Title: Piezo-active Suspension system for Space Interferometry and Broadband Communications

Primary Point of Contact (POC) & email: Algis Karpavičius , algis.karpavicius@gmail.com
Co-authors: Darius Gailius, Domantas Bručas, Andrius Vilkauskas, Vidmantas Tomkus, Valdas Grigaliūnas
Organization: Kaunas University of Technology

(x) We apply for Student Prize.
(x) Please keep our idea confidential if we are not selected as finalist/semi-finalist.

Need

Space observatories of the last decade like NASA Wilkinson Microwave Anisotropy Probe (WMAP) and ESA Planck mission played the key role in establishing the current Standard Model of Cosmology. ESA Infrared Herschel mission and Gaia Space telescope provide with the new knowledge about the position, distance and luminosity of the stars and it's formation.

Proposed mission idea of piezo-active suspension system enables the compensation of the disturbances and precise pointing of the laser mirrors or antennas used in space interferometry missions and long distance communications.

Future ESA Laser Interferometer Space Antenna (LISA) and Japanese DECI-Hertz Interferometer Gravitational wave Observatory (DECIGO) planned for the detection and measurement of gravitational waves of astronomical sources use extremely accurate accelerometers with picometer resolution. Precision pointing is crucial for the Link budget of long distance optical and submilimeter communications. Conventional large space systems are more affected by solar pressure, atmospheric drag and sensitive to vibrations of the elements of the Altitude and Control systems.

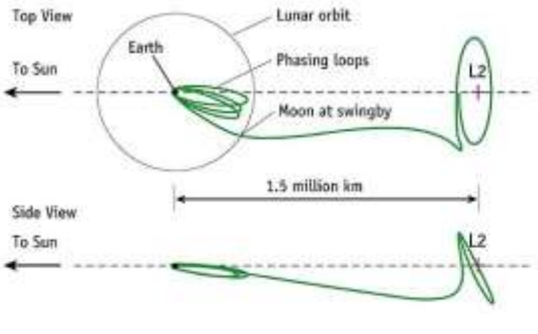

Fig 1. WMAP L2 Lagrange point mission.

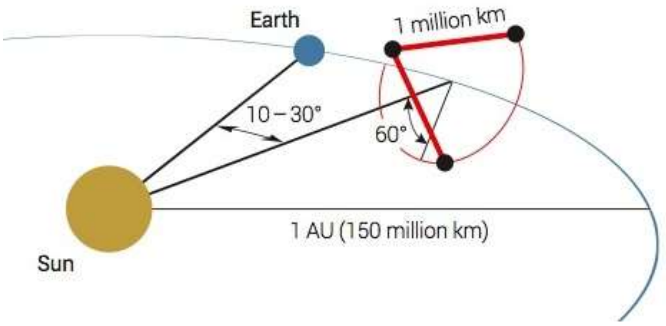

Fig 2. LISA space interferometer configuration.

Mission Objectives

- Launch the microsatellite with the mass <50 kg into the highly elliptical orbit with its apogee 340,000 kilometers or insert it into Earth-Moon Lagrange L2 Halo orbit
- Establish Duplex S-band communication link for TT&C
- Establish Duplex 1.55 μm Laser link between the Spacecraft and Ground terminal

- Test the accuracy of Attitude control of the Spacecraft provided by Field-emission electric propulsion (FEEP) or Colloid thrusters
- Compensate the vibrations of the satellite platform and the pointing resolution error by means of piezo –active suspension to less than $<10^{-12}$ rad

Concept of Operations

For the implementation of the mission goals one microsatellite with the mass <50 kg to Earth-Moon L2 point will be launched. The spacecraft will be inserted into the 200 km LEO or GTO orbit and using additional propulsion module will be transferred to Halo orbit with the radius of 3500 km. This position has advantage of the permanent coverage for data relay satellite of far side of the moon. Optionally the satellite can be launched into the highly elliptical orbit with its apogee of 340,000 kilometers. The spacecraft will contain precise attitude control provided by Field-emission electric propulsion (FEEP) or Colloid thrusters and piezoactive suspension system. The pointing accuracy and optical communication through output will be measured by 1.55 μm Laser duplex system. Ground terminal will comprise S-band TT&C and optical payload ground terminal.

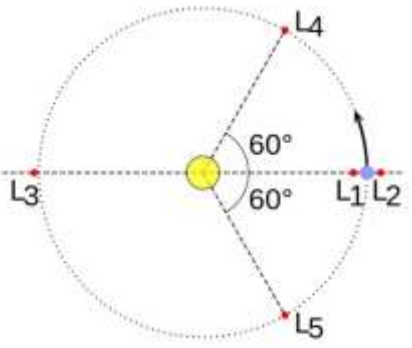

Fig 3. Lagrangian points.

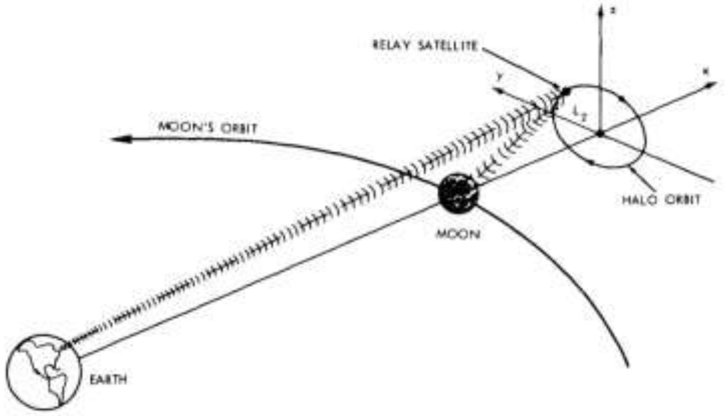

Fig.4. Earth - Moon L2 Relay satellite at Halo orbit.

Key Performance Parameters

The goals of the future LISA mission is to demonstrate the test feasibility of laser interferometry with picometer resolution at low frequency – approaching 10^{-12} m $Hz^{-1/2}$ in the frequency band 1-30 mHz. The pointing accuracy of LISA mission at the scientific mode is required at 1.7×10^{-6} degree corresponding 30×10^{-9} rad. It is reported that the resolution Gaia mission achieved is in the range of 24 μarcsec corresponding 0.12×10^{-9} rad. FEEP thruster provides the thrust from 0.1 to 150 μN, with thrust resolution ≤0.1 μN and specific impulse ≥4000 s. Resolution of the interferometer can be defined as $\theta_{\text{interferometer}} = \lambda/2b$ rad, where λ is the observing wavelength and b is the baseline of the interferometer. In the Table 1 the resolution limits for the interferometer arms at Earth – Sun and Earth – Moon L2 point distances for 1 micron Laser wavelength and 1 mm radio waves are calculated.

Table 1.

	Distance from Earth, 10^9 m	Wavelength, 10^{-6} m	Resolution angle θ, rad 10^{-15}	Actuator resolution*, 10^{-15} m	Delta V from LEO, km/s**
Earth – Sun L2	1.5	1	0.33	0.033	3.4/7.4
Earth – Sun L2	1.5	1 000	330	33	3.4/7.4
Earth – Moon L2	0.45	1	1.1	0.11	3.0/7.0
Earth – Moon L2	1.5	1 000	1 100	110	3.0/7.0

* - for 20 cm diameter laser mirror or antenna dish, ** - high trust/low trust

Thruster system

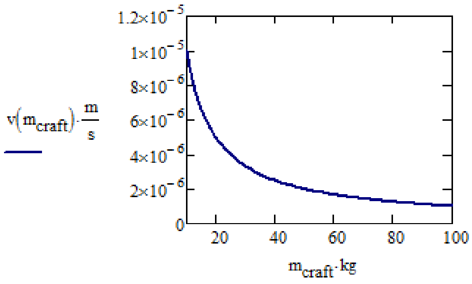

Fig. 5 Craft speed dependence on mass per one thruster cycle

One of the main problems in case of the mission (especially for small scale spacecraft) is the vibration noise caused by multiple factors (mainly by satellite systems) and the spatial position inaccuracies. These factors are often caused by rough actions of the propulsion systems (which is far more evident for small satellites). Thrust (IL-FEEP prototype) $F_{thrust} = 100\,\mu N$, total propellant mass $m_{total} = 67\,g$, total impulse $J_{total} = 2000\,Ns$, total operation time *230 days* (1 987 200 s). $F_{thrust} = v_e\,\dot{m}$, *where* v_e – *effective exhaust velocity,* $\dot{m}$ – *exhaust gas mass flow* $v_e = F_{thrust}/\dot{m} = 29659.7\ km/s$. Exhausted mass during one thruster cycle (assumed 1 s): $m_{cycle} = m_{total}/t_{total} = 3.372\cdot10^{-9}\ kg/s$, therefore excitation velocities for various spacecraft weights (which corresponds to displacement during 1 s period) can be evaluated and it shows that for low-weight space crafts it is essential to reduce impulse/velocities ($v_{craft} = v_e\cdot m_{cycle}/m_{cract}$) to achieve better displacement resolution (Fig. 5).

Fig 6. 3-axis piezoelectric actuators based on radial resonant travelling wave oscillations.

To change trust resulted speed step nature (characteristics) the piezoactive suspension is introduced. Hereafter the piezoactive suspension system is proposed which is able to work in two modes: passive energy dissipation and active velocity shape regulation. For the first mode the piezoactuator is connected in series with resistor ($R=1/2\pi fC$, f – is related to the damped oscillation frequency) to dissipate energy as heat. Vibrations energy dissipations are up to ~50%, so it is expected that the energy 1,585J (100uN thrust; 1s) will be decreased by half. The second mode is active velocity changing system where the piezoactuator is used in conjunction with FEEP system and to influence absolute velocity of the main construction mass. Quasistatic suspension could actively control the vibration noise from the thruster (pushing the thruster “outwards” or pulling it “inwards”). Additionally in some cases it could be used to provide the nanometer movement to the entire spacecraft by pushing or pulling the inactive thruster.

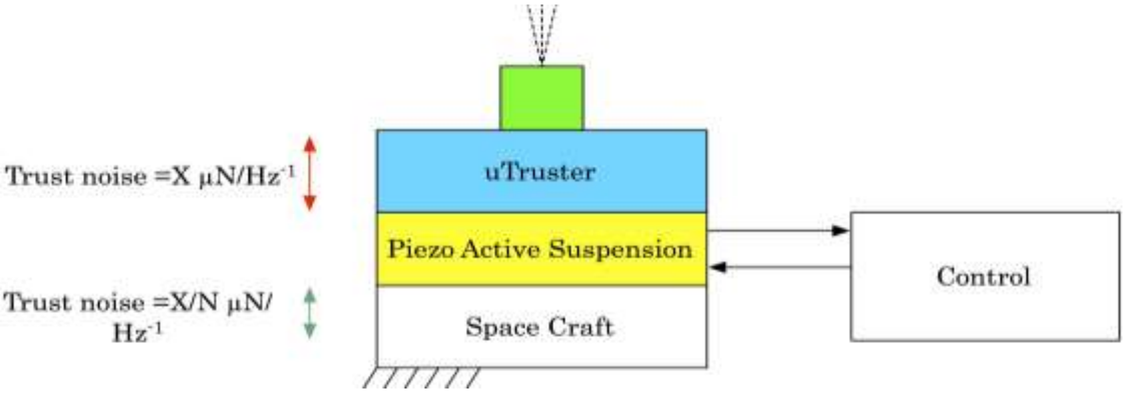

Fig 7. Piezoactive suspension of microthruster.

In the Fig. 7 the concept of operation of quasistatic piezoactive suspension is provided.
(Atitude control system will be supplemented with the 3-axis reaction piezo sphere (Fig. 6) which will be used for rough attitude control ~0,2mNm.

Space Segment Description

According to the NASA Lunar LADEE mission heritage the telecommunication laser module LLST budget consist of the Space Terminal:

– 10 cm aperture mirror, 0.5 W, 1.55 μm
– 40-622 Mbit/s in downlink, 10-20 Mbit/s in uplink
  – Duplex operation, fully gimbaled
  – LLST mass, power 32.8 kg (with margin),
  – 136.5 W

and Ground Terminal:

– Downlink Receiver
4 @ 40 cm aperture; 40-622 Mbit/s
Superconducting Nanowire Detector Arrays
– Uplink transmitter: » 4 @ 15 cm aperture, 10 W; 10-20 Mbit/s

For the insertion from LEO into the L2 Hallo orbit using High thrust propulsion 3 km/s and 7 km/s for Low thrust propulsion Delta V is required.

Orbit/Constellation Description

Advantage of L2 point allows the consumption of keeping in L2 point of 30–100 m/s delta-v per year. After the validation of the technology the system could be implemented in data relay satellite or Lunar orbital station.

Implementation Plan

The project is planned for implementation in the collaboration of Kaunas University of Technology, Space Science and Technology Institute from Lithuania. The design cycle of the critical payload of piezoelectric components is planned in the period of 15 months from Aug

2014 – November 2015. The project is planned to be financed by Lithuanian Agency of Science and Innovation and will be applied for the future ESA Lithuanian Partnering Co-operating State call. The satellite bus platform containing electrical ion propulsion has to be developed in parallel. Complimentary ridesharing possibilities of the system at NASA ARC spacecraft platforms in the middle of 2016 will be discussed. The top 5 project risks are:

- Development of piezoelectric closed control loop positioning system for 1- and 3-axis piezoelectric actuators at subnanometer level
- Testing of positioning system in 1g gravitational environment will not allow to reproduce the microgravity conditions in full scale
- Optical communication module is planned to be provided by subcontractor
- The success of the mission depends on launch or ridesharing availability
- Insertion into the Moon-Earth Lagrange point raising special requirements for launcher

References

1) Optical interferometry in astronomy, John D Monnier, University of Michigan Astronomy Department, 941 Dennison Building, 500 Church Street, Ann Arbor, MI 48109, USA, URL: http://dept.astro.lsa.umich.edu/~monnier/Publications/ROP2003_final.pdf
2) Basics of Radio Astronomy for the Goldstone-Apple Valley Radio Telescope, Diane Fisher Miller Advanced Mission Operations Section: URL http://www.jpl.nasa.gov/radioastronomy
3) Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Sky Maps, Systematic Errors, and Basic Results" URL: http://lambda.gsfc.nasa.gov/product/map/dr4/pub_papers/sevenyear/basic_results/wmap_7yr_basic_results.pdf
4) LISA Science Requirements Document, Reference LISA-ScRD-004, URL: http://lisa.nasa.gov/Documentation/LISA-ScRD_v4.1a.pdf
5) Planck: The Scientific Programme" (http://www.rssd.esa.int/SA/PLANCK/docs/Bluebook-ESA-SCI%282005%291_V2.pdf). European Space Agency. 2005. ESA-SCI(2005)1
6) A Halo-Orbit Lunar Station, Robert W. Farquhar, NASA Goddard Space Flight Center, URL: http://www.nasaspaceflight.com/_docs/haloOrbitLunarStation.pdf
7) Strategic Considerations for Cislunar Space Infrastructure, Wendell W. Mendell, Steven Hoffman. NASA Johnson Space Center, URL: http://ares.jsc.nasa.gov/HumanExplore/Exploration/EXLibrary/DOCS/EIC042.HTML
8) Benefits of Optical Communications, URL: http://spaceflightsystems.grc.nasa.gov/PlanetaryScience/documents/LADEE-LLCD.pdf
9) Bernard L. Edwards, Dave Israel, Keith Wilson, John Moores, Andrew Fletcher, "Overview of the Laser Communications Relay Demonstration Project," Proceedings of SpaceOps 2012, The 12th International Conference on Space Operations, Stockholm, Sweden, June 11-15, 2012, URL: http://www.spaceops2012.org/proceedings/documents/id1261897-paper-001.pdf
10) Piezoelectric actuator for micro robot used in nanosatellite. Vibroengineering PROCEDIA : international conference "'Vibroengineering- 2013", Druskininkai, Lithuania, 17-19 September 2013, URL: http://www.jve.lt/Vibro/VP-2013-1/VP00113090010.pdf
11) Synthesis of trajectories in piezoelectric altitude control devices for nanosatellites, R. Bansevicius, G. Kulvietis, D. Mazeika, A. Drukteiniene, I. Tumasoniene, V. Bakanauskas. 11-th International Conference on Vibration Problems, Lisbon, Portugal, 9-12 September 2013. URL: http://www.icovp.com/components/com_breezingforms/uploads/484_paper0.pdf