Unified Analysis
Workshop 2007, Dec 5-7

Session 5

New Products Based on Inter-Technique Combinations

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Outline

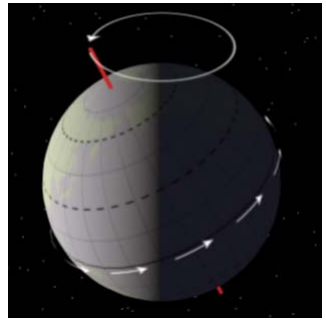
- Product groups
  - Earth orientation parameters (EOP)
  - Troposphere parameters
  - Ionosphere
  - Station coordinates
  - Gravity, geometry and Earth rotation
  - Height reference and sea level change
  - Geodynamic parameters
  - Miscellaneous
- Conclusions, further aspects and ideas
- Session programme

EOP products

- "Final" products:
  - Daily resolution: Nutation, polar motion, dUT1
  - Hourly resolution: polar motion, dUT1

➡ Input observations:

- VLBI – selected sessions
- GNSS – GPS, GLONASS, (GALILEO)
- DORIS
- SLR
- LLR
- Ringlaser



Recent studies - EOP

- **Thaller et al. 2007**: “Combined Earth orientation parameters based on homogeneous and continuous VLBI and GPS data”, (JoG, VLBI special issue)

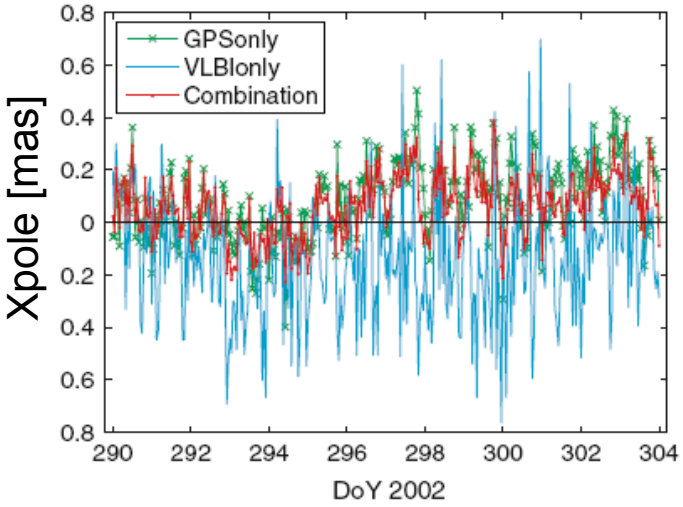
  - Observation time period: CONT02
  - Combined techniques: VLBI, GPS
  - Combination on NEQ-level
  - Combined parameters w.r.t. Earth rotation:

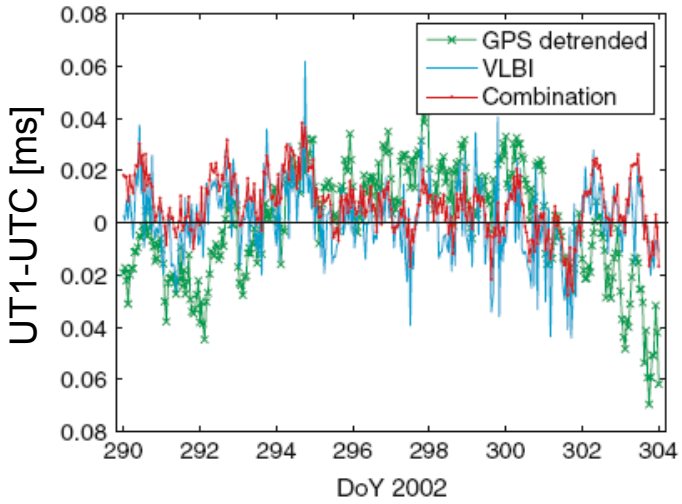
    - Xpole, Ypole
    - UT1-UTC

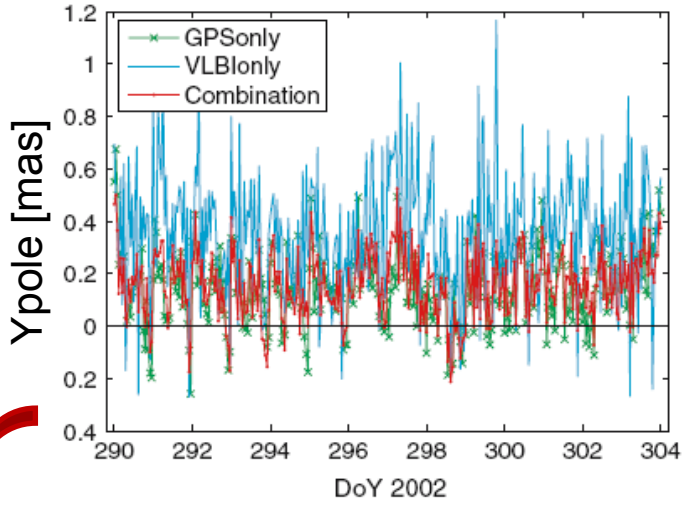
    } → *hourly resolution*

    - $\Delta\varepsilon$, $\Delta\psi$ → *14-day resolution*

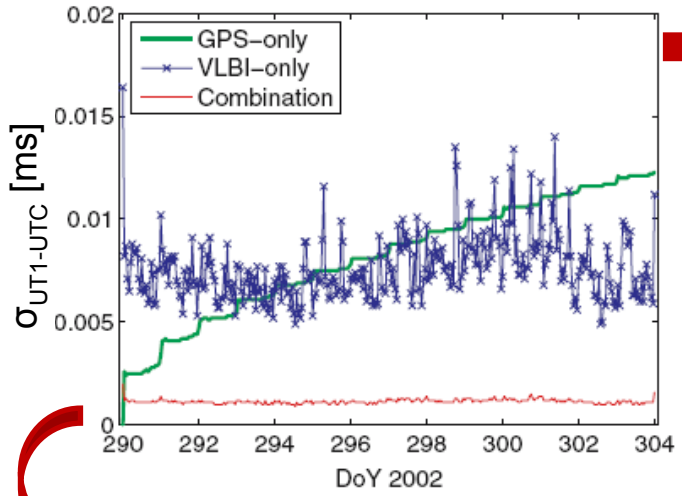
Hourly estimates w.r.t. C04 + IERS Conventions 2003 sub-daily model







known bias: C04 Ypole - TRF



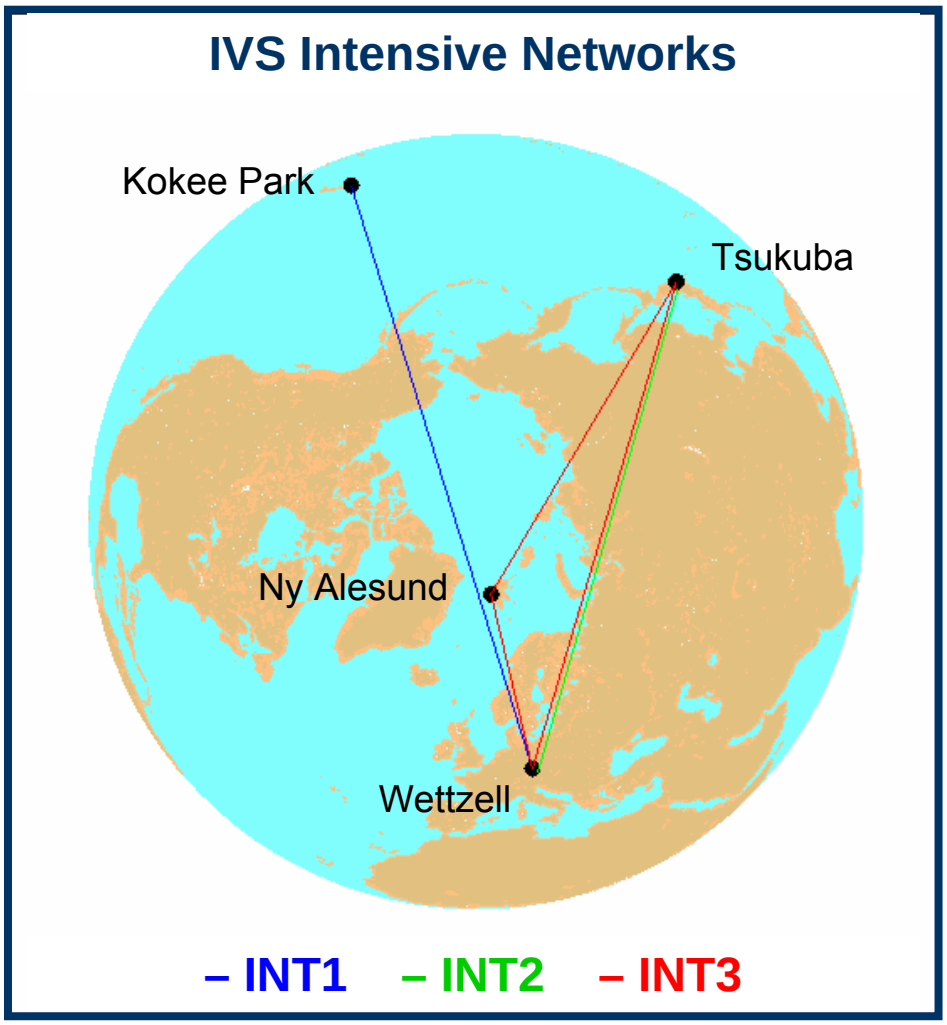
decrease due to large number of GPS obs.

Compare **temporal behaviour** not level of formal errors!

EOP products

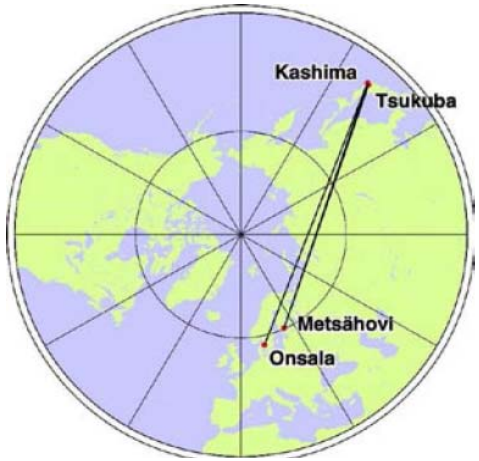
- "Rapid" products (near real-time)
  - Input observations:
    - VLBI (1h IVS-Intensive sessions)
    - GPS (IGS rapid)
    - Other possible data: SLR, AAM
  - Time delay:
    - Intensive sessions: INT1/2 3-5 d, INT3 <24h
    - IGS rapid products: 17h
    - IGS ultra-rapid products: 3h → performance still needs to be improved

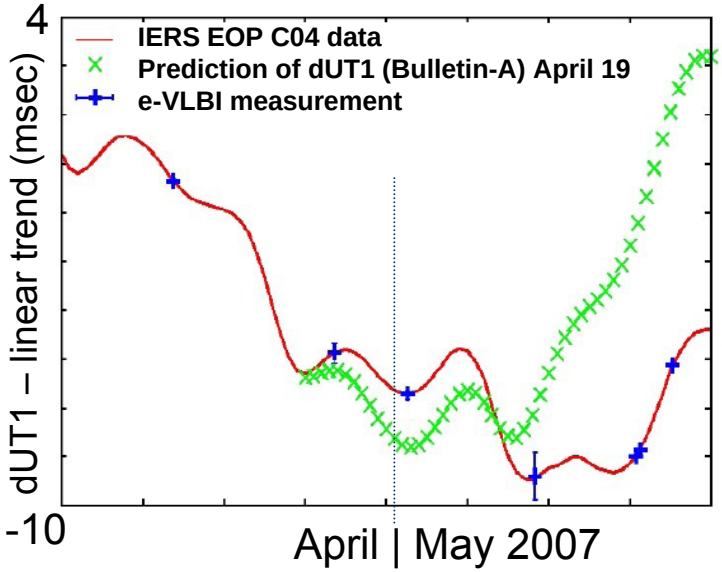
VLBI Intensive Sessions



- **INT1**
  - Mo-Fr ~18:30
  - Kokee - Wettzell
- **INT2**
  - Sa-Su ~7:30
  - Tsukuba - Wettzell
- **INT3**
  - Mo ~6:00
  - Tsukuba - Wettzell - Ny Alesund
  - Operational since August 2007

Ultra-rapid dUT1 e-VLBI sessions





- e-INT: near real time dUT1
  - Currently tested 1h experiments
  - Two almost parallel baselines:
    - Onsala - Tsukuba
    - Metsähovi - Kashima
  - Real time data transfer, quasi real time correlation
  - Correlation by software
- Results from Kashima - Onsala pilot experiment
  - Time delay of < 30 min!!

Troposphere products

- Combined long-term series
- Routine combination: along with station coordinates and EOP combination
  - ➡ Input observations:
    - VLBI
    - GNSS – IGS reprocessing underway
    - DORIS – enhancement of spatial distribution
    - Radio occultation measurements from CHAMP and GRACE
    - Numerical weather model data?
- Parameters to be combined:
  - Zenith Wet Delay (ZWD)
  - Zenith Total Delay (ZTD)
  - Gradients

Recent studies –TROPOSPHERE comparison

- **Snajdrova et al. 2006**: “Multi-technique comparison of tropospheric zenith delays derived during the CONT02 campaign” (JoG)
  - Time series
    - VLBI: combined estimates of ZTD and ZWD from seven IVS Analysis Centers
    - GPS: combined IGS series (ZTD)
    - DORIS: IGN/JPL estimates of ZTD
    - Numerical weather model: ZTD and ZWD from ECMWF
    - Water Vapour Radiometer data at 3 sites of CONT02
  - Comparison of ZTD

Recent studies – Snajdrova et al.

Mean offsets and standard deviations of **ZTD** in mm between VLBI, GPS, ECMWF, DORIS and WVR:
(ZTD-WVR = ZWD-WVR + hydrostatic zenith delays from VLBI)

	nyal	koke	gilc	hart	algo	onsa	west	wett
VLBI–GPS	+0.1±3.3	−5.7±6.6	−0.3±3.5	−3.4±5.8	0.0±3.8	+0.7±4.1	−6.5±3.5	−2.1±4.5
VLBI–ECMWF	+7.1±4.7	−8.8±21.0	−8.4±12.6	−4.8±19.4	−11.8±3.4	+8.1±5.7	−16.2±5.9	+13.2±8.8
VLBI–DORIS	+1.5±7.9	−7.2±32.1	−2.4±8.3	+2.7±14.0				
VLBI–WVR		−17.9±12.4				−2.8±6.7		−17.2±9.0
GPS–ECMWF	+6.6±3.5	−1.9±17.4	−8.3±11.8	−0.3±18.6	−9.8±2.1	+7.6±5.5	−9.1±7.1	+15.1±7.8
GPS–DORIS	+1.2±8.1	+2.7±34.7	−1.5±8.7	+5.5±14.5				
GPS–WVR		−11.9±11.6				−3.7±5.4		−14.7±8.1
ECMWF–DORIS	−6.8±8.5		+8.3±12.6					
ECMWF–WVR		−7.7±23.6				−11.7±10.2		−26.2±7.5
DORIS–WVR		−10.0±34.4						

- Good agreement between space geodetic techniques
- Worst agreement at Kokee and Hartebeesthoek: high variability of temperature and humidity
- Problems with DORIS at station Kokee Park due to old equipment
- DORIS results are at an accuracy level worse by a factor of 2-3 – but the biases to VLBI and GPS are small
- The agreement with WVR and ECMWF is at a lower accuracy level

Recent studies –TROPOSPHERE comparison

- **Heinkelmann et al. 2007**: “Long-term trends of water vapour from VLBI observations” (Proceedings of the 18th EVGA-Meeting)
  - Trend representation of zenith delay time series using B-spline wavelets
  - Time series
    - VLBI: combination of long-term series of ZTD and ZWD of eight IVS Analysis Centers
    - GPS: combined IGS series (ZTD)
    - Numerical weather model: ZWD from ECMWF re-analysis
  - Comparison of trends

Recent studies – Heinkelmann et al.

co-located site IVS	co-located site IGS	IVS	IGS
GILCREEK	fair	2.6 ± 0.2	2.8
WETTZELL	wtzr	-0.4 ± 0.1	-0.6
WESTFORD	wes2	3.3 ± 0.2	3.1
KOKEE	kokb	2.1 ± 0.1	1.8
FORTLEZA	fort	2.1 ± 0.1	2.2
HOBART26	hob2	-1.2 ± 0.3	-1.4

- Linear trends of ZTD of IGS and IVS combined series in mm/year

	IVS	ECMWF
GILCREEK	0.6 ± 0.1	0.6
WETTZELL	0.3 ± 0.1	0.5
WESTFORD	0.3 ± 0.2	-0.2
KOKEE	0.8 ± 0.1	0.3
FORTLEZA	1.4 ± 0.2	-1.9
HOBART26	-1.1 ± 0.7	-0.9

- Linear trends of ZWD of ECMWF and IVS combined series in mm/year

Recent studies – TROPOSPHERE comparison

- **Steigenberger et al. 2007**: “Comparisons of homogeneously reprocessed GPS and VLBI long time-series of troposphere zenith delays and gradients”, (JoG, VLBI special issue)

  - Time series
    - VLBI: ZWD and gradients from solution Tesmer et al. 2004
    - GPS(1): ZTD, ZWD and gradients from reprocessed solution Steigenberger et al. 2006
    - GPS(2): combined IGS series (ZTD)

  - Comparison of:
    - VLBI/GPS - ZWD and gradients
    - GPS(1)/GPS(2) - ZTD

Heinkelmann et al. (JoG) – Steigenberger et al.

Bias and RMS between IGS and IVS combined **ZTD** series at co-located sites (1997-2005)

Station		Common epochs		Bias (mm)	RMS (mm)
IVS	IGS	(%)	Total		
ALGOPARK	algo	15.5	5354	9.9	5.7
FORTLEZA	fort	16.7	5264	12.8	15.2
GILCREEK	fair	25.0	8270	4.2	5.0
HARTRAO	hrao	12.5	3746	6.5	9.0
HOBART26	hob2	6.2	1984	7.6	19.6
KOKEE	kokb	24.0	7769	8.1	8.5
MATERA	mate	10.6	3635	4.8	5.9
NYALES20	nyal	17.3	5232	3.3	5.2
SESHAN25	shao	2.7	553	4.0	8.2
TSUKUB32	tskb	6.8	2264	4.4	9.8
WESTFORD	wes2	15.9	5048	9.4	6.1
WETTZELL	wtzr	26.8	9258	4.6	5.2

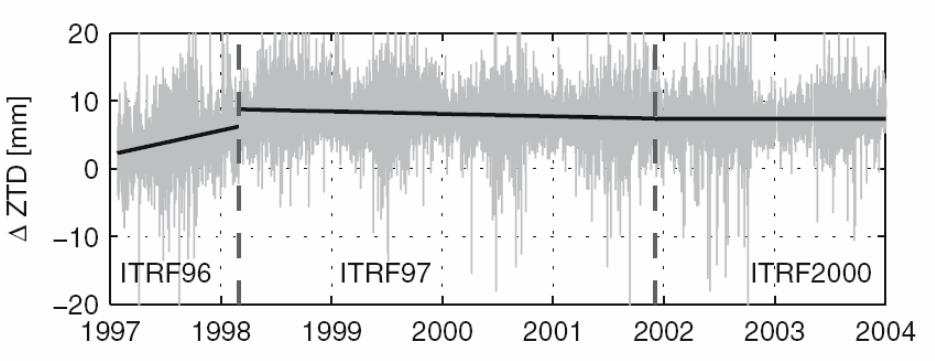
Comparison of GPS reprocessing and VLBI **ZWD** estimates (1994-2004)

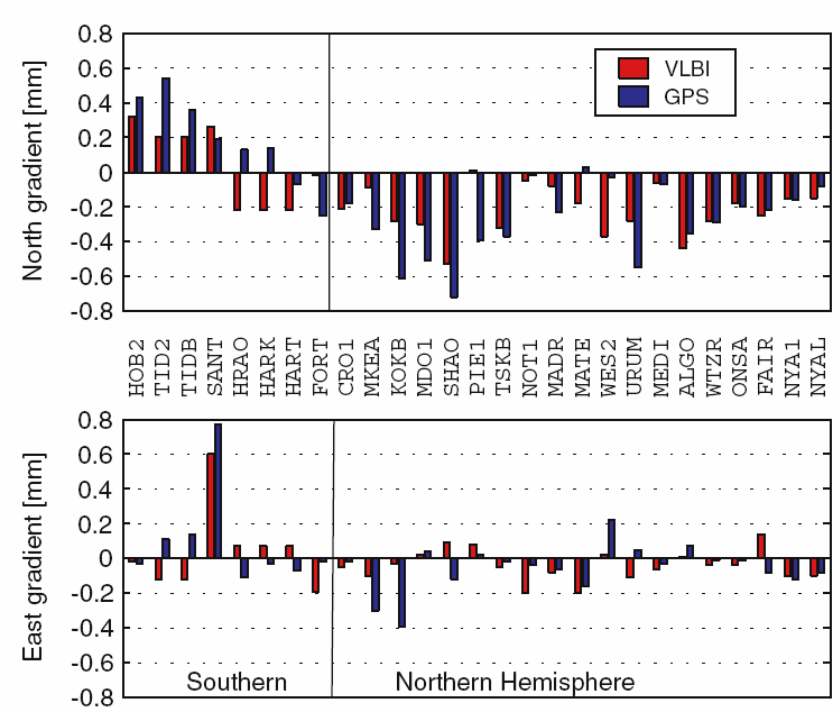
Bias (mm)	RMS (mm)
−0.5	5.8
+7.2	14.1
−4.5	5.9
−9.2	8.9
−2.3	8.3
+5.1	10.9
−0.8	6.7
−0.9	4.6
−0.3	7.5
−2.0	8.1
+4.2	6.8
−1.1	4.6

- All biases positiv → systematic difference (relative antenna phase center corrections in IGS solution!)
- IGS product: only ZTD

- No systematics (absolute antenna phase center corr-ections, homogeneous parmeterization), ZWD

Recent studies – Steigenberger et al.





- GPS/GPS: Differences between IGS and reprocessed ZTD for Algonquin Park (ALGO)
- VLBI/GPS: Mean north–south and east–west troposphere gradients determined by VLBI and GPS

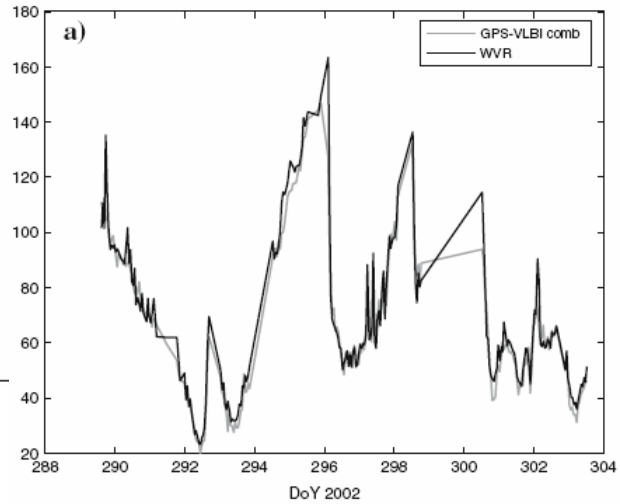
Recent studies – TROPOSPHERE combination

- **Krügel et al. 2007**: "Tropospheric parameters: combination studies based on homogeneous VLBI and GPS data", (JoG, VLBI special issue)
  - Observation time period: CONT02
  - Combined techniques: VLBI, GPS
  - Combination on NEQ-level
  - Combined parameters w.r.t. troposphere:
    - Zenith delays → *hourly resolution*
    - Horizontal gradients → *daily resolution*
  - Comparison of ZWD with Water Vapour Radiometer (WVR) data

Recent studies – Krügel et al. 2007

Site	Correlation between the time series	Offset (mm)	RMS of the hourly differences, mean offset (column 3) removed (mm)
Comparison WVR–GPS			
Onsala	0.98	2.2	6.0
Wettzell	0.96	23.8	13.9
Kokee Park	0.96	2.1	7.4
Comparison WVR–VLBI			
Onsala	0.95	–0.5	6.9
Wettzell	0.95	24.8	14.8
Kokee Park	0.94	8.1	9.1
Comparison WVR–combination GPS/VLBI			
Onsala	0.98	2.2	6.0
Wettzell	0.96	21.9	10.1
Kokee Park	0.96	–0.9	7.4

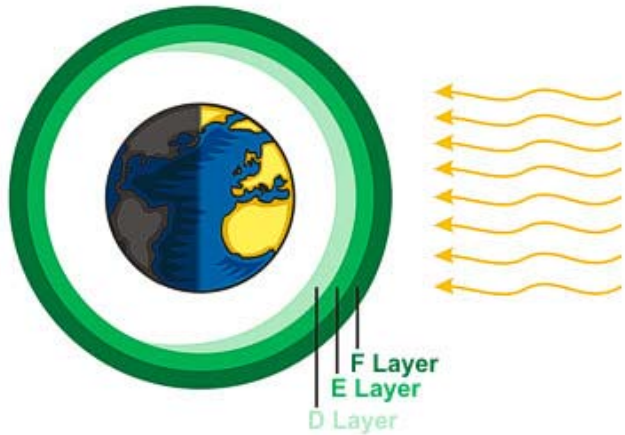
ZWD[mm] Onsala



- Temporal variations of WVR and ZWD agree quite well – still unexplained biases → extensive validation with WVR is currently not possible.
- Horizontal gradients are useful for an independent validation of horizontal local tie components.
- Tropospheric parameters should be used for the validation of local ties and be included into the combination.

Ionosphere products

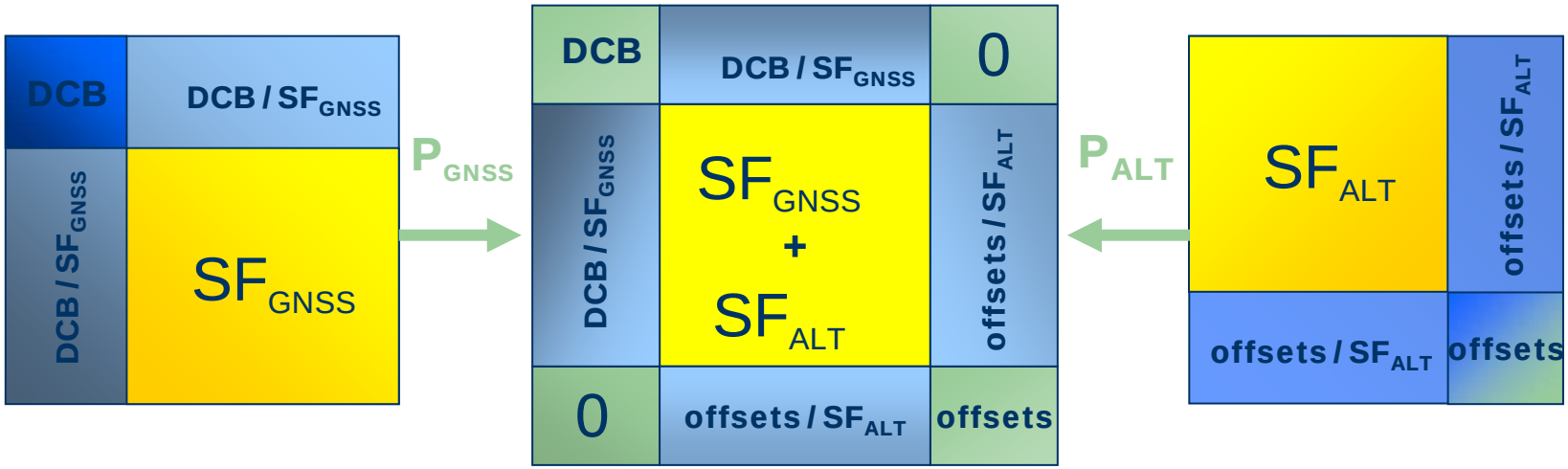
- Combined global ionosphere maps (GIM)
  - Input observations:
    - GNSS – GPS, GLONASS
    - Satellite Altimetry
    - DORIS
    - VLBI
    - CHAMP
    - COSMIC/FORMOSAT-3



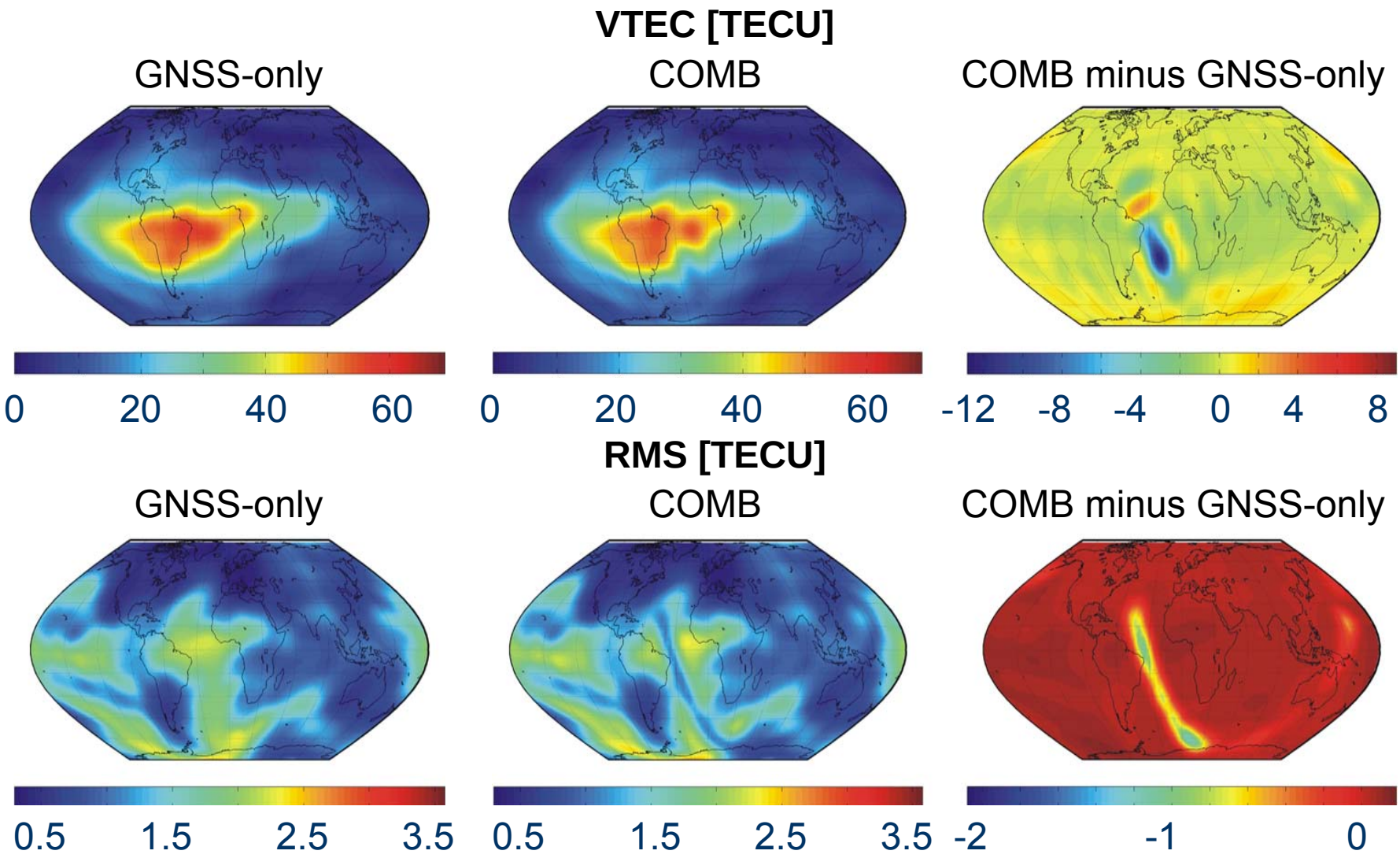
- Parameters to be combined:
  - Vertical total electron content (VTEC)
  - Technique specific instrumental biases (like DCB)

Recent studies – ionosphere combination

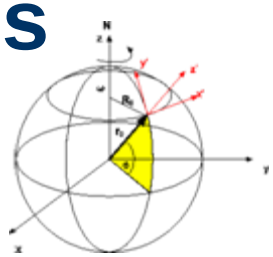
- **Todorova et al. 2007**: “Using the Global Navigation Satellite System and Satellite Altimetry for combined Global Ionosphere Maps”, (Advances in Space Research)
- Combination approach (software COMBION):



IGG Global Ionosphere Maps, GNSS-only and combined solution (doy 22, 2005, 17:00UT)

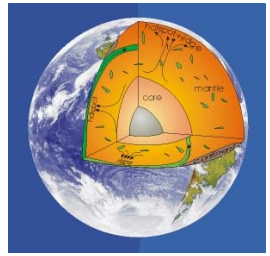


Station coordinates and velocities

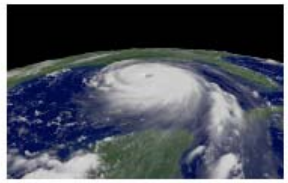


- Low resolution:
  - ITRF2005 (combination by CATREF): combination of coordinate time series (weekly from satellite techniques, 24 h session wise from VLBI), consistent with EOP (combination only w.r.t. polar motion)
- Higher resolution: daily coordinate time series → new future product?
  - Possible input observations: VLBI, satellite techniques
- Rigorous combination including EOP, troposphere parameters, and CRF.

Gravity – Geometry – Earth rotation

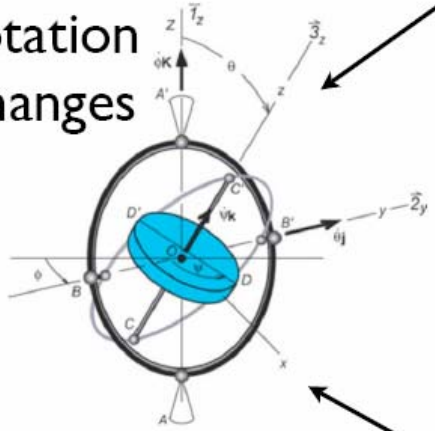


Inter-relations

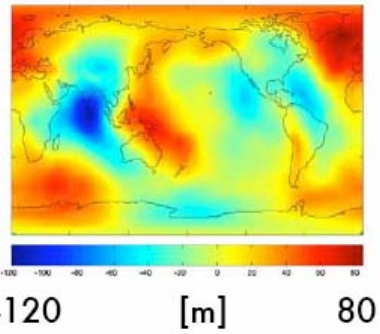


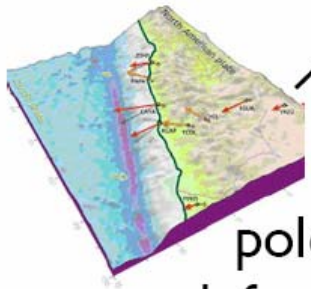
surface mass redistribution

Earth rotation changes



geoid variations





relative angular momentum fields

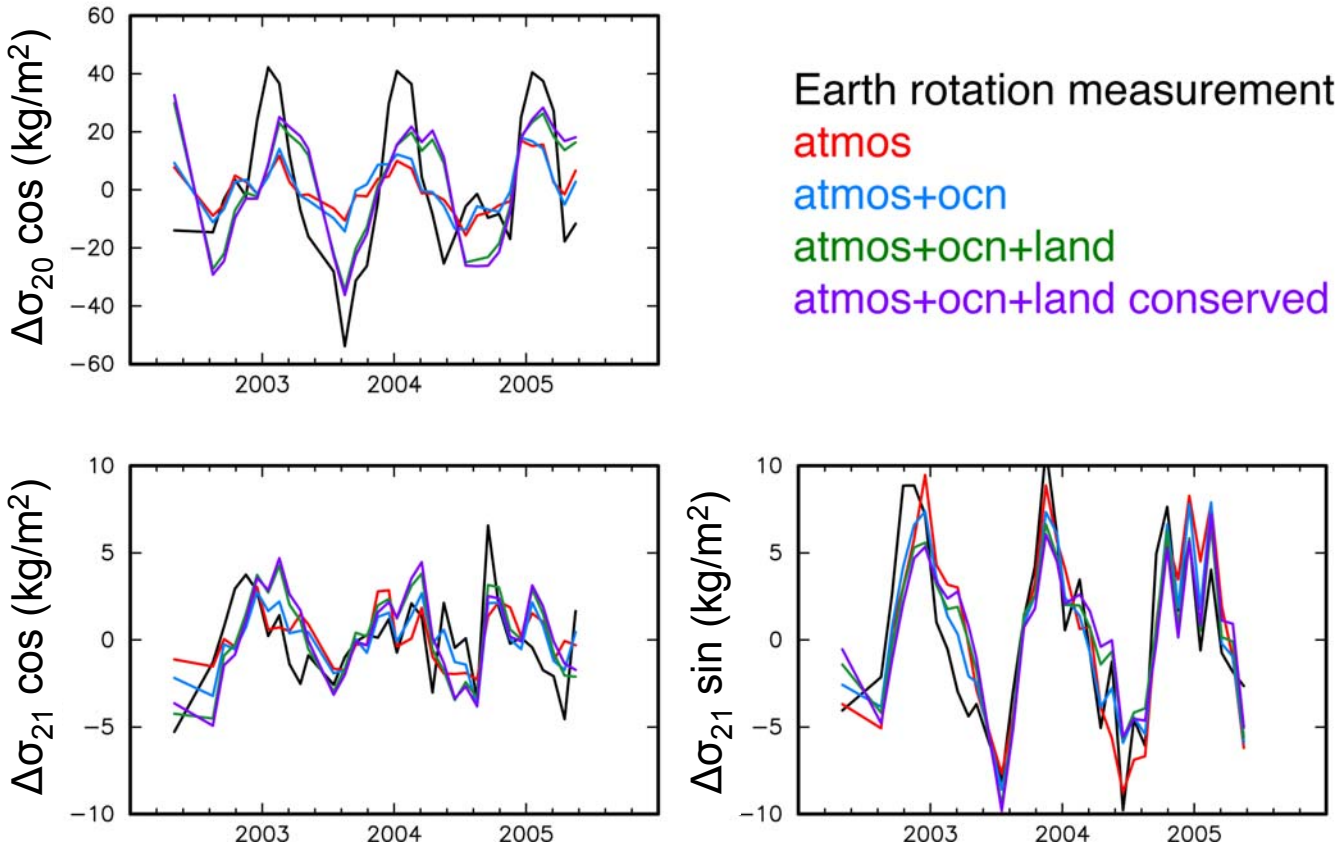
poloidal deformation

Comparison/Integration of geodetic measurements and geophysical models

- Measurements:
  - CHAMP, GRACE, ...
  - Terrestrial gravimetry (absolute and superconducting gravimeters)
  - Earth Rotation (GPS, VLBI, ...)
  - Global deformation (GPS, ...)
  - Geocenter (SLR)
- Models (for determination of spherical harmonics):
  - Atmospheric surface pressure
  - Ocean bottom pressure
  - Land hydrology
  - Global surficial fluid mass conservation
- Recent studies – Surface mass variations
  - **Gross et al. 2007**: ”Low-degree surface mass loads estimated from geodetic measurements and geophysical models.” EGU 2007
  - **Wu et al. 2007**: “Solid Earth signatures of surface mass variations and improved global monitoring using multi-satellite data combination.” EGU 2007

Earth rotation & models

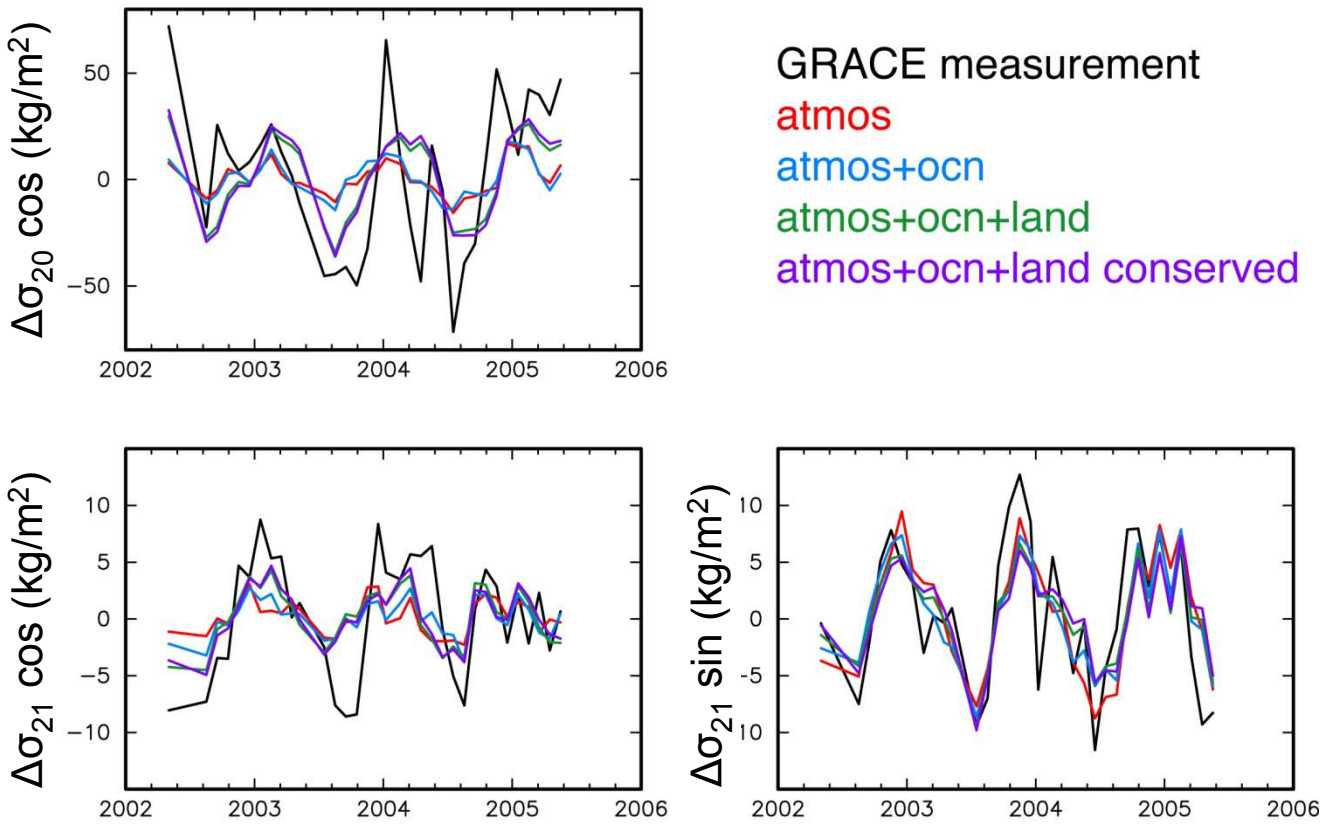
degree-2 mass load coefficients



By courtesy of Richard Gross (EGU, 2007)

Gravity & models

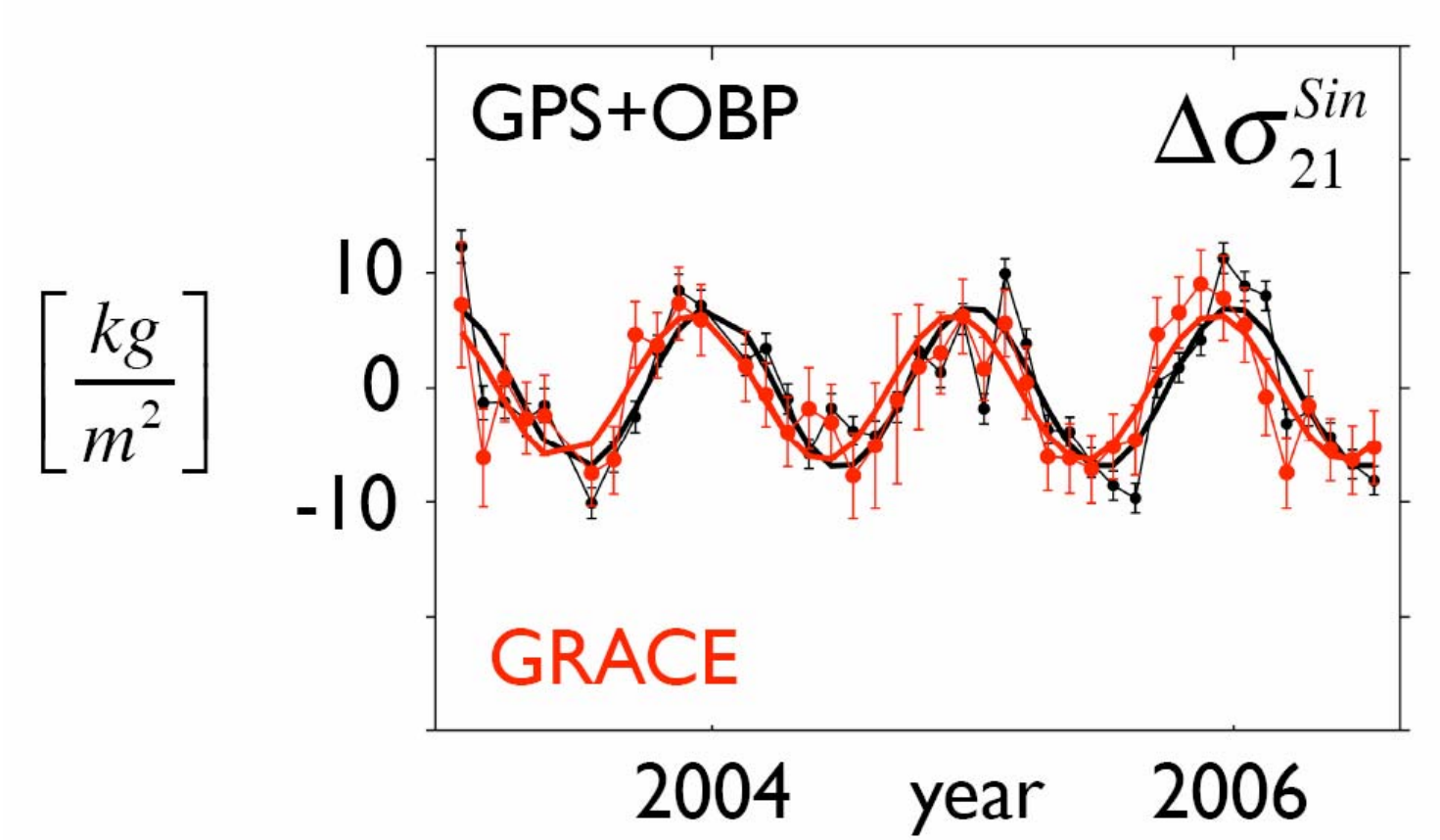
degree-2 mass load coefficients



By courtesy of Richard Gross (EGU, 2007)

GPS/OBP & GRACE

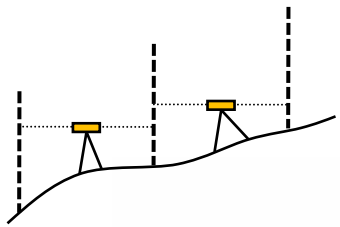
tesseral sine degree-2 load

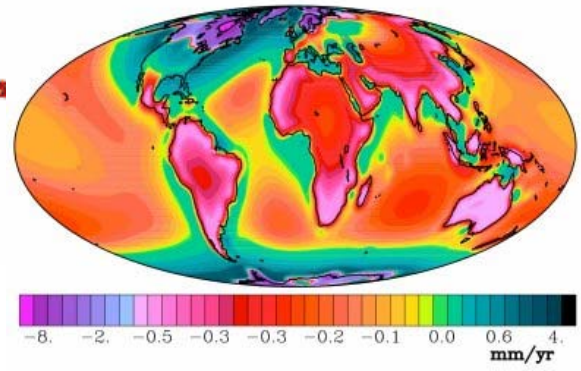


By courtesy of Xiaoping “Frank” Wu (EGU, 2007)

Global height reference and sea level change

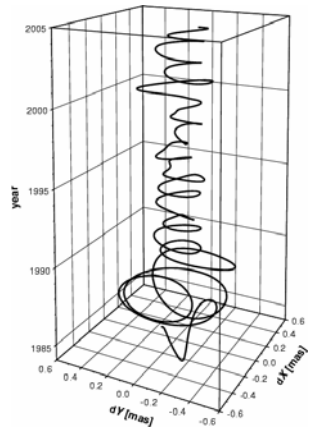
- Interlace global measurements:
  - Global geoid (by combination of various techniques)
  - Satellite altimetry
  - Tide gauges
  - GPS heights
  - Levelling
  - Satellite clocks



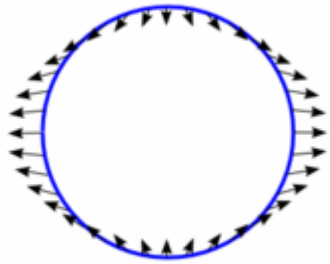


Geodynamic parameters

- Free core nutation (FCN)
  - Parameters: period, Q, resonance strength
  - Deduced from observations of:
    - VLBI nutation
    - Gravity tides
    - Tidal displacements



- Love and Shida numbers
  - Deduced from observations of:
    - VLBI, GNSS, SLR: tidal site displacements
    - Gravity tides



Further...

- Combination of celestial reference frames:
  - Inertial reference frame
  - Dynamical reference frame (LLR)
  - ➡ Frame tie
- Combination of satellite orbits
- Combination of geocenter coordinates
  - Satellite techniques
  - Global absolute gravimeter (AG) network
- Relativity parameters:
  - Lense-Thirring (SLR, LLR), space curvature (LLR, VLBI)

Conclusions

- Recent **studies on comparison** of results of different techniques show great potential for combination
- Work on **NEQ-combination** done so far demonstrates the feasibility and expedience of the inter-technique combination

- **Standardized observation information** of the different techniques will have to be provided by the corresponding services
- **Institutions/services** have to be identified to generate and allocate the products (combination centers?)

Further aspects and ideas

- Possible clients?
- Time frame for generating the new products
- Possible resolution today / in the future
- Possible accuracy of the products
- Checking the technical feasibility by campaigns and pilot projects (e.g. CONT08)

Programme Session 5

15:30 – 15:50 H. SCHUH and S. ENGLICH

New products based on inter-technique combinations – An overview

15:50 – 16:00 E. PAVLIS

New ILRS products available now and in the near future

16:00 – 16:10 J. MÜLLER

LLR perspectives

16:10 – 16:20 G. TAVERNIER

The role of DORIS in inter-technique combination

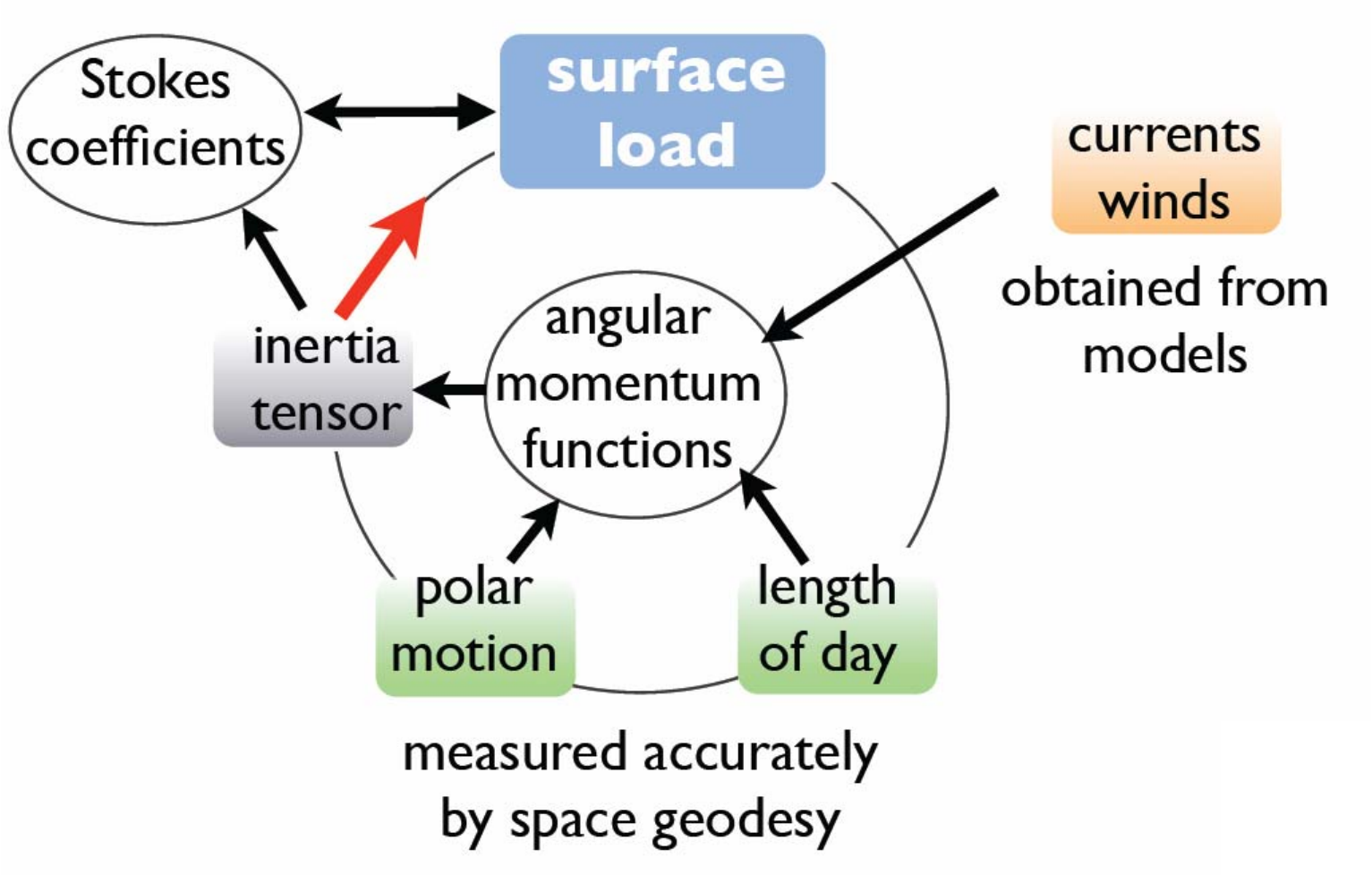
16:20 – 16:30 V. TESMER

Comparison and combination of long troposphere time series from GPS and VLBI

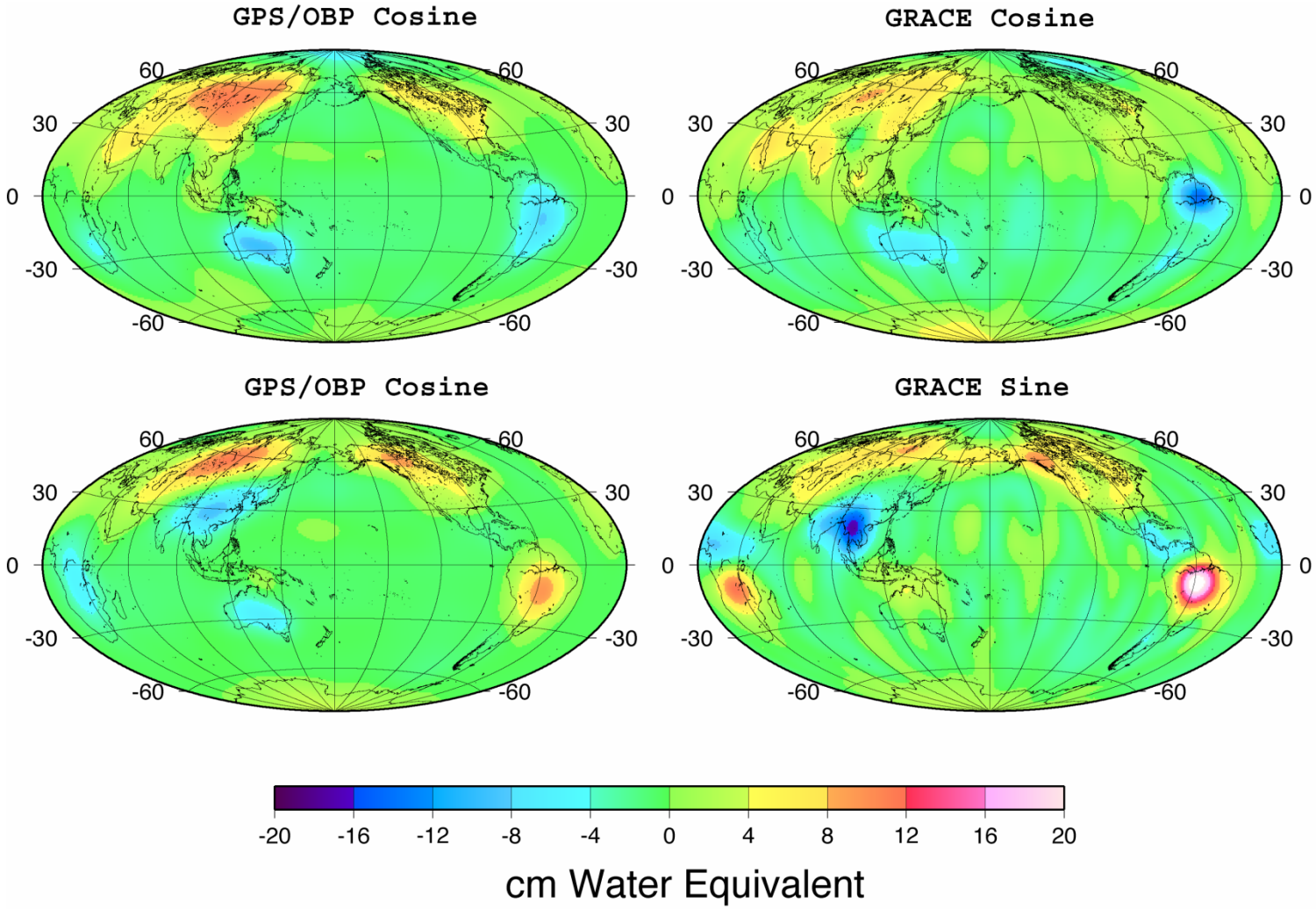
16:30 – 17:00 DISCUSSION, ACTION ITEMS


THANK
YOU!
F Layer
E Layer
D Layer

Gravity – Geometry – Earth rotation



GPS/OBP & GRACE



By courtesy of Xiaoping “Frank” Wu (EGU, 2007)