MATRAG – Measurement of Alpine Tropospheric Delay by Radiometer and GPS

Petra Häfele[1], Matthias Becker, Elmar Brockmann, Lorenz Martin, Michael Kirchner
[1] University of the Bundeswehr Munich, 85577 Neubiberg, Germany
Petra.Haefele@unibw-muenchen.de

1. Introduction

Tropospheric delay is one of the main error sources in precise GPS positioning nowadays. This limiting factor mainly deteriorates the height component, mainly due to the fact that tropospheric delay – if estimated – is a very sensitive parameter in the adjustment. Additionally, other error sources of the GPS signal, which are not properly modeled, are absorbed in these parameters during GPS processing. Ground based Water Vapor Radiometers (WVR) represent an independent technique to measure the atmospheric integrated water vapor along a specified line of sight as well as the integrated liquid water. Therefore, this data is used to assess the accuracy of the GPS derived tropospheric delay and station height.

2. The MATRAG campaign

Within the MATRAG project, water vapor was observed at three permanent GPS stations in Central Switzerland. At the AGNES (Swiss permanent GPS network) sites Bern (EXWI), Jungfraujoch (JUJO) and Zimmerwald (ZIMM), two Radiometrics WVR's (WVR42, WVR43) and ASMUWARA, a radiometer of the Institute of Applied Physics of the University of Bern were installed in September 2003 (see Fig.1).
For calibration purposes, all three radiometers measured simultaneously three days collocated at the University of Bern in the beginning and the end of the experiment. The remaining ten days of the campaign, the stations EXWI, ZIMM, and JUJO with a height difference of about 3000 m were observed simultaneously with the WVR and GPS technique.
For the first three days (DOY 248 to 250) the GPS data of EXWI is missing completely as well as ZIMM partly on days 253 and 255. Gaps in the WVR data are due to rain periods, when the WVR data are not useable (see Fig. 2).

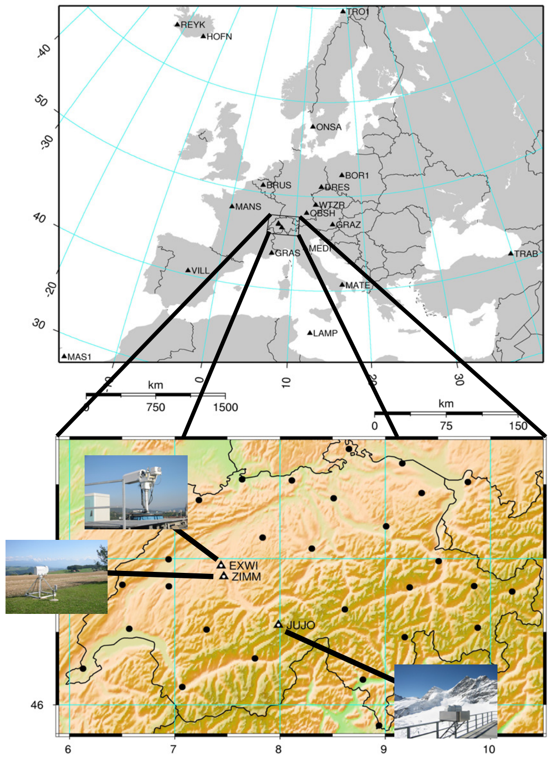

Fig. 1: Distribution of UBW (triangles) and AGNES-sites (circles)

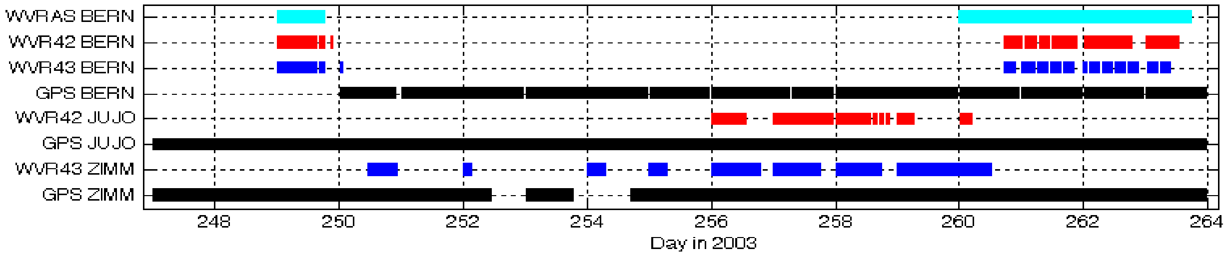

Fig.2: Data Availability of the different techniques

3. Radiometer Calibration

[mm]	WVR43	WVR42	ASMUW.	GPS-AGN.
WVR42	7.3 ± 1.0	-	-	-
ASMUWARA	-11.9 ± 7.1	-19.3 ± 7.2	-	-
GPS-AGNES	-0.5 ± 3.3	-8.9 ± 4.0	9.7 ± 7.8	-
GPS-UBW	2.1 ± 3.5	-6.0 ± 3.4	12.6 ± 8.2	2.9 ± 3.0

Tab. 1: ZWD-Bias and –RMS between GPS and WVR during calibration

The beginning and ending three-day calibration part is used to determine characteristics and biases between the different radiometers and techniques. The two Radiometrics WVRs show a stable offset (see Tab. 1 and Fig. 4a) which can be confirmed with other measurements of previous campaigns. Fig. 3 shows the ZWD estimates for the three radiometers and the GPS station EXWI during the last three calibration days, Fig. 4 shows the correlation between the different techniques.

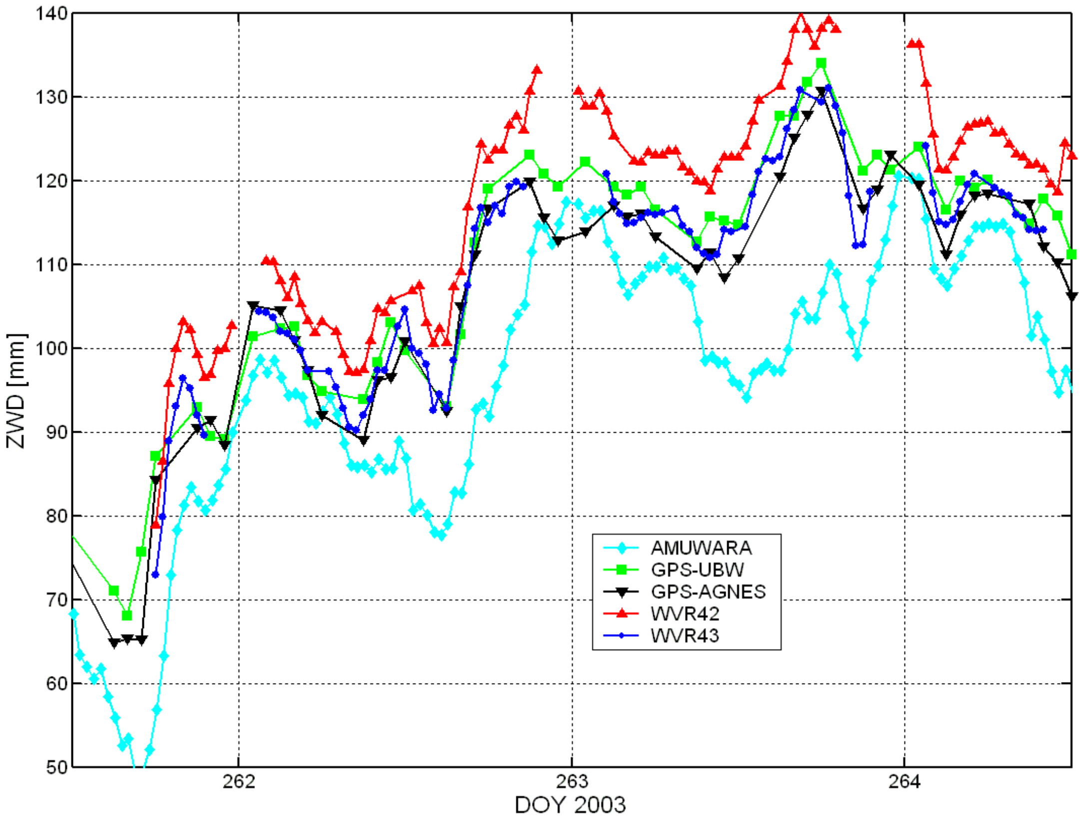

Fig. 3: ZWD measured by WVR and GPS at EXWI

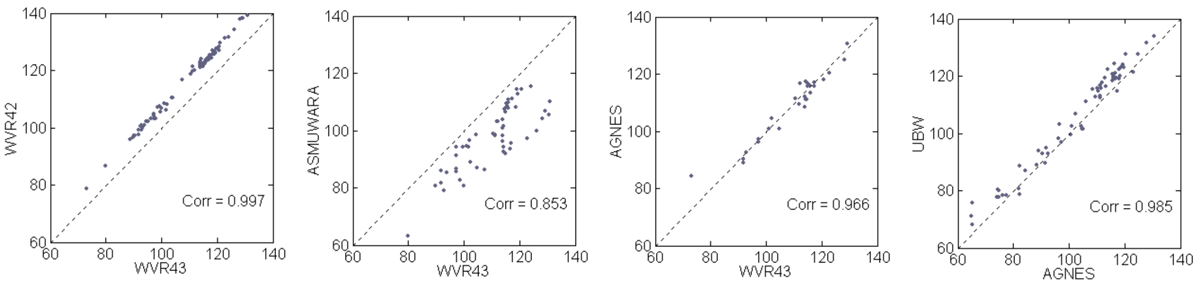

Fig. 4: Scatter plot of ZWD and correlation of inter-comparison between instruments and GPS

4. Comparisons of WVR and GPS

Fig. 5 shows the tropospheric delay of different GPS solutions in comparison with WVR observations. The GPS-UBW values were estimated using a continental network; the GPS-AGNES solution was provided by SwissTopo from a network of 29 GPS stations (see Fig. 1). Tab. 2 shows the good agreement of GPS and WVR for ZIMM. A significant difference of both GPS solutions is limited to time spans of several hours (black boxes on Figures below). For these times the radiometer measurements provide valuable additional information to decide if GPS derived results are reliable and which solution has to be improved.

[mm]	GPS-AGNES	GPS-UBW
ZIMM (WVR43)	-0.4 ± 3.5	6.6 ± 3.7
JUJO (WVR42)	5.0 ± 5.3	9.9 ± 3.9
EXWI (ASMUW.)	1.8 ± 8.9	7.7 ± 8.2

Tab. 2: ZTD-Bias and -RMS (GPS-WVR) during campaign

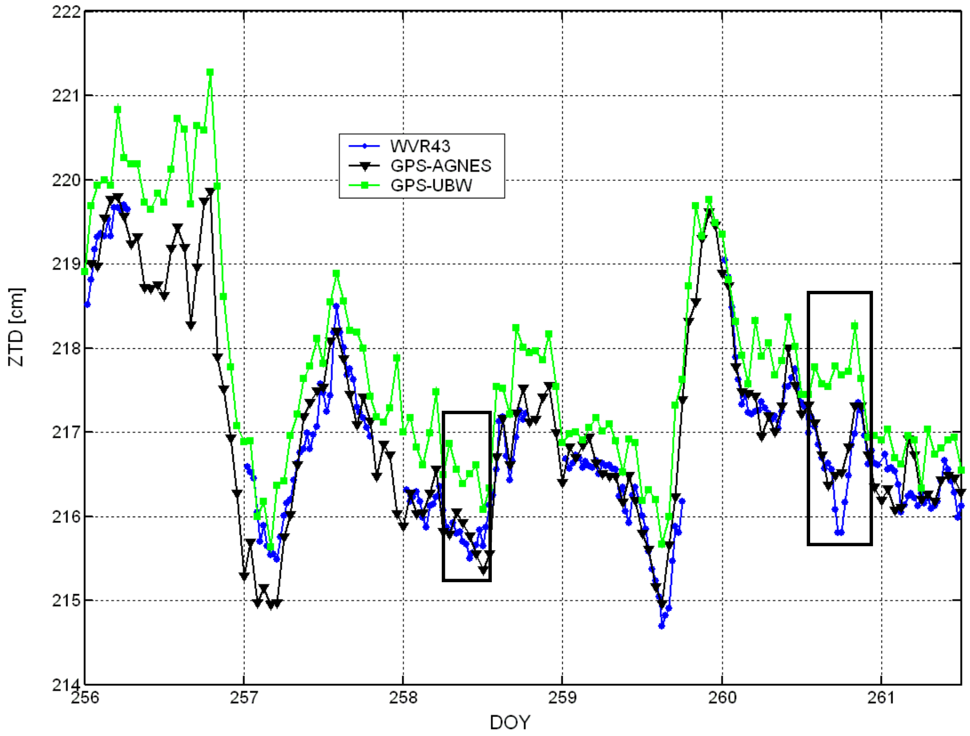

Fig. 5a: ZTD measured by WVR and GPS at ZIMM

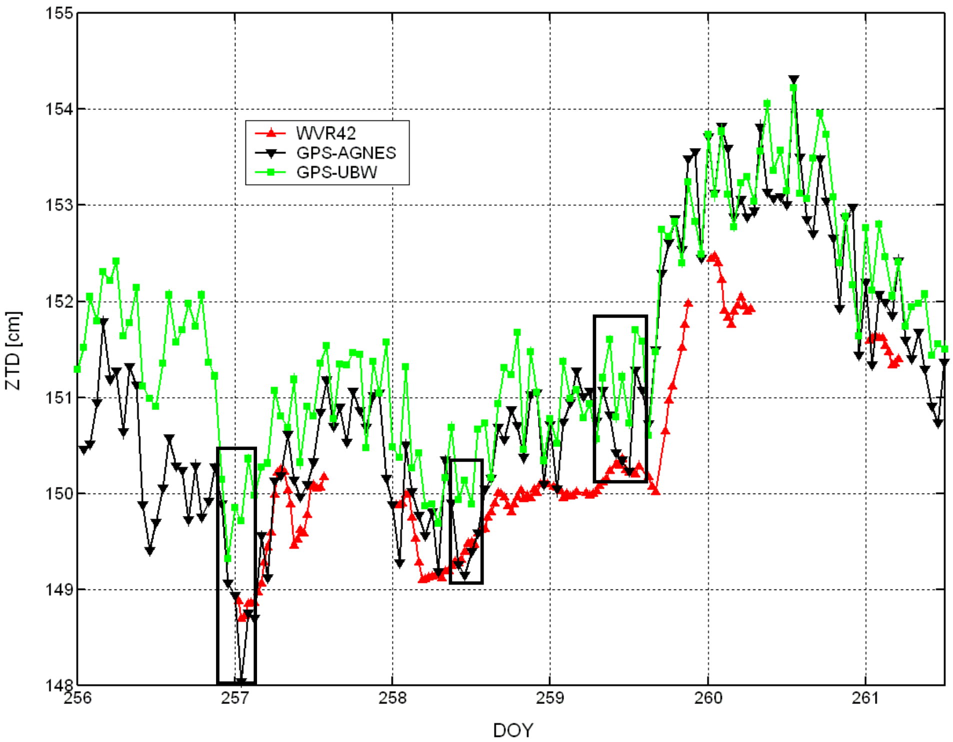

Fig. 5b: ZTD measured by WVR and GPS at JUJO

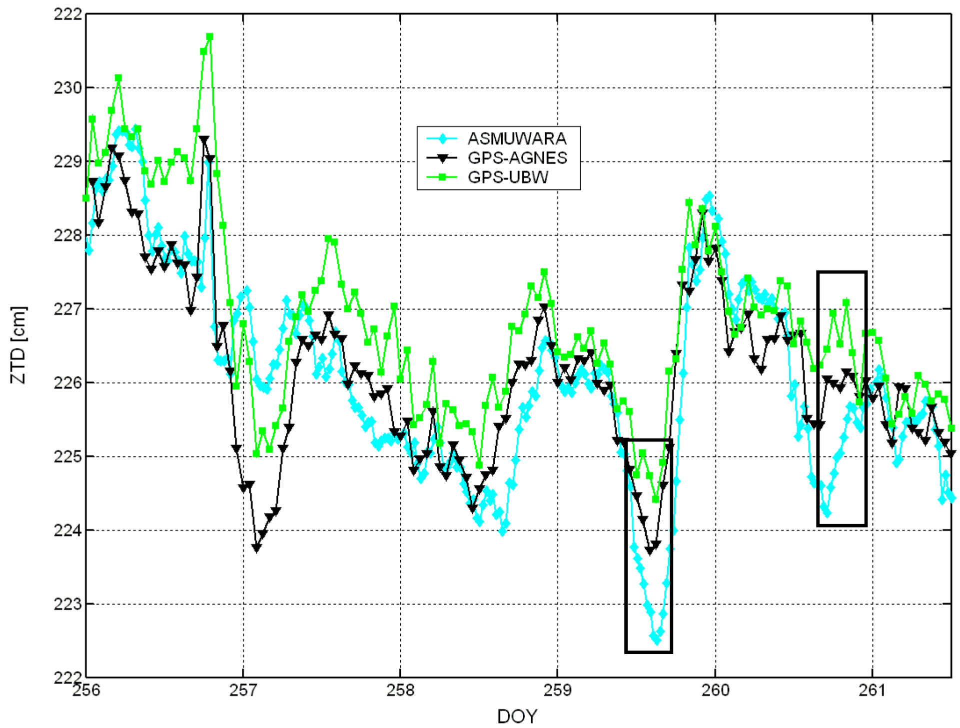

Fig. 5c: ZTD measured by WVR and GPS at EXWI

5. GPS processing

For further comparisons, the local GPS network of ZIMM, EXWI and JUJO was studied in more detail for days 256 to 260, when all of the GPS and WVR data is available. The two baselines ZIMM – JUJO (55 km) and ZIMM – EXWI (8.5 km) with height differences of 2700 m and -330 m respectively, were analyzed. Three types of solutions were computed (see Tab. 3), each with 4 different elevation cut-off angles (10°, 15°, 20°, 25°) and 2 different mapping functions (Niell and Hopfield). The resulting height estimates and the repeatability over the 5 days are shown in Fig. 6a for EXWI and in Fig. 6b for JUJO. The following characteristics are obvious:

- SOL1 and SOL3 depend on the applied cut-off and show a better repeatability than SOL2. This may be due to the fact, that errors here are assimilated by the estimated parameter(s).
- SOL2 is very stable and independent to a changing cut-off angle. However, the constant bias between the radiometers introduces an error into the tropospheric delay, which results in a corresponding height offset.
- The one estimated parameter in SOL3 absorbs these offsets in the radiometer data.

At station JUJO the antenna is individually calibrated due to its special construction. The phase center corrections are significantly different from the IGS-Table values for this antenna type and cause an absolute height difference of 6 cm or 2 cm in ZTD between those two solutions.

<table>
<tr><th>SOL1</th><th>SOL2</th><th>SOL3</th></tr>
<tr><td colspan="3">• Final IGS orbits
• 30 sec. observation interval
• ZIMM: no estimation of coordinates
• CODE ionosphere model
• L3 fixed solution</td></tr>
<tr><td>• A-priori model for troposphere: Saastamoinen (dry part only)</td><td>• ZWD values introduced from WVR, ZHD from METEO measurements</td><td>• ZWD values introduced from WVR, ZHD from METEO measurements</td></tr>
<tr><td>• ZIMM: no estimation of tropospheric parameters
• EXWI, JUJO: Estimation of 1 (relative) troposph. parameter per hour and baseline</td><td>• No estimation of tropospheric parameters at all</td><td>• ZIMM: no estimation of tropospheric parameters
• EXWI, JUJO: Estimation of 1 troposph. parameter per day and baseline</td></tr>
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Tab. 3: Characteristics of the different GPS-solutions

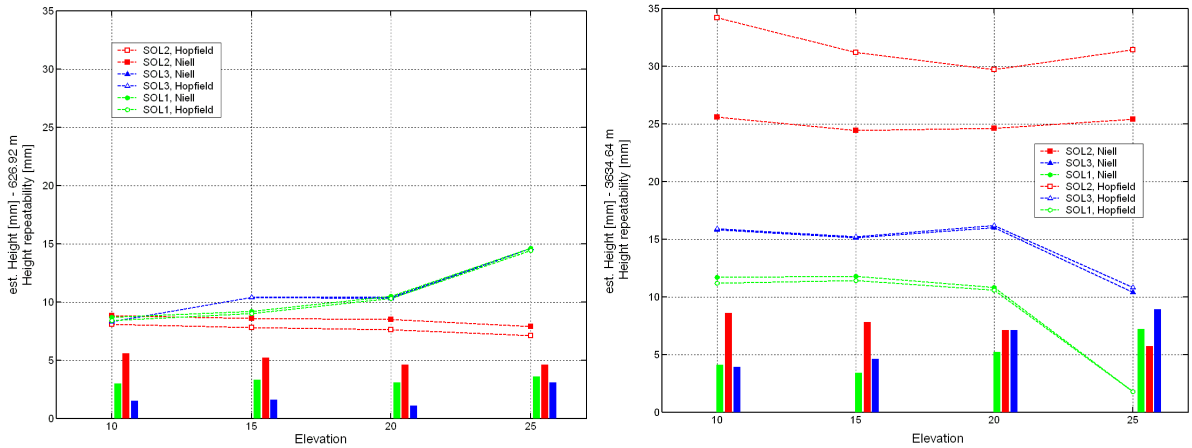

Fig. 6: Variation of height estimates and repeatability (RMS of daily height estimates for SOL1, SOL2, SOL3, left to right) as function of elevation cut-off angles for EXWI (left) and JUJO (right)

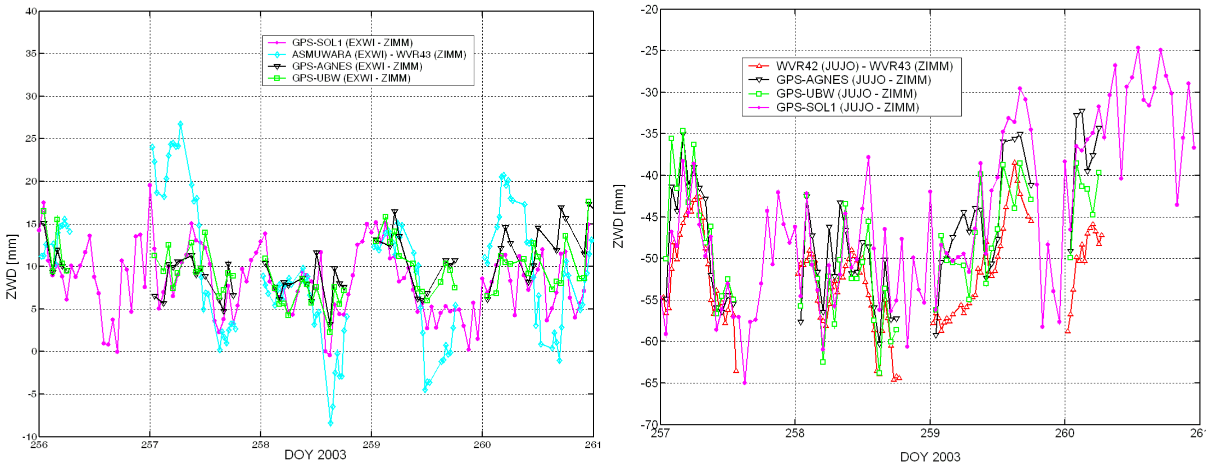

Fig. 7: ZWD at EXWI (left) and JUJO (right) relative to ZIMM

[mm]	WVR42 (JUJO) – WVR43 (ZIMM)	ASMUWARA (EXWI) – WVR43 (ZIMM)
GPS-SOL1	5.2 ± 5.7	0.9 ± 6.1
GPS-AGNES	4.5 ± 4.9	0.7 ± 6.9
GPS-UBW	3.4 ± 5.0	0.2 ± 6.6

Tab. 4: ZWD Bias and RMS of ZWD relative to ZIMM for DOY 257 to 260

6. Conclusions and outlook

During the MATRAG campaign, the performance of the two Radiometrics WVRs was very stable with the exception of periods with rain, which are difficult to detect in the WVR data.

From the inter-comparison of the WVRs we find a significant, but very constant bias.

The WVR measurements can be helpful to select the most reliable GPS solution in terms of troposphere estimates, see Fig. 5.

The estimated tropospheric parameters using a local GPS network (SOL1), see Fig. 7 and Tab. 4, are comparable to the ones estimated in a continental network.

Introducing the WVR measurements into the GPS processing without estimating tropospheric parameters (SOL2) is not recommended due to an usually poorly known bias.

SOL1 and SOL3 show comparable results. Further studies will have to show the reason for the differences between estimated heights of SOL1 and SOL3.

Future work will deal with the introduction of slant delays into the GPS-processing of the local network.

7. Acknowledgments

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