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# Future prospects of troposphere delay modelling in GNSS analysis

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Newcastle, 1 July 2010



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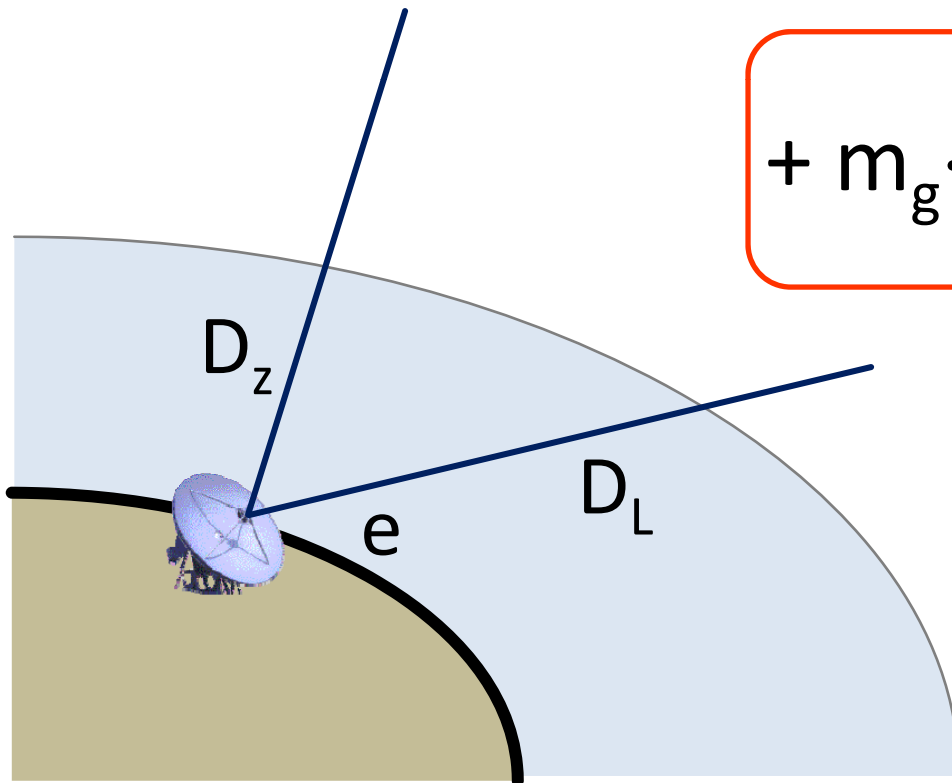
- A. IERS Conventions - State of the art
  - A priori gradients
- B. Ray-traced slant delays
- C. Tropospheric parameters during CONT08

# IERS Conventions

$$D_L(e) = D_z \cdot m(e) = D_{zh} \cdot m_h(e) + D_{zw} \cdot m_w(e)$$

$$+ m_g \cdot [G_N \cdot \cos(a) + G_E \cdot \sin(a)]$$

gradients



# Mapping Functions

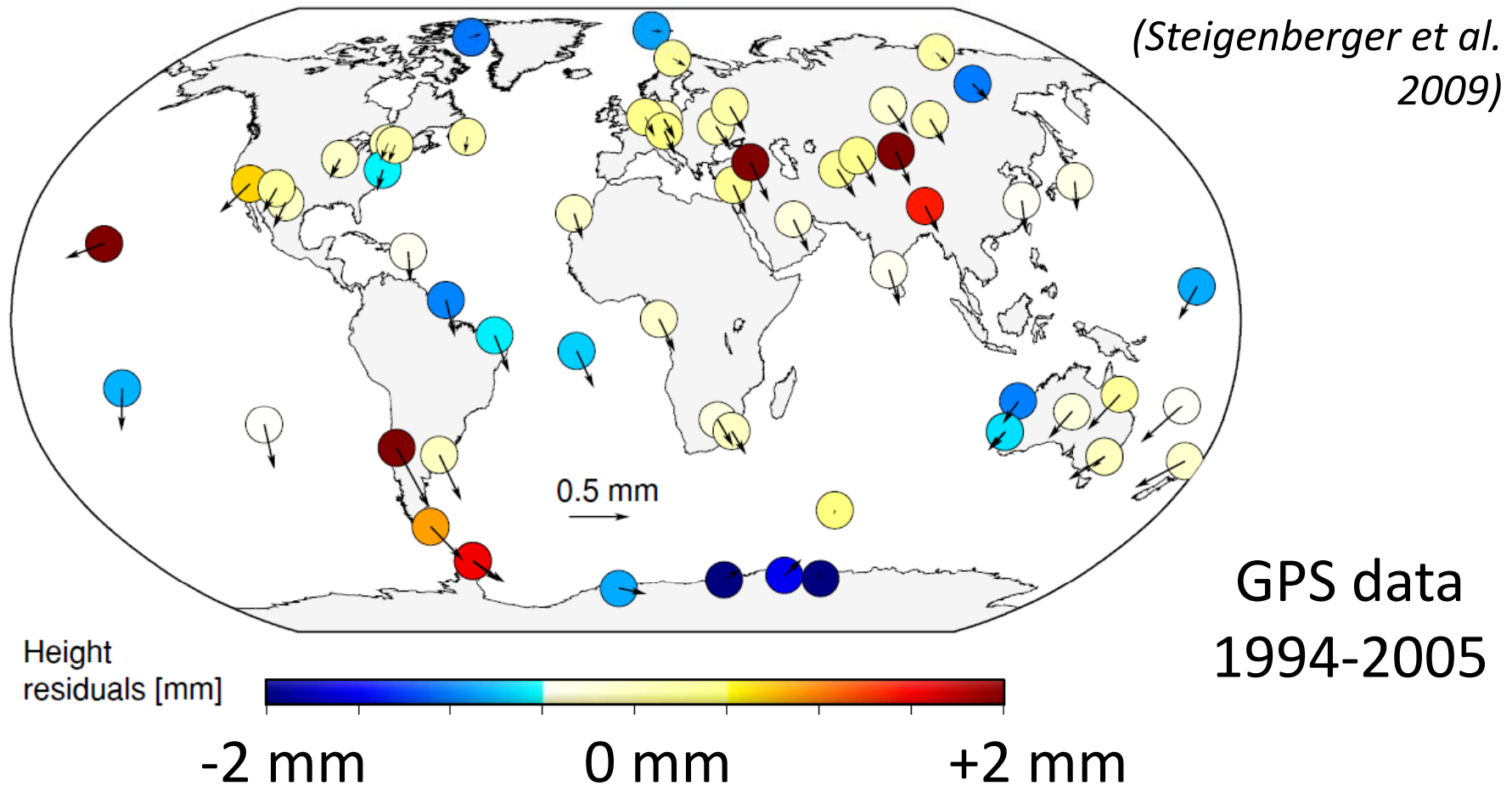
- **empirical functions** (doy,  $\varphi$ ,  $\lambda$ , h)
  - GMF Global Mapping Functions
- **from numerical weather models** (6-h time series)
  - VMF1 Vienna Mapping Functions

# A priori hydrostatic zenith delay

- **observations**
  - in situ measurements
  - numerical weather models (6-h series), e.g. ECMWF
- **empirical functions** (doy,  $\varphi$ ,  $\lambda$ , h)
  - GPT    Global Pressure/Temperature
    - *not for geophysical applications*

# GMF/GPT vs. VMF1/ECMWF

Residuals of a 14 par. similarity transformation



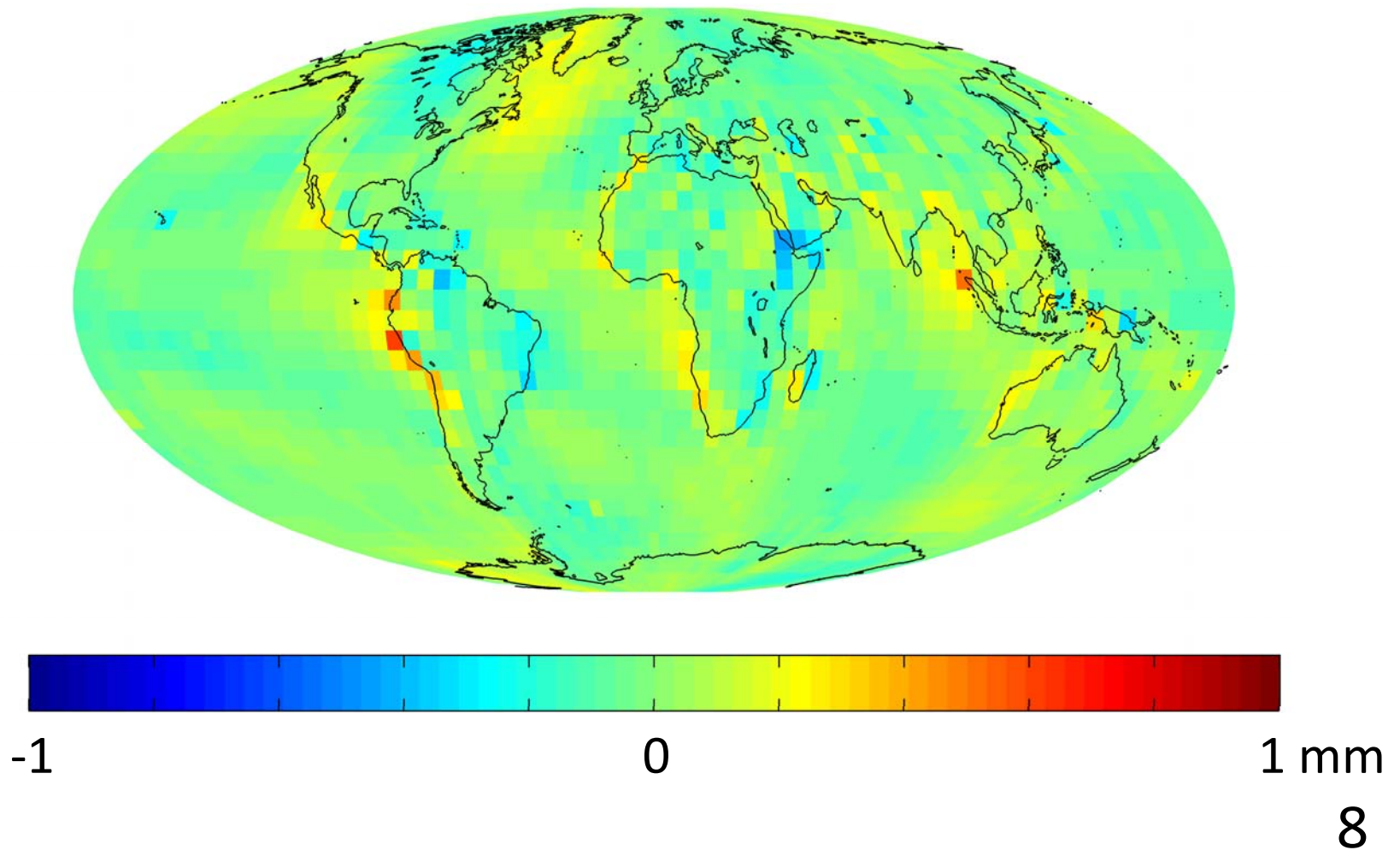
# Total gradients

from numerical weather models

- ECMWF 40 years re-analysis monthly means
- 5° x 5° resolution
- UNB Raytracer

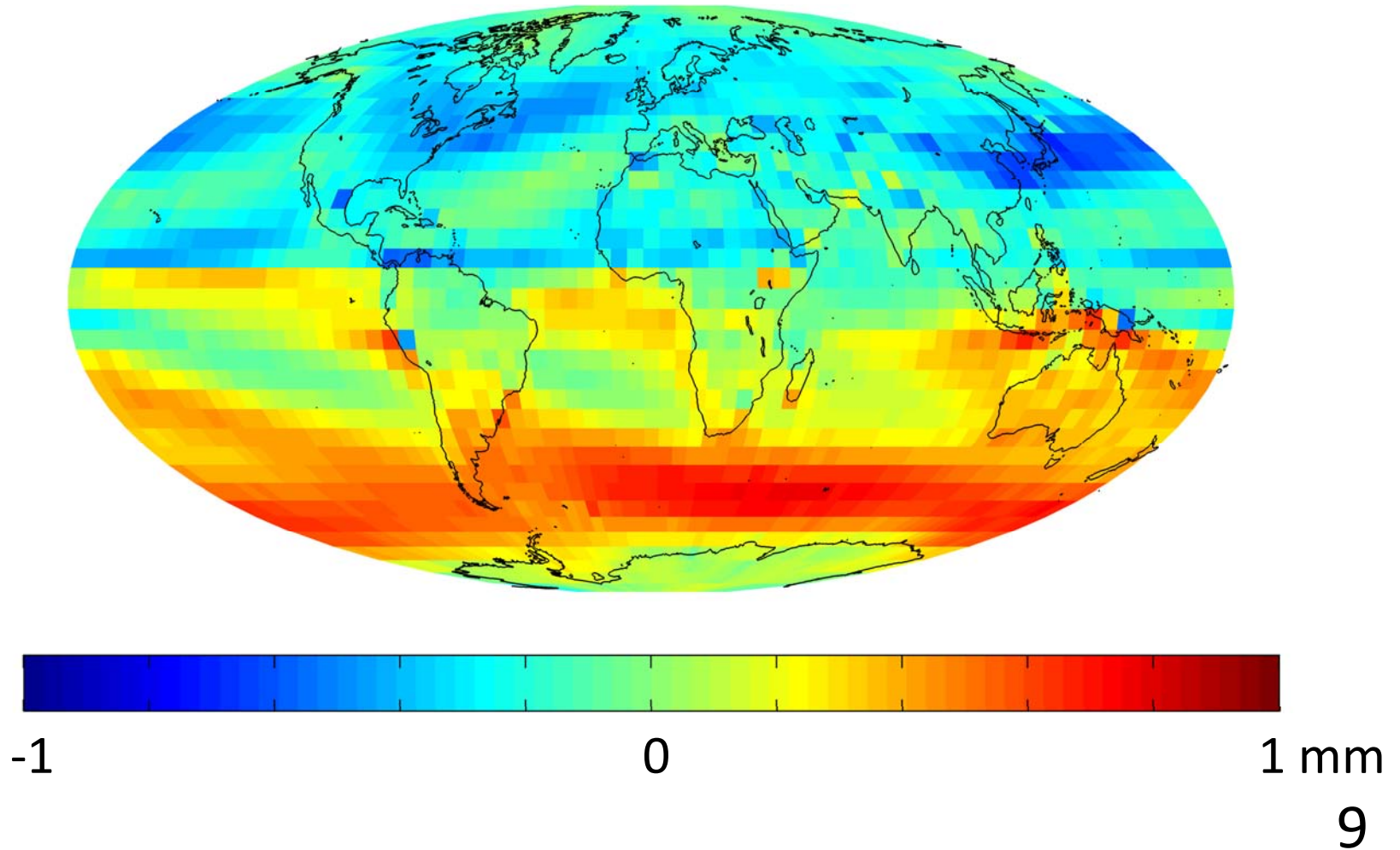
# East gradients

averaged over 12 months



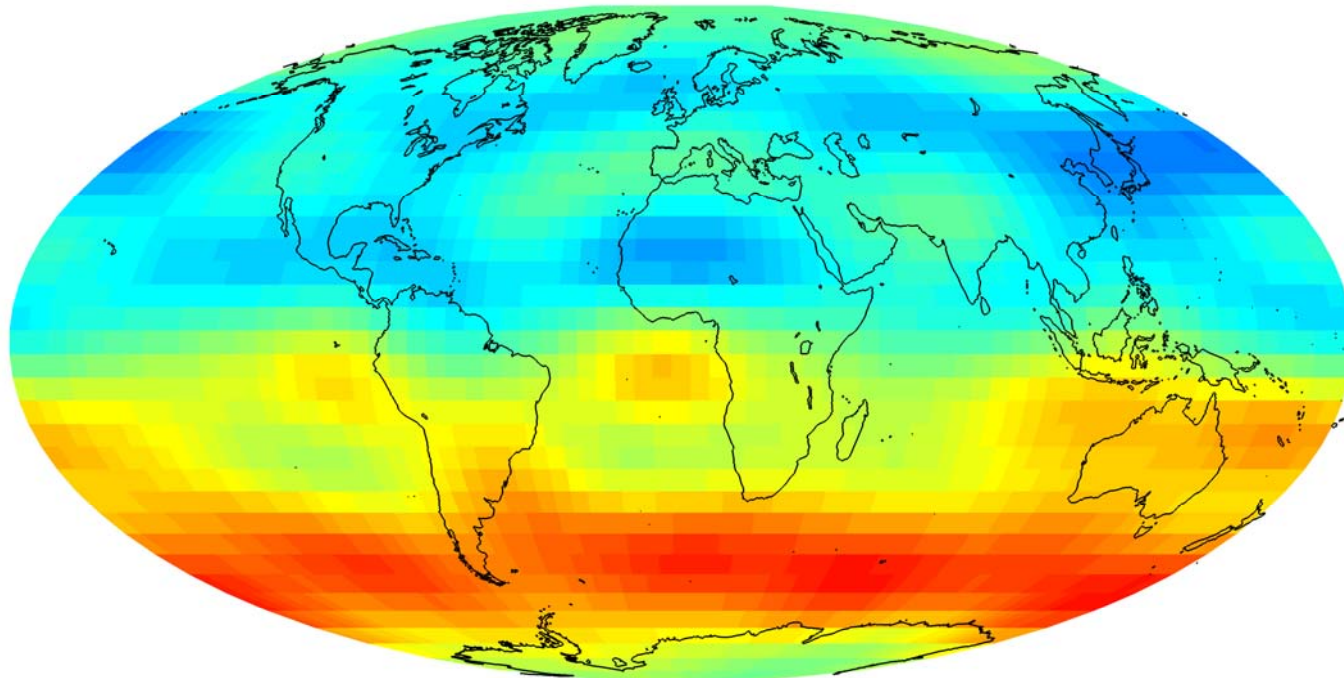
# North gradients

averaged over 12 months



# Spherical harmonic expansion up to degree and order 9

<http://ggosatm.hg.tuwien.ac.at/DELAY/SOURCE/apg.f>



-1

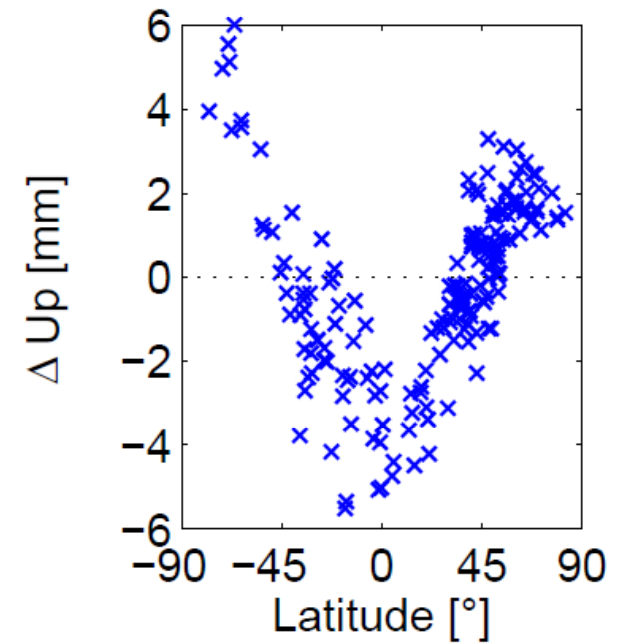
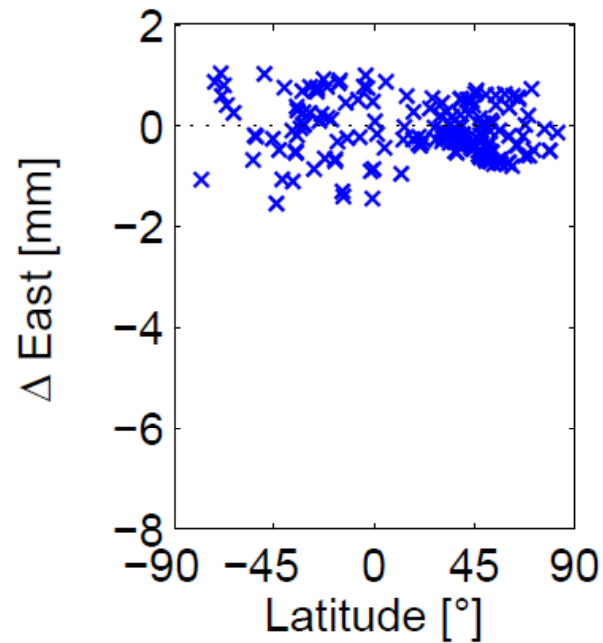
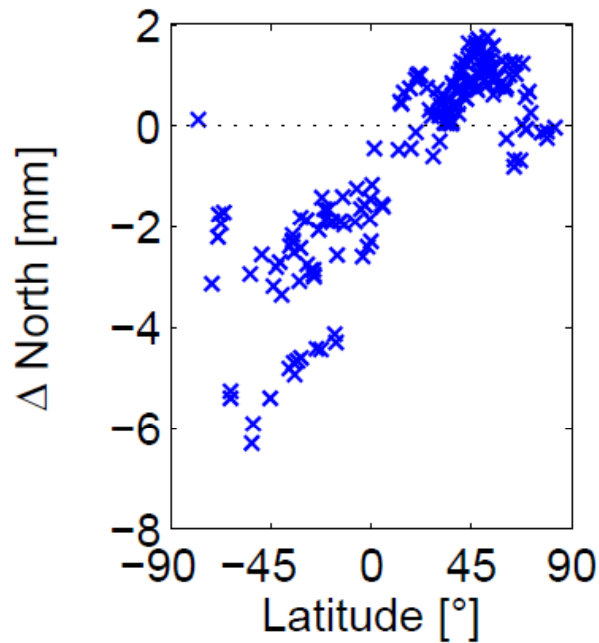
0

1 mm

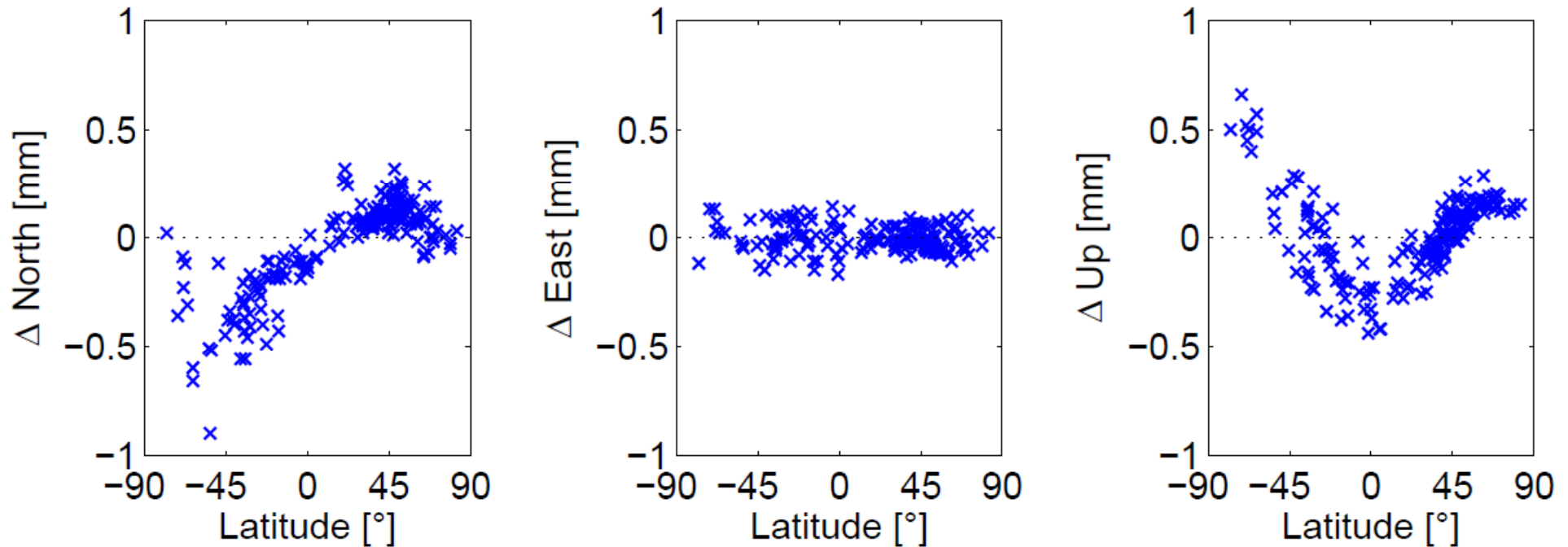
10



# GNSS analysis: mean coordinate differences w/wo apriori gradients, no gradients estimated



# GNSS analysis: mean coordinate differences w/wo apriori gradients, gradients estimated



- No constraints
- Apriori: Chen & Herring '97; Est.: MacMillan '95.

# Conclusions

- A priori gradients change north and radial station components by up to 1 mm.
- Should an a priori gradient model be added to the IERS Conventions?
- We need to define the gradient model in the IERS Conventions, e.g. Chen and Herring 1997.

# Ray-tracing

- For every observation
  - Hobiger et al. (2009) with GPU
- Adaptive Mapping Functions
  - Pascal Gegout et al.
- ....



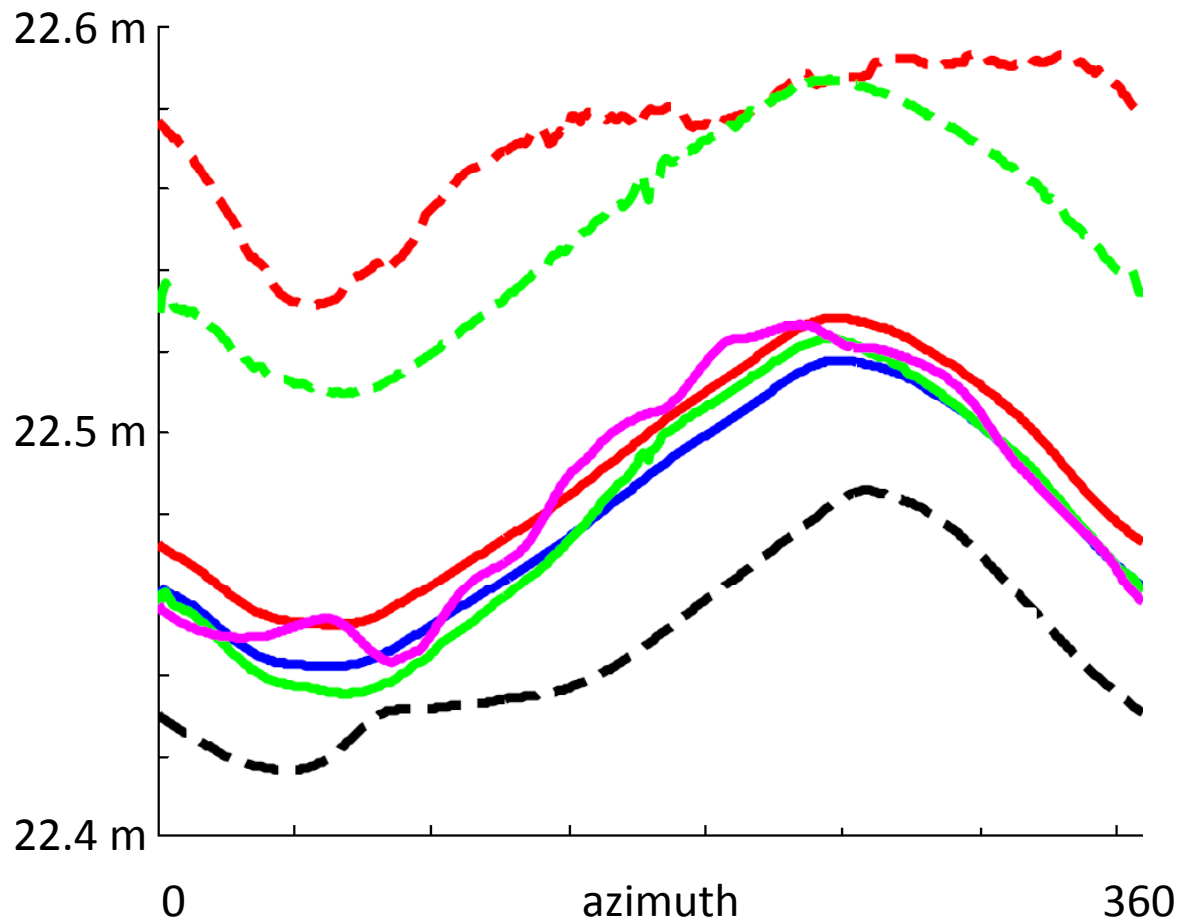
# Applications

- Hobiger et al. (2010) found improvement for GPS with CReSS data during extreme weather conditions in Japan
- NASA/GSFC found improvement for VLBI
- ...

# Ray-tracing Comparison Campaign

IAG WG 4.3.3 and IAG SC 1.1 WG3

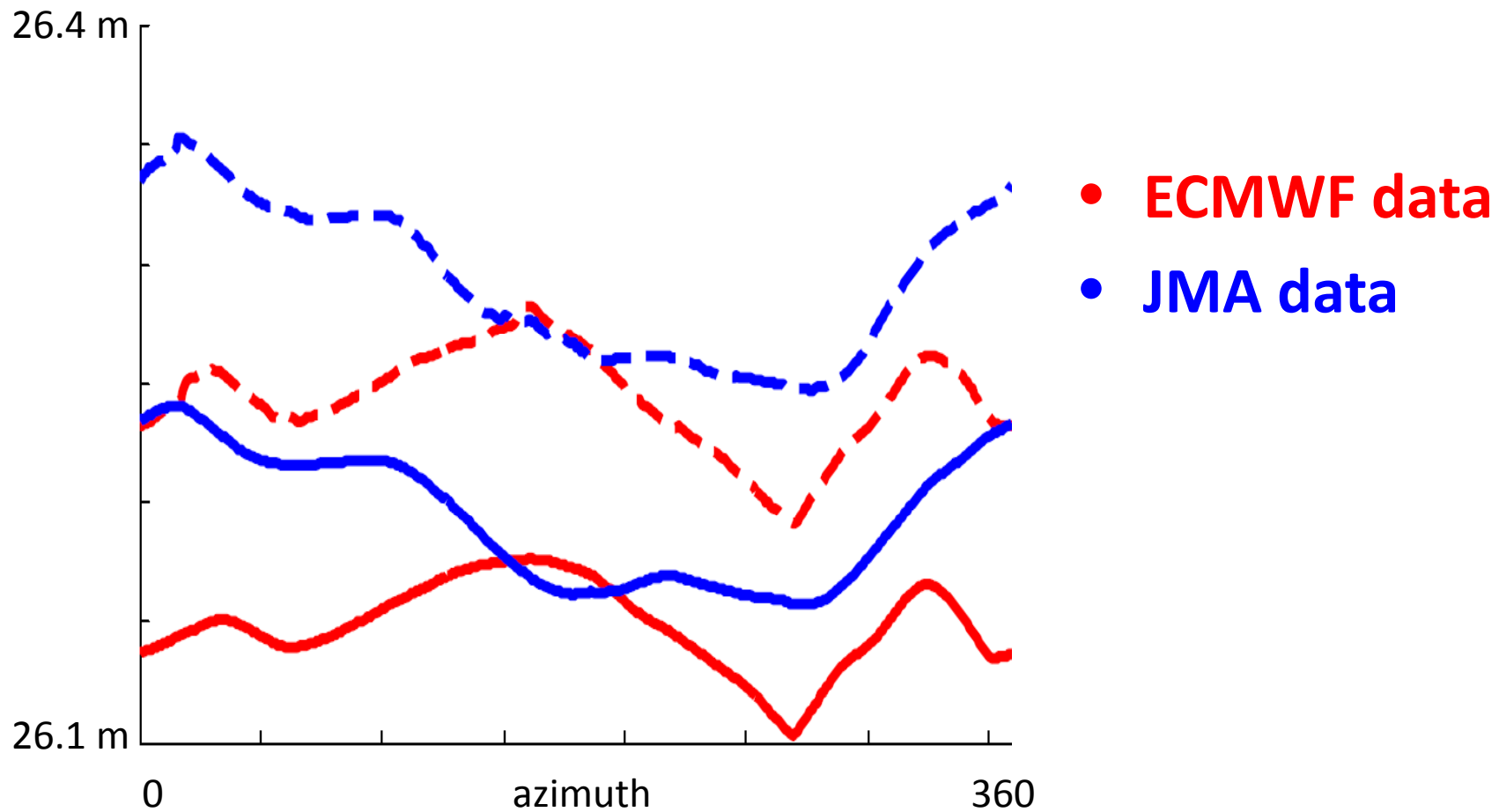
- Slant delays at 5° elevation, 1 Jan 2008 0 UT Wettzell



- ECMWF data
- KARAT, Horizon, UNB, VIE, GFZ

# But ...

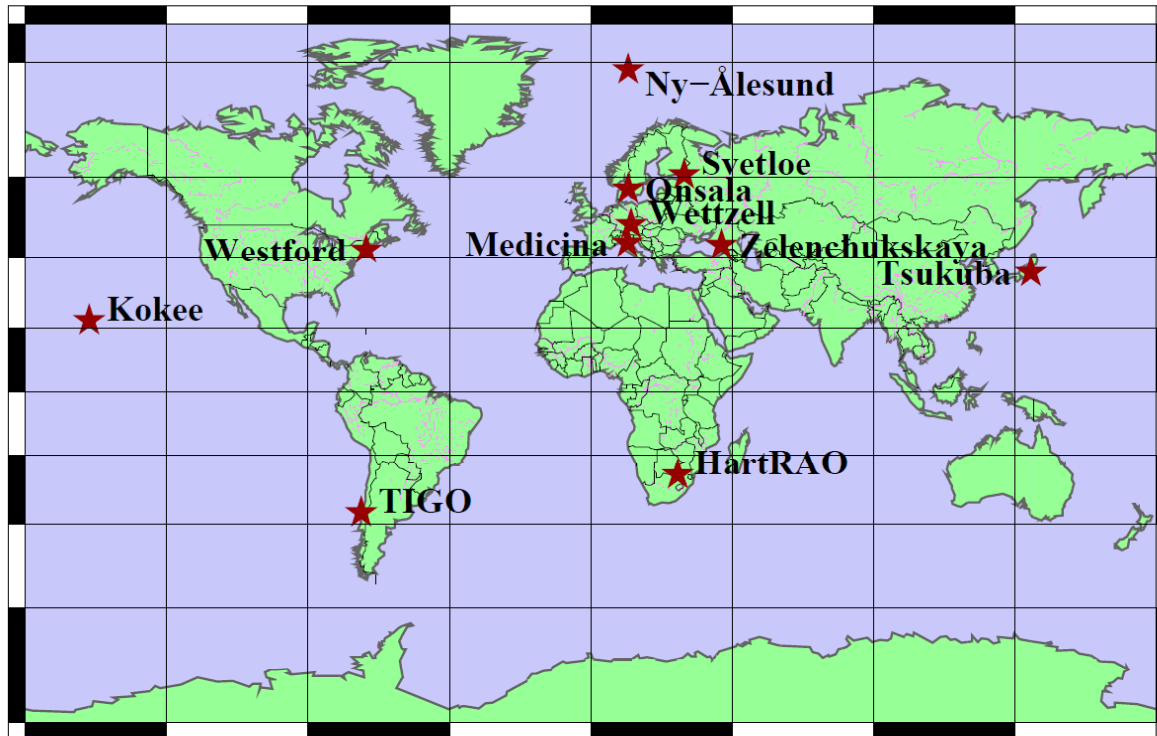
- Slant delays at 5° elevation, 12 Aug 2008 0 UT Tsukuba



# Outlook

- Presently, symmetric mapping functions together with estimation of gradients yield accurate and 'stable' results.
- With improved numerical weather models (of high time and spatial resolution) in future ray-traced slant delays will become standard in GNSS analysis.

# Comparison of zenith delays during CONT08



- IGS
- CODE
- VLBI
- DORIS
- WVR
- NWM

*Teke et al. 2010 (submitted)*

# Comparison with CODE zenith delays for CONT02 and CONT08

Standard deviations in mm

	VLBI	
	'02	'08
NyAlesund	3.3	3.9
Onsala	4.1	5.0
Wettzell	4.5	4.6
Westford	3.5	6.4
Kokee Park	6.6	9.5
HartRAO	5.8	5.2

# CODE zenith delays at Wettzell

## Standard deviations

- Different receivers: 1.5 mm
- w.r.t. IGS Kalman Filter: 3.4 mm
- w.r.t. VLBI: 4.5 mm

# Conclusions

- There is a latitude- and season dependence of the accuracy of zenith delays (and consequently of station heights).
- Different estimation setup adds a large part to the total uncertainty.

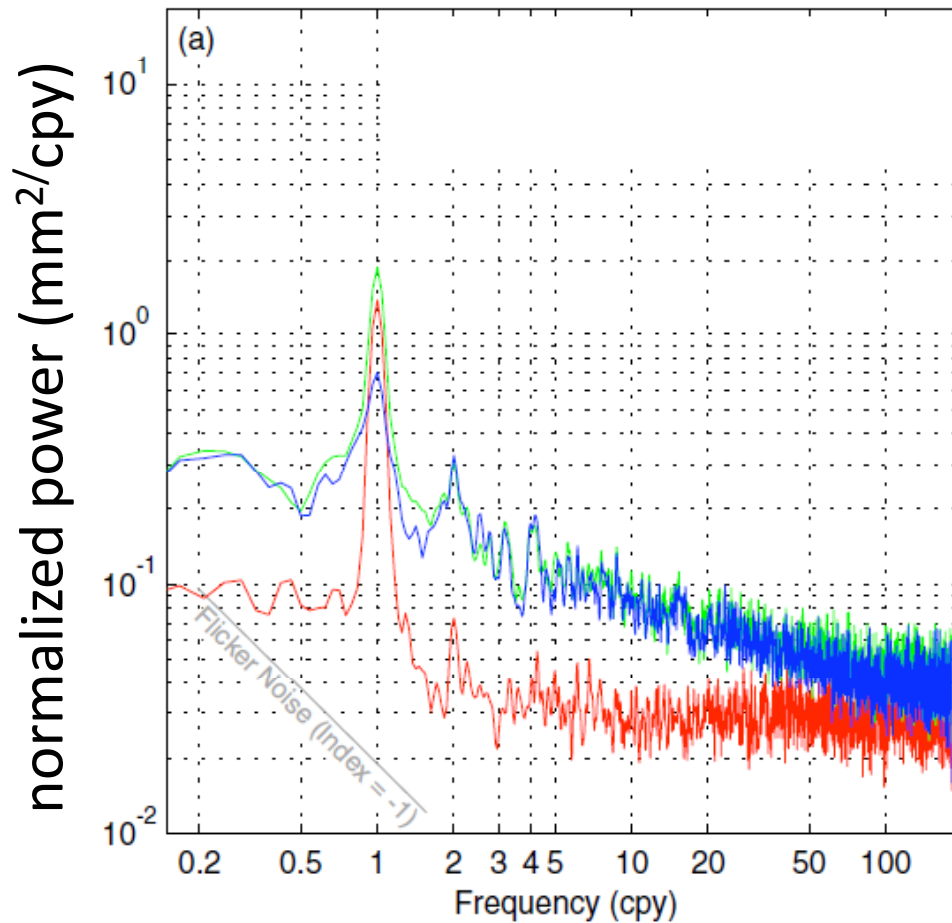
# Overall summary

- We presented an a priori gradient model that can be used for GNSS (and VLBI) analysis.
- There is a large potential in ray-tracing for future applications in GNSS analysis. Various groups worldwide are researching in that field.
- The accuracy of GNSS zenith total delays at mid-latitude sites is about 4-5 mm.

**Thanks for your attention!**

# ECMWF vs. GPT vs. SPT

Stacked power spectra of height differences

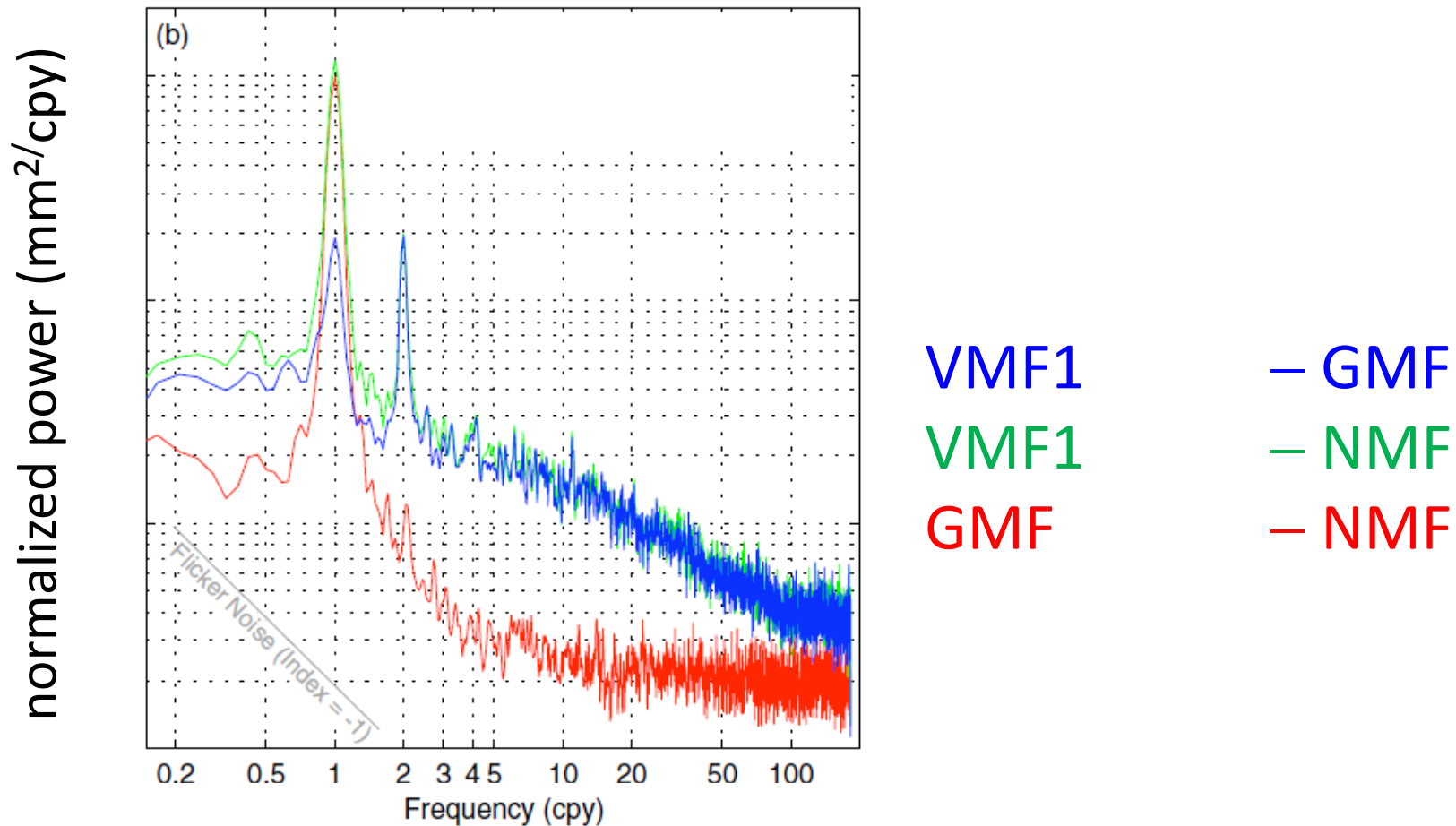


ECMWF — GPT  
ECMWF — SPT  
GPT — SPT

(Tregoning and Watson 2009)

# VMF1 vs. GMF vs. NMF

Stacked power spectra of height differences



(Tregoning and Watson 2009)

# Hydrostatic zenith delay errors

true pressure (ECMWF): 1020 hPa

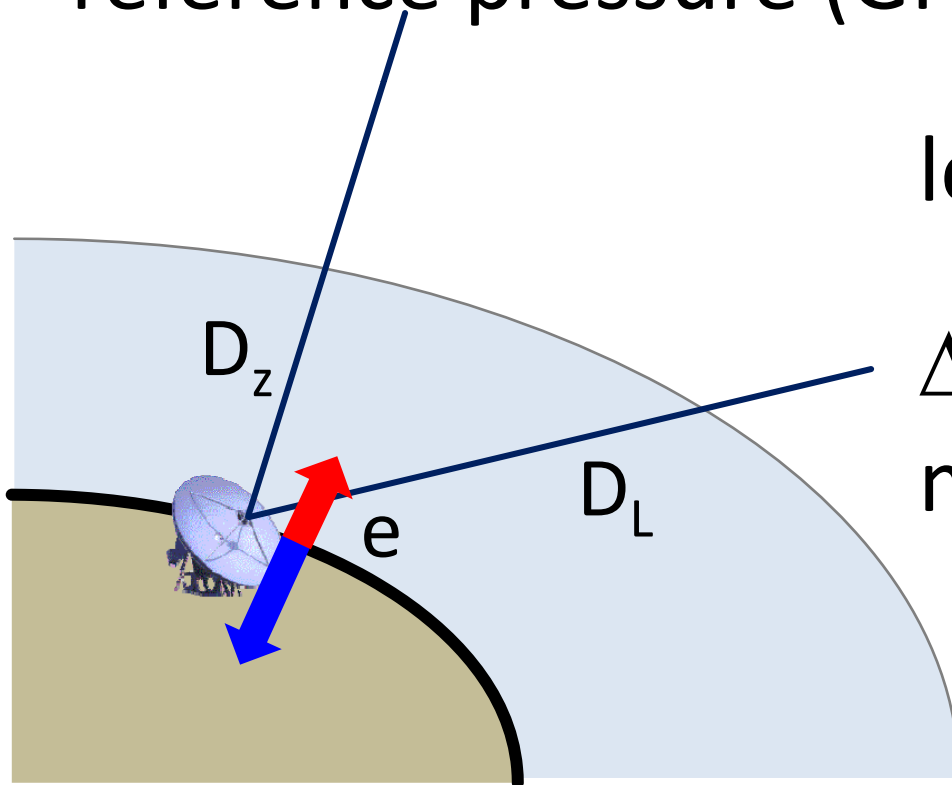
reference pressure (GPT): 1000 hPa

loading: 8 mm ↓

$\Delta D_{hz}$ : -46 mm

$m(e)$ : +28 mm @5°

$\Delta$  height: 5.5 mm ↑



# Hydrostatic zenith delay errors

- When using GPT (or any other empirical model) for the determination of a priori hydrostatic zenith delays, someone implicitly applies atmosphere loading corrections.

# Rule of thumb

- The station height error is about 1/5 of the delay error at the lowest elevation ( $5^\circ$ ).  
(*MacMillan and Ma, 1994*)

# Zenith delay - clock - height

$$D_L(e) = D_z \cdot m(e)$$

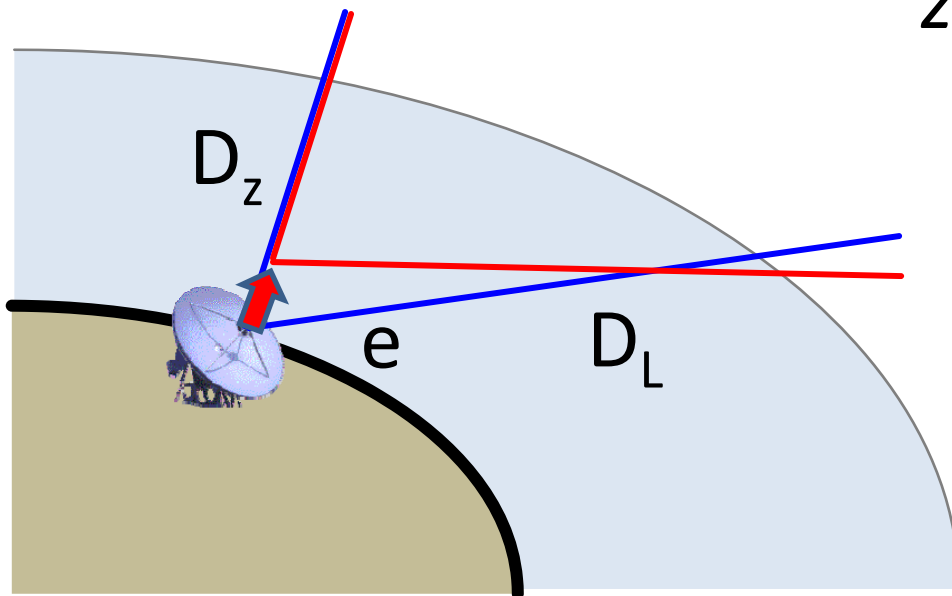
$$D_L(e) = D_z' \cdot m(e)'$$

Partials:

*clock:* = 1

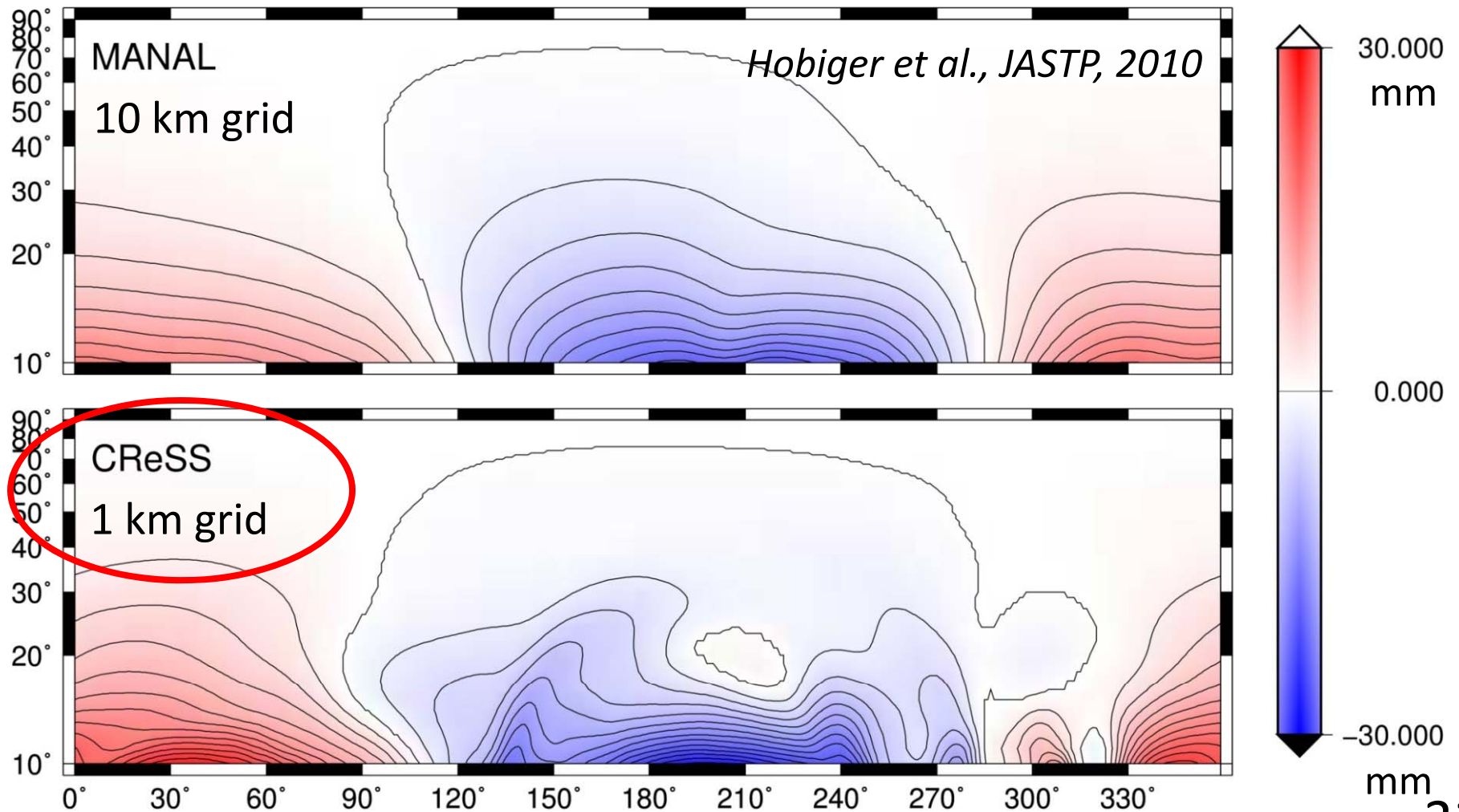
*height:* =  $\sin(e)$

*zenith delay*  $\approx m(e)$



# KAshima Ray-tracing Tools (KARAT)

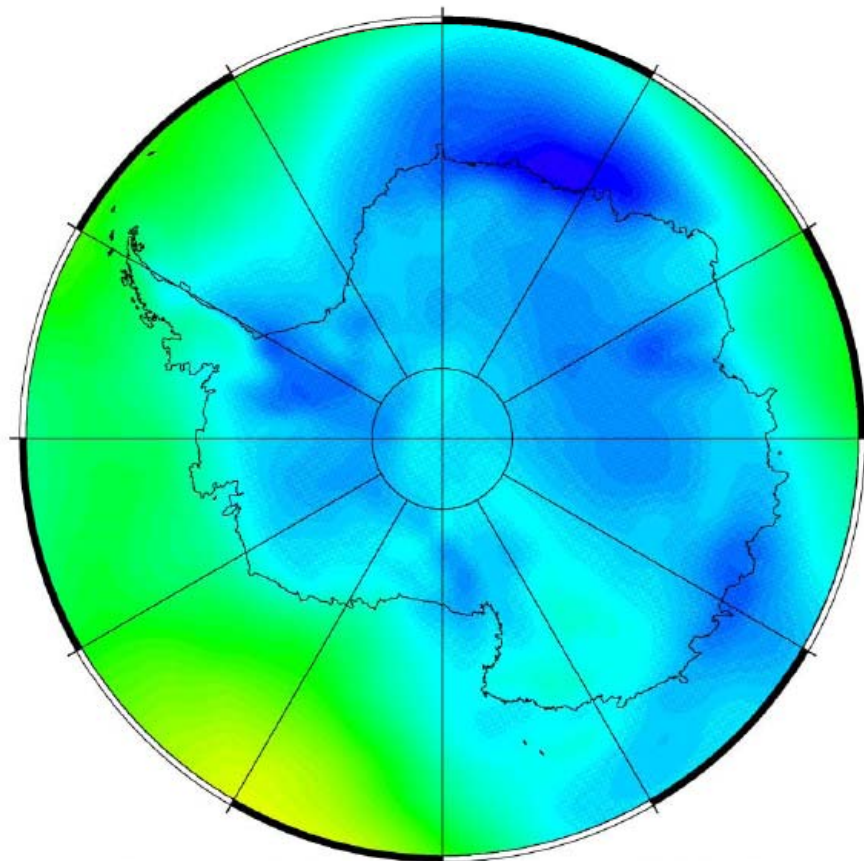
Example: GEONET site 3017, 7 Sep 2007 12h UT



# GPT vs. ECMWF

## Simulation of height velocities

*(King et al., 2010)*

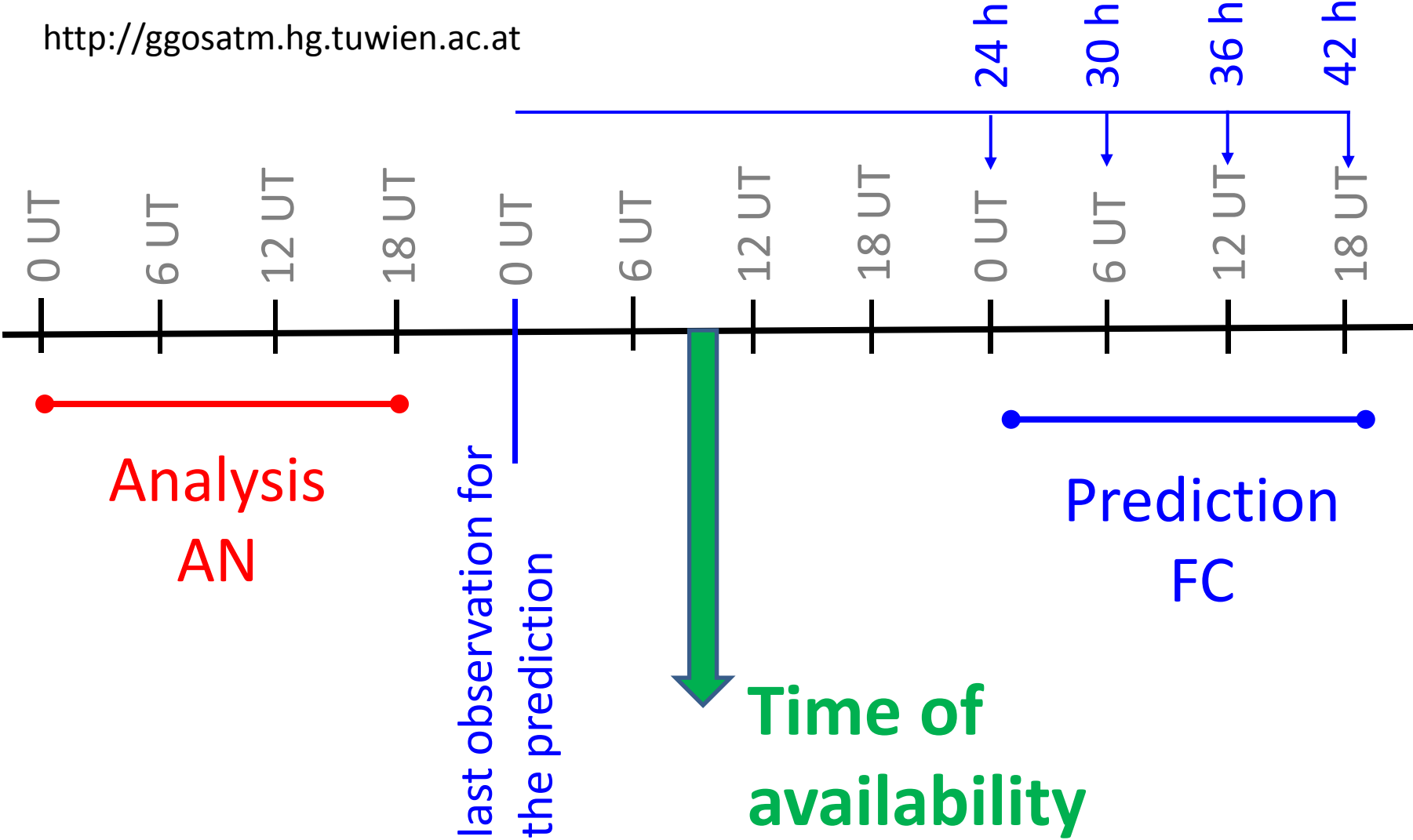


2003-2008

-0.5                      0                      +0.5 mm/year

# Availability of VMF1/ECMWF

<http://ggosatm.hg.tuwien.ac.at>



# GNSS analysis: mean coordinate differences

Est.: Chen & Herring '97 vs. MacMillan '95.

