Combination of Microwave and Optical Observations for minimizing Atmospheric induced variations in Parameter Estimation

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Abstract

Atomic Clock Ensemble in Space (ACES) is an ESA future space mission, with focus on fundamental physics and time transfer. The basic configuration consists of a Two-Way Microwave-Link (MWL) in space and ground, an optical detector and reflector, as well as a new generation of atomic clocks. To use their full fractional frequency stability and accuracy, all observation errors have to be minimized before post-processing. Especially electronic delays of MWL systems in transmitting and receiving are correlated with clock estimations. For that, the hardware will be pre-calibrated on ground, but there is no guarantee that the electronic delays of the system calibration will be static. Therefore, we develop a strategy to calibrate the MWL in downlink as well as in uplink direction. Due to the fact, that the official launch date is in 2025, there is a lack of real observation data. For that, we focus in our work first on near-realistic error simulation and afterwards on the calibration process. The developed simulation software, produces MWL code and phase observations in downlink and uplink, as well as one- and two-way laser observations. For calibration, we combine MWL- and optical-data in a Least-Square-Adjustment (LSA). Our studies show, that minimizing the atmosphere induced errors, is crucial for a proper hardware calibration. Assuming a common atmosphere for simultaneous optical and microwave observations, minimizes the tropospheric delay on the MWL observations sufficiently. We tested our calibration strategy with one month of simulation data, which corresponds to about 100 passes over a specific ground station. The delays could be estimated within sufficient accuracy, but there is still some space for improvements. Our further research will be focused on common troposphere estimation, as well as the impact of different observation weights on parameter estimation in LSA.

1. Introduction

The ACES mission (Cacciapuoti, et al., 2009) will be an opportunity to test a new generation of atomic clocks in space (Salomon, et al., 2001) together with a collocation of several high-precise geodetic observation techniques on the ISS and on different ground stations (ESA, 2010). This combination will enable investigations in time transfer as well as in fundamental physics with an accuracy and precision, which would not be reachable with traditional observation configurations (Salomon, et al., 2006). The observation techniques consist of a Microwave-Link- (MWL) and an Optical-Link-System (OPT), which consist of an optical one-way link and classic SLR. To carry out experiments in fundamental physics and time transfer with sufficient accuracy and precision, there is the need of a proper MWL system calibration. Due to the high correlation between the MWL measurement parameters (Wang, et al., 2017), it is necessary to additional use OPT measurements in one and two-way for the calibration process.

2. Simulation

Due to the fact, that the ACES mission will not start before 2025 (ACES, 2022), we implemented a full-scale simulation software, enabling us to develop a first concept of calibration strategy. With the awareness that a simulation cannot beat the reality, we tried to keep the artificial observations as realistic as possible. Which is why the main focus during the implementation of the simulator was set on a realistic troposphere simulation. Table 1 lists the parameters of the simulated measurements for both, OPT and MWL:

Table 1 Simulation Parameters

Parameter	Model	MWL	OPT
Troposphere	ERA5	X	X
Ionosphere	NeQuickG	X	/
Orbit	TLE	X	X
Clocks	Colored-Noise	X	X
Height Offset	-	0 mm	1 mm
Time Offset	-	0 ps	1 ps
Electronic Delay	-	1/0.9 ns (stable)	/
Noise	White Noise	0.2 ps	37 ps

For simulation of the tropospheric delay we used raytracing techniques based on the RADIATE software of TU Vienna (Hofmeister, et al., 2017), with the ERA5 weather model as input (Muñoz Sabater, 2019). For the simulated tropospheric influence on MWL observations, we also take dispersive tropospheric effects for the different wavelengths into account (Hobiger, et al., 2013). The ionospheric influences are simulated with the 3D-layer model NeQuickG (Aragon-Angel, et al., 2021). For orbits a TLE-propagator of the java toolbox Orekit (CS, 2018) is used. Clock Errors were calculated with colored-noise processes, based on Allan-Deviation parameter specifications (Cacciapuoti, et al., 2009). We also introduced a constant height error in the local geodetic network, as well as a time offset in the time distribution system between the OPT and MWL terminals on ground. Measurement noise was assumed to be pure white noise with an amplitude of 0.2 ps for MWL and 37 ps for OPT. The sampling rate for microwave based geodetic technique is 12.5 Hz, 100 Hz for the OPT one-way link and 300 Hz for classic SLR. The sum of the electronic delay in transmitting and receiving is assumed as stable with 1 ns in downlink- and 0.9 ns in uplink-direction.

The simulated dataset that we used to develop and test our calibration strategy consist of 100 passes of the ISS over Wettzell station in July 2021. A mean pass has a duration of 7 minutes and the culmination at 65° elevation. This high number of passes in one month was only possible due to the assumption of clear sky. Further assumptions are that all OPT measurements are in single-photon mode, as well as a stable electronic delay for all passes.

3. Parameter Estimation

For the calibration, which is nothing else than a parameter estimation, we chose a Least Square Adjustment (LSA), which is a classic and proven geodetic approach. The functional model was evolved based on observation equations for MWL and OPT measurements. With the additional OPT observations, we wanted to achieve two things. First, the additional OPT observations enables a better decorrelation of troposphere, orbit and clock errors. Second, the electronic delay can be estimated. Table 2Table 1 gives an overview about the parameters of interest:

Table 2 Estimation Parameters

Parameter	Description	LSA	Model
Troposphere	Common Troposphere	X	/
Orbit	Stochastic Model	X	/
Clocks	Offset	X	/
Ionosphere	STEC	/	X
Height/Time Offset/Noise	neglected	/	/

Introduced offsets in local tie, in common time between OPT and MWL ground stations, as well as measurement noise are not estimated. The ionospheric influence on MWL observations, are corrected by calculating a third order ionospheric correction based on STEC values and following IERS recommendations (Petit, et al., 2010). The remaining parameters are estimated and considered in LSA functional model. One parameter is set-up for the whole pass for electronic delay in up- and downlink and clock error, respectively. For orbit adjustment a stochastic model, based on four parameters for a short arc is used. Due to high correlations, no cross-track values can be determined. Therefore, only one radial bias and one value each for acceleration, velocity and bias in along-track direction are estimated. As a priori, a new orbit is propagated with slightly false TLE-Parameters. Table 3 lists the differences between the orbit used for simulation and the orbit used for LSA process. Like during the simulation, the main focus of the calibration strategy was on minimizing the tropospheric influence. A proper consideration will allow a stable electronic delay calibration for every pass, which is essential for experiments in fundamental physics (e.g. gravitational redshift). Therefore, we estimate a common troposphere for OPT and MWL observations. The idea behind, is that both signal types should pass nearly the same atmosphere and thus experience an attenuation for their respective physical properties. This means that we estimate two common atmosphere parameters out of both observation techniques. For the wet part of the troposphere, water vapor pressure and for the dry part air pressure, both at station height are estimated. These parameters are sufficient to calculate a technique specific zenith delay. Together with VMF1 (Böhm, et al., 2006) for MWL and VMFO (Boisits, et al., 2020) for OPT observations, we can minimize the isotropic part of the tropospheric delay. For the non-isotropic influence, we estimate tropospheric gradients based on common atmosphere parameters.

4. Assessment of Parameter Estimation

After evolving a functional model and before developing a calibration strategy, it is necessary to check if the chosen parameter approximations or models are adequate. Therefore, we calculated a so called best possible solution (BPS) for each parameter. This means that in each case, no other errors besides the error we want to check the model for are simulated. In the LSA, we then also only use the corresponding error model to set up the functional model.

4.1 Orbit

To assess the stochastic model for orbit estimation, we calculated the error free range between ground- and space-station and used it as simulation. For LSA processing we propagated a new orbit, based on slightly false TLE parameters and introduced this as an a priori orbit. Table 3 lists the median errors before and after the LSA process:

Table 3 Orbit errors a priori/posteriori (BPS)

Type [mm]	Median		Factor
	a priori	a posteriori	
Radial	2.40	-0.14	~14
Along-Track	14.39	-0.38	~38
Range	2.09	0.03	~67

The results show that the chosen functional model, can minimize the a priori orbit errors at least by a factor of 14.

4.2 Troposphere

Similar to the assessment of the orbit error model, we also tested our functional model for tropospheric delay mitigation. Therefore, we simulated only tropospheric induced errors for OPT and MWL observations. Therefore, the functional model considers only a common isotropic and non-isotropic troposphere based on VMF1 (Böhm, et al., 2006) and VMFO (Boisits, et al., 2020) data as a priori values. Table 4 lists the median errors before and after the LSA process:

Table 4 Troposphere Total Slant Delay Errors a priori/posteriori (BPS)

Type [mm]	Median		Factor
	a priori	a posteriori	
MWL	41.67	0.27	~150
OPT	0.90	0.09	~10

The biggest improvement can be achieved for MWL specific tropospheric delay with an improvement factor of approximately 150. This was expected, due to the fact that the wet part of the troposphere is very difficult to model and needs therefore to be estimated. The improvements for OPT are less, which is due to the weak influence of water vapor on optical signals. Most of the attenuation comes from the troposphere's dry part, which can be modeled with sufficient accuracy.

5. Strategies

During our research we tested several calibration strategies, but will only refer to the two most promising ones. The tested strategies differ only in troposphere gradient estimation. Gradient corrections are applied to all observations after the LSA. Table 5 lists the two most promising calibration strategies:

Table 5 Calibration Strategies

Name	WVPR		Press.		Wet Gradient		Dry Gradient	
	MWL	OPT	MWL	OPT	MWL	OPT	MWL	OPT
wet-both	**X**		**X**		**X**	**X**	**-**	**-**
wet/dry-both	**X**		**X**		**X**	**-**	**X**	**X**

In both strategies we have estimated a common isotropic troposphere. The difference is in the gradient estimation, where for the "wet-both" strategy only a wet-gradient out of MWL and OPT observations is estimated. For the "wet/dry-both" strategy, a wet-gradient is estimated only based on MWL observations and a dry-gradient is estimated based on all observations. Also, each strategy was tested with different weightings. The standard method is a noise-dependent weighting (NW), based on the parameters in Table 1. The new weighting method has a ten times higher weight on OPT observations (LW), than on MWL observations.

6. Results

Figure 1 shows the results of the three most promising configurations of calibration strategy and weighting method. The differences between the results indicate that a parameter dependent calibration strategy should be chosen for further experiments. On the one hand NW method with the strategy "wet/dry-both" shows the best results for an electronic delay calibration. On the other hand, NW method with "wet-both" calibration strategy shows the best results for the geometric part, which contains orbit and troposphere. For the clock offset estimation all combinations of weighting method and calibration strategy show similar results, minimizing the clock error with sufficient accuracy. Interestingly, the LW method seems to be a good trade-off to estimate all parameters with sufficient accuracy. For all cases the median offset is not too high, and especially for the LW "wet-both" configuration also the pass to pass variations are small. This will help to improve the quality of some experiments in fundamental physics. The results of all strategies are within sufficient accuracy and precision for a proper calibration. Nevertheless, there are differences and advantages of some strategies with regard to different parameter estimates.

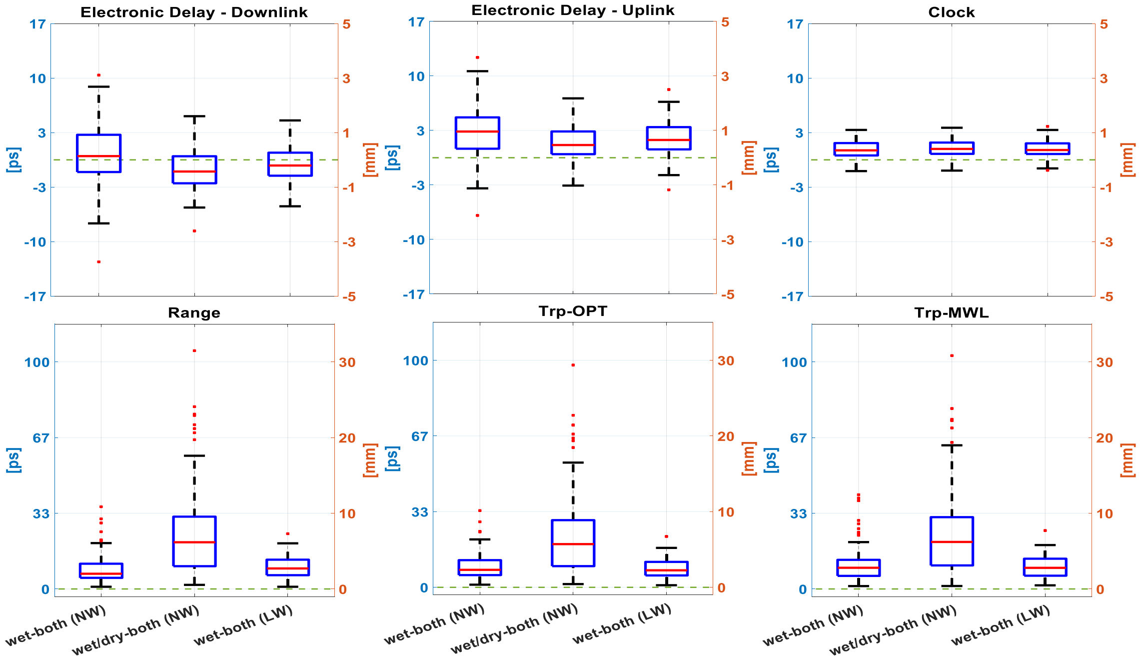

Figure 1 Differences of simulated and estimated parameters for different calibration strategies

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