IAC-16,B4,1,12,x34041

SWEET CUBESAT – WATER DETECTION AND WATER QUALITY MONITORING FOR THE 21ST CENTURY

Kelly Antonini[a]*, Martin Langer[a], Ahmed Farid[b,c], Ulrich Walter[a]

[a] *Institute of Astronautics, Technical University of Munich, Boltzmannstraße 15, 85748 Garching, Germany,* kelly.antonini@tum.de
[b] *German Space Operations Center, Telespazio VEGA, Münchener Straße 20, 82234 Weßling, Germany*
[c] *IAF-Africa Co-Chairman*
* Corresponding Author

Abstract

Water scarcity and contamination of clean water have been identified as major challenges of the 21st century, in particular for developing countries. According to the International Water Management Institute, about 30 percent of the world´s population does not have reliable access to clean water. Consequently, contaminated water contributes to the death of about 3 million people every year, mostly children. Access to potable water has been proven to boost education, equality and health, reduce hunger, as well as help the economy of the developing world. Currently used in-situ water monitoring techniques are sparse, and often difficult to execute. Space-based instruments will help to overcome these challenges by providing means for water level and water quality monitoring of medium-to-large sweet (fresh) water reservoirs. Data from hyperspectral imaging instruments on past and present governmental missions, such as Envisat and Aqua, has been used for this purpose. However, the high cost of large multi-purpose space vessels, and the lack of dedicated missions limits the continuous monitoring of inland and coastal water quality. The proposed CubeSat mission SWEET (Sweet Water Earth Education Technologies) will try to fill this gap. The SWEET concept is a joint effort between the Technical University of Munich, the German Space Operations Center and the African Steering Committee of the IAF. By using a novel Fabry-Perot interferometer-based hyperspectral imager, the mission will deliver critical data directly to national water resource centers in Africa with an unmatched cost per pixel ratio and high temporal resolution. Additionally, SWEET will incorporate education of students in CubeSat design and water management. Although the aim of the mission is to deliver local water quality and water level data to African countries, further coverage could be achieved with subsequent satellites. Finally, a constellation of SWEET-like CubeSats would extend the coverage to the whole planet, delivering daily data to ensure reliable access to clean water for millions of people worldwide.

Keywords: CubeSat**,** Hyperspectral**,** Africa, Water Quality, Mission Design, Constellation

Nomenclature

A = surface area [m^2]
B = Earth magnetic field [T]
c = speed of light [m/s]
C_d = drag coefficient
c_g = center of gravity [m]
c_{pa} = center of aerodynamic pressure [m]
c_{ps} = center of solar pressure [m]
D = residual dipole [Am^2]
F_s = solar constant [W/m^2]
G = gravitational constant [Nm^2/kg^2]
θ = maximum deviation of the z axes from local vertical [rad]
i = Sun angle of incidence [°]
I_y = moments of inertia about y axes [kgm^2]
I_z = moment of inertia about z axes [kgm^2]
M = Earth magnetic moment [Tm^3]
μ = Earth gravity constant [m^3/s^2]
q = reflectance factor
R = orbit radius [m]
ρ = atmospheric density [kg/m^3]
T_a = aerodynamic torque [Nm]
T_g = gravity gradient torque [Nm]
T_m = magnetic torque [Nm]
T_{min} = minimum torque [Nm]
T_{sp} = solar radiation pressure [Nm]
T_{tot} = total torque [Nm]
V = spacecraft velocity [m/s]

Acronyms/Abbreviations

Attitude Determination and Control Subsystem (ADCS)
Cyanobacterial blooms (cHABs)
CubeSat Design Specification (CDS)
Commercial off-the-shelf (COTS)
German Aerospace Center (DLR)
Electrical Power Systems (EPS)
International Space Station (ISS)
Institute of Astronautics (LRT)
Micro-Electro-Mechanical Systems (MEMS)
MEdium Resolution Imaging Spectrometer (MERIS)

Multi-layer insulation (MLI)
Moderate Resolution Imaging Spectroradiometer (MODIS)
Munich Orbital Verification Experiment (MOVE)
Not Applicable (N/A)
Near infrared (NIR)
On Board Computer (OBC)
Operating System (OS)
Printed Circuit Board (PCB)
Right Ascension of the Ascending Node (RAAN)
Random-access memory (RAM)
Real Time Operating System (RTOS)
Secure Digital (SD)
Single Event Effect (SEE)
Space Mission Analysis and Design (SMAD)
Sun-synchronous orbit (SSO)
Semi-analytic Tool for End of Life Analysis (STELA)
Systems Tool Kit (STK)
Sweet Water Earth Education Technologies (SWEET)
Secure World Foundation (SWF)
To Be Determined (TBD)
Total Ionizing Dose (TID)
Technical University of Munich (TUM)
Ultra High Frequency (UHF)
United Nations Educational Scientific and Cultural Organization (UNESCO)
Very High Frequency (VHF)
Visible (VIS)
Women in Aerospace (WIA)

1. Introduction

The aim of the proposed Sweet Water Earth Education Technologies (SWEET) CubeSat mission is to provide water quality and water level data to African countries. The objective is to image inland sweet water lakes which are a source of drinking water to millions of people in Africa. The mission is currently at a Phase-0 [1] stage, the work presented here consists of an initial mission identification and analysis, and a feasibility study. This paper addresses the question if water quality measurements using a hyperspectral camera are possible on CubeSats. The study is mainly limited to the analysis of the satellite systems needed to support the mission. The SWEET project will initially focus on a precursor mission, demonstrating the usefulness of the generated data. Subsequently, a constellation of SWEET-like CubeSats will be built to increase the temporal resolution, essential in detecting rapid changes in water quality, sometimes occurring at an hourly rate. SWEET will also have an educational purpose: students at the Technical University of Munich (TUM), collaborating with African universities and students, shall build the precursor mission. Presently the SWEET team is looking for financial and development partners.

This paper will initially provide background information about past hyperspectral instruments and CubeSats, and motivate the intent of the proposed mission. Section 2 introduces the chosen instrument and how it fulfils the mission's objectives. Section 3 focuses on the orbit selection process, and section 4 on the SWEET bus, which is subdivided into 6 subsystems. Section 5 shows the results obtained from this initial analysis and discusses the outcomes. Finally, section 6 concludes the paper.

1.1 Background & Motivation

Hyperspectral imaging from space has traditionally been carried out by large vessels aiming at several scientific goals. Instruments like Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua [2] or MEdium Resolution Imaging Spectrometer (MERIS) on Envisat [3] provided hyperspectral images in a spatial resolution of several hundreds of meters. Since their introduction in 1999, CubeSats [4] have evolved from purely educational missions to spacecraft with a broad variety of scientific and commercial applications. Hyperspectral imaging on CubeSats has been proposed for natural hazard response [5], to improve weather forecasts [6], for measuring the ozone concentration in the stratosphere [7], for land use classification, and for vegetation mapping and algae detection [8].

According to the United Nations, by 2025, two-thirds of the world's population could be living under water-stressed conditions, with Sub-Saharan Africa being the region with the largest number of water-stressed countries [9]. Human-made factors such as increasing water usage and climate change [10] will increase the scarcity of water, threatening successful achievement of most of the Millennium Development Goals. Amongst others, harmful cyanobacterial blooms (cHABs) have significant socioeconomic and ecological impact [11-13].

As reported by the United Nations Educational Scientific and Cultural Organization (UNESCO), cHABs are present in African sweet water lakes [14]. Although the information is very scarce, they confirm that the cyanobacterial blooms have caused animal death and a few cases of human casualties due to contaminated drinking water [14]. Many factors influence the time it takes to form cHABs, ranging from water temperature, wind speed, solar radiation, and rainfall, making it difficult to determine how often a lake should be imaged [15]. According to [16], the lake water quality monitoring procedures currently in place in Northern Egypt rely on monthly in situ measurements, though the development of cHABs can occur in timespans ranging from hours to weeks. Remote sensing from spacecraft has reduced this time interval in the past. MERIS used to provide data at 1 to 3 day intervals [15], with several research groups applying the data for cHABs assessment [17-21].

Similar to what the MERIS instrument achieved in the past, CubeSats could provide continuous monitoring of inland water reservoirs, saving lives, time, and at a fraction of the cost of a traditional mission. The proposed SWEET precursor mission will study the cHABs trend in the interested areas, and subsequently adapt the constellation revisit time accordingly.

2. Instrument

The SWEET CubeSat main objectives could only be achieved by selecting an appropriate payload, a hyperspectral imager. The requirements of the payload include: appropriate size and power consumption, accommodated into a CubeSat; wavelength bands in near infrared (NIR) to measure inland sweet water height and quality; good spatial resolution, to image a large variety of lake sizes; and cloud cover quantification in the hyperspectral image.

The imagers which met the SWEET requirements were: HyperScout built by cosine [22], and the CubeSat imager shown in Figure 1 built by the VTT Technical Research Centre in Finland [23].

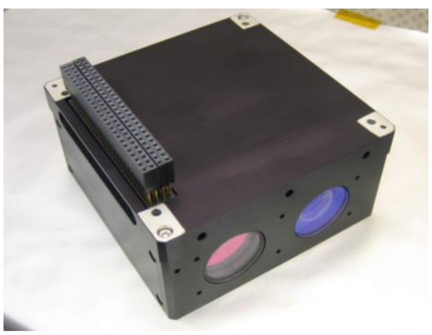

Fig. 1. VTT hyperspectral imager [24]

The imager from VTT was selected for SWEET, as the combination of NIR and visible (VIS) wavelength bands best fulfilled the payload requirements. At the time of this writing, the instrument is to be flown on CubeSats: Aalto-1 (Aalto university) [8, 25-28] and PICASSO (ESA) [7, 23, 29], verifying its usefulness on CubeSats. Table 1 summarizes its characteristics.

Table 1. VTT hyperspectral imager properties

Parameter	Values
Wavelength range [26]	500 - 900 nm (VIS-NIR)
Spectral resolution [26]	10 to 30 nm
Field of view [30]	10 x 10°
Mass [30]	< 600 g
Cubesat Unit Size [30]	0.5 U
Power consumption [26]	3 W
Image size [30]	512 x 512 pixel

The instrument can be accommodated into a 2U-CubeSat and configured for a selection of bands. The most appropriate will be selected to address the most dangerous and common substances affecting the quality of drinkable water. The instrument's spatial resolution is expected to be similar to MODIS on Aqua, 250 m at 700 km altitude, at a fraction of the hardware size [28, 31]. The imager uses a Fabry-Perot-based interferometer to capture the image, and it is provided with a built-in optical VIS camera, capable of determining the cloud fraction [28]. Each hyperspectral image is expected to be 0.5 MB in size.

3. Orbit Selection

The orbit selection process considered various orbit options, selecting the one that satisfied the largest number of mission requirements. Out of the many available orbits, an earth-referenced orbit had to be selected to analyze the surface of the Earth. The SWEET orbit shall cover as many African lakes per day as possible.

SWEET has to comply with space debris mitigation guidelines [32], which prescribes satellites to de-orbit from a LEO within 25 years. According to NASA, the altitude cut-off for a CubeSat to naturally de-orbit within 25 years is between 600 and 700 km [33]. As SWEET will have no propulsion, an initial altitude of 650 km would fulfil the rule. This altitude provides relatively large ground coverage, good ground station communication times and mission lifetime, and last but not least, a high payload resolution. Table 2 shows the four possible circular LEO orbit types analyzed.

Table 2. Properties of the four analyzed SWEET orbits

	Altitude (km)	Inclination (°)	Period (min)
SSO	650	97.9	97.7
50° Orbit	650	50	97.7
Polar Orbit	650	90	97.7
ISS Orbit	400	51.6	92.6

The advantage of a Sun-synchronous orbit (SSO) is a constant Sun illumination on ground throughout the mission, therefore generating consistently illuminated images. The 50° orbit promises to best fit the mission's objective by providing more accesses to Africa and the chosen ground segments, however, piggyback launch opportunities to such an orbit are rather rare. The advantage of the SSO and polar orbit is that it provides global coverage, whilst the International Space Station (ISS) orbit, having a lower initial altitude, provides images with higher resolution, but has a shorter lifetime. All considered orbits, except for the 50° orbit, have many launch opportunities. After considerable analysis, simulating coverage of African lakes and ground station communication time, it was decided that the SWEET CubeSat precursor mission shall fly on an ISS orbit. Despite the disadvantage of a short life-time, this orbit has the highest number of launch opportunities and provides higher spatial resolution images (137 m at 400 km altitude) due to its low altitude. Since SWEET is considered to be a precursor mission for a future constellation, launching at a lower altitude will suffice to prove the concept.

4. Bus System

To guide the selection of the bus components, the mission definition approach from Space Mission Analysis and Design (SMAD) [34] was used. The satellite shall take at least 4 hyperspectral images a day, and be able to download two of them (hypothesizing a 50 percent chance of inappropriate cloud cover). The SWEET CubeSat precursor mission will download thumbnails of the optical image to the ground station, to determine whether the cloud fraction is low enough to justify downloading the complete hyperspectral image.

The main requirement for the SWEET bus is to maximize use of the Munich Orbital Verification Experiment 2 (MOVE-II) design. MOVE-II is a CubeSat currently being developed at TUM [35], which is in turn a successor of the first TUM satellite, First-MOVE [36]. Re-using parts of the MOVE-II bus subsystem design reduces risk, uncertainty in the component behavior, and lowers the SWEET development costs. In addition, the SWEET CubeSat shall comply to the CubeSat Design Specification (CDS) [37].

4.1 Communications Subsystem

On the SWEET CubeSat it is planned to use the same transceivers as on MOVE-II: ultra high frequency (UHF) to upload, very high frequency (VHF) and S-band to download [38, 39]. For the VHF channel, a data rate of 9.6 Kbit/s was estimated, choosing an omnidirectional antenna pattern on the satellite and a field of view of the antenna at the ground segment of 160° (due to obstructions and atmospheric interferences, the last 10° close to the horizon were neglected). Preliminary link budget calculations showed that the VHF-channel would allow to download one 0.5 MB image every 8 to 9 minutes of communication time.

For the S-band communication, a rate of 1 Mbit/s is taken to be a realistic value [39]. Using a conservative approach, it was estimated that the download of data using S-band will only be possible on average every two days, due to power and pointing restrictions (and limited field of view of 15° half angle of the S-band patch antenna on the satellite).

To enhance SWEET's educational purpose, university ground stations will be used. In the first simulation, the following three ground stations were selected: the TUM university ground station at the Institute of Astronautics (LRT), in Garching, Munich, and two more ground stations strategically positioned on the African continent (the current simulation has one in Abuja, Nigeria and one in Stellenbosch university, South Africa). With those ground stations, it was possible to download at least 5 images per day. Ongoing work is being carried out to determine an optimum balance between the number of necessary ground stations and resource usage on the spacecraft.

4.2 Power Subsystem

The power subsystem consists of solar cells and a battery to provide power to the payload and all other subsystems. An initial estimate of power to be generated was defined based on the payload's power requirement of 3 W and the MOVE-II bus power requirement. Including a safety margin of 25 percent, the power subsystem shall provide at least 7 W on average. The solar cells selected for SWEET were the AZUR SPACE 3G30 solar cells [40]. The simulation software Systems Tool Kit (STK) (and its solar panel tool) [41] was used to analyze the energy generated per period for different solar panel configurations. The input files were created using the 3D modelling tool SketchUp [42], as shown in Figures 2a, 2b and 2c. Initially, all external panels of the CubeSat were covered with cells (see Fig. 2a), with the exception of the bottom panel, accommodating payload and S-band. This configuration generates an average of only 2.1 W during one orbit period, not even a third of the estimated required power.

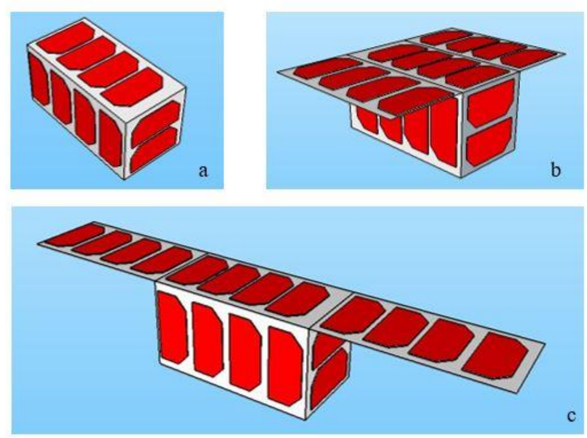

Fig. 2. SWEET solar cell sketches

To counteract this, two deployable solar panels were added, and two configurations considered (see Fig. 2b and Fig. 2c), using the heritage of First-MOVE [43] and MOVE-II. In the ISS orbit, the configuration shown in Figure 2c generated slightly more power and was therefore selected. In total, the SWEET CubeSat's solar panels will have 24 cells and generate on average 6.5 W or 10.1 Wh during one orbit period. A 20 Wh battery was selected, providing a good trade-off between mass and capacity. Table 3 summarizes the properties of the 20 Wh commercial batteries (including electrical power systems (EPS)) analyzed.

Table 3. 20 Wh SWEET battery options

Battery	Clyde Space 20 Wh CubeSat Battery [44, 45]	GomSpace Nano-Power BP4 [46]	Nano-Avionics Power Unit 1P0 [47]
Material	Lithium-Polymer	Lithium-Ion	Lithium-Ion
Nominal Voltage (V)	6 to 8.4	6 to 8.4	7.4
Current (mAh)	2600	5200	2600
Energy (Wh)	15-21	31-43	19.24
Mass (g)	246	270	275
Dimensions (mm)	96x91x27.41	96x90x23	96x90x30
Cost (€)	6725	2450	4700

Due to its flight heritage, the Clyde Space 20 Wh CubeSat battery was chosen as a footprint for SWEET.

4.3 Structure Subsystem

The structure of the SWEET CubeSat will be built in-house, similar to MOVE-II. It shall comply with the CDS [37], and therefore be built in aluminum, provide mounting for the satellite bus and be the correct size to fit into the standard deployment mechanics.

4.4 ADCS Subsystem

For the Attitude Determination and Control Subsystem (ADCS) analysis, external disturbance torques were calculated at SWEET's initial altitude of 400 km using equations 1, 2, 3 and 4 below [34]. The results of these calculations are summarized in Table 4.

$$T_g = \frac{3\mu}{2R^3}\left|I_z - I_y\right| \sin 2\theta \tag{1}$$

$$T_{sp} = \frac{F_s}{c} A\,(1+q)\cos i\,\left(c_{ps} - c_g\right) \tag{2}$$

$$T_m = D\,\frac{2M}{R^3} \tag{3}$$

$$T_a = 0.5[\rho C_d A V^2]\left(c_{pa} - c_g\right) \tag{4}$$

Table 4. SWEET total disturbance torques

Disturbance torque	Value (Nm)
Gravity gradient torque	2.1×10^{-9}
Solar radiation pressure	1×10^{-8}
Magnetic field torque	1×10^{-6}
Aerodynamic torque (drag)	1.1×10^{-6}
Total disturbance torques	**2.2×10^{-6}**

For attitude determination, the same commercial off-the-shelf (COTS) components planned to be used on MOVE-II [48] were selected: five sun sensors and a set of micro-electro-mechanical systems (MEMS) composed of a 3-axes gyroscope, a 3-axes accelerometer, and a 3-axes magnetometer [49]. The selected sun sensors have a field of view of 120° x 120° and an accuracy better than 3°.

The option of using star trackers was considered and discarded, as the added accuracy was not required to guarantee a success of the mission, thus saving on cost and mass. The sun sensors will be positioned on all but the bottom panel, due to virtually complete lack of sunlight on this panel.

For attitude control two scenarios were considered: a simple scenario with three (and three redundant) magnetorquers, as well as a more stable configuration using three reaction wheels in addition to the magnetorquers. The commercially available magnetorquers are standalone boards and too heavy for SWEET. The magnetorquers will therefore be built in-house, custom made to be integrated into the side panels of the satellite.

To estimate the minimum required dipole momentum to be exerted by the magnetorquers (if no reaction wheels are present), equations 5, 6 and 7 were used [34].

$$B = \frac{2M}{R^3} \tag{5}$$

$$T_{tot} = T_g + T_{sp} + T_m + T_a \tag{6}$$

$$T_{min} = \frac{T_{tot}}{B} \tag{7}$$

The result was a minimum magnetic dipole moment of 0.04 Am^2 per axes. The MOVE-II magnetorquer currently being designed can achieve a value of 0.1 Am^2 per axes, providing a realistic margin. The MOVE-II ADCS design has magnetorquer coils on every side panel (except for the bottom panel) and another on the main ADCS panel inside the PC/104 stack [48]. SWEET could have the same layout, or alternatively have a magnetorquer on the bottom panel instead of inside the PC/104 stack, if allowed by the payload.

The reaction wheels selected for the second scenario are the miniature wheels HT-RW200.15 built by Hyperion Technologies [50]. Table 5 summarizes their properties.

Table 5. Reaction wheel properties [50]

Property	Value
Angular momentum	1.5 mNms
Maximum torque	1×10^{-4} Nm
Slew rate (3 reaction wheels)	1.5°/s [26]

4.5 OBC Subsystem

Due to the early stage in the mission design, assessments of on board computer (OBC) and thermal (see Section 4.6) subsystems are preliminary and have to be evaluated further down the design process. Image compression will occur on-board, and the compressed image will measure 0.5 MB [30]. A similar compression algorithm to the Aalto-1 mission will be used. As secure digital card (SD-card) based OBCs are more susceptible to failures, only OBCs with on-board flash memory were considered. Satellite-focused operating system (OS), such as free real time operating system (FreeRTOS) [51], proved difficult to be developed by a purely student team [52], a Linux-OS OBC being more practical. Learning a new OS requires time and effort. The steep learning curve inhibits flexible and rapid satellite development by students. None of the analyzed commercial OBCs satisfied the SWEET requirements: they did not have a Linux-OS, and many of them had an SD-card and not an on-board flash memory. Consequently, it was not possible to select an appropriate OBC at such an early mission phase.

As future work, more SWEET bus components and requirements will be defined, making it possible to refine OBC requirements in terms of random-access memory (RAM), memory and processing speed. Radiation doses on the components will also have to be taken into account. Given the selected ISS orbit, it is expected that the risk posed by single event effects (SEE) and the total ionizing dose (TID) will not be very high due to the short duration of the mission and the relatively low initial altitude.

An alternative OBC solution would be to build an OBC in-house, although this would prove to be a challenge. Other CubeSat teams are currently working on innovative OBC solutions such as Astro Pi, built by Surrey University which is using two Raspberry Pi [53], and Phone Sat, built by NASA which uses a smartphone [54]. The field of OBCs and miniaturization is an expanding one, consequently, faster and smaller computers are expected to become available over the upcoming months and years.

The Nano Avionics OBC [55] is selected as a footprint for the SWEET CubeSat. It does not fulfil the requirement of a Linux-OS, but it is used here as a preliminary subsystem, having sufficient reliable memory and a successful flight heritage of 5 months. The OBC footprint is very similar to the other analyzed OBCs in terms of volume, mass, cost and power and it is predicted that the footprint for the final selected OBC will be also in the same range. Table 6 displays the properties of the Nano Avionics OBC.

Table 6. Properties of the Nano Avionics OBC [55]

Property	Value
OBC name	SatBus 1C0
Company	Nano Avionics
Processor and speed	ARM 4: 8-168 MHz
Max power	287 mW
Dimensions (mm)	PC/104: 96x90x10
Mass	35 g
Flash memory data storage	2x16 MB
SD card data storage	N/A
Flash memory code storage	1 MB
RAM volatile memory	192 kB
OS	FreeRTOS
Possible modes	Run, sleep, stop
Base cost	3000 €
Flight heritage	Successfully flown on CubeSat LituacinaSAT-1 for 5 months

4.6 Thermal Subsystem

The thermal environment of the SWEET CubeSat will be controlled using a passive thermal design. Passive thermal control is the science of organizing components within the cube to facilitate working conditions for all subsystems. Although active thermal control can deal with more extreme situations compared to a purely passive design, the strong CubeSat constraints on volume, mass, and power budget only allow for a passive one (except for the EPS system which is provided with a heater). Table 7 shows the temperature ranges of the SWEET CubeSat components.

Table 7. Component temperature ranges

Component	Operating temperature range
Solar cells [derived from MOVE-II]	-100 to +80 °C
Payload [26, 30]	+15 to +45 °C
Battery (20 Wh Clyde Space) [45]	-10 to +50 °C *
EPS board [derived from MOVE-II]	-40 to +85 °C
Communications (VHF transmitter, UHF receiver and S-band) [derived from MOVE-II]	-40 to +100 °C
ADCS [derived from MOVE-II]	-40 to +85 °C
Reaction wheel	TBD
OBC Nano Avionics [55]	-40 to +85 °C

*battery storage temperature: -20 °C to +45 °C (3 months)

Except for the payload, the SWEET components temperature ranges are very similar to the MOVE-II ones, therefore the same MOVE-II methods will be used:

multi-layer insulation (MLI), appropriate stacking, placement of hotspots, and battery heaters.

Regarding the payload, VTT suggests to maintain a constant temperature within the instrument to achieve the best image quality. The Aalto-1 team showed a temperature range of +15 to +45 °C to be achievable within a CubeSat, while effecting the image quality as little as possible [26]. The First-MOVE mission launched in 2013, measured the internal temperature of the satellite to be between +5 and +15 °C in the printed circuit board (PCB) stack [52], guaranteeing small temperature variations and good image quality. It is possible to ensure the instrument's thermal specification by appropriate stacking or inserting a small heater. The lens of the payload will consistently face the surface of the Earth, receiving Earth's infrared radiation and albedo. Thus, its temperature will not vary significantly, assuming that it does not face the Sun due to an ADCS fault.

Table 8. SWEET subsystems integration

Component	**Volume (cm^3)**	**Mass (g)**	**Energy consumed (Wh)**	**Cost (€)**
Structure [derived from MOVE-II]	N/A	368*	N/A	3,200
Solar cells (24) [40]	11.5	61.9	N/A	12,000
Battery and EPS [44]	236.9	246	0.001	6,725
UHF & VHF antenna [derived from MOVE-II]	259.2	230*	1 (10 min per orbit)	14,000
S-band [derived from MOVE-II]	129.6	35	0.13 (1 min per orbit)	7,000
Payload [30]	451.6	600	0.3 (2 images per orbit: 3 seconds each)	< 150,000
ADCS [derived from MOVE-II]	42.1	90.4	2.46	10,000
ADCS with reaction wheel [50, 56]	70.2	111.4	3.7	37,000
OBC [55, 57]	86.4	35	0.45	3,000
Total	1,217.3	1,666.3	4.3	< 205,925
Total with reaction wheel	1,245.4	1,687.3	5.6	< 232,925
Budget	1,844.6	2,660	10.1	N/A
Budget with 25 % margin	1,383.5	1,995	7.6	N/A

* including development margin,

5. Results and Discussion

The purpose of this section is to first integrate the individually analyzed subsystems (see Section 4) into a standard 2U-CubeSat, in terms of mass, volume and power. This provides an opportunity to make an initial estimate of the costs of SWEET. Subsequently, the SWEET precursor mission orbit lifetime is modelled and discussed, followed by the simulated operations that can be achieved by flying the satellite over Africa. Finally, the capabilities and size of a future SWEET constellation are briefly described.

5.1 Bus Subsystem Integration

When integrating the subsystems, a 25 percent margin for volume, mass and power was considered. The mass budget of 2,660 g was provided by the CDS [37], and the energy budget of 10.1 Wh by the simulated power generated using 24 solar cells. The volume budget of 1,844.6 cm^3 was calculated by multiplying the width and length of a standard PC/104 board (90 mm x 96 mm) with the CDS allowed height within the cube's structure rails (213.5 mm) [37]. The characteristics of the SWEET subsystems are summarized in Table 8.

The thermal subsystem, the side panels and the deployable mechanism (hold down and release mechanisms for the deployable panels), are not present in the table, as their volume, mass, power and cost are very low and can be neglected at this point (they will be included in the 25 percent margin). In Table 8, the volume of the structure is not considered because the budgeted volume is calculated to be the internal space inside the structure.

Despite the stability advantages of installing reaction wheels on SWEET, they will not be used for the precursor mission due to higher cost, complexity, mass and volume. Table 8 shows that it is possible to include reaction wheels in terms of volume, mass and power budget, hence it might be considered to add them after the precursor mission.

5.2 Orbit Lifetime

The SWEET precursor mission will have an ISS orbit with initial altitude of 400 km. The main disadvantage of this orbit is the short lifetime of the satellite. The CNES Semi-analytic Tool for End of Life Analysis (STELA) [58] was used to determine the approximate lifetime of SWEET. The input parameters are summarized in Table 9.

Table 9. STELA input parameters [58]

Parameter	Value
Mass (kg)	2.66
Average Reflecting area (m^2)	0.03
Reflectivity coefficient	1.5
Average Drag area (m^2)	0.03
Constant drag coefficient	2.2
Solar activity	Mean constant

In addition, the orbit parameters generated by STK were inputted [41], and the initial date was set to 1st of January 2019, a realistic launch date allowing enough time for development. The reflectivity and drag areas were calculated by using the average satellite area (including the side wings).

The STELA simulation showed that the precursor mission is expected to deorbit after 0.375 years, approximately 4.5 months. This does not provide any information about whether the satellite will still be functional at such low altitudes.

Equation 8 and 9 were used to estimate the altitude at which the ADCS will not be able to control the satellite any longer, as the external moments will have exceeded the maximum magnetic moment of 0.1 Am^2 [34].

$$V = \sqrt{\frac{G * M}{R}} \tag{8}$$

$$M = \frac{T_a}{B} \tag{9}$$

To calculate the drag and worst-case polar magnetic field equations 4 and 5 were used, respectively (see Section 4.4). Table 10 summarizes the results obtained, and shows that the satellite cannot be controlled below 250 km in altitude due to insufficient control moment.

Table 10. Results of maximum controllable altitude

h (km)	350	300	250	200
ρ_{atm} (kg/m^3)	$6.66e^{-12}$	$1.87e^{-11}$	$5.97e^{-11}$	$2.41e^{-10}$
R (km)	6728.1	6678.1	6618.1	6578.1
V (m/s)	7701.3	7730	7765	7788.6
T_a (Nm)	$6.38e^{-07}$	$1.80e^{-06}$	$5.82e^{-06}$	$2.36e^{-05}$
M (Am^2)	0.014	0.04	**0.13**	0.52

There is an error margin to be considered, as all equations are approximations and the atmospheric density values [59] used were average values. According to the STELA simulation, the satellite is predicted to be below 250 km for about 10 days, lowering the satellite's predicted mission lifetime from 4.5 months to 4.2 months.

5.3 Operations

The operational requirements for the SWEET precursor mission are to take a minimum of four hyperspectral images a day and to download at least two a day (as well as taking and downloading the optical images' thumbnails). A typical power consumption and battery charge plot over one orbit is shown in Figure 4, where one image is taken, and subsequently downloaded using first the VHF antenna over 8 minutes and then the S-band over 4 minutes. The nominal mode is defined as the mode in which SWEET is nadir-pointing, 3-axes stabilized, operating and waiting for commands. Figure 4 assumes that more than three ground stations are available to be able to download for 4 minutes using the S-band. When analyzing the scenario with three ground stations evenly distributed along the satellite path, the average amount of data that can be downloaded in one day using only VHF is 3.74 MB, and by using both VHF and S-band 7.54 MB. As a first estimation and by introducing appropriate margins, the power budget allows to download about 75 percent of what is possible: 5 images only using VHF and 11 images using both VHF and S-band. This is a largely improved result compared to the initial requirement of two images a day, which could be improved further with the use of better satellite pointing.

5.4 Preliminary Mission Analysis

The imager solution is good enough to capture portions of the biggest lakes in Africa down to small lakes that fit into a 10 x 10 pixel area (1370 x 1370 m at 400 km altitude) of the image (in the future it will be evaluated whether an even smaller pixel area can also generate useful information). 62 African lakes were identified ranging from 68,800 km^2 (Lake Victoria), down to 2.15 km^2 (Lake Oguta in Nigeria) in size. All lakes are African sweet water lakes. Salty and alkaline (or soda) lakes are not considered as a source of drinkable water. Lake Victoria is the largest lake in Africa and although the satellite's footprint does not allow capturing the whole lake in one image, imaging a portion of the lake will still be beneficial.

Table 11 displays the result obtained by simulating the amount of flybys over the 62 lakes, using one ISS SWEET orbit. The simulation software STK [41] was used and flybys were simulated only when the lakes were in direct sunlight.

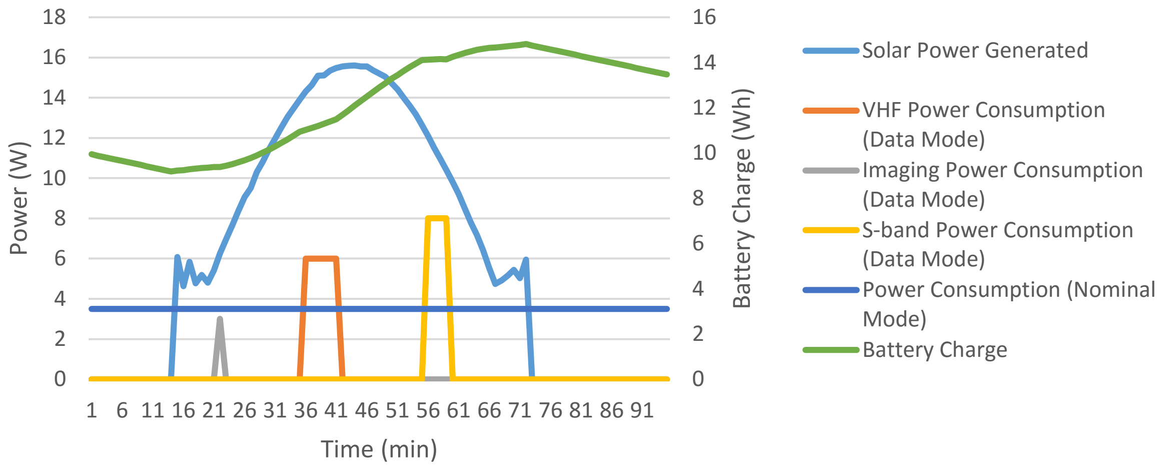

Fig. 4. Typical power consumption and battery charge over one orbit [41]

Table 11. Lake imaging (one satellite)

	Yearly average flybys	Average revisit time
3 biggest lakes	99	3 to 4 days
30 biggest lakes	41	9 days
Total analyzed lakes (62)	31	11.8 days
Smallest lake	17	21 days

5.5 SWEET Constellation

The SWEET satellite properties described so far are related to a precursor mission during which the concept will be proven and the usefulness of the generated data to the African population validated. The long-term plan is to build a small constellation of CubeSats, enabling SWEET to image more lakes with higher temporal resolution.

The most appropriate orbit for the constellation is a Sun-synchronous orbit, with launch opportunities and a good orbit lifetime of 21.63 years with initial altitude of 650 km (calculated using STELA) [58]. The simulated constellation is composed of four CubeSats with two different right ascension of the ascending node (RAAN): 100° and 280°, respectively. The satellites will be launched from two different launchers and be evenly distributed by using differential drag [60]. Table 12 shows the simulated results of flybys.

Table 12. Lake imaging (four-satellite constellation)

	Yearly average flybys	Average revisit time
3 biggest lakes	218	1.5 days
30 biggest lakes	128	2.8 days
Total analyzed lakes (62)	103	3.5 days
Smallest lake	68	5.3 days

It is a challenge to determine how quickly poisonous substances develop in inland sweet water lakes in Africa. Development of cyanobacteria bloom can occur in timespans ranging from hours to weeks. The SWEET constellation will provide data on average every 3.5 days, very similar to what was achieved with MERIS [15], but at a fraction of the cost. Compared to traditional in-situ water monitoring techniques, re-imaging a lake with such a high revisit rate will provide continuous monitoring, saving lives, as well as time and money. The SWEET precursor mission will study the cyanobacteria development trend in the interested areas, and subsequently adapt the constellation revisit time accordingly.

6. Conclusion: is it possible to measure water quality with a CubeSat?

SWEET is the CubeSat mission designed to help Africa tackle its drinking water quality problem. Research conducted so far, and presented here, shows that it is possible to integrate a CubeSat hyperspectral imager into a standard 2U-CubeSat. Using an ISS orbit for the precursor mission, followed by a sun-synchronous four CubeSat constellation, SWEET will generate enough data to fulfil the mission's objective: monitoring 62 fresh water lakes in Africa with an average revisit time of 3.5 days. The majority of subsystems have been defined and integrated into the 2U-CubeSat specification. OBC and thermal subsystem requirements are roughly defined, and will be further refined as the project advances. As for many other CubeSat missions, SWEET also aims to educate students and provide African universities with the knowledge of building a CubeSat constellation. With the successful completion of this project, millions of people, dependent on Africa's inland sweet water, will benefit from the mission.

Acknowledgements

The authors would like to thank the Secure World Foundation (SWF) and Women in Aerospace Europe (WIA-Europe) for funding Kelly Antonini's participation at IAC-2016. In addition, the authors are grateful to STK for providing a free educational license for the purpose of this Master's thesis. The authors acknowledge the funding of MOVE-II by the Federal Ministry of Economics and Energy, following a decision of the German Bundestag, via the German Aerospace Center (DLR) with funding grant number 50 RM 1509.

References

[1] ESA, How a mission is chosen, 2013, http://www.esa.int/Our_Activities/Space_Science/How_a_mission_is_chosen, (accessed 29.08.2016).

[2] D. O. A. Savtchenko, et al., Terra and Aqua MODIS products available from NASA GES DAAC, Adv. Space Res. 34 (2004) 710-714.

[3] J-L. Bezy, et al., MERIS - A new generation of ocean-colour sensor onboard Envisat, ESA bulletin 103 (2000) 48-56.

[4] H. Heidt, et al., CubeSat: A new generation of picosatellite for education and industry low-cost space experimentation, in Proceedings of the AIAA/USU Conference on Small Satellites, 2000.

[5] D. Mandl, et al., Hyperspectral Cubesat Constellation for Natural Hazard Response, in Proceedings of the AIAA/USU Conference on Small Satellites, 2016.

[6] T. S. Pagano, et al., The CubeSat Infrared Atmospheric Sounder (CIRAS), Pathfinder for the Earth Observing Nanosatellite-Infrared (EON-IR), in Proceedings of the AIAA/USU Conference on Small Satellites, 2016.

[7] D. Fussen, et al., PIC.A.S.S.O.: atmospheric remote sensing and in situ space science from CubeSats, in 4S Symposium, Valletta, Malta, 2016.

[8] A. K. Jaan Praks, et al., MULTI PAYLOAD EARTH OBSERVATION MISSION AALTO-1, in 4S Symposium, Valletta, Malta, 2016.

[9] UNESCO, United Nations World Water Development Report 4. Volume 1: Managing Water under Uncertainty and Risk, UN-Water, 2012.

[10] J. Schewe, et al., Multimodel assessment of water scarcity under climate change, Proc. Natl. Acad. Sci. 111 (2014) 3245-3250.

[11] G. A. Codd, et al., Cyanobacterial toxins: risk management for health protection, Toxicol Appl Pharmacol, 203 (2005) 264-272.

[12] I. R. Falconer, An overview of problems caused by toxic blue–green algae (cyanobacteria) in drinking and recreational water, Environ. Toxicol. 14 (1999) 5-12.

[13] W. W. Carmichael, and G. L. Boyer, Health impacts from cyanobacteria harmful algae blooms: Implications for the North American Great Lakes, Harmful Algae 54 (2016) 194-212.

[14] G. A. Codd, et al., CYANONET A Global Network for Cyanobacterial Bloom and Toxin Risk Management, UNESCO Technical documents in hydrology 76 (2005).

[15] R. S. Lunetta, et al., Evaluation of cyanobacteria cell count detection derived from MERIS imagery across the eastern USA, Remote Sens. Environ. 157 (2015) 24-34.

[16] M. F. Mohamed, Satellite data and real time stations to improve water quality of Lake Manzalah, Water Sci. 29 (2015) 68-76.

[17] L. Li, et al., Remote sensing of freshwater cyanobacteria: An extended IOP Inversion Model of Inland Waters (IIMIW) for partitioning absorption coefficient and estimating phycocyanin, Remote Sens. Environ. 157 (2015) 9-23.

[18] S. C. J. Palmer, et al., Validation of Envisat MERIS algorithms for chlorophyll retrieval in a large, turbid and optically-complex shallow lake, Remote Sens. Environ. 157 (2015) 158-169.

[19] E. T. Harvey, et al., Satellite-based water quality monitoring for improved spatial and temporal retrieval of chlorophyll-a in coastal waters, Remote Sens. Environ. 158 (2015) 417-430.

[20] S. C. J. Palmer, et al., Satellite remote sensing of phytoplankton phenology in Lake Balaton using 10 years of MERIS observations, Remote Sens. Environ. 158 (2015) 441-452.

[21] K. Kallio, et al., Validation of MERIS spectral inversion processors using reflectance, IOP and water quality measurements in boreal lakes, Remote Sens. Environ. 157 (2015) 147-157.

[22] cosine, HyperScout, 2016, http://hyperscout.nl/product/, (accessed 17.08.16).

[23] H. Saari, VTT develops a miniaturized spectral camera for ESA's Picasso nanosatellite mission, 2015.

[24] VTT, Personal Communication: VTT Spectral Imager Pictures, 29.06.16.

[25] Aalto-1, Aalto-1 is the 1st Finnish satellite, 2016, http://www.aalto1.fi/aalto1_in_english.html, (accessed 09.08.16).

[26] A. Näsilä, Validation of Aalto-1 Spectral Imager Technology to Space Environment, Aalto University - School of Electrical Engineering, 2013.

[27] ESA, Aalto-1: The Finnish Student Nanosatellite, 2016, https://directory.eoportal.org/web/eoportal/satellite-missions/a/aalto-1 (accessed 09.08.16).

[28] A. Kestilä, et al., Aalto-1 nanosatellite - technical description and mission objectives, Geosci. Instrum. Method. Data Syst. 2 (2013) 121–130.

[29] ESA, PICASSO (Pico-Satellite for Atmospheric and Space Science Observations), 2016,

https://directory.eoportal.org/web/eoportal/satellite-missions/p/picasso (accessed 09.08.16).

[30] VTT, Personal Communication: Instrument Properties, 17.05.16.

[31] A. Kestilä, et al., Aalto–1 Remote Sensing Campaign, in XXXIII Finnish URSI Convention on Radio Science and SMARAD Seminar 2013, Otaniemi, Finland (2013) 143-146.

[32] H. Klinkrad, et al., The ESA space debris mitigation handbook 2002, Adv. Space Res. 34 (2004) 1251-1259.

[33] NASA, STD-8719.14A, Process for limiting orbital debris (change 1), 2012.

[34] W. J. Larson, et al., SMAD III: Space mission analysis and design, third ed., Microcosm Press, El Segundo, 2005.

[35] MOVE-II, 2016, http://www.move2space.de /MOVE-II/ (accessed 09.08.16).

[36] First-MOVE, 2014, http://www.move2space .de/First-MOVE/index.html%3Flang=en.html (accessed on 09.08.16).

[37] The CubeSat Program, CubeSat Design Specification (CDS) Rev. 13, 2014, http://www.cubesat.org/resources/ (accessed 28.08.16).

[38] M. Langer, et al., MOVE-II – der zweite Kleinsatellit der Technischen Universität München, in Deutscher Luft- und Raumfahrtkongress (DLRK) Rostock, Germany, 2015.

[39] N. M. E. Appel, et al., Nanolink: A robust and efficient protocol for Small Satellite radio links, in 4S Symposium, Valletta, Malta, 2016.

[40] AZURSPACE, 30% Triple Junction GaAs Junction Solar Cell Datasheet, 2016, http://www.azurspace.com/images/pdfs/HNR_0003429-01-00.pdf (accessed 04.08.16).

[41] AGI, Systems Tool Kit (STK), 2016, http://www.agi.com/products/stk/ (accessed 09.08.16).

[42] Trimble Navigation Limited, SketchUp, 2016, http://www.sketchup.com/ (accessed 17.08.16).

[43] M. Langer, et al., Deployable Structures in the CubeSat Program MOVE, in Proceedings of the 2nd International Conference Advanced Lightweight Structures and Reflector Antennas, Tbilisi, Georgia, 2014, 224-233.

[44] Clyde Space, CS 2U Power Bundle B: EPS + 20Whr Battery, 2016, https://www.clyde.space /products/38-cs-2u-power-bundle-b-eps-20whr-battery, (accessed 09.08.16).

[45] Clyde Space, User Manual: 3rd Generation CubeSat Battery Family, 2016.

[46] GomSpace, NanoPower BP4, 2016, http://gomspace.com/index.php?p=products-bp4 (accessed 09.08.16).

[47] NanoAvionics, Power Unit 1P0, 2016, http://n-avionics.com/products/eps/ (accessed 09.08.16).

[48] T. Gruebler, Investigating a Mass-Reproducible Attitude Determination and Control System on the nanosatellite MOVE-II, in 8th European CubeSat Symposium, London, UK, 2016, 7-9 September.

[49] Bosch, Bosch Sensortec BNO055 Intelligent 9-Axis Absolute Orientation Sensor, 2016, http://eu.mouser.com/new/bosch-sensortec/bosch-bno55-sensor/, (accessed 17.08.16).

[50] Hyperion Technologies, Hyperion Technologies HT-RW200.15, HT-RW210.30, HT-RW210.60 Data Sheet, 2015.

[51] FreeRTOS, Quality RTOS & Embedded Software, 2016, http://www.freertos.org/, (accessed 09.08.16).

[52] M. Langer, et al., Results and lessons learned from the CubeSat mission First-Move, in: R. Sandau, P. H. Roeser and A. Valenzuela (Eds.), Small Satellite Missions for Earth Observation, Springer, Berlin, 2015.

[53] D. Honess., Compute Module CubeSats, 2015, https://www.raspberrypi.org/blog/compute-module-cubesats/ (accessed 09.08.16).

[54] T. Talbert., PhoneSat Flight Demonstrations, 2013, http://www.nasa.gov/directorates/spacetech/small_spacecraft/phonesat.html (accessed 09.08.16).

[55] NanoAvionics, NanoAvionics Primary Flight Computer Datasheet - SatBus 1C0, 2015, n-avionics.com/wp-content/uploads/2015/04/SatBus1C0_data_sheet.pdf, (accessed 09.08.16).

[56] Hyperion Technologies, Personal Communication: HT-RW200.15 Reaction Wheel Cost, 24.06.16.

[57] NanoAvionics, Personal Communication: SatBus 1C0 Price, 04.07.16.

[58] CNES, STELA, https://logiciels.cnes.fr/content/stela?language=en (accessed 09.08.16).

[59] Rocket and Space Technology, Atmosphere Properties, http://www.braeunig.us/space/atmos.htm, (accessed on 09.08.16).

[60] C. Foster, et al., Orbit Determination and Differential-drag Control of Planet Labs Cubesat Constellations, in AIAA Astrodynamics Specialist Conference, Vail, US, 2015.