Precise Point Positioning Ambiguity Resolution: Are we there yet?

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Precise Point Positioning (PPP)

- PPP is well established within geosciences using the GIPSY OASIS II Software (Zumberge et al., 1997)
- Applications of PPP
  - Environmental and geodynamic monitoring
    - E.g. natural hazard monitoring systems (volcano, earthquakes, etc.)
  - Recently: offshore surveying
- Advantages of PPP
  - Computational and time efficiency of PPP
  - Absolute positioning with homogeneous accuracy
    - Inter-site distance is (largely) irrelevant
    - Site-specific effects do not affect neighbouring sites
- Limitations
  - Precision and accuracy
  - Convergence
  - Ambiguity resolution (at a single station)

Positioning Frequency	Type	3D Positioning Accuracy
daily	static	mm
hourly	static	sub-dm
hourly	kinematic	10-20 cm

e.g. Bisnath & Gao (2009), Landau et al. (2009)

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Ambiguities in Un-Differenced Observables (Ambiguity Resolution at a Single Station)

- Until recently considered as difficult, if not impossible, due to non-integer character of ambiguities in un-differenced observables
- For example, the one-way carrier phase observation equation from receiver k to satellite i with frequency m and wavelength λ_m can be written as (e.g. Goad, 1985; Blewitt, 1989; Gabor & Nerem, 1999; Ge et al., 2008):

$$L_{mk}^{i} = \rho_k^i - \frac{\kappa}{f_m^2} + \lambda_m b_{mk}^{i}$$

- where $$b_{mk}^{i} = n_{mk}^{i} + \phi_{mk} - \phi_m^i$$
- with n_{mk}^{i} being the integer ambiguity, and ϕ_{mk} and ϕ_m^i being the fractional hardware delays in receiver and transmitter
- First attempt to overcome these un-calibrated hardware delays (UHD) was by Gabor & Nerem (1999)

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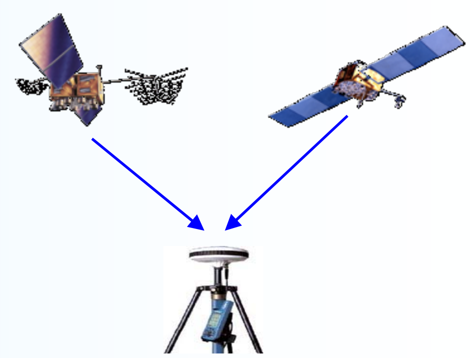
Ambiguity Resolution at a Single Station (cont.)

- Strategies for resolving integer ambiguities in un-differenced observables can be attributed to:
- Un-differenced approaches
  - Mixing of UHD with satellite clocks (e.g. Laurichesse & Mercier, 2007; Delporte et al., 2007; Laurichesse et al., 2008; 2009)
  - Using a “decoupled clock model” (e.g. Collins, 2008; Collins et al., 2008)
  - Ambiguity pseudo-fixing (e.g. Gao & Shen, 2002; Wang & Gao, 2006)
- Single-Difference approaches (between-satellite differences - BSD)
  - BSD remove receiver UHD while preserving the “single station character” for PPP
  - Estimation of transmitter UHD
  - Theoretical model: Gabor & Nerem (1999)
  - Some work (e.g. Ge et al., 2008; Geng et al., 2008; 2009; Mervart et al., 2008)



Determination of UHD

- It can be shown that the carrier phase bias term of the ionosphere-free combination can be written as (e.g. Ge et al., 2008):

$$b_{ck}^{i} = \frac{f_1}{f_1 + f_2} b_{nk}^{i} + \frac{f_1 f_2}{f_1^2 - f_2^2} b_{wk}^{i}$$

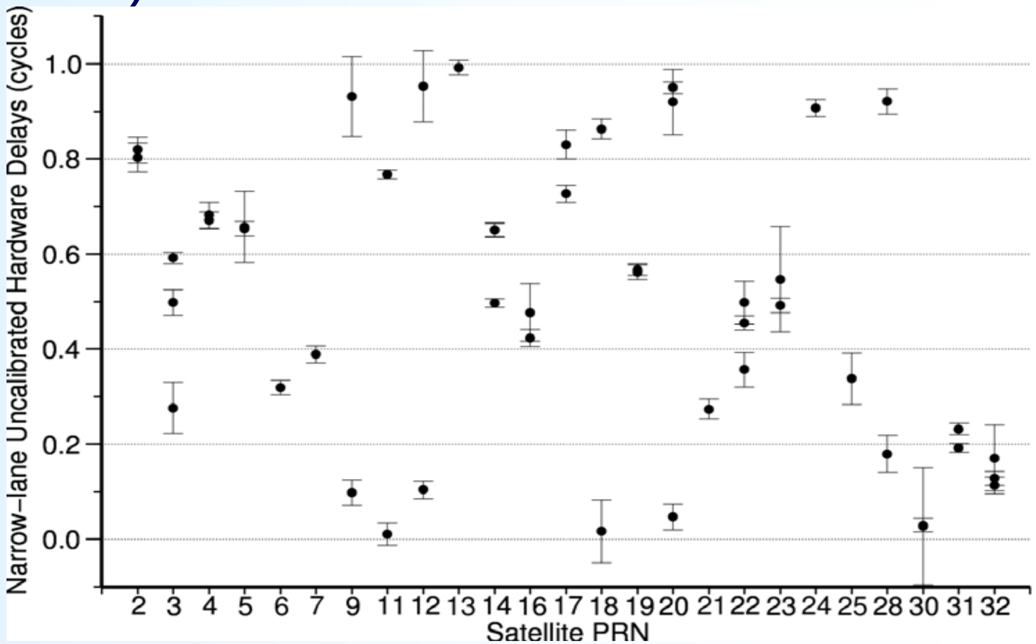
- where b_{nk}^{i} is the narrow-lane (NL) and b_{wk}^{i} the wide-lane (WL) carrier phase bias.
- The BSD carrier phase bias term can be shown to be:

$$b_{ck}^{i,j} = \frac{f_1}{f_1 + f_2} \left(n_{nk}^{i,j} - \phi_{n}^{i,j} \right) + \frac{f_1 f_2}{f_1^2 - f_2^2} \left(n_{wk}^{i,j} - \phi_{w}^{i,j} \right)$$

- where $\phi_{n}^{i,j}$ and $\phi_{w}^{i,j}$ denote the BSD NL and WL UHD, and $n_{nk}^{i,j}$ and $n_{wk}^{i,j}$ the BSD NL and WL integer phase ambiguities, respectively.

Determination of UHD (cont.)

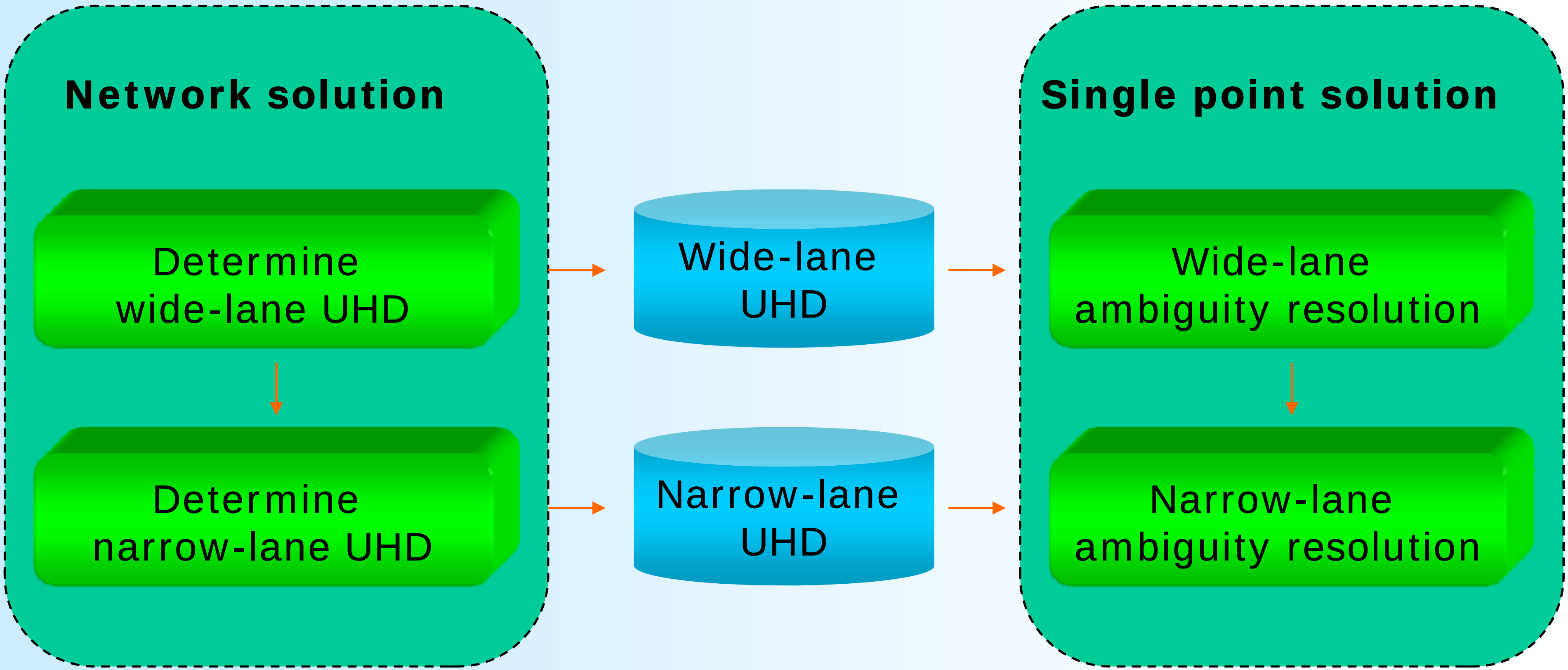
- Daily mean WL UHD can be considered as stable over days to months (e.g. Gabor & Nerem, 1999; Ge et al., 2008; Geng et al., 2009; Laurichesse & Mercier, 2007)
- However, the NL UHD need to be estimated more frequently:
  - Ge et al. (2008) – every 15 minutes
  - Geng et al. (2008; 2009) – once per continuous tracking period of a satellite pair over a regional network
- The latter is more convenient in practise while retaining high precision



NL UHD estimates for all satellites with respect to PRN01 on Day 247 in 2007.

Description of Ambiguity Resolution in PPP

- Method from Ge et al. (2008) and Geng et al. (2009)



Ambiguity resolution in PPP

- With WL and NL UHD determined WL and NL ambiguity resolution can be implemented sequentially
- WL ambiguity resolution follows the sequential bias fixing strategy (Dong & Bock, 1989)
- NL ambiguity resolution uses the LAMBDA (Least-squares AMBiguity Decorrelation Adjustment) method (Teunissen, 1994)
- Only ambiguities with mean elevation bigger than 15 degrees
- Ambiguity validation follows Teunissen et al., (1997) and Han (1997):
  - Unit variance test (compatibility of unit variance between real- and integer-ambiguity solutions
  - Ratio test > 3 (ratio of second to first minimum quadratic form of the residuals)
- More details in Geng et al. (2009), GPS Solutions, online first.

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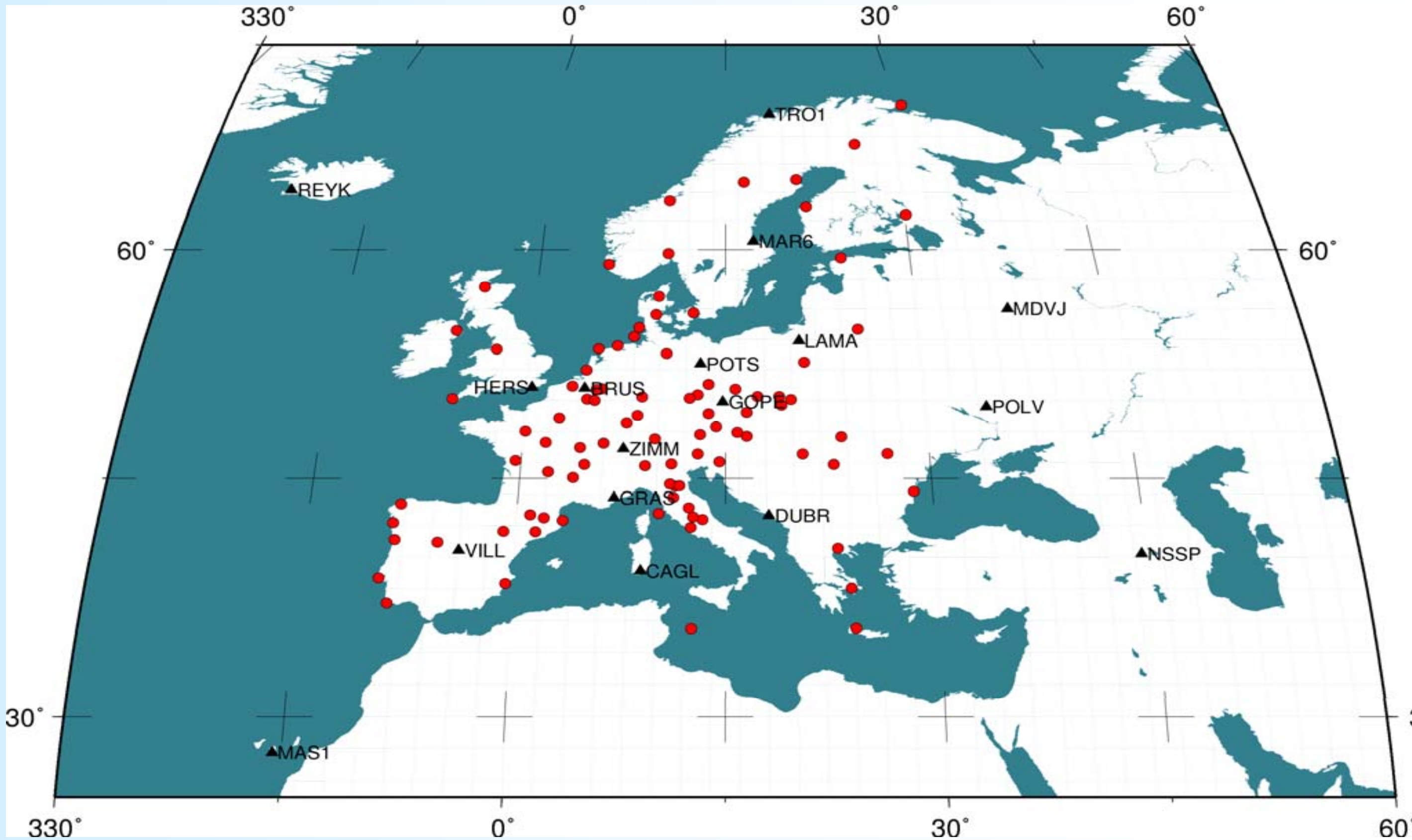
Case Study: Static PPP

- Data from Day 245 to 251 in 2007
- Red circles: EUREF Permanent Network stations to determine UHD
- Black triangles: IGS stations to test ambiguity resolution in hourly PPP



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Static PPP: Efficiency of Ambiguity Resolution

- Ambiguity resolution
  - Successful solutions: correct integer resolution
  - Rejected solutions: integer resolution failed
  - Wrong solutions: wrong integer resolution

Solution Types:	
Est ZTD (1h)	ZTD estimated along with hourly position estimate
Fix ZTD (1h)	ZTD fixed to values from 24h position estimate
Est ZTD (2h)	ZTD estimated along with 2-hourly position estimate

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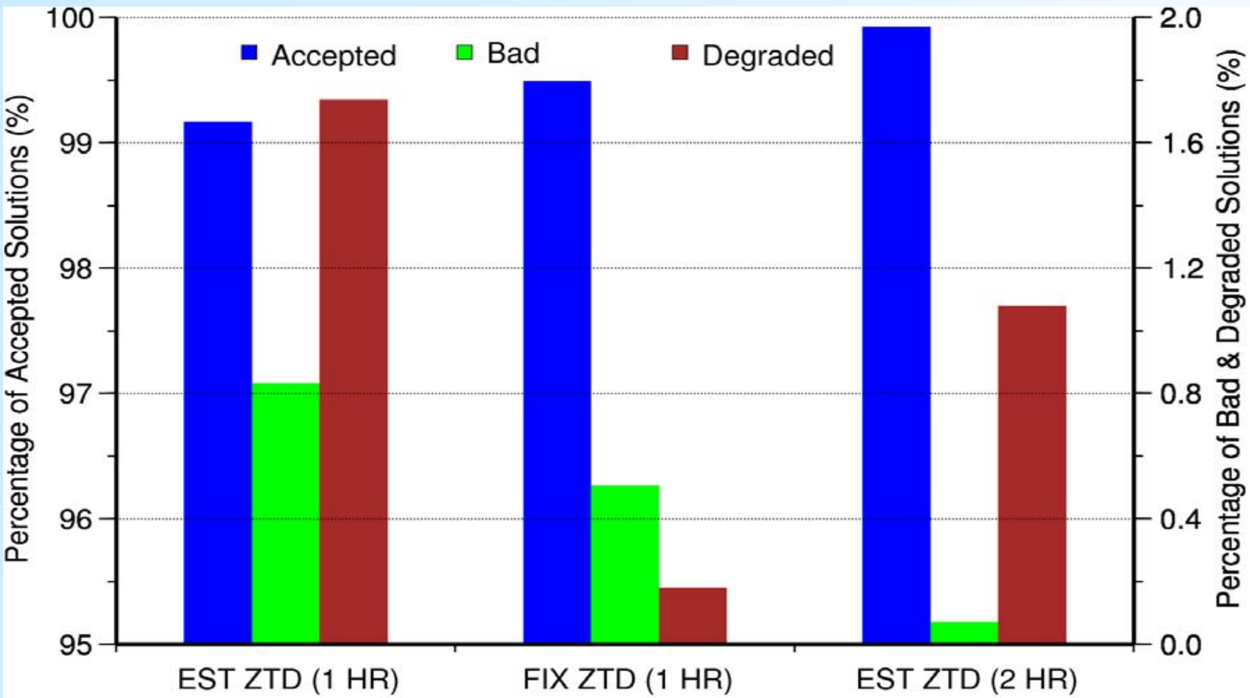
Static PPP: Statistics of Successful Solutions

- Successful solutions
  - Bad solutions: severely biased position estimates
  - Degraded solutions: position precision of fixed solutions is worse than that of float solutions



Solution Types:	
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Static PPP: Accuracy of Hourly Position Estimates

- RMS of hourly position estimates

Station	Float Solutions (cm)				Fixed Solutions (cm)				3D Improvement
	East	North	Up	3D	East	North	Up	3D	
BRUS	3.3	1.4	2.8	4.5	0.4	0.4	1.3	1.5	67.8%
CAGL	4.8	1.9	4.0	6.5	1.0	0.8	2.0	2.4	63.8%
DUBR	5.6	1.9	3.3	6.8	0.4	0.6	1.3	1.4	78.7%
GOPE	4.5	1.8	2.9	5.7	0.3	0.4	1.5	1.6	72.1%
GRAS	2.4	1.1	2.4	3.6	0.4	0.4	1.3	1.4	60.6%
HERS	4.1	1.3	2.4	5.0	0.3	0.4	1.2	1.3	74.1%
LAMA	3.8	1.5	2.6	4.8	0.7	0.6	1.4	1.7	65.1%
MAR6	3.3	1.6	2.3	4.3	0.7	0.7	1.5	1.8	58.7%
MAS1	5.4	1.4	4.6	7.2	0.5	0.6	2.5	2.6	64.0%
MDVJ	3.1	1.2	2.2	4.0	0.4	0.7	1.6	1.8	55.7%
NSSP	3.8	1.3	3.1	5.1	0.5	0.5	1.8	1.9	62.3%
POLV	4.0	1.9	3.0	5.3	0.4	0.5	1.7	1.8	66.2%
POTS	3.6	1.4	2.8	4.8	0.3	0.4	1.3	1.4	70.0%
REYK	4.0	2.0	3.2	5.5	0.5	0.6	2.2	2.3	58.2%
TRO1	1.5	1.1	1.8	2.6	0.3	0.3	1.2	1.3	51.6%
VILL	4.1	1.5	3.4	5.6	0.4	0.5	1.5	1.6	70.5%
ZIMM	3.1	1.2	2.4	4.1	0.4	0.4	1.2	1.3	68.2%
Total	**3.9**	**1.5**	**3.0**	**5.1**	**0.5**	**0.5**	**1.6**	**1.7**	**66.1%**

- RMS improvements: East 87.2%, North 66.7% and Up 46.7%

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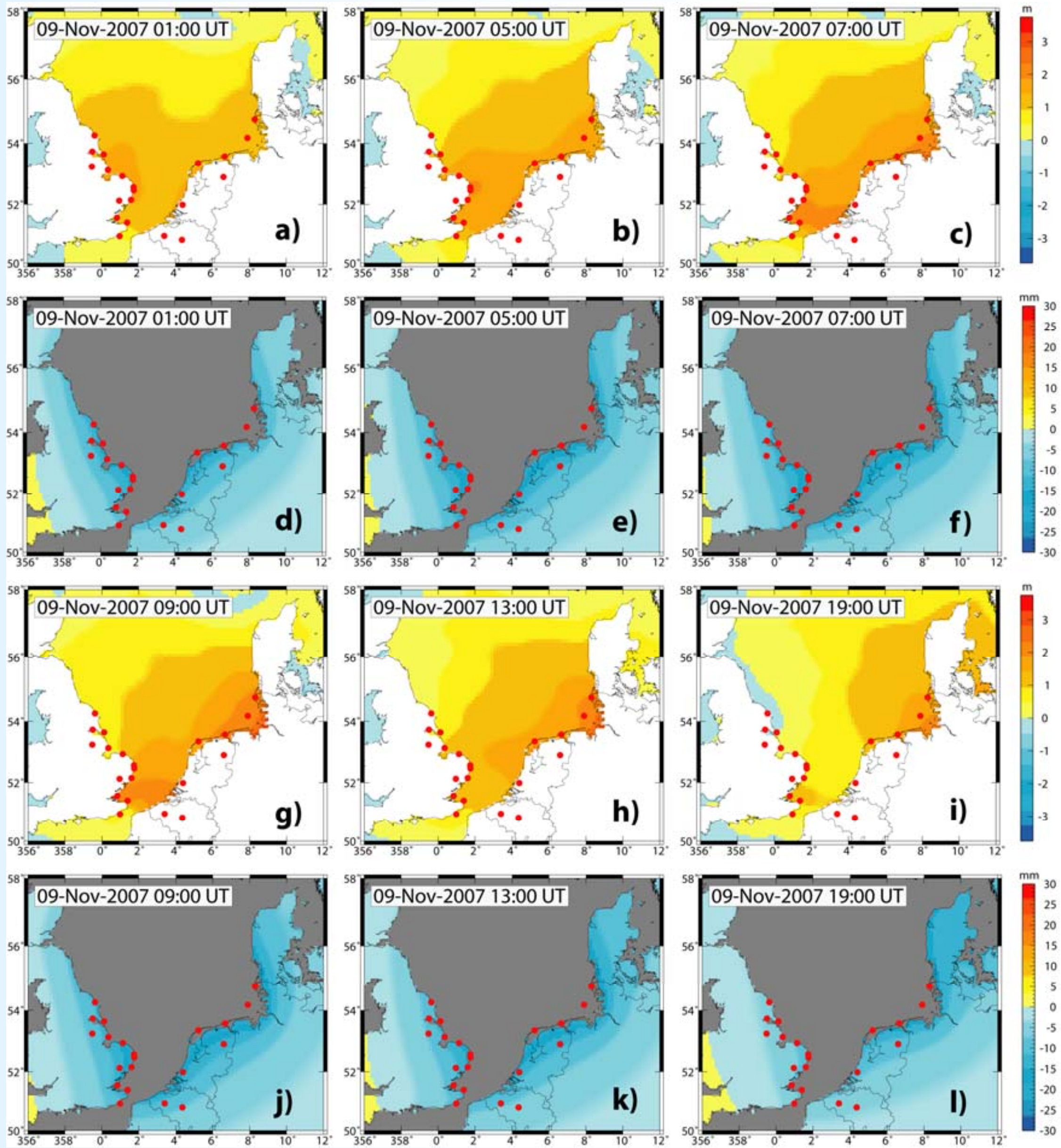
Case Study: Storm Surge Loading

- North Sea Storm Surge of 9 November 2007
- Surge Height and Modelled Vertical Displacement provided by S.D.P Williams, POL.
- Presented at AGU FM 2008, Teferle et al., Abstract G51A-0608.



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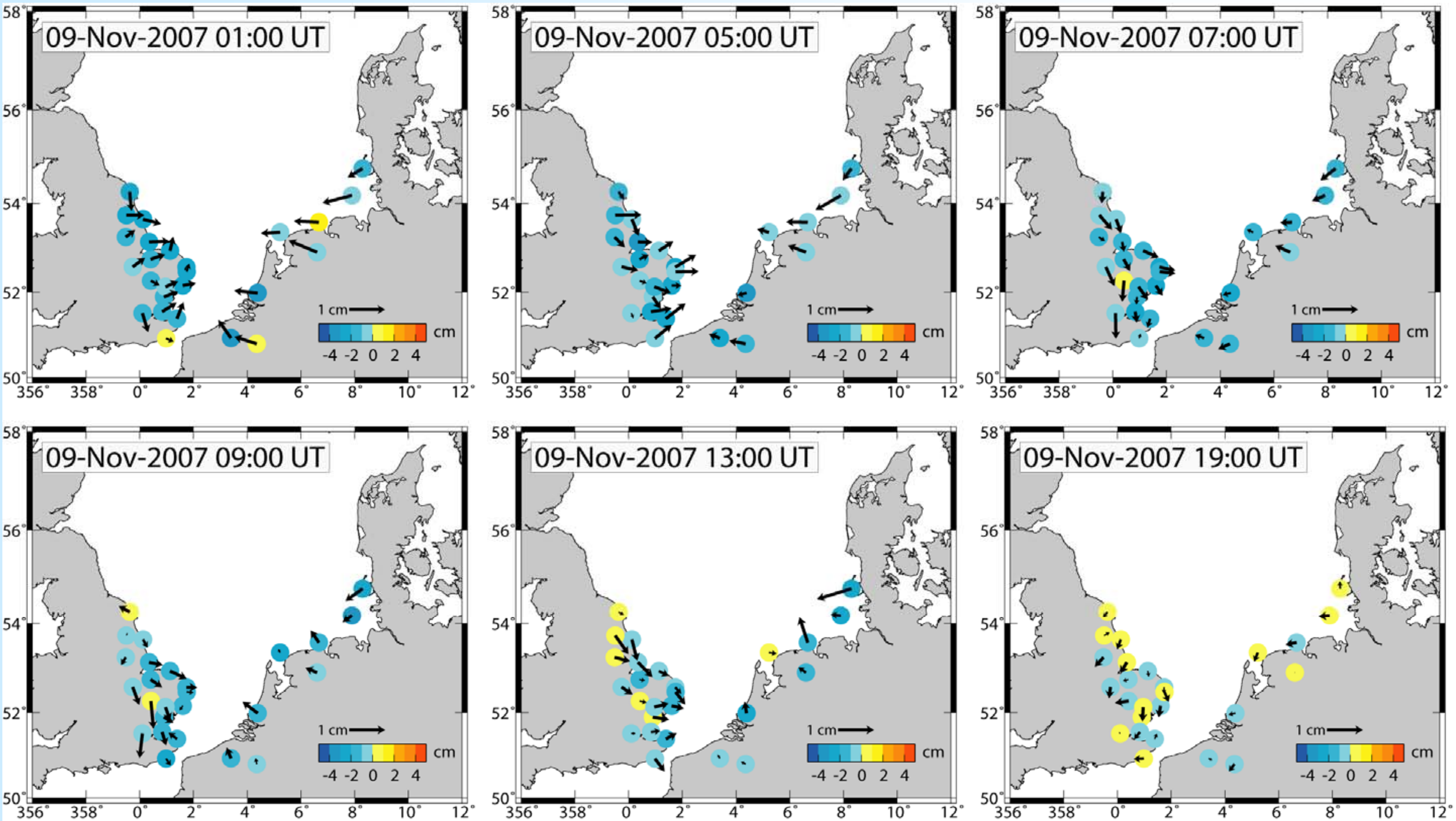
Storm Surge Loading: Observed 3D Station Displacements



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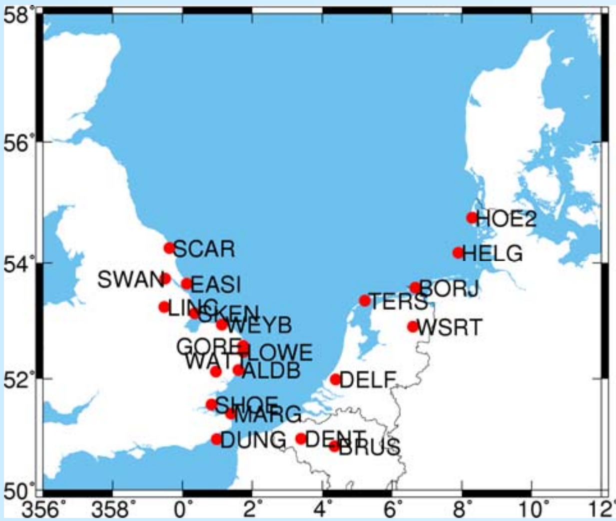
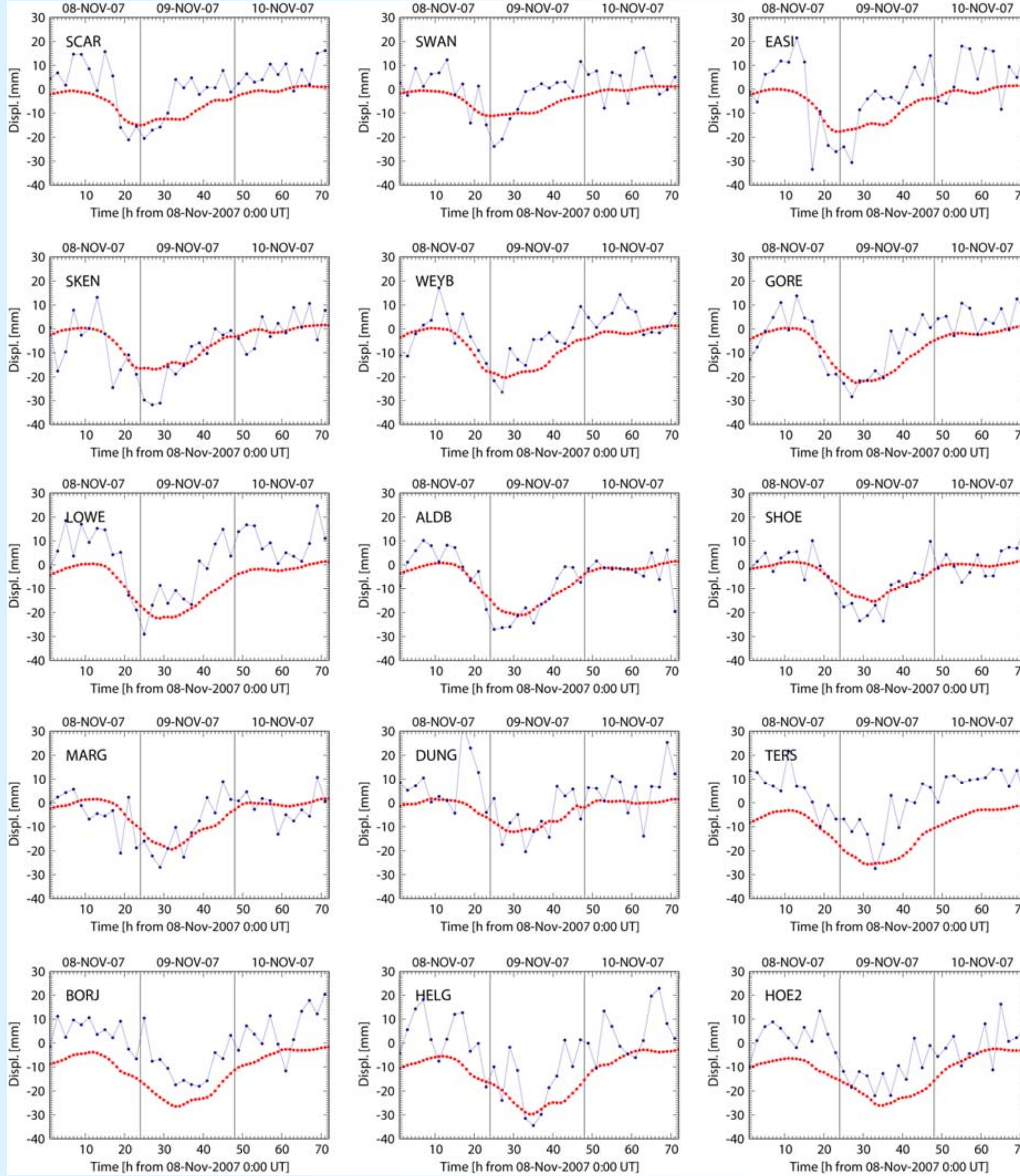
Storm Surge Loading: Vertical Displacement Comparison





Conclusions

- Reviewed current strategies for PPP ambiguity resolution (at a single station)
- Between-satellite difference UHD can be determined accurately within a regional network (global network shown by Ge et al., 2008)
- PPP ambiguity resolution can achieve high fixing rates and is highly reliable
- Ambiguity resolution in hourly static PPP can improve the 3D position accuracy by more than 66%
  - The horizontal accuracy achieves sub-cm level (Improvements of 87.2% (E) and 66.7% (N))
  - The vertical accuracy is better than 2 cm (Improvement of 46.7%)
- PPP ambiguity resolution enables new applications that require sub-daily position updates: e.g. determination of storm surge loading
- The PPP ambiguity resolution strategy demonstrated can also be applied to real-time and kinematic, or both, PPP.
  - See the presentation by Jianghui Geng on “Real-time PPP with ambiguity resolution for geosciences.”

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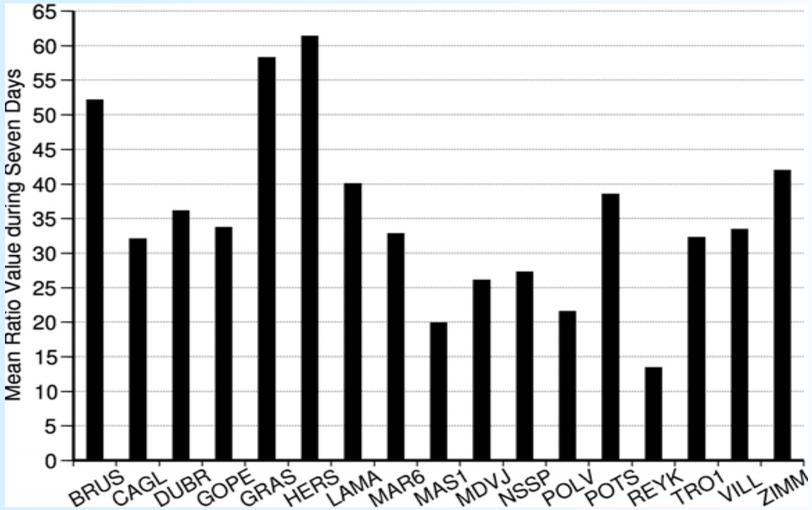
Static PPP: Ratio values

- Ratio values provide an index of the reliability of AR
- For solution type EST ZTD (1 HR)



- These results demonstrate that
  - Ambiguity resolution at a single station is fairly reliable
  - A total fixing rate of 97.8% can be achieved

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Fixing rates

- Total fixing rates of independent SD wide-lane (WL) and Narrow-lane (NL) ambiguities

SOLUTION TYPES	SD WL (%)	SD NL (%)	SD (%)
EST ZTD (1 HR)	98.9	98.9	97.8
FIX ZTD (1 HR)	98.9	99.1	98.0
EST ZTD (2 HR)	98.9	99.6	98.5

- Column 4 is the product of Column 2 and 3
- Demonstrate:
  - Reliability and precision of initial phases are confirmed
  - ZTD and length of observation period influence fixing rates

Static PPP: Success Rate of AR

Station	# of All solutions	# of Rejected solutions	# of Wrong solutions
BRUS	168	1	1
CAGL	168	1	6
DUBR	167	3	2
GOPE	168	0	2
GRAS	161	1	1
HERS	168	0	0
LAMA	166	0	0
MAR6	157	0	2
MAS1	166	2	0
MDVJ	167	0	0
NSSP	168	0	1
POLV	145	5	2
POTS	165	2	2
REYK	160	0	1
TRO1	168	0	0
VILL	168	0	0
ZIMM	168	0	1
Total	**2798**	**15 (0.54%)**	**21 (0.75%)**

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Impact of ZTD & observation period

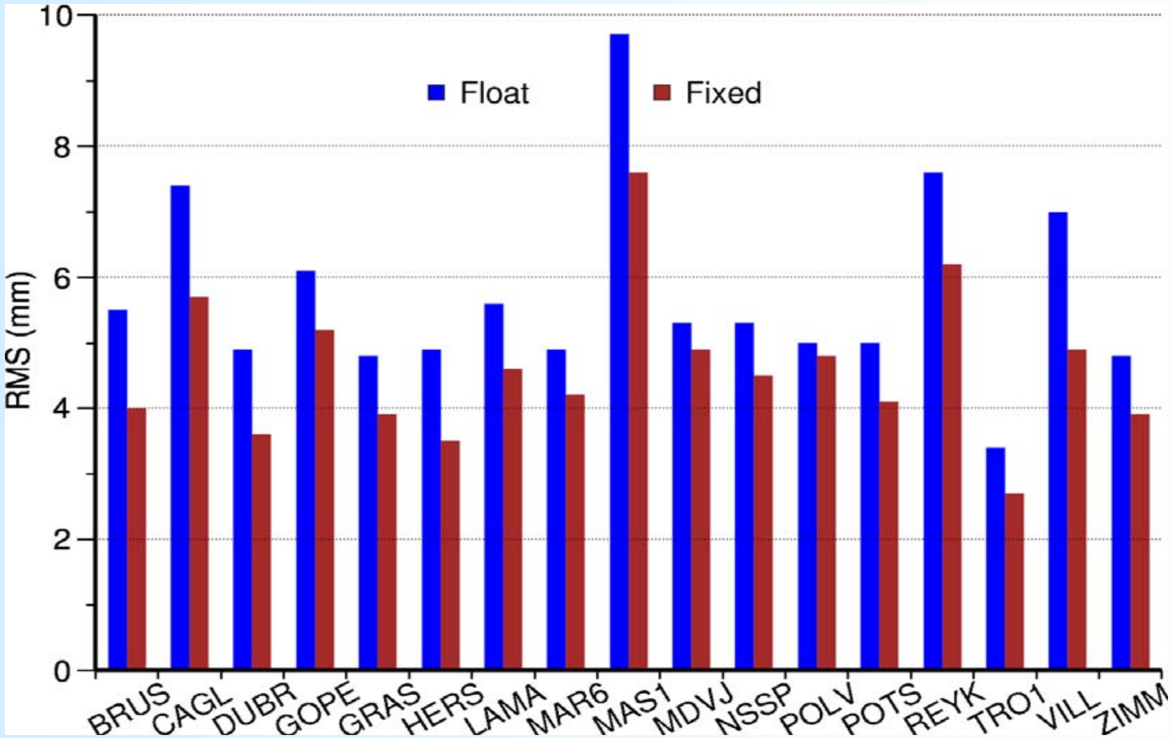
- Three solution types

Solution Type	Float Solutions (cm)				Fixed Solutions (cm)				3D Improvement
	East	North	Up	3D	East	North	Up	3D	
EST ZTD (1 HR)	3.9	1.5	3.0	5.1	0.5	0.5	1.6	1.7	66.1%
FIX ZTD (1 HR)	3.7	1.5	1.8	4.4	0.5	0.6	0.7	1.0	76.4%
EST ZTD (2 HR)	2.1	0.9	1.9	3.0	0.4	0.4	1.1	1.3	57.5%

- Demonstrate
  - ZTD is crucial to precision of Up component
  - Longer period is beneficial for float solutions

ZTD precision improvement

- For solution type EST ZTD (1 HR)



- 20.3% of improvement

Static PPP: Accuracy of Daily Position Estimates

Station	Float Solutions (cm)				Fixed Solutions (cm)				3D Improvement
	East	North	Up	3D	East	North	Up	3D	
BRUS	0.2	0.9	0.9	1.3	0.2	0.8	0.9	1.3	2.4%
CAGL	0.3	0.9	0.7	1.2	0.3	1.1	0.8	1.4	-13.4%
DUBR	0.2	0.9	0.7	1.2	0.3	0.9	0.8	1.2	-2.2%
GOPE	0.3	0.9	0.8	1.2	0.3	0.8	0.8	1.1	7.4%
GRAS	0.4	1.0	0.7	1.3	0.2	1.0	0.7	1.3	2.2%
HERS	0.2	0.8	1.0	1.3	0.1	0.8	0.9	1.2	4.3%
LAMA	0.5	1.3	1.5	2.0	0.4	1.1	1.3	1.8	12.6%
MAR6	0.1	1.0	1.1	1.5	0.3	1.0	1.2	1.5	-3.3%
POTS	0.3	1.1	1.1	1.6	0.3	1.0	1.1	1.5	2.9%
TRO1	0.3	0.8	1.6	1.8	0.2	0.8	1.7	1.8	-3.1%
VILL	0.3	0.8	0.6	1.0	0.2	0.7	0.5	0.9	15.4%
ZIMM	0.1	1.0	0.8	1.3	0.2	1.0	0.8	1.3	-5.9%
Total	**0.3**	**0.9**	**1.0**	**1.4**	**0.2**	**0.9**	**1.0**	**1.4**	**0.0**

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