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CONDITIONS AND APPLICATION DOMAINS FOR POCKETQUBES

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ABSTRACT

PocketQubes are a new form factor of highly miniaturized satellites with a body of one or more cubic units of 5 cm. The characteristics of PocketQubes in terms or legal and regulatory aspects, the technological readiness levels and financial considerations are assessed. In particular, an analysis of orbital decay characteristics has been carried out which together with existing space law suggest that PocketQubes should preferably be launched in very low Earth orbits below 500 km altitude. To make PocketQubes attractive platforms, not only the launch cost, but also the development, production and operations cost should be significantly lower than CubeSats . Due to technical constraints, such as form factor, power and attitude control, the domain of applications is, especially for single PocketQube mission constrained. Still, they can act as low cost training or technology demonstration platforms. When launched in high numbers, networks of PocketQubes can enable new applications for Earth observation and niche communication services. Applications considered feasible are in the field of (but not limited to) continuous surveillance using optical instruments, gravity field monitoring using precise orbit determination, in-situ measurements of the space environment and low data rate or bandwidth communication services.

1 INTRODUCTION

PocketQubes have been introduced by Prof. Bob Twiggs in 2009 [1]. They are satellites comprising of one or more cubic units of 5 cm and with a maximum mass of 250 g per unit. The number of units is typically presented with suffix ‘p’ instead of ‘U’ as for CubeSats. The original idea was that 8 PocketQubes would fit in a single unit CubeSat (in 2 x 2 x 2 configuration) and could be deployed through existing CubeSat deployers. A cooperation between Morehead State University and GAUSS Srl. has led to the development of a dedicated PocketQube deployment system (MRFOD). Instead of using the corners to slide in the deployment system, like for CubeSats, a baseplate extending a few millimetres from the main body is used which slide in guide rails of the PocketQube deployer. This concept is used for the launch of the first four PocketQubes in 2013 and is currently used by the majority of PocketQube developers as de facto standard. Given this deployment system and the additional external envelope, PocketQubes cannot be economically fitted into CubeSat deployers anymore. A publicly available mechanical standard definition document is still lacking, but is currently in development and expected to be released in 2018.

Delft University of Technology is currently developing a 3p PocketQube called Delfi-PQ. A bottoms-up iterative development approach is implemented to improve and demonstrate PocketQube capabilities [2]. Meanwhile, the potential of operational applications with PocketQubes is currently investigated to provide a vision and long term technology development roadmap. This paper provides the first results of this investigation.

At present, the pioneers developing PocketQubes perform research on the limits of satellite miniaturization and use the platform for small satellite technology demonstration. On the long term the sustainability of PocketQubes requires a clear advantage in terms of financial cost effectiveness compared to larger satellites for scientific or commercial applications. In terms of quantity, CubeSats are currently dominant and there is a very good availability of CubeSat components, subsystems or even complete spacecraft busses. For PocketQubes, the investments needed to achieve a similar maturity demands not only a bottoms-up technology development but also on an outlook towards future applications.

This paper provides the boundary conditions for a sustainable future for PocketQubes in terms of legal, regulatory, technical aspects and financial aspects. Also the application domains for PocketQubes are discussed and several examples are provided which look worthy of further investigation. In chapter 2 the conditions for PocketQubes are presented and in chapter 3 potential applications are presented, followed by final conclusions in chapter 4.

2 CONDITIONS FOR POCKETQUBES

2.1 Legal & Regulatory Guidelines

Most promising opportunities for applications of PocketQubes are in vast distributed networks. A very important aspect related to this is their risk of contributing to space debris. The Inter-Agency Space Debris Coordination Committee (IADC) stated in 2007: “This IADC and some other studies and a number of existing national guidelines have found 25 years to be a reasonable and appropriate lifetime limit.” [3].

The orbital lifetime has been analysed using the free ESA-DRAMA software tool [4]. First, the effective cross-section in the flight direction has been calculated using the CROC module within the tool. Analysis has been performed on 1p, 2p and 3p satellites with solar panel configurations ranging from solely body mounted up to four-folded solar panel wings. It is expected that deployable solar panels are used on advanced PocketQubes with some form of attitude control for which a uni-directional solar array would be most advantageous. Figure 1 and Figure 2 show the 3D models as used in the CROC module for the most minimalistic and extreme configuration respectively. The solar panels are 2mm smaller (in both dimensions) than the sides of the satellite body. The results are presented in Table 1.

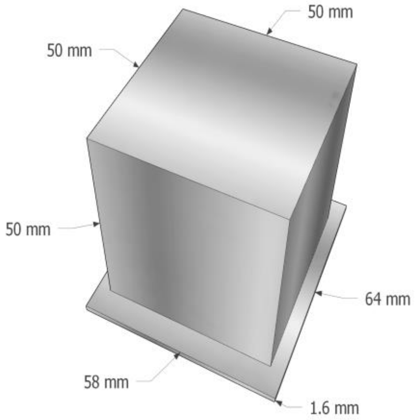

Figure 1. 1p PocketQube with body mounted solar cells

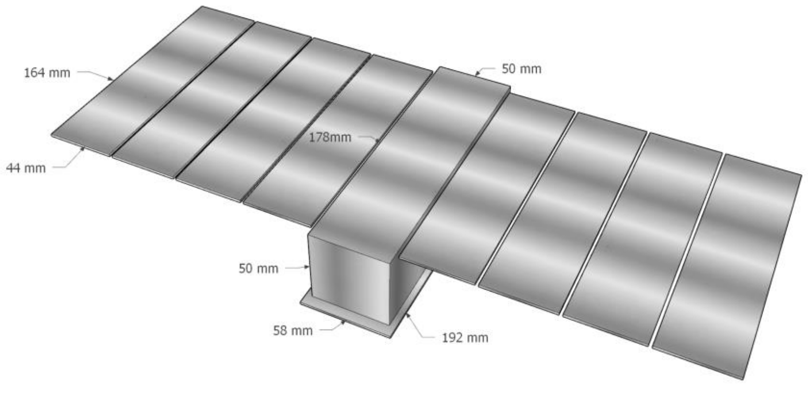

Figure 2. 3p PocketQube with two quadruple solar panel wings

Table 1. Cross Section Area for Different PocketQube Configurations

Satellite Configuration		**Calculated Effective Cross Section Area [m^2]**		
Unit Size	**Solar Panel Configuration**	**Minimum**	**Geometric Average**	**Maximum**
1p	body mounted	0.0029	0.0042	0.0048
	single panel wings	0.0030	0.0057	0.0075
	dual panel wings	0.0031	0.0077	0.0112
	triple panel wings	0.0031	0.0096	0.0150
	quadruple panel wings	0.0031	0.0117	0.0189
2p	body mounted	0.0033	0.0076	0.0092
	single panel wings	0.0035	0.0108	0.0156
	dual panel wings	0.0037	0.0150	0.0244
	triple panel wings	0.0039	0.0194	0.0332
	quadruple panel wings	0.0041	0.0239	0.0420
3p	body mounted	0.0038	0.0109	0.0138
	single panel wings	0.0039	0.0160	0.0244
	dual panel wings	0.0041	0.0228	0.0387
	triple panel wings	0.0043	0.0300	0.0531
	quadruple panel wings	0.0045	0.0373	0.0674

As can be seen in Table 1, there is a large spread in effective cross section (drag) area depending on the satellite configuration as well as its attitude. The minimum drag area can be achieved with attitude control in order to extend the orbital life time. Likewise, attitude control can be used to maximize the drag for a de-orbit at the end of the operational lifetime. Since active de-orbit manoeuvres are complex and it can be expected that some PocketQubes may fail prematurely, the best way to assess the orbital life time with respect to space debris mitigation is the non-operational case. In this case, the satellite is expected to be freely tumbling around an arbitrary axis, for which the geometric average drag area can be used. Next to the drag area, the mass of the satellite is an important parameter for the orbital lifetime. The maximum mass per PocketQube unit is 250 g as defined in the to-be-released standard. The minimum is assumed to be at least 125 g per unit for a satellite without deployable panels and an additional 8 g per unit per panel. The maximum mass-over-area ratio is found to be 69 kg/m^2 for a 3p PocketQube with body mounted solar cells and a mass of 750 g in de randomly tumbling scenario. The minimum case is 15 kg/m^2 for a 3p PocketQube with two quadruple panel wings (see Figure 2) and a mass of 567 g. With these values, the orbital life time for circular orbits is predicted using the OSCAR module of the ESA-DRAMA tool. A final important input parameter is the launch date since atmospheric densities in low Earth orbit are varying due to the 11-year solar cycle. A sensitivity analysis was carried out which revealed that a launch at the 01-01-2019 provides average results on orbital life-time, while launch dates on 01-01-2024 and 01-01-2028 provides results which are near the lower and upper orbital life time, respectively. Figure 3 provides the results for both the minimum and maximum mass-over-area cases for the three different launch dates.

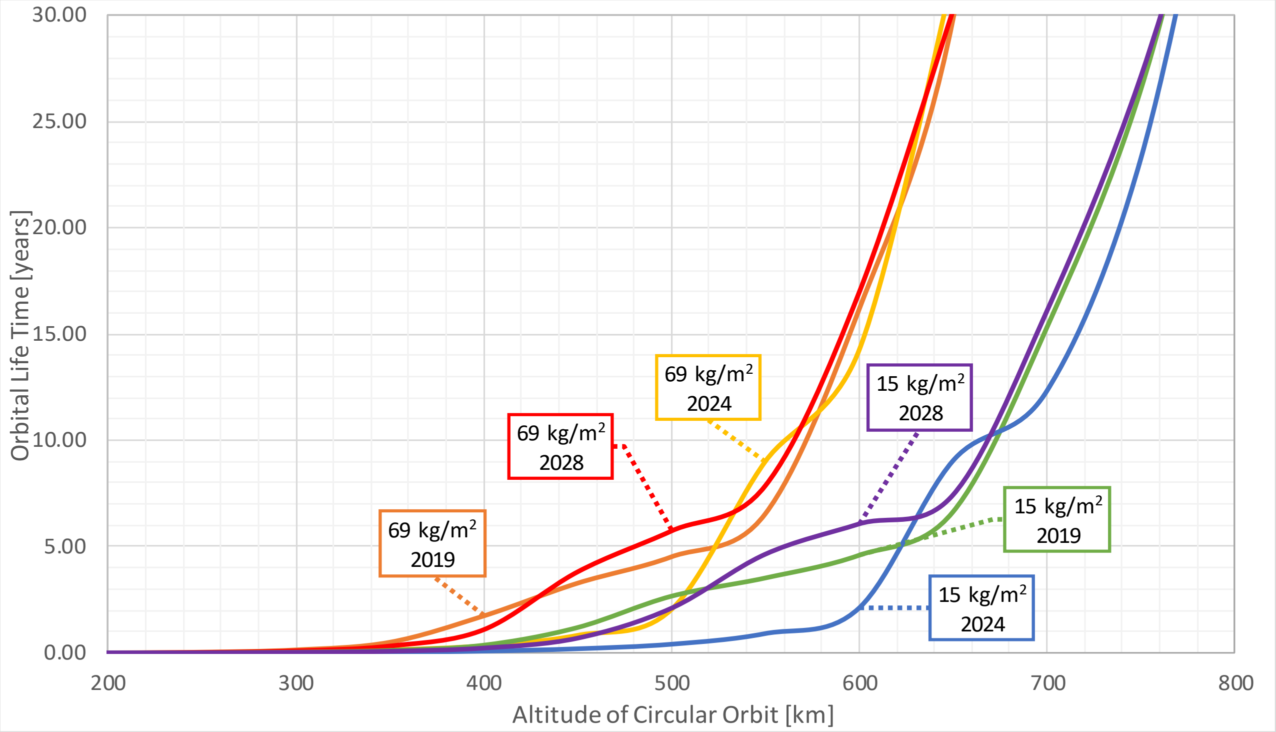

Figure 3. Orbital life time predictions for PocketQubes ejected into circular orbits

As can be concluded from the results presented in Figure 3, a maximum orbital life time of 25 years for PocketQubes can only be guaranteed for circular orbits lower than 630 km altitude. As the guideline of 25 years has been established before the rapid growth of very small satellite and the emerging plans for mega-constellations, it can be expected that this guideline will be revised in the near future. The authors of this paper therefore propose to implement a maximum orbital of approximately 5 years, which yields a maximum of 480 km altitude for circular orbits.

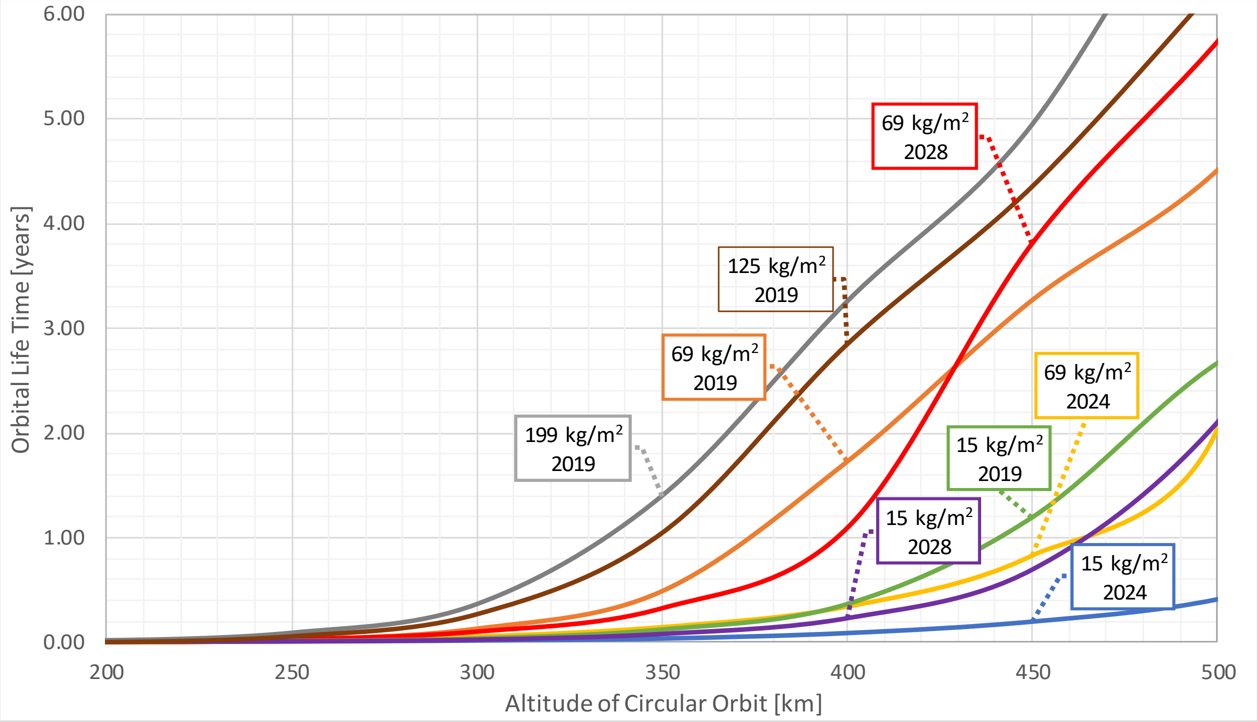

Figure 4. Orbital life time predictions for PocketQubes ejected into circular orbits (zoomed in)

Figure 4 provides a zoomed-in graph. In this figure also the orbital life time of the two satellite configurations are presented in case active attitude control is used to minimize the drag over the operational life time. For education and technology demonstration, orbital lifetimes of 3 months to 2 years would be appropriate For scientific and commercial missions of very small satellites, life times between 1 and 7 years would be appropriate. However, it would be acceptable that active orbit maintenance using on-board propulsion would be required to extend the natural lifetime. Because of the low natural orbital life time of Very Low Earth Orbits (VLEO) below 400 km, this orbital regime is not densely populated with space objects as shown in Figure 5. Therefore, the ideal orbital regime for PocketQubes is between 300 km and 400 km altitude for circular orbits. For elliptical orbits it can be stated that the orbital lifetime is always lower than for a circular orbit with the same semi-major axis. If the mean of apogee and perigee is below 500 km, a maximum orbital lifetime of 5 years is guaranteed.

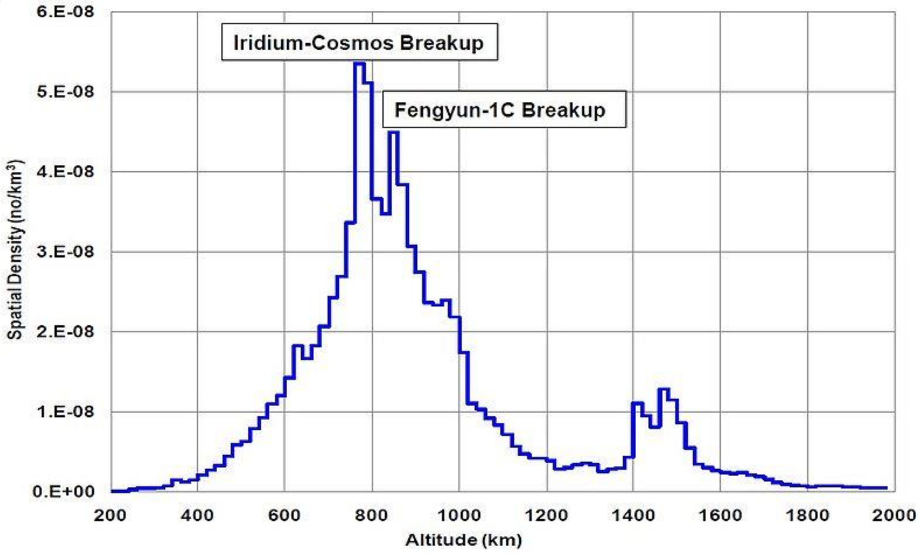

Figure 5. Density of space objects versus altitude, NASA (CC-PD) [3]

Next to orbital life time, the observability by radar facilities (such as from NORAD) is important as these systems are used to track satellite orbits and calculate collision risks between satellites. Public repositories such as Celestrak provide the tracked orbital parameters by these facilities in the form of Two-Line-Elements (TLEs). A recent study has been performed on the trackability of PocketQubes [5].The four launched PocketQubes are in a near-circular orbit of approximately 600 km altitude. All four have been tracked successfully and TLEs have been updated several times per day. However, PocketQubes show a higher covariance between subsequent TLEs compared to larger satellites in similar orbits. Thus, the accuracy of orbit determination with radar detection reduces with spacecraft size. This would also yield a lower accuracy in predicting potential orbital collisions. A lower orbit will, however, increase the observability by radar facilities on the ground. The reflected radar signal is linearly proportional to the effective radar cross-section of the object and inversely proportional to the 4th power of the distance (which would be altitude in zenith direction). Although further study should provide evidence, a simple theoretical approach would mean that a single unit PocketQube at 400 km has similar observability to a single unit CubeSat at 600 km. This would again be an argument to launch PocketQubes in the propose orbital regime of 300 to 400 km altitude.

2.2 Technical Limits and Considerations

The PocketQube is first of all volume- and mass-constraint. Based on a mechanical interface standard which will soon be released, the maximum mass per PocketQube unit is 250 g compared the 1.33 kg of the CubeSat mechanical interface standard [6], a ratio of approximately five. The volume of a 1U CubeSat is 1000 cm^3 and for a 1p PocketQube this is 125 cm^3, yielding a ratio of eight. However, the allowed thickness of external components and the stand-off distance between single unit satellites outside the main body is for both type of satellites 6.5-7.0 mm for all sides and is thus not scaled. For multiple unit satellites, the stand-off distance is accumulated in the internal body volume. Taking the external volume as reference, the practical volume ratio between CubeSats and PocketQubes would be slightly below six. Considering that PocketQube deployers cannot be scaled down linearly in terms of volume and mass compared to CubeSat deployers as well, it can be assumed that one can launch about four times the number of PocketQubes compared to CubeSats in an allocated launch vehicle (slot). This is ratio is a factor two less than the original concept of PocketQubes.

It should be noted that trading PocketQubes against its larger CubeSat brother will only make sense if the required subsystems and the intended payload do fit in a PocketQube. If the latter is not the case, the PocketQube is simply discarded as an option and only the larger platforms can be considered. This may seem trivial, but it means that one cannot just simple take an existing mission concept for CubeSats (or larger) and trade the utility indicators of a single satellite for a larger number of satellites.

Next to mass and volume, power is an important technical consideration as well. The orbit average available power for a PocketQube can be just a few hundred milli-Watts for a 1p body-mounted solar panel configurations up to values beyond 10 Watts for a sun-pointed multi-foldable solar array on a 3p PocketQube. Compared to CubeSats, the amount of available power is, based on basic scaling laws, approximately four times less for similar solar panel configurations and the same number of units.

Communication downlink is typically limited by the amount of power. When all other radio link parameters are equal, there is a linear relationship between radio transmission energy and the achievable downlink volume. If the utility of the satellite scales with the amount of data which can be downlinked, this would mean that the utility of a single 1p PocketQube is approximately one fourth of that of 1U CubeSat. Considering that the same ratio applies to number of PocketQubes which can be launched compare to the number of CubeSats, the effect of the technical trade-off between the two platforms for networks of satellites would be neutral from a utility perspective, provided that all subsystems and payload can be fitted on both platforms.

Active thermal control on PocketQubes is very challenging due to the limited available power. With passive thermal control it is possible to limit the cold and hot temperatures for typical operational ranges for electronic components. Active cooling for instruments is very difficult to achieve with PocketQubes.

Potential payloads are constrained by the volume of the PocketQube. This poses physical boundaries on what can be measured, for instance on the signal-to-noise ratio and the resolution. For optical instruments, the diffraction limit is provided by Eq. 1.

$$\theta_{min} = asin\left(1.22\frac{\lambda}{D}\right) \qquad (1)$$

where:
θ_{min} is the diffraction limited angular resolution
λ is the wavelength
D is the diameter of the entrance pupil (aperture) of the imaging lens

The aperture for a PocketQube camera would practically be limited to approximately 4 cm. However, the limited length of the optics inside the camera can also be a driving factor which may lead to an even smaller achievable aperture. In Figure 6, the diffraction limited Ground Sampling Distance (GSD) is provided for a 2 cm and 4 cm aperture camera for at 300 km and 400 km altitude looking in zenith direction. The achievable GSD is approximately half of what can be achieved with a linearly scaled CubeSat camera at the same orbit.

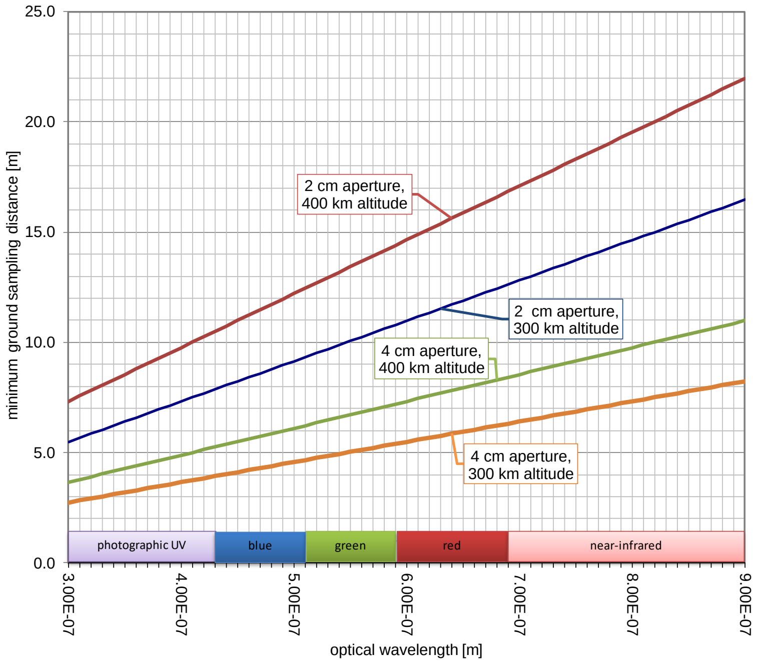

Figure 6. Ground sampling distance of diffraction limited cameras

Given a maximum total launch volume and/or mass, the advantage of the PocketQubes could be that it provides more simultaneous measurements (for in-situ monitoring). As long as all payload data can be downlinked by each PocketQube, there will not be any penalty. If this is not the case, the utility of the mission is a trade between the number of simultaneous measurements (satellites) versus the amount or rate of sequential measurements which can be downlinked. Likewise, temporal resolution of Earth observation of the same areas on Earth can be increased with PocketQubes compared to CubeSats, potentially at cost of the amount of coverage due to reduced downlink volume per satellite. For single satellite PocketQube missions there is no technical advantage over CubeSats. They can, at best, be equal if the utility of the satellite is not limited by the size of the PocketQube in any way (mass, volume, data downlink, duty cycle, etc.).

2.3 Financial Conditions

According to a study in 2014 on small launch vehicle, the specific launch cost to LEO ranges from 7 kUSD/kg (~5 k€/kg) for a PSLV-CA launch to 45 kUSD/kg (~33 k€/kg) for a Pegasus XL launch [7]. These are gross prices based on the total mass capacity. For PocketQubes and CubeSats, the actual price will also be based on the mass of the deployer, the administrative overhead at the launch provider and the services provided by the any intermediary parties (launch brokers / service providers). According to the same study, the launch of a 3U Cube. Sat in a P-POD on an Athena-IIc launch vehicle is 300 kUSD fir a 5kg 3U CubeSat, yielding a net satellite specific launch cost of 60 kUSD/kg, while the gross specific launch cost for this vehicle is specified to be 20 kUSD/kg [7]. Emerging very small launch vehicles, such as the Vector-R and the Electron are estimated (based on information in public announcements) to provide launch at gross specific cost of 25 kUSD/kg. This is significantly higher than for the medium class PSLV. However, since these vehicles can launch CubeSats and/or PocketQubes only, it is expected that the administration, handling, safety procedures and services can be tailored and optimized such that the net specific cost per satellite will approach similar figures as for larger launch vehicles. At the PocketQube workshop held in 2018 in Delft, the prices presented for PocketQube launches were 20 k€ per unit. With a maximum mass of 250 g per unit, this yields a net specific launch cost of 80 k€/kg (~100 kUSD/kg as of April 2018). This is slightly higher than the specific launch cost for CubeSats, which can be explained by the fact that administrative overhead and services does typically not scale down linearly with satellite mass. There are several ways to achieve a lower launch cost per PocketQube unit:

- Optimizing the mass of a (containerized) deployment system with respect to the satellite mass. This could potentially be achieved by batch deployment systems (e.g. a 96p deployer as proposed by Alba Orbital Ltd.)
- Standardizing and automating launch procurement, administration and pre-launch procedures to reduce overhead and service cost.
- Increased competition in the field of (small) launch vehicles, driving down the gross specific launch cost.

Depending on the success and implementation on the developments described above, it is expected that the net specific cost for PocketQubes of 40 k€/kg (50 kUSD/kg) should be feasible in the future. This would yield 10 k€ (13 kUSD) per PocketQube unit. The ideal ratio of launch cost between CubeSats and PocketQubes would be a factor four based on the effective volume and mass ratio provided in section 2.2.

The launch cost is part of the overall mission cost. The potential utility of PocketQubes per satellite is smaller than that of CubeSats as explained in the previous section. When PocketQubes have grown beyond their infancy and reached a maturity level comparable to CubeSats, satellite developers will be required to select the appropriate size of satellite to maximize the cost in relation to the utility. A paper on ‘right-sizing small satellites’ has investigated this [8]. According to D. Barnhart: “A concerning trend in small satellite industry is our fixation on a particular small satellite standard, namely the 3U CubeSat. While the 3U CubeSat is an excellent choice when the payload can readily fit without modification, the mission cost can skyrocket when the payload is purposefully miniaturized to fit 3U CubeSat. The primary author has personally witnessed several payload development programs with this aim. The result, in every case, was program failure. These efforts to force-fit high functioning payloads within a 1.5U payload space proved to be cost-prohibitive” [8]. These are lessons learnt which should also be taken into account when PocketQubes are considered.

When considering mission applications for PocketQubes, a simple guideline would be that the total of the development, production and operations cost per satellite should ideally be on par with the launch cost. The rationale behind this is that if the development, production and operations cost would grossly exceed the launch cost, it would be appropriate to consider larger spacecraft (such as

CubeSats) to increase the utility per satellite to optimize the overall utility per total cost. Likewise, if the launch cost would very dominant, it would make sense to investigate if further miniaturization would be physically feasible and be more cost-effective. Development cost is mainly based on human resources and the difference between a sophisticated CubeSat or PocketQube development may not be very different when looking at effort. The only way to reduce the development cost per satellite is by producing and launching many identical satellites such that development cost can become a minor contributor to the overall cost. If for example the development cost of a sophisticated small based mission is 10 M€, the development cost per satellite is still 100 k€ per satellite for network a 100 satellites which could be justified for CubeSats, but at 1000 satellites it becomes 10 k€ for which PocketQubes could be financially attractive. Also production cost (including unit testing, assembly and integration) should be significantly lower than for CubeSats. This will not be achieved by the reduction of materials only. Smart architectural concepts such as the integration of several subsystems and a quick assembly of integrated outer panels [9] as well as automated unit testing can be ways to make a larger differentiation in terms of cost per satellite.

3 POTENTIAL APPLICATIONS FOR POCKETQUBES

Taking the conditions into account, this chapter provides some insight into potential applications of PocketQubes. This is not meant as an exhaustive analysis or a complete overview, but to show the potential of PocketQube platforms and provide some of the main considerations to this respect.

3.1 Training & Education

Education and training on real satellite platforms is more inspiring and provides a deeper learning experience than only theory or exercises. While each class of satellites has differences in development approach and technology, the basics of spacecraft technology are platform independent and it is always possible to apply the more extensive approaches of larger spacecraft on the smaller platform for training and education purposes. Therefore, the cost-effectiveness of a PocketQube platform is a major advantage for training and education. While CubeSats have opened space to many new players around the world, it is still cost-prohibitive for many small companies and a majority of educational institutions. PocketQubes have the potential to open the doors for an even wider range of players. For PocketQubes the technology is not yet as mature as for CubeSats and for many (advanced) subsystems. There are not many modules on the market while for CubeSats the commercial available subsystems are advanced and diverse, which poses a dilemma for academic teams as educational/training objectives are sometimes in conflict with the desire to keep up with the state-of-the-art which typically would require procurement of commercial subsystems. For PocketQubes there is still a need for development of this technology starting from a low technology readiness level and basic performance, which at present provides excellent opportunities to align research, development and education objectives at universities.

3.2 Technology Demonstration

PocketQubes are excellent platforms for low cost technology demonstration, provided that the demonstrated object or concept fits in a PocketQube platform. Demonstration of technology can be that of PocketQube-sized subsystems or components itself, but it can also be performed for technology which is meant for larger platforms. For instance, sun sensors of a large spacecraft are typically still small enough to fit in a PocketQube. If this would be the only demonstration payload, the technical requirements would be relatively modest. A technical challenge however may be that for perfect in-orbit demonstration or even characterization, the PocketQube should be able to provide additional high quality and reliable reference measurements and the platform should therefore be mature. In the case of the Sun Sensor example, the attitude determination of the PocketQube should provide a good independent attitude reference.

PocketQubes could also be good platforms to demonstrate novel concepts and algorithms which are in principle platform-size independent. Concepts can be based on new architectural approaches [9], novel communication techniques but also on distributed systems such as formation flying and rendezvous and docking. Novel attitude algorithms can be tested on PocketQubes, provided that it fits within the available computational power and does not require large attitude sensors.

3.3 Earth Observation

Earth radiation, the combination of the reflection of Sunlight (Albedo) and its own body radiation (infrared dominant), provides valuable information for climate models. In a study on CubeSats for Earth observation it has been found that uncooled micro-bolometers are suitable for CubeSats [10]. As these instruments are not diffraction limited, require little power without the need for active cooling and provide relatively low data volumes if they measure only one ground sample at a time, they could also be suitable for PocketQubes. With a well distributed constellation of small satellites, it would be possible to monitor the whole Earth continuously and even provide insight into regional differences.

Earth imagery can be performed with very small satellites, such as the 3U CubeSats of Planet using a platform optimized diffraction limited camera. Planet has the ambition to monitor the Earth daily at a ground sampling resolution of 3-5 m with a network of about 200 satellites [11]. For PocketQubes, the diffraction limit will limit the achievable GSD to half of that of a CubeSat of similar configuration (see section 2.2). As the data produced per satellite has a quadratic relationship with GSD, just like the required power to downlink the data, the amount of imaged land area per satellite per time unit can be identical between PocketQubes and CubeSats. As there are already many CubeSat developers active in the field of Earth imagery, using PocketQubes only makes sense for those applications which can still provide a complimentary function. Potential applications are those in which the required ground sample resolution is not so important, but the required temporal resolution is such that even a network of CubeSats becomes cost-prohibitive. Performing the same type of mission as Planet at half the GSD and four times the temporal resolution may not be the right approach since starting from scratch will make it difficult to be cost-competitive against a scale-up of the existing constellation of CubeSats. It is therefore recommended to differentiate further from the CubeSat constellations by increasing the temporal resolution with a much higher factor at cost of even lower GSD and/or Earth coverage. Near-continuous monitoring of areas of interest would be possible with a dense constellation of a few thousand PocketQubes, yielding always one or more satellites in view of those locations of Earth at useful elevation angles. An example of a useful application would be to monitor cloudy regions, such as the Netherlands, to maximize the change that images can be shot. Other ideas would be to investigate mission concepts for monitoring CO2 emissions or micro-dust in industrial areas at a continuous basis. While it has been identified as challenging for CubeSats sized instruments [10], it was not deemed impossible. If it is only used to identify trends over time and to monitor the regional spatial distribution due to winds, the required measurement quality in terms of GSD, signal-to-noise ratio, spectral resolution and absolute accuracy may be relatively low, especially if the it is complementary to single satellite missions or small constellations providing high quality and absolute measurements.

For Earth observation in general, it may pay off to investigate if commercial available cameras or integrated imaging sensors for terrestrial applications can be used as-is or with minor modifications for specific purposes. If successful, this may lead to cost-effective solutions which are very different from how CubeSat instruments are currently being developed and implemented.

Science grade magnetometers can (be developed to) fit in a PocketQube. They are relatively small, consume low power and the amount of data produced is low. The influence of the other electronics in the satellite can potentially be mitigated by a smart approach such as flying several magnetometers to differentiate between the external magnetic field and local disturbances or a classical approach by putting the instrument on a deployable boom. As the geomagnetic field is very dynamic, “Multiple satellite missions measuring simultaneously over different regions of the Earth offer the only way to take full advantage of the enormous improvement in instrumentation that has been achieved during the last years.” [12]. A constellation of PocketQubes can push the limits of in-orbit spatial resolution in a cost effective way.

Particle radiation instruments can be fitted inside a PocketQube, such as the design Highly Miniaturized particle Radiation Monitor (HMRM) of only 1.7 cm x 2.4 cm x 2.2 cm [13]. Other novel methods to study particle radiation are currently studied at TU Delft, such as the use of 3D NAND memory as detector based for measuring single events and the use of other type of commercial electronic components for monitoring total ionization dose in a cost effective and relatively easy-to-implement manner. As the LEO environment is protected by the Earth magnetic field, the potential scientific applications for PocketQube based particle radiation instruments are limited. A network of PocketQubes can however provide insights in the dynamic interaction between radiation and the Earth magnetic field at very low orbits.

Global Navigation Satellite System (GNSS) receivers receiving two or more frequencies from GPS and Galileo can fit inside a PocketQube. They could be used for measuring the gravity field of Earth such as performed for GOCE, CHAMP and GRACE [14]. According to the study on Earth observation for CubeSats, this was deemed infeasible “as it requires extremely fine attitude control and a very low orbit that would necessitate a continuously operating propulsion system”[10]. The advantage of PocketQubes however is that it approaches the ideal point-mass for these type of measurements and as such the requirements on the attitude can be relaxed to a few degrees to ensure that the receiver can lock onto the signals and the physical measurement offset is limited to less than a millimetre. For the L1 GPS frequency at 1575 MHz, an effective quarter-wavelength patch antenna would 48 mm wide, which is exactly possible on a PocketQube. A maximum determination offset of 1 mm would yield a maximum phase offset of just 0.03 rad and would be excellent for precise orbit determination. As discussed in section 2.1, the ideal orbital regime for PocketQubes is actually in line with the required very low orbits for GNSS based gravity field measurements. It is affordable to dispose the PocketQubes after a limited lifetime and replace them regularly, provided that the launch frequency of very small launch vehicles will ramp up over the coming years. At TU Delft, micro-propulsion for PocketQubes is being developed [15] which can potentially be used to extend the lifetime.

3.4 Communication Services

Communication as a service for PocketQubes is extremely limited by the available electrical power. The data volumes and/or signal bandwidth which can be achieved is prohibitive for commercial services base on mass market telephony or internet. However, it is still possible to use PocketQubes for services which require low data volume downlinks and/or bandwidth. The areas of interest are spectrum monitoring, Internet-of-Things (IoT) and individual communication services.

Spectrum monitoring using software defined radios can be used to identify the global, regional and local use of the radio frequency spectrum. This can be used to identify which bands are still under-utilized, but also to discover perpetrators (radio pirates) or for defence related intelligence (e.g. use of radars, jammers, etc.). With a dense constellation of PocketQubes with an on-board spectrum monitor, continuous global coverage can be achieved and the origin of the signals can be localized better with an increase in number of satellites.

With the advance of IoT devices on Earth, in-situ monitoring vast amounts of areas and objects of interest becomes possible provided that the signals of these monitoring devices can be picked up. For remote locations, such as the arctic [16], a satellite constellation may be more cost-effective than installing ground based reception systems. The data rates produced by the ground based sensors are very limited, typically in short messages of a few bytes sent only once per few minutes to hours. With an increasing number of sensors, it becomes interesting to perform a trade-off between several classes of satellites to optimize for the total data bandwidth but also to properly deal with mutual interference. In the absences of an in-depth investigation and trade-off it is currently hard to say if a densely populated network of PocketQubes would be better or worse than a less densely populated network of CubeSats or larger satellites.

The final application related to commercial services could be to allocate a single PocketQube to one or only a few telephony or low bandwidth data communication channels. This should in principle be feasible with a PocketQube. While a constellation can improve the continuous availability and linearly scale up the amount of available channels, it will not be feasible to address the bulk consumer market. The applications would therefore be limited to military and emergency purposes. As they are likely not competitive to (existing and emerging) networks of larger satellites, the potential advantage can be found in the fact that a dense network of PocketQubes would be very difficult to taken out of operation. Also in case of a major disaster, for example related to a soler eruption, PocketQubes may be used to quickly set up a global communication network for critical (but limited) communication services

3.5 Beyond Low Earth Orbit

PocketQubes could potentially go beyond Earth orbit, e.g. to the Moon or other planets in our solar system, using ride-share capacity of larger satellite missions. The main advantage is this case is that the cost per mass or volume unit to these orbits is significantly higher compared to LEO, which would be a stronger motivation for further miniaturization. This could justify a higher development cost per satellite following the argumentation in section 2.3.

Because of the electrical power limitations and the large communication distance, a large 'mother-satellite' acting as relay would most likely be required. Applications could be in the field of distributed networks of PocketQubes to increase temporal resolution or for spatially distributed in-situ measurements around other celestial bodies. Other applications with distributed networks of PocketQubes around other celestial bodies are the creation of a constellation to create a navigation system at that specific body (similar to GPS) and space weather monitoring (for space situational awareness).

There are major technical challenges are in the field of radiation tolerance and thermal control. Most PocketQube technology at present is developed with commercial of the shelf electronics for terrestrial purposes, which is unsuitable as-is for the large particle radiation flux and ionization doses encountered outside the LEO environment. PocketQubes have a relatively high ratio of outer surface area over internal heat capacity compared to larger satellites, making thermal control outside the Earth's orbit around the Sun very challenging. The very limited available electrical power makes it difficult to compensate this with active heating or cooling. Studies on using CubeSats on interplanetary missions provide a roadmap for these class of satellites beyond LEO [17]. In this study, an 8 mm thick Aluminium shielding is proposed to tackle the radiation issue. While it is questionable if such shielding provides adequate protection against all types of particle radiation effects, such shielding would in any case be prohibitive for PocketQubes. The question whether PocketQubes can provide useful and cost-effective platforms beyond LEO requires a dedicated study with a critical comparison with larger platforms at a mission level, taking the utility and overall cost into account.

4 CONCLUSIONS

PocketQubes are a new class of very small satellites which can enable new types of applications provided that technical, legal, regulatory and financial constraints are properly taken into considerations. Single PocketQube missions are ideal for education and training purposes as well as a limited set of technology demonstration objectives.

For Earth observation and communication services, the will most likely only show their true potential in vast distributed networks of hundreds to thousands of satellites. With these numbers, a conservative approach should be taken on the risk to create space debris. The orbit of PocketQubes should be below 500 km of (average) altitude to limit the orbital life time to 5 years, with a preference to limit it further in the future to circular orbits between 300 km and 400 km while using the potential of on-board propulsion to extend the operational lifetime.

For a sustainable PocketQube mission, the launch cost should be approximately four times less than that of a CubeSat and the total of development, production and operations cost per satellite should ideally be on par with the launch cost. The volume and mass constraints of a PocketQube lead to less available electrical power compared to CubeSats and also physically limits the achievable measurements or services. Instead of simply scaling down the instruments of CubeSats and increasing the number of satellites, it is advocated that further differentiation from existing and planned CubeSat missions may be more promising. For Earth observation, continuous monitoring of dedicated areas of Earth would be vastly different from the concepts of today where the whole Earth is monitored on a daily basis. For communication services, low data rate and/or bandwidth applications could enable niche applications, but further investigation is required to compare those concepts with respect to larger satellites in lower numbers. Also for PocketQube missions beyond Earth, further investigation is required to identify if the particle radiation and thermal challenges can be tackled sufficiently.

Overall, it can be concluded that PocketQubes provide sufficient potential for present and future applications. Instead of being competitive platforms to CubeSats, they should be regarded as a complementary class of satellites which enable new cost-effective applications.

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