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Review

A survey and assessment of the capabilities of Cubesats for Earth observation

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A B S T R A C T

In less than a decade, Cubesats have evolved from purely educational tools to a standard platform for technology demonstration and scientific instrumentation. The use of COTS (Commercial-Off-The-Shelf) components and the ongoing miniaturization of several technologies have already led to scattered instances of missions with promising scientific value. Furthermore, advantages in terms of development cost and development time with respect to larger satellites, as well as the possibility of launching several dozens of Cubesats with a single rocket launch, have brought forth the potential for radically new mission architectures consisting of very large constellations or clusters of Cubesats. These architectures promise to combine the temporal resolution of GEO missions with the spatial resolution of LEO missions, thus breaking a traditional trade-off in Earth observation mission design. This paper assesses the current capabilities of Cubesats with respect to potential employment in Earth observation missions. A thorough review of Cubesat bus technology capabilities is performed, identifying potential limitations and their implications on 17 different Earth observation payload technologies. These results are matched to an exhaustive review of scientific requirements in the field of Earth observation, assessing the possibilities of Cubesats to cope with the requirements set for each one of 21 measurement categories. Based on this review, several Earth observation measurements are identified that can potentially be compatible with the current state-of-the-art of Cubesat technology although some of them have actually never been addressed by any Cubesat mission. Simultaneously, other measurements are identified which are unlikely to be performed by Cubesats in the next few years due to insuperable constraints. Ultimately, this paper is intended to supply a box of ideas for universities to design future Cubesat missions with high scientific payoff.

Contents

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1. Introduction

TIROS-1, a US meteorological satellite launched in 1960, was the first satellite to be launched for the purpose of observing the Earth [1]. Since then, hundreds of Earth observation satellites have been launched that provide useful measurements to all the disciplines of the Earth sciences: hydrology, climatology, meteorology, aeronomy, atmospheric chemistry, oceanography, geology, biology, and so on [2].

The power of space-based measurements compared to ground-based or airborne measurements lies on their global or regional coverage and their relatively high temporal resolution. These two characteristics have made satellite measurements a key asset for a variety of societal applications including amongst others weather forecasting, disaster monitoring, water management, pollution, and agriculture.

Trends in Earth observing mission architectures have certainly changed over the years. The mass of past and present Earth observing satellites ranges from only a few kgs to 8 mt. The peak of mass was achieved in the 1990s and early 2000s with the launch for example of ESA's Envisat (2002, 7.9 mt), NASA's UARS (1991, 5.9 mt), and NASA's TERRA (1999, 5.2 mt) for example.

Large satellites such as Envisat were advertised to be great in terms of science as one could easily cross-register a variety of highly synergistic measurements taken at the same time from the same platform. Also, a reduction in cost per kg of payload was expected, as several instruments shared a single bus and a single launch. In reality, these cost reductions did not fully materialize due to the emergence of a plethora of engineering and programmatic problems during development: electromagnetic incompatibility between RF instruments; scanning instruments inducing vibrations on the platform that affect sensitive instruments; technologically ready instruments having to wait for less mature instruments to be ready for launch, and so forth.

Perhaps as a reaction to the problems found in these multi-billion programs, the increase in mass has stopped in the last decade, and both NASA and ESA have created programs based on smaller satellites around 1 mt, such as ESA's Earth Explorers or NASA's Earth System Science Pathfinders. Smaller programs based on single instrument satellites are more desirable from the engineering standpoint, as all the aforementioned issues related to several instruments sharing a platform are avoided. Furthermore, programs based on smaller satellites have desirable programmatic properties, for example in terms of robustness to schedule slippage, to launch failure, or to budgetary instability.

Continuing this miniaturization trend in spacecraft, minisatellites have been used in the last years for technology capability demonstration (ESA's PROBA program, NASA's Edison and Franklin programs), and for education (MIT Spheres, Stanford Gravity Probes). In the educational world, several universities around the world started nanosatellites programs to teach their students the fundamentals of satellite engineering and project management, as well as to provide them with excellent hands-on experience. These satellites were very diverse in mass, size, and capabilities until Stanford University and Cal Poly developed the Cubesat standard in 1999.

The Cubesat standard was created by Professor Jordi Puig-Suari at Cal Poly and Professor Bob Twiggs at Stanford. The standard specifies that a standard 1-unit (1 U) Cubesat shall measure $10 \times 10 \times 10\,cm^3$ and shall weigh no more than 1.33 kg. Typical power consumption is on the order of a few Watts, and available data rates do not exceed 1 Mbps. Cubesats are designed, built, tested, and launched by universities at a price between \$50,000 and \$200,000. Incentivized by this relatively low cost, many universities around the world have created new Cubesat programs in the last few years. Typical payloads include GNSS receivers, CCD cameras, etc. A recent survey of pico- and nanosatellite missions is given in [3].

Although science started as a secondary objective in most Cubesat programs – with education or capability demonstration being the primary ones – in some cases researchers have been surprised by the potential quality of the science that could be achieved using constellations of Cubesats. For example, CanX-2 successfully acquired total column measurements of CO_2 as well as GNSS radio occultation measurements [4]. In the near future, it is expected that MIT's MICROMAS Cubesat for hyperspectral microwave atmospheric sounding achieves a retrieval performance similar to that of their homolog instruments in the current NOAA POESS spacecraft [5]. Similarly, NASA's Cloud Cubesat is expected to provide state-of-the-art polarimetry data of clouds and aerosols [6]. Recently, the Applied Physics Laboratory at John Hopkins University (APL) has suggested a Cubesat-based architecture to occupy the hosted payload slots that Iridium is offering for each of the 66 satellites of their next generation constellation of LEO communication satellites. In the context of this project, APL has partnered with a number of universities such as MIT and research labs such as Draper Laboratory, in order to identify the optimal set of Cubesat-size sensors to be flown in the Iridium satellites.

The questions at this point are almost inevitable: can Cubesats by themselves do world-class Earth science, or should they stay primarily focused on educating students in universities? What capabilities have already been demonstrated? What capabilities are currently under development? What limitations do Cubesats have that preclude high performance in Earth Science? Which scientific applications are most affected by these limitations?

The goal of this paper is to try to help answer these questions. Some relevant information is provided in existing references such as Pang's and Twigg's article in Scientific American [7], or even the aforementioned survey [3]. However, none of these references provides details on the capabilities and limitations of Cubesats for Earth science.

The rest of the paper is organized as follows. First, a succinct but exhaustive survey of current Cubesats for Earth observation is provided in Section 2. Based on this survey, a summary of the existing and developing scientific and technological capabilities in Earth observation Cubesats is given in Section 3, focusing on three aspects: (1) Cubesat bus technology limitations; (2) impact of these limitations on the feasibility of Cubesat-based missions carrying Earth observation payloads; (3) impact of these limitations on the scientific value of Cubesat-based Earth observing missions. Finally, some concluding remarks are provided in Section 4.

2. A survey of Earth observation Cubesats

Cubesats have been mentioned as possible future platforms for scientific missions [8], and a number of surveys of nanosatellites, picosatellites, and Cubesats are available in the literature. Bouwmeester and Guo published a survey of pico- and nanosatellite missions [3]. Reference [9] gives a general overview of Cubesat capabilities. Klofas et al. wrote a survey of Cubesat communication systems [10]. Woellert et al. have a section devoted to Earth observation in his paper on "Cubesats as cost effective science and technology platforms for emerging and developing nations", but the section was not exhaustive [11]. Greenland and Clark published an assessment of the capabilities of Cubesats as platforms for science and technology validation missions [12]. However, to the best of our knowledge, no exhaustive survey has been done for Earth observation Cubesats.

In this section, we present the results of an exhaustive survey of Cubesats for Earth observation, both existing and under development as of August 2011. Information in this section comes from the individual mission websites, unless when other references are provided.

As mentioned before, a big majority of Cubesat missions are primarily educational, or used as technology demonstrators (e.g., CP-1 [13], BeeSat [14], and NanoSail-D [15]). Therefore, most Cubesats do not have stringent scientific requirements. However, they sometimes carry some instruments related to Earth science, either as primary or secondary payloads, typically low resolution CMOS cameras, or space weather sensors. For instance, Aerocube-2 and 3, Compass-1, CAPE Libertad 1 , HiNCube, and ITÜpSAT [16–18], carried modest resolution (e.g., VGA 640×480 pixel) CMOS cameras, and the KUTESat Pathfinder, ICECube 1 and 2, AAUSat-2 Explorer-1 Prime, Goliat, UniCubeSat, Heidelsat, XatCobeo, Robusta, AtmoCube, Sacred, HawkSat-1, and Merope all carried space weather sensors [19–25].

For the purpose of this paper, we decided to focus on missions with scientific requirements closer to those of larger satellites, which are much less frequent. Missions with such requirements are listed in Table 1. Note that low resolution cameras and space weather sensors are not included in this list.

We observe that there have been some spectrometric measurements for atmospheric chemistry, especially around

Table 1
List of Earth observation Cubesat missions in chronological order.

Cubesat	Institution	Payload	Measurements	Launch date and status	Reference
QuakeSat	Stanford University and Quakesat LLC	AC magnetometer	Ultra low frequency (ULF) magnetic signals from large (Richter >6) earthquakes	2003 (success)	[26]
ION	University of Illinois at Urbana-Champaign	Photometer (Photomultiplier Tube) and 640×480 pixel CMOS color camera	0.76 μm oxygen emission band in the 100 km upper atmosphere	2006 (launch failure)	[27]
CanX-2	University of Toronto	Atmospheric spectrometer, and GNSS receiver in occultation geometry	1-km horizontal resolution tropospheric CO_2 total column Atmospheric humidity and total electron content	2008 (success)	[4]
SwissCube-1	Polytechnic School of Lausanne	Passive optical telescope, with 188×120 pixel camera	0.76 μm oxygen emission band in the 100 km upper atmosphere	2009 (success)	[28]
Micromas	Massachusetts Institute of Technology	mm-wave multi-channel radiometer	Hyperspectral microwave atmospheric sounding (vertical profiles of atmospheric temperature and humidity)	In development	[5]
Cloud Cubesat	NASA Goddard Space Flight Center (GSFC)	VIS camera NIR camera Polarimeter	Aerosol and cloud properties	In development	[6]
M-Cubed (Michigan Multipurpose minisatellite)	University of Michigan	25.4 mm aperture, 17.6 mm focal length telescope, with 1628×1236 pixel CCD	Medium resolution optical imaging (200 m)	In development	[29]
Aalto-1	Aalto University	5–10 nm, 6–20 channel imaging VNIR Fabry–Perot interferometer spectrometer	Aerosol and cloud properties, vegetation measurements, fire monitoring, water monitoring, land use, atmospheric chemistry	In development (launch targeted 2013)	[30]
FireFly	NASA GSFC	VLF receiver, photometer	Lightning detection	In development	[31]

the 0.76 μm O_2 band, and the 1.6 μm and 2.0 μm CO_2 bands. The passive hyperspectral microwave atmospheric sounding application (i.e., Micromas) is perhaps the highest performance one with respect to missions based on larger satellites, together with the polarimetry measurements (Cloud Cubesat) for aerosol, clouds and vegetation applications. Furthermore, all-purpose medium-resolution imaging in the visible and near infrared has been demonstrated. Only the mission with highest performance in this class has been included in Table 1. Finally, one mission used state-of-the-art magnetometers to measure extremely low magnetic signals originated during strong earthquakes (Quakesat). Another mission is expected to do lightning detection using a combination of a photometer and a very low frequency radiometer.

In summary, a large number of Cubesats with some Earth observation capability have been developed in the last years, although most of them carried space weather sensors, or modest resolution optical cameras. A few instances of Cubesats carrying more advanced remote sensing payloads have been identified and summarized in Table 1.

It is clear from this analysis that some technologies are more appropriate than others for use in Cubesats, arguably because they are more prone to miniaturization. The reasons for that are analyzed in Section 3.

3. Technological capabilities of Cubesats

In this section, we identify technological gaps of Cubesats for Earth observation. We used the instrument categories defined in the Committee on Earth Observing Satellites (CEOS) on-line database[1] as a baseline for the analysis.

This section is organized as follows. First, we identify the major Cubesat bus limitations in Section 3.1, and in Section 3.2 we analyze the impact of these limitations in terms of remote sensing payloads.

3.1. Cubesat bus limitations

3.1.1. Avionics and on-board data handling

The usage of COTS micro controllers on Cubesats enables, at the risk of higher susceptibility to space radiation, high data processing capabilities compared to space qualified components. Bouwmeester and Guo found in their survey of Cubesats that despite sporadic use of USB and CAN, I^2C is the standard bus system in current Cubesat missions [3]. Flown on-board data handling hardware includes commercially available PIC, MSP, and ARM controllers of 8–33 MHz, 16–32 bit [3,32].

Concerning data storage, typical Cubesats have an on-board memory ranging between 32 kB and 8 MB, although some of them have employed additional flash memory up to 8 GB [9]. Considering for instance a VGA camera that takes a 640×480 pixel image in a single band in the visible, with 8 bit/pixel, and no data compression, 8 GB are roughly equivalent to 3500 images. For a

[1] http://database.eohandbook.com/

hypothetical multispectral push-broom imager with 32 bands and 1 K $\times$ 1 K pixels per image, 8 bit/pixel, 8 GB can store 32 multispectral cubes.

This storage capability is not useful if the data rates are not increased accordingly. In fact, it is trivial to show that there is a linear relationship between storage capability and data rate if the constraint is enforced to have enough storage capability to store all the images that can be downloaded in one access to the ground station:

$$Storage(MB) = \frac{15}{2}\Delta T\left(\frac{min}{access}\right)R_b(Mbps)$$

where $Storage(MB)$ is the storage capability required to be able to empty the memory during one access to the ground station in MB; $\Delta T(min/access)$ is the average duration of an access to the ground station in minutes, $R_b(Mbps)$ is the downlink data rate in Mbps, and the factor $15/2=60/8$ comes from transforming bits into bytes and minutes into seconds. For $R_b=0.25$ Mbps, and $\Delta T=5(min/access)$, a storage capability of $Storage(MB)=9.3$ MB is required, which is much lower than what can be achieved in Cubesats. It follows that the real limiting factor is data rates, and not data storage. Furthermore, we note that payloads that would have high requirements in terms of data storage such as hyperspectral imagers are probably also incompatible with current Cubesat technology because of other limitations, namely available power and space.

3.1.2. Attitude determination and control

Determination: Due to the lack of high performing star trackers, the best performing technology currently available for attitude determination is miniaturized sun sensors, which are usually utilized in combination with magnetometers. Achieved accuracies of less than 2° have been reported by CanX-2 [33]. Target determination accuracies for star trackers currently in development are 0.01° and 0.05° for yaw, pitch, and roll, respectively [34].

Control: Attitude control is mostly performed by passive and active magnetic control, with achieved pointing accuracies better than 5° [35,36]. There are also a few cases of technology demonstration of reaction wheels, such as BeeSat and CanX-2. In CanX-2 in particular, a residual ripple noise of 1 μN s was caused by reaction wheels, achieving overall control accuracies better than 2° [33]. However, various suppliers state overall accuracies achievable with their current technologies to be as good as 1° (Pumpkin CubesatKit: magnetometers and sun sensors in combination with active magnetic coils and reaction wheels, [37]) or even 0.5–0.6° (Satellite Services Ltd, [38]). Stated determination accuracies for a future system including sun sensors, gyros, and star trackers are even of 1–3 arcs in determination (Pumpkin CubesatKit [37]). Thus, accuracies at a level of 1° and below are readily available for attitude determination and control, but, as Greenland and Clark mentioned, are yet to be proven in operation, [12].

Geolocation: The ability to accurately determine the satellite's attitude at time of measurements directly impacts the quality of the measurement, as it determines the precision with which a certain scene is geolocated. This becomes especially important in the case of cross-registered measurements coming from multiple Cubesats. In this case, the ability to precisely align the individual measurements may heavily affect the quality of the outcoming data. Assuming a typical orbit altitude of 500 km, an attitude determination uncertainty of 2° (CanX-2) for a nadir instrument leads to a spatial uncertainty on ground of 17.5 km, whereas the future accuracies for Cubesats, estimated to 0.02° would lead to an uncertainty on ground of 175 m. The latter value is complying with the geolocation requirements of several of the missions found in the sections hereafter, with noticeable exceptions such as land topography which have much more stringent geolocation requirements.

Note that these calculations relate to the achievable attitude accuracy according to attitude determination only, without taking control into account. For a 500 km altitude orbit, 0.5° attitude control accuracy translates into approximately 4.5 km of spatial uncertainty on ground.

3.1.3. Communications

Bouwmeester and Guo found in their survey that 75% of the Cubesats they investigated use UHF band with maximum typical data rates of 9600 bps, whereas only 15% use S-band with a possible maximum data rate of 256 kpbs [3]. The latter data rate has been proven in space operation by CanX-2 [4]. The remaining Cubesats employed VHF with limited maximum data rates similar to UHF.

Downlink powers for typical Cubesats range from 0.1 W (Cute-1) to 1 W (GeneSat-1, CanX-2) [11]. Bouwmeester and Guo concluded in their survey that data rates are primarily limited by available link power budget, rather than by the existence of available electronics [3]. Indeed, let us write a simplified link budget equation for a general digital modulation scheme:

$$\frac{E_b}{N_0} = \frac{P_r}{kTR_b} = \frac{P_tG_tG_rL}{(4\pi r)^2kTR_b} > \left.\frac{E_b}{N_0}\right|_{\min}$$
$$\Rightarrow R_b < \frac{P_tG_tG_rL}{(4\pi r)^2kT(E_b/N_0)\big|_{\min}}$$

where P_t is transmitted power; G_t,G_r are the gains of the transmitting and receiving antennae, L are all losses terms due to connectors, atmospheric propagation, ionosphere, and rain; r is the distance between the satellite and the ground station, k is the Boltzmann constant, T is the noise equivalent temperature of the ground receiver, and $(E_b/N_0)\big|_{\min}$ is the minimum E_b-over-N_0 required to ensure a certain maximum bit error rate (BER) in the transmission, which depends on the modulation of choice. Assuming $P_t=1$W, $G_t=1$, $G_r=200$ (corresponding to a 2 m dish in UHF), $L=0.25$ (conservative), $r=600$ km/cos(45) to account for a 45° off-nadir angle, $T=300$ K (i.e., noise factor of 2), and $(E_b/N_0)\big|_{\min}=20$ (corresponding to a BER$=10^{-5}$ for BPSK with 3 dB of margin), we obtain an R_b maximum of 512 kbps.

This is a real limitation for Earth science, since 512 kpbs is not enough to take advantage of an imaging instrument's capabilities. In order to show this, let us consider again the two aforementioned cases of a simple VGA camera, and a hyperspectral imager. For the VGA camera, the size of an image is 2.34 Mbit; for the hyperspectral sensor, the size of a cube is 256 Mbit. The number of images that can be downloaded per pass in each case is given by the access time and the data rate:

$$\frac{\#images}{access} = \frac{60 \cdot \Delta T(min/access) R_b(Mbps)}{image\ size(Mbit/image)}$$

Assuming again an average access duration of 5 min, a data rate of 0.5 Mbps yields 64 images for the VGA camera, and 0.58 cubes for the hyperspectral sensor, which is a very limited amount of data. This argument is emphasized when we take into account typical Cubesat lifetimes, on the order of the year, much lower than larger satellites lifetimes due to the absence of orbit control, and decreased reliability.

To partially overcome the limited downlink capabilities, we notice efforts in ground station networking to achieve longer accumulated access time per orbit and therefore increased download capabilities [39]. However, for a given maximum downlink rate, these efforts have only limited capabilities in increasing the total amount of data downlinked in the order of one magnitude and come at the price of reduced scientific duty cycle.

3.1.4. Mass and dimensions

The Cubesat specification constrains its total mass to be below 1.33 kg for a 1 U Cubesat [40].

Dimensions according to the Cubesat standard for one unit are $10 \times 10 \times 10\ cm^3$ with no protuberant parts at launch, [40]. Configurations using 1, 2, and 3 Cubesat units (1 U, 2 U, 3 U) have already been launched, and 6 U and bigger configurations have been proposed.

Dimension constraints are sometimes the most stringent constraints on the payload, as payload performance often depends strongly on its dimensions. For example, the aperture of an optical system determines its diffraction-limited angular resolution and thus its ground spatial resolution:

$$\Delta x \approx h \cdot \Delta\theta = h \cdot 2.44 \frac{\lambda}{D}$$

where Δx is the ground spatial resolution, $\Delta\theta$ is the diffraction limited angular resolution, h is the orbit altitude, λ is the wavelength, and D is the instrument aperture. Thus, for example, simple physics dictates that it is impossible to obtain a spatial resolution on ground better than 9.8 m from 800 km using a nadir-looking passive optical instrument (wavelength of 0.5 μm) on a Cubesat (i.e., with a diameter of 10 cm).

Similarly, the diameter of an RF antenna determines its gain G and therefore affects signal-to-noise ratio (SNR). In particular, for aperture antennae:

$$G \approx \eta \cdot \left(\frac{\pi D}{\lambda}\right)^2$$

where typical values for η are around 0.55. For long wire antennae (i.e., length comparable to wavelength), gain also increases with the square of the length for a fixed wavelength. In other words, in order to have high antennae gains or SNR, it is necessary to have lengths or diameters that are at least on the order of the wavelength. One can conclude that the frequency or bandwidth of the antenna or sensing system will thus be limited by the maximum dimension of the Cubesat, i.e., 10 cm, which corresponds to 3 GHz, i.e., C-band. Therefore, lower bands that are commonly used in remote sensing such as L-band or even P-band cannot be considered for Cubesats. The consequences of this limitation in terms of science will be discussed in the next subsection.

One could argue that this limitation can be at least partially overcome by using deploying mechanisms. However, this comes at the expensive price of increased risk, complexity, mass, power, and ultimately cost.

3.1.5. Power

A conservative rough order of magnitude estimation of the available power in Cubesats reveals that it should be on the order of 1 W, as solar panels provide on the order of $10^2\ W/m^2$ when all efficiencies are considered [41], and one side of the Cubesat has a surface area of $10^{-2}\ m^2$. This is consistent both with the data provided in [3] (which gives <2 W for 1 kg picosatellites), and with actual average powers achieved in state-of-the-art Cubesats that use small deployable solar arrays: Delfi-n3Xt, a 3 U Cubesat, will provide 5.5 W of average power, i.e., about 1.8 W for a 1 U Cubesat [32]. CanX-2 reported 6 W peak power for the body mounted 3 U solar panels [4]. These power levels are incompatible with high energy instruments such as imaging radars, lidars, radar altimeters, scatterometers, and almost any instrument requiring an active illumination source. This is again dictated by physics. Consider in particular a pseudo-radar equation:

$$P_r = k_1 \frac{P_t A^2 f^2}{h^4}$$

where P_r is the received power, P_t is the transmitted power; G_t is the gain of the antenna; A is the antenna area; k_1 is a constant that includes propagation losses, the target radar cross-section, and the antenna efficiency; and h is the orbit altitude. For the following conservative values: $h = 10^2$ km, $A = 10^{-1}\ m^2$ (limited by Cubesat dimensions), $k_1 = 5500\ 16\pi^4$ (vacuum, no interference, corner reflector), and a frequency f of 1 GHz, we obtain $P_r/P_t = 10^{-17}$. This implies that in order to receive a power of 1 nW, a peak transmitting power of the order of hundreds of MW would be needed. This is obviously unattainable on Cubesats.

3.1.6. Propulsion

As of August 2011, the only space proven propulsion system successfully employed on a Cubesat is a sulfur hexafluoride (SF_6) pressurized cold gas thruster (NANOPS) onboard of CanX-2 with an experimentally determined specific impulse of $I_{sp} = 46.7$ s at a maximum thrust of 35 mN. Minimum impulse bits achieved with this system have been reported in the range of $I_{Bit} = 0.15$ mNs (full tank) to $I_{Bit} = 0.07$ mNs (empty tank) [33], enabling fine orbit maneuvers for potential formation flight. The propulsion system was estimated to deliver a $\Delta v < 35$ m/s to the 3 U Cubesat. Total subsystem mass was reported to be below 500 g [42]. Another cold gas thruster, based on solidified nitrogen storage is scheduled to be tested onboard of Delfi-n3Xt, yielding expected thrust levels of

6–100 mN at an estimated specific impulse $I_{sp} > 30$ s. The subsystem, which takes approximately 1/3 unit, stores 2.5 g of propellant at a total subsystem mass of 120 g [43,44].

The only electrical propulsion system employed in a Cubesat mission has been a Vacuum Arc Thruster (VAT) module mounted on the 2 U Cubesat ION, which was lost due to launch failure. The thruster was expected to produce impulse bits in the range of $I_{Bit}=0.25$–50 μN s at an estimated specific impulse of $I_{sp}=1000$ s [45,46]. As of August 2011 we noticed at least three research organizations aiming at the development of Pulsed Plasma Thrusters for Cubesats, with expected impulse bits in the range of 5–20 μN s and total lifetime impulses delivered to the satellite of 10–25 N s, yielding Δv in the order of 10 m/s for a double or triple unit Cubesat. System volumes are expected to be in the order of 1/2 a Cubesat unit [47–50].

Based on the above data, minimum Δv values theoretically possible for the different satellites have been determined as 0.5 μm/s for ION, 330 μm/s for CanX-2 and predicted values, based on a 2 U Cubesat of 3 μm/s for the μPPT from [47]. This is compared to the tandem formation flight mission requirements of TanDEM-X with a minimum $\Delta v=50$ μm/s at an expected daily correction budget of $\Delta v=3$–15 mm/s [51]. Assessment of relative drift of jointly deployed Cubesats UWE-2, ITUpSat1, Swisscube and Beesat-1 showed drift rates that can be corrected with a Δv budget below 5 m/s [52]. From this analysis it can be concluded that future Cubesats will be able to meet formation flight requirements given the proper ADCS capabilities.

In addition, we note that in the field of formation flying, another approach based on differential drag of two or more satellites has emerged, which has the potential for propellant-less control of relative distances between Cubesats [53]. However, this method is strongly dependent on accurate attitude control of the individual Cubesats and has yet to be proven in space.

The above given performance data for Cubesat propulsion systems also allow for an estimation of the total Δv available over the mission lifetime. These values range from 10 m/s [47], 11–40 m/s for the Strand mission [49] to <35 m/s for CanX-2. While these values are incompatible with significant inclination change maneuvers, distribution of Cubesats within an orbital plane, as in the case of a scenario in which multiple Satellites are sharing a launch, seems feasible. In addition, these velocity budgets can be useful to estimate deorbiting capabilities at the end of lifetime to avoid space debris in compliance with debris mitigation efforts [54]. Different approaches to tackle the problem of limited Δv budget for deorbiting base on either increasing the atmospheric drag coefficient (e.g., Nanosail-D), reflective balloons [55], or electromagnetic tethers [15,56]. These techniques would allow to passively deorbit a Cubesat in less than 2 years [55].

3.1.7. Thermal control

Thermal control of Cubesats is usually passive with heat sinks and optical tape on the outer structure, keeping the structure, with the exception of the solar panels, in a range of approximately $-15\,^{\circ}$C to $40\,^{\circ}$C for sun synchronous orbits [16,33,57]. Due to the limited outer surface area of Cubesats, the effectiveness of passive cooling by radiators is limited, since radiated power is linearly dependent on surface area A facing cold space, as can be expressed by:

$$Q = k_2 A T^4$$

where Q is the power radiated to space in W, k_2 is a constant that depends on the material of the radiator (more particularly, k_2 is the product of the emissivity and the Stefan–Boltzmann constant, and is on the order of 10^{-8}), and T is the temperature in K. A rough order of magnitude calculation reveals that given a surface area of 10^{-1} m^2, and at a temperature of 3×10^2 K, a heat flux of the order of a few tens of Watts is obtained, which precludes the utilization of payloads dissipating several hundreds of Watts.

Active thermal control strategies on Cubesats usually consists of coarse battery pack temperature control by joule heating [58], as the one developed for Compass 1, even though this particular one failed due to heater malfunction [59].

However, none of these thermal control strategies comply with stringent requirements for photodiodes, which accordingly have to employ some sort of active temperature control and cooling technique. Perhaps the only exception is the thermoelectric cooler of the Cloud Cubesat, which while it is still under development, was designed to regulate temperature at 243 K with a stability of ± 0.1 K [6]. Cooling photodetectors down improves their SNR because dark noise from thermal excitation increases with temperature, as it follows the temperature dependence of the concentration of electrons in the conduction band, shown in the equation below:

$$n_0 = k_3 T^{-1.5} e^{-(k_4/T)}$$

where n_0 is the concentration of electrons in the conduction band, T is the temperature, and k_3 and k_4 are constants that depend on technology. Using this equation one can compute the Noise Equivalent Power NEP (i.e., the signal power required to achieve an SNR of 1) due to thermal noise as a function of temperature [60]. The signal power that would be available around 1 μm from an orbit of 500 km can also be computed, and is on the order of 10^{-14} W for a sensor with a ground spatial resolution of 10 m. Therefore, in order to obtain an SNR of 100, an NEP of 10^{-16} is needed, which corresponds to a temperature of about 187 K using the previous equation. While this is just a particular example, it is general truth that in order to achieve reasonable SNR, cooling down the sensor becomes a necessity [60].

The Argus-1000 instrument onboard of CanX-2 uses a programmable Peltier cooler to enhance the SNR of their linear gallium arsenide CMOS detector [61]. A different approach in FIR detection coping with limited cooling capabilities is to use uncooled bolometers such as the VO_x micro-bolometers onboard of JC2Sat, using a differential technique of two line arrays with one being solely sensitive to thermal influences [62].

More advanced active techniques, such as the space proven Stirling and Joule–Thomson cryocoolers surpass volume and mass capabilities of Cubesats. Examples of these include the 4.3 kg Oxford cryocooler employed on UARS with cooling capability of 0.8 W at 80 K (see [2], page 61).

The dependence of noise on temperature together with the limited cooling capabilities available on Cubesats renders measurements in the short-wave and mid-infrared regions are particularly challenging, as in those regions the problem of high noise is combined with low signal strength, due to the shape of the Planck function, and to Wien's law. Indeed, solar radiation (blackbody temperature of around 6000 K) presents a maximum in the visible, while Earth's radiation (blackbody temperature of 300 K) has a maximum in the thermal infrared region. In both cases, the intensity in the MIR between 2 μm and 6 μm is far from a maximum and is thus several orders of magnitude smaller than the signal in the visible or in the thermal infrared.

As it will be explained later, this will imply lower sensitivity for atmospheric chemistry because most vibrational–rotational lines of the main greenhouse gas molecules are to be found in this spectral region.

Finally, note that the constraints that have been presented in this subsection are not independent. For example, mass and dimensions are intimately related, so that violation of one constraint may often imply violation of other constraints. For the rest of the discussion, whenever a constraint is found that makes a technology problematic or infeasible, related violated constraints will not be necessarily exhaustively enumerated.

3.2. Instrument technology capabilities

Given the limitations of current Cubesat technology described in the previous subsection, we analyzed the feasibility of the major remote sensing technologies in a Cubesat environment. The list of 17 technologies considered was directly taken from the publicly available CEOS database. For each technology, feasibility was qualitatively assessed as "Feasible", "Problematic", or "Infeasible". If a Cubesat mission using this technology, or a sensor compatible with the Cubesat standard, had already been developed, the technology was classified as "Feasible", If a technology is clearly incompatible with the Cubesat standard for at least one of the arguments presented in the previous subsection, it was categorized as "Infeasible". All other technologies were classified as "Problematic". "Problematic" technologies typically include cases in which an instance of the instrument could be developed to fit the Cubesat standard, but at the expense of significantly reduced data quantity and/or quality. The results of this analysis are summarized in Table 2. Although this classification may be biased by the knowledge of the authors and the extent of the literature review, a justification column was added to ensure transparency in the classification process. We invite the scientific community to challenge this classification by providing evidence that certain technologies are feasible as opposed to problematic, or vice-versa.

Seven remote sensing technologies were identified as most likely feasible for Cubesat missions: atmospheric sounders, Earth radiation budget radiometers, gravity instruments, lightning imagers, magnetic field instruments, ocean color instruments, and precision orbitographers. Note that the fact that a technology is categorized as feasible does not imply that there is no loss in terms of data quality with respect to a larger instrument.

Six other technologies were identified as most likely infeasible given the state-of-the-art of Cubesat technology: essentially all types of radars, lidars, and high resolution optical imagers.

Table 2
Preliminary assessment of the feasibility of Cubesat-based missions carrying different remote sensing technologies.

Technology	Feasibility assessment (feasible/problematic/infeasible)	Justification
Atmospheric chemistry instruments	**Problematic**	Low sensitivity in SWIR-MIR because of limited cooling capability
Atmospheric temperature and humidity sounders	**Feasible**	e.g., GNSS radio occultation, hyperspectral millimeter-wave sounding
Cloud profile and rain radars	**Infeasible**	Dimensions, power
Earth radiation budget radiometers	**Feasible**	[63]
Gravity instruments	**Feasible**	[64]
High resolution optical imagers	**Infeasible**	Not enough resolution-swath, because limited space for optics and detectors
Imaging microwave radars	**Infeasible**	Limited power
Imaging multi-spectral radiometers (vis/IR)	**Problematic**	Limited imaging capability
Imaging multi-spectral radiometers (passive microwave)	**Problematic**	Limited imaging capability
Lidars	**Infeasible**	Limited power
Lightning imagers	**Feasible**	[30]
Magnetic field instruments	**Feasible**	[65]
Multiple direction/polarization radiometers	**Problematic**	Limited dimensions for receiver electronics
Ocean color instruments	**Feasible**	[4]
Precision orbit	**Feasible**	[66]
Radar altimeters	**Infeasible**	Dimensions
Scatterometers	**Infeasible**	Dimensions

The four remaining technologies – atmospheric chemistry, imaging multispectral radiometers (both optical and microwave), and polarimeters – were categorized as "Problematic", meaning that a Cubesat-based mission using these technologies could be feasible in the near future mediating some investment on these technologies, and/or some descoping in terms of scientific requirements.

It is noticeable that from the technologies that we assessed as feasible according to the discussion in Section 3.2, ocean color instruments have had the least attention from the Cubesat community. Ocean color is nevertheless a key measurement in ocean biology, and one that is threatened by a potential data gap after the retirement of MODIS, SeaWiFS, and MERIS and before the arrival of NPOESS and Sentinel-3.

4. Cubesat capabilities and Earth science mission requirements

Using words from the system architecture jargon Section 3 of this paper focused on form as opposed to function, i.e., technology as opposed to science, or more precisely instruments as opposed to measurements or data products. We did that because that is a very common practice in the remote sensing field. However, in Earth observation missions, as in all other systems, the majority of the benefit (i.e., satisfaction of scientific and societal objectives) is in the measurements being taken by the spacecraft, not in the instruments – as a matter of fact, the cost is in the instruments. Therefore in this section of the paper, a measurement-centric view is taken. The goal of this section is thus to conduct an analysis of the limitations of Cubesats from the perspective of measurement requirements. As in the technology case, the CEOS database was used to obtain a reference set of measurements and measurement categories. CEOS identifies 21 measurements relevant to Earth observation missions, divided in five categories: atmosphere; land; ocean; snow, and ice; gravity and magnetic fields. This section is organized following this division in five categories. For each of these 21 measurements, the impact of Cubesat limitations on scientific requirements is analyzed, in order to assess the utility of a Cubesat-based mission taking this measurement. Conducting an exhaustive literature review of the state-of-the-art of satellite remote sensing for each one of these 21 measurements is an extremely challenging and time-consuming task, arguably out of the scope of any single individual in a limited timeframe. Although several expert interviews were conducted at MIT and NASA to gain insight into the current state-of-the-art of different remote sensing applications, we would like to extend our previous invitation to the scientific community in order to contribute to the discussion in this section.

4.1. Atmosphere

4.1.1. Aerosols

King et al. suggest that aerosol properties (optical thickness, concentration, size, and composition) can be retrieved from space by a combination of well-calibrated multispectral radiometers and polarimeters in the UV, VIS, and NIR spectral regions [67]. MODIS and MISR, two multispectral imaging radiometers, have both provided reliable aerosol optical depth products for several years. Polarimetric or multi-angular measurements such as the ones taken by POLDER or APS are particularly important to obtain information about aerosol size, shape, and composition [68, 69] . Active measurements using lidar have also been found to be extremely useful and complementary to passive techniques, not only because of their day/night capability, but also because of their higher vertical spatial resolution, and enhanced sensitivity over bright surface such as deserts, snow, or bright clouds [70]. However, lidar measurements are not feasible from Cubesats as explained in the previous section.

Both Aalto-1 and the Cloud Cubesat will potentially provide aerosol optical depth measurements. In particular, polarimetric infrared passive measurements like the ones done by the Cloud Cubesat can provide information about the aerosol shape through the size distribution and single-scattering albedo, provided that calibration is good enough. The Aalto-1 Cubesat is expected to provide useful measurements of aerosol optical thickness, but it lacks the polarimetric capability [30].

In [67] it is further suggested that observations in the UV would improve existing aerosol products. At this point, we have not found any Cubesat that performs measurements in the UV. However, we do not see any technological limitation that would preclude measurements in this spectral region using spectrometers similar to those used in the VIS and NIR [4].

4.1.2. Atmospheric temperature and humidity fields

Atmospheric sounding (i.e., obtaining vertical profiles of atmospheric temperature, humidity, and pressure) can be done through different techniques. The classical approach is the use of multispectral or hyperspectral nadir infrared sounders, such as METOP/IASI [71–73] or AQUA/AIRS [74–76], typically including hundreds or even thousands of channels around several major spectral features, such as the 4.3 μm CO_2 band.

Microwave (MW) nadir sounders, such as Aqua/AMSU have also been successfully used [75,76]. MW sounders have the advantage of being less affected by weather than IR sounders, at the expense of reduced spatial resolution.

Limb sounders complement nadir sounders by providing enhanced sensitivity through cirrus clouds, as well as in the upper stratosphere. However, they typically have worse vertical resolution and poor sensitivity in the lower troposphere.

More recently, Blackwell et al. demonstrated the utility of hyperspectral microwave and millimeter wave atmospheric sounding [5]. Hyperspectral sensors enhance the vertical spatial resolution of the retrieval, since more channels can be chosen with weighting functions peaking at different levels of the atmosphere.

Finally, the quality of atmospheric sounding through GNSS occultation measurements was demonstrated with missions such as CHAMP [77].

CanX-2 performs water vapor total column measurements in the 1.4 μm spectral line. On-orbit calibration is done actively, through use of five different infrared lasers, and a calibrated standard illumination source [78].

Micromas features a hyperspectral millimeter wave atmospheric sounder with 4 channels near the 118 GHz O_2 rotational feature, and 4 channels near the 183 GHz water rotational feature [5]. The combination of these eight channels allows the retrieval of $\sim$1 km vertical profiles of atmospheric temperature and humidity with an expected rms error on the order of 1–2 K for temperature and 10–30% for humidity.

Note that water vapor measurements have been used for decades in conjunction with transportation models to infer atmospheric winds [79]. However, these indirect retrievals are not comparable to direct measurements performed using Doppler lidar. Although the trend in wind retrieval is towards a combination of coherent and non-coherent Doppler lidar, indirect retrievals through the use of water vapor imaging will probably remain to be useful data products, and in fact they are still listed as one of the objectives for the US Earth science program for next decade [80].

4.1.3. *Cloud properties, liquid water, and precipitation*

Sensors that provide aerosol particle measurements can typically perform cloud particle measurements, with a few exceptions. For instance, multi-angular measurements are more effective than multi-polarization measurements to infer information about cloud particle shape (the opposite is true for aerosol particles). The Cloud Cubesat will provide measurements of cloud particle size and optical thickness. Polarization is also useful to infer information about cloud particle phase.

Passive microwave measurements have successfully been used to recover liquid water and precipitation inside clouds. Thus, Micromas should also provide some useful precipitation measurements. Note however, that the accuracy of this measurement is not as high as the one obtained with active instruments, i.e., cloud profiling and rain radars using the 94 GHz band.

Furthermore, CanX-2 features a GNSS receiver in occultation mode [42]. As explained in [81], part of the signal received by GNSS occultation receivers is due to hydrometeors and therefore at least theoretically, retrievals of cloud liquid water should be possible using CanX-2 data.

4.1.4. *Atmospheric chemistry (ozone and trace gases)*

Passive infrared spectrometry is typically used to retrieve total column measurements of ozone and important trace gases such as CO_2, CH_4, and CO. Achieving some vertical resolution is hard, especially in the lower troposphere and boundary layer, which is also the most interesting region for health and pollution studies. Limb sounders typically achieve higher vertical resolutions than nadir sounders, on the order of several hundreds of meters or 1km. Active sensors (i.e., lidars) have also been suggested as potential ways to get better sensitivity overnight, over regions with scattering clouds and aerosols, and in the lower troposphere [82].

Vibrational–rotational features of interesting molecules are naturally located in the mid and thermal infrared, in the region between 4 and 16 μm [83]. In particular, the strongest CO_2 lines are located at 15.0 μm and 4.3 μm. For O_3, the strongest vibrational–rotational features are centered at 9.6 μm and 4.75 μm [84].

As explained before, features in the mid infrared – between 2 μm and 8 μm – are extremely hard for Cubesats to use because due to high dark thermal currents in this region, photodetectors need to be cooled down to achieve acceptable signal to noise ratios, and small and low-power cooling systems are very hard to build. Therefore, the performance of atmospheric chemistry measurements using Cubesats is limited. However, overtone and combination bands at lower wavelengths can be measured using uncooled photodetectors. Thus, Cubesats can use alternative features, such as the 1.6 μm band for CO and CO_2, or the 2.0 μm for CO_2 [78]. Furthermore, note that there has been some evidence that uncooled sensors can perform measurements in the thermal infrared (15.0 μm CO_2 band by JC2SAT [62].

Ozone measurements can also be done using electronic transitions in the UV and blue visible spectral region [83] As mentioned before, no Cubesats have been found that perform spectrometric measurements in this spectral region, even though miniature spectrometers exist in the 200–400 nm range.

In addition to dark thermal current, there is another major problem with atmospheric chemistry measurements using Cubesats, which is the very limited imaging capability that miniature spectrometers have. In fact, most Cubesats to date performing some kind of spectrometric measurement lack any kind of imaging capability, as their field of view consists of a single pixel. This drawback could be partially alleviated by the use of a large number of Cubesats in a constellation.

A good comparison between the performance of typical satellite-based spectrometers such as SCIAMACHY on ENVISAT or AIRS on AQUA, and the state-of-the-art of miniature spectrometers represented by the Canadian Space Agency Microsatellite Earth Observation Satellite (MEOS), is provided in [85]. In this paper, the CSA reports adequate spatial resolution, spectral resolution, and signal-to-noise ratio for their miniature spectrometers, in a spectral range between 1 and 5 μm, which includes the valuable 4.3 μm CO_2 absorption band. Note however, that this particular technology is still slightly too big to be considered as Cubesat-class technology ($\sim$10 kg).

Finally, we note two Cubesats missions [27]and [28], that intended to study airglow emission from O_2 molecules in the upper stratosphere (100 km).

4.1.5. *Earth radiation budget*

Earth radiation budget measurements are generally achieved using broadband radiometers measuring the intensity of the incoming and/or reflected solar (shortwave) radiation, as well as the outgoing thermal (longwave) radiation emitted from the Earth's surface and atmosphere, with high accuracy (i.e., 1σ rms $\sim$10 W/m^2 [86]). The trend seems to be towards the inclusion of hyperspectral capabilities, as described in the Decadal Survey CLARREO mission [80], although this particular mission was recently canceled due to budgetary restrictions [87]. With the loss of the Glory mission as well, the continuity of the Earth radiation budget measurements is compromised, which opens an opportunity for a gap-filler Cubesat-based mission.

Existing broadband radiometers typically use uncooled microbolometers (e.g., [86]), a technology which is likely to be compatible with the Cubesat standard. Current sensors are slightly bigger and more massive than required. For example, the ACRIM-III solar irradiance instrument measures 18.5 cm × 36 cm, weighs 10 kg, and consumes about 10 W on average [2,63].

No Cubesats have been developed at the moment that can provide accurate and reliable measurements of the Earth radiation budget. However, recent advances in uncooled microbolometers make us optimistic concerning the on-going miniaturization of such sensors.

4.1.6. Lightning detection

Originally, lightning data was retrieved from satellites carrying photodiodes [88]. Passive measurements in the very low frequency (VLF) spectral region were studied later [89]. More recently, it was proposed that lightning releases gamma ray bursts into the atmosphere, and the potential to design a space mission to study this phenomenon in more detail was studied. FireFly is a Cubesat mission that combines all of the above. FireFly will do remote sensing of lightning using photodiodes especially designed to study the effect of Terrestrial Gamma ray Flashes (TGFs) on lightning. In addition, the payload will also include a VLF receiver. The feasibility of high science return lightning detection from Cubesats will therefore be demonstrated once FireFly is successfully deployed.

4.2. Land

4.2.1. Land topography

State-of-the-art land topography missions use SAR interferometry, such as the SRTM mission [90] or the Tandem-X mission [91]. Spatial resolutions on the order of 30–90 m horizontally and ~10 m vertically are achieved. The next generation of altimetry missions will include laser altimeters to achieve cm-level precisions; see in particular the Decadal Survey LIST mission [92].

According to what has been found in the technology subsection, both SAR and laser altimetry requires power levels not achievable in the Cubesat context, and thus state-of-the-art land topography measurements are not realistically possible from Cubesats.

However, one potential opportunity for modest accuracy land topography from Cubesats would be the use of GNSS reflectometry, i.e., sensing GNSS signals reflected from land from different angles. Several teams in the world are currently doing research in this area, including universities such as Telecom BCN [93], space agencies like JPL [94], and private companies like SSTL [95]. However, the quality of altimetry observations over land from GNSS reflected signals is yet to be fully demonstrated.

4.2.2. Soil Moisture

Traditionally, soil moisture measurements were done using passive microwave radiometers (e.g., SMMR, SMMI, AMSR-E [96]) at relatively low frequencies, where the sensitivity to soil moisture is higher.

State-of-the-art soil moisture measurements from space are taken using a combination of active and passive microwave instruments together with advanced on-board data processing, typically in L-band. ESA recently launched the SMOS mission, an L-band 2D passive interferometer that will provide soil moisture images of ~30 km spatial resolution with 5% accuracy [97]. NASA's SMAP mission [98], currently in the latest development phases, features an active L-band radar and a passive L-band radiometer that share a common dish.

Active soil moisture measurements are not viable in Cubesats due to both size and power limitations, again with the potential exception of GNSS reflectometry, as explained before.

Soil moisture measurements in the thermal infrared provide another possibility that was demonstrated long ago, but their capacity to penetrate the soil is much smaller than that of microwave sensors, as soil penetration is inversely proportional to a certain power of frequency that depends on soil characteristics (e.g., square root of frequency). Thus, they can only provide an estimation of moisture in the first millimeters of soil surface, whereas MW measurements can provide up to a few centimeters of soil penetration [99]. Indeed, assuming a square root dependency there is a factor of 10 between the soil penetrations at 1 mm and 10 μm:

$$\frac{\delta_p(\lambda = 1\ \text{mm})}{\delta_p(\lambda = 10\ \mu\text{m})} = \left(\frac{10^{-3}}{10^{-5}}\right)^{0.5} = 10$$

4.2.3. Vegetation

The vegetation measurements with the longest heritage are perhaps spectral assessments of vegetation state and biomass, and more particularly Normalized Differential Vegetation Index (NDVI). NDVI measurements require a channel in the NIR and another one in the red region of the visible with moderate spatial and spectral resolutions. Traditionally, NDVI measurements were done with low spectral resolution radiometers such as LANDSAT/TM and NOAA/AVHRR [100] (~100–300 nm spectral resolution). Other vegetation parameters related to stress and chlorophyll, such as the transformed chlorophyll absorption in reflectance index/optimized soil-adjusted vegetation index (TCARI/OSAVI), or Photochemical Reflectance Index (PRI) are also computed from a combination a few channels in the VNIR. Leaf Area Index (LAI), and Chlorophyll content (C_{ab}) can be estimated from these three indices [101].

The next generation of vegetation instruments improved almost an order of magnitude in spectral resolution with MODIS [102] and VEGETATION (10–15 nm) [103]. Additional bands in the VNIR and SWIR can improve spectral vegetation measurements by providing for example atmospheric correction, or more spectral data for better vegetation classification.

As of August 2011, no Cubesats have done vegetation measurements. However, current miniature VNIR spectrometers such as the one CanX-2 carries do achieve the required spectral and spatial resolutions for NDVI measurements like the ones done by TM or AVHRR [100]. Similar techniques have been demonstrated in Unmanned Aerial Vehicles (UAV) as well [101]. Higher performance vegetation measurements (e.g., MODIS) including sensible imaging and hyperspectral capabilities are more difficult to achieve in a Cubesat-based mission, due to the trade-off between number of channels, spectral resolution, and swath in a very confined space.

In addition to NDVI and other spectral indices related to the state of the vegetation, structural parameters such as vegetation height or canopy density are also interesting for biomass calculations. State-of-the-art vegetation structure measurements are done through the use of SAR and lidars (for example the ESA BIOMASS mission features a P-band SAR [104], while the NASA DESDYNI mission includes an L-band SAR and a lidar [105]). However, as mentioned before, these technologies are out of the scope of Cubesats, and GNSS reflectometry appears to be the most advanced technology at the moment for an active measurement from a Cubesat.

4.2.4. Surface temperature

Remote sensing of land surface temperature from space has been traditionally done by measuring the radiance at a wavelength at which the atmosphere is essentially transparent, typically inside the so-called window region (8–12 μm). High radiometric accuracy (i.e., a small value of noise-equivalent power NEP or delta-temperature NEΔT), is needed in order to achieve accurate surface temperature measurements. Instruments like AVHRR, ASTER have followed this strategy. ASTER in particular has an NEΔT=0.3 K in all its TIR channels, with absolute accuracies ranging from 1 K to 3 K depending on the value of the temperature (best accuracy around 300 K) [106].

Although no Cubesats have performed surface temperature measurements, current uncooled or thermoelectrically cooled microbolometers can measure radiance with reasonable accuracy at medium spatial resolution in the desired spectral regions [107,108].

An alternative approach to measure surface temperature is to use a multispectral or hyperspectral microwave passive sounding instrument that includes transparent channels, e.g., AMSU [109]. A similar approach could be utilized with a Cubesat like Micromas, though the utility of this measurement has yet to be demonstrated.

4.3. Ocean

4.3.1. Ocean color

State-of-the-art ocean color retrieval from space requires high spectral resolution measurements in several bands in the UV, VIS, and NIR. Traditional ocean color algorithms such as the SeaWiFS algorithms described in [110] utilized only a few bands in the visible, namely 443, 490, 510, and 555 nm. UV and NIR bands were added subsequently with sensors like MODIS on EOS/Terra and Aqua, in order to improve distinction between phytoplankton and dissolved organic matter, and to add a more accurate atmospheric correction (absorption by water vapor, aerosols, ozone, and other trace gases) [111,112]. The spectral resolution required is on the order of 14 nm [113].

No Cubesats were found that perform ocean color measurements. However, state-of-the-art miniaturized spectrometers are compatible with the requirements laid out in the previous paragraph, as mentioned in the previous section. Different Cubesats flying on a train configuration could for example carry detectors on the different bands required for high accuracy ocean color retrieval.

4.3.2. Ocean altimetry

Ocean altimetry measurements with accuracies on the order of a few centimeters provide useful information for ocean current determination, sea level height, as well as bathymetry. Typically, ocean altimetry has been accomplished through real aperture radar altimeter such as ERS/RA, Envisat/RA-2 [114], or Topex/Poseidon [115].

Although there has been some effort from industry to miniaturize Ka-band radar altimeters [116], the miniaturization accomplished so far is not yet compatible with the Cubesat standard.

Once again, one option to explore is the use of reflected GNSS signals as exposed before for the case of land topography, with the additional benefit that GNSS reflectometry has better sensitivity over ocean than over land because the ocean is dark in the microwave regions [95]. For a detailed description of the application of GNSS reflectometry to ocean altimetry, see [93] or [94]. Note that the expected accuracies would be on the order of ~10 cm [117], far from the ~2–3 cm achieved by state-of-the-art altimeters [115,116]. Therefore, these sensors could be used for coarse spatial resolution measurements of sea level height, but probably not for finer measurements, unless the loss of accuracy is compensated by averaging out many samples in time, coming from a populated network of sensors. Another interesting possibility would be to use a disaggregation scheme in which the coarse frequent measurement from the Cubesat constellation is combined with a sparse, higher spatial resolution measurement to yield a data product with relatively good temporal and spatial resolution, similarly to what has been proposed for the SMOS mission [118]. A strategy based on a disaggregation scheme can be used in other applications as well: Cubesat-based architectures provide frequent low spatial resolution data, which can be complementary to sparser high resolution dataset achieved by larger sensors.

4.3.3. Ocean surface winds

Ocean surface wind speed and direction have been typically inferred indirectly from ocean surface roughness using active microwave scatterometers such as ERS/SCAT or QuikSCAT [119]. Expected enhancements include the use of on-board SAR data processing techniques to increase spatial resolution [120].

Passive microwave measurements in L-band, X-band, and K-band have also been known for years to be correlated to sea surface wind speed [121], and in the case of polarimetric measurements, to direction as well

[122,123]. The sensitivity to wind speed of active and passive approaches has been found comparable, or slightly favorable to passive measurements (1 m/s expected for CMIS for 1.6 m/s realized for QuikSCAT [124]), with an advantage in terms of spatial resolution for active measurements.

As explained in the technology subsection, active scatterometers are not a viable technology for Cubesats for the same reasons as radar altimetry, and GNSS reflectometry appears again to be the only viable option to replace them [95]. Polarimetric or multi-angular passive measurements using miniature microwave radiometers could be another viable option. The utility of such measurements is yet to be demonstrated.

4.3.4. Ocean surface temperature

Ocean surface temperature is a key parameter to study ocean thermohaline circulation. The techniques for measuring ocean surface temperatures are very similar to those mentioned for land surface temperature. High radiometric accuracy passive measurements in a transparent band of the thermal infrared region of the spectrum are required. Therefore, both microbolometers, and to a lesser extent millimeter wave sounders appear as viable options for retrieval of ocean surface temperature from Cubesats.

4.3.5. Ocean surface salinity

State-of-the-art ocean surface salinity measurements are performed with L-band passive radiometry, as demonstrated by ESA's SMOS [97] and NASA's Aquarius [125]. As in the case of soil moisture, sensitivity of thermal emissivity to ocean salinity is maximized in this spectral band.

The utility of GNSS reflectometry to complement L-band radiometry measurements of sea surface salinity has also been studied [126], although the size of GNSS receiver for reflectometry is still slightly bigger than allowed by the Cubesat requirements.

Finally, the dependence of TIR emissivity with sea surface salinity has also been characterized [127], which could be exploited by Cubesats carrying microbolometers to obtain salinity measurements. The utility of such measurements has not yet been demonstrated, the main concern being about the very low spectral resolution of bolometers.

4.4. Snow and ice

4.4.1. Ice sheet topography

Three approaches are used to obtain glacier and ice sheet topography from space. The first approach is to perform multiangular, multi-wavelength observation in the visible such as the High Resolution Stereoscopic (HRS) instrument on SPOT 5 [128]. While the spectral content does not pose a real problem for current Cubesat technology, the challenge is in the accurate control of the relative attitude of the satellites. Recent experiments at MIT with the Spheres picosatellites have demonstrated formation flying with high control precision (2 cm metrology resolution [129]).

The second approach is to use the same radar altimeter used for oceanography to obtain ice sheet topography data, like it has been done with RADARSAT [130]. The third and more modern approach is to use laser altimeters like ICESAT/GLAS [131]. As explained before, the last two options are not possible for Cubesat technology at this point.

4.4.2. Snow cover

Snow cover has traditionally been measured from space using multispectral passive microwave radiometry in the X and Ka bands with instruments like DSMP/SMM-I or SMMR [132]. Multi-spectral measurements in the visible and infrared have also been demonstrated that exploit ice absorption features such as the one at 1.03 μm (e.g., MODIS [133], AVIRIS [134]).

State-of-the-art snow cover measurements are typically X, Ku, or Ka-band SAR to achieve higher spatial resolutions – see for example ESA's CoReH2O and NASA's SCLP planned missions [135].

Finally, millimeter-wave measurements such as the ones performed by AMSU-A have been used to retrieve snowfall rates [136], which can be used to estimate snow cover.

No Cubesats have been found that measure snow cover. Although SAR is discarded, there is no apparent reason to discard VNIR spectrometers, or Ka band and millimeter wave passive radiometers, albeit the lower spatial resolution.

4.4.3. Sea ice cover

Similarly to snow cover, sea ice cover was traditionally measured using passive microwave radiometry. In addition, the utility of millimeter wave measurements up to 157 GHz for retrieval of ice cover was demonstrated on an airborne instrument [137]. Active measurements using SAR have also been proposed and explored.

Therefore, as in the case of snow cover, it would in principle be possible to do remote sensing of sea ice from space with Cubesats using millimeter-wave radiometers.

4.5. Gravity and magnetic fields

4.5.1. Gravity

There are several techniques for measuring the Earth's gravity field from space. The first one is the use of precise gradiometers like ESA's GOCE [138]. This option does not seem feasible for Cubesats as it requires extremely fine attitude control and a very low orbit that would necessitate a continuously operating propulsion system.

The second one is the use of accelerometers to measure the contribution of all non-conservative forces into the satellite motion, in order to retrieve a pure gravitational orbit that will provide an estimation of the gravity field. An example of this process is CHAMP [64]. This option appears as the most viable one, and as a matter of fact, accelerometers are currently being considered as a system sensor for the Iridium NEXT Hosted Payload program, due to the very wide applicability of gravity measurements in several Earth science disciplines (e.g., geodesy, ocean bathymetry, hydrology, or cryospheric sciences) [139].

Finally, inter-satellite ranging systems can also be used to retrieve very precisely the geoid (see for example NASA's GRACE mission [140]). This third approach poses two problems: first, the power constraints on the active ranging system; second, the attitude control accuracy.

4.5.2. Magnetic field

Measurements of the Earth's magnetic field are typically done using precise scalar and vector magnetometers (e.g., CHAMP [141], or SAC-C [142]). Current magnetometers are small and low in power and thus a Cubesat configuration could be designed.

A more modern approach is a cluster of satellites flying in formation like ESA's SWARM [143]. In this configuration, satellites flying side by side allow correction of some sources of error.

The simplest option for a Cubesat-based measurement of the Earth's magnetic field would be to use currently available flux gate magnetometers like the one used by the Ørsted mission [65]. However, this would require: (1) a long boom to separate the magnetometer from the spacecraft; (2) a high accuracy attitude determination and control system.

4.6. Disaster monitoring

Disaster monitoring is an extremely broad term encompassing natural catastrophes such as floods, fires, earthquakes, tsunamis, and volcanoes, as well as other disasters that benefit from a large field of view from space, e.g., nuclear disasters.

Most of these applications have a few common characteristics: they are related to phenomena occurring in very fast time scales on the order of the hour or tens of minutes; they occur at a regional scale, with relatively small spatial scale, on the order of tens of meters or less, even though we may want to capture regional events globally; they require some situational awareness, which translates into a reasonable swath; they typically have relatively low spectral content and resolution requirements, with a few channels in the visible and one in the infrared usually being sufficient, with the possible exception of fire monitoring which benefits greatly from a channel in the MIR.

Cubesat architectures represent the promise of affordable, global, sub-hour disaster monitoring. However, given the state-of-the-art of Cubesat technology, the combination of high spatial resolution and large swath together with the stringent data rate requirements seems infeasible.

Several Cubesats have been specifically designed for disaster monitoring. For example, the M-Cubed is designed to provide 200 m spatial resolution imagery in the visible [29]. Although M-Cubed lacks a channel in the NIR for atmospheric correction that would improve several disaster monitoring data products, other Cubesats such as Ion [27] and SwissCube [28] have proven that it is technologically possible for a Cubesat to incorporate a NIR band. Finally, QuakeSat is capable of monitoring and even predicting the presence of earthquakes by sensing Ultra Low Frequency waves [26].

4.6.1. Conclusion

In this section we have identified several potential opportunities for future Cubesat missions. These opportunities include missions to do atmospheric sounding, ocean color retrieval, vegetation measurements, and gravity measurements amongst others.

Table 3 presents a summary classification of the feasibility of the 21 measurements based on the findings of this section. This classification incorporates the information presented in Table 2 about technology readiness, and augments it with new insights from the scientific perspective. In particular, for each measurement parameter from the CEOS database, we provide: (a) one or several potential selected measurement concepts based on Cubesats (e.g., mm-wave atmospheric sounding, GNSS radio occultation); (b) a comparison of the scientific utility of the Cubesat-based concept with respect to existing traditional mission architectures (e.g., for atmospheric sounding, we compare the scientific utility of a constellation of Micromas-like Cubesats with that of POESS/AMSU-A); (c) an assessment of the readiness level of the Cubesat technology required to implement this concept; (d) an assessment of the maturity of the scientific principle to retrieve data from the proposed measurements (i.e., the maturity in the development of the necessary models and algorithms).

For scientific utility, three rubrics were used: "Comparable" to standard mission architectures, if the scientific data produced by the Cubesat architecture is expected to be of comparable utility to that of current traditional mission architectures when data quality and quantity are considered; "Marginal", if expected data utility is expected to be significantly lower than that of current traditional mission architectures; and "Lower" in all other cases in between.

Concerning the technology readiness level classification, the rubrics are: "Flight proven", if the technology has already been employed on Cubesats; "Unavailable", if the analysis predicts the almost certain unavailability of the technology in the next few years; and "In development" in all other cases in between, i.e., those in which the above analysis allows the prediction of availability in the near future with some confidence; Note the correspondence between these rubrics and the feasibility rubrics in Table 2.

Finally, for the scientific maturity of the proposed measurement, three rubrics are used: "Mature" denotes that the employed principle is well known and has already been successfully utilized for years with similar space-based data; "Exploratory" denotes that the proposed measurement principle readily exists on a theoretical basis, and some relevant validation has been done, but its general applicability has yet to be proven in flight. "Conceptual" is employed in cases where the measured data is expected to possibly contribute to a certain scientific output, but no experimental verification has been conducted yet.

Table 3
Preliminary assessment of the utility of Cubesat-based missions measuring different land, ocean, and atmospheric parameters.

Parameter	Selected measurement concepts	Utility compared to traditional architectures (comparable, lower, marginal)	Cubesat technology readiness (flight proven, in development, unavailable)	Scientific readiness (mature, exploratory, conceptual)	Justification
Aerosols	Uncooled miniature spectrometers (VNIR, with polarimetry and/or multi-angular measurements)	Lower	In development	Exploratory	[6]'
Atmospheric chemistry (ozone and trace gases)	Uncooled miniature spectrometers (UV+ SWIR)	Lower	In development	Mature	[62]
Atmospheric temperature and humidity fields	mm-wave atmospheric sounding/GNSS radio occultation	Comparable/lower	In development/flight proven	Exploratory/mature	[5,4]
Cloud properties, liquid water and precipitation	mm-wave atmospheric sounding	Lower	In development	Exploratory	[5]
Disaster monitoring	High resolution cameras	Comparable	In development	Mature	[29]
Earth radiation budget	Uncooled microbolometers	Comparable	In development	Mature	[86]
Gravity	Precise accelerometers	Comparable	Flight proven	Mature	[64]
Ice sheet topography	Uncooled miniature spectrometers (VNIR, with multi-angular measurements)	Marginal	In development	Mature	[4]
Land surface temperature	Uncooled microbolometers	Lower	In development	Mature	[107,108]
Land topography	GNSS reflectometry	Marginal	In development	Conceptual	[93]
Lightning detection	Photodiodes	Comparable	In development	Mature	[31]
Magnetic field	Vector magnetometers	Lower	Flight proven	Mature	[26]
Ocean altimetry	GNSS reflectometry	Marginal	In development	Conceptual	[95]
Ocean color	Uncooled miniature spectrometers (UV+VNIR)	Lower	In development	Mature	[4]
Ocean surface salinity	GNSS reflectometry	Lower	In development	Conceptual	[126]
Ocean surface temperature	Uncooled microbolometers	Lower	In development	Mature	[107,108]
Ocean surface winds	GNSS reflectometry	Lower	In development	Mature	[95]
Sea ice cover	mm-wave atmospheric sounding	Lower	In development	Exploratory	[136]
Snow cover	Uncooled miniature spectrometers (NIR)/mm-wave atmospheric sounding	Lower/lower	In development/In development	Mature/mature	[134,136]
Soil moisture	GNSS reflectometry	Lower	In development	Conceptual	[126]
Vegetation	Uncooled miniature spectrometers (VNIR)	Lower	Flight proven	Mature	[4]

If more than one measurement principle has been evaluated, the classification is based on the more promising candidates.

Note that this classification is based on many assumptions and simplifications, and therefore its contents should be treated as guidelines, rather than as absolute truth. Furthermore, some of the information in Table 3 is redundant with Table 2, but it is presented from the science perspective as opposed to the technology perspective, which adds new insight into it.

5. Conclusion and next steps

This paper started with a historical review of past and current Cubesat missions for Earth observation. From the plethora of Cubesat missions designed in the last decade, only nine missions were identified that perform or would perform Earth observation measurements other than space weather. These missions carry optical cameras, GNSS receivers for occultation measurements, photometers, and millimeter-wave sounders. The small number or missions, and the lack of variety in their payloads, are noticeable.

The reasons for that were analyzed in the survey of the capabilities of Cubesats for Earth observation missions. The major conclusions are not much of a surprise: the stringent mass and dimension requirements of the Cubesat bus translate into reduced mass, power, and data rate capabilities offered to payloads when compared to those of larger missions. Many of the currently used Earth observation payload technologies (SAR, lidar, high-resolution optical imagers, hyperspectral imagers) are simply not compatible with these constraints, as was shown from first principles in Section 3.

However, our analysis identified at least a few technologies that are likely to be compatible of these stringent constraints, and yet have not been used in any Cubesat mission so far. These technologies include spectrometers with limited imaging capability, precise accelerometers, and broadband radiometers. These technologies would enable a broad variety of measurements with high societal and scientific return including ocean color, ocean mass distribution, glacier mass distribution, vegetation state, and Earth radiation budget amongst others.

A Cubesat-based component having large constellations of Cubesats carrying these technologies and taking these measurements would be an extremely high value-added asset for the Earth Observing System-of-Systems (EOSS). First, such a system could take care of a fraction of the requirements for the EOSS, thus reducing the burden on larger satellites, and allowing them to focus on the highest performance missions, which Cubesats are incapable of. Second, it would help close some of the expected data gaps in key measurements (e.g., gravity measurements). And finally, they would provide unprecedented data products with very high temporal resolution and relatively high spatial resolution, which could potentially create new opportunities for science. In particular, such measurements could be combined with data products from higher performance instruments using disaggregation schemes.

It is well known that Cubesats are excellent platforms for education and technology demonstration. However, this paper supports the idea that they can be much more than that: they can be enabling instruments for a richer and more sustainable Earth science program. In particular, it is our hope that universities around the world that are planning to conceive, design, implement, launch, and operate Cubesats in the next few years will be inspired by some of the mission ideas proposed in this paper, and will make the decision of making a major contribution to science and society while educating their students.

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References

[1] Radio Corporation of America, Final Operational Report TIROS I Meteorological Satellite System, Princeton, NJ, 1960.
[2] H. Kramer, Observation of the Earth and its Environment, Springer-Verlag, Berlin, 2002.
[3] J. Bouwmeester, J. Guo, Survey of worldwide pico- and nanosatellite missions, distributions and subsystem technology, Acta Astronaut. 67 (7–8) (2010) 854–862.
[4] K. Sarda, et al., Canadian advanced nanospace experiment 2: scientific and technological innovation on a three-kilogram satellite, Acta Astronaut. 59 (1–5) (2006) 236–245.
[5] W.J. Blackwell, et al., Hyperspectral microwave atmospheric sounding, IEEE Trans. Geosci. Remote Sens. 49 (1) (2011) 128–142.
[6] M. Farison, K. Hicks, M. Schmidt, and S. Yang, Cloud CubeSat Thermoelectric Cooler Controller System, Baltimore, MD, 2010.
[7] A.S.-K. Pang, R. Twiggs, Citizen satellites, Sci. Am. 304 (2) (2011).
[8] R. Sandau, Status and trends of small satellite missions for Earth observation, Acta Astronaut. 66 (1–2) (2010) 1–12.
[9] A. Toorian, K. Diaz, and S. Lee, The CubeSat approach to space access, in: Proceedings of the 2008 IEEE Aerospace Conference, 2008, vol. 1, no. 1, pp. 1–14.
[10] B. Klofas, J. Anderson, and K. Leveque, A survey of CubeSat communication systems, in CubeSat Developers Conference, 2008.
[11] K. Woellert, P. Ehrenfreund, A.J. Ricco, H. Hertzfeld, Cubesats: cost-effective science and technology platforms for emerging and developing nations, Adv. Space Res. 47 (4) (2011) 663–684.
[12] S. Greenland and C. Clark, Cubesat platforms as an on-orbit technology validation and verification vehicle, in European Small Satellite Service Symposium, 2010.
[13] J.A. Schaffner and J. Puig-Suari, The electronic system design, analysis, integration, and construction of the Cal Poly State University CP1 CubeSat, in Proceedings of the 16th Annual AIAA/USU Small Satellite Conference, 2002.
[14] H. Kayal, F. Baumann, and K. Briess, BEESAT: a pico satellite for the on orbit verification of micro wheels, in: Proceedings of the 3rd International Conference on Recent Advances in Space Technologies, 2007, pp. 497–502.
[15] L. Johnson, M. Whorton, A. Heaton, R. Pinson, G. Laue, C. Adams, NanoSail-D: a solar sail demonstration mission, Acta Astronaut. 68 (5–6) (2011) 571–575.
[16] A. Scholz, W. Ley, B. Dachwald, J.J. Miau, J.C. Juang, Flight results of the COMPASS-1 picosatellite mission, Acta Astronaut. 67 (9–10) (2010) 1289–1298.
[17] J. Laberteaux, J. Moesta, B. Bernard, Advanced picosatellite experiment, IEEE Aerosp. Electron. Syst. Mag. 24 (9) (2009) 4–9.
[18] K. Can et al., ITU-pSAT I: Istanbul Technical University Student Pico-Satellite Program, in 3rd International Conference on Recent Advances in Space Technologies, 2007, pp. 725–732.
[19] T.C. Sorensen, M. Villa, and K.D. Brown, The Kansas Universities Technology Evaluation Satellite Program, in: Proceedings of the AIAA Space 2005 Conference & Exhibition, 2005.
[20] L. Alminde, M. Bisgaard, and D. Bhanderi, Experience and Methodology gained from 4 years of Student Satellite Projects, in: Proceedings of the 2nd International Conference on Recent Advances in Space Technology, 2005, pp. 94–99.
[21] F. Santoni, F. Piergentili, F. Graziani, Broglio Drag Balance for neutral thermosphere density measurement on UNICubeSAT, Adv. Space Res. 45 (5) (2010) 651–660.
[22] A. Elbrecht and S. Dech, 1U CubeSat design for increased power generation, in: Proceedings of the 1st IAA Conference on University Satellite Missions, pp. 1–7.
[23] S. Jarrix, et al., Robusta: un satellite pédagogique, J3eA: Journal sur L'enseignement des Sciences et Technologies de L'information et des Systemes 8 (1) (2009) Jan.
[24] A. Gregorio, T. Bernardi, S. Carrato, I. Kostadinov, M. Messerotti, and R. Stalio, AtmoCube: observation of the earth atmosphere from the space to study 'space weather' effects, in: Proceedings of the 1st International Conference on Recent Advances in Space Technologies, 2003, pp. 188–193.
[25] L. Dusseau et al., CUBESAT SACRED: a student project to investigate radiation effects, in: Proceedings of the 2005 Conference on Radiation Effects on Components and Systems, 2005, pp. 3–6.
[26] M. Long et al., A cubesat derived design for a unique academic research mission in earthquake signature detection, in: Proceedings of the 16th AIAA/USU Small Satellite Conference, 2002, pp. 1–17.
[27] G. Swenson, P. Thakker, F. Kamalabadi, M. Frank, V. Coverstone, and H. Voss, Optical sensing of atmospheric emissions with Cubesats and Nanosats, in: Proceedings of SPIE, 2007, vol. 6555, p. 655506.
[28] M. Noca et al., Lessons Learned from the First Swiss Pico-Satellite: SwissCube, in: Proceedings of the 23rd Annual AIAA/USU Conference on Small Satellites, 2009.
[29] K.A. Dontchev, K. Ghorakavi, C.E. Haag, T.M. Liu, and R. Ramos, M-Cubed: University of Michigan Multipurpose MiniSatellite with Optical Imager Payload, in: Proceedings of the AIAA Space 2010 Conference & Exhibition, 2010.
[30] J. Praks et al., AALTO-1 – an experimental nanosatellite for hyperspectral remote sensing, in: Proceedings of the 2011 IEEE International Geoscience and Remote Sensing Symposium, 2011.

[31] D.E. Rowland et al., The NSF Firefly CubeSat Mission: Rideshare Mission to Study Energetic Electrons Produced by Lightning, in: Proceedings of the 2011 IEEE Aerospace Conference, 2011.

[32] J. Bouwmeester, G.F. Brouwer, E.K.A. Gill, G.L.E. Monna, and J. Rotteveel, TU Delft, Design Status of the Delfi-Next Nanosatellite Project, in: Proceedings of the 61st International Astronautical Congress, 2010, pp. 1–13.

[33] K. Sarda, C. Grant, S. Eagleson, D. Kekez, and R. Zee, Canadian Advanced Nanosatellite Experience 2 Orbit Operations: Two Years of Pushing the Nanosatellite Envelope, in: Proceedings of the 61st International Astronautical Congress, 2010.

[34] T. Segert, S. Engelen, M. Buhl, and B. Monna, The Pico Star Tracker ST-200: a new approach in miniaturized star Sensor systems, in: Proceedings of the 1st IAA Conference on University Satellite Missions, 2011.

[35] A. Aydinlioglu and M. Hammer, COMPASS-1 pico satellite: magnetic coils for attitude control, in: Proceedings of the 2nd International Conference on Recent Advances in Space Technologies, 2005, pp. 90–93.

[36] F.M. Pranajaya and R.E. Zee, Advanced Nanosatellite Development at Space Flight Laboratory, in: Proceedings of the 1st IAA Conference on University Satellite Missions, 2011.

[37] Pumpkin Inc., Miniature 3-Axis Reaction Wheel & Attitude Determination and Control System for CubeSat Kit. [Online]. Available: 〈http://www.cubesatkit.com/docs/datasheet/DS_CSK_A DACS_634-00412-A.pdf〉. [Accessed: 25-Aug-2011].

[38] M. Pastena and J. Barrington, ADCS Subsystem for CubeSat: 3-axis high precision control in less than 0.5U, in: Proceedings of the 1st IAA Conference on University Satellite Missions, 2011.

[39] M. Schmidt and K. Schilling, A scheduling system with redundant scheduling capabilities, in: Proceedings of the 6th International Workshop on Planning and Scheduling for Space, 2009.

[40] California Polytechnic State University, CubeSat Design Specification, San Luis Obispo, CA, 2009.

[41] E.I. Reeves, Spacecraft Design and Sizing, in Space Mission Analysis and Design, 3rd edn., W. J. Larson and J. R. Wertz, (Eds.) Microcosm, 1999, pp. 301–352.

[42] D. Rankin, D. Kekez, R. Zee, F. Pranajaya, D. Foisy, a Beattie, The CanX-2 nanosatellite: expanding the science abilities of nanosatellites, Acta Astronaut. 57 (2–8) (2005) 167–174.

[43] S.D. Jong, R. Hamann, and E. Maddox, The Delfi-N3XT nanosatellite: space weather research and qualification of microtechnology, in: Proceedings of the 59th International Astronautical Congress, 2008.

[44] P.P. Sundaramoorthy, E. Gill, C.J.M. Verhoeven, and J. Bouwmeester, Two Cubesats with Micro-Propulsion in the QB50 Satellite Network, in: Proceedings of the 24th Annual AIAA/USU Conference on Small Satellites, 2010.

[45] J. Schein, A. Gerhan, F. Rysanek, and M. Krishnan, Vacuum arc thruster for cubesat propulsion, in: Proceedings of the 28th International Electric Propulsion Conference, 2003, vol. 100.

[46] F. Rysanek, J.W. Hartmann, J. Schein, and R. Binder, Microvacuum Arc Thruster Design for a CubeSat Class Satellite, in: Proceedings of the 16th Annual AIAA/USU Conference on Small Satellites, 2002, no. 217, pp. 1–7.

[47] D. Krejci and B. Seifert, Miniaturized pulsed plasma thruster for Cubesats: modelling and direct thrust measurement, in: Proceedings of the 61st International Astronautical Congress, 2010.

[48] D. Krejci, B. Seifert, and C. Scharlemann, Thrust measurement of a micro pulsed plasma thruster for Cubesats, in: Proceedings of the 1st IAA Conference on University Satellite Missions, 2011.

[49] P. Shaw, V. Lappas, and C. Underwood, Development of the μPPT propulsion module for STRaND a 3U CubeSat, in: Proceedings of the 1st IAA Conference on University Satellite Missions, 2011.

[50] F. Guarducci, M. Coletti, and S.B. Gabriel, Design and testing of a μPPT for Cubesat application, in: Proceedings of the 1st IAA Conference on University Satellite Missions, 2011.

[51] S. D'Amico, O. Montenbruck, Proximity operations of formation-flying spacecraft using an eccentricity/inclination vector separation,, J. Guidance Control Dyn. 29 (3) (2006) 554–563.

[52] K. Ravandoor, M. Drentschew, M. Schmidt, and K. Schilling, Orbit and drift analysis for swarms of picosatellites, in: Proceedings of the 1st International SPACE World Conference, 2010.

[53] E. Gill, P. Sundaramoorthy, J. Bouwmeester, B. Zandbergen, and R. Reinhard, Formation flying within a constellation of nano-satellites: the QB50 Mission, in: Proceedings of the 6th International Workshop on Satellite Constellation and Formation Flying, 2010.

[54] N.L. Johnson, E.G. Stansbery, The new NASA orbital debris mitigation procedural requirements and standards, Acta Astronaut. 66 (3–4) (2010) 362–367.

[55] C. Luecking, C. Colombo, and C. Mcinnes, A passive de-orbiting strategy for high altitude CubeSat missions using a deployable reflective balloon, in: Proceedings of the 8th IAA Symposium on Small Satellites for Earth Observation, 2011.

[56] M. Iai et al., A PDA-controlled pico-satellite, Cute-1.7, and its radiation protection, in: Proceedings of the 8th Annual AIAA/USU Conference on Small Satellites, 2004.

[57] R.J. Hamann, J. Bouwmeester, and G.F. Brouwer, Delfi-C3 Preliminary mission results, in: Proceedings of the 23rd annual AIAA/USU Small Satellite Conference, 2009.

[58] S. Jayaram, SLUCUBE: innovative high performance nanosatellite science and technology demonstration mission, Acta Astronaut. 65 (11–12) (2009) 1804–1812.

[59] S. Czernik, Design of the thermal control system for Compass-1, Diploma Thesis, 2004.

[60] G.H. Rieke, Detection of Light: From the Ultraviolet to the Submillimeter, Cambridge University Press, Cambridge, UK, 2003.

[61] R.K. Jagpal, B.M. Quine, H. Chesser, S.M. Abrarov, R. Lee, Calibration and in-orbit performance of the Argus 1000 spectrometer – the Canadian pollution monitor, J. Appl. Remote Sens. 4 (1) (2010) 049501.

[62] Marleen van Mierlo, K. Yoshihara, A. Ng, L.N. Phong, and F. Châteauneuf, Earth observation using Japanese/Canadian formation flying nanosatellites, in: Proceedings of the 7th IAA Symposium on Small Satellites for Earth Observation, 2010.

[63] R. Willson, The ACRIMSAT/ACRIM III experiment-extending the precision, long-term total solar irradiance climate database, Earth Obs. 13 (3) (2001) 14–17.

[64] P. Visser, Verification of CHAMP accelerometer observations, Adv. Space Res. 31 (8) (2003) 1905–1910.

[65] N. Olsen, New approaches to explore the Earth's magnetic field, J. Geodyn. 33 (1–2) (2002) 29–41.

[66] M. Dorrer, B. Laborde, P. Deschamps, DORIS (Doppler orbitography and radiopositioning integrated from space): system assessment results with DORIS on SPOT 2, Acta Astronaut. 25 (8–9) (1991) 497–504.

[67] M.D. King, Y.J. Kaufman, D. Tanré, T. Nakajima, Remote sensing of tropospheric aerosols from space: past, present, and future, Bull. Am. Meteorol. Soc. 80 (11) (1999) 2229–2260.

[68] P.-Y. Deschamps, et al., The POLDER mission: instrument characteristics and scientific objectives, IEEE Trans. Geosci. Remote Sens. 32 (3) (1994) 598–615.

[69] R.J. Peralta et al., Aerosol polarimetry sensor for the Glory Mission, in: Proceedings of SPIE, 2007, Vol. 6786, p. 67865L.

[70] D.M. Winker, et al., Overview of the CALIPSO Mission and CALIOP Data Processing Algorithms, J. Atmos. Oceanic Technol. 26 (11) (2009) 2310–2323.

[71] G. Chalon, F. Cayla, and D. Diebel, IASI- An advanced sounder for operational meteorology, in: Proceedings of the 52nd International Astronautical Congress, 2001.

[72] D. Blumstein, IASI instrument: technical overview and measured performances, in: Proceedings of SPIE, 2004, vol. 5543, p. 19.

[73] J. a Lerner, Temperature and humidity retrieval from simulated infrared atmospheric sounding interferometer (IASI) measurements, J. Geophys. Res. 107 (14) (2002) 1–11.

[74] H.H. Aumann and C.R. Miller, Atmospheric infrared sounder (AIRS) on the Earth observing system, in: Proceedings of SPIE, 1995, Vol. 2583, p. 332.

[75] H.H. Aumann, et al., AIRS/AMSU/HSB on the aqua mission: design, science objectives, data products, and processing systems, IEEE Trans. Geosci. Remote Sens. 41 (2) (2003) 253–264.

[76] E. Fetzer, et al., AIRS/AMSU/HSB validation, IEEE Trans. Geosci. Remote Sens. 41 (2) (2003) 418–431.

[77] J. Wickert, et al., Atmosphere sounding by GPS radio occultation: first results from CHAMP, Geophys. Res. Lett. 28 (17) (2001) 3263.

[78] R.K. Jagpal, B.M. Quine, H. Chesser, S.M. Abrarov, R. Lee, Calibration and in-orbit performance of the Argus 1000 spectrometer – the Canadian pollution monitor, J. Appl. Remote Sens. 4 (1) (2010).

[79] J. Schmetz, et al., Operational cloud-motion winds from Meteosat infrared images, J. Appl. Meteorol. 32 (7) (1993) 1206–1225.

[80] NRC Committee on Earth Science and Applications from Space, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, Washington DC, 2007.

[81] F.S. Solheim, J. Vivekanandan, R.H. Ware, C. Rocken, Propagation delays induced in GPS signals by dry air, water vapor,

hydrometeors, and other particulates, J. Geophys. Res. 104 (8) (1999) 9663–9670.
[82] J.B. Abshire et al., Laser sounder for global measurement the CO_2 concentrations in the Troposphere from space, in: Proceedings of the 2007 NASA Science Technology Conference, 2007, vol. 500.
[83] K.N. Liou, An Introduction to Atmospheric Radiation, 2nd edn., Elsevier Science, San Diego, CA, 2002.
[84] J.H. Seinfeld, S.N. Pandis, Atmospheric Chemistry and Physics – From Air Pollution to Climate Change, 2nd edn., John Wiley and sons, Hoboken, NJ, 2006.
[85] R.V. Kruzelecky et al., Advanced Microphotonic and MEMS Technologies for the MEOS Microsatellite Earth Observation Mission, in: Proceedings of the 2005 International Conference on MEMS, NANO and Smart Systems, 2005, pp. 255–260.
[86] K. Wallace, N. Wright,D. Spilling, K. Ward, and M. Caldwell The broadband radiometer on the EarthCARE spacecraft, in Proceedings of SPIE, 2009, vol. 7453, p. 74530H.
[87] T. Brinton, Two High-priority Climate Missions Dropped from NASA's Budget Plans, Space News, Feb-2011.
[88] B.N. Turman, Analysis of lightning data from the DMSP satellite, J. Geophys. Res. 83 (10) (1978) 5019–5024.
[89] S.A. Cummer, Lightning and ionospheric remote sensing using VLF / ELF radio atmospherics, PhD Thesis, 1997.
[90] J.J. van Zyl, The Shuttle Radar Topography Mission (SRTM): a breakthrough in remote sensing of topography, Acta Astronaut. 48 (5–12) (2001) 559–565.
[91] G. Krieger, et al., TanDEM-X: a satellite formation for high-resolution SAR interferometry, IEEE Trans. Geosci. Remote Sens. 45 (11) (2007) 3317–3341.
[92] A.W. Yu et al., Development of an airborne lidar surface topography simulator, in: Proceedings of the 2011 CLEO: Applications and Technology Conference, 2011.
[93] R. Acevo, A. Aguasca, E. Valencia, A. Camps, M. Vall-llossera, and U.P. De, Altimetry study performed using an airborne GNSS-reflectometer, in: Proceedings of the 2010 IEEE International Geoscience and Remote Sensing Symposium, 2010, pp. 3833–3836.
[94] S.T. Lowe, J.L. LaBrecque, C. Zuffada, L.J. Romans, L.E. Young, G.A. Hajj, First spaceborne observation of an Earth-reflected GPS signal, Radio Sci. 37 (1) (2002).
[95] S. Gleason, M. Adjrad, and M. Unwin, Sensing ocean, ice and land reflected signals from space: results from the UK-DMC GPS reflectometry experiment, in: Proceedings of the 2005 ION GNSS Technical Meeting, 2005, pp. 13–16.
[96] M. Owe, R. de Jeu, T. Holmes, Multisensor historical climatology of satellite-derived global land surface moisture, J. Geophys. Res. 113 (1) (2008) 1–17.
[97] H. Barre, B. Duesmann, Y.H. Kerr, SMOS: the mission and the system, IEEE Trans. Geosci. Remote Sens. 46 (3) (2008) 587–593.
[98] D. Entekhabi et al., The soil moisture active/passive mission (SMAP), in: Proceedings of the 2008 IEEE International Geoscience and Remote Sensing Symposium, 2008, vol. 3, p. III–1.
[99] J.C. Price, Estimation of regional scale evapotranspiration through analysis of satellite thermal-infrared data, IEEE Trans. Geosci. and Remote Sens. 20 (3) (1982).
[100] N.T. Boelman, The effect of spatial and spectral resolution in determining NDVI, in: Proceedings of the 2003 American Geophysical Union Fall Meeting, 2003.
[101] J. Berni, P.J. Zarco-Tejada, L. Suarez, E. Fereres, Thermal and narrowband multispectral remote sensing for vegetation monitoring from an unmanned aerial vehicle, IEEE Trans. Geosci. Remote Sens. 47 (3) (2009) 722–738.
[102] X. Xiong, N. Che, W.L. Barnes, Terra MODIS on-orbit spectral characterization and performance, IEEE Trans. Geosci. Remote Sens. 44 (8) (2006) 2198–2206.
[103] J. Durpaire, Spot-4 vegetation instrument: vegetation monitoring on a global scale, Acta Astronaut. 35 (7) (1995) 453–459.
[104] F. Heliere, C.C. Lin, F. Fois, M. Davidson, A. Thompson, and P. Bensi, BIOMASS: a P-band SAR earth explorer core mission candidate, in: Proceedings of the 2009 IEEE Radar Conference, 2009.
[105] R. Dubayah et al., Global vegetation structure from NASA's DESDynI Mission: an overview, in AGU Fall Meeting Abstracts, 2008, Vol. 1, p. 01.
[106] Y. Yamaguchi, a B. Kahle, H. Tsu, T. Kawakami, M. Pniel, Overview of advanced spaceborne thermal emission and reflection radiometer (ASTER), IEEE Trans. Geosci. Remote Sens. 36 (4) (1998) 1062–1071.
[107] F. Niklaus, C. Vieider, and H. Jakobsen, MEMS-based uncooled infrared bolometer arrays: a review, in: Proceedings of SPIE, 2007, vol. 6836, p. 68360D-68360D-15.
[108] H. Geoffray, Uncooled infrared microbolometer arrays for Earth remote sensing, in: Proceedings of SPIE, 2000, Vol. 4130, p. 527.
[109] F. Karbou, E. Gerard, F. Rabier, Microwave land emissivity and skin temperature for AMSU-A and B: assimilation over land, Q. J. R. Meteorol. Soc. 132 (620) (2006) 2333–2355.
[110] J.E. O'Reilly, et al., Ocean color algorithm for SeaWIFS, J. Geophys. Res. 103 (11) (1998) 24937–24953.
[111] H.R. Gordon, M. Wang, Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: a preliminary algorithm, Appl. Opt. 33 (3) (1994) 443–452.
[112] V. Kulkarny et al., The impact of VIIRS polarization sensitivity on ocean color, in: Proceedings of the 2010 IEEE International Geoscience and Remote Sensing Symposium, 2010, pp. 220–223.
[113] C.O. Davisa, M. Kavanaugha, R. Leteliera, W.P. Bissettb, and D. Kohlerb, Spatial and spectral resolution considerations for imaging coastal waters, in: Proc. of SPIE 6680, 2007, Vol. 6680, p. 66800P–1.
[114] C. Zelli, A. Aerospazio, ENVISAT RA-2 advanced radar altimeter: instrument design and pre-launch performance assessment review, Acta astronaut. 44 (7–12) (1999) 323–333.
[115] R. Cheney, L. Miller, R. Agreen, N. Doyle, J. Lillibridge, TOPEX/POSEIDON: the 2-cm solution, J. Geophys. Res. 99 (12) (1994) 24555–24563.
[116] J. Richard, V. Enjolras, L. Rys, J. Vallon, I. Nann, and P. Escudier, Space altimetry from nano-satellites: payload feasibility, missions and system performances, in: Proceedings of the 2008 International Geoscience and Remote Sensing Symposium, 2008, vol. 3, no. 5, p. III–71-III-74.
[117] S.C. Wu, L.J. Romans, and L.E. Young, A novel GPS-based sensor for ocean altimetry, in: Proceedings of the 1998 IEEE International Geoscience and Remote Sensing Symposium, 1998, vol. 4, p. 818.
[118] O. Merlin, A.G. Chehbouni, Y.H. Kerr, E.G. Njoku, D. Entekhabi, A combined modeling and multispectral/multiresolution remote sensing approach for disaggregation of surface soil moisture: application to SMOS configuration, IEEE Trans. Geosci. Remote Sens. 43 (9) (2005) 2036–2050.
[119] Y. Quilfen, C. Prigent, B. Chapron, a a Mouche, N. Houti, The potential of QuikSCAT and WindSat observations for the estimation of sea surface wind vector under severe weather conditions, J. Geophys. Res. 112 (9) (2007) 1–18.
[120] E. Rodriguez et al., A scatterometer for XOVWM, the extended ocean vector winds mission, in: Proceedings of the 2009 IEEE Radar Conference, 2009.
[121] J. Hollinger, Passive microwave measurements of sea surface roughness, IEEE Trans. Geosci. Electron. 9 (3) (1971) 165–169.
[122] S.H. Yueh, W.J. Wilson, S.V. Nghiem, F.K. Li, and W.B. Ricketts, Polarimetric passive remote sensing of ocean wind vectors, in: Proceedings of the 1994 IEEE International Geoscience and Remote Sensing Symposium, 1994, vol. 4, pp. 2416–2418.
[123] G. Lin, L. Li, P. Weiser, Sea ice retrievals from windsat data, IEEE Trans. Geosci. Remote Sens (2006) 730–733.
[124] S. Gasster and G.M. Flaming, Overview of the conical microwave imager sounder development for the NPOESS program, in: Proceedings of the 1998 IEEE International Geoscience and Remote Sensing Symposium, 1998, vol. 1, p. 268.
[125] D.M. Le Vine, G.S.E. Lagerloef, F.R. Colomb, S.H. Yueh, F. a Pellerano, Aquarius: an instrument to monitor sea surface salinity from space, IEEE Trans. Geosci. and Remote Sens. 45 (7) (2007) 2040–2050.
[126] a Camps, et al., PAU in SeoSAT: a proposed hybrid L-band microwave radiometer/GPS reflectometer to improve sea surface salinity estimates from space, 2008 Microwave Radiom, Remote Sens. of the Environ. (1) (2008) 1–4 Mar.
[127] S.M. Newman, J. a Smith, M.D. Glew, S.M. Rogers, J.P. Taylor, Temperature and salinity dependence of sea surface emissivity in the thermal infrared, Q. J. R. Meteorol. Soc. 131 (610) (2005) 2539–2557.
[128] J. Korona, M. Bernard, E. Belin, F. Remy, Topography of glaciers and ice caps with spot 5 h, Int. Arch. Photogramm., Remote Sens. Spat. Inf. Sci. XXXVII (8) (2008) 1425–1430.
[129] D. Miller et al., SPHERES: a testbed for long duration satellite formation flying in micro-gravity conditions, in: Proceedings of the 2000 AAS/AIAA Space Flight Mechanics Meeting, AAS 00, 2000, vol. 110, pp. 23–26.
[130] R.K. Raney, A.P. Luscombe, E.J. Langham, S. Ahmed, RADARSAT, Proc. of the IEEE 79 (6) (1991) 839–849.
[131] B.E. Schutz, H.J. Zwally, C. a Shuman, D. Hancock, J.P. DiMarzio, Overview of the ICESat Mission, Geophys. Res. Lett. 32 (21) (2005) 1–4.

[132] N.C. Grody, a N. Basist, Global identification of snowcover using SSM/I measurements, IEEE Trans. Geosci. Remote Sens. 34 (1) (1996) 237–249.
[133] D. Hall, MODIS snow-cover products, Remote Sens. Environ. 83 (1–2) (2002) 181–194.
[134] A.W. Nolin, Snowcover mapping with the airborne visible/infrared imaging spectrometer, in Proceedings of the 1994 International Geoscience and Remote Sensing Symposium, 1994, Vol. 4, pp. 2081–2083.
[135] H. Rott, et al., Cold regions hydrology high-resolution observatory for snow and cold land processes, Proc. of the IEEE 98 (5) (2010) 752–765.
[136] C. Surussavadee, D.H. Staelin, Satellite retrievals of Arctic and Equatorial rain and snowfall rates using millimeter wavelengths, IEEE Trans. Geosci. Remote Sens. 47 (11) (2009) 3697–3707.
[137] T.J. Hewison, S.J. English, Airborne retrievals of snow and ice surface emissivity at millimeter wavelengths, IEEE Trans. Geosci. Remote Sens. 37 (4) (1999) 1871–1879.
[138] A. Albertella, F. Migliaccio, F. Sansó, GOCE: the earth gravity field by space gradiometry, Celestial mechanics and dynamical astronomy 83 (1) (2002) 1–15.
[139] O.P. Gupta and C.S. Fish, Iridium NEXT: a global access for your sensor needs, in: Proceedings of the 2010 American Geophysical Union Fall Meeting, 2010.
[140] J. Kim, S.W. Lee, Flight performance analysis of GRACE K-band ranging instrument with simulation data, Acta Astronaut. 65 (11–12) (2009) 1571–1581.
[141] S. Maus, et al., Fifth-generation lithospheric magnetic field model from CHAMP satellite measurements, Geochem. Geophys. Geosyst. 8 (5) (2007).
[142] R. Colomb, C. Alonso, I. Nollmann, SAC-C mission and the international am constellation for earth observation, Acta Astronaut. 52 (9–12) (2003) 995–1005.
[143] E. Friis-Christensen, H. Luhr, G. Hulot, Swarm: a constellation to study the Earth's magnetic field, Earth Planets Space 58 (4) (2006) 351–358.