

IAC-14-B4.2.11

STATUS OF THE QB50 CUBESAT CONSTELLATION MISSION

J. Thoemel, F. Singarayar, T. Scholz, D. Masutti, P. Testani, C. Asma, R. Reinhard, J. Muylaert
von Karman Institute, Belgium, jan.thoemel@vki.ac.be

Cubesats have emerged as powerful tools for a new class of space missions that is recognized by academia and the space industry. They have served many objectives but are mainly used to educate young space engineers through hands-on design and manufacturing experience. The QB50 project aims to use the cubesat concept to further facilitate access to space for future generations, to carry out unprecedented science, to demonstrate new space technologies, and train young engineers. To this end, the Project, coordinated by the von Karman Institute for Fluid Dynamics in Belgium, has invited universities from all over the world to submit proposals for cubesats to be embarked on the mission.

The QB50 Consortium is managing the mission. In particular, it is developing the deployment system and the common sensors that will be placed on all scientific satellites, and procures the launch service. In addition, it provides a number of key technologies and services such as an attitude control system and satellite control software for the teams participating in the project.

This article introduces the project, describes the technologies developed, the management approach taken and summarizes the current status.

I. INTRODUCTION

With the definition of the cubesat standard, an entire new approach in the space domain has emerged. It allows cheaper access to space by a number of rethought principles. Among them are:

- a standardized size of 10x10x10 cm and a mass of 1 kg as 1 unit (1U), and multiples of it
- increased permissible risks
- delivery of satellite into orbit in a securing container
- piggy-back launching

This new approach now allows many universities to build and have launched their own satellites, thereby providing hands-on educational experience to their students.

In 2011, a consortium of 15 partners formed to contribute to this movement and to open the concept to further applications. The Consortium*, under the leadership of VKI, proposed a multi-satellite project to the European Commission's Framework 7 research programme and succeeded in obtaining partial funding. Consequently, the Project, now called QB50, aiming at launching approximately 50 2-unit cubesats into low Earth orbit started its implementation in November 2011.

II. OBJECTIVES

The new space approach promises many more satellite launches. Improved access to space is therefore the important objective of the QB50 Project, called here:

- facilitating access to space

The launch of 50 satellites is also an opportunity to make use of this large constellation for multi-space craft concerted science. Hence the second objective is:

- to carry out an unprecedented science campaign using distributed sensors

QB50 also involves a large community of universities in the world. Hence, it will:

- contribute to the education of the next generation of space engineers.

In addition, the eased access to space also allows to increase the maturity of space technology. Hence QB50 also aims at the:

- in orbit demonstration of new technologies

A large network of institutions is working toward the achievement of these goals. Most important are the 50 cubesat teams who form the QB50 cubesat community.

* The QB50 Consortium consists of the following partners: ISIS B.V. (NL), MSSL/UCL (UK), EPFL (CH), SSC (UK), B.USOC (B), TU-Delft (NL), IAP (D), DLR (D), Stanford (US), ITAM (Russia), NPU (China), Airbus (D/Fr), SSLLC (USA), VKI (B)

The Consortium supports the Community by providing guidance and key technologies. Additionally, a large number of collaborators and governmental bodies also help the Project. The von Karman Institute (VKI) acts as the interface between the different groups and as the Project Coordinator. In the following sections, key aspects of the Project are introduced and the status of them are summarized.

III. SCIENCE

QB50's scientific objective is addressed by the unprecedented measurement campaign to explore the middle and lower thermosphere. The latter in particular was largely inaccessible for detailed investigation. Previous measurement campaigns using lidar systems [1] or sounding rockets[2] probe only few points for a short period of time. Previous large satellites allowed for long duration measurements but only of limited spatial resolution [3][4].

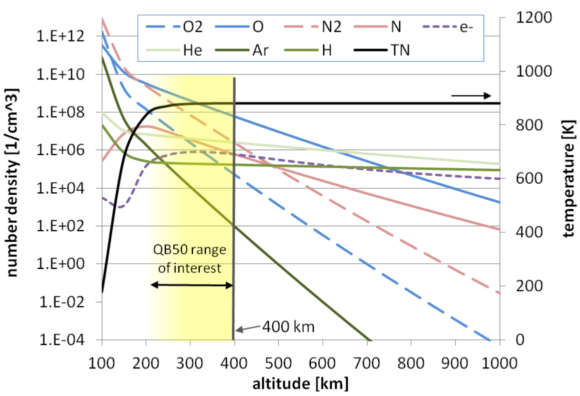

Figure 1: Composition and temperature of thermosphere: O_2 [32 g/mol], 16 [g/mol], N_2 [28 g/mol], N [14 g/mol], He [4 g/mol], Ar [40 g/mol], H [1 g/mol], e^- [5.5 e^{-4} g/mol], $T_{neutral}$ [K] (latitude/longitude 0 deg, June 21st 2013, 1 am.)

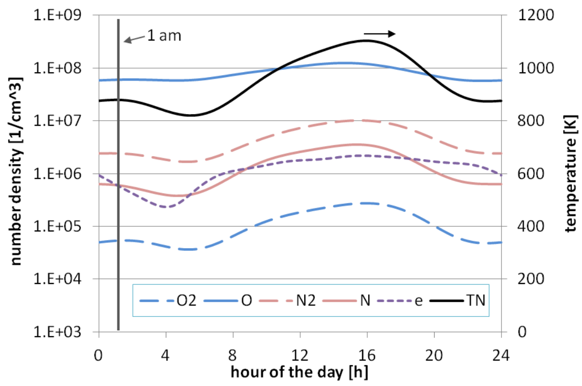

Figure 2: Composition of selected species and temperature of the thermosphere over one day (altitude 400 km, latitude/longitude 0 deg, June 21st 2013).

From previous measurement and from modeling, one presumes that the middle and lower thermosphere will exhibit some scientifically interesting features. Of particular interest to the QB50 mission is the altitude range below 400 km. Here the cubesats will be ejected from the launcher and will carry out their initial scientific measurement campaign towards lower altitudes. It is expected that most cubesats will continue their scientific measurements until the failure of their attitude control due to excessive aerodynamic forces and moments consequent to increasing atmospheric density. This is expected at an altitude around 200 km.

The atmospheric composition has been modeled by various scientists. For the purpose of this paper the models MSISE-90 [5], [6] and IRI2012 [7], [8], available online, are being used. According to these models, the number density of all major constituents exhibits strong decreasing gradients with increasing altitude while the neutral temperature only slightly increases and reaches a plateau of around 900 K† at 250 km (at 1:00 am). This is illustrated in Figure 1.

At 100 km the atmosphere mostly consists of molecular nitrogen and oxygen. Above this altitude the atmosphere starts to separate the different species; lighter species are more dominant at increasing altitude. Their higher thermal speed allows them to reach a higher altitude. In addition, solar wind and further

† Satellites flying at this altitude are normally not in thermal equilibrium with the highly diluted atmosphere. Their temperature is determined by the incoming solar heating and its reflection by the Earth, the Earth's albedo and the optical properties of the satellites' surface.

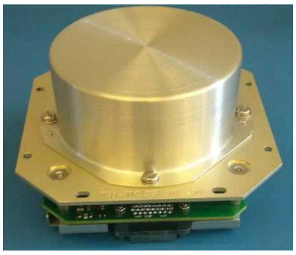

Figure 3: Ion and Neutral Mass Spectrometer (INMS, credit: MSSL, UK)

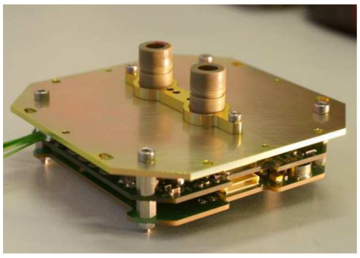

Figure 4: FIPEX (credit TUD, DE).

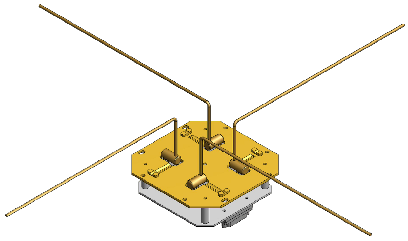

Figure 5: Multi Needle Langmuir Probe (mNLP), deployed (credit UiO, No).

effects determine composition, which is not accounted for here. The characteristics of the thermosphere are highly dynamic: for example, it is very much dependent on the energy influx from the diurnal solar cycle. During daylight, the Earth's atmosphere expands due to solar heating. The increase in number density and temperature during day time, at an altitude of 400 km is illustrated in Figure 2 for a fixed location above ground.

The thermosphere will be explored by the Science Units. These sensors are developed by the Project and serve as the primary payload for majority of the cubesats participating in QB50. The Consortium, with support from additional scientists, has chosen three different types:

- 13 Ion and Neutral Mass Spectrometers (INMS) provided by the Mullard Space Science Laboratory (MSSL) - they will probe the major heavy particles such as O, O_2, NO and N_2 and possibly others. This Sensor Unit is shown in Figure 3.
- 19 Flux Ion Probe Experiment (FIPEX) sensors units supplied by the Technical University of Dresden (TUD) – they will measure atomic and molecular content by means of two separate solid electrolyte sensors. This Sensor Unit is shown in Figure 4.
- 11 multi Needle Langmuir Probe (mNLP) supplied by the University of Oslo (UiO) – they will probe electron density and possibly other electron characteristics of the thermosphere[9]–[11]. This Sensor Unit is shown in Figure 5.

QB50 also embarked on organizing the annual European CubeSat Symposium addressing its fundamental (atmospheric) and technology science goals. In 2014, the symposium will take place in Estavayer-le-Lac, Switzerland from the 14th until the 16th of October. It aims to present the latest developments of cubesat related technologies, satellite concepts or multi-satellite missions, and fundamental science targeted or achieved with cubesats.

IV. SPACE SEGMENT

The space segment of QB50 will consist of 50 cubesats in total that will be delivered into low earth orbit. Among them are 44 satellites that participate in the science campaign and 6 that demonstrate new technologies such as thermal protection systems, de-orbiting sails. Some satellites, such as the TU-Delft satellites Delta and Phi, not only demonstrate new technologies such as cubesat formation flying [12] and but also participate in the science campaign. This also allows the investigation of the added value of such technologies to the science campaign.

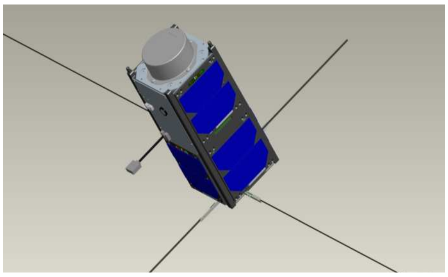

Figure 6: Typical design of a QB50 science cubesat. (credit: ISIS B.V.)

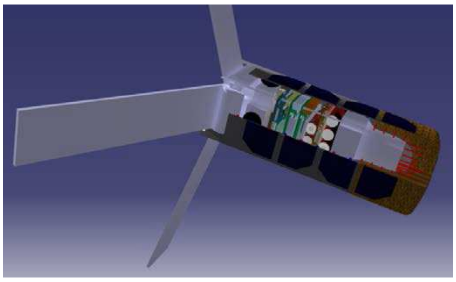

Figure 7: An example of an In-Orbit Demonstration satellite.

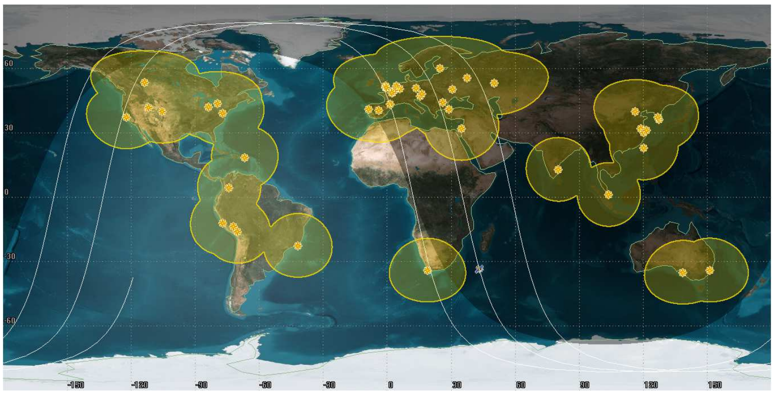

Figure 8: QB50 ground segment coverage for 380 km altitude.

Figure 9: Typical ground station antenna for VHF (left), S-Band (center) and UHF (right). This one is located at the VKI.

An example of such a science satellites is shown in Figure 6. The Science Unit, here the INMS, is visible at the front of the satellite. On of the IN-Orbit Demonstration satellite – VKI's QARMAN – is depicted in Figure 7. It will demonstrate the reentry of a cubesat and characterize related technologies such as the thermal protection system.

Most of the satellites are 2 unit cubesats with a QB50 Sensor Unit attached on their front surface. In addition, many of them also carry additional payloads developed by their respective university or organization. The satellites typically make use of body-mounted solar cells, rechargeable batteries, a radio to communicate in the UHF and VHF radio amateur frequency range, a navigation means such as GPS, attitude control and an on-board computer.

V. GROUND SEGMENT

The QB50 ground segment consists of 50 ground stations in total and a number of central functions such as the central data storage server. The latter will feature:

- hosting and distribution of orbital information in the Two Line Elements (TLE) format from different sources such as:
  - Celestrak
  - cubesat teams
- hosting of important mission information such as the frequency and decoding schemes for the QB50 cubesat radios
- receiving, relaying and conversion of data from the QB50 cubesats such as:
  - Whole Orbit Data (WOD)
  - Science Data (SD)
  - Beacon Data (BD)

The Whole Orbit Data will contain important housekeeping data such as temperatures and space craft bus voltages acquired every 60 seconds and stored until downlink. It will help to monitor the status of the satellites and will be displayed in the QB50 Mission Display Centre website.

The Science Data will include the data obtained by the Science Unit along with its respective orbital information such as position and time of acquisition.

The Beacon Data contains the WOD at the instant of the beacon signal transmission.

The central data storage server, located at VKI, will be the heart of the ground segment allowing central data collection obtained by the cubesats, and interfacing to all 50 ground stations located at or close to the QB50 participating universities. They are the foundation of the ground segment and, due to their wide spread across the globe, they allow a high coverage communication. This is exemplified in Figure 8.

Typically, the cubesat teams own or have access to a radio amateur ground station with UHF and VHF capabilities; some also include an S-band feature. VKI's ground station antenna is shown in Figure 9.

In order to support the cubesat teams, a satellite control software is developed by the project Partner EPFL[13]. It can be used by teams and may therefore relieve them from developing or procuring such software. It also facilitates data submission to the central server.

It is recommended that the teams create mini-networks of at least three ground stations. This will allow regular contact, increased data downlink capability and access to a back-up ground station in case of failure of the home station.

VI. LAUNCH SEGMENT

The satellites will be launched together into low Earth orbit. To this end, ISIS has been charged to design the deployment systems. The multi-satellite dispenser was first made of fifty single satellite slots[14].It was later found to be advantageous to assemble the deployment system from bigger modules allowing each ejecting four satellites, or fewer of larger size. Those modules are called QuadPack. The qualification model is shown in Figure 10. It features the ejections of cubesats from four independents slots of two or three unit size. The modularity allows the use of it on many launch vehicles. The design of a constellation deployment system for QB50 consisting of several QuadPacks will be achieved with the help of a supporting structure.

Important novel features include the integration of the door opening mechanism within the four independent doors, thereby avoiding extrusion from the cuboid shape and as well the late access hatches in the door. The mechanism ejecting the cubesat consisting of the pusher plate and the ejection spring are designed to allow the accommodation of the QB50 Science Unit within the centre of the spiral spring.

Figure 10: QB50 developed Quadpack (credit: ISIS B.V., NL)

VII. COLLABORATION, CUBESAT REQUIREMENTS AND GUIDANCE

The QB50 Project is also an unprecedented undertaking in terms of team work. Its basis is the community of world-wide universities and educational organizations that contribute their satellites, ground stations, time, financial resources, and motivation to the Project. They are supported by the QB50 Consortium. The teams and the Consortium are coordinated by VKI. The European Commission partially finances the Consortium. In addition, the Project receives substantial help from many organizations. Memoranda of Understanding have been signed with Amsat UK/NL/FR/BE, Space Generation Advisory Council (SGAC) and Aalborg University and collaboration with the Journal of Small Satellites has been established. VKI also acts a space mission operator and is therefore responsible for the multiple legal responsibilities towards the Belgian state (BIPT/ BELSPO), the International Telecommunication Union (ITU) and the United Nations Office for Outer Space Affairs (UNOOSA).

VKI guides the cubesat teams by facilitating their efforts to develop and ultimately launch their satellites. To this end, VKI and the Consortium provides technical guidance for cubesat development through the definition of requirements, advice, such as the selection of input parameters for orbital dynamics predictions [15], and milestone reviews.

Important requirements to the cubesats are:

- maintaining a +/-10 (15) degree alignment with the velocity vector/ the Sensor Unit facing ram direction. This allows an accurate measurement
- downlink of at least 2 Mbit/day Science Data.
- use of the AX.25 data format. This format is well established and compatible hardware is available facilitating this aspect of the mission.
- no use of VHF for downlink. This is because only limited number of VHF frequencies are available.
- implementation of the Whole Orbit Data concept
- execution of an End-To-End Hardware-In-the-Loop test. This will prove the functionality of the entire system.
- if not required otherwise, compliancy to the CalPoly CubeSat Design Specification [16]

To facilitate the reviews, templates for the technical documents are provided. They allow for an efficient and effective reporting of the technical design, the development status, and the identification of risks and non-compliances. The review is conducted in part by VKI and Consortium experts, and, in an anonymous way by collaborators and the Community itself via a peer review principle. After the review, VKI can then support the teams to mitigate potential problems. Nevertheless, the reporting requirements imposed by QB50 are very light and focus on the compatibility of the cubesat team with the Project's constraints. This provides the teams with the freedom to develop their cubesat according to their own approach, which could be possibly innovative, yet minimizing the development risks.

Cubesats in general are subject to high mortality particularly during their infancy. [17], [18].

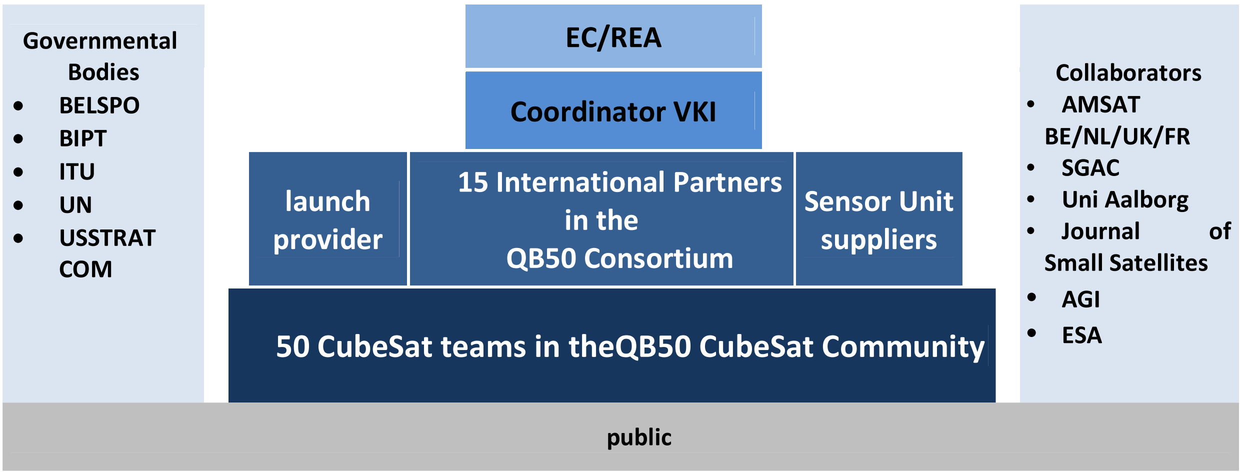

Figure 11: The QB50 network pyramid. The Project is based on a community of universities, coordinated by a Consortium and VKI. The Project is carried out as an initiative of the European Commission and with support from additional collaborators and governmental bodies. It receives attention by the public via our website, social and classical media.

Hence, a priority for VKI is ensuring the high quality of the engineering work

VKI also supports the teams by obtaining all necessary international legal permission for launch. The satellites will be registered [19] [20] by VKI with the state of Belgium. In addition, majority of the cubesats will benefit from the frequency coordination carried out VKI in collaboration with AMSAT and IARU, the Belgian Institute for Post and Telecom (BIPT) and ITU. This approach leaves the cubesat teams to only care about their own national laws such as export/import regulations. Despite being registered in Belgium, each satellite remains the property of the organization that has developed it and will operated by its own ground station.

The end of the cubesat hardware development will be the formal acceptance of the space craft by the Consortium at the Flight Readiness Review. From there on the Partner ISIS will take care of the satellites and transport them to the launch site and install them inside the deployer, which will be mounted onto the rocket upper stage.

IIX. OPERATIONS

The launch of the cubesat constellation is targeted for January 2016. The launch provider will provide predicted orbital information before, and confirmed orbital information immediately after the launch. A major challenge will then be to relate the early TLEs provided by USSTRATCOM/NORAD to the different satellites. The assigned beacon frequencies, the known deployment strategy, the large QB50 community with 50 ground stations ready and the friendly radio amateur community will all help with this large endeavor. After all satellites have been identified the commission phase can start followed by the scientific, nominal operations phase.

IX. PRECURSOR CAMPAIGN

Despite the fact that within the cubesat domain higher risks are acceptable, the Project decided to make reasonable effort to mitigate unnecessary risks. To this end, QB50 carries out its so-called precursor campaign. It consists of launching a QuadPack and two 2-Unit cubesats making use of the QB50 developed ADCS, two of the Sensor Units and a number of operational concepts such as data format conventions. The satellites were designed and assembled by ISIS with the hardware contributions from Surrey Space Centre, MSSL, TUD and VKI within less than 12 months. In addition, QB50p1 carries a linear UV transponder provided by AMSAT-NL, with support from AMSAT-UK, which is similar to that on FUNcube-1. QB50p2 carries an UV FM transponder and FX25 data transmitter from AMSAT-F. It is planned that these payloads will be activated after the scientific missions have been completed

This exercise has proven to be useful; minor hardware defects and documentation errors have been found and corrected.

The two precursor satellites were launched on the Kosmotras Dnepr rocket June 19th, 2014 from Yasni, Orenburg Oblast, Russia, southward into a 630 km, circular, 98 deg orbit. The orbit of the precursor satellites was chosen to be at a higher altitude than the one of the main mission since space debris issues are less pronounced with only two satellites and in particular because of the longer orbital life-time. This allows longer mission operation i.e. trouble shooting if needed, operations training, and AMSAT phase.

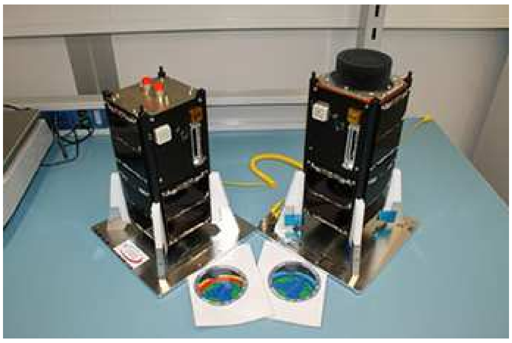

Figure 12: The two QB50 Precursor satellites. On the left P2 carrying the FIPEX Sensor Unit and on the right P1 carrying the INMS Sensor Unit (credit: ISIS B.V.).

The launch, cubesat ejection from the QuadPack, antenna deployment, and beacon data transmission initiation, first of Morse then followed, after a telecommand, of AX25 data type, took place flawlessly with the first telemetry already having been received on the first orbit by Radio Amateurs in South Africa. To date, the satellites are operated by ISIS with their home ground station, assisted by VKI from Belgium; no major problems have been discovered, the commissioning phases takes longer than expected due to careful investigation of minor unexpected observations. Besides this, the early operations phase is nominal.

These technical pre and post launch activities as well as the managerial and legal work that was accomplished during the precursor campaign enable the de-risking of the main mission.

X. STATUS AND FUTURE PLANNING

The first year of the Project was characterized by the detailed definition of the Project and the creation of the cubesat Community. Roles and responsibilities were identified. In the second year, the scientific, engineering and design work was started and the Project was consolidated.

In September 2014, the Project has passed its CDR and has started to procure or to build the flight hardware. In addition, qualification tests are ongoing. The cubesat teams are required to participate in the Assembly, Integration, and Testing Readiness Review taking place in October 2014. Here, the maturity of the cubesat development will be reviewed and if deemed sufficient environmental and functional testing is foreseen thereafter.

The Flight Readiness Review is will take place in June 2015, followed by the launch targeted in January 2016. Upon delivery of the satellites into orbit, the teams will commission their satellites and then start the scientific campaign. Destructive reentry will take place approximately 10 months after launch. Through all these phases the Consortium will support the teams with guidance and concrete help.

XI. ACKNOWLEDGMENTS

QB50 is only possible due to a very large number of passionate individuals. The authors owe their appreciation to many people behind the scenes, such as accountants and lawyers, the cubesat teams members and to the following persons in particular: B. Taylor, D. Kataria, A. Smith (MSSL), C. Bernal, J. Elstak, J. Rotteveel (ISIS), L. Visagie, V. Lappas (SSC), M. Richard, S. Billeter (EPFL), X. Yu (NPU), T. Bekkeng (UiO), Tino Schmiel (TUD), G. Shirville, S. Dombrowski (Amsat), D. Oltrogge (AGI) and F. Beroud (EC/REA). The research leading to these results was supported through the EU FP7 "An international network of 50 CubeSats for multi-point, in-situ measurements in the lower thermosphere and re-entry research" project, which received funding from the European Commission's Seventh Framework Programme under Grant Agreement no. 284427.Further up-to-date information can be found our websites: www.qb50.eu and www.cubesatsymposium.eu.

XII. REFERENCES

[1] M. Gerding, J. Höffner, J. Lautenbach, M. Rauthe, and F.-J. Lübken, "Seasonal variation of nocturnal temperatures between 1 and 105 km altitude at 54 N observed by lidar," *Atmospheric Chem. Phys.*, vol. 8, no. 24, pp. 7465–7482, 2008.

[2] C.-F. Enell, J. Hedin, J. Stegman, G. Witt, M. Friedrich, W. Singer, G. Baumgarten, B. Kaifler, U.-P. Hoppe, B. Gustavsson, and others, "The Hotel Payload 2 campaign: Overview of NO, O and electron density measurements in the upper mesosphere and lower thermosphere," *J. Atmospheric Sol.-Terr. Phys.*, vol. 73, no. 14, pp. 2228–2236, 2011.

[3] S. Bruinsma, E. Doornbos, and B. Bowman, "Validation of GOCE densities and evaluation of thermosphere models," *Adv. Space Res.*, 2014.

[4] C. Stolle, R. Floberghagen, S. Maus, D. Knudsen, P. Alken, E. Doornbos, B. Hamilton, A. W. Thomson, P. N. Visser, and others, "Space Weather opportunities from the Swarm mission including near real time applications," *Earth Planets Space*, vol. 65, no. 11, pp. 1375–1383, 2013.

[5] "MSIS-E-90 Atmosphere Model." [Online]. Available: http://omniweb.gsfc.nasa.gov/vitmo/msis_vitmo.html. [Accessed: 12-Aug-2014].

[6] A. E. Hedin, "Extension of the MSIS thermosphere model into the middle and lower atmosphere," *J. Geophys. Res. Space Phys. 1978–2012*, vol. 96, no. A2, pp. 1159–1172, 1991.

[7] "International Reference Ionosphere - IRI-2007." [Online]. Available: http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html. [Accessed: 12-Aug-2014].

[8] D. Bilitza, L.-A. McKinnell, B. Reinisch, and T. Fuller-Rowell, "The international reference ionosphere today and in the future," *J. Geod.*, vol. 85, no. 12, pp. 909–920, 2011.

[9] T. Bekkeng, K. Jacobsen, J. Bekkeng, A. Pedersen, T. Lindem, J. Lebreton, and J. Moen, "Design of a multi-needle Langmuir probe system," *Meas. Sci. Technol.*, vol. 21, no. 8, p. 085903, 2010.

[10] T. Bekkeng, A. Barjatya, U.-P. Hoppe, A. Pedersen, J. Moen, M. Friedrich, and M. Rapp, "Payload charging events in the mesosphere and their impact on Langmuir type electric probes," in *Annales Geophysicae*, 2013, vol. 31, pp. 187–196.

[11] K. Jacobsen, A. Pedersen, J. Moen, and T. Bekkeng, "A new Langmuir probe concept for rapid sampling of space plasma electron density," *Meas. Sci. Technol.*, vol. 21, no. 8, p. 085902, 2010.

[12] E. Gill, P. Sundaramoorthy, J. Bouwmeester, and B. Sanders, "Formation Flying to Enhance the QB50 Space Network," in *Proceedings of the 4 Symposium, Funchal, Portugal*, 2010.

[13] F. George and Y. Voumard, "SwissCube Ground Segment Software."

[14] C. Bernal and M. van Bolhuis, "Releasing the Cloud: A Deployment System Design for the QB50 CubeSat Mission," in *Proceedings of the Small Satellites Conference*, 2012.

[15] T. Scholz, C. O. Asma, and A. Aruliah, "Recommended set of models and input parameters for the simulations of orbital dynamics of the QB50 CubeSats," 2012.

[16] "CalPoly's CubeSat Design Specification, Rev 12." .

[17] J. Guo, L. Monas, and E. Gill, "Statistical analysis and modelling of small satellite reliability," *Acta Astronaut.*, vol. 98, pp. 97–110, 2014.

[18] J. Guo, J. Kolmas, and E. Gill, "Small satellite reliability research on spacecraft under 50 kg: Analysis on component level.," in *Proceedings of the 4S Symposium*, Porto Pedro, Spain, 2014.

[19] "Convention on Registration of Launched Objects into Outer Space." United Nations, 12-Nov-1974.

[20] "Law of 17 September 2005 on the Activities of Launching, Flight Operation or Guidance of Space Objects." .