LIMITED POSSIBILITIES OF THE GROUND-BASED OPTICAL ASTROMETRY INSTRUMENTATION

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ABSTRACT. A general overview of various types of ground-based telescopes for astrometric programs is presented. Also the limiting accuracy in positional determination with corresponding instruments is shown. Technical possibilities of modern ground-based optical astrometry can provide an accuracy of astrometric parameters about 20-30 mas for significant number of stars up to 18-23 mag. Taking into account expected accuracy of optical interferometers at a level 0.1-0.01 mas, it is possible to hope that ground-based optical astrometry will be necessary as observational base for preparation and maintenance of selected astrometric programs, especially before the future space projects. As to the means of control and research of solar system bodies and near-Earth space objects the progress in the new direction such as near-Earth astronomy has confirmed efficiency of significant number of small telescopes equipped with the modern instrument set together with the large telescopes.

1. INTRODUCTION.

The positional astronomy is in the state of active development. The most impressive facts and steady tendencies of this period are the following:

- On the base of impressing results of space experiment Hipparcos the leading role of space astrometry was ratified as an independent and predominant direction in astronomy, especially, for establishment and maintenance of the ICRF reference coordinate system;
- Future projects of astrometrical satellites of the 21-st century such as DIVA, OSIRIS, SIM, GAIA promise to increase accuracy up to microarcsecond level for tens and hundreds of millions of celestial objects with brightness from 16 to 20 magnitudes;
- The role of ground-based astrometrical researches is undergoing substantial changes. Dominant factors in this process are the following: selection of scientific tasks, solved by ground-based means; formation of new directions (such as near-Earth astronomy, creation of virtual telescopes and virtual astronomical observatories etc); introduction of new generation of ground-based observational techniques with wider possibilities; use of standards in recording, processing and storing of observational data; use of mobile telescopes, differential methods of measurements, etc.

2. PROBLEMS AND LIMITS OF GROUND-BASED ASTROMETRY INSTRUMENTATION

Analysis of observational programs, carried out with telescopes of small and large sizes, shows that majority of them has astrometrical tasks. Let's consider the most known telescopes from the position of their participation in the astrometrical programs.

2.1 *Possibilities of automatic meridian telescope (AMT)*

The latest technical achievements are used to equip modern ground-based AMT:
- CCD sensors with high sensitivity, devices with an active cell (APS);
- automatic control of observations;
- reduction and storage of observational data with high-effective computing means;
- information networks and CD-ROM.

Six most modernized and active AMT are shown in Table 1.
Theyare mentioned on the sites (http://www.ast.cam.ac.uk/ ˜ dwe/AstSurv and http://www.uni-sw.gwdg.de/˜hessman/MONET/links.html) Certainly, it is possible to name some additional meridian telescopes with moderate possibilities.

Table 1. Automatic meridian telescopes

AMT	**Location**	**Current Programs**	**CCD, FOV**	**Declination zone [^{o}], mag.**	**Catalogs Accuracy (mas)**	**Position: CCD active since**
AMC D180, F2480	Nikolaev, Ukraine, +47^o, 52m	Selected fields, ERS, solar system objects	1040x1160, 16mkm, 1.″33/pix, 23′x26′	-20÷+90 9^m-16^m	30-40 V,R $\pm0.05^m$	1996-
MC D190, F2370	Bordeaux, France, +45^o, 75m	Meridian-2000 Survey, catal. 2.3 mln., position and p.m. stars	1024x1024, 19mkm, 1.″65/pix, 28′x28′	-20÷+70 9^m-16^m	30-50 V $\pm0.05^m$	1997-
FASTT D200, F2000	USNO, Flagstaff, +35^o, 2230m	Selected fields for SDSS, solar system objects, ERS	2048x2048, 15mkm, 1.″55/pix, 51′x51′	-2÷+2 $18.^m3$(V)	40 U,B,V $\pm0.03^m$	1996-
CAMC D178, F2665	La Palma, Canaries, +29^o, 2100m	star survey, Schmidt plates, solar system objects	2060x2048, 9mkm, 0.″70/pix, 25′x25′	-30÷+90 7^m-17^m 0.2 mln	30-50 U,B,V $\pm0.05^m$	1997-
SFAMC D176, F2664	El Leoncito Argentine, -31^o, 2330m	star survey in zone 060, s.s.objects, selec. fields	1552x1024, 9mkm, 0.″70/pix, 18′x12′	-60÷+38 7^m-16^m 0.7mln	50 B,V	1999-
Valinhos MC D190, F2590	San Paulo, Brasil, -23^o, 850m	Selected fields, s.s. objects, Radiostars, ERS (QSO)	512x512, 19mkm, 1.″51/pix, 13′x13′	-77÷+30 8^m-16^m	50 V $\pm0.05^m$	1996-

2.2 *General features of modern AMT:*

- The full account of instrumental errors up to the level from 10 to 5 mas can be achieved in different ways, for example:

a) by using telescope with special design for reduction of weight and thermal deformations such as horizontal Axial Meridian Circle (AMC) of Nikolaev Observatory;

b) by using perfect inspection and recording of all instrumental parameters with accuracy of linear measurements up to 0.01mkm.

- The accuracy of CCD coordinate measurements of celestial objects is possible up to 1-2 % of pixel. It allows us to measure their coordinates, including faint objects, at the level of instrumental accuracy. Really CCD micrometer of FASTT can register of celestial objects up to 18.3 mag.

- Automatic computer control of the AMT makes possible to carry out determination of parameters and properties of instrumental orientation, preparation and conduction of observations, reduction and storage of observational data. Therefore, productivity of automatic meridian telescopes (AMT) with drift-scan mode CCD is very high, for example more than 9000 stars per hour can be observed with FASTT.

2.3 *Refraction problems*

The influence of atmosphere is still important and main problem for ground-based astrometry. For differential measurements with sufficient number of reference stars in CCD frame, it is possible to take into account the influence of such anomalous refractions as diurnal and annual ones. High-mountain location of the majority of AMT is a positive factor. Abnormal refraction inside domain is taken into account with the help of automatic meteostation. It is more difficult to remove influence of refraction, caused by atmospheric turbulence of high frequency (up to 20 kHz), which has dominant value. Calculated data for AMT with the generalized parameters such as field of view $30'30'$, exposition 100 seconds show an accuracy up to 20 mas of positional measurements of stars in the range of 9-16 mag [1]. Optimistic estimations show that the achievement of accuracy 10 mas is possible under condition of observation in visible range of waves with the help of the two-colour techniques [2,3]. High precision of HC reference system allows to observe with AMT only in differential mode, that is widely spread now. On the other hand, it is possible to observe CCD strips in drift-scan mode until several hours in right ascention to register sufficient number of reference stars.

AMT programs include ten or hundred thousands celestial objects up to 16^m - 18^m and provide positional accuracy of 30-40 mas for the support and improvement of reference frames, observations of the solar system objects such as asteroids, planets, satellites, selected celestial objects.

2.4 *CCD astrographs in ground-based astrometry*

Many telescopes equipped with CCD cameras participate in the solution of various tasks in differential astrometry (widespread diameter of optics is 0.5 - 3 meters), and some large telescopes with small fields, as well (Table 2). [4-8].

Table 2. Selected CCD astrographs, participating in the solution of astrometric tasks

Telescope (Dm, Fm)	**Location**	CCD, FOV	**Mag, spectral Bandpas**	**Current Program**	**Declination zone (°)**	**Number of stars (mln)**	**Position error (mas)**	**Position: active since**
SLOAN telescope (D 2.5m)	Apache Point observatory, USA	mosaic 22 CCD 2048x400, [2.°2]	10÷23 U, B, V, R, J	SDSS positions, photometry	(North Galactic Zone), 10^4 (π)	100	30	1998- [4]
Astrometric Reflector (D 61″)	USNO, Flagstaff USA	CCD	10÷21	positions, proper motions	-30°± +90°	100	20	1998-
Astrometric Reflector (D 0,9m) UCAC Telescope (D 0.2m, F 2m)	CTIO, Chile USNO, USA	CCD 4096x4096 [9*mkm*] 0.″9/pix [61′x61′]	7÷16 9÷14	UCAC (USNO CCD Astrograph Catalog)	-90°±+2° ±+90°	40	20÷70	1997-2003, 60 mln stars; 2000 - first version UCAC-1 (S), 27 mln stars, -90°± -6° ; [5, 6]
RTT150 (D 1.5m, F 11.6m)	Antalia Turkey-Russia, 37°	ST-8 1530x1020 9x9 mkm 0.″16/pix [4′x3′]	20 U, B, V, R, J	positions, photometry ERS, solar system objects	-40°±+90°		20-30	1999- [7]
VST (D 2.65m) (Italy)	ESO, Cerro Paranal, Chile	mosaic 32 CCD, 16K x 16K [15*mkm*] [1,° 5]	25 U, B, V, R, J	positions, photometry	southern hemis-phere		20-30	2001- [8]
SUBARU (D8.3m, F15m)	Mauna Kea, Hawaii, USA	mosaic of 10 CCD, 2048x4096, [15mkm] 0.″2/pix	Up to 26,6 (V) U, B, V, R, J	deep survey, double stars, asteroids with 40a.u. and more			10	2000- [9]

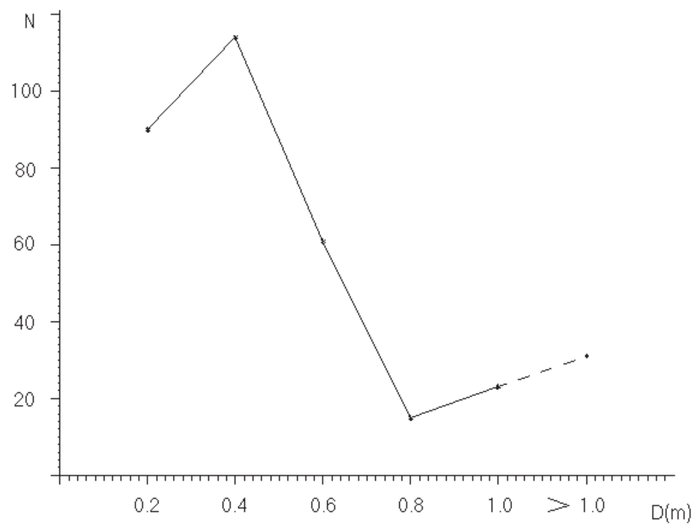
The majority of CCD astrographs have wide possibilities: number of objects up to 21-23 mag achieves in some programs up to 100 millions, expected positional accuracy is 20-30 mas. Let's note also that the majority of the given telescopes have the unique designs and equipment such as adaptive optics, single wide-field CCD and their mosaics, possibility of CCD cameras using in several modes (drift-scan, stare-mode, driving-mode and combined one).

The real results confirming the expected accuracy 20-30 mas are quite achievable (UCAC-1 is already compiled with accuracy 20-70 mas). Considering possibilities and accuracy restrictions of the mentioned types of ground-based astrometrical telescopes, one can note that they are determined by technical means, atmospheric conditions, and methodical features. Taking into account all factors, the optimistic estimation of positional accuracy in narrow fields is about 10 mas. [5]

2.5 *Telescopes for the near-Earth space and observation solar system bodies.*

Significant increase of interest in research of near-Earth space and solar system (space debries - artificial celestial bodies, comet-asteroid hazard - NEO, minor planets, trans-neptunian objects) was accompanied by active use of CCD optical means. Moreover, manufacture of high quality telescopes, equipped with modern CCD cameras and computers of rather low cost, is adjusted now. In accordance with data of reviews, the number of instruments, working in the specified direction, exceeds 300 (see fig. 1) [10-16]. The majority of robotic telescopes, working in the automatic mode, have the mirror sizes from 0.2 to 1 meters and more.

Fig. 1 Number (N) of telescopes for observation of NEO and solar system objects with different mirror diameters (D)



Selected telescopes with diameter more than 100 m, working in the Space Watch system , carrying out observations of space debries, numbered minor planets, and trans-neptunian objects, are given in Table 3.

Table 3. The selected optical telescopes, observing objects in the near-Earth and Solar system space

Telescope, Aperture D, Focal lengh F (m)	Organisation, location	Program	CCD, FOV	Accuracy of single observ.	Limit. mag.	Remarks, additional data from:
USA, 695 MPC, D 3.8m	Kit Peak, USNO	NMP Obsev.	CCD	$\pm0.''15$		[10]
USA, 807 MPC, D4.0m, F14.4m	Cerro Tololo, USNO	NMP Obsev.	CCD $37'$x$37'$, $0.''27$/pix,	$\pm0.''17$		[10]
Australia, 413 MPC, D1.2, 3.6, 1.0m	Siding Spring, USNO	NMP Obsev.		$\pm0.''10$		[10]
Japan, D1.5m	CRL	NEO, space debris	CCD, FOV $0.^o28$	$\pm0.''10$	$18.^m7$	[14,15]
USA, D3.0	NASA	NEO, space debris	CCD, FOV $0.^o30$		$21.^m5$	[14,15]
Russia, Ukraine, D1.0	RAS, CRAO	NEO, NMP	CCD, $12'$x$12'$		19^m	[14,15]
Ukraine,121 MPS, D0.7	AO Kharkiv university	NEO, NMP	CCD, $10'$x$8'$		18^m	[10]
USA, 691 MPC Spacewatch telescop, D0.91 F4.6	Spacewatch	NEO, NMP	CCD, $32'$x$32'$	$\pm0.''20$		[10]
USA, SOR 3.5 3.5 f/1.5	AB Kirtland, New-Mexiko	Near-earth objects	CCD			[16]
USA, 701 MPC D1.0, F2.2, LINEAR telescope	Sokorro, New-Mexiko, Linkoln Lab.	NEO, space debris, NMP	robotics, CCD, $32'$x$32'$	$\pm0.''51$	$15.^m5$	[10,16]

While estimating possibilities of telescopes (Fig. 1, Table 3), it is necessary to note that the telescopes of rather small sizes (D = 0.4m-0.6m), equipped with modern equipment, have found their niche in topical direction of near-Earth astronomy such as observations of solar system bodies and near-Earth objects, allowing to observe objects up to 18-20 mag with high accuracy.

The majority of instruments of professional and amateurs observatories participates in observations of the numbered minor planets. The estimation of their results based on materials of MPC is the range about $\pm0.''1 - \pm0.''5$[10]. Alongside with this, the observations of NEO, exoplanets, trans-neptunian objects, educational programs, world-sky patrol and all-sky survey, service observations under the various astronomical and applied programs are carried out with the large ground-based telescope [12].

3. INTERFEROMETRY COMPLEXES FOR GROUND-BASED OPTICAL ASTROMETRY

New possibility of accuracy increase in positional astronomy has recently appeared on the base of optical interferometry application for the solution of astrophysical tasks.

Table 4. Interferometry complexes for ground-based optical astrometry

Telescopes (D, F)	**Location**	**Base number and lengh (m)**	**Program, Declination zone (^{o})**	**Mag., spectral bandpass**	**Position accuracy (mas)**	**Position**
MARK-III Interferometr (D0.08m)	Mt. Wilson, USA	3, 3-31m	astrometric, double stars, $+15^o$- $+65^o$	5	6-10, 2 (double stars)	1986-92 [17]
NPOI - I (D 0.5m) NPOI - II (D 0.5m)	USNO, Flagstaff, USA	4, 19-38m 6, 2-437m	astrometric, $-30^o \div +90^o$ imaging, double stars	10, $0.45\div$ 0.85mkm	1 0.5	active since 1998, [18 – 21]
VLTI (D 8.2m)	ESO, Cerro Paranal, Chile	4, 130m 8, 8-202m	imaging, micro-arc-second astrometry	18-20, $0.45\div1.2$ mkm	1-0.01	active since 2003, [22 – 24]
KIIA (D 10m)	Mauna Kea, Hawaii, USA	2, 85 6, 165	imaging, solar system objects	19-21, $1.5\div5$ mkm	3-0.03	active since 2002, Since 2005 for 6 bases

At the beginning of 1990es, on the base of MARK-III in USNO, more perfect interferometry complex NPOI (Navy Prototype Optical Interferometer) was created. NPOI-I, intended for the solution of astrometric tasks, consists of four tubes with mirror diameters of 0.5 meters and variable base of 19-38 meters, vacuum delay lines (DL), laser measuring system for the control of DL, necessary optical and mechanical systems, and recording devices. Interferometer is completely automated. Observations of stars up to 10 mag were begun in 1996 with NPOI-I on the program of creation of co-ordinate system of bright stars with mas accuracy [18]. IAU congress in Kyoto (1997) was informed about positional accuracy of stars with NPOI at the level of 1 mas for both co-ordinates [19]. As a whole, ground-based optical interferometer NPOI as one of the largest long-based interferometers is the most developed instrument for precise wide field observations (under thorough account of atmosphere influence, base metrology control and other instrumental parameters) [20,21].

The development of optical fibre communication lines has resulted in creation of interferometry complexes, including large telescopes with diameters of mirrors up to 8 meters and bases up to 200 meters (KIIA, VLTI etc.) [22,23]. Though the main tasks of such complexes lie in the field of astrophysical researches (while forming the images of the observed objects), the unique possibilities are opened in the field of positional determinations for ground-based astrometry such as search and research of faint satellites of planets, new objects of solar system, new planetary systems in vicinities of the nearest stars, detection of microlensing objects, study of single stars, double, and multiple star systems etc.

VLTI includes four telescopes with mirrors of 8.2 meters and a base of 57-130 meters. There is a possibility to include in its structure two telescopes with mirrors of 1.8 meters to increase the base up to 202 meters. The precise measuring system VLTI - PRIMA (Phase-Referenced Imaging and Microarcsecond Astrometry) makes it possible to measure relative angular positions of stars up to 18 mag with accuracy of 10 microarcseconds at angular distances up to $10''$ and interferometry time about 30 minutes. Such accuracy allows to find out planets like Jupiter on distance up to 240 parsec from the central star, like Uranium up to 44 parsec, and planets with mass ten times larger than Earth, on the distance up to 1.5 parsec from the central star [24].
Six large telescopes, located on Hawaii (Mauna Kea), in one of the best astroclimate places on the Earth, including Keck I and Keck II, form a unique interferometry complex with fifteen variable bases from 85 to 165 meters. In a differential mode, it is possible to achieve an accuracy of 30 mas for objects up to 21 mag under exposition about one hour. Among main scientific tasks of Keck interferometer, it is necessary to note the study of new planetary systems in vicinities of one hundred nearest stars under the program NASA- TOPS (Towards Other Planetary systems). Marking importance of scientific potential of such huge interferometry complex for astrophysics of the 21st century, its high angular resolution at a microarcsec level will allow us to solve astrometric tasks at the same time as well.

While estimating the possibilities of ground-based optical interferometers, it is possible to speak about limited accuracy of positional determinations about 1 mas for wide angular distances, and with the use of large interferometers with the narrow field, the limit can be removed up to 0.1-0.01 mas [24,25].

4. CONCLUSIONS

• Technical possibilities of modern ground-based optical astrometry can provide an accuracy of astrometric parameters about 20-30 mas for significant number of stars up to 18-23 mag.
• Taking into account accuracy of optical interferometers at the level 0.1-0.01 mas, it is possible to hope that ground-based optical astrometry will be necessary as an observational base for preparation and maintenance of solution of the selected astrometric programs, especially before the future space projects.
• As to the means of control and research of solar system bodies and near-Earth space objects, it is possible to say that the progress in a new direction - near-Earth astronomy has confirmed efficiency of significant number of small telescopes, equipped with the modern instrument set, along with the large telescopes.
• Also we should note that the modern level of computer facilities, telecommunications, and computer science allows us to carry out association of the distributed astronomical resources (digital archives, databases etc.), containing billions of objects on the whole celestial sphere with high resolution, virtually in all ranges of waves from gamma-rays to radio. This source of information can be available basically to any researcher by means of "the virtual telescope", equivalent to some physical telescope located on the Earth or in space. Interactive archives can be considered as astronomical virtual observatory for the solution of a number of astronomical tasks, including astrometrical ones. It is possible to expect a usage of virtual telescopes in ground-based astrometry in the future. Also, large perspectives will be proposed by Extremely Large Telescopes (ELT) [26].

In conclusion, it is to be noted that many researches of modern ground-based optical astrometry are made with the space means and meathods in all-spectral range. Astrometry over all-spectral range will be assential part of all astrometry [25,27-29]

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