On the Impact of Multi-GNSS Solutions on Satellite Products and Positioning

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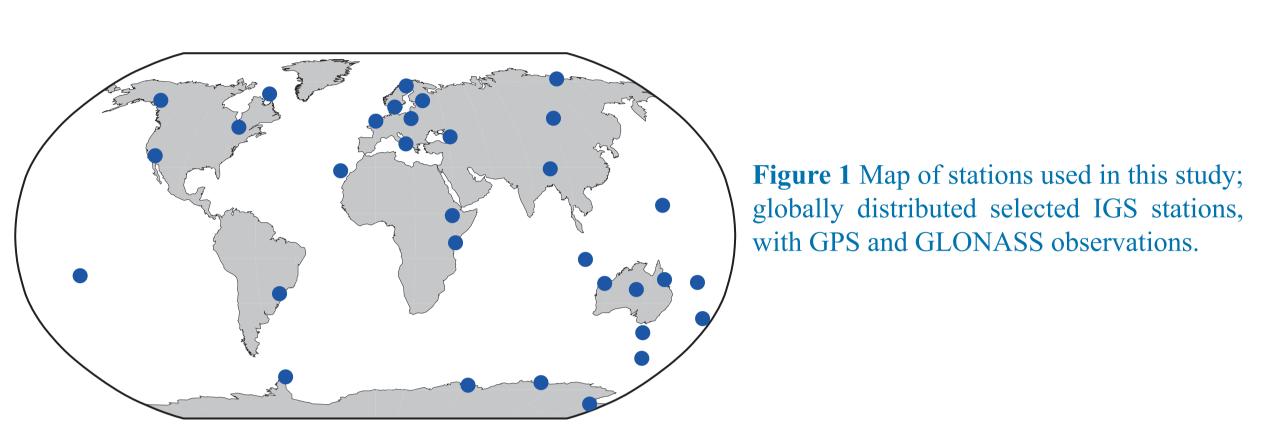
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1 Introduction

In Global Navigation Satellite System (GNSS) coordinate time series unrecognised errors and un-modelled (periodic) effects may bias non-linear motions induced by geophysical signals. Those spurious signals can be caused either due to un-modelled long periodic signals or propagation of sub-daily signals into the time series (Penna et al., 2007). Understanding and mitigating these errors is vital to reduce biases and on revealing subtle geophysical signals. Mostly, the spurious signals are caused by unmodelled errors which occur due to the draconitic years, satellite ground repeats and absorption into resonant GNSS orbits (Ray et al., 2007, 2013). Accordingly, different features can be observed in GNSS-derived products from different single-GNSS or combined-GNSS solutions. Table 1 lists the main differences of the orbit characteristics of the Global Positioning System (GPS) and GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GLONASS). To assess the nature of periodic signals on station coordinate time series Precise Point Positioning (PPP, Zumberge et al, 1997) solutions are generated using the Bernese GNSS Software V5.2 (BSW52, Dach et al., 2015). The solutions consider only GPS, only GLONASS or combined GPS+GLONASS (GNSS) observations. We assess the periodic signals of station coordinates computed using the combined International GNSS Service (IGS, Dow et al., 2009) and four of its Analysis Centers (ACs) products.

Table 1 Main orbit characteristic differences between GPS and GLONASS.

	GPS	GLONASS
Orbital planes	6	3
Satellite per plane	4 to 6	8
Orbital plane inclination	55°	64.8°
Orbit Repeat	1 sidereal day	8 sidereal day
Geometry repeatability	1 sidereal day	1/3 sidereal day
Latitude dependency	Yes	Yes
Longitude dependency	Yes	No

Figure 1 Map of stations used in this study; globally distributed selected IGS stations, with GPS and GLONASS observations.

Data Processing and Methods

In this study we used a PPP processing strategy. As PPP is based on a single station, the effects of site-specific errors such as multipath and certain obstructions can easily be assessed. Moreover, the computational efficiency and the independence of the network configuration makes PPP more attractive. Nevertheless, PPP can still deliver millimeter to centimeter levels of accuracy for static applications if the consistency in models and products is guaranteed.

The PPP solutions are computed by fixing the final satellite orbits and clocks, and Earth Rotation Parameters (ERPs) in BSW52 for a global set of stations (Figure 2). In this study the employed products are from the IGS and four IGS ACs, i.e. the Center for Orbit Determination in Europe (CODE, ftp://ftp.igs.org/pub/center/analysis/code.acn), European Space Agency (ESA, ftp://ftp.igs.org/pub/center/analysis/esa.acn), Jet Propulsion Laboratory (JPL, ftp://ftp.igs.org/pub/center/analysis/jpl.acn) and Massachusetts Institute of Technology (MIT, ftp://ftp.igs.org/pub/center/analysis/mit.acn).

The main PPP processing details can be summarized as:

- Products from CODE, ESA, JPL, IGS and MIT
- All latest models incorporated
- 3 degrees elevation cutoff, elevation dependent weighting and 300 seconds data sampling are applied
- Antenna phase center (igs08.atx)
  - GNSS-specific calibrations applied. If there are no GLONASS-specific calibrations, corresponding values are copied from GPS
- The estimated parameters for each station are daily station coordinates, troposphere parameters, and receiver clock corrections
- Consistency of products and models is guaranteed

2 GPS-only Solution

Processing Details

- PPP solutions based on GPS-only observations and products from CODE, ESA, IGS, JPL and MIT
- 32 globally distributed stations are used (Figure 1)
- All solutions are generated using the same processing settings and models (except for the employed products) for 2008-2015
- The position time series of individual stations are analyzed (detrended, outliers removed and offsets corrected (if any))
- The power spectrum of every station is computed
- Power spectra of all stations are then stacked, smoothed and plotted in Figure 2 as a normalized power versus frequency for the North, East and Up components. Color codes in Figure 2 show solutions generated using CODE (red lines), ESA (green lines), IGS (blue lines), JPL (magenta lines) and MIT (gold lines). The solutions are shifted along the vertical axis for clarity.
- Annual and semi-annual, draconitic harmonics, fortnightly and 8-day periods are highlighted with dashed vertical lines (see caption)

Main Results of the GPS-only solution(s)

- The general picture of the spectra (Figure 2) is similar to the global solution (e.g. Ray et al., 2007)
  - Draconitic periods are evident up to 8-9th harmonics
  - The back ground spectra follow a flicker plus white noise behavior
- 13.6-day period is not discernable in the solution based on JPL products
  - The period is clearly visible in the other solutions
  - Is there an absorption effect in JPL's processing strategy?
- Though the existence of the 13.6-day signal in all our GPS-only PPP solutions based on the IGS and other ACs products might indicate a relation to an error in the IERS model (e.g. for Earth tidal variations), the final nature of the signal in the JPL based solution remains unexplained.
- The well known 5.5-day period in the JPL solution is not discernable from our PPP solutions based on JPL products.
  - Is the 5.5-day period a software issue?
- An 8-day period is evident in solutions based on CODE and ESA products.
- As these solutions are generated using GPS-only observations, the presence of the 8-day period in the solutions based on CODE and ESA products indicates that the GPS orbits contain GLONASS-specific periods.
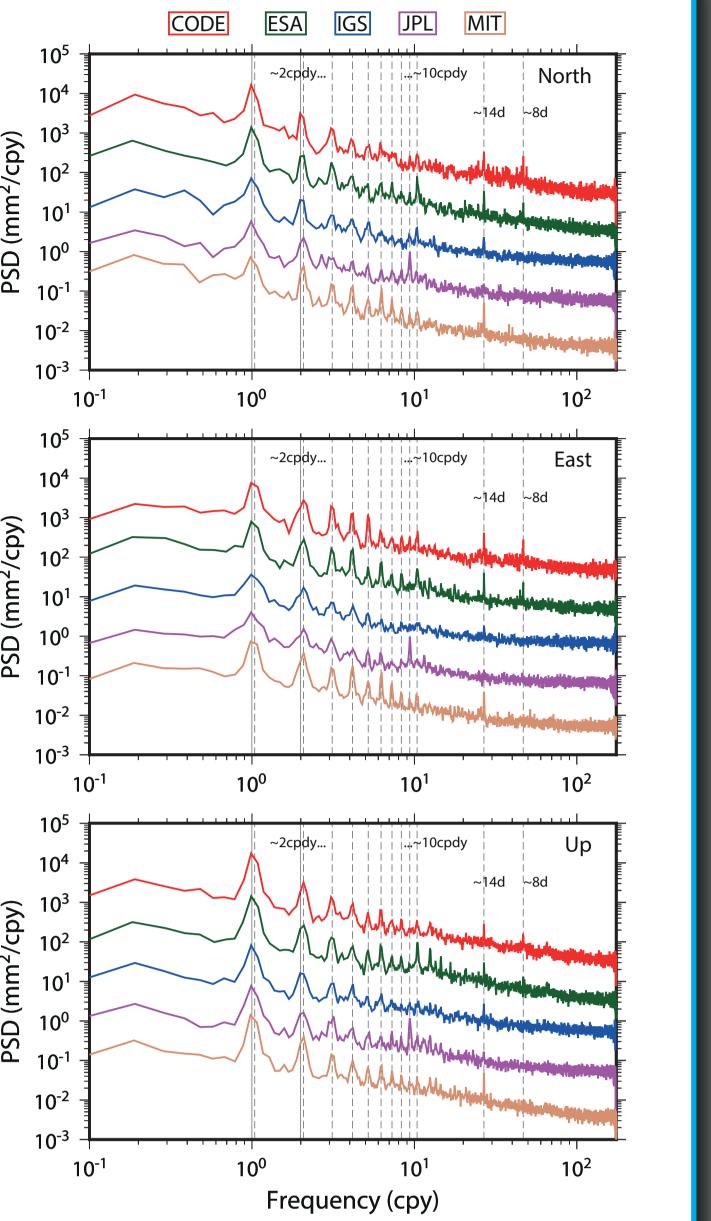
Figure 2. Power spectra of position time series (stacked from all stations in Figure 1) for GPS-only solutions using the CODE, ESA, IGS, JPL and MIT products. The power spectra of the solutions have been shifted along the vertical axis for clarity. The dark gray vertical lines are the annual and semi-annual cycles, the light gray dashed lines are the 1.04 cpy (1 cycle per draconitic year [cpdy]) and its harmonics (until the 10th harmonic), the fortnightly (~14d) and 8-day period cycles.

3 GLONASS-only Solution

Processing Details

- PPP solution based on GLONASS-only observations and products from ESA for 2009-2015
- 32 globally distributed stations are used (Figure 1)
- The position time series of individual stations are analyzed (detrended, outliers removed and offsets corrected (if any))
- The power spectrum of every station is computed
- Power spectra of all stations are then stacked, smoothed and plotted in Figure 3 as a normalized power versus frequency
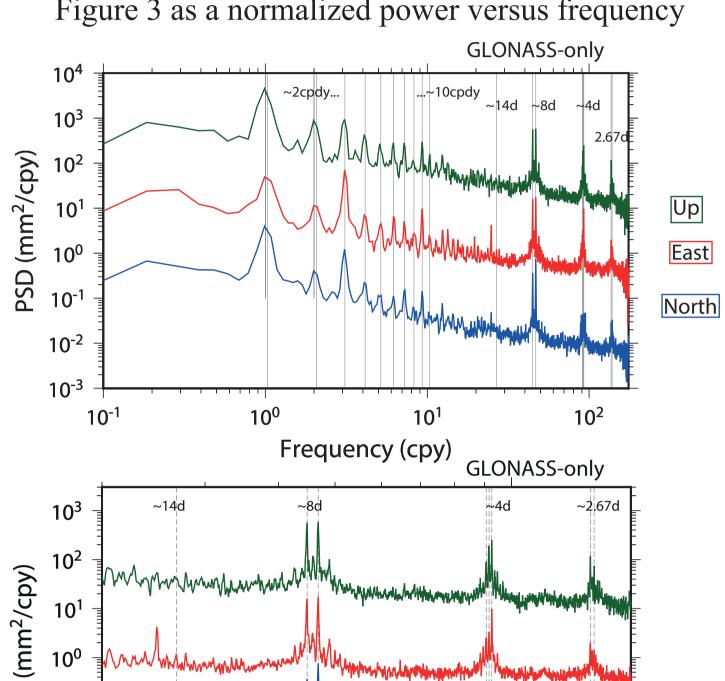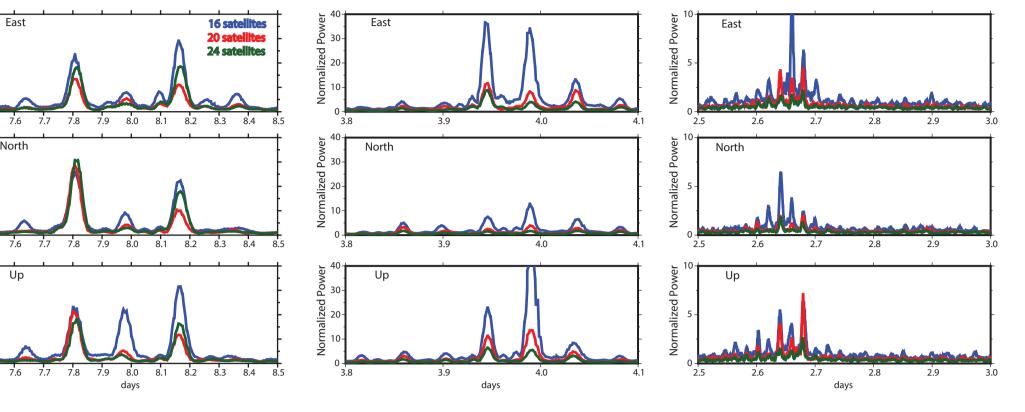
Figure 4. High frequency section of power spectra of position time series (stacked from all stations in Figure 1) for the three GLONASS-only PPP solutions using 16 (blue), 20 (red) and 24 (green) satellites. The three solutions are computed using ESA products with identical processing settings and models except for the number of satellites (constellation gap). The power spectra of the three solutions are normalized to the same scale. The left, middle and right panels are for the 8-day, 4-day and 2.67-day periods, respectively. The X-axis shows the period in days.
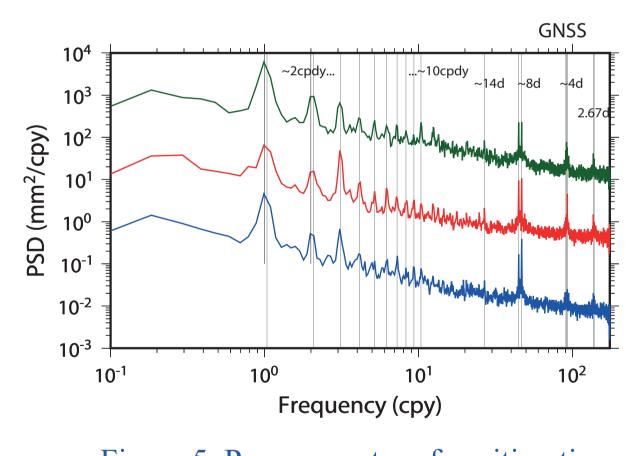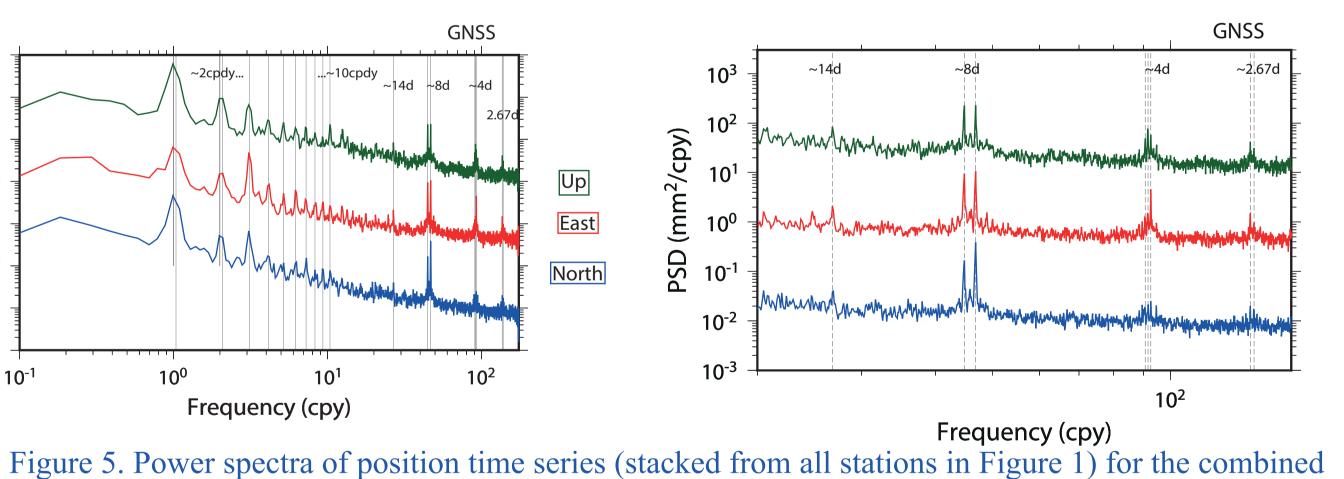
Main Results of the GLONASS-only solution

- Clear draconitic peaks up to 8-9th harmonics (n*1.034cpy, n= 1,2,...)
- Elevated power at ~3rd draconitic harmonics (~120-day period)
- Peaks at 8-day period and it's 2nd (~4-day) and 3rd (~2.67-day) harmonics
- 13.6-day period is not discernable in the GLONASS-only solution
- Series of peaks at the 8-day period and its harmonics. Is there a constellation gap effect?
- An experiment on the effects of the GLONASS constellation gap was performed. Three constellations with 16, 20 and 24 satellites are considered and identical PPP solutions are generated. The processing settings and models are identical except for the considered number of satellites. Stacked, smoothed and normalized power spectra versus period are plotted for the three solutions in Figure 4 with the main results summarized as follows:
- The 8-day period and it's second and third harmonics are affected by the constellation gap
- The period around 7.8 days is the most consistent of the series of peaks in the 8-day period
- The constellation gap highly contributes to the 4-day and 2.67-day periods
- The ~120-day period is also found to be affected by the constellation gap (23% reduction using 24 satellites compared to 16 satellites)

Figure 3. Power spectra of position time series (stacked from all stations in Figure 1) for GLONASS-only solution using ESA products for all (upper panel) and high (lower panel) frequency periods. In both panels the power spectra of the solutions have been shifted along the vertical axis for clarity. The dark gray vertical lines are the annual and semi-annual cycles, the light gray dashed lines are the 1.034 cpy and its harmonics (until the10th harmonic), the fortnightly and 8-day period and its harmonics (4 days and 2.67 days).

4 Combined GPS+GLONASS (GNSS) Solution

Processing Details

- PPP solution based on combined GPS+GLONASS (GNSS) observations and products from ESA for 2009-2015
- 32 globally distributed stations are used (Figure 1)
- Position time series of individual stations are analyzed (detrended, outliers removed and offsets corrected (if any))
- The power spectrum of every station is computed
- Power spectra are then stacked, smoothed and plotted in Figure 5 as a normalized power versus frequency

Figure 5. Power spectra of position time series (stacked from all stations in Figure 1) for the combined GPS+GLONASS (GNSS) solution using ESA products for all (left panel) and high (right panel) frequency periods. In both panels the power spectra of the components have been shifted along the vertical axis for clarity. The dark gray vertical lines are the annual and semi-annual cycles. For the GNSS solution a mean value of 1.037 cpy is adopted as the solution contains signals from both systems and the gray dashed lines indicate the harmonics up to degree 10, the fortnightly and 8-day period and its harmonics (4 days and 2.67 days).

Main Results of the combined GPS+GLONASS solution

- Clear draconitic peaks up to 8-9th harmonics (n*1.037cpy, n= 1,2,...)
- GNSS solution contains system specific periods
  - 8-day and its 2nd and 3rd harmonics from GLONASS
- System-specific signals are largely reduced in the combined GPS+GLONASS solution (Table 2)
  - Power reduction for most of the draconitics, fortnightly and 8-day periods
- GLONASS is more benefited from the combined solution than GPS
- A significant reduction is observed in the GPS+GLONASS solution for the fortnightly and 8-day period compared to the GPS-only solution. The reduction reaches 52% for the horizontal components and 36% for the vertical component (Table 2).
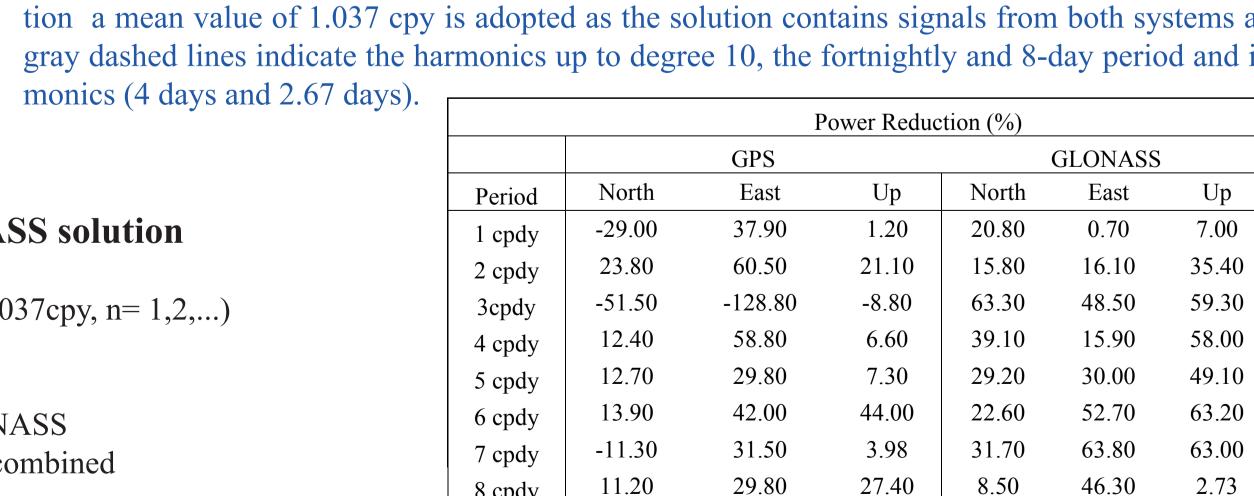
Table 2. Power reduction (in %) over draconitic, fortnightly and 8-day period signals of GNSS solution compared to GPS-only and GLONASS-only solutions using ESA products. The length of the GPS-only solution is reduced to the same period as the GLONASS-only solution for consistency. To avoid the impact of the GLONASS constellation gap on the powers of some of the frequencies, the power comparisons are made for the period 2012 onwards. Positive values show a power reduction while negative values show a power enhancement.

Period	GPS North	GPS East	GPS Up	GLONASS North	GLONASS East	GLONASS Up
1 cpdy	-29.00	37.90	1.20	20.80	0.70	7.00
2 cpdy	23.80	60.50	21.10	15.80	16.10	35.40
3cpdy	-51.50	-128.80	-8.80	63.30	48.50	59.30
4 cpdy	12.40	58.80	6.60	39.10	15.90	58.00
5 cpdy	12.70	29.80	7.30	29.20	30.00	49.10
6 cpdy	13.90	42.00	44.00	22.60	52.70	63.20
7 cpdy	-11.30	31.50	3.98	31.70	63.80	63.00
8 cpdy	11.20	29.80	27.40	8.50	46.30	2.73
13.6-day	52.00	52.20	36.70	-	-	-
8-day	-	-	-	23.50	31.70	55.90

5 On the nature of the periodic signals

Previous studies demonstrated satellite-linked (Amiri-Simkooei 2013) and site-specific contributions (King et al., 2010) to the periodic signals such as draconitics with the former to be more dominating. To further investigate the nature of the periodic signals two filtering methods (mask-filtering and close-pair spatial-filtering) are proposed. The mask-filtering is performed by simulating a mask in a certain part of the horizon and thereby ignoring the observations in that direction. The close-pair spatial-filtering is performed by computing coordinate differences between two very nearby stations.

Mask-Filtering

- An artificial mask is simulated to ignore observations in a certain azimuthal direction. The same mask was then implemented on the real observations for all stations in Figure 1. Figure 6 shows the sky plots for ONSA, Onsala Sweden before and after the mask is implemented. PPP solutions using GPS-only products from CODE with and without masking are computed for all stations.
- Coordinate differences are then computed between the two solutions for all stations
- The power spectrum of the coordinate differences is computed for each individual station
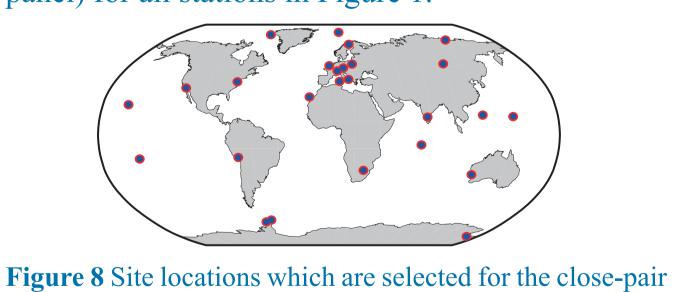- Power spectra of coordinate differences for all stations are then stacked, smoothed and plotted in Figure 7 as a normalized power versus frequency

Figure 6 The actual sky plot for ONSA, Onsala, Sweden, without mask (left panel) and when a simulated mask in the South direction between azimuths 130° and 230° is applied (right panel). The blue and red lines denote the sky-tracks for GPS and GLONASS satellites, respectively. PPP solutions are generated using the full sky coverage (left panel) and the masked constellation (right panel) for all stations in Figure 1.

Close-Pair Spatial-Filtering

- Nearby stations (with baselines of less than 10km) are selected from the IGS network (Figure 8). In Figure 8 blue and red dots show close-pairs of stations. PPP solutions using GPS-only and CODE products are computed for all stations in Figure 7. Coordinate differences are then computed between the close-pair stations.
- The coordinate differences of close-pair stations are computed after coordinates of individual stations are analyzed (detrended, outliers removed and offsets corrected (if any))
- The power spectrum of the coordinate differences for every close-pair is computed
- Power spectra of all close-pair coordinate differences are then stacked, smoothed and plotted in Figure 9 as normalized power versus frequency

Figure 8 Site locations which are selected for the close-pair spatial filtering (blue-red pair on the map). The maximum baseline used for the close-pair spatial-filtering is 10 km.

Main Results

- Mask-filtering shows very clear draconitic and fortnightly signals while they are highly reduced (mostly gone) in the close-par spatial-filtering
- The comparison between the two filters indicates that draconitic and fortnightly periods are mostly satellite-linked and less site-specific
- Some remaining powers in the close-pair spatial-filtering show site-specific contributions to the powers

Figure 7 Power spectra of the coordinate differences due to the simulated mask (stacked from all stations in Figure 1). The power spectra of the components have been shifted along the vertical axis for clarity. The vertical lines are as described in Figure 2. CODE GPS-only products were used to generate the results.
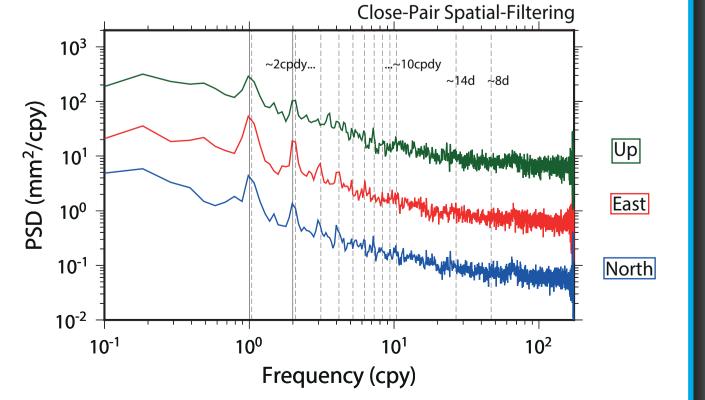
Figure 9 Power spectra of the close-pair spatial-filtering computed and stacked for the 26 close-pair stations in Figure 8. The power spectra of the components have been shifted along the vertical axis for clarity. The vertical lines are as described in Figure 2. CODE GPS-only products were used to generate the results.

6 Conclusions

The main results of the study are:

1) The reduction of powers in the combined GPS+GLONASS solution and the absence of the 13.6-day period in the GLONASS-only solution
   - The combined GNSS solution contains periodic signals from both systems, with most of the powers being reduced
   - A fortnightly period is visible in all GPS-only solutions but faint in the JPL-based PPP solution
   - The period is absent in the GLONASS-only PPP solution (detailed analysis in progress)
   - Combined GPS+GLONASS solution has a reduced 13.6-day peak (36-52% reduction)
   - ACs submitting combined products show lower power at the 13.6-day period in their coordinate time series

2) The impact of the GLONASS constellation evolution on the coordinate power spectra
   - The GLONASS constellation gap before December 2011 is found to be contributing to the power at some frequencies
   - The 8-day period, it's second and third harmonics, and the ~120-day period are affected by the constellation gap

3) The existence of site-specific contributions to the draconitic harmonics
   - The mask causes changes in satellite geometry as seen by a specific station
   - The close-pair spatial-filtering removes common errors between nearby sites
   - Comparison of the mask-filtering and close-pair spatial-filtering indicates that the sources of the draconitic and fortnightly peaks are mostly satellite-linked with some site-specific contributions.

4) The existence of the 8-day peak in PPP solutions from GPS-only data and products from those ACs combining GPS and GLONASS (CODE and ESA)
   - A GPS-only solution using products from the IGS and it's ACs show an 8-day period for solutions from those ACs (CODE and ESA) employing GPS and GLONASS data during product generation.
   - As the period is absent in the solutions from IGS, JPL, and MIT, and as it is close to the ground repeat period of GLONASS, the signal is assumed to be a GLONASS effect.
   - This shows that GPS orbits computed from a combined GPS+GLONASS solution contain GLONASS-specific periods.

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