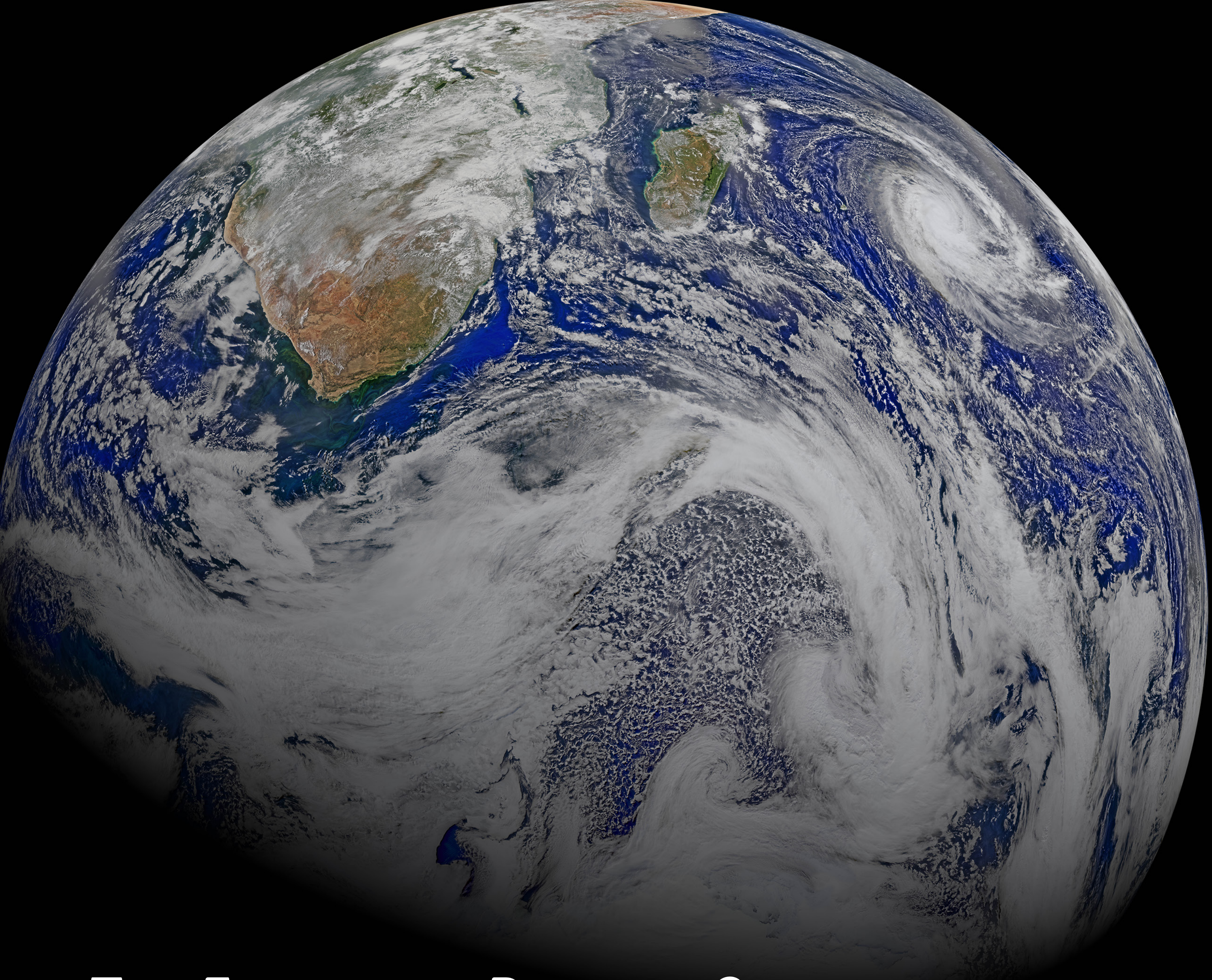

The Emerging Role of Cubesats for Earth Observation Applications in South Africa

Paidamwoyo Mhangara, The University of Witwatersrand

Introduction

Cubesats usage is evolving from scientific demonstration and educational platforms to standardized space-borne scientific instruments that support operational earth observation applications (Liebig 2000, Sandau 2010, Woellert et al. 2011, Qiao et al. 2013, Diaz et al. 2016, Kopacz et al. 2020). The effectiveness of Cubesat technology is being attested to globally as nanosatellites are increasingly used to support innovative scientific and operational missions (Rose et al. 2012, Qiao et al. 2013, Xia et al. 2017, Poursanidis et al. 2019). Cubesats have long been recognized as having the potential to be a disruptive force that could replace large conventional earth observation satellites (Southwood 2000, Diaz et al. 2016, Mhangara et al. 2020).

Cubesats have benefited from the accelerated progression towards miniaturization of space-borne satellite platforms and the availability of Commercial-Off-The-Shelf (COTS) components (Woellert et al. 2011, Matandirotya et al. 2013). Small satellites are generally classified into five groups known as Minisatellite (100–500 kg), Microsatellite (10–100 kg), Nanosatellite (1–10 kg), Picosatellite (0.1–1 kg) and Femtosatellite (0.01–0.1 kg) (Sandau 2010, Woellert et al. 2011). Despite their small size, Cubesats are increasingly being considered as ideal platforms for hosting compact earth observation instruments needed to take critical measurements. Conventional earth observation scientific instruments mounted on Cubesats include visible and near-infrared sensors, near-infrared spectrometers, magnetometers, radiometers and short wavelength radars (Liebig 2000, Qiao et al. 2013, Diaz et al. 2016). To date, at least 1200 Cubesats have been launched into low-earth orbit, and this number is predicted to grow (Sandau 2010, Xia et al. 2017).

Despite their small size, Cubesats are increasingly being considered as ideal platforms for hosting compact earth observation instruments needed to take critical measurements.

Cubesats Around the World

Globally, the development of miniaturized satellite platforms has been pioneered by universities (Sandau 2010, Xia et al. 2017). Initially introduced as low-cost space research and engineering projects for university students, Cubesat technology has proliferated in the industry and has been widely adopted by space agencies internationally (Blouvac et al. 2000, Liebig 2000, Southwood 2000). The growth in Cubesat technology has been augmented by a simultaneous acceleration in technological advancements in nano-, micro-, and miniature technologies in technical fields that include telecommunications, (Opto)electronics, materials, sensors, fluidics, and instrumentation (Woellert et al. 2011, Diaz et al. 2016). This technological wave enabled the development of a variety of miniaturized and novel autonomous instruments and systems to facilitate remote measurements and scientific experiments on a miniaturized platform.

Cubesats have been adopted by space agencies internationally for scientific tests and important scientific missions. Some prominent Cubesat programs include The National Aeronautics and Space Administration's (NASA) CubeSat Launch Initiative program, European Space Agency (ESA)-funded Student Space Exploration and Technology Initiative (SSETI), the National Science Foundation (NSF) initiative in the USA, and the Cubesat Programme at the Cape Peninsula University of Technology's French South African Institute of Technology (F'SATI) whose Cubesats have been funded by the South African National Space Agency (SANSA) (Blouvac et al. 2000, Southwood 2000, Steyn et al. 2013, van Zyl et al. 2013).

The commercial viability of using Cubesats for operational earth observation applications has also gained the attention of private companies (Mhangara et al. 2020). The low capital layout cost, rapid development and related low-risk levels associated with Cubesat platforms are attractive for investors venturing into the space industry. Many academic spin-off companies are being established internationally to develop and integrate Cubesat components and subsystems as well as to provide earth observation data and downstream products and services (Rose et al. 2012, Xia et al. 2017). A business value chain now exists that is comprised of manufacturers of COTS components, suppliers of Cubesat kits, providers of complete Cubesats, companies for launch services, data vendors and providers for downstream value-added products and services. In a recent market study of the satellite industry, the economic value of Cubesats was $152 million in 2018, and projected to rise to $375 million by 2023. The earth observation and traffic monitoring segment constitute a large share of the global Cubesat market (https://www.marketsandmarkets.com/Market-Reports/cubesat-market-58068326.html). Prominent earth observation companies that have emerged include Planet Labs, which has a constellation of more than 100 Cubesats in low earth orbit imaging over 250 million km2 of the earth's landmass daily. The Planet Labs Cubesat weighs about 5kg and is 10x10x30 centimeters in size.

Cubesats are a feasible way of participating in space-related activities due to their cheap manufacturing costs, low launch

Photogrammetric Engineering & Remote Sensing
Vol. 86, No. 6, June 2020, pp. 333–340.
0099-1112/20/334–340

doi: 10.14358/PERS.86.6.333

cost, short development time, small size, light weight, and low power requirements compared to large satellites used in the Landsat satellite missions and Sentinel satellite series (Paules and Luther 2000, Woellert et al. 2011, Diaz et al. 2016). These favorable factors are allowing developing countries to actively participate in satellite development and operations. The potential of Cubesats to accelerate scientific and technological advancement of emerging economies and developing countries has already been articulated (Woellert et al. 2011, Rose et al. 2012). The scholars provide a concise synthesis of the history and a technical overview of Cubesats as well as a synopsis of scientific applications and success stories.

For several decades now, the development of satellites for earth observation applications has been dominated by space-faring nations such as United States, Japan, India, Russia, European Union countries, Japan, Canada and lately China and Brazil (Woellert et al. 2011). Despite the well-established scientific and socio-economic benefits of earth observation, the capital-intensive nature and engineering complexity of conventional satellite building programs limited developing countries in constructing their own satellites. The advent of Cubesats have lowered the barrier to entry for less developed countries and has provided them with an invaluable opportunity to launch space programs. (van Zyl. 2011, Rose et al. 2012, Ngcofe and Gottschalk 2013) The development of Cubesats accompanies some of the achievements by African countries with emerging space capabilities in small satellites such as Algeria, Egypt, Nigeria and South Africa. In Africa, there is growing interest from universities, governments, space agencies and commercial companies to develop small satellites to support earth observation applications (van Zyl. 2011, Steyn et al. 2013, van Zyl et al. 2013). The low development and launch costs associated with small satellites have spurred developing African nations such as South Africa, Nigeria, Egypt, Ghana, Kenya, Algeria and Zimbabwe to launch space programs aimed at advancing technological innovation in space (Ngcofe and Gottschalk 2013, Oyewole 2017). While some studies have focused on the growth of space technology in various countries, little focus has been placed on the evolving role of Cubesats in South Africa.

The advent of Cubesats have lowered the barrier to entry for less developed countries and has provided them with an invaluable opportunity to launch space programs.

Development of Cubesats in South Africa

Early Development

While the evolution of Cubesats in South Africa accelerated with the technological forces towards miniaturization of satellites and electronic systems, the growth was also spurred by the country's preceding satellite engineering capability (Gottschalk 2010, Ngcofe and Gottschalk 2013, Steyn et al. 2013, van Zyl et al. 2013). South Africa has a long history in space science and technology that dates back to the emergence of the space era. The country's heritage in space technology can be traced as far back as the 1950's when it was involved in amateur rocket launches.

In a review of South Africa's space program, Gottschalk (Gottschalk 2010) divides the evolution of the country's space initiative into three epochs. The first phase was from 1947-1962 and was named the age of amateurs. The apartheid government led the second phase called the military era from 1963-1993. This era involved the development of a secret military space launcher program targeted at developing reconnaissance satellites. While the period didn't produce a flight-ready satellite, South Africa developed a comprehensive space infrastructure that included satellite testing, site design and a coastal launch facility with telemetry capacity.

The third phase, named the civilian era, emerged after the country became democratic in 1994. During this period, the country established several legal instruments and policies to regulate space activities and developed institutions and structures to coordinate them. Some of the space laws implemented include the Space Affairs Act 84 of 1993, Space Affairs Amendment Act 64 of 1995 and the South African National Space Agency Act 36 of 2008. Prominent institutions and councils set up include the South Africa National Space Agency (SANSA) and the Space Affairs Council of South Africa (SACSA) (Gottschalk 2010, Ngcofe and Gottschalk 2013, Steyn et al. 2013).

Launched in February 1999, the SUNSAT microsatellite was the first South African satellite that went into orbit. Built by the University of Stellenbosch, the microsatellite project started in 1992 to develop satellite engineering skills for use by the space industry in the country (Steyn et al. 2013). The satellite weighed 64kg and carried a pushbroom multispectral imager with three spectral bands at a ground sampling distance of 15m. SUNSAT had a mission life of two years. In September 2009 a second microsatellite known as Sumbandisat was launched and operated until August 2011. Sumbandilasat carried a pushbroom multispectral imager with six spectral bands capturing data at a ground sampling distance of 6.25m.

University Involvement

In South Africa, the thrust of the development of Cubesats was aimed at education and training, technology demonstration, space weather research and earth observation (van Zyl 2011, van Zyl et al. 2013, Zaidi et al. 2018). The low investment costs involved in developing Cubesats makes them perfect candidates for education and training, particularly for student research groups. The F'SATI program at the Cape Peninsula University of Technology is a postgraduate program in satellite systems engineering that focuses on the development of Cubesats. This initiative enabled students to acquire hands-on technical skills in satellite engineering and to undertake innovative research in the development of Cubesats. The program was funded by the Department of Science and Innovation (DSI), the National Research Foundation (NRF) and the South African National Space Agency.

Three Cubesats have been successfully launched from the program to date, including ZACube-01 and ZACube-02. ZACube-1 is an IU Cubesat ("U" refers to a 100x100x-113.5mm cube) that carries an HF beacon transmitter for ionospheric tomography as its primary payload for monitoring space weather. The payload was developed jointly with scientists at SANSA Science in Hermanus and consists of a simple radio transmitter. It emits a 14 MHz beacon signal received on the ground to characterize the electron density for the zone of the ionosphere traversed by the Cubesat. The data was used to validate and improve the International Reference Ionosphere model and to characterize the ionospheric radar for the Super Dual Auroral Radar Network (SuperDARN) (van Zyl et al. 2013). ZACube-01 also carries onboard a very low-resolution camera to capture pictures of the earth. Launched on December 27, 2018, ZACube-2 is a 3U Cubesat carrying an automatic identification system (AIS) as its primary payload and an additional ocean color and fire detection imager (Zaidi and van Zyl 2017, Zaidi et al. 2018). The K-line and reference infrared camera channels constitute a secondary payload. The AIS is used for detecting and tracking ship movement in the South African territorial waters in support of maritime domain awareness. The K-line and reference camera channels are used for wildfire detection and monitoring.

Recent Activities

In 2017, two South African Cubesats, ZA-AeroSat and nSight-1 were launched from the International Space Station (ISS) as part of ESA's QB50 project for upper tropospheric modeling research. ZA-AeroSat 3U Cubesat was jointly developed by Stellenbosch University, Cape Peninsula University of Technology and CubeSpace. The satellite was used to showcase passive Cubesat aerodynamic stabilization using its four communication antennas as aerodynamic feathers, but the Cubesat was only semi-operational due to weak signal issues.

nSight-1 is a 2Us Cubesat built by a private South African company, Space Commercial Services. It carries onboard IPEX (Flux-Φ-Probe Experiment) scientific instrument that collects atmospheric oxygen data in the lower thermosphere. nSight-1 also carries an additional RGB (Red, Green and Blue) multispectral earth observation imager as a secondary payload that captures images to support remote sensing applications (Mhangara et al. 2020).

The maturity of Cubesats as a space platform to support operational earth observation data has gained the attention of the South African space industry. The last decade has witnessed an increased number of South African companies participating in the development of Cubesats, namely Space Commercial Service, NewSpace Systems, Simera Technology Group, CubeSpace, Spaceteq and Amaya. Most of the companies are collaborating with universities that have satellite engineering capability, such as Cape Peninsula University of Technology and Stellenbosch University,as innovation partners.

Emerging Cubesat Remote Sensing Applications

Cubesats are progressively transforming the space science and technology landscape in South Africa. The four South African Cubesats launched in the last decade demonstrate the feasibility of using nanosatellites as operational platforms to support earth observation applications for socio-economic benefit. It is evident from the review of the Cubesats that imagers were only added as secondary payloads piggy-backing on funded scientific experiments that were the primary missions. An analysis of the images produced by n-Sight-1 nanosatellite and the infrared imager in ZACube-2 shows the feasibility of using Cubesats for operational remote sensing applications as a means of complementing data from current missions such as Landsat 8 and Sentinel-2.

In a recent study, Mhangara et al. (2020) analyzed nSight-1 and observed that the images are valuable for a multitude of remote sensing applications. Some of the identified uses included geological mapping, geomorphological analysis, extraction of surface water bodies, agricultural field demarcation and crop mapping, ship detection, vegetation assessments, differentiation of urbanized areas and other land use and land cover applications. The visual interpretation of n-Sight-1 imagery showed the images were suitable for a range of applications. Land use and land cover types discernable from nSight-1 imagery include agricultural fields, surface water bodies and geomorphological and structural geology features as illustrated in Figure 1, Figure 2 and Figure 3, respectively.

The infrared sensor onboard ZACube-2 is an invaluable tool for fire monitoring. The novelty of this imager is that it is capable of detecting the characteristic potassium spectral emissions of burning vegetation biomass using the near-infrared spectral channel and is valuable in identifying ocean color. Figure 4 displays an infrared image acquired by this sensor.

The practical value of the automatic identification system onboard ZACube-2 is maritime surveillance. AIS data from ZACube-2 is already being used for ocean vessel detection in South African Exclusive Economic Zone (EEZ) in support of a government oceans economy program known as Operations

Figure 1: nSight-1 Image: Agricultural fields in Delano, California, USA (Mhangara et al. 2020 and Credits: SCS).

Figure 2: nSight-1 Image: Water Resources and Agriculture at Bear Lake, Utah, USA (Mhangara et al. 2020 and Credits: SCS).

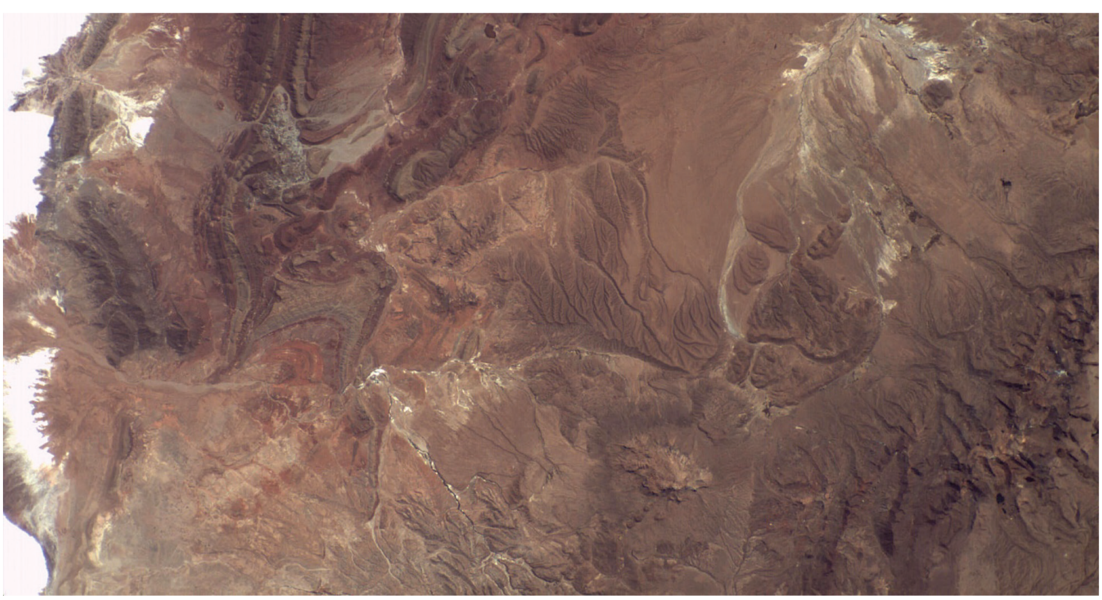

Figure 3: nSight-1 Image: Geomorphological features and structural geology in Salar de Uyuni, Bolivia (Mhangara et al. 2020 and Credits: SCS).

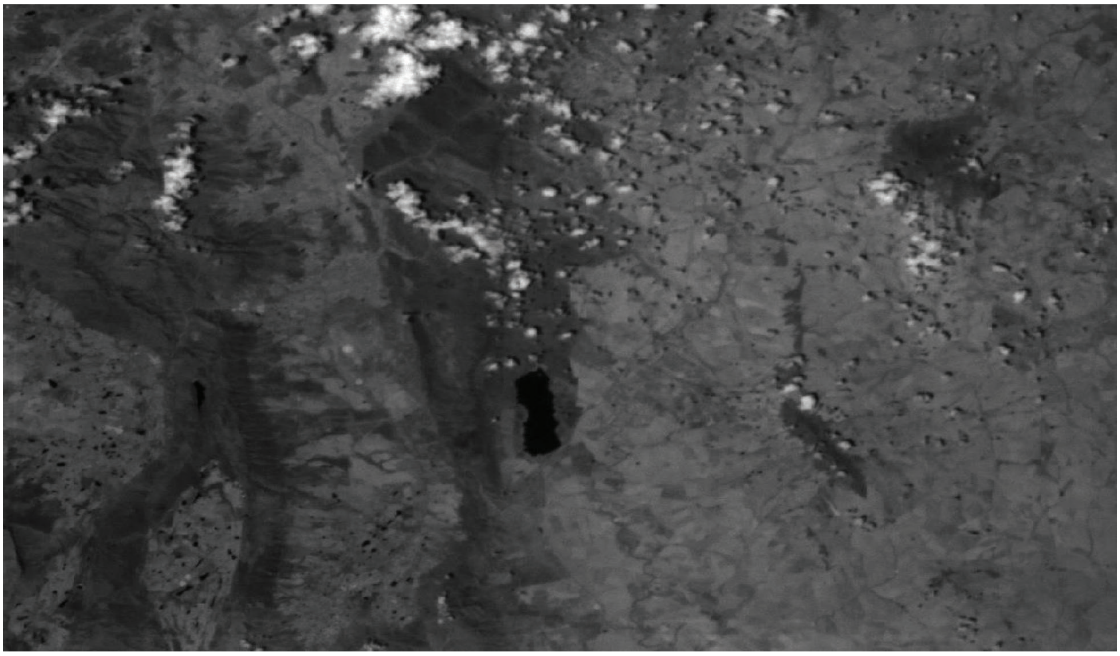

Figure 4. ZACube-2. NIR image over Voëlvlei Dam, Western Cape, South Africa from the K-line sensor (Credits: CPUT).

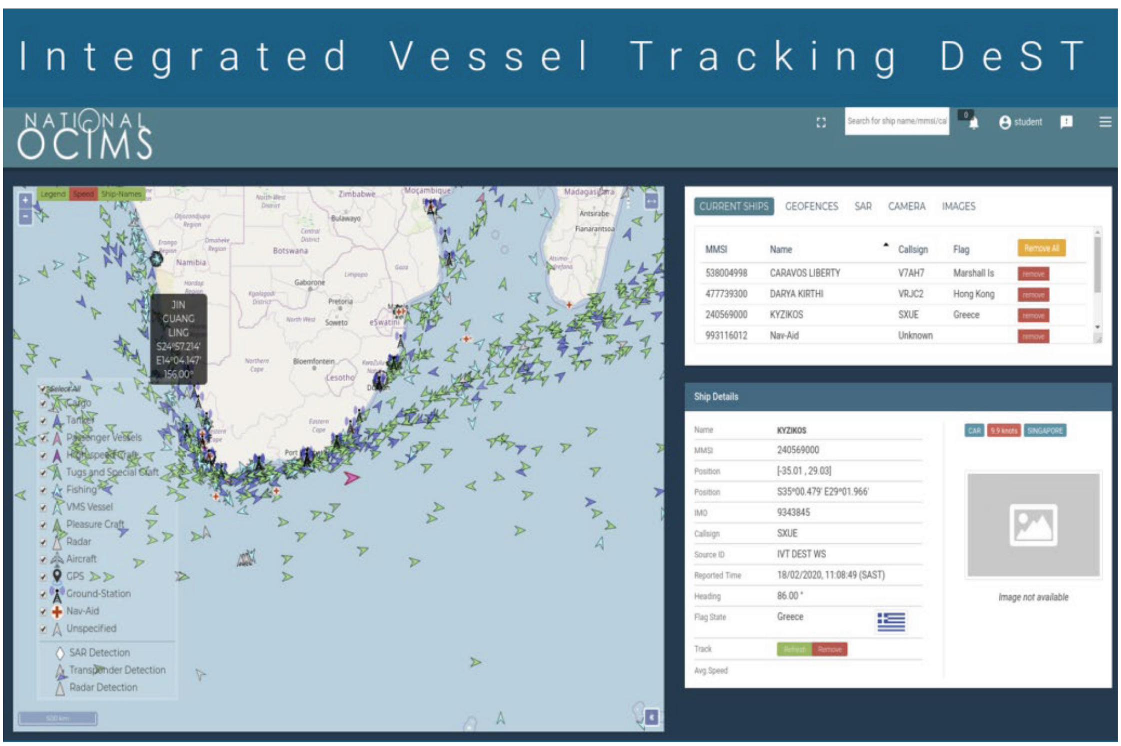

Figure 5: Integrated Vessel Tracking system that uses AIS data from ZA-CUBE 2. https://www.ocims.gov.za/integrated-vessel-tracking-tool/.

Phakisa. The AIS data augments the Radarsat-2 synthetic aperture radar (SAR) satellite data used for monitoring illegal vessels along the coastline and the broader EEZ. AIS also feeds into the Integrated Vessel Tracking Tool in the National Oceans and Coastal Information Management System (OCIMS). Illegal fishing vessels are notoriously known for turning off their AIS transponders during unlawful fishing operations. The AIS data is fed into the Integrated Vessel Tracking Tool shown in Figure 5 to track the movement of vessels using transponder information (such as AIS) and sends out notifications when ships encroach into Marine Protected Areas (MPAs).

The success of the ZACube-2 has prompted the Department of Science and Innovation in South Africa to provide funding for two additional Cubesats, one devoted to maritime surveillance and the other for fire monitoring with the ultimate objective of having a constellation of nine nanosatellites (https://www.itweb.co.za/content/kLgB1MeJPNGq59N4). Similarly, the success of nSight-1 compelled SCS to develop a follow-up compact Cubesat imager known as the Chameleon (http://scs-space.com/payloads/chameleon/).

Discussion

The capability demonstrated by nSight-1 and ZACube-2 nanosatellites in acquiring satellite imagery indicates that Cubesats can play a meaningful role in supporting operational remote sensing applications. Mhangara et al. (2020) analyzed a variety of nSight-1 imagery and concluded that the imagery is capable of supporting several remote sensing applications, including agricultural field mapping, surface water body mapping, soil erosion and other geomorphological assessments, wetlands mapping, urban demarcation, land cover and land use mapping, and a wide range of cartographic applications. The infrared imagery from the ZACube-2 K-line Sensor shows some potential for vegetation mapping, fire detection and wetland assessment. ZACube-2 has shown the remarkable capability to consistently supply AIS data to support the operational tracking of illegal vessels in the South African EEZ.

Lack of onboard radiometric calibration functionality on most Cubesats is a deficiency of current nanosatellites. Cross-calibration with other well-calibrated satellite missions could be used to address this shortcoming. The ability of the nanosatellites to provide reliable and consistent data services is an essential user requirement. This aspect could not be ascertained due to the experimental and short-term nature of the launched nanosatellites. It can, however, be argued that the success of Planet Labs Cubesats provides sufficient evidence of the potential mission life of Cubesats.

The emerging applications for nanosatellites in South Africa are consistent with global trends. A review of remote sensing applications using data from Cubesats is indicative of the pervasive nature of nanosatellites. McCabe et al. (2017) showcased the use of Cubesats in hydrology, especially in assessing vegetation dynamics and terrestrial evaporation. The utility of Cubesats for crop monitoring has been elaborated by many scholars (Houborg and McCabe 2018, Mhangara et al. 2020). Quite recently, Santilli et al. (2016) highlighted that a constellation of Cubesats is capable of supplying timely satellite data in disaster situations due to the more frequent revisiting of disaster areas. The ability of Cubesats to monitor temporal surface water changes was demonstrated by Cooley et al. (2019). Using high-resolution Cubesat imagery, Cooley et al. (2019) detected the daily changes in Arctic-Boreal Lake Dynamics. Houborg and McCabe (2018) demonstrated the feasibility of using Cubesat data to derive vegetation indices such as the Normalized Difference Vegetation Index and Leaf Area Index for crop and general vegetation monitoring. Recently, Poursanidis et al. (2019) demonstrated the utility of Cubesats to derive bathymetric measurements in coastal areas. The feasibility of using Cubesats for global mesopause temperature sensing in support of climate monitoring has been shown by Doe and Watchorn using the Climate Monitoring Cubesat Mission (CM2). The use of Cubesats as platforms for GNSS remote sensing and navigation has been explored by Qiao et al. (2013).

In general, our review suggests that remote sensing data applications undertaken by Cubesats cross the entire spectrum of the earth observation Societal Benefit Areas (SBAS) outlined by the Group on Earth Observation (GEO). Earth Observation SBAs include biodiversity and ecosystem sustainability, disaster resilience, energy and mineral resource management, food security and sustainable agriculture, infrastructure and transportation management, public health surveillance, sustainable urban development and water resources management (https://www.earthobservations.org/sbas.php).

Conclusion

Cubesats are increasingly being used worldwide as educational platforms for training, as a means to demonstrate engineering capability, and as hosts for scientific space-related experiments at low cost. Some of the favorable factors driving the growth in the development of Cubesats include the small size of Cubesats, short development time, access to COTS components and cheap launch costs compared to large satellite missions. In South Africa, while Cubesats were initially aimed as training tools for satellite engineering students at universities, the technology is reaching maturity and being deployed for operational applications. The growth areas for Cubesats include earth observation, surveillance, space weather monitoring, meteorology and telecommunications. A review of earth observation applications articulated in this paper suggests that Cubesats could be used to support a wide range of remote sensing applications to complement the data services offered by prominent missions such as the Landsat and Sentinel series of satellites.

The quality of imagery produced by nSight-1 and ZACubesat-2 is adequate to fulfil a myriad of cartographic and monitoring applications. nSight-1 has shown a capability to map agricultural fields, surface water resources, land degradations and other geomorphological processes. Similarly, the K-Line Infrared Sensor onboard ZACubesat-2 has collected imagery that can be used for fire monitoring, vegetation delineation and detection of wetlands. The ability of the AIS instrument onboard Cube-2 to monitor illegal vessels in the South African oceanic EEZ has been successfully demonstrated. The emergence and growth of small enterprises involved in the manufacturing and component supply chain of Cubesats testify that Cubesat technology is reaching maturity for deployment for operational purposes. In addition, in the last decade, one of the greatest success of Cubesats in South Africa has been for the postgraduate training of satellite engineering students at universities.

References

Blouvac, J., B. Lazard, and J. M. Martinuzzi. 2000. CNES small satellites earth observation scientific future missions. *Acta Astronautica* 46:75–79.

Cooley, S. W., L. C. Smith, J. C. Ryan, L. H. Pitcher, and T.

M. Pavelsky. 2019. Arctic-Boreal Lake Dynamics Revealed Using CubeSat Imagery. *Geophysical Research Letters* 46:2111–2120.

Diaz, M. A., J. C. Zagal, C. Falcon, M. Stepanova, J. A. Valdivia, M. Martinez-Ledesma, J. Diaz-Peña, F. R. Jaramillo, N. Romanova, E. Pacheco, M. Milla, M. Orchard, J. Silva, and F. P. Mena. 2016. New opportunities offered by Cubesats for space research in Latin America: The SUCHAI project case. *Advances in Space Research* 58:2134–2147.

Doe, R.A. and Watchorn, S., 2011, September. Climate-monitoring CubeSat mission (CM2): a project for global mesopause temperature sensing. In *Earth Observing Systems XVI* (Vol. 8153, p. 81530Q). International Society for Optics and Photonics.

Gottschalk, K. 2010. South Africa's space program. *Astropolitics* 8:35–48.

Houborg, R., and M. F. McCabe. 2018. Daily retrieval of NDVI and LAI at 3 m resolution via the fusion of CubeSat, Landsat, and MODIS data. *Remote Sensing* 10.

Kopacz, J. R., R. Herschitz, and J. Roney. 2020. Small satellites an overview and assessment. *Acta Astronautica* 170:93–105.

Liebig, V. 2000. Small satellites for earth observation - the German small satellite programme. *Acta Astronautica* 46:81–86.

Matandirotya, E., R. R. V. Zyl, D. J. Gouws, and E. F. Saunderson. 2013. Evaluation of a Commercial-Off-the-Shelf Fluxgate Magnetometer for CubeSat Space Magnetometry. *Journal of Small Satellites* 2:133–146.

McCabe, M. F., B. Aragon, R. Houborg, and J. Mascaro. 2017. CubeSats in Hydrology: Ultrahigh-Resolution Insights Into Vegetation Dynamics and Terrestrial Evaporation. *Water Resources Research* 53:10017–10024.

Mhangara, P., W. Mapurisa, and N. Mudau. 2020. *Image Interpretability of nSight-1 Nanosatellite Imagery for Remote Sensing Applications*.

Ngcofe, L., and K. Gottschalk. 2013. The growth of space science in African countries for Earth observation in the 21st century. *South African Journal of Science* 109:1–5.

Oyewole, S. 2017. Space research and development in Africa. *Astropolitics* 15:185–208.

Paules, G. and Luther, M., 2000. NASA's Earth science program—increasing science opportunity and payoff through small satellites. *Acta Astronautica*, 46(2-6), pp.61-64.

Poursanidis, D., D. Traganos, N. Chrysoulakis, and P. Reinartz. 2019. Cubesats allow high spatiotemporal estimates of satellite-derived bathymetry. Remote Sensing 11.

Qiao, L., E. Glennon, A. G. Dempster, and S. Chaoui. 2013. Using cubesats as platforms for remote sensing with satellite navigation signals. *International Geoscience and Remote Sensing Symposium* (IGARSS):852–855.

Rose, R., J. Dickinson, and A. Ridley. 2012. CubeSats to NanoSats; bridging the gap between educational tools and science workhorses. *IEEE Aerospace Conference Proceedings*:1–11.

Sandau, R. 2010. Status and trends of small satellite missions for Earth observation. *Acta Astronautica* 66:1–12.

Santilli, G., C. Cappelletti, S. Battistini, and C. Vendittozzi. 2016. Disaster management of remote areas by constellation of CubeSats. *Proceedings of the International Astronautical Congress*, IAC:26–30.

Southwood, D. J. 2000. Future ESA earth-observation strategy and ESA's 'living planet' programme. *Acta Astronautica* 46:55–60.

Steyn, W. H., R. Van Zyl, M. Inggs, and P. J. Cilliers. 2013. Current and future small satellite projects in South Africa. *International Geoscience and Remote Sensing Symposium* (*IGARSS*):1294–1297.

Woellert, K., P. Ehrenfreund, A. J. Ricco, and H. Hertzfeld. 2011. Cubesats: Cost-effective science and technology platforms for emerging and developing nations. Advances in Space Research 47:663–684.

Xia, X., G. Sun, K. Zhang, S. Wu, T. Wang, L. Xia, and S. Liu. 2017. NanoSats/CubeSats ADCS survey. *Proceedings of the 29th Chinese Control and Decision Conference, CCDC* 2017:5151–5158.

Zaidi, Y., R. R. van Zyl, and N. G. Fitz-Coy. 2018. A GMSK VHF-uplink/UHF-downlink transceiver for the CubeSat missions: Thermo-functional performance. *CEAS Space Journal* 10:453–467.

Zaidi, Y., and R. Van Zyl. 2017. A low cost testbed and test-design methodology for nanosatellite sub-/systems. *2017 IEEE AFRICON: Science, Technology and Innovation for Africa, AFRICON* 2017:416–423.

van Zyl, R. R., D. F. Visser, P. J. Cilliers, and B. D. L. Opperman. 2013. ZACUBE-1 space weather mission: Characterize the superDARN HF radar antenna array at SANAE-IV. *Space Weather* 11:52–54.

van Zyl, R. R..2011. *CubeSats – a 21st century revolution.*

Author

Paida Mhangara, paida.mhangara@wits.ac.za, is Head of School of Geography, Archaeology and Environment Studies at the University of the Witwatersrand in Johannesburg, South Africa. Paida previously worked as Earth Observation Manager for Research and Applications Development at the South African National Space Agency until October 2019. Mhangara is a professional geospatial scientist and holds a PhD in Environmental Geography with a specialization in remote sensing , MSc in Geographical Information Systems and an MBA degree with an emphasis in Strategic Planning. Over the last fifteen years Paida led the implementation of several earth observation projects in South Africa and taught remote sensing and GIS courses at undergraduate and postgraduate level. He is a member of the Landsat Technical Working Group led by the USGS and has contributed to the Committee of Earth Observation Satellites (CEOS) initiatives.

Cover image courtesy of NASA.