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The Combination of Kalman Filter and Least-Squares Solutions of Different VLBI Analysis Centers

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The IVS (International VLBI Service for Geodesy and Astrometry) Analysis Centers (BKG (Federal Agency for Cartography and Geodesy), NASA GSFC (Goddard Space Flight Center), DGFI (Deutsches Geodaetisches Forschungsinstitut), SHA (Shanghai Astronomical Observatory), USNO (U.S. Naval Observatory), MAO (Main Astronomical Observatory), AUS (Geoscience Australia)) use various analysis softwares to analyze geodetic VLBI observables. The software packages apply different statistical methods and a priori information to derive the parameters of interest. These statistical methods are the Least-Squares (LSQ) method, the Kalman filter (KF) method, the Square-Root Information Filter (SRIF) and the Least-Squares Collocation (LSQC) method. These statistical approaches differ in the propagation of variance-covariance information and the behaviour of the stochastic parameters. However, it is difficult to state that one solution is better than the other. The quality of products of geodetic Very Long Baseline Interferometry (VLBI) observations are improved in terms of reliability, robustness and accuracy if the results of different analysis software packages are combined using a suitable combination process (intra-technique combination). In our previous combination algorithm, the normal equations in SINEX format were taken on a session-by-session basis from five different IVS Analysis Centers (BKG, GSFC, DGFI, SHA, USNO) which apply only LSQ solutions. With this study, we start to consider Kalman filter and LSQ in our combination, too. It is aimed to present ideas and to discuss problems about such a possible combination. The Kalman filter with stochastic models is an alternative approach to the use of polynomials to model the effects of the clocks and atmospheric delays. The effect of the stochastic models on the

estimates of geodetic parameters and the quality of these estimates will be compared to the conventional LSQ method.

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Introduction

The IVS (International VLBI Service for Geodesy and Astrometry) Analysis Centers (BKG (Federal Agency for Cartography and Geodesy), NASA GSFC (Goddard Space Flight Center), DGFI (Deutsches Geodaetisches Forschungsinstitut), SHA (Shanghai Astronomical Observatory), USNO (U.S. Naval Observatory), MAO (Main Astronomical Observatory), AUS (Geoscience Australia)) use various analysis softwares to analyze geodetic VLBI observables. The software packages apply different statistical methods and a priori information to derive the parameters of interest. These statistical methods are the Least-Squares (LSQ) method, the Kalman filter (KF) method, the Square-Root Information Filter (SRIF) and the Least-Squares Collocation (LSQC) method. These statistical approaches differ in the propagation of variance-covariance information and the behaviour of the stochastic parameters. However, it is difficult to state that one solution is better than the other. The quality of products of geodetic Very Long Baseline Interferometry (VLBI) observations is improved in terms of reliability, robustness and accuracy if the results of different analysis software packages are combined using a suitable combination process (intra-technique combination).

Aim

In our previous combination algorithm, the normal equations in SINEX format were taken on a session-by-session basis from five different IVS Analysis Centers (BKG, GSFC, DGFI, SHA, USNO) which apply only LSQ solutions. With this study, we start to consider Kalman filter and LSQ in our combination, too. For the intra-technique combination of different VLBI Analysis Center solutions, the effect of the stochastic models on the estimates of geodetic parameters and the quality of these estimates should be taken into account.

VLBI Analysis Strategies and Software Packages

The estimated geodetic parameters in VLBI data analysis are station coordinates and velocities, earth orientation parameters, radio source positions, parameters of geophysical models, atmospheric parameters. There are different used VLBI software packages for analysis developed by various IVS components. CALC/SOLVE (LSQ), MODEST (SRIF), OCCAM (LSQ/KF/LSQC), GLORIA (LSQ), STEEL-BREEZE (SRIF), GEOSAT (KF) are the commonly used software packages. The adjustment is carried out using three different methods in OCCAM software. The property of offering estimation results with different adjustment methods within the OCCAM software is an efficient tool to make a comparison of data analysis methods.

Methods

Within this study, CONT05 sessions are analyzed by OCCAM software with KF and LSQ adjustment methods. We used real CONT05 sessions and also simulated CONT05 sessions in which the geophysical effects are set equal. Baseline length is used as a accuracy measure for the make comparison between results taken from KF and LSQ within VLBI software OCCAM.

Data analysis for real CONT05 sessions

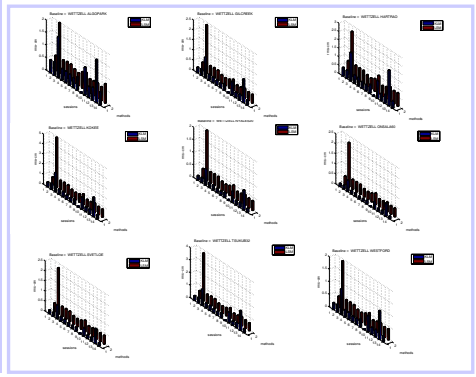


Figure 1: rms values for adjusted baseline lengths in real CONT05 sessions

Data analysis for simulated CONT05 sessions

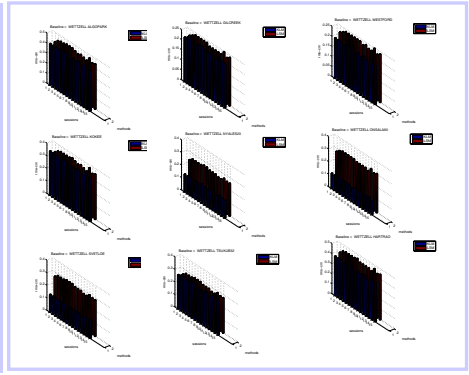


Figure 2: rms values for adjusted baseline lengths in simulated CONT05 sessions

rms values for the baseline lenghts estimated by Kalman Filter for are always smaller than of Least-Squares method. The differences between the results can be seen even inside the same solution (KF or LSQ). To understand the reason of this effect, it is necessary to go in detail in the implemented algorithm for the Kalman Filter solution.

Acknowledgements: Thanks to International VLBI Service for Geodesy and Astrometry (IVS) for providing their data and to Joerg Wresnik for providing simulated data for the CONT05 sessions.

References: Albertella A., Betti B., Sansò F., Tornatore V., "Real time batc navigation solutions: alternative approaches", Arti Grafiche Pisano (Cagliari), Cagliari, Bollettino SIFET, ISSN 1721-971X, Pagg. 82-99, Vol. n.4/2005, No.1.

Kalman Filtering in VLBI Data Analysis

In VLBI analysis, Kalman Filtering (KF) is used to account for stochastic behavior on the clocks and the atmosphere parameters which vary during the course of a VLBI session. Local parameters e.g. clocks, atmospheres, and EOP are estimated with KF by forward and backward applications (filtering and smoothing) in case more than one estimation is applied within a 24-h period. However, for the global parameters, e.g. station coordinates, station velocities, radio source coordinates, only forward solution is applied. The real-time estimate provided by Kalman Filter at time t exploits the information available up to the time t only.

Equivalence of Kalman Filter and Least Squares

The optimal solution of KF has to be derived taking into account all the observations. Under the same starting hypotheses describing the dynamic of a system, the LSQ solution is equivalent to what in Kalman filter literature is called the final estimate or optimal estimate obtained with the full data set by applying first the Kalman Filter and then running back with the Kalman smoother. The equivalence of two procedures has been verified by some simulated numerical examples (Albertella et all. 2005).

It has to be noticed that many software do not often implement the Kalman smoother at all, or if it is applied, it is not implemented in a rigorous way especially for the computation of the variance/covariance matrix of the final estimate. Then one could have a different approach in the rejection of outliers used by LSQ and KF and therefore obtain different results. So, we should understand firstly the effect of using KF on the geodetic parameter estimation (baselines, coordinates, or EOP).

Conclusion

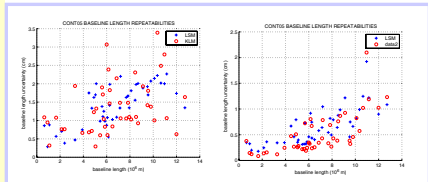


Figure 3: Repeatability of adjusted baseline lengths for real and simulated CONT05 sessions

Baseline length repeatability:
One of the measures of the overall accuracy of the space geodesy technique is the statistics of the baseline length repeatability. The smaller value of the repeatability, the better.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(L_i - L_0)^2}{n-2}}$$

L_i estimated baseline length
L_0 mean value of estimated baseline lengths
n number of estimated baseline lengths

Baseline length repeatability are consistent in each other for KF and LSQ solutions for real CONT05 sessions. The same values of KF solutions are smaller than of LSQ solutions for simulated CONT05 sessions.

In case of using individual AC solutions taken from different adjustment methods (e.g., KF and LSQ), we should consider the effect of using different adjustment methods on the parameter estimation in individual solutions.
From this study we get the first impression of how the parameter estimation differ in different adjustment methods. The second step of our study will be to combine two solutions writing the proper formulas of combination in a way similar to normal equation level combination but using not only Least Squares solutions, but Kalman Filtering, too.