Title: TwinCube – Proposal for Tether Supported Plasma Measurement 3-Unit CubeSat

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(x) We apply for Student Prize.

1. Need

Multi-point measurements are necessary for study of the structure and evolution of key physical processes in the Earth's ionosphere [1]. Such measurements are usually performed by multi-spacecraft formation flying missions, e.g., two-spacecraft AMPTE IRM/UKS mission and four-spacecraft Cluster. Control of multi-spacecraft formations is a challenging task and consequently costs of such missions are high. Therefore, use of spacecrafts connected by a tether is proposed for investigations of plasma spatial and temporal variability [2]. If tether mechanism could be successfully implemented on the CubeSat standard pico-satellites, costs of such missions could be reduced even more, as miniaturized Radio Frequency Analyzers needed for basic plasma measurements were developed for pico-satellites.

2. Mission Objectives

Goal of the TwinCube mission [3, 4] is to demonstrate the possibility of using two pico-satellites (CubeSat standard) connected by a non-conductive tether of variable length (up to 1 km) to perform two-point in-situ measurements of Earth's ionospheric plasma with miniaturized Radio Frequency Analyzers. Main objectives can be presented as follow in order of priority:

Objective 1: To perform two-point measurement of low scale electromagnetic plasma turbulence with frequencies of up to 300kHz. The magnetized solar-terrestrial space plasma is a highly non-linear medium, which exhibits many different types of turbulence and instabilities.

Objective 2: To simulate and verify the dynamics of two-satellite system and to learn how to control its behavior, in particular oscillations (induced by Earth's gravity gradient) and its spin (dependent on the tether). Tether is developed to support two-point plasma measurement, but problems such as system dynamics and its controllability are of importance itself.

Objective 3: To develop miniaturized lock and release mechanism and reliable tether winding and unwinding system for 3U standard CubeSat. Systems with tethers have been already tested in space, yet not all of them with success. Proposed herein CubeSat mission provides technical requirements that were not previously studied in detail for this class of missions.

3. Key Performance Parameters

Course and success of the mission depends on system features such as: 1) **length of a tether** – Tether will ensure constant distance between two sub-satellites; this will allow to conduct small scale plasma oscillations measurements with resolution dictated by tether's length; this parameter also determines the frequency of system oscillations induced by gravity gradient and possibility to control length of the tether will allow to study directly this phenomenon; 2) **initial angular velocity of the system** (before unlocking) - before unlocking of the sub-satellites the angular velocity of the system should be known and controlled to predict or omit the situation in which the sub-satellites bounce back after release causing the tether to wind up around the sub-satellites; it is required to stabilize the initial angular velocity of the system to conduct a reliable release of the system halves; 3) **lock and release** (L&R) of the system and **kick-off velocity** (during unlocking) - the two sub-satellites should stay connected in the early phase of the mission by the mean of L&R mechanism; it is planned to use lock mechanism based on melting Dyneema wire to achieve this goal; L&R mechanisms developed in SRC PAS already posses a long space heritage, they are very reliable and compact; 4) **tether properties** (strength, stiffness and material) - the tether should be non-conductive to omit unwanted current generation; we propose a Dyneema wire (same as in L&R) which is relatively light and has excellent strength properties; the tether should be made as a braid to become more elastic (which is profitable, because of shock reduction during tether deployment) and adds redundancy in case of tether degeneration caused by micrometeorites; 5) **available power** for winding / unwinding the tether to be able to control oscillations caused by gravity gradient; worth mentioning is also that the spool mechanism should be self locking so no power should be used to keep in constant the certain length of tether.

4. Space Segment Description

The proposed satellite will be standard 3 Unit CubeSat dividable in-space into two separate tether-connected sub-satellites: 2 unit sub-satellite A and 1 unit sub-satellite B.

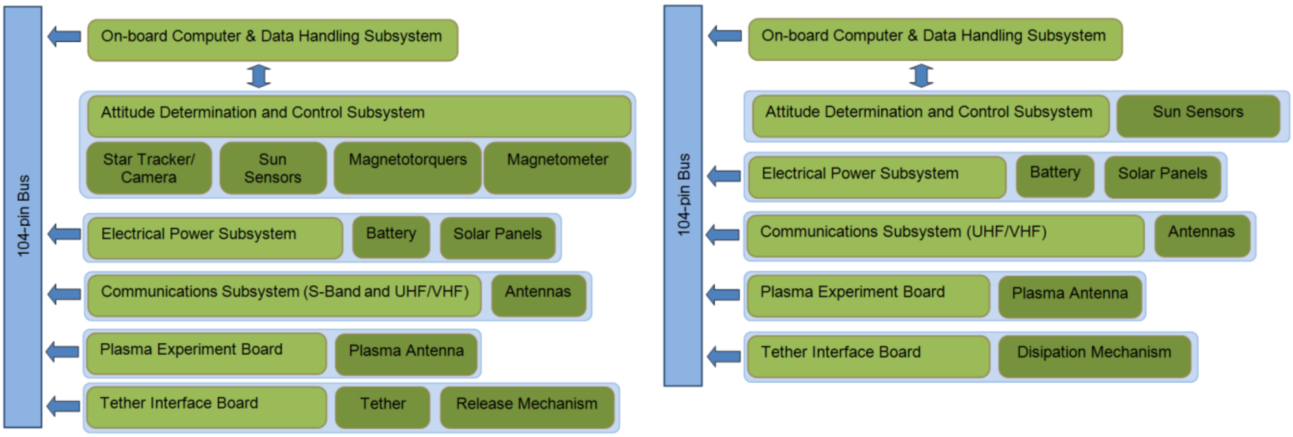

Figure 1 General draft of sub-satellite A subsystems (left) and sub-satellite B subsystems (right).

<u>On-Board Computer (OBC)</u>. The electronic design will be based on standardized PC-104 board. To simplify communication between each subsystem, standard 104-pin header, compatible with most of the commercial components, will be chosen. OBC consists of: computing unit based on 32-bit CPU, volatile RAM memory used as program and temporary data memory, non-volatile storage memory used as buffer for telemetric and scientific data stored for later transmission, peripherals which allow controlling ADCS subsystem and housekeeping sensors.

<u>Electrical Power Subsystem (EPS)</u>. Each sub-satellite will have separate power control unit with battery. Battery capacity is 20 Whr for sub-satellite A and 10 Whr for sub-satellite B. Desired bus voltages provided by EPS should be 3.3V, 5V and Battery Voltage (~8V) needed by radio transceiver. EPS consist of: electronics for monitoring the state of solar panels/battery

and controlling currents on the buses, integrated 10/20Whr Li-Poly battery and solar panels. Preliminary calculations show that in normal operation both sub-satellite will have positive energy budget (energy budget is not shown in abstract).

Attitude Determination and Control Subsystem (ADCS). In the first stages of in-orbit operation ADCS will be responsible for detumbling process that must be performed before the separation of sub-satellites. B-dot control is proposed, which uses magnetometer and three magnetic coils located in perpendicular planes (only sub-satellite A will be equipped with coils). The modified B-dot control will be used to give the initial spin needed for initialization of the separation process. The stabilization of the tethered system will be performed by the passive-active inertial dampers, which will dissipate energy from the system and suppress the oscillations.

Communication Subsystem (COMM). The main function of COMM is a realization of radio link with the ground station using two communications channels: transmission of telemetry (VHF band) and reception of the telecommands (UHF band). In both channels transmission will be realized with bit rate of 1200 bps using AX.25 protocol. Both sub-satellites will be equipped with VHF/UHF communication board. Additionally, to download the scientific data from the payloads, sub-satellite A will be equipped with the S-band transmitter (38 400bps bit rate).

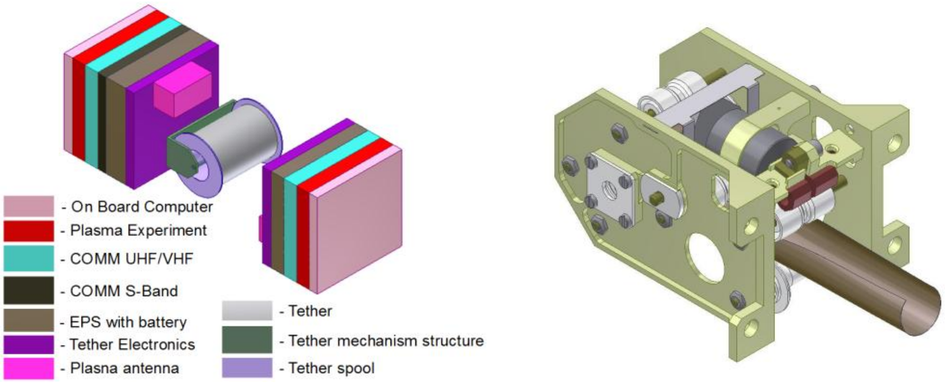

Figure 2 Schematic distribution of TwinCube components between sub-satellites A and B (left) and CAD design of miniaturized Radio Frequency Analyzer antenna (right).

Plasma Experiment (PE). Each sub-satellite will be equipped with miniaturized Radio Frequency Analyzers which will perform measurements of electromagnetic emissions of surrounding plasma. PE unit consist of: light and innovative antenna with low-noise preamplifier, analog Front-End including low-pass filter with cutting frequency around few MHz and low-noise amplifier with variable gain, 12/14-bit Analog to Digital Converter with maximum 10MSambles/sec and Digital Processing Unit with FFT/Wavelet processor. Tubular boom antenna(25x45x25mm in stowed configuration, Figure 2 right) will be made from beryllium bronze allow and will be deployed from rolled-up configuration up to 1m length.

Tether Experiment (TE). Non-conductive tether (about 1km long) will be stored on a spool in sub-satellite A. The tether winding and unwinding mechanism will occupy approximately one-third of the satellite and will be placed at its center. Unwinding and winding of tether will be controlled by stepper/BLDC motor installed inside the spool to achieve compact solution.

Table 1 and Table 2 show mass budgets for both sub-satellites.

Table 1 Sub-satellite A mass budget

Sub-satellite A (2U)	Mass [g]
OBD&OBDH	70
EPS	245
COMM UHF/VHF/S-Band	180
COMM Antennas	146
PLASMA Experiment	100
PLASMA Experiment Antenna	70
ADCS Components	259
Camera	166
Tether Spool	346
Tether Electronics/Mechanics	250
Separation Mechanism	50
Harness	50
Screws & Assembly	50
2U Structure	150
Walls (7 Walls)	196
Total sub-satellite A	**2328**

Table 2 Sub-satellite B mass budget

Sub-satellite B (1U)	Mass [g]
OBD&OBDH	70
EPS	175
COMM UHF/VHF	94
COMM UHF/VHF Antennas	87
PLASMA EXP	100
PLASMA EXP Antenna	70
ADCS Components	25
Dissipation Mechanism	50
Harness	50
Screws & Assembly	50
1U Structure	75
Walls (4 Walls)	112
Total sub-satellite B	**958**

5. Space Operation Scenario

For the proposed CubeSat mission initial mission outline and operation sequence is as follows: 1. Lock and release mechanism binds together sub-satellite A and B. 2. TwinCube is ejected from P-POD as one part. 3. Communication antennas automatic deployment after 30 minutes. 4. Stabilization process and first self-test of mayor subsystems. 5. Plasma antenna deployment and self-test of plasma experiment boards with possible one point measurements. 6. Lock and release mechanism unlocks sub-satellite A from sub-satellite B, kick-off spring separates two sub-satellites. 7. Verification of the release from sensors and camera. 8. Motor starts to unwind tether from spool with a very low speed determined from simulations and experiments (dynamics of separation will be tested before the mission on the planar air-bearing test-bed). 9. Self-test of both plasma experiments and examination of two sub-satellites dynamics. 10. Commencement of plasma experiment. 11. After successful realization of plasma experiment, commencement of tether experiment. 12. Deorbitation and termination of the mission.

6. Orbital Dynamics Simulation

Since two-point plasma measurements relies on successful separation of two sub-satellite and stability of the tethered system, preliminary simulation of two point bodies linked by a simple tether model were performed (Figure 3). In fact, the dynamics is a three body system (Earth and two cubes) with additional potential of tether action

$$U_{tether}(d) = \begin{cases} 0, & d < L \\ \frac{1}{2}k(d-L)^2, & d \geq L, \end{cases}$$

where $d > 0$ is a distance between the points. Further, we assume the Earth rests in inertial reference frame, and the cubes do not affects the gravitational field. Therefore the overall system dynamics is expressed in the cubes positions $\vec{r_1}$, $\vec{r_2}$, by

$$m_1\ddot{\vec{r_1}}(t) = -m_1\nabla U(\vec{r_1}) - \nabla U_{tether} - \vec{F}_{diss}$$
$$m_2\ddot{\vec{r_2}}(t) = -m_2\nabla U(\vec{r_2}) + \nabla U_{tether} + \vec{F}_{diss},$$

where $U = -GM/r$ is the Earth gravitational potential. The friction $\vec{F}_{diss}$ describes energy dissipation in a process of tether extension. The motion is integrated by SimMechanics (part of Matlab/Simulink environment). Preliminary results of dynamics simulation are shown in [3].

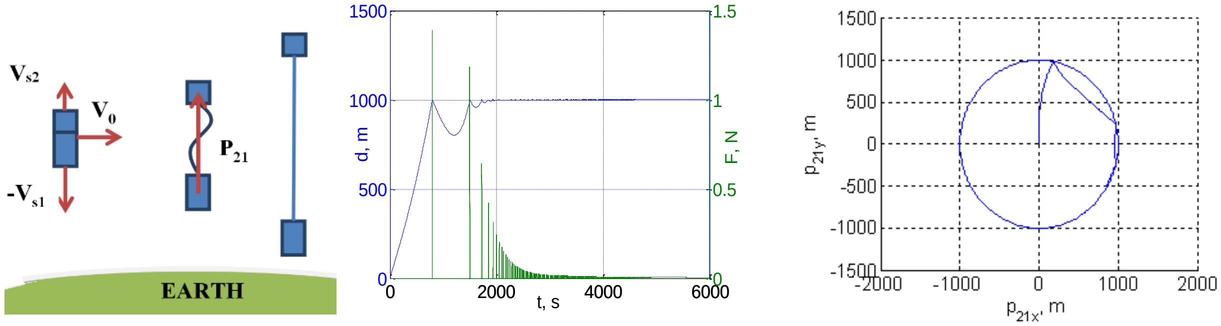

Figure 3 Left: Schematic concept of simulation. Middle: relative distance between the satellites and tension force of the tether. The peaks of force corresponds to the impacts of satellites on stretched tether. Right figure: satellites relative position. After a series of impacts satellites forms a combo which rotates with respect the mass centre.

7. Infrastructure and Ground Segment

SRC PAS has necessary equipment and assembly/test facilities, which were used during developing qualification and flight models of various space devices. This includes the following facilities: 1.) 100 m^2, 10 000 class clean room with separate 100 class clean box; 2.) Thermal vacuum chamber placed in clean room, capable to perform vacuum tests in range of temperature -120 to +100°C; 3.) Two Laminar Flow Clean Bench and two climate testing chambers with temperature range from -50 to +50°C; 4.) Stand for vibration tests with capability to perform test with 10kg device with acceleration up to 20G; 5.)EMC test chamber; 6.) Mechanical workshop with six milling machines. Additionally, air-bearing test-bed consisting of 2x3 meter granite table (flat and precisely leveled, friction coefficient of magnitude 10^{-5}) might be used to test L&R mechanism and dynamics of two sub-satellites.

SRC PAS has access to Ground Station located at near Nicolaus Copernicus Astronomical Center. This station has been developed since 2011 mainly for communication with BRITE satellites. However, it is also capable to communicate with all satellites which have their radio systems working in VHF/UHF amateur bands and S-Band. Additionally, Center for Astronomy at Nicolaus Copernicus University, one of the cooperators of SRC PAS, is equipped with two radio telescopes - 15m and 32m antennae. While the 32-m radio telescope is dedicated to regular radio astronomical observations, the 15-m antenna might be utilized for Ground Station purposes.

Team members have experience in performing test campaigns of small satellites (BRITE-PL, PW-Sat). Moreover, successful stratospheric balloon flights were performed by SRC staff during test campaign of BRITE satellites.

8. References

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[4] Szewczyk T., et al.: TwinCube – Proposal for 3U CubeSat Tethered Satellite System. In: Proceedings of the 5th European CubeSat Symposium, Brussels, Belgium, 2013.