Development of a single selenocentric reference system on the basis of satellite and ground-based observations

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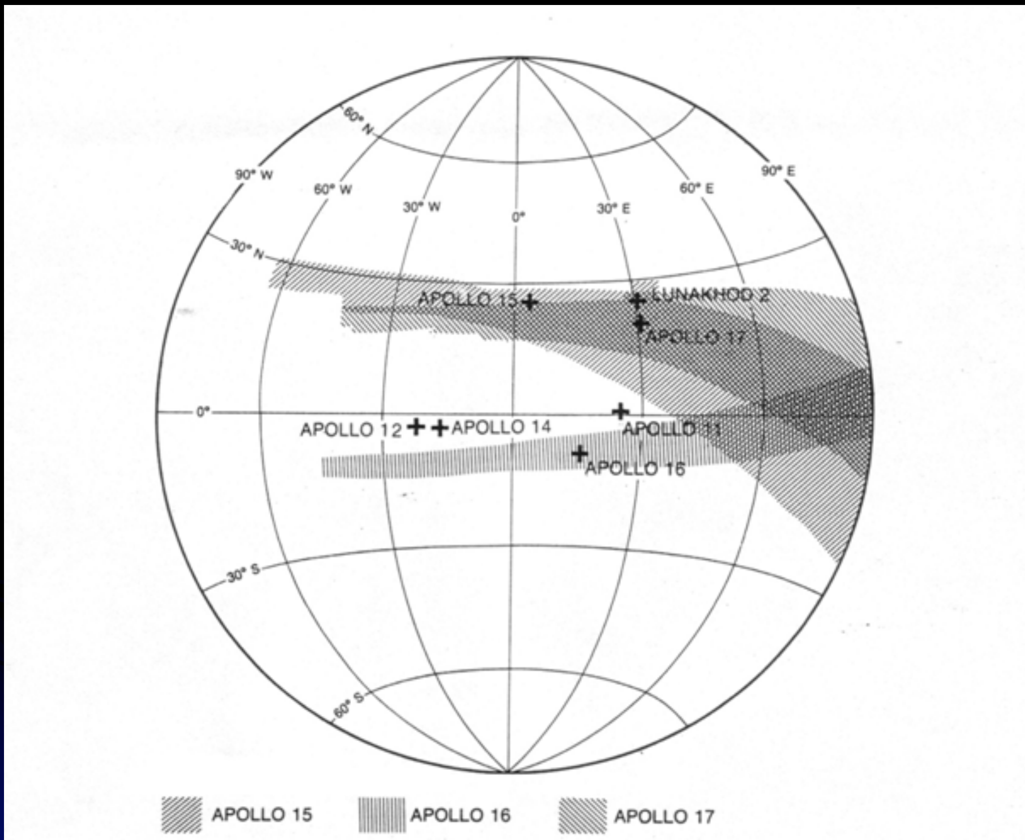
RELEVANCE OF LUNAR COORDINATE AND TIME SUPPORT

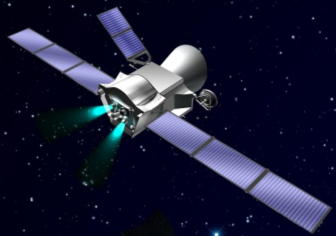
- Lunar missions (ongoing and completed): NASA Clementine (1994); Lunar Prospector (1998 – 1999); Lunar Laser Ranging (LLR) (1969 – 2012); SMART-1 (2003 – 2006); Kaguya (2007 – 2009); Chang'e 1 (2007 – 2009); Chang'e 2 (2010); Chandrayaan-1 (2008 – 2009); Chandrayaan-2 (2013); LRO-LCROSS (2009 – 2012); GAIA (2013 – ...).
- Lunar missions (planned): Russian "Luna-Glob"; joint Russian and Indian "Luna-Resurs".
- Modern experimental studies of external and internal characteristics of the Moon are related to plans on its exploration in the near future
- Construction of a selenocentric reference system is one of the most relevant problems for efficient navigation and landing modules deployment on the lunar surface.
- Space technologies development imposes particular requirements for coordinate and time support including reference systems implementations, establishment of mutual orientation of inertial and dynamic coordinate system, celestial bodies dynamics and geometry investigations.

LUNAR SURFACE COVER BOUNDARIES BY ”APOLLO” AND “LUNOKHOD” MISSIONS



Displacement from ALSEP stations increases error up to ± 400 m, which is major part of the observed area. Errors in coordinates of objects lying near boundaries of the observed areas may reach ± 400 m and even exceed ± 1000 m.

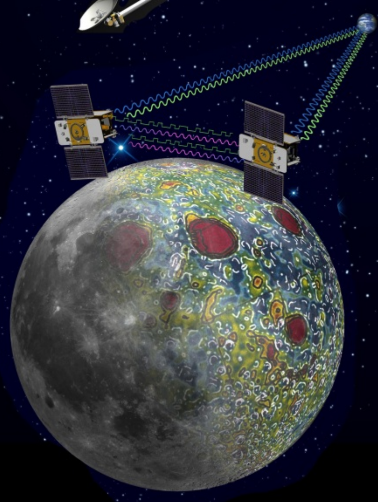
"Clementine" (Deep Space Program Science Experiment) – joint space project between BMDO and NASA; 1994. Results: obtaining altimetry from 60°N to 60°S latitude on both lunar sides, obtaining gravity data for the near side.



"SMART-1" – ESA satellite; 2003. Results: 32000 images of the lunar surface at various resolutions and pointing accuracy.

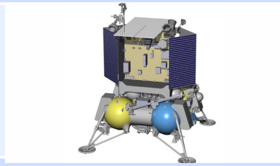
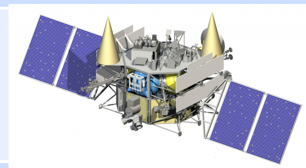
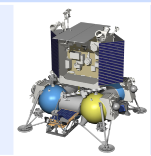
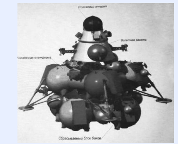
"KAGUYA (SELENE)" – JAXA project; 2007. Results: covering the entire sphere of the Moon with a height resolution of 5 m.

«Lunar Reconnaissance Orbiter» – NASA project; 2009. Results: construction of a global topographic coordinate network.



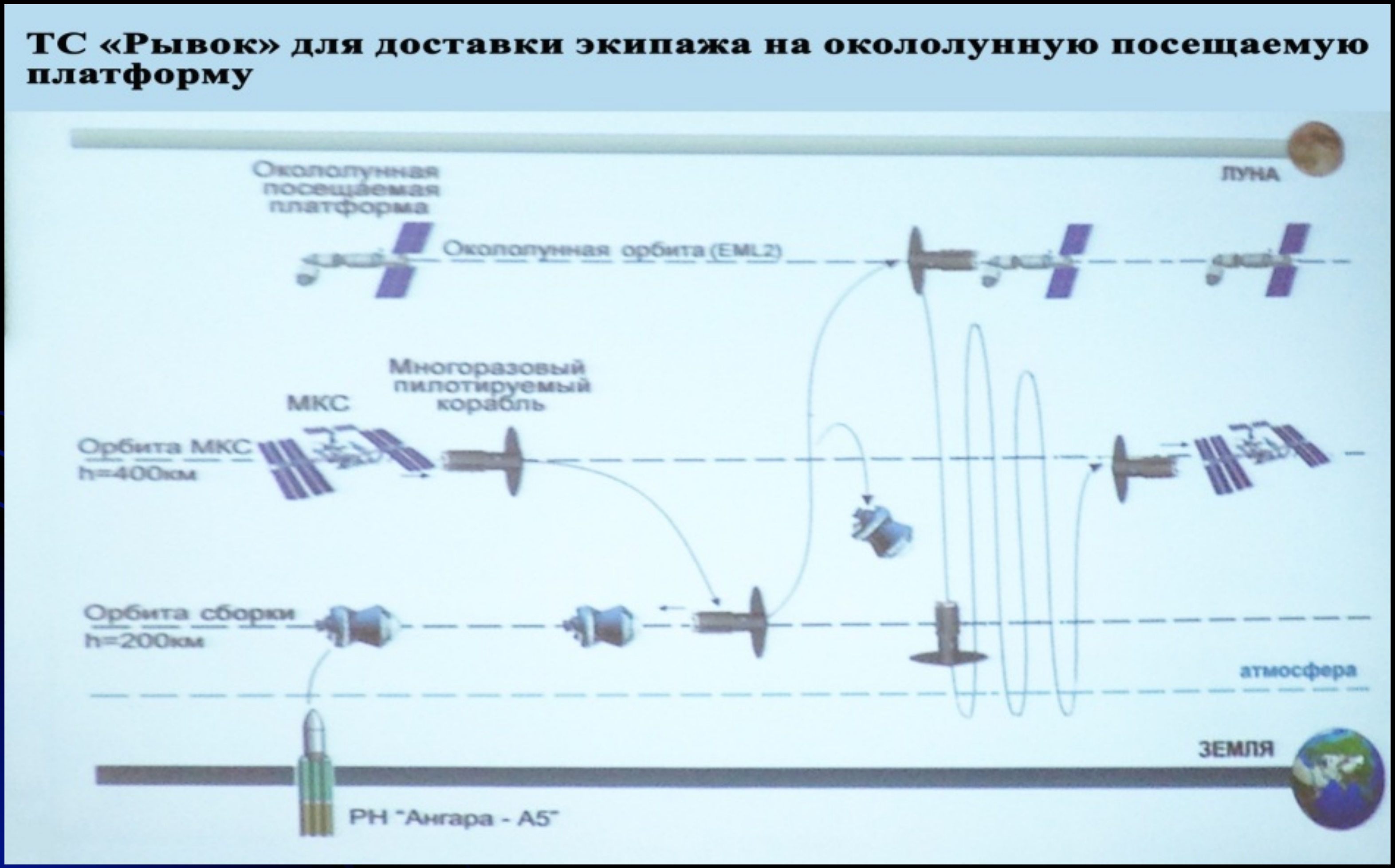
"Gravity Recovery and Interior Laboratory (GRAIL)" – NASA project; 2011. Results: lunar crust thickness is estimated to be 30 km (according to previous reports from Apollo, thickness was about 60 km).

RUSSIAN PLANNED LUNAR MISSIONS

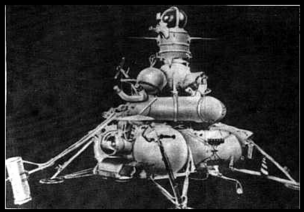
Year of Launch	2021	2022	2023	2025
Project	Luna-25	Luna-26	Luna-27	Luna-28
Type of mission	Landing	Orbital	Landing	Landing and Returned
Spacecraft Configuration				
Carrier Rocket	Soyuz-2.1b	Soyuz-2.1b	Soyuz-2.1b	Angara A3 + Soyuz-2.1b
Landing Procedure	Direct	–	Direct/Adaptive	Adaptive
Technologies Practiced	Soft landing basic technologies	High-detailed lunar imaging, communication with landing facilities	Accurate and safe landing, modified propulsion system, communication with orbiter, cryogenic soil intake	Accurate and safe landing, take-off rocket, jettisonable tanks, cryogenic soil intake
Spacecraft Mass, kg	1750	2200	2150	>3000
Payload	Stationary scientific station	Scientific equipment complex for orbiter	Stationary scientific station, deep soil picker	Take-off rocket, deep soil picker
Payload Mass, kg	30	160	130	250 (including take-off rocket)

“RYVOK”

Space Rocket Corporation “Energiya” (image borrowed from Rafail Murtazin’s talk): “Ryvok” implies flights to the Moon not from the Earth, but from the International space station. From there cargos and astronauts will be delivered to the Moon

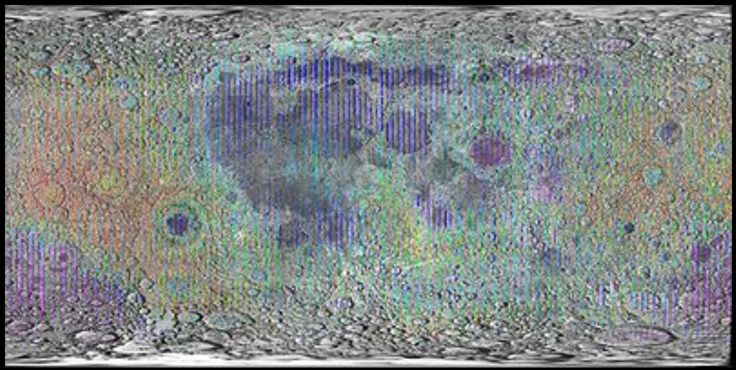


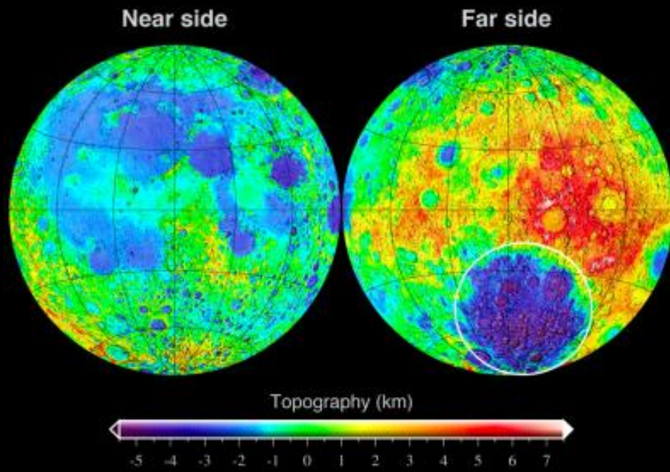
PROBLEMS OF CONSTRUCTING REFERENCE NETWORK



"Luna-16" Space Probe, an analog of "Luna-15" station

1) Most of the modern selenodetic catalogues are constructed in quasi-dynamic coordinate system. Either they have the origin not coinciding with the lunar center of mass, or their axes do not coincide with the lunar axes of inertia.
2) To understand the accuracy problem of coordinate and time support, one should remember terrestrial space navigational groups.
3) The modern value of landing ellipse is 13 by 8 km. E.g. "Luna-15" could have crashed into a mountain because of insufficient navigational support.





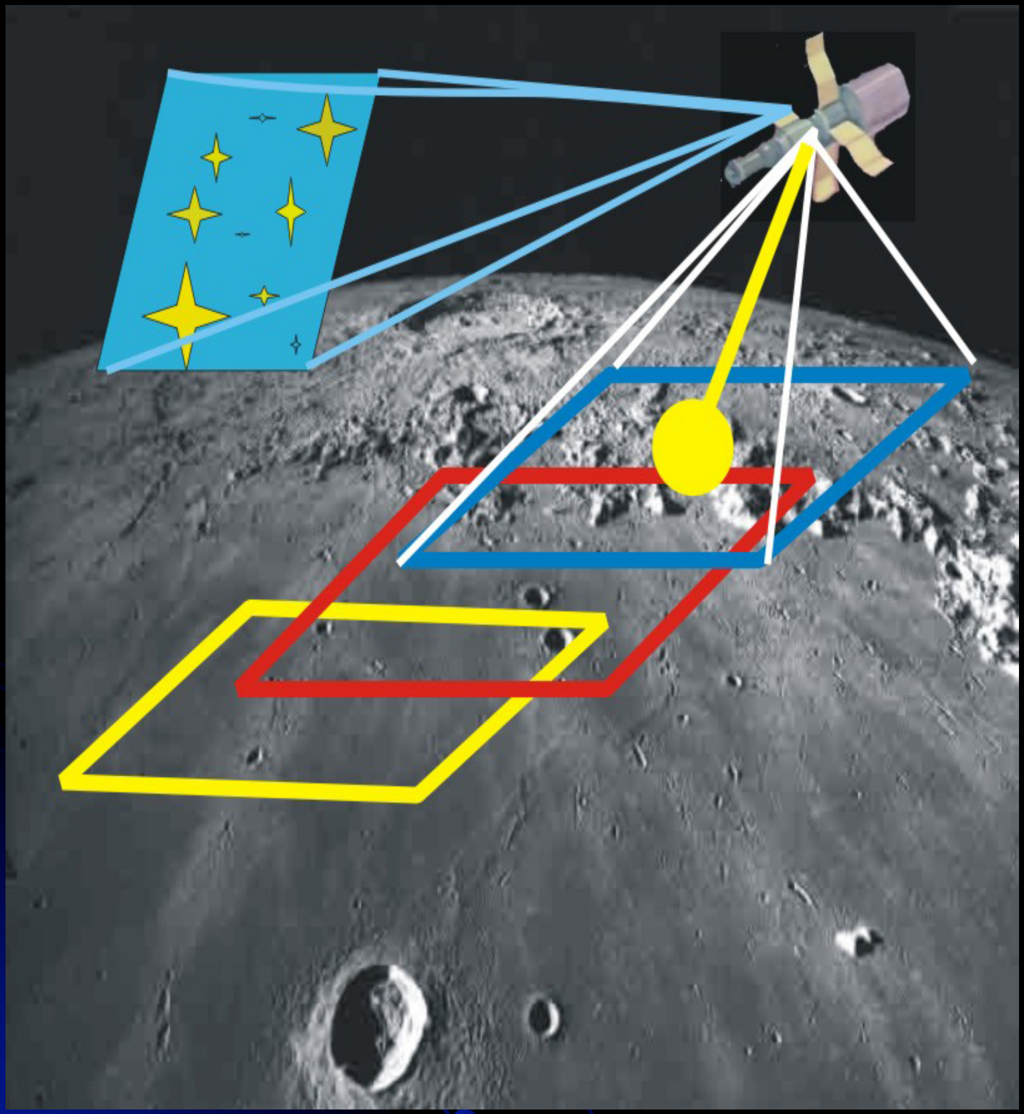
2 methods of obtaining selenographic data:

1) Laser scanning of the lunar surface by on-board satellites. Pros: describes the lunar relief well. Cons: does not provide coordinates for the reference objects on the Moon.

2) Binding lunar objects to stars. Pros: provides precise coordinates of the reference objects. Cons: does not describe the lunar relief with a sufficient accuracy.

Currently, there is no dynamic selenocentric coordinate system covering the sufficient area on the lunar surface built using space observations. There is no method of constructing lunar photogrammetric topographic map based on combining thousands of separate images into a unified system by the absolute method. Thus, satellite topographic data do not allow for the construction of a valid topographic model.

Scheme of simultaneous scanning the lunar surface, accurate laser beam point determination and binding the orbiter to stars



Simultaneous lunar surface scanning and accurate satellite binding of lunar objects may be executed using one of two methods: 1) simultaneous scanning of the lunar surface with an accurate determination of laser beam point's coordinates and binding spacecraft to stars (see the pic.) or 2) Light beacons deployment on the entire lunar surface. Currently, technical capabilities for both of the methods are unavailable.

THE LUNAR PROJECTS OF KAZAN FEDERAL UNIVERSITY OBSERVATORY

1) Construction of global selenocentric dynamic reference network using space and ground-based observations;

2) Conducting studies on the modern selenographic systems’ orientation, determination of the center of mass position and orientation in relation to the inertia axes;

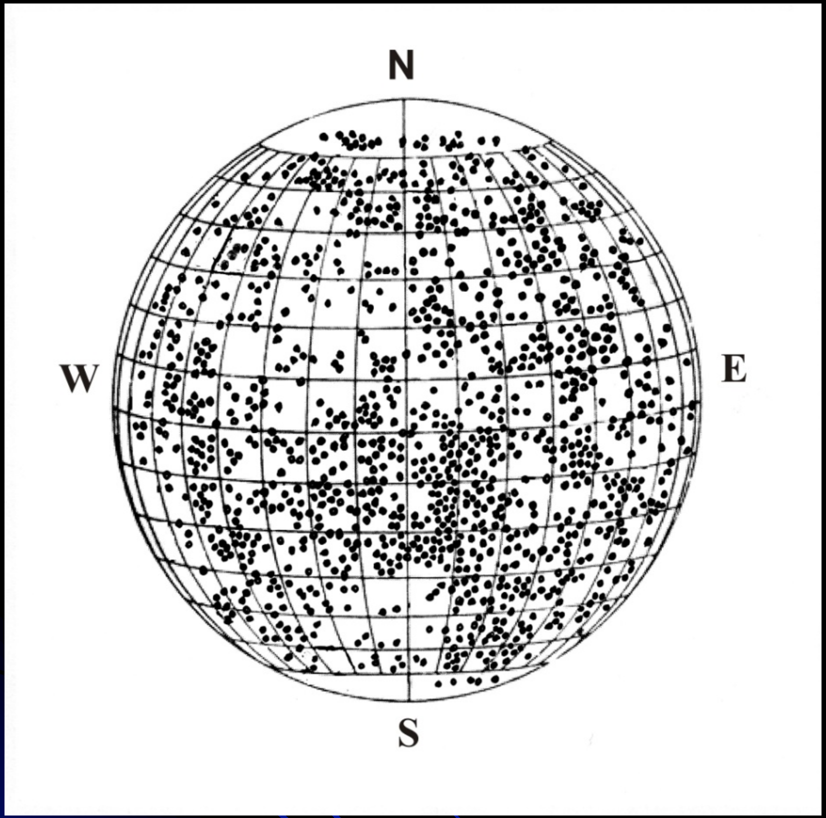
3) Construction of analytical and numerical theories of the physical libration of the Moon;

4) Development of a lunar macrofigure model;

5) Lunar laser ranging (planned);

6) Installation of a radio telescope for VLBI (planned).

Distribution of crater on the surface of the Moon in DSC



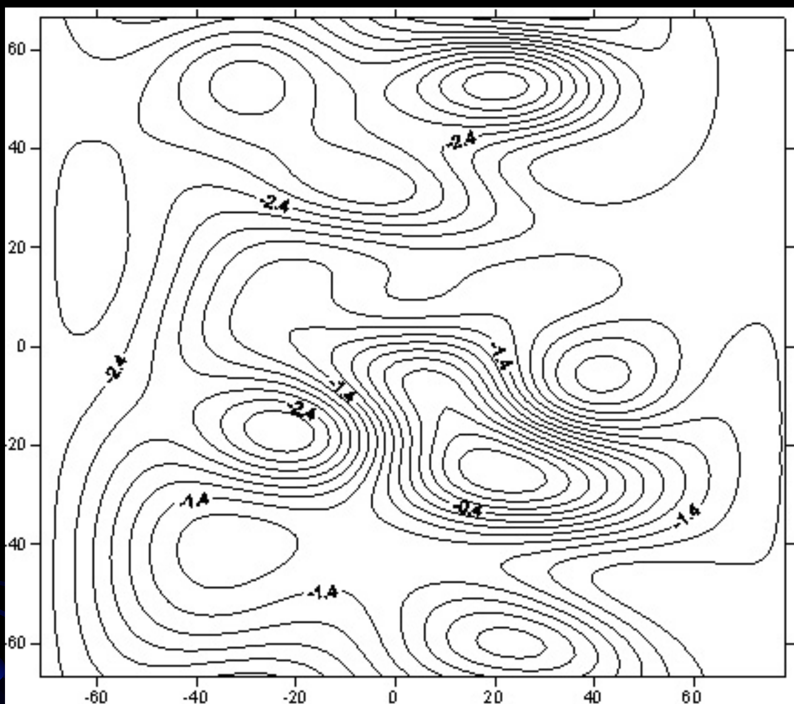
There are a number of lunar dynamic reference catalogues, and dynamic selenocentric catalogue (DSC) built at Engelhardt astronomical observatory is the most informative among them. Plane coordinates in DSC are produced by binding lunar objects to stars, while altitude components were adjusted using LRO data. As soon as the lunar objects bound to stars are determined, they may be considered as selenocentric dynamic coordinates. DSC covers significant part of the Moon and contains enough reference points to construct the figure of the Moon. Plane coordinates accuracy is between ± 40 and ± 80 m, while altitude one is ±80 m on average.

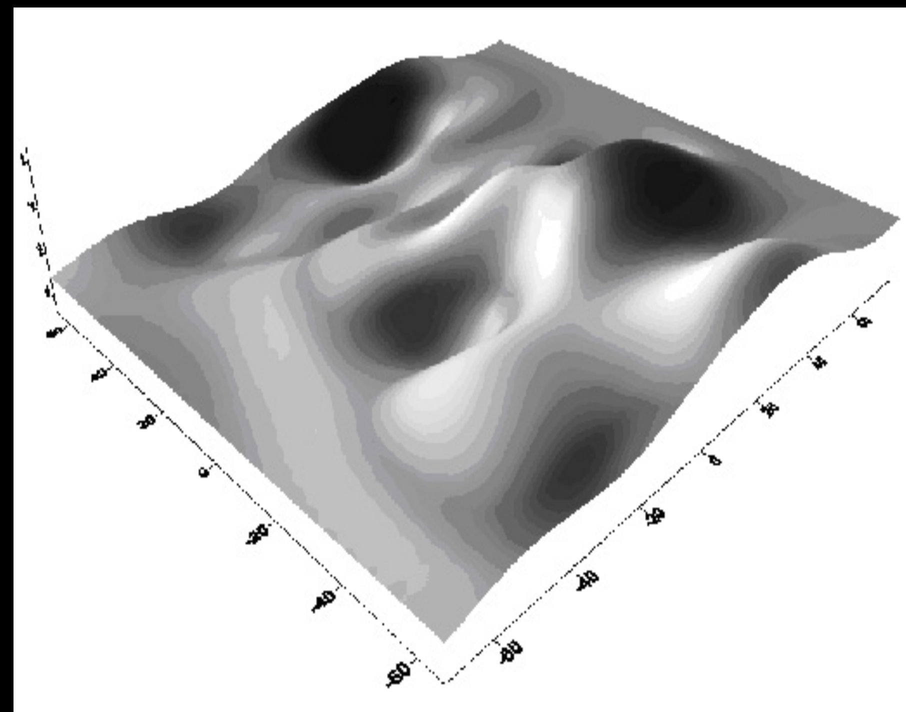
Method of constructing DSC confirms that the catalogue was built in dynamic coordinate system, as the objects on the lunar surface were bound to stars by absolute method, i.e. by absolute connection of lunar objects with stars and using dynamic theory of the Moon. Altitude data are reconciled with LRO mission.

Fragment of DSC

1	0.00543 ±7	0.02071 ±7	0.99922 ±17	0.3114	1.1873	1737.1
2	0.01873 ±5	0.06981 ±8	0.99608 ±18	1.0772	4.0083	1735.8
3	0.02506 ±8	0.02166 ± 8	0.99787 ±14	1.4386	1.2431	1735.4
4	0.04203 ±10	0.05661 ±6	0.99725 ±19	2.4133	3.2461	1737.6
5	0.06282 ±5	0.07236 ±6	0.99508 ±14	3.6123	4.1509	1737.5

Model of the near side of the Moon constructed using DSC





- Pictures show a part of the Moon – a hemisphere with mean radius of 1736,34 km ± 1,20 km with a bulge of 0,9 km in the central part.
- To the North from 10° parallel topographic heights gradually reduce, and in the latitude zone between 30° and 70° radius-vectors are 0,9 km shorter on average than the mean radius.
- At the moment we are constructing a global model of the entire lunar sphere.

LUNAR CENTER OF MASS DETERMINATION IN RELATION TO CENTER OF FIGURE USING SYNTHETIC METHOD

As a model describing lunar surface behavior the heights were expanded in a series of spherical harmonics in regression form:

$$h(\lambda, \varphi) = \sum_{n=0}^{N} \sum_{m=0}^{n} (\bar{C}_{nm} \cos m\lambda + \bar{S}_{nm} \sin m\lambda) \bar{P}_{nm}(\cos \varphi) + \varepsilon,$$

where

λ, φ (longitude and latitude) are known coordinates of lunar objects;

$\bar{C}_{nm}, \bar{S}_{nm}$ are normalized harmonic amplitudes;

$\bar{P}_{nm}$ is associated Legendre function;

ε is random regression error.

Using the method similar to the one used in [1] lunar center of mass position was determined in relation to the lunar center of figure. Formulas as follows were used:

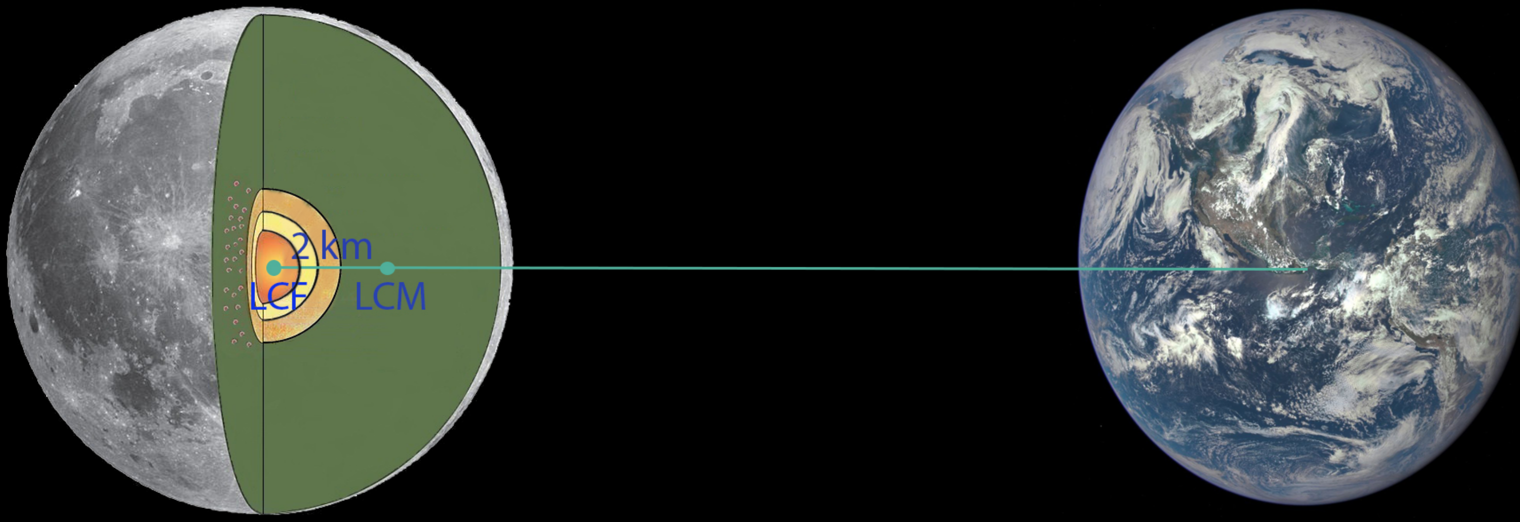
$$\Delta\xi = \sqrt{3}\bar{C}_{11}; \Delta\eta = \sqrt{3}\bar{S}_{11}; \Delta\zeta = \sqrt{3}\bar{C}_{10},$$

where

ξ is axis directed towards Earth; η is equatorial axis directed perpendicularly to ξ; ζ is axis of lunar rotation;

$\bar{C}_{11}, \bar{S}_{11}$, $\bar{C}_{10}$ are normalized harmonic amplitudes of the first order of surface expansion.

[1] Chuikova N. A. Geometric figure of the moon represented as an expansion in spherical and sampling functions //Astronomicheskii Zhurnal. – 1975. – T. 52. – C. 1279-1292.



Lunar center of mass displacement in relation to center of figure, km

	Clementine	Kazan + LRO	Kiev + LRO	SAI MSU	Bills, Ferrari	ULCN	KAGUYA
Δξ	-1,80	-1,49	-0,94	-2,03	-1,82	-1,71	-1,77
Δη	-0,74	-0,69	-0,73	0,07	-0,45	-0,73	-0,78
Δζ	-0,64	0,16	0,35	-2,04	-0,64	0,26	0,24

LUNAR MODELS FRACTAL ANALYSIS

- As a model of a fractal object scale invariant Weierstrass-Mandelbrot is used fractal curve
- Method of determining and analyzing Minkovsky fractal dimension is applied

Let *M* be a limited set on a plane. *N(σ)* is a minimum number of the studied area covers whose sampling covers *M*.

In general case: *M* has a dimension $D = dim\ M,\ 0 \le D \le 2$, if at $\sigma \to 0$ the number of covers goes up as $R/\sigma D$, where *R* is a positive constant called *d*-measure of the set *M*. For *R* in general case we may write:

$$R = \lim_{\sigma\to 0} \sigma^D N(\sigma).$$

And since

$$\lim_{\sigma\to 0} \frac{\ln N(\sigma)}{\ln \frac{1}{\sigma}} = \lim_{\sigma\to 0} \frac{\ln \frac{R}{\sigma^D}}{\ln \frac{1}{\sigma}} = \lim_{\sigma\to 0} \frac{d \ln \frac{1}{\sigma} + \ln R}{\ln \frac{1}{\sigma}} = D,$$

dimension *D* is determined as follows:

$$D = dimM = \lim_{\sigma\to 0} \frac{\ln N(\sigma)}{\ln \frac{1}{\sigma}}.$$

VALUES OF FRACTAL DIMENSIONS FOR HYPSOMETRIC MODELS OF THE MOON

Position Angle	Model 1	Model 2	Model 3	Model 4
0° – 45°	1.42	1.39	1.44	1.40
45° – 90°	1.34	1.34	1.37	1.35
90° – 135°	1.44	1.36	1.40	1.43
135° – 180°	1.30	1.32	1.30	1.34
180° – 225°	1.40	1.34	1.44	1.43
225° – 270°	1.37	1.31	1.40	1.43
270° – 315°	1.33	1.79	1.42	1.38
315° – 360°	1.30	1.27	1.30	1.33

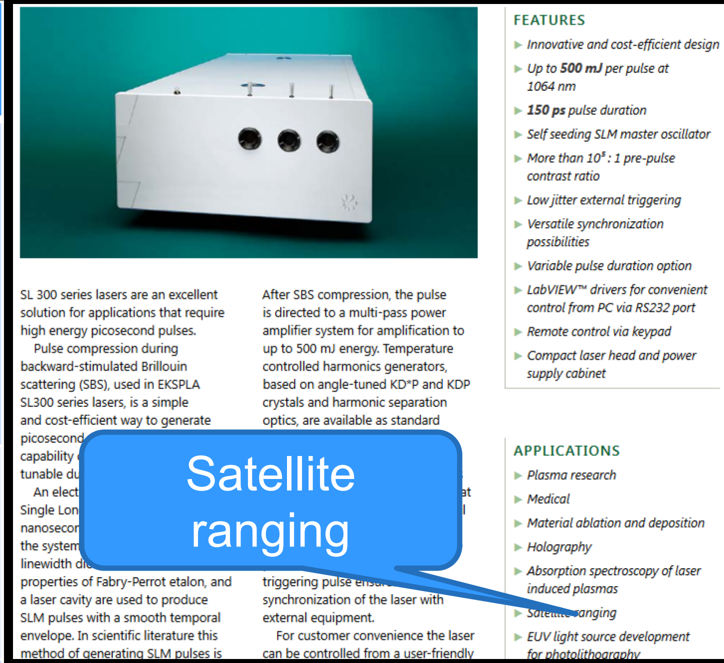
Model 1 – limb points are bound to *Mösting A* crater at given libration;
Model 2 – with an artificial bulge at the southern lunar pole;
Model 3 – limb points are bound to stars (star coordinate system);
Model 4 – DSC catalogue.

Lunar Laser Ranging (LLR) has been implemented for 50 years at the moment. The first Russian LLR system is being developed at Altay observatory

Laser corner reflector installed by ”Apollo” astronauts

Laser and Optics parts of LLR system

Item	Parameters	Price	Comment
Pulse Laser in Thermobox with Chiller	λ=0.53/1.06 μ, E_p=0.25–2 J, τ_p=0.1-10 ns, f_{rep}>5 Hz	10-12 million rubles	Distance measuring accuracy higher than 20-100 cm; mounted on AZT-14
Transmitting telescope	10-50^x, blooming at 532/1064 nm	0.5 million rubles	mounted on AZT-14
Photodetectors and Optics	PMT/avalanche CCD, τ<1 ns	1.3-1.5 million rubles	Photodetectors, interference filters, optical fiber, signal formation system
Registration System	$\Delta\tau$<10 ps at T>4 s	2.0-2.5 million rubles	Start-stop time interval measuring instrument, frequency standard


FEATURES
- Innovative and cost-efficient design
- Up to **500 mJ** per pulse at 1064 nm
- **150 ps** pulse duration
- Self seeding SLM master oscillator
- More than 10^8 : 1 pre-pulse contrast ratio
- Low jitter external triggering
- Versatile synchronization possibilities
- Variable pulse duration option
- LabVIEW™ drivers for convenient control from PC via RS232 port
- Remote control via keypad
- Compact laser head and power supply cabinet

SL 300 series lasers are an excellent solution for applications that require high energy picosecond pulses.
Pulse compression during backward-stimulated Brillouin scattering (SBS), used in EKSPLA SL300 series lasers, is a simple and cost-efficient way to generate picosecond

properties of Fabry-Perot etalon, and a laser cavity are used to produce SLM pulses with a smooth temporal envelope. In scientific literature this method of generating SLM pulses is

After SBS compression, the pulse is directed to a multi-pass power amplifier system for amplification to up to 500 mJ energy. Temperature controlled harmonics generators, based on angle-tuned KD*P and KDP crystals and harmonic separation optics, are available as standard

synchronization of the laser with external equipment.
For customer convenience the laser can be controlled from a user-friendly

APPLICATIONS
- Plasma research
- Medical
- Material ablation and deposition
- Holography
- Absorption spectroscopy of laser induced plasmas
- EUV light source development for photolithography

Existing scientific and technical base of Kazan Federal University (KFU) allowing to significantly lower the price of LLR project

- KFU has a robotic AZT-14 telescope (LOMO);
- Invited researchers on LLR from JPL NASA are working at KFU
- There are qualified professionals at laser technology, radio astronomy and physics of the Moon at KFU

CONLCUSION

1) The modern space methods of lunar surface selenography are considered;
2) System of selenodetic coordinates are investigated in relation to lunar center of mass and axes of inertia;
3) Harmonic analysis of lunar maps is conducted;
4) The main directions of lunar studies in Kazan are described;
5) Selenocentric dynamic reference network with altimetry reconciled with LRO is developed.

THANK YOU

FOR YOUR ATTENTION