In-Orbit Technology Demonstration Missions for Debris Mitigation

Jean Muylaert, Cem O. Asma** and Thierry Magin****
**Director, von Karman Institute for Fluid Dynamics*
jean.muylaert@vki.ac.be
*** Senior Research Engineer, von Karman Institute for Fluid Dynamics*
asma@vki.ac.be
****Professor, von Karman Institute for Fluid Dynamics*
thierry.magin@vki.ac.be

1. Abstract

The QB50 mission has the scientific objective to study the temporal and spatial variations of a number of key parameters in the lower thermosphere with a network of 50 CubeSats, each performing identical in-situ measurements. Besides the 50 CubeSats, there will be other double and triple unit CubeSats to perform in-orbit technology demonstration missions for de-orbiting technologies and debris mitigation. This paper is devoted to the presentation of these flagship CubeSats.

2. **CubeSat Technology**

A CubeSat is a miniaturised satellite (10x10x10 cm, weighing 1 kg) which offers all the standard functions of a normal satellite (attitude determination and control, uplink and downlink telecommunications, power subsystem including a battery and body-mounted solar panels, on-board data handling and storage by a CPU, plus either a technology package or a small sensor or camera). They can even have deployable solar panels, antennas or booms. Limited orbit control using micropropulsion, S-band instead of VHF/UHF and wireless data transfer inside the CubeSat are now beginning to be used. It takes about two years to develop a CubeSat from the provision of funding until delivery of the fully tested CubeSat, ready for launch. The hardware cost of a CubeSat is in the range 50-100 k€. The CubeSat standard was defined in 1999 by Stanford University and Cal Poly (California Polytechnic State University). Up to now, about 50 CubeSats have been successfully launched, worldwide an estimated 100-150 CubeSats are being readied for launch in the next few years.

The CubeSat standard also allows for double (10x10x20 cm) or triple (10x10x30 cm) CubeSats. For in-orbit technology demonstration missions, double-unit or triple-unit CubeSats are foreseen for sophisticated payloads and higher power requirements.

3. **The QB50 Project and In-Orbit Technology Demonstrator CubeSats**

QB50 has the scientific objective to study in situ the temporal and spatial variations of a number of key constituents and parameters in the lower thermosphere (90-320 km) with a network of 50 double CubeSats, separated by a few hundred kilometres and carrying identical sensors. QB50 will also study the re-entry process by measuring a number of key parameters during re-entry. The re-entry process will also be studied by comparing predicted and actual CubeSat trajectories and orbital lifetimes, and by comparing predicted and actual times and latitudes/longitudes of atmospheric re-entry.

The Project will demonstrate the availability of a low-cost launch vehicle, a Russian Shtil-2.1, for launching small payloads into low-Earth orbit (300-600 km); these could be microsatellites or networks of CubeSats or nanosats or many individual small satellites for scientific, technological, microgravity or biology research.

The Project will include the development of a deployment system for the deployment into orbit of a large number of single, double or triple CubeSats. Once the system is developed for QB50 it can be easily adapted to other missions involving numerous CubeSats.

QB50 will also provide an opportunity for key technology demonstration on a few ‘special’ CubeSats

- Two triple CubeSats (Delta and Phi) equipped with micropropulsion for formation flying,
- A double CubeSat (Re-EntSat) equipped with a heat shield of ablative material to survive re-entry down to 70 km,
- A double CubeSat (GT-Sat) for testing the link quality between the satellite and the GENSO ground stations,
- GAMA-Sat, three double CubeSats providing inter-satellite links,
- A triple CubeSat (PICASSO), PICo-satellite for Atmospheric and Space Science Observations,
- A triple CubeSat for GPS radio occultations,
- A triple CubeSat carrying a biological micro-gravity payload,
- A triple CubeSat (Inflate-Sail) for testing a solar sail with inflatable booms,
- A triple CubeSat to demonstrate de-orbiting technologies for debris mitigation.

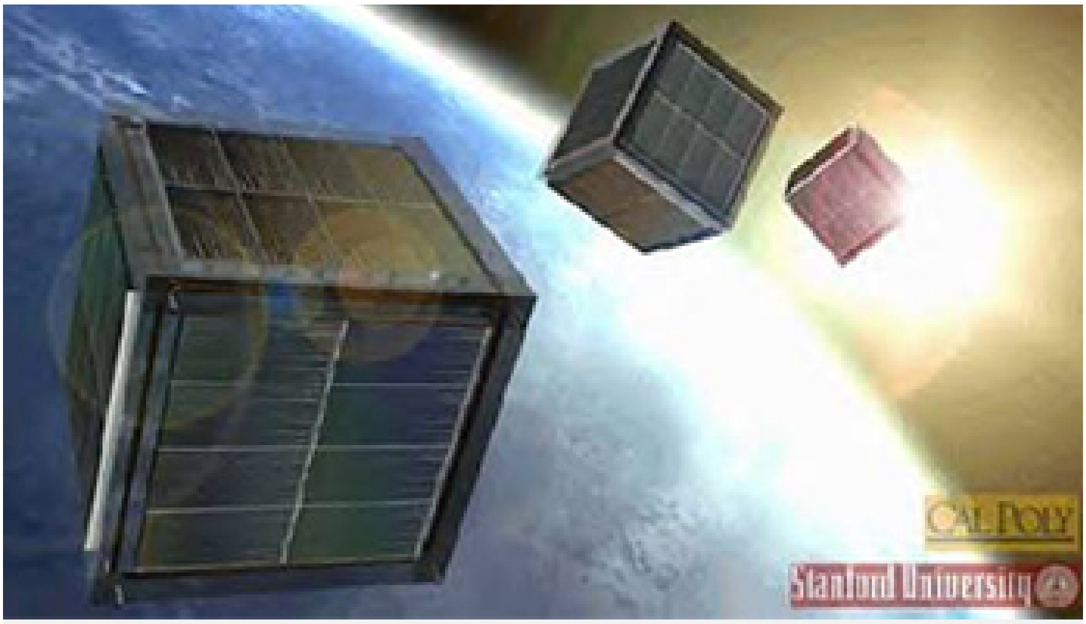


Figure 1. Network of CubeSats

4. The Launch Vehicle

Normally, CubeSats are launched as secondary passengers together with one or several large spacecraft as the primary payload. The primary payload covers almost all of the launch costs and, therefore, the requirements of the primary payload determine the orbital parameters. Launch vehicles that have been used or will be used in the near future to launch CubeSats as secondary passengers include:

- Polar Satellite Launch Vehicle (PSLV) in India
- Dnepr in the Ukraine
- Minotaur in the US
- Falcon 1e in the US
- H2 in Japan
- Vega in Europe
- Tsyklon-4 in the Ukraine
- Soyuz in Russia

Being a secondary payload has two major disadvantages. The CubeSats have to accept the orbital requirements of the primary payload (usually higher orbital altitudes) which are often not ideal for the CubeSats. Also, quite often, the primary payload is not ready in time for the launch. Delays of up to a year are not uncommon, resulting in lack of reliable planning and cost increases for the CubeSats.

To achieve its scientific objectives, the QB50 network has to be launched into a circular orbit at 320 km altitude. It is not realistic to assume that any of the launch vehicles listed above can be used to deploy CubeSats as secondary passengers in this orbit because all large spacecraft, being the primary payload, avoid these low altitudes because of the short lifetime. Only small launch vehicles that can deliver 200-400 kg of payload into an orbit at 320 km can be considered to launch the envisaged network of CubeSats for the exploration of the lower thermosphere. On a small launch vehicle, the QB50 network would automatically be the primary payload.

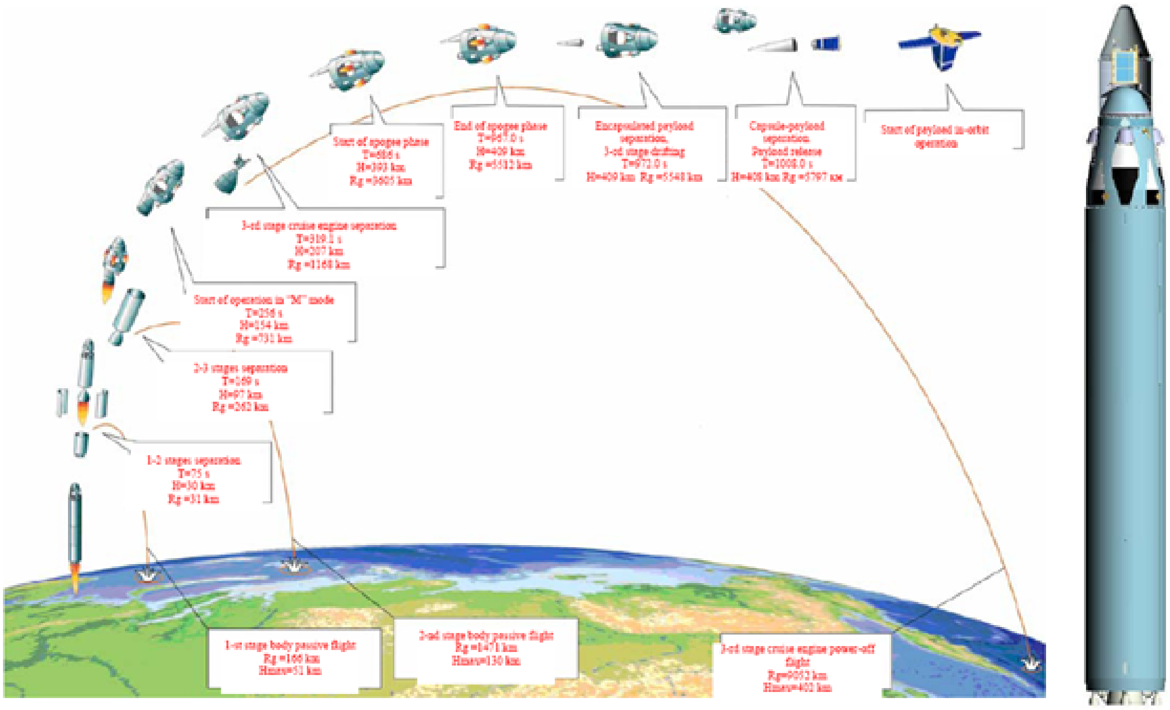


Figure 2. Shtil 2.1 Launch Vehicle

A comprehensive survey of small launch vehicles available or under development worldwide was made. The survey revealed that these rockets either do not yet exist, or have a high probability of failure or are too expensive. The Shtil has a remarkable track record with several hundred successful launches and only one failure and is available at relatively low cost.

The Shtil family of launch vehicles is based on the 3-stage, liquid-propellant R-29RM or RSM-54 SLBM (Submarine Launched Ballistic Missile). The missiles used are withdrawn from active service with the Russian Navy and converted to civilian launch vehicles by removing the warheads and antennas and replacing them by a civilian payload. Shtil is marketed by the State Rocket Center Makeyev.

The Shtil-1 (or just Shtil) is the baseline version of the launch vehicle where the payload is placed inside a special capsule in the space head next to the third stage engine nozzle. It was used to launch on 7 July 1998 from a submarine in the Barents Sea two small satellites from the Technical University of Berlin (TUBSAT-N (8 kg) and TUBSAT-N1 (3 kg)) into a 400 x 776 km orbit (i = 79°). On 26 May 2006, it launched the Russian Kompass-2 satellite (77 kg) into a 402 x 525 km orbit (i = 79°), also from a submarine in the Barents Sea. The Shtil-1 has a launch capacity of 150 kg into a circular orbit at 300 km altitude (i = 79°) and a payload volume of 0.195 m3. However, the actual payload mass is reduced by the mass needed for the encapsulation of the payload.

The Shtil-2.1 is an improved version of the Shtil-1 where the payload is accommodated in a special section (max height 1.24 m, max diameter 1 m) on top of the space head. The payload mass that can be launched by a Shtil-2.1 into a circular orbit at 320 km altitude is 230 kg. The Shtil-2.1 was custom designed to accommodate the South African satellite SumbandilaSat (Pathfinder), an 80 kg microsatellite intended for launch in May 2007 into a 500 km circular orbit, but the launch negotiations could not be successfully completed. The satellite was finally launched on 17 September 2009 as a secondary passenger on a Soyuz from Baikonur.

The Shtil-2.1 is launched from a submarine at sea surface. The fairing is jettisoned at the time of separation of the third from the second stage. After burnout, the third stage engine is jettisoned from the third stage and falls into the Pacific Ocean. The third stage itself remains in orbit. It has small thrusters for attitude and orbit control for 1200 s. After that time the propellant is exhausted. The third stage also carries a telemetry system and a battery which is sized to provide power for 1200 s. During this time interval, the satellite is separated from the third stage by spring pushers. If requested, the size of the battery can be increased to provide power for a longer time period, allowing for a later separation of the payload. Nominally, the onboard Control System Equipment (BCSE) will provide a command signal to ignite the pyro-locks that mate the spacecraft to the upper stage and pusher springs separate the spacecraft from the upper stage, in the flight direction of the launch vehicle with a sufficient difference in velocity to avoid collision between the upper stage and the microsatellite.

The Shtil-2.1 is fully developed and hardware has been built and tested. As there are currently no other customers it is quite possible that the launch of QB50 in June 2014 will be the first launch of a Shtil-2.1.

5. In-Orbit Technology Demonstration CubeSats

5.1. VKI Atmospheric Re-Entry CubeSat

One of the most critical phases of a space mission is while the space craft enters into the atmosphere of the destination planet, or while the spacecraft is re-entering Earth's atmosphere after completing its mission. Thermal protection systems (TPS) are used to shield hypersonic aerospace vehicles from the severe aerothermodynamic heating encountered during the atmospheric entry. Proper design of TPS is one of the most critical stages of the design of the space vehicles as it is indeed a complicated and multi-disciplinary optimisation problem [1]. VKI's expertise in atmospheric re-entry is presented in [2] to [9].

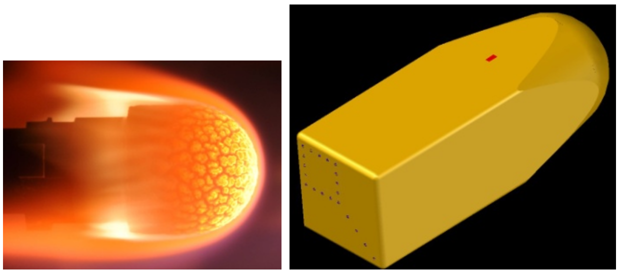


Figure 3. Testing of ablative material in the VKI Plasmatron facility and the conceptual design of the VKI Re-EntSat

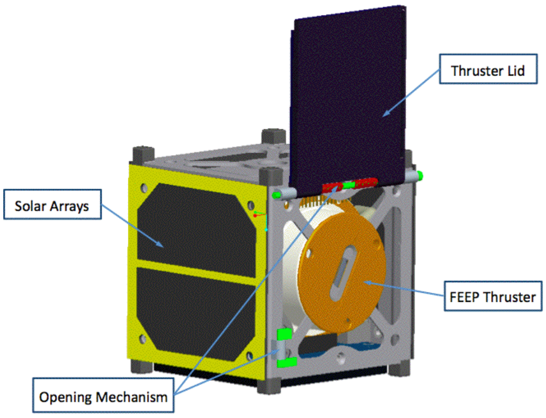


Figure 4. Ionic liquid FEEP on a 1U-CS, developed by ALTA

VKI sees the CubeSat technology as an ideal and very cost-efficient platform to design and perform flight tests for the study of atmospheric re-entry and disintegration of spacecrafts during re-entry. For this purpose, The VKI is committed to provide a hemispherical ablative TPS unit on top of a double unit functional CubeSat, with the standard sub-systems. The CubeSats of the QB50 mission are expected to lose their functions at around 100 km of altitude and then to disintegrate because of increased temperature during the atmospheric re-entry. However, the VKI would like to carry out additional measurements during the re-entry phase. For this reason, the VKI Re-EntSat CubeSat will be equipped with an ablative thermal protection system and relevant instrumentation to monitor the status of the thermal protections system. The nose part of the CubeSat will be hemispherical for an optimal thermal and aerodynamic load. The typical instruments will be thermocouples and pressure transducers, aiming at collecting scientific data during the atmospheric re-entry. Other than these, an inertial measurement unit is to be utilized (3-axis gyroscopes and accelerometers) to perform measurements on the flight trajectory of the CubeSat. An important part of the work will be dedicated to the de-orbiting of the Re-EntSat to start its re-entry. Micro-propulsion systems suitable for CubeSat platforms and aerodynamic de-orbiting techniques will be studied for this purpose. The Field Emission Electric Propulsion FEEP derived thrusters developed by ALTA is one of the candidates for de-orbiting. Application of FEEP to micro- and nano-spacecraft platforms is made possible by the introduction of a simplified, lower cost version of the thruster, replacing alkali metal propellants with more benign ionic liquids and using off-the-shelf high voltage electronics.

According to the initial orbital dynamics and re-entry trajectory calculations [10], the VKI Re-EntSat is expected to have a peak stagnation point heat flux of 3 MW/m^2 at around 70 km of altitude, where the sub-systems will start losing their functionalities and the CubeSat will start to disintegrate because of excessive temperature. The choice of ablative TPS is made considering the relatively high heat flux expected during re-entry and the low density of ablative materials. New generation ablative materials are known for their capability to be much lighter and withstand higher temperatures compared to reusable ceramic and metallic materials, as demonstrated in the recent years, in the VKI Plasmatron facility [11].

5.2. The InflateSail In-Orbit Technology Demonstration Mission (Surrey Space Center)

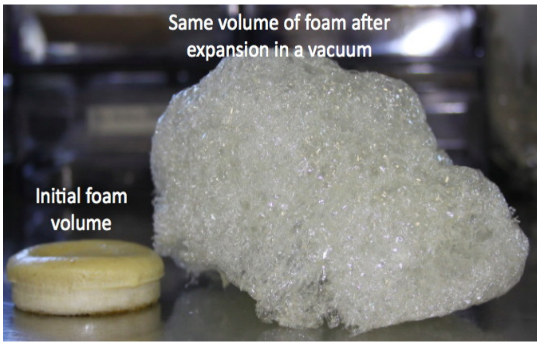
This mission aims to use a low-cost, innovative, robust and ultra light deployable sail designed and developed as a means for satellite/space debris deorbiting. A 5 x 5 m, 3 kg, 10 x 10 x 30 cm deployable sail is being developed as a nanosatellite demonstration mission to be launched in late 2011 as a first step towards demonstrating passive means of deorbiting for future satellites. However, Cubesail has been designed as a de-orbiting system for satellites with a mass less than 400 kg. Furthermore, a lighter 8 x 8 m sailcraft is being developed within the 'DEORBITSAIL' FP7 project recently awarded to Surrey as an improved and more robust de-orbiting system. In this 2.8 million Euro project Surrey is leading a team with DLR, Astrium, SSTL and others to develop a low cost de-orbiting demonstration mission. An improved, inflatable based sail called 'InflateSail' is being developed at the University of Surrey with Astrium as the industrial partner as a generic, scalable de-orbiting solution for any size/mass of satellite/launch vehicle upper stage and is proposed to be flight tested as a CubeSat in-orbit demonstrator in the QB50 program. Surrey is proposing the development of an enhanced, improved and scalable CubeSail derivative, 'InflateSail'. InflateSail is an ultra low mass/volume deployment system of a sail (of any size, 5 x 5, 20 x 20m or larger) based on a gas generator which 'pumps' deployable booms in order to deploy a sail. The gas generator, developed by TNO is about to be flight tested on the ESA Proba satellite in early 2011.

The 10 x 10m sail will deploy from a 3U CubeSat spacecraft in what will be a demonstration mission within the QB50 programme. While orbiting in LEO the sail will use drag to decelerate the spacecraft, thus decreasing its altitude and its orbital velocity. Within days from its launch and from a 320 km orbit, Inflatesail will re-enter in the earth's atmosphere and burn during its re-entry thus demonstrating rapid de-orbiting of satellites.

The main advantages of using inflatable technologies are scalability and low mass/volume. All technologies to be used are space rated/tested based on heritage from the Cubesail and DEORBIT-SAIL (FP7 project) while a novel gas generated deployment system based on a low cost generator developed by TNO is proposed to be used. InflateSail will be a scalable system to be used on satellites larger than 400 kg and for launch vehicle upper stages.

5.3. Triple CubeSat to demonstrate de-orbiting technologies using Foam and Tethers

Two new potential concepts will be analysed for space debris mitigation and studied for potential in-orbit demonstration using triple CubeSats. The first one is the foam assisted de-orbiting concept. The core idea of the proposed de-orbiting system is to engulf the debris in a foam ball in order to increase its area-to-mass ratio such that the atmospheric drag can exert a significant deceleration. Foam is sprayed on the debris from a service vehicle operating in proximity, but without direct contact. Such drag augmentation system requires no docking with the target debris and results in natural re-entry with no need for active control. Development of the system is underway in the frame of an ESA Ariadna study.



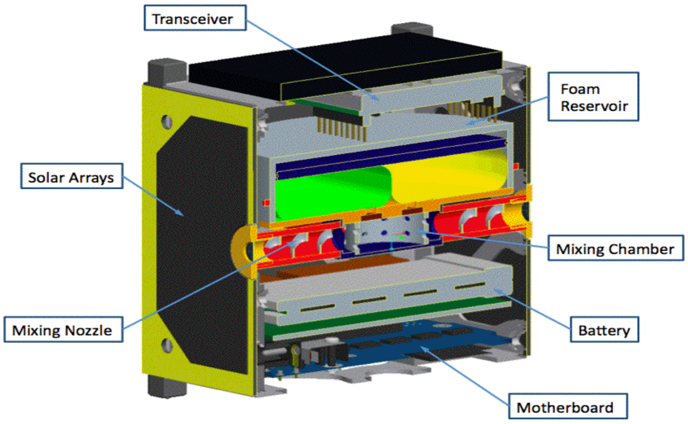


Figure 5. Foam before and after expansion in a vacuum

Figure 6. Foam assisted de-orbiting CubeSat

Figure 5 shows the same amount of foam before and after undergoing expansion in a vacuum test performed at Alta in September 2010. The foam expanded to a cross section approximately 7 times larger. Recent models show the potential to reach a cross section expansion ratio of more than a factor 20 with a properly selected foam composition, with a corresponding reduction of the debris ballistic coefficient.

The CubeSat demonstration of foam-assisted de-orbiting will be performed using two externally identical 1U or 2U CubeSats. One of the CubeSats will be equipped with the foam ejection system, while the other will contain ballast so to have the same mass and inertia properties. This latter CubeSat will be used as a reference to assess the difference in de-orbiting ratio after simultaneous (or nearly-simultaneous) deployment of the two satellites via ground tracking/telemetry. The second CubeSat will also be equipped with wide-angle miniature cameras to take pictures of the foam expansion.

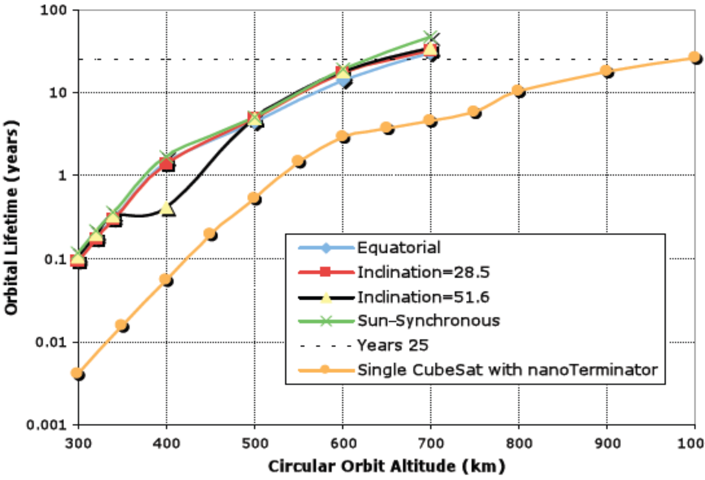


Figure 6 shows a schematic of the demonstrator CubeSat in the 1U configuration. The two-component foam is initially contained in a reservoir. At deployment, the components flow into a mixing duct prior to be ejected by a number of surface nozzles. The system also includes temperature sensors and electrical heaters to perform the experiment at the proper thermal conditions.

The second one is the electrodynamic tether concept by Tethers Unlimited Inc., WA, USA. The principle is as follows: Gravity gradient force aligns conducting tape (electrodynamic tether) along local vertical. The tape enhances aerodynamic drag and generates passive electrodynamic drag as observed in balloon tests. The figure on the right shows the principle and the results of an analysis confirming that an electrodynamic tether concept could well be very effective for de-orbiting LEO satellites. Integration of the electrodynamic tether (called Terminator Tape™) with 30 m length and 80 gram on a single CubeSat will be studied.

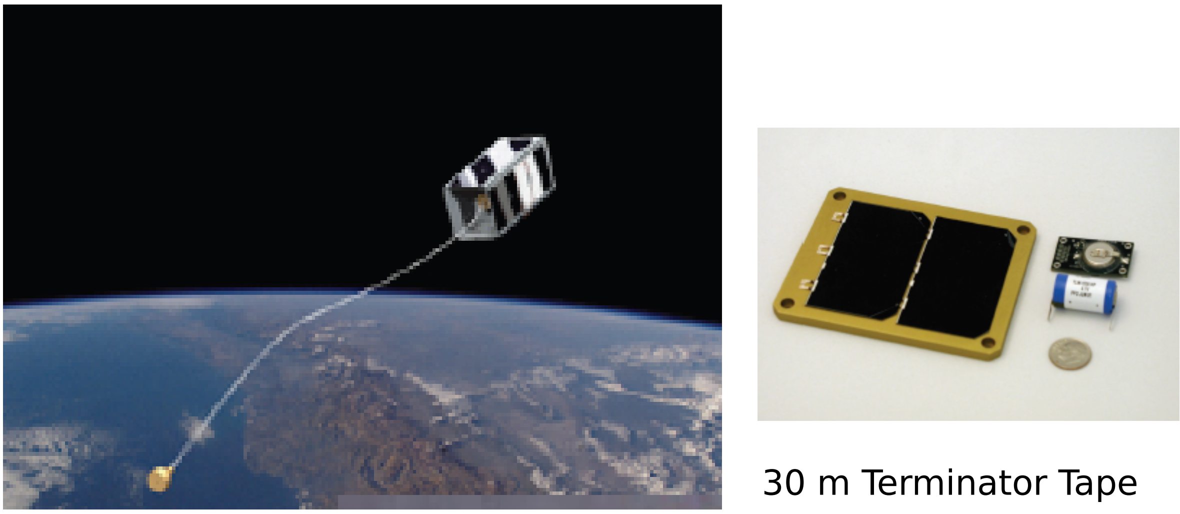


Figure 7. Double unit CS with de-orbiting tether deployed (left); the tape unit (right)

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