satellites, a country can train a few dozen capable satellite engineers and build a strong and sustainable space program.

Section 5 of this paper illustrates this point using the example of Rwanda, in which TRICOM satellites are currently being used to initiate a domestic space program. In particular, a modified TRICOM satellite became Rwanda’s first satellite, JPRWASAT, that was used to carry out an ambitious capacity building program.

3. TRICOM-class Satellites

3.1. General description

TRICOM-class satellites are S&F—machine-to-machine–CubeSats with a size of 3U and having a mass of approximately 3 kg. Apart from the main S&F mission, TRICOM satellites are equipped with five small cameras for Earth observation. As the bus and S&F main mission only require 2U, there is one “free U” for customized secondary missions.

3.2. First attempt: TRICOM-1

The first satellite of the TRICOM family was TRICOM-1 (Fig. 2), which was completed at the end of 2016 and scheduled for launch on the experimental rocket SS-520-4 (Fig. 3) from Uchinoura Space Center in Kagoshima, Japan. The basic specifications of TRICOM-1 can be found in Table 1.

As the main mission, TRICOM-1 was equipped with a very sensitive multidirectional radio-frequency (RF) receiver, described in Table 2. The innovative aspect of this receiver is its reliance on long-range (LoRa) modulation. LoRa uses low-power, wide-area network (LPWAN) technology, allowing the transmission of small data packets (e.g., temperature, soil moisture, water level, etc.) over very long distances using very limited transmission power. The development of LoRa standards is being overseen by an association called the LoRa Alliance, which has a membership of more than 500, including companies such as IBM, Orange, Cisco, etc. The TRICOM-1 RF receiver, based on Hodoyoshi’s RF receiver, was designed to receive a 20 mW ground signal from an altitude of 500 km. Finally, the 920 MHz band was chosen because low-power transmissions on this frequency band do not require a license in Japan and many other countries.

![Fig. 1. Concept of store-and-forward communications.](image1)

![Fig. 2. TRICOM-1 before launch.](image2)
TRICOM-1 was launched on January 14, 2017 at 08:33 am Japan Standard Time. However, 20s after ignition, the Uchinoura Space Center’s ground station lost contact with the telemetry transmitter of the rocket. It was then decided not to send the second-stage ignition command to the rocket. Although the second-stage engine did not start, the rocket reached a maximum altitude of 190 km and automatically released TRICOM-1 following the original timing for deployment. This allowed TRICOM-1 to transmit interesting housekeeping data and demonstrate bus system functions before crashing into the Pacific Ocean along with the SS-520-4.3,4)

3.3 Second and successful attempt: TRICOM-1R

After the launch failure of TRICOM-1, the ISSL developed an identical satellite, TRICOM-1R, and launched it from the Uchinoura Space Center on JAXA’s sounding rocket SS-520-5 on February 3, 2018.5) It was placed in a very elliptical orbit with a perigee of 183 km and apogee of 2,010 km.

The operations of TRICOM-1R went as planned, confirming the quality of the design made by ISSL teams. In particular, a test campaign was carried out to check the functioning of the S&F system at various locations around the world.

3.4 S&F worldwide test campaign

In order to evaluate the functioning of the S&F system onboard TRICOM-1R, tests were conducted while traveling over various locations around the world (e.g., Chile, Costa Rica, Japan, and Rwanda) using ultrahigh-frequency ground transmitters developed at the ISSL. Detailed specifications of the S&F transmitters are listed in Table 3.

The results of the S&F communication tests were very positive, as ISSL engineers were able to upload data to TRICOM-1R using a UHF ground transmitter with a signal power as low as 8 mW, well below the original target of 20 mW.

During these tests, the bit rate was 293 bps when sending data packets of simple texts symbolizing temperature, hygrometry or GPS measurements, and the highest successfully tested altitude was 1,048 km. Signal transmission was initiated manually by operators based on the forecasted orbital position of TRICOM-1R.

4. Need for Redesign: TRICOM-2

The failed launch of TRICOM-1 and successful launch of TRICOM-1R onboard two rockets from the SS-520 family of dedicated small satellite launchers contributed to the development of 3U CubeSats without strict size constraints. Such launches were exceptional opportunities and therefore cannot be repeated ad libitum. Looking for more frequent and reliable launch opportunities, it was decided to adapt TRICOM satellites so as to be useable with the deployment system onboard the ISS’s Japanese Kibo module. TRICOM was therefore slightly reduced from its original size (116 × 116 × 346 mm, L × W × H) to fit the Small Satellite Orbital Deployer (JSSOD) size requirements (100 × 100 × 341 mm, L × W × H) of the Japanese Experimental Module (JEM).6)
Seizing the opportunity of this redesign, the ISSL decided to: 1) improve the communication system for command and control from UHF to S-band, and 2) further standardize the satellite bus for simplified assembly, integration and testing (AIT). The new design produced by the ISSL was named the TRICOM-2 Standard Bus (TC2).7)

Other elements of TRICOM-2 remained the same as those of TRICOM-1/1R; in particular, the S&F receiver (see Table 2) and its great modularity that enables incorporating an additional 1U of mission equipment to the bus and S&F mission, which occupy the other 2U.

5. First Pilot Project Cooperation: JPRWASAT

As explained earlier in this paper, the TRICOM project was initiated with international collaboration in mind, and a strong focus on space technology development and utilization capacity building for the benefit of developing countries. The first international collaboration of the TRICOM project was initiated in 2018 with the Government of Rwanda, represented by the Rwanda Utilities Regulatory Authority (RURA). This cooperation has two main goals: 1) providing Rwanda with its first satellite, JPRWASAT, a modified version of TRICOM-2, and 2) training local engineers in the field of satellite technology development and utilization.

5.1. JPRWASAT

JPRWASAT (Japan-Rwanda Satellite), also called RWASAT-1 (Rwanda Satellite 1), is the first satellite in the history of the Republic of Rwanda co-developed and co-built with The University of Tokyo based on the latter’s TRICOM-2 design.

Following the results of a mission idea contest carried out in Rwanda in early 2018, it was decided to place two multispectral cameras in the “third U” of JPRWASAT. The specifications of these cameras can be found in Table 4 and the overall design of JPRWASAT in Fig. 4.

The satellite was developed from December 2018 to May 2019 by a joint Japanese-Rwandan team working in the facilities of the ISSL at The University of Tokyo. Various industrial partners, mostly from Fukui Prefecture (i.e., western Japan), were part of the project for the manufacturing of satellite parts and the testing of the satellite.

After its completion and official delivery to the government of Rwanda at the 2019 Transform Africa Summit in Kigali in May 2019, the final inspection of JPRWASAT was conducted at JAXA’s Tsukuba Space Center on June 4, 2019, after which it was consequently handed over to JAXA (Fig. 5). After launch to the ISS onboard HTV-8, it was subsequently deployed from the Japanese Kibo module using the JSSOD on November 20, 2019. Tests are currently being carried out and results are not presented in this paper. For more technical details on the JPRWASAT bus design, please refer to Aoyanagi et al.7)

5.2. JPRWASAT missions

JPRWASAT missions are focused on issues faced by Rwanda and can be divided into two categories based on the two main payloads of JPRWASAT.

- Mission 1: S&F communication for data gathering in remote areas. While Rwanda has good cellular phone data penetration, some areas of the country are still disconnected from the rest of the world, such as the deep forests at the borders with the Democratic Republic of the Congo and Uganda. The tracking of wildlife, such as the endangered Mountain Gorillas, could be an appropriate mission for JPRWASAT. Similar applications can be introduced in eastern Rwanda to track savannah animals. Environmental monitoring of river-water quality, river level, soil moisture, temperature, etc., are also potential missions for JPRWASAT. The deployment of ground sensors for various applications throughout Rwanda will be carried out before JPRWASAT deployment in the summer of 2019.

Table 4. Multispectral mission camera specifications.

| Ground sample distance | 10–20 m (nominal: 17.6 m@alt 400 km) |
|------------------------|--------------------------------------|
| Swath                  | 45 km (FOV: 6.4 deg)                 |
| Bands                  | 2 x 3 band spectral cameras using multi-band-pass filters with color imagers |
|                        | • Band 1: Blue = 457 nm              |
|                        | • Band 2: Green 1 = 530 nm           |
|                        | • Band 3: Green 2 = 560 nm           |
|                        | • Band 4: Red 1 = 628 nm             |
|                        | • Band 5: Red 2 = 670 nm             |
|                        | • Band 6: Infrared = 910 nm          |
| Lens                   | f = 50 mm, F/2.0                     |

Fig. 4. JPRWASAT layout.

Fig. 5. JPRWASAT flight model before being handed over to JAXA in early June 2019 at the ISSL.
Mission 2: Multispectral observation. The multispectral cameras, request from the Rwandan side, will be used for many applications such as forest health conservation and agriculture monitoring.

5.3. Capacity building programs

Apart from placing the first Rwandan satellite in orbit, the JPRWASAT project aims to develop infrastructure capacity in Rwanda. In particular, local capacity building programs can be divided into two categories: satellite engineering, and data analysis and utilization.

The main target of the JPRWASAT project is the development of a pool of capable space engineers in Rwanda, starting at different levels. At the time of redaction of this paper, two space engineering capacity building programs have been carried out. The first saw three Rwandan engineers stay three months in Japan so that they could participate in the joint development, integration and tests of JPRWASAT (Fig. 6), at which time they acquired specialized knowledge in satellite engineering based on their existing high-level knowledge in related fields (e.g., mechanical, aeronautical and electrical). In terms of capacity building timeline, the idea is to have parallel short-term and long-term approaches that: 1) quickly provide specialized knowledge to experienced engineers (i.e., three-month stay in Japan), and 2) introducing the future generation of Rwandan engineers to satellite development.

At an earlier level, training focusing on basic space engineering was carried out with undergraduate students from the College of Science and Technology of the University of Rwanda using the HEPTA-Sat learning program developed by two our partner organizations: NPO UNISEC-Global and Nihon University (Fig. 7).

5.4. Continuing collaboration with Rwanda

The JPRWASAT project is only the beginning of the ISSL collaboration with the government of Rwanda. While JPRWASAT is a joint Japan-Rwanda satellite, discussions are underway for manufacturing and deploying Rwanda’s second satellite, RWASAT-2. Moreover, capacity building efforts are not stopping with the delivery of JPRWASAT. Future milestones of the program will include, in the short term, establishing a remote ground station in Kigali to use S-band stations, and in Japan, subsequent satellite operations training, as well as training on building affordable ground transmitters adapted to the TRICOM and JPRWASAT S&F system. In the long term, the ISSL is working to install an actual S-band ground station in Kigali, Rwanda.

On the data analysis side, Japanese organizations such as The University of Tokyo and Japan Space Systems have been carrying out training for remote sensing data analysis and big data analysis using general-purpose computing on graphics processing units (GPGPU) and supercomputing systems in March and May 2019. The use of supercomputing is not primarily motivated by the analysis of data collected by JPRWASAT, but also enables the integration of numerous sources of open-source geospatial data provided by universities, government agencies and private companies around the world.

6. Long-term Vision: Global TRICOM Constellation

After the successful Rwandan pilot project with JPRWASAT, the ISSL and its Rwandan partners envision to scale up the project with numerous other international partners. Rwanda being a core member of the Smart Africa Alliance, priority will be given to establishing cooperation agreements with “Smart African” countries. The Smart Africa Alliance is a regional organization based in Kigali, Rwanda. It has 24 members countries working together for the advancement information and communication technologies on the continent.

During the Smart Africa Alliance’s annual Transform Africa Summit in May 2018, Professor Nakasuka and Professor Shibasaki of The University of Tokyo signed a Memorandum of Understanding on space development and building utilization capacity, as well as on establishing a regional constellation of S&F satellites (Fig. 8).

Similar partnerships are currently under preparation in other regions in the world; namely, Latin America and Southeast Asia.

7. Conclusion

The TRICOM project is a long and ambitious venture aimed at solving two of the main issues faced by developing
countries around the world: the lack of communications services in remote areas and the very limited or non-existent understanding of space technology by, respectively, providing affordable access to satellite communications around the world and developing convenient tools for building the capacity of space engineering. After having demonstrated the robustness of the TRICOM design and exceptional performance of its S&F communication system through an international test campaign on all continents with TRICOM-1R, the ISSL launched the first stage of its international development plans through a collaboration with the Republic of Rwanda. Rwanda is a perfect target for the TRICOM project as it is a very young and ambitious country with a strong desire to promote the use of information and communication technologies nationally and regionally through the Smart Africa Alliance, which is chaired by the President of Rwanda, Paul Kagame. Moreover, it had no space engineering capabilities. JPRWASAT, the first Rwandan satellite and second TRICOM-class satellite, is a stepping-stone towards the large-scale production and deployment of TRICOM satellites. In particular, establishing the first African constellation of satellites in collaboration with the Smart Africa Alliance heavily depends on the success of JPRWASAT and its ability to contribute to sustainable development in the region.

References

1) Matsumoto, T., Matsui, M., Nakasuka, S., Fukami, T., Aoyanagi, Y., Inamori, T., Tokaji, A., Tsuruda, Y., Tanaka, T., Yamaguchi, K., and Shibayama, Y.: Development of Store and Forward System for Hodoyoshi-3&4 Microsatellites, Trans. JSASS Aerospace Technology Japan, 14, iss.30 (2016), pp. Pf.125–Pf.130.
2) Institute of Space and Astronautical Science: Sounding Rockets SS-520, http://www.isas.jaxa.jp/en/missions/sounding_rockets/ss-520.html (accessed April 22, 2020).
3) Verspieren, Q., Obata, T., and Nakasuka, S.: Innovative Approach to Data Gathering in Remote Areas Using Constellations of Store & Forward Communication CubeSats, 31st International Symposium on Space Technology and Science (ISTS), June 2017, Ehime-Matsuyama, Japan.
4) Institute of Space and Astronautical Science: SS-520 No. 4 Launch Results, http://www.isas.jaxa.jp/en/topics/000827.html (accessed April 22, 2020).
5) Institute of Space and Astronautical Science: Successful Launch Experiment, SS-520 No. 5, http://www.isas.jaxa.jp/en/topics/001233.html (accessed April 22, 2020).
6) JAXA: JEM Payload Accommodation Handbook, Vol. 8, Small Satellite Deployment Interface Control Document, JAXA Technical Documentation, JX-ESPC-101132-C, 2017.
7) Aoyanagi, Y., Matsumoto, T., Obata, T., and Nakasuka, S.: Design of 3U-CubeSat Bus Based on TRICOM Experience to Improve Versatility and Easiness of AIT, 32nd International Symposium on Space Technology and Science (ISTS), June 2019, Fukui, Japan.
8) University of Rwanda, College of Science and Technology: 25 Engineering Students Get Tips for Advancing Satellite Technology, https://est.ur.ac.rw/?q=node/829 (accessed April 22, 2020).
9) Smart Africa: Memorandum of Understanding (MoUs) Signed at TAS 2018, http://smartafrica.org/memorandum-of-understanding-mous-signed-at-tas-2018/ (accessed April 22, 2020).

Shujiro Sawai
Associate Editor