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Influence of the dynamic classification of asteroids on observation astrometric errors: a statistical analysis

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ABSTRACT
The ephemerides of minor planets are computed on the basis of astrometric observations. The asteroid Orbit Determination process requires these observations to be properly weighted to take into account the expected accuracy of the data. If not directly provided by the observers, the weights are, in general, computed after a station-specific statistical analysis on the observation residuals, where the influence of external factors such as epoch of observation, magnitude and employed catalogue has been proven. In this paper we perform a statistical analysis on observation residuals of the major surveys taking into account a new factor, i.e. the dynamical classification of asteroids, to understand if the observation quality may have a dependency on the different type of observed object. If an influence is actually found, then it will be possible to develop a new weighting system based on these results. The weights will be easily applicable once one knows the asteroid orbit. In particular, four stations have been found having different quality depending on whether they are observing Near-Earth Asteroids (NEAs) or Main Belt Asteroids (MBAs). Moreover, the cross-correlation between the dynamic classification and epoch, magnitude, catalogue is investigated, as well as the influence of these factors on observations quality.

Key words: Asteroids – Astrometry – Catalogues – Methods: statistical – Surveys

1 INTRODUCTION

More than 1.2 million asteroids have currently been discovered thanks to increasing dedicated observation campaigns and technical improvements in the equipments such as CCD cameras and automatic surveillance pipelines. Moreover, it is thanks to the available observations for each of the detected objects that it is possible to define their orbits and trajectories, leading to accurate predictions of the positions of minor planets in future epochs.

The asteroid Orbit Determination (OD) process, indeed, integrates all the available astrometric points through numerical algorithms to compute the minor planets orbits. In particular, the trajectory is obtained solving a least-square problem in the osculating orbital elements, in which the proper dynamic model is considered and each observation is weighted to take into account the expected accuracy of the data.

The reason for the need of a weighting system is the presence of errors in measures, and how they are made and processed, that lead to uncertainties in the results of the OD process. These are in general due to factors such as the quality of astrometric catalogues, employed for the determination of the asteroids' positions in the sky, the stations responsible for carrying out the measurement or physical parameters of the observing objects.

The errors introduced by the catalogues have been been significantly reduced thanks to the introduction of more recent and accurate reference star catalogues such as 2MASS and Gaia DR2. Moreover, methods to debias old observations reduced with old and less reliable catalogues, referring them to the new ones, have been proposed and applied (Farnocchia et al. 2015; Eggl et al. 2020), leading to a subsequent general improvement of previous observations too.

If it is possible to say that the errors due to the star catalogues are, at the state of the art, under control, thanks to the quality of the most recent ones, the same can not be said for the uncertainties introduced by the observing stations themselves. These are responsible for the quality of the instruments such as telescopes, the seeing of the station, the resolutions both spatial and temporal, the adopted working procedures, the number of observations performed per night, the errors due to human operators. Moreover, also other factors can create more or less biases and decrease the accuracy of the measure such as the magnitude and the motion rate of the object.

It has been shown that the distribution of these errors, either of random or systematic origin, does not follow a Gaussian distribution in agreement with the Central Limit Theorem (Carpino et al. 2003). Furthermore, for most observations performed before the introduction of the ADES astrometric format in 2015, information on the accuracy adopted in time and angular quantities are in general not available.

Due to this lack of a-priori information on the measurement quality, a weighting system based on the expected accuracy of the single observation has been introduced to account for the quality of the integrated data. Indeed each observation, in the solution of the least-square method, has its own weight, which is based on the overall performance of the single observatories (Chesley et al. 2010; Farnocchia et al. 2015). These weights are computed taking as a parameter the Root Mean Square (RMS) of the Observed-Computed (O-C) residuals of the observations made earlier by the same station. It is clear

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how the computation of these weights requires the statistical treatment of a high amount of data, i.e. observations residuals, as per the probabilistic approach to the matter.

The idea under a station-specific weighting scheme is that the equipment, the technical precision, the methodology change station by station and must be considered when assessing the quality of any current or future observations. However, it has soon became clear that, within the same station, other factors exist that can vary the quality of the observations, and that should be accounted in the computation of the weights in order to achieve better results in the OD process. The effects of the epoch of observation, the light curve of the object, the motion rate have been statistically analysed (Vereš et al. 2017) and some of these introduced in the current weighting scheme. Again, the idea is that, speaking of the epoch, over the time, some improvements both technical and to star catalogues, while the physical parameters of the asteroids are expected to have an influence on the observation performance.

In this framework, the aim of this paper is to introduce the study of a dynamic classification of asteroids as a possible parameter to be considered to further enhance the observations weighting scheme.

1.1 Influence of asteroids dynamic classification on observation quality

The Solar System minor planets are divided into three dynamical macro-classes, i.e. Near-Earth Asteroids (NEAs), Main Belt Asteroids (MBAs), Trans-Neptunian Objects (TNOs), and it is possible to state that objects belonging to each one of these families have different characteristics when observed from planet Earth. The magnitude, the number of oppositions, the motion rate are in general different class by class and it is already known that these parameters can influence the observation quality. Also the observing techniques and procedures sometimes change, within the same stations, when dealing with asteroids of one or another class, as in the case of the observatories particularly focused on NEAs, like the *NEO follow-ups*. It is not rare that they manually remeasure with particular care a NEA when it is detected by the automated pipeline, with the aim of providing the astrometric data with the highest accuracy for this class of objects.

In light of these facts, studying the statistics on residuals divided on the basis of the asteroid dynamic classification, is not the same as analysing the impact of factors as magnitude or rate of motion individually, as done in previous works. Considering the residuals for the distinct classes of NEAs or MBAs allows us to consider also other influencing factors of different nature. Then, in case an influence on the residuals is actually found, it will be possible to develop a weighting system that can mitigate this bias and that is only based on the dynamic class. This direct dependency would make the weights relatively easy to be applied to the observations once the orbit of an asteroid is determined, rather than, for instance, considering for any observation the rate of motion or the magnitude, factors that are not even included in the current weighting scheme.

To analyse this influence, the asteroids and their observations are clustered following these dynamic classes and the observation residuals are statistically studied in order to understand if an effect exists. This study will consider the observation performance of the most productive asteroid surveys towards the already mentioned dynamic classes, following the baseline presented in a previous work (Vereš et al. 2017), including also data from four stations that were not considered there. The effects of observation epoch, magnitude and catalogue used for the astrometric reduction on the obtained results will be analysed too.

The structure of this paper can be summarised as follows: in Section 2 a description of how the data are selected and gathered is provided; the results of the RMS analysis is presented in Section 3; Section 4 introduces the influence of other factors such as epoch of observation, magnitude and catalogue.

2 DATA GATHERING

The Minor Planet Center orbit (MPCORB) database[1] included more than 1.2 million asteroids as of January 2023, 619 999 of which numbered. The observations of most of these bodies can be collected from the ESA's Near-Earth Objects Coordination Centr (NEOCC)[2] database, where the .rwo files containing the observations per each object are available. These files list, in each line, the provided observations and it is possible to extrapolate data on the time when it has been taken, the two angular positions RA and DEC and the MPC code of the station. These alphanumeric strings uniquely identify each observatory, and in the following sections they will be used to address the stations for the sake of brevity[3].

The lines contain also the (O-C) residuals in RA and DEC, where the *computed* trajectory is provided by the ESA's NEOCC OD pipeline (Cano et al. 2019) that applies the most suitable dynamical model and an outlier rejection algorithm. These values are used to perform the analyses on RMS values.

As already said, the asteroids are divided in dynamical families for the statistical studies. The classification in NEAs, MBAs and TNOs is made comparing the perihelion q of the computed orbit. Although fixed boundaries establishing if an asteroid belongs to a class or another have never been objectively defined, we divide the minor planets upon the following conditions: NEA if $q < 1.3$ au, MBA if q is between 1.78 and 5 au, TNO if $q > 30$ au.

Furthermore, the asteroids have also been filtered on the basis of the number of oppositions for which they have been observed. The interest in having a reasonably high number of oppositions is that in such a way the astrometric points are more spaced in time and the OD is more likely to provide reliable results, making the RMS statistics more significant. That is why only asteroids with strictly more than 2 oppositions have been considered, allowing us to study the residuals for both numbered and many non-numbered minor planets.

2.1 RMS computation

The 17 analysed stations are listed in the first column of Table 1 and are responsible, overall, for the production of more than 80% of the whole amount of observations. For each of these surveys the residuals are collected from the NEOCC database as of January 2023 and the RMS of residuals are computed dividing the data not only by station but also by class of asteroid. The results are shown in Table 1 together with the total number of observations N used to compute the statistics.

The total number of available astrometric data provides information on the statistical degree of confidence of the analysis and on the data distribution in the three asteroid classes. From it, MBAs turn out to have a higher availability of data, due to the fact that MBAs are more present in the Solar System, with almost 92% of asteroids

[1] https://minorplanetcenter.net/iau/MPCORB.html
[2] https://neo.ssa.esa.int/
[3] https://minorplanetcenter.net/iau/lists/ObsCodesF.html

Table 1. RMS of the residuals in RA and DEC for 17 of the most productive surveys subdivided among the different asteroids macro-families. The number of available observations for each station for each class of asteroid is shown.

Obs code	NEAs			MBAs			TNOs		
	RMS_{RA} ($''$)	RMS_{DEC} ($''$)	N. obs	RMS_{RA} ($''$)	RMS_{DEC} ($''$)	N. obs	RMS_{RA} ($''$)	RMS_{DEC} ($''$)	N. obs
704	0.62	0.61	98 059	0.65	0.65	30 972 048	0.22	0.31	8
G96	0.29	0.27	124 120	0.29	0.27	56 769 122	0.32	0.32	72
F51	0.12	0.12	110 009	0.10	0.10	55 106 503	0.13	0.13	84 201
F52	0.11	0.11	36 608	0.10	0.10	17 862 574	0.11	0.11	5 988
703	0.59	0.55	141 209	0.63	0.59	32 115 514	0.82	0.62	11
691	0.44	0.40	30 272	0.35	0.28	13 366 691	0.56	0.54	315
G45	0.33	0.33	30 167	0.34	0.35	16 318 465	0.35	0.45	176
699	0.60	0.55	10 613	0.61	0.56	5 082 880	N/A	N/A	0
644	0.34	0.40	9 985	0.28	0.35	3 786 679	0.35	0.36	816
D29	0.40	0.38	18 819	0.41	0.40	10 885 377	0.46	0.44	1 311
C51	0.53	0.57	40 524	0.60	0.68	3 403 771	N/A	N/A	0
E12	0.38	0.39	14 564	0.47	0.50	2 085 989	N/A	N/A	0
608	0.59	0.65	5 385	0.59	0.72	1 147 931	0.38	0.39	85
J75	0.41	0.38	2 051	0.42	0.40	1 112 119	N/A	N/A	0
I41	0.31	0.27	34 232	0.21	0.15	13 707 787	0.13	0.11	739
T05	0.31	0.31	83 962	0.34	0.34	20 556 412	0.27	0.26	2 141
T08	0.32	0.33	90 321	0.35	0.36	22 261 667	0.30	0.32	2 780

belonging to this class[4], and that they can benefit of more oppositions from Earth.

The opposite should be said about TNOs for which a very low number of astrometric data is available. There are even five stations (699, C51, E12, J75), mostly characterised by small-aperture telescopes, that have never reported observations of a TNO, while the most productive survey in this sense is F51 with more than 80000 observations provided. For it, and given a general low availability of data on TNOs, it has been decided not to further analyse the statistics for these objects.

3 STATISTICAL ANALYSIS OF RMS RESULTS

From the RMS values reported in Table 1 and represented also in Figure 1 one can see the global measure accuracy of the 17 stations towards the two considered asteroid classes: MBAs and NEAs.

First of all it is possible to compare the observation quality of the stations, from which it stands out that those with the lower RMS level are F51 and F52, the two Pan-STARRS stations on Haleakala. The similarity in the observation quality between these two surveys is not surprising as they share the same location, instruments, equipment, searching algorithms. However, F52 has a slightly lower RMS value, due to the subsequent installation with respect to F51, so that its findings have led to improvements in F52 equipment (Wainscoat 2016).

If we then focus our attention on the differences standing between NEAs and MBAs observations, it is possible to see that they are in general small enough to be considered within the signal noise. The stations that in this sense show the smallest gap, lower than $0.08''$, are G96 (Mt. Lemmon Survey) and F52 (Pan-STARRS 2, Haleakala). However, there are also four observatories that have high differences in the RMS of residuals in both RA and DEC.

E12 (Siding Spring Survey) and C51 (WISE) have low RMS on NEAs measures while I41 (Palomar Mountain) has a better accuracy for MBAs. This could be explained by the scopes and working procedures of these three stations. The operators of E12, which is currently no longer in operation, were used to manually reprocess and remeasure NEAs detection, fact that could have caused the higher precision on NEAs data. In a similar way C51, named WISE (Wide-field Infrared Survey Explorer), has since 2013, with the introduction of the NASA mission Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE), the target of providing NEAs observations. This effort, again, could explain the better accuracy for this particular class of objects. I41, instead, has a lower RMS on MBAs data. Since I41 is not a station purely dedicated to asteroids observations (Dekany et al. 2020) it might be reasonable to think that the detection of a relatively faster moving object like a NEA could lead to a worse accuracy.

The same better quality on MBAs data has been found also for 691 (Steward Observatory, Kitt Peak-Spacewatch), which is a productive survey still operating since 1984. For this station a deeper statistical analysis on the residuals is presented below to further investigate the reasons for the discrepancy on observation quality.

3.1 Statistics on astrometric data from 691 (Steward Observatory, Kitt Peak-Spacewatch)

In this section a deeper statistical analysis on the residuals provided by station 691 is presented in order to interpret the differences in the RMS levels between NEAs and MBAs.

In Figure 2 the histograms of the error distributions in RA and DEC are shown, superimposing the bar charts for MBAs and NEAs for each of the two angular quantities. The curves representing the normal Gaussian distributions, plotted on the basis of the mean and standard deviation values listed in Table 2, are represented for comparison. Both the histograms and the Gaussian curves have been normalised according to the definition of probability density function (pdf).

From Table 2 is easy to see that the average of the residuals is different from zero, as it would be expected in case of an ideal Gaussian distribution dominated just by random errors. It has already been discussed how also other external and perhaps systematic factors can affect the observations, contributing to a non-zero average of

[4] https://minorplanetcenter.net/mpc/summary

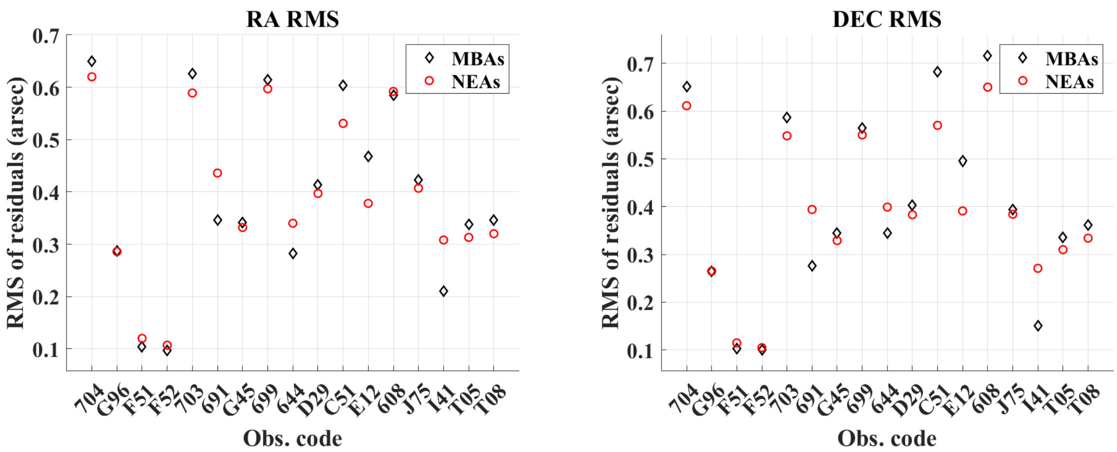

Figure 1. RMS of resdiuals in RA (left panel) and DEC (right panel) for all the stations, considering the values for NEAs and MBAs

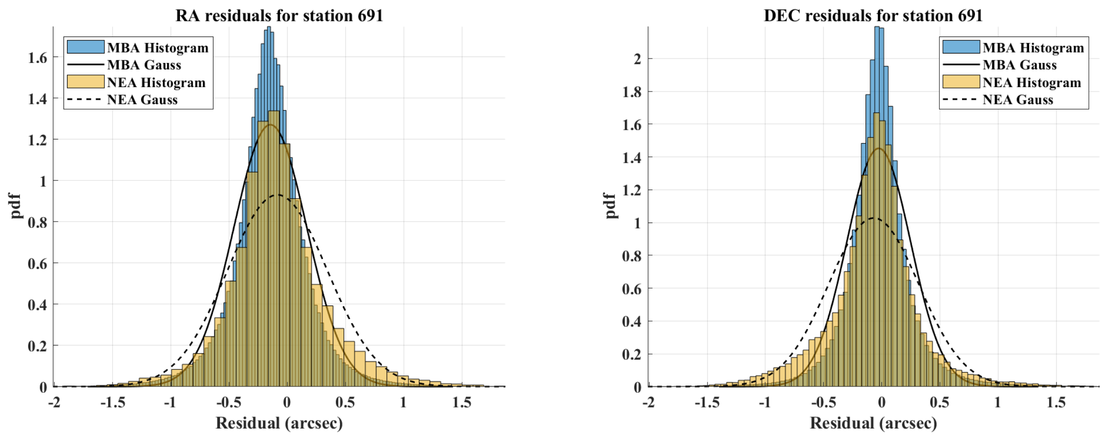

Figure 2. Probability density function (pdf) of the distribution of the residuals for station 691 in Right Ascension (left panel) and Declination (right panel). The histogram and the Gaussian Normal Distribution are represented superimposed for the residuals of MBAs and NEAs observations distinctly.

Table 2. Average ($\overline{res}$) and standard deviation (σ) of the astrometric data available for station 691 in RA and DEC, divided between MBAs and NEAs.

Ast. Class	$\overline{res}_{RA}$ ($''$)	σ_{RA} ($''$)	$\overline{res}_{DEC}$ ($''$)	σ_{DEC} ($''$)
MBA	−0.15	0.31	−0.026	0.27
NEA	−0.085	0.43	−0.069	0.39

errors, which can be seen as the global bias of the station. This bias seems to be overall smaller for the DEC measures if compared to those in RA. However, the standard deviations of the four cases are similar to the RMS values for this station (Table 1), which is typical of data sets with zero or, as in this case, almost-zero averages.

The non compliance to the Gaussian behaviour of the errors can also be deduced by comparing the histograms to the relative ideal Gaussian curves. The concentration of values in the central bins of the plot and the asymmetric tails suggest once again the presence of systematic biases in the observations.

The bias of the station can be numerically evaluated though the ($\overline{res}\,/\,RMS$) ratio, that can be computed for both the asteroid classes and the two angular quantities. For NEAs it is −0.20 in RA and −0.18 in DEC while for MBAs −0.42 in RA and −0.25 in DEC.

These results lead to the conclusion that 691 achieves, statistically speaking, in general a better accuracy for NEAs observations and a higher precision (smaller standard deviation) for MBAs data. These behaviour might by explained by the working procedures or the technical equipment that may have difficulties in providing the same precision for both the dynamical classes.

4 INFLUENCE OF OTHER FACTORS

Observation accuracy has been proved to be affected by many factors (Vereš et al. 2017), such as the epoch of the measure, the magnitude, the catalogue used. In this section, in addition to confirming the outcomes already presented in previous works as a secondary scope, adding information that became available recently especially with reference to observation years and adopted catalogues, a correlation is searched between these factors and the asteroids classification.

4.1 Dependency on the observation epoch

In Figures 3 and 4 the RMS of residuals over the years up to 2022 are plotted, highlighting the values for RA and DEC and for MBAs and NEAs. In the following graphs, also the error bars for RMS values (Faber 1999) are represented, in order to indicate the statistical degree of accuracy of the values. It is especially important to understand whether, when a RMS is anomalously high or low, it is due to actually data accuracy or low data availability in that particular bin.

The behaviours highlighted in Fig. 1 are here generally confirmed: the stations that had an overall better accuracy for one of the two classes of asteroids show the same trend in these plots for almost all the period of observation. These are the cases of the already analysed E12, C51, I41, 691.

C51 (Fig. 4b) has always provided an overall better accuracy for NEO in both the measured quantities, though it experienced a worsening of RMS between 2020 and 2021 for this class of asteroids, fact that might be connected with the approaching end of life of the spacecraft.

E12 case (Fig. 4c) is similar, but it is evident from the graph that it is no more in operation since the last available data are from 2013. However, it also shows that from 2005 on the RMS values for MBAs and NEAs started showing very different trends, with clear better performance on NEAs observations.

Also I41 (Fig. 4f) shows a similar behaviour. It started producing a high number of NEAs observations, more than 1000 per year, since 2018, approximately when the survey definitely changed denomination and equipment from Palomar Transient Factory (PTF) to Zwicky Transient Facility (ZTF) (Dekany et al. 2020; Bellm et al. 2019), although the RMS values shown on the graph have an oscillating behaviour. The accuracy for these objects has been relatively low if compared to that for MBAs, but it is evident how the RMS values for NEAs started lowering in 2021, rapidly reaching the same accuracy as Main Belters, probably also thanks to new automated pipelines introduced for the observation of NEAs (Duev et al. 2019; Mahabal et al. 2019).

691 (Fig. 3e) ensures a better accuracy for MBAs during almost all the period of observation. Also in this case the oscillations from 1984 to 1990 could be affected by the low number of astrometric measures produced during that period of time, when also no observations for MBAs have been registered for year 1990. Moving to more recent epochs, more clearly shown in the detailed graph 3f, although one can see that this station has overall better performances for MBAs, some improvements are highlighted in the observations of NEAs starting from 2010. This may lead to the same RMS value for the two classes of asteroids in future, since it is also evident that from 2018 the RMS_{RA} for NEAs are constantly lower than those for MBAs.

All the stations but the already discussed E12, show the same trends over the years for both MBAs and NEAs, meaning that, also for those stations that have an accuracy gap based on the asteroids classes, the eventual improvements in the observation pipeline are implemented regardless of the measured object. These changes may reasonably be due to technological improvements or the adoption of new catalogues and in general it is possible to assess a better data quality as time passes.

4.2 Dependency on the magnitude

Figures 5 and 6 illustrate the trend of the RMS of residuals over the magnitude of the observed objects, always subdivided between NEAs and MBAs. To compute the graphs the collected astrometric data have been gathered in bins wide 0.4 units of magnitude from a minimum of 10 to a maximum of 24. All the values have been corrected in order to indicate a magnitude in band V. To try to reduce the visualization of outliers, bins containing less than 40 observations have not been plotted.

In general, for all the stations and for both the asteroid classes the curves follow the same trend according to which the fainter objects, characterised by an higher magnitude value, have a worse accuracy. However, also low magnitudes in most of the cases lead to greater RMS values due to the fact that too bright objects tend to saturate the detector and so worsen the quality of the astrometric data (Vereš et al. 2017).

With respect to the differences between the two asteroid classes, it appears that NEAs are observed in a narrower magnitude range with respect to MBAs. It is indeed rare for a station to observe a Near-Earth Object brighter than mag = 14 and fainter than mag = 22, for reasons related to to the limits imposed by NEAs physical characteristics. Observations of bright NEAs are rarer than MBAs, and the higher motion rate makes it difficult to detect faint NEAs for most of the stations.

In general, the measure of magnitude seems to be less conditioned by the type of observed asteroid. Also for C51, MBAs and NEAs have the same behaviour (Fig. 6a), even if for this survey some considerations on the magnitude must be done.

WISE is an orbiting telescope that provides thermal infrared and not optical observations, which leads to a difference in the definition of the magnitude perceived by this station. In fact, it is not comparable to the *optical* one derived just from the brightness of the object, but also from other parameters such as heat and reflectance. Moreover, WISE way of reporting magnitude data for their astrometric points has been object of dispute (Myhrvold 2018; Myhrvold et al. 2022), also due to the presence of bias and systematic errors. It is also interesting to notice that just 6% of NEAs observations and 3.5% of MBAs observations have a magnitude value reported, and always characterised by an integer value. These reasons in particular make the graph relative to WISE magnitude performance not comparable with the other results, but has been reported for the sake of completeness.

For the other three surveys that had a high sensibility on the asteroid class, the situation is instead that for 691 the accuracy, with the same magnitude, is better for Main Belters on the whole range, as expected. This is verified also for I41, which, however, shows the same RMS level at higher magnitudes. E12 behaves better with NEAs on all the range.

4.3 Dependency on the catalogues

The two angular quantities that describe the position of celestial objects are measured with respect to a set of reference stars, which positions are known thanks to proper star catalogues. Relying on accurate catalogues to perform the astrometric data reduction is crucial as they may introduce biases that can affect the goodness of the measure. Previous studies have dealt with the analysis and correction of systematic errors introduced by these catalogues, and the aim of this section is to verify if a residual bias has remained following the corrections applied in the considered data. Furthermore, the whole analysis can help to assess whether a correlation between catalogues and asteroid class exists and if the accuracy of the catalogues are independent or not from the performance of the station.

Many factors can determine the accuracy of a catalogue. In general, those that are space based, i.e. not affected by atmospheric refraction and with a higher star density, are likely to guarantee a better accuracy. Also more recent catalogues tend to ensure a better quality than the old ones, as it happened with the second release of Gaia catalogue (Gaia-DR2) (Gaia Collaboration et al. 2018), which since its introduction in 2018 increased the accuracy of astrometric observations. This catalogue's major improvement is the addition of

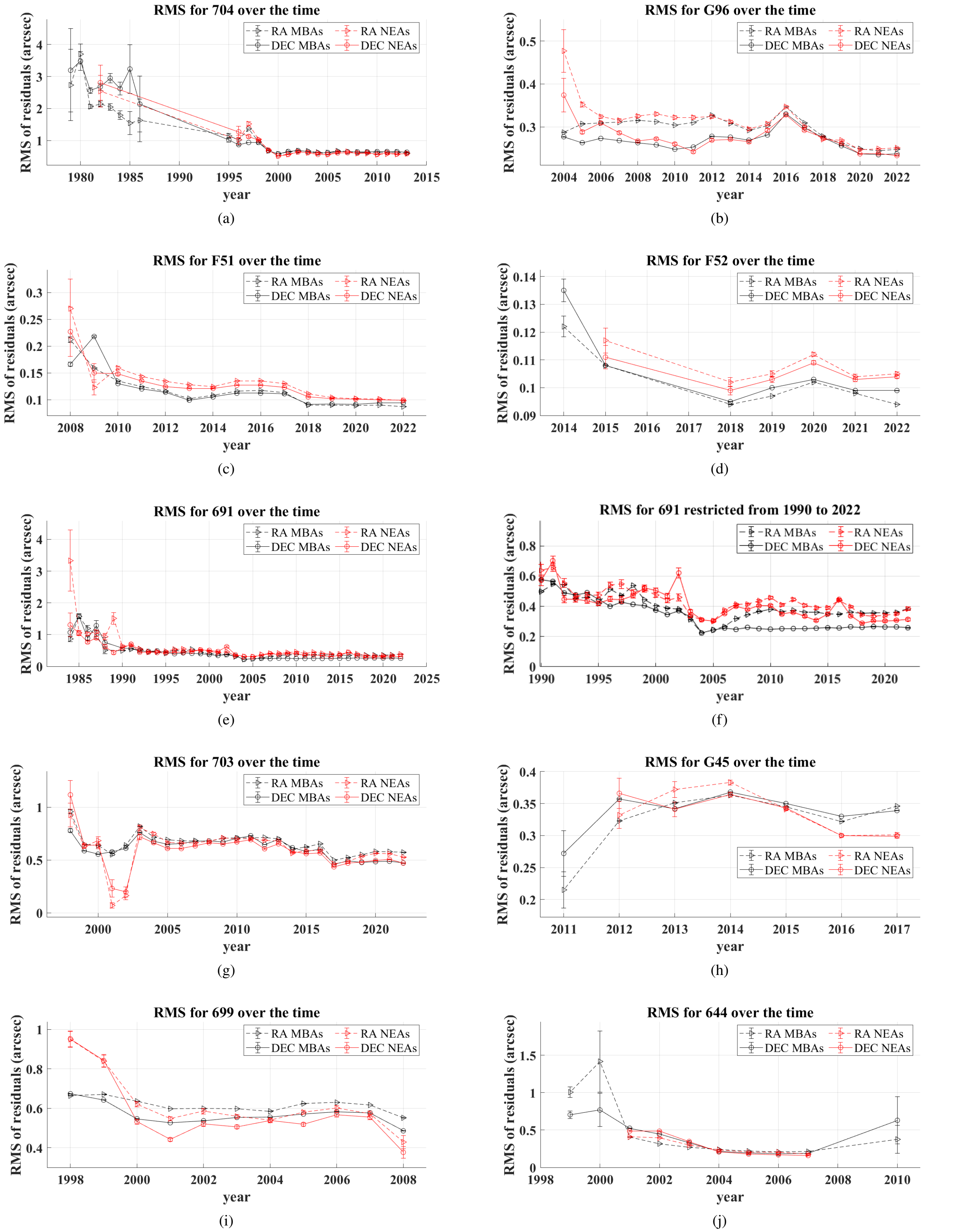

Figure 3. RMS of residuals over the years of observation for the considered stations. The plots for Main Belters and Near-Earth asteroids are plotted differentiating between the residuals for Right Ascension and Declination.

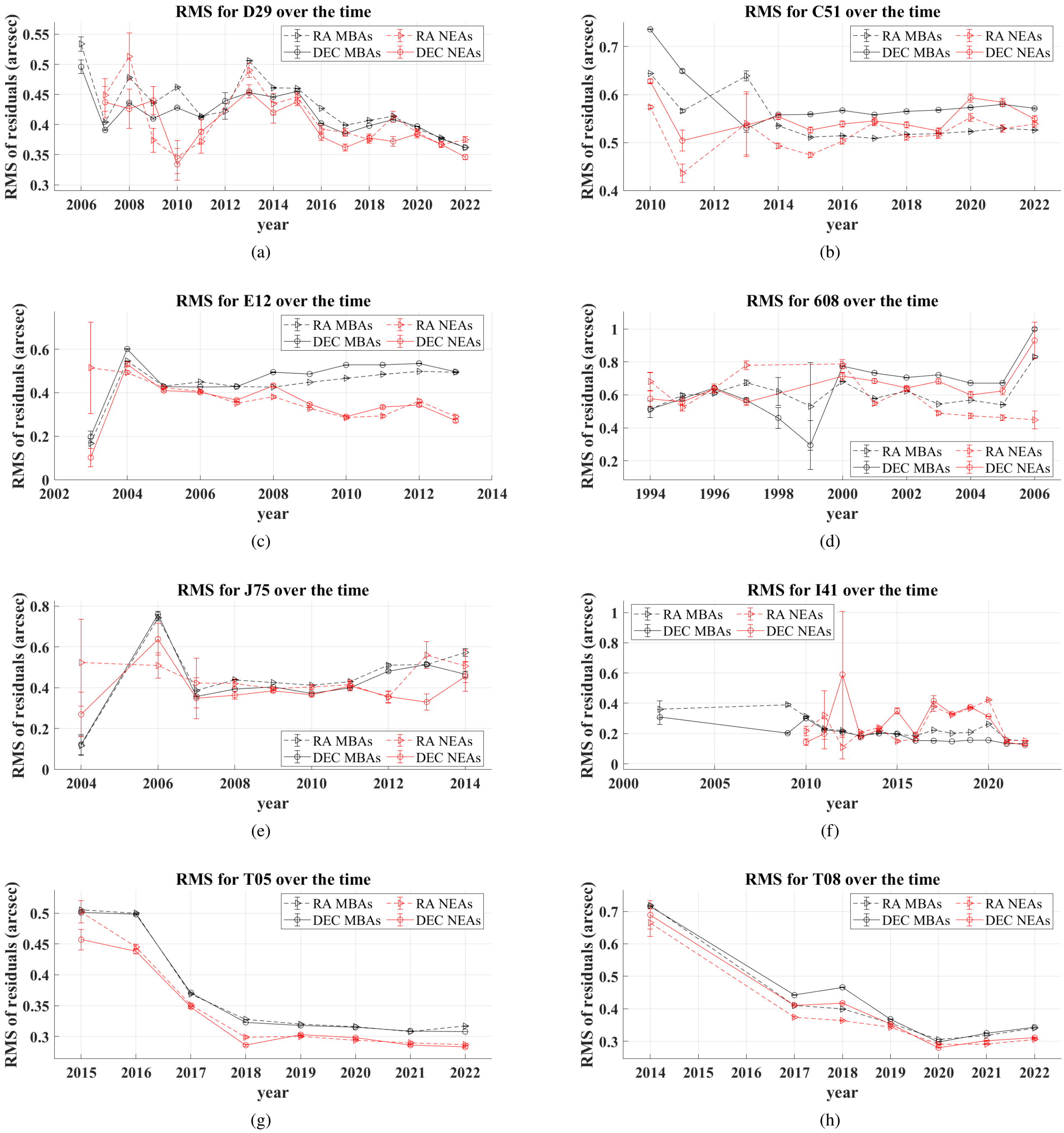

Figure 4. RMS of residuals over the years of observation for the considered stations. The plots for Main Belters and Near-Earth asteroids are plotted differentiating between the residuals for Right Ascension and Declination.

proper motions for more than 1 billion stars, which lowered catalogue errors by allowing observers to use stellar positions for the epochs of their observations. Proper motions will of course be present in all subsequent versions of Gaia, starting from the recently released Gaia-DR3 (Gaia Collaboration et al. 2022).

From the analysis of the astrometric data, it is possible to know the nine most used catalogues for the reduction of both MBAs and NEAs, listed in Table 3 in descending order. The name of the catalogue, the identification code and the number of observations related to the given catalogue are also shown.

These catalogues have been used to reduce, according to the data, more than 98.8% of the total observations, leaving the remaining to other less represented ones.

The most used is Gaia-DR2, followed by its first release, for both MBAs and NEAs. Then, 2MASS and USNO-A 2.0 mark a big gap with the remaining catalogues on the list.

Similarly to the previous sections, Figures 7 and 8 show the RMS of residuals for the given stations again divided in MBAs and NEAs. In the graphs only those catalogues that, for each station, provide more than 1‰ of the observations provided by the catalogue which

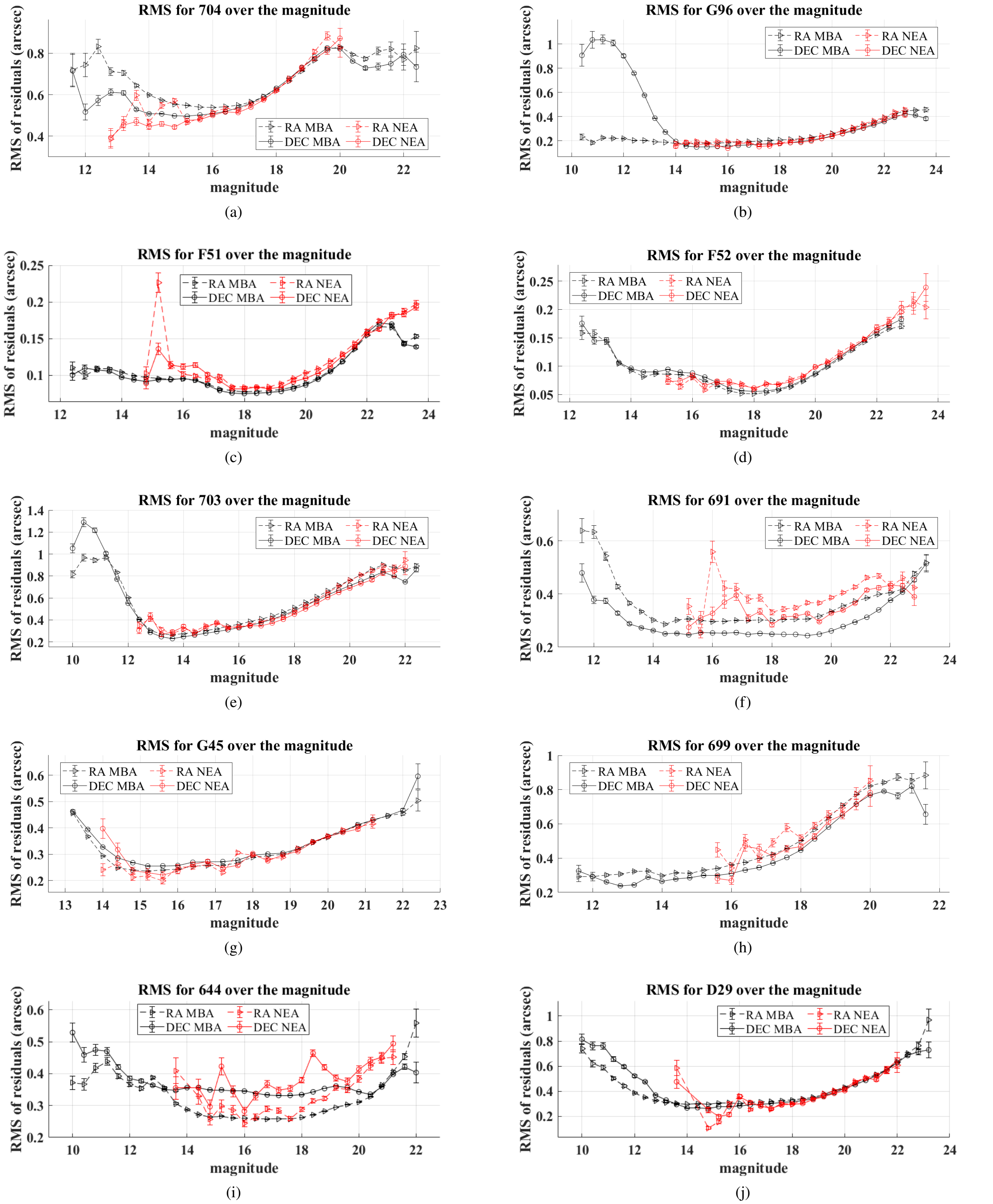

Figure 5. RMS of residuals over the magnitudes of observation. The plots for Main Belters and Near-Earth asteroids are plotted differentiating between the residuals for Right Ascension and Declination.

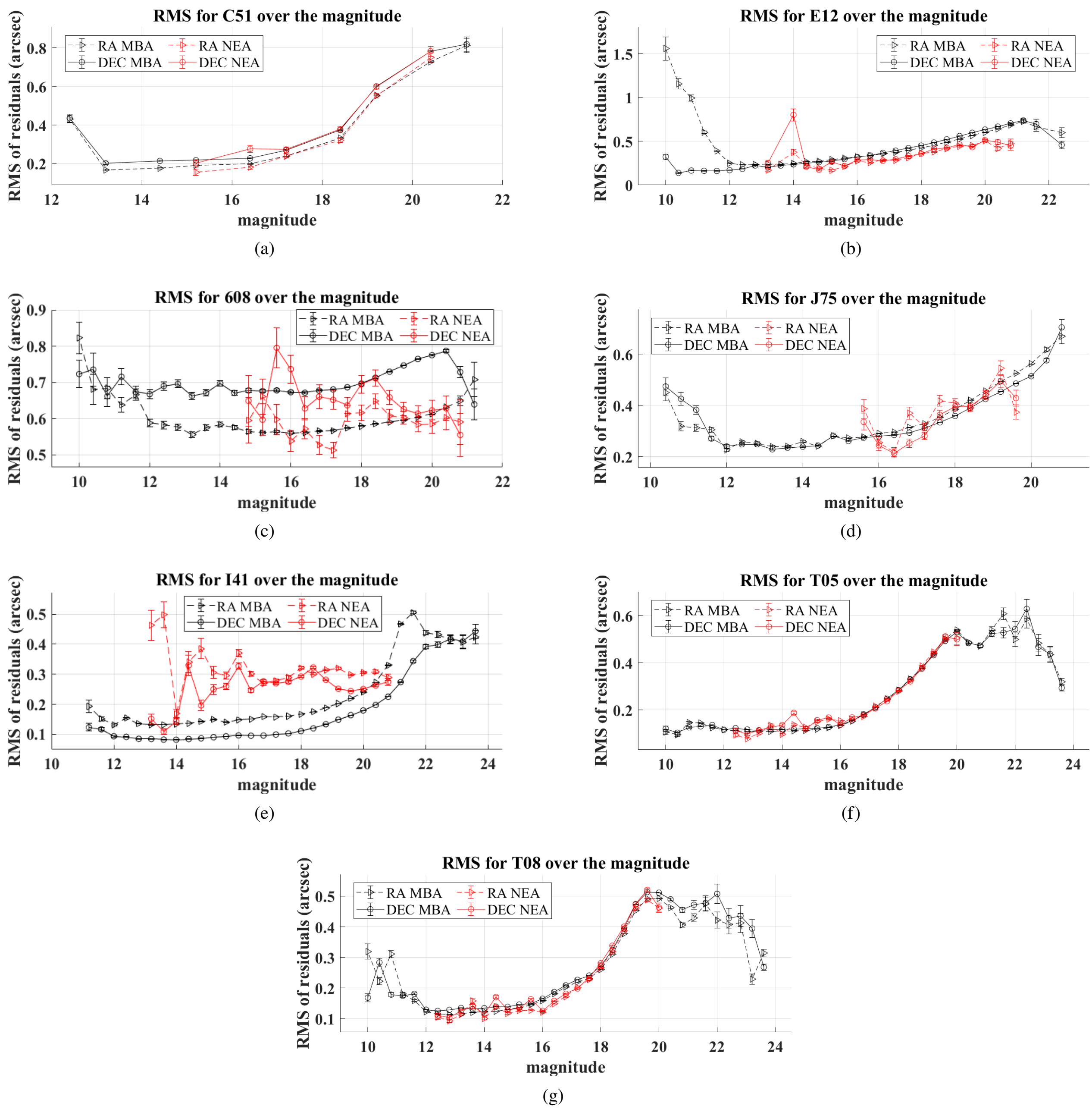

Figure 6. RMS of residuals over the magnitudes of observation. The plots for Main Belters and Near-Earth asteroids are plotted differentiating between the residuals for Right Ascension and Declination.

provides the highest number of observations are represented to avoid outliers.

The plots describe pretty well the level of accuracy of the catalogues. *U* and *V* (Gaia-DR1 and DR2) seem in general to have the lowest RMS levels, even if, as expected, the actual performance depend on the stations and the number of observations available for the two catalogues. As an example, F51 and F52 have a higher accuracy with *U* (Gaia-DR1) while G96 with *V* (Gaia-DR2), but this happens just because the first ones have much more observations reduced with Gaia-DR1, and probably kept, historically, this catalogue for their reduction and improved their performance with it.

One can also see that, while most of the catalogues have the same accuracy regardless of the station, a few of them show a dependency on it, such as *L* (2MASS), that has low RMS when used by F51 and F52, with a considerable number of observations, but behaves worse with T05, T08, C51 just to name a few. This implies that a statistics on the performance and accuracy of the catalogues, and studies on the biases and systematic errors derived by them, must not neglect the dependency on the station, on how the astrometric data are collected and treated.

It is also true, in fact, that these graphs can not highlight the performance of the catalogue alone, but of the station as a whole. The observations are, in general, characterised by an error which is the sum of several sources of error of different magnitude. One of these could be, if not corrected at the source, the intrinsic bias of the catalogue, that, however, is expected to have the same precision

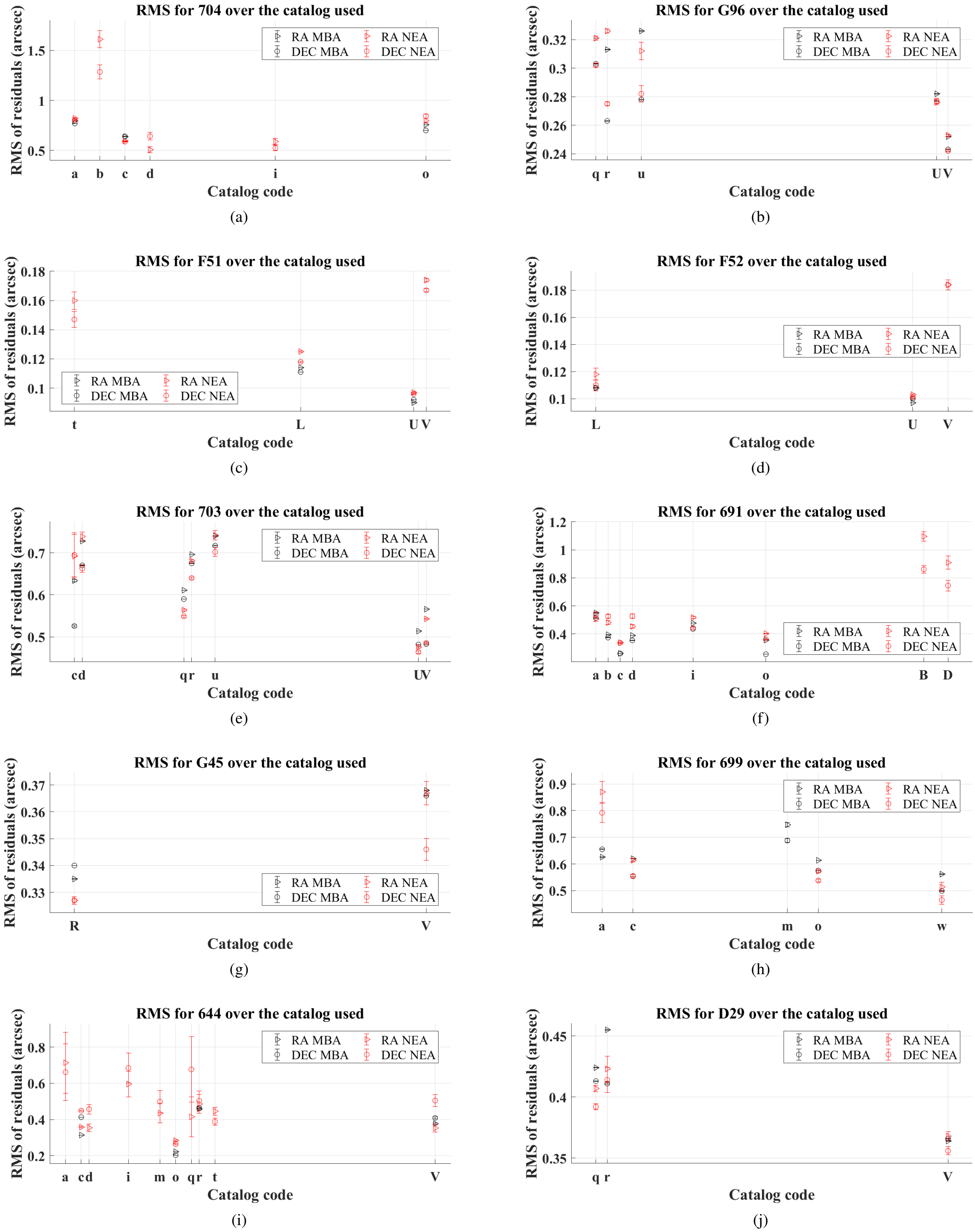

Figure 7. RMS of residuals over the catalogues of observation. The plots for Main Belters and Near-Earth asteroids are plotted differentiating between the residuals for Right Ascension and Declination.

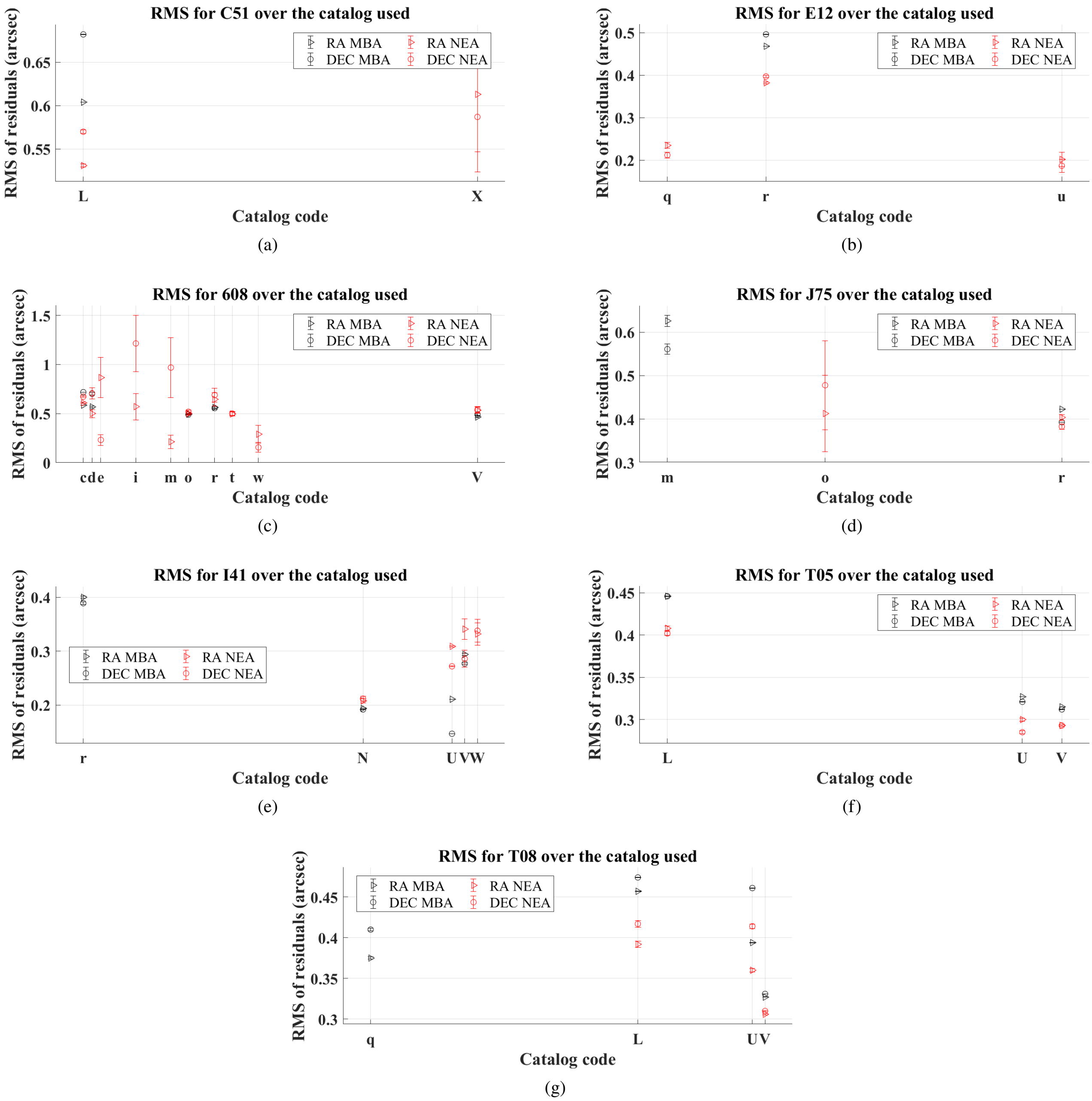

Figure 8. RMS of residuals over the catalogues of observation. The plots for Main Belters and Near-Earth asteroids are plotted differentiating between the residuals for Right Ascension and Declination.

regardless of the station, while others, such as the already mentioned technical equipment, depend strongly on the observatory. This is why, when an observation is performed with high accuracy, the catalogue's precision becomes perceptible, but when the measure is of bad quality itself, the relatively small error induced by the catalogue is overwhelmed by the other sources. It would be interesting, for this purpose, when available, to check how these results would change applying any correction introduced by the newest Gaia release.

Moreover, in the charts, there are no differences in the catalogues accuracies between MBAs and NEAs. It is in fact expected that a catalogue does not behave differently with respect to the observed body, as it is just used to determine the position of the object. However, it may be interesting to investigate the usual four stations that showed a gap between NEAs and MBAs to see if a certain catalogue influence can be found.

691 uses or used *a* (USNO-A1.0), *b* (USNO-SA1.0), *c* (USNO-A2.0), *d* (USNO-SA2.0), *i* (GSC-1.1), *o* (USNO-B1.0) for both the classes with the same RMS level, but it relied on *B* (SAO 1984) and *D* (AGK 3) for a small amount of NEAs observations (respectively 552 and 185). These catalogues are only used by this station with its earliest data and are old and characterised by a low accuracy.

For E12 it is unlikely that the difference between MBAs and NEAs is given by the catalogues as it exploited only *r* (AGK 3) for the first ones and *q* (UCAC-4), achieving the highest accuracy registered for this catalogue, *r* (AGK 3), *u* (UCAC-3) for the others with globally higher RMS levels for MBAs.

Table 3. Most used catalogues for astrometry reduction of MBAs and NEAs observations.

Cat. name	Cat. code	N. obs (MBAs)	N. obs (NEAs)
Gaia-DR2	*V*	72 509 341	276 363
Gaia-DR1	*U*	67 990 790	162 350
2MASS	*L*	37 770 003	109 592
USNO-A2.0	*c*	37 210 202	108 127
UCAC-2	*r*	29 581 421	81 311
UCAC-4	*q*	26 943 310	59 780
USNO-B1.0	*o*	13 582 457	32 127
SST-RC4	*R*	13 449 616	26 602
USNO-A1.0	*a*	2 028 455	7 864

The vast majority of observations for MBAs in I41 are reduced with *U* (Gaia-DR1), characterised by a much higher accuracy than *r* (AGK 3), which, however, represents a minority of the observations. Anyway, also in this case, as it is in most of the stations, the differences in RMS are definitely low.

C51 uses only *L* (2MASS), which is an expected outcome since WISE observes in the infrared and near-infrared band as well as 2MASS is a catalogue in the infrared band. The results in Figure 8a are therefore the same highlighted in Fig. 1.

5 CONCLUSIONS

A statistical analysis on the astrometric residuals of asteroids observations from 17 among the most productive surveys has been performed focussing our attention on the influence of the dynamic classification of minor planets in the results. The RMS of residuals in Right Ascension (RA) and Declination (DEC) have been computed for the stations and for Main Belt Asteroids (MBAs) and Near-Earth Asteroids (NEAs) and it turned out that for most of the stations the type of asteroid does not influence the quality of the measure.

However, four stations have shown to have different accuracies when observing either MBAs or NEAs.

An analysis of the mutual influence of this asteroids dynamic classification and other factors such as year of observation, magnitude, reference catalogue for astrometric reduction is presented. In general, the stations that have differences in measure quality according to the asteroid type keep these over the years and magnitude, but no influence of the catalogue has been registered. The absence of the discrepancy in the catalogue can be explained by the fact that the observations have been properly de-biased with respect to the catalogue reduction. The result on the magnitude instead underlines that for those stations an influence on the object class is present. Indeed, otherwise, one would expect, for the same magnitude, the same result in RMS for MBAs and NEAs, which is not the case especially in I41, 691, E12.

Future developments of this work will lead to the definition of a weighting scheme for minor planets observations based on the outcomes of this statistical analysis, that takes into account this dynamic classification. For those stations that show different accuracies when observing different types of asteroids, having observation weights that change with the dynamic class may improve the whole OD pipeline. This could be the case of the so-called *NEO Follow-up stations*, that may have better accuracies when observing NEAs as it is shown in the previous paragraphs for E12.

DATA AVAILABILITY

The data underlying this article were accessed from ESA NEOCC asteroids observations database (https://neo.ssa.esa.int/). The derived data generated in this research will be shared on reasonable request to the corresponding author.

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Influence of the dynamic classification of asteroids on observation astrometric errors: a statistical analysis

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