# An Evaluation of the Accuracy of Real-Time Zenith Total Delay Estimates

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# Overview

- Introduction
- From Near Real-Time to Real-Time
- Real-time systems
- Test and Reference datasets, methodology
- Results
- Conclusions

# GNSS Meteorology

- Assimilation of GNSS derived Zenith Total Delay (ZTD) in Numerical Weather Prediction (NWP) models
  - Has a reported positive impact on weather forecasting
  - In practice at various meteorological institutions

- Low-latency ZTD estimates needed for high update-rate NWP models

- Meteorology user requirements for nowcasting (TOUGH, 2004):

| Integrated Water Vapour (IWV) | | |
|---|---|---|
| | **Target** | **Threshold** |
| **Horizontal Domain** | Europe to National | |
| **Repetition Cycle** | 5 min | 1 hour |
| **Integration Time** | MIN(5 min, rep cycle) | |
| **Relative Accuracy** | 1 kg/m$^2$ | 5 kg/m$^2$ |
| **Timeliness** | 5 min | 30 min |

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≈ 6 mm, 30 mm in ZTD

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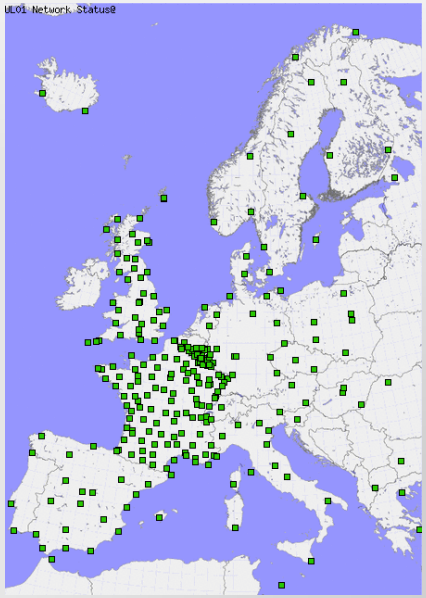
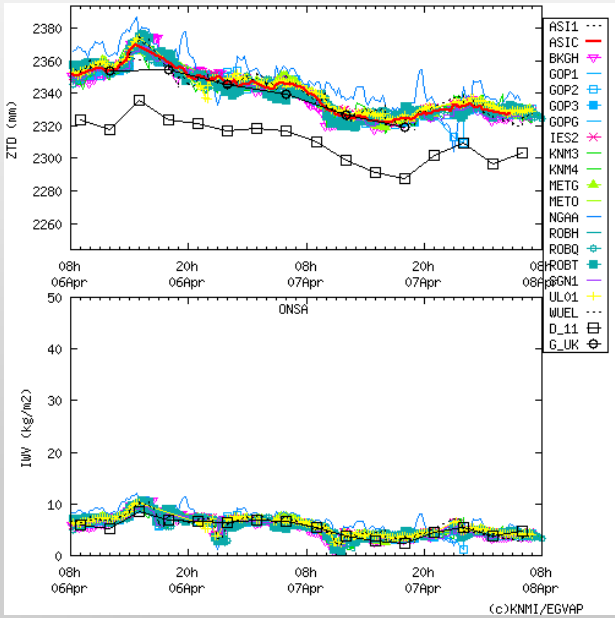
Motivation for real-time processing

# Near Real-Time ZTD Estimation at University of Luxembourg

- Hourly NRT solution “UL01” submitted to EGVAP
  - Sub-millimetre level agreement with IGS Final Troposphere Product
  - Based on Bernese GPS Software 5.0, upgrade to 5.2 is in preparation
  - Uses IGS Ultra-Rapid products




- Sub-hourly (15min) NRT solution “UL04” run internally
  - Millimetre level agreement with IGS Final Troposphere Product

We use the UL01 solution for comparison of the RT solutions.

# Towards Real-Time…

- "Nowcasting" leads to a drive for real-time processing
- Experimental setup at the University of Luxembourg with two real-time GNSS software packages
- Europe-wide network
- Precise Point Positioning (PPP)
- ZTD estimates every 10 minutes

# Towards Real-Time… (2)

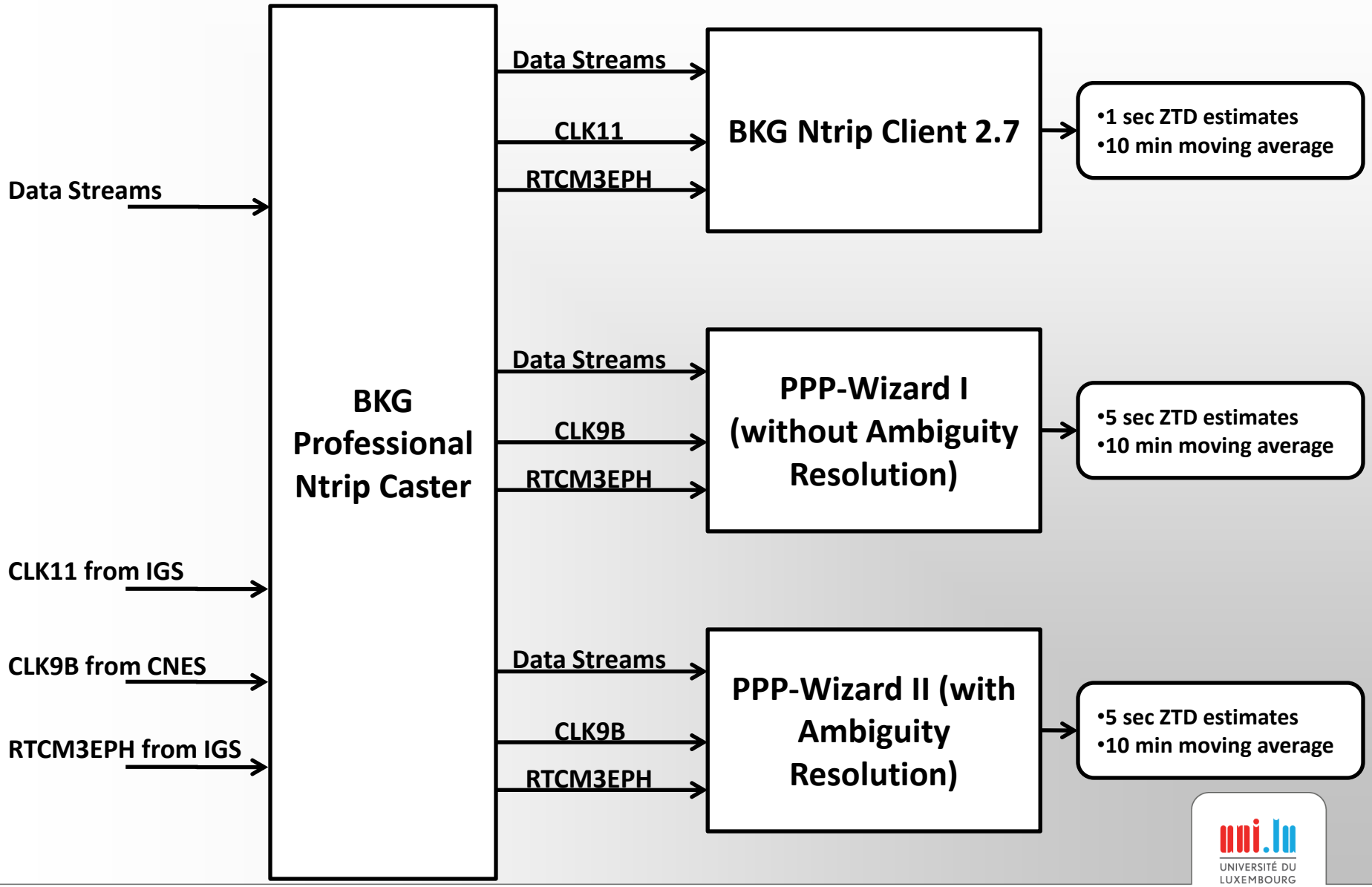
- Three real-time ZTD solutions generated using:

| Software: | BNC2.7 | PPP-Wizard I (*) | PPP-Wizard II (**) |
|---|---|---|---|
| **Update Cycle** | Real-time | Real-time | Real-time |
| **Output Interval** | 1 second | 5 seconds | 5 seconds |
| **GNSS Used** | GPS | GPS | GPS |
| **Input Raw Data** | Real-time streams (RTCM3) | Real-time streams (RTCM3) | Real-time streams (RTCM3) |
| **Input Clock Stream** | CLK11 (IGS) | CLK9B (CNES) | CLK9B (CNES) |
| **Input Ephemeris Stream** | RTCM3EPH (IGS) | RTCM3EPH (IGS) | RTCM3EPH (IGS) |
| **Ambiguity Resolution** | No | No | Yes |

- Accuracy assessment of ZTD estimates needed!

* Modified version to disable ambiguity resolution
** Version with ambiguity resolution enabled

# Test Real-Time Systems



# Test Dataset and Products

- 8 IGS stations selected for comparison
- Time period: 2013-02-22 0000UTC ~ 2013-02-29 00:00UTC

Stations used for comparison

| Station ID | Latitude (degree) | Longitude (degree) |
|---|---|---|
| **CAGZ** | 39.14 | 8.97 |
| **GOPE** | 49.91 | 14.79 |
| **HOFN** | 64.27 | 344.81 |
| **MATE** | 40.38 | 16.42 |
| **ORID** | 41.07 | 20.47 |
| **PADO** | 45.41 | 11.90 |
| **POTS** | 52.19 | 13.07 |
| **REYK** | 64.08 | 338.43 |

Products streams used

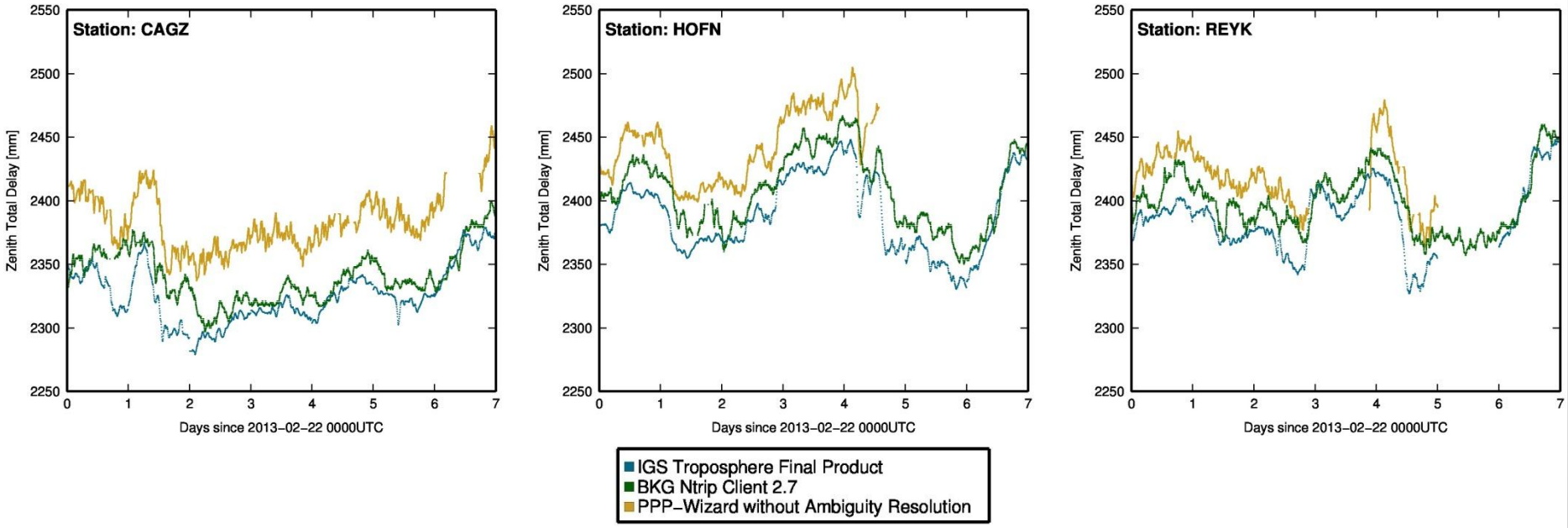
| Stream | Content | Analysis Center |
|---|---|---|
| **CLK11** | Orbit and Clock corrections to Broadcast Ephemeris | BKG |
| **CLK9B** | - Orbit and Clock corrections to Broadcast Ephemeris<br>- Corrections for Integer Ambiguity Resolution | CNES |
| **RTCM3EPH** | Broadcast Ephemeris | BKG |

# Reference Dataset

- IGS Final Troposphere Product
  - IGS Final Orbit/Clock products
  - Precise Point Positioning using BSW5.0
    - (without integer ambiguity resolution)
  - Sampling: 300 sec

- Comparison strategy:
  - Period: 2013-02-22 0000UTC ~ 2013-02-29 00:00UTC
  - Statistics computed using common epochs

# Results: Real-Time vs IGS Final




| Mean Biases (Station: CAGZ) | |
|---|---|
| BNC2.7 vs IGS Final Trop. | 15.2 ± 12.8 mm |
| PPP-Wizard I vs IGS Final Trop. | 60.7 ± 9.6 mm |
| BNC2.7 vs PPP-Wizard I | 44.4 ± 14.0 mm |

| Mean Biases (Station: HOFN) | |
|---|---|
| BNC2.7 vs IGS Final Trop. | 18.4 ± 11.5 mm |
| PPP-Wizard I vs IGS Final Trop. | 44.9 ± 6.4 mm |
| BNC2.7 vs PPP-Wizard I | -26.9 ± 10.2 mm |

| Mean Biases (Station: REYK) | |
|---|---|
| BNC2.7 vs IGS Final Trop. | 16.2 ± 12.4 mm |
| PPP-Wizard I vs IGS Final Trop. | 41.6 ± 9.2 mm |
| BNC2.7 vs PPP-Wizard I | -21.4 ± 11.2 mm |

**Similar biases have been reported before but a constant bias in the ZTD for a particular station is not a problem for the assimilation into NWP models as a monthly station-bias is estimated. However, this remains under investigation for us.**

# Results: Comparison Statistics

| Biases between Real-Time ZTD and IGS Final Troposphere Product | | | | | |
|---|---|---|---|---|---|
| **BNC 2.7** | | | **PPP-Wizard I** | | |
| Bias [mm] | SD [mm] | RMS [mm] | Bias [mm] | SD [mm] | RMS [mm] |
| 14.9 | 12.2 | 19.4 | 47.8 | 7.7 | 48.4 |

| Biases between Real-Time ZTD and UL01 solution (near real-time) | | | | | |
|---|---|---|---|---|---|
| **BNC 2.7** | | | **PPP-Wizard I** | | |
| Bias [mm] | SD [mm] | RMS [mm] | Bias [mm] | SD [mm] | RMS [mm] |
| 13.8 | 11.1 | 18.1 | 47.2 | 7.7 | 47.9 |

| Bias between BNC2.7 and PPP-Wizard I | | |
|---|---|---|
| Bias [mm] | SD [mm] | RMS [mm] |
| -34.7 | 12.1 | 36.8 |

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**A large bias between two real-time solutions is believed to be because of the difference in strategy to compute ZTD**

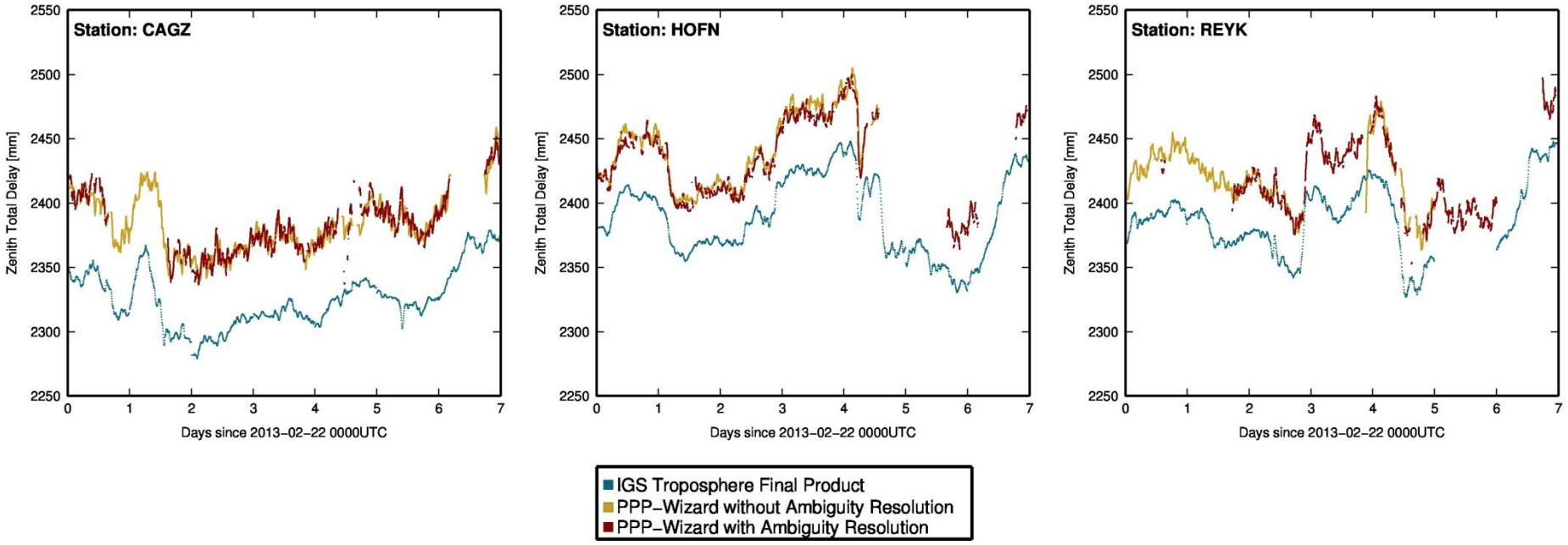
# Results: Comparison to Requirements for Nowcasting

- RMS of bias between real-time and IGS Final solutions supposed as a measure of relative accuracy

- ZTD accuracy translated to IWV accuracy

| Real-Time Solution | Relative Accuracy (IWV) | Agreement with Accuracy Requirement |
|---|---|---|
| **BNC2.7** | 3.2 kg/m$^2$ | Lies within the threshold |
| **PPP-Wizard I** | 8.0 kg/m$^2$ | Exceeds the threshold by 3 kg/m$^2$ |

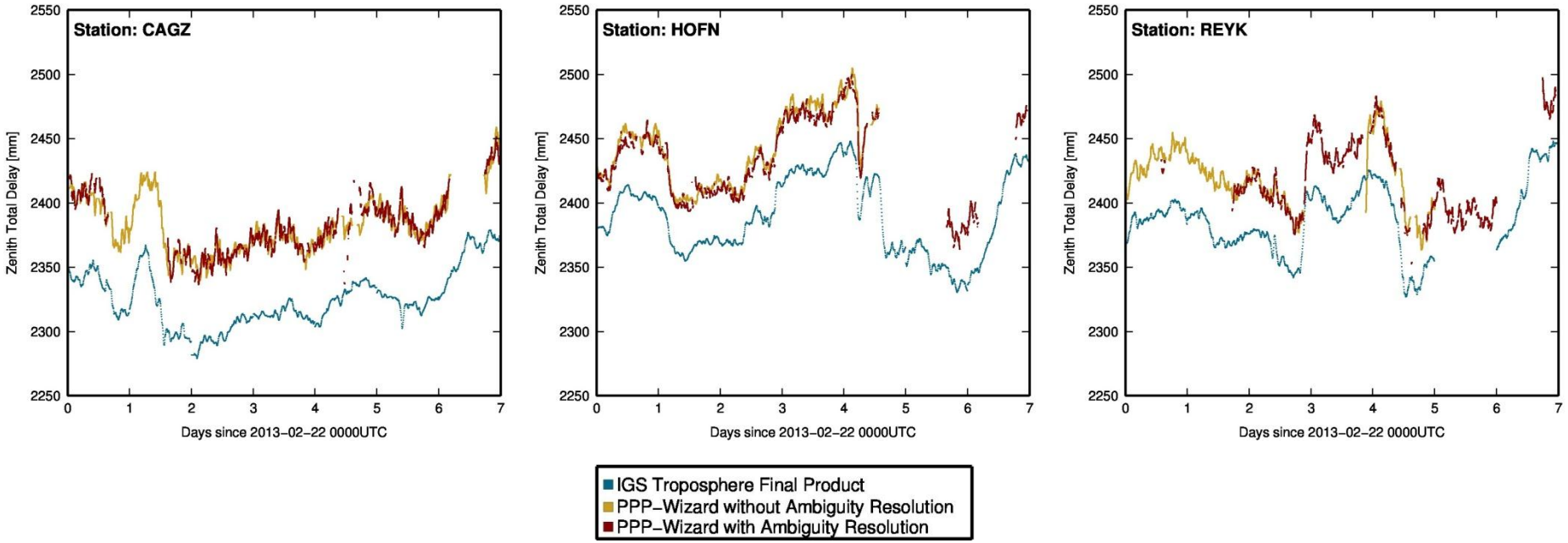
# Results: Ambiguity Resolution




| Mean Bias between Ambiguity Fixed and Float Solution (Station: CAGZ) | Mean Bias between Ambiguity Fixed and Float Solution (Station: HOFN) | Mean Bias between Ambiguity Fixed and Float Solution (Station: REYK) |
|---|---|---|
| -0.9 ± 6.3 mm | 3.9 ± 5.1 mm | 1.0 ± 5.0 mm |

=> Mean difference between fixed and float solution: 1.3 ± 5.5 mm (ZTD) ≈ 0.2 ± 0.9 kg/m$^2$ (IWV)

# Results: Ambiguity Resolution

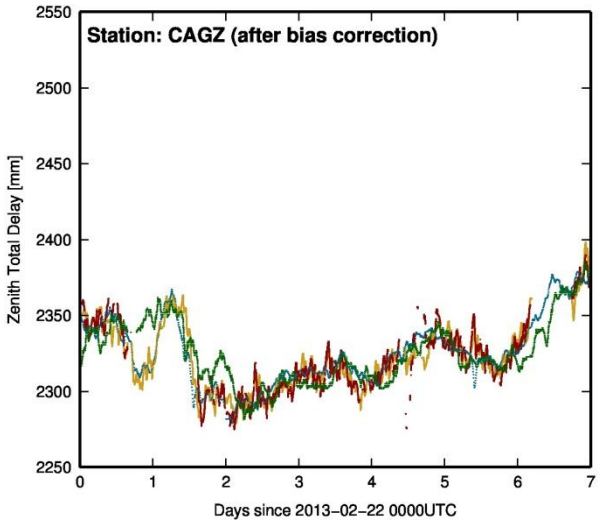


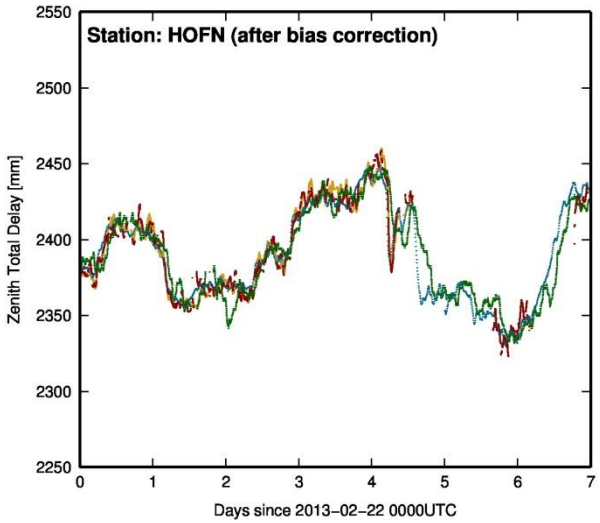

| Biases between PPP-Wizard solutions and IGS Final Troposphere Product | | | | | |
|---|---|---|---|---|---|
| **Without Ambiguity Resolution** | | | **With Ambiguity Resolution** | | |
| Bias [mm] | SD [mm] | RMS [mm] | Bias [mm] | SD [mm] | RMS [mm] |
| 47.8 | 7.7 | 48.5 | 46.5 | 8.6 | 47.4 |

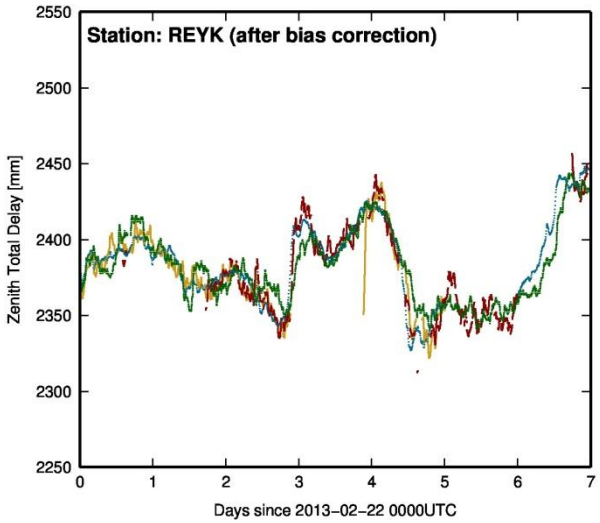
=> Ambiguity fixed solution agrees to IGS Final Trop. Product slightly better

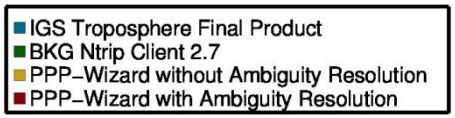
# Results: Bias corrected time-series

New time-series after subtracting mean station-specific bias from the corresponding ZTD estimates:




| Mean Difference with IGS Final Trop. after bias correction (Station: CAGZ) | |
|---|---|
| BNC2.7 | 4 x 10^-8 ± 12.8 mm |
| PPP-Wizard without Ambiguity Resolution | -4 x 10^-8 ± 9.6 mm |
| PPP-Wizard with Ambiguity Resolution | -3 x 10^-8 ± 8.7 mm |

| Mean Difference with IGS Final Trop. after bias correction (Station: HOFN) | |
|---|---|
| BNC2.7 | 3 x 10^-8 ± 11.5 mm |
| PPP-Wizard without Ambiguity Resolution | -3 x 10^-8 ± 6.4 mm |
| PPP-Wizard with Ambiguity Resolution | -5 x 10^-9 ± 6.4 mm |

| Mean Difference with IGS Final Trop. after bias correction (Station: REYK) | |
|---|---|
| BNC2.7 | -3 x 10^-8 ± 12.4 mm |
| PPP-Wizard without Ambiguity Resolution | 1 x 10^-8 ± 9.2 mm |
| PPP-Wizard with Ambiguity Resolution | -4.5 ± 8.6 mm |

# Conclusions

- Two real-time ZTD systems (three solutions) have been introduced and compared
- The real-time ZTD solutions show an agreement of about 3.5 cm with each other
- The real-time ZTD solutions show an agreement of 1.9 cm to 4.8 cm with the IGS Final Troposphere product
- The current results suggest that ambiguity resolution in real-time Precise Point Positioning has a very small effect on the ZTD estimates
- BNC2.7 solution meets the accuracy threshold requirement for nowcasting
- PPP-Wizard exceeds the accuracy threshold for nowcasting by 3 $kg/m^2$

# Thank you!

## • References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