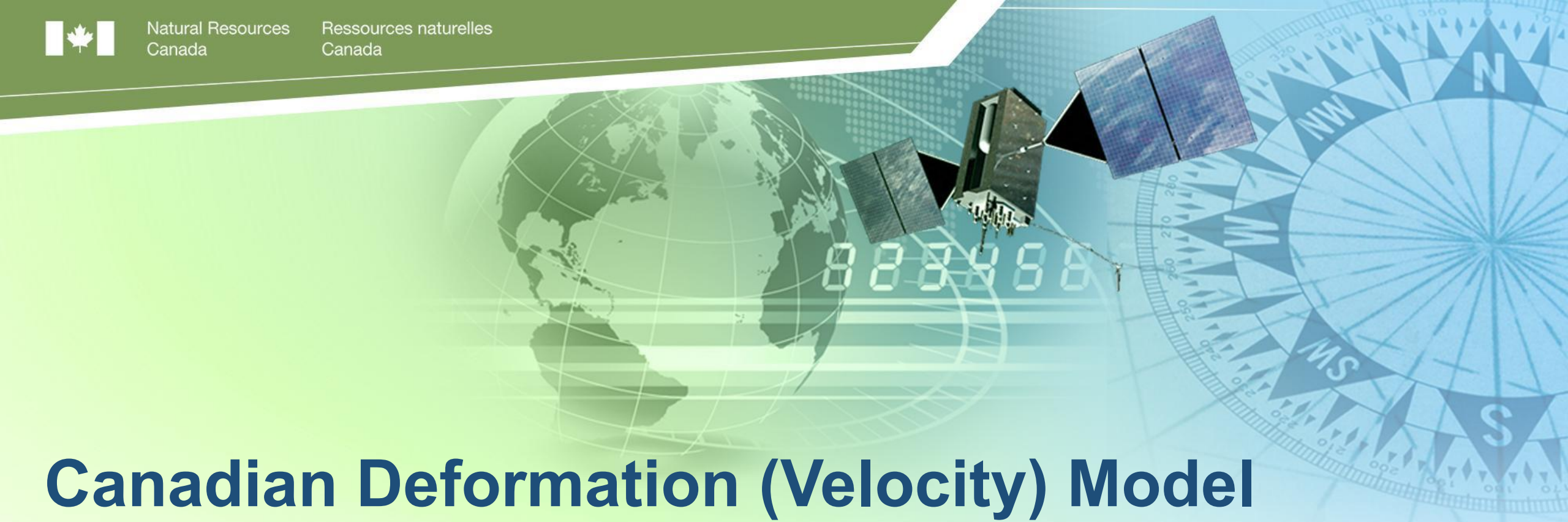


Canadian Deformation (Velocity) Model

~~Michael Craymer (~~Catherine Robin)
Canadian Geodetic Survey, Natural Resources Canada

Binational Geospatial Software Developers Summit
November 30, 2022

Canada

Outline

- NAD83(CSRS) – static to dynamic
- NAD83v70VG
- Comparisons of CSRS versions & epochs

Static vs Dynamic Reference Frames

Static reference frames

- Coordinates don't change
- Traditional horizontal reference frames (NAD27, NAD83(Original))
  - Based on an adjustment of observations from many different epochs/eras
  - Lower accuracy observations unable to detect crustal motions

Dynamic reference frames

- Allows for epoch changes reflecting crustal or local motions
- Velocities (+uncertainties) estimated along with coordinates
- Often accompanied with a velocity model (+ uncertainty grid) to predict coordinates at other epochs

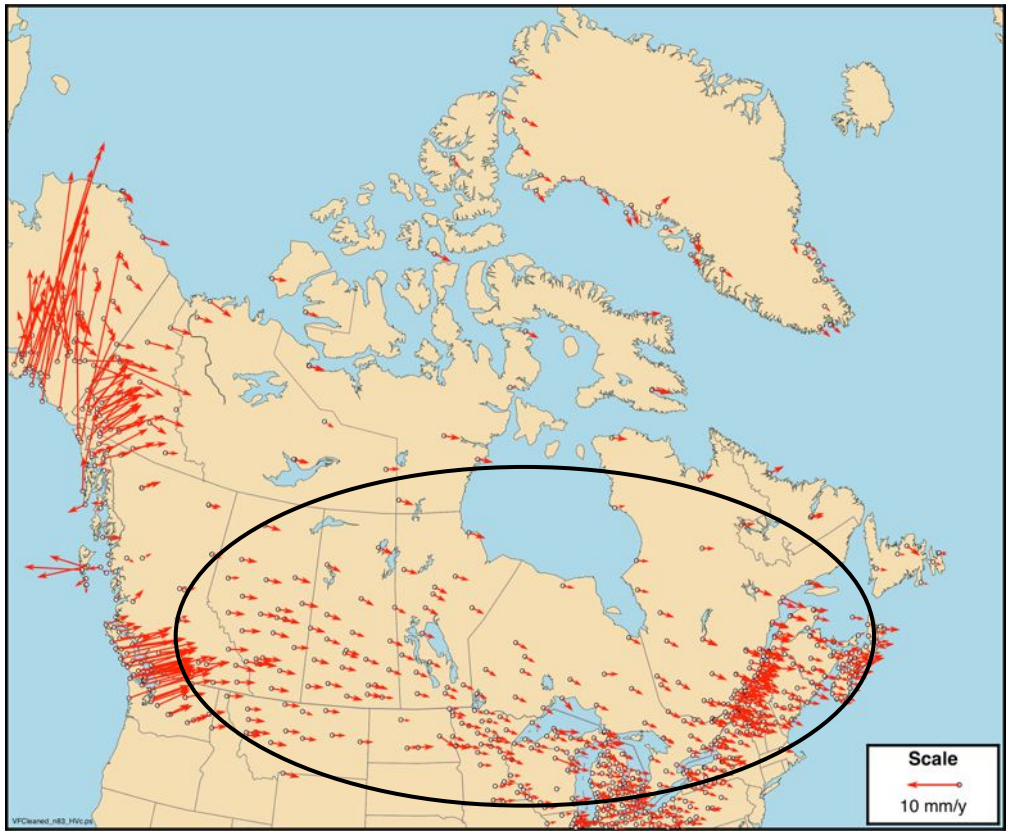
Static NAD83(CSRS) Realizations

- NNR-NUVEL-1A plate motion model
- Began using version numbers & ref. epoch to identify realizations

NAD83(CSRS) Version 2 – epoch 1997

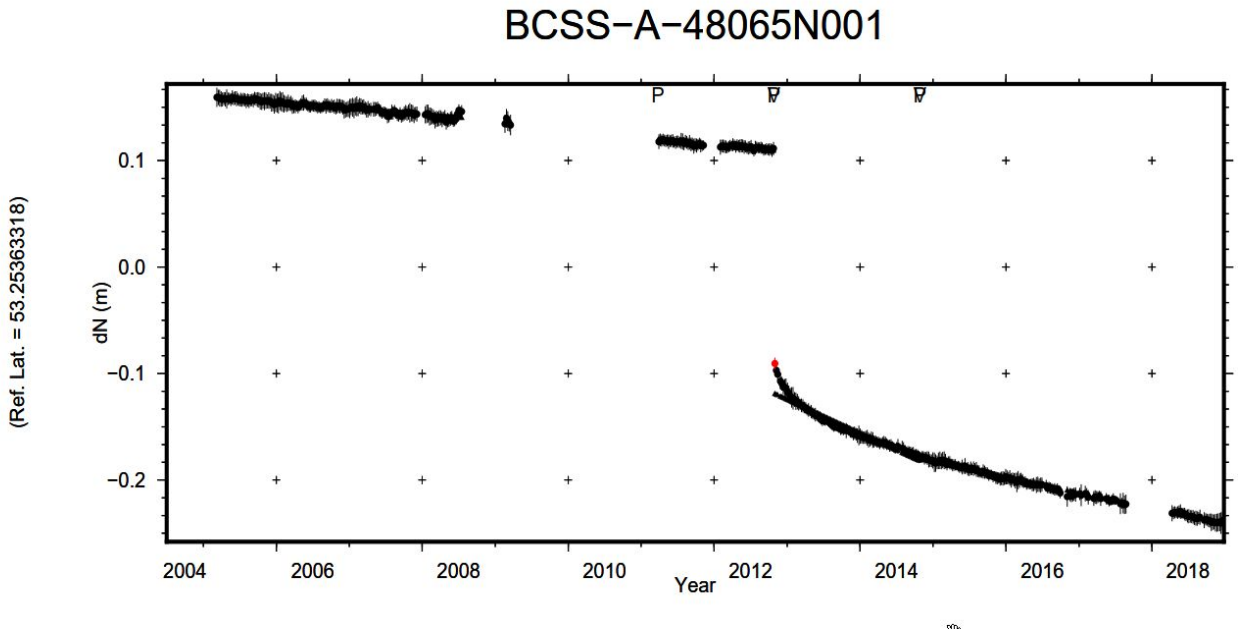
NAD83(CSRS) Version 3 – epoch 1997

NAD83(CSRS) Version 4 – epoch 2002



Dynamic NAD83(CSRS) Realizations

- Positions change due to
  - Episodic movements (e.g. earthquakes)
  - Ongoing movements – (tectonic, GIA)
- Modern GNSS can easily measure these
- Dynamic reference frames needed to account for movements using
  - Coordinates at a reference epoch
  - Velocities to propagate coordinates to other epochs



Time series showing crustal motion following the Haida Gwai earthquake of 2012. Velocities and uncertainties estimated using in-house SINEX combination software.

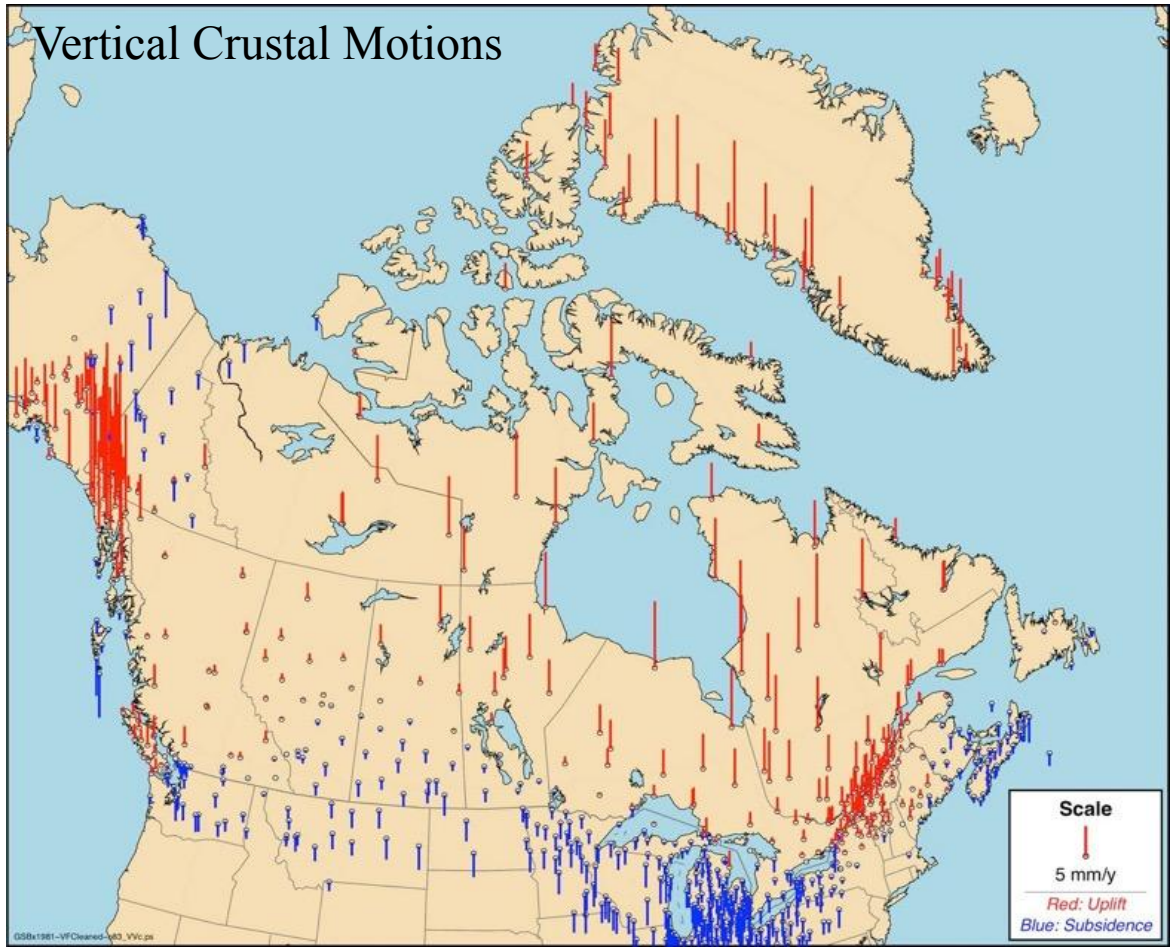
Dynamic NAD83(CSRS) Realizations

NAD83(CSRS) Version 5

- Proof of concept

NAD83(CSRS) Version 6

- First velocity model (grid) based on simple linear interpolation
- Velocity model only useful in southern Canada east of west coast plate boundary deformation zone

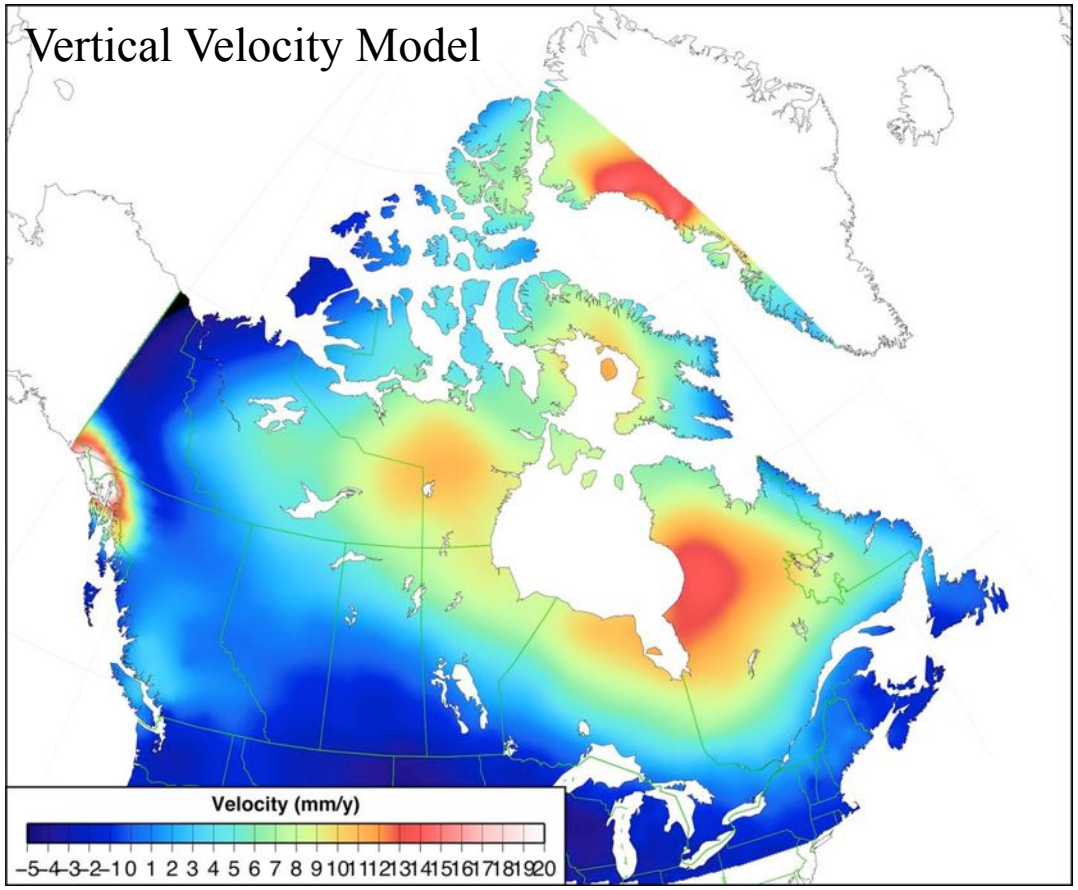


Dynamic NAD83(CSRS) Realizations

NAD83(CSRS) Version 7

- Epoch 2010
- Compatible with version 6 (Differences at the mm-level)

- Velocity model greatly improved
  - Hybrid model incorporating a GIA model with GPS velocities in the vertical
  - Better able to model GIA in the north where GPS stations are sparse
  - More data, better methods



Dynamic NAD83(CSRS) Realizations

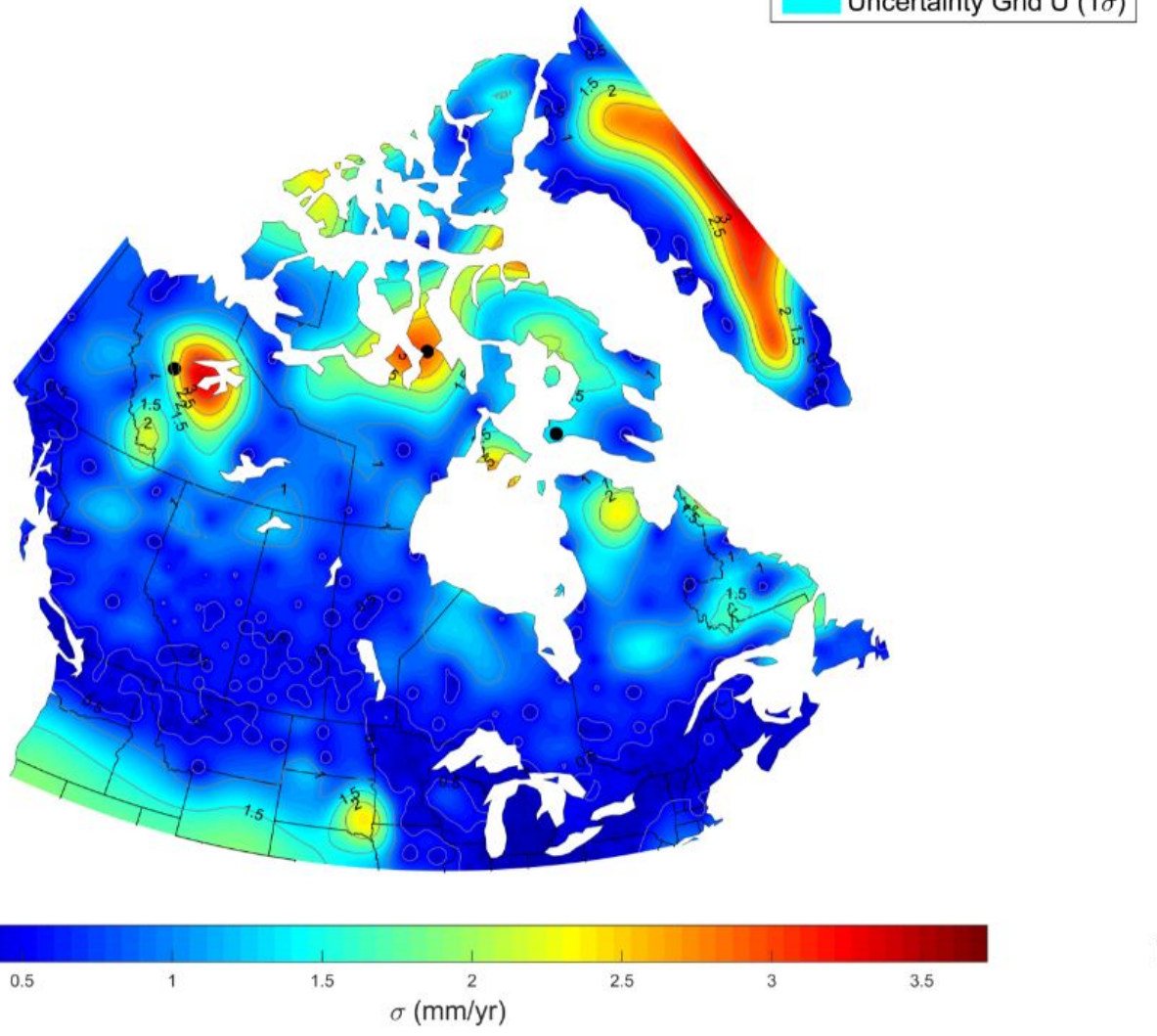
NAD83v70VG

- Error grid (N,E,U)
- Error propagation (Tools TBD):

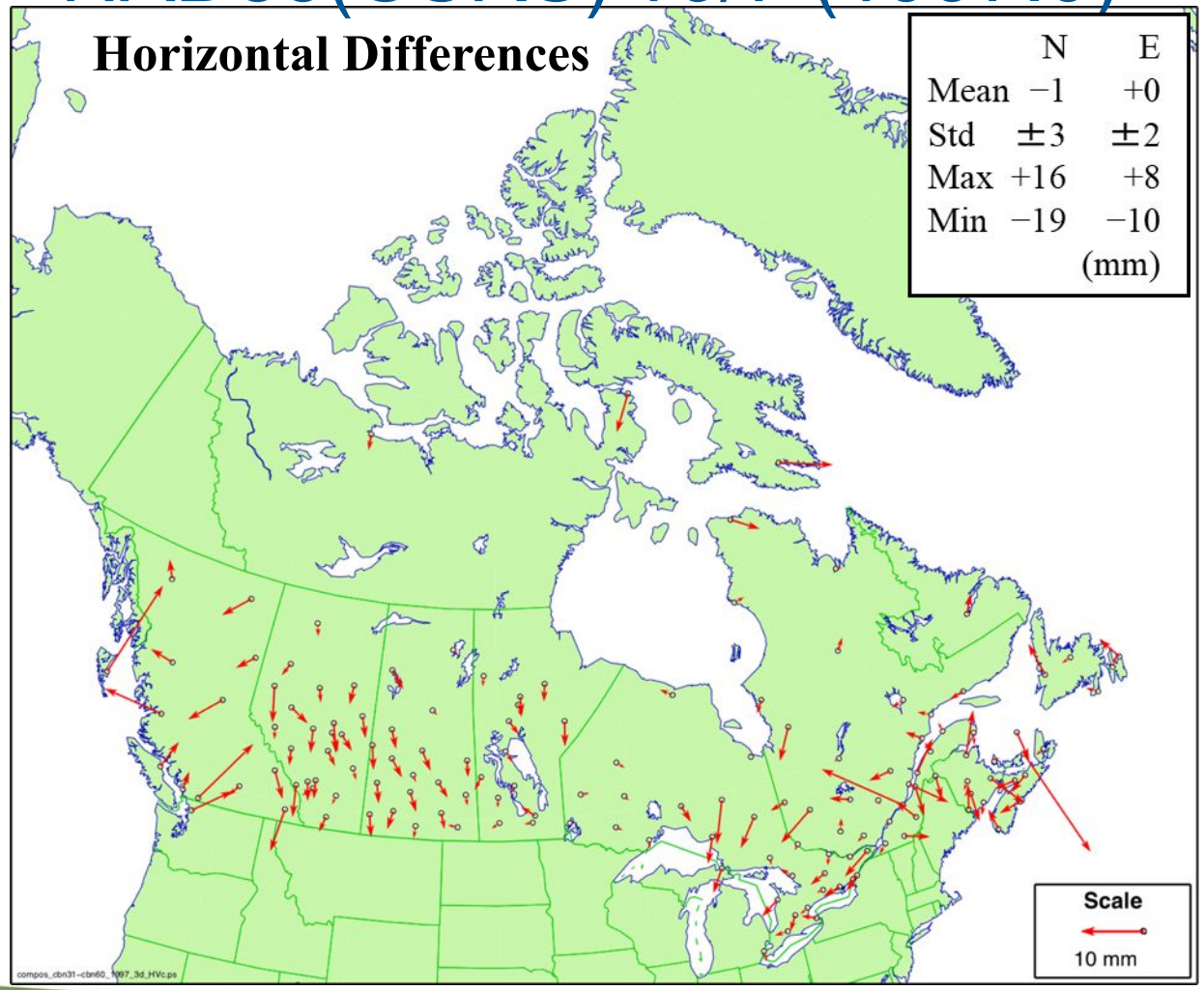
2019 Oct-17: Addition of uncertainties related to epoch transformation

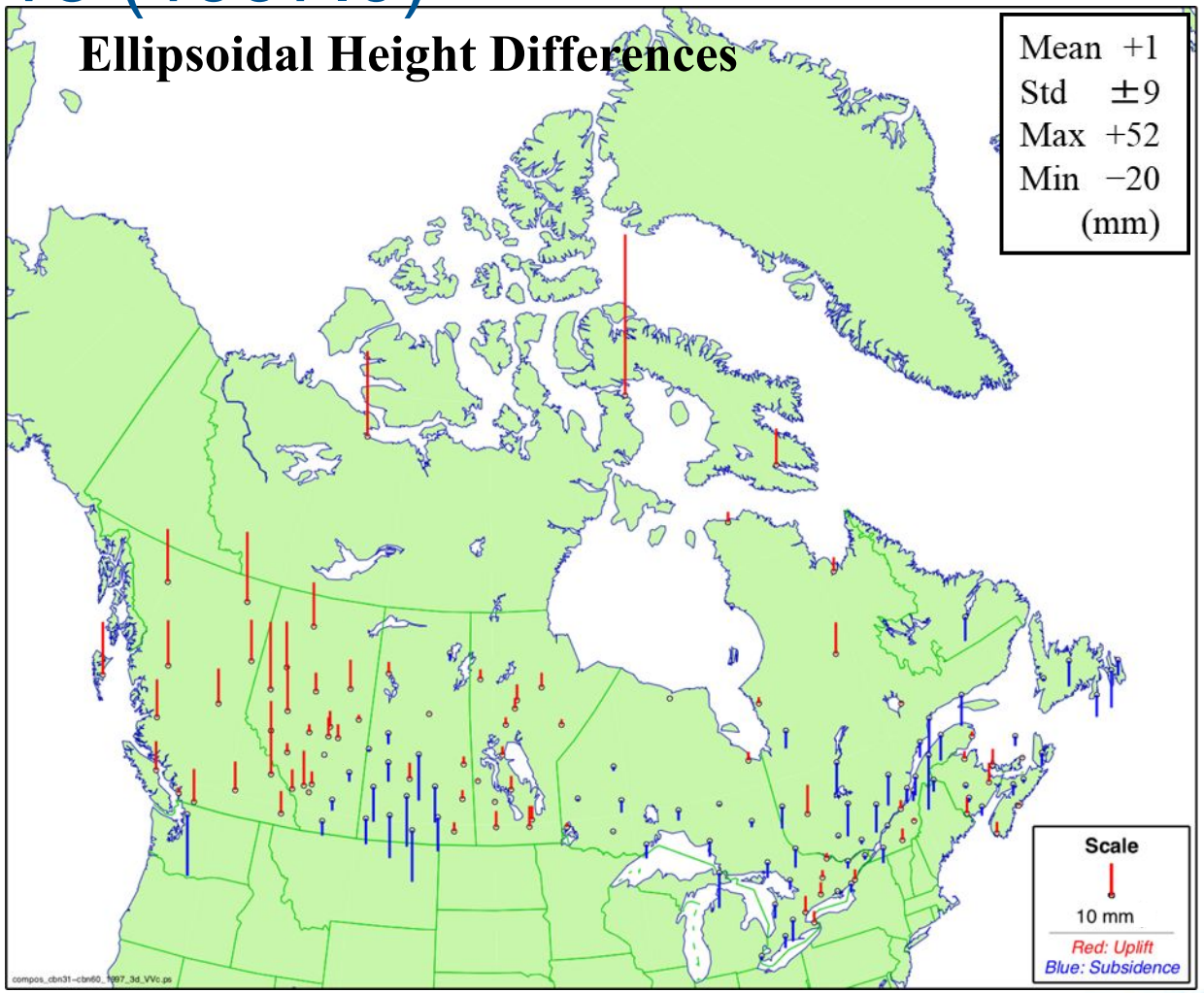
POS	CRD	SYST	EPOCH	A_PRIORI	ESTIMATED	DIFF	SIG_PPP(95%)	SIG_TOT(95%)
POS	X	NAD83	97:001:00000	-937405.8622	-937405.8375	0.0247	0.0106	0.0496
POS	Y	NAD83	97:001:00000	-3744787.7657	-3744788.1807	-0.4150	0.0176	0.0388
POS	Z	NAD83	97:001:00000	5060763.6195	5060761.4059	-2.2136	0.0159	0.0310
POS	LAT	NAD83	97:001:00000	52 50 56.91895	52 50 56.86548	-1.6528	0.0093	0.0494
POS	LON	NAD83	97:001:00000	-104 3 13.14275	-104 3 13.13609	0.1246	0.0106	0.0361
POS	HGT	NAD83	97:001:00000	427.8382	426.3133	-1.5249	0.0219	0.0344

SIG_TOT includes the uncertainty of propagating to reference epoch

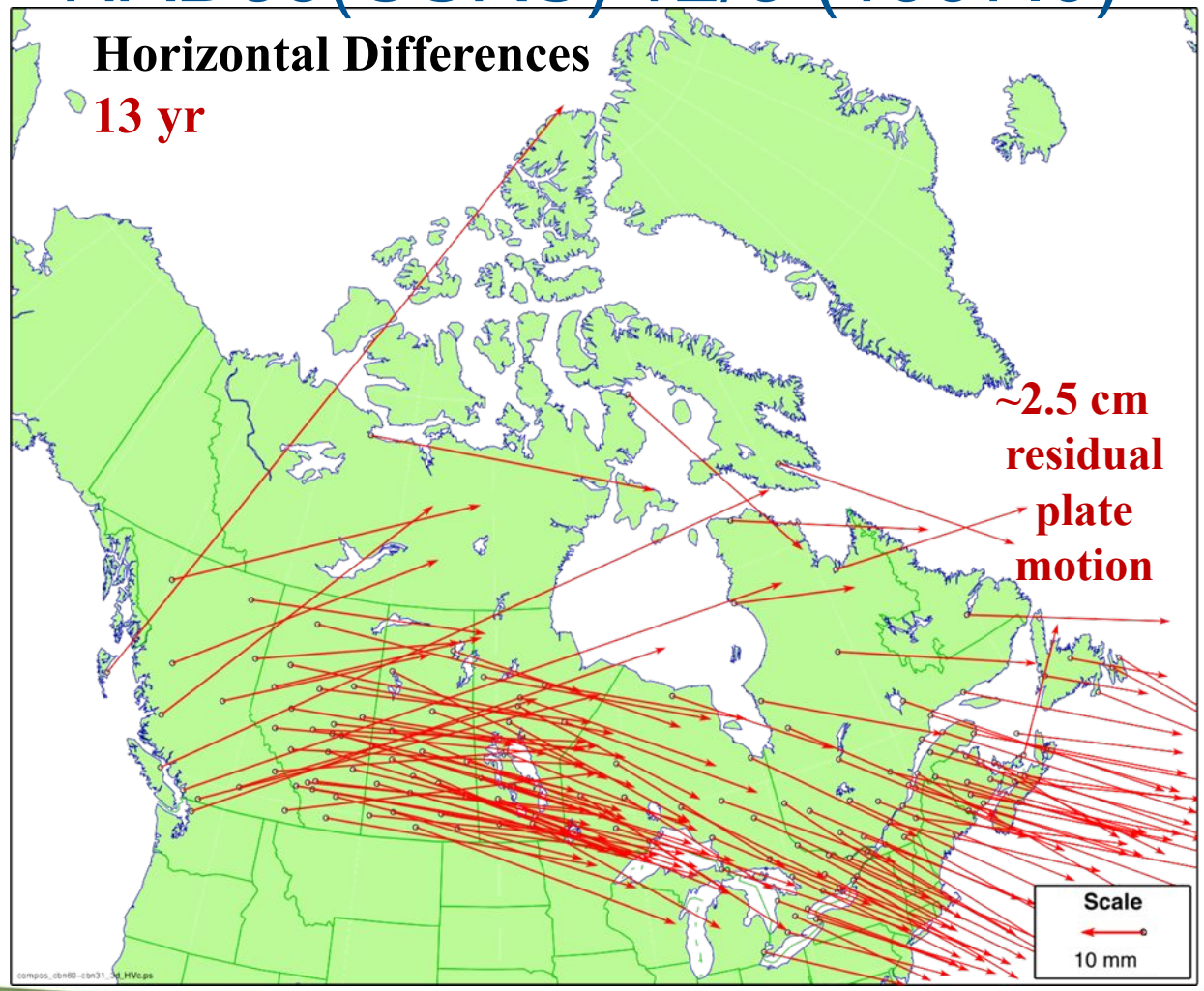


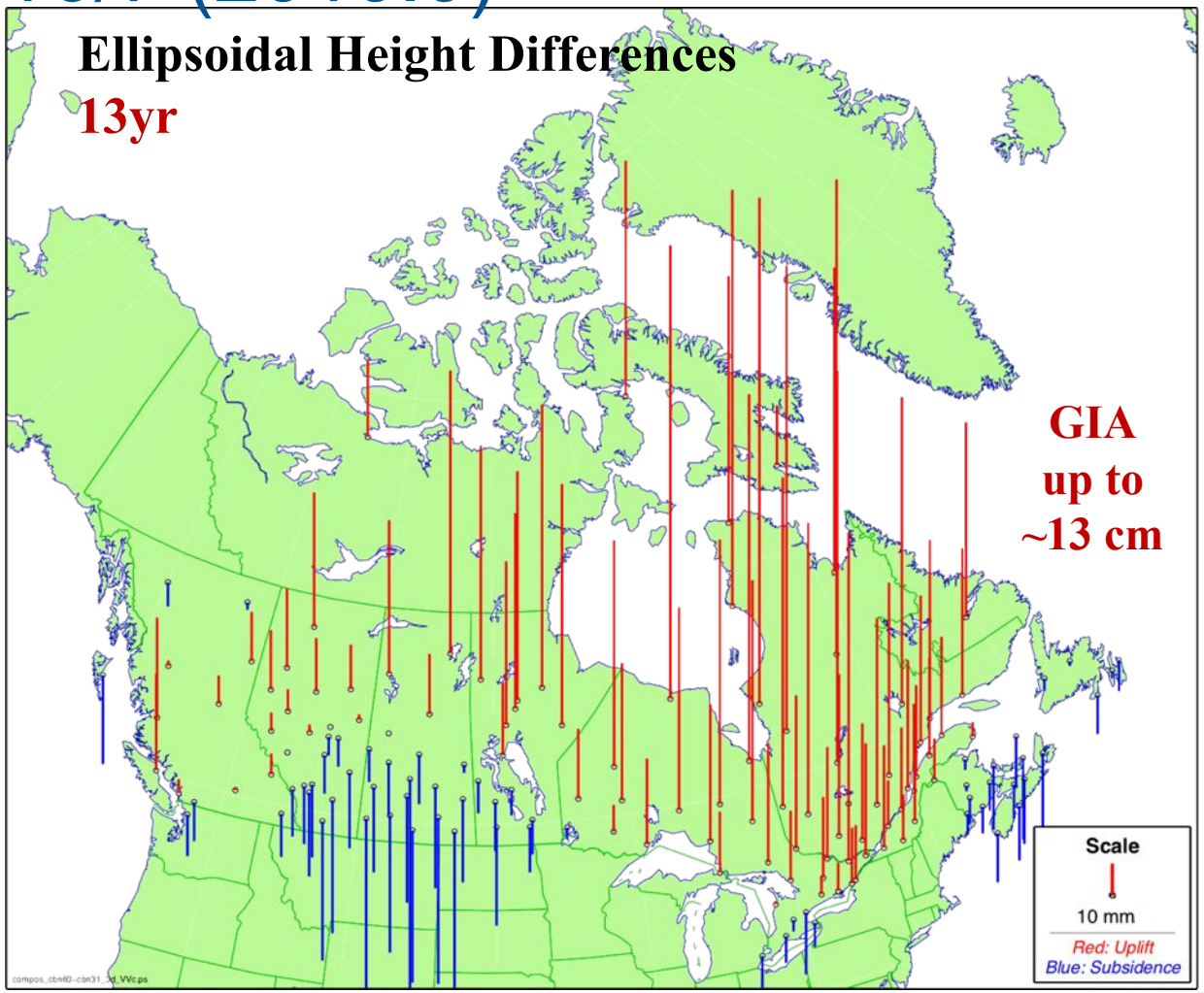
Impact of version change
NAD83(CSRS) v6/7 (1997.0) – v3 (1997.0)





Impact of epoch change
NAD83(CSRS) v2/3 (1997.0) – v6/7 (2010.0)





Summary

- Difference between epochs is LARGE (several cm)
- Difference between versions is SMALL (~1 cm)
- Velocity model for v.8 will have a number of gaps filled
- Next steps:
  - horizontal block modeling
  - improved GIA models
  - coordination of data with NGS

For more information

nrcan.geodeticinformation-informationgeodesique.rncan@canada.ca

https://www.nrcan.gc.ca/maps-tools-and-publications/tools/geodetic-reference-systems/18766

http://cgrsc.ca

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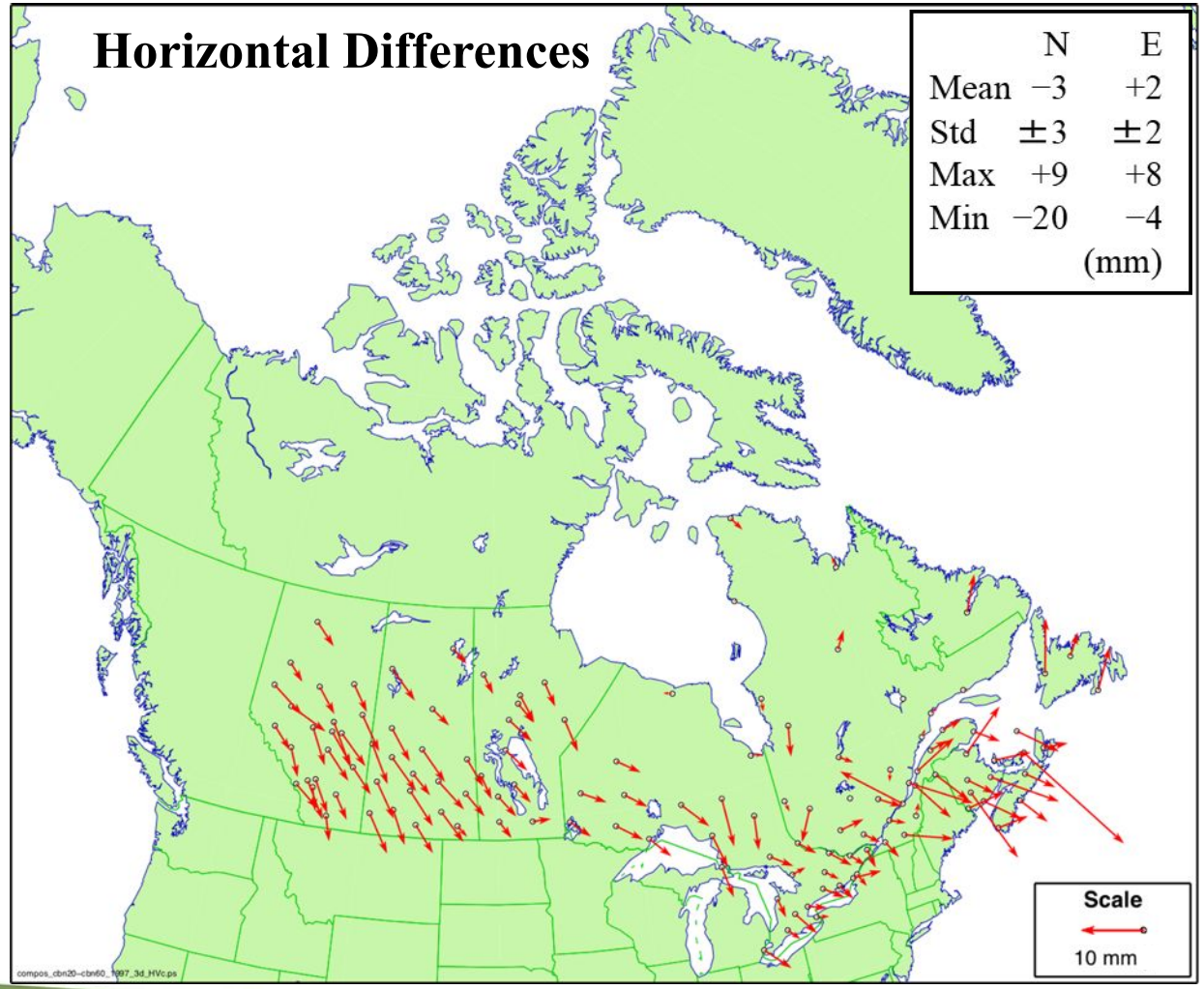
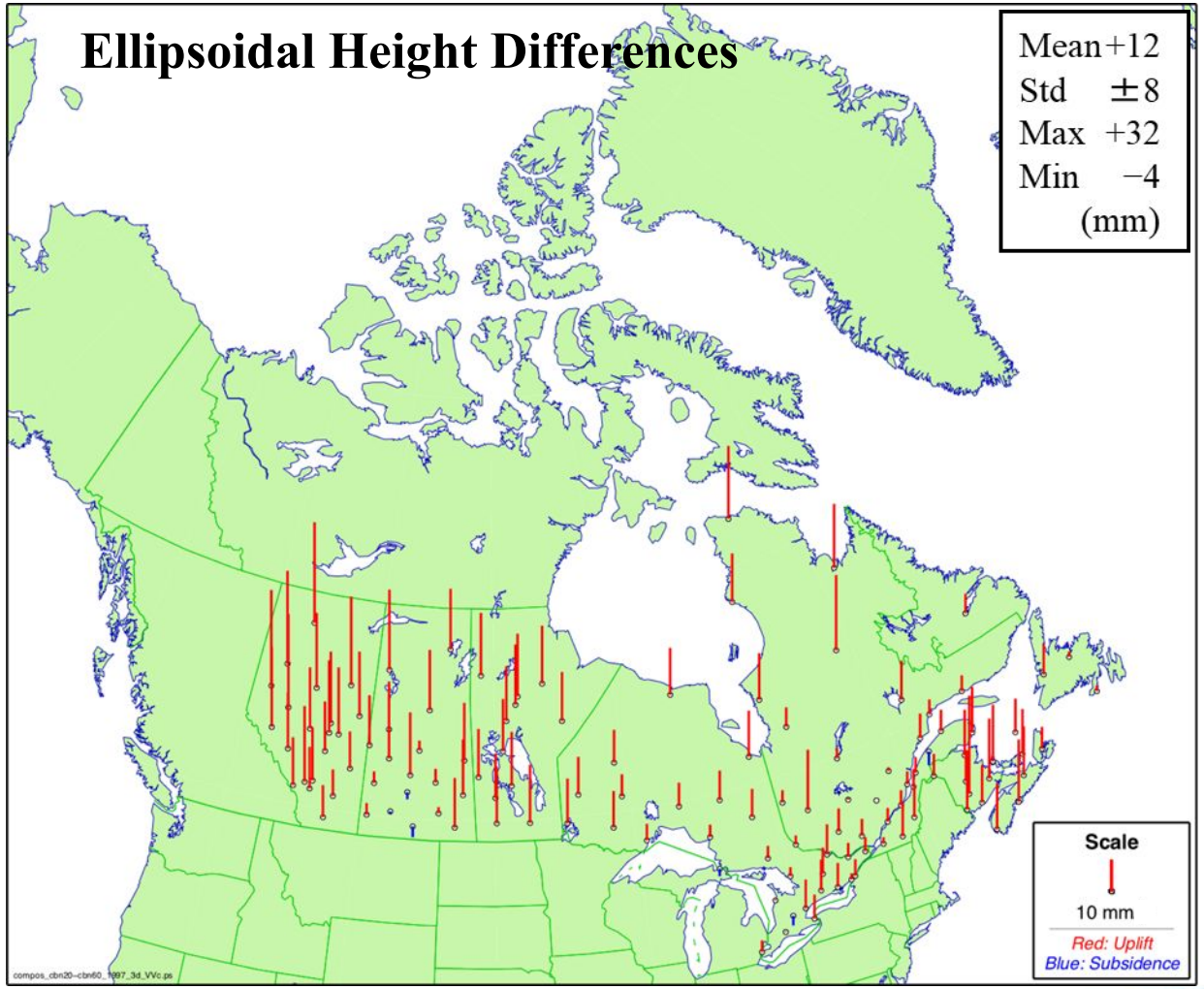
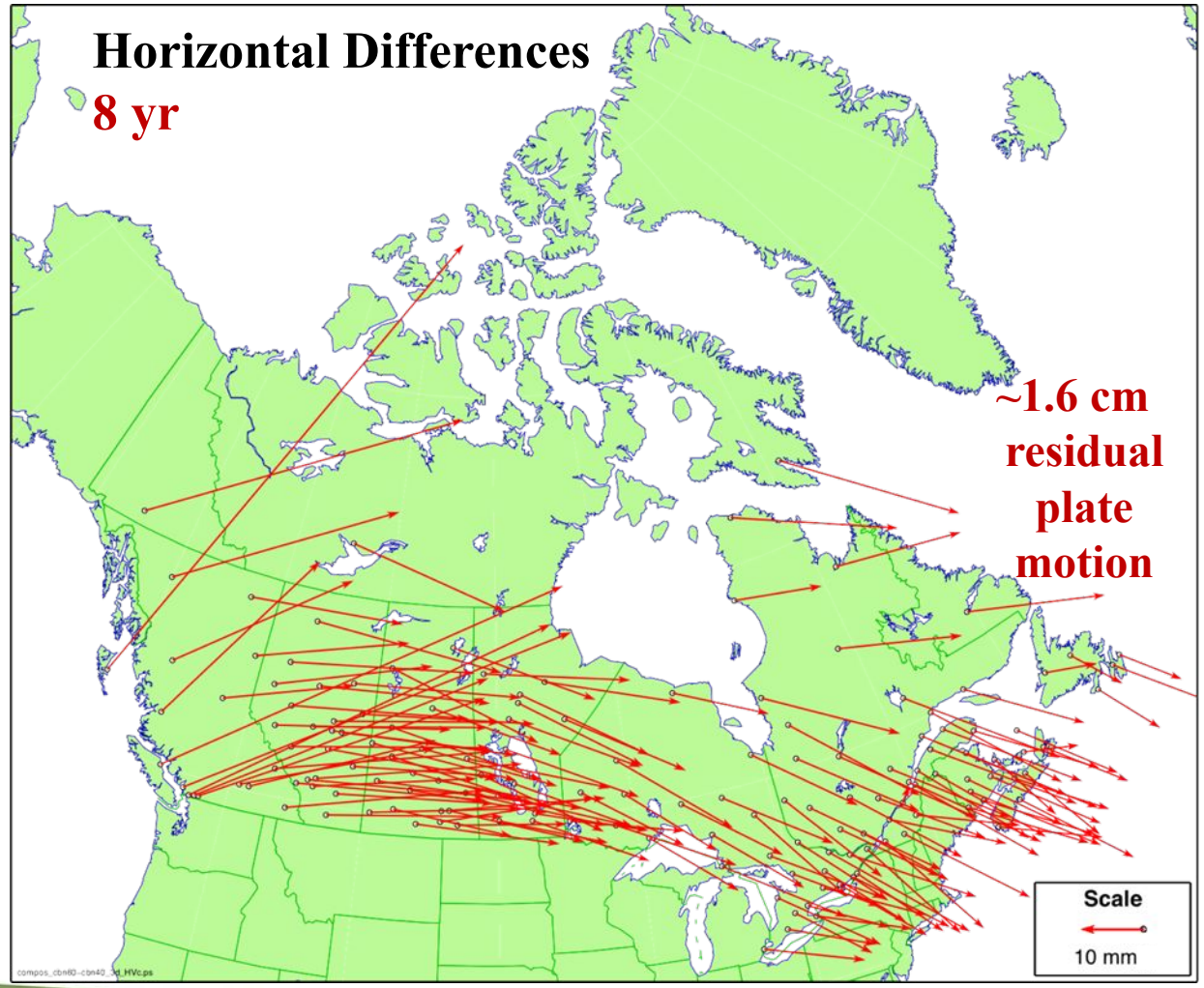
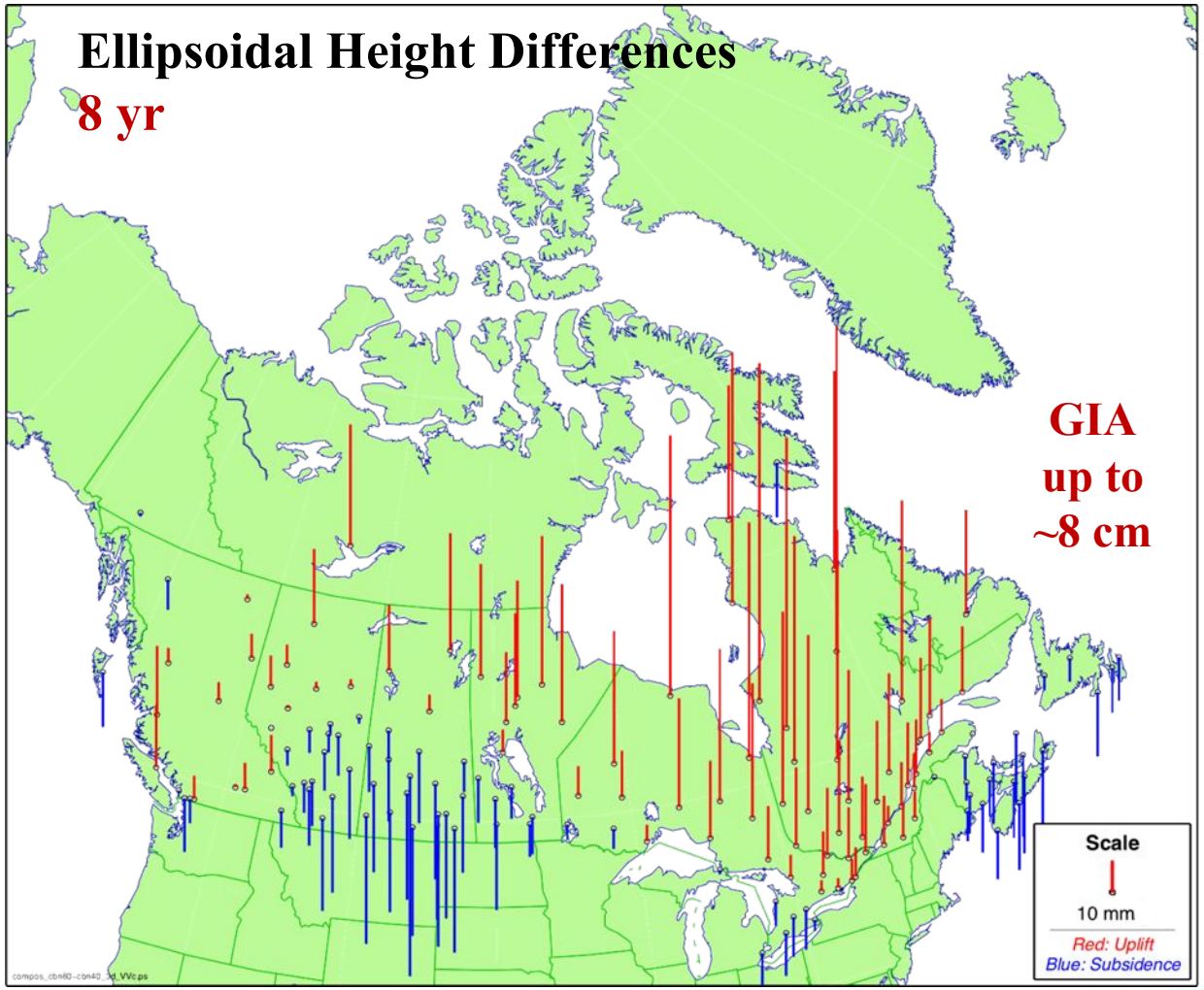
NAD83(CSRS) v6/7 (1997.0) – v2 (1997.0)





NAD83(CSRS) v4 (2002.0) – v6/7 (2010.0)





U.S. Realizations of NAD83

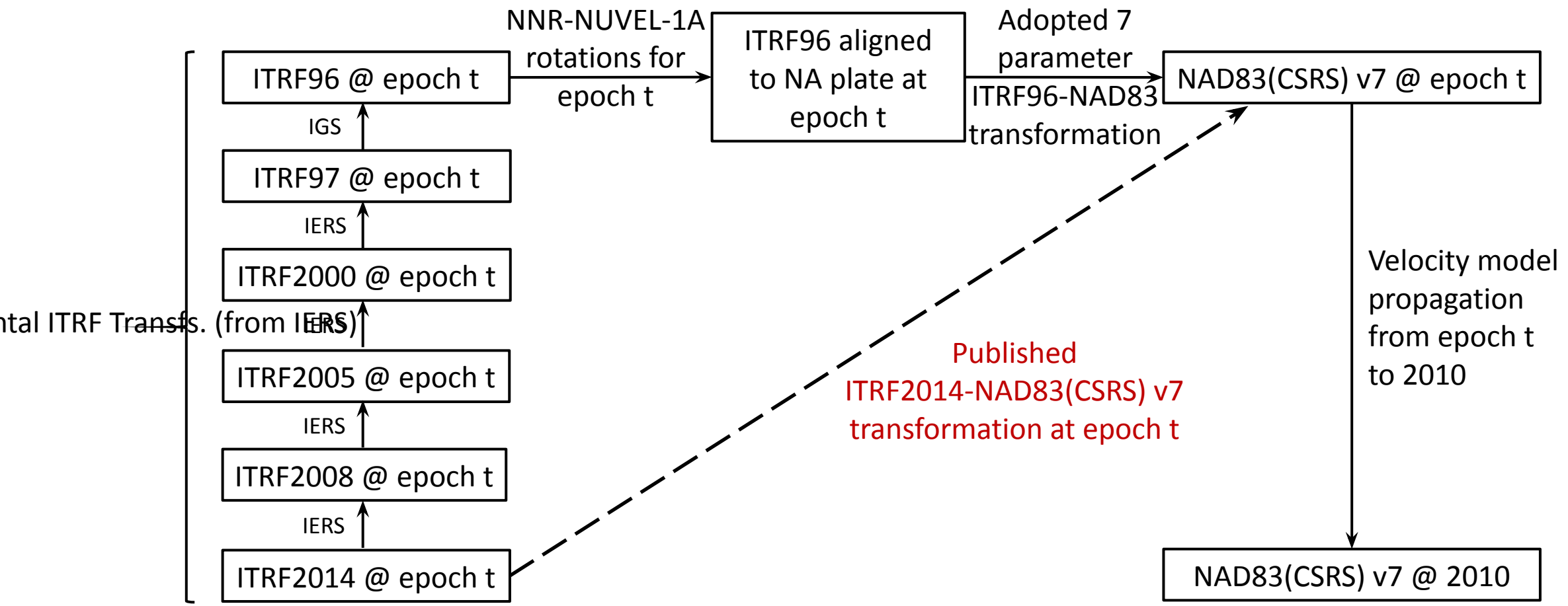
- The U.S. & Canada have always collaborated closely
- The U.S. has adopted the same definition as NAD83(CSRS) but…
- Have not always updated to the latest ITRF realization => not as compatible with IGS products (GNSS orbits)
- U.S. equivalence with NAD83(CSRS)

US Realization	Canadian Realization	ITRF
NAD 83(CORS96) epoch 1997	NAD83(CSRS) v2/3	ITRF96/97
NAD 83(CORS96) epoch 2002	NAD83(CSRS) v4	ITRF2000
NAD 83(2011) epoch 2010	NAD83(CSRS) v6/7	ITRF2008/14

NAD83(CSRS) v6/7 vs Previous Realizations

Version 6/7 propagated to previous epochs using velocity model

ITRF2014 to NAD83(CSRS) v7 Transformation



Summary of NAD83(CSRS) Realizations

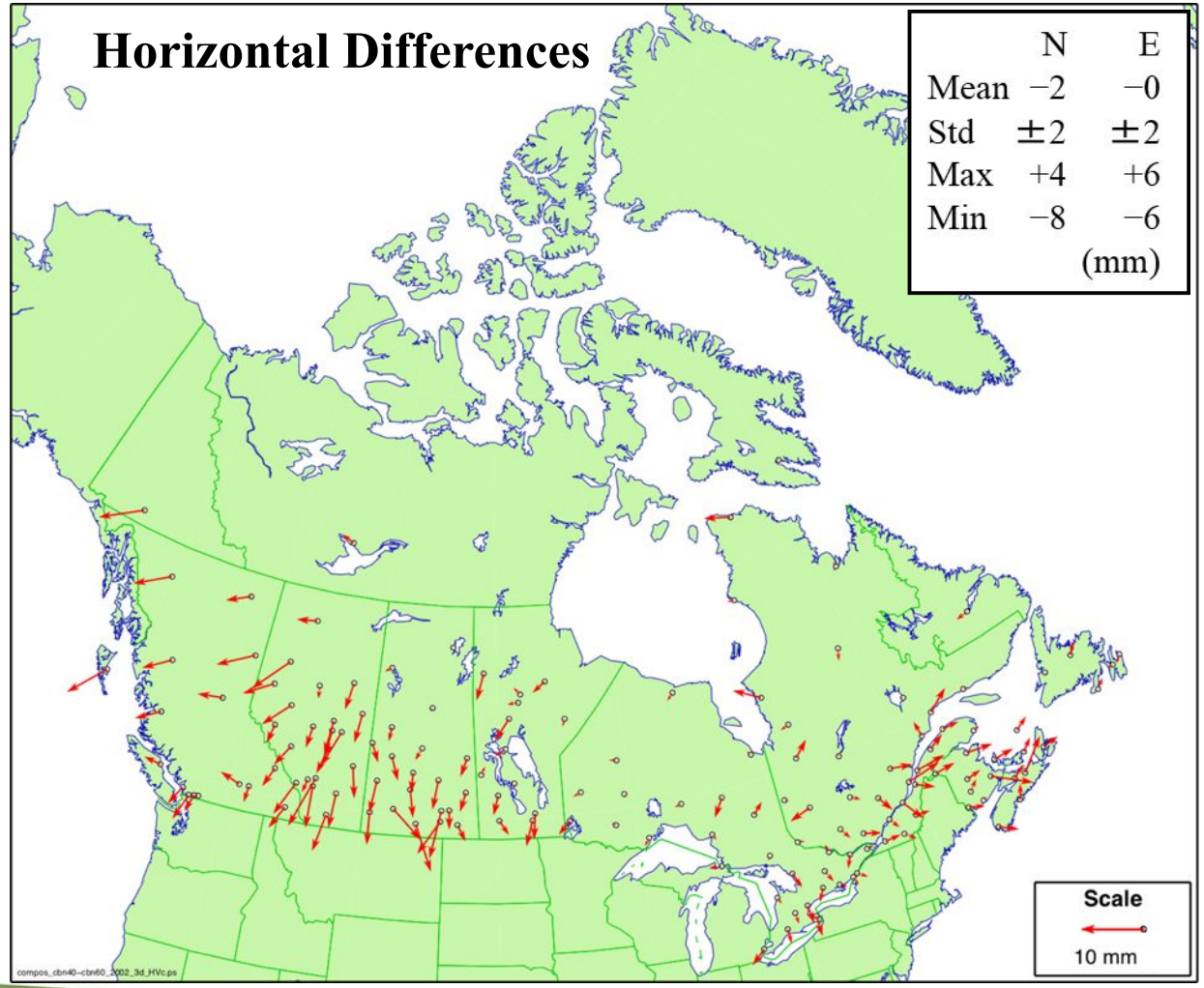
Version	Epoch	Based On	Released	Velocity Model	Comments
0	N/A	BTS84	1986	none	Original horizontal network
1	1997.0	ITRF94	1996	none	Preliminary realization (CSRS96)
2	1997.0	ITRF96	1998	none	Redefined transformation with US
3	1997.0	ITRF97	2000	none	Canada-wide CBN coverage
4	2002.0	ITRF2000	2002	none	Epoch update for crustal motion
5	2006.0	ITRF2005	2009	NAD83v5VG	First dynamic realization with velocity model
6	2010.0	ITRF2008	2012	NAD83v6VG	Epoch update for crustal motion First widely-used velocity model
7	2010.0	ITRF2014	2019	NAD83v70VG	Improved velocity model Compatible with version 6

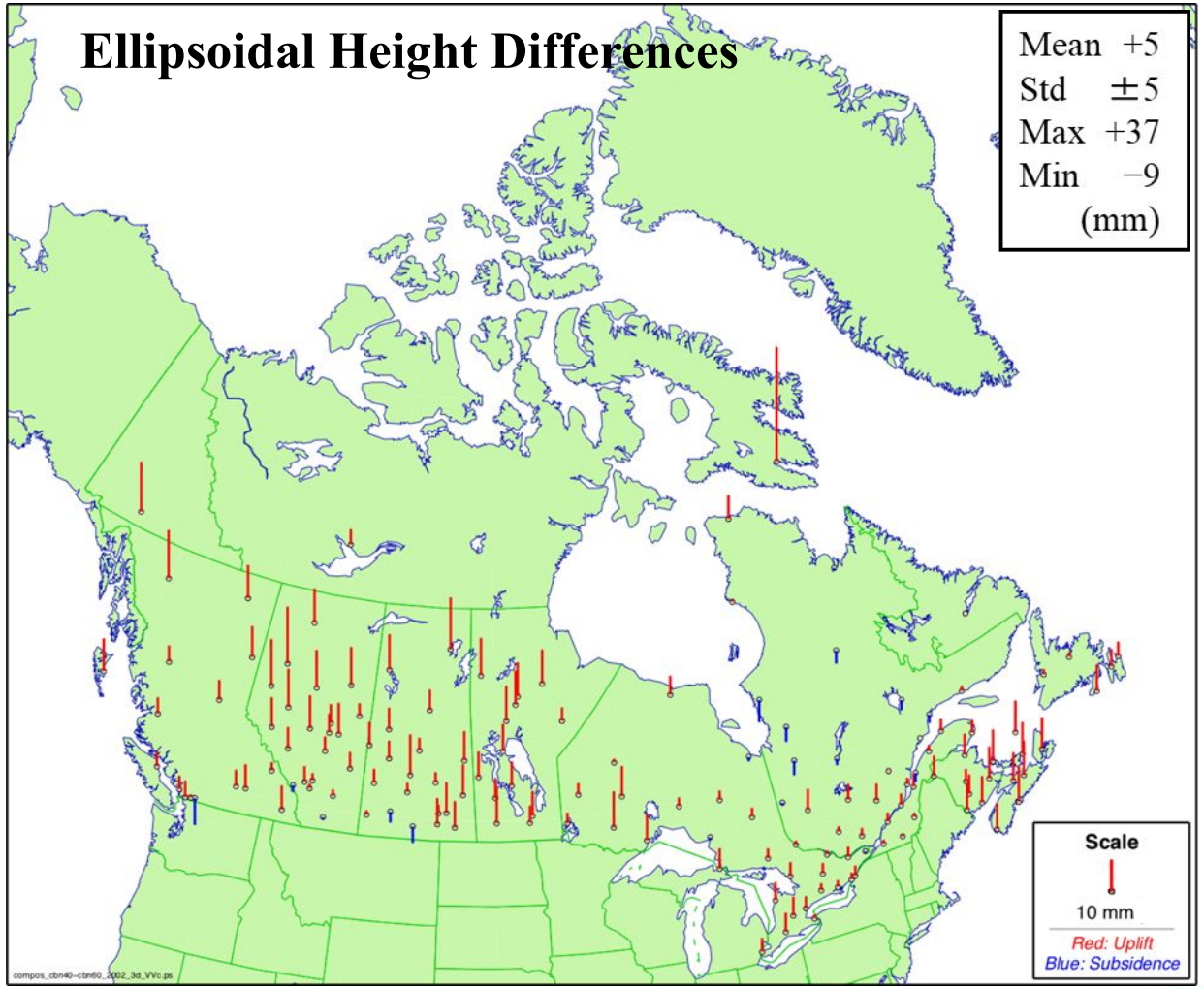
NAD83(CSRS) v6/7 Epoch 2010 vs Previous Realizations

At published reference epochs

Little difference between v2 & 3 and v6 & 7 – same epoch

NAD83(CSRS) v6/7 (2002.0) – v4 (2002.0)





Dynamic NAD83(CSRS) Realizations

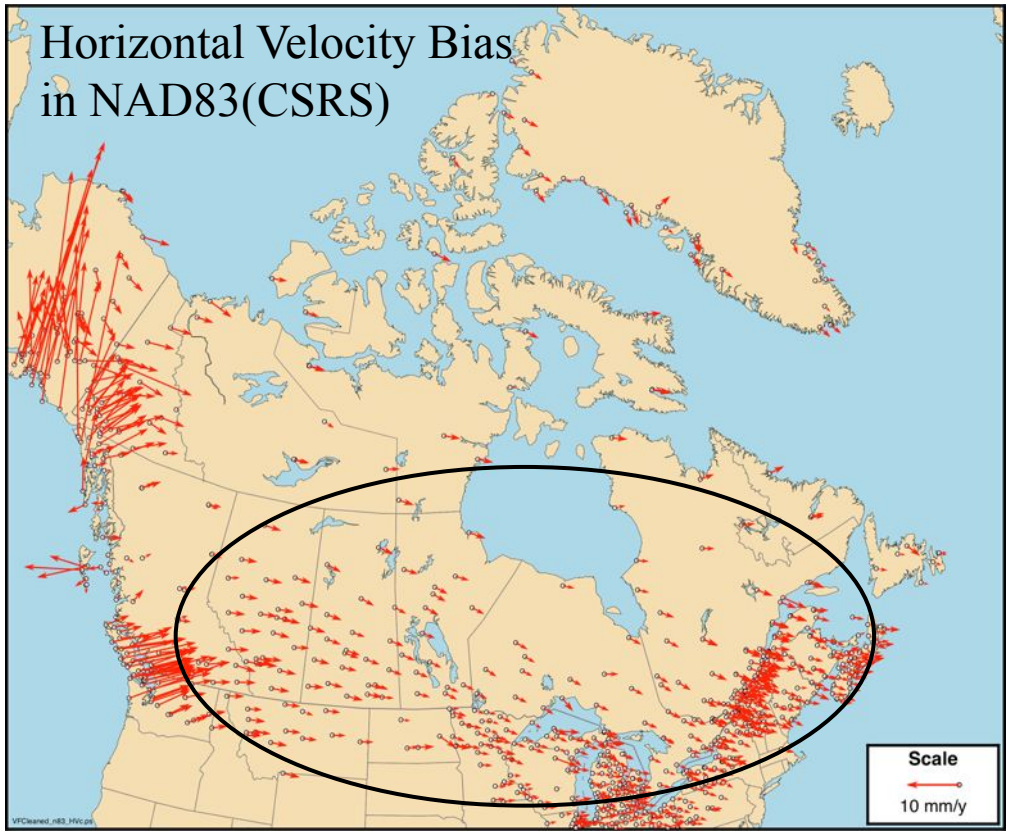
NAD83(CSRS) Version 6

- Transformation from ITRF2008 at reference epoch 2010.0
- First dynamic realization widely used
- Included
  - Coordinates and velocities of CACS & CBN stations
  - More accurate velocity model (grid) but still not recommended for the Arctic and west coast deformation boundary zone
- Epoch updated in collaboration with U.S.
  - To remove accumulation of residual bias in plate motion for U.S.
  - Bias modelled in Canadian velocity grid but not in U.S. grid

Static NAD83(CSRS) Realizations

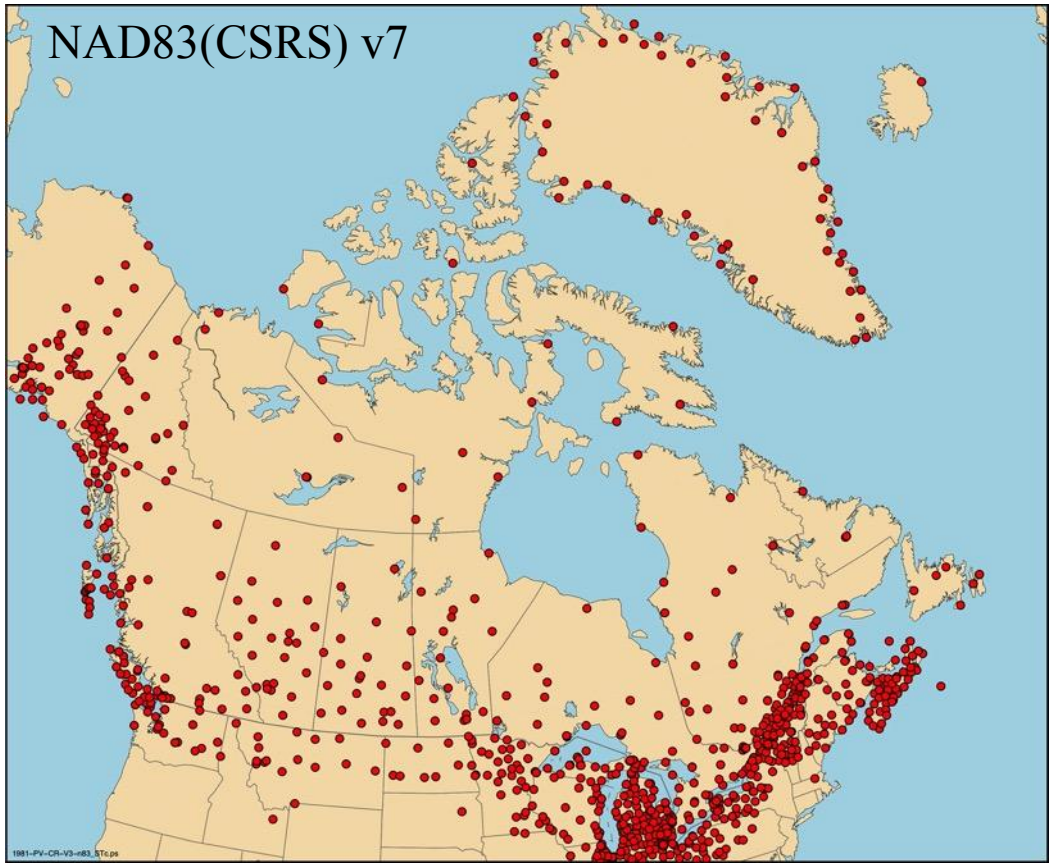
NAD83(CSRS) Version 4 – epoch 2002

- Transformation from ITRF2000 at epoch 2002.0
- Updated reference epoch to account for ~2 mm/yr velocity bias in fixing NAD83(CSRS) to the N.A. tectonic plate
- Velocity bias accumulated to more than 1 cm by 2002



Reference Frames

- Reference frames are the physical realization of a reference system
- Defined by the coordinates assigned to physical markers
- Updated as new data, markers and models become available and techniques improve
- Example: NAD83(CSRS) v7



Relationship with WGS 84

WGS 84 (TRANSIT)

- Defined the same way as NAD83(Original) => WGS 84 (TRANSIT) = NAD83
- Metre level accuracy
- WGS 84 & GRS80 ellipsoids differ only by a max of 0.1 mm at the North Pole

WGS 84 (Gwwww), wwww = GPS week number put into use

- Redefined WGS 84 in 1994 to be aligned with the ITRF
- Periodically updated to newer ITRFs
- Created a 2 m shift in origin from WGS 84 (TRANSIT) & NAD83
- WGS 84 (Gwwww) = ITRF ≠ NAD83

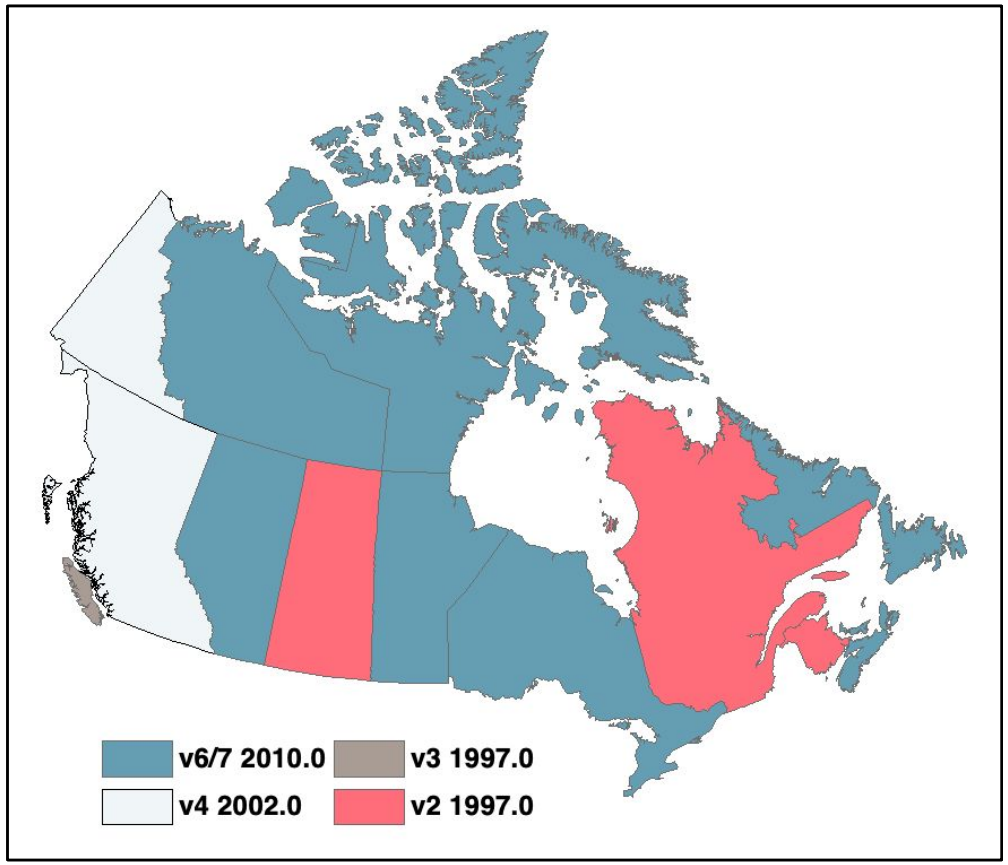
Realizations of WGS 84

Realization	Ref. Epoch	Based on	Implemented	Accuracy
WGS 84 (TRANSIT)*	None	BTS84	1987	1-2 m
WGS 84 (G730)	1994.0	ITRF92	1994-06-29	10 cm
WGS 84 (G873)	1997.0	ITRF94	1997-01-29	5 cm
WGS 84 (G1150)	2001.0	ITRF2000	2002-01-20	1 cm
WGS 84 (G1674)	2005.0	ITRF2008/IGS08	2012-02-08	<1 cm
WGS 84 (G1762)	2005.0	ITRF2008/IGb08	2013-10-16	<1 cm
WGS 84 (G2139)	2016.0	ITRF2014/IGb14	2021-01-03	<1 cm

* Compatible with NAD83

NAD83(CSRS) Adoption Across Canada

- Reference frame adoption is a provincial mandate
- Different NAD83(CSRS) versions & epochs adopted across Canada
- Differences between epochs can be up to several cm
- Confusing when working across borders and for commercial RTK services => need to unify

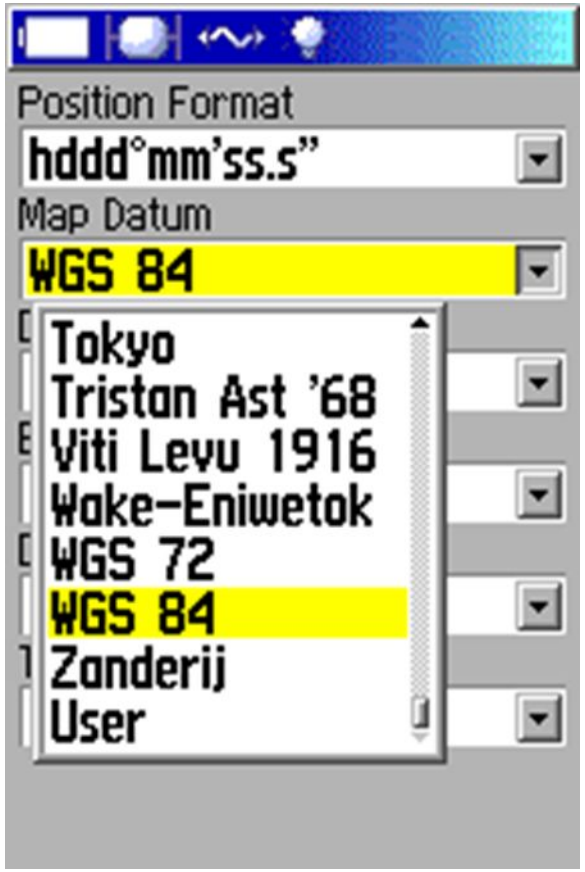


Working in NAD83(CSRS)

- Built-in receiver transformations to NAD83
- Absolute positioning (PPP)
- Relative positioning (baseline processing)
- RTK positioning

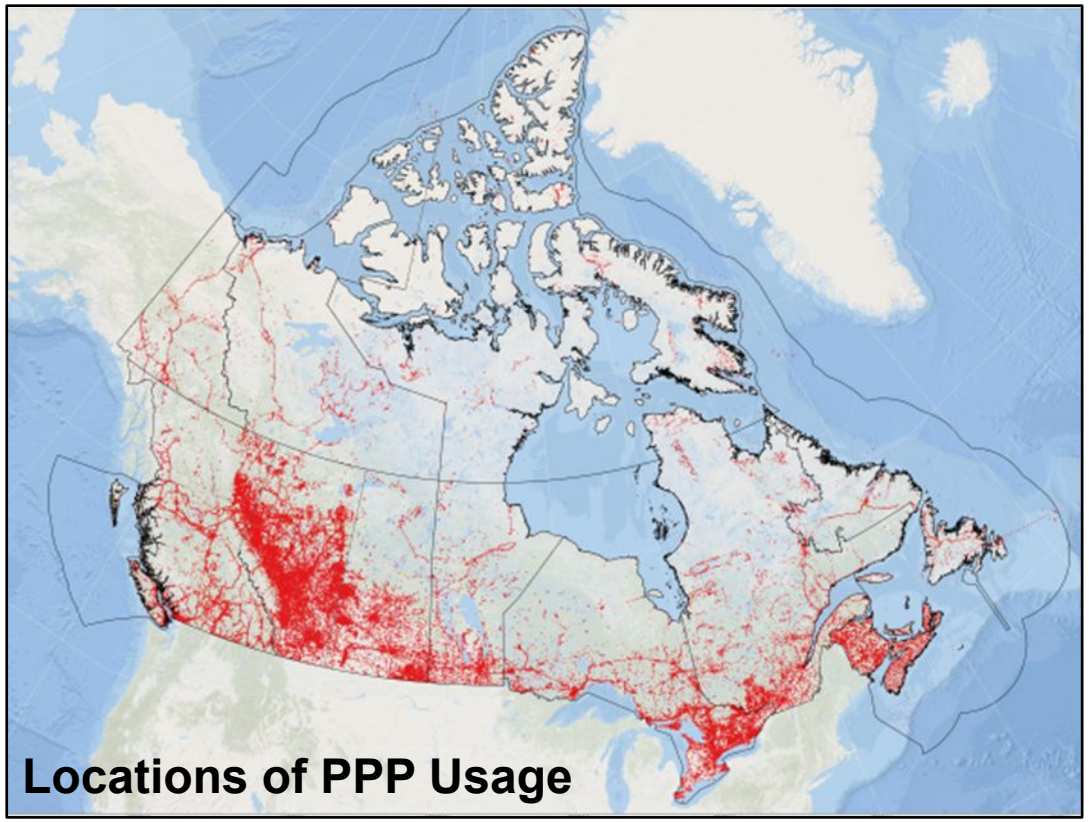
Receiver Transformations

- Most GNSS receivers have a transformation from WGS 84 to NAD83 built-in
- Warning – Many have it wrong
  - Incorrectly assume newer WGS 84 (G-series) = WGS 84 (TRANSIT) = NAD83 when there is a 2 m offset
  - Using the null transformation to NAD83 will result in WGS 84 (G2139)/ITRF2014 coordinates, not NAD83
  - Will need to transform to NAD83(CSRS) after the fact unless the receiver implements the NAD83 transformation
  - Results at epoch of data => need to propagate to desired epoch with velocity model



Absolute Positioning (PPP)

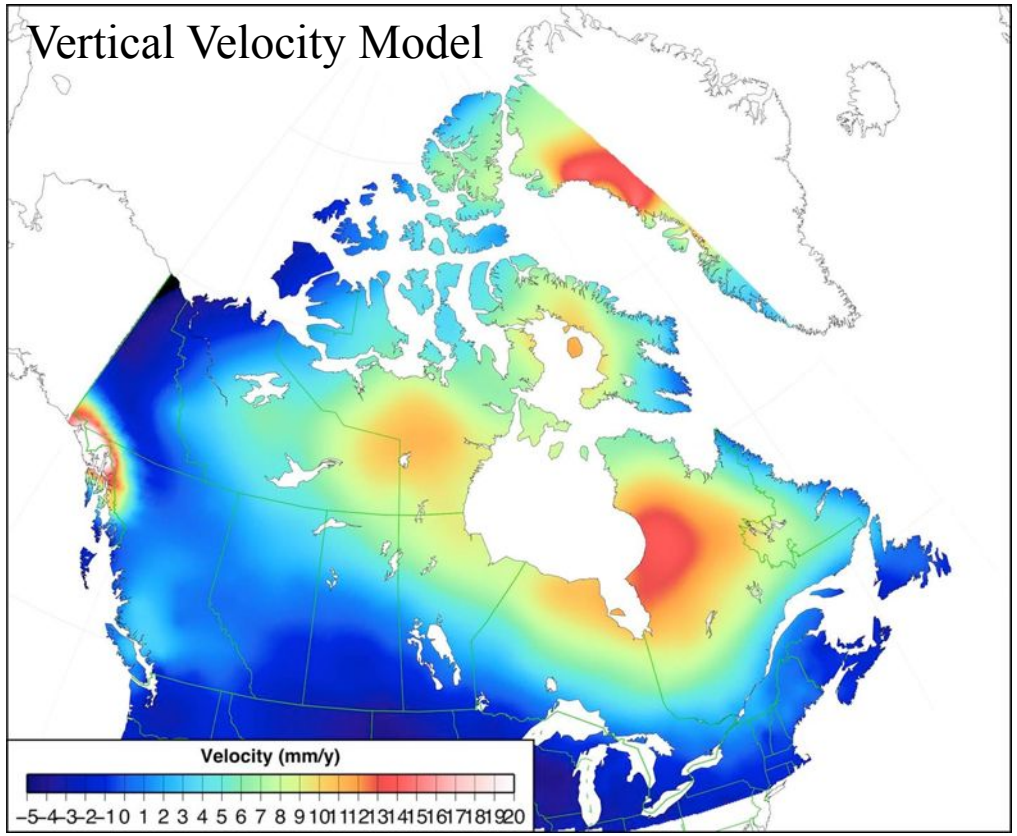
- Precise Point Positioning (PPP) uses precise orbits in current ITRF
- CSRS-PPP used extensively, esp. in remote areas
- Results at epoch of data
- Need to transform to NAD83(CSRS) & propagate to desired epoch – done by CSRS-PPP
- Doesn't provide a direct tie to local control which is a requirement in some jurisdictions – will see differences shown in previous maps



Locations of PPP Usage

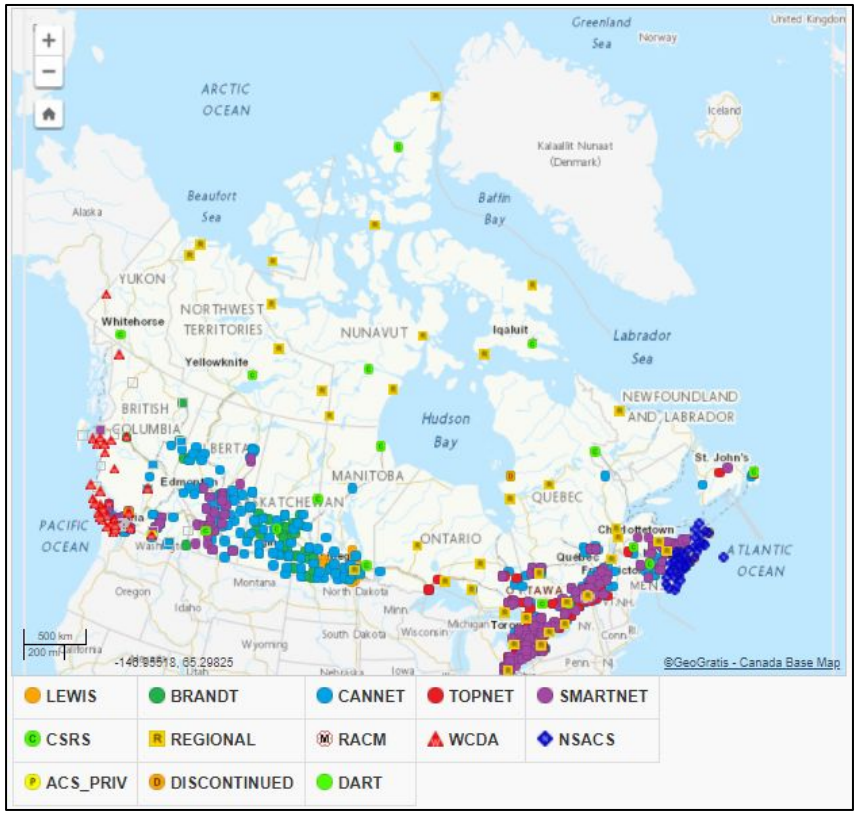
Relative Positioning

- Effects of (relative) crustal motion
  - Affects baselines from different years
  - May be significant over longer baselines and larger project areas
  - Motions dominated by predictable GIA over much of Canada
  - West coast on a plate boundary deformation zone – experiences significant motions over smaller areas that are difficult to model
- Use NAD83(CSRS) v7 and its velocity model to account for crustal motions
- Keep baselines and project areas small



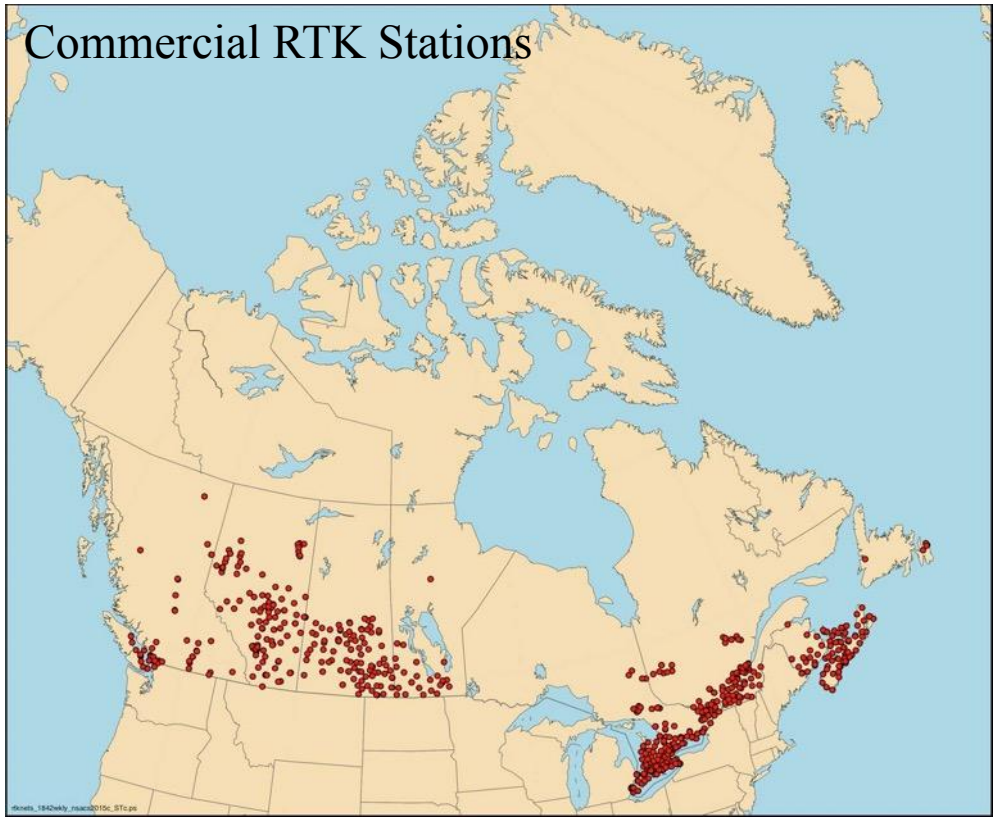
Relative Positioning

- Baselines from existing active or passive control in NAD83(CSRS)
- Baselines processed with broadcast or precise orbits are in current ITRF/WGS 84
  - Misoriented with respect to NAD83(CSRS) by about 1.2 cm / 100 km (effect of 26 mas rotation in ITRF-NAD83 transformation)
  - Will accumulate over entire project area
  - Will directly affect long baselines to active control stations
- For highest accuracy, process in ITRF and transform to NAD83(CSRS) after, or use NRCan orbits in NAD83(CSRS)



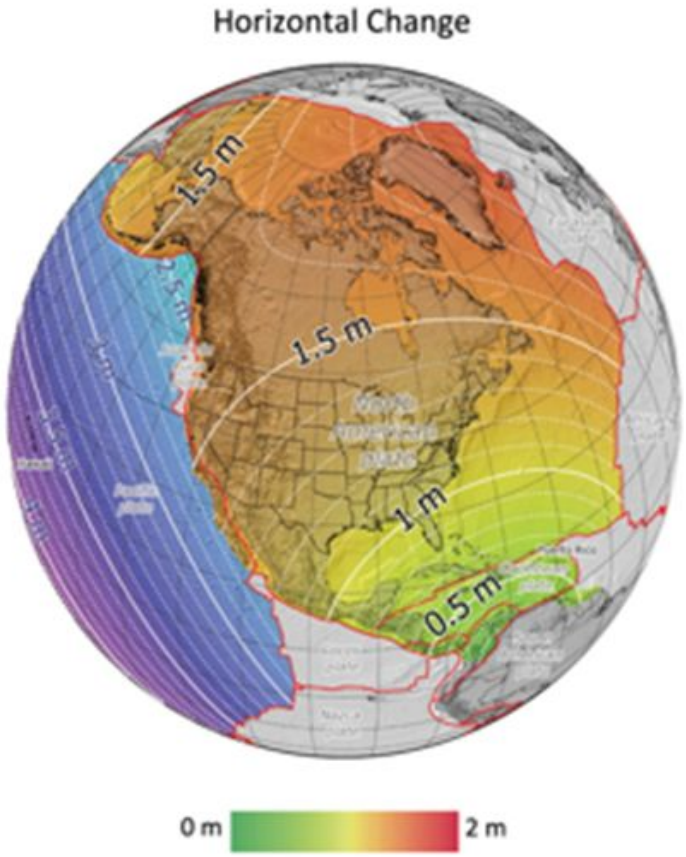
RTK (Relative) Positioning

- Real-time relative positioning with respect to RTK base stations
- Generally restricted to southern Canada
- RTK base stations usually much closer => less bias from WGS 84 orbits & relative crustal motion
- Compliance agreements with NRCan helps ensure they are properly aligned with NAD83(CSRS)
- Need to be aware which reference epoch correction streams use (eg, border areas)



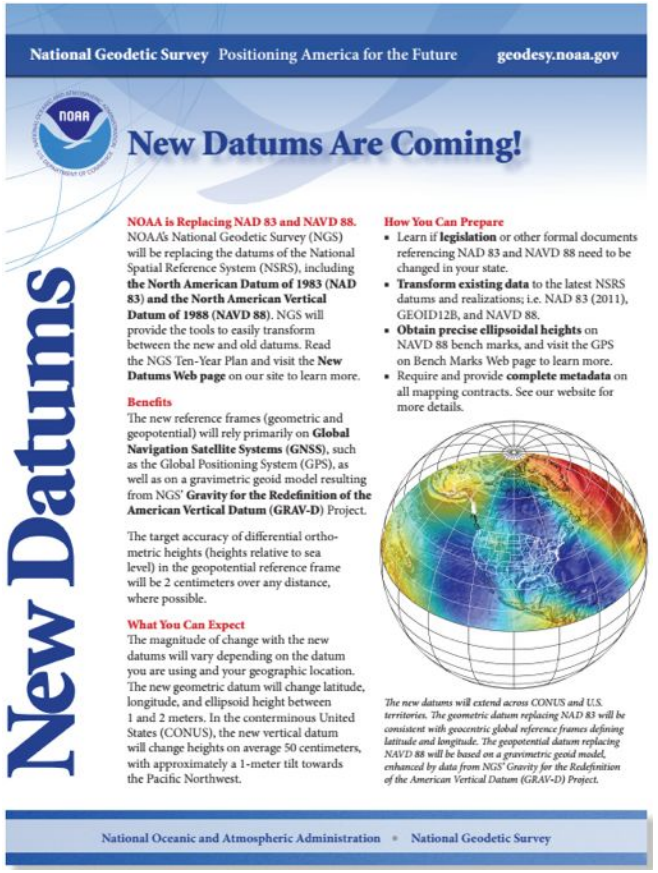
NATRF2022 vs NAD83

- NATRF2022 and NAD83 will have a 1-2 m horizontal difference along the Canada-U.S. boundary
  - Will be the largest ever difference between our reference frames
- NATRF2022 will be truly geocentric and more compatible with GNSS
- Canada needs a plan forward…



U.S. Reference System Modernization

- U.S. plans to replace (*sometime after 2025*)
  - **NAD 83** with a new dynamic geometric reference system called the North American Terrestrial Reference Frame of 2022 (**NATRF2022**) – ITRF2020 fixed to N.A.
  - **NAVD 88** with a new vertical datum called the North American-Pacific Geopotential Datum of 2022 (**NAPGD2022**) – compatible with CGVD2013
- NATRF2022 won't be much different from working in NAD83(CSRS) – both dynamic
- Provides an opportunity to unify reference frames across Canada



National Geodetic Survey Positioning America for the Future geodesy.noaa.gov

New Datums Are Coming!

New Datums

NOAA is Replacing NAD 83 and NAVD 88.
NOAA's National Geodetic Survey (NGS) will be replacing the datums of the National Spatial Reference System (NSRS), including **the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88)**. NGS will provide the tools to easily transform between the new and old datums. Read the NGS Ten-Year Plan and visit the **New Datums Web page** on our site to learn more.

Benefits
The new reference frames (geometric and geopotential) will rely primarily on **Global Navigation Satellite Systems (GNSS)**, such as the Global Positioning System (GPS), as well as on a gravimetric geoid model resulting from NGS' **Gravity for the Redefinition of the American Vertical Datum (GRAV-D)** Project.

The target accuracy of differential orthometric heights (heights relative to sea level) in the geopotential reference frame will be 2 centimeters over any distance, where possible.

What You Can Expect
The magnitude of change with the new datums will vary depending on the datum you are using and your geographic location. The new geometric datum will change latitude, longitude, and ellipsoid height between 1 and 2 meters. In the conterminous United States (CONUS), the new vertical datum will change heights on average 50 centimeters, with approximately a 1-meter tilt towards the Pacific Northwest.

How You Can Prepare
- Learn if **legislation** or other formal documents referencing NAD 83 and NAVD 88 need to be changed in your state.
- **Transform existing data** to the latest NSRS datums and realizations; i.e. NAD 83 (2011), GEOID12B, and NAVD 88.
- **Obtain precise ellipsoidal heights** on NAVD 88 bench marks, and visit the GPS on Bench Marks Web page to learn more.
- Require and provide **complete metadata** on all mapping contracts. See our website for more details.

The new datums will extend across CONUS and U.S. territories. The geometric datum replacing NAD 83 will be consistent with geocentric global reference frames defining latitude and longitude. The geopotential datum replacing NAVD 88 will be based on a gravimetric geoid model, enhanced by data from NGS' Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Project.

National Oceanic and Atmospheric Administration • National Geodetic Survey

Preparing for NATRF2022

- CGS is collaborating with the U.S.:
  - To define NATRF2022 and NAPGD2022 so they also meet Canadian needs
  - Sharing data and testing models to ensure consistency across the border
  - Will integrate NATRF2022 & NAPGD2022 into the CGS toolset (e.g., CSRS-PPP, TRX, GPS-H)
- Canadian Geodetic Reference System Committee (CGRSC)
  - Working on a plan to adopt NATRF2022 in Canada
  - Initiating stakeholder outreach and engagement
  - Publications, webinars
  - Preparing implementation options for the provinces

More NATRF2022 information

- GEOMATICA Technical Note: *The U.S. is replacing NAD83 with NATRF2022: what this means for Canada* https://www.nrcresearchpress.com/doi/full/10.1139/geomat-2019-0021

- NATRF2022 pamphlet http://cgrsc.ca/publications/NATRF2022-reference%20pamphlet.pdf

- US National Geodetic Survey https://geodesy.noaa.gov/datums/newdatums/index.shtml

Definition of NAD83(CSRS)

- Following IAG recommendations, NAD83 was redefined in collaboration with the U.S. based on the International Terrestrial Reference Frame (ITRF)
  - ITRF is the most accurate reference frame available today
  - It is a dynamic system providing (1) coordinates at a specific epoch and (2) velocities to propagate those coordinates to other epochs
- New definition called NAD83(CSRS)
  CSRS = Canadian Spatial Reference System

Definition of NAD83(CSRS)

- NNR-NUVEL-1A plate motion model used to fix NAD83 to N.A. plate
- The transformation is treated as errorless => effectively defines NAD83(CSRS) realizations as accurately as ITRF