Astronomy and Astrophysics in the Gaia sky
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Astrometric surveys in the Gaia era

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Abstract. The Gaia first data release (DR1) already provides an almost error free optical reference frame on the milli-arcsecond (mas) level allowing significantly better calibration of ground-based astrometric data than ever before. Gaia DR1 provides positions, proper motions and trigonometric parallaxes for just over 2 million stars in the Tycho-2 catalog. For over 1.1 billion additional stars DR1 gives positions. Proper motions for these, mainly fainter stars ($G \geqslant 11.5$) are currently provided by several new projects which combine earlier epoch ground-based observations with Gaia DR1 positions. These data are very helpful in the interim period but will become obsolete with the second Gaia data release (DR2) expected in April 2018. The era of traditional, ground-based, wide-field astrometry with the goal to provide accurate reference stars has come to an end. Future ground-based astrometry will fill in some gaps (very bright stars, observations needed at many or specific epochs) and mainly will go fainter than the Gaia limit, like the PanSTARRS and the upcoming LSST surveys.

Keywords. astrometry, surveys, catalogs, reference systems, stars: kinematics.

1. Introduction

This paper is limited to a review of current and future ground-based, optical to near-IR, wide-field astrometric survey research in the Gaia era. There are 2 distinct phases. We are now in the first phase which will last until the second Gaia data release, DR2, scheduled for April 2018. In this period of time ground-based efforts concentrate on a) using DR1 data for almost error-free reference stars to re-calibrate CCD data, and b) derive proper motions for large numbers of stars, not available in DR1. The second phase is after DR2 when full astrometric solutions including proper motions and parallaxes will become available for almost any star and many compact extragalactic sources in the about 4 to 20.5 magnitude range at unprecedented accuracy.

2. Gaia DR1

The astrometric properties of Gaia DR1 data are described in detail by Lindegren *et al.* (2016). A short summary of the important numbers is provided in Table 1.

The Tycho-Gaia Astrometric Solution (TGAS) of DR1 uses the Hipparcos Catalogue (van Leeuwen 2007) and the Tycho-2 catalog (Høg *et al.* 2000) to resolve the degeneracy between proper motion and parallax over the short time span Gaia data. The major difference between the Hipparcos stars subset and the entire TGAS set of stars is the over 10 times smaller error in the Hipparcos set proper motions. This difference is not very important when using the Gaia DR1 data for reference stars in astrometic solutions of ground-based CCD data because there are few Hipparcos stars and most of them are too bright for the purpose.

The DR1 data do provide highly precise and accurate positions at a near current epoch (2015). However, of great importance here is the lack of proper motions of all

Table 1. Overview of Gaia DR1 astrometry. Errors are given for the 10 and 90 percentile according to Lindegren *et al.* (2016).

	Hipparcos		TGAS		secondary	
number of sources	93,635		2,057,050		1.14 billion	
main magnitude range	6 - 10		8 - 11		12 - 21	
position error [mas]	0.15	0.39	0.14	0.60	0.26	12.9
proper motion error [mas/yr]	0.03	0.13	0.44	2.67	—	—
parallax error [mas]	0.23	0.50	0.24	0.64	—	—

Table 2. Recent proper motion surveys utilizing Gaia DR1 data.

survey name	1st epoch date [year]	number of stars [million]	proper motion error [mas/yr]	based on what 1st epoch data
HSOY	1950 - 1975	583	$1-5$	PPMXL, USNO-B1, Schmidt plates
UCAC5	1998 - 2004	107	$1-5$	UCAC, CCD data, no photogr.plates
GPS1	multiple	350	$1.5-3$	PS1, SDSS, 2MASS
PMA	$\approx$ 2000	421	$2-10$	2MASS

non-TGAS stars in DR1. This fact prompted a flurry of efforts to supplement Gaia with preliminary proper motions. These are better than anything offered by ground-based, global astrometry before. Of course, the life-span of these products will be short. The Gaia DR2 will make those products obsolete. However, in the meantime they provide much needed support for astrometric reductions of ground-based CCD imaging.

3. Phase 1: between DR1 and DR2

3.1. *New proper motions*

A summary of these new proper motion surveys and their properties is given in Table 2. All are using the Gaia DR1 (secondary sources) as their 2nd epoch and all are constructed to be on the International Celestial Reference Frame (ICRF). Most are claiming quasi absolute proper motions with a direct link to extragalactic sources. All are based on a single set of early epoch data, except the GPS1. All cover the entire sky, except for GPS1.

The first product of new proper motions to become available is the Hot Stuff for One Year (HSOY) catalog (Altmannn *et al.* 2017). It is based on PPMXL (Röser *et al.* 2010) using USNO-B1 Schmidt plate survey data (Monet *et al.* 2003) as first epoch. There is a big difference in epoch difference between the northern part (early Palomar data) and the remaining southern hemisphere area which was observed much later. The epoch difference of course propagates into the proper motion errors.

The UCAC5 (Zacharias, Finch & Frouard 2017) proper motions are based on a completely new reduction of the USNO CCD Astrograph Catalog (UCAC) observations using TGAS and then combine the about epoch 2000 data with DR1. This has the advantage of having both sets of data on the exact same reference frame to begin with and avoiding any photographic plate data which are often subject to large systematic errors depending on a combination of magnitude, color and location in the field. However, the UCAC data are not entirely free of these systematic errors (along right ascension) due to the poor charge transfer efficiency (Zacharias *et al.* 2004) of the particular detector used.

The GPS1 proper motion catalog (Tian *et al.* 2017) uses several early epoch data: the first PanSTARRS (panstarrs.stsci.edu) data release (PS1) (Chambers *et al.* 2017), Sloan Digital Sky Survey (SDSS) (Munn *et al.* 2004) and near-IR 2MASS data (Skrutskie *et al.* 2006). The GPS1 proper motion catalog covers about 3/4 of the sky (the PS1 area) and claims systematic errors below 0.3 mas/yr. Using more than just one early epoch to calculate new proper motions should result in realistic error estimates. However, the scatter of observed proper motions of extragalactic sources in GPS1 is significantly larger than expected from their formal errors.

The Proper Motion Absolute (PMA) catalog (Akhmetov *et al.* 2017) uses 2MASS data as first epoch. It was constructed to be independent of the ICRF and Hipparcos Celestial Reference Frame (HCRF) using extragalactic sources for the zero-point of its proper motion system and covers the large 8 to 21 magnitude range.

3.2. *New parallaxes*

Not directly linked to Gaia data but also a temporary product until the Gaia DR2 becomes available is the URAT Parallax Catalog (UPC) (Finch & Zacharias 2016) based on the USNO Robotic Astrometric Telescope (URAT) nothern hemisphere observations. UPC gives results for over 112,000 stars in the 6.5 to 17 mag range. This is the largest catalog of trigonometric parallaxes since the Hipparcos space mission.

The UPC parallaxes compare very well with previously published trigonometric parallaxes, however, the precision is limited with typical errors of about 3 to 10 mas, which is not surprising considering that the telescope used for these observations has a focal length of only 2.06 m. Selection criteria for stars in common with other, previously available data have been relaxed (e.g. number of required observations, formal error on parallax), while for stars without previously published trigonometric parallax the selection criteria are tighter to avoid contamination of the sample by false positives. Nevertheless UPC provides first published trigonometric parallaxes for over 53,000 nearby stars.

3.3. *Example: UCAC5*

How much do Gaia DR1 reference stars actually help in the re-reduction of earlier astrometric catalog data? As an example the UCAC5 data are used here (see also above). Over 250,000 CCD exposures were taken with the USNO "redlens" astrograph for the UCAC project between 1998 and 2004. Observing begun at Cerro Tololo, Chile, covering the sky from $\delta = -90°$ to about $\delta = +25°$. The rest of the northern sky was observed from Flagstaff, AZ. While the field of view of the astrograph lens is about 9° in diameter, only a 1.0 square degree area near the optical axis was used with a Kodak 4k by 4k CCD at a scale of 0.905 arcsec/pixel. At the time this was the largest CCD on the mountain. A single, fixed bandpass (579 to 643 nm) was used. The survey covers the about R = 8 to 16 mag range with a 2-fold overlap pattern and a long (100 to 150 sec) and a short exposure (1/5 of long) on each field.

Results based on Tycho-2 reference stars were published previously (UCAC4, Zacharias *et al.* 2013). Systematic errors of the CCD data were corrected as a function of magnitude, location in the field and subpixel phase using 2MASS data allowing for residuals covering the entire UCAC magnitude range. However, due to the poor charge transfer efficiency of the 4k CCD systematic errors mainly along RA remain on the 10 mas level.

Now TGAS was used as reference star catalog for a re-reduction of the UCAC exposures. These positions were published as UCAC5 together with new proper motions in combination with Gaia DR1 data. Both UCAC4 and UCAC5 astrometric solutions use a 6-parameter, linear "plate" model in a weighted least-squares adjustment. The same systematic error correction model as function of magnitude (CTE) was adopted for UCAC5

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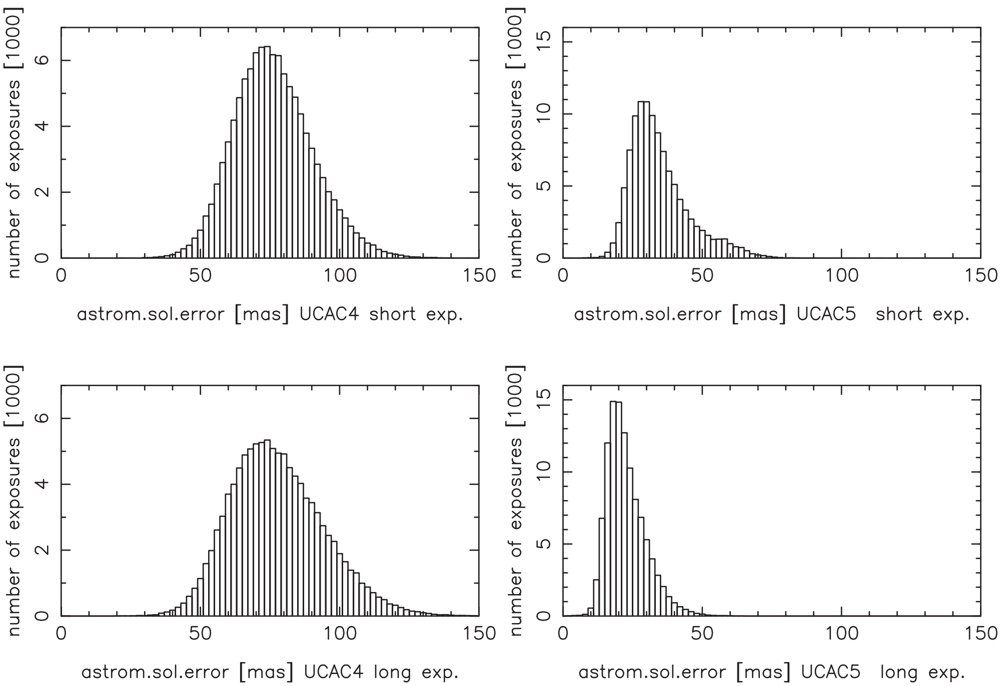

Figure 1. Astrometric solution error for UCAC4 (left) and UCAC5 (right).

as was used with UCAC4. The field distortion pattern and sub-pixel corrections were updated for UCAC5. Deriving new corrections as a function of magnitude (most needed here) could not be accomplished due to the limited magnitude range of TGAS, ending at about V = 11.5. The distribution of the astrometric solution errors for these about 250,000 individual exposures is shown in Fig. 1 with the same binning, separately for the long and short exposures.

A dramatic decrease in astrometric solution error (about factor of 3) is seen when using Gaia data instead of Tycho-2 reference stars. Interesting to note is that the mean astrometric solution error for UCAC4 is slightly smaller for short than for long exposures. The opposite, with significant difference is true for the UCAC5 data. This is because the error contribution from the turbulent atmosphere is much smaller for the long than the short exposures. However, for the UCAC4 data the long exposures are impacted by larger than average Tycho-2 reference star errors while the more precise, brighter reference stars are saturated and not used in the reductions. The short exposures have the benefit of using more, in particular brighter, more accurate Tycho-2 reference stars. These 2 factors (atmospheric turbulence and reference star errors) cancel each other about out for UCAC4. For UCAC5 however, the reference star errors (TGAS) are very small for all stars including the faint end and “plate” solutions of the long exposures are not significantly degraded. Thus for UCAC5 the benefit of the longer integration times (smaller errrors from the atmopshere) becomes dominant.

But how much does the Gaia data help for the field star positions obtained from the UCAC exposures? This is a matter of error propagation of the “plate” parameters. Over 50 years ago a monumental paper was published on this topic (Eichhorn & Williams 1963). The answer to our question strongly depends on the complexity of the “plate” model. It is highly recommended for anyone dealing with astrometric reductions of CCD image data to read this paper. Often a complex model, like a full 2nd or even 3rd order

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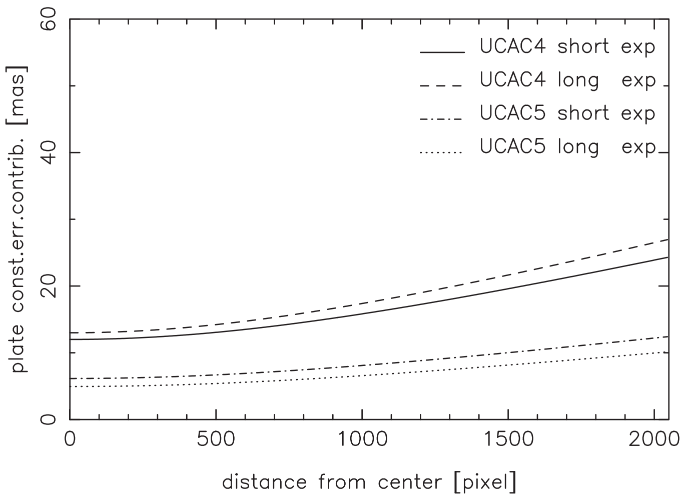

Figure 2. Contribution from plate parameter error propagation.

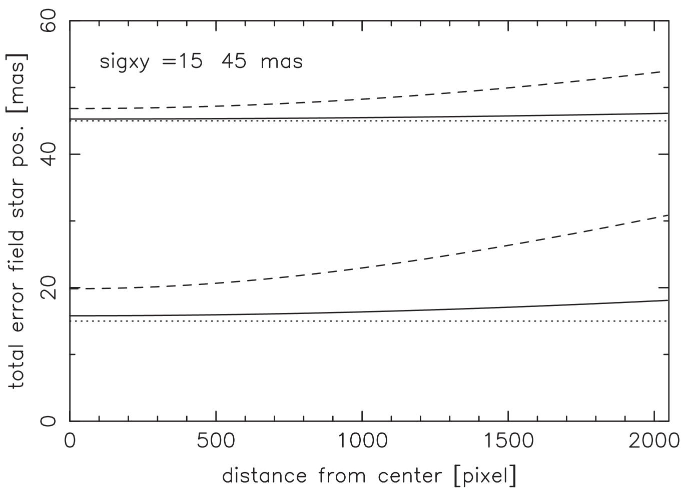

Figure 3. Total position errors of field stars.

polynomial is used to "make sure" possible systematic effects in the focal plane mapping are covered, without noticing what harm is done by doing so. Although the residuals of such a reduction look "very good" the parameters bear large errors which are propagated into field star positions.

For the UCAC4 / UCAC5 example this fortunately is benign due to the simple linear "plate" model. Figure 2 shows the "plate" parameter error contribution for field star positions as a function of distance from the CCD center, separately for long/short exposures and UCAC4 / UCAC5 case. As can be seen the increase in error contribution toward the edge of the field is moderate. These error contributions are about a factor of 2 smaller for UCAC5 data (TGAS reference stars) than for UCAC4 data (Tycho-2 stars).

Going a step further, Fig. 3 shows the root-sum-square (RSS) of image center position errors (sigxy) and the "plate" parameter error propagation contribution to field star positions. Results for 2 cases are shown for sigxy = 15 and 45 mas (lower and upper set

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of lines, respectively). For each case the larger error line is for UCAC4 data, the lower for UCAC5 and the dashed line for the limiting case with sigxy only and no "plate" parameter error contribution. The smallest image center error in UCAC4 data has sigxy = 9 mas, for a bright star just under saturation of high quality data. The sigxy = 15 mas case is a typical star of high S/N ratio and the 45 mas case is an average field star at S/N = 20.

As can be seen the improvement in positions obtained from UCAC data using Gaia reference stars is largest for high S/N, bright targets, while for most field stars the improvement near the center of the CCD is minimal and not much larger at the edge of the field. This just means that in the case of UCAC (1 square degree field, with typically about 25 to 100 Tycho-2 reference stars) the astrometric solution is already very good despite the relatively large errors of individual Tycho-2 star positions.

More important than the small random errors are the very small systematic errors of the Gaia DR1 data. Re-reduction of ground-based survey data will be on the Gaia coordinate system with much smaller local systematic errors than previously achieved. As for random errors, the big improvement of TGAS over Tycho-2 reference stars is not so important if enough reference stars are in the field. The quality of the CCD data (image center positions) now becomes the limiting factor for the overall result. Major improvements for re-calibration of ground-based astrometric survey data will likely have to wait until the Gaia DR2, when a much wider magnitude range becomes available with very small position errors, allowing to eliminate the critical systematic errors as function of magnitude and combinations of magnitude with other parameters.

4. Phase 2: after DR2

The Gaia DR2 will likely have an even bigger impact on optical astrometry than DR1. DR2 will provide a full astrometic solution (position, proper motion and parallax) for most stars (and compact, extragalactic sources) in the 4 to 20.7 mag range on the 0.1 to 1 mas level (depending on magnitude). All above mentioned, preliminary proper motion catalogs based on Gaia DR1 and earlier, ground-based data will become obsolete. In fact, all traditional, optical, ground-based surveys like CMC, GSC, NPM, SPM, PPM, PPMXL, UCAC, URAT, USNO-B, and others will become obsolete for astrometric data. At this point the era of optical, ground-based, wide-field astrometric surveys which begun with the Astrographic Catalogue project in the 1880s (Eichhorn 1974) is coming to an end. No optical reference frame densification effort will be needed, Gaia DR2 and later releases will provide the reference frame and the most dense realization possible (all objects to a limiting magnitude) at the same time.

So, is there anything left for ground-based astrometry, is there life after Gaia? Yes, there is. Ground-based, wide-field astrometry has already and will in future branch out into the few remaining areas not covered by Gaia. These are:

(*a*) Very bright stars ($G \leqslant 4$), until near final Gaia DR, likely after 2020.
(*b*) Faint objects ($G \geqslant 20.7$).
(*c*) Other than optical bandpass, like near-IR.
(*d*) Complex motion cases, or variable center objects.

Each of these areas will be described in more detail below. Astrometry will continue to support astrophysics in this new era. It is important not to forget the mindset, methods and skills needed for astrometry in this transition. Many of the ideas and tools of past astrometric projects are still applicable today and in the future. A big help for students in this respect is the recent textbook (van Altena 2013) on this subject.

Table 3. Current and future, deep, wide-field surveys.

survey name	first light	survey begin	telescope aperture	bandpass	camera size Mpx	field of view sq.deg	R mag range
SDSS	1998	2000	2.5 m	u,g,r,i,z	120	1.5	14-23
Skymapper	2008	2014	1.3 m	u,v,g,r,i,z	268	5.7	13-22
PanSTARRS	2008	2009	1.8 m	g,r,i,z,y	1000	7.0	14-23
CFHT	2003		3.6 m	u,g,r,i,z +	340	1.0	15-24
DECam	2012	2013	4.0 m	u,g,r,i,z,Y	520	3.0	15-24
ZTF	2017	2018	1.2 m	g, R	576	47.0	14-21
LSST	2020	2022	8.4 m	U,G,R,I,Z,Y	3000	9.6	18-26
Vista	2009	2010	4.1 m	near-IR	67	0.6	

Note: Limiting magnitudes given here are for stacked images except for ZTF. The saturation limit is approximate, strongly depending on exposure time and seeing conditions.

4.1. *Very bright stars*

Accurate positions of nacked-eye stars are important for navigation. The currently best data are still based on Hipparcos observations (ESA 1997) and Tycho-2 proper motions, which are often more reliable than the Hipparcos proper motions due to the much longer time baseline (about 100 years vs. 3.5 years). Northern Hemisphere URAT observations are limited to stars of about magnitude 6 and fainter, while the Gaia DR1 lists only few stars brighter than 5th magnitude. Positions of stars brighter than the DR1 limit are only on the 30 mas level at current epochs with a good fraction of stars showing much larger inconsistencies likely due to unresolved multiplicity issues.

The UBAD program (Subasavage, private com.) uses the 61in telescope at the Naval Observatory Flagstaff Station (NOFS) with very dense neutral density spots of 9 and 12.5 magnitude attenuation to observe bright stars. URAT, operated from CTIO uses a neutral density spot with about 4 mag attenuation in combination with an objective grating, targeting all stars from Sirius to R = 4.5 mag within about $-89° \leqslant \delta \leqslant +23°$. For most targets several exposures of 30 or 60 sec are taken per night, while the handful of brightest stars are observed with about a dozen 5 or 10 sec exposures. This results in mean positions of 10 mas precision per night. Each target star is observed multiple times during a year. These observations begun in October 2015 and are still ongoing. Results from both programs will be published soon.

4.2. *Faint objects*

Going deeper than Gaia is the main area of research for wide-field, ground-based, astrometric surveys these days and in the coming years. However, astrometry is only a part of these programs with photometry being another major objective. These programs fall under the umbrella of “time domain astronomy” with high cadence observations to achieve multiple science goals. A main driver for photometric time domain observations is the discovery and characterization of rare or transient phenomena. The astrometric relevance of these high cadence observations is described in more detail in the following section. Table 3 provides an overview of current and future, deep, ground-based surveys with relevance to astrometry.

The Sloan Digital Sky Survey (SDSS) project was the first of its kind (Gunn *et al.* 2006) aiming at a deep, wide-field survey. Beyond imaging SDSS also can obtain spectra

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of thousands of objects via fibers. SDSS is operated from Apache Point, New Mexico and was used for various projects, now being past its 13th data release.

Skymapper (Keller *et al.* 2007) is the southern hemisphere counterpart to SDSS operating from Siding Spring, Australia. An early data release was in May 2016 with a first full-sky data release expected in 2017.

The Panchromatic Survey Telescope and Rapid Response System (PanSTARRS) operates from Haleakala, Hawaii with now 2 of the planned 4 telescopes. The focal plane consists of 60 orthogonal-transfer CCDs. PanSTARRS had its first data release (PS1) in Dec. 2016. PS1 consists of several surveys with the 3π steradian survey covering all of the sky north of $\delta = -30°$. A second data release is scheduled for early 2018.

The Canadian-Frensh-Hawaii Telescope (CFHT) MegaCam instrument was used for deep, wide-field imaging from its Mauna Kea location on Hawaii. It is used for many projects and the telescope also has other instruments than the imaging camera, including the near-IR WIRCam.

The Dark Energy Camera (DECam) operates at the prime focus of the Blanco telescope at Cerro Tololo, Chile (Abbott *et al.* 2016). It is currently working on a 5-year survey of a 5000 sq.deg area in the southern sky.

The Zwicky Transient Facility (ZTF) (Bellm 2014) is the follow-up project to the successful Palomar Transient Factory (PTF), both using the 48in Palomar Schmidt telescope. While the PTF had a relatively small focal plane detector, the ZTF utilizes the full field of view of this survey telescope which undertook the famous Palomar Schmidt Surveys in the 1950s and 1970s on photographic plates.

The Large Synoptic Survey Telescope (LSST) will operate from Chile. Construction begun in August 2014. Full survey operation is expected to start in 2022 for 10 years. The telescope has a primary mirror of 8.4 m diameter but a very large central obstruction resulting in an effective collecting area equivalent to a 6.7 m diameter, unobstructed mirror. LSST will take 15 sec exposures every 20 sec on 189 CCDs with 0.2 arcsec/px sampling. The technological and data reduction challenges, and its budget is comparable to a mid-size space mission.

The Visible and Infrared Survey Telescope for Astronomy (VISTA) currently has a single, large, near-IR imaging instrument and is operated from Paranal, Chile. A variety of surveys have been undertaken with different sky coverage and depth. A multi-object spectrograph is under development.

4.3. *Complex motion, variable center location*

Understanding the dynamics of natural satellites in our solar system and deriving accurate ephemerides is an example where a very long time span of moderately accurate observations is more important than a short time span with very accurate observations. Digitizing photographic plates taken over many decades and reducing these data with modern reference stars provided significantly better results than Hipparcos observations alone can do (Robert *et al.* 2011).

These are cases where the motion of targets is complex. Although Gaia will observe each target on average about 50 to 100 times, the cadence is pre-determined by the scanning law and observations are limited to a relatively short lifetime of the mission. Astrometric objectives which require a target specific cadence, more observations or a longer timespan will resort to ground-based observations in addition to Gaia data.

Other examples of supporting ground-based observations are mass determination of asteroids from close encounters (Ivantsov 2017) and observations of binary star systems, where typically 50% or more of an orbital motion needs to be seen to obtain a high quality orbit solution. Things can become even more complex when the observed center shifts due to brightness variation or color induced motion (Makarov *et al.* 2017).

4.4. *Other than optical bandpass*

Using different wavelength or bandpass observations is mainly performed to sample the flux of a target, i.e. for photometry. However, in some cases there are also astrometric implications. A shift of the center of an object may be wavelength (frequency) dependent. Different astrophysical phenomena are seen at different wavelengths. An example even relevant for the definition of the reference frame itself are possible center shifts of active galactic nuclei (AGN) e.g. between optical and radio data due to source structure seen differently at different wavelengths (Petrov 2017).

Thus ground-based surveys performed in the near-IR can offer additional astrometric data beyond what Gaia data can provide. For most tagets (like ordinary stars) the difference between optical and near-IR positions will be very small. However, those objects which display a significant difference will be of astrophysical importance.

5. Summary

(*a*) The primary Gaia DR1 catalog (TGAS) with its 2 million stars is the new optical reference frame surpassing Hipparcos and Tycho-2 in accuracy. Zonal systematic errors in Tycho-2 proper motions are seen which are no longer present in TGAS.

(*b*) The main short-term ground-based, astrometric activities (until DR2) are:

- use TGAS data to reduce earlier epoch observations
- combine the DR1 position data of 1.14 billion stars with earlier deep surveys to obtain improved proper motions on the Gaia system
- derive trigonometric parallaxes from recent gound-based, high precision surveys, mainly the URAT parallax catalog

(*c*) All traditional, ground-based, wide-field, astrometric surveys in the 4 to 20.7 mag range will become obsolete with Gaia DR2 by about April 2018.

(*d*) Current and future ground-based, astrometric surveys go into areas of reseach not covered by Gaia:

- Very bright stars ($G \leqslant 4$) are currently observed with UBAD and URAT.
- Many surveys go deeper than Gaia, like PanSTARRS and LSST. This is a major area of reseach but not limited to astrometry, rather including also photometry and time-domain astronomy in general.
- Complex motions (solar system, masses of asteroids, multiple star systems, exoplanets, object center motion as function of variability) need many observing epochs, often at specific times or over very long periods of time, where Gaia plays a role but needs to be supplemented by additional ground-based observations.
- Astrometric observations at other than optical bandpasses (like near-IR and radio) are sometimes needed to investigate position shifts as function of wavelength, as for example seen in some AGN objects or double stars with different color components.

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Discussion

?: What is the percentage of double stars causing problems? Most stars are multiple, what is the impact on these catalog data?

ZACHARIAS: This is not very well known at this point. The impact on wide-field astrometric surveys strongly depends on the type of double star, i.e. depending on their separation and magnitude difference. An approximate estimate is 10 to 20% of stars are seen as "astrometric problematic" in many surveys.

HØG: What is the status of LSST, when will it become online?

ZACHARIAS: LSST is on schedule. The ground has been broken in Chile and constructions are underway. Major parts of the telscope have already been completed. First light is expected in 2020. Routine survey observing will begin about 2 years after first light.