

3.5.4 ICRS Centre

Maintenance of the International Celestial Reference Frame Construction of the ICRF3

Part of the activities of the ICRS Centre team at Paris Observatory have been related to the construction of the third realization of the International Celestial Reference Frame (ICRF3). These activities are a contribution to the Working Group on ICRF3 created at the XXVIII IAU General Assembly in 2012. The mission of the WG-ICRF3 is to propose to the XXX IAU General Assembly in 2018 a catalogue of radio source positions to realize the ICRS, which would include a larger interval of observation than that of ICRF2 for the computation of precise coordinates, assuring the representation of the axes of ICRS through a set of position-stable radio sources, namely defining sources. Objects in the new frame should allow the orientation of the Gaia catalogue onto ICRS.

The contribution to this task focused on (a) the comparison and analysis of different VLBI prototype solutions for a study of systematic effects and deformations, (b) the analysis of positional stability and statistics for improving the set of defining sources of the frame, (c) the implementation of a strategy for selecting stable sources respecting a homogeneous special distribution.

An important improvement with respect to ICRF2 has been the possibility of providing a multi-frequency catalogue. With this aim, prototype solutions on S/X, K, and X/Ka bands were included in the analysis. The ICRF2 (Fey et al., 2015) and the Gaia catalogue issued for the Data Release 2 (GDR2; Prusti et al., 2016; Brown et al., 2016, 2018; Mignard et al., 2018) were used as references for catalogue comparisons. The model used for the catalogue comparisons is that adopted since 2016 at Paris Observatory, which includes the three classical rotation angles, three deformation (glide) parameters and ten quadrupole parameters (see Section 3 of this report for the formulae and a discussion). Eight analysis centres produced prototype solutions for testing various effects, included the Galactic aberration correction. Complete independence between solutions had not been possible due to the use of common software for some. In all cases the no-net-rotation condition was imposed to the ICRF2 defining sources. Results of these comparisons will be available in Charlot et al. (2018). The three final ICRF3 catalogs at S/X, K, and X/Ka bands are publicly available at the ICRS Centre web site at <http://iers.obspm.fr/iers-pc/newwww/icrf>.

Monitoring of the ICRS

One mission of the IERS ICRS Centre is the monitoring of the ICRS, which includes verifications of the stability of the axes of the system materialized through the frame, the possible deformations of the frame and the astrometric evolution of its defining sources. The comparisons realized as a contribution to the WG on the ICRF3 gave indication of the

existence of deformations in the ICRF2 depending on the declination, mostly visible for sources at high south declination. This could be confirmed by the comparison with the Gaia DR2 catalogue, under the hypothesis that the Gaia frame is not subject to any significant deformation.

The IERS ICRS Centre at Paris Observatory developed the tools for analyzing the astrometric quality of radio source positions (Lambert, 2014). These analyses focused on the monitoring of the defining sources in ICRF2, and on the detection of possible candidates for defining sources in ICRF3. Coordinate time series for a number of sources have been analyzed, ranking them according to their statistical behavior. We used as indicators the weighted root-mean-square of the time series in the direction of the maximum variance (computed from the major axis of the error ellipses), and the chi-square computed along this direction. Also, a visual inspection of the time series was made to detect special features (noise level, slopes, etc.). Structure indices had also been considered, but a formal inspection by the Bordeaux team completed the evaluation. These analyses were also performed on the so called “special handling sources” of the ICRF2. These are 39 sources which had been detected unstable at the elaboration of the ICRF2, and consequently treated as arc parameters in the VLBI solutions. The ensemble of analyses gave the following results:

- A number of ICRF2 defining sources presents positional instability and should be excluded from this category;
- There is no clear evidence of significant instability in the position time series of the special handling sources, suggesting that they could be resolved as global parameters in the VLBI solutions.

Based on these results, it is clear that a major revision is necessary on the set of defining sources of the new frame. The criteria adopted in the elaboration of the previous versions of the celestial reference frame focused on the position stability without considering the spatial distribution of objects. This could be one of the reasons for the deformations present in the ICRF2. The sources observed by the VLBI programs has increased in number, but a big progress happened with the observation of objects south from the equator. With this improved distribution it is possible to design a method privileging a homogeneous spatial distribution. The method retained consisted on dividing the celestial sphere into 324 equal sectors, and in each one to select the best source, considering positional stability shown in the time series and radio structure. This resulted on only two empty sectors. The classification of sources in the sectors permitted to retain a list of 303 sources qualified to be defining sources in ICRF3; 54% of them are defining sources of ICRF2, 83% are in Gaia DR2.

**Analysis of recent
VLBI catalogs**
Data

We analyzed three catalogs submitted to the International VLBI Service (IVS) in 2017. One catalog was submitted by the Italian Space Agency (ASI; solution asi2017a); one catalog was submitted by Geoscience Australia (aus2017b); one catalog was submitted by BKG (bkg2017a). The aus2017b catalog was obtained with the OCCAM geodetic VLBI analysis software package (Titov et al., 2004), whereas the other two catalogs were obtained with Calc/Solve (Ma et al., 1986). As reference catalogs, we considered the current reference recommended by the International Astronomical Union (IAU), i.e., the second realization of the International Celestial Reference Frame (ICRF2; Fey et al., 2015) and the second data release of Gaia (DR2; Prusti et al., 2016; Brown et al., 2016, 2018; Mignard et al., 2018). These two reference catalogs, that were obtained by independent techniques and analyses, are of comparable accuracy but, though the former provides positions measured at the standard VLBI S/X frequency, the latter gives the positions of the same objects in the optical domain.

Overview of the catalogs

The distribution on the sky of the radio sources in each catalog is plotted in Figure 1 together with the distribution of the standard errors. In the sky maps, the color indicates the overall error computed as the major axis of the error ellipse, calculated using the correlation information between the coordinates as provided in the catalogs. The number of sources in each catalog, the mean epoch of the observations, and the median positional errors are reported in Table 1.

The ASI solution contains a smaller number of sources than the other two catalogs. However, these are sources that have the best positional errors, so that the median error is neatly lower than for other catalogs. The comparison, restrained to 920 sources that are common to all three catalogs and to the two references, shows that ASI and BKG have similar accuracy while standard errors of AUS are larger by a factor of two. Over this common sample, the median error of the ICRF2 is a bit larger than that of AUS while the median error of Gaia DR2 is larger than that of the ICRF2 by a factor of 1.3.

An overall comparison of the error distribution with that of the reference catalogs as well as the dependence of the error on the declination are displayed in Figure 1, for which we took the running median error within windows of 15 degrees. Note that the ICRF2 standard errors were inflated and a noise floor of 0.04 mas was imposed a posteriori, whereas the initial values of the standard errors could be much lower than this threshold, as they are for the three analyzed catalogs of this report.

The declination-dependent error in Figure 1 reflects the results of Table 1 with an additional aspect: both AUS and ASI solutions show larger errors at mid-latitudes in the southern hemisphere, likely in association

with the network asymmetry and the lower number of observations in the south. This feature does not show up clearly for BKG. The Gaia DR2 solution does not show such systematic effects (the Gaia scanning law allows to cover both hemispheres symmetrically).

Comparison with ICRF2 and Gaia DR2

Figure 3 displays the differences in declination between the catalogs and the references averaged within bins of 15 degrees. All three catalogs share the common feature of large (0.1-mas level) zonal differences with the ICRF2. A similar comparison with Gaia DR2 reveals that the zonal deformation is much smaller, concluding that recent VLBI catalogs are closer to Gaia than to the ICRF2. Since Gaia DR2 is not expected to present zonal deformations, Figure 3 suggests that recent VLBI catalogs are less deformed than ICRF2.

Table 1: *Statistics of the catalogs, including the two references (ICRF2 and Gaia DR2) used in this report. N is the number of sources. The mean epoch corresponds to the average of the mean observational epochs of each source. Unit is μas .*

	N	Mean Epoch	Median Error		
			RA*	Dec	EEMA
ICRF2	3414	2001.41	396.7	739.0	756.9
Gaia DR2	2820	2015.50	233.1	211.0	263.7
asi2017a	1406	2007.53	53.2	88.3	92.5
aus2017b	4166	2009.41	313.7	551.0	579.1
bkg2017a	3606	2005.17	238.1	428.3	450.9
920 common sources					
ICRF2	920	2001.06	119.7	147.5	185.3
Gaia DR2	920	2015.50	207.5	189.0	232.9
asi2017a	920	2007.42	42.7	66.1	67.2
aus2017b	920	2008.53	114.0	147.5	154.0
bkg2017a	920	2006.48	48.2	68.5	71.2

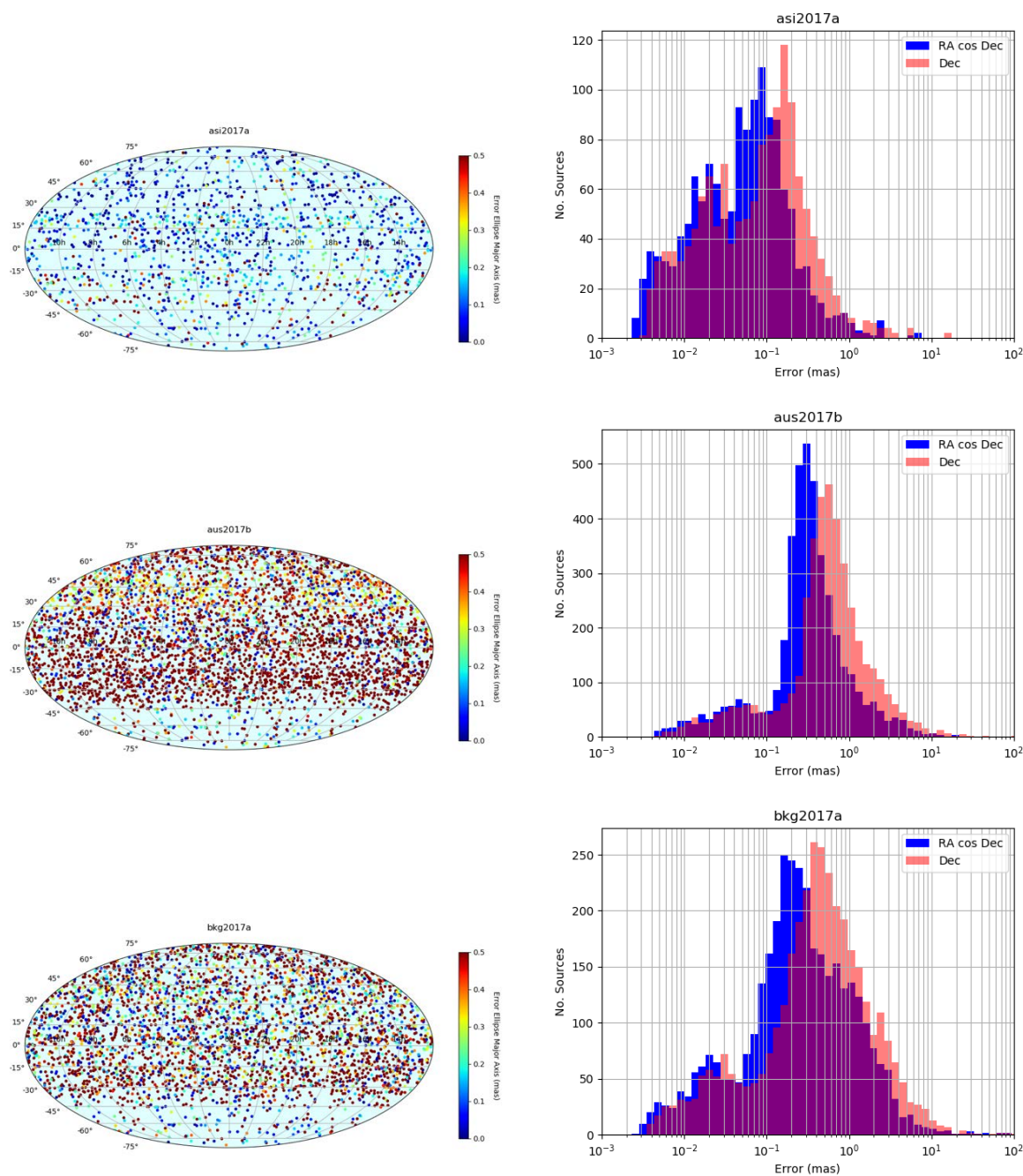


Fig. 1: Left: sky distribution of the catalogs highlighting the overall positional error computed as the major axis of the error ellipse. Right: distribution of the standard errors on source position.

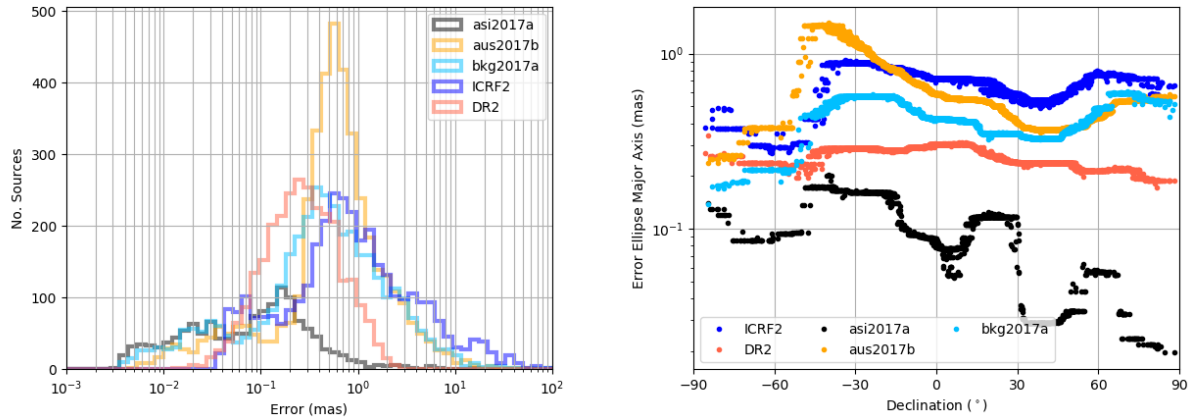


Fig. 2: Left: overall comparison of the standard error distribution. Right: standard errors in source positions as a function of the declination smoothed by taking the running median within bins of 15 degrees.

Before further comparison, we removed sources that have (i) less than three observations in one catalog, or (ii) an error ellipse major axis larger than 5 mas in one catalog, or (iii) a normalized separation between catalogs larger than 5.

To model large-scale systematics, we used a 16-parameter transformation accounting for rotations around the three axes, a glide, and degree-2 electric- and magnetic-type deformations (see, e.g., Mignard and Klioner, 2012). With respect to earlier works, we added therefore ten parameters mainly because the examination of the coordinate differences as a function of the declination revealed a $\sin 2\delta$ pattern that was not accountable by the glide alone. The coordinate differences $\Delta\alpha$ and $\Delta\delta$ between a catalog and a reference catalog read

$$\begin{aligned}
 \Delta\alpha \cos \delta &= R_1 \cos \alpha \sin \delta + R_2 \sin \alpha \sin \delta - R_3 \cos \delta - D_1 \sin \alpha + D_2 \cos \alpha + M_{20} \sin 2\delta \\
 &+ (E_{21}^{\text{Re}} \sin \alpha + E_{21}^{\text{Im}} \cos \alpha) \sin \delta - (M_{21}^{\text{Re}} \cos \alpha - M_{21}^{\text{Im}} \sin \alpha) \cos 2\delta \\
 &- 2(E_{22}^{\text{Re}} \sin 2\alpha + E_{22}^{\text{Im}} \cos 2\alpha) \cos \delta - (M_{22}^{\text{Re}} \cos 2\alpha - M_{22}^{\text{Im}} \sin 2\alpha) \sin 2\delta, \\
 \Delta\delta &= -R_1 \sin \alpha + R_2 \cos \alpha - D_1 \cos \alpha \sin \delta - D_2 \sin \alpha \sin \delta + D_3 \cos \delta + E_{20} \sin 2\delta \\
 &- (E_{21}^{\text{Re}} \cos \alpha - E_{21}^{\text{Im}} \sin \alpha) \cos 2\delta - (M_{21}^{\text{Re}} \sin \alpha + M_{21}^{\text{Im}} \cos \alpha) \sin \delta \\
 &- (E_{22}^{\text{Re}} \cos 2\alpha - E_{22}^{\text{Im}} \sin 2\alpha) \sin 2\delta + 2(M_{22}^{\text{Re}} \sin 2\alpha + M_{22}^{\text{Im}} \cos 2\alpha) \cos \delta,
 \end{aligned}$$

where α and δ are the coordinates of the object in the reference catalog. We used weighted least-squares to solve the system, with weights computed using the available covariance information (i.e., the standard errors on individual source coordinates and their correlation). The values of transformation parameters adjusted to the catalogs compared to the ICRF2 and Gaia DR2 and their standard errors are reported in Figure 4. The resulting statistics corresponding to that of Table 2 after removal of systematics are reported in Table 3. Figure 5 clearly reveals that the only really significant deformations between the catalogs and the ICRF2 lie in the D_3 and E_{20} parameters, that are associated to

the purely zonal deformations in $\cos \delta$ and $\sin 2\delta$, respectively, along the polar axis of the celestial frame. Such deformations show up in all three catalogs at comparable levels of about $100 \mu\text{as}$. No significant deformations are seen with respect to Gaia DR2. A part of the detected zonal differences between ICRF2 and the three analyzed catalogs is imputable to the uncorrected Galactic aberration that moves sources towards the Galactic centre following a glide of amplitude close to $5 \mu\text{as/yr}$ (e.g., Kovalevsky, 2003; Titov et al., 2011). Nevertheless, given the median epochs of the catalogs, this effect is expected to be of 20 to $40 \mu\text{as}$ in D_2 and D_3 so that it cannot explain all the present results. Another part of the zonal differences is likely an evidence that the VLBI network has improved since the construction of the ICRF2 (and, especially, it was enforced in the southern hemisphere).

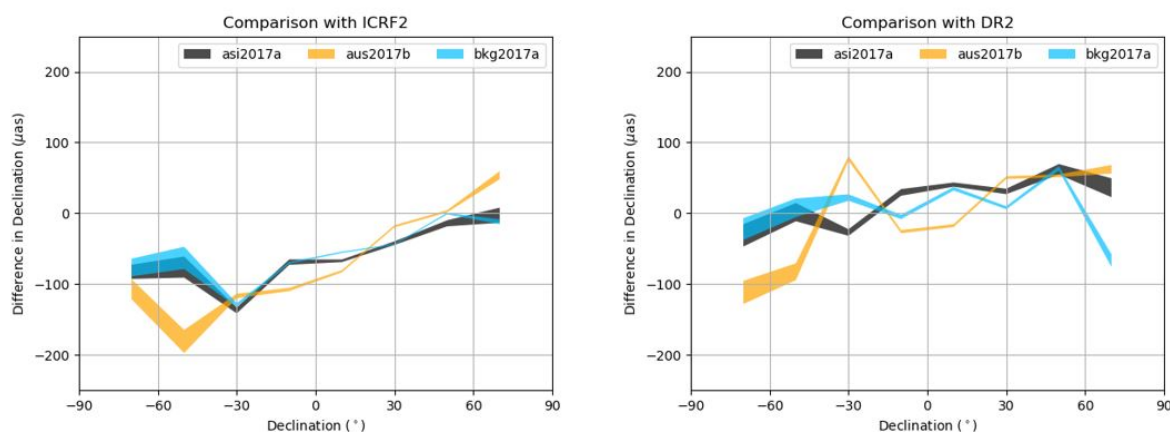


Fig. 3: Differences in declination between the catalogs and the references (ICRF2: left; Gaia DR2: right) averaged in bins of declination of width 15° .

Conclusions and recommendations

Three catalogs were submitted in 2017. They are all consistent with ICRF2 at the level of $30 \mu\text{as}$ except for zonal deformations in $\cos \delta$ and $\sin 2\delta$ for which the amplitude of the difference reaches about $100 \mu\text{as}$ (likely a combination of effects including the Galactic aberration and a network improvement). All three catalogs are consistent with Gaia DR2 within $50 \mu\text{as}$.

For a better evaluation of the consistency of the VLBI products and a better maintenance of the reference frame, especially in the frame of the next realization (ICRF3, Charlot et al., 2018) that will replace the ICRF2 as of 1 January 2019, we encourage analysis centres to submit catalogs. These catalogs should be as complete as possible, i.e., processing as much VLBI sessions as possible since 1979. Analysis strategies should be rigorously documented and motivated (e.g., why estimating some source coordinates as session parameters instead of global parameters?). The main points that will be scrutinized in the next

Table 2: Statistics of the differences of the catalogs to ICRF2 (top) and Gaia DR2 (bottom) before and after removal of large-scale systematics. N represents the number of sources used in the comparison. Unit is μas .

Before						After					
-----						-----					
		Wrms		χ^2				Wrms		χ^2	
		-----	-----	-----	-----			-----	-----	-----	-----
	N	RA*	Dec	RA*	Dec	N	RA*	Dec	RA*	Dec	

With respect to ICRF2											

asi2017a	1367	82.4	101.8	0.8	0.9	1264	79.3	93.4	0.8	0.8	
aus2017b	3282	121.1	153.5	0.6	0.7	2780	120.2	142.2	0.6	0.6	
bkg2017a	3133	86.0	109.3	0.4	0.5	2782	83.7	100.9	0.4	0.4	

With respect to Gaia DR2											

asi2017a	1048	231.4	244.5	2.4	2.6	856	229.0	240.8	2.4	2.6	
aus2017b	2696	320.8	336.1	1.8	1.6	2375	318.3	334.0	1.8	1.5	
bkg2017a	2454	317.3	337.4	2.1	2.1	2089	315.9	335.1	2.1	2.0	

reports will be the 100- μas level zonal systematics, their relation with the Galactic aberration, and the agreement with the current (DR2) and future releases of Gaia.

Photometric follow-up of quasars

As in the radio domain, it can be reasonably postulated that quasar optical flux variations can alert us to potential changes in the source structure. These changes could have important implications for the position of the target photocenters (together with the evolution in time of these centers) and in parallel have consequences for the link of the reference systems. In the continuity of what was done in the preceding years, a set of nine optical telescopes was used to monitor the magnitude variations, often at the same time as Gaia, thanks to the Gaia Observation Forecast Tool. In 2017, the Allan variances, which are statistical tools widely encountered in the atomic time and frequency community, were used to quantify the stability of the magnitude time series previously obtained.

A study concluded by a paper (Taris et al., 2017) describes the magnitude variations of 47 targets that are suitable for the link between reference systems. In this paper, we also report on some implications for the Gaia catalog. For 95% of the observed targets, new information about their variability is reported. In the case of some targets that are well observed by the TAROT telescopes, the Allan time variance shows that the longest averaging period of the magnitudes is in the range 20–70 d. The observation period by Gaia for a single target largely exceeds these values, which might be a problem when the magnitude variations

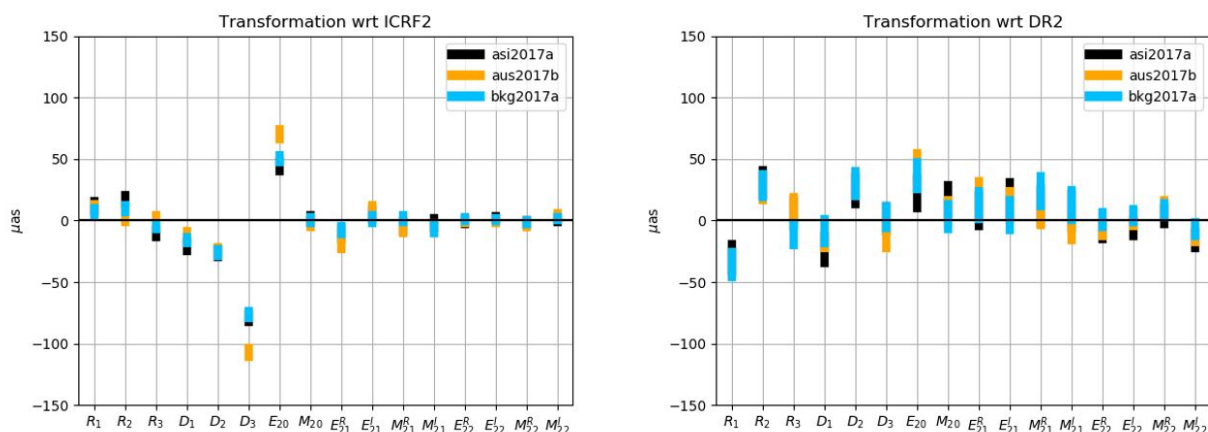


Fig. 4: Transformation parameters between the catalogs and the references (ICRF2: left; Gaia DR2: right).

exhibit flicker or random walk noises. Preliminary computations show that if the coordinates of the targets studied in this paper were affected by a white-phase noise with a formal uncertainty of about 1 mas (due to astrophysical processes that are put in evidence by the magnitude variations of the sources), it would affect the precision of the link at the level of 50 μas .

Construction of a robotic telescope

The SyRTE department of Paris Observatory plan to build a robotic telescope dedicated to the monitoring of QSO magnitudes. The first part of this project began in 2015 by the choice of a site with a good atmosphere, characterized by its seeing. Saint-Véran (alt. 3000m), in the French Alps, near the Italian border, was chosen to implement a site seeing monitoring campaign (<http://stveran.obspm.fr/index.php?page=statistiques>). It has been demonstrated in 2016 that the median value of the seeing is 1" (mode seeing is 0.7") which made this site a very good one, probably one of the best in Europe. In the second step of this project, the SyRTE laboratory proposed to robotize a test telescope (0.50m) already on site since 2015. This part of the project has been achieved in 2017. The first images are scheduled to be obtained by the test telescope at the beginning of 2018. During 2018 it is also planned to observe intranight magnitude variations of quasars suitable for the link between reference frames and to begin to start building the telescope's shelter.

Validation of the Gaia catalogue in the CU9

The Gaia mission goal is to create an extraordinarily precise three-dimensional map of about one billion stars throughout our Galaxy and beyond. The Gaia mission through its successive releases delivers an astronomical catalogue and data archive of unprecedented scope, accuracy and completeness. A large pan-European team of expert scientists and software developers known as DPAC (Data Processing and

Analysis Consortium) is responsible for the processing of Gaia's data with the final objective of producing the Gaia Catalogue. Coordinated by the DPAC Executive, the consortium is sub-divided into nine smaller, specialist units known as Coordination Units, or CUs, with each unit being assigned a unique set of data processing tasks.

Some members of the ICRS Centre belong to the CU9 / WP944 group, responsible for validation of Gaia Catalogue Data Release with the validation Test Report. The aim of these tests is to check that Gaia data is coherent compared to other known catalogues, so to accept or not them for publication. This year, we have written tests code and reports (VTS 060) to validate quasars included in Gaia Catalogue Data Release DR2. These tests include rotation, crossmatching and completeness of these sources compared with quasars from external catalogues as ICRF2, LQAC4, GIQC and SDSS DR12Q.

Here are some results of our VTS :

LQAC4GMAG crossmatched with GAIA DR2 (VTS_060_01):

```
Crossmatch radius:      1.0 arcsec
Crossmatched size and
percentage:             323 774 / 443 725 : 73%
Not found in Gaia:      127 238 / 443 725 : 29%
Multiple cross matches: 7 230 / 323 774 : 2 %
NonDuplicated Sources: 309 257/443 725 : 70%
NaN or 0 values in Gaia data need
for VTS: 0/323774 : 0.0%
```

Rotation between ICRF3 and GAIA DR2 (VTS_060_04) :

Rotation angles R1 R2 R3, Deformation D1 D2 D3,
with respective errors, in μ as

R1	R2	R3	D1	D2	D3
13.18	-7.94	0.23	62.42	-69.84	-147.31
σ R1	σ R2	σ R3	σ D1	σ D2	σ D3
26.92	25.79	23.98	25.73	24.51	25.71

Study of the quasars with the Gaia DR2

The Gaia Data Release 2 (GDR2) contains more than 550,000 quasars (Liao et al., 2018). This number comes from the cross matching to bona fide quasars repositories as allWISEagn (Assef et al., 2017) and the LQAC4 (Souchay et al., 2017), providing that the matched sources have zero proper motion and parallax as computed from Gaia sequence of measurements. And yet the direct comparison of the GDR2 to other, denser quasar repositories, as the Gaia Initial Quasar Catalog (Andrei et al., 2014) and the MilliQuas (Flesh, 2017), leaves out as many as 50% of that number (Liao et al., 2018b) or more, within the range of Gaia observable magnitudes. The discrepancy arguably arises because of morphological issues as optical jets and emitting blobs along the jets, or magnitude variability which can be associated to transient changes

of the photocenter or simply deterioration of its determination due to photon noise. As a result spurious proper motion or even parallax can turn up, and the quasar would not at principle be shorthanded as such.

Liu et al. (2018) investigate the systematic errors in the very long baseline interferometry (VLBI) positions of extragalactic sources (quasars) and the global differences between Gaia and VLBI catalogs, using the GDR1 positions as the reference and study the positional offsets of the second realization of the International Celestial Reference Frame (ICRF2). They select a sample of 1032 common sources among the catalogs and adopt two methods to represent the systematics: considering the differential orientation (offset) and declination bias; analyzing with the vector spherical harmonics (VSH) functions. They find that: the significant declination bias between Gaia DR1 and ICRF2 catalogs reported in previous studies is possibly attributed to the systematic errors of ICRF2 in the southern hemisphere. Declination-dependent systematics may exist in the VLBI positions and need further investigations in the future Gaia data release and the next generation of ICRF.

Also, there is great interest in building unbiased catalogues of quasars for a range of important astrophysical questions. These include understanding the quasar phenomenon itself and the growth and occurrence of supermassive black holes through cosmic time, the use of quasars as probes of intervening material and their role in re-ionisation of both hydrogen and helium, and for the UV background levels throughout the universe. Thus the more diverse are the ways to assert a quasar amid the Gaia data releases, the less biased is the approach to those astrophysical questions. Conversely, the most varied are the means employed for the analysis, the largest is the sureness on the answers and the best becomes the chance to spot interesting objects or spurious detections.

Andrei and colleagues (2018, submitted) used observational data to check the power of the Maximum Entropy Principle on finding the behavior of the luminosity function of quasars. They carry out statistical tests showing the evaluation of the results. Even from limited observational information, over the number of quasars with a certain magnitude, at a given redshift, they find the probability for all values of the luminosity in that redshift from the principle. In this work it is not assumed any form of the luminosity function of the quasars. The research concludes that the approach from the Maximum Entropy Principle can be used to make estimates outside observational limits. The method therefore is promising when applied on large scale over the Gaia quasars data releases, either to check the luminosity function itself and its extension beyond the Gaia range of magnitudes, as well as an auxiliary form to spot outliers.

Construction of the LQAC-4 catalogue

During the whole year 2017 we constructed the fourth release of the Large Quasar astrometric Catalogue. Since the previous release LQAC-3 (Souhay et al., 2015), a large number of quasars have been discovered, in particular those coming from the DR12Q release of the SDSS. Moreover, for cross-matched objects, we have taken advantage of the very accurate determinations of the quasars identified within the recent Gaia DR1 catalogue. Following the same procedure as in the three previous releases of the LQAC, we have compiled the large majority of all the quasars recorded so far. Our goal was to record their best coordinates and substantial information concerning their physical properties such as the redshift as well as multi-bands apparent and absolute magnitudes. Emphasis was given to the results of the cross-matches with the recent Gaia DR1 catalogue.

New quasars coming from the DR12Q release were cross-matched with the precedent LQAC-3 compilation with a 1" search radius, in order to add the objects without counterpart to the LQAC-4 compilation. A similar cross-match was done with Gaia DR1 to identify the known quasars detected by Gaia. Thus we could improve significantly the positioning of these objects, and in parallel we could study the astrometric performance of the individual catalogues of the LQAC-4 compilation. Finally, a new method was used to determine absolute magnitudes.

The LQAC-4 contains 443 725 objects. This is roughly 37.82% more than the number of objects recorded in the LQAC-3. Among them, 249 071 were found in common with the Gaia DR1, with a 1" search radius. That corresponds to 56.13% of the whole population in the compilation. The LQAC-4 delivers to the astronomical community a nearly complete catalogue of spectroscopically confirmed quasars (including a small proportion of compact AGNs), with the aim of giving their best equatorial coordinates with respect to the ICRF2 and with exhaustive additional information. For more than 50% of the sample, these coordinates come from the very recent Gaia DR1. The LQAC-4 catalog is only available at the CDS via anonymous ftp to <http://cdsarc.u-strasbg.fr>.

USNO IERS ICRS Center Activities During 2017

USNO concentrated on four primary areas of work in support of maintenance and improvement of the Celestial Reference Frame: (1) support to the International Celestial Reference Frame-3 (ICRF3) working group, (2) generating new proper motions based on USNO CCD Astrograph Catalog (UCAC) and Gaia Data Release 1 (DR1) data, (3) operation of the USNO Bright Star Astrometry Database (UBAD) program in the Northern and USNO Robotic Astrometric Telescope (URAT) in the Southern Hemisphere to collect bright star data, and (4) partnering in operations of the Very Long Baseline Array (VLBA).

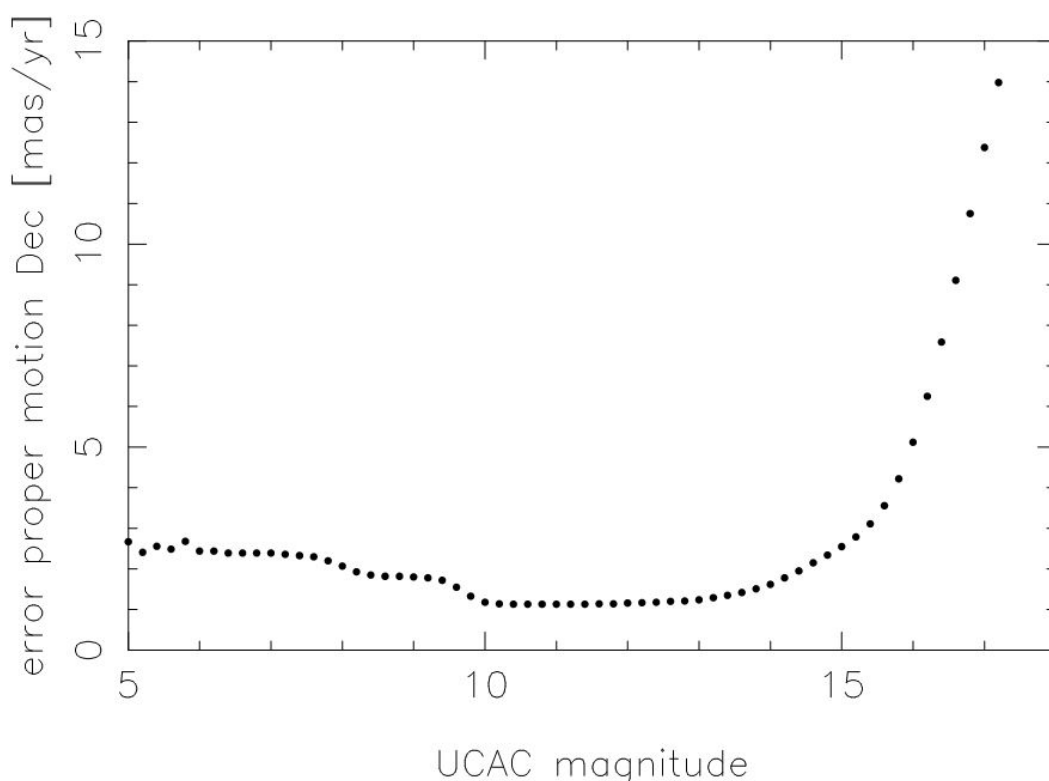


Fig. 5: Formal errors of proper motions of UCAC5 as a function of magnitude. Results are shown for declination, while results for RA are very similar.

ICRF3 USNO participated as a member of the IAU-sanctioned ICRF3 Working Group. Work included support for the execution and analysis of VLBA Calibrator Survey (VCS)-type Very Long Baseline Array (VLBA) S/X-band observing sessions under USNO's 50% timeshare agreement with the National Radio Astronomy Observatory and support for VLBA K-band and X/Ka band observations as candidates for inclusion in ICRF3. Work also included generation and analysis of numerous ICRF3 prototype global VLBI solutions for comparison with those generated by other ICRF3 Working Group members at different Very Long Baseline Interferometry (VLBI) analysis centers. The USNO continues to host the Radio Reference Frame Image Database (RRFID), a Web accessible database of radio frequency images of ICRF sources, at <http://rorf.usno.navy.mil/rrfid.shtml>.

UCAC5: New Proper Motions

The Gaia DR1 contains full astrometric parameters (including proper motions and parallaxes) for only about 2 million of the Hipparcos-Tycho stars from the Tycho Gaia Astrometric Solution (TGAS). The remaining ~billion stars in DR1 have accurate positions at the mean Gaia epoch (2015.0) but no proper motions. As shown in Figure 5, these position data were combined with a new reduction of the UCAC observations (all sky) with mean epoch of between 1997 and 2003 to derive new,

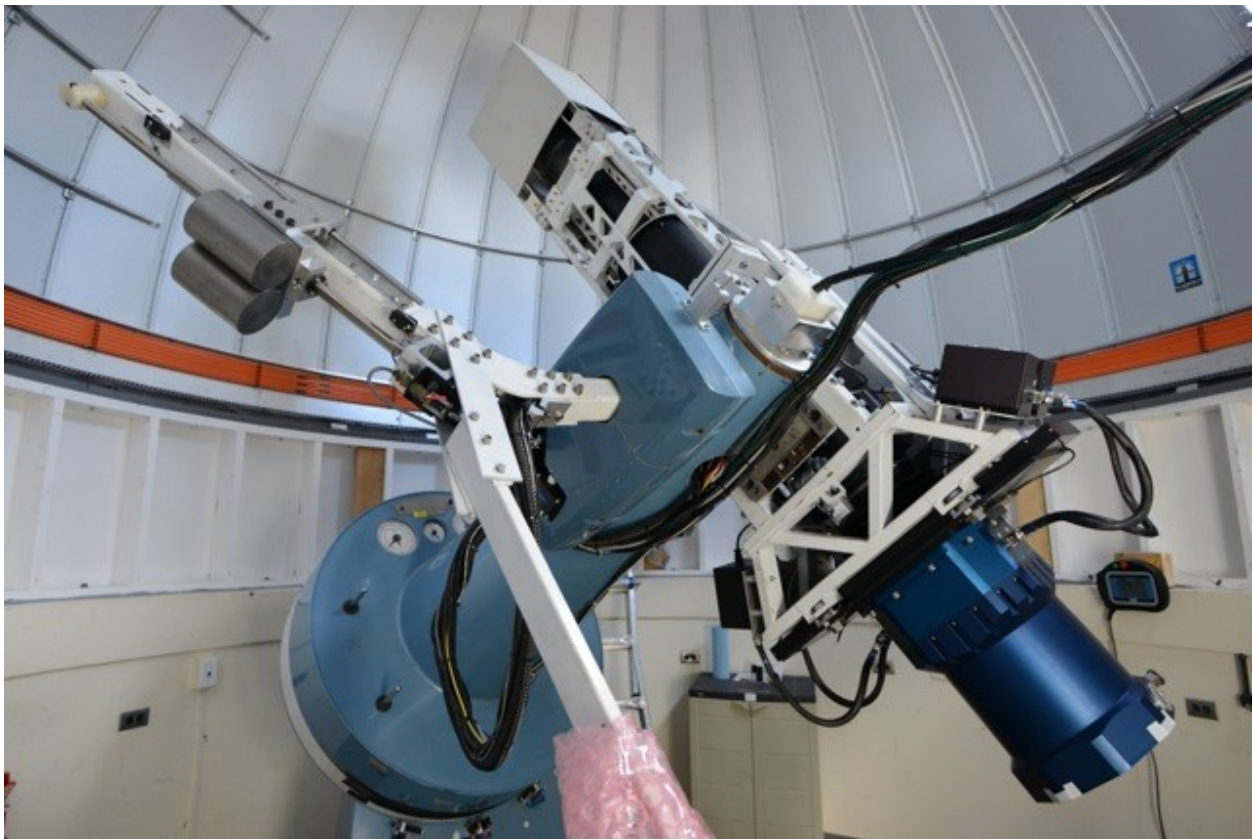


Fig. 6: *USNO Robotic Astrometric Telescope (URAT) deployed to and operating at Cerro Tololo Interamerican Observatory (CTIO) during 2017. URAT is being operating with both a full aperture grating and a neutral density spot that allows it to observe all the brightest stars in the Southern Hemisphere, up to a declination of $\sim +25^\circ$*

accurate proper motions of about 107 million stars with typical errors in the 1 to 2 mas/yr range for $R = 10$ to 15 mag, and about 5 mas/yr at $R = 16$, the limiting magnitude of the UCAC data (Zacharias, Finch & Frouard, 2017). External comparisons for selected open clusters show an improvement over currently best proper motion data in this magnitude range. The data were made public as catalog I/340 on the VizieR system at the CDS, Strasbourg and its mirror sites.

Compared to UCAC data, the TGAS data is nearly error (specifically, random and systematic) free, and was used as reference star catalog in the UCAC5 reductions. This allowed for an external error estimate of the UCAC x, y data (image centers). The UCAC data error floor thus was shown to be better than 1/100 pixel for well exposed stars.

The slight increase in errors for stars brighter than about magnitude 10 shown in the figure is due to the fact that UCAC long exposures saturate and results for those bright stars are drawn only from the short exposures. Between about magnitude 10 and 14.5 both long and short exposures contribute to the derived proper motions.

**URAT Southern Hemisphere
Bright Star Survey**

While the core of optical astrometric data for the next few decades is expected to come from the Gaia data, there are limitations with Gaia. Specifically, the Gaia focal plane physically saturates at $G=12$ under normal observing conditions. The Gaia focal plane includes “bright star modes” that allow it to get up to $G \sim 5-6$ before these modes are saturated. The Gaia DR1 results show large levels of “astrometric noise” for sources brighter than about $G=6$. The Gaia data processing team is looking at approaches to extending the Gaia results to the brightest stars in the sky, but there is currently no clear method for delivering high accuracy results for the brightest stars in the sky.

In order to address this gap in the optical reference frame, USNO has been operating the UBAD survey on its 61” (1.55 m) Strand astrometric telescope located at Flagstaff Station in Arizona for the Northern Hemisphere, and deployed the URAT 8” telescope to Cerro Tololo Inter-American Observatory (CTIO) in October 2015 (see Figure 6). URAT was modified from its Northern Hemisphere configuration by adding an ND +4.5 spot to one of the detectors, and operating in aperture grating mode (another 4.5 magnitudes of attenuation) for the entire year. Both systems (UBAD and URAT configured for bright stars) are able to observe the brightest stars in the sky (on the bright end), and Gaia stars on the faint end. During data processing and reduction, Gaia results will be used for the reference frame against which the UBAD and URAT data are located with high accuracy. In 2017 URAT observed during 293 nights. About 25 nights were lost due to a hardware issue. During 2017 a total of 64,914 exposures were taken by URAT, each about 0.9 GB (445 million pixels) in size.

It is anticipated that the bright star work will conclude in 2018 in time to supplement the Gaia DR2 catalog. At that point, an assessment will be made as to the availability of quality of the Gaia bright star data (and thus, the necessity for USNO to continue to observe and process bright stars for astrometry and photometry).

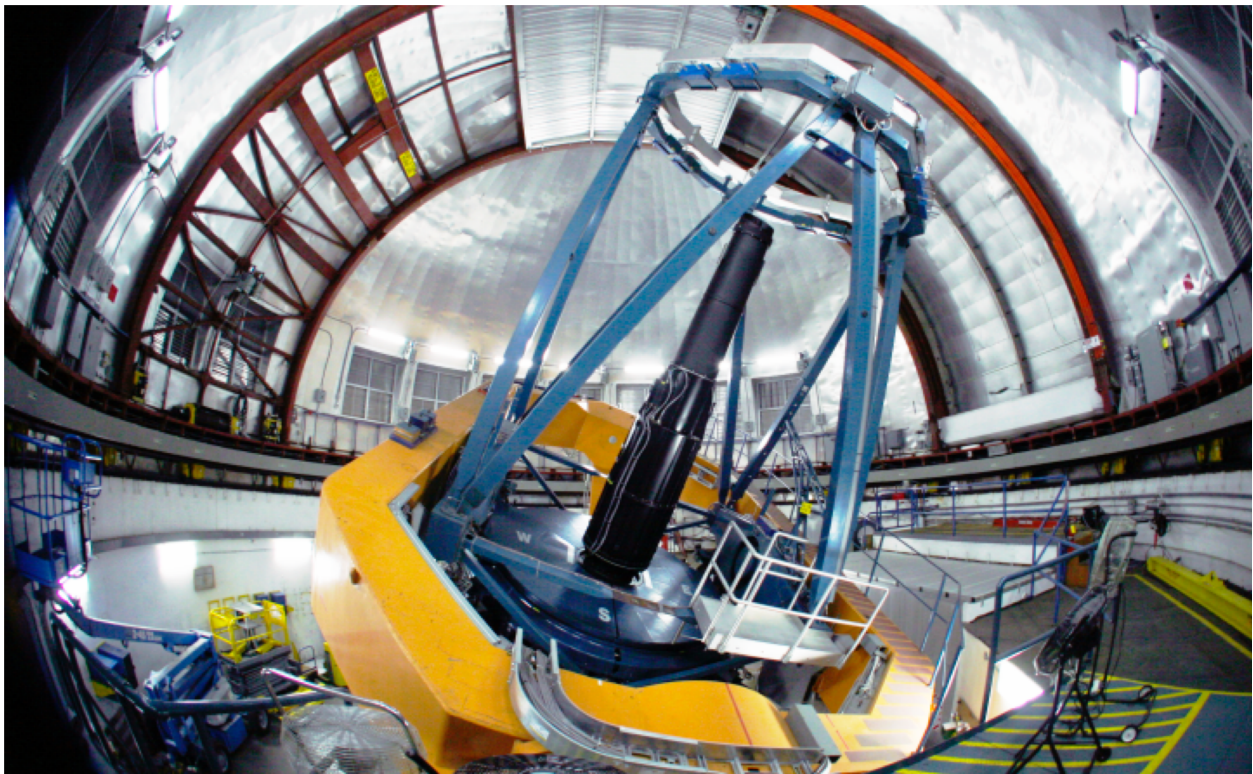


Fig. 7: An image of the 3.8m UKIRT with WFCAM installed at the forward Cassegrain focus. UKIRT, with WFCAM installed, is optimal for large area infrared surveys, yielding an impressive entendue of $\sim 2.4\text{m}^2\text{deg}^2$

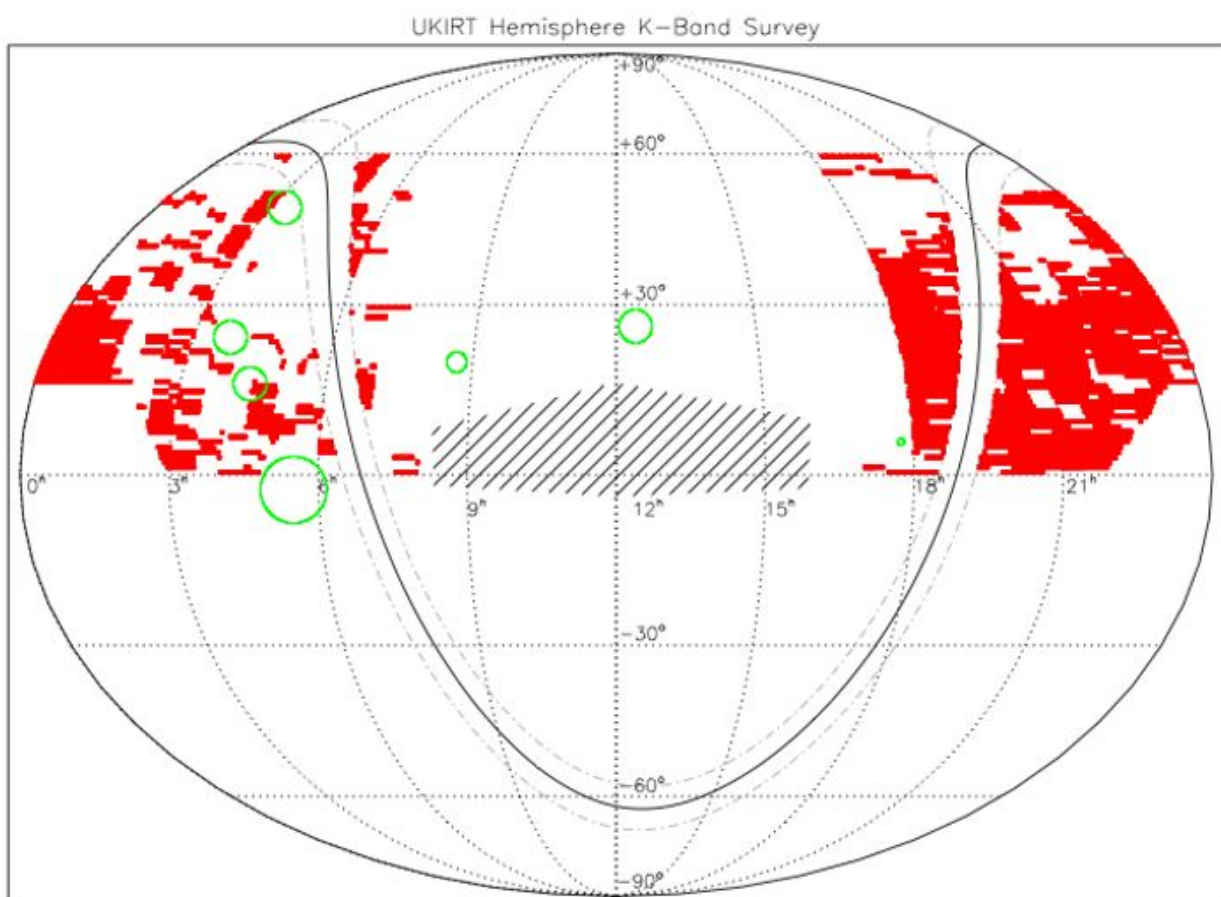


Fig. 8: UKIRT K-band survey coverage through November 2017.

USNO UKIRT K-Band Hemispherical Survey

USNO, in collaboration with the Institute for Astronomy at the University of Hawaii; the School of Physics and Astronomy, Nottingham University; Institute of Astronomy, University of Cambridge; and the Institute for Astronomy, University of Edinburgh, began a multi-year, northern hemisphere K-band survey using the UKIRT telescope, located in Hawaii on the summit of Mauna Kea (see Figure 7). When completed in the 2019/2020 timeframe, this K-band survey will provide a catalog down to below 18th magnitude that complements the VISTA Hemisphere Survey in the southern hemisphere (McMahon, 2013). When combined with the H-band UKIRT survey (Dye, 2018), the K-band data will provide deep photometric and astrometric data for two of the three standard Near IR (NIR) astronomical photometry bands. Figure 8 shows the progress of the survey through November 2017. When incorporating K-band data from earlier, directed surveys, approximately 30% of the northern sky had been completed through the end of 2017.

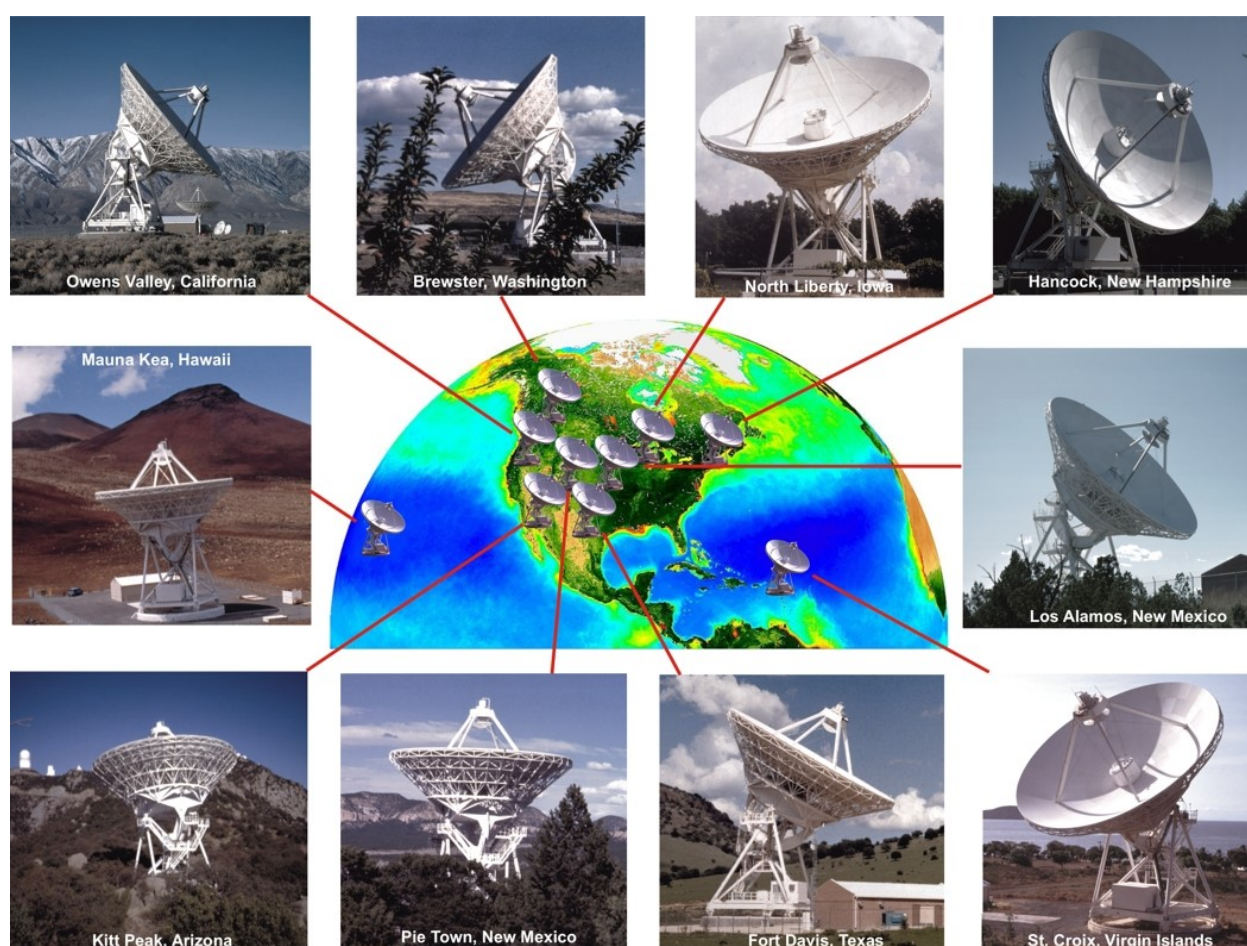


Fig. 9: The Very Long Baseline Array (VLBA) sites span the US from Hawaii in the west to the Virgin Islands in the East.

USNO 50% timeshare of the Very Long Baseline Array (VLBA)

Beginning in 2017, USNO provided funding for and was allocated 50% of the observing time on the Very Long Baseline Array (VLBA) (see Figure 9). The VLBA is an array of ten homogenous 25 m radio telescopes deployed across the United States from Hawaii in the west, to the Virgin Islands in the east, that are operated as an interferometric array. VLBA is operated by the Long Baseline Observatory (LBO) under cooperative agreement with the National Science Foundation (NSF). Working directly with LBO personnel, USNO provided monthly scheduling requests for VLBA time to support a wide variety of USNO mission and research areas. These included geodesy, Earth orientation parameter and celestial reference frame observations and measurements. Specifically, over the course of the year, USNO allocated significant S/X observing and K-band observing time to support development of the ICRF3, and also supported CONT17, an intensive geodesy observing campaign involving numerous radio telescopes around the world. It is expected that VLBA observing time scheduled via USNO will enable significant enhancements to the accuracy, the anticipated multi-wavelength nature, and the total number of sources for the ICRF3 when released in 2018.

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