Implementation of VLBI Near-Field Delay Models in the c5++ Analysis Software

Klopotek G, Hobiger T, Haas R

Abstract We describe the implementation of two near-field delay models in the c5++ analysis software. The motivation for this work is to allow the calculation of a priori delay information for the correlation of VLBI raw observations of near-field targets and to prepare for the analysis of VLBI data of near-field objects. The software is tested by correlating VLBI observations of the Chinese Chang'E lunar lander on the Onsala–Wettzell baseline.

Keywords VLBI near-field models, geodetic VLBI, Chang'E-3, Moon, c5++

1 Introduction

During recent years, the geodetic VLBI community has become more and more interested in VLBI observations of objects located at a finite distance. One of the main drivers for an increasing interest in this topic are ideas of future co-location satellites that will be equipped with VLBI transmitters together with other space geodetic equipment, including GNSS receivers and Satellite Laser Ranging (SLR) reflectors. It is expected that such co-location satellites could be used to improve the International Terrestrial Reference Frame (ITRF). However, so far only a single prototype satellite exists and only a few experimental test sessions have been performed. Other near-field objects tracked with VLBI during the last years are GNSS satellites which were observed with regional VLBI networks in Europe, Australia and Asia on an experimental basis (Tornatore et al., 2014). Missions to other planets in the solar system and the Moon have been also areas of interest for utilization of VLBI observations (Lebreton et al., 2005; Kikuchi et al., 2009; Jones et al., 2015).

In late 2013 a robotic lander and a rover was deployed to the surface of the Moon within the Chang'E-3 (CE-3) mission of the Chinese Lunar Exploration Program (CLEP). The main scientific goal of this project was to examine the geological structure of the Moon and observe celestial bodies in the visible/near-infrared spectrum (Li et al., 2015). First European observations of the CE-3 signals with geodetic VLBI telescopes were performed in April 2014 on the Onsala–Wettzell baseline. Following these, an observational program was proposed to the IVS Program Committee to regularly observe the lunar lander with a global network of IVS stations (Behrend, 2013). Four OCEL-sessions (Observing the Chang'E Lander with VLBI) each year were granted by the IVS in 2014, 2015 and 2016.

An object is considered to be at a finite space ("near-field") if the distance between the source and a pair of telescopes creating a baseline is significantly smaller than the ratio of the squared baseline length divided by the observed wavelength (Born and Wolf, 1970). For these situations the commonly used plane-wave approximation is no longer valid and so-called "near-field models" have to be used for the data correlation as well as data analysis. Practical

---

Grzegorz Klopotek
Department of Earth and Space Sciences, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

Thomas Hobiger
Department of Earth and Space Sciences, Chalmers University of Technology, Observatorievägen, SE-439 92 Onsala, Sweden

Rüdiger Haas
Department of Earth and Space Sciences, Chalmers University of Technology, Observatorievägen, SE-439 92 Onsala, Sweden

approaches for the computation of VLBI near-field delays can be found e.g. in Moyer (2000), Klioner (2003), Sekido and Fukushima (2006) or Duev et al. (2012). However, there is a lack of comprehensive comparison of these models, in particular the latter two approaches which are used in VLBI spacecraft tracking. Therefore, we present their brief comparison using delays from both approaches computed in the c5++ analysis software (Hobiger et al., 2010) for the target source located on the surface of the Moon. Moreover, we use the two aforementioned models for correlation of observations of the Chang'E-3 lander carried out in April 2014 during a test experiment at the Onsala Space Observatory and at the Geodetic Observatory Wettzell. In addition, we highlight the role of the c5++ analysis software in the processing pipeline of lunar VLBI data with the main aim of obtaining multi-band group delay observables. Finally, we formulate the outlook concerning observations to artificial radio sources on the Moon through the use of the VLBI technique.

2 Method & Data

First European test observations to the Chang'E-3 lander were carried out on April 8, 2014, at the Onsala Space Observatory and at the Geodetic Observatory Wettzell. The test session LUN04b consisted of 2 hours of lunar observations with scans of 15 second length when observing the lunar lander signal. Three blocks of observations to natural radio sources were included in the schedule, using a frequency setup with four S- and X-band channels each of 8 MHz bandwidth. For the lunar lander observations, the strong X-band signal of the Chang'E communication channel was observed, also with 8 MHz bandwidth. In this test session no DOR-tones were observed.

Data gathered during this experiment were correlated at the Onsala Space Observatory using the DiFX software (Deller et al., 2007). A simplified flowchart of the processing pipeline used in this study is depicted in Fig. 1. Manually created VLBI experiment (VEX) files were used to produce inputs to the mpifxcorr utility. After correlation, the resulting DiFX output files were converted to Mark4 format so that the Fourfit program could be used for fringe fitting.

Theoretical VLBI delays can be computed by default in the DiFX environment with the *calcif* tool that produces so-called "IM" (interferometer model) files containing VLBI delays expressed in polynomial form. However, *calcif* only includes a VLBI far-field models and thus is not suitable for lunar observations. Instead the *difxcalc* tool could be used, since it also includes VLBI near-field models. An alternative approach followed in this study is to use c5++ to replace the far-field model delays by near-field model delays.

For the LUN04b experiment data correlation was carried out using theoretical delays from the c5++ analysis software. This program is mainly utilized in the analysis of VLBI, SLR and GNSS data (Hobiger et al., 2014, 2015). However, a recently developed module was used to include a priori VLBI near-field delays into correlation process of this session. This was achieved by replacing the default delay polynomials in the IM files by those computed from the c5++ software which can provide near-field delays in accordance to the models described by Sekido and Fukushima (2006) and Duev et al. (2012). In c5++, VLBI delays or delay polynomials of a given degree can be computed using the spacecraft state vector in the body-fixed reference frame of a planet or the Moon (Archinal et al., 2011). The latter requires information from JPL's ephemeris files (Folkner et al., 2009). In case of satellites, NASA/NORAD Two-Line Elements (TLE) data or Multi-GNSS Experiment (MGEX) orbit products can be used to calculate position of objects either in ITRF or ICRF.

The aforementioned analysis software supports transformation of object's state vectors and reference points of telescopes to the Barycentric Celestial Reference System (BCRS) in which computed difference of reception times at both stations is expressed in the barycentric dynamical time (TDB) (Sekido and Fukushima, 2006). The conversion of the computed delays to the time-scale at observing stations is also supported in the c5++ software.

Delay differences between the near-field models described in Sekido and Fukushima (2006) and Duev et al. (2012) during a period of 30 days for an object located on the lunar surface are presented in Fig. 2.

For short baselines such as ONSALA60–WETTZELL, the delay differences show a variation on the level of tens of picoseconds, see Fig. 2 . This level of disagreement tends to scale with the increasing distance between VLBI stations.

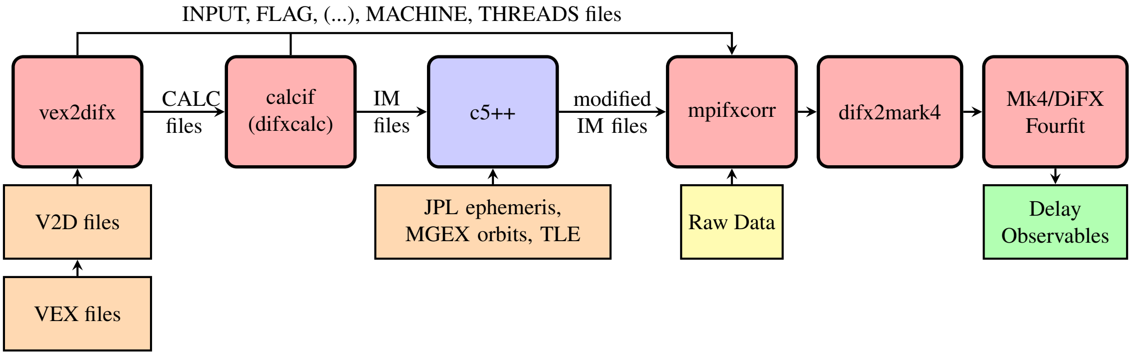

Fig. 1 Simplified schematics of the VLBI data correlation with DiFX using the common processing chain supplemented by the c5++ analysis software. After the DiFX processing is finished, the program Fourfit program can be used for fringe-fitting.

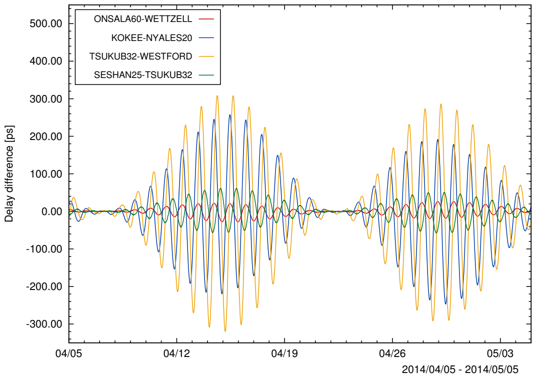

Fig. 2 Delay differences for a period of 30 days computed with the c5++ analysis software for a stationary object located on the Moon (44.12 N, 19.51 W) using the models of Sekido and Fukushima (2006) and Duev et al. (2012). No technique-specific, atmospheric nor tidal effects contributing to the VLBI delays have been considered here.

For intercontinental baselines such as KOKEE–NYALES20 the delay differences reach up to hundreds of picoseconds at several epochs during the considered period. Conclusions on the origin of such large discrepancies and pattern cannot be made at this stage and further investigations are needed, both in terms of baseline length and configuration as well as distance and type of the tracked source.

3 Results

Correlation of VLBI observations of the communication channel of the Chang'E lunar lander using the processing chain presented in Fig. 1 was carried out for session LUN04b twice, each time applying a different near-field delay model. Results from the fringe-fitting with Mk4/DiFX Fourfit for a single scan on the ONSALA60–WETTZELL baseline are shown in Fig. 3

Almost identical single band delay values were obtained in the two runs. The difference between the estimated single band delays is a few ps. The signal to noise (SNR) as well as the mean amplitude values of the cross-correlated signal are almost identical. A slope of the correlator phase and amplitude w.r.t. time for a single reference frequency of 8491.98 MHz is not seen on the plot.

4 Conclusions and Outlook

In this study we compare a priori VLBI delays for the target source on the Moon that were computed using two near-field models commonly used in VLBI spacecraft tracking. In addition, we present results of data correlation from the test observations of the Chang'E-3 lander located on the surface of the Moon. We also describe the role of the c5++ analysis software in correlation of VLBI data. Near-field delays calculated in c5++ for the source on the Moon using approaches described in Duev et al. (2012) and Sekido and Fukushima (2006) differ at the level of tens of picoseconds for the shorter baselines ($<$ 2000 km). However, this fact did not affect the obtained delays on the ONSALA60–WETTZELL baseline in a significant manner. Differences between delays

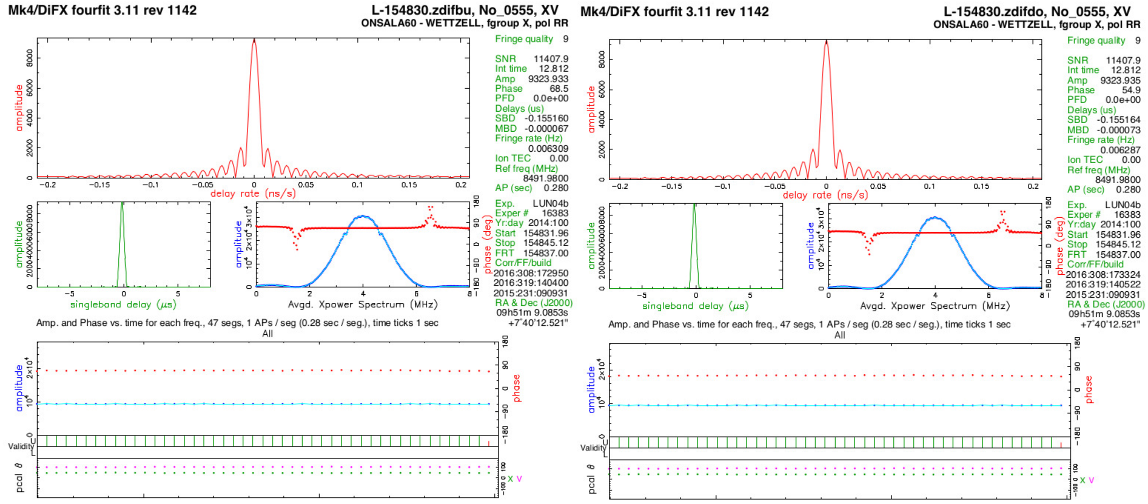

Fig. 3 Fringe-fitting results for the X-band carried out in the Mk4/DiFX Fourfit ver. 3.11 using VLBI near-field models described in Duev et al. (2012) (left) and Sekido and Fukushima (2006) (right) on the ONSALA60–WETTZELL baseline. A priori delay polynomials for the DiFX correlation were determined with the c5++ analysis software and then fed into IM files for DiFX.

from both models tend to scale with the distance between stations and they can reach up to 300 ps at some epochs on intercontinental baselines such as TSUKUB32–WESTFORD. This needs to be investigated in the future. Moreover, the correlation of lunar observations on intercontinental baselines using these two theoretical models could also be beneficial for such a comparison.

No major problems related to the correlation and fringe-fitting processes have been identified. The high SNR and amplitude values obtained on the ONSALA60–WETTZELL baseline indicate that the observation time of the Chang'E-3 lander could be decreased in this case in order to schedule more lunar observations within the same session.

Incorporation of the c5++ analysis software into the data correlation chain described here allowed us to identify numerical issues, correct bugs concerning calculation of VLBI delays in a finite space and develop a module capable of processing of IM files used in the DiFX software.

Our results can provide new insights into the correlation of lunar observations from previous, recent and future lunar exploration missions. Further work related to the observation of radio transmitters on the Moon is considered in order to validate the two VLBI near-field models within the c5++ environment. It is also planned to carry out simulations concerning determination of the position of an object on the lunar surface through the use of geodetic VLBI. Furthermore, we will also study optimized observation schedules dedicated for lunar observations and the potential impact of those observations on estimation of Moon and Earth-based parameters. This is thought to enable geodetic VLBI to observe and monitor artificial radio sources on the surface of the Moon.

5 Acknowledgments

The authors would like to thank Dmitry Duev for his feedback concerning VLBI near-field model, as well as Alexander Neidhardt from the Technical University of Munich for providing data from lunar observations carried out at the Geodetic Observatory Wettzell.

References

Archinal, B.A., A'Hearn, M.F., Bowell, E., Conrad, A., Consolmagno, G.J., Courtin, R., Fukushima, T., Hestroffer, D., Hilton, J.L., Krasinsky, G.A., Neumann, G., Oberst, J., Seidelmann, P.K., Stooke, P., Tholen, D.J., Thomas, P.C., Williams, I.P., 2011. Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2009.

Celestial Mechanics and Dynamical Astronomy 109, 101–135. doi:`10.1007/s10569-010-9320-4`.

Behrend, D., 2013. Data Handling within the International VLBI Service. *Data Science Journal* 12, WDS81–WDS84. doi:`10.2481/dsj.WDS-011`.

Born, M., Wolf, E., 1970. Principles of Optics. Fourth ed., Pergamon Press Inc., Bath, Great Britain.

Deller, A.T., Tingay, S., Bailes, M., West, C., 2007. DiFX: A Software Correlator for Very Long Baseline Interferometry Using Multi-processor Computing Environments. *Publications of the Astronomical Society of the Pacific* 119, 318–336. doi:`dx.doi.org/10.1086/513572`.

Duev, D.A., Calves, Molera, G., Pogrebenko, S.V., Gurvits, L.I., Cimo, G., Bahamon, T.B., 2012. Spacecraft VLBI and doppler tracking: algorithms and implementation. *Astronomy & Astrophysics* 541, A43. doi:`10.1051/0004-6361/201218885`.

Folkner, W.M., Williams, J.G., Boggs, D.H., 2009. The Planetary and Lunar Ephemeris DE 421. IPN Progress Report 42-178.

Hobiger, T., Otsubo, T., Sekido, M., 2014. Observation level combination of SLR and VLBI with c5++: A case study for TIGO. *Advances in Space Research* 53, 119 – 129. doi:`http://dx.doi.org/10.1016/j.asr.2013.10.004`.

Hobiger, T., Otsubo, T., Sekido, M., Gotoh, T., Kubooka, T., Takiguchi, H., 2010. Fully automated VLBI analysis with c5++ for ultra rapid determination of UT1. *Earth Planets Space* 62, 933–937. doi:`10.5047/eps.2010.11.008`.

Hobiger, T., Rieck, C., Haas, R., Koyama, Y., 2015. Combining GPS and VLBI for inter-continental frequency transfer. *Metrologia* 52, 251. doi:`10.1088/0026-1394/52/2/251`.

Jones, D.L., Folkner, W.M., Jacobson, R.A., Jacobs, C.S., Dhawan, V., Romney, J., Fomalont, E., 2015. Astrometry of Cassini With the VLBA to Improve the Saturn Ephemeris. *Astronomical Journal* 149, 28. doi:`10.1088/0004-6256/149/1/28`.

Kikuchi, F., Liu, Q., Hanada, H., Kawano, N., Matsumoto, K., Iwata, T., Goossens, S.J., Asari, K., Ishihara, Y., Tsuruta, S., Ishikawa, T., Noda, H., Namiki, N., Petrova, N., Harada, Y., Ping, J., Sasaki, S., 2009. Picosecond accuracy VLBI of the two subsatellites of SELENE (KAGUYA) using multifrequency and same beam methods. *Radio Science* 44. doi:`10.1029/2008RS003997`.

Klioner, S.A., 2003. A Practical Relativistic Model for Microarcsecond Astrometry in Space. *The Astronomical Journal* 125, 1580. doi:`10.1086/367593`.

Lebreton, J.P., Witasse, O., Sollazzo, C., Blancquaert, T., Couzin, P., Schipper, A.M., Jones, J.B., Matson, D.L., Gurvits, L.I., Atkinson, D.H., Kazeminejad, B., Perez-Ayucar, M., 2005. An overview of the descent and landing of the Huygens probe on Titan. *Nature* 438, 758–764. doi:`10.1038/nature04347`.

Li, C., Liu, J., Ren, X., Zuo, W., Tan, X., Wen, W., Li, H., Mu, L., Su, Y., Zhang, H., Yan, J., Ouyang, Z., 2015. The Chang'e 3 Mission Overview. *Space Science Reviews* 190, 85–101. doi:`10.1007/s11214-014-0134-7`.

Moyer, T.D., 2000. Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation. JPL Deep-Space Communications and Navigation Series.

Sekido, M., Fukushima, T., 2006. A VLBI Delay Model for Radio Sources at a Finite Distance. *Journal of Geodesy* 80, 137–149. doi:`10.1007/s00190-006-0035-y`.

Tornatore, V., Haas, R., Casey, S., Duev, D., Pogrebenko, S.V., Calvés, G.M., 2014. Direct VLBI Observations of Global Navigation Satellite System Signals, in: Rizos, C., Willis, P. (Eds.), *Earth on the Edge: Science for a Sustainable Planet: Proceedings of the IAG General Assembly*, Springer Berlin Heidelberg, Berlin, Heidelberg. pp. 247–252. doi:`10.1007/978-3-642-37222-3_32`.