Advances in the implementation of the International Height Reference System (IHRS)

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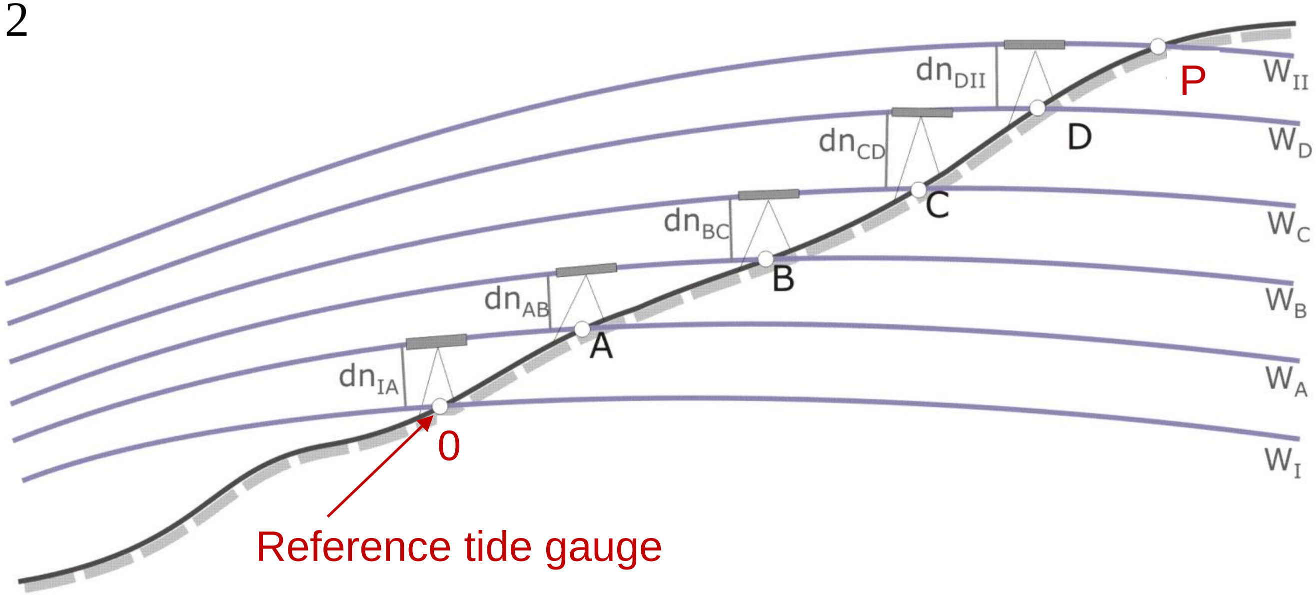
Usual (physical) height determination

– Levelling with gravity corrections:

$$H_P = \frac{W_0 - W_P}{\hat{g}} = \frac{C_P}{\hat{g}}$$

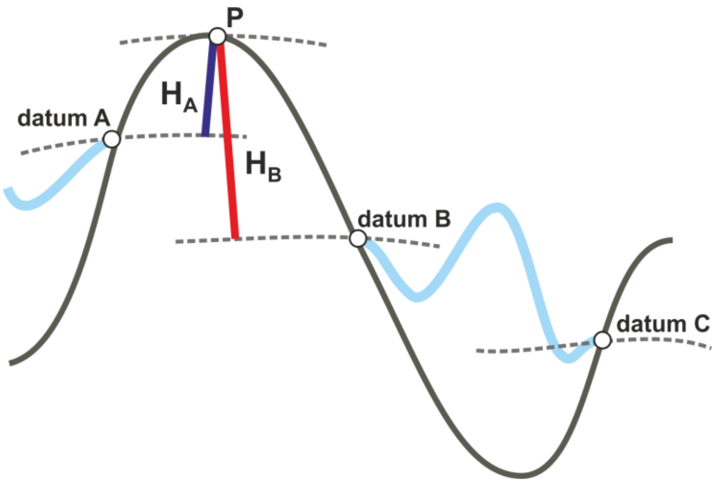
$$C_P = \Delta W_{P,0} = \left(\bar{g}_{0A} \cdot dn_{0A}\right) + \left(\bar{g}_{AB} \cdot dn_{AB}\right) + \left(\bar{g}_{BC} \cdot dn_{BC}\right) + \ldots + \left(\bar{g}_{DP} \cdot dn_{DP}\right)$$

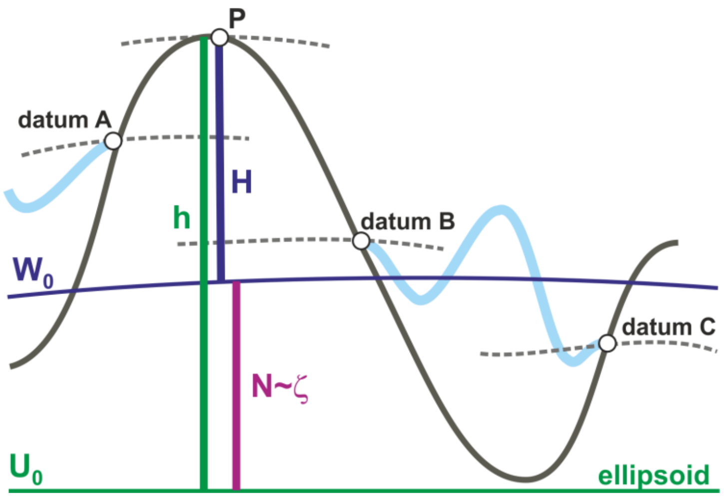
$$\bar{g}_{AB} = \frac{g_A + g_B}{2}$$



Existing height systems

- As the mean sea level varies with time and location, there are so many reference levels as tide gauges.
- To ensure consistency between physical heights worldwide and with geometric (GNSS) heights, a unified global height system should be implemented.
- Objective: all physical heights (or geopotential differences) shall be referred to one and the same reference surface W_0 realised globally.





Primary vertical coordinates

- In levelling, we determine geopotential numbers C_P:

$$H_P = \frac{W_0 - W_P}{\hat{g}} = \frac{C_P}{\hat{g}} \quad ; \qquad C_P = \cong \sum_0^P g \, dn$$

- Based on the state-of-the-art, we aim at determining potential values W_P directly:

$$-\Delta W_P = C_P = W_0 - W_P$$

- This is only possible with a high-precise modelling of the Earth‘s gravity field.

Determination of 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) Satellite-to-satellite tracking (CHAMP, GRACE) Satellite gravity gradiometry (GOCE) *Satellite altimetry (oceans only)*		*Satellite altimetry (oceans only)* Gravimetry, astro-geodetic methods, levelling, etc. 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):

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

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

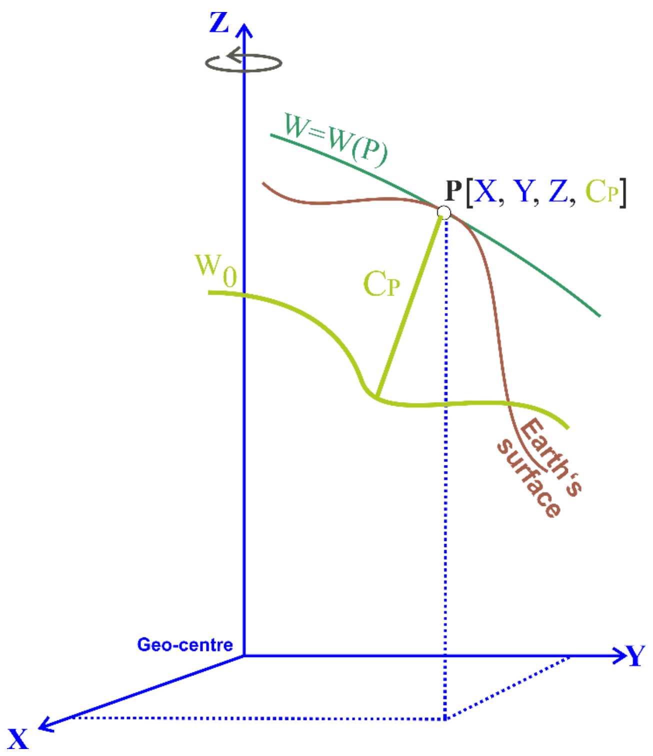
   $$W_0 = \text{const.} = 62\ 636\ 853.4\ \mathrm{m^2s^{-2}}$$

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

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

4) Mean-tide system / Mean (zero) crust.

5) SI Units (meter and second).



Ongoing actions regarding the IHRS

A reference frame realizes a reference system in two ways:

- physically, by a solid materialization of points (or observing instruments),
- mathematically, by the determination of coordinates referring to that reference system.
- The coordinates of the points are computed from the measurements, but following the definition of the reference system.

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 $\mathbf{X}_P$, $\dot{\mathbf{X}}_P$, W_P, $\dot{W}_P$ at the IHRF reference stations
2) Identification and preparation of 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.

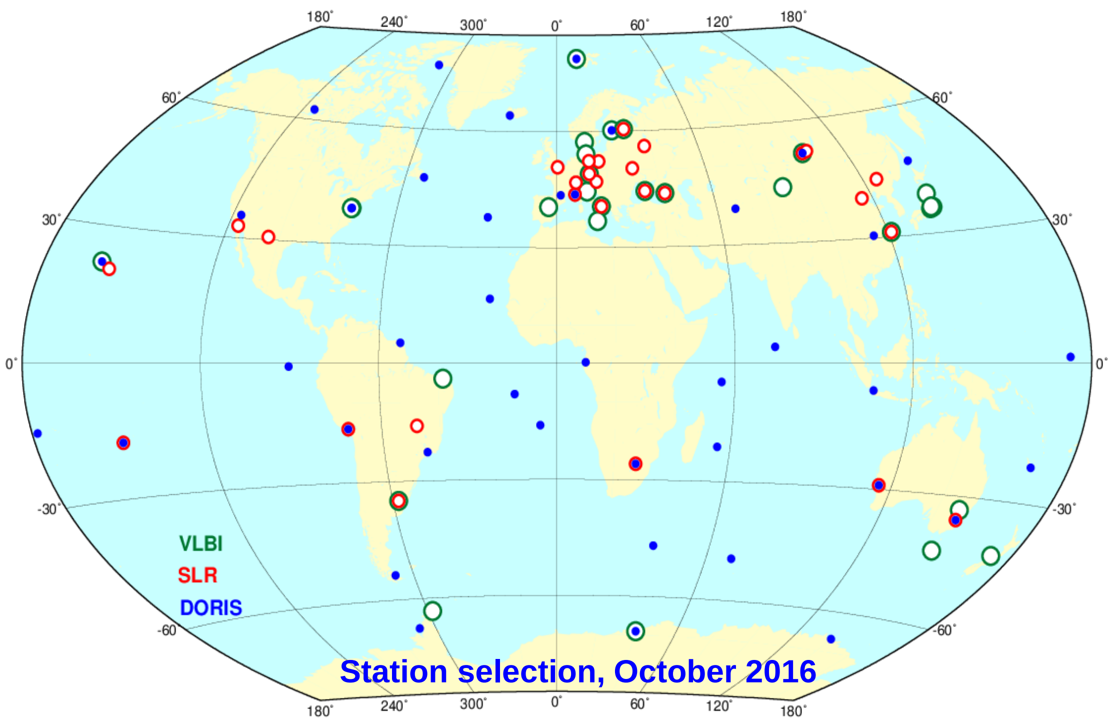
Advances in the IHRS/IHRF implementation

1) Activities faced by the Joint Working Group on the Strategy for the Realization of the International Height Reference System (IHRS), (https://ihrs.dgfi.tum.de).
2) Coordinated work between:
   - GGOS Focus Area Unified Height System
   - GGOS JWG Establishment of the GGRF
   - 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, Cambridge): 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) Apr. 2017: First proposal for the IHRF reference network.
7) Since May 2017: Numerical experiments for the computation of potential values $W(P)$ at the IHRF stations.
8) Since Aug. 2017 (IAG-IASPEI Assembly, Kobe): Discussion on standards and conventions for the IHRS/IHRF.

Preliminary selection of IHRF reference stations (Oct. 2016)

Preliminary selection based on VLBI, SLR and DORIS reference sites co-located with GNSS:

- VLBI and SLR sites guarantee a long-term perdurability/maintenance of the geodetic facilities.
- DORIS and GNSS guarantee a homogeneous distribution worldwide.
- The GGOS Bureau for Networks and Observations supports this task with an inventory about further co-located observables at each site (e.g. absolute gravity, superconducting gravity-meter, reference clocks involved in the TT realization, etc.).
- Main requirement: availability of terrestrial gravity data around the IHRS reference stations for high-resolution gravity field modelling (i.e., precise estimation of W_P).



Refined station selection for the IHRF

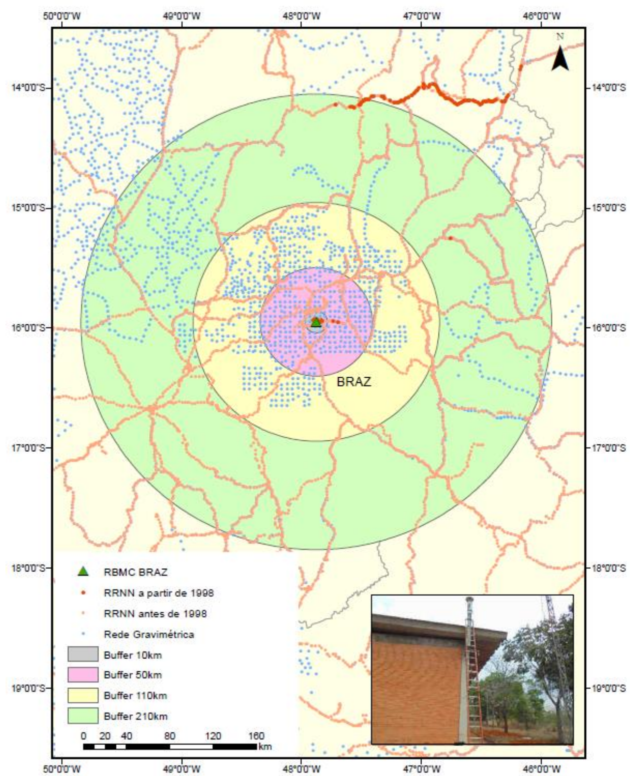
Based on the preliminary station selection of Oct. 2016, national/regional experts were asked to

1) evaluate whether these sites are suitable to be included in the IHRF: Are gravity data around these sites available? If not, is it possible to survey gravity around them?

2) propose additional geodetic sites to improve the density and distribution of the IHRF stations in their regions/countries:

   - proposed sites shall be materialized by a continuous operating GNSS station;
   - stations belonging to the regional reference frames (like SIRGAS, EPN, APREF, etc.) are preferred;
   - gravity data around the proposed stations must be available;
   - GNSS stations co-located with the reference tide gauges and connected to the national levelling networks are required.

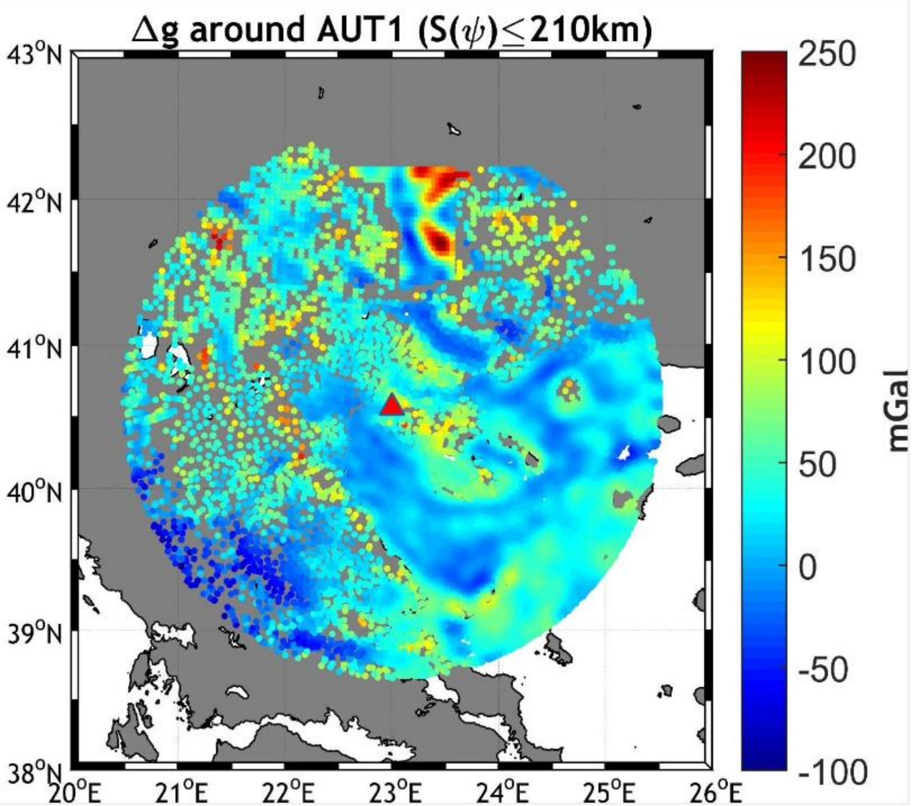
BRASÍLIA
ESTAÇÃO BRAZ



S. Costa and R. LUZ, IBGE, Brazil

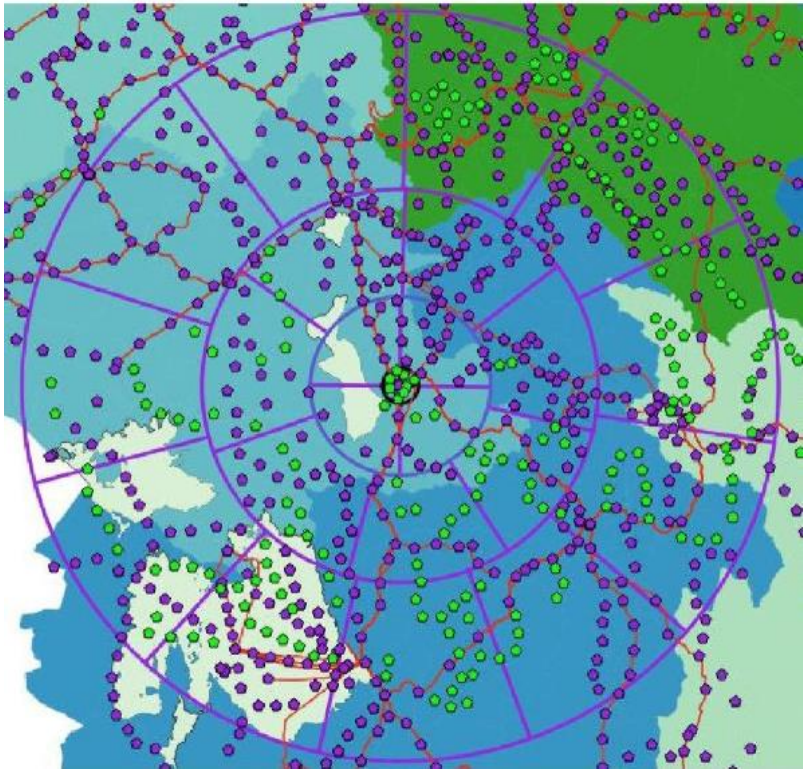
Refined station selection for the IHRF

EUREF station AUT1
Thessaloniki, Greece



G.S. Vergos and I.N. Tziavos, AUTH, Greece

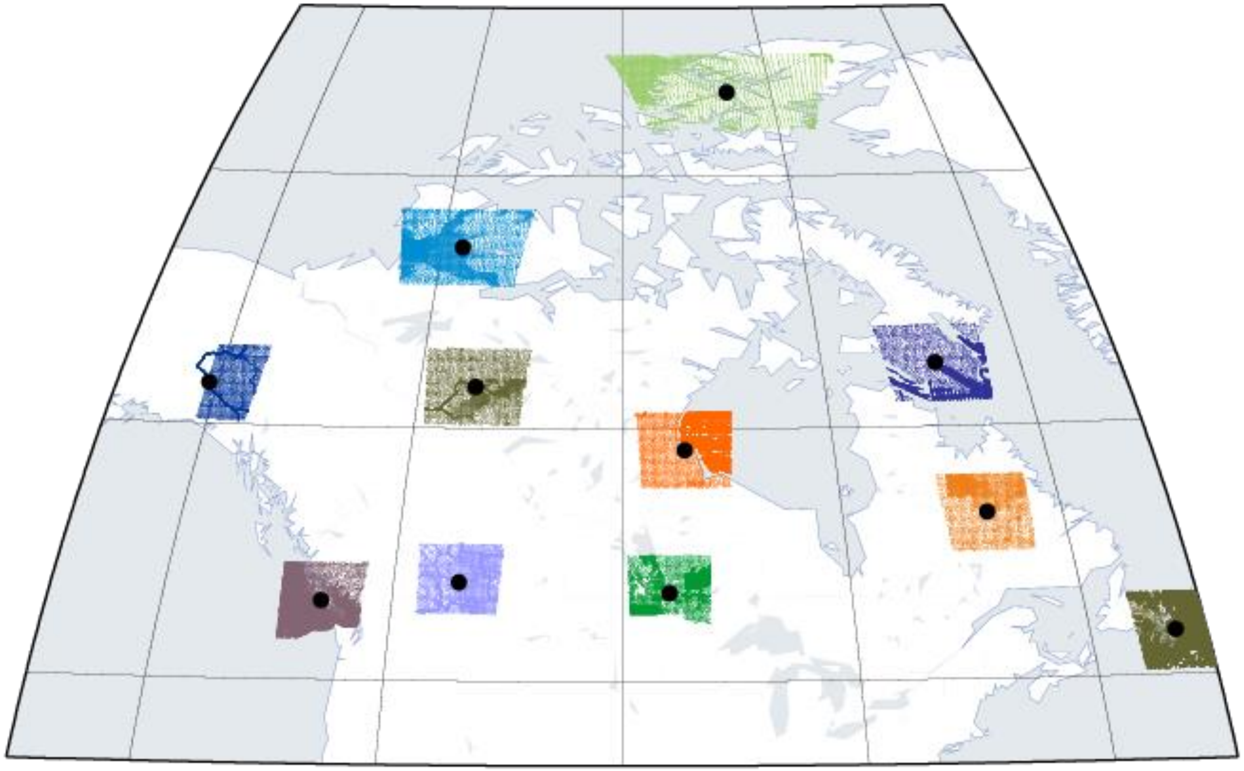
SIRGAS station RDEO
Challapata, Bolivia



A. Echalar, IGM, Bolivia

Refined station selection for the IHRF

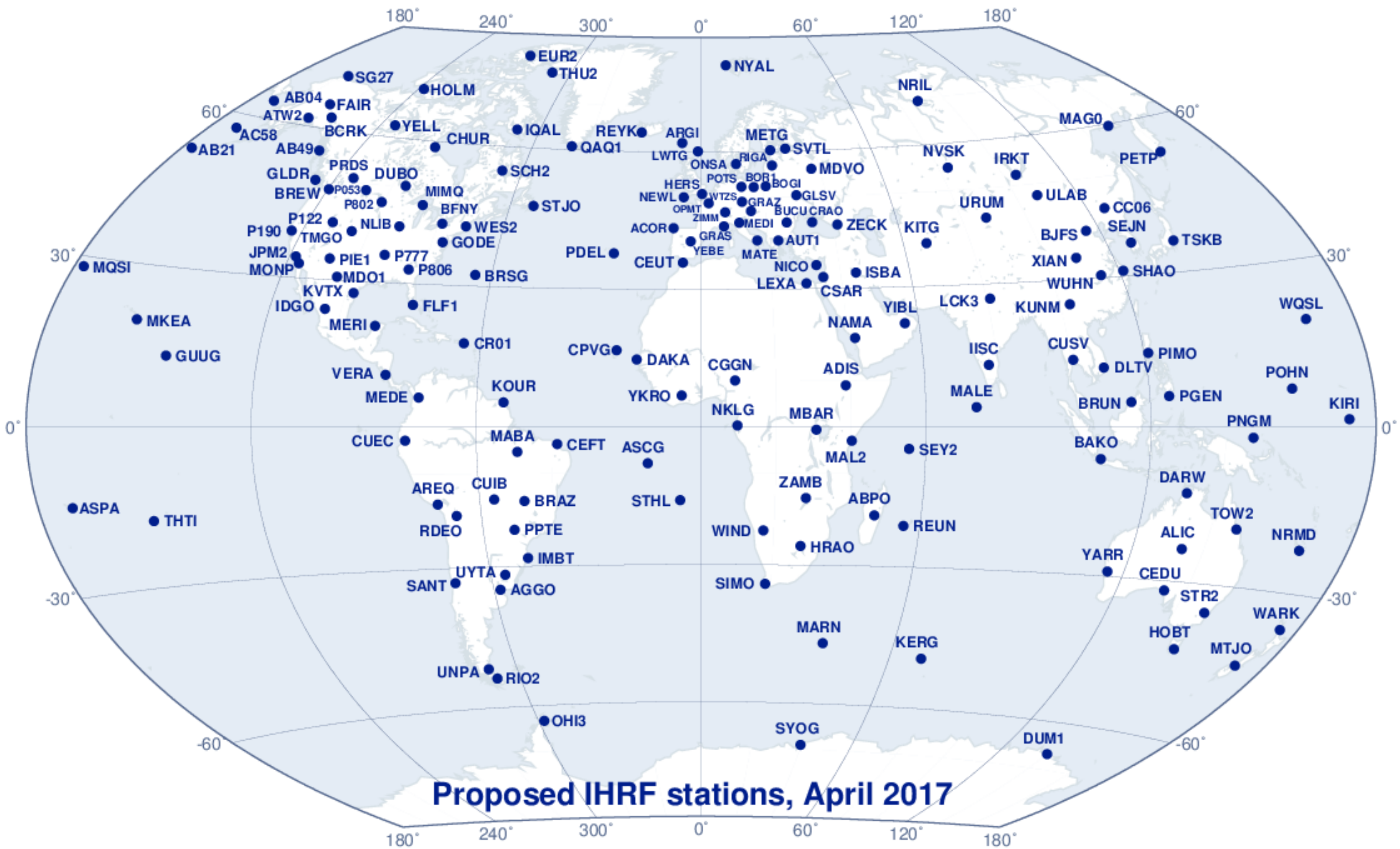
Canadian stations



M. Véronneau, J. Huang, NRCan, Canada

First proposal for the IHRF reference network (Apr. 2017)

163 proposed stations after the feedback from the regional/national experts. In those regions with poor coverage (specially in Africa and Asia), other IGS stations were added.



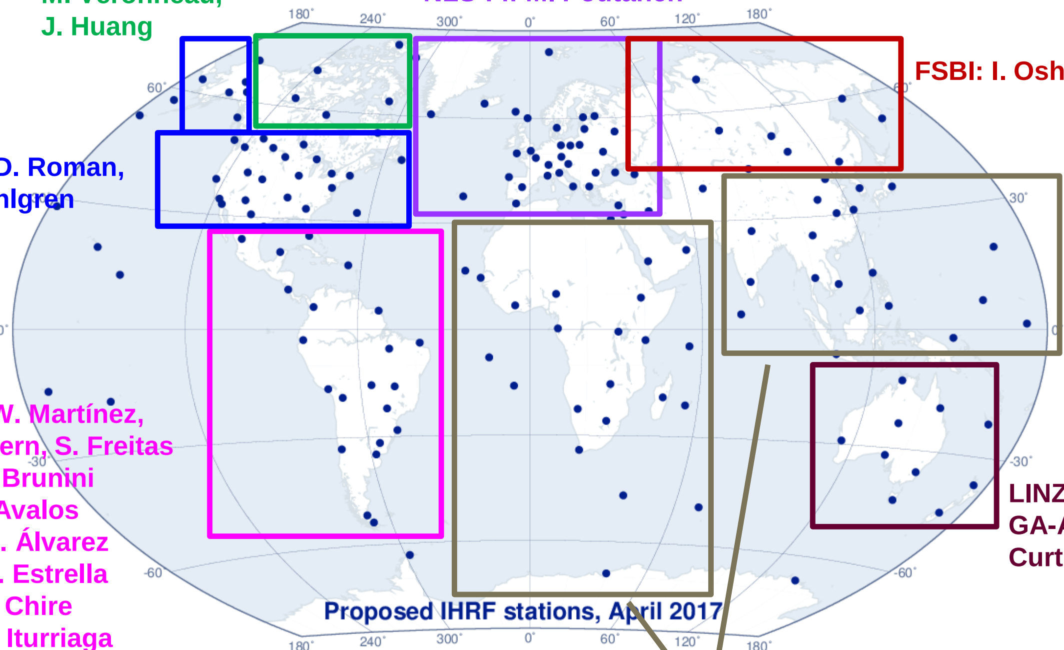
Interaction with regional/national experts for the IHRF station selection

IGIK-Pl: 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



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

IGS stations
<u>Since Aug. 2017</u>:
H.A. Abd-Elmotaal (Egypt)
K. Matsuo (Japan)

Numerical experiments for the computation of the potential values $W(P)$ (1/2)

1) Based on this station selection, current efforts concentrate on the computation of the potential values $W(P)$ and the assessment of their accuracy.

2) Different approaches are being evaluated.

   – Simulations about the distribution and quantity of gravity points needed around the IHRF stations,
   – Simulations about the variation of potential values with time; i.e., $\dot{W}(P)$,
   – Comparison of different mathematical formulations (least-squares collocation, FFT, radial basis functions, etc.),
   – Computation of potential values (and their accuracy) based on global gravity models of high-degree (like XGM2016, EIGEN-6C, EGM2008, etc.),
   – Recovering potential values from existing local quasi-geoid models.

3) Objective: to identify detailed standards and conventions for the IHRS realization after the comparison of the results obtained from these different approaches.

Numerical experiments for the computation of the potential values $W(P)$ (2/2)

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.

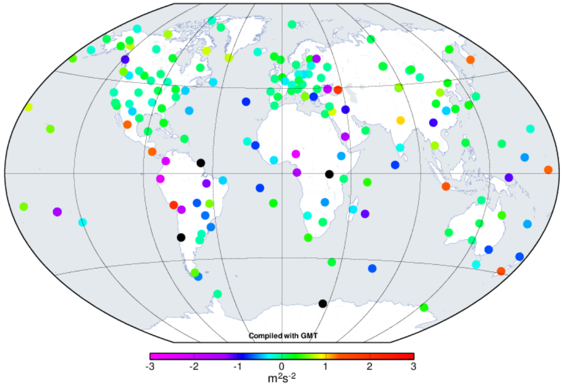
$W(P)$ from global gravity models (GGM) of high-degree

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

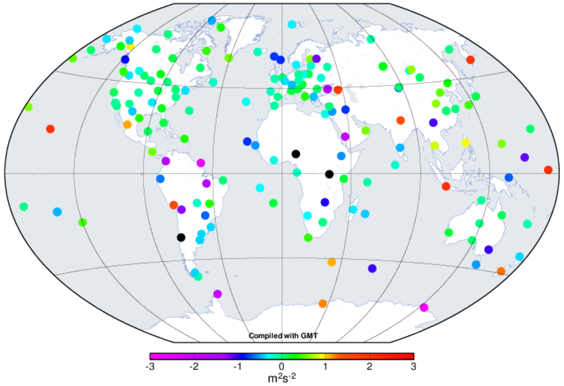
Differences between the GGM-based potential values at the IHRF stations

EIGEN-6C4 vs EGM2008



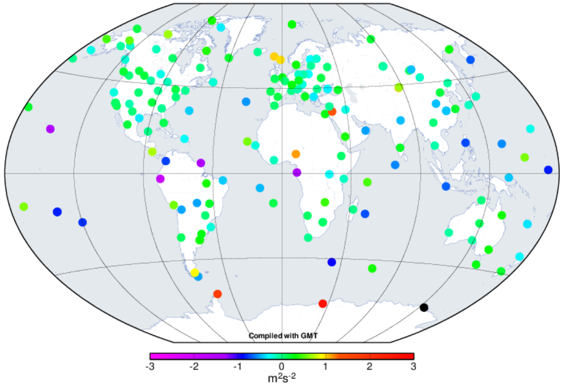
	ΔW [m^2s^{-2}]	ΔH^N [m]
mean	0.00	0.00
stddev	0.93	0.09
min	-3.94	-0.40
max	3.85	0.39

XGM2016 vs EGM2008



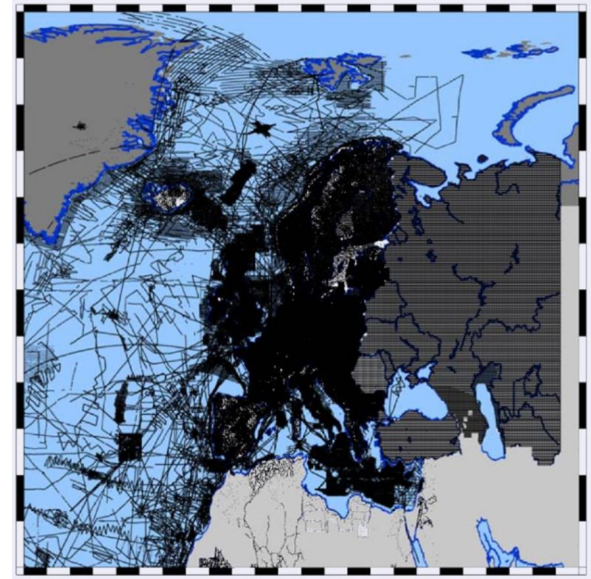
	ΔW [m^2s^{-2}]	ΔH^N [m]
mean	0.01	0.00
stddev	0.87	0.09
min	-3.75	-0.38
max	4.01	0.41

EIGEN-6C4 vs XGM2016



	ΔW [m^2s^{-2}]	ΔH^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



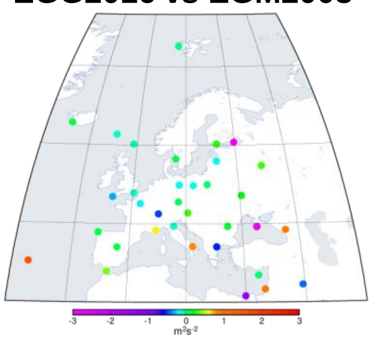
Example Europe:

- 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)

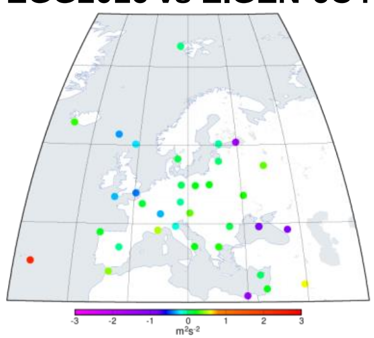
Differences between high-resolution and GGM-based potential values at the European IHRF stations

EGG2016 vs EGM2008



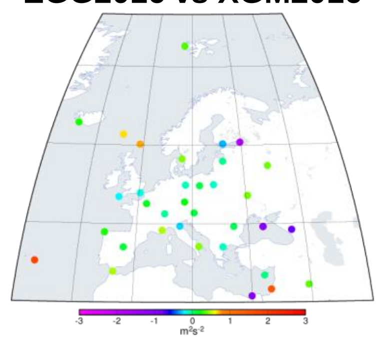
	ΔW [m^2s^{-2}]	ΔH^N [m]
mean	0.00	0.00
stddev	0.73	0.07
min	-2.89	-0.29
max	1.53	0.16

EGG2016 vs EIGEN-6C4



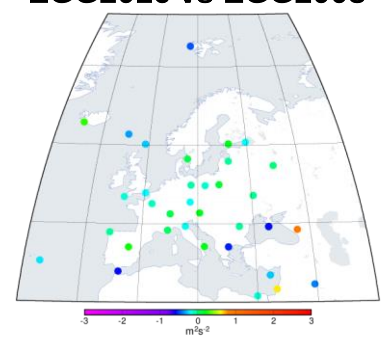
	ΔW [m^2s^{-2}]	ΔH^N [m]
mean	0.00	0.00
stddev	0.60	0.06
min	-1.53	-0.16
max	2.33	0.24

EGG2016 vs XGM2016



	ΔW [m^2s^{-2}]	ΔH^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



	ΔW [m^2s^{-2}]	ΔH^N [m]
mean	-0.04	0.00
stddev	0.29	0.03
min	-0.63	-0.06
max	0.93	0.09

Main conclusions after the numerical experiments on $W(P)$

1) For highest accuracy, especially in mountain areas, it is not sufficient to use a combined GGM of high resolution (e.g. EGM2008, EIGEN-6C4, XGM2016), differences up to ±4 m^2s^{-2} (± 40cm).
2) High resolution local/regional gravity potential modelling is needed to realize IHRS, at least for the more accurate applications (at the 1 cm-level).
3) However, different processing strategies produce different potential values (up to ±1.2 m^2s^{-2} $\rightarrow$ ±12 cm). How can we ensure that the different computations are realising the same IHRS?
4) A “standard” procedure may not be suitable, as
   - different data availability and different data quality around the world exist (e.g. terrestrial gravity data, terrain models, GPS/levelling, etc.)
   - regions with different characteristics require particular approaches (e.g. modification of kernel functions, size of integration caps, geophysical reductions like GIA, etc.)
5) A “centralised” computation (like in the ITRF) is (still) complicated due to the restricted accessibility to terrestrial gravity data
6) To ensure consistency, we have to standardize as much as possible to get as similar and compatible results as possible with the different methods.

Present activities and outlook (1/2)

1) Discussion on primary standards (started in Kobe, Aug 2017):
   - GGOS JWG: Strategy for the Realization of the IHRS (chair: L. Sánchez)
   - GGOS JWG: Establishment of the GGRF (chair: U. Martí)
   - IAG SC 2.2: Methodology for geoid and physical height systems (chair: J. Ågren)
   - ICCT JSG 0.15: Regional geoid/quasi-geoid modelling - Theoretical framework for the sub-centimetre accuracy (chair: J. Huang)
   - IAG JWG 2.2.2: The 1 cm geoid experiment (chair: Y.M. Wang)
   - IGFS: International Gravity Field Service (chair: R. Barzaghi, director Central Bureau: G. Vergos)
   - J. Mäkinen – tide system issues for the IHRS/IHRF
   - Recommendations of the GGOS-BPS Inventory (Angermann et al. 2016)

Present activities and outlook (2/2)

2) Experiment for "calibrating" computation methods:

- NGS/NOAA (Y.M. Wang) will provide terrestrial gravity data, airborne gravity, a digital terrain model, deflexions of the vertical and GPS/levelling data for an area of about 700 km^2 in Colorado, USA.
- With these data, the different processing groups should compute potential values for some virtual IHRF stations in that region.
- The results obtained individually should be compared to identify sources of discrepancy between the different computation methods.
- At present, the airborne gravity is being measured. It is expected to get access to the complete data set by spring 2018.
- Initial contributors: J. Ågren, J. Huang, L. Sánchez, Y.M. Wang, I. Oshchepkov, V. Grigoriasis, S. Claessens, G. Vergos (more colleagues are welcome!).
- First results to be presented at the Symposium GGHS2018, Sep 17 - 21, 2018, Copenhagen, Denmark.

Conclusions

- A first approximation to the realisation of the IHRS is achieved.
- The next step concentrates on the definition of standards and conventions for the computation of potential values at the IHRF reference stations.
- These standards and conventions must guarantee that the realisation (the IHRF) is consistent with the definition (the IHRS) of the height system.
- This work is possible thanks to the contribution of many colleagues within the IAG. 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...
- More information at http://ihrs.dgfi.tum.de, www.ggos.org