593 Seminar on AUTONOMOUS SPACECRAFT NAVIGATION
Physics Center Bad Honnef, 8-11 June 2015, Germany

Orbital Stellar Stereoscopic Observatory Project and its Autonomous Navigation in the Heliocentric Transfer and Operational Orbits

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INTRODUCTION

Project "**O**rbital **St**ellar **S**tereoscopic **O**bservatory" (**OStSO**) [1] is derived from the **I**nterplanetary **S**olar **S**tereoscopic **O**bservatory (**ISSO**) project [2], which was designed as a long-live "space stereoscope observatory" [3]. Of the two main design options of the ISSO, we present here the "stellar" option for observations of stellar-like and extended objects to solve problems of astrometry and celestial mechanics, including the ACH problem, stellar astronomy and astrophysics [4, 5]. We present:

- A brief outline of the **OStSO** and its scientific goals;
- Main and navigation instruments and approach to their use;
- Our views and approaches to solving technical problems and a proposed scientific program;
- First modelling results, accuracy, assessment of the output expected.

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1. *Chubey, M.S., et al.* Stereoscopic Principle in Space Observatory. Kinematics and Physics of Celestial Bodies, Suppl. Nr 5, 2005, pp.172–175.

2. Grigoriev V.M., et al. Interplanetary Solar Stereoscopic Observatory. J. Opt. Technol. 2006, 73, pp. 251–255.

3. *Chubey, M., et al.* On the Long-life Solar Stereoscopic Observatory. Abst. XXV IAU GA, Sydney, Jul 13-26 2003 No.1371, p.182

4. *Abalakin, V., Chubey, M., Eroshkin, G., and Kopylov, I..* Triangulation Measurements in the Solar System. Proceed. IAU Coll. 180. (Kenneth J. Johnston et al. eds) USNO, Wash.. DC, USA, 2000, pp.132–163.

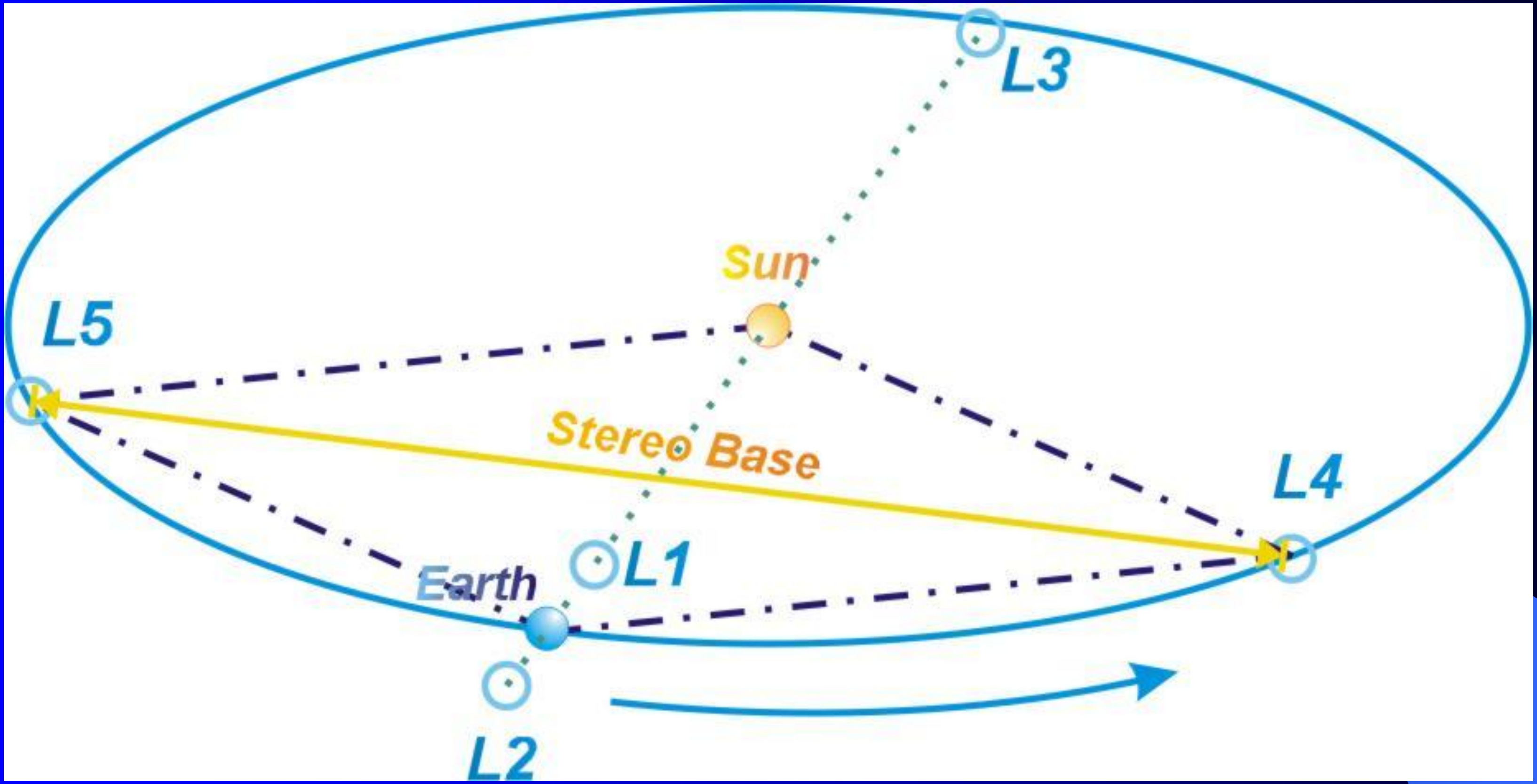
5. *Chubey, M.S., et al.* Solving of the ACH Problem in the Project "Interplanetary Solar Stereoscopic Observatory". Proc. Intl. Conf. «ACH-2009» (A.M.Finkelstein, et al., *eds*.), Saint-Petersburg, "Nauka", 2010, pp. 110-114.

The major technological aspects of creating the ISSO have been evaluated in 2007 and 2010 with participation of S.A.Lavochkin's and M.F.Reshetnev's corporations' specialists, with a thorough discussion. As the output from these discussions and evaluation, we have the following conclusion and recommendation:

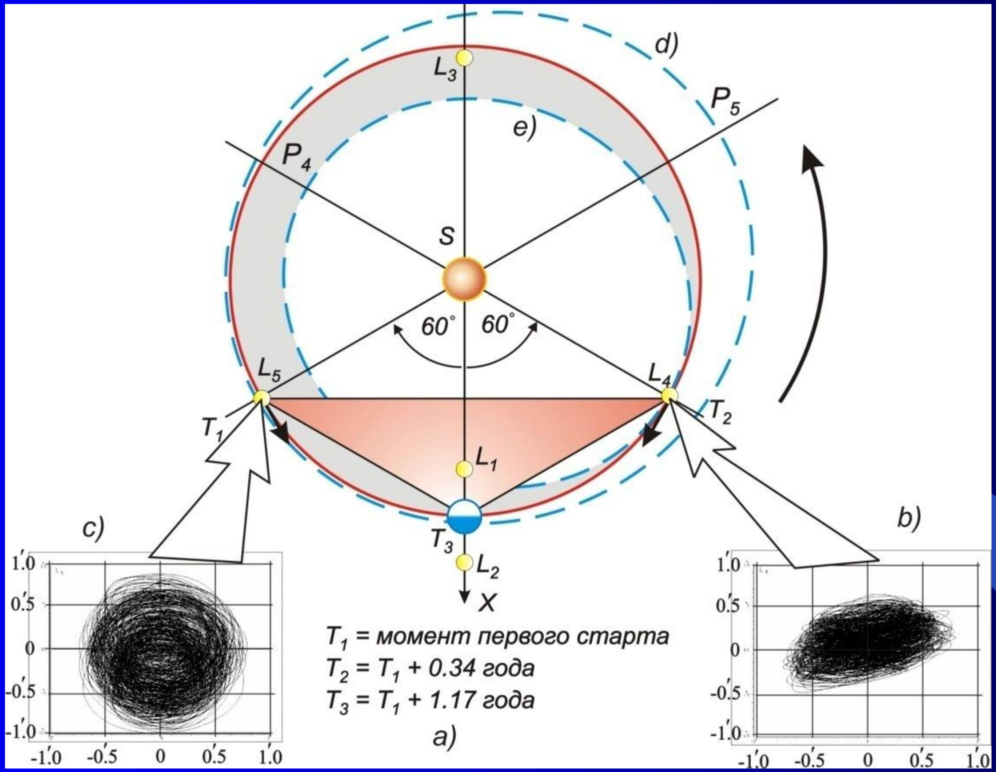
1) Implementation is possible on the base of the "Navigator" platform on the rocket "Soyuz-2" with the "Frigate" booster;
2) Split the layout into "solar" (properly ISSO) and "stellar" (OStSO) options.

Both options demand a **star sensor** for **navigation and control**. The principal differences between these options are:

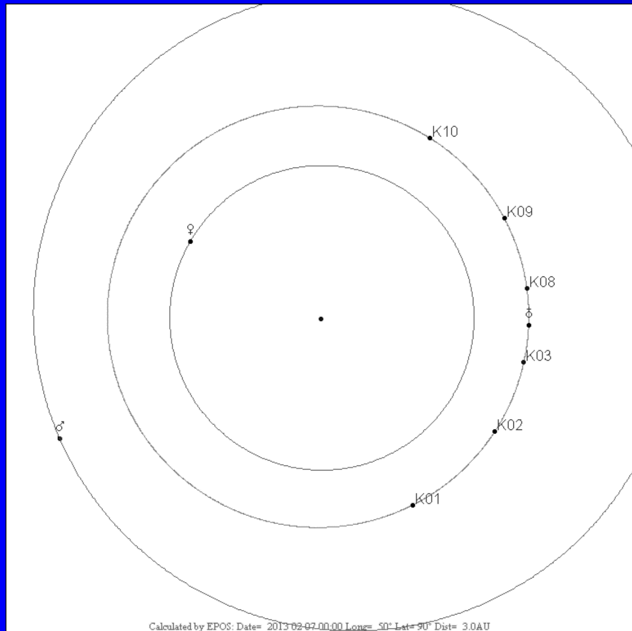
1) their basically different pointing systems and programs;
2) an extensive and complicated set of solar instruments that should deal with the strong solar radiation flux, which will require the use of special devices for protecting instruments and detectors;
3) only a single astrograph as the main instrument on board is necessary in the "stellar" option.



Placement of instruments at Lagrange centers ***L4, L5***. Vector connecting triangle libration centers *L4* and *L5* forms the main baseline of the OStSO. Installing an extra spacecraft in the near-Earth space (for instance, the Euler's centers ***L1*** or ***L2***) would add two more 1AU baselines. 5/6 of the solar surface can be observed simultaneously.



Spatial configuration and deployment to the operational orbits near the Lagrangian libration points L_4, L_5 (projected onto the ecliptic plane) for two spacecrafts. T_3 denotes the Earth, and S denotes the Sun. The triangle $L_4L_5T_3$, with vertices always lying in the ecliptic plane is subject to a quasi-solid rotation around the Sun S with the period of one year. Dashed circles are the calculated one-year Earth-L_5 (*d*) and Earth-L_4 (*e*) heliocentric transition orbits. Panel (*a*) shows the time sequence of spacecraft deployment. Panels (*b*) and (*c*) show the enlarged vicinities of the points *L4, L5* and libration motions of the spacecrafts on the timescale of about 160 years. Extent of these regions is ~65000 km, which is about $2.5{\cdot}10^{-4}$ of the length of the baseline B (~0.025%). B undergoes eccentric annual variation by 1.7%.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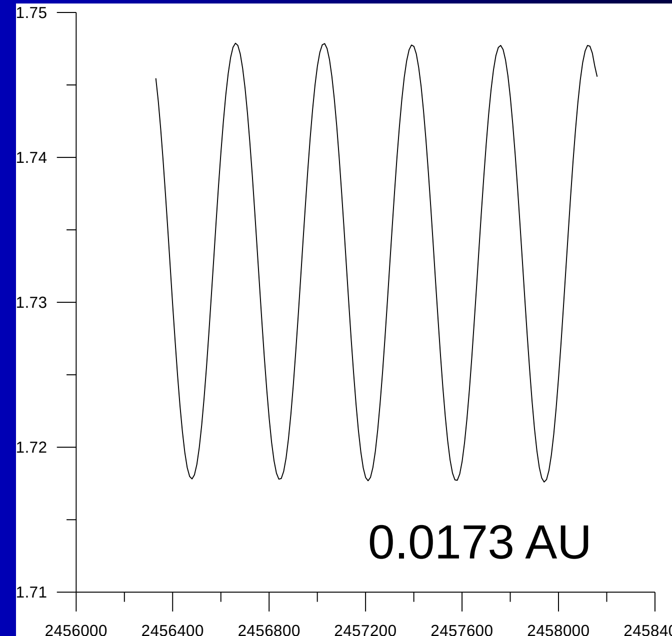
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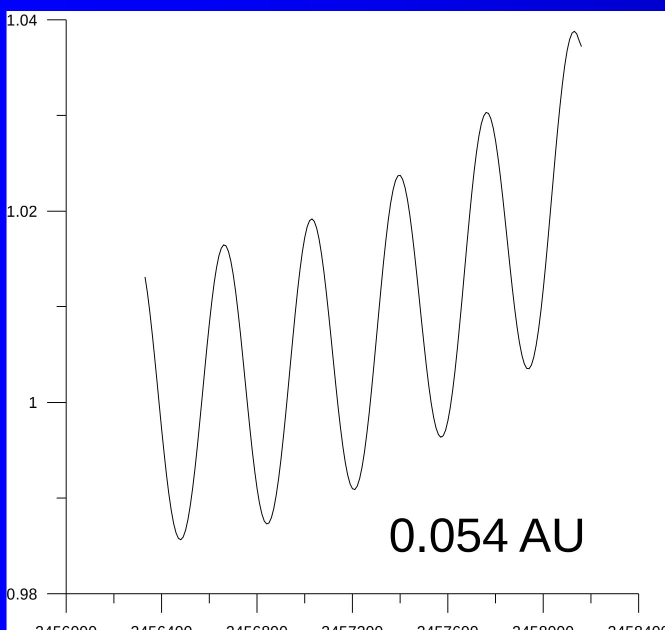
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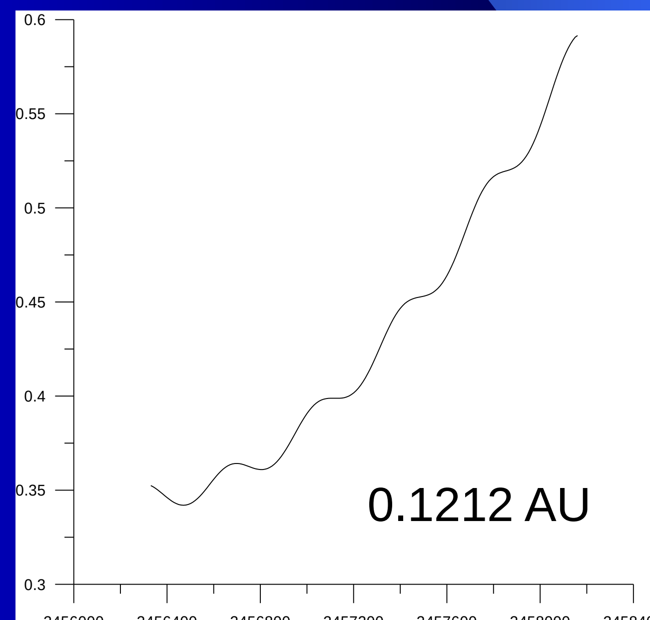
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0.55
0.5
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2456800
2457200
2457600
2458000
2458400
0.1212 AU

SCIENTIFIC OBJECTIVES

Five instrumental and scientific arguments:

1) the environmental conditions for the on-board equipment are similar and even milder that those near the Earth: strong radiation from van Allen radiation belts and considerable temperature changes while crossing the Earth´s shadow are absent;

2) these points are at 1 AU from the Sun, so there is no need in developing and testing any extra instrument-protecting systems other than those used for near-Earth orbits;

3) spatial separation between the Sun-Earth Lagrangian points L4 and L5 allows for synchronous triangulation observations with the effective baseline of $\sqrt{3}\ AU \simeq 259.1$ million kilometres for studying the Sun and solar-terrestrial physics and solving the problems related to the Asteroid and Comet Impact Hazard and other branches of astronomy as a whole.

Beyond any doubts, synchronous astrometric and photometric observations from two points in a wide field of view will provide a very stimulating material for researches in stellar and galactic astronomy, astrometry, and astrophysics.

4) Physical properties of space in the vicinities of the centers are similar to properties of space in the geostationary orbit, densely occupied since the end of the past century; certainly these points will be used in the current century as being convenient for long-term monitoring and research programs in stable conditions. No pollution of the near-Earth environment.

5) We support the European vision:

The XXI century will concentrate its efforts on the fundamental research of the Solar system on the base of modern technologies.

We solve the following problems in our project:
- Stability;
- Installation scenario;
- Autonomous navigation;
- Operational orbit control;
- Long-term program outlining.

- Perspective range for the baseline L_4L_5 reaches 5 kpc at $\sigma_1 = \pm 0.0005''$
- Objects of Solar system are in the nearest zone of thid range

- Tolerances on installation of the spacecrafts:
- **ΔRL** $\leq$ 1000 km, **δVL** $\leq$ 0.1 m/s, Δ***L*** ~ 30 000 km

Only such problems are included **in the scientific program** that have evident advantaged in **OStSO** compared to near-Earth and ground-based observations, i.e. to observations from a single direction.

SCIENTIFIC PROGRAM includes 3 principal kinds of the tasks:

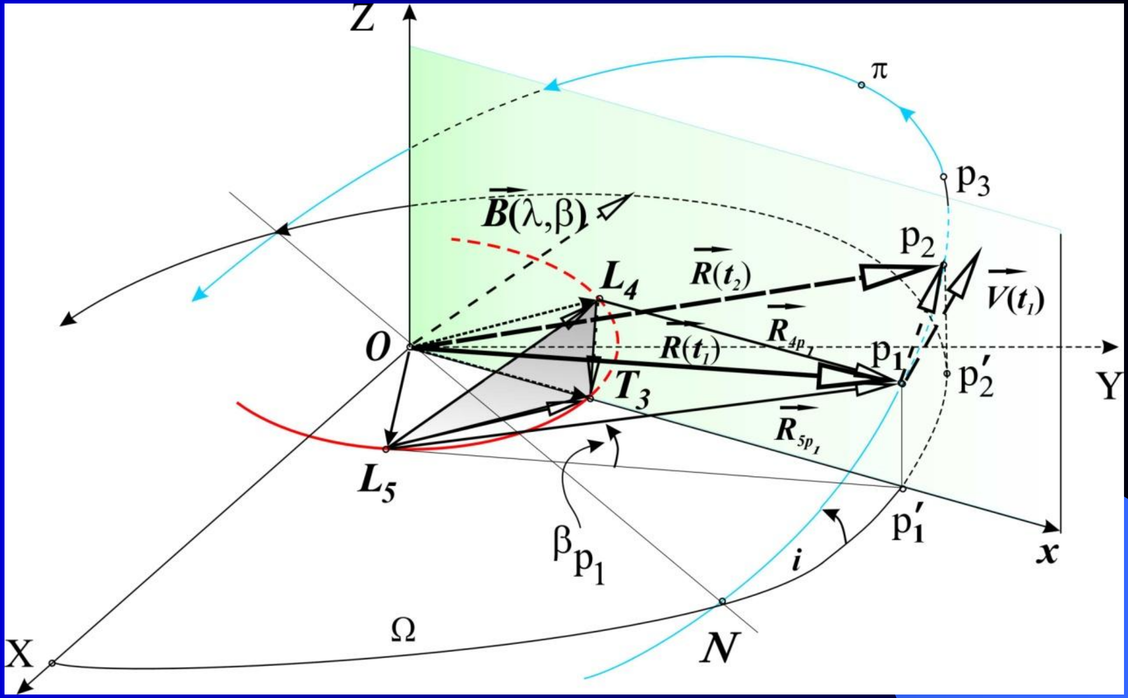
I. *Celestial mechanics*. Quasi-synchronous trigonometric observations of Solar system bodies and solving the fundamental tasks of the *Asteroid and **C**omet **H**azard* (***ACH***) problem on the base of high-resolution astrometric and photometric observations. Studying motions of small bodies of the Solar system –main-belt asteroids and transneptunian objects (TNOs) *in the Edgeworth-Kuiper Belt (**EKB**)* that still lack observations. The mechanism of migration of ***EKB*** bodies into the inner area of the Solar system and its influence on the evolution of the Solar system is not yet clear. OStSO can be used for measuring physical properties and motions of Solar system bodies at distances of 0.6 AU to 2000 AU.

3D determination of orbits of Solar system bodies

$$\left.\begin{aligned}\overrightarrow{R_i}(t_i) = \overrightarrow{R_0(t_0)} + \overrightarrow{V_0}(t_i - t_0) + \overrightarrow{\delta R_i} \\ \left[\overrightarrow{\delta R_i}\right] = \vec{0}, \quad i = 1, 2, \ldots n,\end{aligned}\right\} \quad (1)$$

System of vectorial equations, least-squares adjustment of ***n*** observations

Observations of solar system bodies, including TNOs



Result:

$$\overrightarrow{R_0(t_0)} = \{R_x, R_y, R_z\} - \textit{radius vector},$$

$$\overrightarrow{V_0(t_0)} = \{V_x, V_y, V_z\} - \textit{barycentric velocity} =$$

$$= \textit{barycentric orbit}.$$

II. *Astrometry, stellar astronomy, and astrophysics*

Determination of *trigonometric parallaxes from synchronous observations of stars at distances of up to 5 kpc*. The method is more accurate than the traditional asynchronous one.

Observations in a set of middle-band filters in the wide field of view allow one to obtain *spectral energy distribution (SED) curves* for all objects in the field of view. Such observations are vital in solving the various problems of Galactic kinematics and dynamics and in astrometry and astrophysics.

OStSO has the advantage in the determination of parallaxes of double and multiple stellar systems as it has no need in reductions for observer's motion and that of the object being studied.

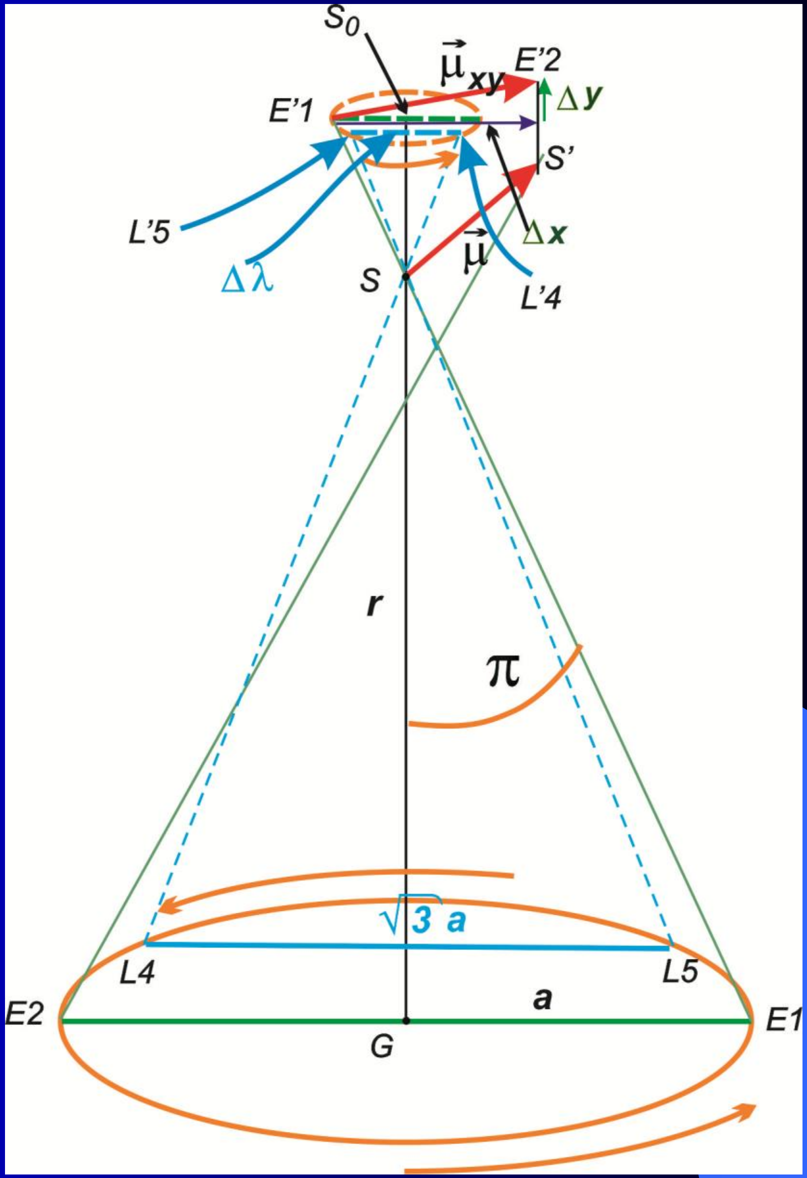
Stellar parallaxes in the Solar vicinity can be determined for stars as faint as ~22^m.

Classical method:

$$\lambda_0, \beta_0, \mu''_\lambda, \mu''_\beta \ \ and \ \ \pi$$

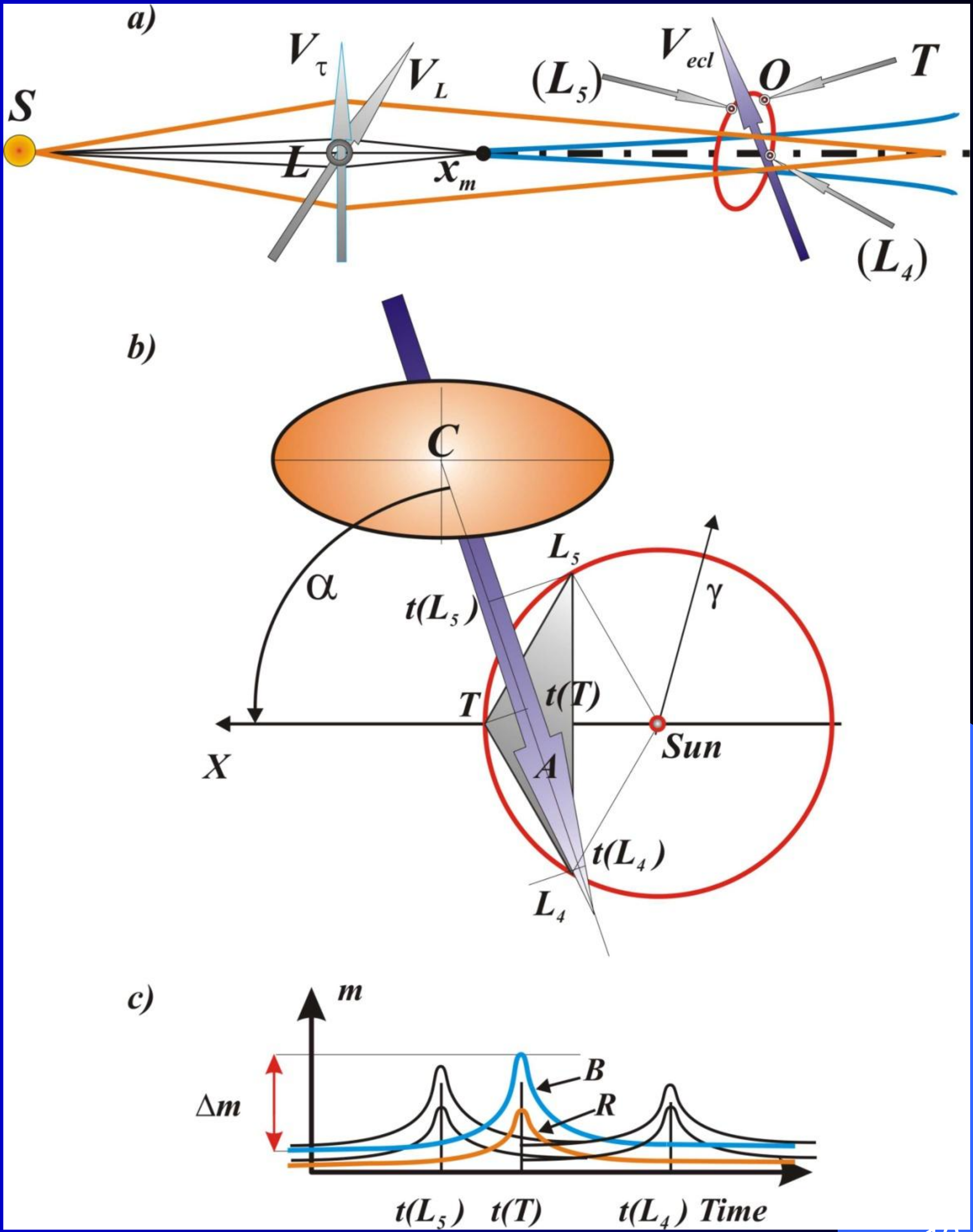
Synchronous method:

$$\sqrt{3}\pi = \Delta\lambda$$

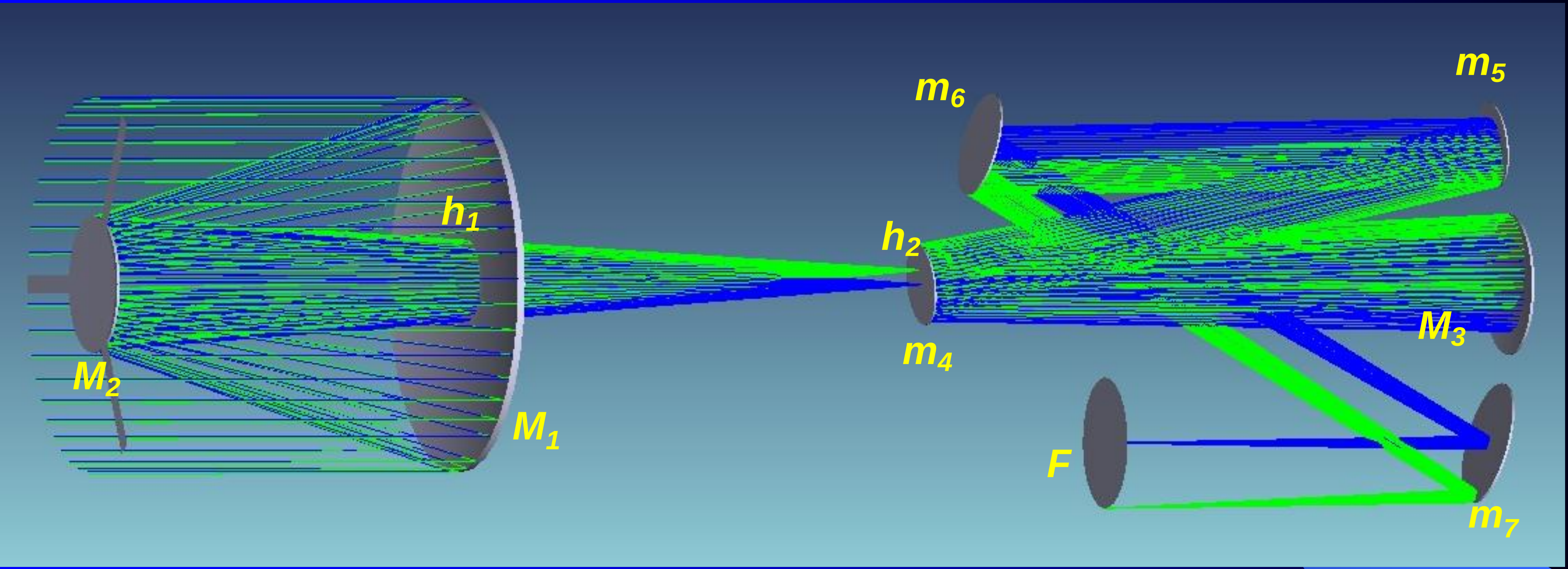


III. *Support* for ground-based observations of microlensing in programs like OGLE, EROS, MACHO (**and other transients, including the extrasolar planets by transit method).**

It will be possible to make the plot ***c)*** and the luminosity distribution in the focal zone (***O*** in panel ***a***). This is a difficult but interesting problem of observational astronomy that strongly gains from stereo observations.



Optical design of astrograph (first scheme)



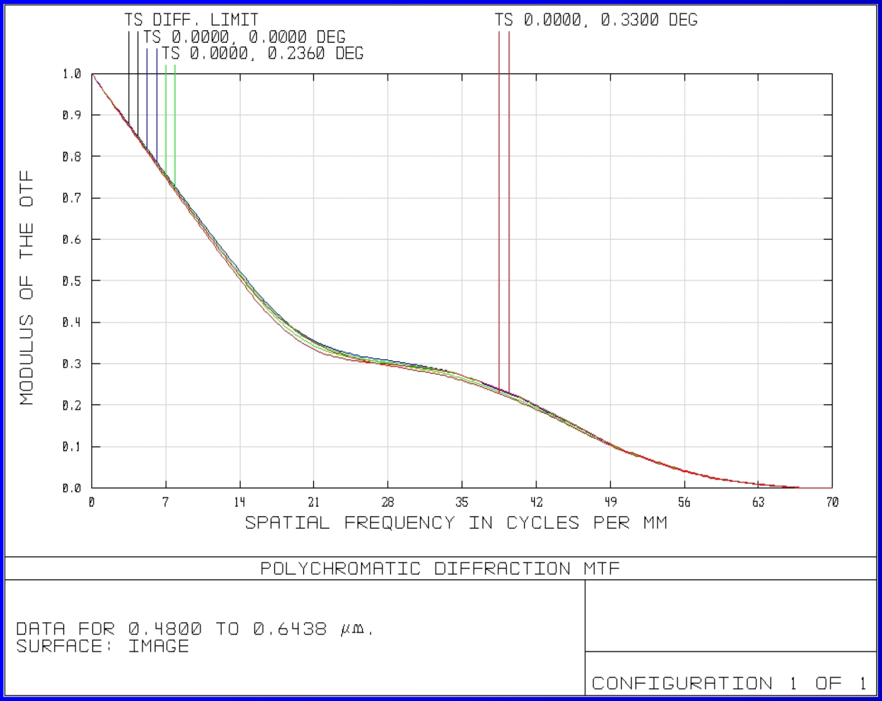
D_1=1 m

f', m	2ω, min	$2y'$, mm	η
5	60	87.3	0.28
10	60	174.5	0.28
15	60	261.8	0.3
20	45	261.8	0.32
30	40	345.6	0.4

Tikhomirova (Tsukanova) G.I. Three mirror astronomical lenses. // Izv. VUZ USSR. Instrumentation. **1967.** V.10. No.12.

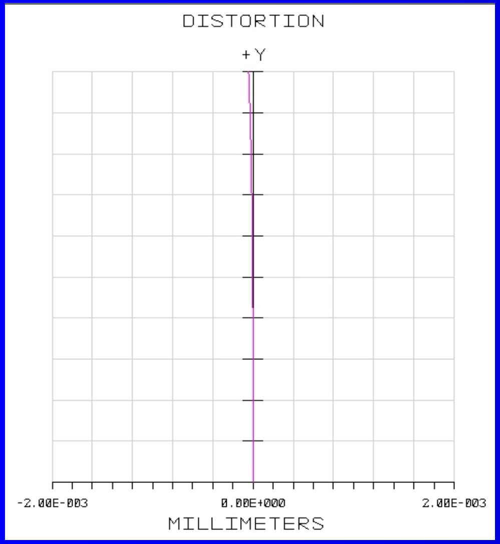
Korsch D. Anastigmatic three-mirror telescope // Appl. Opt. **1977**. No.8. Pp. 2074–2077.

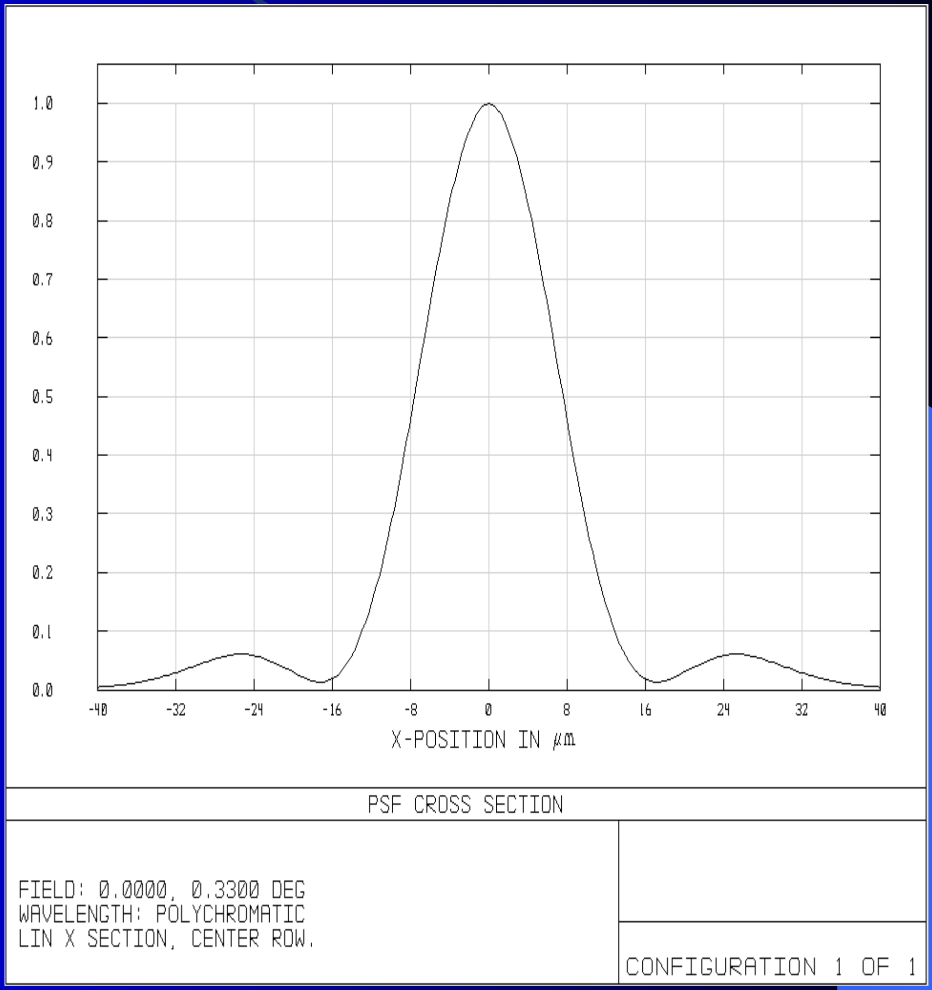
Orthoscopic mirror lens with diffraction image points over the whole field



f'=30m D_1=1m η=0.35

2ω=40', $2y'$=345.6mm



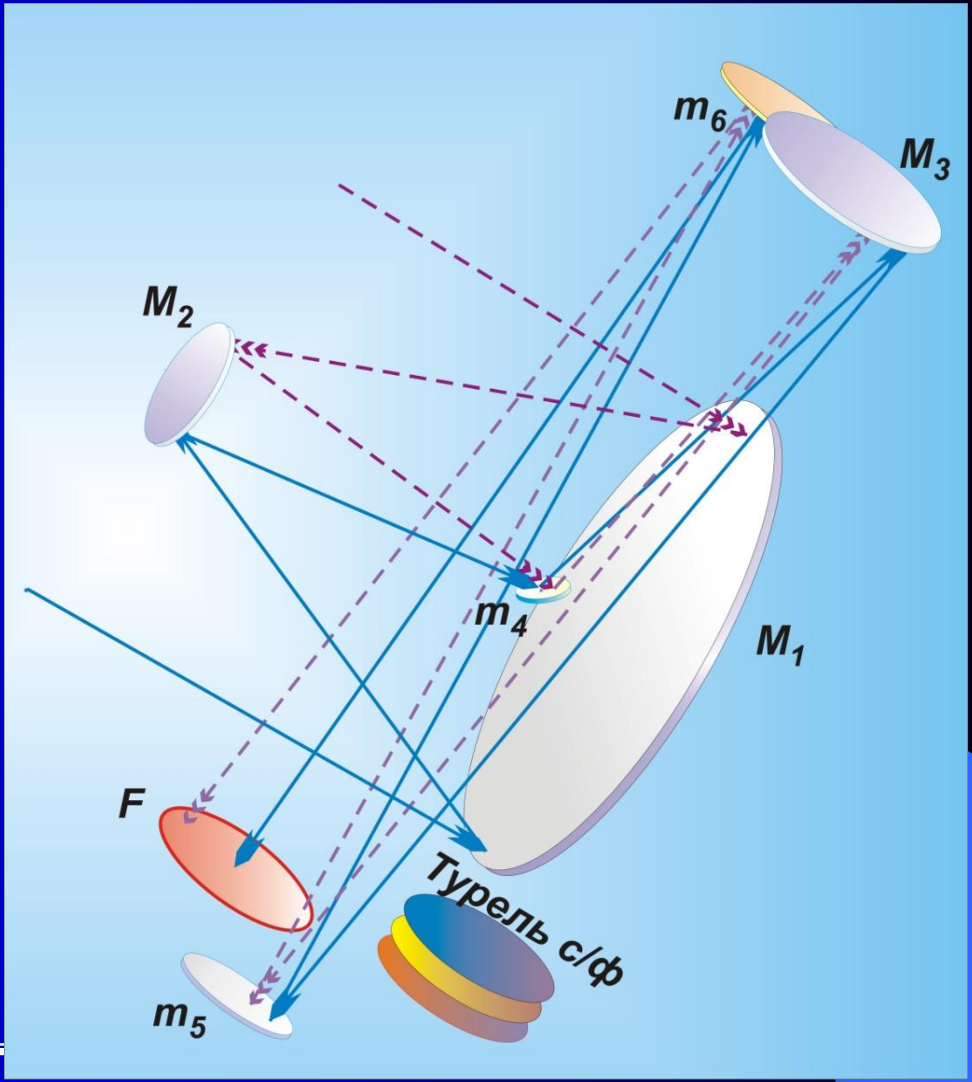


ASTROGRAPH:

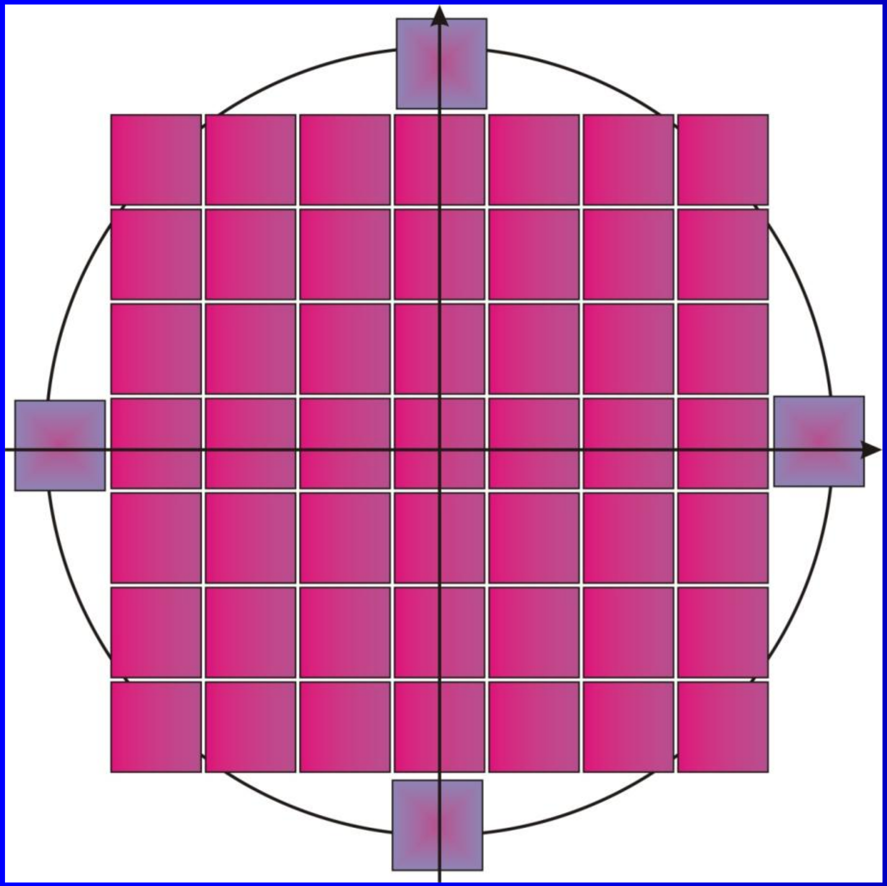
Tree-mirror anastigmatic orthoscopic optical system.

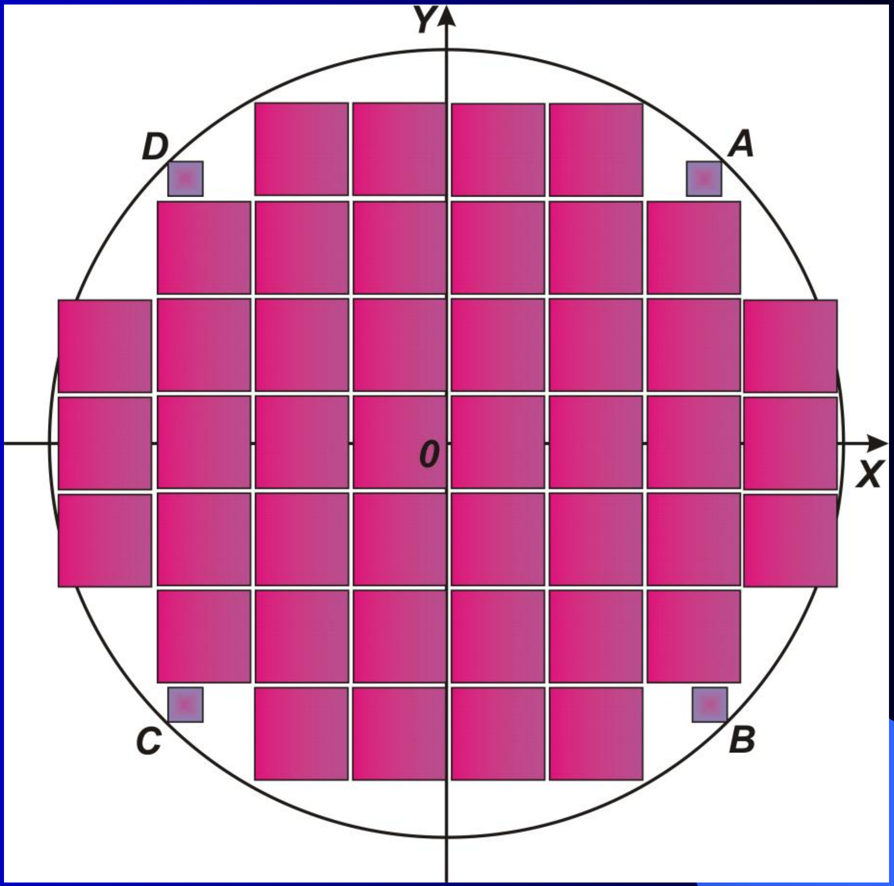
The second scheme: overall dimensions 2.70 × 2.10 × 1.50 m^3, Field of view: 2ω = 1°, linear size is 350 mm,
***f* = 20m.**
***D* = 1m**
Obscuration *η* = 0.32.

M_1 and M_3 – ellipsoids, M_2 – hyperboloid, m_4, m_5, m_6 – planes, *F* – focal plane. Color filter wheel is placed before detector.

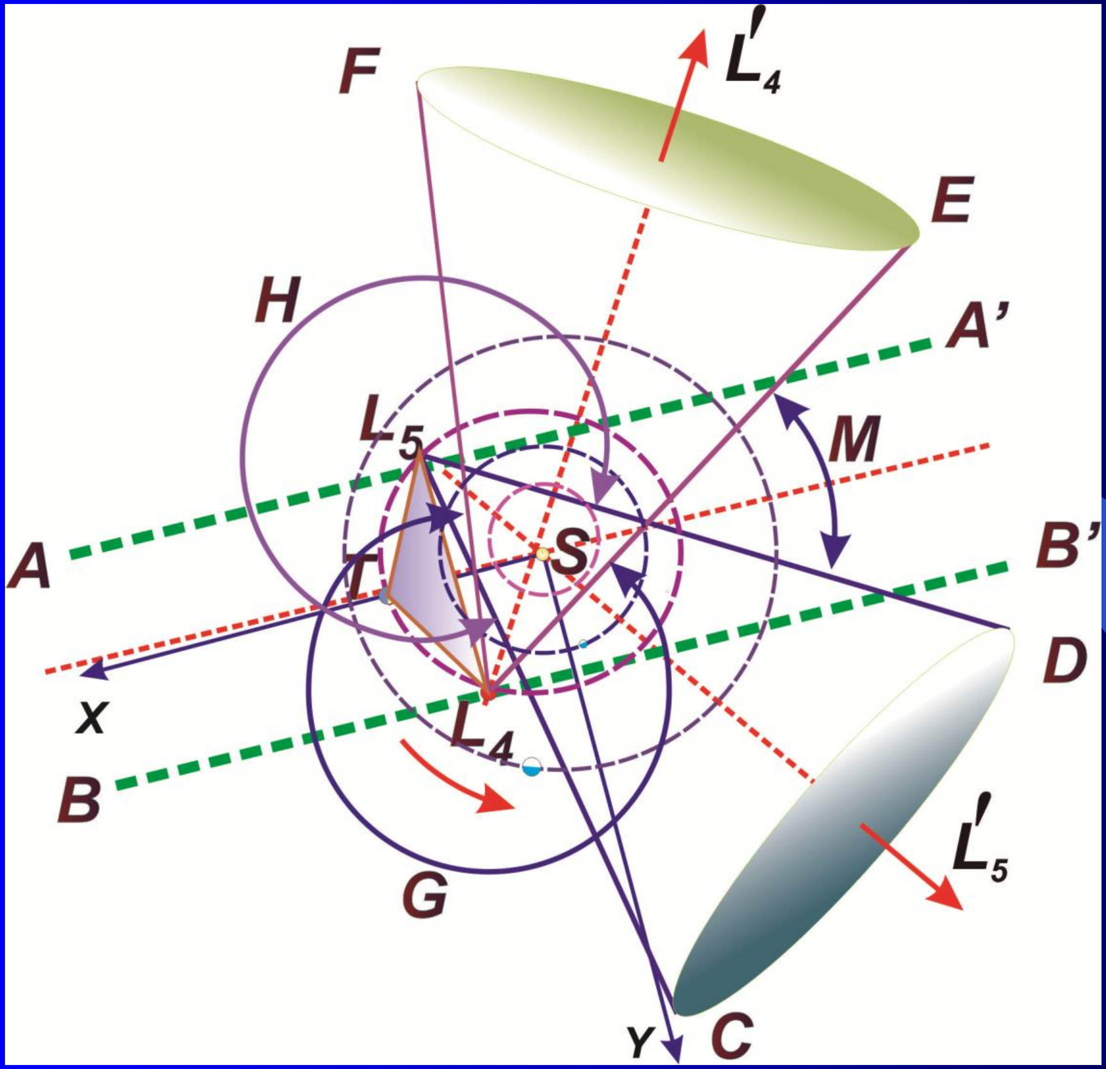


- Tsukanova G., Bakholdin A., Chubey M. Specifics of the design of the optical system of an astrograph for the Interplanetary Solar Stereoscopic Observatory Project // Journal of Optical Technology. - 2007. - Iss. 74. - N 7. - P. 467-470.
- Tsukanova G., Bakholdin A., Chubey M. Protection from direct illumination in the system of the astrograph for the Interplanetary Solar Stereoscopic Observatory. - 2009. - Iss. 76. - N 8. - P. 504-506.

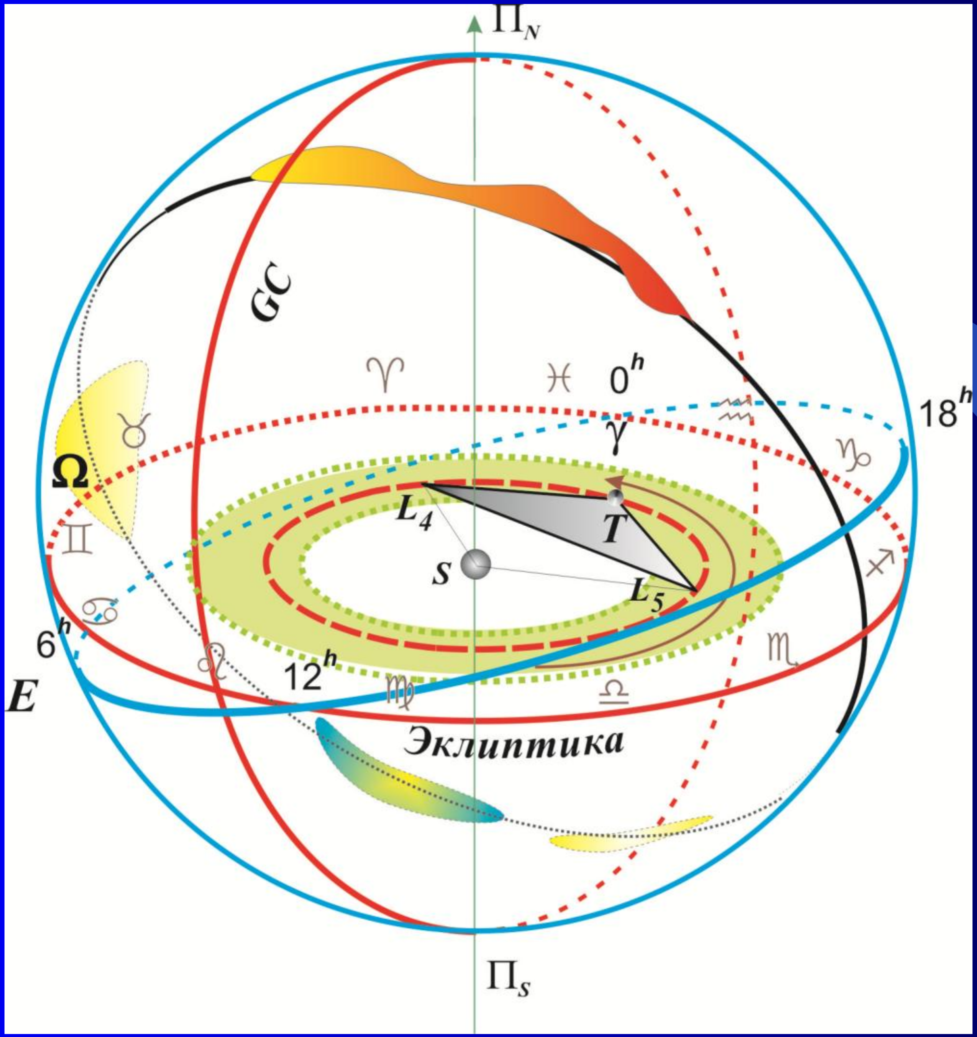




CCD mosaic options: 44 (or 49) p-channel 4K×4K CCDs inscribed into a circle 350 mm in diameter. Every CCD has 2 sections and 4 output nodes with programmed video signal output through any node, for the case of a damage of any register or node element. The p-channeled CCD is more durable than n-channeled one with respect to high-energy particles, and hence a longer lifetime. Given a 10μm pixel, this leads to ~0.86 Gigapixels per frame.



OStSO has meridian TSM and cones of avoidance of the edge flare zones.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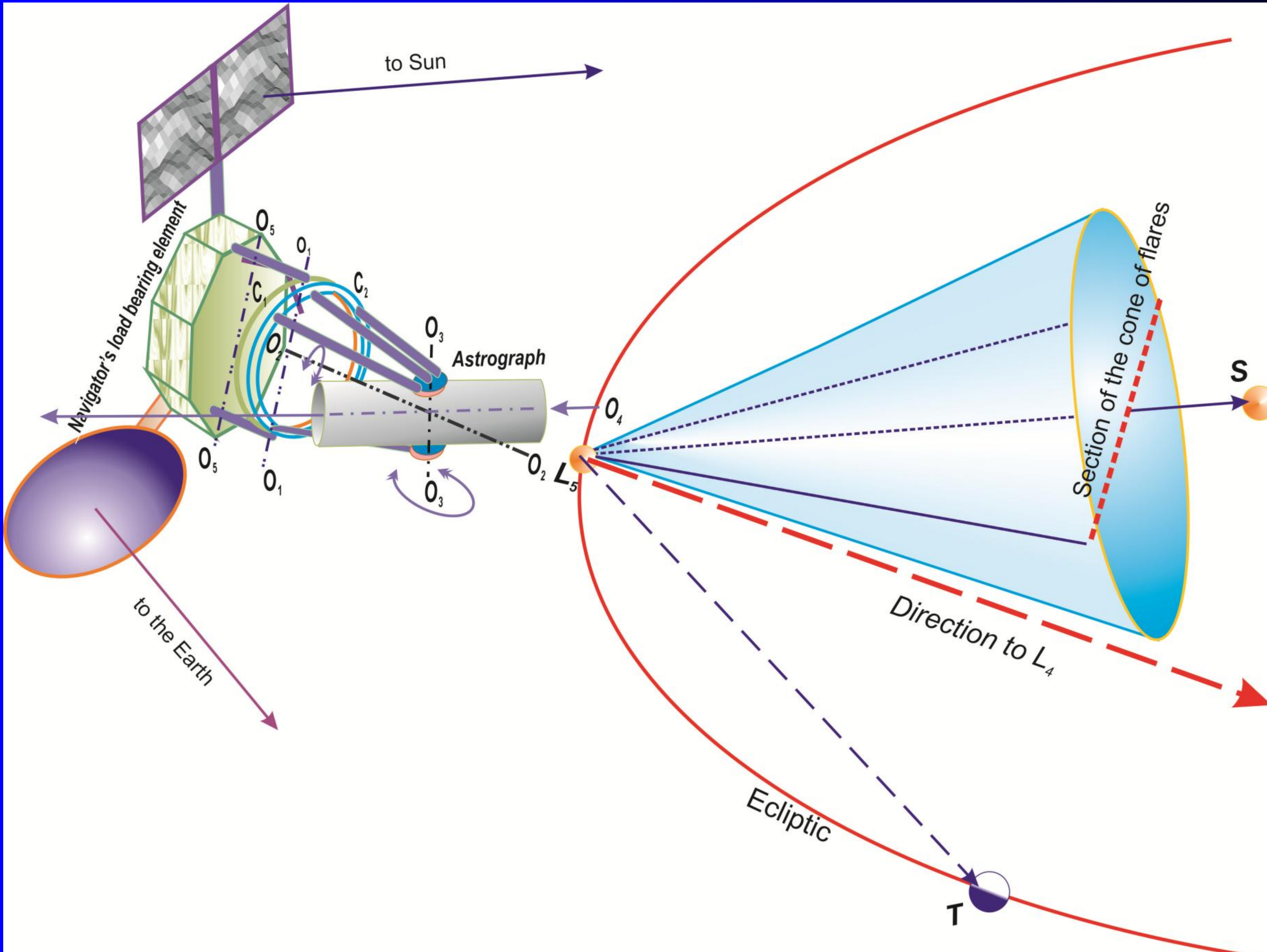

to Sun
Navigator's load bearing element
O5
O1
C1
C2
O2
O3
Astrograph
O4
O2
L5
O5
O1
O3
to the Earth
Section of the cone of flares
S
Direction to L4
Ecliptic
T

Solving autonomous navigation tasks in transfer and operational orbits

The majority of the navigation systems have been developed for near-Earth SCs. (Avanesov G.A. group from IKI – BOKZ series; Mark L. Psiaki group and others). For deep space, e.g. the group of *Jo Ryeong Yim* develops navigation methods and equipment based on the Doppler shift of the lines in the solar spectrum and radar ranging.

Our approach was inspired by the desire to have an additional stellar sensor that could be useful for navigation, control functions, and possibly some kinds of observations. We plan to implement our own purely astronomical autonomous navigation on board.

We are planning to use a two-channel high-resolution (0.″01) star sensor [1]. Observations are done on the principle of alignment of directions “planet →SC→ stellar field”.

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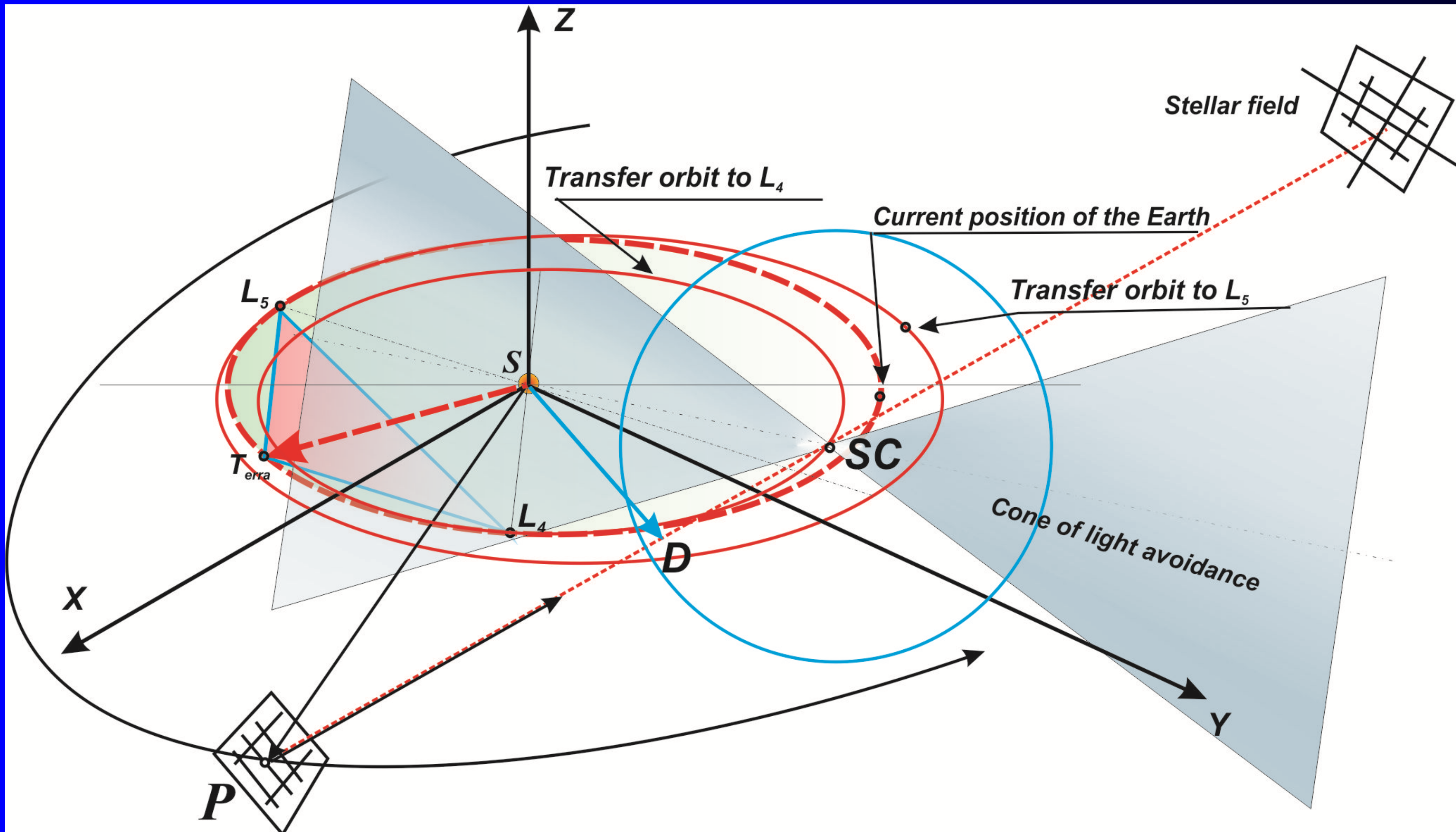
[1] *Chubey et al.*, 2007. J. Opt. Techn., 2007, **74**, №2, pp. 40–48.

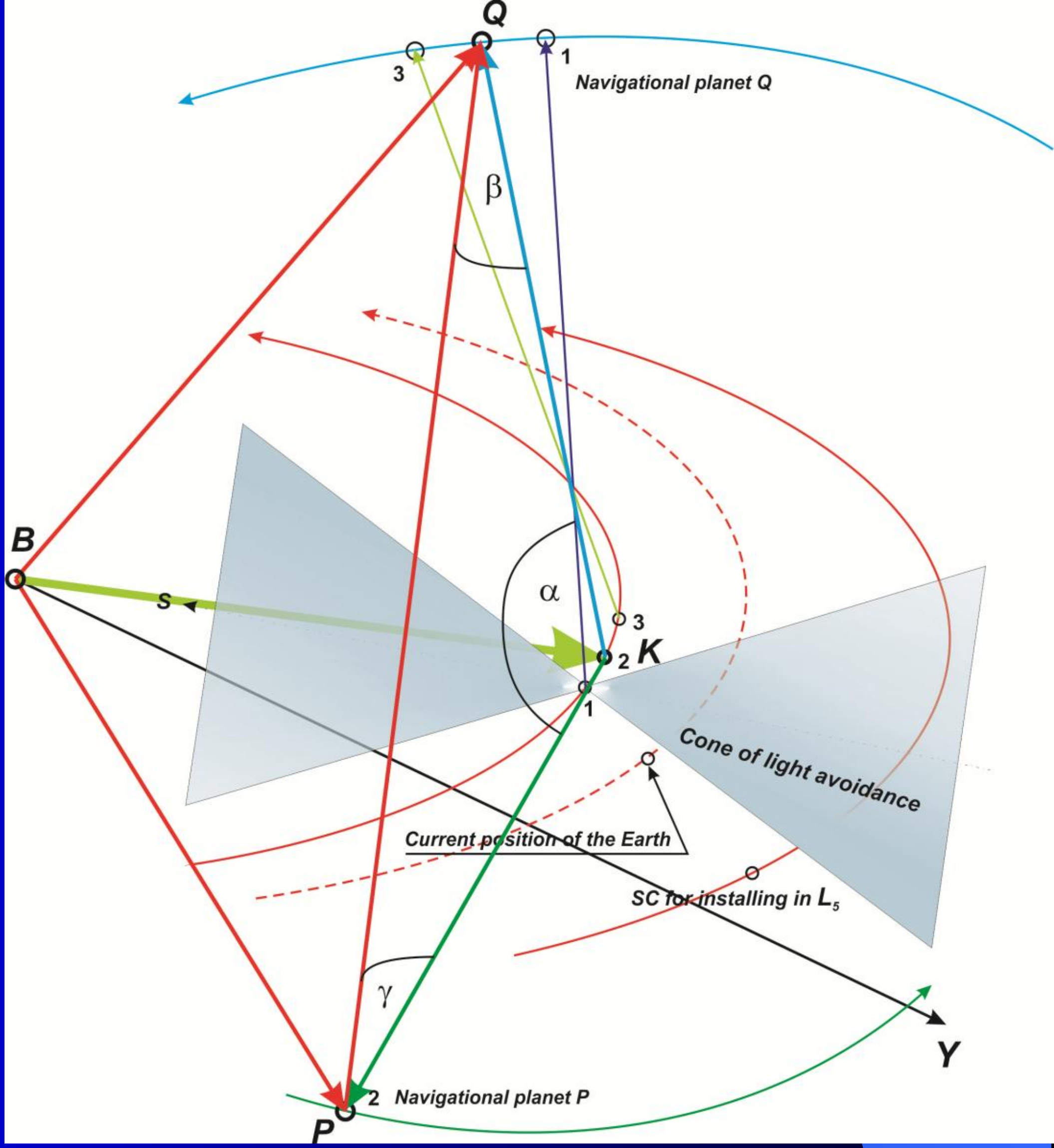


Schematics of a star sensor working on the principle of alignment "P→SC→stellar field (PS)". An image of the planet with theoretical position from DE/LE (JPL) or ERM (IPA RAS) – usually a bright object (Earth+Moon, Mars and others) – is on the line PS. An image of a stellar field with no bright objects gives a reference frame determining the direction SC→P.

Construction of the triangle ***PQK*** by observing planets P and Q at alignments 1→1, 2 → 2 and 3 → 3. From DE/LE or ERM IPA we have

$$\left.\begin{aligned}\overrightarrow{BP} &= \overrightarrow{r_P} = \{r_P, \alpha_P, \delta_P\}, \rightarrow \dot{\overrightarrow{r_P}}, \ddot{\overrightarrow{r_P}};\\ \overrightarrow{BQ} &= \overrightarrow{r_Q} = \{r_Q, \alpha_Q, \delta_Q\}, \rightarrow \dot{\overrightarrow{r_Q}}, \ddot{\overrightarrow{r_Q}}.\end{aligned}\right\}$$

$$\overrightarrow{PQ} = \overrightarrow{r_{PQ}} = \overrightarrow{r_p} - \overrightarrow{r_Q} = \{r_{PQ}, \alpha_{PQ}, \delta_{PQ}\}.$$



Observations give

$$KP = \{\alpha_{KP}, \delta_{KP}\}; \quad KQ = \{\alpha_{KQ}, \delta_{KQ}\}.$$

Calculation gives

$$\left.\begin{aligned}\left|\overrightarrow{KP}\right| &= \left|\overrightarrow{PQ}\right|\frac{\sin\beta}{\sin\alpha};\\ \left|\overrightarrow{KQ}\right| &= \left|\overrightarrow{PQ}\right|\frac{\sin\gamma}{\sin\alpha}.\end{aligned}\right\}$$

Barycentric radius is $\overrightarrow{BK} = \overrightarrow{r_K} = \overrightarrow{r_P} + \overrightarrow{PK} = \overrightarrow{r_Q} + \overrightarrow{QK}.$

The orbit of SC by solution (1) (Slide 10)

The algorithm is simple; relativistic correction for light time is also taken into account:

If we have the coordinates of two planets, indexed by 1 and 2, for the moment t

$x_1, y_1, z_1,$ *and* $x_2, y_2, z_2,$ while α_1, δ_1 *and* α_2, δ_2 are their spherical

coordinates, we can calculate parameters

$l_i = \cos\alpha_i \cos\delta_i,\ m_i = \sin\alpha_i \cos\delta_i,\ n_i = \sin\delta_i, \quad i = 1, 2$. Then we get SC coordinates (x_0, y_0, z_0) from equations

$$\left.\begin{aligned} x_0 &= \frac{n_1 l_2 x_1 - n_2 l_1 x_2 - l_1 l_2 (z_1 - z_2)}{n_1 l_2 - n_2 l_1} \\ y_0 &= \frac{l_1 m_2 y_1 - n_2 m_1 y_2 - m_1 m_2 (x_1 - x_2)}{l_1 m_2 - l_2 m_1} \\ z_0 &= \frac{m_1 n_2 z_1 - m_2 n_1 z_2 - n_1 n_2 (y_1 - y_2)}{m_1 n_2 - m_2 n_1} \end{aligned}\right\}$$

If τ is the time of travel of signal from the Earth to SC, measured by radio chronometry, we have

$$x_0 = x_1 - lc\tau, y_0 = y_1 - mc\tau, z_0 = z_1 - nc\tau. \qquad (2)$$

Here $c = 299792.458 km / \sec = 173.14 AU / date$ is the velocity of light. From 2 or more observations, we get the SC velocity solving the system (1).

We obtain the dispersion equation of the procedure by differentiating (2):

$$\sigma^2 = c^2\tau^2\left(\cos^2\delta \cdot \sigma_\alpha^2 + \sigma_\delta^2\right) + c^2\sigma_\tau^2 .$$

Let $\left.\begin{array}{l} \sigma_\alpha \cos\delta = \sigma_\delta = 0''.001 = 0.5\times10^{-8},\ c\tau \approx 1 \text{ a.e.}, \\ \tau \approx 10^{-9} \text{ сут.} = 10^{-4} \text{ сек.},\ c = 173.14 \text{ a.e./сут.} \end{array}\right\}$

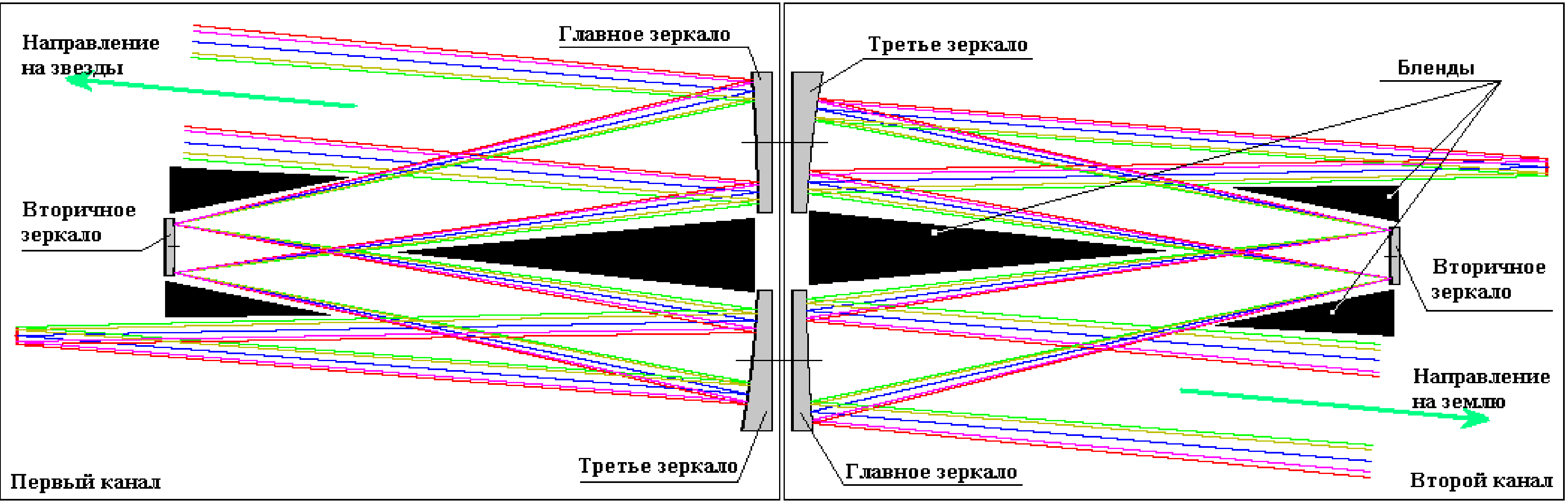
Then

$$\sigma \approx 25.9 \text{ km}$$

So, the accuracy of interval τ **strongly affects the resulting accuracy.**

Star sensor: Optical design

$f' = 2500$ mm, $D_1 = 250$ mm, $\omega = 1°$



Star sensor for independent navigation in deep space. Chubei, M.S.; Koval'chuk, L.V.; Kholodova, S.I.; Es'kov, D.N.; Seregin, D.A.; Miloradov, A.B. 2007 Journal of Optical Technology 74(2) 107-114

SUMMARY

The OStSO project presented here has been thoroughly worked out in the aspect of theory and instrumentation design solutions, with approbation in the professional auditoriums, conferences, periodic. Our small group is ready to write the technical documentation in collaboration with designers of SCs. The space-based observatory is efficient in solving problems of ACH and kinematics and dynamics of Solar system bodies.

Results planned:

1) a first modern extensive database of direct synchronous observations of high astrometric and photometric quality, obtained in stereo mode, as a base for research in orbital evolution of Solar system bodies, fundamental aspects of the ACH problem, stellar dynamics research, and studying the evolution of Galactic and extragalactic structures on homogeneous material of space observations;

2) a unique experience of creating a long-living space-based observatory in the vicinity of Lagrangian libration centers, which are very promising for future space exploration due to their stability and to advantages of the stereo vision as an evolutionary principle in nature;

3) this experience is also very important for the forthcoming Solar Stereoscopic Observatory for research in the field of solar-terrestrial interactions and solar physics.

Thank you for your attention!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