Seminar at National Space Organization, Taiwan

Research Fields and Projects in Keldysh Institute for Applied Mathematics

Dr. Danil Ivanov

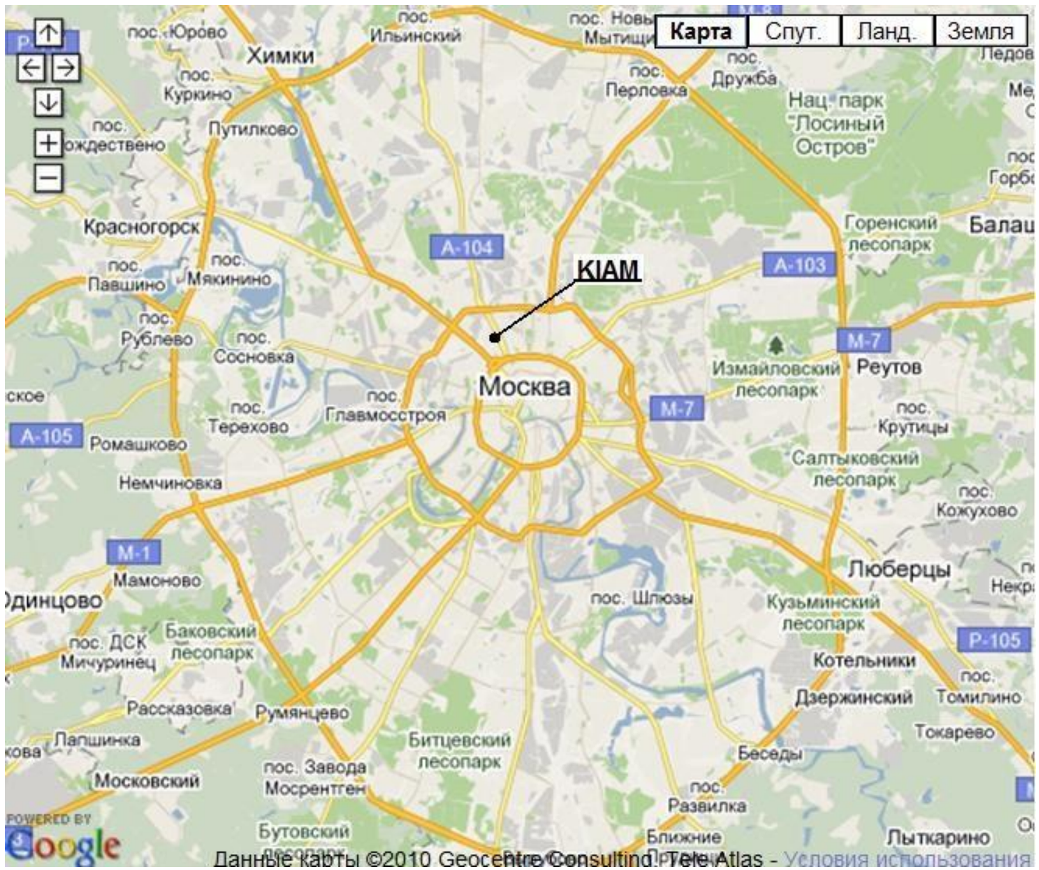
Senior Researcher, Associate Professor

Keldysh Institute for Applied Mathematics, Moscow, Russia

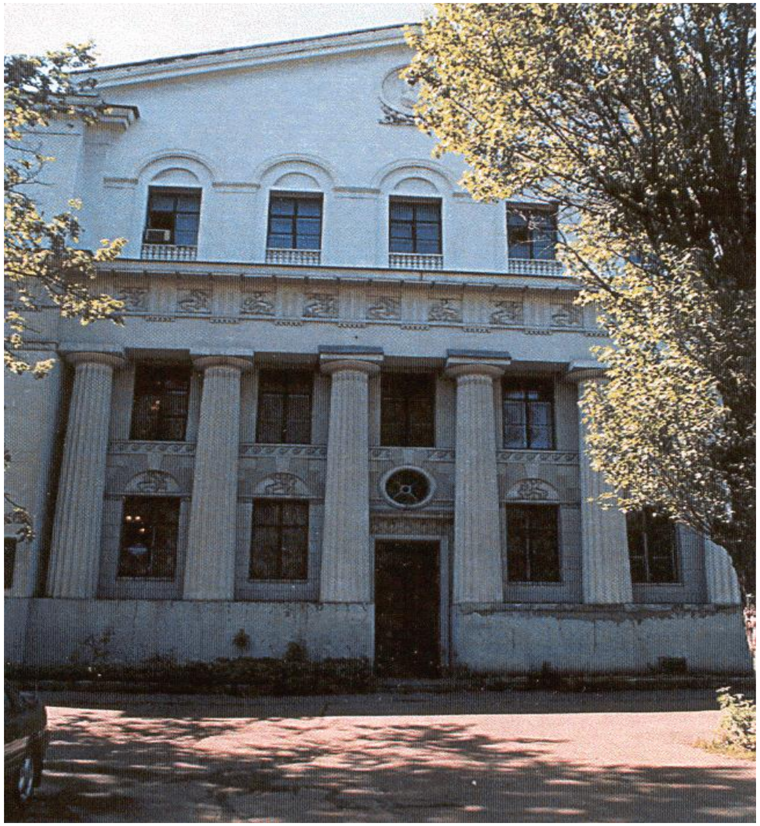
Content

- What we are and who we are
- Collaboration with Taiwanese organizations
- Attitude control for microsatellite missions
- Non-rigid structures in space
- Remote sensing by microsatellites
- Space Formations
- Cleaning the space
- Interplanetary missions by microsatellites
- Conclusion

Keldysh Institute for Applied Mathematics of Russian Academy of Sciences (KIAM)



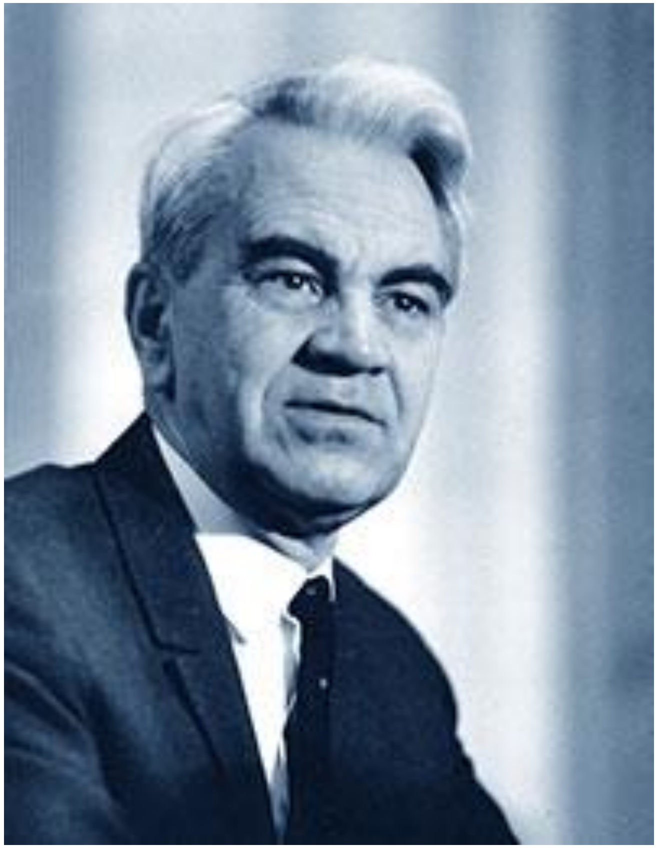
Keldysh Institute for Applied Mathematics of Russian Academy of Sciences (KIAM)



KAM was established in 1953 to lead in the principal National Programs:

- exploration of space
- nuclear energy use
- development and application of numerical methods (for computers only growing)

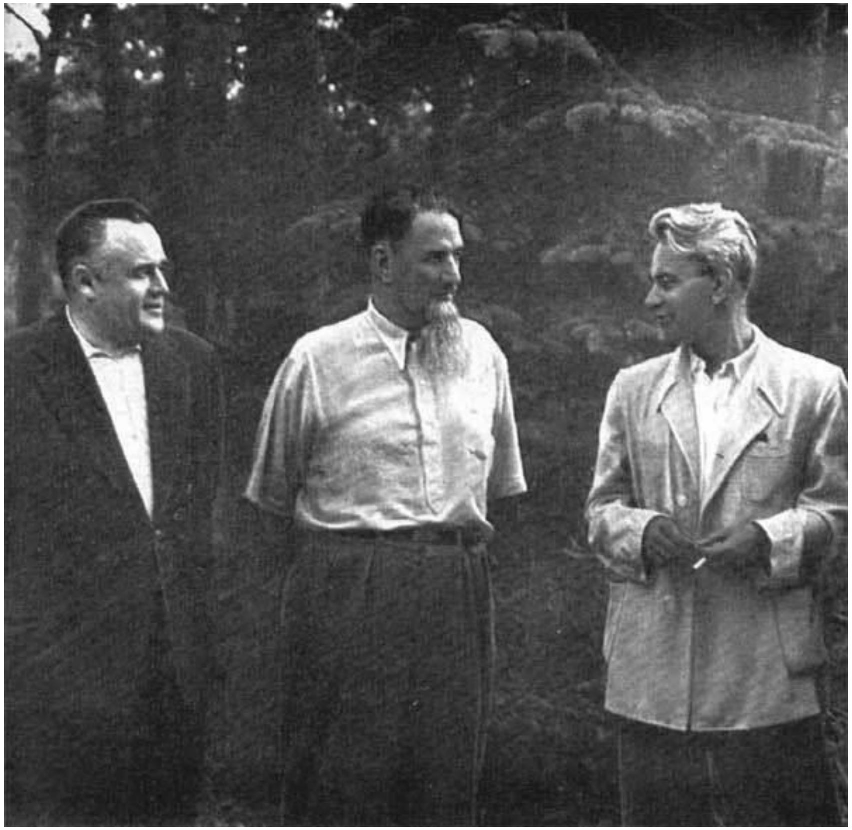
Founder of the Institute



Academician Mstislav Keldysh was a Founder and a first Director in 1953-1978

In 60th he was officially named Principal Theoretician of the Soviet Cosmonautics but he is also known as a outstanding mathematician and mechanician

The famous 3K
(Koroljev, Kurchatov, Keldysh)



From left to the right:

Sergey Koroljev – "the Chief Designer of the Soviet Cosmonautics"

Igor Curchatov – "the Father of the Soviet Nuclear Programm“

Mstislav Keldysh – "the Chief Theoretician of the Soviet Cosmonautics"

Main issues of KIAM's research activity

- Mathematical modeling and computer simulation to solve modern problems in science and technology
- Mathematical problems and theory of numerical methods development
- Fundamental and applied research in space flight mechanics
- Software development, parallel computing and multimedia application

Our scientists first applications in space

- Since First Artificial Satellite – Sputnik (4.10.1957) computing and multimedia application
- Through 1959 - first taking picture of the Moon back side & first fly-by maneuver
- And another …

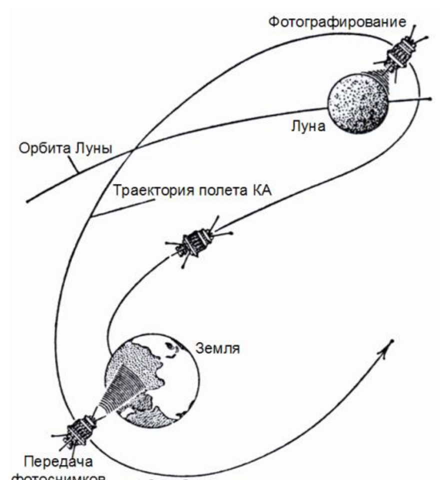
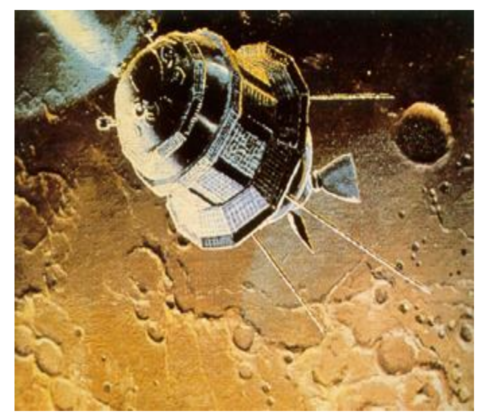


Схема полета КА «Луна-3»



Luna-3 exterior

Brief details about KIAM

- KIAM comprises 23 Departments and above 350 researcher including 3 Members and 4 Corr.-Memebrs of RAS, 60 Doctors of Sci. and 140 PhDs.
- KIAM's Ballistic Center is involved with the Mission Control Center (Korolyev City near Moscow) in a circus of mission control for manned and automatic SC.
- Main branches of research:
  - Fluid- and aeromechanics, nuclear processes,
  - numerical methods of computing and calculations,
  - theoretical mechanics, fundamental and applied celestial mechanics and control, robotics control,
  - IT and computer vision
- Educating Chairs of the Moscow State University, the Moscow Institute for Physics & Technology, the Bauman State Technological University located at KIAM

Our team

Areas of our competence

- space mission dynamics simulation,
- math models of dynamics development,
- attitude and orbital control algorithms synthesis,
- lab facilities implementation to validation campaign,
- small satellite strategy development,
- mission design

Branches of applications:

- single satellites for various applications within near-Earth missions including large communication and small-micro-nano-Cube satellites
- formations and constellations of satellites
- interplanetary missions to libration points and another planets

KIAM's collaboration with Taiwan

Joint events (Workshops and Conferences held together):

- COSPAR Colloquium on Scientific Microsatellites. Microsatellite as Research Tools, National Cheng Kung University, December 1997, Tainan;
- Joint Taiwan Russian Symposium "Advanced Problems of Mechanics in Geology, External Geomonitoring and Wind Engineering", Ching Yun University, December, 2007, Jung-Li;
- 6th IAA International Workshop on Satellite Constellation and Formation Flying, November, 2010, National Space Organization (NSPO), Taipei;
- Remote Sensing Satellite Technology Workshop – RSSTW2012, November, 2012, NSPO, Hsin-Chu

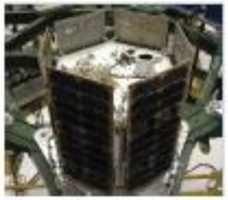
Projects:

- Dynamics and Control of Small Satellites in the Geomagnetic Field, Joint project # 07-01-92001 of the National Science Council of Taiwan and the Russian Foundation for Basic Research (2007-2010);
- **Generic spacecraft dynamics simulation, Contract No.: NSPO-S-102089 (2013);**
- **Satellite multiple solar panel dynamics model development, Contract No.: NSPO-S-103132 (2014)**

MoI between NSPO and KIAM (2010)

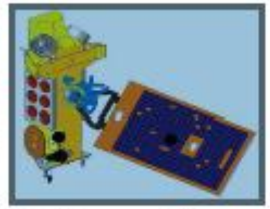
Dr. An-Ming Wu (Vice-Chair), Dr. Guey-Shin Chang (Chair),
Prof. Mikhail Ovchinnikov, Dr. Andrey Baranov

Partners' Small Sats with ACS developed by the team

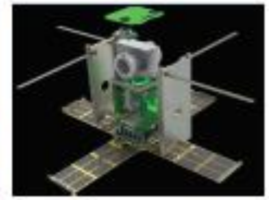


The first Russian private microsatellite TabletSat-Aurora (launched in 2014), active attitude control system, 26 kg (credit Sputnix Ltd)

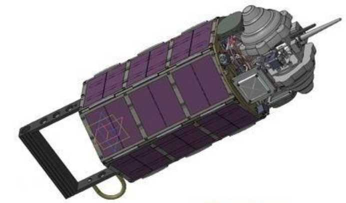
The Russian microsatellite Chibis-M (launched in 2012), active attitude control system, 43 kg кг (credit SRI of RAS)



The Taiwanese satellite Formosat-7 (13), active attitude control system, 250 kg(credit NSPO)



The American nanosatellite CXBN-2, active attitude control system, 2.5 kg (credit Morehead State University)



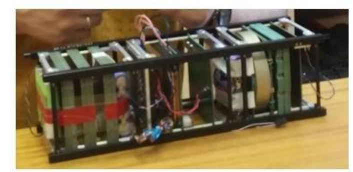
The Russian nanosat TNS-0 #2 (launched in 2017) passive magnetic attitude control system, 6 kg (credit JSC Russian Space Systems)

The German picosatellite (cubesat) BeeSat-3 (launched in 2013), passive attitude control system with hysteresis plate, 1 kg (credit TUB)

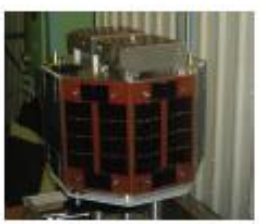
The Russian nanosatelliteSamSat-QB50,aerodynamical attitude control system with hysteresis rods, 2 kg(creditSamara State Aerospace University)

The first Russian nanosatellite TNS-0 №1 (launched in 2005), passive magnetic attitude control system, 4.5 kg (credit JSC "Russian Space Systems")

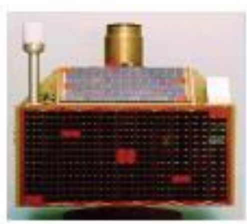
The Russian nanosatellite TNS-1, active magnetic attitude control system, self-rotation stabilization, 10 kg (credit JSC "Russian Space Systems")



The Russian AIS-Cubesat, active magnetic ACS, 3 kg (credit JSC Russian Space Systems)

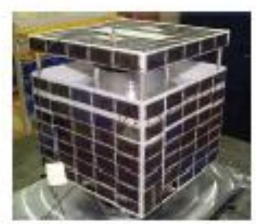


The Italian microsatellite UniSat-4 (launched in 2004), passive magnetic attitude control system, 12 kg (creditUniversity of Rome "La Sapienza")



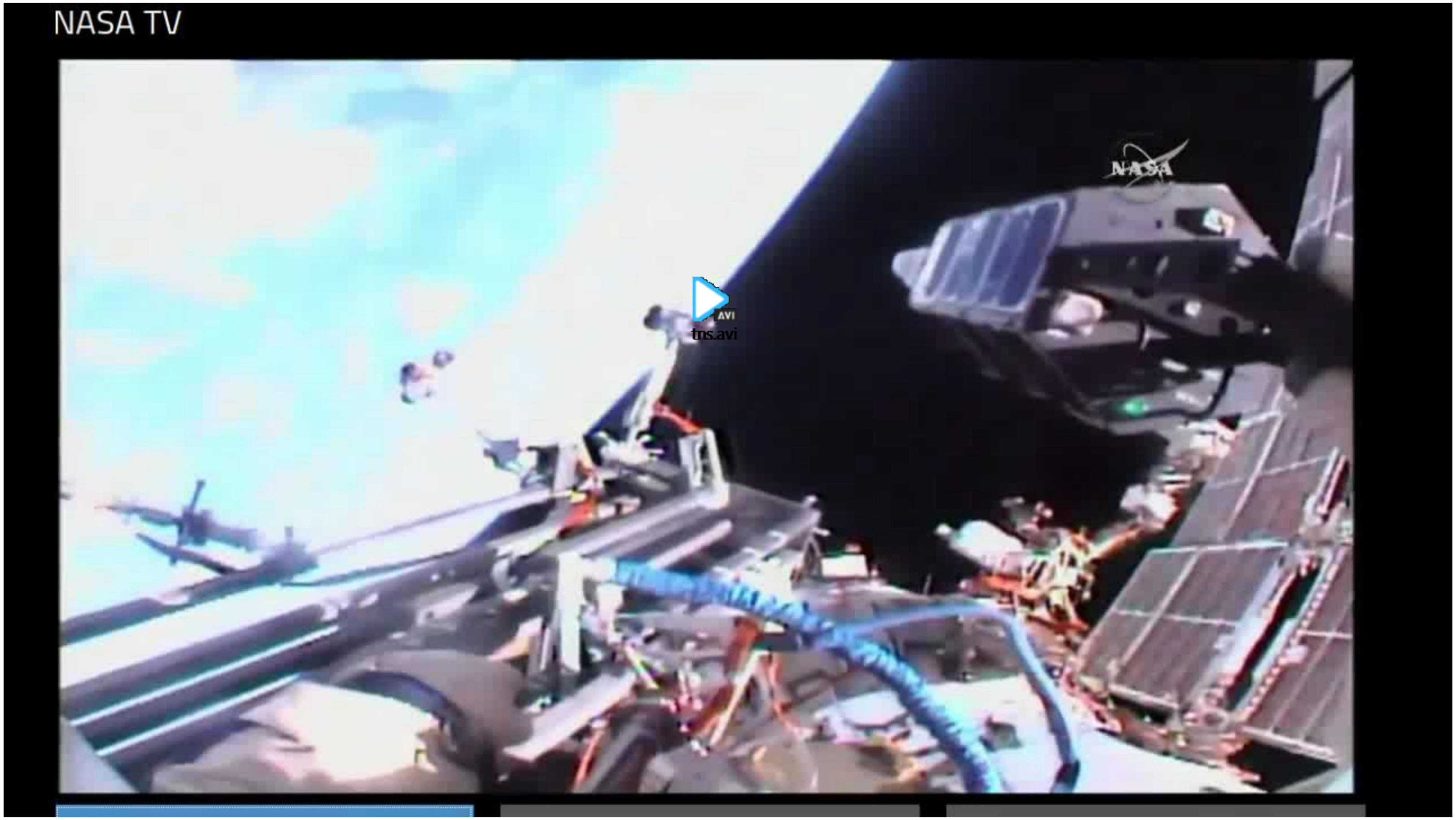
The Pakistani microsatellite BADR-B (launched in 2001), semiactive gravitational attitude control system, 70 kg (credit SUPARCO)

The Russian nanosatellite REFLECTOR (launched in 2001), passive gravity gradient attitude control system, 7 kg (credit Institute of Precision Instrument Engineering)

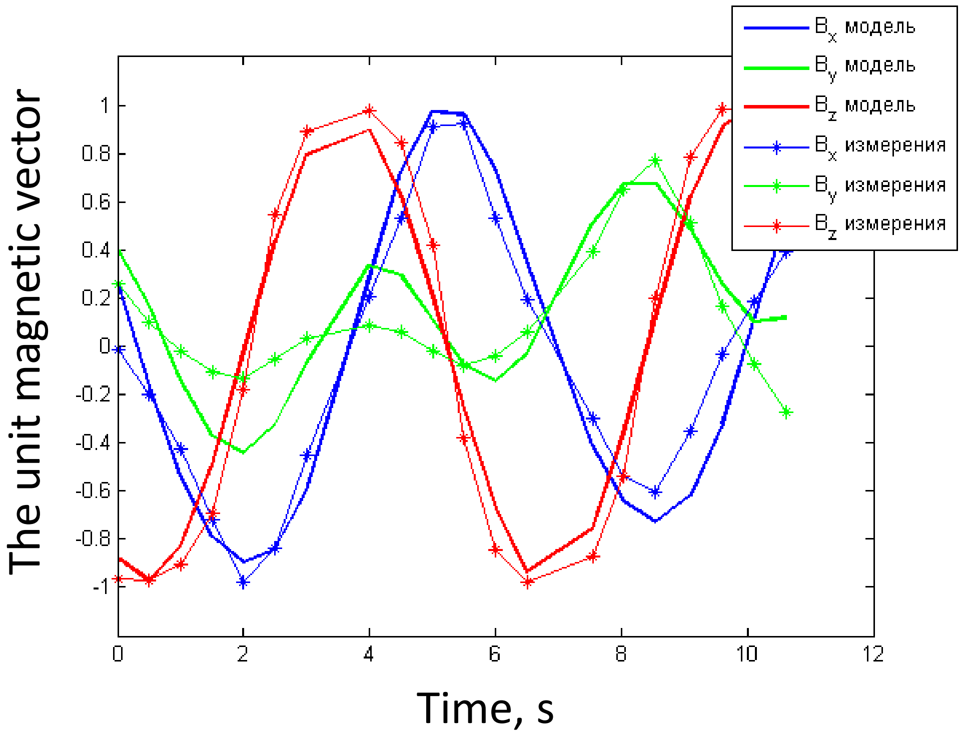


The Swedish nanosatellite Munin, (launched in 2000), passive magnetic attitude control system, 6 kg (credit IRF)

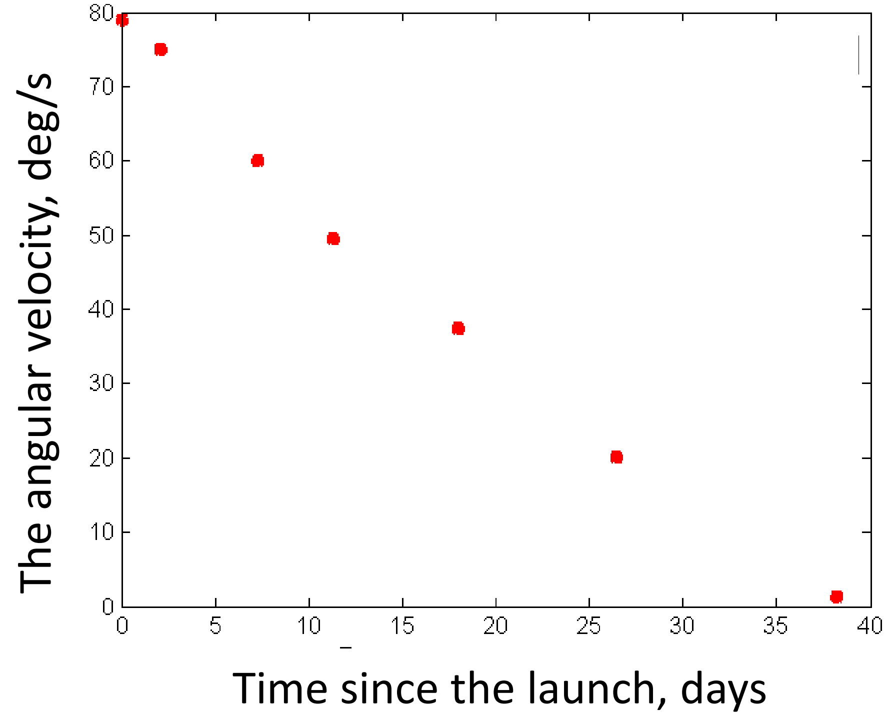
The recent launch: TNS-0 №2 nanosatellite 17/08/2017



TNS-0 №2 nanosatellite angular motion



The estimated and measured unit magnetic vector



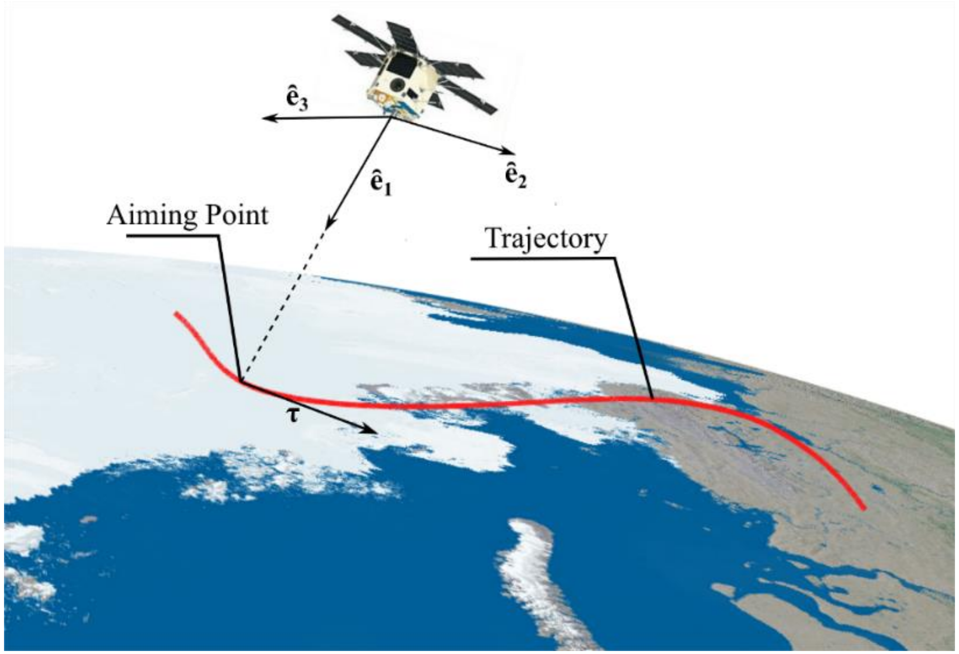
The estimated angular velocity

A current projects of our team

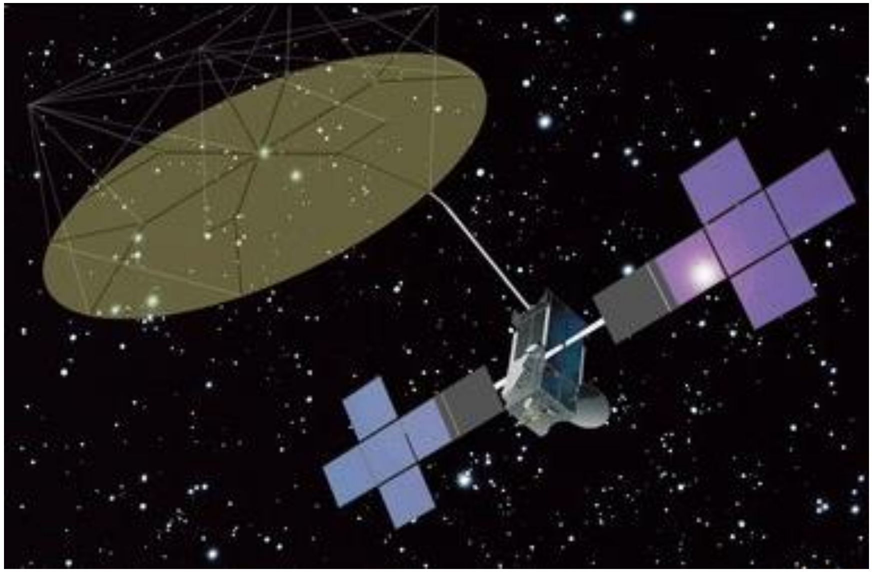
A few projects are under development in

- attitude control,
- orbital control,
- formation flying control,
- debris removal,
- interplanetary mission design

Satellite Attitude Control for Earth Remote Sensing and Communication



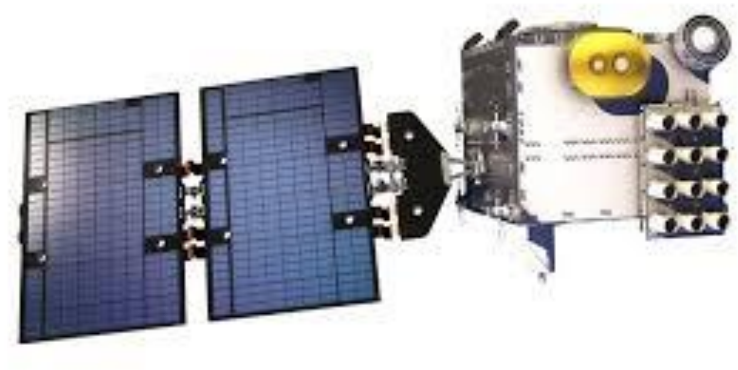
Complex trajectory tracking



Attitude stabilization of spacecraft with flexible elements

Mathematical model for Formasat-7 solar panel

To identify and control motion the mathematical model was developed and implemented



FORMOSAT 7

$$\mathbf{S}\begin{pmatrix}\dot{\boldsymbol{\omega}}_1\\ \dot{\boldsymbol{\psi}}\end{pmatrix}=\begin{pmatrix}\mathbf{N}_1\\ \mathbf{N}_2\end{pmatrix}$$

Here **S** is 8x8 matrix and for example is

$$\mathbf{N}_1=\sum_{i=1}^{4}\mathbf{M}_i-\boldsymbol{\omega}_i\times\mathbf{I}_i\boldsymbol{\omega}_i-\mathbf{I}_2\mathbf{f}_2-\mathbf{I}_3\mathbf{f}_3-\mathbf{I}_4\mathbf{f}_4-m_{1,2}\mathbf{d}_{1,2}\times\mathbf{j}_{1,2}-m_{1,3}\mathbf{d}_{1,3}\times\mathbf{j}_{1,3}-$$
$$-m_{1,4}\mathbf{d}_{1,4}\times\mathbf{j}_{1,4}-m_{2,3}\mathbf{d}_{2,3}\times\mathbf{j}_{2,3}-m_{2,4}\mathbf{d}_{2,4}\times\mathbf{j}_{2,4}-m_{3,4}\mathbf{d}_{3,4}\times\mathbf{j}_{3,4}$$

Satellite Formation Flying design

Two main directions of research:

- Direct and indirect optimization problems solution implementation (the control thrust can be directed wherever is needed)
- External forces implementation (aerodynamic resistance, Colomb interaction, mass exchange, solar pressure etc) and existed natural configurations seeking (subject of our interest)

Tetrahedron formation maintenance

Problem statement:

- Given four satellites on closed, possibly elliptical, orbits
- Need to obtain a reference orbit in order that the corresponding tetrahedron maintains over time
- Also provide a control algorithm for several satellites to neglect perturbations

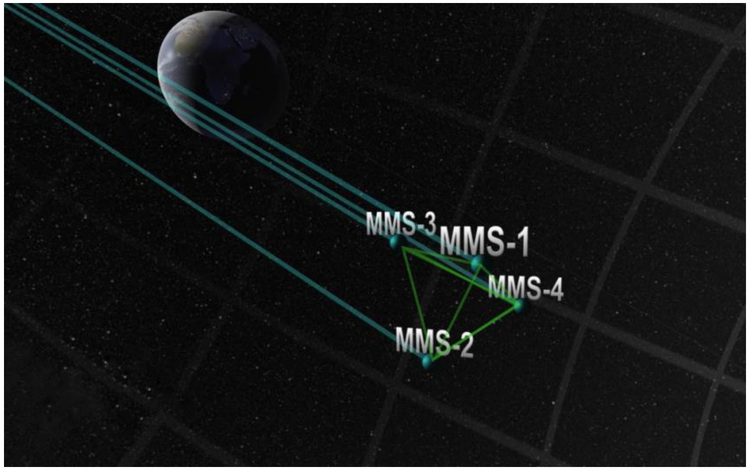


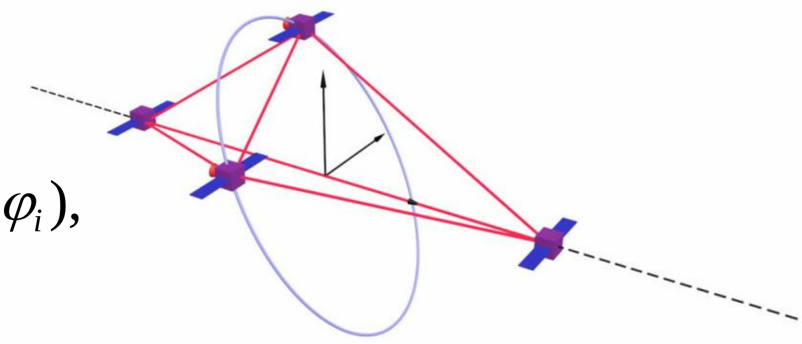
image from NASA, MMS mission

Reference orbit for circular motion

- For reference orbit search we use linearized HCW model, closed orbits estimation

$$\ddot{x} - 2n\dot{y} - 3n^2 x = 0,\quad \ddot{y} + 2n\dot{x} = 0,\quad \ddot{z} + n^2 z = 0$$

$$x_i = A_i \sin(nt + \varphi_i),\quad y_i = C_i + 2A_i \cos(nt + \varphi_i),\quad z_i = B_i \sin(nt + \psi_i)$$



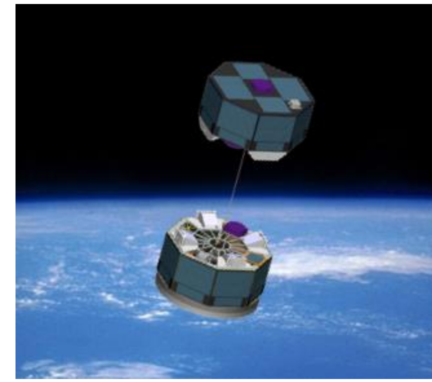
- Introduce the *quality of the tetrahedron*

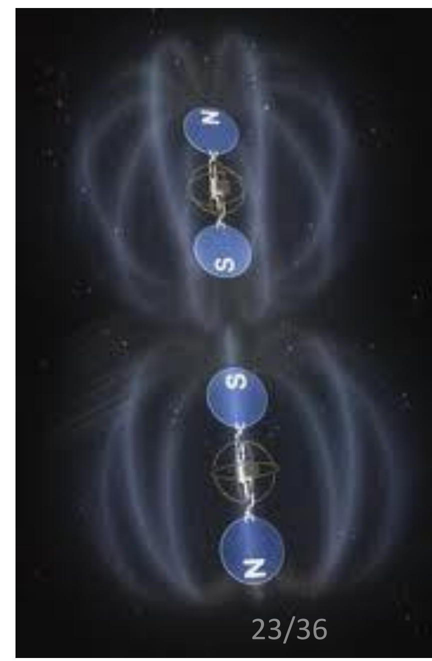
$$Q = 12\frac{(3|V|)^{2/3}}{r_{12}^2 + r_{13}^2 + r_{14}^2 + r_{23}^2 + r_{24}^2 + r_{34}^2} = 12\frac{(3|V|)^{2/3}}{L}$$

- Volume conservation is the conservation of the size
- Quality conservation is the conservation of the shape

Fuelless FF Control Concepts

- Aerodynamic drag
- Electro-magnetic interaction
- Solar pressure
- Momentum exchange



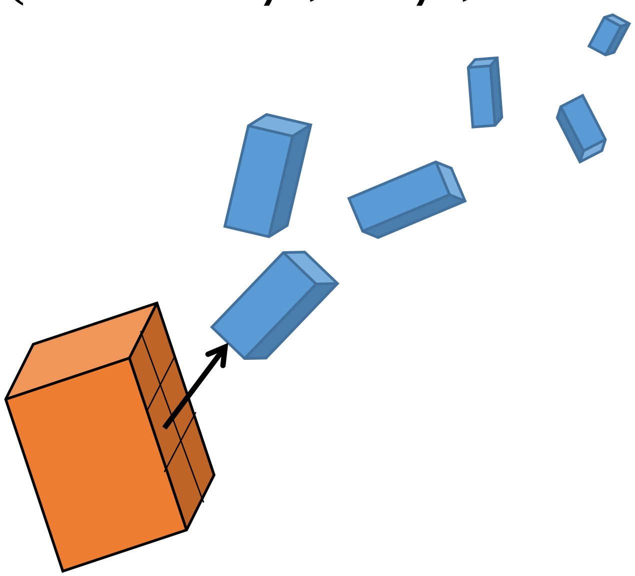


Swarm construction using aerodynamic force

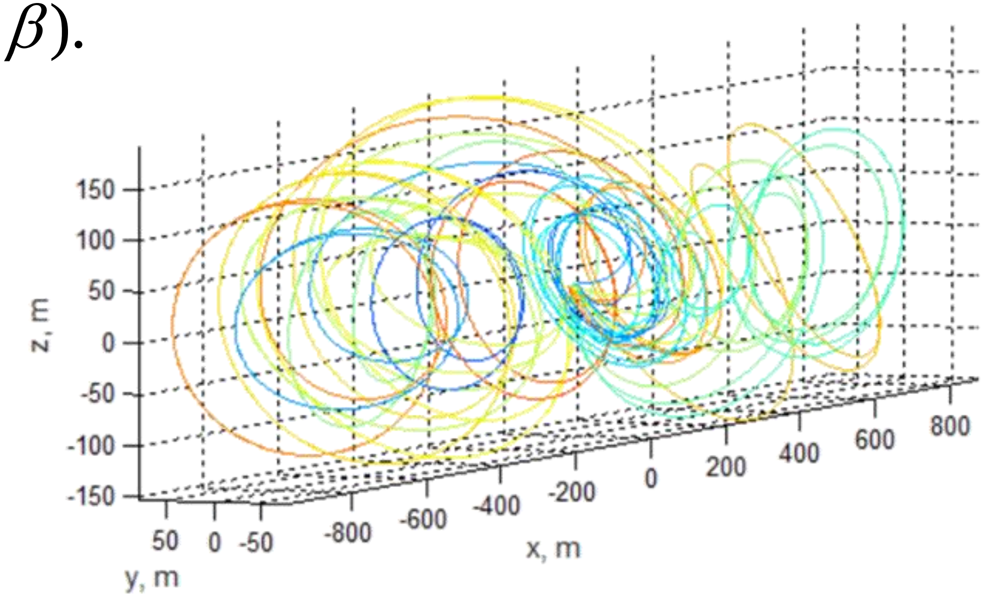
- Aerodynamic force

$$\mathbf{f}_i = -\frac{1}{m}\rho V^2 S\{(1-\varepsilon)(\mathbf{e}_V,\mathbf{n}_i)\mathbf{e}_V + 2\varepsilon(\mathbf{e}_V,\mathbf{n}_i)^2\mathbf{n}_i + (1-\varepsilon)\frac{\upsilon}{V}(\mathbf{e}_V,\mathbf{n}_i)\mathbf{n}_i\}^*,$$

$$\mathbf{n} = (\cos\alpha\cos\beta;\sin\beta;\sin\alpha\cos\beta).$$



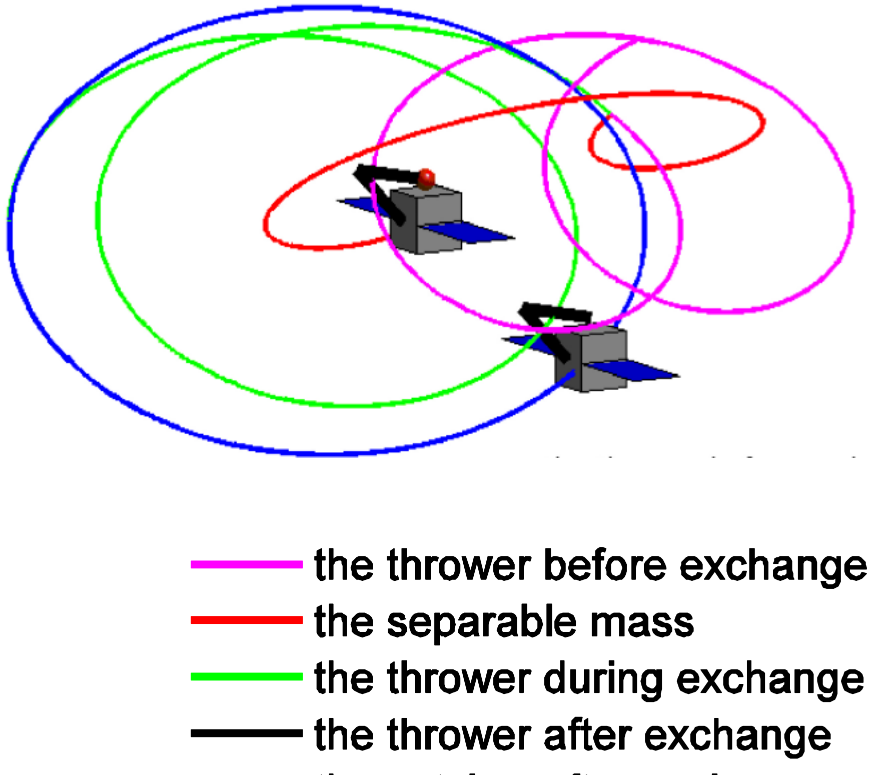
Scheme of satellites launch



Example of relative trajectories

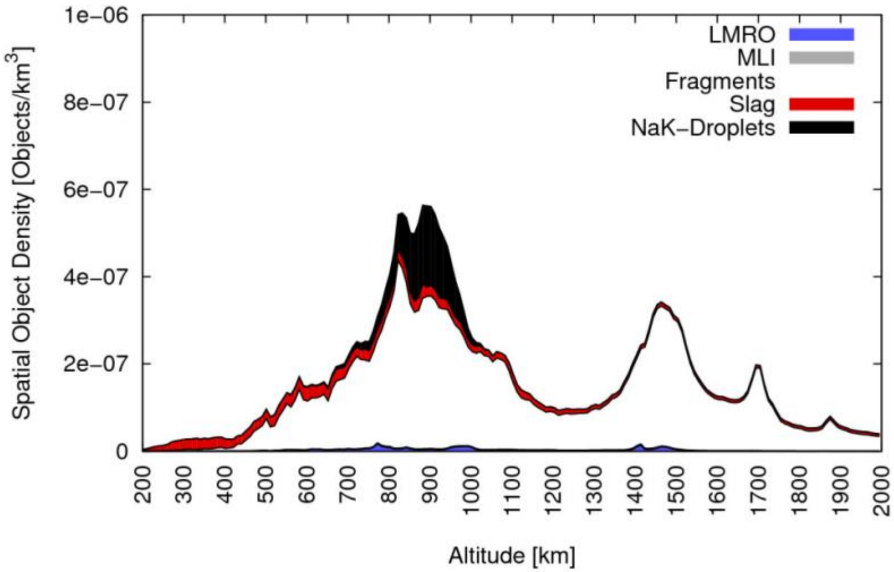
Single mass exchange control concept

- At command the single mass separates from the satellite
- The separated mass moves to the other satellite and impacts it absolutely inelastically
- After the whole mass transfer the resulting relative trajectory changes in adjustable way

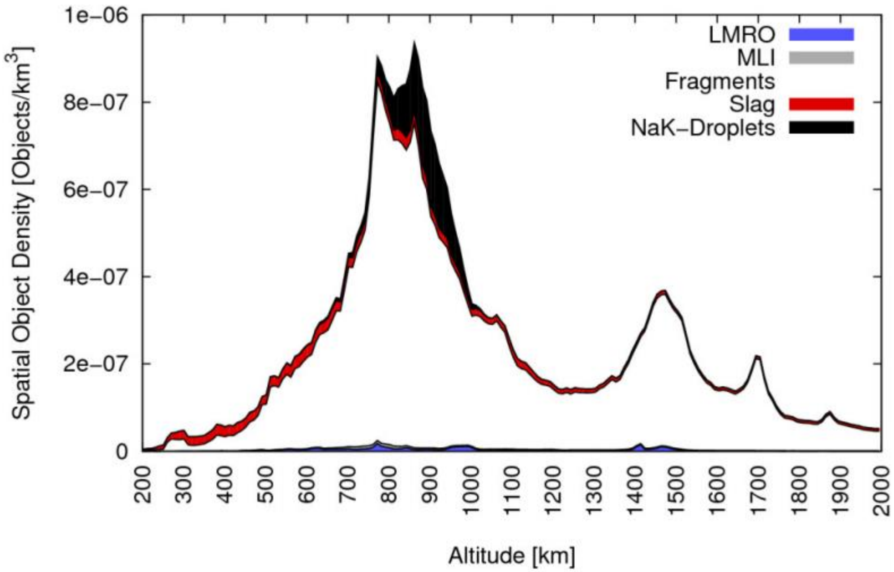


Space Debris in Low-Earth Orbits

- Kessler effect: a cascade of collisions of debris objects
- For low-Earth orbits, Kessler effect is likely to happen by mid-century



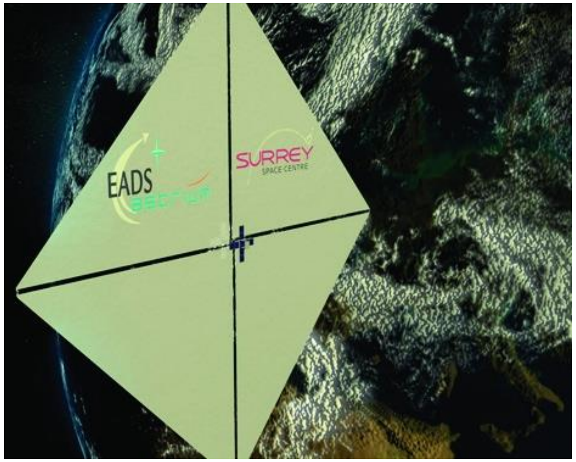
2005



2009

Sail-Assisted Deorbiting of LEO Nanosatellites

- Sail-assisted deorbiting is available even for the upper segment of LEO!
- The deorbit force is the SRP force rather than the drag force
- The required attitude regime can be established using the miniature CubeSat magnetorquers only



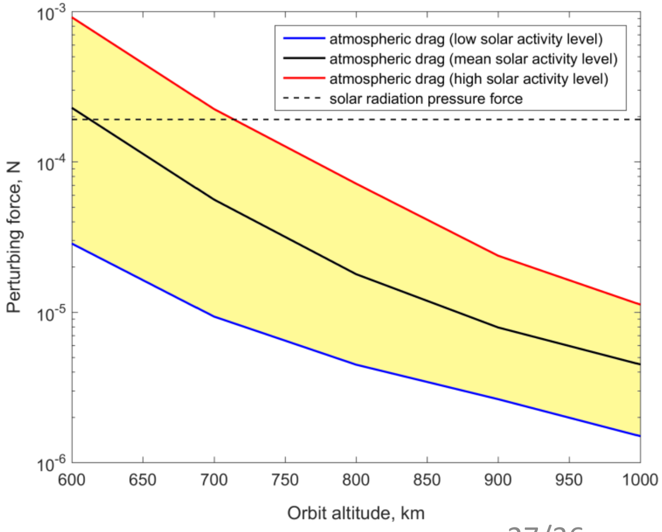
- Relative angular velocity damping

$$\boldsymbol{m}_1 = k_m \, \boldsymbol{\omega}_{rel} \times \boldsymbol{B}$$

- Differential spin rate damping

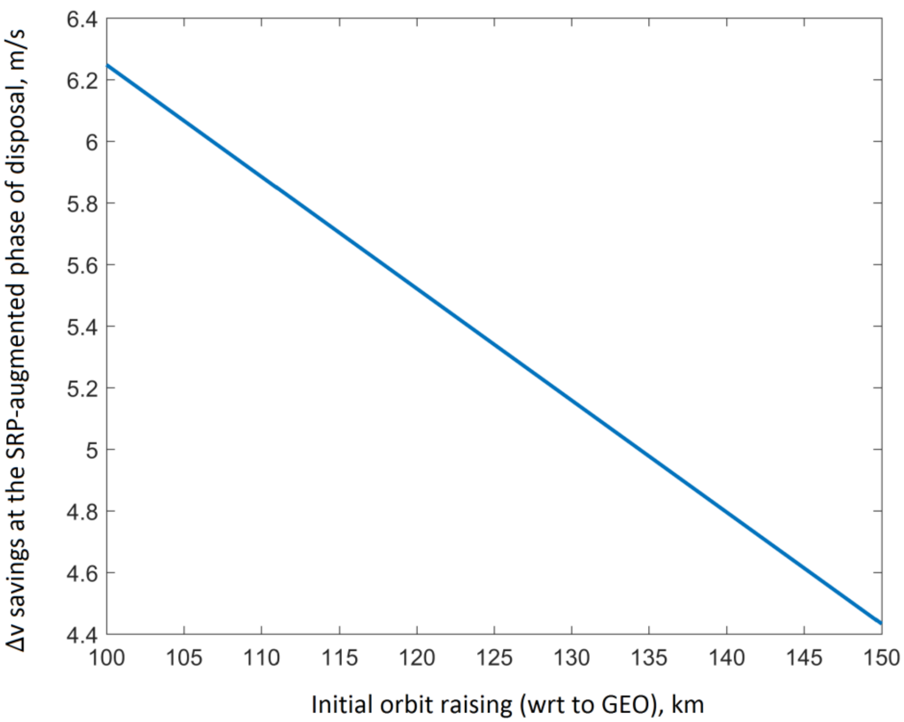
$$\boldsymbol{m}_2 = k_m \left(\omega_\zeta - \hat{\omega}_\zeta \right) \boldsymbol{n} \times \boldsymbol{B}$$

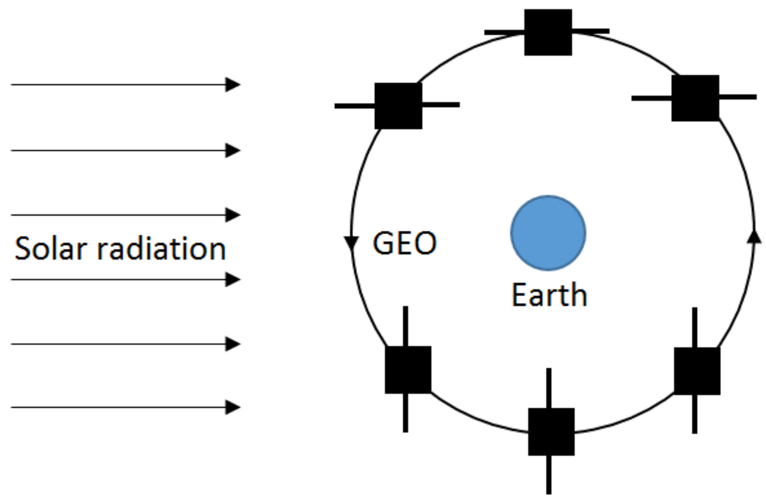
$$\boldsymbol{m} = \begin{cases} \boldsymbol{m}_1 + \boldsymbol{m}_2, & \left| \omega_\zeta - \hat{\omega}_\zeta \right| \geq 10^{-4} \text{ rad/s} \\ \boldsymbol{m}_1, & \left| \omega_\zeta - \hat{\omega}_\zeta \right| < 10^{-4} \text{ rad/s} \end{cases}$$



SRP-Augmented Disposal of GEO Satellites

The SRP force can be exploited at the final stage of transferring GEO satellites to a graveyard orbit





The initial phase of raising the orbit by 100-150 km with the use of thrusters is followed by the SRP-augmented phase (3–7 years)

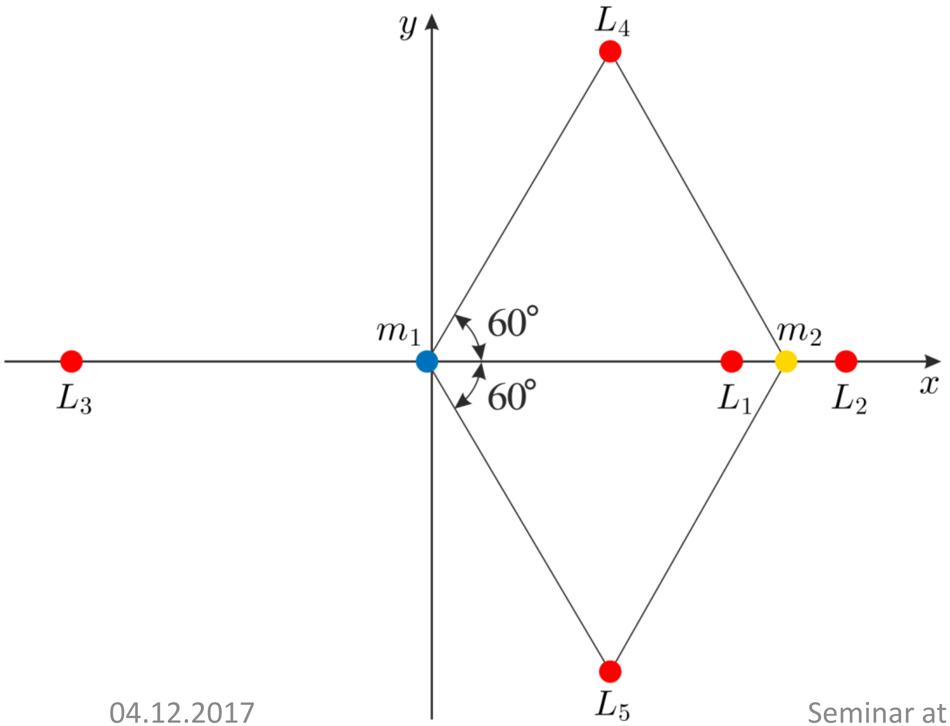
Our competence in interplanetary mission design

- Libration point orbit (LPO) design
- Station-keeping and stability analysis of the LPOs
- Transfer trajectory design to the LPOs of the Earth-Moon or the Sun-Earth system
- Transfer trajectory design between the LPOs of the same or different three-body systems
- Low-thrust low-energy trajectory design suitable for small spacecraft in the Earth-Moon system

Equations of motion in the CR3BP

In the rotating frame $\ddot{x} - 2\dot{y} = U_x,\ \ddot{y} + 2\dot{x} = U_y,\ \ddot{z} = U_z$

where $U(x, y, z) = \dfrac{x^2 + y^2}{2} + \dfrac{1-\mu}{r_1} + \dfrac{\mu}{r_2} + \dfrac{\mu(1-\mu)}{2}$

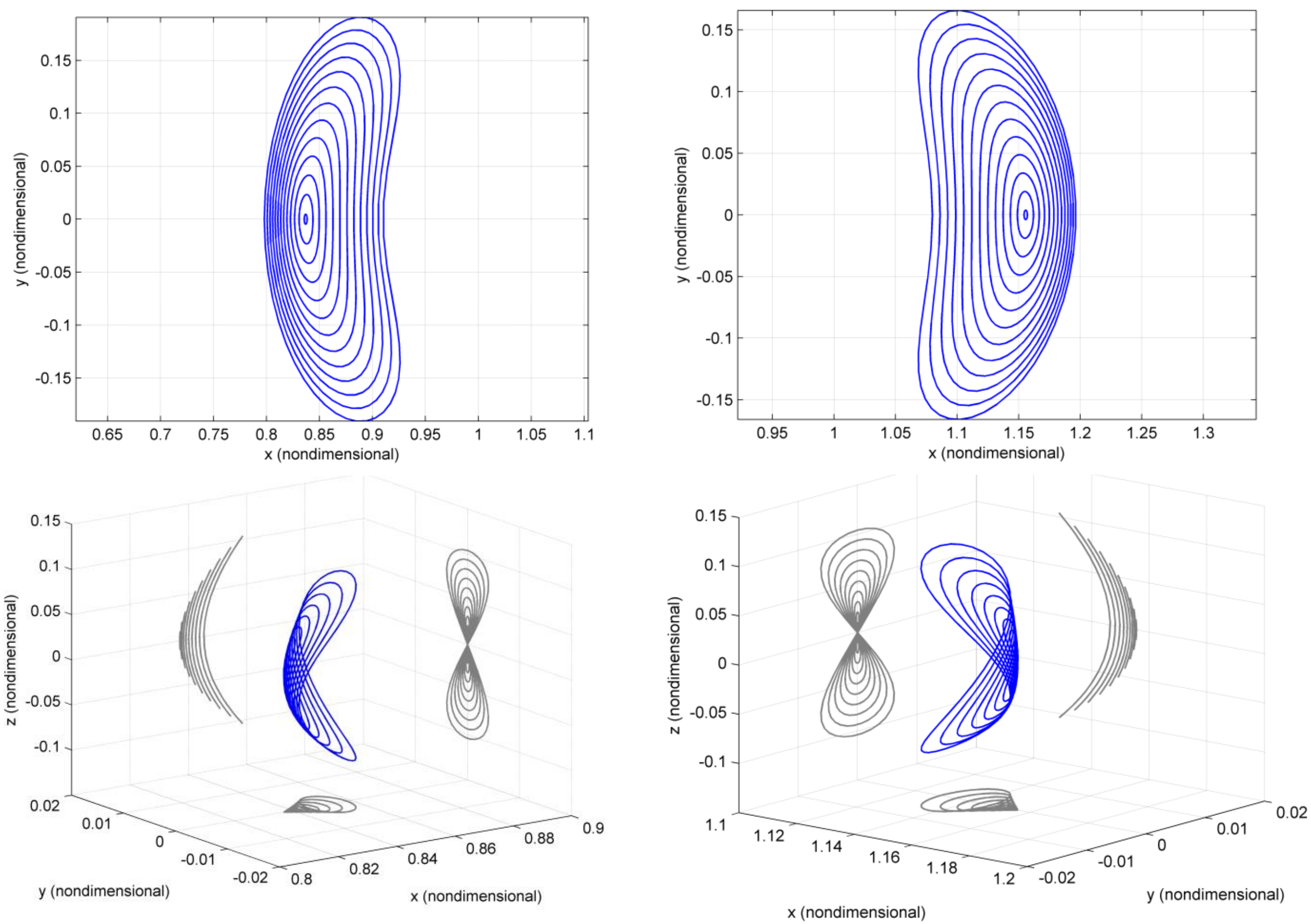


Equilibrium points meet conditions

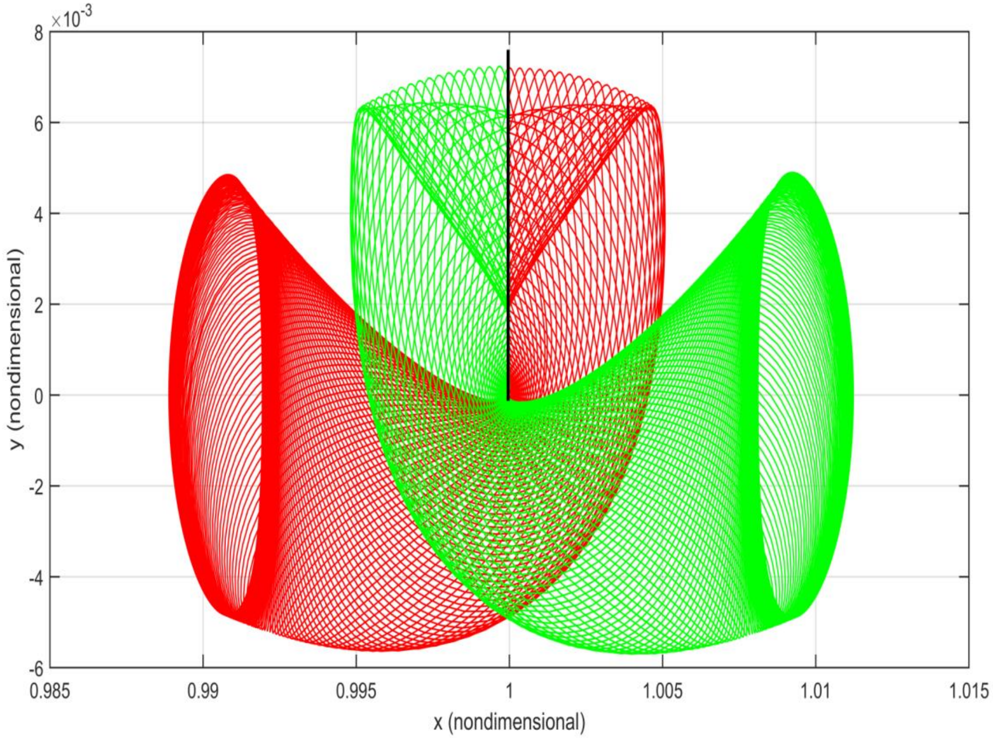
$$U_x = U_y = U_z = 0$$

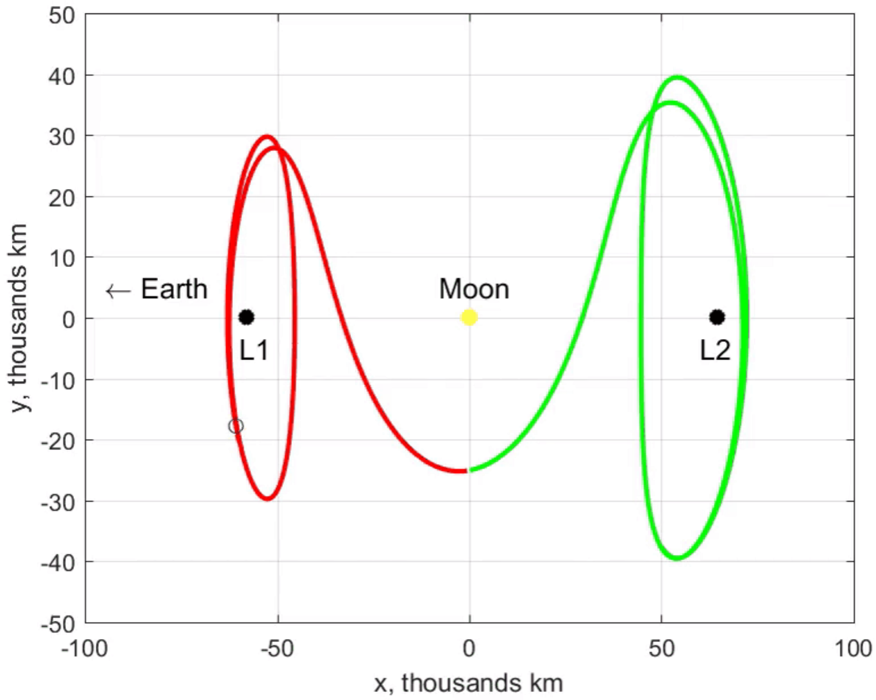
and are called the *libration points*

Planar and vertical Lyapunov orbits in the EM system



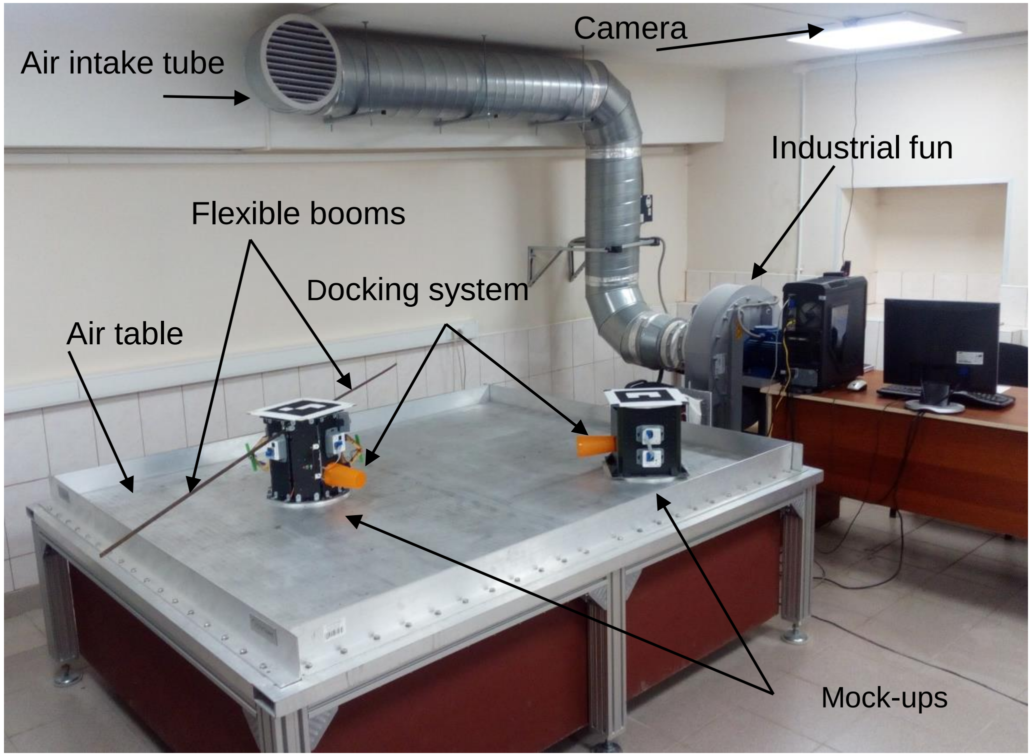
Transfers between L1 and L2 halo orbits



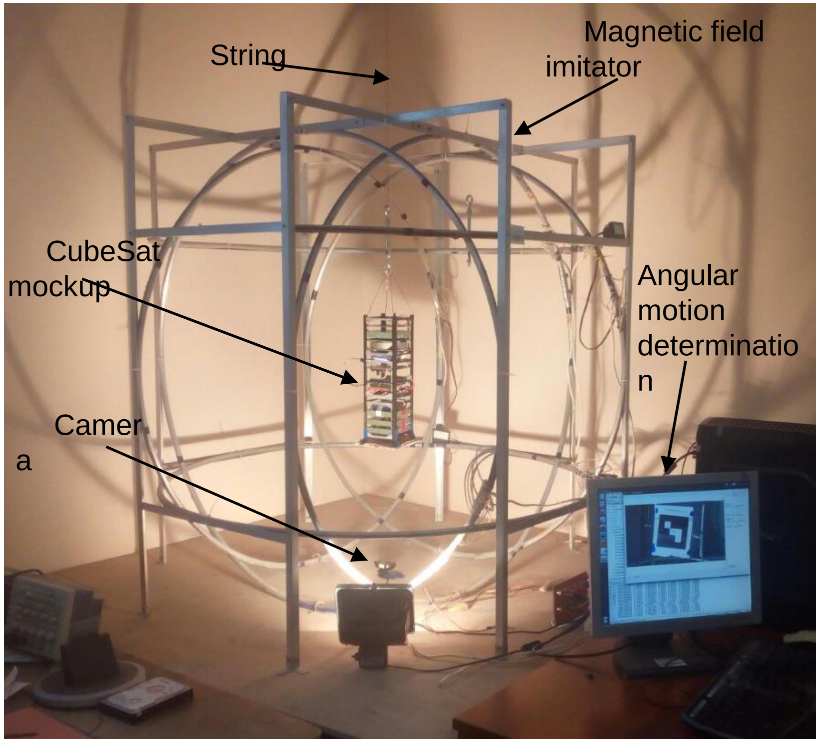


Red line denotes unstable manifold around LP L1.
Green line denotes stable manifold around LP L2

Lab facilities in KIAM



Planar air bearing test bench COSMOS
(COmplex for Satellites MOtion Simulation)



One-axis attitude control test bench

Conclusion

Only a few examples have been given to represent wide area of our competence and directions of activity in dynamical models and control algorithms development for small satellites, laboratory testing and validation, flight data processing, mission design

Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences:

- within competence open for collaboration
- ready to conduct studies for a customer
- ready to initiate joint projects in space area including Formation Flying and interplanetary missions

Thank you for your attention!

The full text publications in English
are available at our web-site:
http://keldysh.ru/microsatellites/eng/