DIVA – TOWARDS MICROARCSECOND GLOBAL ASTROMETRY

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ABSTRACT

DIVA (Deutsches Interferometer für Vielkanalphotometrie und Astrometrie) is a small satellite designed to perform astrometric and photometric observations of at least one million stars. The instrument simultaneously observes two celestial fields of 0.5 degrees diameter each, separated by at least 60 degrees. The optical configuration consists of two Fizeau interferometers with a baseline of 10 cm, one for each field of view. A beam-combining mirror feeds light from both fields into a single telescope. Fringe dispersion is created by objective prisms, one per field of view. DIVA operates in a revolving scanning mode with a scanning law similar to that of Hipparcos. Light is recorded in the focal plane by a CCD mosaic operated in time-delayed integration mode, clocked synchronously with the satellite's rotation. The maximum diameter of the satellite will be about 1 m, the total mass about 100 kg.

DIVA will exceed the performance of Hipparcos in all important parameters. It will perform an all-sky survey complete to at least $V = 10.5$ mag. The limiting magnitude will be about $V = 15.0$ mag. After two years of mission DIVA will provide (for $V = 10.5$ mag): parallaxes accurate to 0.3 milliarcseconds (mas); proper motions accurate to 0.5 mas/yr; broad-band photometry with a typical precision of 0.003 mag; and multi-channel intermediate-band photometry with a typical precision of 0.01 mag.

For the more than 100 000 stars observed by the ESA satellite Hipparcos, proper motions with a typical accuracy of 0.1–0.2 mas/yr will be obtained after combining the DIVA measurements with the Hipparcos results.

DIVA will be a technologically ambitious, low-cost space mission. It will be a successor to Hipparcos and an important step towards the proposed ESA astrometric Cornerstone Mission, GAIA. A launch in 2002 is aimed at.

Key words: space astrometry.

1. INTRODUCTION

Hipparcos, ESA's astrometry satellite, has started a new era in astrometry. The absence of the atmosphere and of gravitational bending of instruments as well as the coverage of the whole sky with a single instrument led to astrometric measurements of unprecedented accuracy. This was made possible by the excellent design of the satellite (using the space technology available at the end of the seventies), the operation strategy and the dedicated work of the scientific consortia preparing the mission and reducing the data.

The Hipparcos results are now available for everybody, and in the years to come their exploitation will answer relevant scientific questions in many areas of astronomy. But the demand for even better astrometric data has already been put forward. Within the long-time planning of its scientific space programme, ESA charged a Survey Committee to give recommendations for the Horizon 2000+ programme. The Survey Committee voted for an interferometric mission as a Cornerstone Mission, with first priority to an astrometric survey aiming at 10 microarcsec accuracy.

A possible concept for such a mission has been proposed by Lindegren et al. (1994) under the name of GAIA (Global Astrometric Interferometer for Astrophysics). This mission shall observe some 50 million stars at least to $V = 15$ mag, yielding positions and parallaxes better than 10 μas, proper motions better than 10 μas/yr and photometry in at least 6 narrow bands with a typical accuracy of a few milli-mag. The design for GAIA is presently under study, and an alternative to the Lindegren et al. (1994) layout has been proposed by Høg et al. (1996) and is called GAIA95. With this concept, the GAIA mission will be able to measure even fainter stars.

GAIA is a very ambitious mission, not only from the scientific point of view, but also technologically. According to ESA's schedule, GAIA, if selected, could be launched around or later than 2010; results are

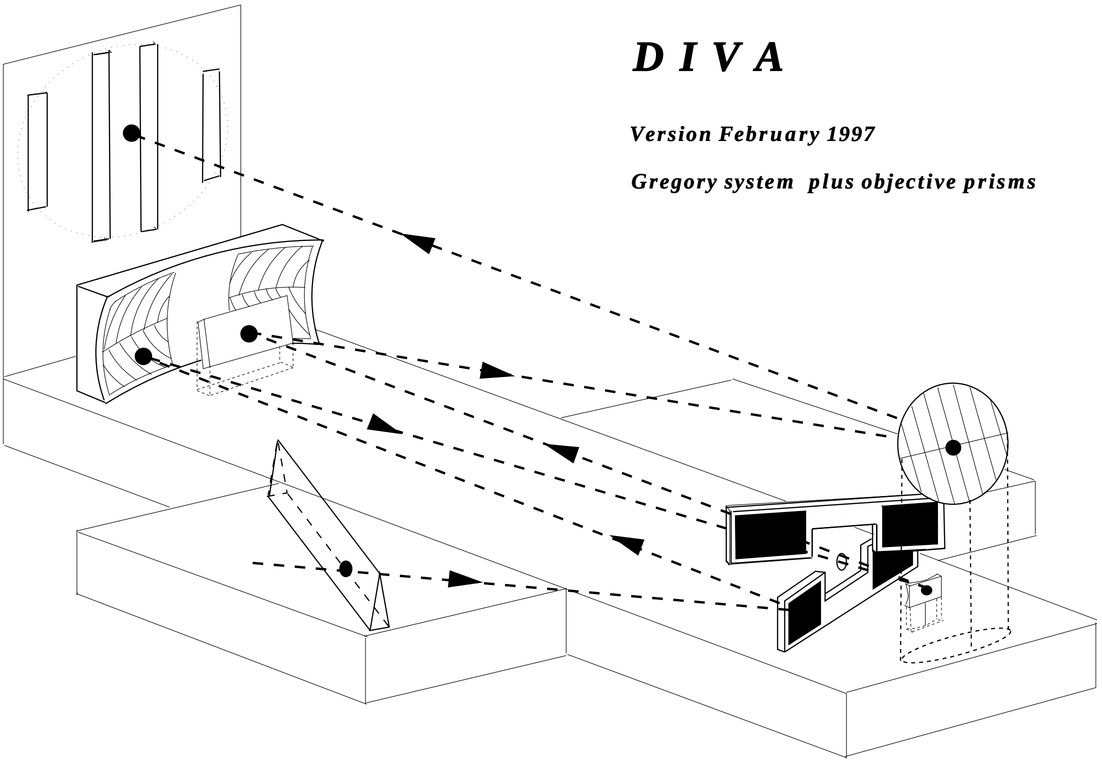

Figure 1. Schematic layout of the DIVA interferometer. The light path for one line of sight and for one aperture is shown. The second objective prism is not drawn.

expected in about 8 to 10 years after launch. As the quality of the Hipparcos positions is rapidly deteriorating with time, an astrometric mission of better or at least similar quality is needed early in the next decade. DIVA is able to play this role, and by using roughly the concept of GAIA95, important conclusions for the final GAIA design can be drawn from the performance of DIVA.

2. INSTRUMENT DESIGN

2.1. Optical Layout

DIVA is a small Fizeau interferometer with a baseline of 10 cm and square apertures of 5×5 cm^2 each. The essential design driver for the optics is given by the requirement of direct fringe direction and fringe dispersion. This determines the effective focal length and the specifications for the dispersing element. A further constraint is given by the size of the satellite setting the maximum length for the instrument to about 70 cm. The general optical layout of the instrument is shown in Figure 1. DIVA simultaneously observes two fields of view of about 0.5 degrees diameter separated by at least 60 degrees. The first optical element in each line of sight is an objective prism to create dispersed fringes orthogonal to the scanning direction. The two lines of sight are combined by a complex mirror feeding the light into a single telescope. The layout of the telescope is about to be completed and will be published soon. It will have an effective focal length of 16.2 m set by the detectors presently available (see below).

2.2. Focal Plane Assembly

The layout of the focal plane assembly for DIVA is shown in Figure 2. The field of 0.5 degrees diameter (corresponding to about 13 cm linear size) is partly covered with CCD mosaics. The two long mosaics in the centre consist of 10 CCDs, each having 1024×1024 pixels of 13.5μm $\times$ 13.5μm. They will collect the scientific measurements. The scanning rate of the satellite of 180 arcsec/s yields an effective exposure time of 1 s. The CCDs are clocked such that the charges move synchronously with the stellar images, i.e. in drift-scan mode. At λ=500 nm the monochromatic diffraction fringes created by the optics have a size of about 81 μm (along scan) by 324 μm (perpendicular to the scan, i.e. in the direction of the spectral dispersion). Thus, we have 6 pixels per fringe spacing along scan at 500 nm and correspondingly more at larger wavelengths. Presently available CCDs, e.g. EEV's 42 series, give an acceptable quantum efficiency in a range from 400 to 1000 nm. In the direction perpendicular to the scan, on-chip binning of 6 pixels at read-out will be implemented, so that the effective pixel size will be 13.5μm $\times$ 81μm. This binning significantly reduces the read-out noise per effective pixel. Moreover, it reduces the total data rate for the on-board computer and increases the maximum number of electrons per (effective) pixel. In other words, it extends the dynamic range of the instrument, both at the faint and at the bright end of the magnitude range. After binning, there will be 2

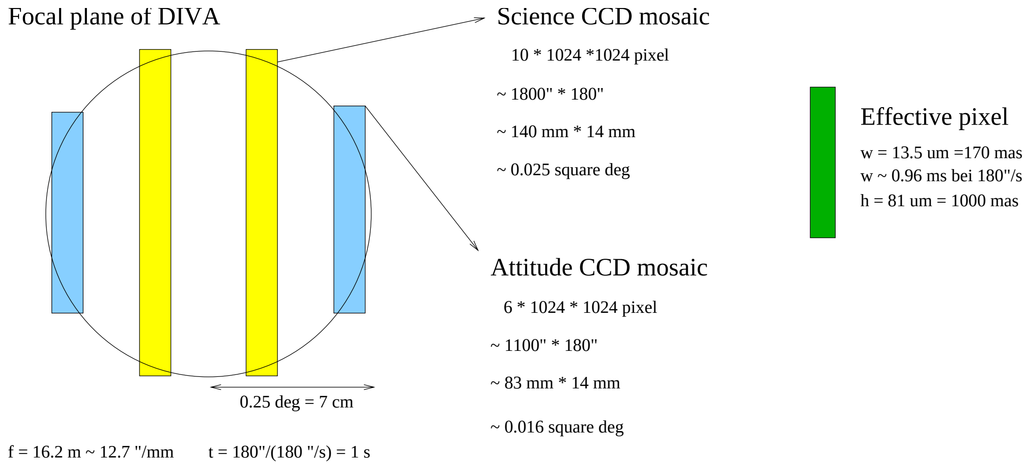

Figure 2. Layout of the focal plane of DIVA. The effective pixel (shown at right) of 13.5 μm × 81 μm consists of 6 hardware pixels of 13.5 μm × 13.5 μm binned together.

effective pixels per spectral resolution element. The two shorter CCD mosaics to the right and to the left in Figure 2, consisting of the same type of CCD, will be used for attitude determination mainly.

Detailed simulations of the images are ongoing presently (Scholz & Bastian 1997). Their results will have implications on the final specification of the telescope, the selection of the CCDs, and form the basis for the determination of DIVA's performance. Figure 3, taken from Scholz & Bastian (1997), shows a simulated portion of the DIVA images (here 500×100 effective pixels). Stars of different spectral type and different apparent magnitude can be seen. For the simulation, a theoretical point spread function (psf) has been adopted so far. The true psf of the actual DIVA instrument will be very similar.

The concept of fringe dispersion was chosen for DIVA because it enables astrometric and spectrophotometric observations at the same time with the same equipment. Fringe dispersion avoids the smearing-out of the fringes due to the large wavelength range of the detector. The gain in spatial resolution is considerable. Thus DIVA should be able to resolve double stars at a separation of 0.2 arcsec and a magnitude difference up to 3 mag. Without fringe dispersion the first minimum would be smeared out and a value of about 40 per cent of the maximum must be expected. This strongly hinders the measurement of double stars and deteriorates the performance. The only advantage, if fringe dispersion is dropped, is the higher signal-to-noise ratio at the faintest objects. In passing we note that DIVA can detect double stars of different spectral type very effectively, even at the milliarcsec level, due to the concept of fringe dispersion.

2.3. Performance

Bastian & Scholz (1997) have made a preliminary accuracy assessment for DIVA on the basis of the simulations of Scholz & Bastian (1997). They present limiting magnitude, astrometric and photometric performances as functions of various parameters such as

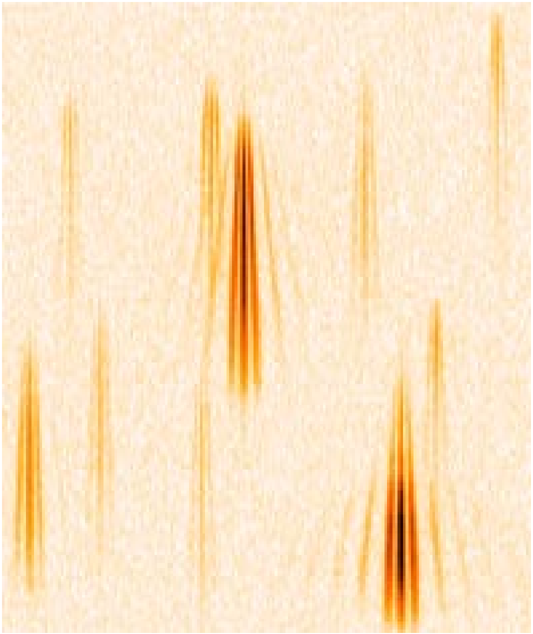

Figure 3. Simulations of the DIVA observations. Shown is the read-out of a part of a CCD, containing several stars with different spectral type and apparent magnitude. From Scholz & Bastian (1997).

apparent magnitude, spectral type of the stars and of the read-out noise of the CCDs. Summarizing their results, we find a limiting magnitude of at least $V = 15$ mag, which increases to $V = 18.5$ mag for spectral types as late as M5. As an example Table 1 gives the performance for an unreddened K3 star assuming a read-out noise of 4 e^- per pixel. For more details the reader is referred to the paper by Bastian & Scholz (1997). Interpreting Table 1, we conclude that, compared with Hipparcos for a 37-months mission (Mignard 1995), DIVA will be able to perform parallax and position measurements about a factor of 3 better than Hipparcos, assuming a two-years mission. The precision of the proper motions will be about a factor of two better than that of Hipparcos, and they will be obtained for ten times as many stars.

Table 1. Astrometric and photometric rms errors of DIVA for a mission duration of 2 years. These hold for a K3 star, assuming a read-out noise of 4 e$^-$ per pixel. After Bastian & Scholz (1997). Note that error sources such as attitude jitter, which limit the precision for bright stars are not considered in this table. Improvement of the proper motions of Hipparcos stars by combination with the Hipparcos results is not shown here.

	Astrometry (mas; mas/yr)		Photometry (10^{-3} mag)	
V(mag)	α, δ, π	μ_α, μ_δ	broad band	intermediate band
8	0.1	0.2	0.7	1.5 - 3.5
10	0.25	0.4	2.5	3.5 - 10
12	1.1	1.9	7	15 - 50
14	7	12	40	$\geq$ 100

If combined with the measurements from Hipparcos, the improvement in accuracy for proper motions is dramatic. Assuming an operational phase for DIVA in 2002, the mean epoch difference between DIVA and Hipparcos would be about 11 years, so that for 100 000 Hipparcos stars with median magnitude of $V = 8.5$ mag proper motions with rms errors of 0.1 mas/yr will be obtained. This is a factor of 10 better than supplied by Hipparcos. With DIVA we will enter the regime of sub-milliarcsecond optical astrometry for the first time.

The observing programme of DIVA will be compiled into an input catalogue which facilitates the star recognition at the level of a CCD transit. As the observing programme has to be restricted to about one million stars because of data rate constraints, an input catalogue has the nice feature that it enables the observation of astrophysically interesting stars and galaxies down to $V = 15$ mag. Without an input catalogue, star transits through the CCDs would have to be recognised by the instrument without a priori knowledge. The knowledge of a forthcoming star transit given by an input catalogue is a prerequisite to reach $V = 15$ mag, else the actually achievable limiting magnitude would be at least one magnitude brighter.

2.4. Some Requirements

2.4.1. Size and shape of the satellite

Major constraints are set by the requirements for power supply and to minimize external torques. The DIVA telescope needs a cylindrical space of about 80 cm diameter and 30 cm height. The ideal envelope would be a spherical one which is technically not feasible. A conical envelope covered with solar arrays is chosen which yields the cross-section to solar radiation to be constant over a rotation period. A polyedrical configuration with rotational symmetry shall ensure that torques exerted by solar radition pressure are minimised. Masses are distributed such that the principal moment of inertia is parallel to the rotation axis, and e.g. cold-gas tanks are integrated such that the diminishing mass of the gas during the mission will have a minor effect on the orientation of the main axis of inertia. The total mass of the satellite will be about 100 kg, and the maximum outer diameter about 110 cm.

2.4.2. Data rate

In the present configuration the data rate would amount to 60 Megabit/s, if all pixels are read out and transmitted to the ground. It can be drastically reduced by on-board data processing.

If only the 40 × 35 pixels (on-chip binning assumed) containing the dispersed image are read out, the data rate amounts to 54 kbit/s per million of stars on the average. Crossing the galactic equator this rate can be about a factor of 20 larger. A 1 Gbit mass-storage on board is used for temporarily storing the measurements and for maintaining a constant down-link data rate.

2.4.3. On-board attitude determination

The most stringent requirements for the knowledge of the on-board attitude stem from the data rate reduction process described above. To read out the complete image of a star, the along-scan attitude has to be known to 0.5–1 arcsec, perpendicular to this direction to 2–3 arcsec. This is of the same order of magnitude as with Hipparcos.

2.4.4. Scanning rate

We select a nominal scanning rate of 180 arcsec/s. An asynchronous shifting of the charges leads to a smearing-out of a stellar image during the crossing through the CCD. The smearing-out must not exceed half a pixel. This requires knowledge of the scanning motion to 0.1 arcsec/s along scan and to 0.5 arcsec/s perpendicular to the scanning direction.

2.4.5. Internal metrology

Any interferometer requires constancy of the relative positions of the optical elements to fractions of the wavelengths used. An astrometric interferometer such as GAIA95 needs monitoring of these quantities to a few tenths of a nanometer. This is one of the essential technological challenges for an astrometric interferometer.

Experience with the geometrical stability of optical elements is available from the Hipparcos mission. There, the two parts of the Hipparcos beam combiner had to be stable to better than 0.4 nm over 24 hours. The calibration of the beam combiner angle was performed as a part of the scientific data reduction. For GAIA95 it is expected that the collection of scientific data will not suffice to continously calibrate the optical configuration. Therefore, sub-nm-metrology on-board will be needed. Studies have to be carried out to investigate whether this is necessary for DIVA. However, the experience from Hipparcos suggests that it is not.

3. SCIENTIFIC OBJECTIVES OF DIVA

The unique combination of homogeneous astrometric and photometric data obtained with DIVA is expected to have a huge scientific impact on many fields of astronomy and astrophysics. In the following, we will list some major topics without claiming completeness.

3.1. Cosmic Distance Scale

DIVA will determine trigonometric parallaxes of typical Hipparcos stars with a factor of 3 increase in accuracy. This implies that the volume in space for which DIVA obtains the same relative accuracy for parallaxes of stars is a factor of 30 larger than with Hipparcos. As a consequence, parallaxes of some 30 to 35 Cepheids will be determined with relative accuracy better than 10 per cent. Distances of many other Cepheids and RR Lyr stars of the Hipparcos programme will be considerably improved. Due to its accurate multi-channel photometry, DIVA will also determine highly accurate photometric parallaxes, which will be calibrated by the trigonometric parallaxes obtained with the same instrument. It will be the first time that such a homogenous set of astrophysically important data will be obtained.

3.2. Structure of the Galaxy

Due to the multicolour observations of at least one million stars, DIVA will provide interstellar extinction of unprecedented accuracy as a function of coordinates and distances up to about 1 kpc.

The factor of ten improvement in proper motions compared to Hipparcos will allow us to measure the tangential velocity of a star at 5 kpc with an accuracy of 3-4 km/s. This is at the level of a few percent of its typical space velocity. After the link of DIVA proper motions to an inertial reference system (by direct AGN observations or/and by additional ground based observations similar to those in the case of Hipparcos), the data will have a large impact on the kinematics of the spiral arms, the thin and thick disk and the galactic halo. This will contribute to our understanding of the dark halo and to the determination of the total mass of the Galaxy.

3.3. Stellar Physics and Populations

The photometry and the parallaxes obtained by DIVA determine the positions of about one million stars in the Hertzsprung-Russell diagram. Hipparcos detected about 10 000 new variable stars. With the ten times larger data base of DIVA the statistics of variable stars will be so improved that the importance of the variable star phenomenon in stellar evolution will become clearer.

Precise distances of many stars in the solar neighbourhood allow the age determination of the galactic disk and the detection of special stellar types. Hipparcos has for the first time demonstrated the existence of clump giants in the solar neighbourhood. Such investigations will be extended by DIVA.

Our knowledge on the stellar density in the solar neighbourhood is incomplete. Jahreiß & Gliese (1993) find that the density of stars contained in the Third Catalogue of Nearby Stars decreases from 0.11 stars/pc^3 between 0 and 5 pc to 0.04 stars/pc^3 between 20 and 25 pc, a clear hint to so far undetected nearby stars. Hipparcos has already found some 100 hitherto unknown stars closer than 25 pc. DIVA will again probe a much larger sample.

3.4. Brown Dwarfs

Hipparcos could test some 100 nearby stars for the presence of Brown Dwarfs in binary systems. DIVA will extend this search by a factor of 100 and therefore will be able to investigate many more stars than is presently possible by ground-based radial velocity measurements. Especially for wide pairs astrometric measurements are of great importance.

3.5. Kinematics of Star Clusters and Associations

At the distance of the Hyades an accuracy of proper motions of 0.2 mas/yr corresponds to a mean error of the tangential velocity of 50 m/s, at the distance of the Pleiades, the Taurus-Auriga and the Scorpio-Centaurus associations to about 150 m/s, and in the Orion complex to 500 m/s. The relative velocities between stars in associations are of the order of a few km/s. Thus, DIVA will make its major contributions to the kinematics of aggregates up to a distance of 0.5 kpc.

3.6. Star Forming Regions

DIVA will give essential contributions to the kinematics of pre-main-sequence stars. Mesurements of the proper motions of classical T Tauri stars (cTTS) and of weak-line T Tauri stars (wTTS), detected recently as follow-up of the ROSAT survey, will answer questions of the birth-places of these stars, especially the question whether isolated star formation can occur. Accurate trigonometric parallaxes of nearby young stars give first reliable determinations of their absolute luminosities. Statistics on the duplicity of PMS stars will be obtained.

3.7. Kinematics of the Magellanic Clouds

Hipparcos observed 35 stars in the LMC and 12 in the SMC. After the additional measurements by DIVA their individual tangential velocities will be known to about 25 to 50 km/s. For the first time, a reliable dynamical mass determination as well as a determination of rotation axes and space velocities of the Magellanic Clouds will be possible.

3.8. Extragalactic Objects

The sensitivity of DIVA will allow more than 60 quasars to be included in an input catalogue. While astrometric accuracies at the faintest accessible limits will be reduced, the mission will be capable of comparing the extragalactic optical and radio reference systems with about 30 radio loud quasars. Spatial offsets between radio- and optical emission due to dust obscuration are likely to be detected. Variations of the centroid of emission due to variability of off-centered components can be detected as well.

3.9. Maintenance of the Hipparcos System

The proper motion errors deteriorate the Hipparcos positions to about 40 mas in the year 2010. With DIVA these positions will have an rms error of 1 to 3 mas, i.e. about a factor of 15 improvement. This is shown in Figure 4.

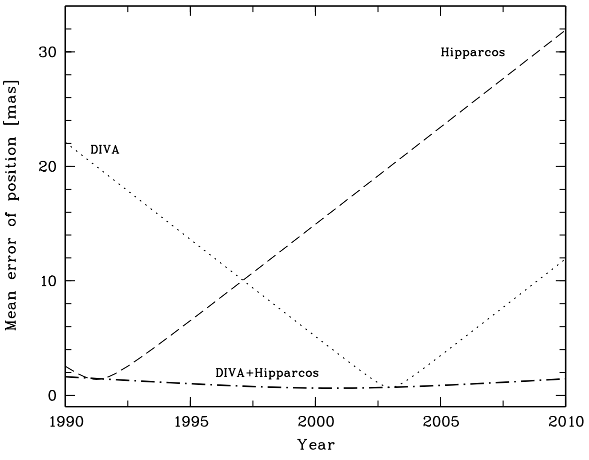

Figure 4. Mean error of a star position as a function of time. The curves show this effect for Hipparcos as well as for DIVA measurements alone, and the dramatic improvement obtained by combining Hipparcos and DIVA measurements.

The rotation of the Hipparcos system with respect to the VLBI-defined ICRF (International Celestial Reference Frame) is determined with an accuracy better than 0.5 mas/yr. Provided that VLBI observations are continued, the new optical reference system given by Hipparcos and DIVA will have an uncertainty of only 50 μas/yr. So, the galactic rotation will be determined with a relative accuracy of one percent. This will have strong implications for our understanding of galactic kinematics and dynamics.

4. SUMMARY

The characteristics and the scientific importance of the DIVA mission can be summarized as follows:

DIVA will be a technologically ambitious, low-cost precursor mission for a proposed ESA Cornerstone Mission, GAIA. Many of the critical aspects of the overall system, of the operations and of the data reduction for GAIA can be tested with DIVA. On the other hand, DIVA has its own outstanding scientific importance. In many aspects, it will surpass the scientific results of Hipparcos at a fraction of the Hipparcos cost. Especially, the proper motions of the Hipparcos stars will be improved by a factor of 10. For the first time a homogenous sky survey will be performed in at least 6 wavelength bands in the optical regime. We are planning to launch DIVA in 2002. Then, the scientific data will be available in 2005. To summarize, DIVA is the astrophysical mission filling the gap between Hipparcos and GAIA.

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