Combination of Microwave and Optical Observations for Minimizing Atmospheric Induced Variations in Parameter Estimation

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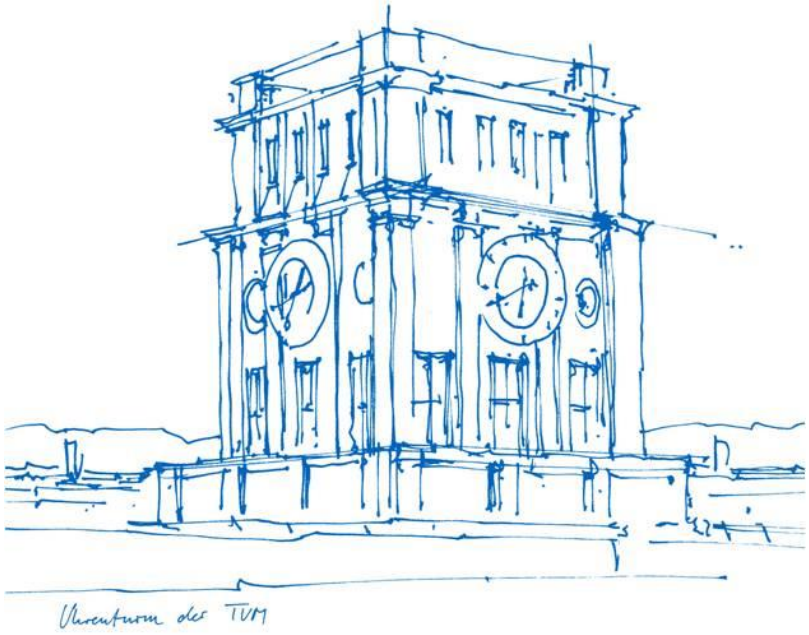
Guadalajara, 10. November 2022



Motivation – **A**tomic **C**lock **E**nsemble in **S**pace (2025)

Objectives:

- Time and frequency applications
- Fundamental physics (e.g. gravitational redshift)

Hardware:

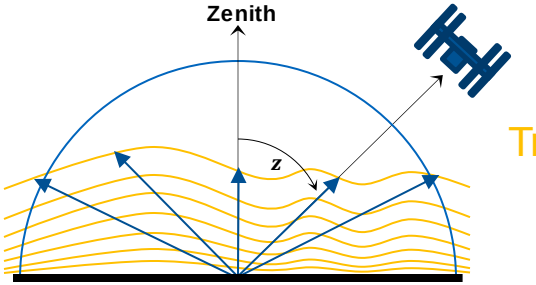
- **ACES**
  - Combination of high-precise clocks
- **M**icro**w**ave-**L**ink-System (**MWL**)
  - Up-/Downlink (S-/Ku-Band)

  → Combined-One-Way Link
- **Opt**ical-Links (**OPT**)
  - ELT/SLR

  → One-/Two-Way Link

Figure 1: ISS [ESA, 2011]

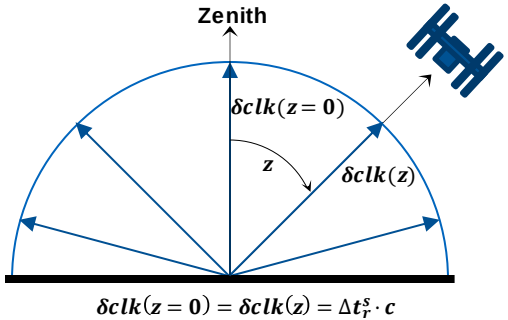
Motivation



Troposphere

$$\delta trp(z) = \frac{1}{\cos(z)} \cdot \delta trp(z=0)$$

Clock



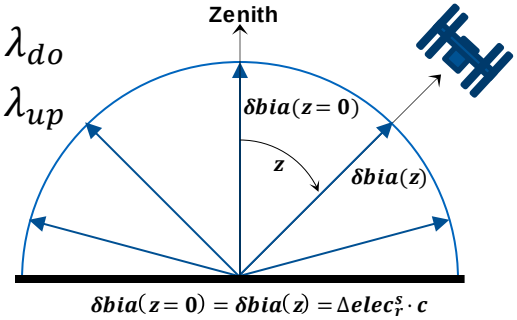
$$\delta clk(z=0) = \delta clk(z) = \Delta t_r^s \cdot c$$

$$\phi_{do} = \rho_r^s + \delta clk_r^s + \delta orb + \delta trp + \delta bia + N_{do} \cdot \lambda_{do}$$

$$\phi_{up} = \rho_r^s - \delta clk_r^s + \delta orb + \delta trp + \delta bia + N_{up} \cdot \lambda_{up}$$

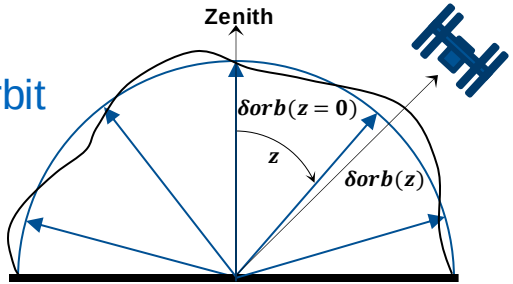
$$\tau_{ELT} = (\rho_r^s - \delta clk_r^s + \delta orb + \delta trp) \cdot c^{-1}$$

$$\tau_{SLR} = (\rho_r^s + \delta orb(\delta clk_r) + \delta trp) \cdot 2c^{-1}$$



$$\delta bia(z=0) = \delta bia(z) = \Delta elec_r^s \cdot c$$

Electronic Delay



Orbit

$$\delta orb(z=0) \neq \delta orb(z)$$

Figure 2: Parameter Correlations (Figures adapted from Wang, 2011)

Simulation

Parameter	Model	MWL	OPT
Troposphere	ERA5	X	X
Ionosphere	NeQuickG	X	-
Orbit	TLE	X	X
Clocks	Noise-Modeled	X	X
Height Offset	1 mm	-	X
Time Offset	1 ps	-	X
Electronic Delay	1.0 ns / 0.9 ns delay (stable)	X	-
Noise	White Noise	0.2 ps	37 ps
Sampling (Hz)	12.5 (MWL) / 100/300 (ELT/SLR)	100 %	10 %

Dataset:	▪ 100 passes	▪ ~ 7 min. mean duration	▪ ~ 65° mean max elevation
Assumptions:	▪ Good weather	▪ Single-Photon-Mode	▪ Stable electronic delay

Parameter Estimation – **L**east **S**quares **A**djustment

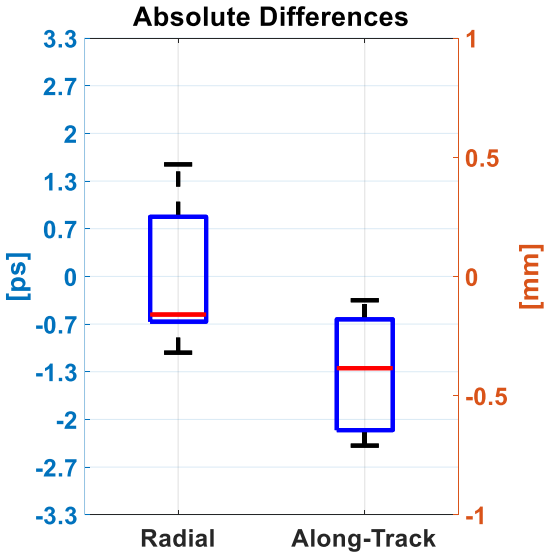
Parameter	Description	LSA	Model
Troposphere	- A priori values from VMF - Estimate a common troposphere - Gradient estimation	X	-
Ionosphere	- Linear Combination (STEC)	-	X
Orbit	- Stochastic model - 4 parameter	X	-
Clocks	- Clock offset	X	-
Electronic Delay	- MWL Delay in up/down	X	-
Height Offset	/	-	-
Time Offset	/	-	-
Noise	/	-	-

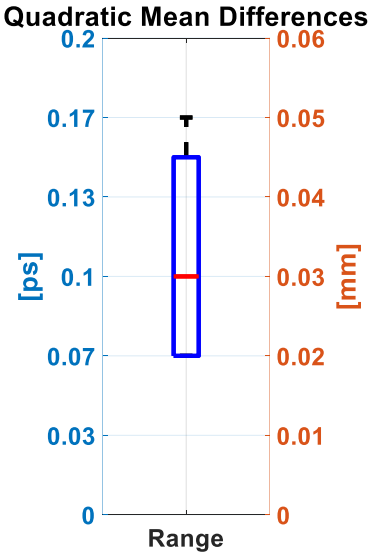
Assessment of Parameter Estimation - Orbit

- Best possible solution shows the limits of what is feasible

- Simulation with no errors
- Estimation of only orbit parameters by using wrong a priori orbit

Type / [ps]	Median		Factor
	a priori	a posteriori	
Radial	8	-0.5	~14
Along-Track	48	-1.3	~38
Range	7	0.1	~67



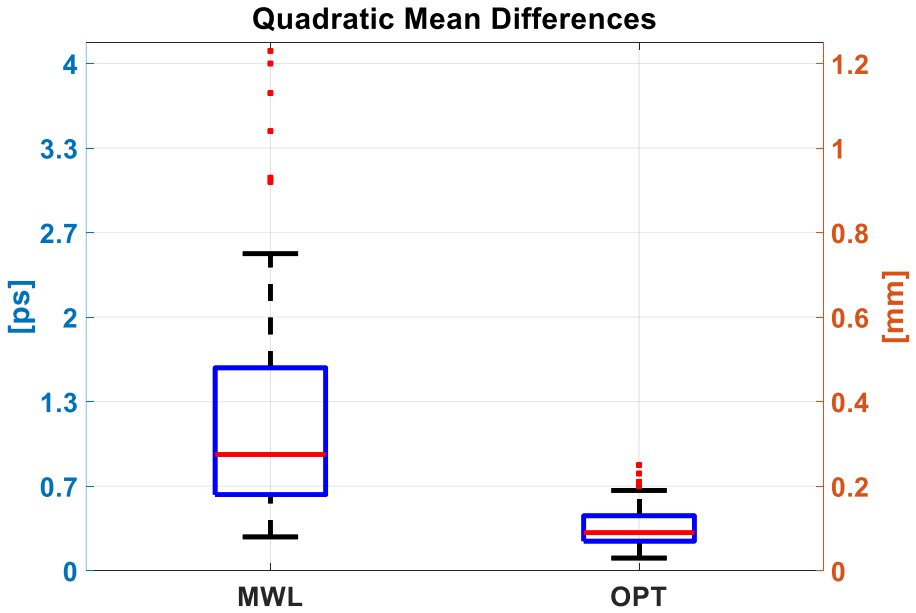


Assessment of Parameter Estimation - Troposphere

- Best possible solution shows the limits of what is feasible

- Simulation with troposphere errors only
- Estimation of a common isotrop troposphere and seperate gradients for both, MWL and OPT

Type / [ps]	Median		Factor
	a priori	a posteriori	
MWL	139	0.9	~150
OPT	3	0.3	~10



Strategies

- Several estimation strategies were tested
- Differs only on troposphere gradient estimation
- Gradient corrections are applied to **all** observations

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

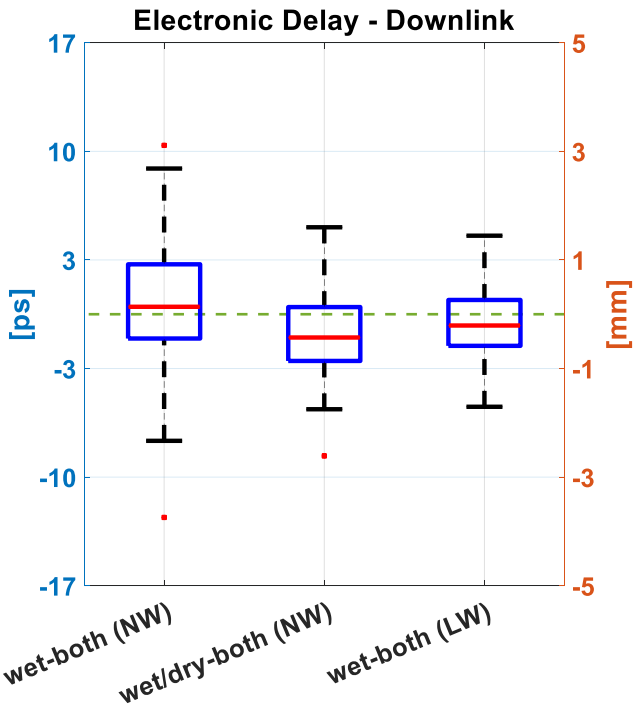
Two different weighting strategies:

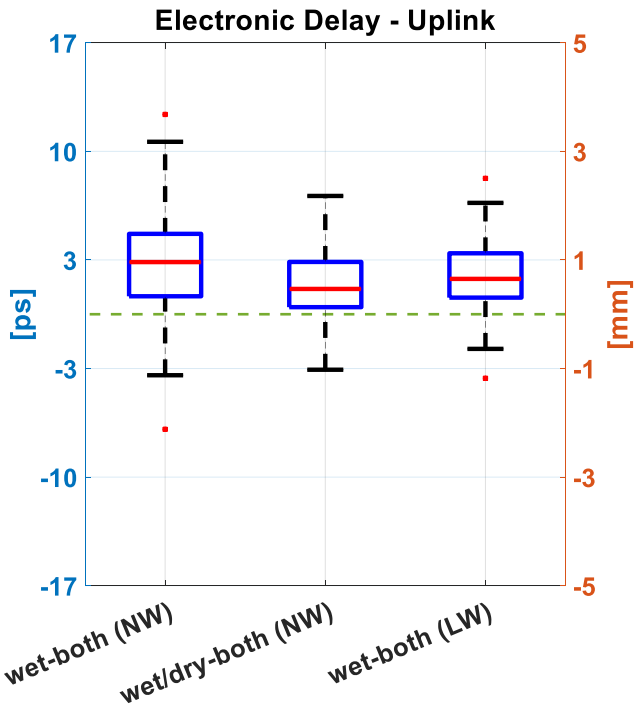
- **noise**-dependent (**NW**)
- **laser**-dependent (**LW**)

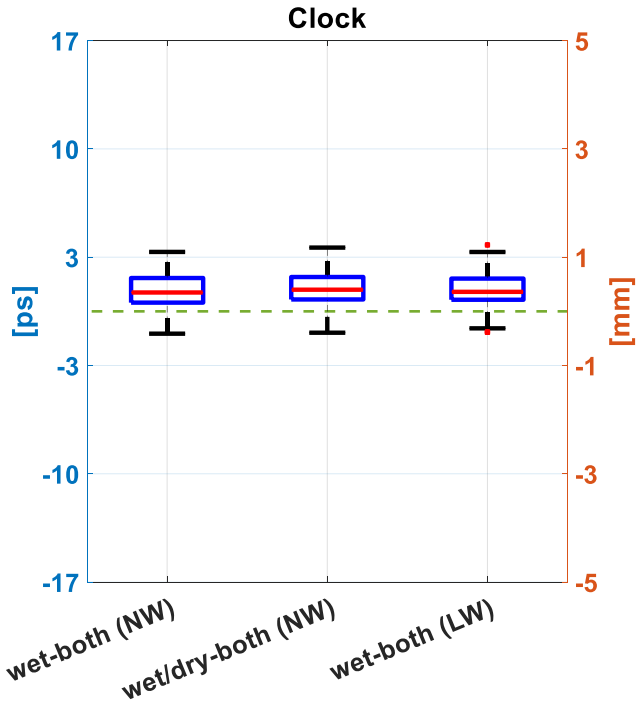
Weighting Type	MWL	OPT
Noise Weighting (**NW**)	200	1
Laser Weighting (**LW**)	1	10

Results (1)

- Parameter differences: simulated – estimated parameters

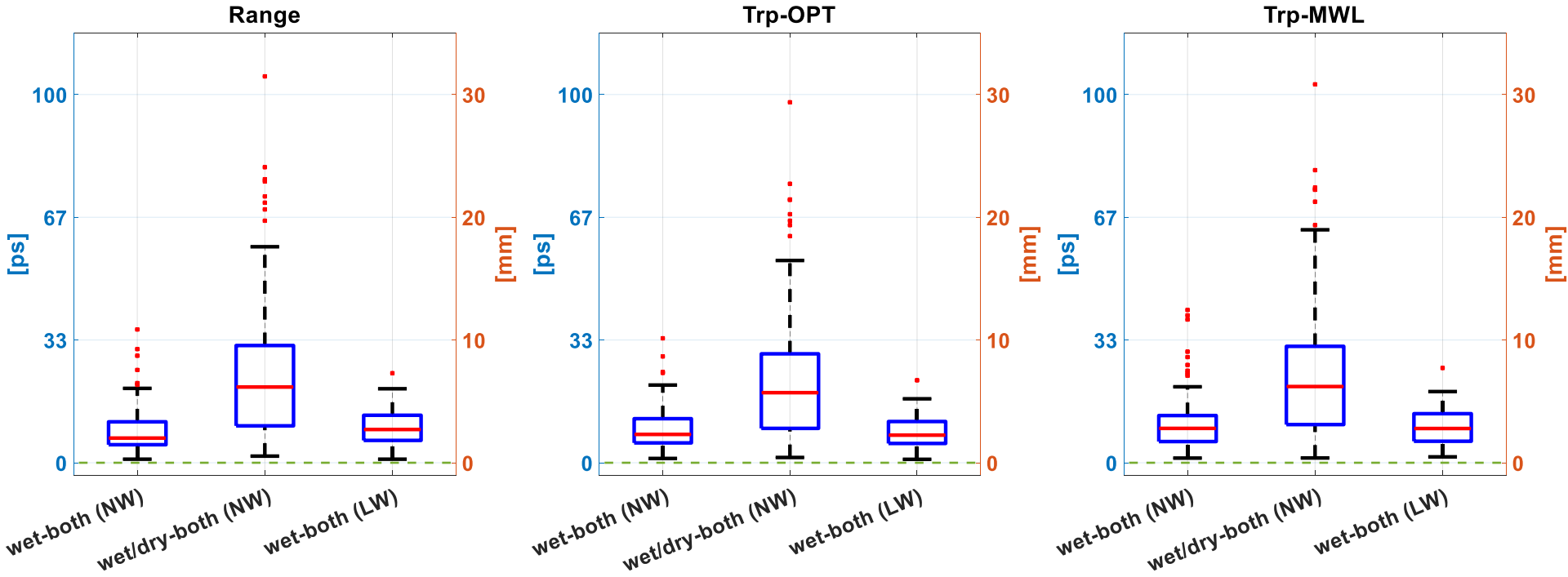




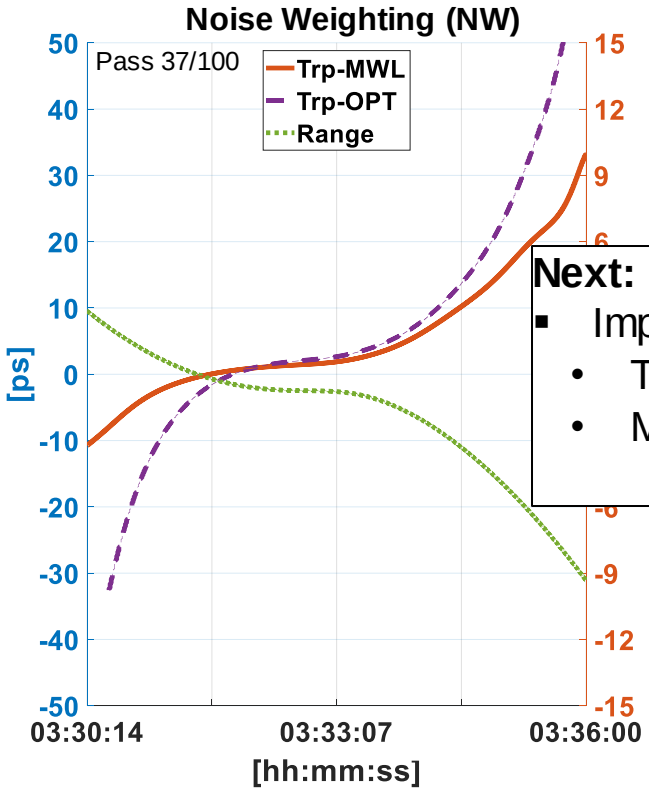


Results (2)

- Quadratic Mean difference of all epochs for all passes



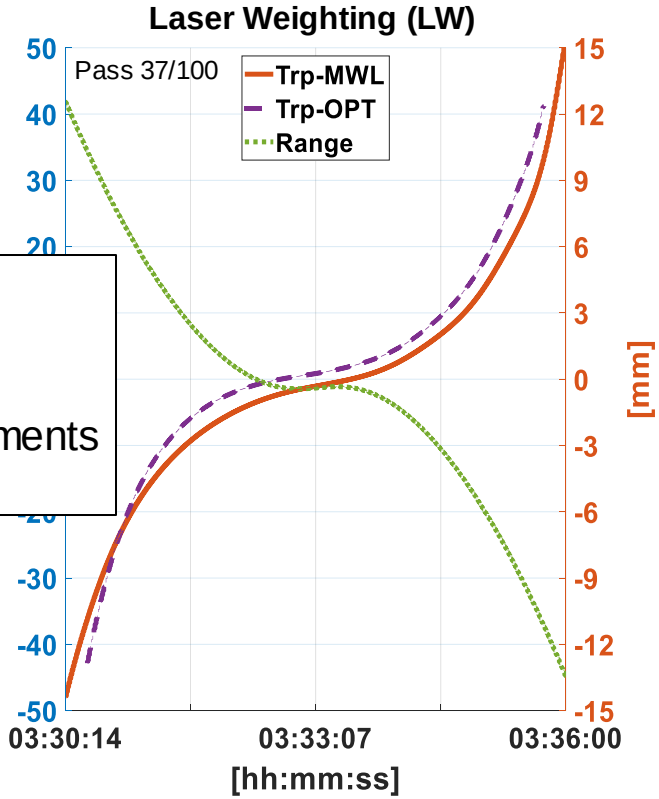
Results (3)



Weighting Type	Electronic Delay Differences [ps]	
	Downlink	Uplink

Next:

- Improve simulation/estimation:
  - Tropospheric fluctuations
  - Multi-wavelength-SLR measurements



Thanks for your attention!

References

Figure 1: CC BY-SA 3.0 IGO, ESA, 2011, “the_international_space_station[…]22“ Link
Figure 2: modified by author after Wang:
K Wang, M Rothacher, M Meindl, E Schoenemann, W Enderle; 2017; „Improvement in the estimation of troposphere zenith delays using high-accuracy clocks“