Arnaud Collioud et al.: VLBI2010 Imaging and Structure Corrections, IVS 2010 General Meeting Proceedings, p.45–49
http://ivscc.gsfc.nasa.gov/publications/gm2010/collioud.pdf

VLBI2010 Imaging and Structure Corrections

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Abstract

Simulations show that the next generation VLBI system is generally well suited for imaging extragalactic radio sources. In addition to revealing the morphology of the sources, simulated VLBI2010 images may also be used to generate structure correction maps, which characterize the impact of source structure on the VLBI measurements. By comparing structure corrections for a set of simulated images based on Monte-Carlo generated visibilities with theoretical structure corrections derived from the model, we assess the accuracy of VLBI2010 structure corrections. In the most favorable case (32-station network, source at declination +40°), statistics demonstrate that the structure corrections obtained from simulated images are statistically close to the theoretical model ones, which seems very promising for the VLBI2010 system.

1. Introduction

In the forthcoming years, the successor of the current geodetic VLBI system—the VLBI2010 system—is expected to become operational. This new system is based on 12m-class fast-moving antennas associated with broadband recording systems, as prescribed by the VLBI2010 Committee [1]. Significant progress in the determination of IVS products is anticipated with this new system, such as the improvement of the International Celestial Reference Frame (ICRF) source positions.

The ICRF sources, as most of the extragalactic radio sources, are generally not point-like on VLBI scales [2]. The source structure introduces an additional unmodeled delay, called "structural delay" or "structure correction", to the group delay measurements. This structural delay has a direct impact on the source position accuracy derived from VLBI observations. The magnitude of this delay is related to the complexity of the structure, ranging from a few picoseconds for compact structures to tens of picoseconds for more extended structures, as shown in Figure 1. Moreover, the source structure, and hence the structural delay, may evolve in time, which requires monitoring the sources over time.

Until now, efforts were put into the selection of sources with minimal structure. This method was used for example to select the defining sources of the ICRF2, adopted by the IAU General Assembly in August 2009 [3]. On the other hand, the additional structural delay, as a systematic effect, may be removed from the group delay measurements if source structure is known, which should lead to an improvement of the final source positions. In the future, it is anticipated that such structure corrections may be routinely determined and applied with the new VLBI2010 system.

Studying the accuracy of the structure corrections achievable with the VLBI2010 system based on simulated images is a prerequisite in order to reach this goal. In this paper, we first summarize the imaging capabilities of the VLBI2010 system. The simulated images are then used to infer structure corrections, the accuracy of which may be estimated by comparison with theoretical structure corrections derived from the model. Results of this estimation are discussed in Section 3.

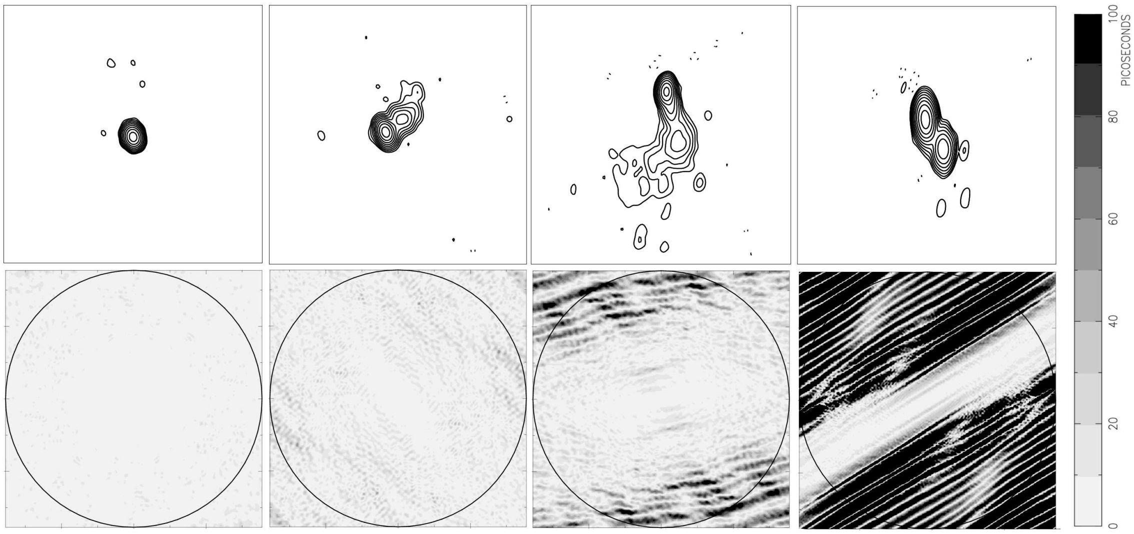


Figure 1. VLBI images and structure correction maps showing the magnitude of the structural delay for a sample of sources with different structure complexity. The scale of the structure corrections is given on the right-hand side of the panel. The four VLBI images and corresponding structure correction maps are excerpted from the Bordeaux VLBI Image Database (http://www.obs.u-bordeaux1.fr/BVID).

2. Simulation of VLBI2010 Images

Imaging capabilities of the VLBI2010 system have been studied thanks to a dedicated processing pipeline that generates VLBI images using VLBI2010 test schedules with different network configurations and observing strategies. In this study, simulations are carried out using the traditional S/X frequency setup. Details about the pipeline and initial results obtained in the case of high SNR sources were presented in [4]. Since then, additional simulations have been carried out for weaker sources (40 mJy) assuming a typical noise level equivalent to an SNR of 20 [1].

The simulations demonstrated that the VLBI2010 schedules lead to a better coverage of the u-v plane compared to the current geodetic sessions due to the increase of the number of observations per session and the better station distribution on the Earth. Simulated images are found to be high-quality, with a dynamic range ranging from 1:200 to 1:1000, depending on the configuration. Simulations also show that the standard hypothetical 16-station network is generally well suited to producing high-quality images. However, it is to be noticed that extended structures for sources at low declination are not well reconstructed with only 16 stations due to the lack of short baselines in the southern hemisphere [4]. Additional simulations demonstrate that the addition of two stations at carefully selected locations in the southern hemisphere could help fill the central hole in the u-v plane and hence mitigate this image reconstruction problem of the 16-station network. The resulting image quality clearly improves, giving simulated images at southern declinations a quality comparable to that of northern sources when such two stations are added [1].

3. Structure Corrections

In addition to revealing the morphology of the sources, simulated VLBI2010 images may be used to generate structure correction maps. These represent the effects of source structure on the delay observable as a function of interferometer resolution. Additionally, structure correction maps serve as a basis for calculating structure indices, which characterize the astrometric suitability of the sources [2].

In order to assess the accuracy of the structural corrections derived from VLBI2010 images, a sample of 25 similar VLBI2010 images was generated as described in Section 2. These images were produced from the same input source model (presented in [4]) but using a different input noise level in each simulation (as obtained by a Monte Carlo method). An additional image was generated from a simulation without additive noise. Structure correction maps were then derived from all such images and were compared with the theoretical structure correction map calculated from the "true" source model, thereby allowing us to estimate the accuracy of the corrections.

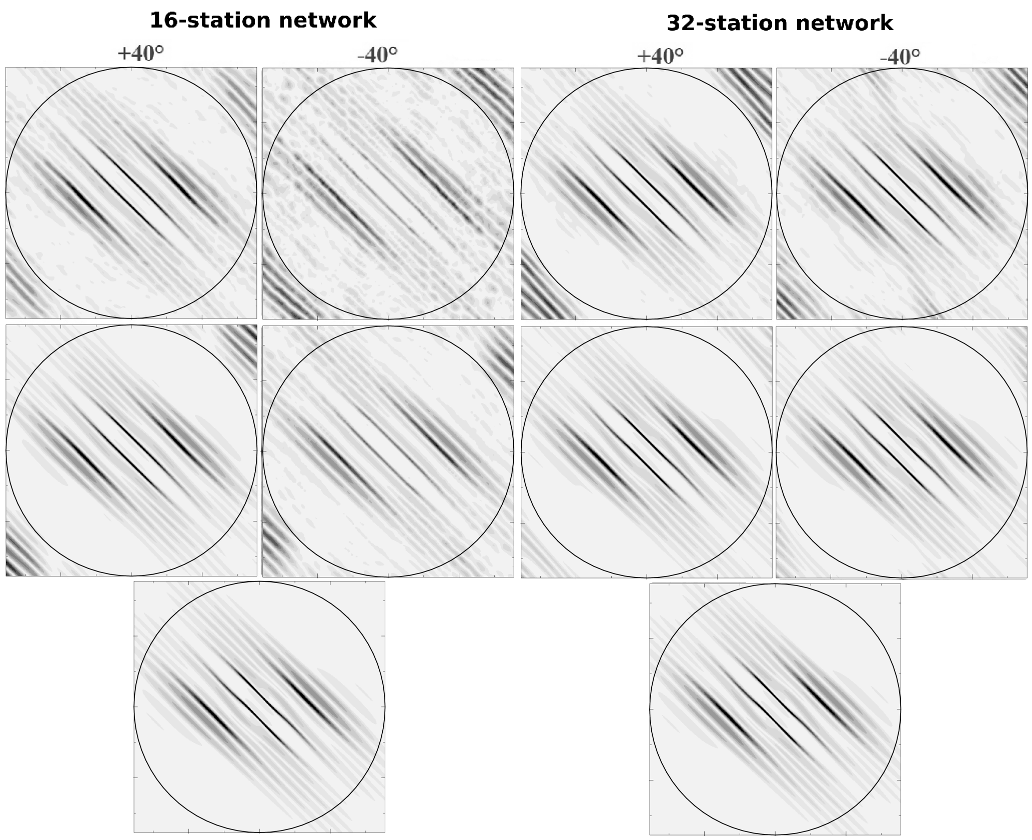
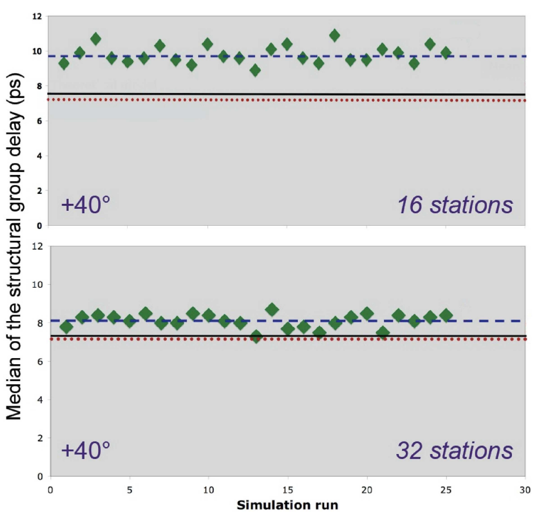


Figure 2. Structure correction maps derived from simulated VLBI2010 images for 16- and 32-station networks (left and right panels, respectively) and for two identical sources placed at declination +40° and −40°, respectively. The upper (middle) panels show the results obtained with (without) additive noise, while the lower panels show the results obtained for the theoretical model. The scale of the structure corrections is the same as the one used in Figure 1.

By examining these structure correction maps (Figure 2, above), it appears that the noise level is larger (compared to the theoretical structure correction map) when the structure is not fully reconstructed, as for the 16-station network and a source at declination $-40°$. In the case of the 32-station network, the structure corrections resulting from the simulated images are closer to the theoretical structure corrections.

Statistics may be calculated using the median correction from these maps. For example, the study of the difference between the mean of the median corrections and the theoretical model correction helps us to understand the systematic error due to imperfect u-v coverage. Additionally, the study of the RMS of the median corrections provides indications on the impact of the noise on the simulations. See Figure 3 for a graphical representation of these errors in the case of the sample source at declination $+40°$. In this case, the difference between the mean of the median corrections and the theoretical model correction is 2.2 ps with the 16-station network, and only 0.5 ps with the 32-station network. The corresponding RMS values are 0.5 and 0.4 ps, respectively.

These statistics were calculated for several network configurations and source declinations. The results are shown in Figure 3. In the most favorable case (source at declination $+40°$ and 32-station network), the corrections obtained from the simulated images are statistically very close to the theoretical model corrections, which seems very promising for implementing such corrections in future VLBI2010 operations.



(Statistics in picoseconds)		- 40°	0°	+ 40°
16 stations	Median diff.	4.2	6.0	2.2
	RMS	0.4	0.8	0.5
32 stations	Median diff.	1.9	2.1	0.5
	RMS	0.4	0.4	0.4

Figure 3. Left: Plot of the median structural delay in picoseconds (green diamond) for each simulation run when the sample source is placed at declination $+40°$. The mean of the distribution is plotted as a blue (dashed) line while the median correction for the theoretical model is plotted as a black continuous line. Additionally, the median correction for the simulation obtained without additive noise is plotted as a red (dotted) line. Right: Differences between the mean of the distribution and the median correction for the theoretical model, and RMS of the corrections around the mean of the distribution for several configurations of network and source declination.

4. Conclusion

Previous studies showed that the VLBI2010 system is well adapted to produce high-quality images of extragalactic radio sources. In addition, such studies highlighted that 32-station networks should be preferred over 16-station networks since the latter fails to reconstruct extended structures for sources at low declination.

In this paper, we calculated statistics on structure corrections for a set of simulated images based on Monte-Carlo generated visibilities and for theoretical structure corrections derived from the model. These statistics demonstrated once again that 32-station networks are recommended to obtain structure corrections statistically close to the theoretical model ones.

Future prospects include studying such statistics not for the whole u-v plane as done here, but for the individual u-v points actually observed during hypothetical VLBI2010 sessions. It will also be important to extend this study in the context of the broadband system, noting that some difficulties may arise, such as the change of structure with frequency or the position dependency of the source core with frequency (known as "core-shift").

References

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