Source Structure of 0642+449 Derived from CONT14 Observations

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Abstract The CONT14 campaign features state-of-the-art VLBI data. Therein, the radio source 0642+449 was observed with about one thousand observables each day during the continuous observing period of fifteen days, providing tens of thousands of closure delays, the sum of the delays around a closed loop of baselines. The closure delay is independent of the instrumental and propagation delays and provides valuable additional information about the source structure. An example of the use of this new "observable" for the determination of source structure is given for the radio source 0642+449. This source, as one of the defining sources in the second realization of the International Celestial Reference Frame (ICRF2), is found to have two point-like components with a separation of 425 microarcseconds in right ascension and 47 microarcseconds in declination. The two components are almost equally bright with the flux-density ratio up to 0.92. With the help of recent space VLBI observations at 1.6 GHz, the morphology of 0642+449 could be identified to some extent. The closure delays larger than 1 ns are found to be caused by source structure as well, demonstrating that the structure effect of a source with this simple structure could reach up to tens of nanoseconds, which is at least one magnitude larger than expected. We anticipate our study to be a starting point for more effective determination of the structure effect in VLBI observations without the involvement of radio source images.

Keywords Astrometry, VLBI, galactic nuclei, individual quasar 0642+449

1 Introduction

It is well known that radio source structures are generally asymmetric, time dependent, and frequency dependent. The effect of source structure, however, has been ignored as noise in routine geodetic VLBI data analysis so far. The source structure effect is still very important and challenging for astrometric VLBI, as shown in simulation studies [4, 5]. If VLBI is to achieve its full potential of the realization of the extragalactic Celestial Reference Frame with accuracy at the microarcsecond level and that of the Terrestrial Reference Frame with accuracy of the millimeter level, it is necessary to study and handle the source structure effect more effectively based on the astrometric observations themselves. This is the purpose of this research.

We make use of the closure delay, the sum of the delays around a closed loop of baselines, as a new observable and propose a method to use this new observable for the determination of the source structure effect on the astrometric VLBI observable. We calculate the closure delays, investigate the characteristics of the source structure, and then solve for the source structure effect on each observable. The source 0642+449, one of the ICRF2 defining sources, is selected as a demonstration case for this method. This work has been presented in our journal paper [7].

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2 Data

The data from CONT14[1] observations [3] at X band were used. CONT14, as a campaign of continuous VLBI observations over 15 days with 17 globally distributed stations, was intended to acquire state-of-the-art VLBI data with the highest accuracy of which the then existing VLBI system was capable. Because only 71 radio sources were observed in this campaign, one could expect that most of these radio sources would have enough observations with good *uv* coverage to get meaningful statistical information from closure delays.

Closure delay is the sum of the delays around a closed loop of baselines. To the accuracy of the second order in delay, the closure delay $\tau_{abc}(t)$ at reference epoch t for three stations a, b, and c, is calculated from geodetic VLBI observations[2] by using

$$\begin{aligned}\tau_{abc}(t) =&\tau_{ab}(t)+\tau_{bc}(t)-\tau_{ac}(t)\\ &+[\dot{\tau}_{bc}(t)\cdot\tau'_{ab}(t)+\frac{1}{2}\ddot{\tau}_{bc}(t)\cdot\tau'_{ab}(t)^2],\end{aligned} \qquad (1)$$

where, for instance, τ_{ab} is the group delay observable from station a to station b, and τ_{bc} is the group delay observable from station b to station c, for the same wavefront received by three stations. A prime on a delay symbol indicates an absence of dependence on station clock offset, that is, referring to the geometric delay, and a superposed dot and double superposed dots denote differentiation with respect to time once and twice, respectively. The definition and model of closure delay was discussed in detail in our original paper [7]. In geodetic VLBI measurements, by convention, the time tag of VLBI observables is referred to the epoch when the wavefront passes the first station in the baseline. In order to have the three delay observables in the closure refer to the same wavefront, Equation 1 includes the corrections in brackets for the delay for the second baseline in the triangle.

3 Measurement Noise in VLBI Group Delays

Closure delay is a direct and important criterion of how much the source structure affects delay observables. It also demonstrates the measurement noise in geodetic VLBI observables and thus indicates the accuracy level of delay observables. For a comparison to demonstrate the measurement noise in VLBI observables, the standard deviations of closure delays for unresolved sources, such as 0016+731 and 0727-115, were calculated as well. Source 0016+731 has about 23∼300 closure delays and 0727-115 has about 11∼200 closure delays. The standard deviation for source 0016+731, which showed a little resolved structure, is about 11 ps, and that for source 0727-115 is about 8 ps. The closure delays for source 0727-115 over 15 days are shown in Figure 1. This figure demonstrates that the closure delays for this source are exclusively smaller than 30 ps.

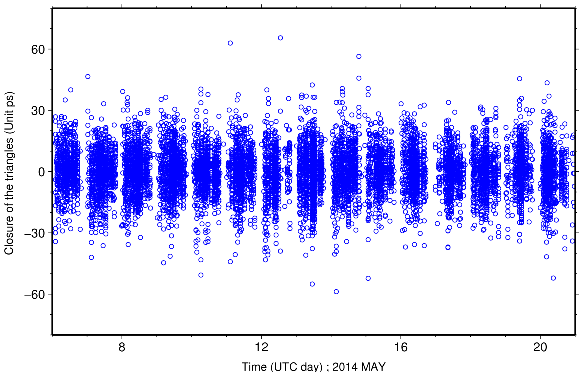

Fig. 1 The closure delays for source 0727-115.

4 Structure of Source 0642+449

The closure delays for source 0642+449 are shown in Figure 2. There are 21∼400 closure delays. The mean value and the standard deviation of closure delays is 0.3 ps and 139 ps, respectively, for the closure delays in the range 0 to 1.0 ns. Variations in the closure delays for source 0642+449 sufficiently far away from zero, so that they are unlikely to be caused by random mea-

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[1] http://ivscc.gsfc.nasa.gov/program/cont14/

[2] For astronomical observations that reference all observables in one scan to the same wavefront, the model of closure delay is quite simple: $\tau_{abc}(t)=\tau_{ab}(t)+\tau_{bc}(t)-\tau_{ac}(t)$.

surement noise, should, in principle, only be observed for sources with significant structure.

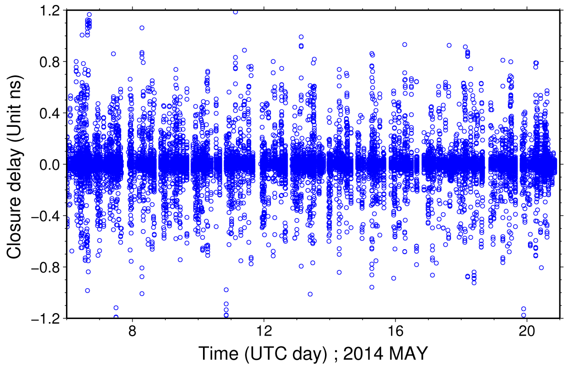

Fig. 2 The closure delays for source 0642+449.

A method was developed to determine the structure delay for each observable based on the closure delays. In an array of N stations, there are at most $N(N-1)/2$ baselines and $N(N-1)(N-2)/6$ closure delay relations. But only $(N-1)(N-2)/2$ of these relations are independent. There are therefore $(N-1)$ too few closure delays to determine the source structure effect for each standard baseline-delay observable, and an independent estimate of the structure delay on $(N-1)$ baselines has to be derived. The investigations in Section 3 give some insight into this; the proposed method uses the assumption that source 0642+449 is a point-like source with respect to the baselines shorter than a certain value. We then choose 7,100 km as the threshold and select a necessary and minimum number of $<$ 7,100 km baselines to connect as many stations as possible in each scan. The structure effects on these selected baselines are assumed to be zero. Taking a fifteen-station array as an example, ideally there are fourteen baselines shorter than 7,100 km connecting fifteen stations as a complete connection. Setting the source structure effect on these selected baselines to be zero allows us to solve for the structure effects on other baselines utilizing the closure delays. The next step is to solve as many triangles as possible based on the connection with the threshold of 7,100 km, scan by scan.

Finally, 16∼941 triangles were solved, and the source structure effects on 8,492 baseline delays were determined. In this solution, 2,179 observables of short ($<$ 7,100 km long) baselines were assumed to have no source structure effect to build up the connection.

Figure 3 shows the *uv* coverage with color marking the magnitude of the derived source structure effect on each point. In general, the source structure has a strong effect on long baselines along two opposite directions of, approximately, the *u* axis. The results are divided into two groups for the detailed study of learning the source structure effect.

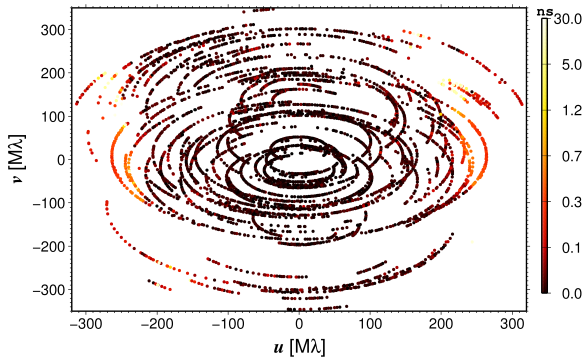

Fig. 3 Coverage of the Fourier domain (*uv* coverage) of the CONT14 observations of 0642+449 at 8.4 GHz (λ = 3.6 cm), plotted in units of Mega lambda. Color marks the absolute magnitude of the source structure effect on each of 8,492 observables derived from closure delays [7].

We can determine that the source exhibits a structure with two compact components on baselines with lengths of around 9,000 km. The ratio of the flux densities of the weaker component to the stronger one, K, is about 0.92, because the peak structure effect for these baselines is approximately 0.7 ns.

Thomas (1980) referred the source position in his model to the middle point of the separation between the two components [6], while Charlot (1990) took the centroid point of brightness as the reference point [1]. The reference point does not matter for the closure delay, but we apply the centroid model here, because we assume that observables of short baselines have zero source structure effect, and in practice they are referred very closely to the center of brightness. According to this model, the structure delay τ_s on baseline $\mathbf{B}$ is given as

$$\tau_s = \frac{K(1-K)[1-cos(2\pi R)]R}{f(1+K)[K^2+2Kcos(2\pi R)+1]}, \qquad (2)$$

where f is the observing frequency, $R = \mathbf{B}\cdot\mathbf{S_{12}}/\lambda$, λ is the wavelength, and $\mathbf{S_{12}}$ is the relative position vector in the *uv* plane of the weaker component P_2 with respect to the stronger one P_1.

Because the closure delay is not sensitive to the reference point in the source structure at all, this study lets all observables refer to an unknown point, in this case to the centroid of brightness by the choice of the model, per scan. This reference point will finally be determined through VLBI data analysis. We further assume that the source structure does not change within the fifteen days of observations. A “guess” estimation for the unknown parameters in Equation 2 was made from the results of baselines with lengths from 8,400 km to 9,600 km derived in Section 5. The final estimation was done by model-fitting the closure delays based on the a priori values from the guess estimation. The flux-density ratio is then estimated to be 0.916 ± 0.012 and the relative position vector to be -426 ± 12 μas in right ascension and -66 ± 19 μas in declination. According to the detected morphology, a baseline with a length of 7,100 km has $R = 0.41$, and the peak structure effect is only 13 ps, which explains the foundation of the assumption that short baselines have no structure effect, which is used for the connection.

One can easily compute the source structure effect for each observable based on Equation 2 and the two-component model. After using the model to correct the structure effect, the standard deviation of the closure delay was decreased from 139 ps to 90 ps for all triangles, with a closure delay less than 1 ns, which is a significant improvement.

5 Discussion and Conclusions

Using CONT14 observations, the source structure effect is demonstrated at the level of each individual VLBI group delay for the first time. The study reveals that at X band (8.4 GHz) during the CONT14 sessions, the source had two point-like components. The standard deviation of the corrected closure delay was reduced by 36%. Recently, space-VLBI (RadioAstron) observations of this source at 1.6 GHz in 2013 with a resolution of 0.8 mas, $\sim$ four times better than that of ground VLBI images at this wavelength, found that this source has two compact cores separated by 0.76 mas [2] with a position angle of 81° in the sky plane. Because the space VLBI observations were made fourteen months earlier than the CONT14 observations, one may not expect that they were necessarily observing the same blob, but the position angle of the two components should be approximately in the same direction. Our result domnstrates that the two components are in the direction of position angle about 261.2°, which is the same direction detected by space VLBI.

It is still challenging to implement the identified source structure to correct the effect in VLBI data analysis. First, an accurate model for the BWS group delay to the level of at least 10 ps needs to be derived. This model should be able to reduce the magnitudes of the closure delays of triangles with the longest baselines to the level of that of small triangles, a few tens of ps. Second, a careful re-study of the linear combination of S and X band data with the presence of source structure would be essential to have an accurate correction for the source structure effect on the combined S/X observable. The attempt to correct structure effect in VLBI data analysis recently has been made by Xu et al. (2016b) [8]. This significant effect should and will be handled in geodetic VLBI.

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