AN OPTICAL/INFRARED ASTROMETRIC SATELLITE PROJECT LIGHT

M. Yoshizawa, K. Sato, J. Nishikawa, T. Fukushima, M. Miyamoto
National Astronomical Observatory, Mitaka, Tokyo 181, Japan

ABSTRACT

LIGHT is the name of a scanning astrometric satellite for stellar and galactic astronomy planned to be launched between 2007 and 2010. Four sets of Fizeau-type interferometers with a beam combiner unit of 1m baseline are the basic structure of the satellite optics. LIGHT is expected to observe the parallaxes and proper motions of nearly a hundred million stars up to $V = 18$ mag ($K = 15$ mag) magnitude with the precision better than 0.1 milliarcsec (about 50 microarcsec in V-band and 90 microarcsec in K-band) in parallaxes and better than 0.1 milliarcsec per year in proper motions, as well as the precise photometric characteristics of the observed stars. Almost all of the giant and supergiant stars belonging to the disk and halo components of our Galaxy within 10 to 15kpc from the sun will be observed by LIGHT to study the most fundamental structure and evolution of the Galaxy. LIGHT will become a precursor of a more sophisticated future astrometric interferometer satellite like GAIA (Lindegren & Perryman 1996).

Key words: space astrometry; interferometry; galactic dynamics.

1. INTRODUCTION

After nearly a quarter of a century from the presentation of the original idea of an astrometric satellite, the Hipparcos and Tycho Catalogues are now available as a result of the combined efforts of so many persons involved in the Hipparcos project. The direct determination of trigonometric parallaxes of about 120 000 stars of various kinds is epoch-making with its precision of about 1 milliarcsec. A large fraction of the catalogued stars are located within a few hundred parsecs from the sun. The accuracy of the distances determined by using the observed parallaxes for those near stars are relatively high, and the derived distances will be used, as presented partly in the papers of this symposium, to calibrate absolute magnitudes of various kinds of stars.

The precision and the total number of Hipparcos catalog, although they are magnificent at the present standard, are still not enough, however, for the direct studies of kinematics and dynamics of global features of our Galaxy. The understanding of the global structure and evolution of the Galaxy must be one of the most important scientific targets of next generation space astrometry missions. European GAIA (Lindegren & Perryman 1996) is the largest among the space astrometric interferometers considered at present that perform scan-mode type observations. Although its target accuracy of 20 microarcsec is very attractive, the technical requirements to realize the figure are all challenging and need to be investigated for a long time.

Meanwhile, several other space interferometers for astrometry are planned that are relatively lighter than GAIA, namely post-Hipparcos and pre-GAIA missions. Among them LIGHT is a Japanese Fizeau-type space interferometer to observe parallaxes and proper motions of millions of stars, i.e. disk and halo components of our Galaxy. FAME is the name of US mission of an intermediate size astrometry interferometer (Johnston 1995), whereas German group is studying a mini-interferometer named DIVA (Röser et al. 1997).

2. SCIENTIFIC TARGETS OF LIGHT

LIGHT (Light Interferometer for the studies of Galactic Halo Tracers) is an scanning astrometric satellite for stellar and galactic astronomy planned to be launched between 2007 and 2010. LIGHT is expected to observe parallaxes and proper motions of nearly a hundred million stars up to $V = 18$ mag (or $K = 15$ mag) magnitude; the precision of parallax observation will be better than 50 microarcsec for $V < 15$ mag and better than 90 microarcsec for $K < 12$ mag, whereas proper motions better than 50 microarcsec per year in V-band and 90 microarcsec per year in K-band.

The above mentioned abilities enable us to observe the stars ($M_{\rm v} < +3.5$ mag) located within 2 kpc from the sun in the disk and halo directions with the precision better than 10 per cent error in distances and ± 0.5 kms^{-1} in tangential space velocities. Even for stars at 5 kpc distance from the sun the error in distance determination is 25 per cent, and ± 1 kms^{-1} in proper motions. The precision is high enough for a complete statistical investigation of kinematic and dynamic features of the disk and halo components of the Galaxy. It is noted that with less precisions almost all of the giants/super giants within 10 kpc from the sun will be observed. The number of observable stars is so large that the stars can be divided into various subgroups according to the contents of metal abundances or their photometric/spectroscopic characteristics. The understanding of the history of dynamical and chemical evolution of our Galaxy based on the reliable astrometric and spectroscopic data will become one of the scientifically most preponderate targets in astronomy in the coming decades. The main items of the scientific targets of LIGHT are shown in Table 1.

3. OPTICAL SYSTEM OF LIGHT

The essential features of the optical system of LIGHT is four Fizeau interferometers combined with a beam combiner unit of baseline length of $B = 1$ m. The beam combiner has four flat apertures (mirror diameter = 175 mm) at the both end of the baseline, and connects the four different directions within a plane perpendicular to the spin axis of the satellite; each of the four directions defines the direction of the line of sight of the corresponding interferometer. An off-axis Ritchey-Chretien-type telescope with focal length of about 20 m is used to get stellar fringes. The astrometric field occupies the central part of the focal plane of the telescope. The field of view of the astrometric field is about $0.3° \times 0.3°$, and nine chips of V-band and K-band array detectors cover the astrometric field. The multi-color photometry region are considered to surround the astrometric field. The rotation rate of the spin axis is about 10 revolutions a day. The satellite scans the whole sky within a few months by gradually precessing the spin axis.

With the interferometers and the beam combiner unit the fringe patters of the stars in four different directions along the scanning great circle can be observed simultaneously with the array detectors at the focal plane of the optical system. Then, assuming that the separation angles between any pair of two interferometers are kept unchanged during one revolution of the spin axis (about 2.4 hours period), the photocenter of each star can be related to that of any other star.

The photon noise is the dominant source of random fluctuations of the photocenter position of a star, and it determine the accuracy with which the directions of two different stars separated by a large angle are connected. It is very essential that the basic angles among the four interferometers are chosen so that the distribution of the final connection errors is as uniform as possible irrespective of the connection angles. We assume that the size of the astrometric field is about a tenth square degree and the spin rate of the satellite 150 arcsec s^{-1}. Then the photon noise contribution in determining the location of the photocenter of a bright star (V <15 mag) is less than ±1 milliarcsec after a passage of the star through the astrometric field (integration time $\approx$7 s). With an optimized set of three basic angles among the fields of view of the four interferometers, the connection errors for any pair of stars within a scanning great circle can be reduced to a half of a milliarcsec. On the basis of this figure it is expected for us to perform 50 microarcsec astrometry with LIGHT after a mission life of about four years.

4. ASTROMETRIC AND PHOTOMETRIC DETECTORS

The central area $0.3° \times 0.3°$ of the focal plane of the telescope is assigned to the astrometric field to perform high precision astrometry. A system of array detectors is used for the direct measurements of the stellar fringes in V-band and K-band; a total of nine chips of CCDs and K-band detectors consists 3×3 mosaic array, and will be operated under a scan-synchronized mode (drift scanning). Within an annular region outside the astrometric field up to 0.6° in diameter we set multi-color photometry array detectors to get precise wide-band and/or intermediate-band spectroscopic information of the observed stars.

With the baseline $B = 1$ m the width of a stellar fringe in V-band is 0.11 arcsec at $\lambda = 550$ nm. One fringe width should be covered by at least four pixels in order to get the phase information of stars in the scanning direction (i.e. along the scanning great circle). This requirement is fulfilled by using a CCD of 3 μm/pixel in the scanning direction under the focal length of the optical system of $f = 20.6$ m. The condition in Z-axis direction (perpendicular to the scanning plane) will be relaxed considerably by a factor of 50; i.e. $\sim$1.5 arcsec/pixel. The physical dimension of one CCD chip is 36 mm$\times$36 mm for $0.1° \times 0.1°$ field of view of a chip, and the total number of pixels per chip is $12000 \times 240 = 2.88 \times 10^6$, a feasible figure under the most modern semiconductor technology.

As for the K-band detectors the feasibility might be less ascertain than for V-band CCDs. At $\lambda = 2.2\mu$m the same optical design as for V-band requires 0.12 arcsec/pixel in the scanning direction, whereas 6 arcsec/pixel in Z-axis direction. Assuming the same field of view $0.1° \times 0.1°$ and physical dimension of 36 mm$\times$36 mm as before, one pixel size is $12\mu\text{m} \times 600\mu\text{m}$ and the total number of pixels per chip $3000 \times 60 = 1.8 \times 10^5$. These requirements seem to be not impossible considering the current rate of development in near-infrared region detector technology.

The mirrors and other optical surfaces must be cooled to suppress the thermal noises. The passive cooling will work, except for detectors, if thermal environments of the satellite are designed appropriately. As for the detectors, especially of K-band ones, a kind of cryostat or cooling by liquid He may better be considered. Under those thermal circumstances 4 μJy per frame time (2.4 s) will be enough as a 1-σ sensitivity of a K-band array detector.

5. STABILITY OF BASIC ANGLES

One of the most severe conditions to be fulfilled by a Hipparcos-type scanning astrometric satellite is the condition on the stability of basic angle(s) of the beam combiner. In the case of Hipparcos the random part of the basic angle variation ($\gamma \approx 58°$) was shown to be kept under ±0.2 milliarcsec (Kovalevsky et al. 1995). The amount of the random fluctuations must be kept at least an order of magnitude less than 0.1 milliarcsec for the successful operation of

Table 1. Scientific Targets of LIGHT.

(A) Non-rotating celestial coordinate system (reference frame) fixed to QSOs + a unified frame of optical and radio (VLBI) systems

(B) Trigonometric parallaxes of stars within a volume of 3–5 kpc cube ($\pi = 0.1$ milliarcsec → 10 kpc)

Cosmic distance scale
Fine structure of the C-M diagram
→ post-main-sequence evolution
absolute luminosity
stellar mass and radius
(C) Multi-color photometry
Stellar luminosity, temperature, metallicity, and extinction
→ photometric distance estimate
stellar evolution (together with B)
galactic chemical evolution
(D) Absolute proper motion of stars precise to < 0.1 milliarcsec per year ($0.5\ \mathrm{kms}^{-1}\mathrm{kpc}^{-1}$)
Spatial variation of stellar velocity dispersions
Correlations between chemical abundance and kinematics of stars
Dark halo structures (galactic rotation curve)
Deviations from axisymmetric feature (warp, barred structure)
Spatial motion of the magellanic system. (E) Relative separations and monthly proper motions of special objects precise to < 0.1 mas
MACHO mass, distance, and trajectory
→ IMF for stellar masses $<1 M_\odot$
dark halo structures
Multiple stellar system (mass, formation process)

the next generation astrometric interferometer satellite with which we aim at achieving 50 microarcsec level astrometry. GAIA is designed to be equipped with a powerful set of laser metrology to monitor and measure the basic angle variations. Without introducing such a heavy metrology system we instead try to keep the temperature stability of the optical components at the level of 1 mK. Furthermore the interferometers and beam combiner are constructed by using a material of ultra-low thermal expansion rate, i.e. $10^{-8}\ \mathrm{K}^{-1}$. A possible selection of the material is Zerodur or ULE glass for optical mirrors, and CFRP (Carbon Fiber Reinforced Plastic) for frames and supporting elements of the optical system.

6. SUMMARY

The Fizeau-type astrometric interferometer LIGHT is the name of the project of Japanese medium size space astrometry satellite. LIGHT aims at the post-Hipparcos high precision astrometry of 50 microarcsec level, and is expected to perform the observations of parallaxes and proper motions of about a hundred million stars mainly within our Galaxy. One of the most important scientific targets of LIGHT is the determination of kinematic and dynamic structure of our Galaxy, especially halo component, and investigation of dynamical and chemical history of the Galaxy.

Light also stands as a precursor of future more sophisticated, and so *heavy*, space interferometers, like GAIA. Various kinds of problems will be encountered through the development of LIGHT mission; new techniques or methods to manage or solve the problems must be applied to the future space astrometry projects.

From a scientific point of view it is important for the astronomical community of the world to have an astrometric mission at every fifteen to twenty year interval. One short-lived satellite is not enough for the better understanding of the kinematic and dynamic characteristics of stars, and, therefore, of our Galaxy.

REFERENCES

Johnston, K. 1995, Fizeau Astrometric Mapping Explorer (FAME): Step 2 Proposal

Kovalevsky, J., Lindegren, L., Froeschlé, M., et al. 1995, A&A, 304, 34

Lindegren, L., Perryman, M.A.C. 1996, A&A S, 116, 579

Röser, S., Bastian, U., deBoer, K.S., et al. 1997, ESA SP–402, this volume