VLBI-Art: VLBI analysis in real-time

M. Karbon, T. Nilsson, C. Tierno Ros, R. Heinkelmann, H. Schuh

Abstract Geodetic Very Long Baseline Interferometry (VLBI) is one of the primary space geodetic techniques providing the full set of Earth Orientation Parameters (EOP) and it is unique for observing long term Universal Time (UT1). Accurate and continuous EOP obtained in near real-time are essential for satellite-based navigation and positioning, enable the precise tracking of interplanetary spacecraft and thus are the aim of the VGOS (VLBI2010 Global Observing System). With this next generation VLBI system and network, the International VLBI Service for Geodesy and Astrometry (IVS) increased its efforts to reduce the time span between the collection of VLBI observations and the availability of the final results. Project VLBI-Art contributes to these objectives by considerably accelerating the VLBI analysis procedure by implementing an elaborate Kalman filter, which represents a perfect tool for analyzing VLBI data in quasi real-time. The Kalman filter will be embedded in the Vienna VLBI Software (VieVS) as a completely automated tool, i.e. with no need of human interaction.

Keywords VLBI2010, Kalman filter

1 Introduction

Geodetic Very Long Baseline Interferometry (VLBI) ist the only space geodetic technique that allows the estimation of the full set of Earth Orientation Parameters (EOP), especially Universal Time (UT1) and celestial pole offsets. Furthermore, it is the only technique for the ralization of the International Celestial Reference Frame (ICRF). Additionally estimates of the tropospheric delay and other geodynamical and astronomical parameters can be provided (Sovers et al., 1998; Krásná et al., 2013).The International VLBI Service for Geodesy and Astrometry (IVS) currently conducts two to four 24-hourly VLBI sessions every week; the results are usually available within two weeks (Schuh and Behrend, 2012). The so-called intensive sessions are about one hour long and are observed by two to four stations with a particular focus on the UT1 determination. They are carried out almost every day and the results usually have a delay of one to two days. However, for (near) real-time navigation and positioning on the Earth and in space, real-time continuous EOP are necessary. For example, for the precise orbit determination of GNSS (Global Navigation Satellite Systems) satellites, accurate EOP are needed. Also for the tracking of interplanetary spacecrafts the exact orientation of the Earth in space is required (Ichikawa et al., 2004).To reach these goals, the VLBI2010 Global Observing System (VGOS; Petrachenko et al. (2009)) was proposed, where a dense network of very fast moving 'VLBI2010' antennas (slewing speed >6°/s) is foreseen, which are able to provide a high number of observations per time and are continuously operating. The aim is to reach an accuracy of 1 mm (position), 1 mm/year (velocity), respectively, from a global solution of 24-hour sessions, and near real-time operation with the help of electronic transfer of the data to the correlators. In order to retrieve the analysis results in near real-time, a solution algorithm is also required applying completely automated processes.

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2 Concept

The aim of the project VLBI-Art is to considerably shorten the time between the availability of VLBI observations and the availability of their respective results. The Kalman filter is a convenient method for real-time applications and it already proofed its suitability for VLBI analysis some time ago (Herring et al., 1990; Titov et al., 2004). However, the algorithms in the existing software packages implement the Kalman filter in the form of a post-processing tool, as the applied Kalman filters are not designed for true real-time applications. Within project VLBI-Art a Kalman filter will be realized that is in particular designated for analyzing VLBI data in (near) real-time. Since 2008, a VLBI analysis software has been developed at the Department of Geodesy and Geoinformation at Vienna University of Technology, called Vienna VLBI Software (VieVS) (Böhm et al., 2011; Nilsson et al., 2011). The Kalman filter developments of this project will be inserted into VieVS enabling the software package to automatically analyze VLBI data in real-time. The VieVS software consists of several parts. A schematic diagram is shown in Fig. 1, which includes how the near real-time VLBI data flow is intended to be realized. VIE_INIT reads the observed group delays currently from the so-called NGS-files. In VIE_MOD the theoretical VLBI delays and the partial derivatives of the observations w.r.t. the unknown parameters are calculated according to the most recent IERS Conventions (2010) and IVS standards (`http://vlbi.geod.uni-bonn.de/IVS-AC/`). The planned extensions of the existing program code, labeled as VIE_KALMAN, will include the new code, where the unknown parameters are estimated through the Kalman filter instead of the least-squares method, which is usually applied in VLBI analysis. To optimize the performance of the algorithm and to tweak the real-time capabilities of the Kalman filter, various investigations are foreseen in project VLBI-Art with real as well as simulated data. The results will be compared to other VLBI analysis packages and to corresponding parameter series from other techniques such as the Global Navigation Satellite Systems (GNSS). As VieVS contains a scheduling (VIE_SCHED) as well as a simulation tool, we will be able to simulate artificial observations for the complete future VLBI2010 network and assess the real-time accuracy which can be achieved. Moreover we will investigate the promising possibility of feeding data provided by other sensors into the Kalman filter, like atmospheric angular momentum calculated from numerical weather models or tropospheric delays from GNSS or water vapor radiometer.

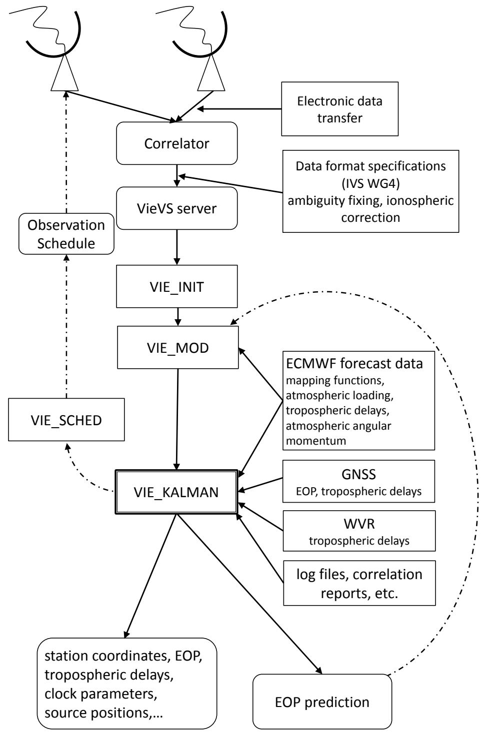

Fig. 1 Flowchart of automated real-time VLBI data processing with VieVS

3 Method

The Kalman filter is widely applied in various fields of research and developement including the analysis of space geodetic data (c.f. Morabito et al. (1988); Herring et al. (1990); Nilsson et al. (2011)). The advantage of such a filter over ordinary least-squares is that the estimation is made sequentially, epoch by epoch, by combining the observations at each epoch with the estimation of the previous epochs, making it ideal for real-time applications (Kalman, 1960). If $\mathbf{x_k}$ is the state vector containing all unknown parameters to be estimated at epoch k, it can be related to the estimates at a previous epoch $\mathbf{x_{k-1}}$ through

$$\mathbf{x_k} = \mathbf{F_k}\mathbf{x_{k-1}} + \mathbf{w_k} \,, \tag{1}$$

where $\mathbf{F_k}\mathbf{x_{k-1}}$ is the prediction of $\mathbf{x_k}$ based on $\mathbf{x_{k-1}}$ and $\mathbf{w_k}$ is the error in the prediction. The covariance matrix of the total error $\mathbf{P}_k^-$ can be calculated by

$$\mathbf{P}_k^- = \mathbf{F_k P_{k-1} F_k^T} + \mathbf{Q_k}\,, \tag{2}$$

with $\mathbf{P_{k-1}}$ denoting the variance-covariance matrix of $\mathbf{x_{k-1}}$ and $\mathbf{Q}_k$ the variance-covariance matrix of the prediction error $\mathbf{w}_k$. The observations $\mathbf{z}_k$ at epoch t_k are introduced through

$$\mathbf{z_k} = \mathbf{H_k x_k} + \mathbf{v_k}\,. \tag{3}$$

$\mathbf{H_k}$ is the observation matrix and v_k is the observation noise. To get the optimal estimation for $\mathbf{x_k}$ and its covariance matrix $\mathbf{P_k}$ the prediction $\mathbf{x_k^-}$ and the observation $\mathbf{z_k}$ can be combined

$$\mathbf{x_k} = \mathbf{x_k^-} + \mathbf{K_k}(\mathbf{z_k} - \mathbf{H x_k^-})\,, \mathbf{P_k} = (\mathbf{I} - \mathbf{K_k H_k})\mathbf{P_k^-}\,, \tag{4}$$

with the Kalman gain $\mathbf{K_k}$

$$\mathbf{K_k} = \mathbf{P_k^- H_k^T}(\mathbf{H_k P_k^- H_k^T} + \mathbf{R_k})^{-1}\,, \tag{5}$$

where $\mathbf{R_k}$ is the variance-covariance matrix of the observation noise $\mathbf{v_k}$.

4 Conclusions

Within project VLBI-Art we will develop a software module for near real-time analysis of VLBI data extending the existing analysis software VieVS. This step will enable the software to process VLBI data in near real-time and to predict various parameters, like EOP, necessary for example for space craft navigation or tropospheric parameters, which are of interest for meteorology. We will compare our Kalman filter solution with the results from other software packages and from other data series and test the effects of feeding additional data like atmospheric angular momentum functions or information about the local water vapor content into the filter. With this software we aim to be prepared for the VLBI2010 analysis requirements with its huge data amount and its ambitious goals to continuous observations and derive results in near real-time. Since VieVS is a freely available software for registered users, also this module will be freely available after the Kalman filter is correctly implemented and thoroughly tested.

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