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# A first approximation to the International Height Reference Frame (IHRF)

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Joint Scientific Assembly of the International Association of Geodesy and the International Association of Seismology and Physics of the Earth's Interior (IAG-IASPEI 2017), August 3, 2017, Kobe, Japan

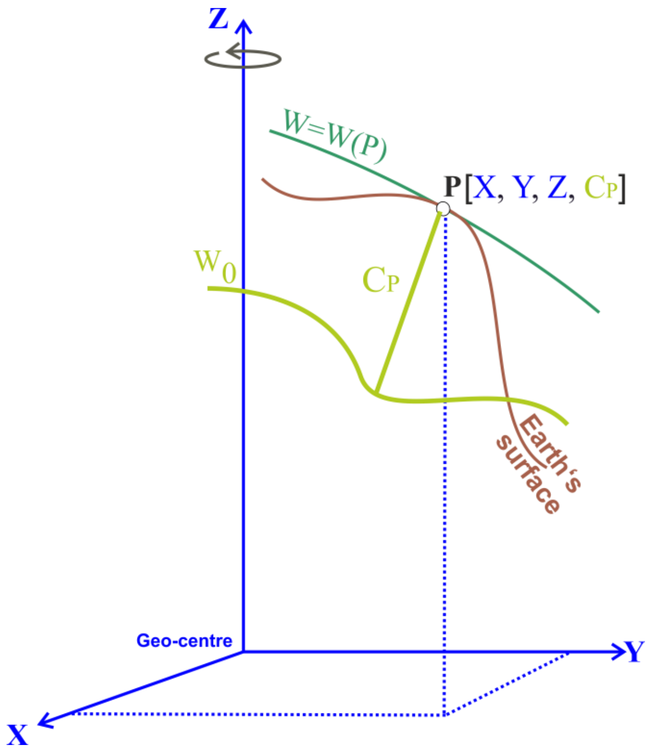
# International Height Reference System (IHRS)
# IAG Resolution No. 1, Prague, July 2015

1) Vertical coordinates are potential differences with respect to a conventional $W_0$ value:
   - $C_P = C(P) = W_0 - W(P) = -\Delta W(P)$
   - conventional fixed value
     $$W_0 = const. = 62\,636\,853.4 \text{ m}^2\text{s}^{-2}$$

2) The position $P$ is given by the coordinates vector $\mathbf{X}_P$ $(X_P, Y_P, Z_P)$ in the ITRF; i.e., $W(P) = W(\mathbf{X}_P)$

3) The estimation of $\mathbf{X}(P)$, $W(P)$ (or $C(P)$) includes their variation with time; i.e., $\dot{\mathbf{X}}(P)$, $\dot{W}(P)$ (or $\dot{C}(P)$).

4) Coordinates are given in mean-tide system / mean (zero) crust.




Remark: The determination of $\mathbf{X}$, $\dot{\mathbf{X}}$ follows the standards (and conventions) adopted within the IERS for the ITRS/ITRF. Similar standards for the determination of $W$, $\dot{W}$ are (still) missing.

# Immediate objectives regarding the IHRS

1) Establishment of an International Height Reference Frame (IHRF):
   - Station selection for a global network (worldwide distribution) with regional and national densifications (local accessibility).
   - Determination of high-precise primary coordinates $X_P$, $\dot{X}_P$, $W_P$, $\dot{W}_P$ at the IHRF reference stations.
2) Identification and compilation/outlining of the required standards, conventions and procedures to ensure consistency between the definition (IHRS) and the realization (IHRF); i.e., an equivalent documentation to the IERS conventions is needed for the IHRS/IHRF.

# Advances in the IHRS/IHRF implementation

1) Activities faced by the Joint Working Group on the Strategy for the Realization of the International Height Reference System (IHRS), (http://ihrs.dgfi.tum.de).

2) Coordinated work between:
   - GGOS Focus Area Unified Height System
   - International Gravity Field Service (IGFS)
   - IAG Commissions 1 (Reference Frames) and 2 (Gravity Field)
   - IAG Inter-commission Committee on Theory (ICCT)
   - Regional sub-commissions for reference frames and geoid modelling
   - GGOS Bureaus: Networks and Observations (BNO); Products and Standards (BPS).

3) Sep. 2016 (first meeting of the WG at GGHS2016, Thessaloniki): Brainstorming and definition of action items; criteria for the selection of IHRF stations.

4) Oct. 2016 (GGOS Days 2016, Cambridge, MA): Preliminary station selection for the IHRF.

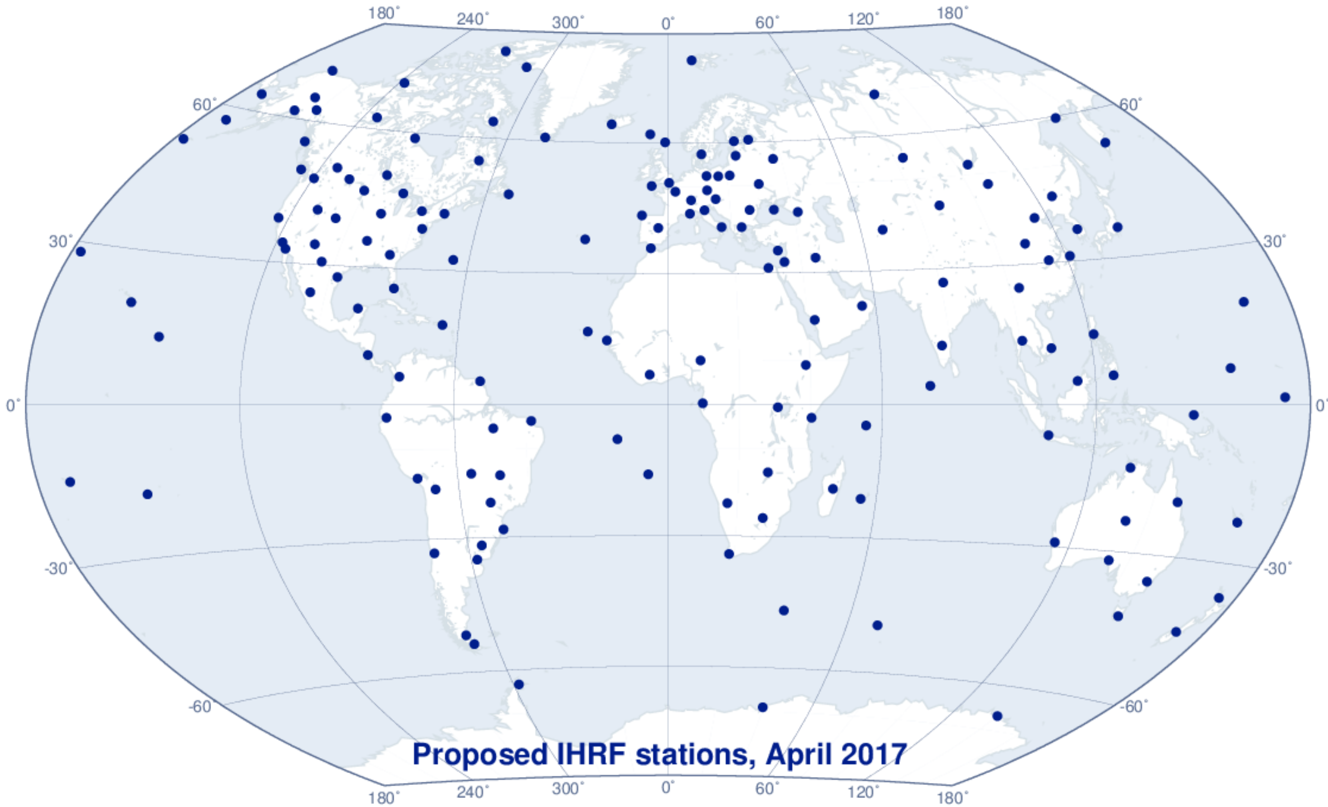
5) Nov. 2016 – Mar. 2017: Interaction with regional/national experts about the preliminary station selection and proposal for further geodetic sites.

6) Since May 2017: Numerical experiments for the computation of potential values $W(P)$ at the IHRF stations.

# First proposal for the IHRF reference network

163 selected sites:

- Continuously operating reference stations (preference for ITRF and regional reference stations, like SIRGAS, EPN, APREF, etc.).
- Availability of terrestrial gravity data around the IHRF stations (at least ~ 250 km) for high-resolution gravity field modelling (i.e., precise determination of $W(P)$).
- Co-located with VLBI, SLR, DORIS, absolute gravity and reference clocks.
- Preferably co-located with reference tide gauges and connected to the national levelling networks.



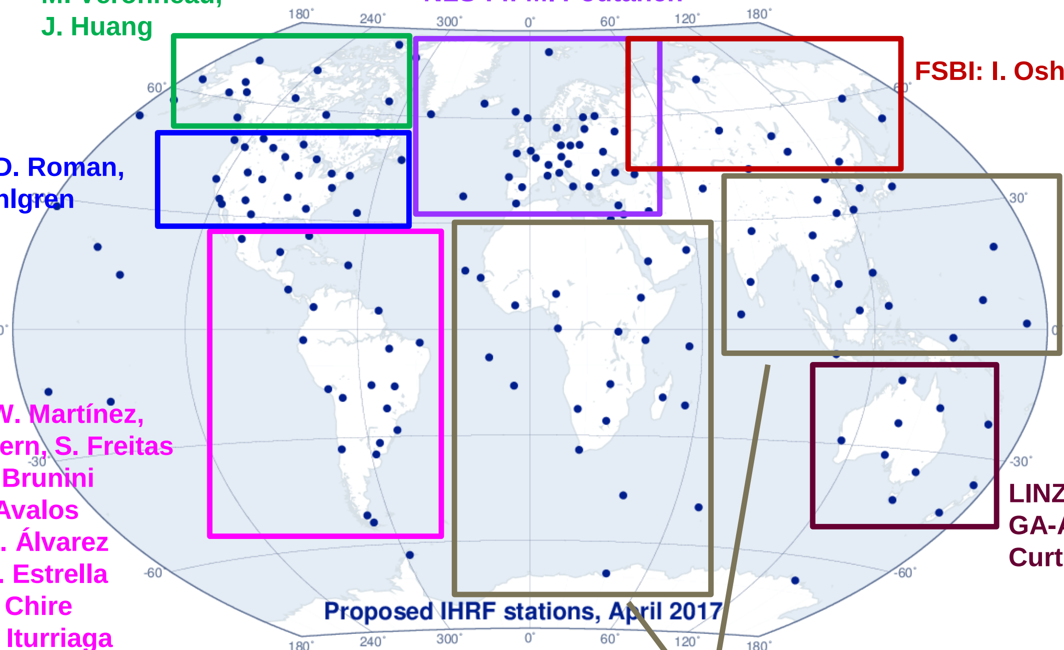
# Interaction with regional/national experts for the IHRF station selection

IGIK-PI: J. Krinsky
DTU-Dk: R. Forsberg
AUTH-Gr: G. Vergos
LGIA-LV: I. Liepins
LM-Se: J. Ågren, Nordic Geodetic Commission (NGK)
Swisstopo-Ch: U. Martí
IGN-Es: P. Vaquero
NLS-Fi: M. Poutanen

NRCan:
M. Véronneau,
J. Huang

FSBI: I. Oshchepkov

NGS/NOAA: D. Roman,
K. Choi, K. Ahlgren




IGS stations

SIRGAS: W. Martínez,
M.V. Mackern, S. Freitas
AGGO: C. Brunini
INEGI: D. Avalos
IGN-CR: A. Álvarez
IGM-Ec: C. Estrella
IGN-Pe: J. Chire
IGM-Cl: C. Iturriaga
IGM-Bo: A. Echalar
IGN-Ar: D. Piñon
SGM-Uy: N. Suárez
IBGE: S. Costa, R. Luz
EPUSP: D. Blitzkow, A.C.O.C. Matos

LINZ-Nz: M. Amos
GA-Au: R Ruddick
Curtin-Au: W. Featherstone

# Numerical experiments for the computation of the potential values $W(P)$

1) Global gravity models of high-degree (with RTM)

$$W_P = f\left(X_P, GGM\right)$$

2) High-resolution gravity field modelling:

$$W_P = W_{P,satellite-only} + W_{P,high-resolution}$$

| Satellite-only gravity field modelling: Satellite orbits and gradiometry analysis | + | High-resolution gravity field modelling: Stokes or Molodenskii approach |
| --- | --- | --- |
| Satellite tracking from ground stations (SLR)<br>Satellite-to-satellite tracking (CHAMP, GRACE)<br>Satellite gravity gradiometry (GOCE)<br>*Satellite altimetry (oceans only)* | | *Satellite altimetry (oceans only)*<br>Gravimetry, astro-geodetic methods, levelling, etc.<br>Terrain effects |

3) Potential values recovered from existing (quasi)-geoid models:

$$C_P = W_0 - W_P = H_P^N \bar{\gamma} = \left(h_p - \zeta\right)\bar{\gamma}$$

4) Levelling + gravimetry (after vertical datum unification):

$$W_P = \left(W_0^{local} + \delta W\right) - C_P; \quad \delta W = W_0^{IHRF} - W_0^{local}$$

# Numerical experiments for the computation of the potential values $W(P)$

1) Computation of potential values using the latest GGMs of high-resolution:
   - EGM2008 (Pavlis et al., 2012), lmax = 2190
   - EIGEN-6C4 (Förste et al., 2014), lmax = 2190
   - XGM2016 (Pail et al., 2017), lmax = 719, extended to lmax = 2190 with EIGEN-6C4
2) Canada (M. Véronneau, J. Huang) provided terrestrial gravity data, we, at DGFI-TUM, are using different approaches for the computation of the potential values. They also provided potential values at the Canadian IHRF stations inferred from the current Canadian geoid.
3) H. Denker (IFE/LUH, Germany) computed potential values for the European IHRF stations using the same data and methodology he applies for the determination of the European quasi-geoid.
4) D. Blitzkow and A.C.O.C. Matos (EPUSP, Brazil) are computing potential values for the Brazilian IHRF stations using the same data and methodology they apply for the determination of the South American geoid.
5) G. Vergos (AUTH, Greece) performed different computations at the station AUT1 (Thessaloniki).
6) S. Freitas and J.L. Carrión-Sánchez (UFPR, Brazil) are testing different computation methods with different kinds of data at the reference tide gauge of Ecuador.

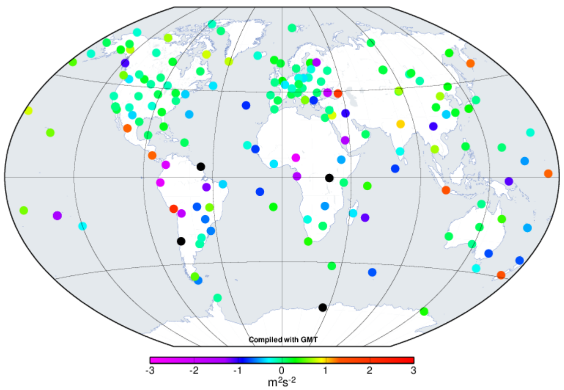
# $W(P)$ from global gravity models (GGM) of high-degree

Formal errors of the GGM-based potential values at the IHRF stations (XGM2016 values provided by R. Pail, IAPG-TUM)

| GGM (lmax=2190) | mean | | stddev | | min | | max | |
|---|---|---|---|---|---|---|---|---|
| | $W$ [m²s⁻²] | $H^N$ [m] | $W$ [m²s⁻²] | $H^N$ [m] | $W$ [m²s⁻²] | $H^N$ [m] | $W$ [m²s⁻²] | $H^N$ [m] |
| EGM2008 | 3.90 | 0.40 | 6.04 | 0.62 | 0.82 | 0.08 | 40.18 | 4.10 |
| EIGEN-6C4 | 0.70 | 0.07 | 0.59 | 0.06 | 0.33 | 0.03 | 4.27 | 0.44 |
| XGM2016 | 0.21 | 0.02 | 0.12 | 0.01 | 0.09 | 0.01 | 1.04 | 0.11 |

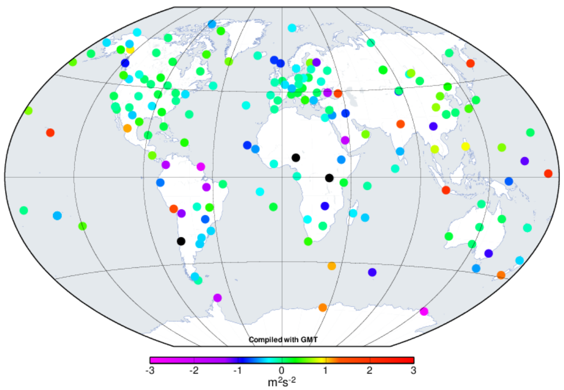
Differences between the GGM-based potential values at the IHRF stations

**EIGEN-6C4 vs EGM2008**



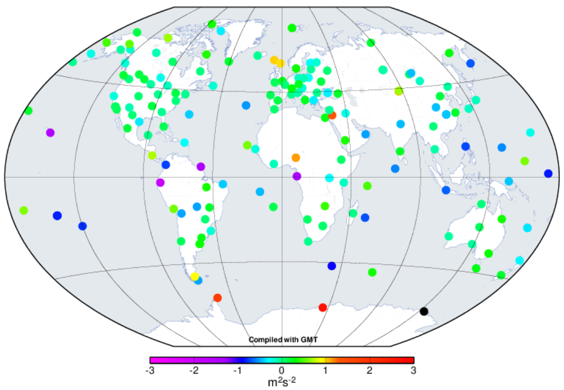

| | $\Delta W$ [m²s⁻²] | $\Delta H^N$ [m] |
|---|---|---|
| mean | 0.00 | 0.00 |
| stddev | 0.93 | 0.09 |
| min | -3.94 | -0.40 |
| max | 3.85 | 0.39 |

**XGM2016 vs EGM2008**




| | $\Delta W$ [m²s⁻²] | $\Delta H^N$ [m] |
|---|---|---|
| mean | 0.01 | 0.00 |
| stddev | 0.87 | 0.09 |
| min | -3.75 | -0.38 |
| max | 4.01 | 0.41 |

**EIGEN-6C4 vs XGM2016**

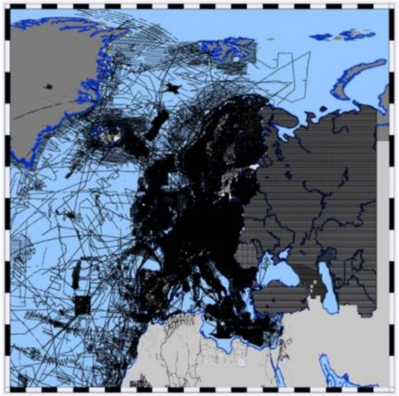



| | $\Delta W$ [m²s⁻²] | $\Delta H^N$ [m] |
|---|---|---|
| mean | -0.01 | 0.00 |
| stddev | 0.57 | 0.06 |
| min | -1.88 | -0.19 |
| max | 3.18 | 0.32 |

# $W(P)$ from high-resolution gravity field modelling

Example Europe:

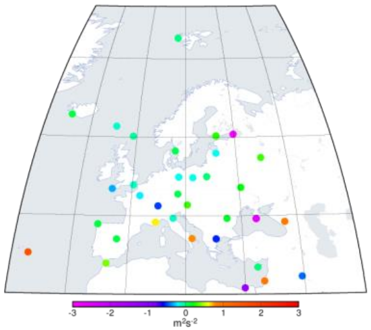
- The same terrestrial gravity data used for the European Gravimetric (Quasi-)Geoid: EGG2008 (combined with EGM2008, lmax=360/2190) and EGG2016 (combined with GOCO05S, lmax=280)
- Remove-restore technique, spectral combination (1DFFT), zero-tide
- Computation performed by H. Denker, IFE/LUH (Denker 2008, 2015, 2017)



*After Denker (2015)*

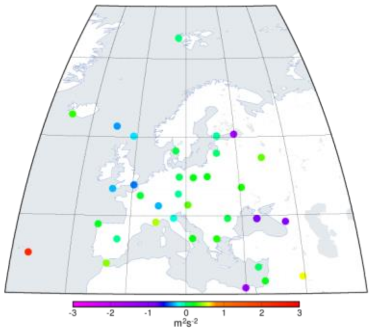
Differences between high-resolution and GGM-based potential values at the European IHRF stations

**EGG2016 vs EGM2008**



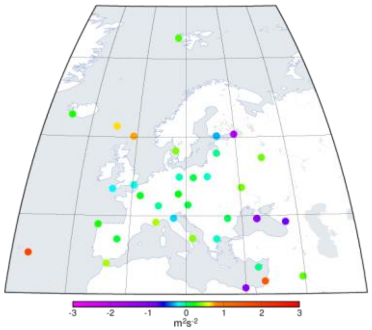
| | $\Delta W$ [m²s⁻²] | $\Delta H^N$ [m] |
|---|---|---|
| mean | 0.00 | 0.00 |
| stddev | 0.73 | 0.07 |
| min | -2.89 | -0.29 |
| max | 1.53 | 0.16 |

**EGG2016 vs EIGEN-6C4**



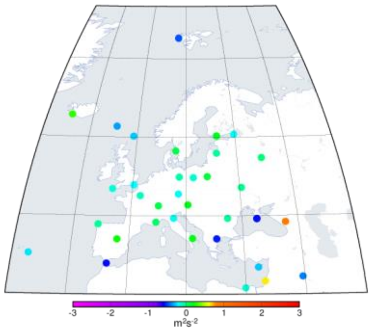
| | $\Delta W$ [m²s⁻²] | $\Delta H^N$ [m] |
|---|---|---|
| mean | 0.00 | 0.00 |
| stddev | 0.60 | 0.06 |
| min | -1.53 | -0.16 |
| max | 2.33 | 0.24 |

**EGG2016 vs XGM2016**



| | $\Delta W$ [m²s⁻²] | $\Delta H^N$ [m] |
|---|---|---|
| mean | 0.06 | 0.01 |
| stddev | 0.55 | 0.06 |
| min | -1.72 | -0.18 |
| max | 1.78 | 0.18 |

**EGG2016 vs EGG2008**

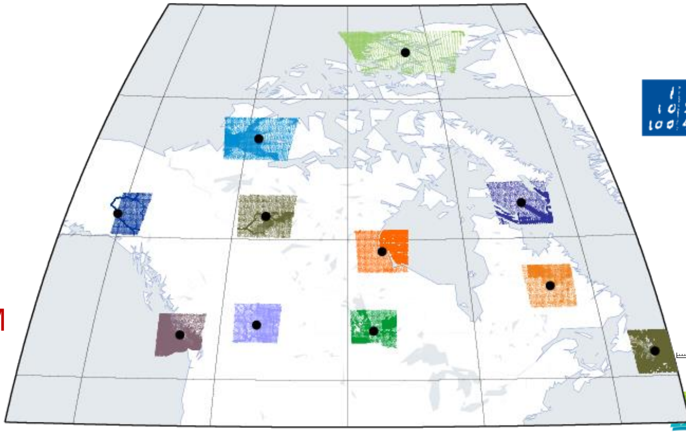


| | $\Delta W$ [m²s⁻²] | $\Delta H^N$ [m] |
|---|---|---|
| mean | -0.04 | 0.00 |
| stddev | 0.29 | 0.03 |
| min | -0.63 | -0.06 |
| max | 0.93 | 0.09 |

# $W(P)$ from high-resolution gravity field modelling

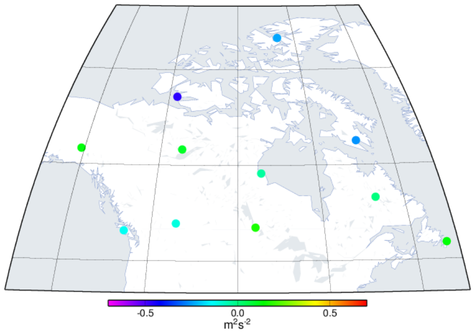
Example Canada:

- Terrestrial gravity data around the Canadian IHRF stations provided by NRCan: M. Véronneau, J. Huang
- Different approaches for the computation of the potential values (GGM:GOCO05S, lmax=280)
  - Multi-Resolution Representation (MRR) based on spherical radial basis functions (SBF), V. Lieb, DGFI-TUM (Lieb 2017)
  - Molodensky, remove-restore, 1D-FFT, L. Sánchez, DGFI-TUM (GRAVSOFT, Schwarz et al. 1990)
  - Molodensky, remove-restore, LSC, L. Sánchez, DGFI-TUM (GRAVSOFT, Tscherning 1986)



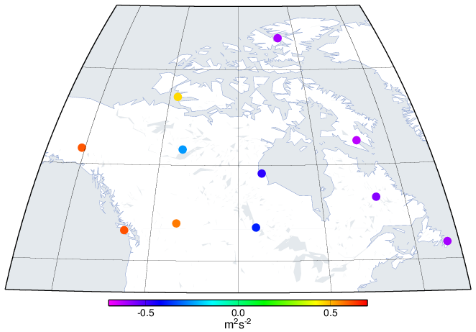
## Differences between potential values after different approaches

**LSC vs FFT**



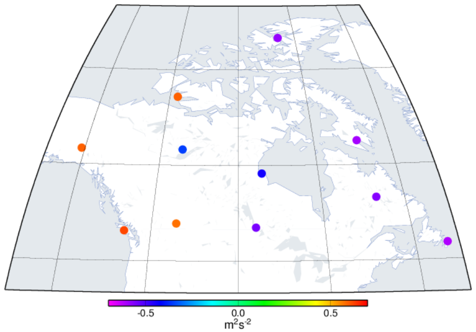

| | $\Delta W$ [$m^2s^{-2}$] | $\Delta H^N$ [m] |
|---|---|---|
| mean | -0.09 | -0.01 |
| stddev | 0.27 | 0.03 |
| min | -0.67 | -0.07 |
| max | 0.24 | 0.02 |

**LSC vs MRR-SBF**




| | $\Delta W$ [$m^2s^{-2}$] | $\Delta H^N$ [m] |
|---|---|---|
| mean | -0.24 | -0.02 |
| stddev | 1.16 | 0.12 |
| min | -1.82 | -0.19 |
| max | 1.59 | 0.16 |

**FFT vs MRR-SBF**




| | $\Delta W$ [$m^2s^{-2}$] | $\Delta H^N$ [m] |
|---|---|---|
| mean | -0.15 | -0.02 |
| stddev | 1.20 | 0.12 |
| min | -1.64 | -0.17 |
| max | 1.77 | 0.18 |

# Conclusions and next steps (1/2)

1) High-resolution gravity field modelling is the preferred method.
2) The use of existing (quasi-)geoid models may provide good results in areas with good models.
3) Levelling+gravimetry allows the integration of existing vertical networks into the IHRS; vertical datum unification is required. This method offers the highest relative accuracy.
4) The use of GGMs is not (at present) suitable for the estimation of precise potential values. It may be used if „no other way“.
5) The computation of potential values at the IHRF stations is far away of being an easy task:
   - Different data availability and different data quality around the world (e.g. terrestrial gravity data, terrain models, GPS/levelling, etc.)
   - Different processing strategies produce different potential values. However, a “standard” procedure may not be suitable, as regions with different characteristics require particular approaches (e.g. modification of kernel functions, size of integration caps, geophysical reductions like GIA, etc.)
   - A “centralised” computation (like in the ITRF) is (still) complicated due to the restricted accessibility to terrestrial gravity data.

# Conclusions and next steps (2/2)

6) To exploit at maximum the existing data, national/regional experts on geoid modelling should determine the potential values at the IHRF stations located in their countries/regions.

7) They should use **all** the data they have and may apply their own methodologies.

8) However, to minimize discrepancies, a basic set of standards should be set up (e.g. zero degree correction, $N_1 = \zeta_1 = T_1 = 0$, reference frames for heights and horizontal positions of the terrestrial gravity data, satellite-only GGM, etc.).

9) This task started on last Monday (July 31, 2017) and it is supported by:
   - IAG SC 2.2: Methodology for geoid and physical height systems (chair: Jonas Ågren)
   - ICCT JSG 0.15: Regional geoid/quasi-geoid modelling - Theoretical framework for the sub-centimetre accuracy (chair: Jianliang Huang)
   - New JWG 2.2.2: The 1 cm geoid experiment (chair: Yan Ming Wang)
   - Jaakko Mäkinen – tide system issues for the IHRF

10) Further empirical experiments will be performed in parallel to detect the sensitivity of the potential values to gravity and coordinate changes with time, different ITRF solutions; spatial resolution (potential values at co-located geometric stations; i.e., consistency with the so-called geometrical *local ties*).

# Closing remarks

This work is possible thanks to the contribution of many colleagues. Their support is deeply acknowledged: M. Véronneau, J. Huang, D. Roman, M. Amos, I. Oshchepkov, S.R.C. Freitas. R.T. Luz, M. Pearlman, C. Estrella, C. Brunini, U. Marti, D. Piñon, D. Avalos, S.M.A. Costa, J. Mäkinen, Y.M. Wang, H. Denker, V. Lieb, D. Blitzkow, J. Ågren, A.C.O.C. Matos, R. Pail, J. Ihde, R. Barzaghi, M. Sideris, J. Chire, A. Álvarez, C. Iturriaga, I. Liepiņš, N. Suárez, J. Krynski, R. Forsberg, G. Vergos, J.L. Carrión-Sánchez...

Further reading:

– Ihde J., Sánchez L., Barzaghi R., Drewes H., Foerste Ch., GruberT., Liebsch G., Marti U., Pail R., Sideris M.: **Definition and proposed realization of the International Height Reference System (IHRS)**. Surveys in Geophysics 38(3), 549-570, 10.1007/s10712-017-9409-3, 2017

– Sánchez L., Sideris M.G.: **Vertical datum unification for the International Height Reference System (IHRS)** . Geophysical Journal International 209(2), 570-586, 10.1093/gji/ggx025 , 2017

– Sánchez L., Čunderlík R., Dayoub N., Mikula K., Minarechová Z., Šíma Z., Vatrt V., Vojtíšková M.: A conventional value for the geoid reference potential W0. Journal of Geodesy 90(9), 815-835, 10.1007/s00190-016-0913-x, 2016

– http://ihrs.dgfi.tum.de, www.ggos.org

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