Absolute & Relative Movement in the Great Lakes Basin Based on GPS Measurements

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Outline

Available GPS data

- Continuous GPS
- Episodic (campaign) GPS

GPS Velocity Solutions

- NAREF solution
- CBN solution

Factors affecting GPS velocities

- Monument stability
- Multipath
- Unloading from lower water levels

Other Velocity Solutions

- Other GPS solutions
- Non-GPS solutions

Available GPS Data

Continuous GPS in North America

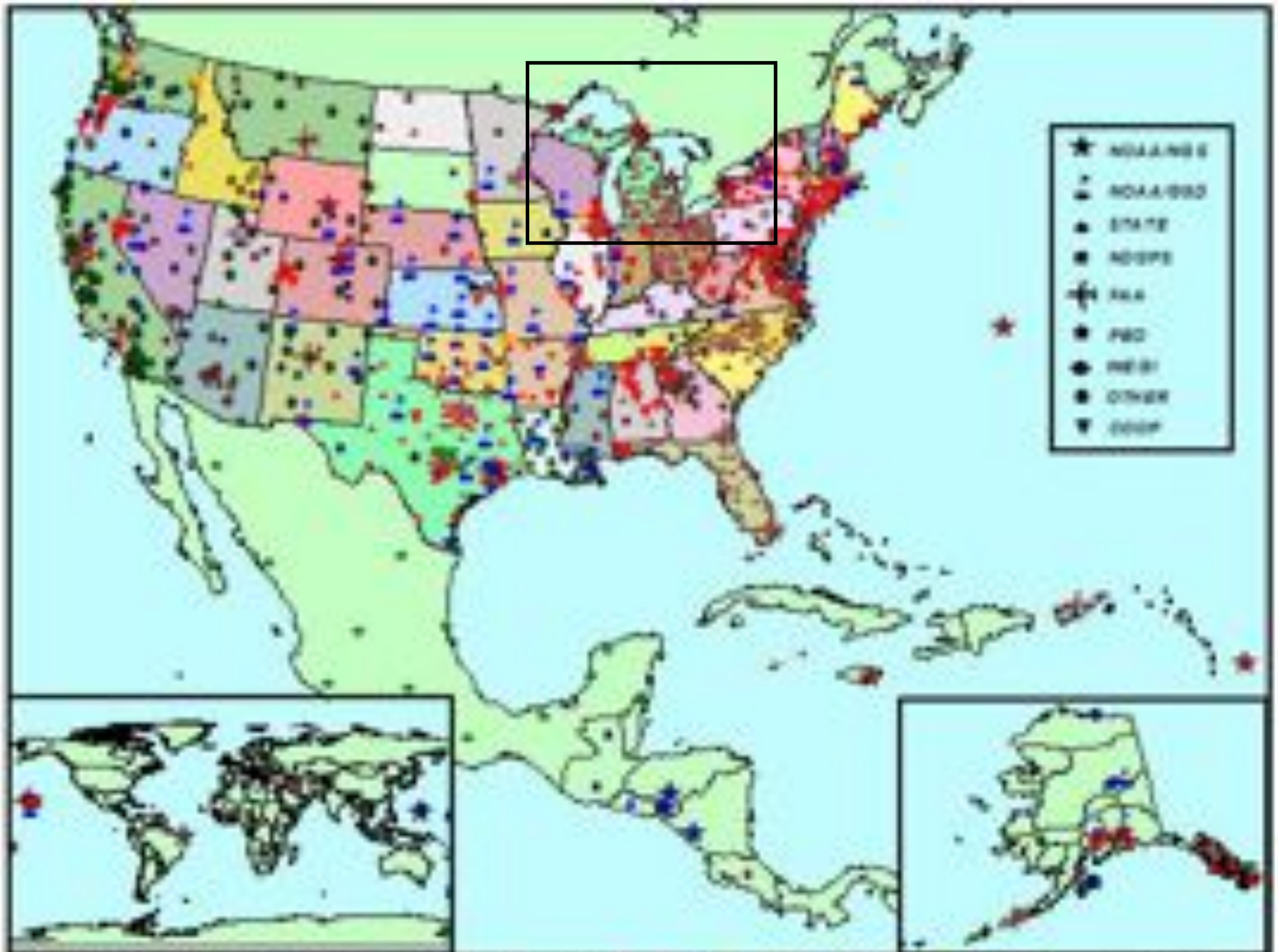
- Permanent GPS stations
- Canadian Active Control System (CACS)
- Provincial DGPS systems (BC, QC, NB)
- U.S. Continously Operating Reference Stations (CORS)
- EarthScope Plate Boundary Observatory (PBO)

Episodic GPS

- Repeated campaign surveys
- Canadian Base Network (CBN)
- IGLD network (not observed to same accuracy as CBN)

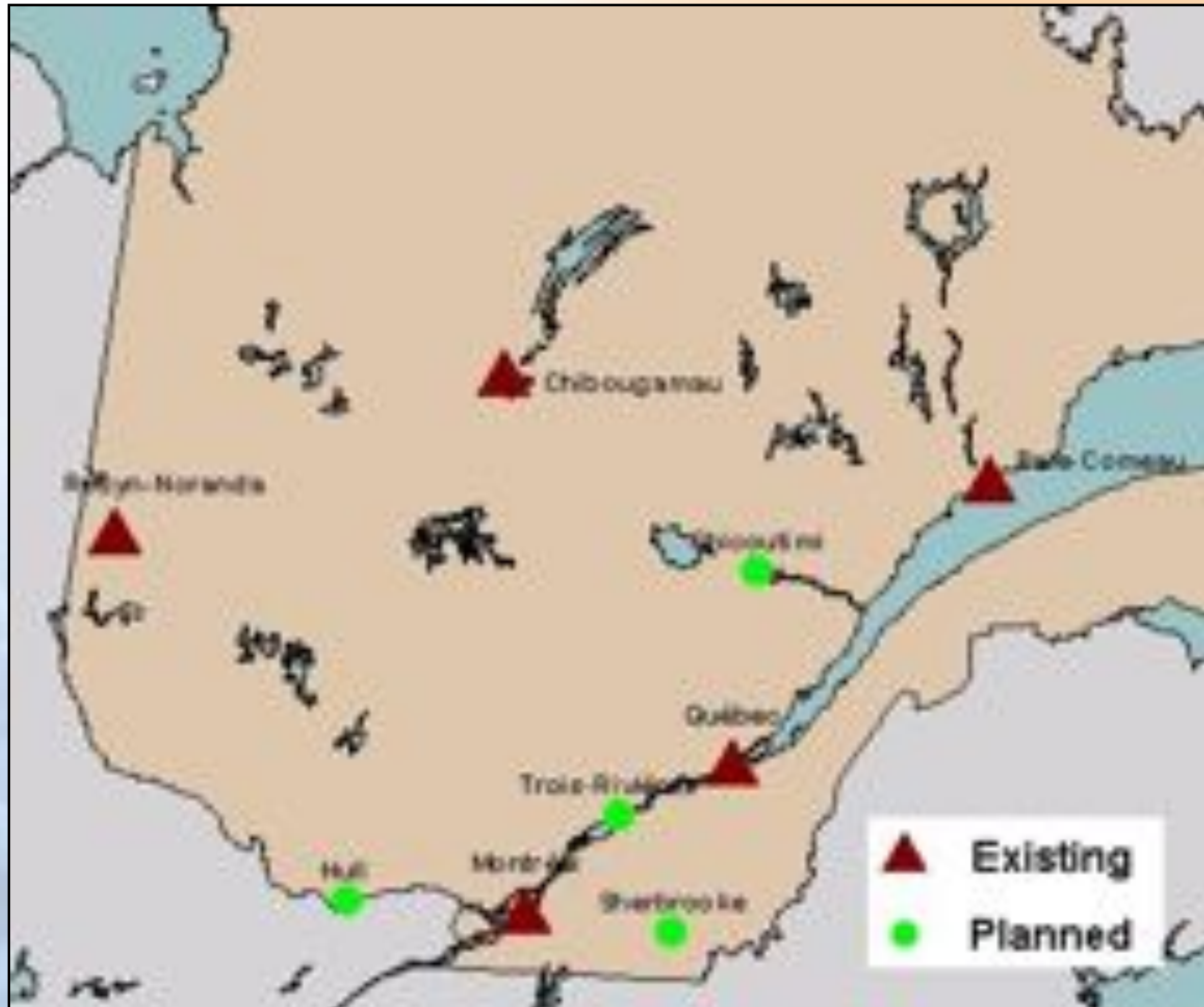
Canadian Active Control Network

U.S. CORS Network



Symbol color denotes sampling rates:(1 sec)(5 sec)(10 sec)(15 sec)(30 sec) Decommissioned

Quebec DGPS Network



Canadian Base Network

NAREF Velocity Solutions

Based on weekly NAREF coordinate solutions

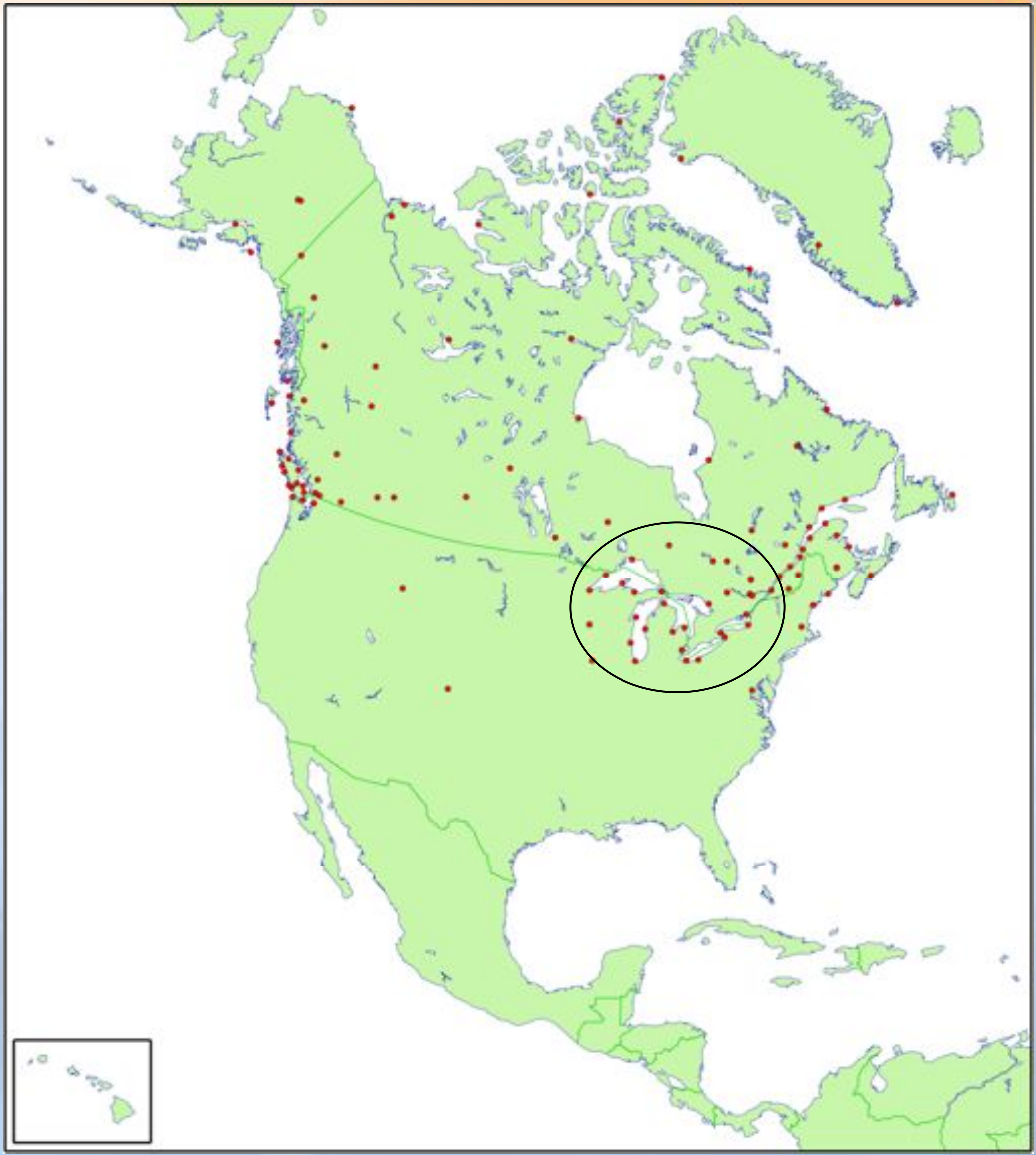
- Combination of 6 weekly regional solutions
- Using 4 different GPS software
- Many stations in multiple solutions
- Redundancy needed to detect outliers/errors
- Need more redundant solutions for CORS sites (SIO to do)

Descriptive statistics

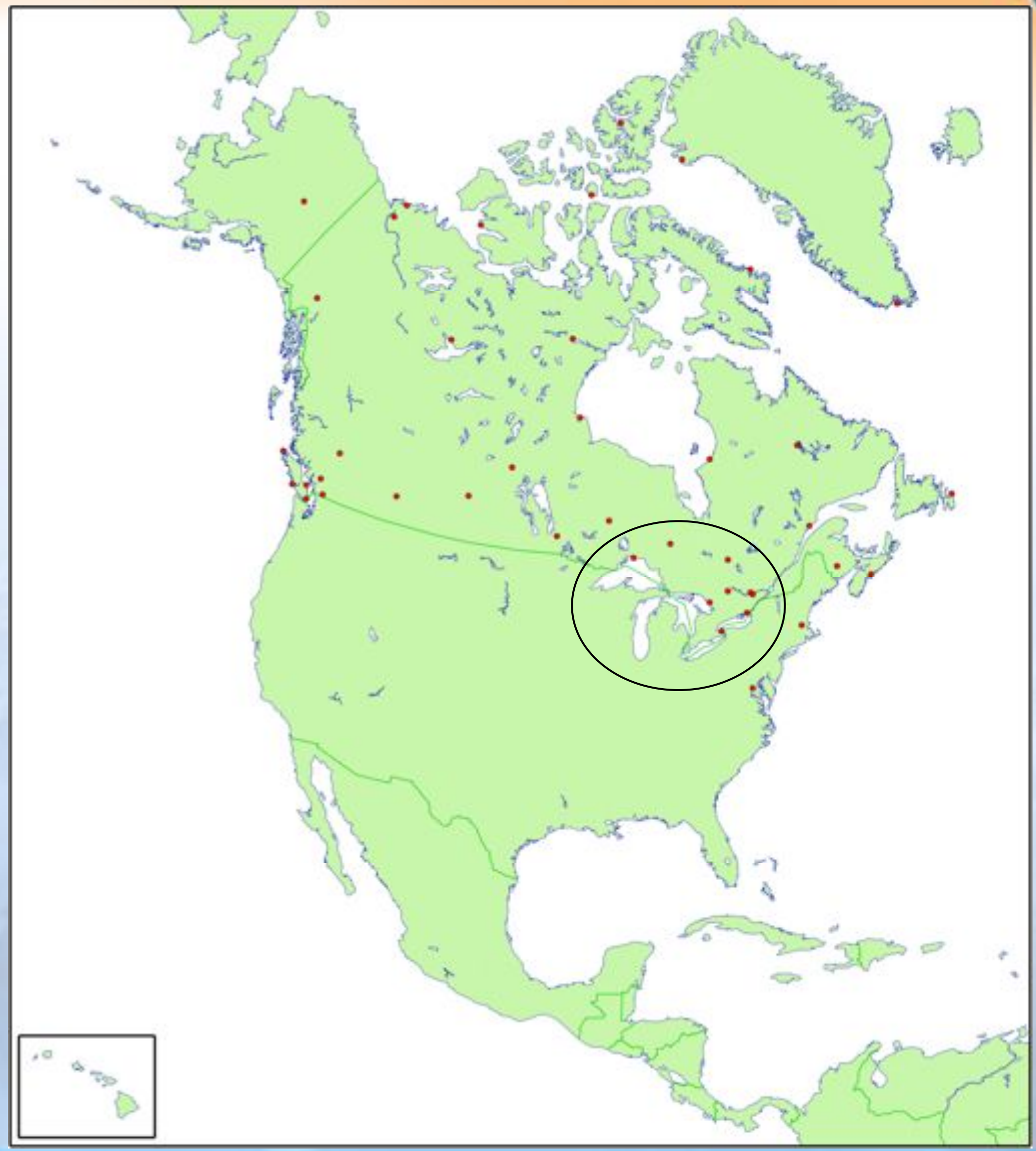
Time span of (GPS weeks)	1095-1399
Total number of stations	906
Number of stations used	578 (omitted site with <1 yr data)
Number of input solutions	305 weeks
Number input coord. obs.	119,435 x 3
Number of parameters	4,164
Degrees of freedom	354,141

GSD Bernese Canadian Solution

GPS Week 1399
112 stations



GSD GIPSY Canadian Solution



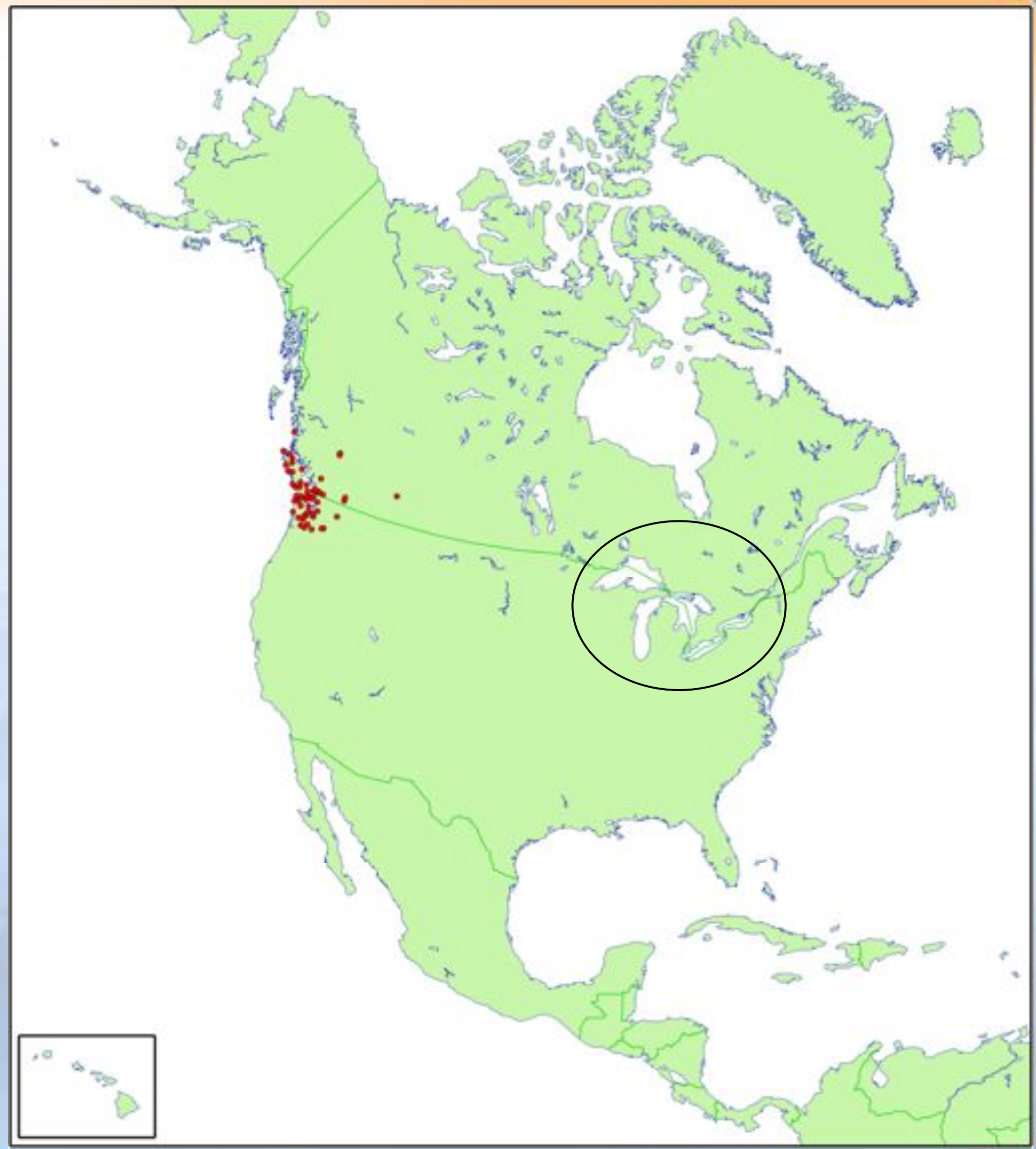
GPS Week 1399

46 stations

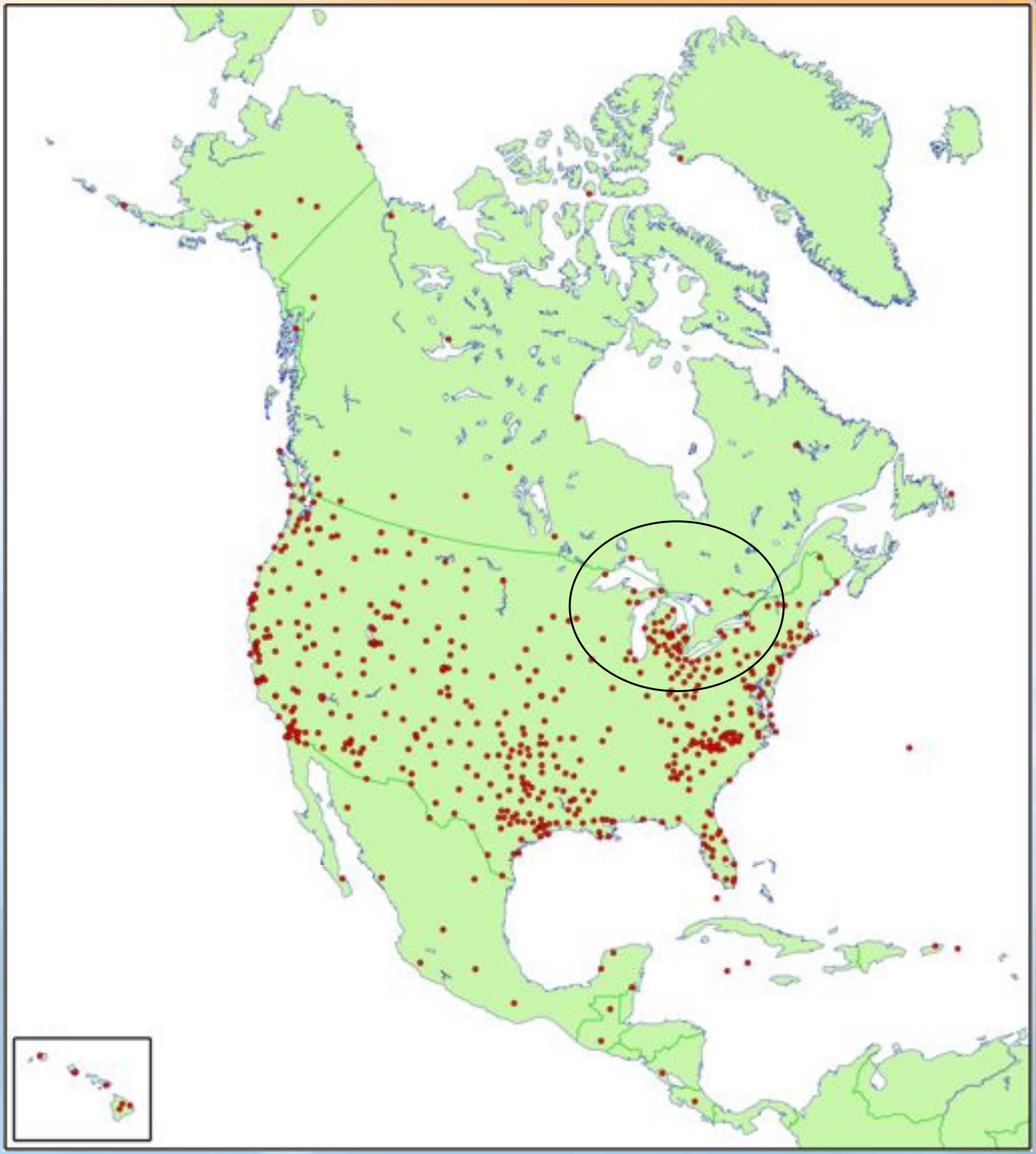
PGC Bernese
WCDA
Solution

GPS Week 1399

55 stations



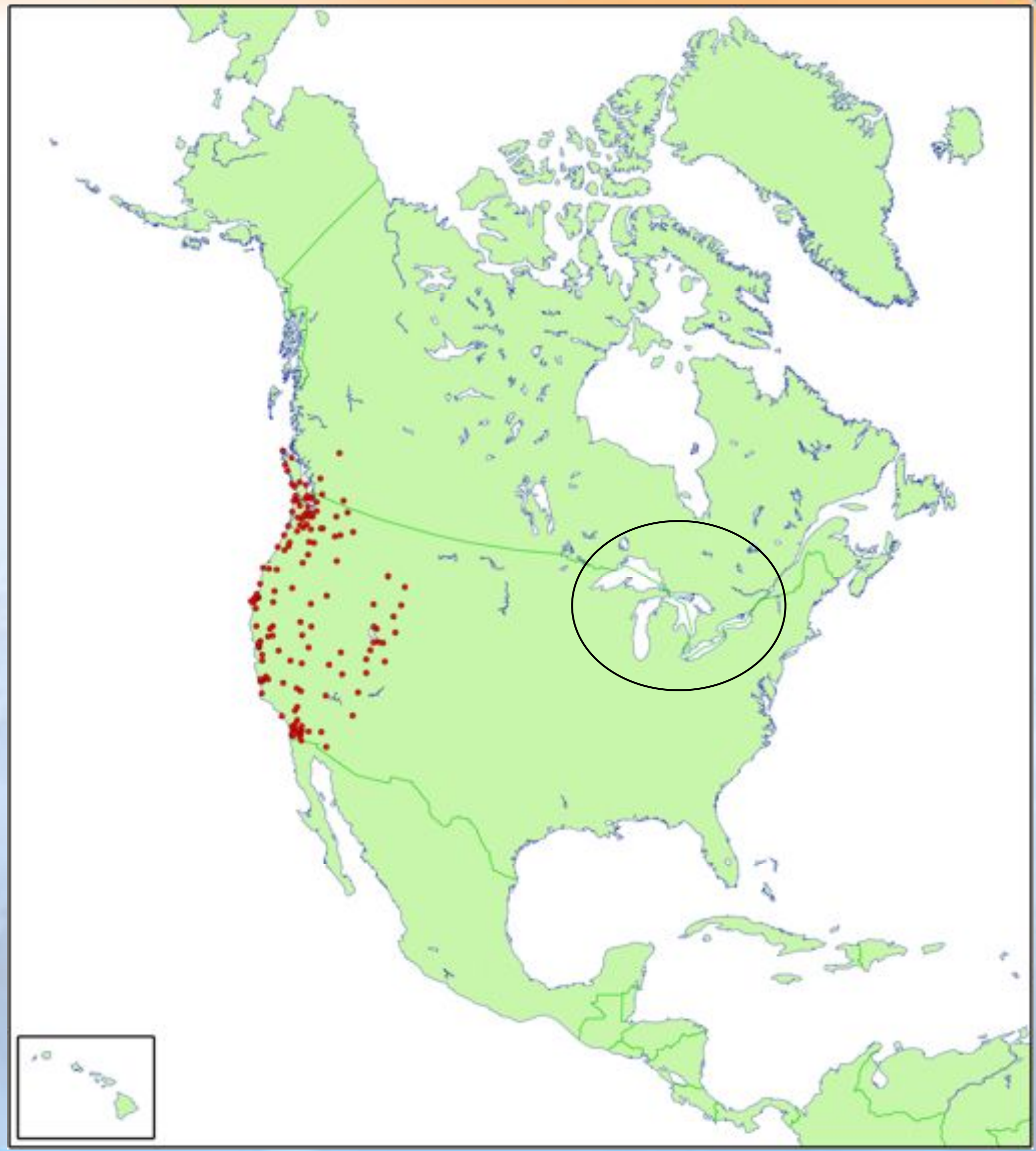
NGS U.S. CORS Solution



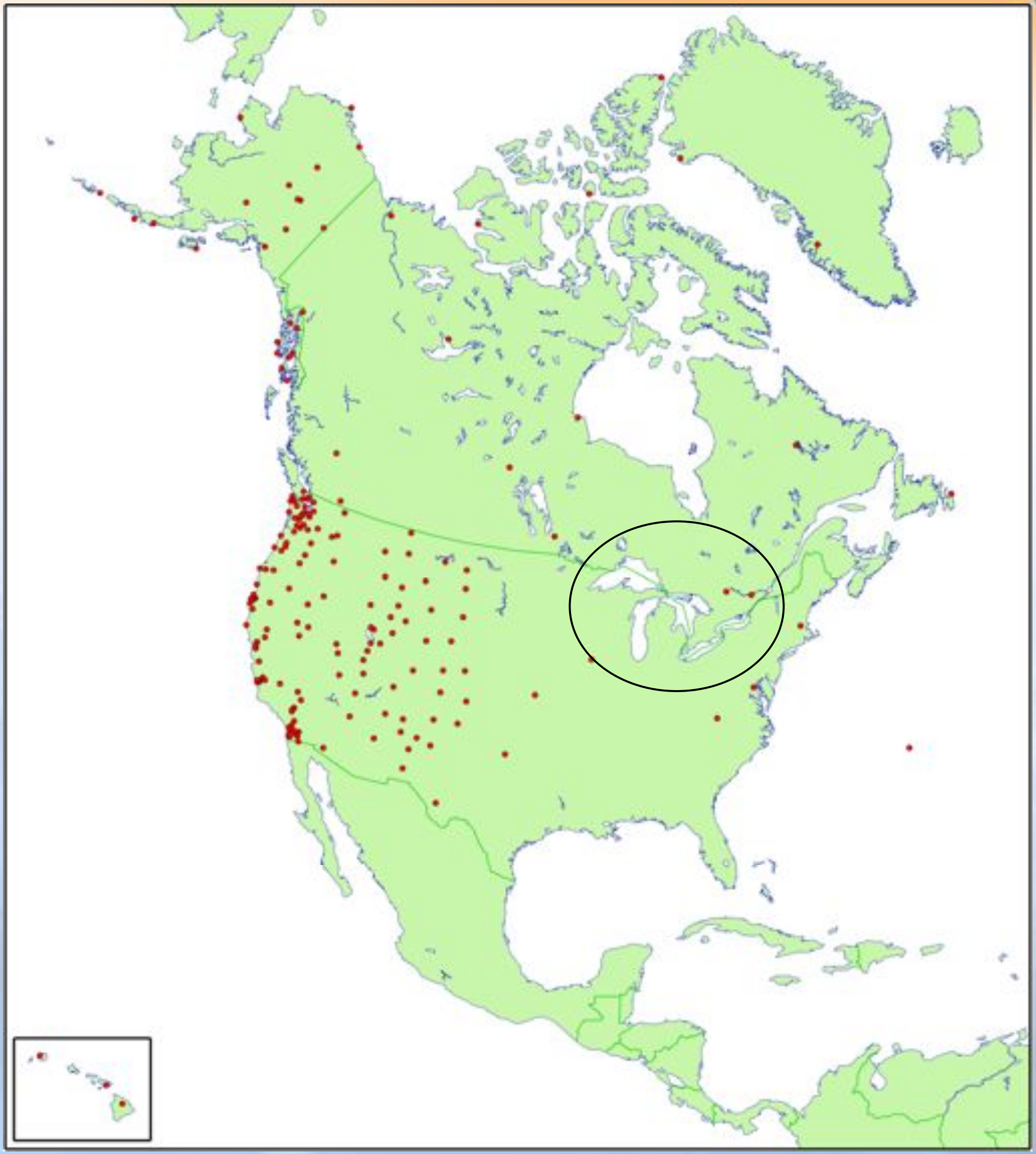
GPS Week 1399
962 stations
565 used

SIO GAMIT Prelim PBO Solution

GPS Week 1399
139 stations

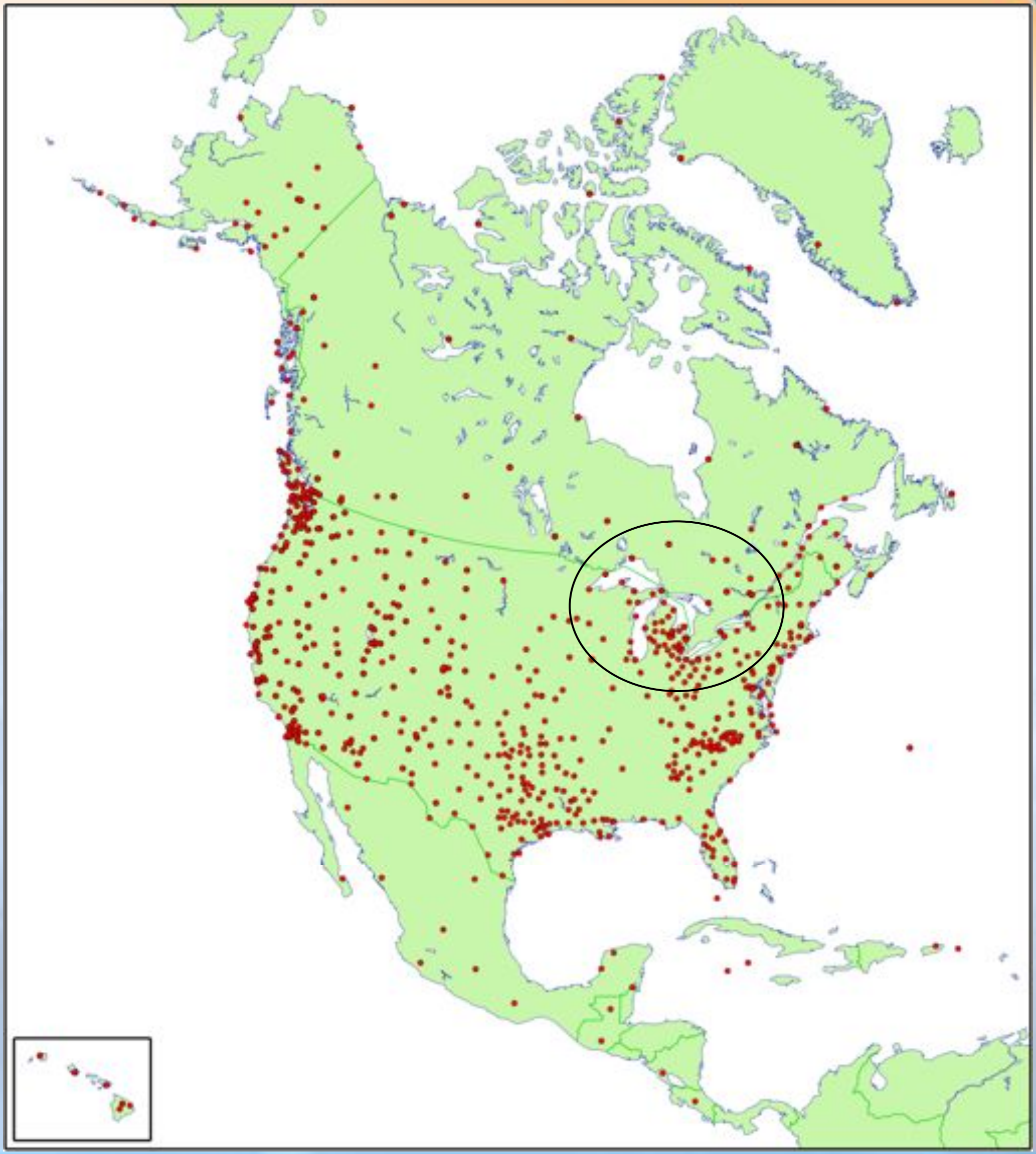


MIT Official PBO Solution



GPS Week 1399
182 stations used

NAREF Combination Solution



GPS Week 1399

708 stations

Common Stations Between Regional Solutions

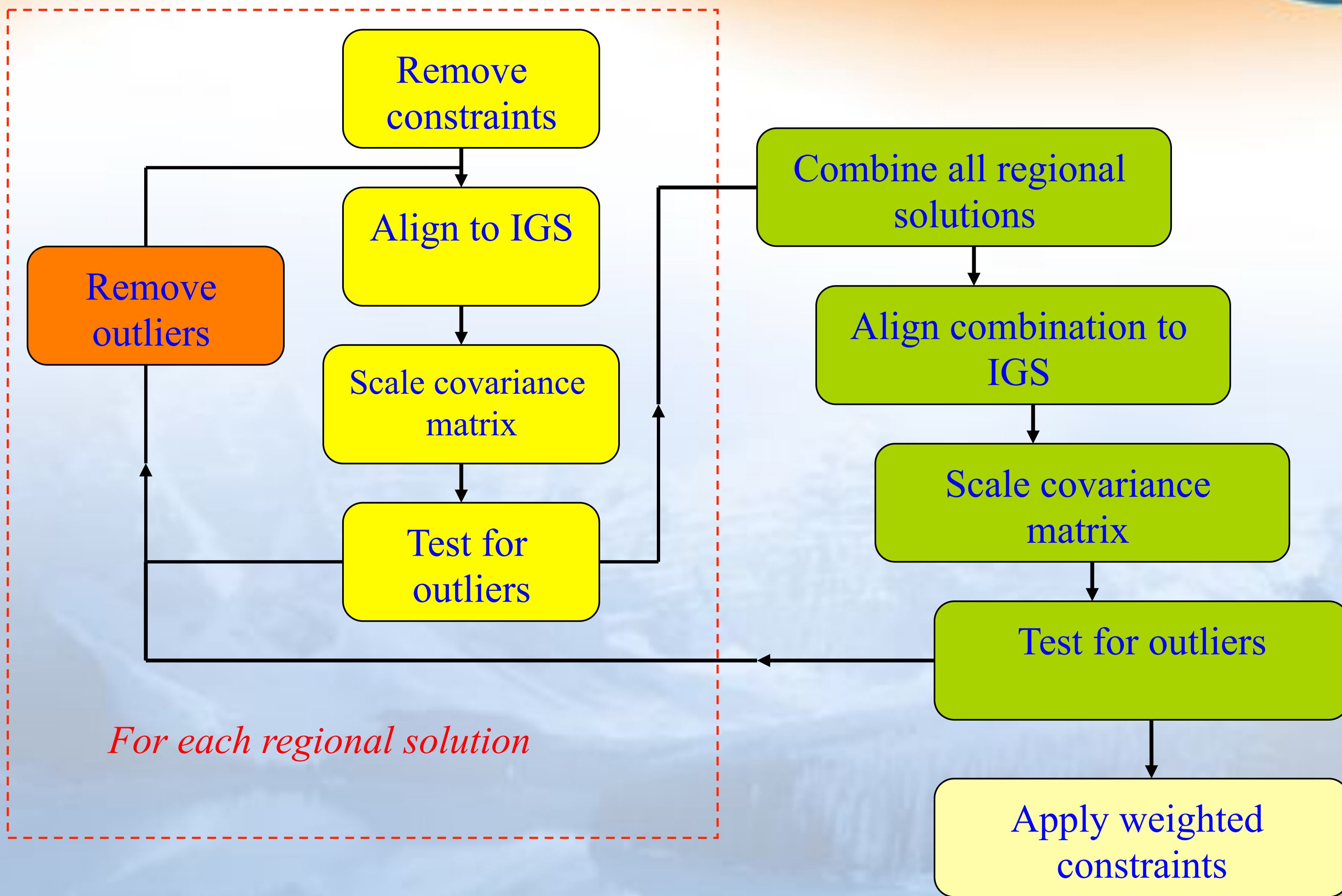
Common Stations for GPS Week 1399						
Solution	NRCan Bernese	NRCan Gipsy	MIT	NGS	PBO	NRCan WCDA
NRCan Bernese	112	43	28	45	16	20
NRCan Gipsy	43	43	17	38	8	9
MIT	28	17	183	121	99	25
NGS	45	38	121	569	99	19
PBO	16	8	99	99	140	37
NRCan WCDA	20	9	25	19	37	55

Stations in Multiple Solutions
(Stations with Redundant Solutions)

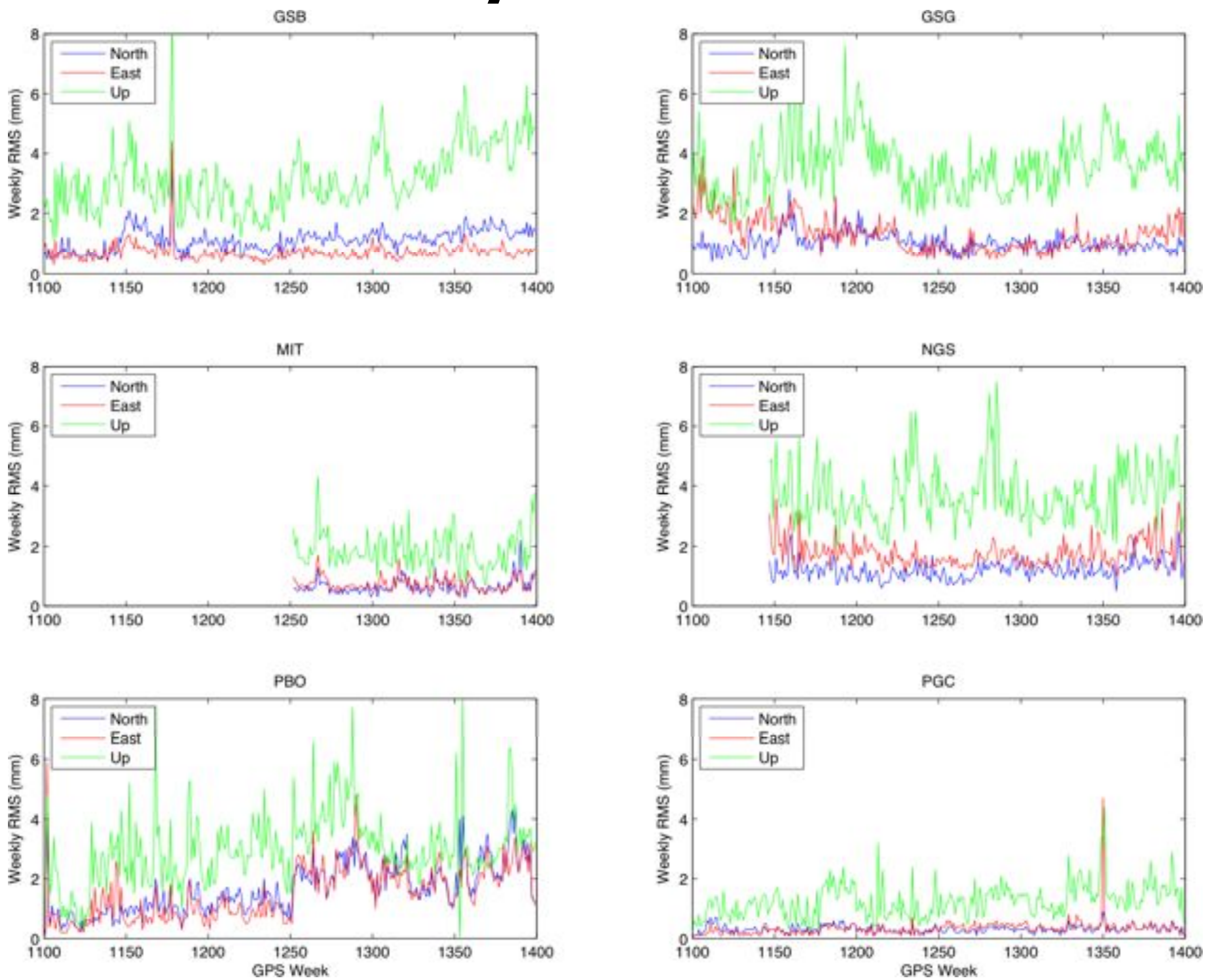
GPS Week 1399

6 solutions	5 solutions	4 solutions	3 solutions	2 solutions	1 solutions
3	7	21	95	94	488

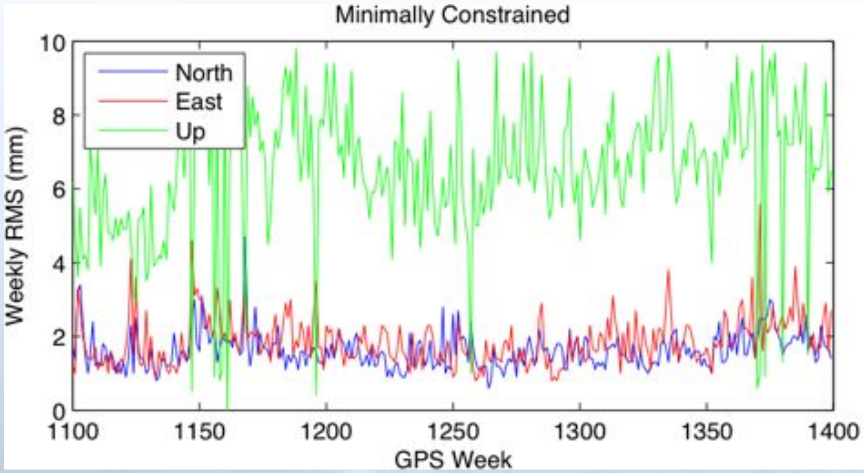
Combination Procedure

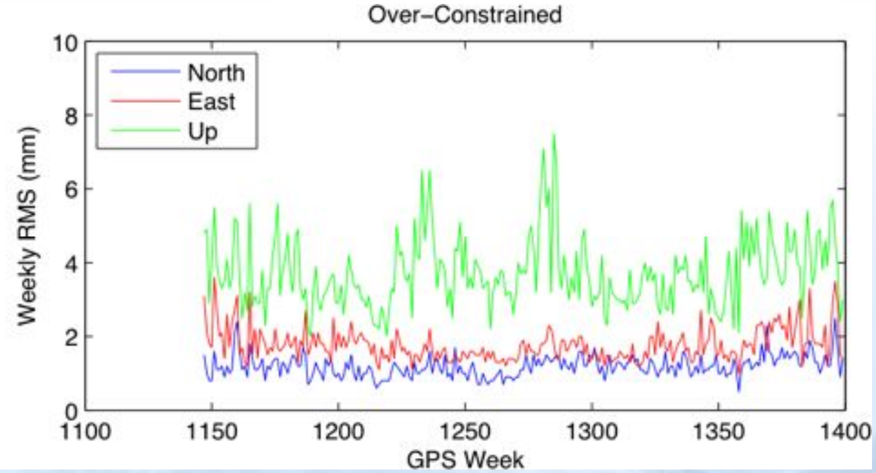


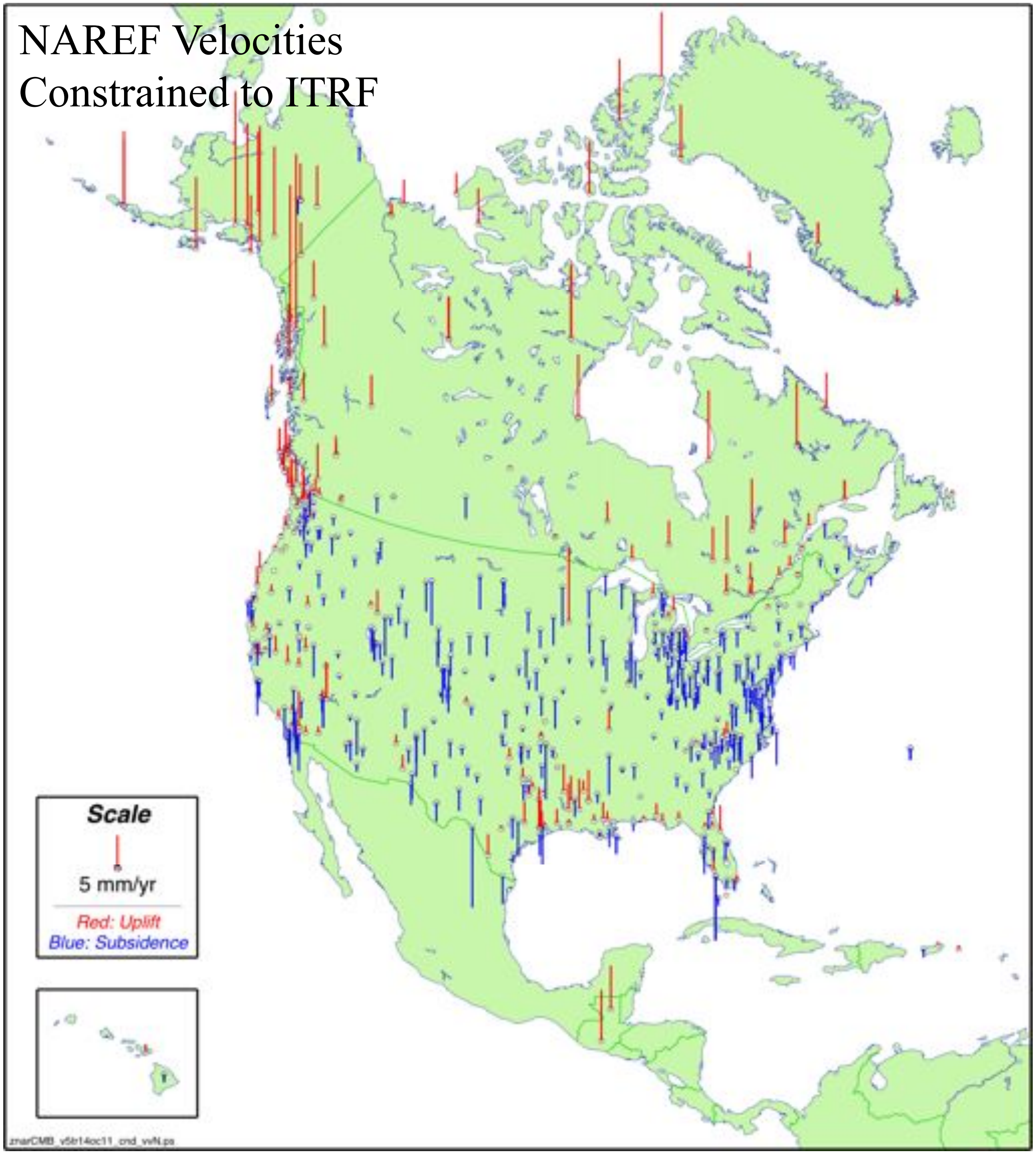
RMS of Weekly Regional Solutions vs. Weekly Combinations



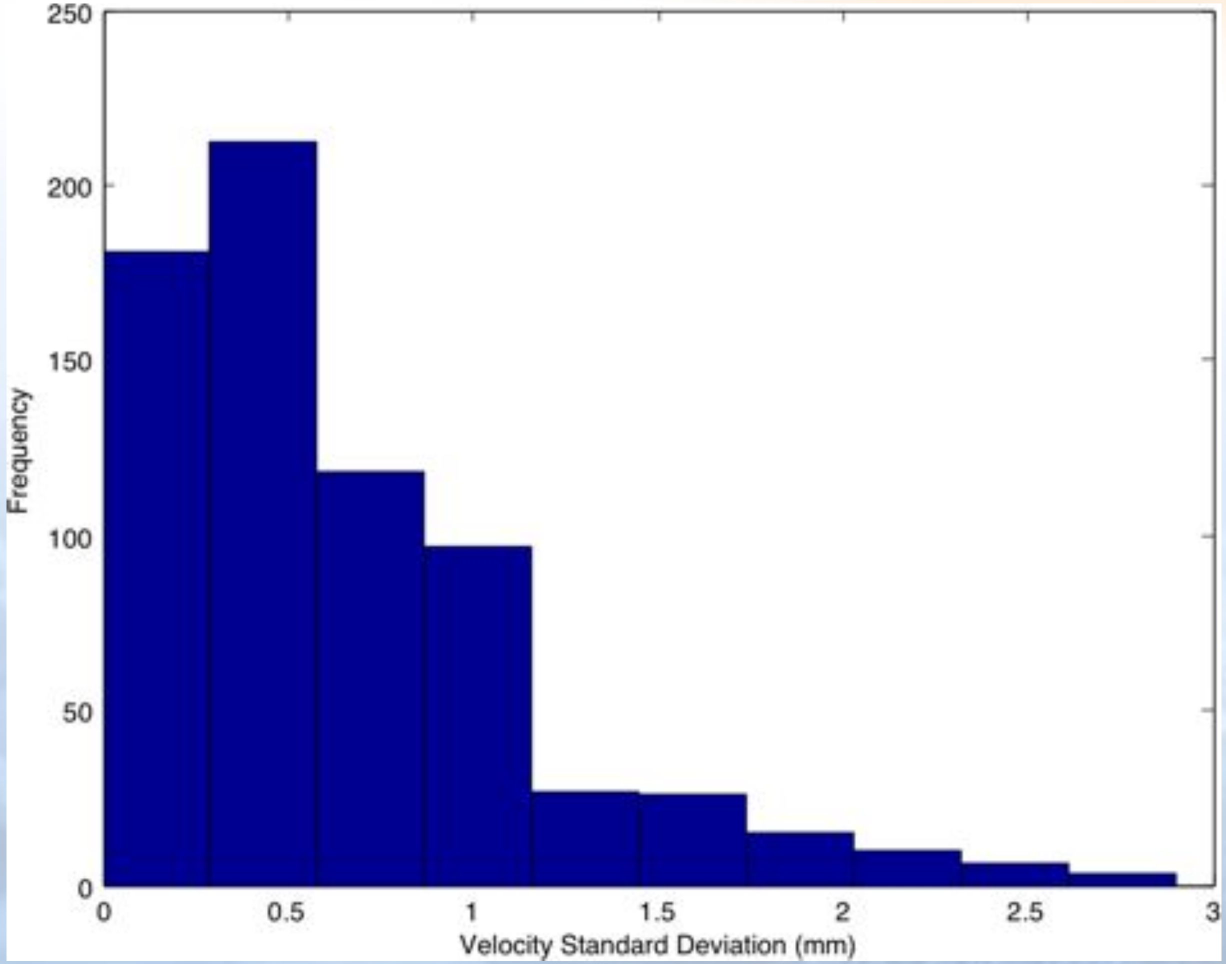
RMS of Weekly NAREF Combinations vs. IGS/ITRF Reference Frame

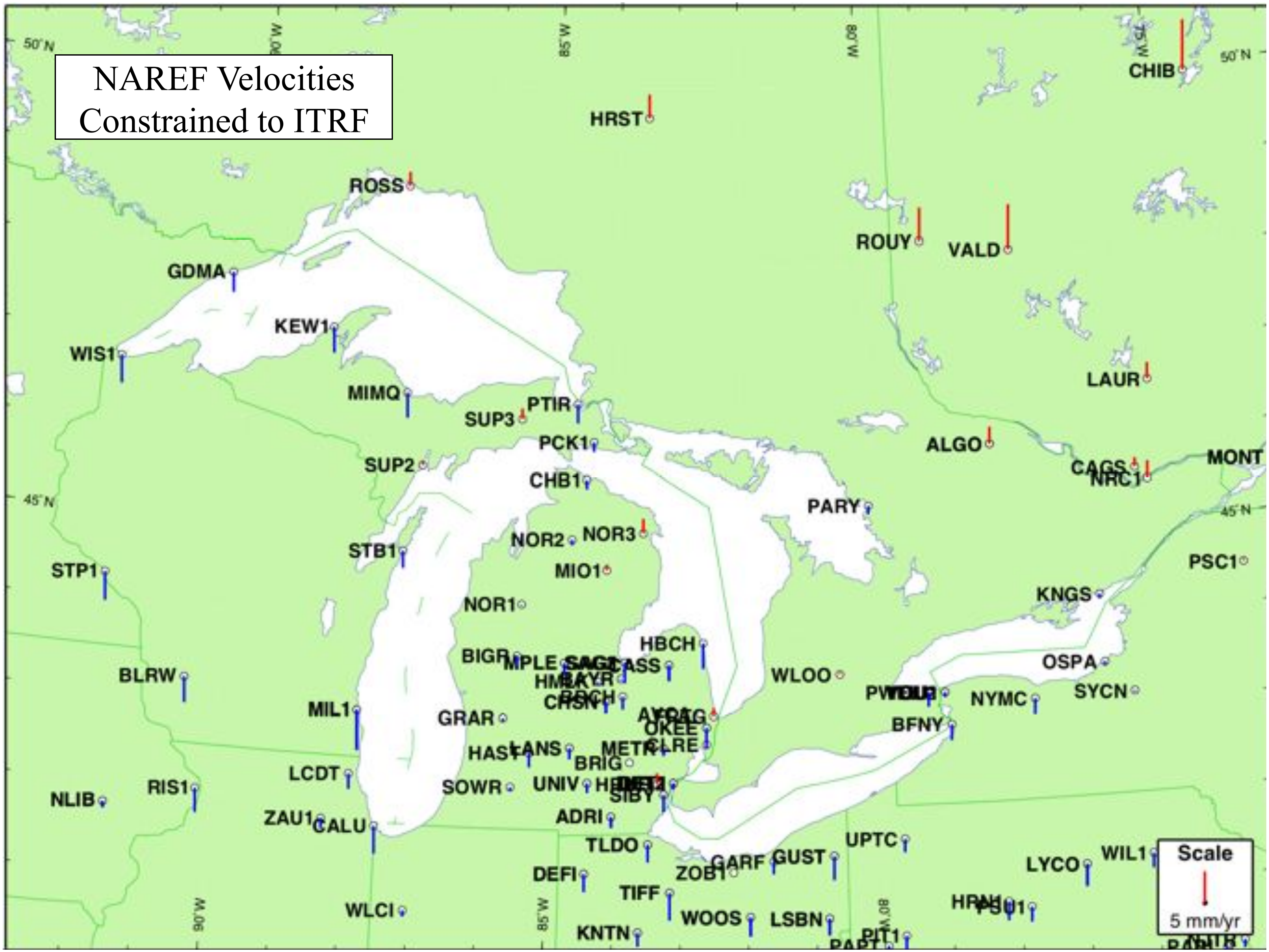




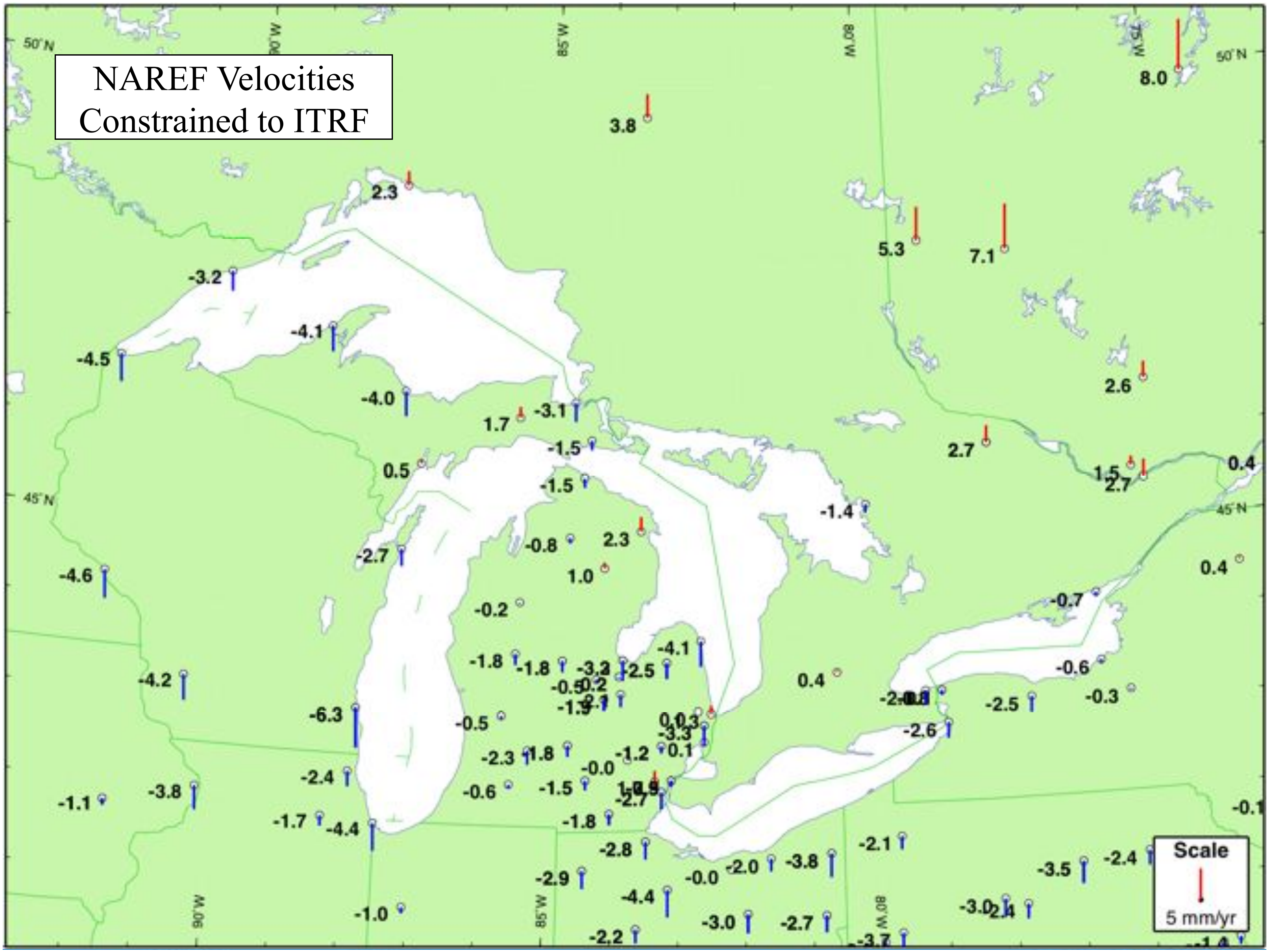

NAREF Velocities
Constrained to ITRF
Scale
5 mm/yr
Red: Uplift
Blue: Subsidence

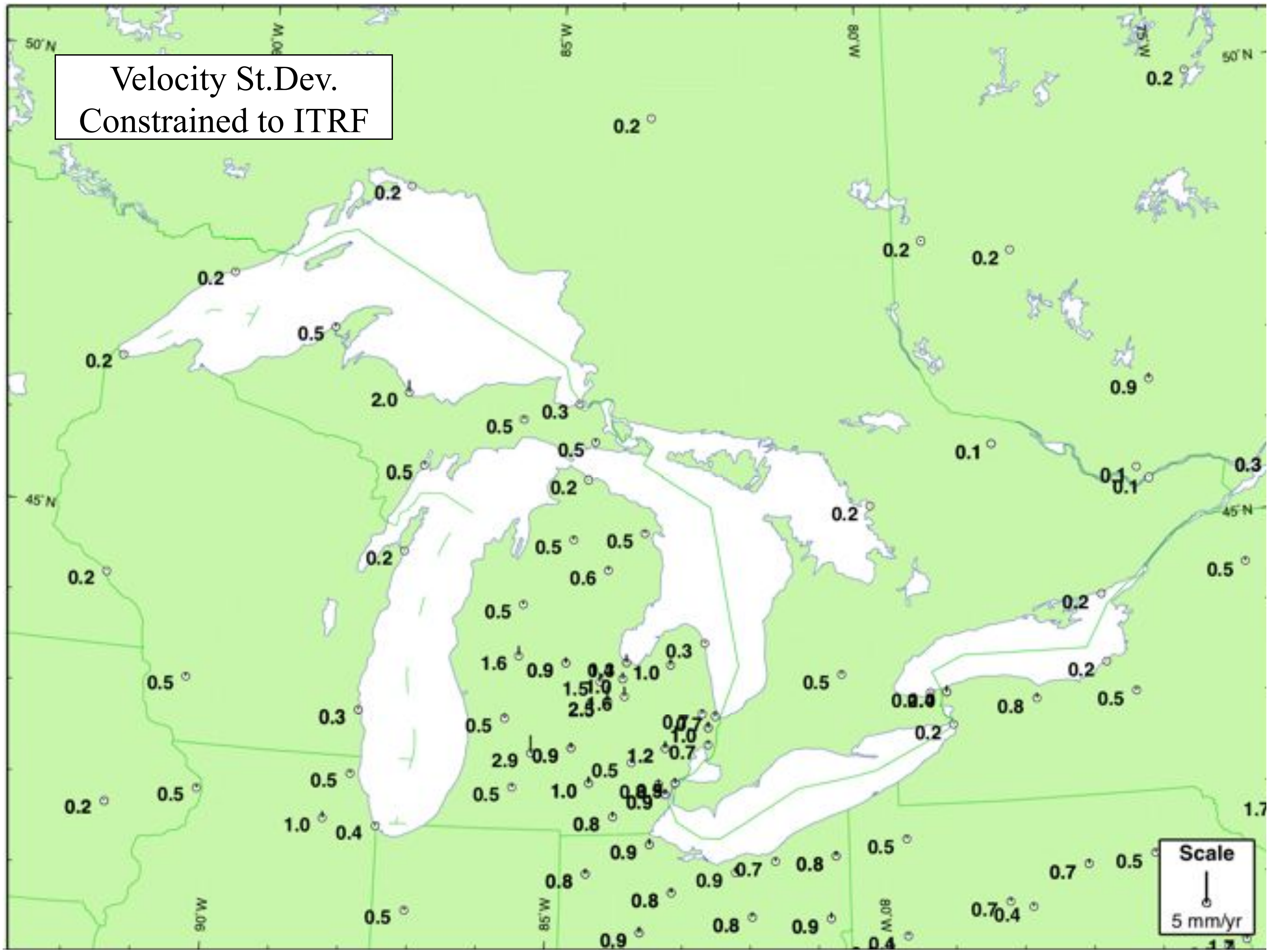
Velocity Standard Deviations

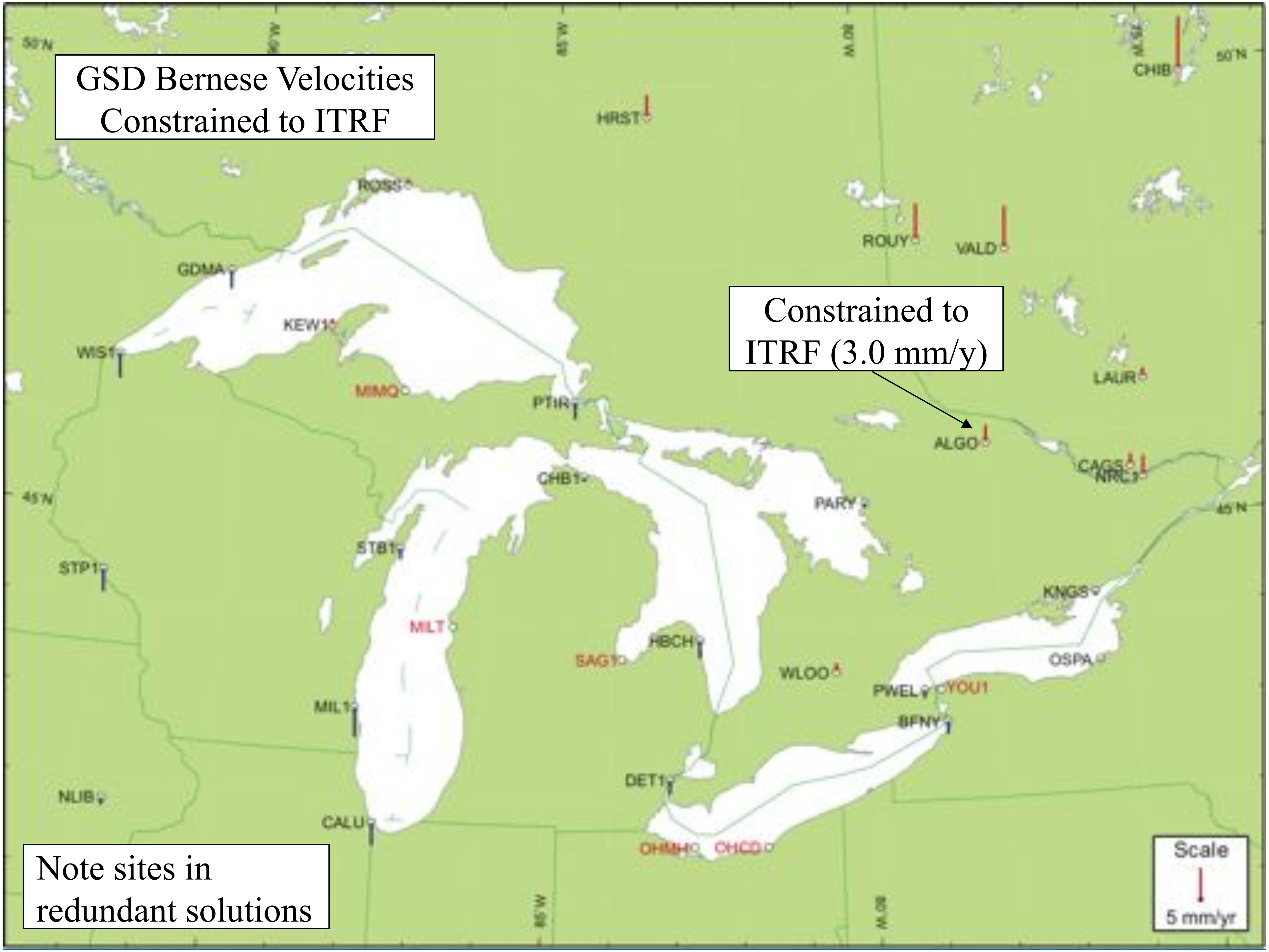




NAREF Velocities
Constrained to ITRF
50°N
45°N
90°W
85°W
80°W
75°W
CHIB
HRST
ROSS
ROUY
VALD
GDMA
KEW1
WIS1
LAUR
MIMQ
PTIR
SUP3
PCK1
ALGO
CAGS
NRC1
MONT
SUP2
CHB1
PARY
NOR2
NOR3
STB1
STP1
MIO1
PSC1
KNGS
NOR1
HBCH
BIGR
CASS
OSPA
WLOO
BLRW
SYCN
NYMC
MIL1
GRAR
BFNY
OKEE
CLRE
HAST
LANS
METR
BRIG
LCDT
RIS1
SOWR
UNIV
SIBY
NLIB
ZAU1
CALU
ADRI
UPTC
TLDO
GARF
GUST
WIL1
LYCO
DEFI
ZOB1
TIFF
WLCI
WOOS
LSBN
PIT1
KNTN
Scale
5 mm/yr

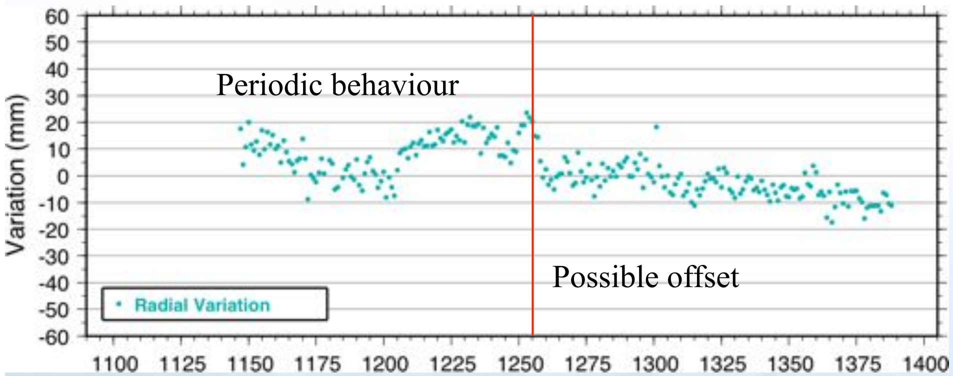

NAREF Velocities
Constrained to ITRF
50°N
45°N
90°W
85°W
80°W
75°W
Scale
5 mm/yr


Velocity St.Dev.
Constrained to ITRF
50°N
45°N
90°W
85°W
80°W
75°W
Scale
5 mm/yr

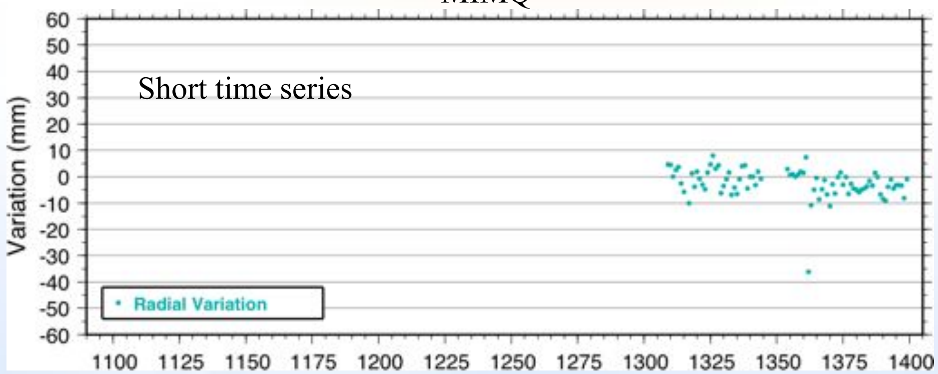

GSD Bernese Velocities
Constrained to ITRF
Constrained to
ITRF (3.0 mm/y)
Note sites in
redundant solutions
HRST
CHIB
ROSS
ROUY
VALD
GDMA
KEW1
WIS1
MIMQ
PTIR
LAUR
ALGO
CAGS
NRC1
CHB1
PARY
STB1
STP1
MILT
KNGS
HBCH
SAG1
WLOO
OSPA
PWEL
YOU1
BFNY
MIL1
DET1
NLIB
CALU
OHCD
Scale
5 mm/yr
50°N
45°N
85°W
80°W

Residual Time Series Plots

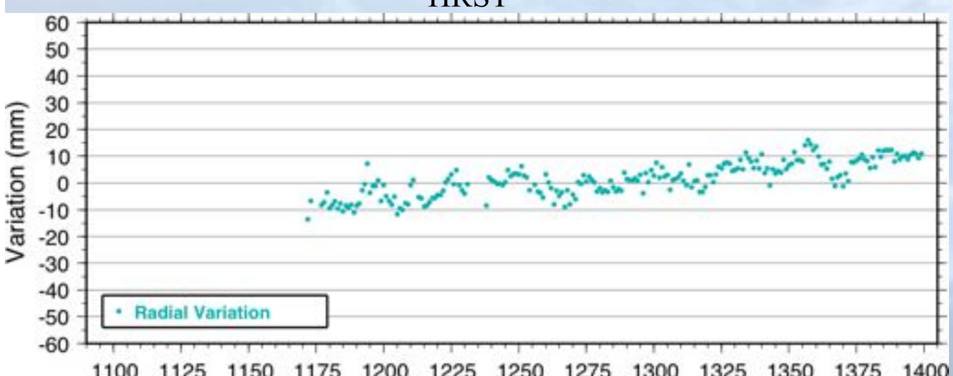
KEW1



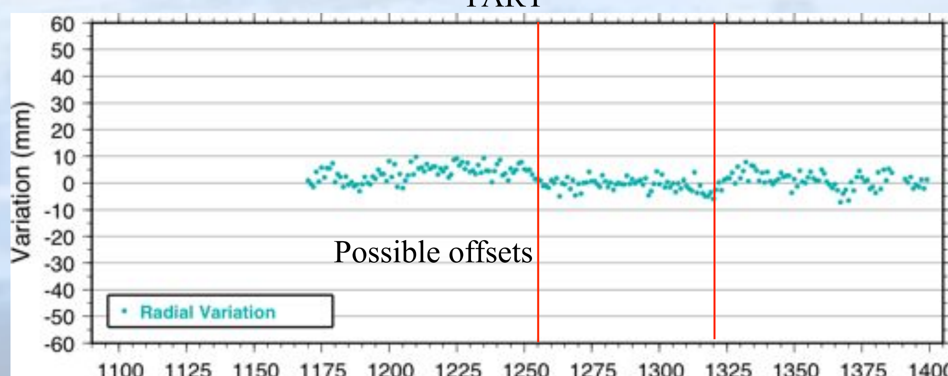
MIMQ



HRST

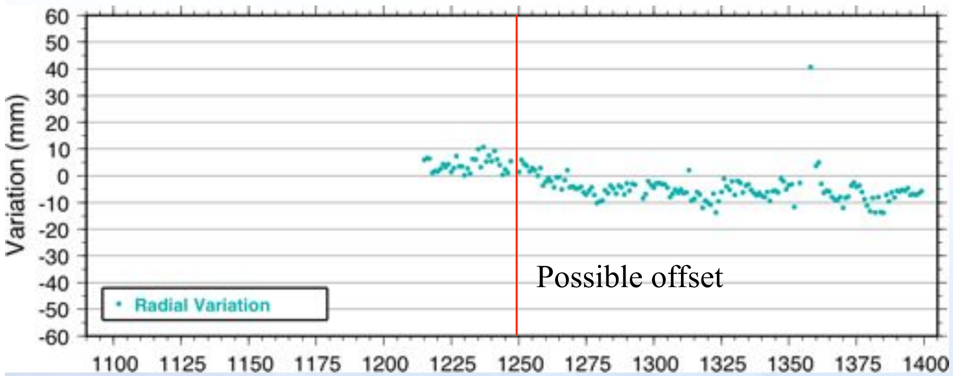


PARY

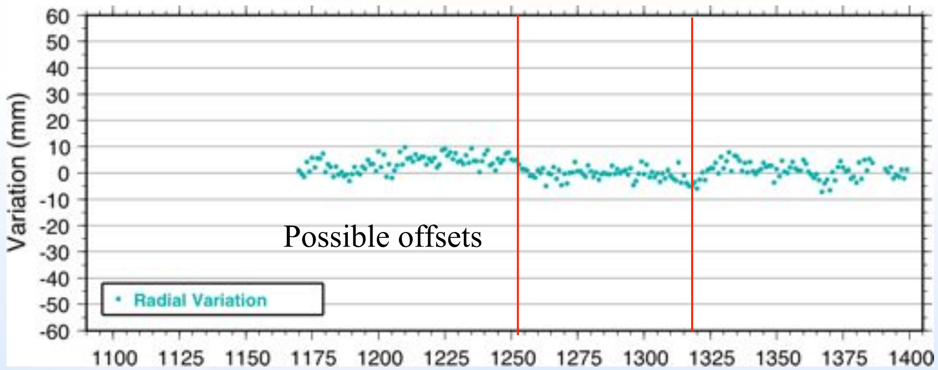


Residual Time Series Plots
(Extra)

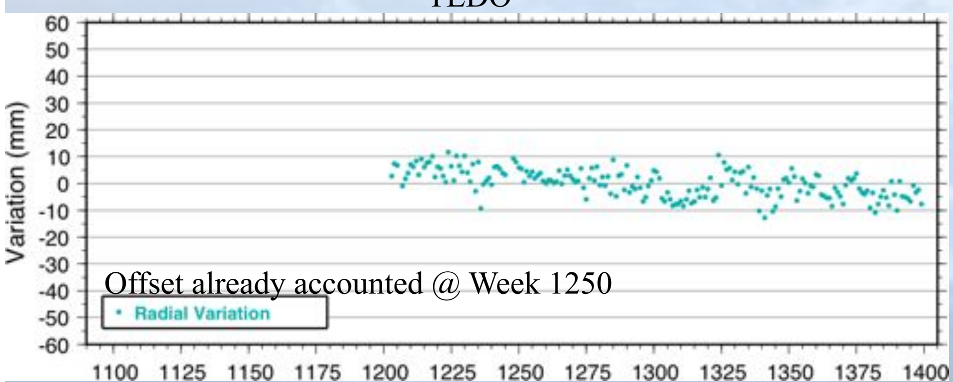
HBCH



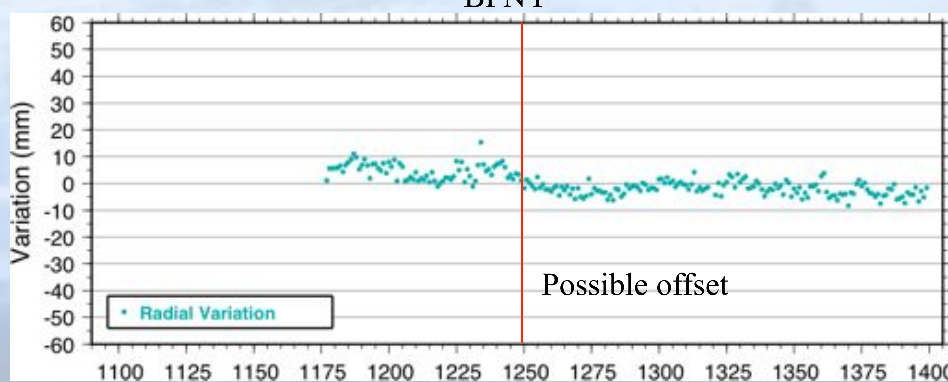
PARY



TLDO



BFNY



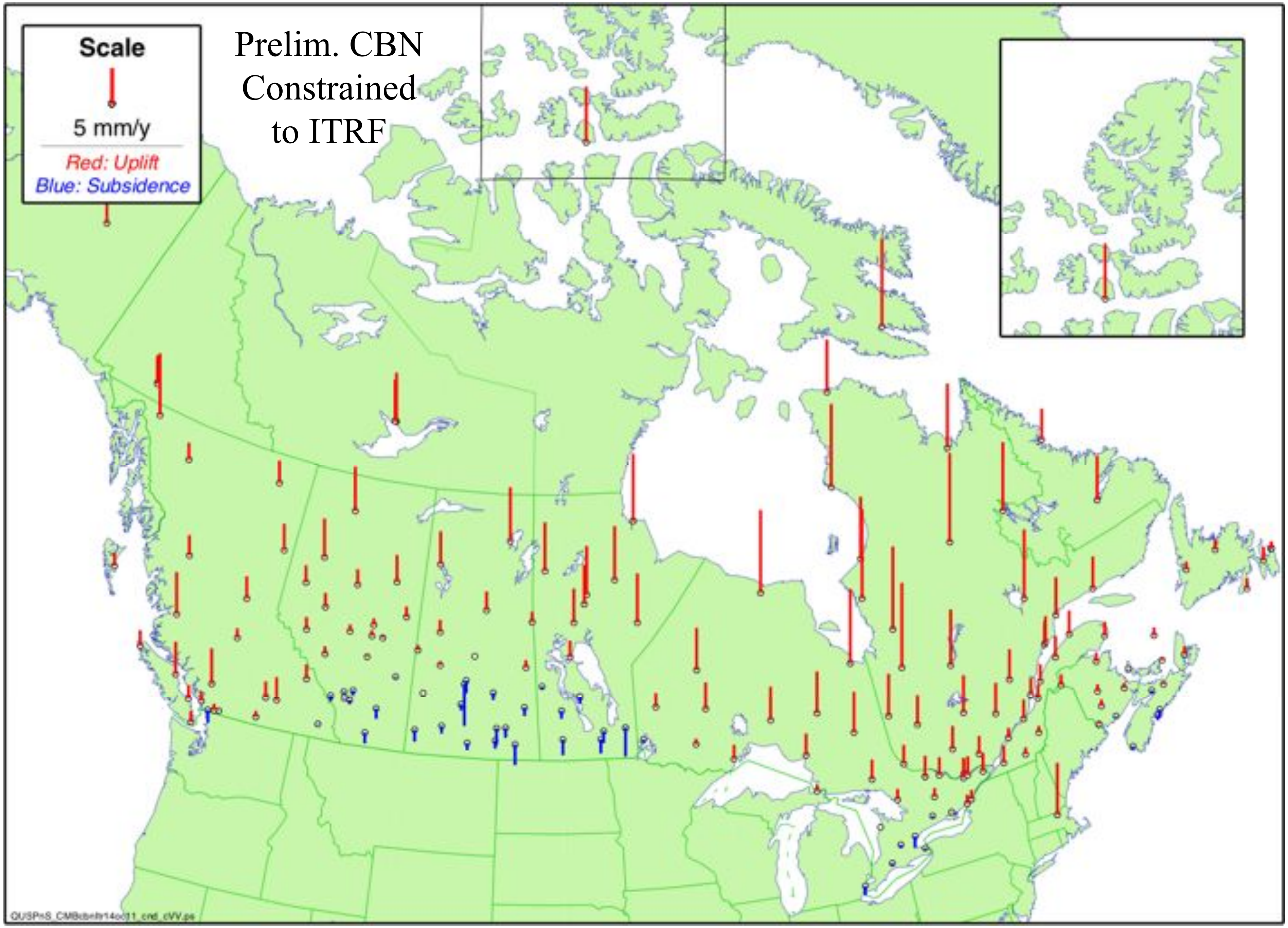
CBN Solutions

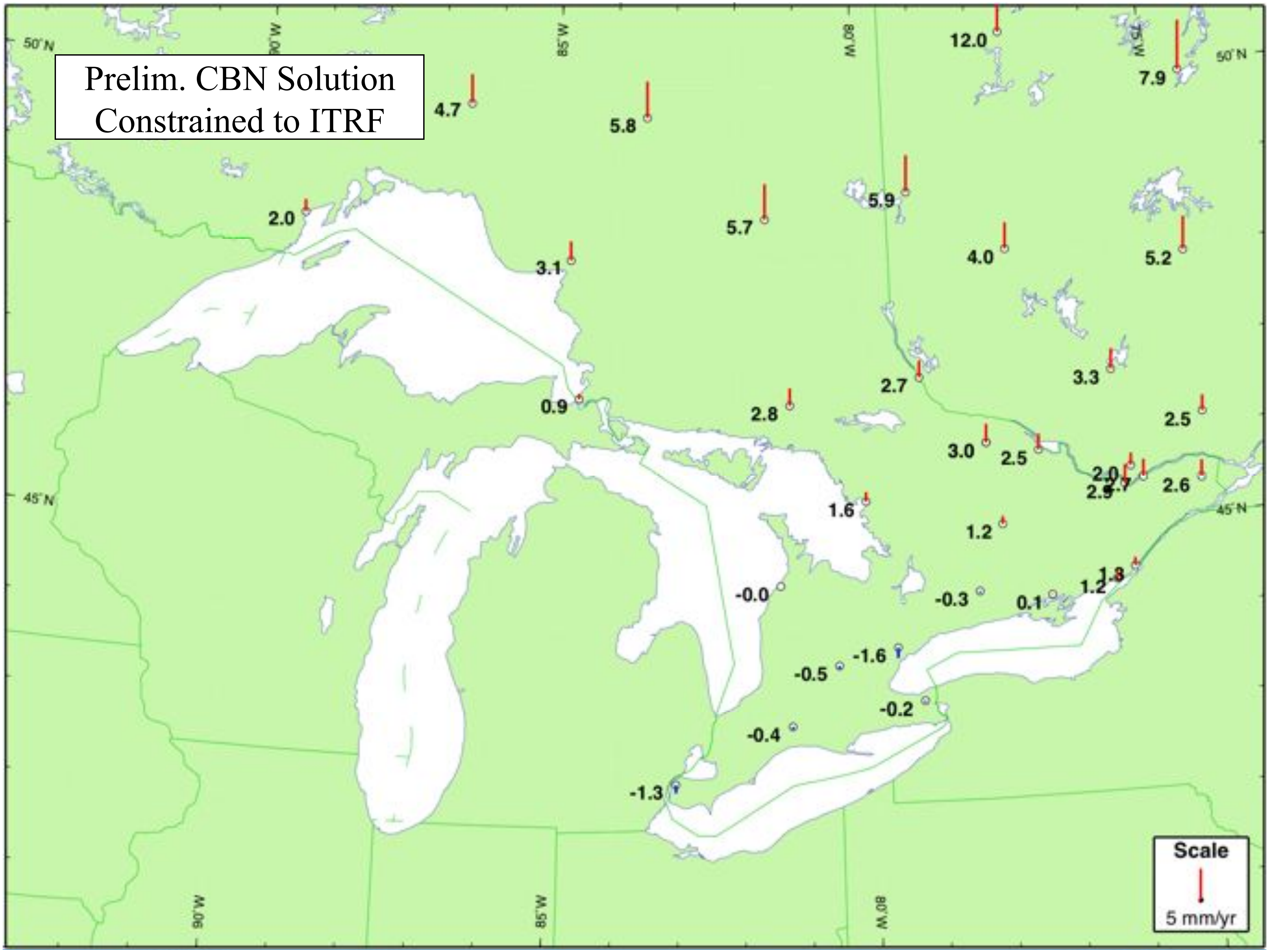
CBN Velocity Solution

- Using repeated campaign surveys from 1994 to 2006
  - 1st campaign 1994-1999 (no 1998)
  - 2nd campaign 2001/2002
  - 3rd campaign 2005/2006
  - Several other smaller campaigns
  - IGLD not included (not observed to same accuracy)
- Each stations occupied
  - 24 hr observation sessions
  - 3-5 independent occupations
- All data reprocessed with latest version of Bernese GPS Software

Solution still in progress

- Optimizing weighting and reference frame realization
- Preliminary results available


Scale
5 mm/y
Red: Uplift
Blue: Subsidence
Prelim. CBN
Constrained
to ITRF
QUSPnS_CMBcbnItr14oct11_cnd_cVV.ps



Prelim. CBN Solution
Constrained to ITRF
50°N
90°W
85°W
80°W
75°W
45°N
12.0
7.9
4.7
5.8
5.9
5.7
2.0
4.0
5.2
3.1
2.7
3.3
0.9
2.8
2.5
3.0
2.5
2.6
1.6
1.2
-0.0
-0.3
0.1
1.2
-1.6
-0.5
-0.2
-0.4
-1.3
Scale
5 mm/yr

Factors Affecting GPS Velocities

Monument stability

- Most monuments anchored to bedrock or on stable buildings
- Not sure about some monuments on tide gauge huts (PARY, PWEL)

Multipath

- GPS signal reflections from nearby buildings, fences, etc.
- ROSS: large building building right beside monument *after* installation
- PARY: cruise boat moored close to monument
- Luckily haven’t seen any problems yet
- Trimble antennas very good at rejecting multipath

Unloading effects

- From loss of weight of water as a result of falling water levels

Typical Monuments

HRST

PWEL

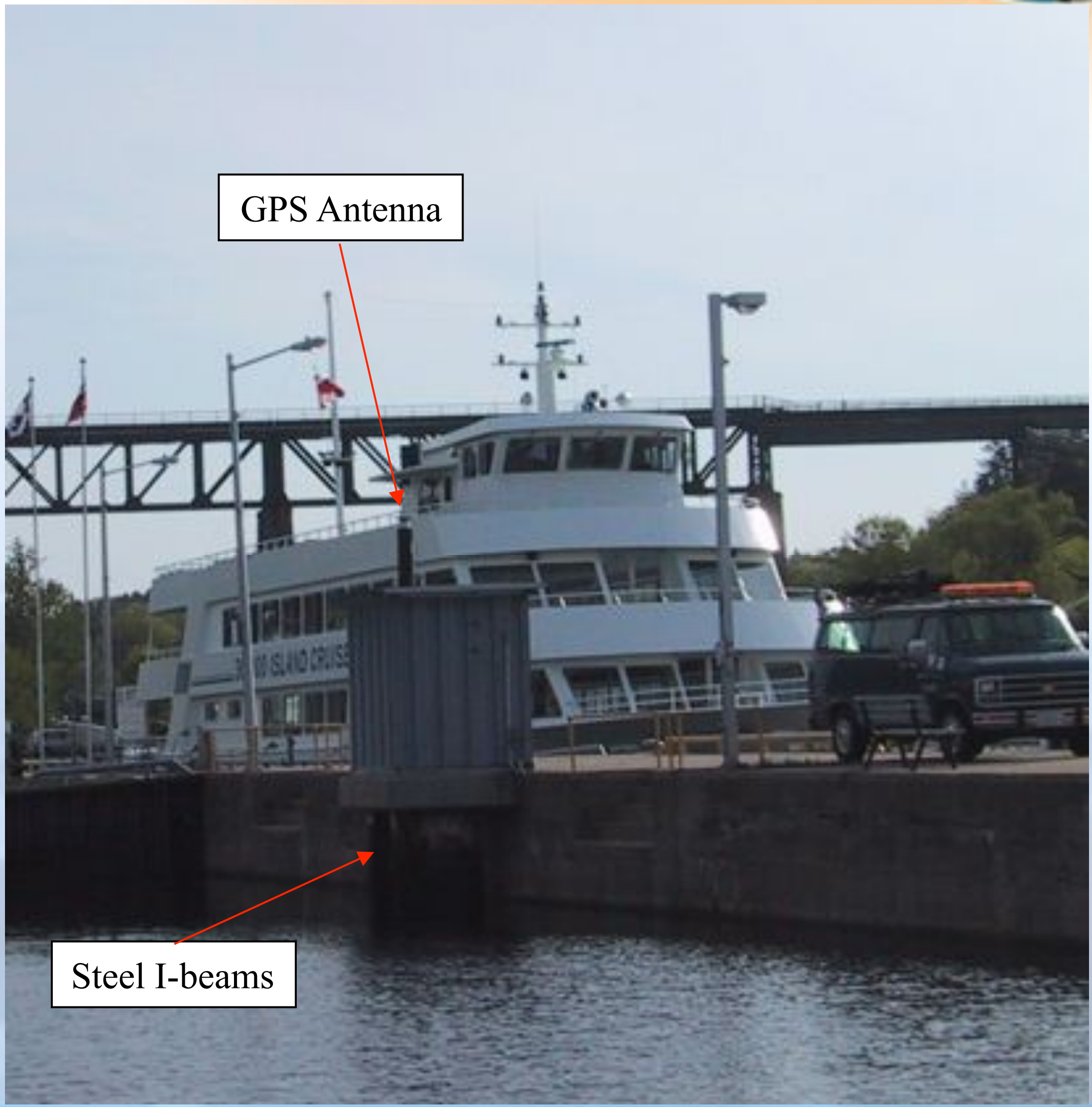
PWEL

Monument Stability & Multipath

Parry Sound
(PARY)

Possible multipath from cruise boat

Not sure if I-beams are into bedrock



Possible Multipath

Rossport (ROSS) Before

ROSS After

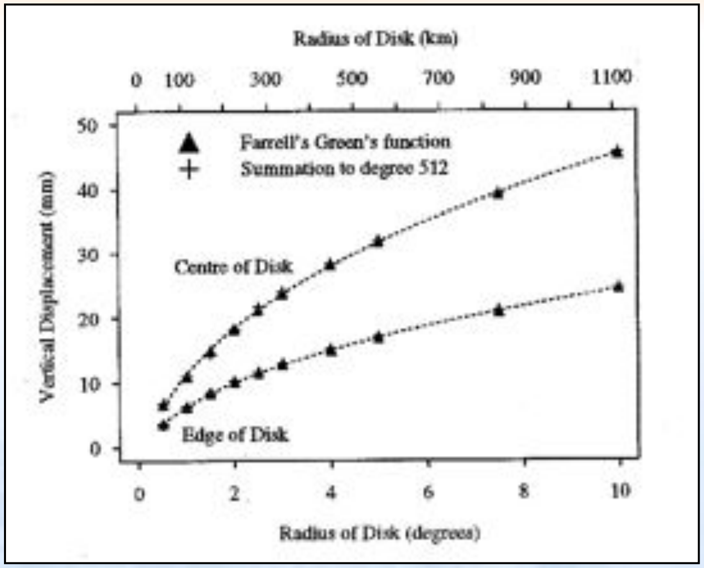
Unloading Effects

Unloading from lower water levels

- Release of weight of water as levels fall
- Will cause elastic rebound at short times scales

James & Ivins (1998)

- Elastic rebound estimated for 1 m thick spherical ice disk as a function of radius of disk



Application to Upper Great Lakes

- 1 m roughly equivalent to loss of water in Upper Great Lakes over last 20 years?
- Assuming 1000 km disk radius similar to a Great Lake
  2 cm rebound at edge of 20 years = 1 mm/yr

New NAREF Solutions

Need to reprocess all data again!

- Current IGS orbits using absolute PCV & accounting for antenna domes
- Inconsistency with previous solutions based on relative PCV and no domes
- Bias in time series at Nov 2006
- Must wait for reprocessed precise orbits to reprocess all weeks prior to Nov 2006
- Will also include more global station for better tie to ITRF

Including more global ITRF stations

- For better reference frame realization

SIO will process all Canadian & more CORS stations

- For more redundancy, especially for CORS stations (incl. Great Lakes sites)

Other Velocity Solutions

GPS Solutions

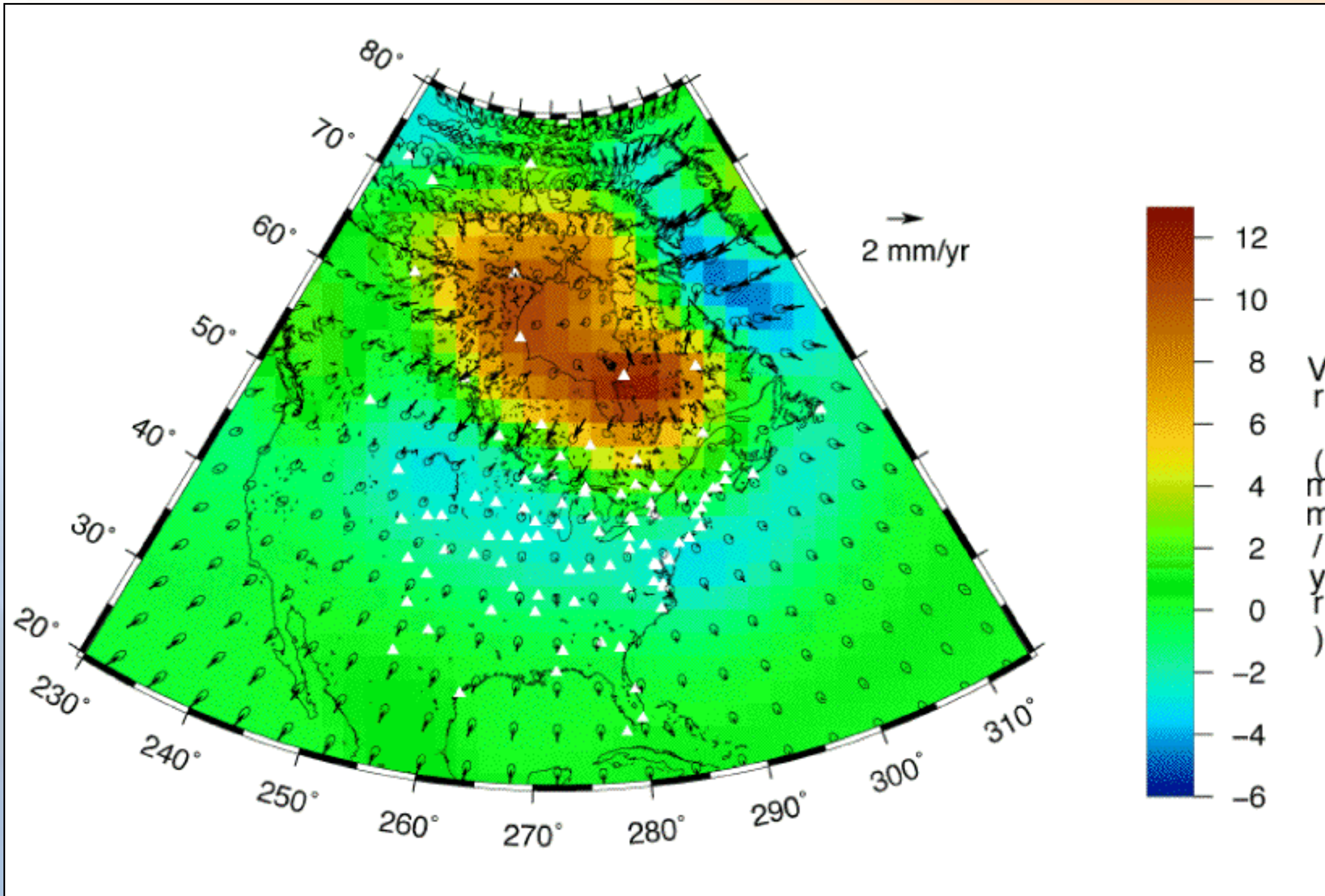
- SNARF v1.0 GIA model
  - "Assimilation" of GPS velocities with an Earth model
  - Based on earlier NAREF solution that contained some biases (software bug)
  - Not as much data included (up to end of 2005)
  - Using new NAREF solution in v2.0
- Sella et al. (2007) GPS solution
  - Using CPGS and CBN data with GIPSY precise point positioning
  - Missing some CGPS data and 3rd CBN epoch

Non-GPS Solutions

- Mainville & Craymer (2005) tide gauge solution
  - Based on more fundamental point data (estimates various biases at each point)
  - Avoids inconsistencies in gauge differences (used to cancel lake-wide biases)
  - ICE-3G used to link lakes together
- Map of Vertical Crustal Movements (Carrera et al., 1990?) – levelling
- GRACE satellite mission
  - Provides rate of change of gravity since 2002

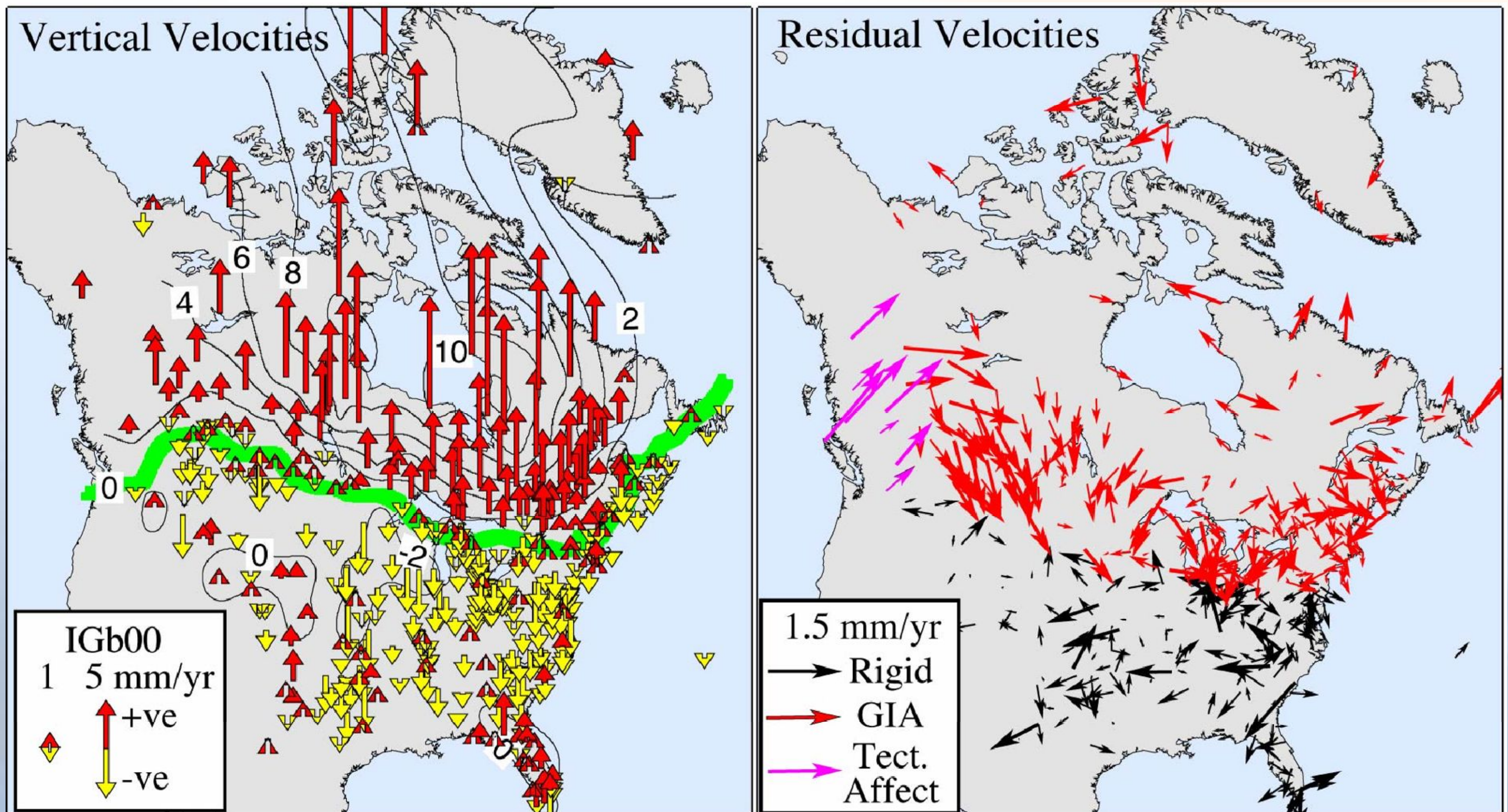
SNARF v1.0 GIA Model

"Assimilation" of GPS velocities & Earth model



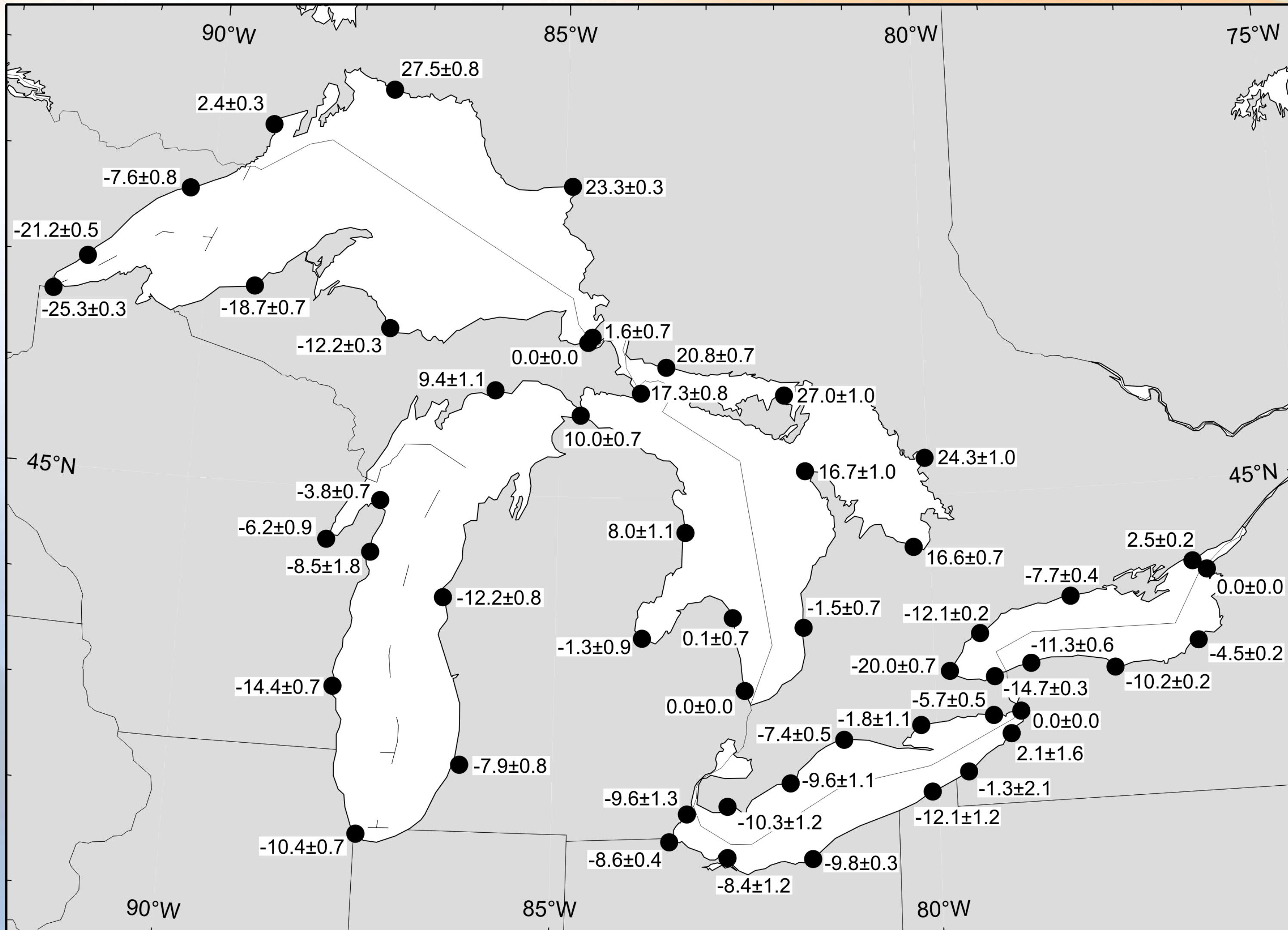
Sella et al. Solution

Includes CGPS (1994-2006) & CBN (1994-2005) data
Uses GIPSY Precise Point Positioning (not optimized)



Sella, Stein, Dixon, Craymer, James, Mazzotti & Dokka. Observation of glacial isostatic adjustment in stable North American with GPS. Geophysical Research Letters, 34(2), 2007.

Mainville & Craymer (2005) Tide Gauge Soln



GRACE (Gravity) Solution

GRACE Satellite Mission

Rate of change of geoid

Much smoother picture of GIA

Trend agrees well with GPS and latest ICE-5G (largest ice dome west of Hudson Bay)

From Tamisiea, Mitrovica & Davis. GRACE satellite data constrain acient ice geometries and continential dynamics over Laurentia. Science 316 (881), 2007.

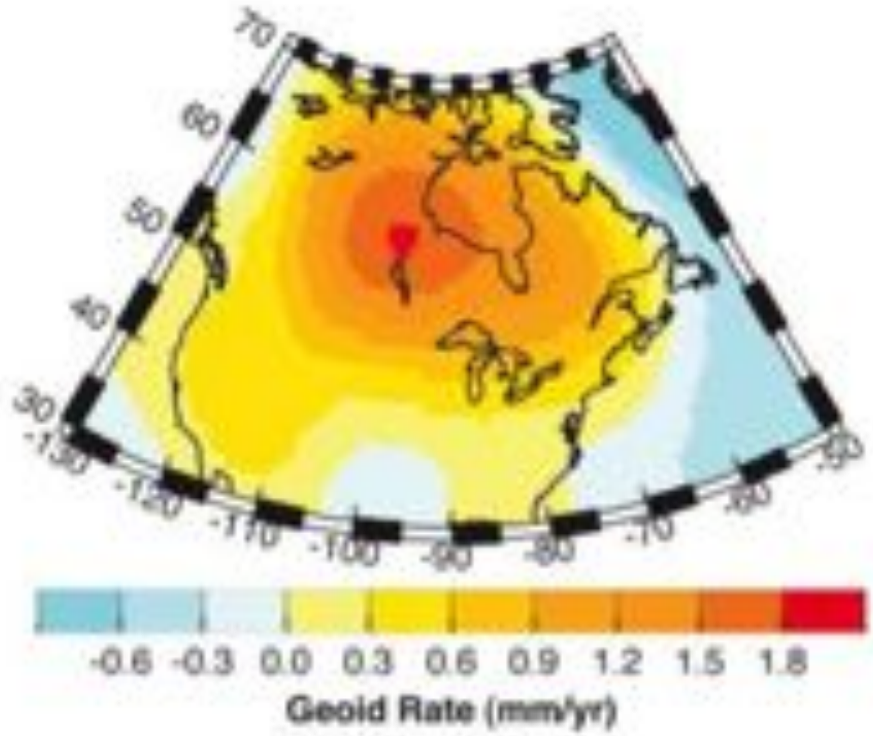


Fig. 1. Observed time rate of change of the geoid over Laurentia from CSR RL01 GRACE solutions from April 2002 to April 2006.