Combinations: state-of-the-art and prospective

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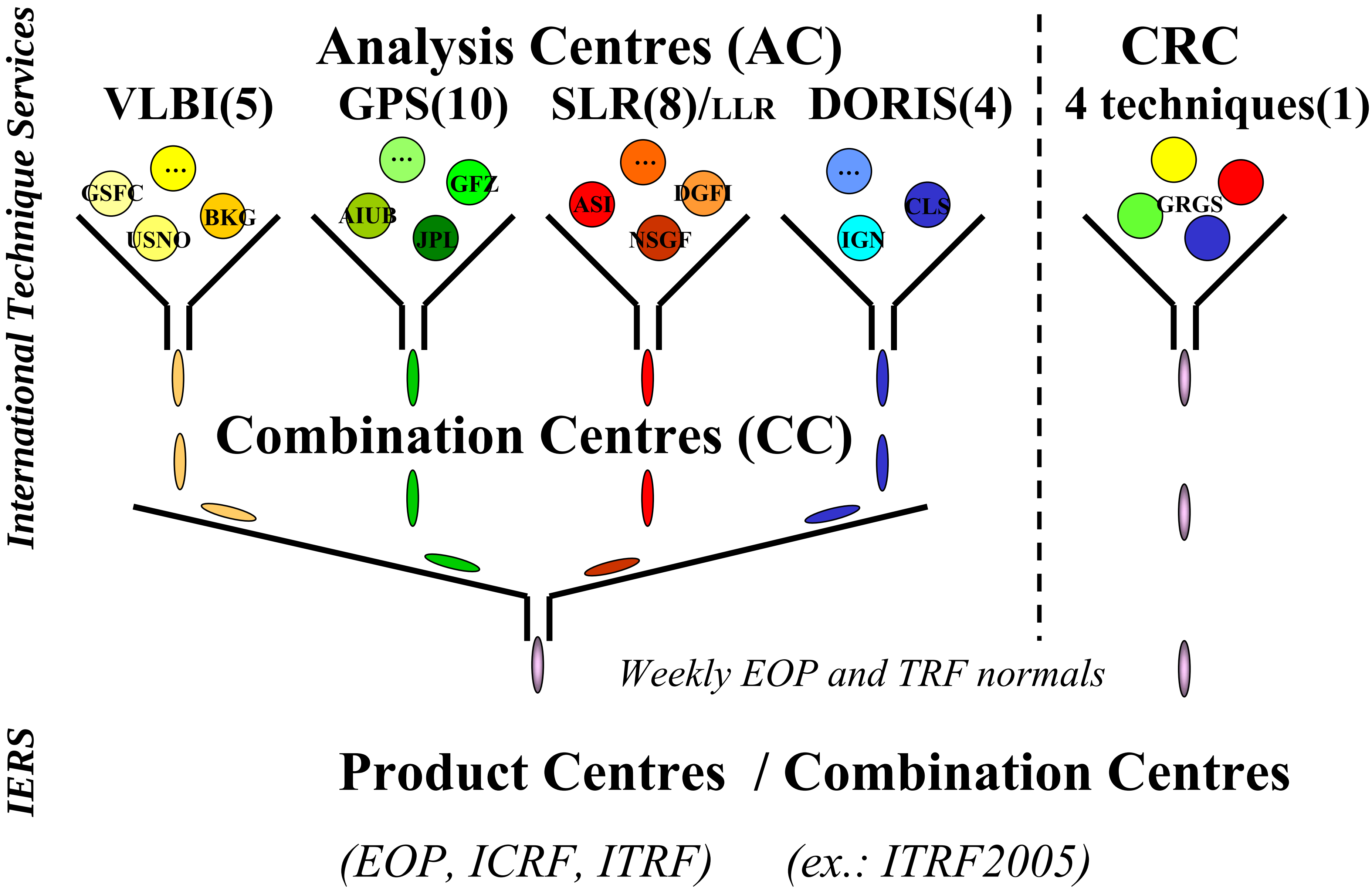
IERS *(International Earth Rotation and Reference Systems Service)* has organized itself in Product Centres which deliver mainly the products of EOP, ITRF, ICRF.

For that purpose IERS relies on Techniques Centres themselves organized in International Services (IGS, IVS, ILRS, IDS) whose first role is to promote the appropriate use of the technique. Moreover these Services gather EOP and RF inputs from different Analysis Centres and generate combined products or normal equation files in an commonly adopted format (SINEX).

Usually these products are achieved independently per technique by the Technical Centres without having necessarily consistency in the data processing (for instance a priori models, common parameterization).

IERS **Combination Research Centres** have the task to study rigorous combination procedures of space geodetic techniques to insure homogeneity and consistency in products.


International Technique Services
Analysis Centres (AC)
VLBI(5)
GPS(10)
SLR(8)/LLR
DORIS(4)
CRC
4 techniques(1)
GSFC
…
USNO
BKG
…
AIUB
GFZ
JPL
…
ASI
DGFI
NSGF
…
CLS
IGN
GRGS
Combination Centres (CC)
Weekly EOP and TRF normals
IERS
Product Centres / Combination Centres
(EOP, ICRF, ITRF)
(ex.: ITRF2005)

Basic principle of Combination:

1. Merging all sources of pertinent space information
2. Searching for homogeneity through the same a priori models:
   - Geodetic and geophysical
   - But technique dependent modeling (centre of phase, empirical…)
3. Getting resolution through the same parameterization:
   - Daily or sub-daily EOP (Xp, Yp, UT1); need of LOD?
   - Daily nutation
   - Weekly stations coordinates
   - Quasar coordinates
   - Tropospheric parameters
4. Helping decorrelation through additional constraints between techniques
   - Helmert's constraints
   - Ties

Interest of combination:

- Merging inertial observations with dynamical ones
- Merging satellite techniques:

  In orbit

  > using satellites tracked by several techniques (e.g. Jason)
  >
  > (can help detecting technique dependent systematic errors; ex. CoM GPS/SLR)

  In propagation

  > by common (hourly) tropospheric parameters

  On the ground

  > through ties between technique references

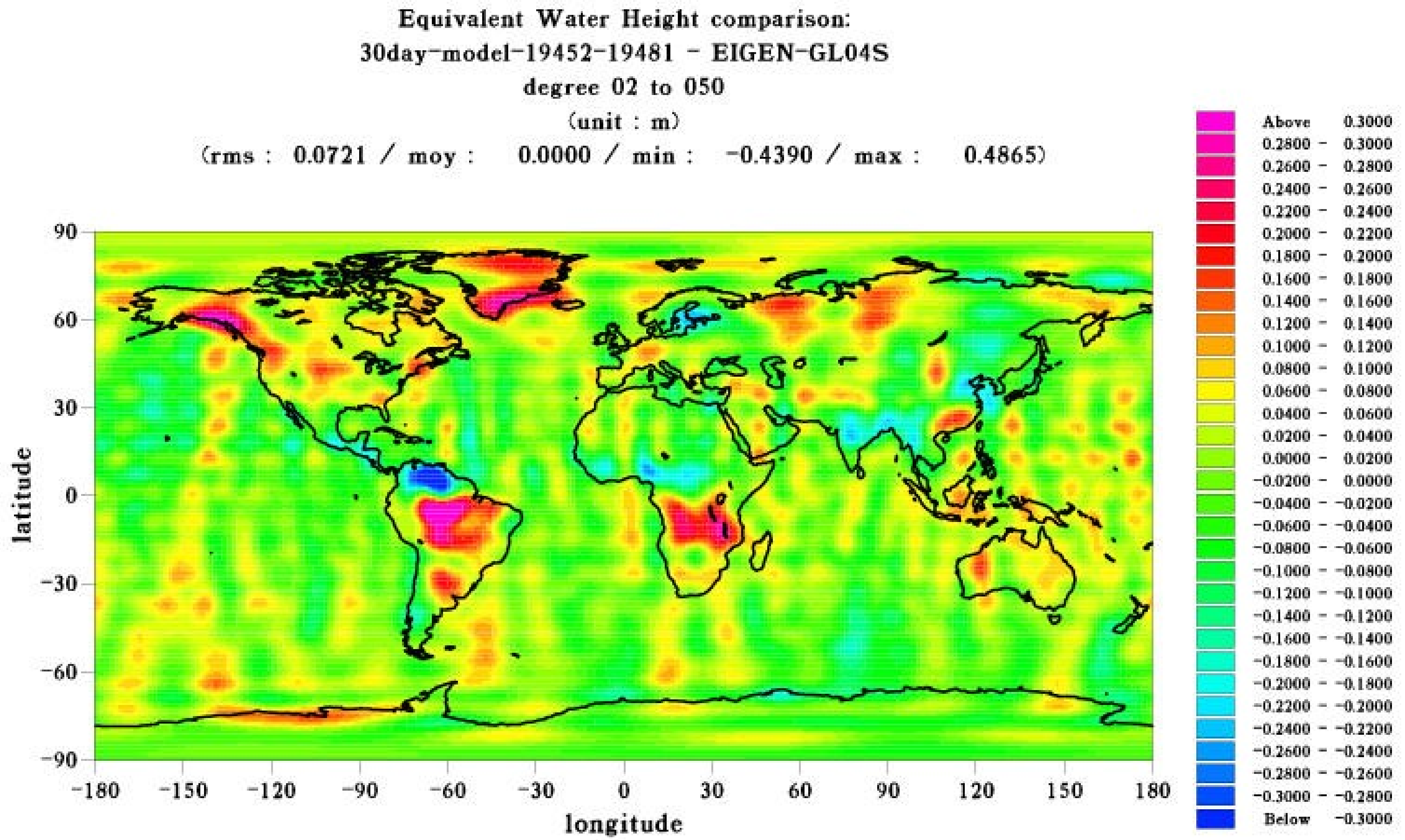
⚠ Weighting process remains a strategic issue

A priori dynamical models:

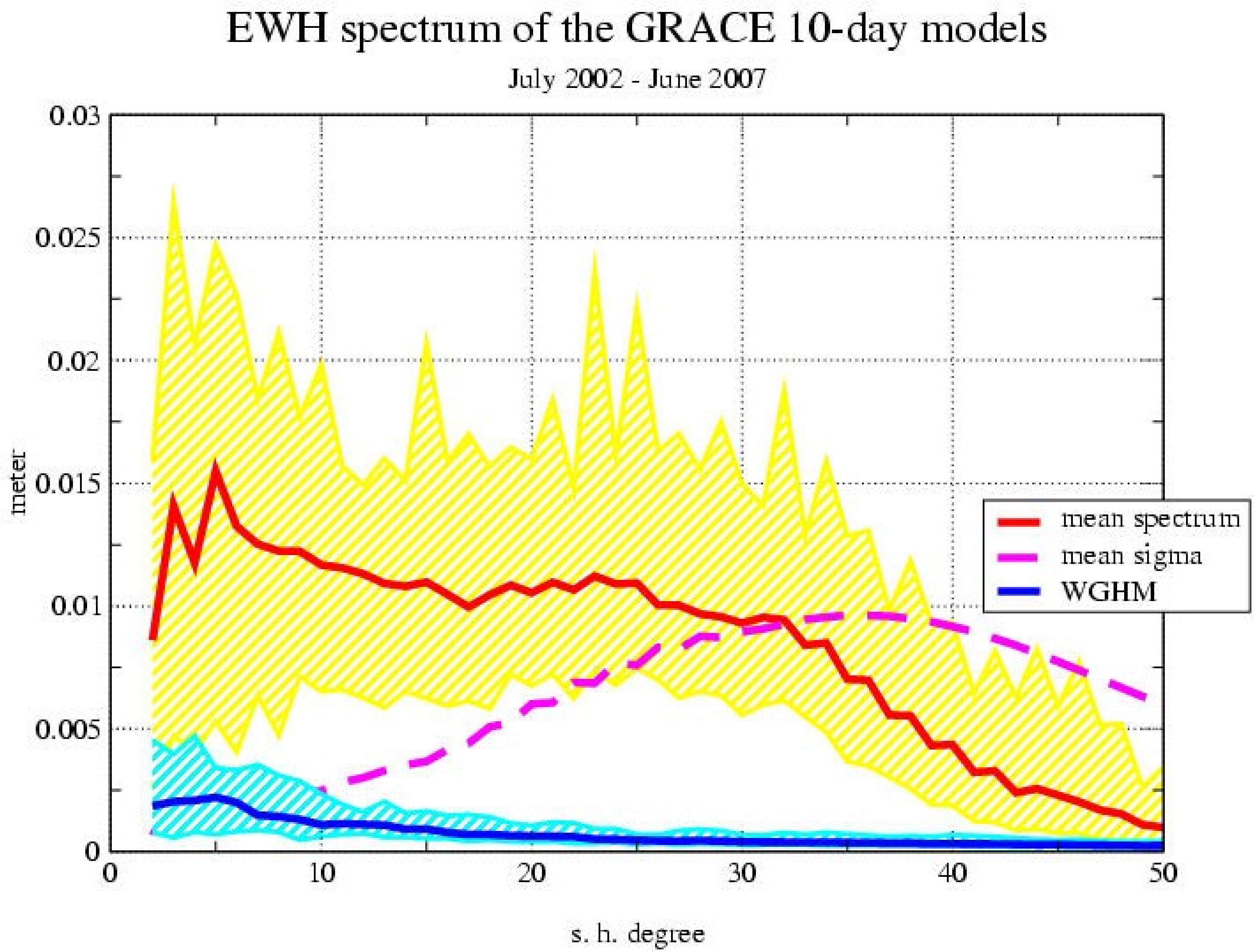
Gravitational:

1. Gravity field (actually based on GRACE + LAGEOS models)
2. Third body
3. Tides
    1. Earth
    2. Ocean (FES2004, GOT00…)
    3. Atmosphere (B&B, Ray…)
    4. Pole (solid and oceanic)
4. Non tidal
    1. Ocean (barotropic models, i.e. MOG2D, AODOC GRACE products)
    2. Atmosphere (ECMWF, NCEP pressure variations – need of a unique mean model)
    3. Hydrology (LaD, WGHM, ECMWF…)

GRACE model



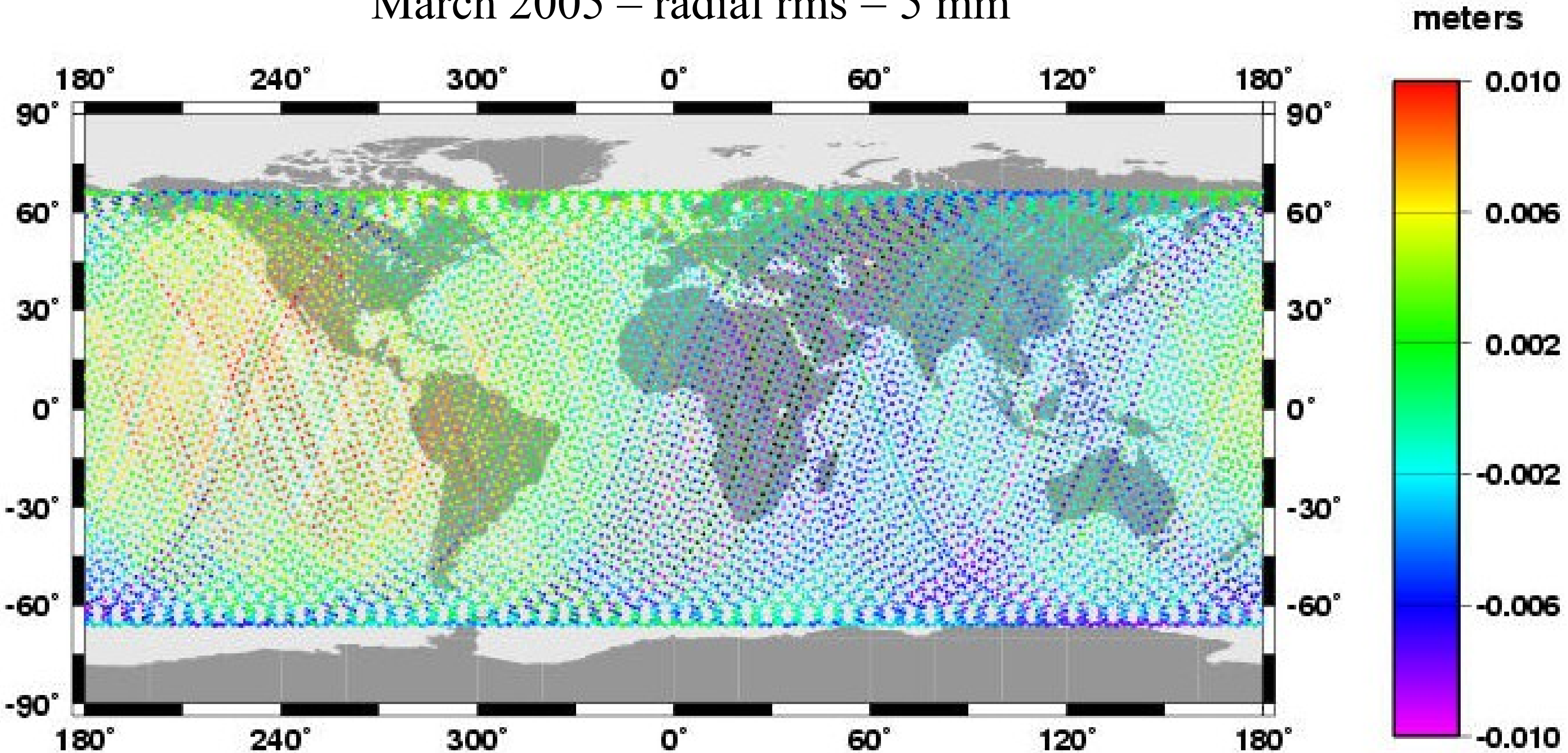
Equivalent Water Height comparison:
30day-model-19452-19481 - EIGEN-GL04S
degree 02 to 050
(unit : m)
(rms : 0.0721 / moy : 0.0000 / min : -0.4390 / max : 0.4865)
latitude
longitude
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
Above 0.3000
0.2800 - 0.3000
0.2600 - 0.2800
0.2400 - 0.2600
0.2200 - 0.2400
0.2000 - 0.2200
0.1800 - 0.2000
0.1600 - 0.1800
0.1400 - 0.1600
0.1200 - 0.1400
0.1000 - 0.1200
0.0800 - 0.1000
0.0600 - 0.0800
0.0400 - 0.0600
0.0200 - 0.0400
0.0000 - 0.0200
-0.0200 - 0.0000
-0.0400 - -0.0200
-0.0600 - -0.0400
-0.0800 - -0.0600
-0.1000 - -0.0800
-0.1200 - -0.1000
-0.1400 - -0.1200
-0.1600 - -0.1400
-0.1800 - -0.1600
-0.2000 - -0.1800
-0.2200 - -0.2000
-0.2400 - -0.2200
-0.2600 - -0.2400
-0.2800 - -0.2600
-0.3000 - -0.2800
Below -0.3000

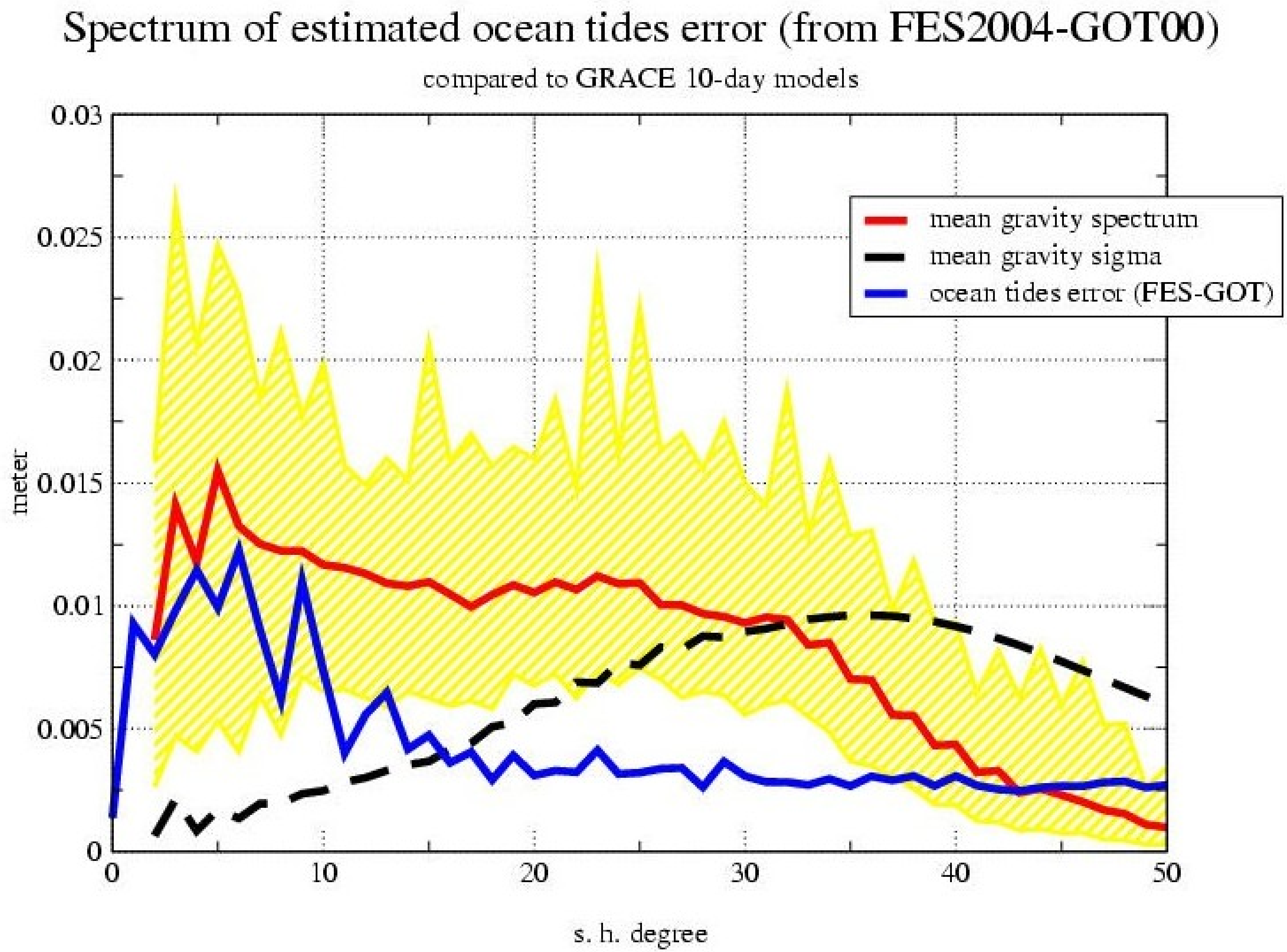

EWH spectrum of the GRACE 10-day models
July 2002 - June 2007
meter
s. h. degree
0.03
0.025
0.02
0.015
0.01
0.005
0
0
10
20
30
40
50
mean spectrum
mean sigma
WGHM

Jason radial orbit comparison

over 10 days using a 10-day model vs. EIGEN-GL04S

March 2005 – radial rms = 5 mm





Spectrum of estimated ocean tides error (from FES2004-GOT00)
compared to GRACE 10-day models
mean gravity spectrum
mean gravity sigma
ocean tides error (FES-GOT)
meter
s. h. degree
0
0.005
0.01
0.015
0.02
0.025
0.03
0
10
20
30
40
50

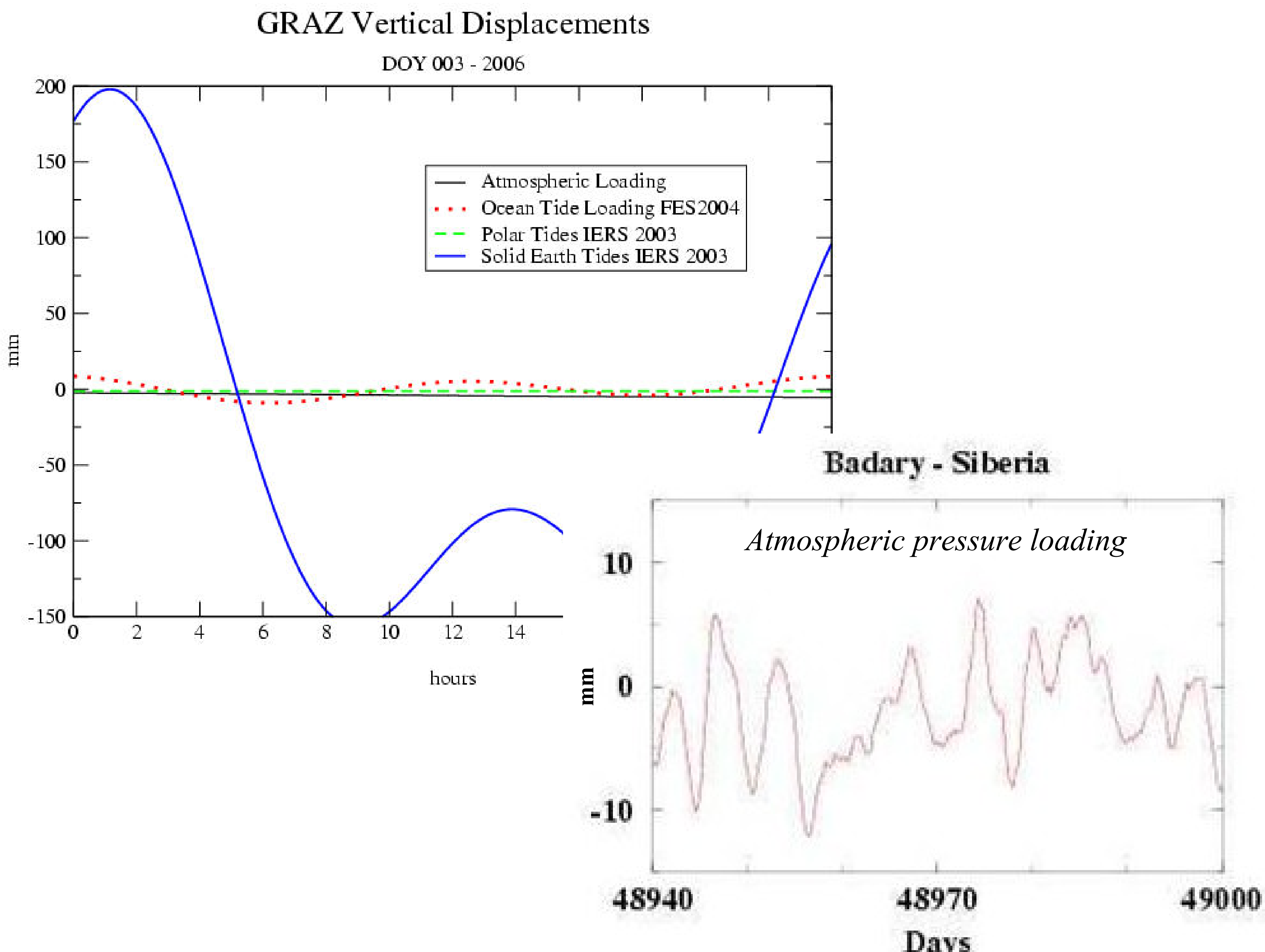
A priori dynamical models:

Non gravitational:

1. Drag (new DTM-2008 in developpement based on accelerometry)
2. Solar radiation
3. Earth radiation (albedo and IR models or from ECMWF)
4. Satellite thermal thrust (based upon surface temperature models)
5. Antenna power thrust
6. Magnetic (ignored)
7. Accelerometry (need calibration)

A priori geometrical models:

1. Earth orientation in space (precession, nutation)
2. Terrestrial reference frame
3. Geocentre (connected to s.h. degree 1 → gravity modelling) (up to 5 mm)
4. Earth tides (up to 30 cm)
5. Pole tide (solid, up to 1 cm)
6. Loading (consistent with gravitational models)
    1. Ocean tides (up to 5 cm)
    2. Atmosphere mass variations (up to 1 cm)
    3. Ocean non tidal mass variations (a few mm)
    4. Hydrology mass variations



GRAZ Vertical Displacements
DOY 003 - 2006
Atmospheric Loading
Ocean Tide Loading FES2004
Polar Tides IERS 2003
Solid Earth Tides IERS 2003
mm
hours
Badary - Siberia
Atmospheric pressure loading
mm
Days

Satellite models

1. "Box & wing" macro or micro models (with self shadowing function) (cf. UCL)
2. CoM definition and variations
3. Electronic antenna pattern (azimuth/elevation)
4. Attitude (quaternions) knowledge

Propagation

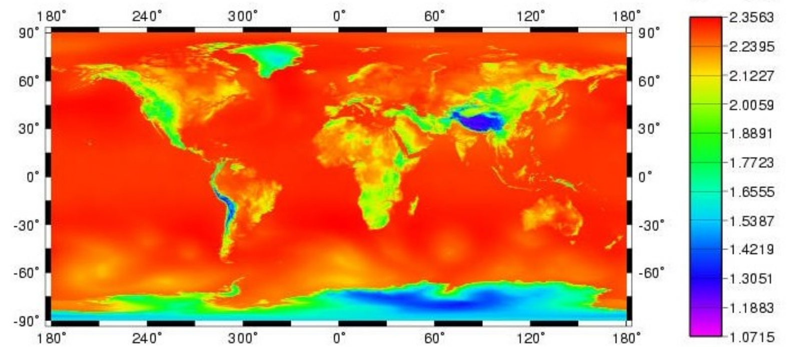
1. Ionosphere (second order correction in $1/f^3$)
2. Troposphere (same a priori → ground data, ECMWF dry and wet delays, new mapping function with zenithal gradients)

Troposphere

Vertical dry tropospheric delay:

$$\Delta L_d^z = 2.277 \cdot 10^{-3} \cdot P_{surf} \cdot [\,1 + 0.0026 \cdot \cos(2 \cdot \varphi)\,]$$

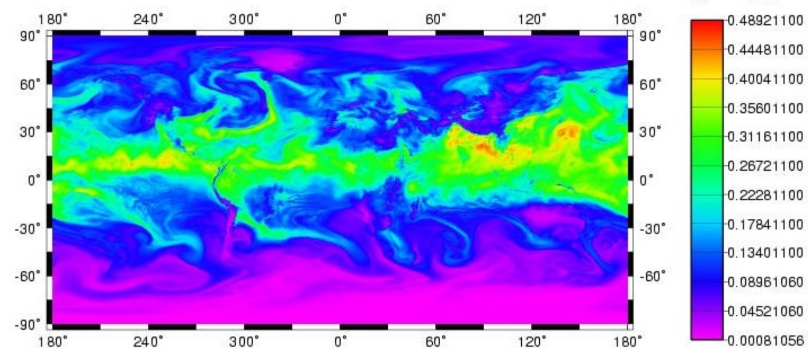
Dry tropospheric delay – Meteo-France (.225°)



Vertical wet tropospheric delay:

$$\Delta L_w^z = [\,1 + 0.0026 \cdot \cos(2 \cdot \varphi)\,] \cdot$$
$$\left\{ 1.116454 \cdot 10^{-3} \cdot \int_{Psat}^{Psurf} q \cdot dP + 17.66543928 \cdot \int_{Psat}^{Psurf} \frac{q}{T} \cdot dP \right\}$$

Wet tropospheric delay – Meteo-France (.225°)



Adjusted mapping function:

(based upon ECMWF models; numerical integration of delays between all 91 layers for elevation and azimuth angles each 10 deg.)

(CLS/CNES study, 2007-2008)

$$f(\varepsilon) = \frac{1 + \dfrac{a_1 + a_2 \cdot z + a_3 \cdot \cos(\varphi)}{1 + \dfrac{b}{1 + c}}}{\sin(\varepsilon) + \dfrac{a_1 + a_2 \cdot z + a_3 \cdot \cos(\varphi)}{\sin(\varepsilon) + \dfrac{b}{\sin(\varepsilon) + c}}}$$

(Guo & Langley)

Use of vertical gradients: $\Delta L(\varphi,\lambda,H) = f_{sec}(\varepsilon)\,.(\Delta Lz_{sec} + H_{sec} \cot(\varepsilon)\,.(GE_{sec} \sin(\theta) + GN_{sec} \cos(\theta)))$
$+ f_{hum}(\varepsilon)\,.(\Delta Lz_{hum} + H_{hum} \cot(\varepsilon)\,.(GE_{hum} \sin(\theta) + GN_{hum} \cos(\theta)))$

(GE, GN derived from ECMWF models, H: reference altitude)

Ionosphere

Phase propagation: $L_0 + L_1 + L_2 + L_{31} + L_{32} + P_r$

	400Mhz			2GHz		
elevation angle:	**2°**	**42°**	**90°**	**2°**	**42°**	**90°**
$L_0 = \int dl$						
$L_1 = l_1/f^2 = a/f^2 \int N_1\, dl$	*486m*	*225m*	*161m*	*19m*	*9m*	*6m*
$L_2 = l_2/f^3 = b/f^3 \int N_1\, B_0\, \lvert\cos\theta\rvert\, dl$	*1.1m*	*0.6m*	*.4m*	*.01m*	–	–
$L_{31} = l_{31}/f^4 = c/f^4 \int N_1^2\, dl$	*.1m*	*.04m*	*.03m*	–	–	–
$L_{32} = l_{32}/f^4 = d/f^4 \int N_1\, B_0^2 \cos^2\theta\, dl$	–	–	–	–	–	–
$P_r \sim$ *order 3 (refraction term)*	*.84m*	*.03m*	–	–	–	–

for: N_T=64 10^{16} m^{-2}, $\theta = 0°$, B_0 = 0.45 Gauss, L_0 = 1000km

(CNET study)

IERS Combination Pilot Project (CPP)

- Started in 2004
- Routine generation of weekly combined intra- and inter-technique solutions
- Available in SINEX format on the IERS BKG site

Was it a success?

Combination Pilot Project (CPP)

File Archive Statistics file:///D|/DONNEES/GGOS/StatisticsCPP.php.htm

Technique	Institution	FROM	TO	DELAY	SINEX	SUMMARY	SUM
DORIS	IGN/JPL	003 / 1993	294 / 2007	34	772	773	1545
GPS	IGS/NRCan	059 / 1999	308 / 2007	20	454	454	908
SLR	ILRS/ASI	362 / 1992	287 / 2007	41	2667	2668	5335
VLBI	IVS/GIUB	208 / 1980	309 / 2007	19	3856	1	3857
combination	GRGS	002 / 2005	358 / 2006	335	104	0	104
SUM					**7853**	**3896**	**11749**

Technique	Institution	YEAR	SINEX	SUMMARY	SUM
DORIS	IGN/JPL	1993	52	52	104
		2005	52	52	104
		2006	53	53	106
		2007	42	42	84
GPS	IGS/NRCan	1999	44	44	88
		2005	52	52	104
		2006	53	53	106
		2007	44	44	88
SLR	ILRS/ASI	1992	3	3	6
		2005	135	135	270
		2006	60	60	120
		2007	47	47	94
VLBI	IVS/GIUB	1980	18	0	18
		2005	182	0	182
		2006	149	0	149
		2007	110	0	110
combination	GRGS	2005	52	0	52
		2006	52	0	52

Combination Research Centres (CRCs)

1. Centro di Geodesia Spaziale / ASI (Matera)
2. Astronomical Institute - Academy of Sciences of the Czech Republic – Department of Geodesy of the Czech Technical University (Prag)
3. Deutsches Geodätisches ForschungsInstitut (Munich)
4. ForschungsEinrichtung SatellitenGeodäsie, Technical University of Munich
5. Forsvarets ForskningInstitutt (Kjeller/Norway)
6. Geodetic Institute of the University of Bonn
7. GeoForschungsZentrum Potsdam
8. Groupe de Recherches de Géodésie Spatiale (Paris, Toulouse, Grasse-Marne-la-Vallée, Bordeaux)
9. Institut Géographique National (Marne-la-Vallée)
10. Institute of Applied Astronomy (St. Petersburg)
11. Jet Propulsion Laboratory (Pasadena)

CGS Combination Research Centre

Centro di Geodesia Spaziale / ASI

Giuseppe Bianco, Roberto Lariotte, Vincenza Luceri, Cecilia Sciarretta

- **ILRS Combination Centre**
- **combination methodologies**

CEDR Combination Research Centre

Centre for Earth Dynamics Research (Prague)

Jan Vondrak, Cyril Ron, Jan Kostelecky, Cyril Ron, Leos Mervart, Ivan Pesek, Ales Cepek

- **combined smoothing algorithm**
- **non-regular combination of techniques**

DGFI Combination Research Centre

Deutsches Geodätisches ForschungsInstitut (Munich)

Detlef Angermann,Hermann Drewes, Rainer Kelm, Manuela Krügel, Barbara Meisel, Volker Tesmer

- **simultaneous estimation of TRF, EOP, CRF**
- **combination of homogeneously processed VLBI and GPS data**

FESG Combination Research Centre

Technical University Munich

Daniela Thaller, Peter Steigenberger, Urs Hugentobler

- **comparison of troposphere parameters from GPS and VLBI**
- **GPS/VLBI combination studies**

FFI Combination Research Centre

Norwegian Defense Research Establishment

Per Helge Andersen

- **development of the GEOSAT software package for the combined analysis of VLBI, GNSS, SLR… satellite data**
- **completed by a Combined Square Root Information Filter and Smoother program (CSRIFS)**

GIUB Combination Research Centre

Geodetic Institute of the University of Bonn

Alex Nothnagel, Sarah Böckmann, Markus Vennebusch

- **IVS Combination Centre**

GFZ Combination Research Centre

GeoForschungsZentrum Potsdam

Markus Rothacher, Jürgen Kusche, Rolf König, Karl Hans Neumayer

- **IGS Combination Centre**
- **integrated approach with LEO**

GRCS Combination Research Centre

Groupe de Recherches de Géodésie Spatiale

Daniel Gambis, Richard Biancale, Jean-Michel Lemoine, Jean-Charles Marty, Florent Deleflie, Patrick Charlot, Géraldine Bourda, Sylvain Loyer, Laurent Soudarin, Zuheir Altamimi, Arnaud Pollet

- **capacity of processing and combining all satellite data (GINS/DYNAMO)**
- **producing weekly SINEX of EOP and TRF**

IGN Combination Research Centre

Institut Géographique National

Zuheir Altamimi, Xavier Colilieux, David Coulot, Arnaud Pollet

- **ITRF combination activities**
- **combination research**

IAA Combination Research Centre

Institute of Applied Astronomy

Zinovy Malkin, Natalia Panafidina, Yulia Sokolova

- **experimental combinations**

JPL Combination Research Centre

Jet Propulsion Laboratory

Richard Gross

- **KEOF's real time determinations of UT1**

Issues of a rigorous Combination (Jim Ray, Sheng Yuan Zhu)

Proceedings of the IERS Workshop on Combination Research and Global Geophysical Fluids (Munich, 18-21 November 2002)

- CRCs pursue independent research objectives
- Not directly involved in current IERS product formation
- Weakness:
  - Research effort not well coordinated and poorly directed to improve IERS products
  - Role of CRCs in IERS is not well defined
  - No established mechanism for research gains to be transferred to operational Product Centres
  - Results from CRCs not well publicized

… but several recent publications (non exhaustive list):

• Is there utility in rigorous combinations of VLBI and GPS Earth orientation parameters? J. Ray, J. Kouba, Z. Altamimi, J. Geod., 2005

• Simultaneous determination of Earth orientation parameters and station coordinates from combination of results of different techniques, I. Pesek, J. Kostelecky, Studia Geophys. & Geod., 2006

• Towards a direct combination of space-geodetic techniques at the measurement level: methodology and main issues, D. Coulot, Ph. Berio , R. Biancale , S. Loyer , L. Soudarin , A.-M. Gontier, JGR, 2007

• Combined Earth Orientation Parameters based on Homogeneous and Continuous VLBI and GPS data. D. Thaller, M. Krügel, M. Rothacher, V. Tesmer, R. Schmid, D. Angerman, J. Geod., 2007

• Tropospheric parameters: combination studies based on homogeneous VLBI and GPS data, M. Krügel, D. Thaller, M. Rothacher, D. Angerman, R. Schmid, J. Geod., 2007

• Combination of Earth Orientation Parameters and terrestrial frame at observation level, D. Gambis, R. Biancale, T. Carlucci, J.-M. Lemoine, J.-C. Marty, G. Bourda, P. Charlot, S. Loyer, T. Lalanne, L. Soudarin, GRF2006, 2007

…

Do have CRCs a future? → next step

Proposal for a **Combination Analysis Working Group** (need of more concerted activities within IERS)

- GRGS combination activities to be extended to other groups
- Activities of the CAWG could be studying:
  - Weighting strategy (between techniques)
  - Unified troposphere
  - Role of ties
  - Resolution and continuity of EOPs (xp,yp,UT1/LOD) and nutation (ΔX,ΔY)
  - Stations stability strategy
  - Including quasar coordinates
  - Correlation (i.e. diurnal retrograde nutation and sub-daily pole)
  - Quality analysis of results
  - …

Combination Analysis Working Group (CAWG)

Stages:

1. Motivating groups to participate
2. Evaluation of group capabilities
3. Definition of adequate common or similar standards (models, parameterization…)
4. Elaboration of benchmarks (software intercomparison)
5. Inter technique SINEX files compatibility
6. Research and tests on combination strategies
7. Quality evaluation and control
8. Production in parallel to International Technique Services
9. Toward an International Combination Service (ICS)

International Earth Rotation and Reference Systems Service