GAIA-VLBI: PHASE-REFERENCING CONTINUUM EMISSION OBSERVATIONS OF OPTICALLY BRIGHT STARS WITH THE VLBA (PLANNED PROPOSAL)

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ABSTRACT. For independent verification of the global orientation and spin of optically bright objects obtained from the Gaia mission, positional VLBI observations of radio stars are identified as being the most precise technique for the upcoming data releases (Lindegren, 2019). Here, we propose three radio star surveys in the continuum emission phase-referencing mode with the VLBA for the (re-)detection of stars with promising characteristics for the VLBI-Gaia link to meet the demand of more VLBI data for this task. In the first proposal we revisit stars that have been detected by continuum VLBI/VLA observations in the past. To optimize the sky distribution we plan to find new radio stars in the second and third proposal, either by searching for radio emission of suitable nearby single stars that have never been observed at radio wavelengths before or by observing stars that already have detected radio emission.

1. NECESSITY OF NEW VLBI-OBSERVATIONS OF RADIO STARS IN THE VIEW OF GAIA

Gaia's ability to determine an accurate optical frame and a distance scale is important for many scientific topics, such as the study of star and Galaxy kinematics, better calibration of the cosmic distance ladder and constraining physical properties of a wide range of celestial objects. Since satellite navigation systems, such as GPS, are not available beyond the immediate vicinity of the Earth, the Gaia catalog will play a key role in the navigation and attitude control of spacecraft in the future. The Gaia data already outperform any other optical realization today and will most likely remain the most accurate source for optical positions for several decades in the future. Verifying Gaia's orientation and spin accuracy, especially for the optically bright objects, is essential for high-precision astro-navigation and orientation, particularly in the post-mission period when spin and proper motion errors dominate the position errors. Gaia Data Release 2 (DR2, Gaia Collaboration et al. (2018)) comprises around 1.7 billion objects gathered during the first 22 months of Gaia's operational phase. For astrometry, it provides an independent reference frame with an accuracy that is comparable to the Third International Celestial Reference Frame (ICRF3, Charlot et al. (2018)) derived from geodetic VLBI measurements of extragalactic radio sources, providing a unique historical opportunity to identify systematics in both measurement techniques as well as to study scientific subjects including frequency-dependent time varying core-shifts using common objects.

The orientation of Gaia DR2 is tied to the radio frame through quasars. The orientation was constrained to the ICRF3 prototype whereas the spin parameters were constrained to the ICRF3 prototype and AllWISE data of quasars (Secrest et al., 2015), as described in Gaia Collaboration et al. (2018). In terms of calibration, Gaia data are separated into several magnitude dependent parts due to instrumental reasons (Lindegren et al., 2018). The faint part of the Gaia reference frame behaves as expected in both orientation and spin when validating it against external data (Lindegren et al., 2018). For the verification of the orientation and spin of the bright (<13 mag) Gaia frame, stars can be used that are also visible in radio frequencies. The Gaia team used VLBI data of around 20 radio stars from the literature to verify the orientation, but because of the sparseness of the data, the large epoch differences and the non-linear motions of many of the stars the orientation could not be determined sufficiently well (Lindegren et al., 2018). Clearly, systematic errors in individual objects as well as in the measurement techniques are limiting the ability to determine an accurate tie. In contrast, the spin of the bright reference frame was calculated from proper motion differences of 88,091 bright stars in DR2 and the Tycho-Gaia astrometric solution (TGAS, Lindegren et al. (2016)) in Gaia DR1 (Gaia Collaboration et al., 2016). The proper motions of DR2 were derived from the 22 months of Gaia observations only, whereas the proper motions of DR1 (TGAS) were computed with the help of Hipparcos positions of stars at epoch 1991.25, a time span of about 24 years. The spin shows a significant deviation from the spin calculated from data of fainter objects of about 0.15 mas/yr, and thus disagrees at more than a 5 sigma significance (see Figure 4 in Lindegren et al. (2018)). The spin difference results not from bad data in DR1 (TGAS), but instead from DR2, due to uncalibrated instrumental effects on proper motions of bright objects. These could be effects in the gated observations or the observations of window class 0, which are also clearly related to the dependence of the change of difference in parallax as a function of magnitude (Lindegren et al., 2018). In future Gaia DRs, analysis methods will be used that should minimize the difference between the bright and faint frame. The improved positions, parallaxes and proper motions expected for subsequent Gaia DRs will not be comparable to Hipparcos data in terms of accuracy anymore. Then, only VLBI measurements will provide sufficient accuracy to enable the verification of future Gaia DRs.

Unfortunately VLBI data of radio stars are sparse till today and more observations would be very beneficial for this task. The effect of more VLBI data was studied by Lindegren (2019). Using only VLBI data, he simultaneously estimated six spin and orientation parameters from VLBI and Gaia data of 26 best fitting stars, also based on single-epoch measurements. The calculations resulted in a similar rotation of the bright reference frame at a rate of 0.1 mas/yr relative to the faint reference frame. Still, one of the limitations of his calculations is the sparseness of available VLBI observations of (suitable) radio stars. Also the resulting orientation parameters are biased by the heterogeneous sky distribution of the stars observed in more recent years, as their data contribute most to these parameters.

Lindegren (2019) shows, that new single-epoch measurements of positions of the best fitting stars will most of all improve the determination of spin parameters, if they are taken in later years (rather in 2030 than in 2020). From our point of view, taking measurements now can already improve and validate earlier data releases, and thus will be valuable for the scientific community right away. His study also shows that the error of spin parameters significantly decreases with subsequent Gaia data releases even without additional VLBI observations, which is due to smaller uncertainties in the Gaia proper motions due to a longer time span of available observations, whereas for the orientation new VLBI data will present a significant improvement for current and later Gaia data releases. We propose three approaches to fulfill the various needs of new radio star observations.

2. PLANNED PROPOSALS

Our proposals are planned to be observed with the VLBA network. All stars for proposed observations are within its declination limit and are optically brighter than 13 mag, as required for the bright Gaia frame. The sky coverage for the various proposals is shown in Figure 1 and the respective brightness histograms in Figure 2. The selected stars are well represented in Gaia data having a full valid 5-parameter solution in DR2 if not stated otherwise. In addition, they show a good fit to a single star model from this data, which is expressed by parameter RUWE (re-normalized unit weight error, calculated from Gaia DR2 data, Lindegren (2018)) being smaller than 1.4, which indicates that they are not resolved as binary stars in Gaia DR2. The stars were additionally selected to provide a good sky coverage, i.e., in areas with many stars we selected only the radio-brightest ones.

2.1 Re-observation of already known radio stars

A re-observation of radio stars that have already been observed by VLBI not only has the advantage to get refined proper motions and parallaxes as well as positions during the observation time of Gaia with few input of new observing time, but also a high probability of successful detection. The optically bright stars are highly variable and faint in radio frequencies if compared to extragalactic radio sources that are usually used for geodetic VLBI. For this proposal, we excluded stars with radio spectral-line observations, since we want to focus on continuum emission only. We further consider the suitable spectral types for the link between optical and radio frequencies. This leads to main sequence stars with the exception of stars of type O and B, since the probability of radio-optical offsets is higher for these types due to stellar winds and complex structures, as well as to the exclusion of M and L type stars due to the higher possibility of resolved binaries in VLBI observations. As recommended by Lindegren (2019), they are neither Mira type nor red supergiants. We took the information of spectral classes from the SIMBAD database (Wenger et al., 2000).

The final selection of 46 stars consists of seventeen stars that are from the list of recommended candidates for Gaia-VLBI link by Lindegren (2019). Four of them are of spectral type O or B but they are still selected because they fit a single-star model well and thus a higher priority was given to the precious longer data set that is available when combining the new data with data from the archive. One of the 17 stars (V2248 Oph) is known to be a triple star system, but shows a low discrepancy between VLBI and Gaia. More observations are useful for an enhanced study of the VLBI and Gaia offset for this object. With a view to future Gaia DRs and the availability of orbits for some objects as well as the verification of these orbits, four additional stars were selected which show the probability of a binary companion but are promising for orbital modeling. Two more stars were selected from the list of Xu et al. (2019). One of them, bet Per, was chosen because it is the only one of the eleven link stars for the Hipparcos mission that was not yet in the selected sample. This is because it does not have a full astrometry solution in DR2 yet. We made an exception for this star and took it into our selection of stars to be observed, because again, new observations for this star would provide a long positional time series when combined with the observations from the 1980s and 1990s, and in addition we will be able to do tests using the same set of stars as for Hipparcos comparisons. It is a future task to look for more possible candidate stars for the Gaia/VLBI link that have extensive VLBI observation history and were detected by Gaia but do not have a full astrometric solution in DR2 yet. Using the same general approach, we additionally selected 23 radio stars of Boboltz et al. (2003) and Boboltz et al. (2007), who did phase-referenced continuum observations in X-band of in total 52 radio stars for the Hipparcos CRF link using the VLA and Pie Town telescopes.

2.2 Detection of nearby stars

Our second proposal aims to increase the number of radio-optical counterparts in order to improve the sky distribution. We selected optically-bright stars that are both in Hipparcos and Gaia DR2 subsets, in order to have a good chance of accurate Gaia data at the end of the mission. We excluded stars that were identified as double or multiple star systems by Hipparcos. We further filtered for main sequence stars that are of suitable spectral types using data from SIMBAD. From the r-squared law, we assume that the nearest such stars would be the brightest, so if these stars produce any significant radio emission, the nearest would be the best objects to observe. Our final selection contains stars that are within 20 pc of the Earth.

It consists of 102 stars that to our knowledge have not been observed by VLBI yet. The set was chosen to provide a rather uniform sky coverage and a variety of spectral classes that are most suitable for the tie (see Figure 3).

2.3 VLBI-observation of previously detected stars

The third proposal aims to re-observe stars that have already been detected by continuum radio observations in the past. The catalog of Wendker (2015), a collection of radio detections until the late 1990s, was used to find promising objects for re-observation with the VLBA. The 75 selected stars were detected with a minimum flux density of 0.5 mJy in a frequency range from 1 to 100 GHz. We chose a somewhat lower detection limit than our observations will allow, since we assume that variability in the brightness of the stars can be great, and therefore we do not want to exclude a star prematurely. Also, we assume that the possibility of detection does not vary dramatically within the frequency range. The stars have not been observed in phase-referencing mode before. Therefore, there is no overlap with proposal 1. We prioritized the non-binarity and higher number of possible new candidates for a successful search survey, which is why the proposed candidates can belong to various spectral classes as seen in Figure 3. It is certainly possible to filter for preferred spectral classes, if desired.

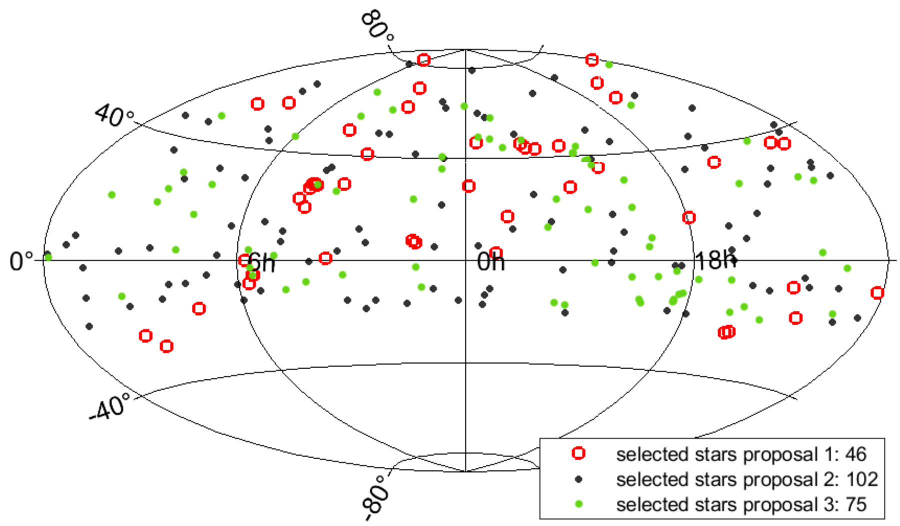

Figure 1: Stars selected for observations with color-coding according to the type of proposal.

3. SUMMARY

VLBI observations of optically bright radio stars will be the only method to improve the validation of the orientation and spin of the Gaia bright reference frame in future Gaia DRs. So far there are too few observations for this purpose, and the sky distribution of these is not homogeneous enough to get sufficient results. We present three different strategies for observations to improve the determination of the spin as well as the orientation parameters using the VLBA network. It is clearly promising to re-observe already known radio stars and to make use of longer observation intervals by adding data from the archive for improved estimates of the star's parameters. But this is not enough for the precise alignment in both orientation and spin, because there are not enough

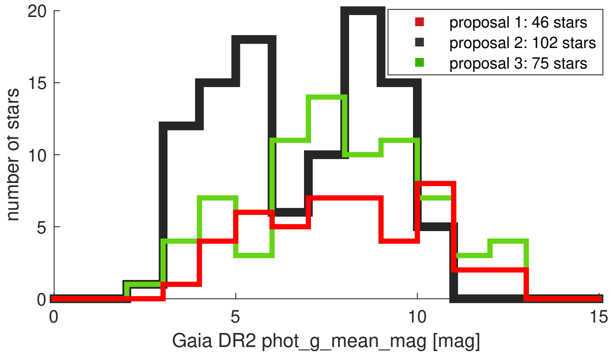

Figure 2: Histogram of G-magnitude of the stars selected for the observations.

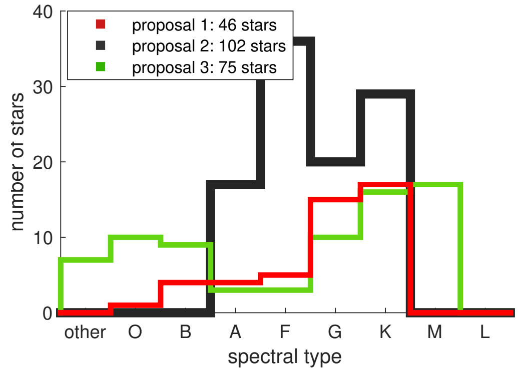

Figure 3: Histogram of the spectral types of the stars selected for the observations. For proposal 3, a stricter selection for the most suitable spectral types would be possible.

suitable stars known yet, as discussed in Lindegren (2019). Therefore, radio stars have to be found which have not been observed by VLBI in the past. We offer two approaches for a selection of suitable candidates to be observed.

For each of the proposals, we would like to conduct a search survey to find stars that are visible for the VLBA in phase-referencing mode. In a second step, more observations need to be carried out to get precise positions, proper motions and parallax for those objects which could be detected in the surveys. In addition, precious data from the archive should get collected and re-processed if necessary.

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