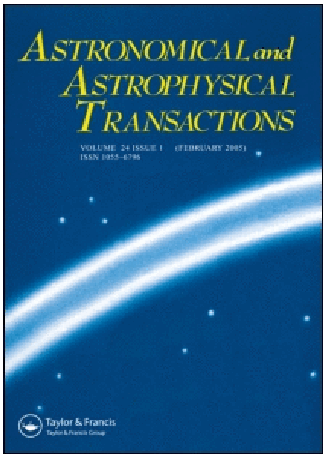

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

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Online Publication Date: 01 July 1997
To cite this Article: Yershov, V. N., Tsukanova, G. I., Starichenkova, V. D. and Zakharenkov, G. F. (1997) 'Optical scheme for the "Struve" space astrometric project', Astronomical & Astrophysical Transactions, 13:1, 29 - 34
To link to this article: DOI: 10.1080/10556799708208112
URL: http://dx.doi.org/10.1080/10556799708208112

Astronomical and Astrophysical Transactions, 1997, Vol. 13, pp. 29–34
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OPTICAL SCHEME FOR THE "STRUVE" SPACE ASTROMETRIC PROJECT

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(Received June 20, 1996)

A few options of the optical scheme for the future Russian astrometric satellite ("Struve") are discussed. Interferometric and single-aperture options of the on board telescopes are compared from the points of view of optical resolution, quality of image, achievable positional accuracy, and feasibility of the scheme. Two telescopes are planned to be used on board the Struve satellite in order to scan the sky with two basic angles. With these two telescopes one can make observations using two different photodetectors: for example, the visual ($\lambda_{\max} = 0.7\mu$) and the ultraviolet one ($\lambda_{\max} = 0.15\ \mu$). In addition, middle-band photometry will be made at the visual channel which gives data on spectral features, chemical composition, and the evolution of stars. A tree-mirror reflector optical scheme is concluded to be optimal in the astrometric satellite.

KEY WORDS Struve astrometric satellite, telescopes

1 INTRODUCTION

The Struve astrometric satellite which is being developed at the Pulkovo Observatory in cooperation with the Krasnoyarsk Institute of Applied Mechanics, S. I. Vavilov's State Optical Institute and some other space instrumentation institutes, will produce observations of a second epoch for the Hipparcos stars. The project is devoted to maintaining the Hipparcos coordinate system as well as extending it to a density of ≈ 100 stars per square degree. Being launched a decade after Hipparcos, the new satellite will improve proper motions and will essentially decrease the degradation of the Hipparcos reference system.

The satellite is being designed to rotate very smoothly in order to minimize errors of observations. Wide arcs of the sky will be measured by combining separated fields of the sky in one telescope. The basic measuring angle will be formed by a special beam combiner placed in front of the telescope. Two different basic angles and two

Table 1. Minimal values of the telescope focal lengths (expressed in 10^6 pixels) given for different entrance pupils D, m, and effective wavelengths λ_{eff}, nm

$D(m)$	$\lambda = 700$	600	500	400	300	200	100
0.4	0.23	0.27	0.34	0.41	0.54	0.86	1.7
0.5	0.29	0.34	0.41	0.52	0.69	1.0	2.1
0.6	0.35	0.41	0.49	0.61	0.86	1.3	2.4
0.7	0.41	0.47	0.57	0.74	0.94	1.5	2.6
0.8	0.47	0.54	0.64	0.86	1.1	1.7	3.2
0.9	0.52	0.61	0.73	0.94	1.2	1.9	3.7
1.0	0.57	0.69	0.86	1.0	1.4	2.1	4.5
1.5	0.86	1.0	1.3	1.5	2.1	3.4	5.2
2.0	1.1	1.3	1.7	2.1	2.6	4.3	7.4
2.5	1.5	1.7	2.1	2.6	3.4	5.2	10.3
3.0	1.7	2.1	2.6	3.4	4.3	6.4	12.9
4.0	2.6	2.6	3.4	5.2	5.4	10.3	17.2

telescopes are planned to be used on board the Struve satellite, since it will reduce periodic systematic errors of observations.

The telescope field of view is to be at least $1^\circ \times 1^\circ$ in order for the half year coverage of the sky to be possible. The image should be of a diffraction quality within this square degree field of view because a submilliarcsecond accuracy of observations is planned to be achieved. Both telescopes are to be folded inside a limited volume of the satellite (a cylinder 3 m in diameter and 1.5 m in height).

2 PARAMETERS OF THE OPTICS

Two parameters of the on-board telescopes are critical for achieving the prescribed accuracy and limiting magnitude. They are the focal length and the entrance pupil. The focal length defines the scale and, hence, the resolution of the instrument. The resolution is limited by diffraction from the entrance pupil and the working spectral range of the instrument. The shape of the entrance pupil is also important. Taking into account the fact the measurements are one-dimensional one may choose a optimal shape of the aperture.

One may enlarge the entrance pupil in the measuring direction or separate two parts of the aperture by some distance. In the latter case one will observe an interferometric fringe with the first dark band separated by $1.22\lambda/d$ from the image center, where d is the distance between two entrance pupils of the interferometer. An essential increase of the accuracy might be achieved at $\lambda_{\text{eff}} = 700$ nm with a 2–3 m diameter aperture or with a 2–3 m base interferometer. Using shorter wavelengths (for example, the ultraviolet, $\lambda_{\text{eff}} = 150$ nm) one may achieve similar results for a single moderate aperture (≈ 0.4 m).

In order to be able to determine the coordinates of the image one should project the star image onto a few pixels of the detector. So, the focal length of the telescope depends on the resolution of the detector. The minimal focal lengths are given in Table 1. For example, with 10 μ resolution elements of the detector one should use $\approx$2–3 m focal length of the telescope.

The focal length is to be enlarged up to $\approx$ 17 m for the case of the UV-registration. In this case the linear sizes of the detector prove to be rather big 30 × 30 cm^2), and it is very desirable to improve the resolution capacity of the detector up to 1–2 μ.

3 SCHMIDT OPTION

Initially, a Schmidt optical scheme of the on-board telescopes has been considered with a 40 cm diameter entrance pupil and with a glass correction plate (Figure 1). The focal length was chosen to be 2.5 m, and a 1° × 1° field of view was considered as a minimal one having no aberrations.

Two on-board telescopes are assumed to be directed one to another with a beam combiner placed in front of their entrance pupils at the center of the instrument. It is supposed that the temperature variations are smaller there.

The telescopes are to be folded in the 3 m diameter inner space of the satellite, and additional flat mirrors are used in order to place the optics on two-level cells of the instrument (Figure 2).

A similar Schmidt optical scheme was used for the Hipparcos satellite (except that it was a full reflective Schmidt with the corrector polished on the flat surfaces of the beam combiner). The diffraction limited quality and central symmetry of the images within a wide field of view are very attractive properties of the Schmidt telescope. But its focal surface is curved, and CCDs are very difficult to fit on this surface. Additionally, the Schmidt telescope is not a compact one because its corrective plate should be located on the double focal length distance from the primary mirror, and the diameter of the primary mirror is to bigger than the entrace

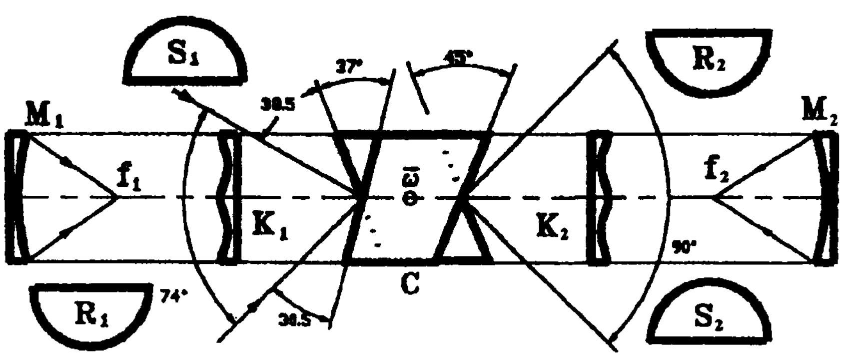

Figure 1 Schmidt option of the on-board telescopes.

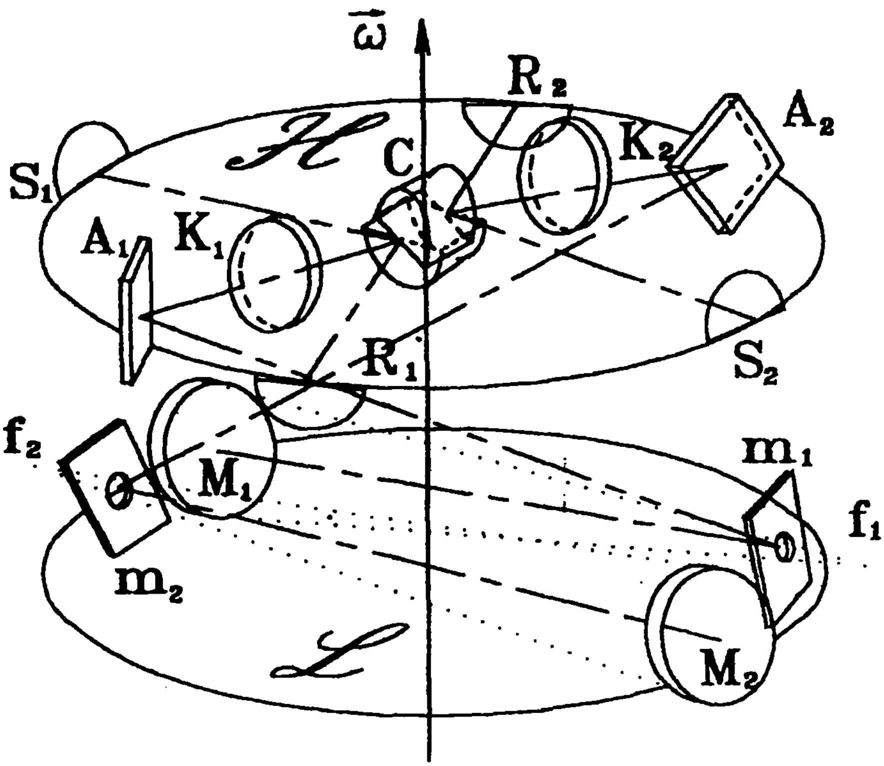

Figure 2 Two-level scheme of the placement of the Schmidt optics.

pupil (it is approximately proportional to $2F \tan \omega$). That is why a three-mirror optical scheme has been considered for the Struve telescopes.

4 THREE-MIRROR SCHEME

It was decided to make the Struve telescopes more compact and with a better light-collecting capacity keeping approximately the same mass as the Schmidt telescopes.

It proved to be possible to increase the entrance pupil up to 610 mm keeping the 2.5 m focal length and more than one square degree field of view (Figure 3).

The primary mirror is of ellipsoidal shape close to parabolic. The secondary mirror is hyperbolic and the third is an ellipsoid close to a sphere. A small flat mirror is used in order to direct the light beams to the third mirror. This flat mirror is placed in front of the equivalent focal point of the first pair of mirrors. So, the convex of the light beams is directed to the third mirror, and the divergent light falls to this third mirror which is to have a rather big diameter in order to reflect all the beams.

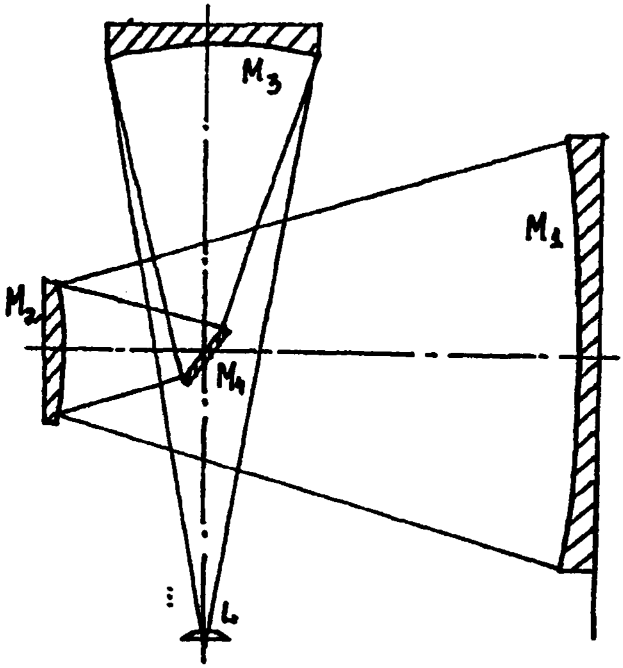

Figure 3 Three-mirror optical scheme.

The first pair of the mirrors form an image which has dimensions which are approximately twice as small than is necessary. The third mirror forms the final scale and makes the final correction of aberrations. Scattered light which may penetrate between the third and flat mirrors is cut off with special small blends.

Two options of the optical scheme have been calculated: a totally reflective one and the scheme with a lens corrector in front of the focal plane. The first scheme provides wave aberrations less then 0.2λ within the field $2\omega = 1°50'$ for $\lambda = 0.5\ \mu$ except for distortion. So, the second scheme with a lens corrector has been chosen as a principal solution. The scheme has a small-chromaticism but the wave spherochromatic aberration does not exceed 0.16λ for $\lambda = 0.45$–$0.6\ \mu$; the introduced chromaticism is 0.00087 for $2\omega = 77'$ and 0.001 for $2\omega = 110'$. The total wave aberration does not exceed 0.25λ for $\lambda = 0.45$–$0.6\ \mu$ and $2\omega = 110'$.

The energy concentration in a 0.0067 mm circle is 84% for $\omega = 0°$, 84.3% for $\omega = 39'$, 83.5% for $\omega = 47'$, and 80.9% for $\omega = 55'$ (taking into account diffraction but not screening which is rather small and does not exceed 15%). For $2\omega = 110'$ and the spectral range $\lambda = 0.3$–$0.7\ \mu$ the geometrical circle of scattering does not exceed 10 μ. Distortion for $\lambda = 0.4\ \mu$ does not exceed 0.00007 mm, and if one takes $\lambda = 0.86\ \mu$, the distortion increases upto 0.00024 mm.

Variations of temperature arise from changes of the distortion which are not greater than 0.0000005 mm per 1° C and of the focal length which are less than 0.006 mm.

The geometrical sizes of the three-mirror optical scheme are rather small ($\approx 0.6 \times 1 \times 1$ meters), and it gives more space for other scientific equipment on board the satellite.

5 CALIBRATIONS

Many of the parameters of the telescopes will be included in equations for the great circle solution. So, they will be determined within the flight. But some of the optical parameters are planned to be calibrated both on the ground and on board the spacecraft. Variation of the scale would be possible to measure with a special hologram placed on the surface of the primary mirror. This hologram will focus the light emitted by illuminated marks at the focal plane of the telescope forming their images close to the original marks that gives the possibility of controlling the focal length. One may use the same marks to check distortion and chromaticism. The hologram is made with the use of a special ion-polishing technique. It allows for 4–5% of incoming light to be reflected in another way than the rest of light from the basic optical surface. So, a single optical surface may have, for example, two radii of curvature: the principal one and that which is formed by a reflecting hologram placed onto its surface.

6 CONCLUSIONS

The two optical schemes of the Struve on-board telescopes discussed provide a close to diffraction limited quality of images within more than a 1.5° field of view. But the second scheme, of approximately the same mass and of smaller sizes gives the possibility to increase the accuracy limiting magnitude of the instrument (down to 20–21 magnitudes) because it has more than twice as great the light collective area.