Multi-GNSS Positioning with the New M-PAGES Software

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Outline

- Background on the evolution of GNSS, motivating the development of M-PAGES
- Discuss the products and services at NGS that will use M-PAGES
- Overview of the M-PAGES processing strategy, and how it compares to the legacy PAGES software
- Demonstrate M-PAGES performance for a range of use cases
- Preview the expected timeline for M-PAGES integration into NGS products and services

Key Points

- M-PAGES is capable of processing GNSS data for all dual-frequency systems
- Improved positioning with multi-GNSS data can be demonstrated with M-PAGES
- M-PAGES is still under active development, but OPUS-S integration is underway

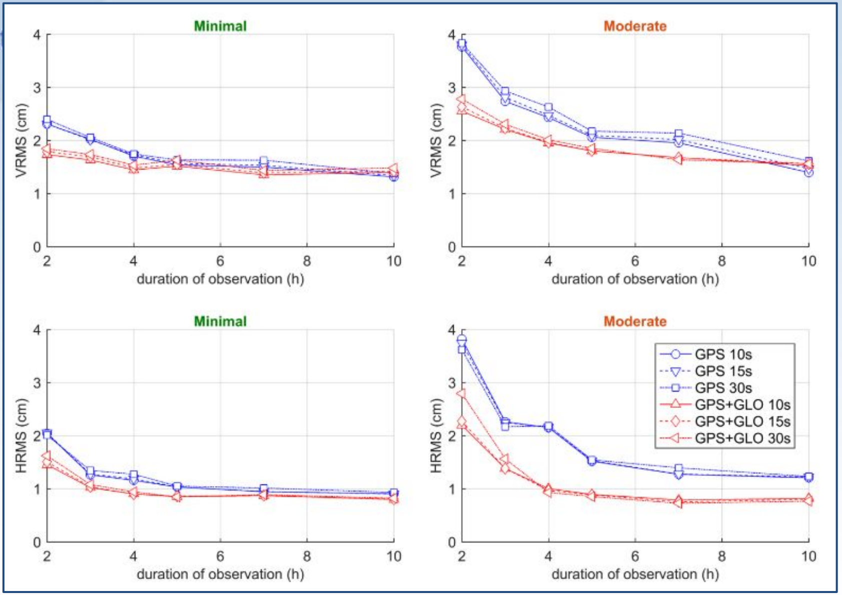
Why replace PAGES?

- PAGES = **P**rogram for the **A**djustment of **G**PS **E**phemerides
- Double-difference baseline processing (GPS L1/L2 only)
- Currently used in production at NGS for:
    - Online Positioning User Service (OPUS)
    - NOAA CORS Network (NCN) monitoring
    - Precise orbit determination
- ***Unable to make use of new GNSS constellations or new frequencies***

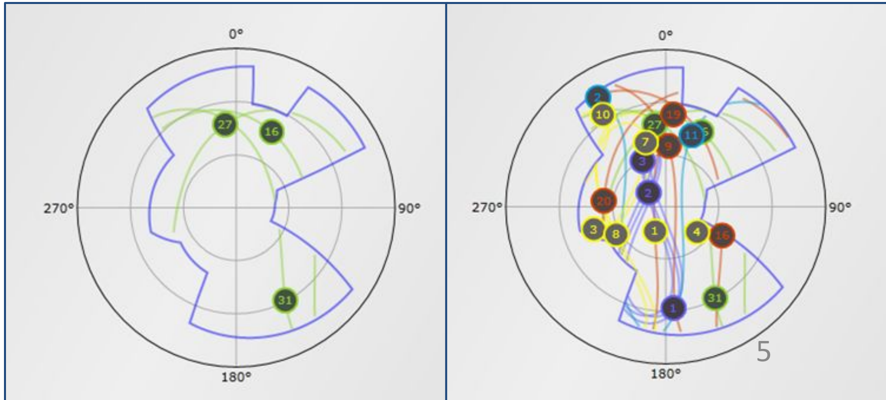
Why replace PAGES?

- More satellites = better positioning!
  - Improved geometry
  - Better coverage when signals are obstructed (bottom right)

- Various studies have already demonstrated the improvements in positioning with added systems (top right)



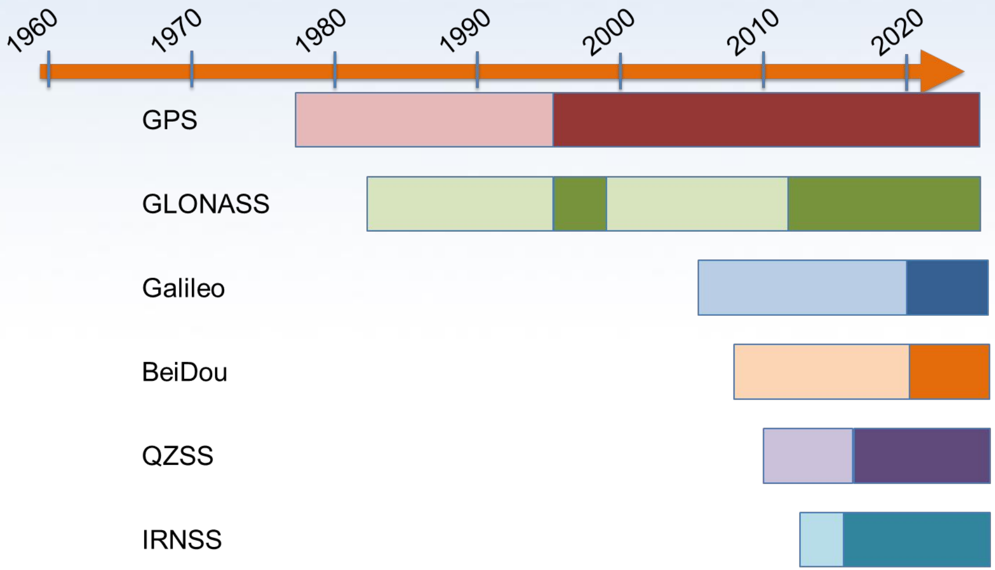
From Jamieson & Gillins 2018 (Above)



http://www.gnssplanningonline.com

Background

- GNSS = Global Navigation Satellite System
- GNSS constellations:
  - GPS (US)
  - GLONASS (Russia)
  - Galileo (EU)
  - BeiDou (China)
  - QZSS (Japan; regional)
  - IRNSS (India; regional)
- Currently there are >100 GNSS satellites in orbit!



From Heck 2017. For additional background on multi-GNSS see: https://www.ngs.noaa.gov/web/science_edu/webinar_series/positioning-multi-gnss-world.shtml

GPS

- Constellation consists of satellites in medium earth orbit (MEO)
  - ~20,000 km orbit altitude
  - 2 revolutions per day
- Code division multiple access (CDMA) system
- GPS satellites historically transmitted signals on two frequencies
  - L1: 1575.42 MHz
  - L2: 1227.60 MHz
- Ongoing GPS modernization since the 2000s
  - New civil signals L1C, L2C
  - New L5 frequency: 1176.45 MHz

https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/gps

GLONASS

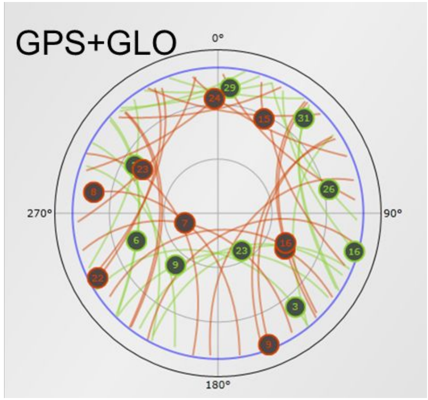
- Originally launched in 1980s
- MEO orbits with higher inclination angle = better coverage at polar latitudes
- Legacy satellites use frequency division multiple access (FDMA) based around G1 and G2 frequencies:
  - FDMA poses challenges for ambiguity resolution
- GLONASS modernization ongoing
  - Third frequency (G03): 1202.025 MHz
  - Future CDMA satellites planned

Table 11 : RINEX Version 4.00 GLONASS Observation Codes

GNSS System	Freq. Band / Frequency	Channel or Code	Observation Codes			
			Pseudo Range	Carrier Phase	Doppler	Signal Strength
GLONASS	G1/ 1602+k*9/16 k= -7….+12	C/A	C1C	L1C	D1C	S1C
		P	C1P	L1P	D1P	S1P
	G1a/ 1600.995	L1OCd	C4A	L4A	D4A	S4A
		L1OCp	C4B	L4B	D4B	S4B
		L1OCd+ L1OCp	C4X	L4X	D4X	S4X
	G2/ 1246+k*7/16	C/A	C2C	L2C	D2C	S2C
		P	C2P	L2P	D2P	S2P
	G2a/ 1248.06	L2CSI	C6A	L6A	D6A	S6A
		L2OCp	C6B	L6B	D6B	S6B
		L2CSI+ L2OCp	C6X	L6X	D6X	S6X
	G3 / 1202.025	I	C3I	L3I	D3I	S3I
		Q	C3Q	L3Q	D3Q	S3Q
		I+Q	C3X	L3X	D3X	S3X

https://igs.org/news/rinex-4-now-available/

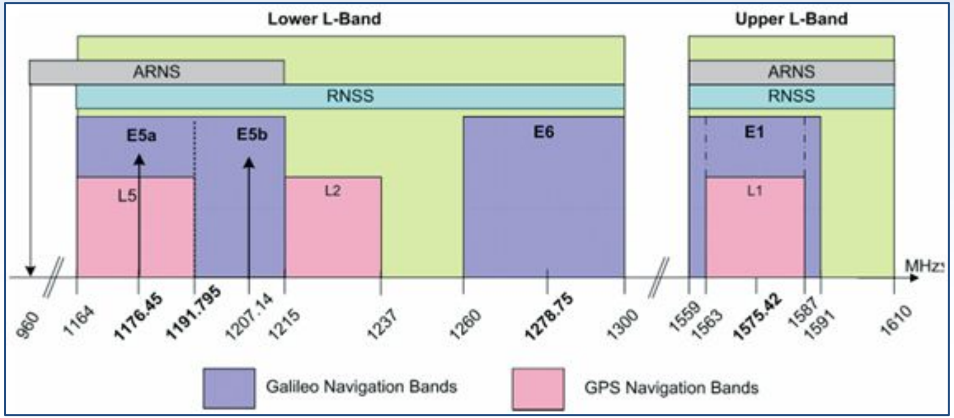
Sky plot for GNSS station at polar latitude



http://www.gnssplanningonline.com

Galileo

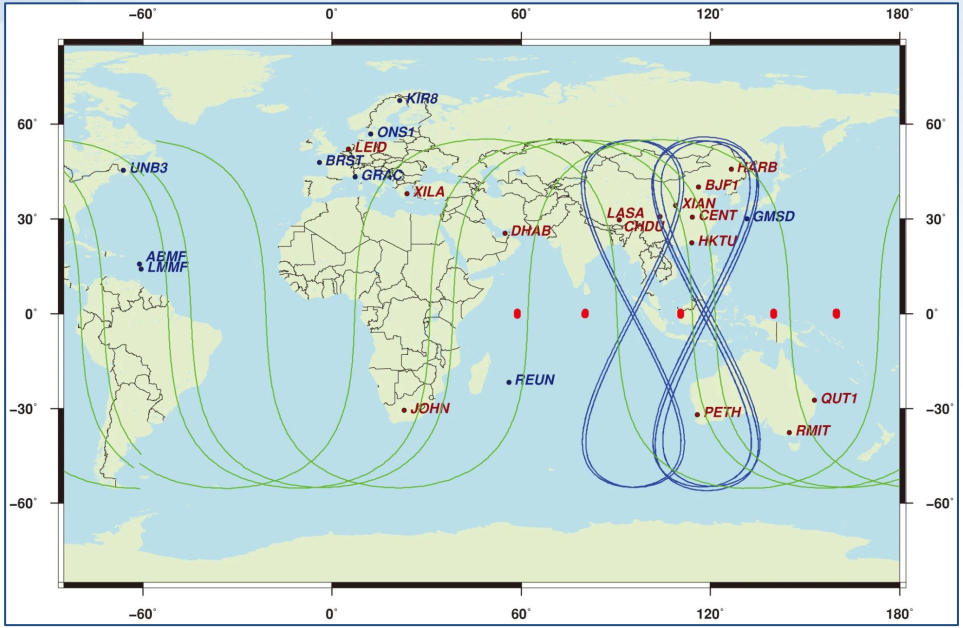
- Galileo system launched by the EU
- MEO orbits
- Global system with three frequencies:
  - E1, E5, E6
  - E5 consists of E5a and E5b frequencies
  - E1/E5a align with GPS L1/L5
- CDMA system



https://galileognss.eu/galileo-frequency-bands/

BeiDou

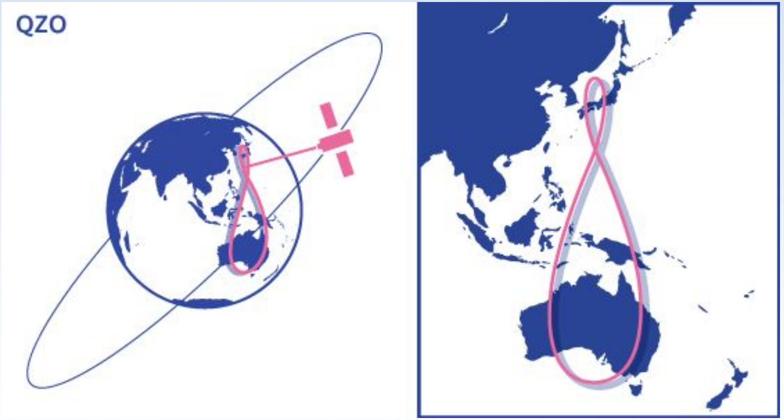
- Constellation consists of satellites in three types of orbit:
  - MEO
  - Inclined geosynchronous orbit
  - Geostationary orbit
- Multiple satellite generations already launched
  - BDS I-III
- Transmits signals on three frequencies
- CDMA system



Lou et al., 2014

QZSS

- QZSS = Quasi Zenith Satellite System
- Regional system
- Frequencies: L1/L2/L5/L6
  - Designed for consistency with GPS

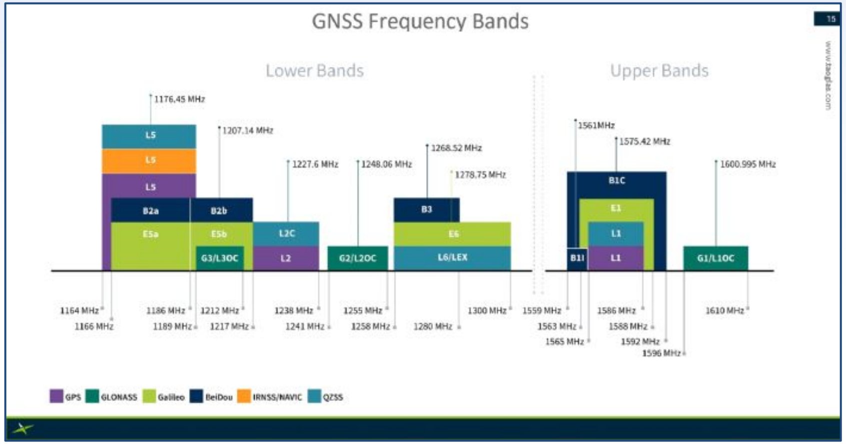


https://qzss.go.jp/en/technical/technology/orbit.html

https://qzss.go.jp/en/overview/services/sv01_what.html

Challenges of Multi-GNSS Positioning

- Different time systems
- Frequency-dependent errors
- Availability of antenna calibrations
- Availability of reference stations tracking all GNSS
- GLONASS ambiguity resolution (FDMA)



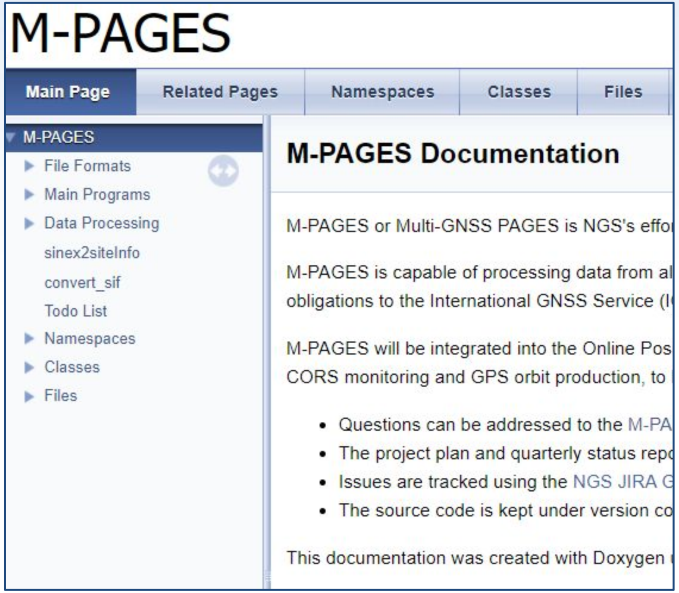
https://www.everythingrf.com/community/navigating-the-l1-l2-and-l5-band-options-for-gnss

Why replace PAGES?

- Written in Fortran; Difficult to extend/maintain with current staff
- Does not support RINEX versions > 2
  - RINEX version >= 3 required for all GNSS and all new signal types
- Unable to make use of new GNSS constellations or new frequencies

M-PAGES Software

- M-PAGES = Multi-GNSS PAGES
- Single difference baseline processing using pseudorange and carrier phase measurements
- Capable of processing data from all GNSS constellations with two or more frequencies
- Written primarily in C++ with supporting scripts in Python

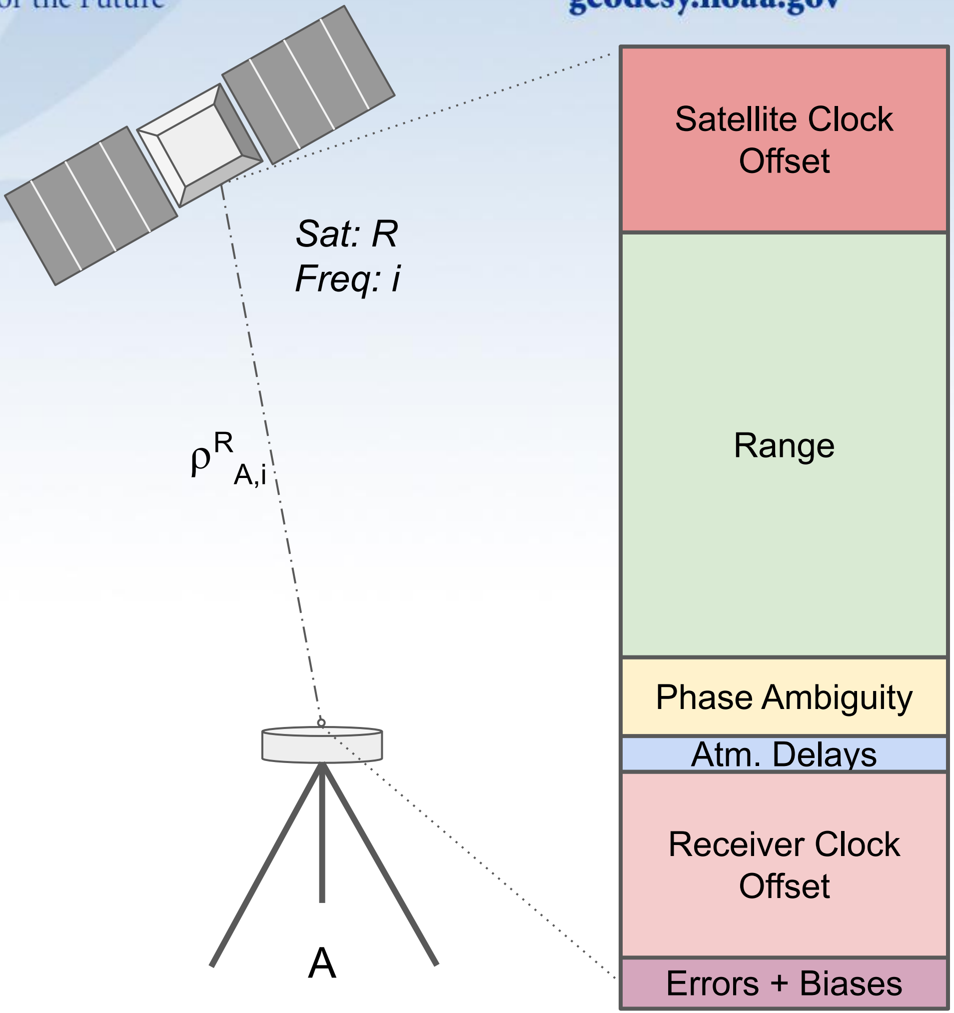


GNSS Measurements

Pseudorange and **carrier phase** measurements are comprised of the following:

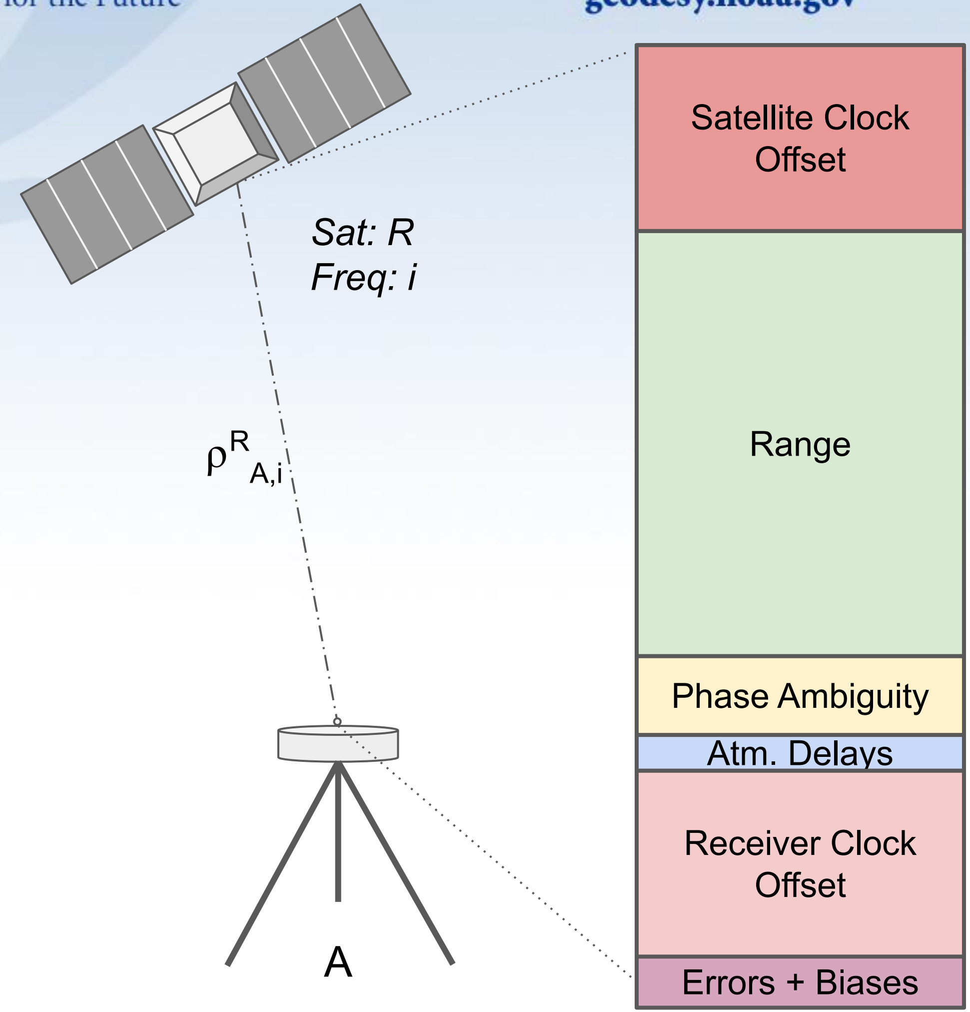
- Range = true satellite-receiver distance
- Satellite clock offset = satellite time offset relative to GPS system time
- Atmospheric delays = signal path delays through ionosphere and troposphere
- Receiver clocks offset = receiver time offset relative to GPS system time
- Carrier phase ambiguity (arbitrary integer value- phase only)
- Other errors = measurement errors, biases, etc.

We must estimate, model, or try to cancel out the error sources!



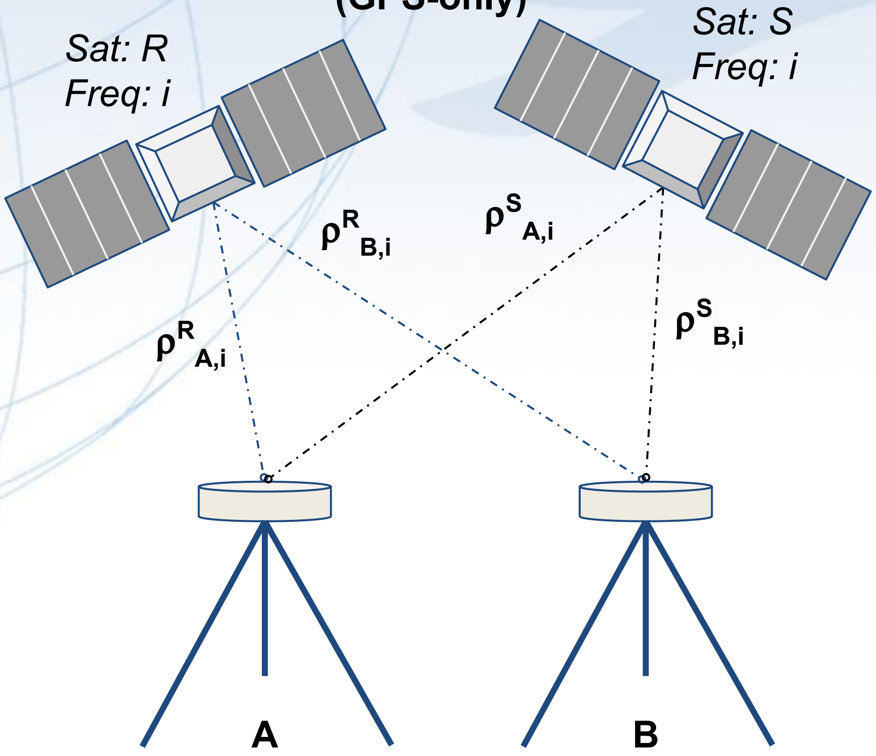
Why not PPP?

- PPP = Precise Point Positioning
- PPP is an attractive alternative to baseline positioning; especially in regions where CORS coverage is sparse
- NGS operations rely heavily on GNSS vectors/network adjustments
- The M-PAGES software has been designed in a modular way to make future development easier



Double-Difference Processing (PAGES)

(GPS-only)



DD: $\rho^{RS}_{AB,i} = SD^{R} - SD^{S}$

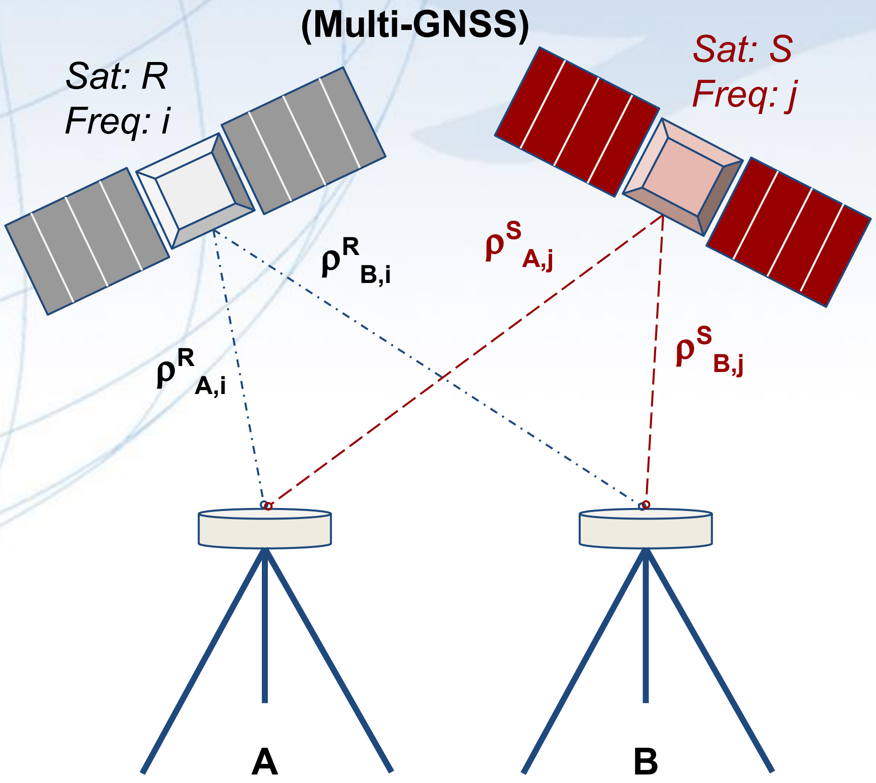
- Satellite **and** Receiver terms cancel
- For short baselines, atmospheric delays cancel
- Same frequencies for each satellite → phase ambiguities can be resolved

Double-Difference Range

Double-Difference Ambiguity

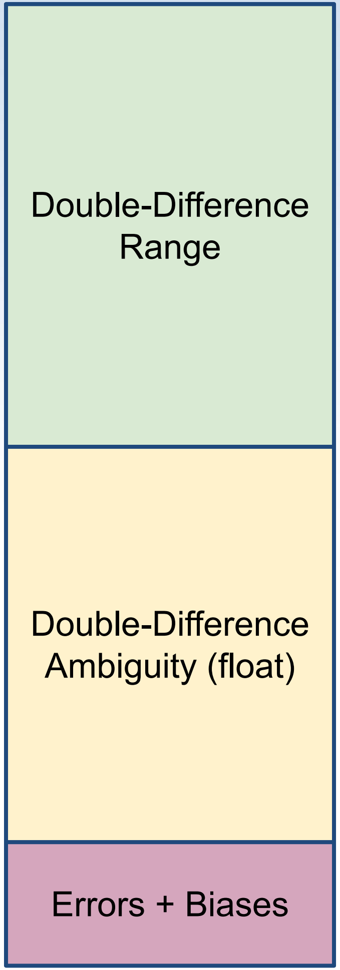
Errors

Why not double-difference?

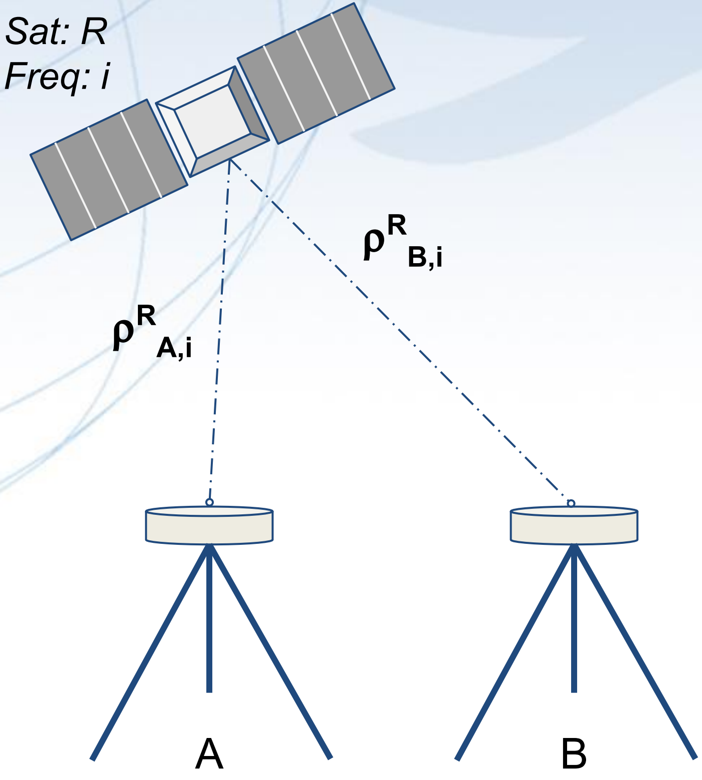


DD: $\rho^{RS}_{AB,i} = SD^{R} - SD^{S}$

- Frequency $i \neq j$
- Different frequencies prohibit ambiguity resolution!
- Could process each system separately then combine



Single-Difference Processing (M-PAGES)



SD^R: $\rho^R_{AB,i} = \rho^R_{A,i} - \rho^R_{B,i}$

- Satellite-specific terms cancel
- Receiver clock terms do not cancel and must be estimated!
- Same frequencies for each satellite → phase ambiguities can be resolved
- Flexible for multi-GNSS

Single-DifferenceRange

Single-Difference Ambiguity

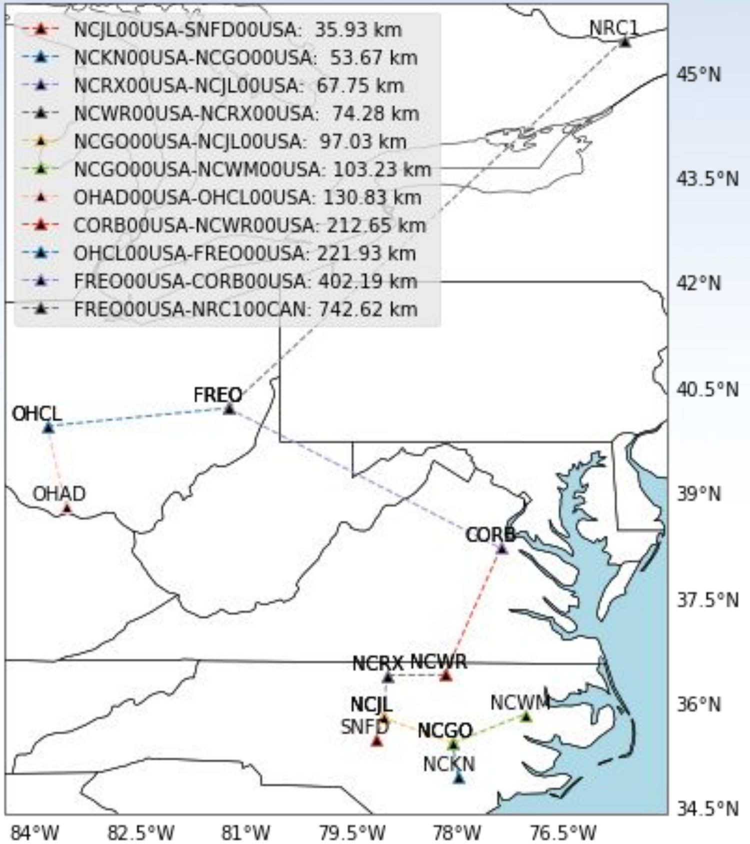
Relative Receiver Clock Offset

Errors + Biases

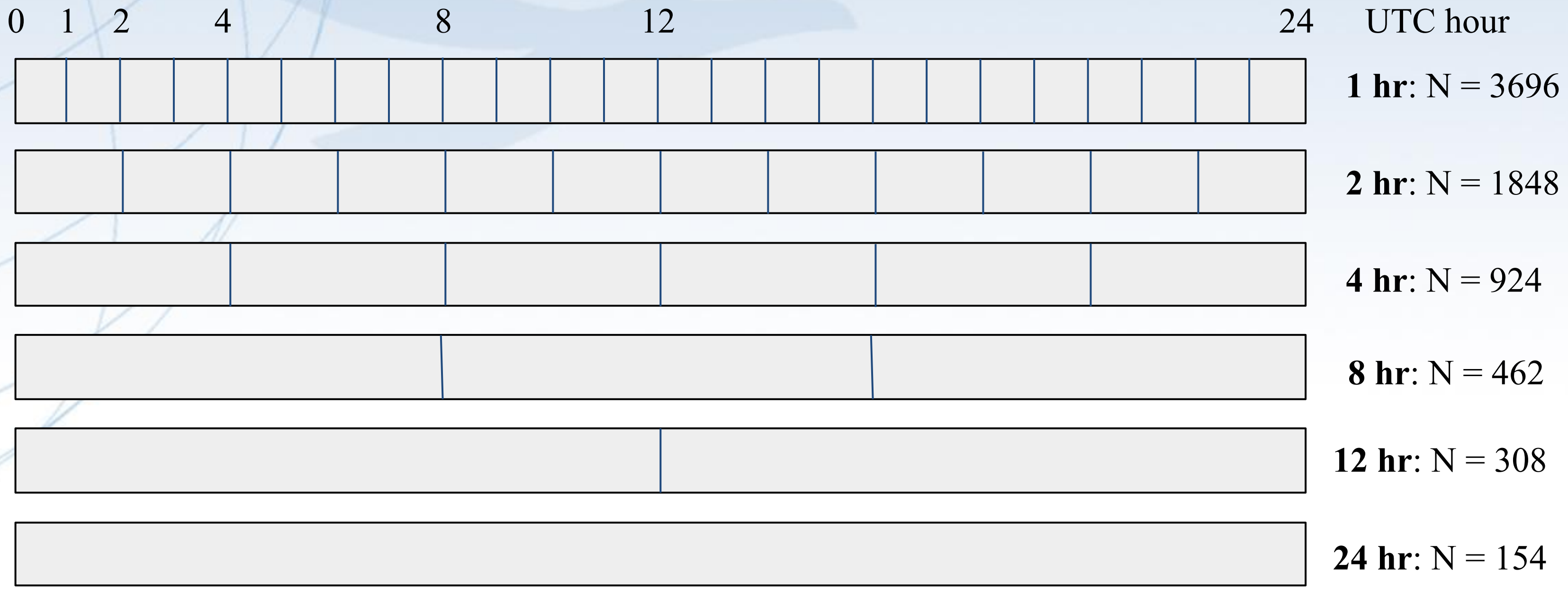
M-PAGES Testing: CORS data

Multi-GNSS CORS Tests

- 11 baselines picked from high quality CORSs
- Single baseline solutions
  - "Reference" CORS tightly constrained
  - "Rover" CORS coordinates estimated and compared to MYCS2 coordinate functions
- All stations track GPS+GLO+GAL (GRE)
- All possible sub-sessions processed for:
  - 14 consecutive days for each baseline (May 2022; doy 121-134)
  - Durations: 1, 2, 4, 8, 12, and 24 hours
  - G/GR/GE/GRE
- GLONASS (R) ambiguities = float

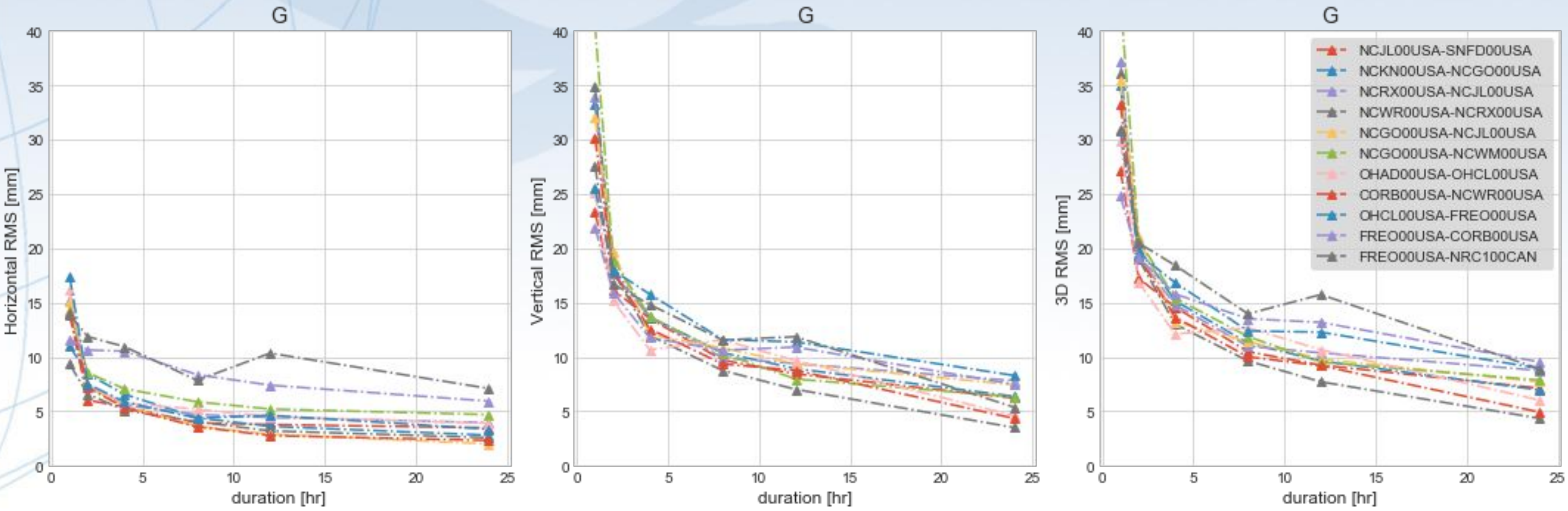


Multi-GNSS CORS Tests



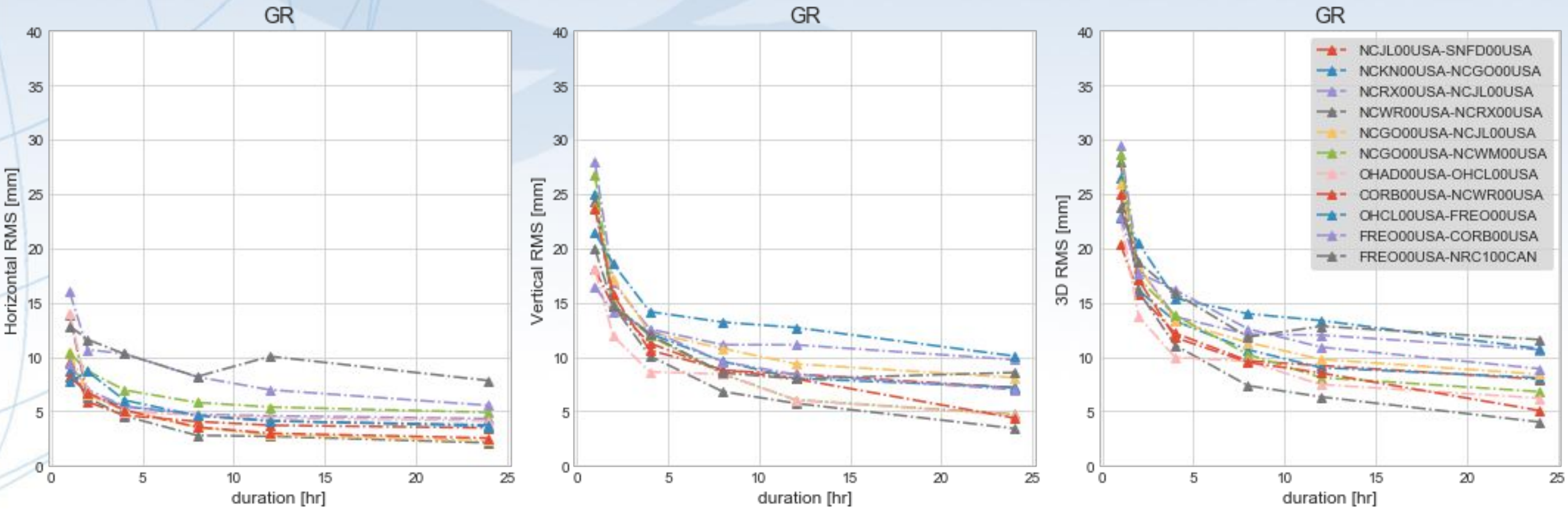
- Each 24 hour RINEX file (represented by a block) is divided into sub-sessions for each duration
- Total sessions (N) = (# of baselines) * (# of days) * (sessions per day)
  - Example: 24 hr → 11 * 14 * 1 = 154

GPS



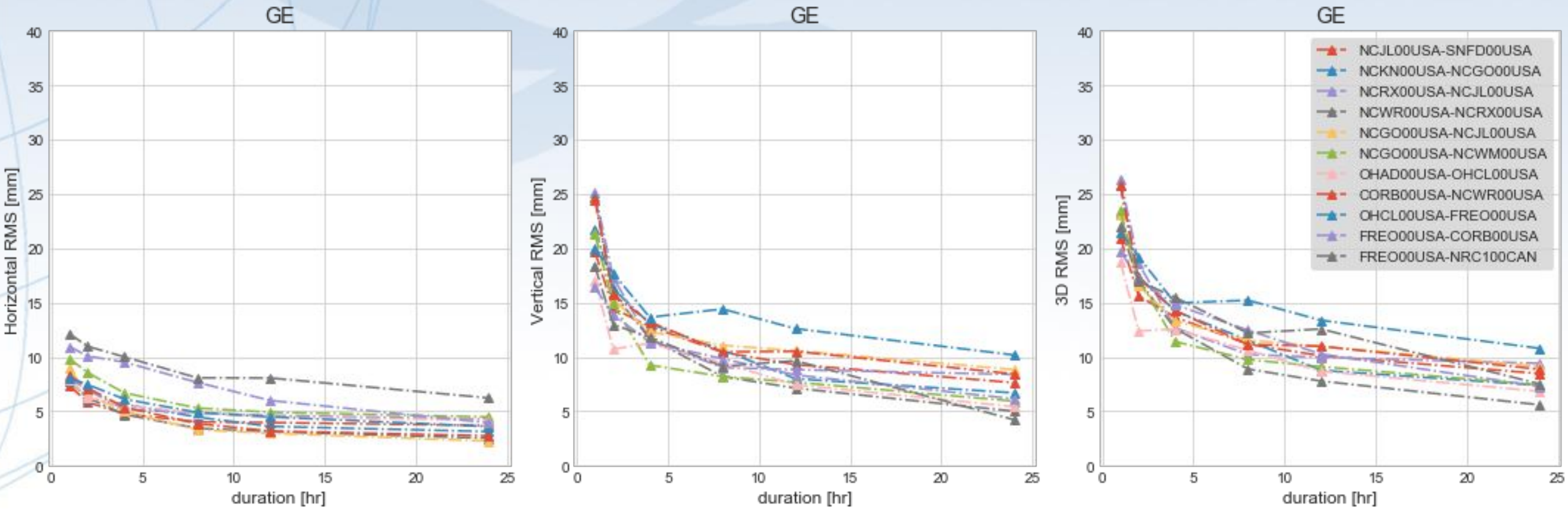
- RMS values computed per baseline and per session duration
- Large outliers removed using 4 * RMS for each component

GPS + GLO



- RMS values computed per baseline and per session duration
- Large outliers removed using 4 * RMS for each component

GPS + GAL



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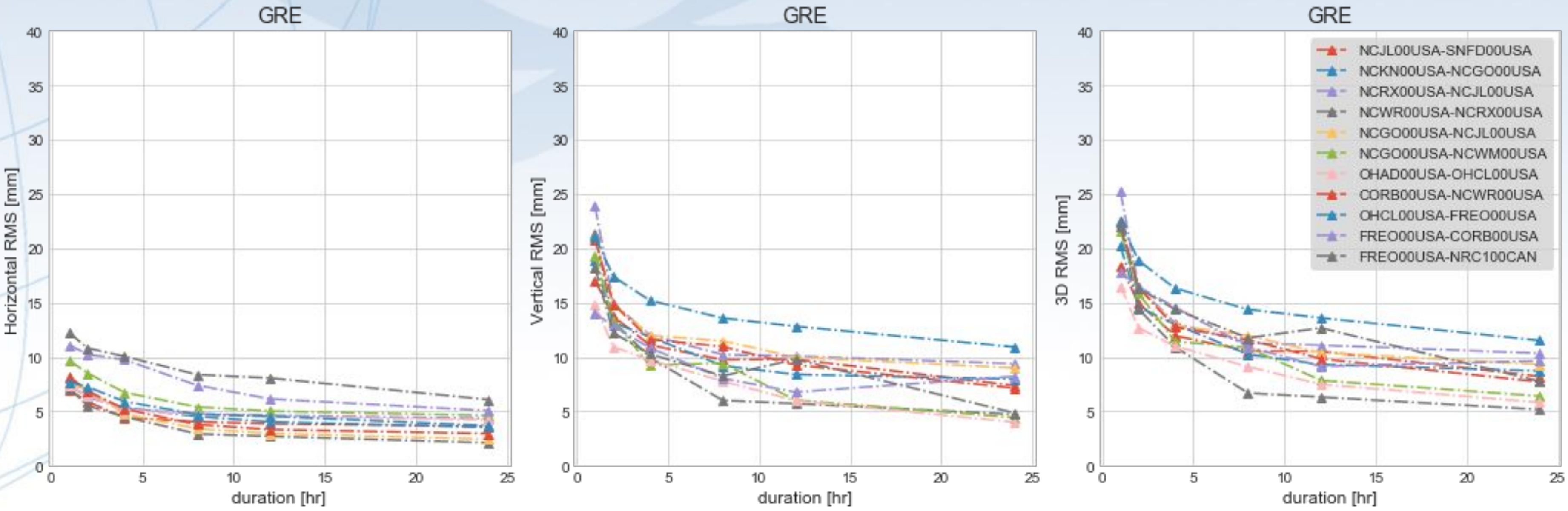
GPS + GLO + GAL



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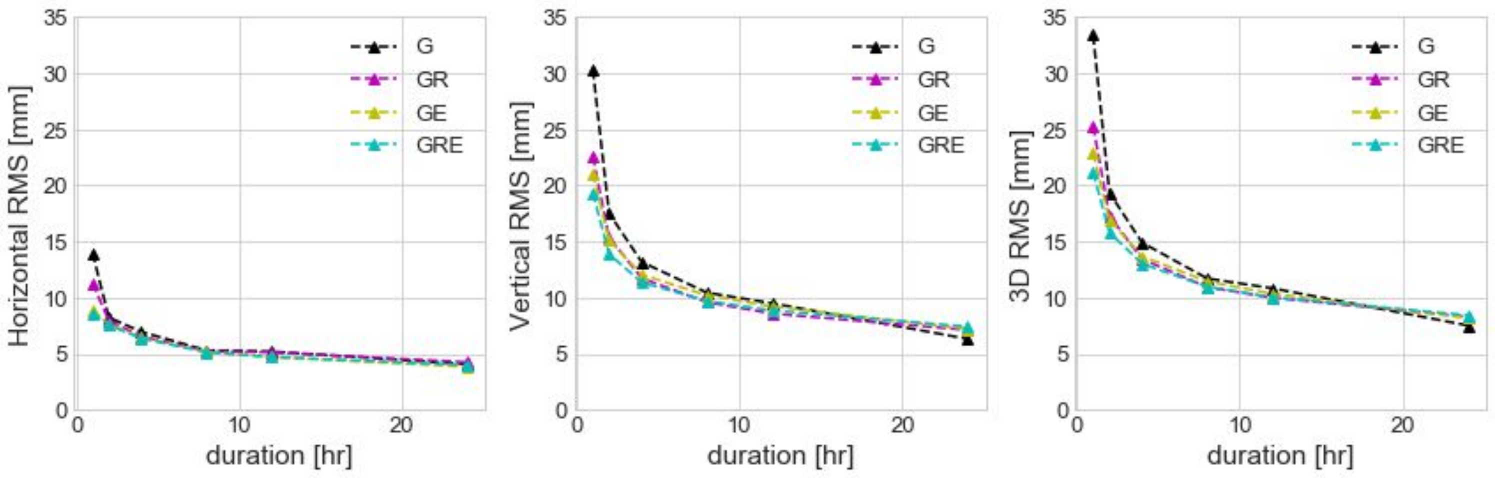
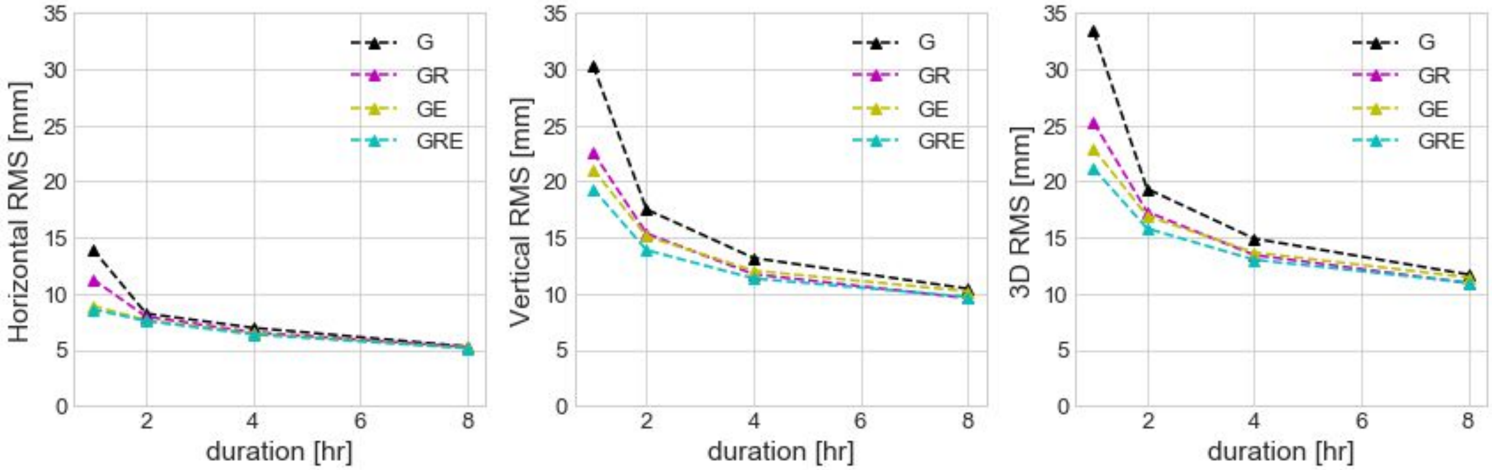


- RMS values for all baselines processed
- Significant improvements with added GNSS for shorter sessions
- Large outliers removed

		Percent Improvement (wrt GPS-only)		
GNSS	Duration [hr]	HRMS	VRMS	3D
GR	1	19.2	25.5	24.3
	2	3.4	12.2	10.6
	4	5.7	11.0	9.8
	8	1.2	8.1	6.7
GE	1	36.1	30.5	31.4
	2	7.4	13.7	12.5
	4	7.2	8.6	8.3
	8	2.3	2.3	2.3
GRE	1	38.4	36.2	36.6
	2	8.1	20.7	18.3
	4	8.5	13.8	12.6
	8	2.9	7.0	6.2



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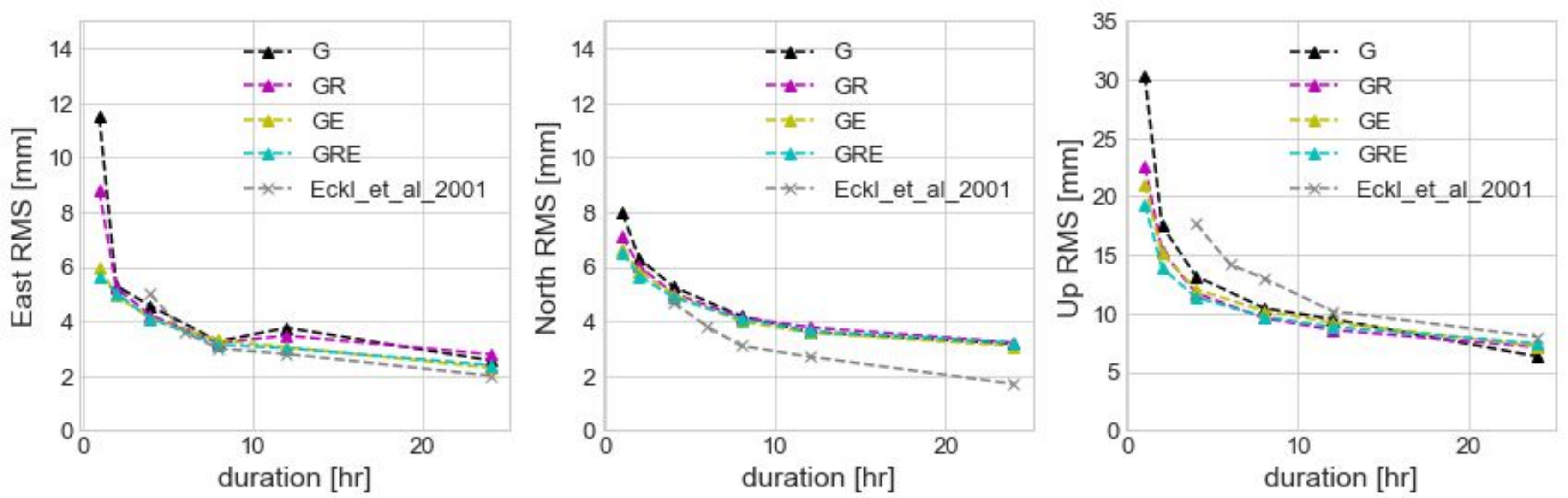
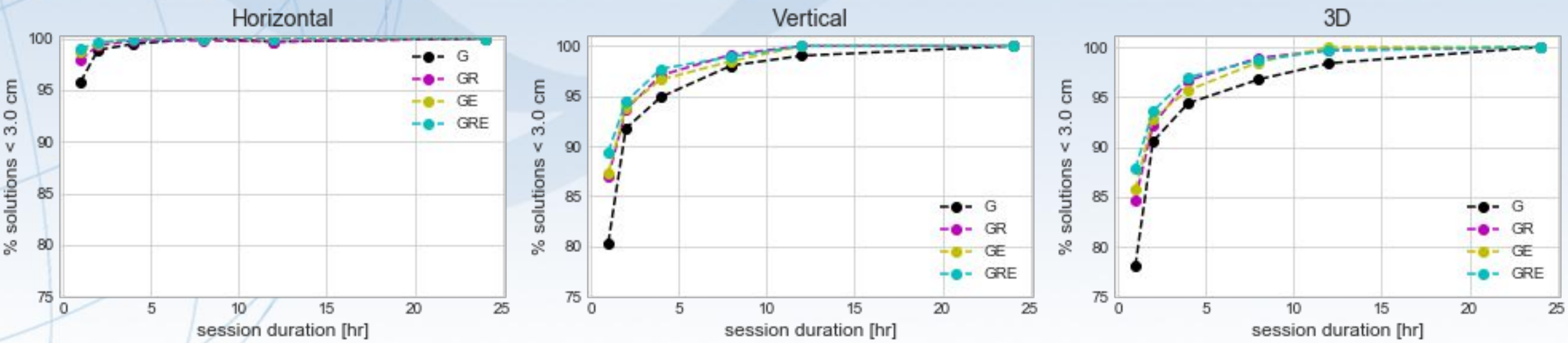
	2	7.4	13.7	12.5
	4	7.2	8.6	8.3
	8	2.3	2.3	2.3
GRE	1	38.4	36.2	36.6
	2	8.1	20.7	18.3
	4	8.5	13.8	12.6
	8	2.9	7.0	6.2

So how does this compare to PAGES?

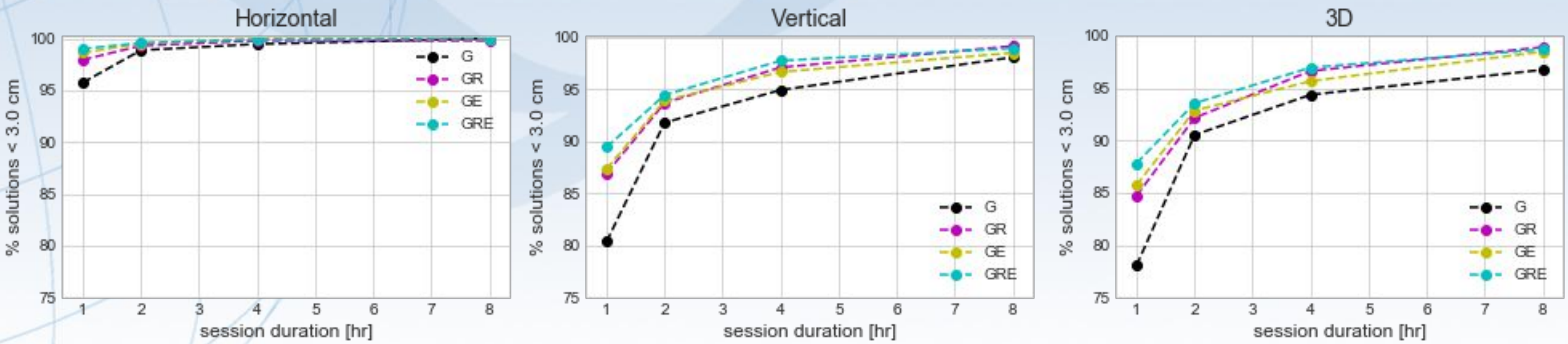


- Eckl et al. (2001) performed a similar study using PAGES
- Imperfect comparison due to difference time window and baseline selection
- M-PAGES results are quite consistent!



- Plots show percentage of solutions that agree with MYCS2 coordinates at 3 cm level (including outliers)

- Notable improvements for G→GRE solutions for shorter sessions



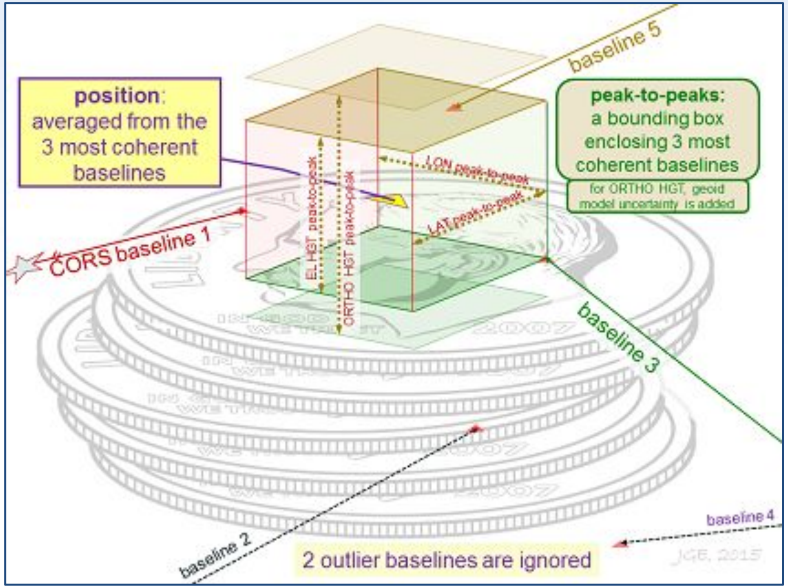
(Zoomed in on 1-8 hours)

- Plots show percentage of solutions that agree with MYCS2 coordinates at 3 cm level (including outliers)
- Notable improvements for G→GRE solutions for shorter sessions

M-PAGES Testing: OPUS data

OPUS-Static

- User submits a rover RINEX file along with antenna height/type
- Five single baseline solutions are processed to nearby CORS
- OPUS-S solution = average of best three baseline solutions
- OPUS-S uncertainties = peak to peak errors of best three (right)

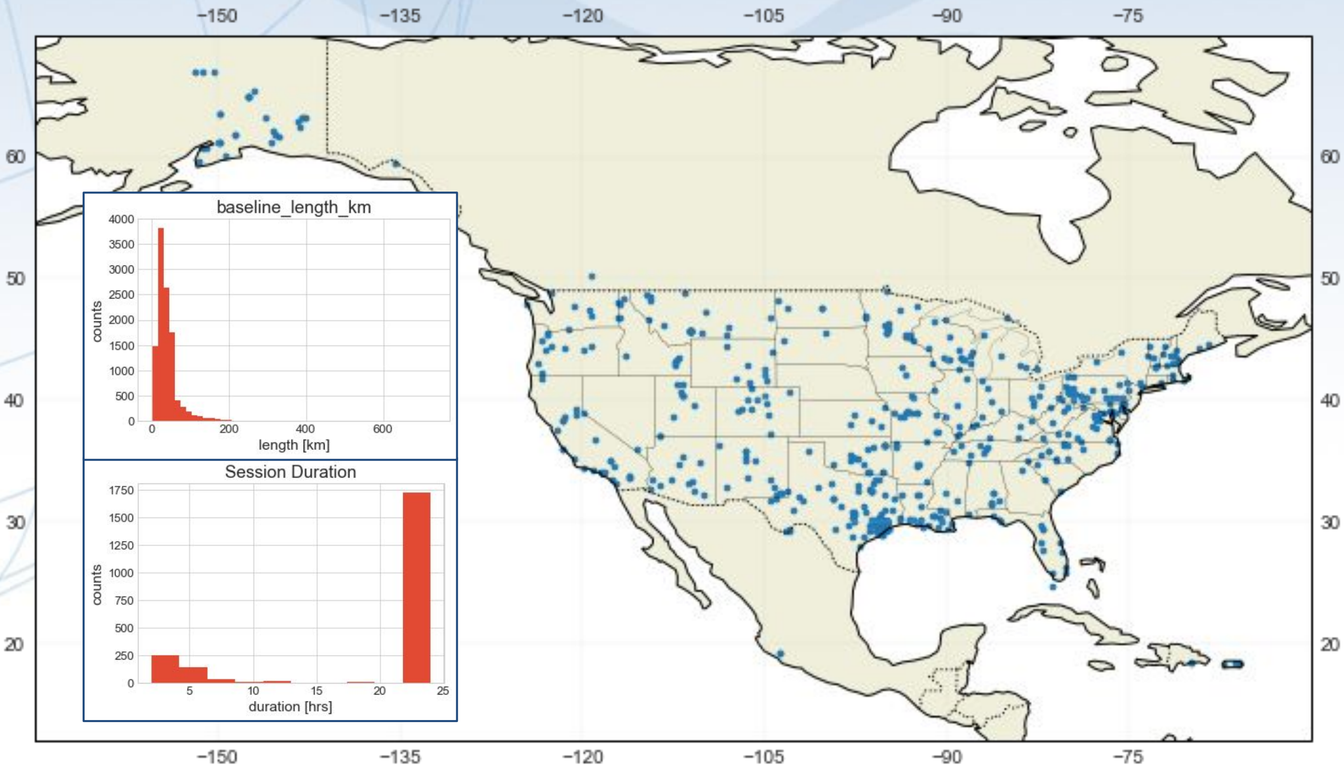


https://geodesy.noaa.gov/OPUS/about.jsp

OPUS-S Testing

- For a selection of ~2500 OPUS submissions:
  - Process each of the 5 baselines with M-PAGES (**GPS only**)
  - Compare each single-baseline solution with the corresponding PAGES solution
  - Compare the OPUS-S solution for M-PAGES with PAGES
    - i.e., Average of the best three baselines

https://geodesy.noaa.gov/OPUS/

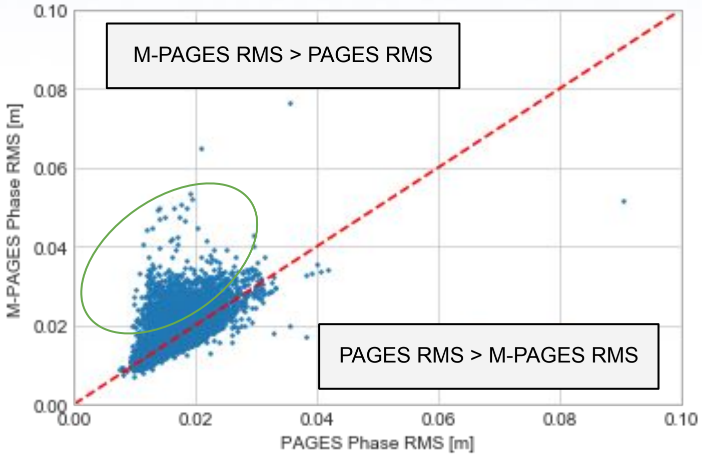


- The majority of data processed:
    - < 200 km baselines
    - 24 hour sessions
- Large quantity of submissions in Texas

Consistency of individual baseline solutions

- Percentage* of solutions that PAGES and M-PAGES solutions agree within threshold
- Population of solutions with higher RMS for M-PAGES (Bottom right; Green oval)
- Room for improvement!

Component < 3 cm	N	%
Horizontal	11792	95.55
Vertical	11711	94.90
3D	11029	89.37

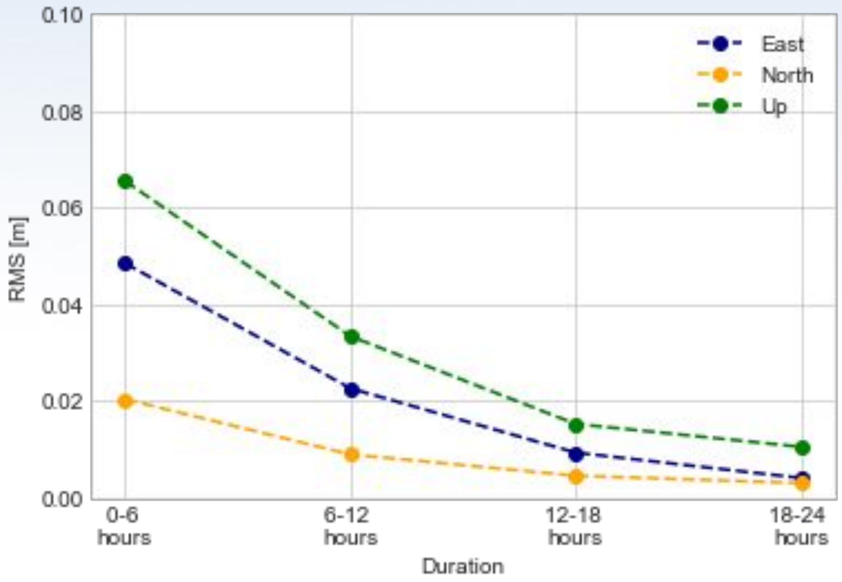


* Total baseline solutions = 12430

Consistency of individual baseline solutions

- RMS of coordinate differences between M-PAGES and PAGES

- Values averaged for sessions grouped by duration with large outliers removed



Consistency of OPUS-S solutions

(1) Percentage* of solutions that M-PAGES/PAGES OPUS-S coordinates agree below threshold
- OPUS-S coordinates = average of best three baseline solutions

(2) Percentage* of solutions with peak to peak (P2P) error magnitude < threshold
- Each software package yields solutions with large P2P error (see figure)

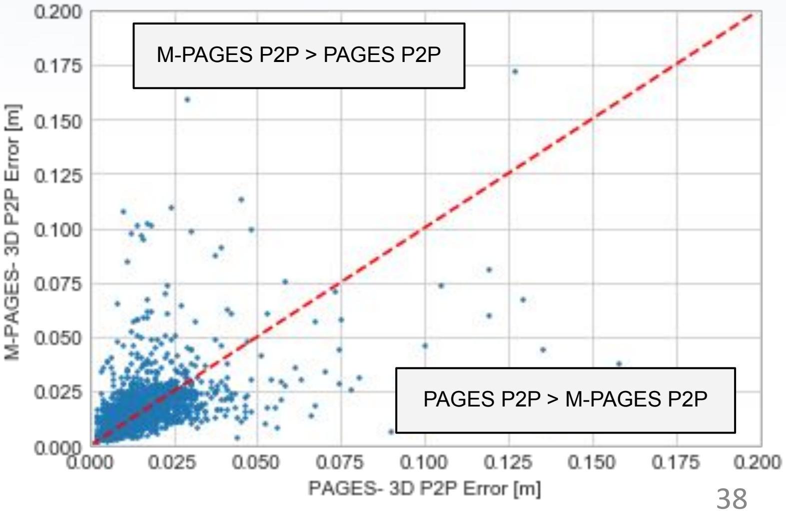
*Total solutions = 2471

(1)

Component < 3 cm	N	%
Horizontal	2371	95.95
Vertical	2388	96.64
3D	2281	92.31

(2)

P2P < 3 cm	N	%
M-PAGES	2296	92.92
PAGES	2302	93.16



Looking Ahead

- Planned integration of M-PAGES in Beta OPUS-S by end of calendar year (2022)
  - Once released, please test and provide feedback!

- Future OPUS User Forum will provide more detail about M-PAGES integration- stay tuned!

- Ongoing R&D:
  - Improved ambiguity resolution, cycle slip/outlier detection
  - Testing, testing, testing
  - Prep for integration into OPUS-Projects and GNSS orbit determination

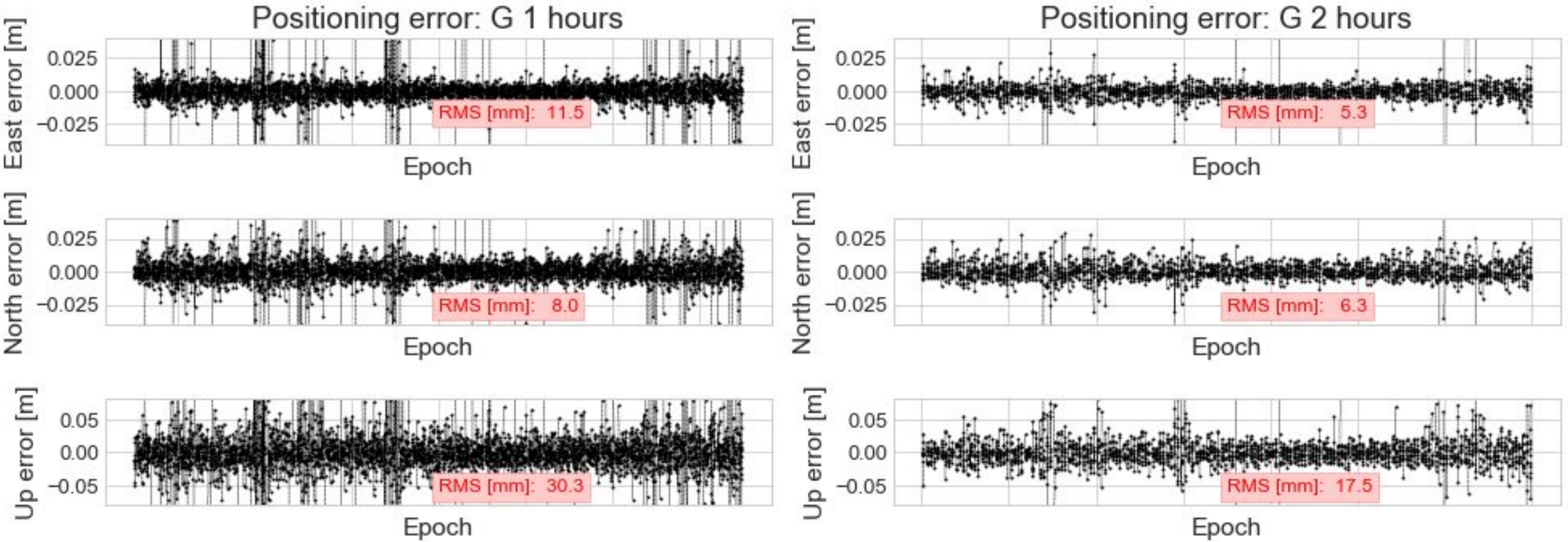
Key Points

- M-PAGES is capable of processing GNSS data for all dual-frequency systems

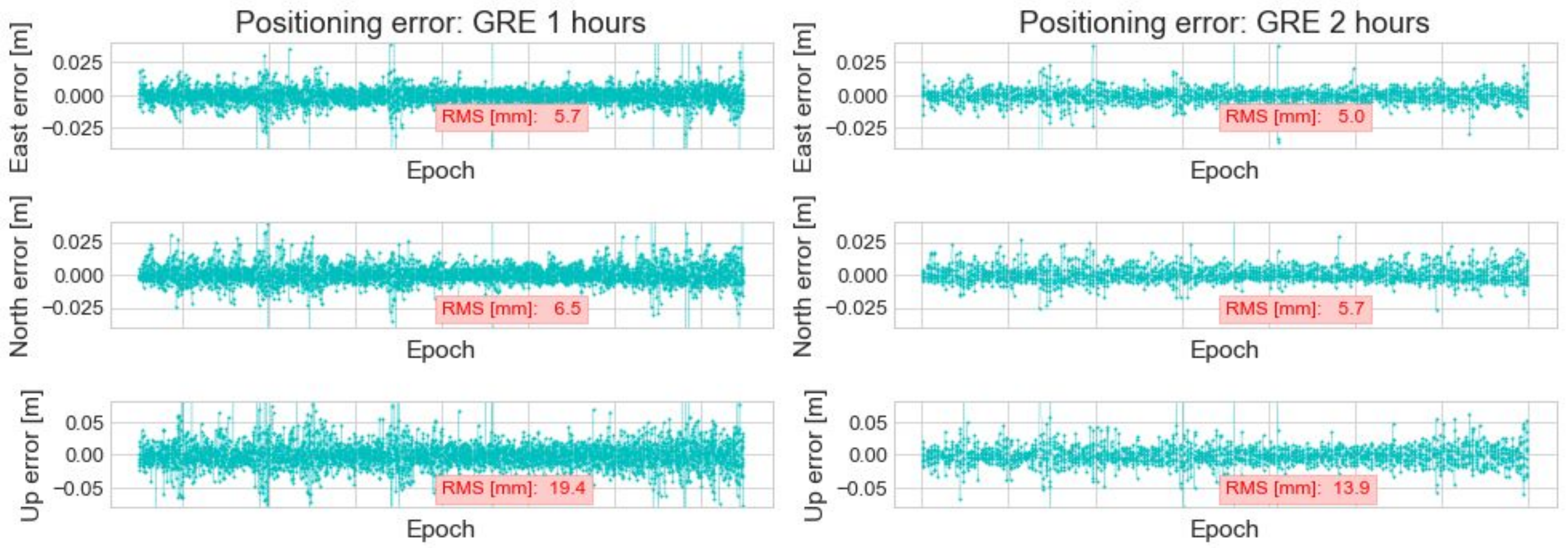
- Improved positioning with multi-GNSS data can be demonstrated with M-PAGES

- M-PAGES is still under active development, but OPUS-S integration is underway

Extra Slides



- X-axes: mean epoch of each session
- Y-axes: positioning errors wrt MYCS2 coordinates for all baselines
- Outliers are included in these plots



- X-axes: mean epoch of each session
- Y-axes: positioning errors wrt MYCS2 coordinates for all baselines
- Outliers are included in these plots
- **Notable improvements and fewer outliers with GLO+GAL added!**