RADIO SOURCE STRUCTURES IN VLBI ASTROMETRY

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ABSTRACT

In astrometry, celestial radio sources with extended structures are useful. An algorithm to correct for structure in VLBI delays and delay rates is developed. The radio source NRAO140 is mapped from data with limited u-v coverage by the hybrid method and the Maximum Entropy procedure. The magnitude of the structure corrections in astrometry is discussed in the case of NRAO140.

1. INTRODUCTION

Most of the celestial radio sources with flux density higher than 0.5 Jansky exhibit complex spatial structures at the milliarcsecond scale and are used in geodesy, astrometry and for the determination of the Earth orientation parameters by the Very Long Baseline Interferometry (VLBI) technique.

In geodesy and for the determination of Earth orientation ten to twenty radio sources are usually observed by VLBI. Sources with the smallest structures are usually selected and their averaged structure effects are probably small in geodetic measurements. However, new geodetic techniques using the VLBI phase on long baseline might require structure corrections in the future.

In astrometry, sources with extended structures but angularly close to some targets are useful. This is the case of navigation of interplanetary spacecrafts by VLBI (Voyager, Galileo), of the link of the optical and radio celestial reference frames via VLBI observations of radio stars and, more generally, for the densification of the VLBI celestial reference frame. Moreover, the 'historic' but possibly unfortunate choice of the superluminal source 3C273 for the arbitrary origin of the VLBI right ascensions might induce a rotation of the whole VLBI celestial reference frame at some level. We are developing an algorithm to calculate source structure corrections in the VLBI observables (delay, delay rate, phase).

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2. THEORY

The complex visibility function V of a source with an extended structure is :

$$V = V_0 e^{i(\phi_g+\phi_s)}$$

where:

$$\phi_g = -\frac{2\pi}{\lambda}\vec{B}.\vec{k}_{P_0}$$

and:

$$\phi_s = arg\left[\int\int_{source} I(P,\omega,t)e^{(-\frac{2\pi i}{\lambda}\vec{B}.(\vec{OP}-\vec{OP_0}))}d\Omega\right] \tag{1}$$

A local coordinate system with origin O is chosen in the plane of the sky near the source. A reference point P_0 is chosen in this local system and the corresponding unit-vector pointing towards P_0 is $\vec{k}_{P_0}$. If ϕ_g is the geometric phase of a point source located at P_0, ϕ_s would be the additional structure phase of the actual source. The brightness distribution $I(P,\omega,t)$ depends on the running point P, the observing frequency f ($\omega = 2\pi f$) and the time t . $\vec{B}$ is the baseline vector and $d\Omega$ is the differential area on the sky. The VLBI position determined in astrometry will be the position of the reference point P_0 if the structure phase correction is applied. Adopting the mathematical form used by Thomas (1980), ϕ_s can be written as:

$$\phi_s = \frac{2\pi}{\lambda}\vec{B}.\vec{OP_0} + tan^{-1}\left(\frac{Z_s}{Z_c}\right)$$

where :

$$Z_c = \int\int_{source} I(P,\omega,t)cos(\frac{2\pi}{\lambda}\vec{B}.\vec{OP})d\Omega$$

$$Z_s = -\int\int_{source} I(P,\omega,t)sin(\frac{2\pi}{\lambda}\vec{B}.\vec{OP})d\Omega$$

The structure corrections for the bandwith synthesis delay ($\Delta\tau_{BWS}$) and the delay rate ($\Delta\dot{\tau}$) are cast into a form devised by Thomas (1980):

$$\Delta\tau_{BWS} = \frac{\partial\phi_s}{\partial\omega} = \frac{1}{c}\vec{B}.(\vec{OP_0} - \vec{OP_E}) + \Delta L_\omega \tag{2}$$

$$\Delta\dot{\tau} = \frac{1}{\omega}\frac{\partial\phi_s}{\partial t} = \frac{1}{c}\dot{\vec{B}}.(\vec{OP_0} - \vec{OP_E}) + \Delta L_t \tag{3}$$

where :

$$\vec{OP_E} = \frac{Z_c\vec{C} + Z_s\vec{S}}{Z_c{}^2 + Z_s{}^2}$$

with :

$$\vec{C} = \int\int_{source} I(P,\omega,t)cos(\frac{2\pi}{\lambda}\vec{B}.\vec{OP})\vec{OP}\ d\Omega$$

$$\vec{S} = -\int\int_{source} I(P,\omega,t) sin(\frac{2\pi}{\lambda}\vec{B}.\vec{OP})\vec{OP}\ d\Omega$$

ΔL_ω and ΔL_t account for the frequency and time dependence of the brightness distribution. Hereafter these two terms will not be considered and will be investigated in a further study.

The point P_E in (2) and (3) is called the effective position of the source according to the terminology used in Thomas (1980). If this point P_E is chosen as the reference point P_0, then the structure effects in the VLBI observables are null. The effective position P_E of the source changes with baseline and time. Hence, the effective position is not appropriate to locate a source in precise astrometry. The position of the source should be rather a specific feature that should be recognizable over time and frequency. Such feature is not easy to find, it could be the peak intensity of the source although this is arguable. The choice of this feature should be made on a source by source basis.

The computation of the above structure corrections requires in practice a representation of the brightness distribution $I(P)$. The hybrid mapping procedure (Readhead and Wilkinson 1978) with CLEAN (Högbom 1974) is used to map VLBI sources with a finite number of delta-functions (CLEAN components) :

$$I(P) = \sum_{k=1}^{n}(I_k\ \delta(\vec{OP} - \vec{OP_k}))$$

where the pair (P_k, I_k) defines the position and intensity of the k^{th} CLEAN components. These delta-functions are usually convolved with a Gaussian beam when displaying maps produced by this method. It can be shown that the structure corrections are identical when calculated with delta-functions or with Gaussian components.

The Maximum Entropy Method (Ables 1974) is also used to produce VLBI maps. In this case, a two-dimension piecewise brightness distribution is obtained and $I(P)$ is constant over a pixel.

3. THE CASE OF THE RADIO SOURCE NRAO140

The extragalactic radio source NRAO140 was observed at 6 cm on 1983 July 27 with a six-station VLB array formed by Effelsberg, Haystack, Greenbank, Fort Davis, Owens Valley and the phased-VLA. The Mark III data acquisition system was used since NRAO140 was scheduled as a calibrator in a VLBI experiment designed to survey weak radio stellar systems. The correlation was conducted with the NASA-NSF Mark III correlator at Haystack Observatory. These data are typical of geodetic or astrometric observations since there are only a few scans on NRAO140 distributed over a few hours. The VLB array was calibrated with 0106+013, 0235+164 and 0016+73 which were assumed to be point sources. The raw amplitudes were calibrated according to the standard procedure (Cohen et al 1975).

First, we mapped NRAO140 with the hybrid mapping procedure and CLEAN. The resulting map is in figure 1 (left). It shows that NRAO140 is elongated along a north-west direction and exhibits two bright components (A and B) and two weak components (C and D). The structure of NRAO140 in this map is similar to the one found by Marscher and Broderick (1985). Then we used the Maximum Entropy algorithm of Gull and Daniell (1978) and produced the map of NRAO140 in figure 1 (right). In this map, the weaker component C does not appear but the stronger component A is resolved into 2 subcomponents A_1 and A_2 which were also cautiously noticed by Marscher and Broderick (1985). This is an interesting example where the Maximum Entropy Method (MEM) can achieve superresolution. It is discussed in a paper in preparation.

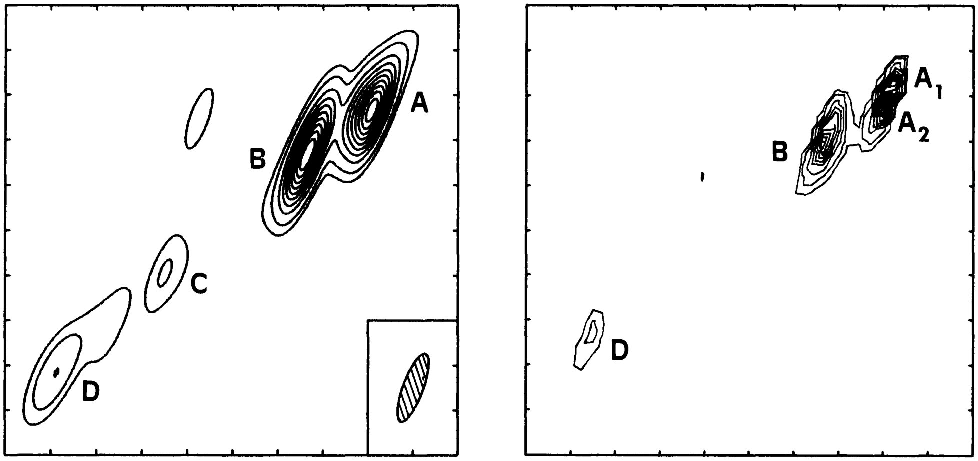

Figure 1. CLEAN map (left) and Maximum Entropy map (right) of NRAO140 at 6 cm on epoch 1983 July 27. Contour levels are 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% of the peak brightness. The tick marks are 1 milliarcsecond apart.

We calculated structure corrections for the observed VLBI delays and delay rates of NRAO140 in using the component B as the reference point of the source P_0. An histogram of the correction magnitude for the delays on intercontinental baselines is shown in figure 2. There are a total of 30 scans on these baselines. The effect is larger than 0.1 nanosecond (ns) for 12 scans and the maximum effect is about 1 ns. On the US continental baselines, no effect is larger than 0.1 ns. The differences between the corrections derived from the Maximum Entropy map and the values obtained with the CLEAN map give an estimation of the errors on these structure corrections. The root mean square of these differences is 0.03 ns for the delay and 0.003 picosecond/second for the delay rate.

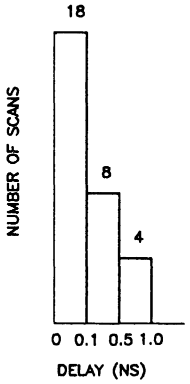

Figure 2. Histogram of the structure correction magnitude for VLBI delays on intercontinental baselines.

In figure 3 and in figure 4, we have plotted the variations of the structure corrections for the delays over five hours for the two baselines Effelsberg - VLA and Effelsberg - Owens Valley. One curve represents the correction calculated with the CLEAN map and the other the correction calculated with the MEM map. The two curves are in a good agreement for the two baselines.

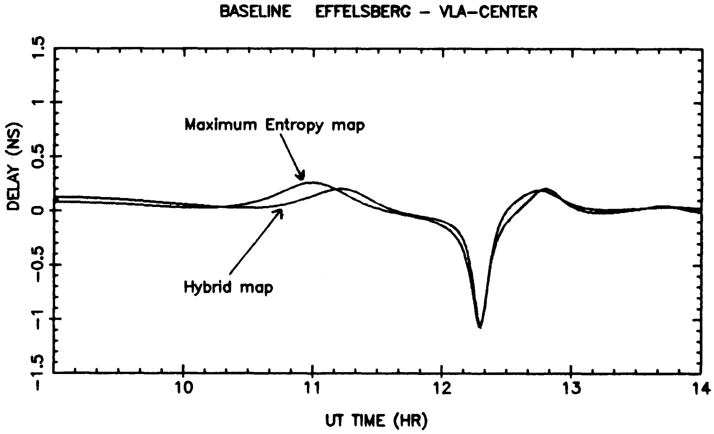

Figure 3. Variation of the structure correction for the delay from 9 UT to 14 UT for the baseline Effelsberg - VLA.

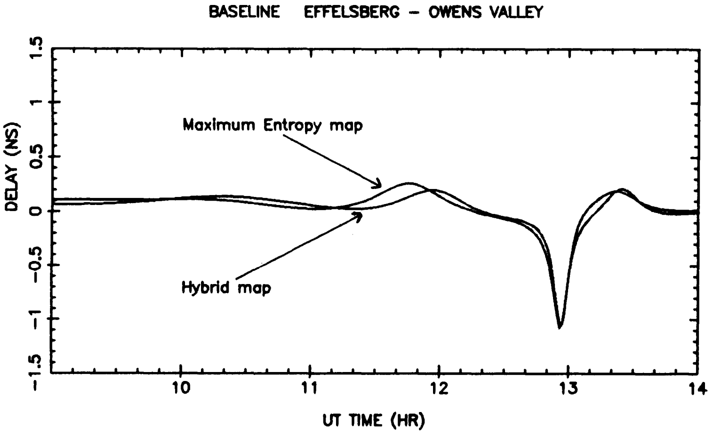

Figure 4. Variation of the structure correction for the delay from 9 UT to 14 UT for the baseline Effelsberg - Owens Valley.

On the intercontinental baselines Effelsberg - VLA and Effelsberg - Owens Valley, the structure corrections exhibit rapid variations reaching a maximum of 1.1 ns in a few minutes. On short and intermediate baselines, the structure corrections are small and show very little variations with time. The same behaviors have been found for the delay rate corrections.

4. CONCLUSION

The VLBI data on NRAO140 are typical data for geodesy or astrometry. They were sufficient to map this radio source either by the hybrid method or MEM procedure and to calculate structure corrections for the delays and delay rates. For our observations, the corrections derived from the two maps are consistent at better than 10% if the correction is larger than 0.2 ns. For fictitious observations at UT times largely away from the scheduled scans, we have found that the corrections provided by the two maps show larger discrepancies.

The magnitude of the structure corrections during our observations reaches 1 ns and this shifts the position by 17 mas on the corresponding baseline Effelsberg - VLA . The mean of all the structure corrections at the points with the largest components in the u-v plane is 0.25 ns corresponding roughly to a position shift of 4 mas . Hence, precise astrometry cannot ignore these corrections.

We are now applying these additional corrections to the 'standard' VLBI model to analyse a 24-hour Crustal Dynamics VLBI experiment and solve for the astrometric or/and geodetic parameters.

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