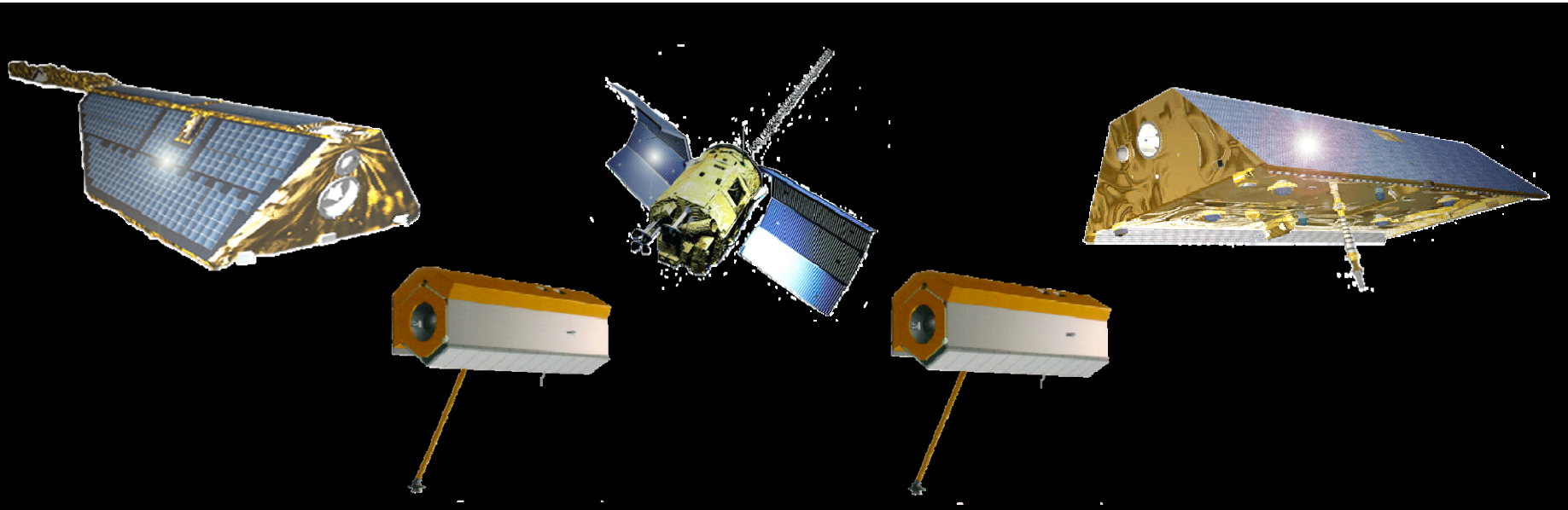
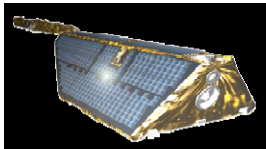


# CHAMP, GRACE, SAC-C, TerraSAR-X/Tandem-X:

## Science results, status and future prospects

*J. Wickert, C. Arras, C.O. Ao, G. Beyerle, C. Falck, L. Grunwaldt, S.B. Healy, S. Heise, A. Helm, C.Y. Huang, N. Jakowski, R. König, T. Mannucci, C. Mayer, G. Michalak, M. Rothacher, T. Schmidt, R. Stosius, B. Tapley*

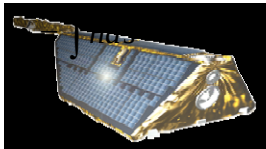
DLR JPL Center for Space Research CSR The University of Texas at Austin GFZ Potsdam



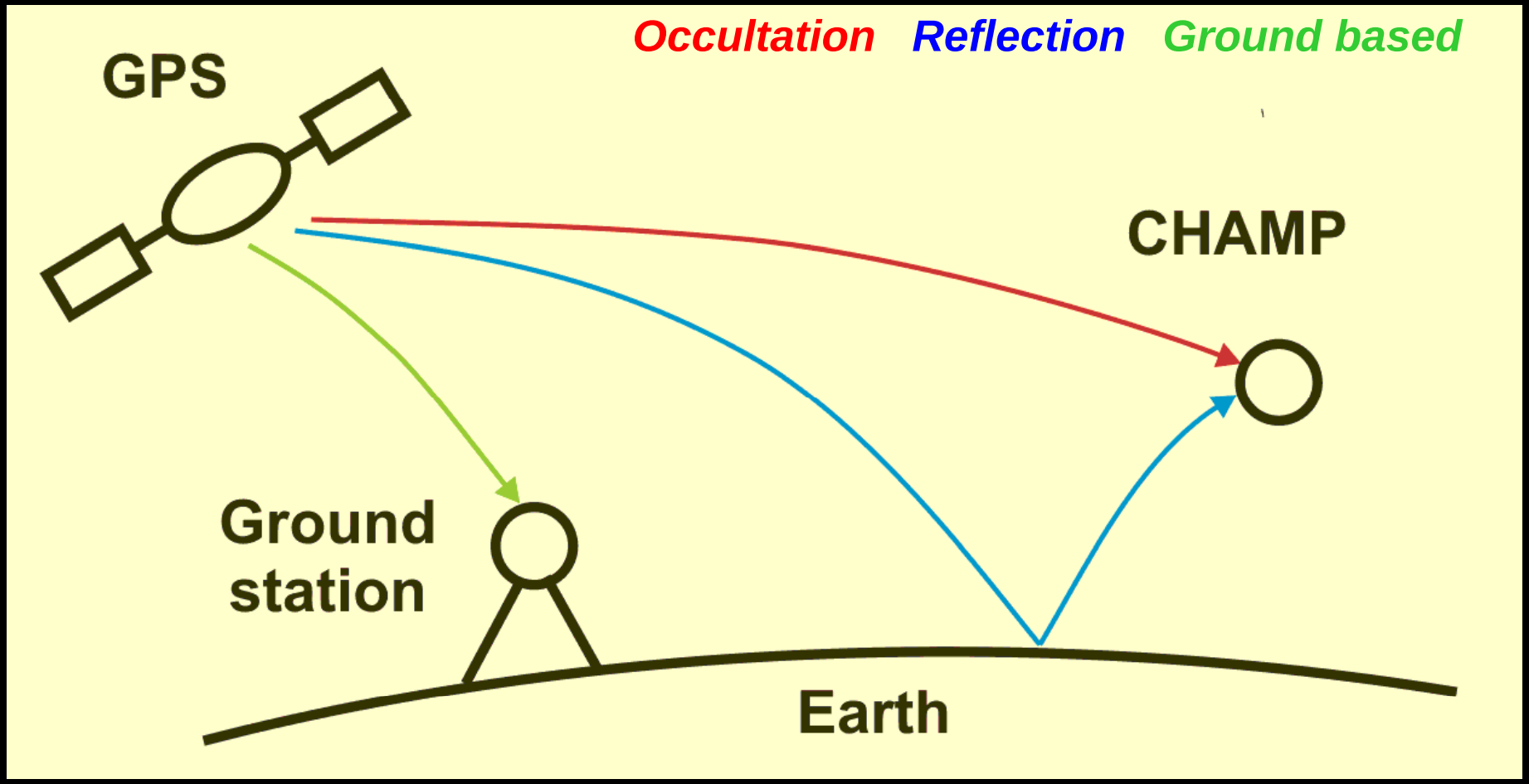
# *Content:*

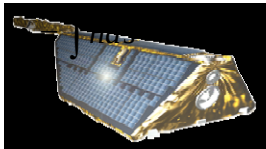
- *Intro*
- *CHAMP*
- *GRACE*
- *SAC-C*
- *TerraSAR-X/Tandem-X*
- *Future prospects*

# *Atmosphere sounding with GPS*

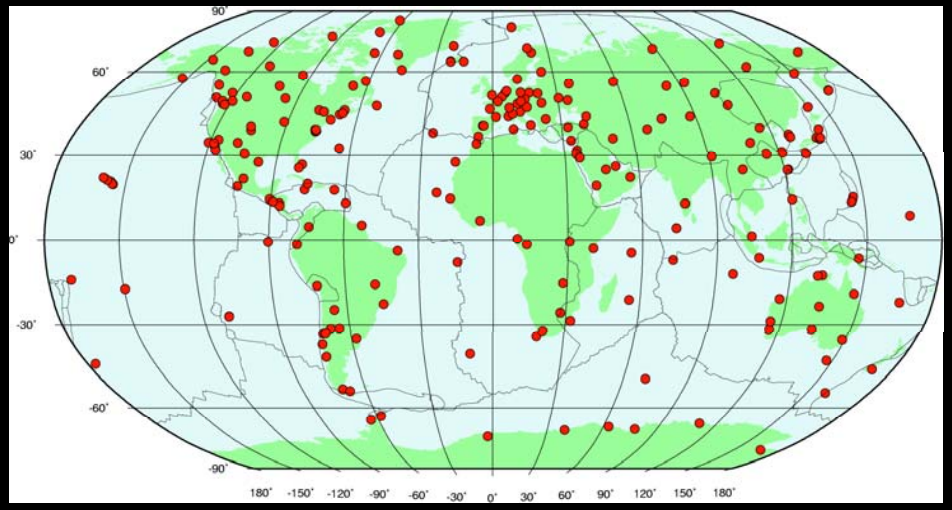


# GPS remote sensing at GFZ

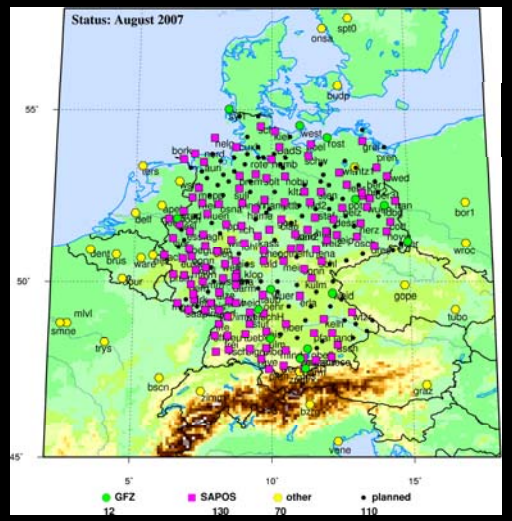




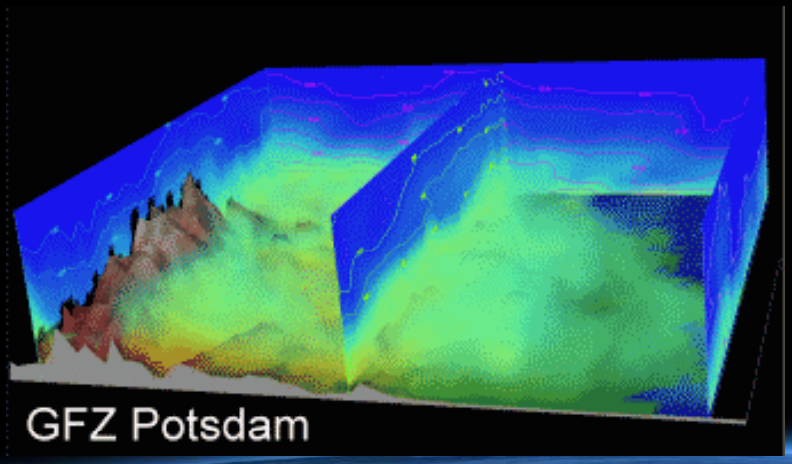
# E.g., ground based GPS at GFZ




*Global ~200 stations (IGS Network)*



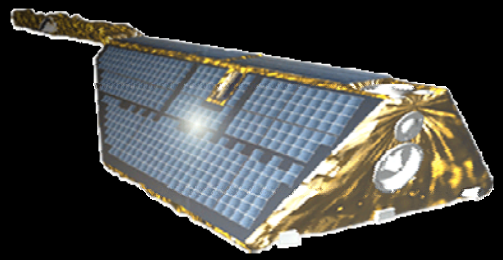

*Regional ~230 stations (Germany)*



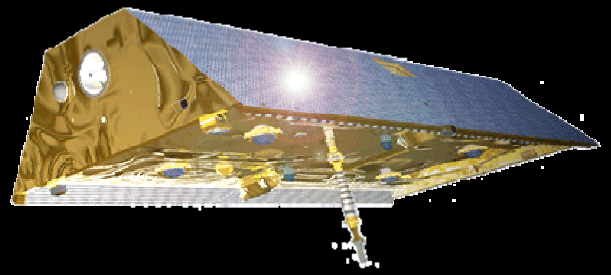

*Research project:*
*Operational GPS Tomography*

# *Space based sounding (Radio occultation)*

# GNSS receivers for occultations on satellites

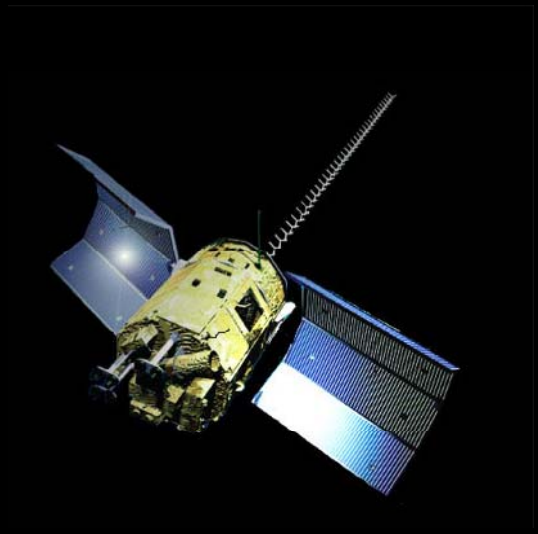


CHAMP (since 2000)

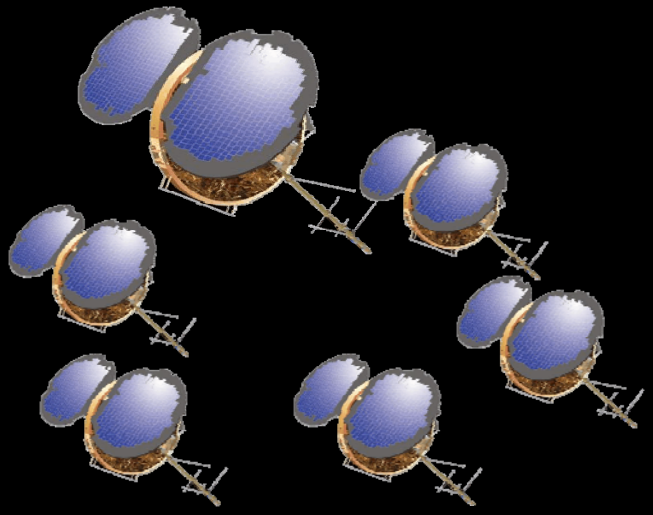


GRACE (since 2002)

TerraSAR-X (2007)
Tandem-X (plan 2010)

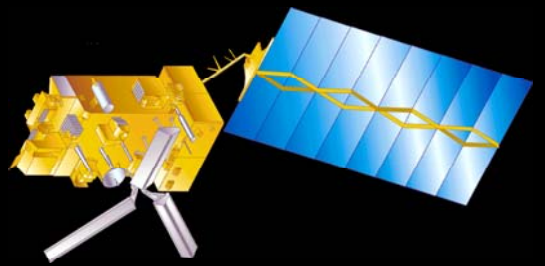


SAC-C (since 2000)



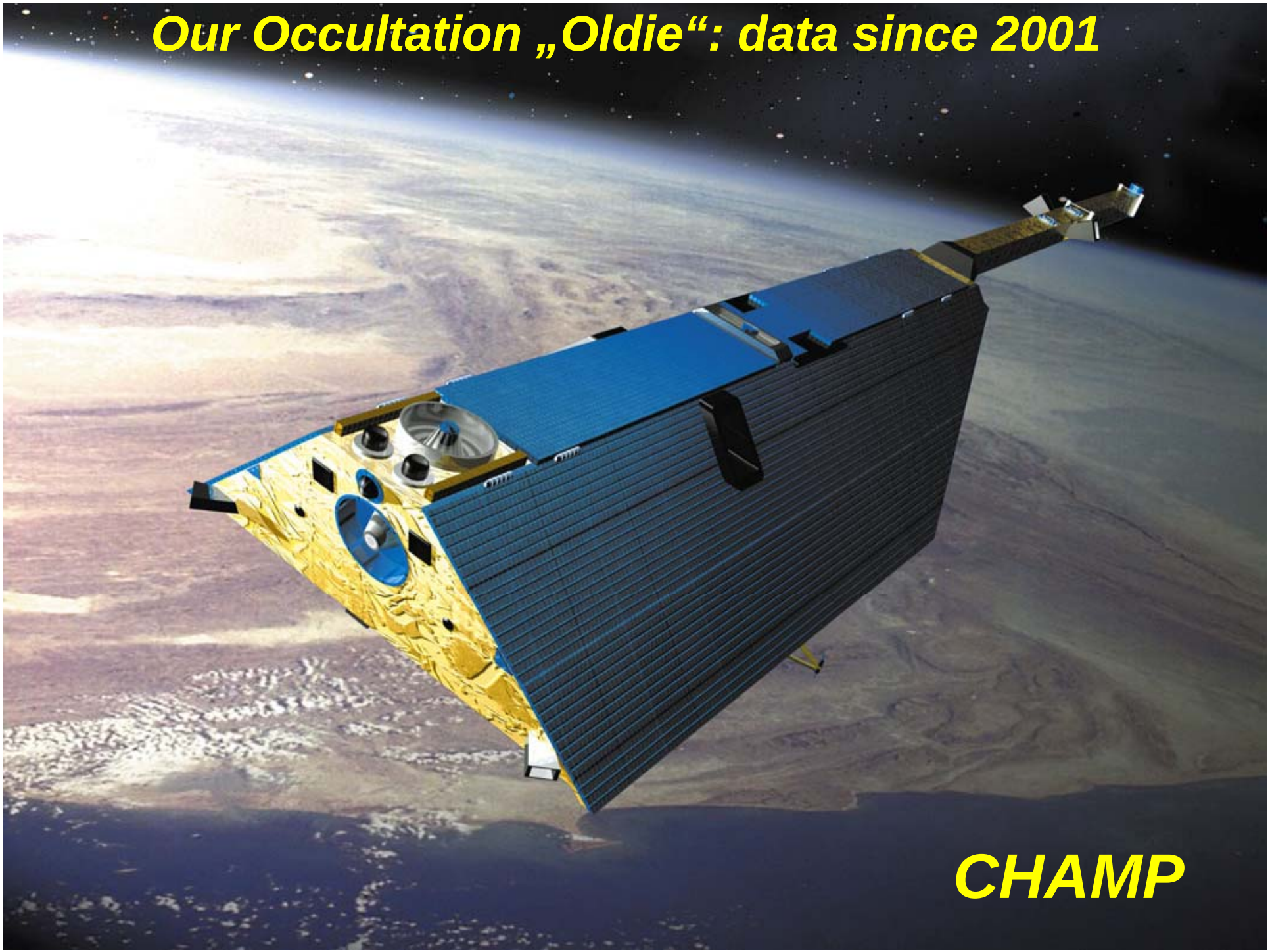
COSMIC (6; since 2006)

GFZ

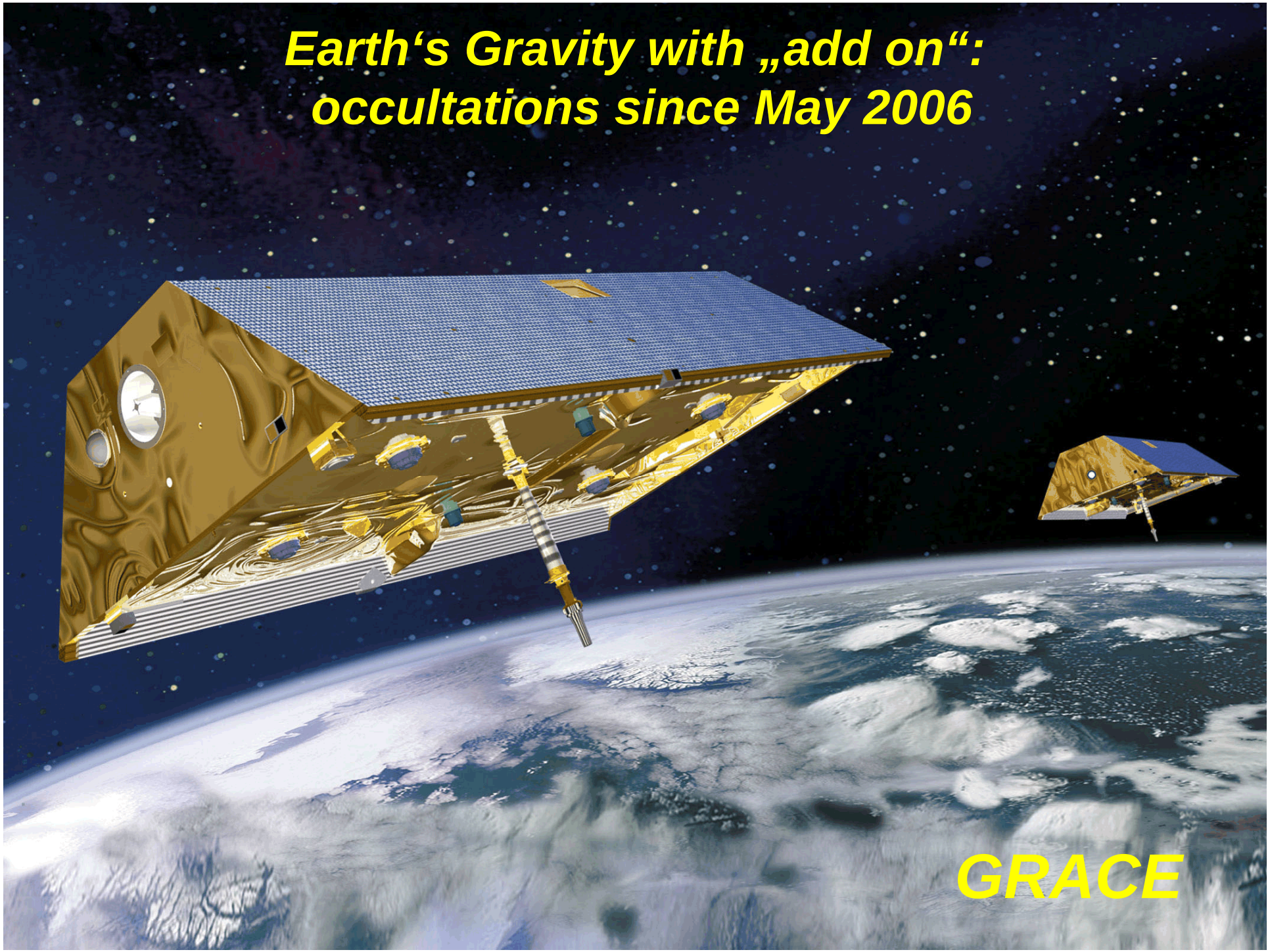


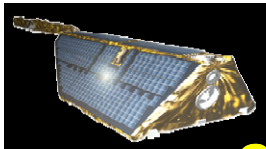
Metop (since 2006)

# Our Occultation „Oldie“: data since 2001



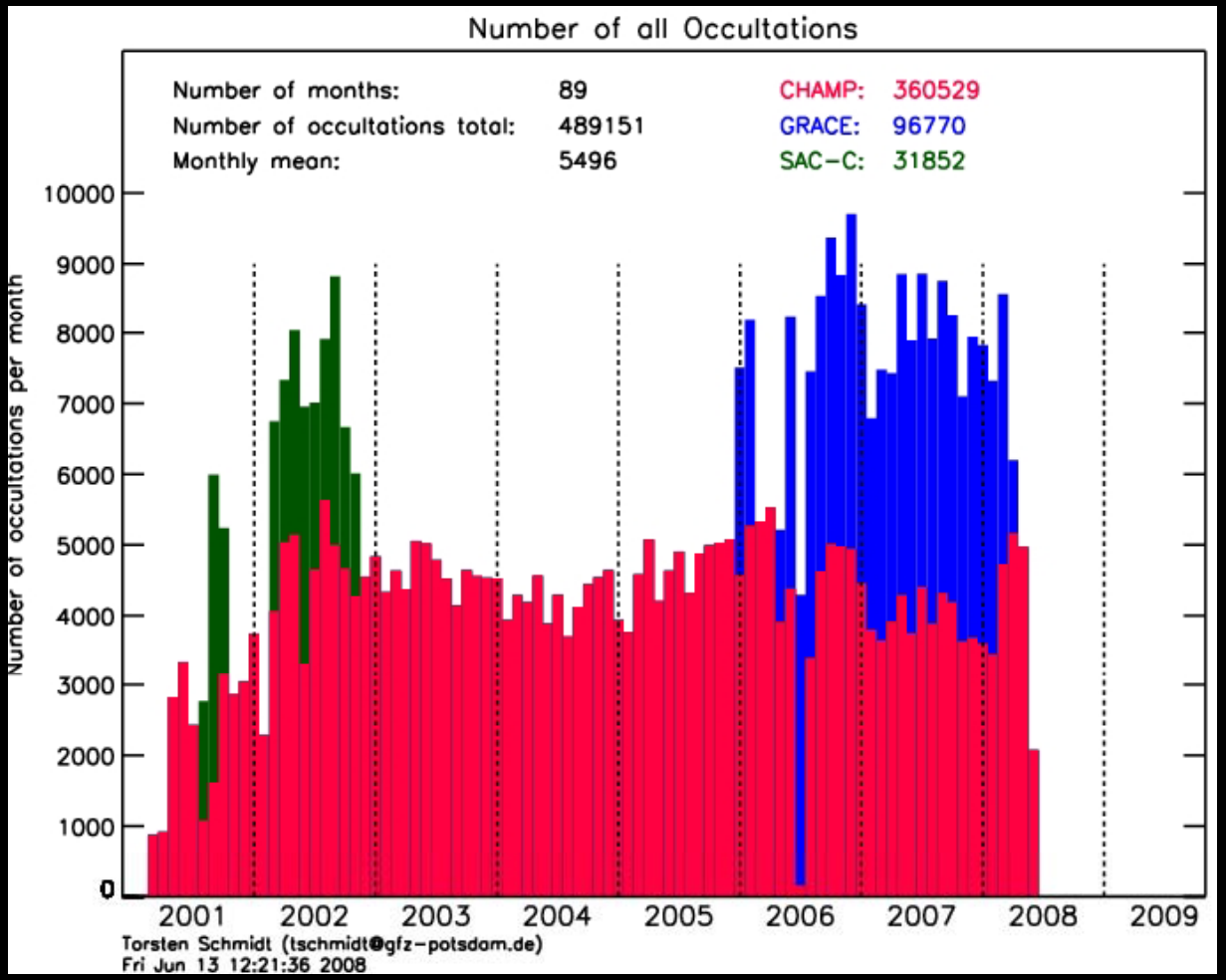
# *Earth‘s Gravity with „add on“: occultations since May 2006*



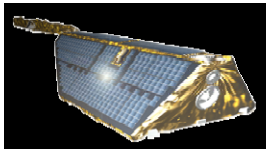


# Occultations 2001-2008

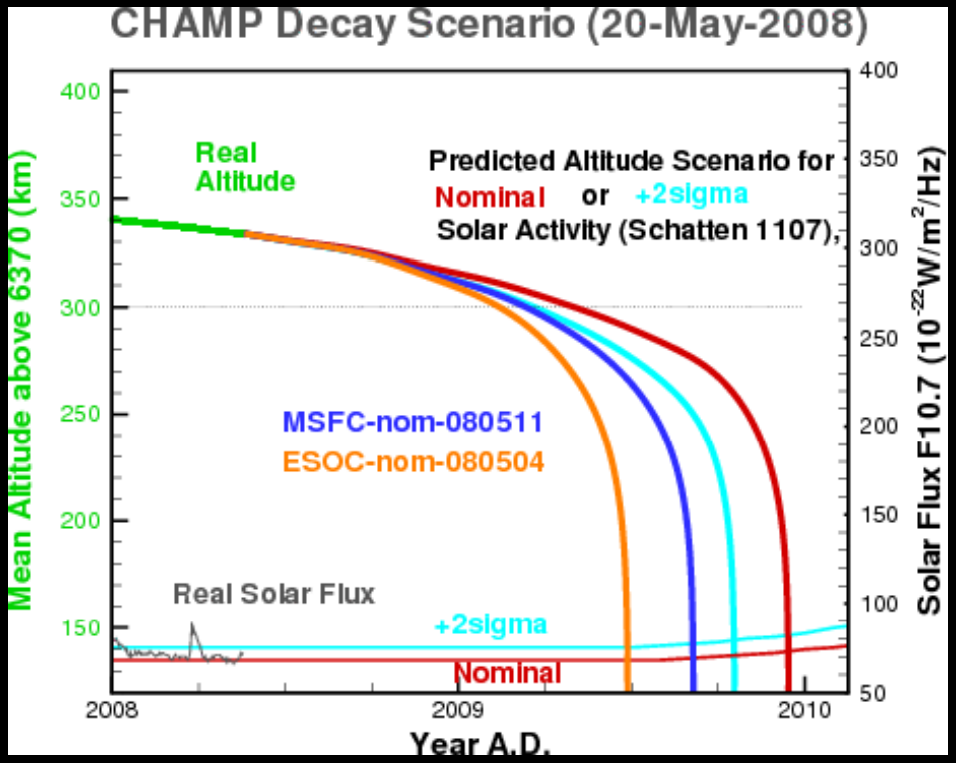
## complete GFZ processing chain from raw data




**First long-term RO data set from CHAMP**

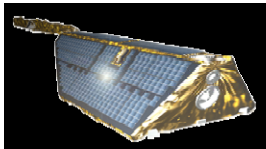


# Good job CHAMP! Bye Bye soon

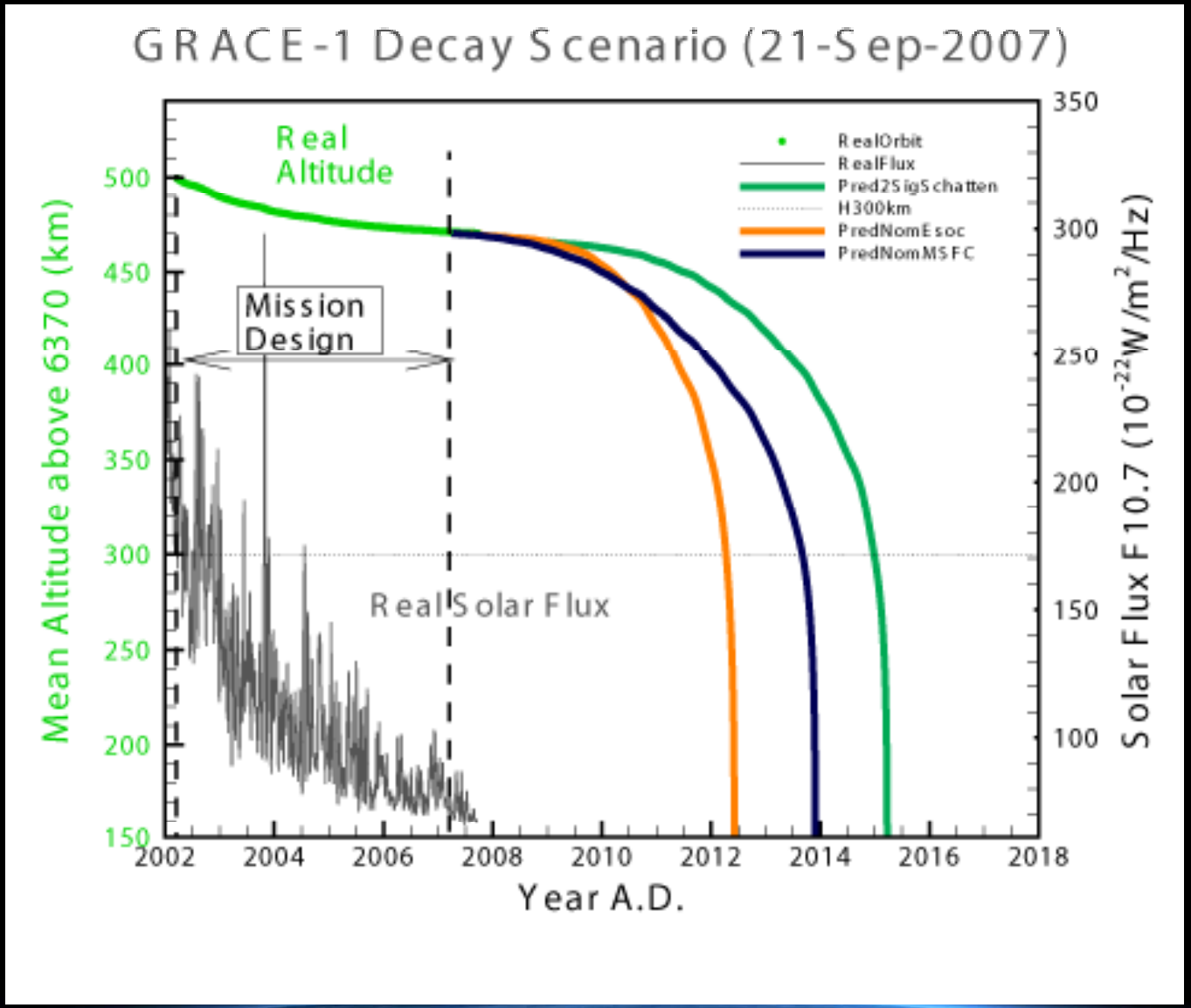



*Estimated live-time: September 2009 (5 years was nominal LT)*

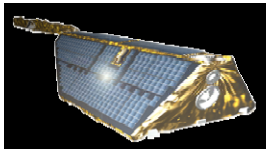
*But there is some cold gas (~3 kg), Orbit manoeuvre planned for spring 2009 (uplift) prolongation until end 2009 seems to be feasible*

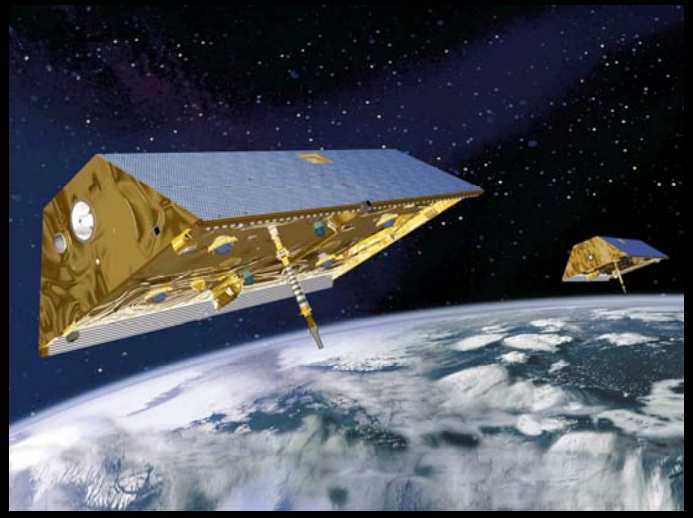


# GRACE decay scenario



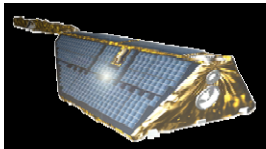
# *Science results CHAMP (examples)*

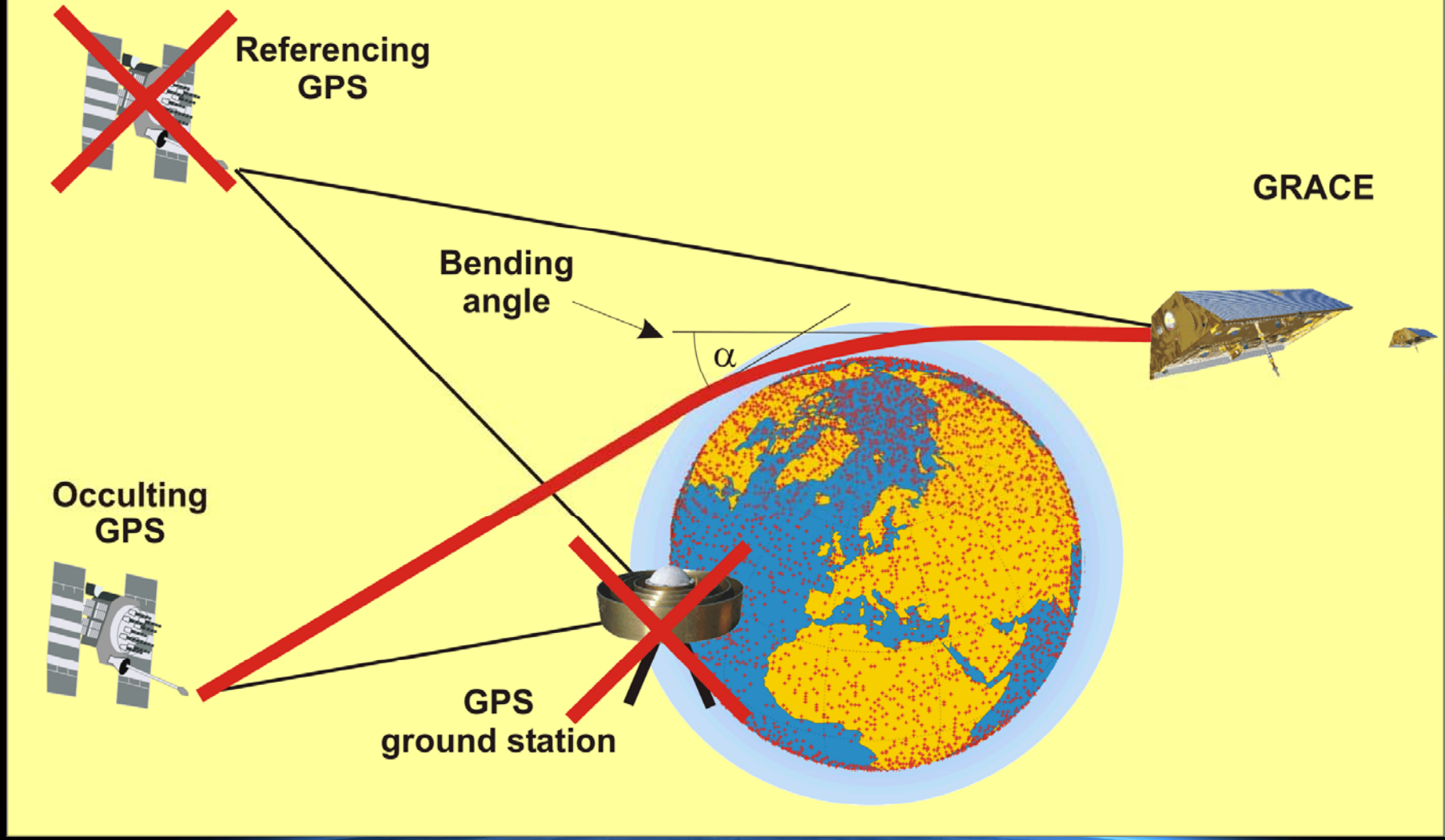


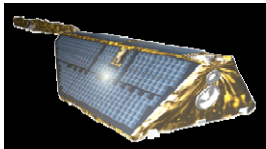


# GRACE processing: Zero Differencing

# Zero differencing
# (no more reference links!)

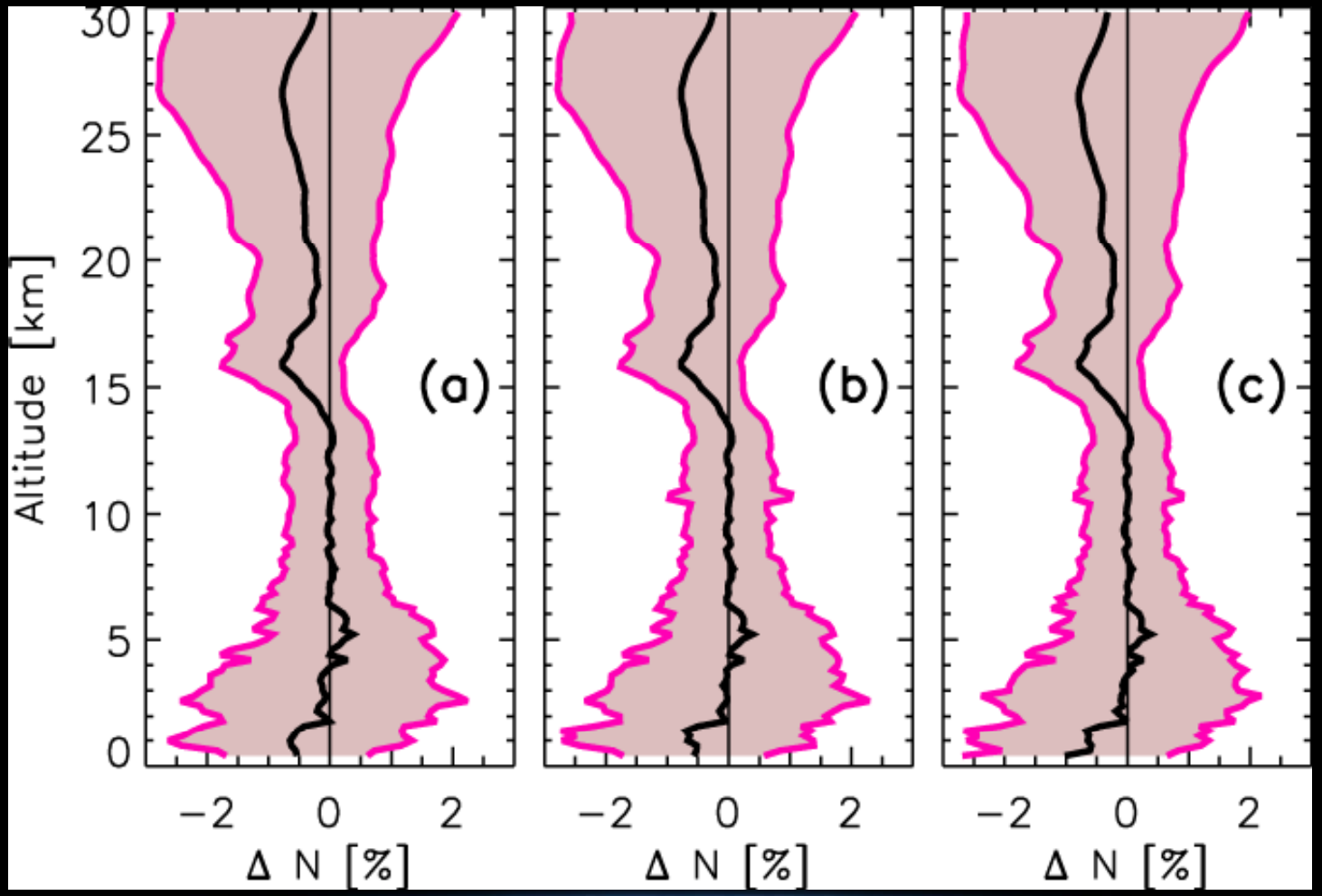






# Zero Differencing: GRACE-B

*Deviations in relation to ECMWF (96 profiles)*

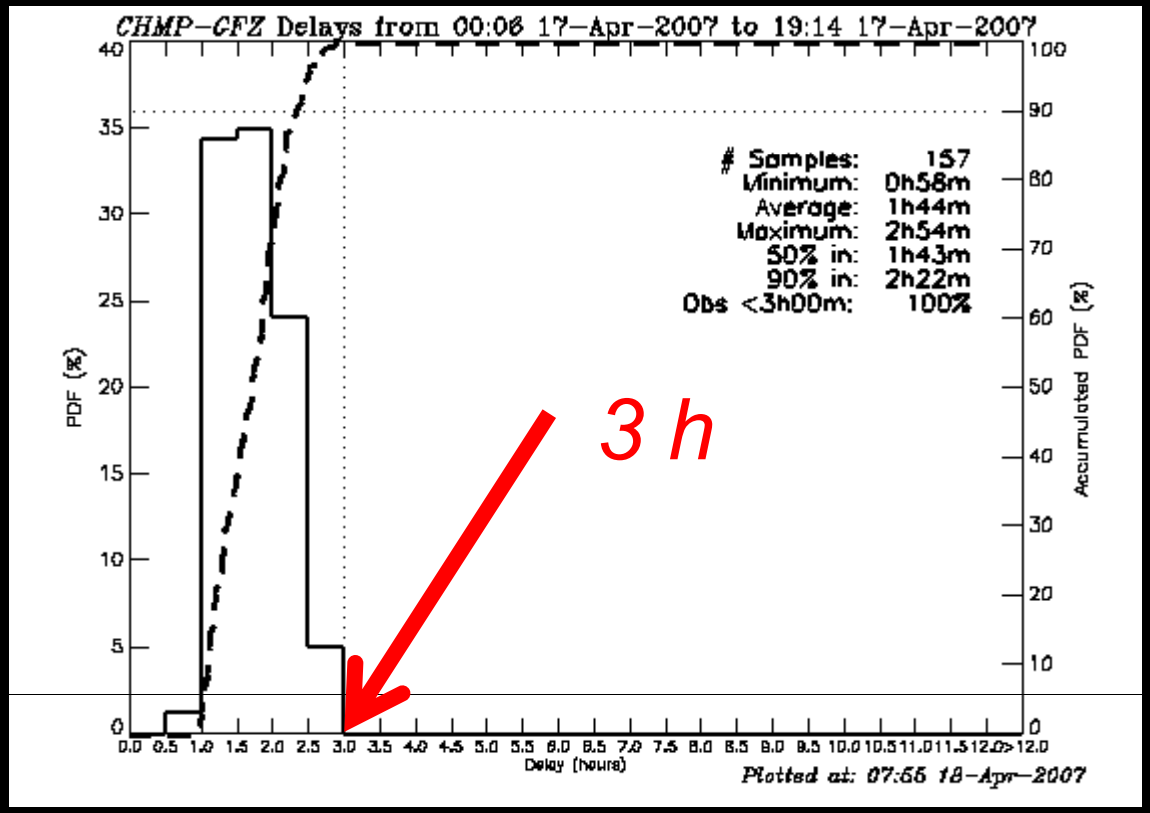



*Differencing a) double b) single c) zero*

# *NRT data and weather forecast*

# 2 GFZ antennas at Ny Alesund

# NRT data from CHAMP

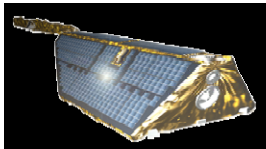



*Monitoring by GRAS-SAF at Metoffice*

*(for April, 17)*

*Average delay of 1h44,*

*100% of the data in 3h!*



# NRT data use CHAMP/GRACE-A

*MetOffice (U.K.) currently monitoring*

*ECMWF currently monitoring*

*JMA assimilating*

*MeteoFrance assimilating*

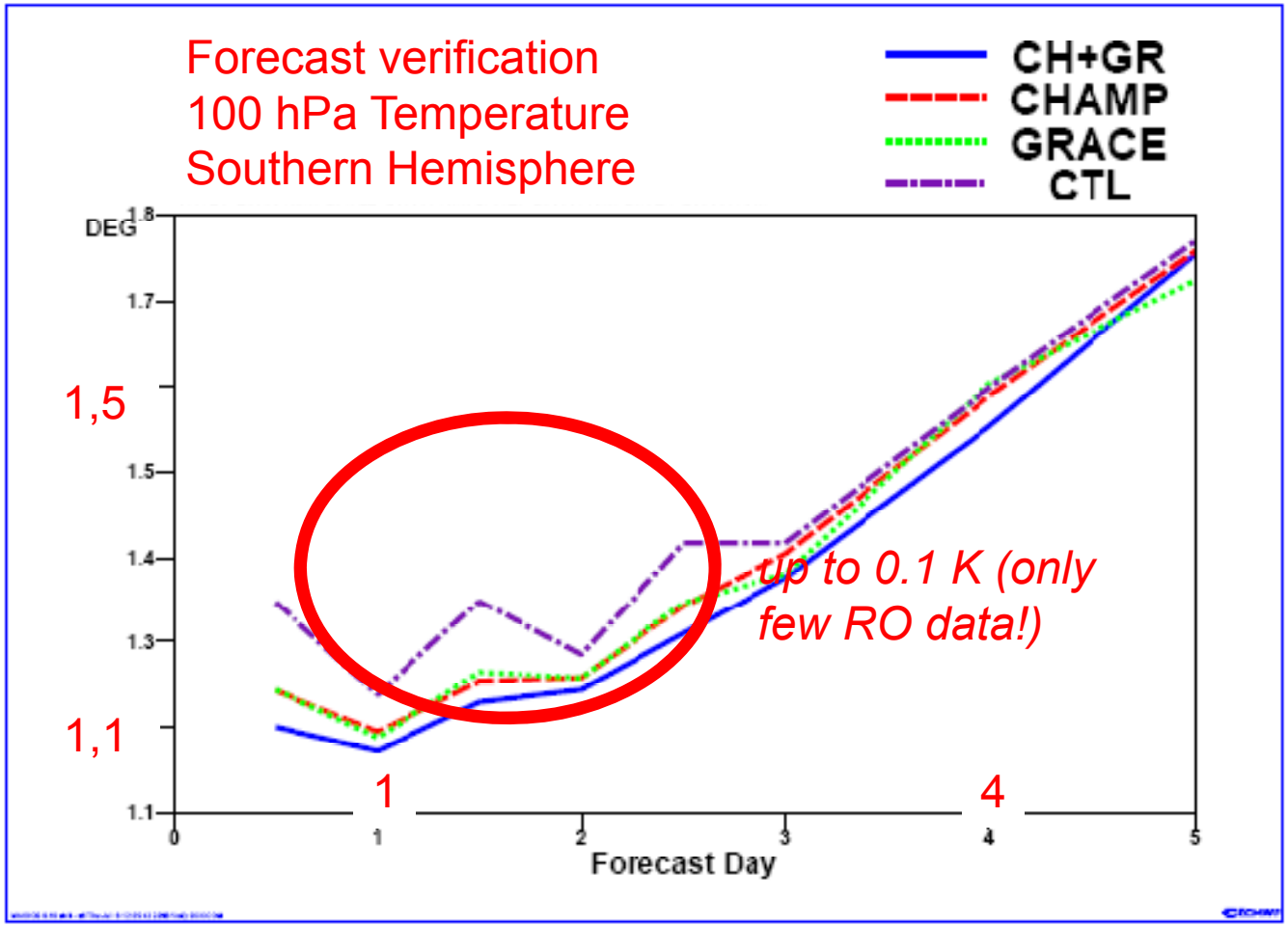
*DWD monitoring*

*NCEP monitoring*

*Kanada monitoring*

# Improvement of global forecasts (ECMWF)

*(CHAMP + GRACE-A, Jan/Feb 2006)*



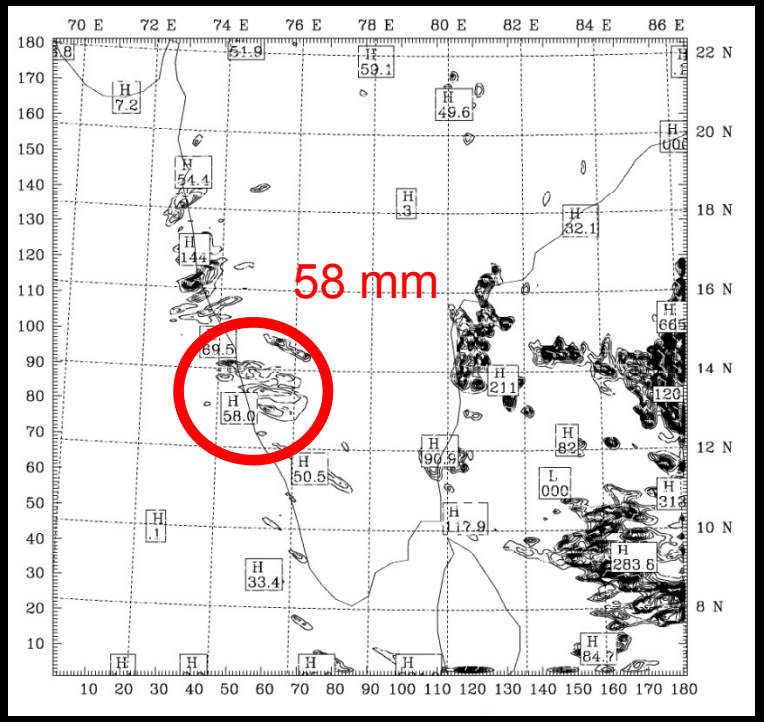

*Healy et al., ASL, 2007*

# Precipitation forecast India Monsoon 2002

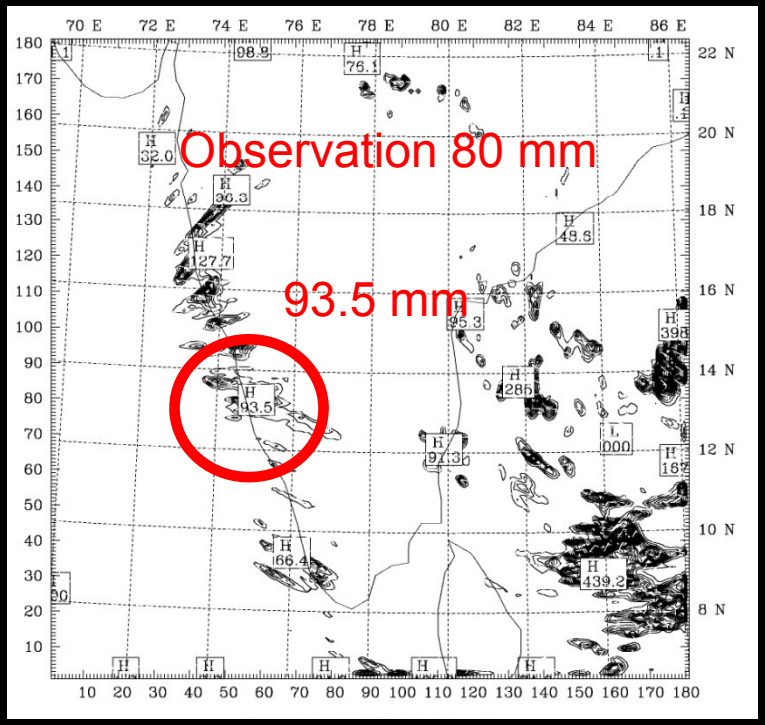
*10 CHAMP 3 SAC-C occultations 3dvar WRF, NCU*

*accumulated 24-48 h precipitation*

*Control*

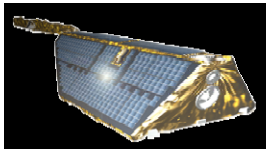



*+ 13 GPS RO*

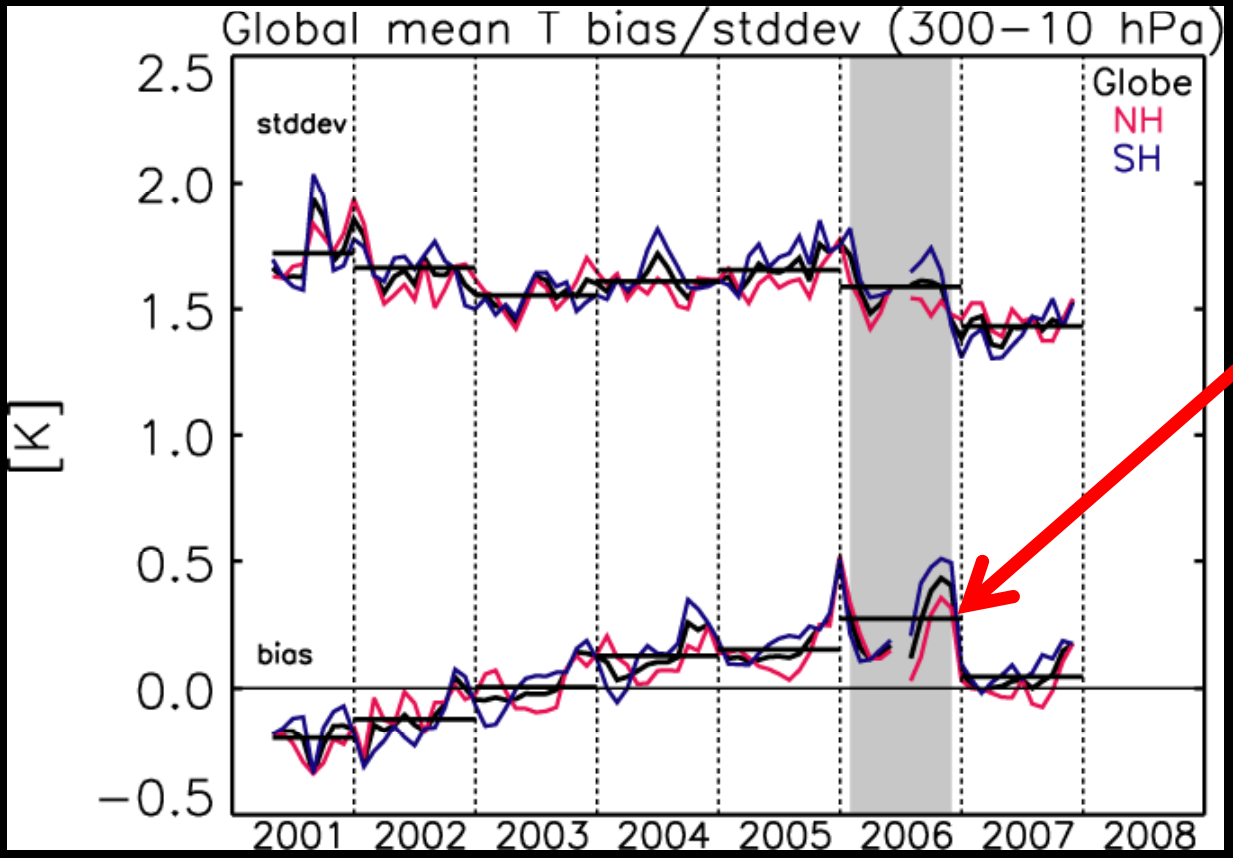



*Underprediction of rainfall 2nd day at west coast improved*

*For details see Huang et al., 2006*



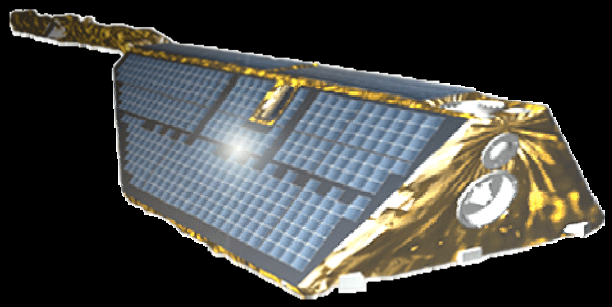
# GPS RO improves ECMWF analyses




***Begin assimilation GPS RO***

*Monthly mean temperature bias and stddev between CHAMP and ECMWF for the pressure (altitude) range 300 -10 hPa*

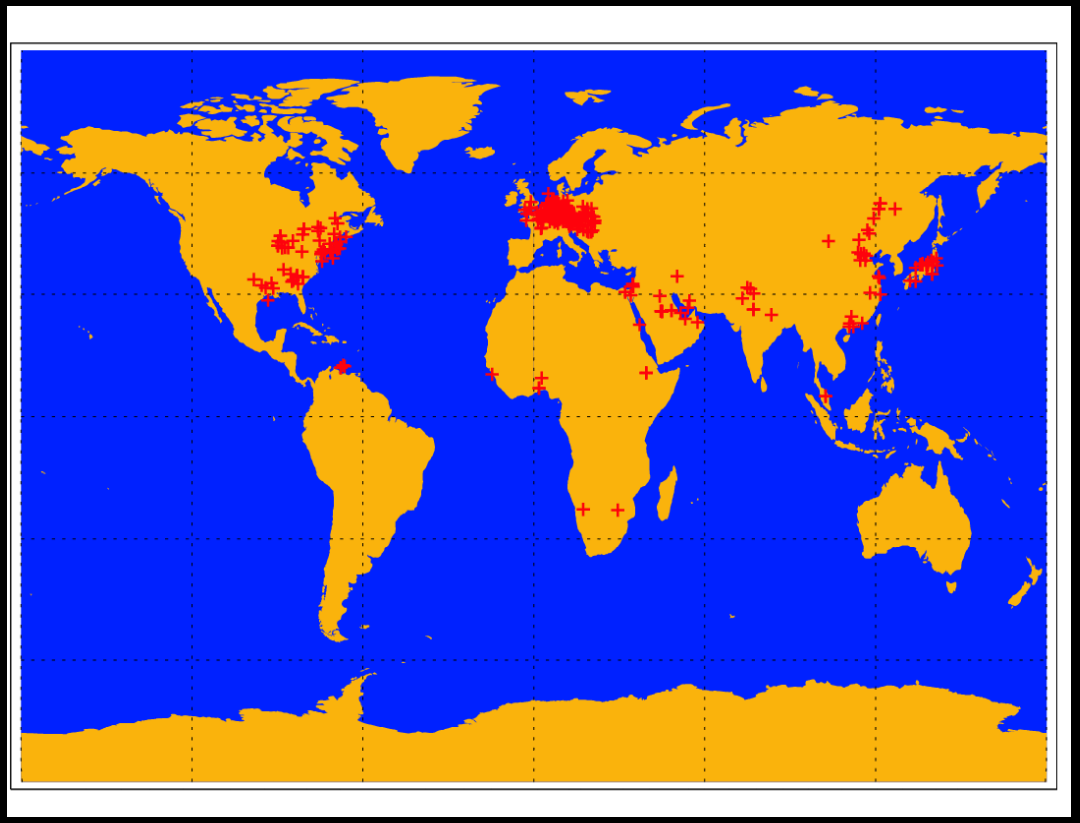
*Schmidt et al., 2008*




# Comparison CHAMP with MOZAIC data


***Recent and unique validation study, Heise et al., 2008***

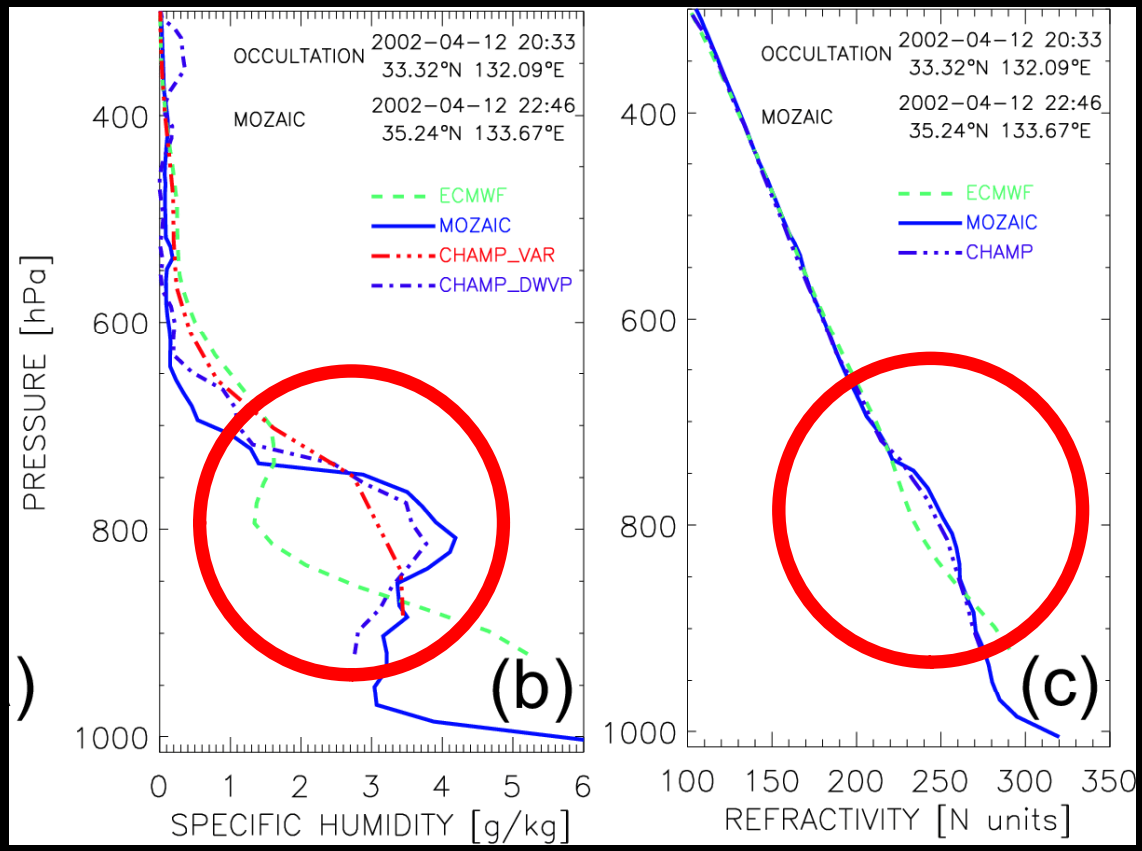
# Humidity comparisons



*Δt<3h, d<300 km, March 2001- March 2006,*
*324 coincidences found (MOZAIC, CHAMP)*
*Indicate the airport locations approached by the 5 aircrafts*

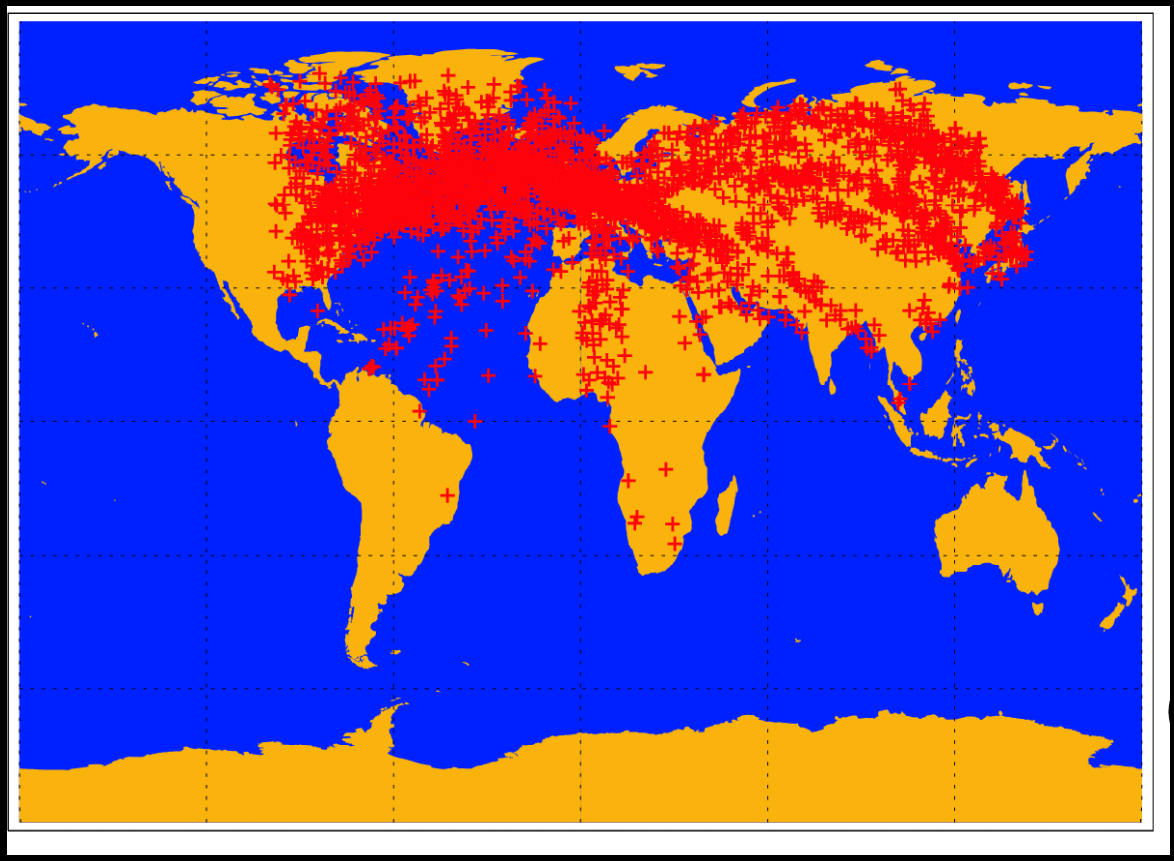
# Comparison example

*April 12, 2002; 20:33 UTC; 33.32°N 132.09°E*

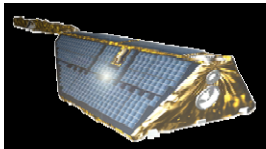



- *Temperature (not shown) MOZAIC and ECMWF in good agreement*
- *Refractivity agrees better with CHAMP compared to ECMWF (900-750 hPa)*
- *Corresponds to better agreement of humidity profiles MOZAIC/CHAMP*

# Refractivity and Temperature comparison

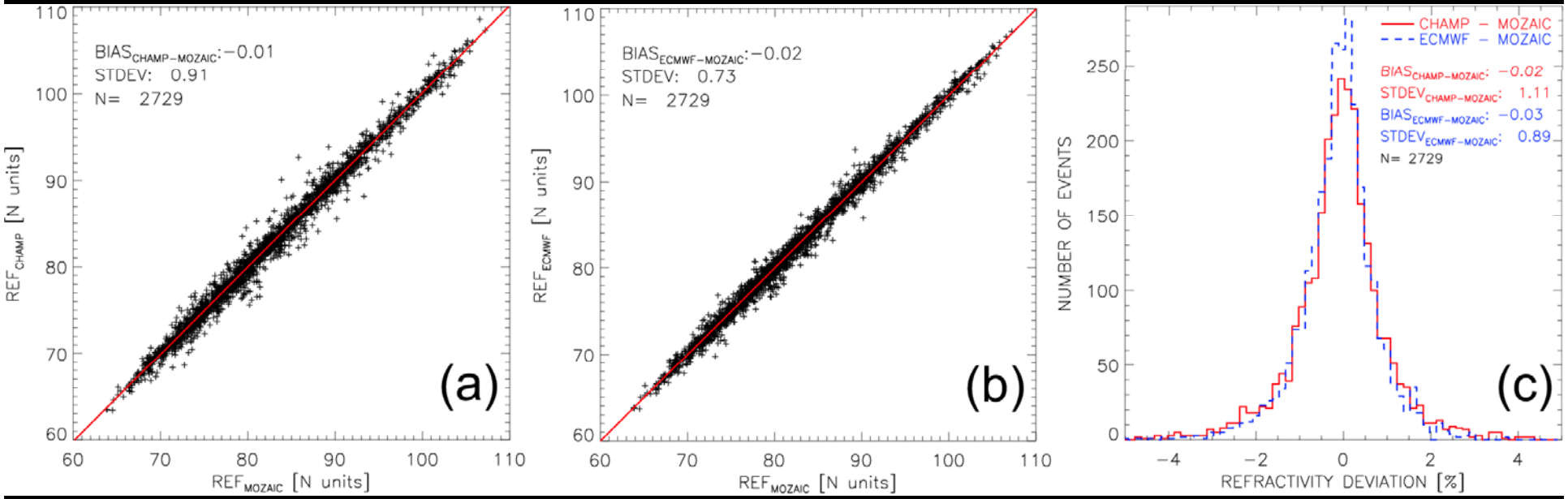


- $\Delta t<3h$, $d<300$ km, March 2001- March 2006
- 2700 coincidences used for comparisons
- (dry) temperature and refractivity, $h>300$hPa (dry air assumption)

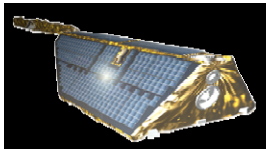


# Refractivity comparison (cruise)

**CHAMP-MOZAIC** **ECMWF-MOZAIC**



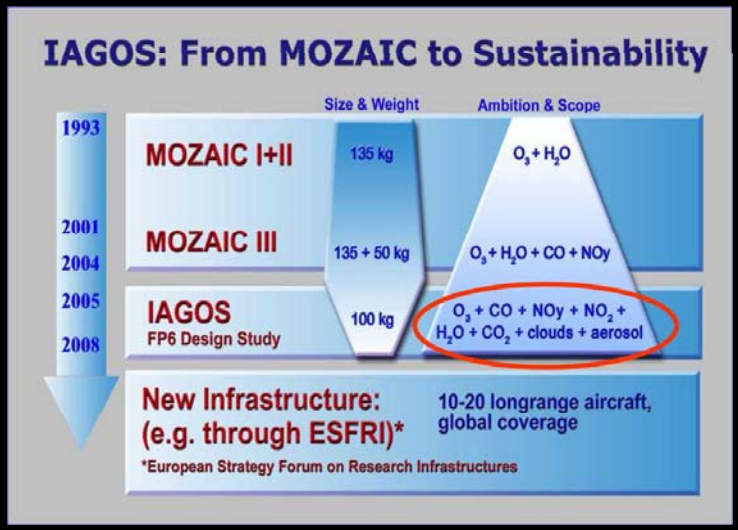

- *Excellent agreement of MOZAIC with CHAMP and ECMWF*
- *Comparison with CHAMP shows more scatter (assimilation of aircraft data to ECMWF, high accuracy in this region and altitude)*



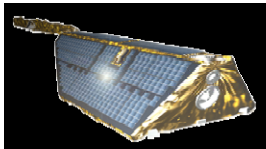
# Conclusion and outlook


- *MOZAIC is valuable data source for GPS RO retrievals (for the first time demonstrated with CHAMP)*
- *IAGOS (follow-on) in the pipeline*

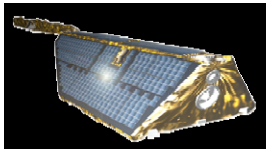

*Taipeh, June 2008*




***20 aircrafts planned***

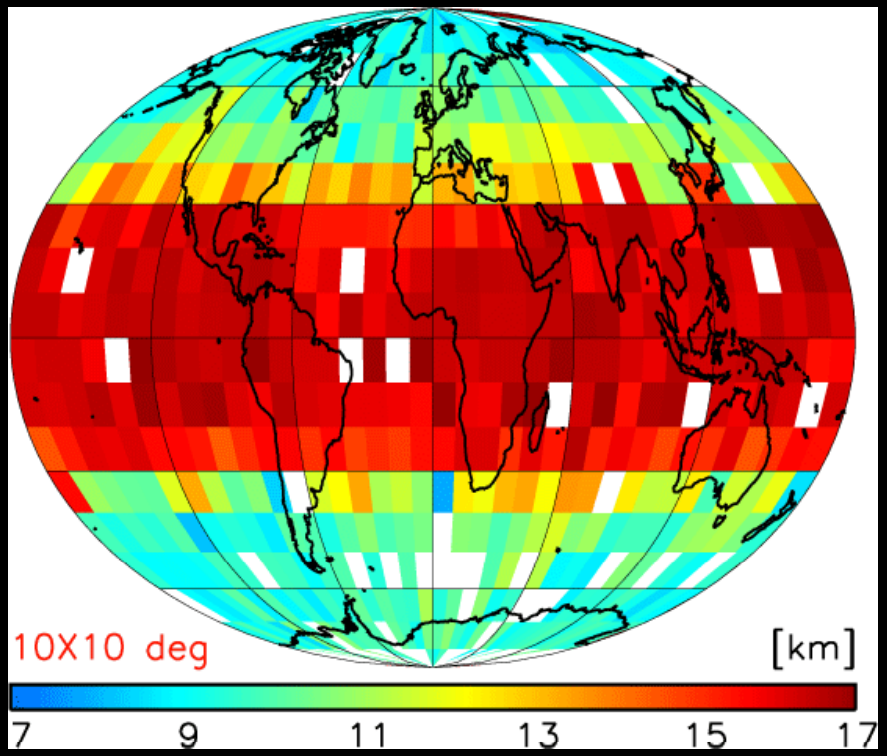


# Climate



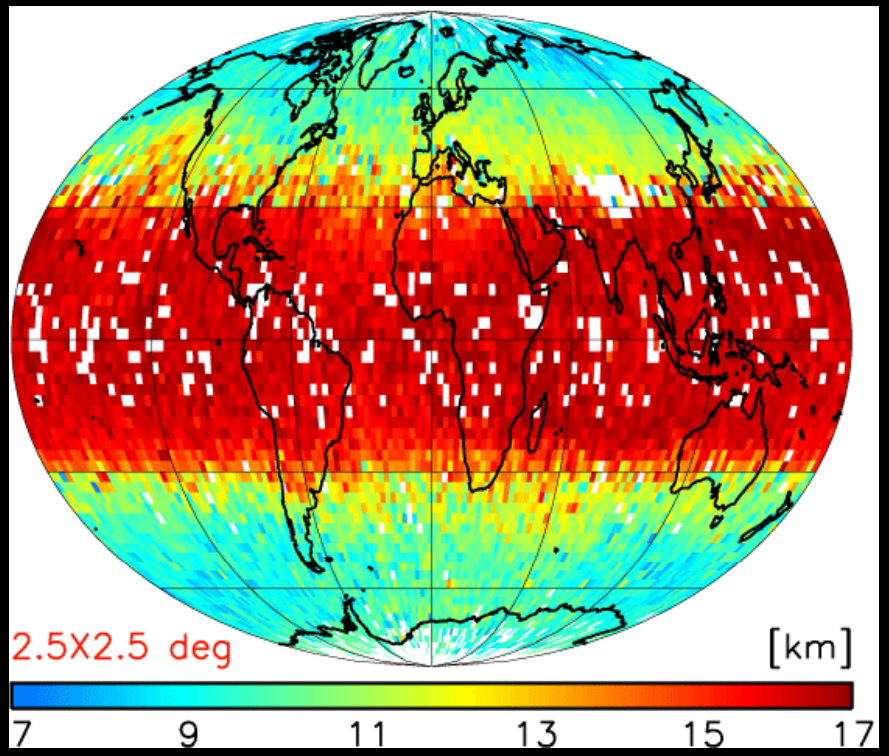
# Tropopause altitude (October 2006)

## CHAMP




**~ 5,000 profiles**

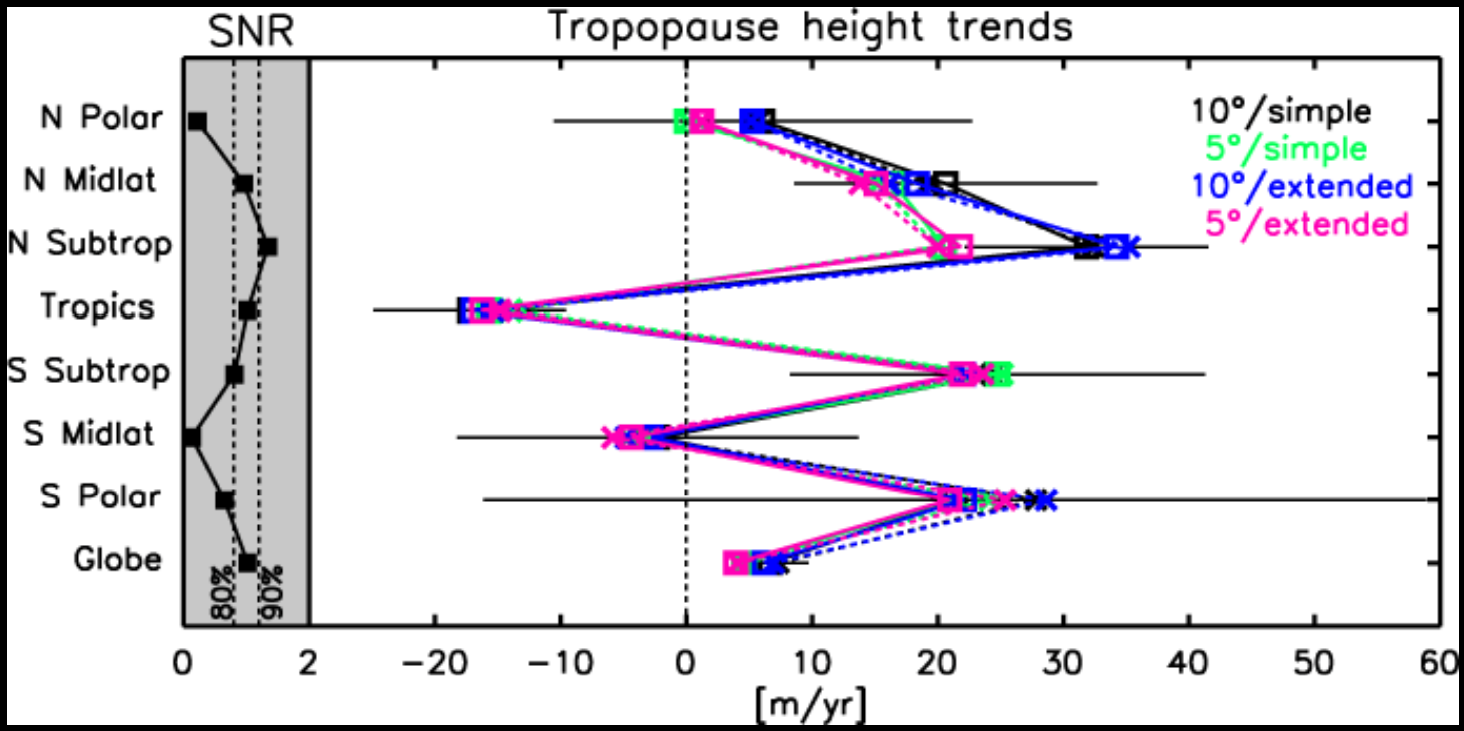
## CHAMP+GRACE+COSMIC




**46.235 profiles**

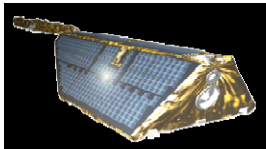
*High resolution in time and space!!*

# Tropopause climatology



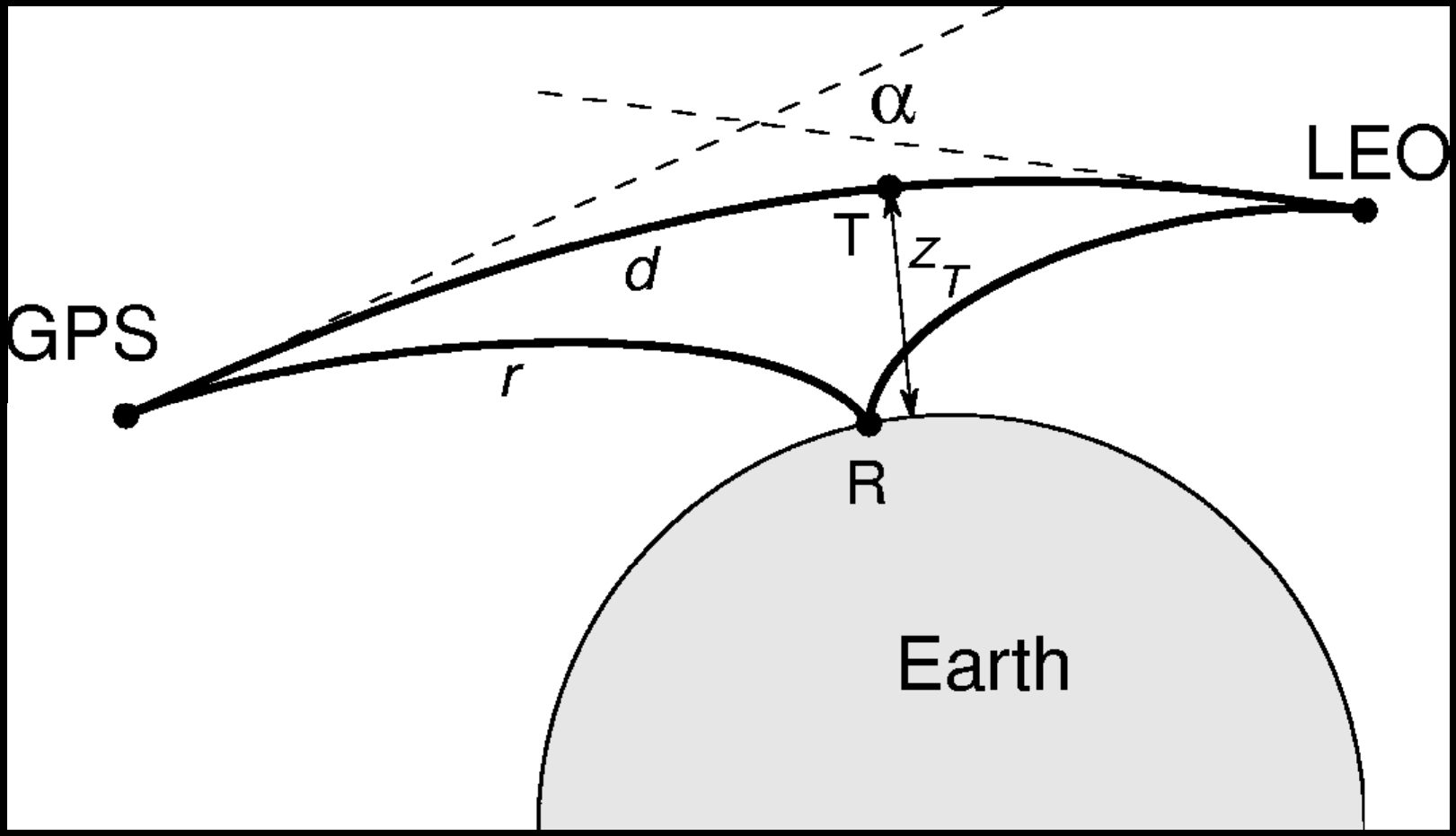

*LRT height trends [m/yr] based on GPS RO data from May 2001-December 2007 (80 months) for different binning methods and tropopause algorithms. Error bars (2-sigma confidence intervals). (left) SNR with the one-sided 80% and 90% confidence intervals. For details see Schmidt et al. (2008), Figure 3.*

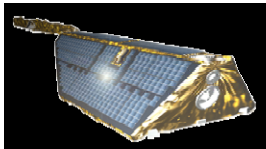
*Schmidt et al., GRL, 2008*



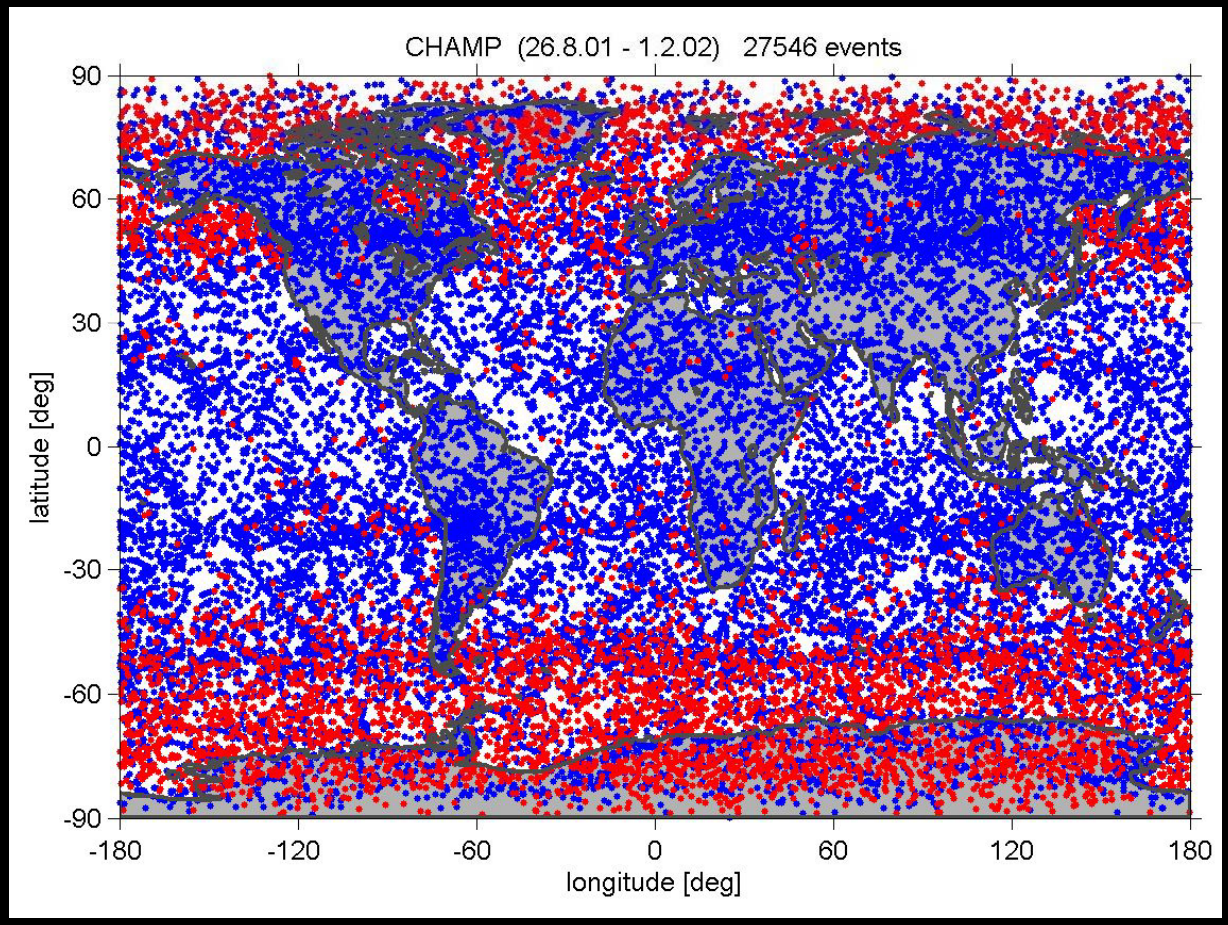
# *Reflections*

# Reflections and RO data





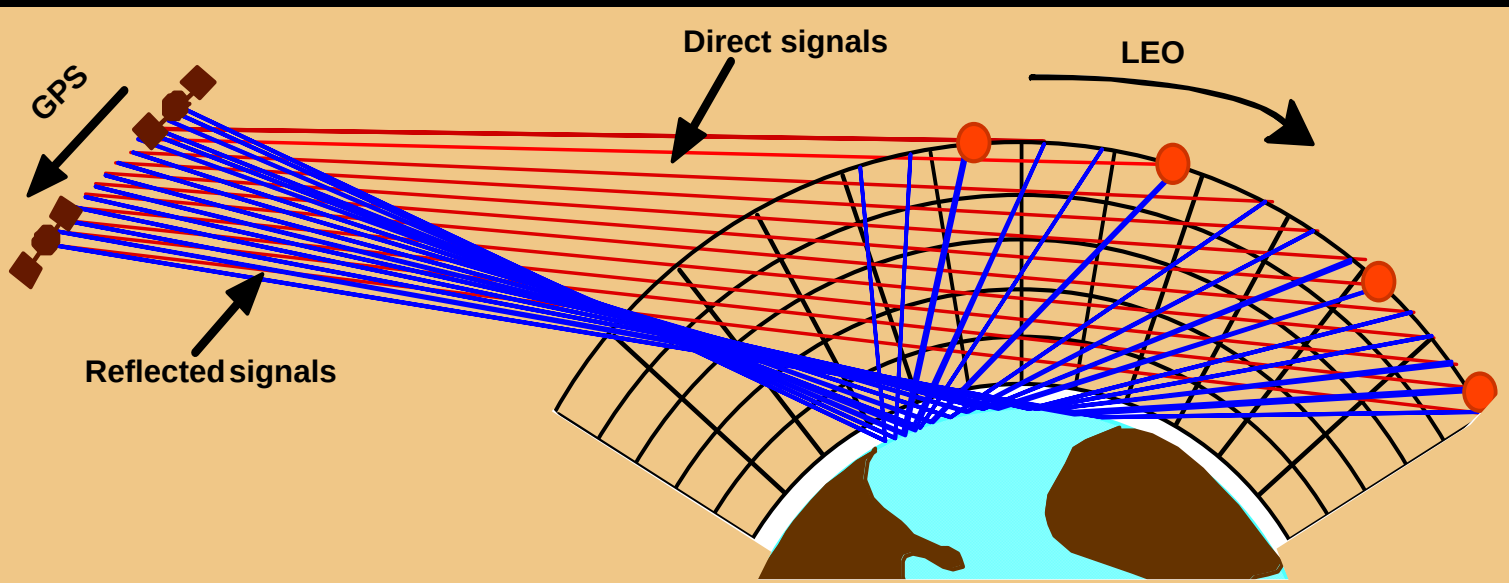
# Space based ocean and ice reflections (as already seen by CHAMP)




*(red – with reflection; blue - without reflection)*

*5 months of CHAMP occultation data (Beyerle et al., JGR, 2002)*

# Remote sensing with reflected GNSS



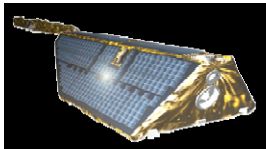

Applications

- Ocean Altimetry (topography, circulation)
- Scatterometry (sea state, surface winds)
- Atmospheric and Ionospheric Imaging

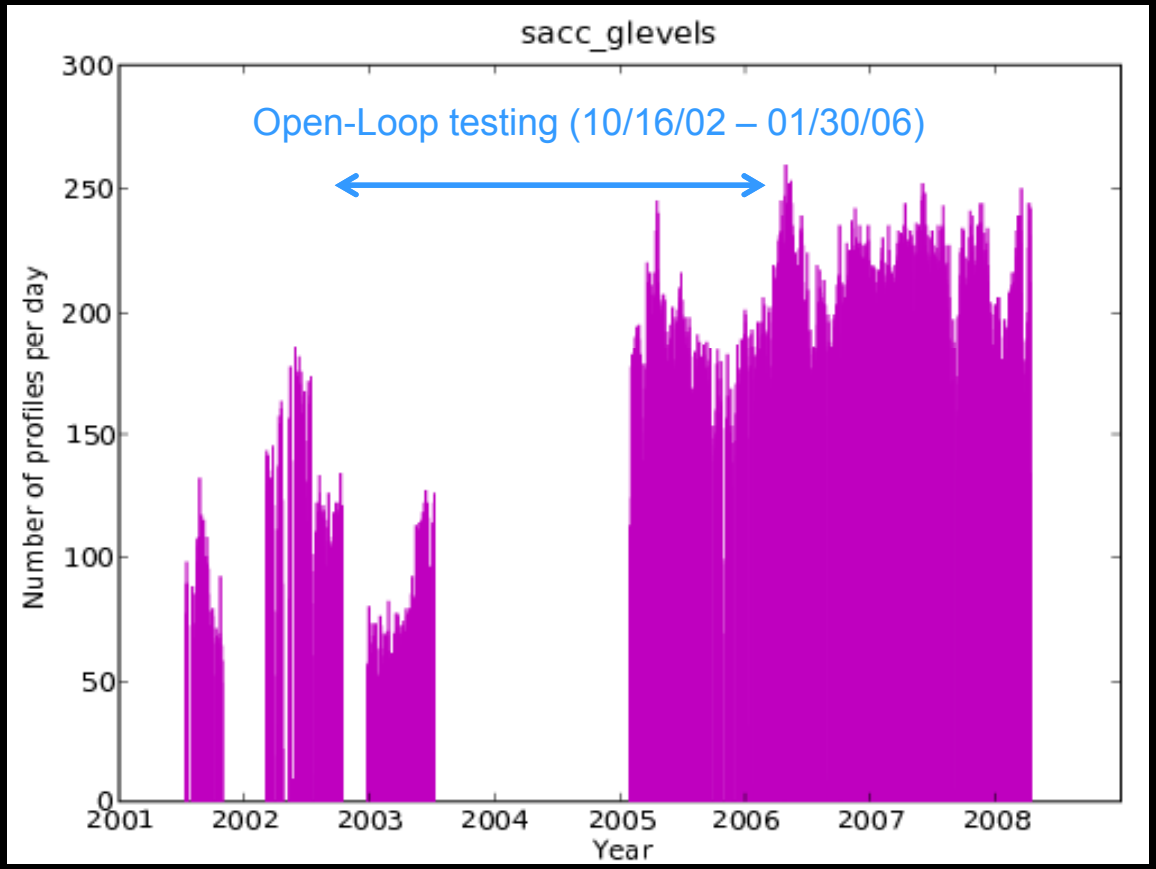
***Thanks: Tom Yunck***

# SAC-C

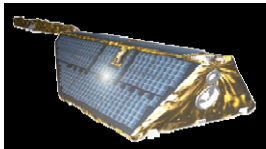
- *Delta-2 Vandenberg, Nov. 21, 2000*
- *U.S. (JPL) Argentina (RO)*



# SAC-C: occultations (JPL)

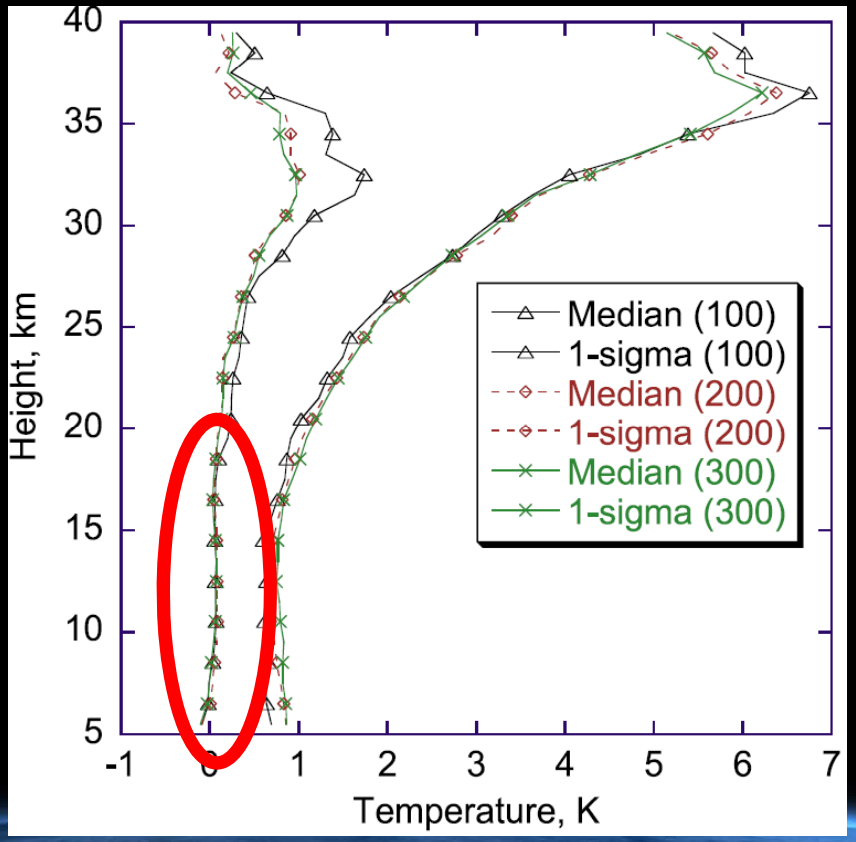



- *First investigation with Open Loop Tracking since 2002*
- *Currently more than 200 profiles daily*
- *Recent joint community effort for NRT data reception and processing*



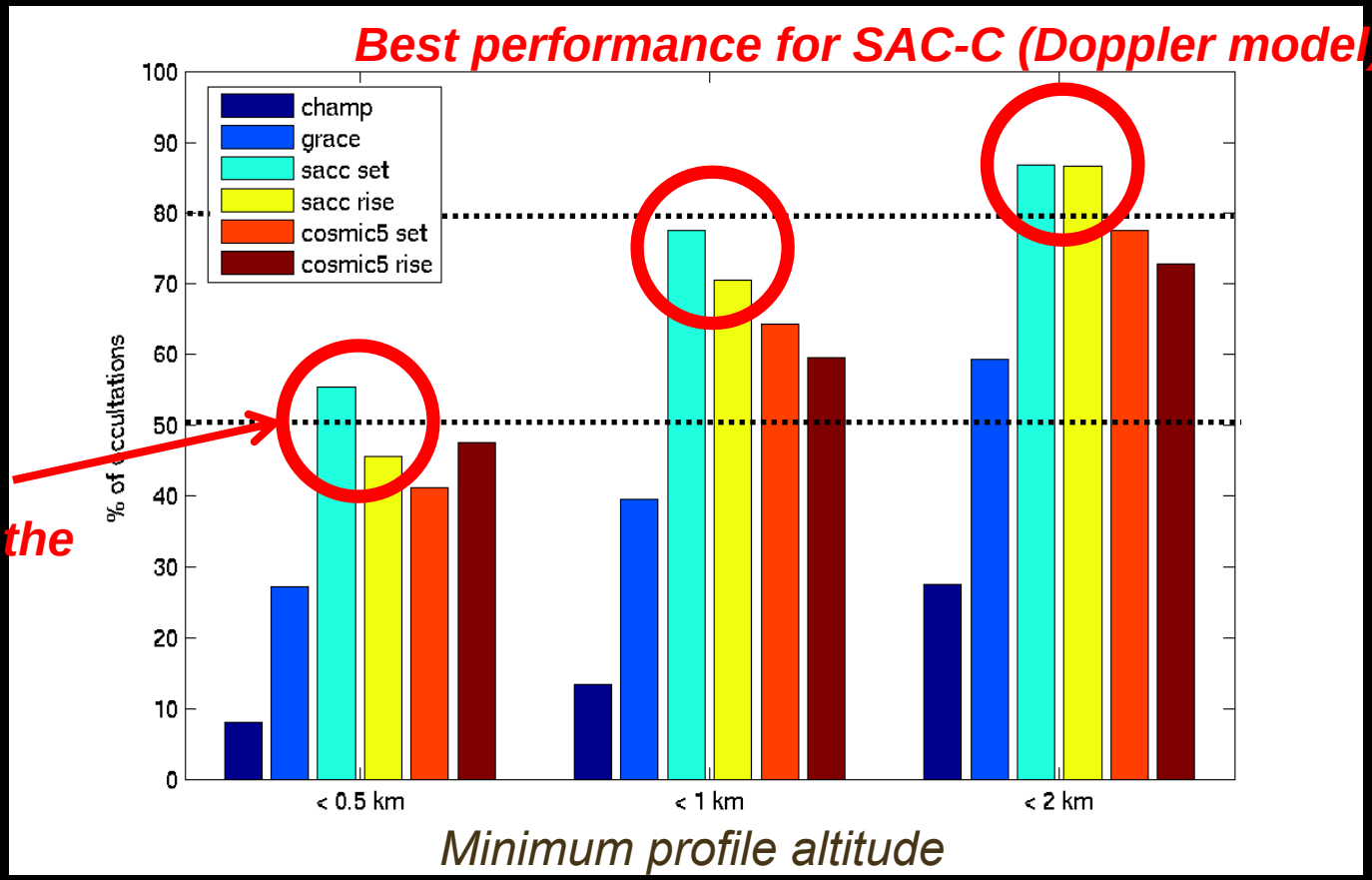
# *First intersatellite RO comparisons (SAC-C; CHAMP)*

212 coincidences (July 2001 … March 2003) (<1/2hr and <200 km) consistent mean $\Delta T$ to < 0.1K (below 18 km). By contrast mean temperature of analysis (NCEP) shows differences of ~0.5K to SAC/C or CHAMP




*Hajj et al., 2004*

# Lower troposphere sounding with SAC-C

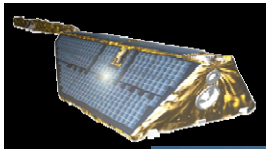



***50 % of profiles reach 0.5 km in the Tropics***

*Minimum altitude statistics over the Pacific ocean (JPL)*
*(160 - 230 deg longitude, -35 to 35 deg latitude)*

*For details talk from Ao et al.*


New colleague in space:TerraSAR-X



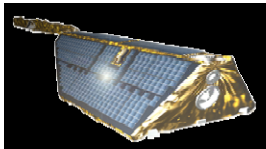
# TerraSAR-X

*Launch with Dnepr-2 from Baikonur, Orbit 514 km 98° incl. 5 years planned*

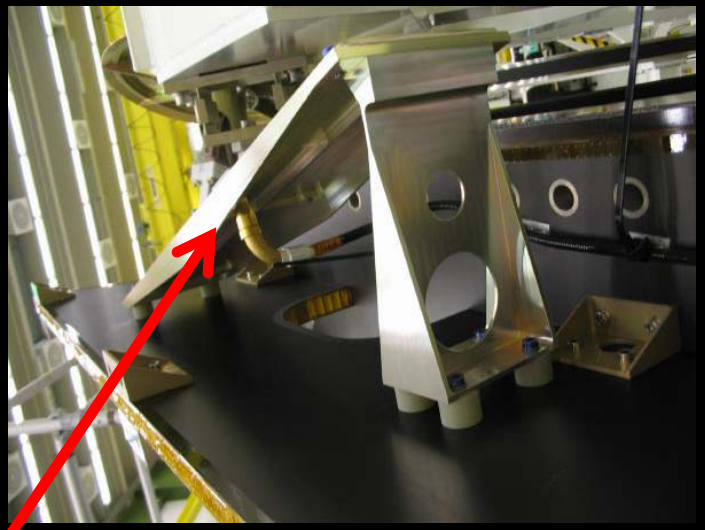
*GPS orbit antennas*

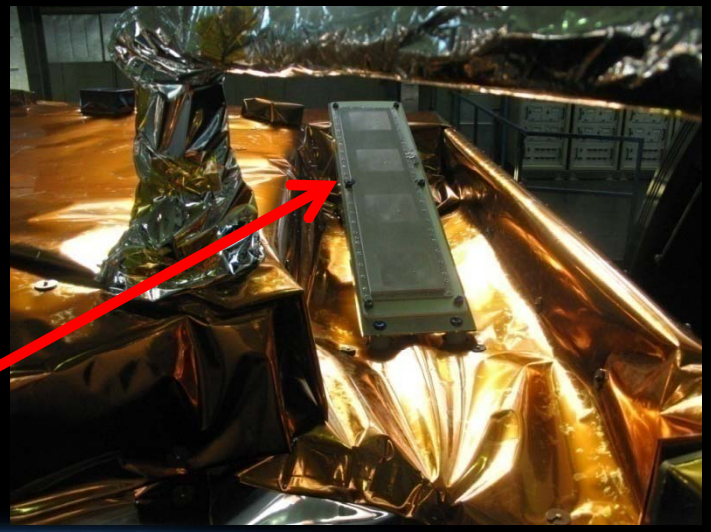

*Is quite large … 5 m, 1,2 ton*

*Source: web DLR*



# TerraSAR-X has GPS

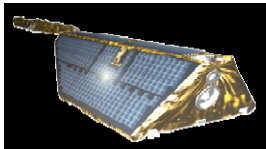




*IGOR (Broadreach)*

*Adapter for*

*OccAntennas (same as for COSMIC)*
*fore and aft-looking*



# Status of TerraSAR-X GPS

*Orbit determination: Operational and high quality*

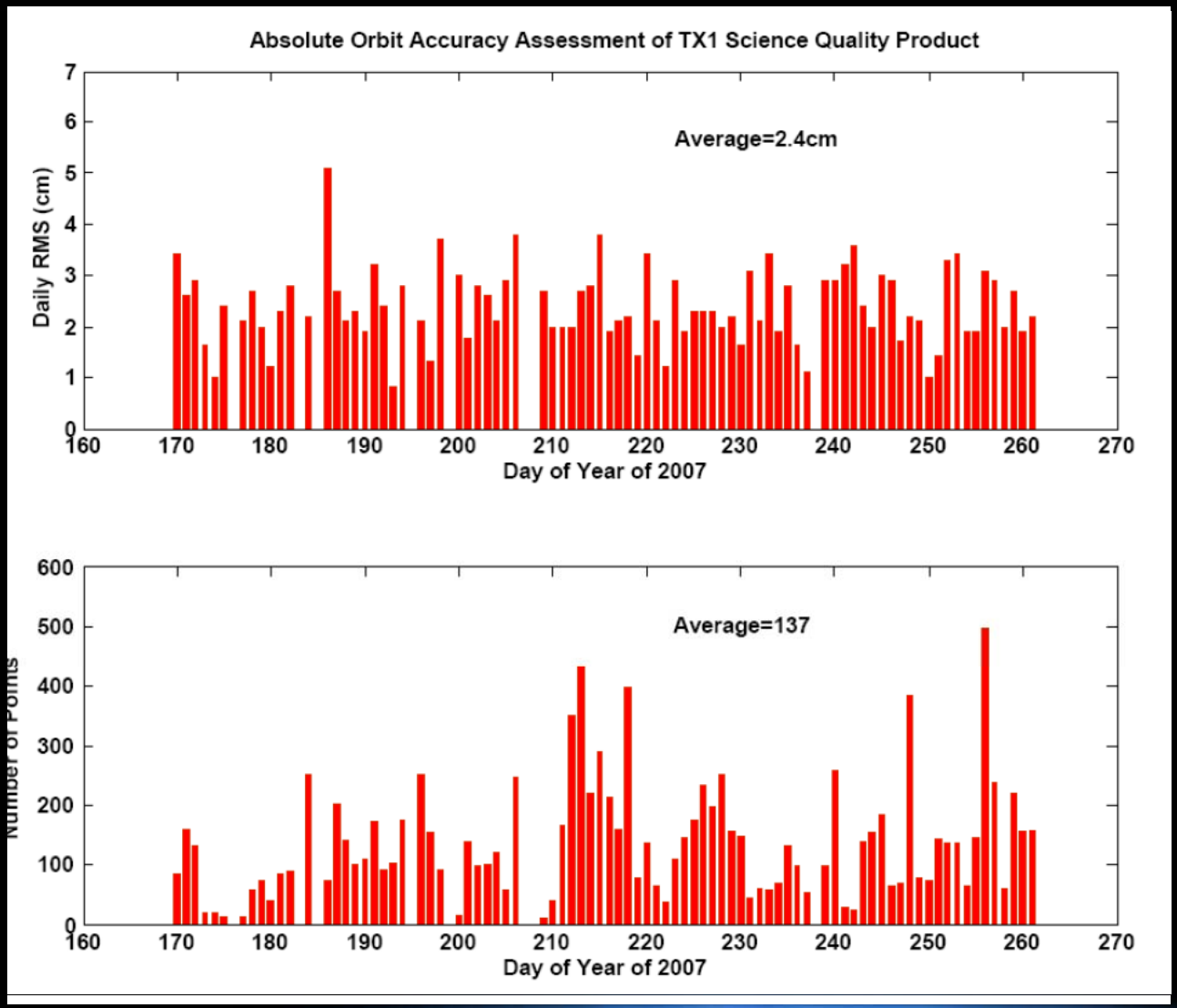
*Occultations (neutral gas and ionosphere in commisiong phase) not primary mission goal*

*Preliminary results for neutral gas occultations in open loop mode (worse statistics compared to CHAMP, low number of occultations, initial ionospheric profiles, ground network für navigation bit provision installed and operational, data can be provided*

*NRT data reception, tested with 3 satellites in parallel at Ny Alesund*

*Contract situation difficult*

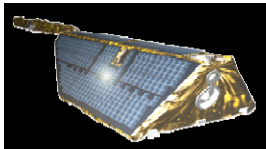
# Orbit accuracy TerraSAR-X




*DLR orbits*

*Comparison with SLR data*

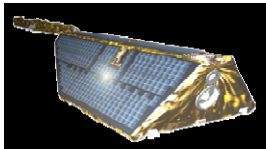
*Daily RMS 2.4 cm*



# *Initial analyses of RO data TerraSAR-X*

*(January/February 2008)*

| | *TerraSAR-X* | *CHAMP* |
|---|---|---|
| *time period* | *32 days* | *32 days* |
| *# occultation events* | *1378* | *3904* |
| *signal tracking method* | *closed-loop, open-loop below 25 km* | *closed-loop, fly-wheeling in lower troposphere* |

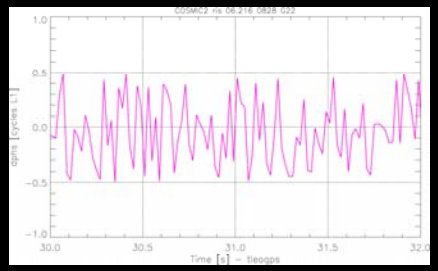


# OpenLoop processing

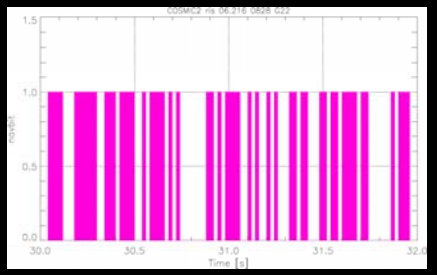
*delta phase*

*nav. bit data*

*Model* +



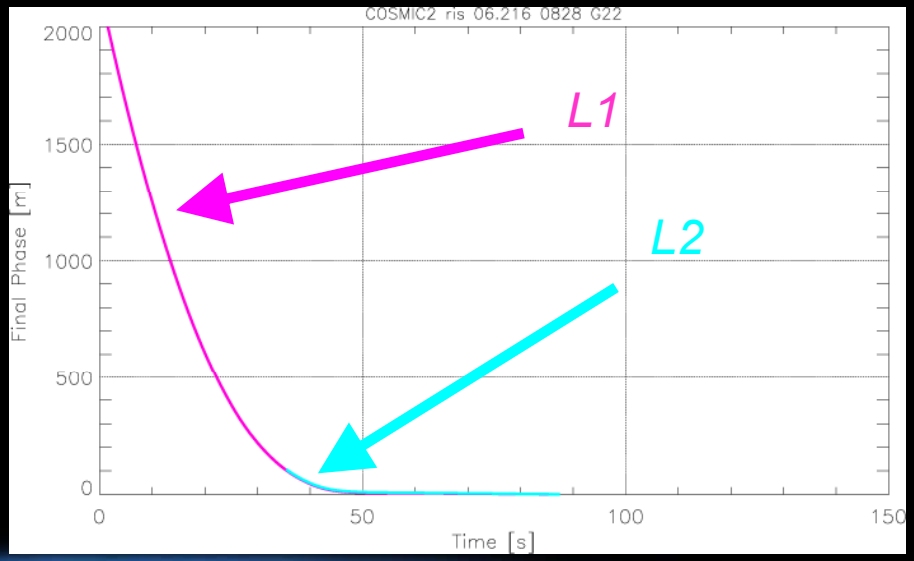
+



*+ phase adjustment*

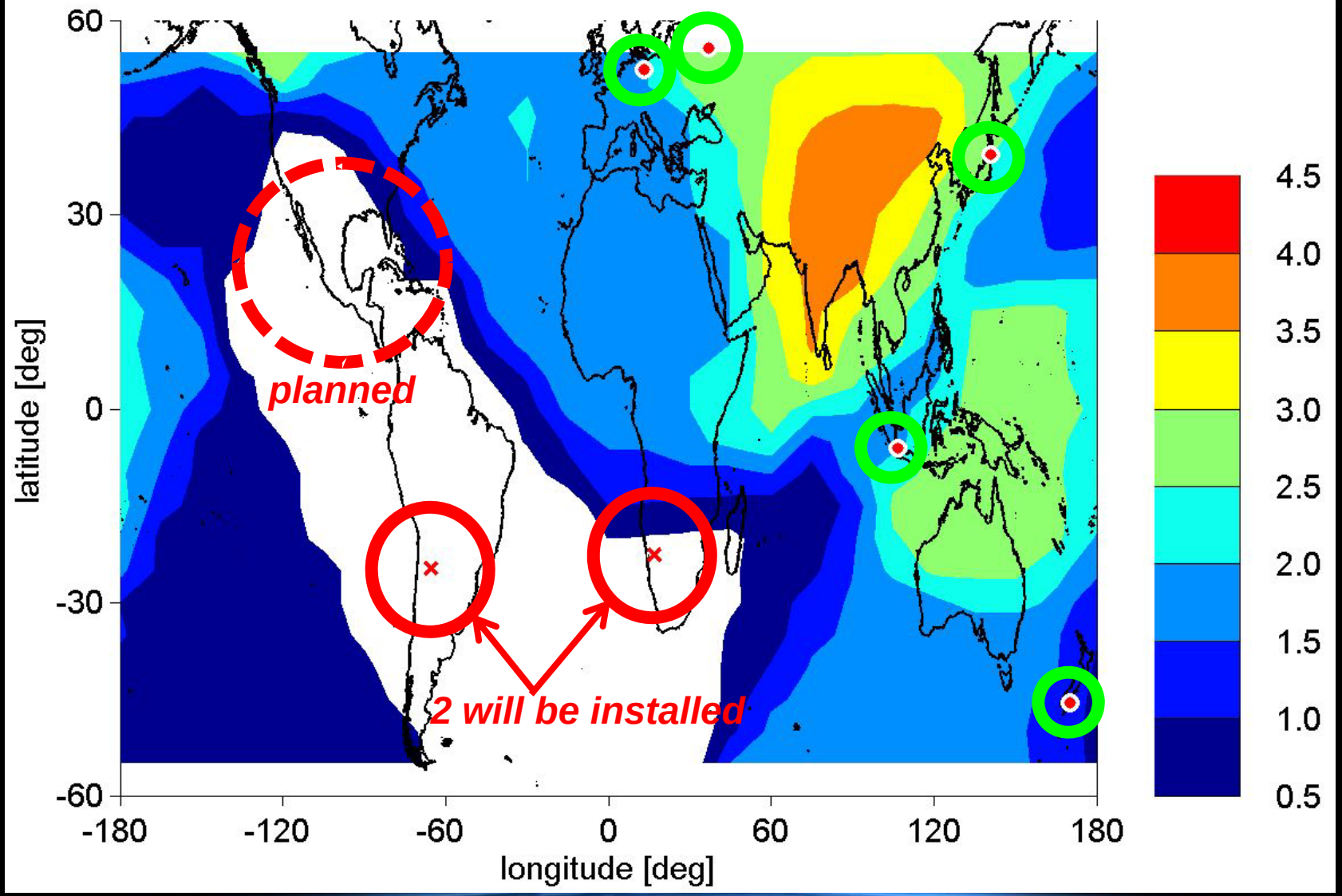
*according to Sokolovskiy, GRL, 2006*

*results in final phase L1*



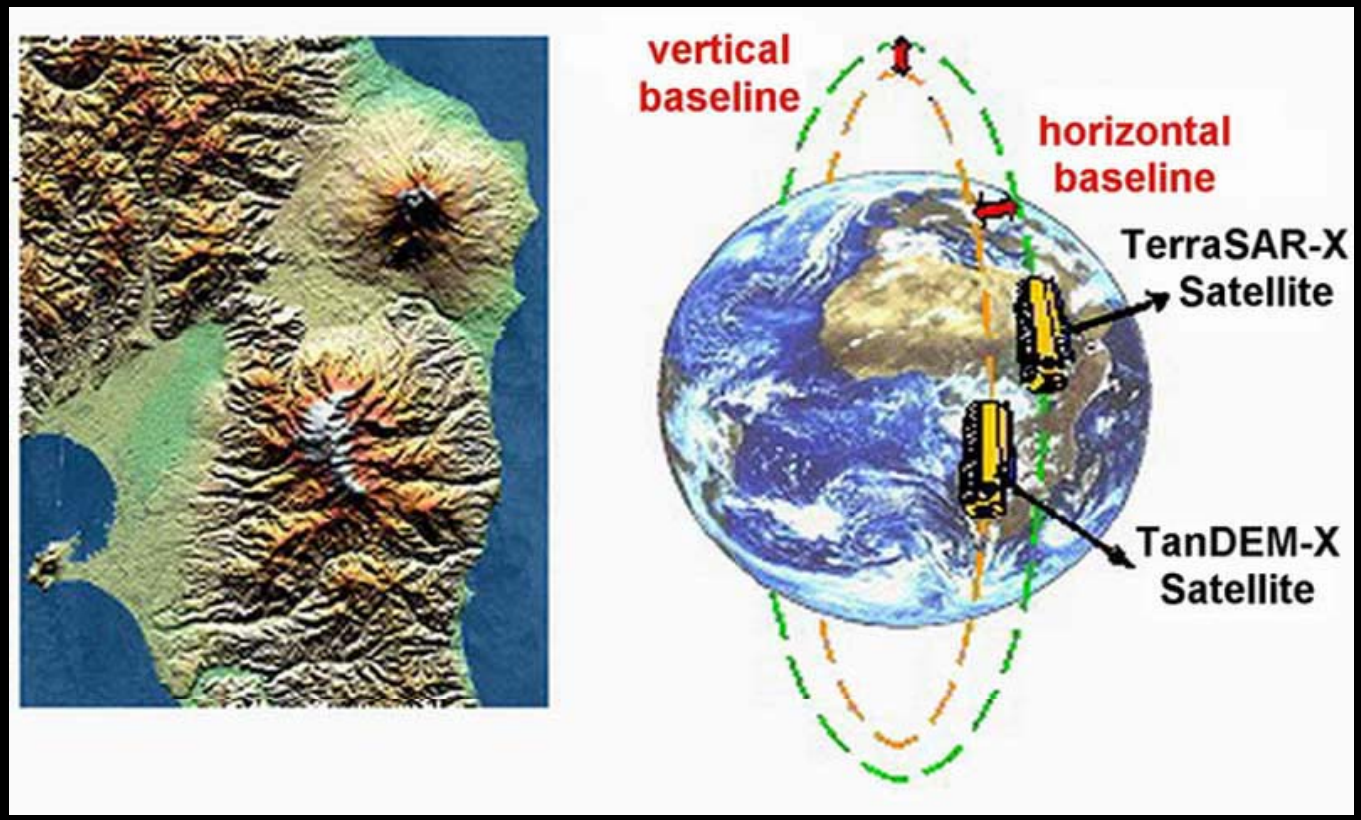
# Global coverage NavBit Data GFZ

## 5 stations operational



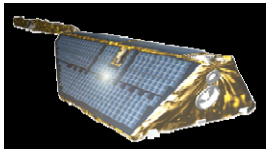

*Beyerle et al., GPS Solutions, 2008.*

# TerraSAR-X will not stay alone ..

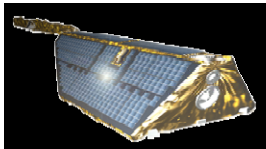



*Source: DLR web*

*View to the Earth in stereo ..*
*planned launch in 2010 again with IGOR*

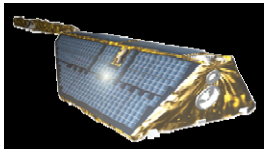


# *Some activities for future projects*



GALILEO

# GPS-M and GALILEO

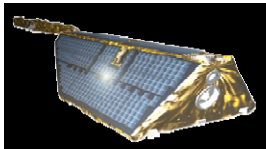


# Successful launched!

Giove-A (Dec. 28, 2005)

Giove-B (Apr. 27, 2008)


# GNSS receivers

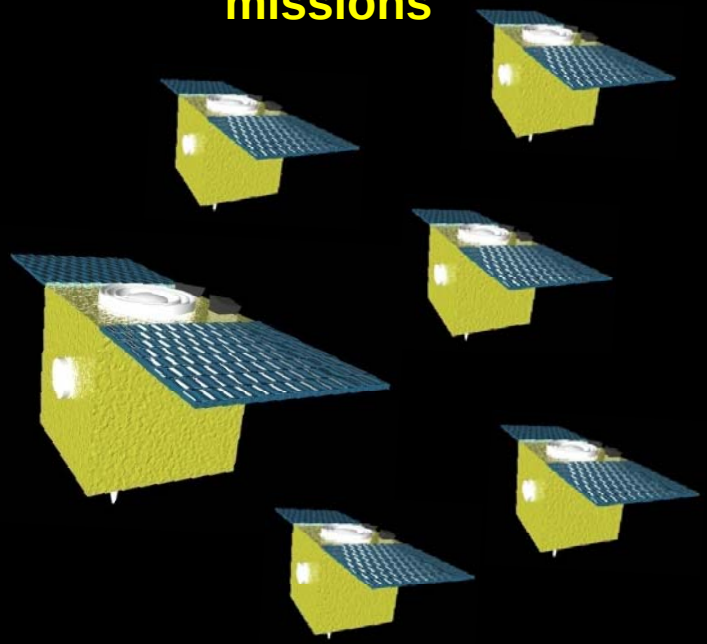


# GFZ receiver development

**GORS receiver (with JAVAD, GITEWS)**


**GPS, GLONASS, GALILEO**

**New satellite missions**

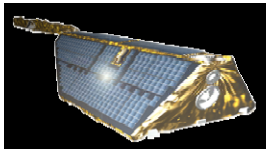


**GFZ receiver (Open GPS)**

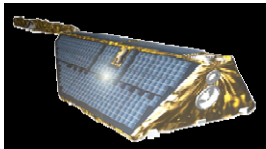

**GPS**

***e.g. NanoGEM (6 satellites) for occultation/reflection***

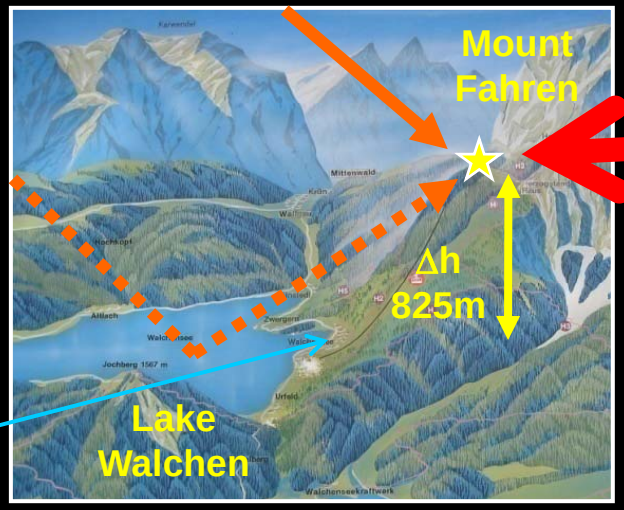
***new scientific quality for sounding and reflectometry activities – GNSS receiver as a remote sensing sensor!***



# *GNSS receiver application for reflectometry*

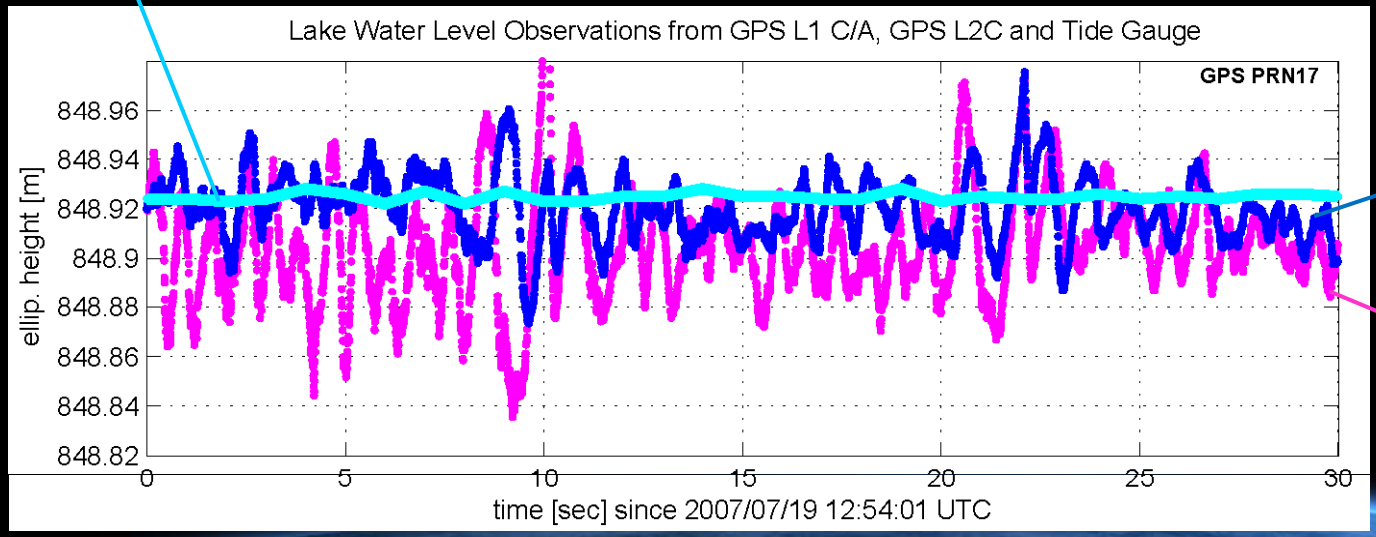


# COTS-receiver: Use of new signals




Tide Gauge

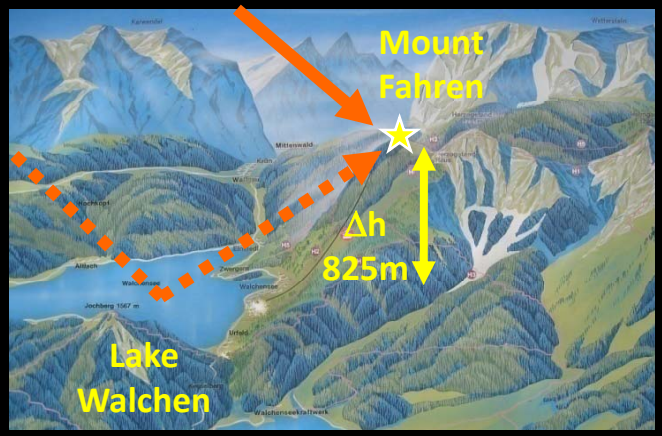

~ 2 cm
accuracy

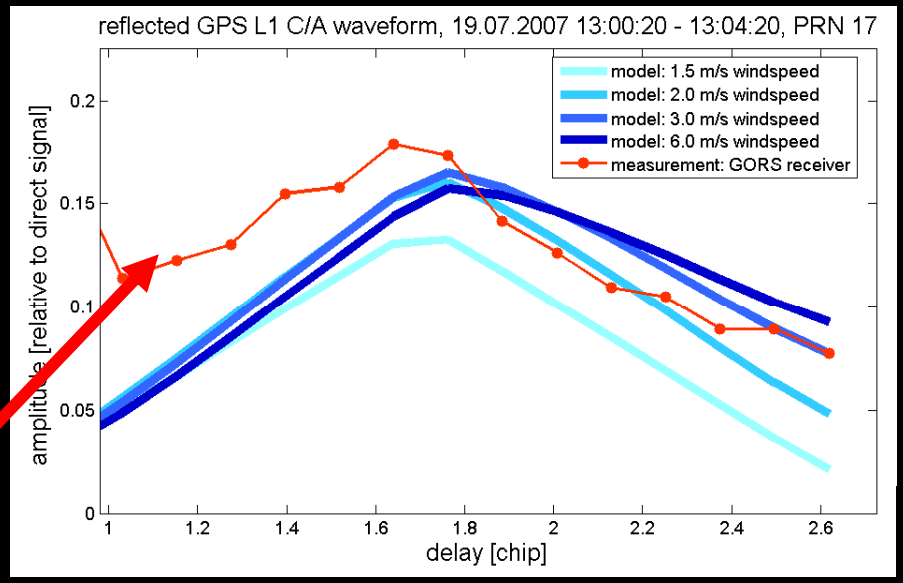


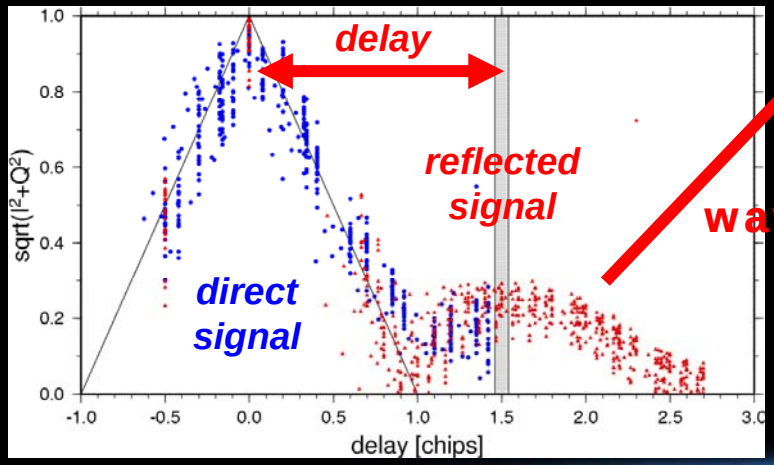

GPS
L1 C/A

GPS
L2C

# Wind speed above water surfaces from reflected signals



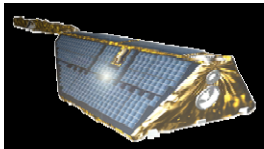



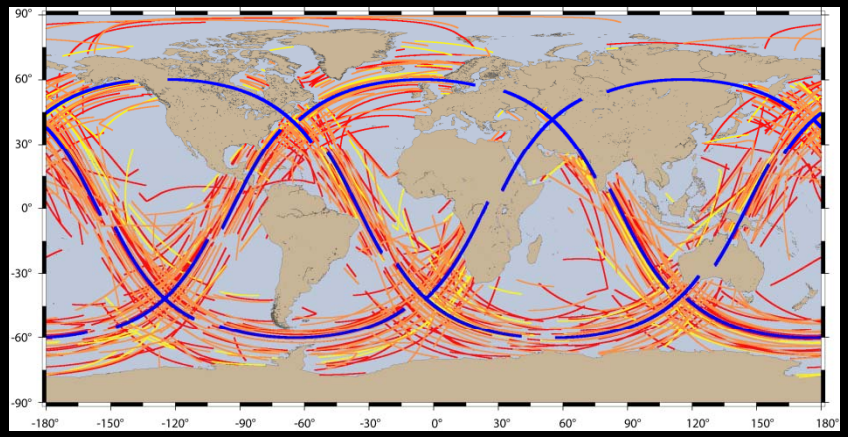

**waveform**

**Receiver correlator**

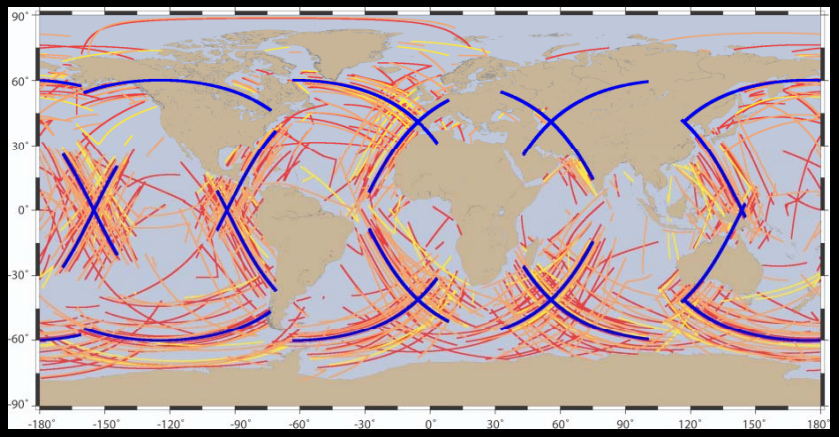
**Scatterometry Model (provided by IEEC Barcelona)**



# Satellite constellations for reflectometry



18 sat., 3 planes, 15 min

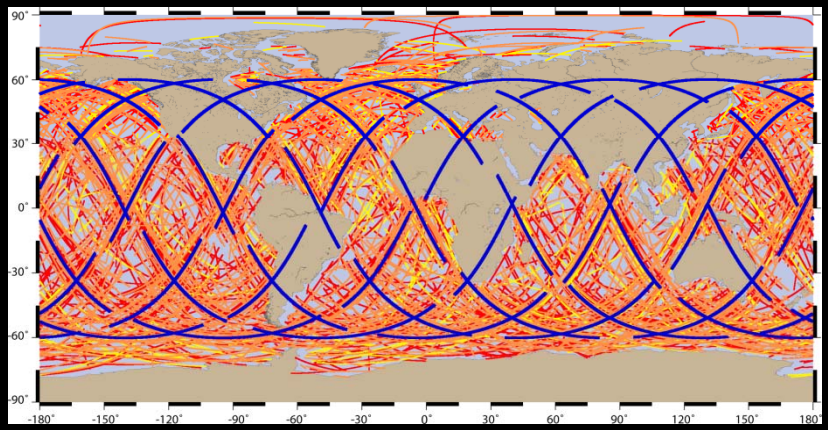


18 sat, 6 planes,15 min

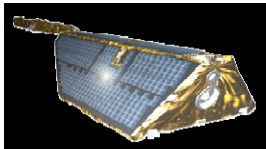
**LEO groundtracks**

**(450 km altitude, 60° Inklination)**

**GPS GLONASS GALILEO**

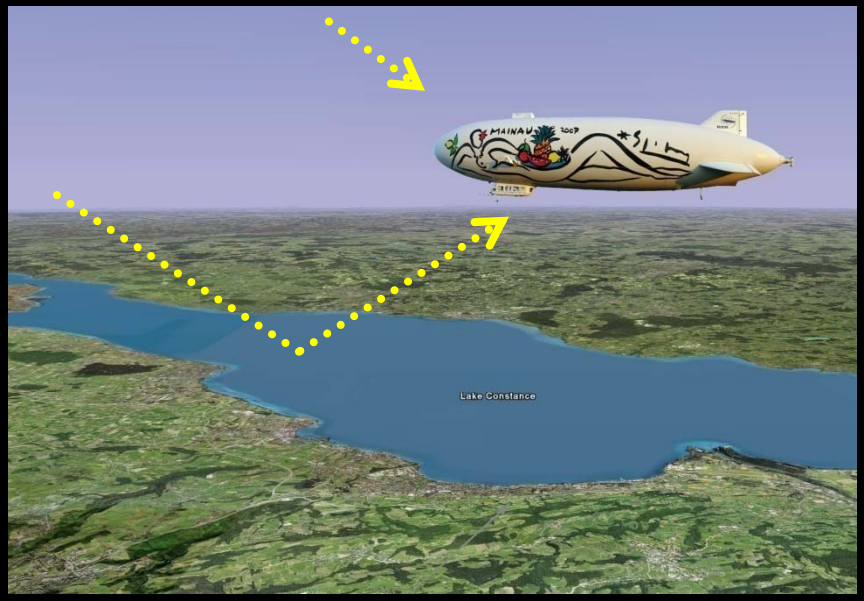


48 sat, 8 planes,15 min

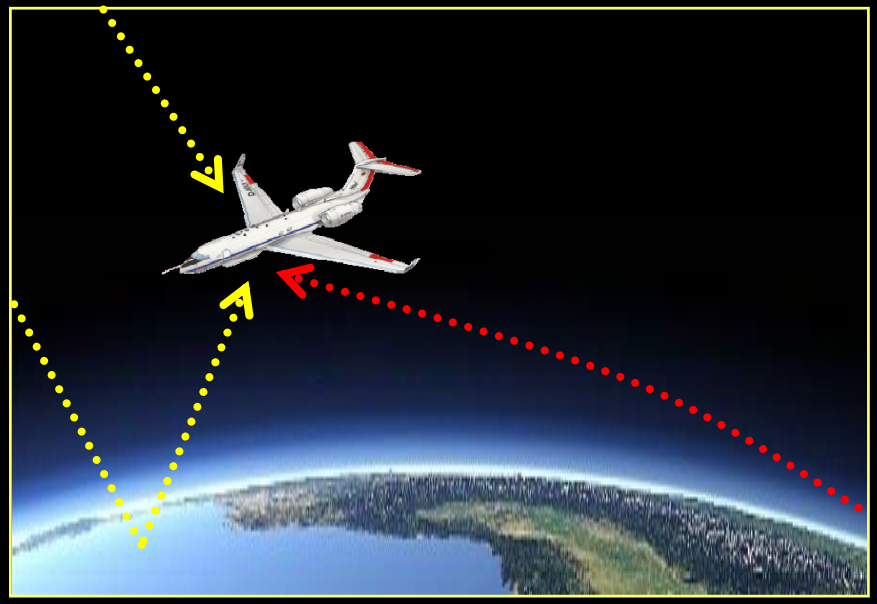


# Airborne platforms

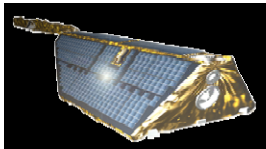
## Zeppelin NT



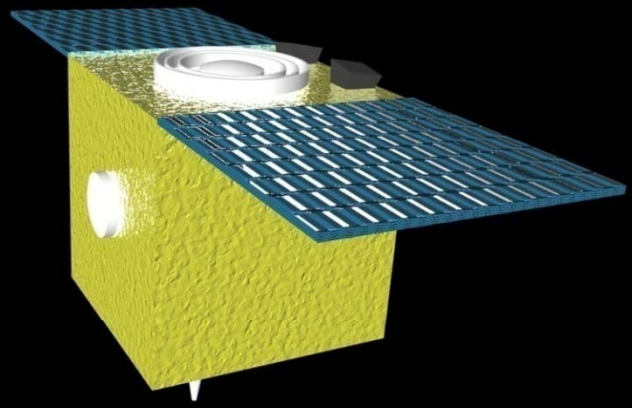

## Research aircraft HALO

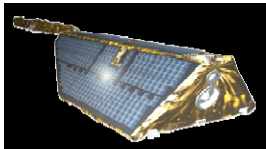


**Reflectometry/Scatterometry; Occultations (HALO)**



# *From ground via aircraft to space*: *Multi-nanosatellite missions*





# Conclusions and outlook

*The „science driven“ missions CHAMP, GRACE, SAC-C brought significant progress for the RO technique (retrieval, applications, preparation of COSMIC and Metop) TerraSAR-X/Tandem-X „hopefully“ bring new aspects (calibration, error characterization)*

*Budget for operational activities is existing but limited at science institutes as GFZ, better cooperation with GRAS-SAF feasible ?*

*There are serious thinkings on new missions from science side with new scientific aspects (GPS-M, Galileo, GLONASS, receiver technology, reflections etc.), for realisation international cooperation necessary, also with COSMIC FO*