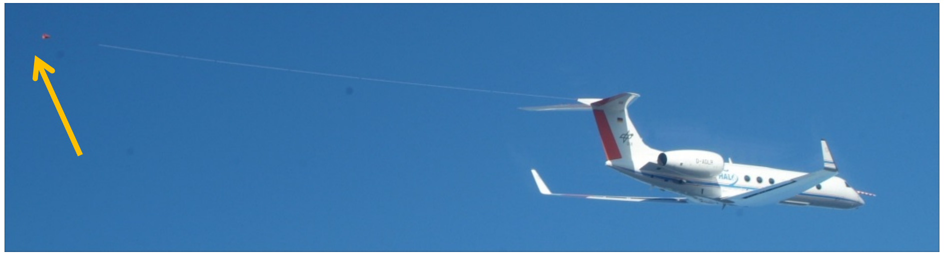
 

Comparison of Static Pressure from Aircraft Trailing Cone Measurements and Numerical Weather Prediction Analysis

Andreas Giez, Christian Mallaun, Martin Zöger,

Andreas Dörnbrack and Ulrich Schumann

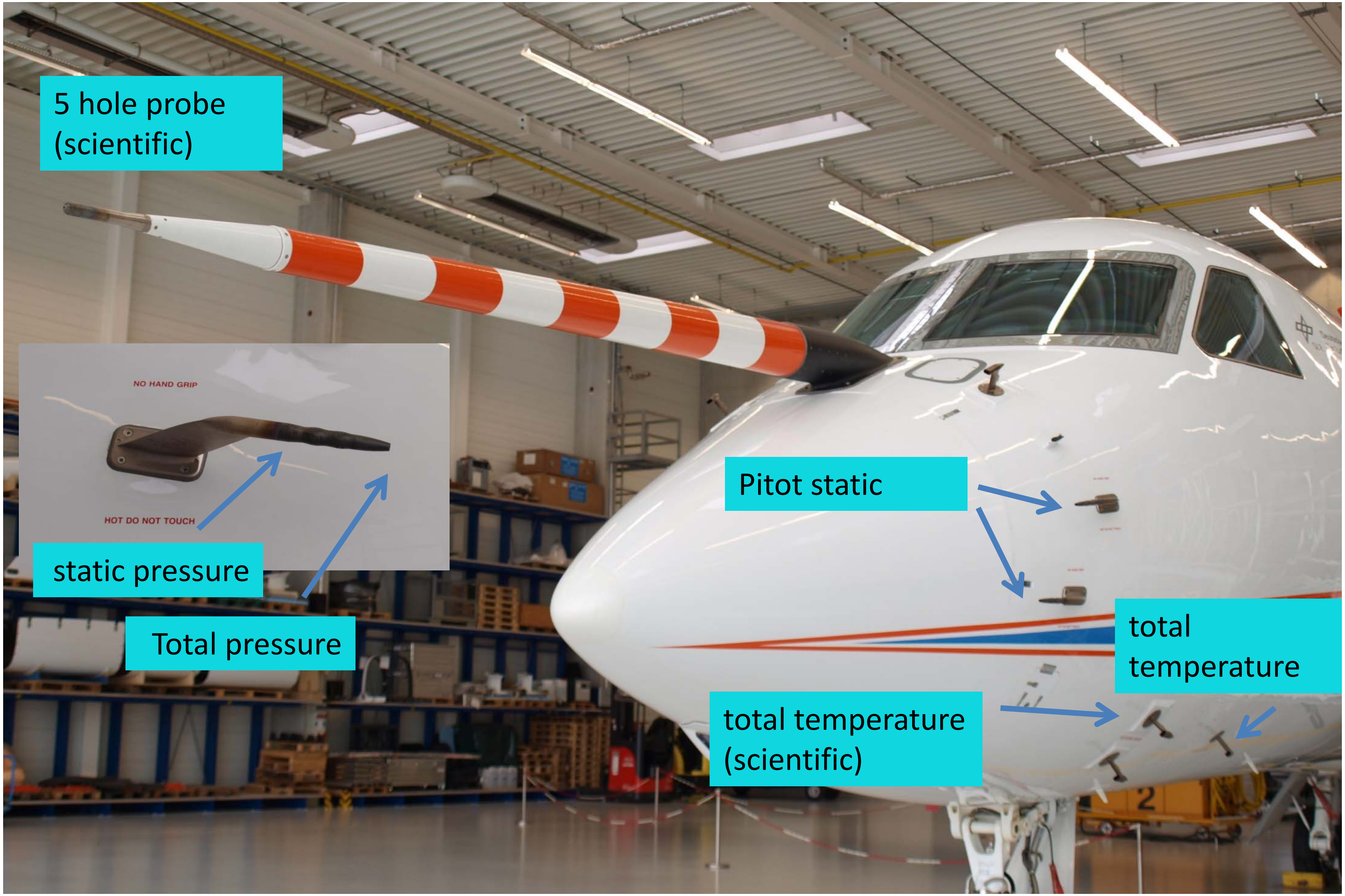
German Aerospace Center,
Flight Experiments and Institute of Atmospheric Physics,
Oberpfaffenhofen, Germany

- Height-keeping performance of aircraft is a key element in ensuring safe operations in RVSM airspace.
- Accurate pressure –geopotential relation is fundamental for meteorology
- We compare Trailing Cone (TC) and Numerical Weather Prediction (NWP) data
- The accuracy of the TC and NWP data is useful for control of height keeping performance and assessment of weather analysis

DLR

Pressure sensors on HALO

the German High Altitude and Long Range Research Aircraft, a Gulfstream G550

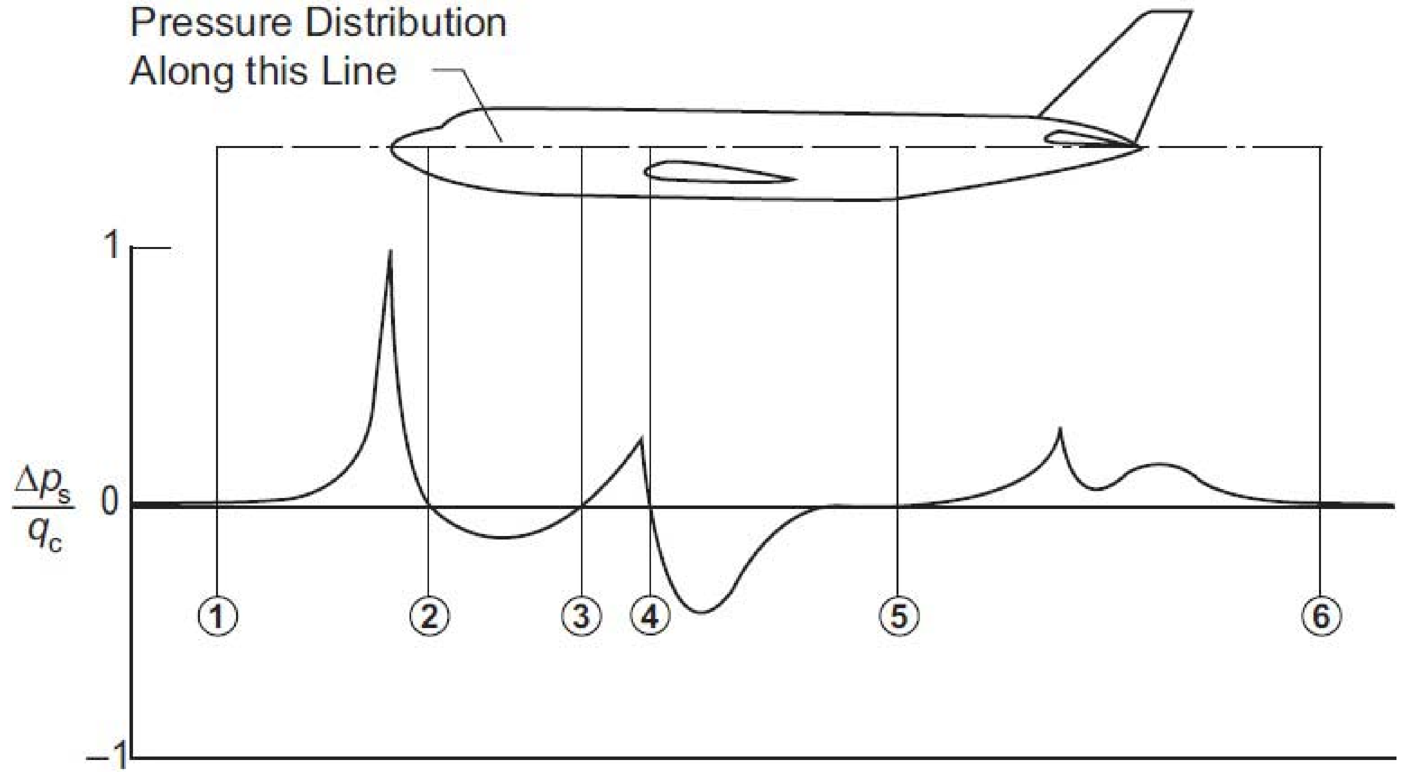


Pressure sensors on FALCON

a Dassault Mystère Falcon 20-E5

DLR

A well-known problem: Aerodynamic disturbance of static pressure distribution along an aircraft



DeLeo and Hagen (1966)

DLR

Importance of static pressure p

- aviation

height in standard atmosphere

$$z = H_{ICAO}(p)$$

static temperature from total

$$\frac{T_{tot}}{T} = \left(\frac{p_{tot}}{p}\right)^{\frac{\gamma-1}{\gamma}}$$

Mach number

$$M = \left(\frac{2}{\gamma - 1}\right)^{1/2} \left[\left(\frac{p_{tot}}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right]^{1/2}$$

$$\gamma = \frac{c_p}{c_v} = 1.4$$

Anderson (2010)

- meteorology

hydrostatic pressure

$$dp = -\rho g dz = -\frac{p}{R_{dry} T_V} d\Phi$$

equation of state

$$\rho = \frac{p}{R_{dry} T_v}$$

$$T_v = T(1 + \varepsilon q)$$

$$\varepsilon = R_{dry} / R_{vap} - 1$$

geopotential

$$\Phi(z) = \int_0^z g(z') dz'$$

geostrophic wind

$$\vec{V} = \frac{\vec{k}}{f} \times \nabla_p \Phi$$

Holton (2012)

DLR

Method for determination of pressure/height deviations, Δz and Δp

A) Measurement at aircraft (AC):
GNSS -> Height above NN: z_{AC}
AC sensor -> Static pressure: p_{AC}

B) Numerical weather prediction (NWP) from analysis or prediction

1) Altitude for given pressure $p_{AC} = p_{NWP}$
-> z_{NWP}

2) Pressure for given height $z_{AC} = z_{NWP}$
-> p_{NWP}

C) Height and pressure deviation

$\Delta z = z_{AC} - z_{NWP}$

$\Delta p = p_{AC} - p_{NWP}$

DLR

Is NWP accurate enough?

Can it be used for checking pressure altitude measure-ments?

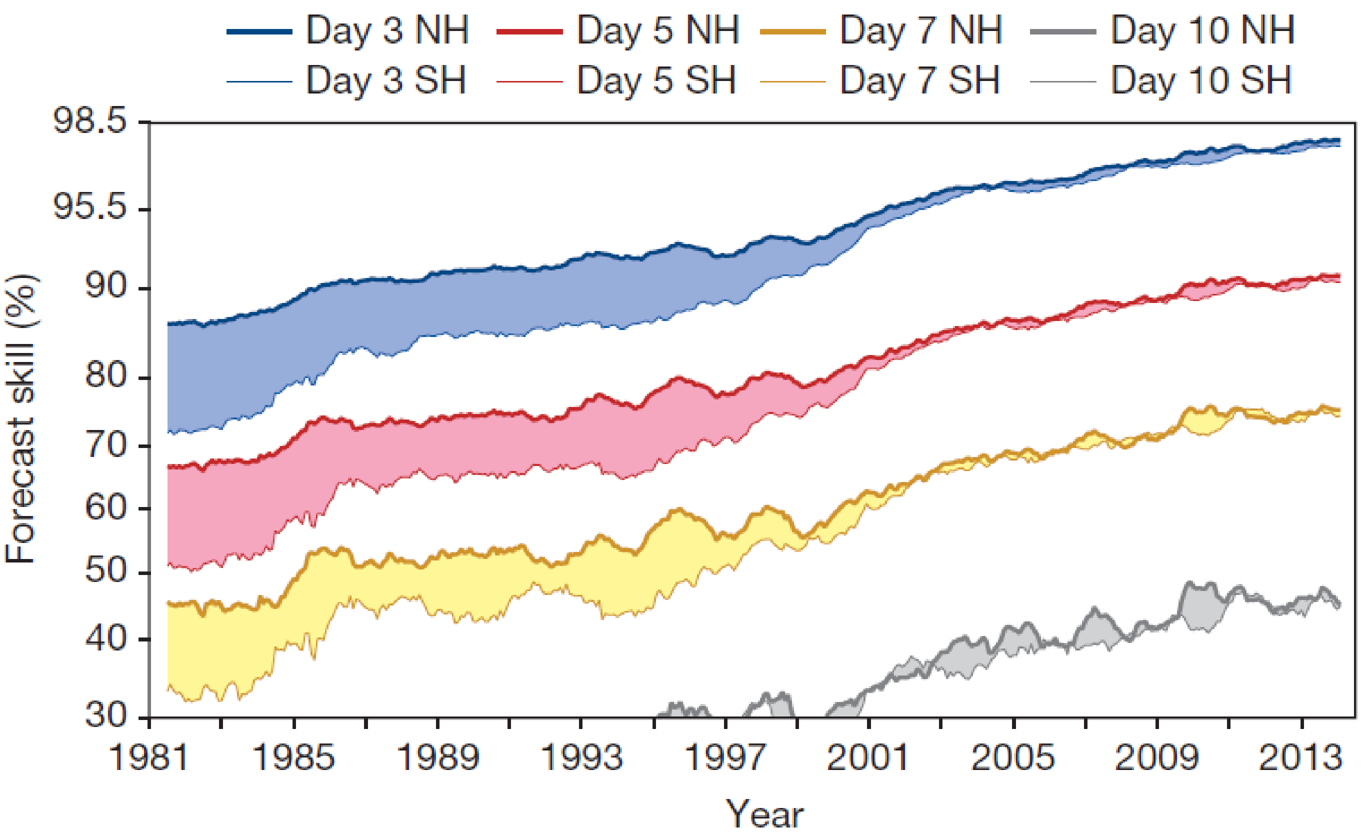
REVIEW

(Nature: September 2015)

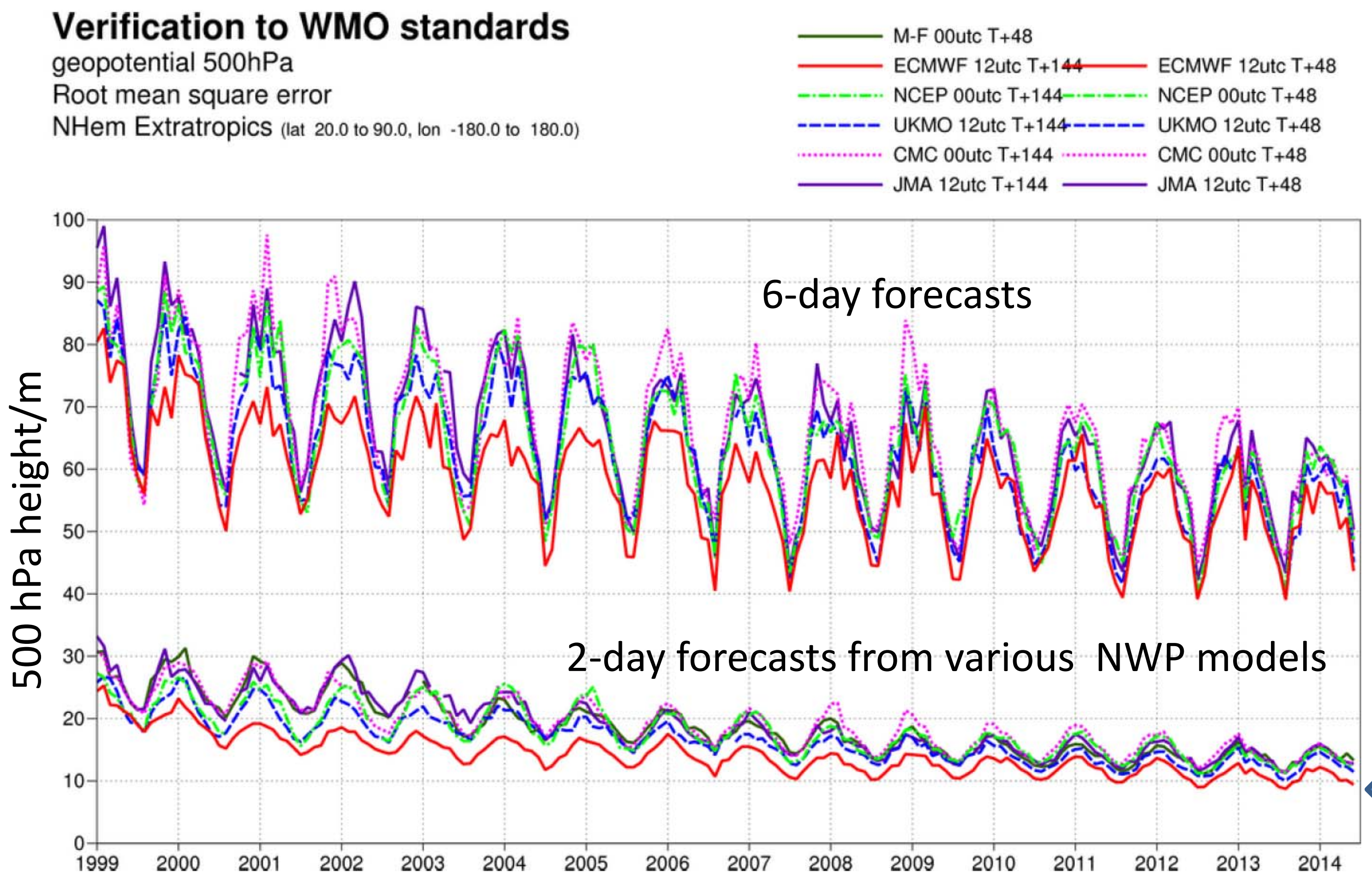
doi:10.1038/nature14956

The quiet revolution of numerical weather prediction

Peter Bauer[1], Alan Thorpe[1] & Gilbert Brunet[2]



2-day forecast, 500 hPa geopotential: rms order 15 m



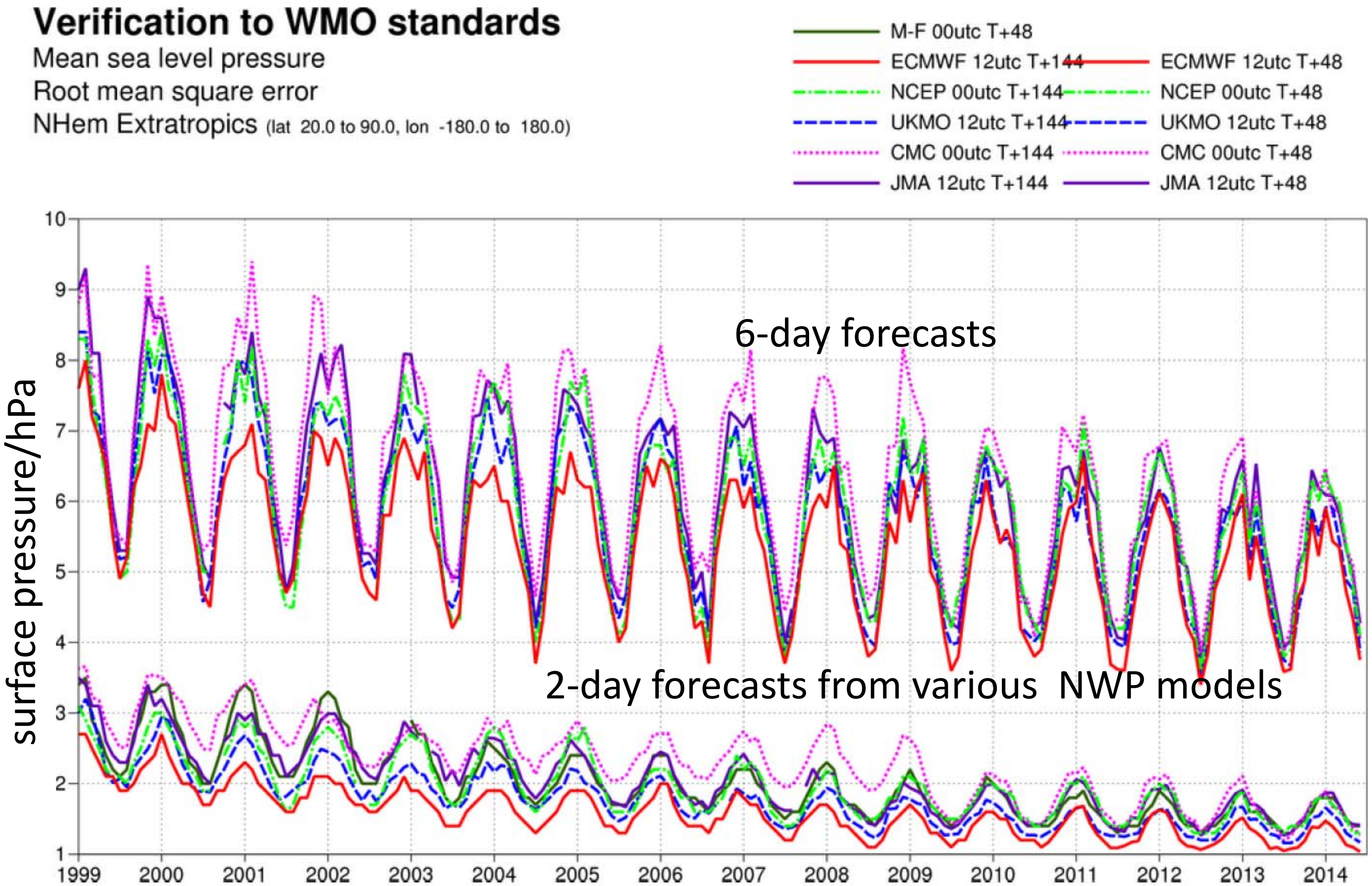
Decreasing errors over the years.

Seasonal cycle.

Haiden et al., ECMWF Techn. Memo. 742, 2014

Figure 15: WMO-exchanged scores from global forecast centres. RMS error over northern extratropics for 500 hPa geopotential height (. In each panel the upper curves show the six-day forecast error and the lower curves show the two-day forecast error. Each model is verified against its own analysis. JMA = Japan Meteorological Agency, CMC = Canadian Meteorological Centre, UKMO = the UK Meteorological Office, NCEP = U.S. National Centers for Environmental Prediction, M-F = Météo France.

Same for surface pressure: rms order 1 hPa



Haiden et al., ECMWF Techn. Memo. 742, 2014

Figure 15: WMO-exchanged scores from global forecast centres. RMS error over northern extratropics for [illegible] mean sea level pressure (bottom). In each panel the upper curves show the six-day forecast error and the lower curves show the two-day forecast error. Each model is verified against its own analysis. JMA = Japan Meteorological Agency, CMC = Canadian Meteorological Centre, UKMO = the UK Meteorological Office, NCEP = U.S. National Centers for Environmental Prediction, M-F = Météo France.

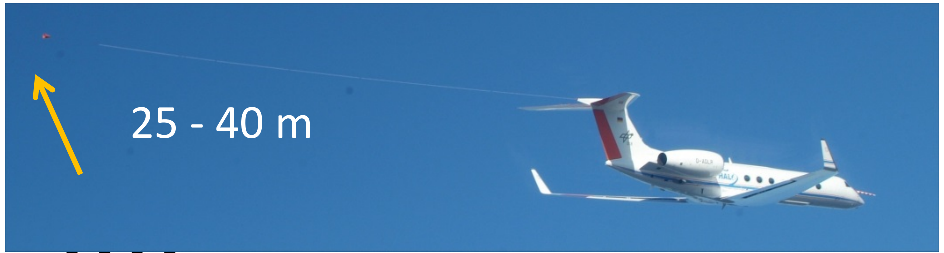
Falcon with Trailing Cone

Photo: WTD61, Manching, 2011
(provided by Oliver Brieger)

Trailing cone measurements behind DLR aircraft:
159 data points, 20-160 s leg-mean values, Germany

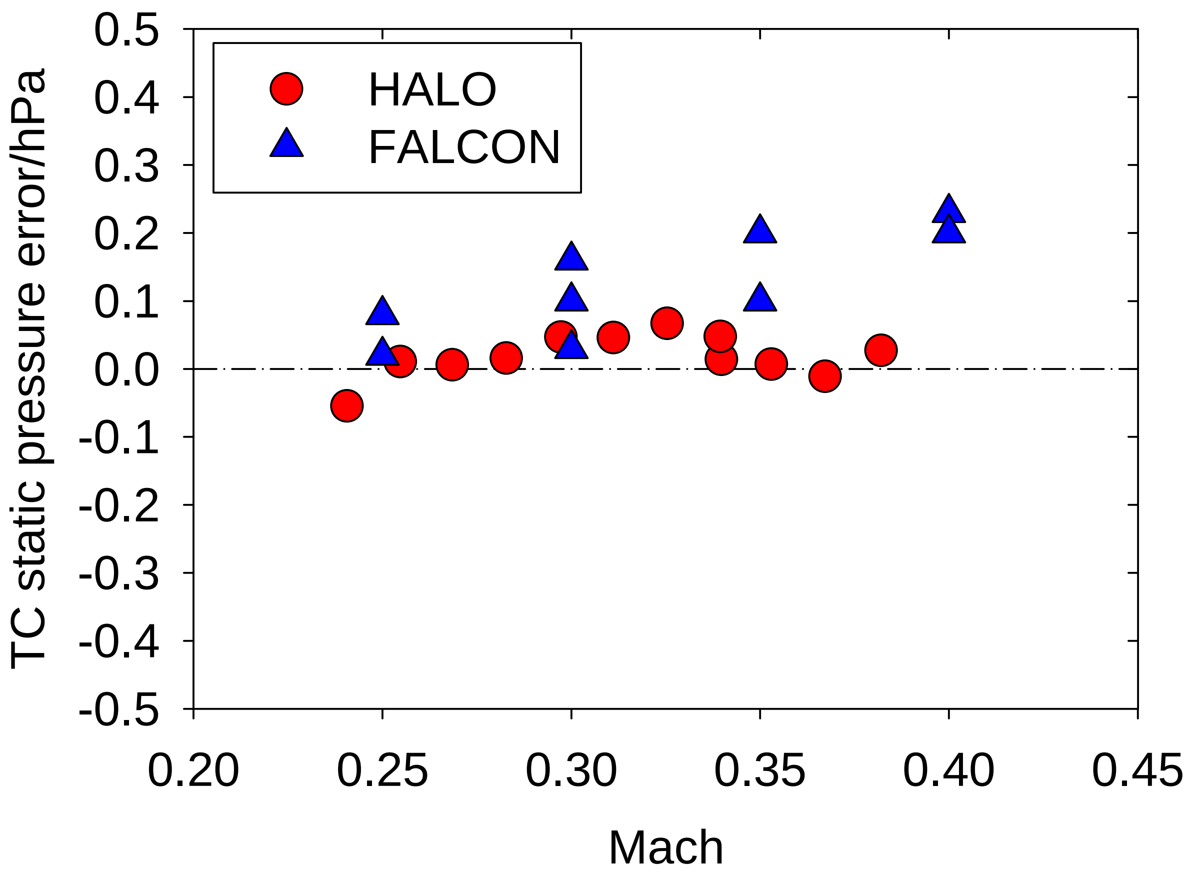
- HALO p: Weston Aerospace Digital Pressure Module DPM 78851BA, $\Delta p < 0.006$ hPa
- FALCON p: Rosemount Model 1201FS Sensor with Ruska 7750i reference, $\Delta p < 0.4$ hPa.
- Altitude above WGS84 with differential GPS, $\Delta z < 0.5$ m, after post-processing < 0.1 m
- corrected for geoid undulation N = h-z (about 50 m)

Aircraft	Region	Date	FL in hft
HALO	ALLGÄU	15 April 2010	350, 250,150
	SAXONY	22 June 2010	430, 350,250, 40
	ALLGÄU	24 May 2011	150, 250,270 ,350,400
	ALLGÄU	16 September 2011	430,350,250
	ALLGÄU	23 September 2011	290,350,410, 150
FALCON	ALLGÄU	20 May 2011	250,330,150



DLR

TC pressure measurement error from flyby maneuvers



accuracy:
Δp = 0.12 hPa for HALO
Δp = 0.5 hPa for Falcon

corresponding to

Δz = 1 m for HALO
Δp = 4 m for Falcon

at ground

Falcon:
upper bound from Gaussian error propagation

DLR

Differences between trailing cone pressure sensor reading and hydrostatically corrected pressure on the ground for HALO and Falcon

NWP analysis:

- NWP data from the Integrated Forecasting System(IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF)
- 0.25° horizontal resolution
- 91 layers ($\Delta p \approx 14$ hPa, $\Delta z \approx$ 400 m at tropopause)
- 3-h time resolution
- combined analysis + forecast
- model levels, interpolation: linear temporally and horizontally,
- vertically in log(p)
- Somigliana-type gravity formula, height dependence from DoD/NIMA TR8350.2
- Including surface gravity anomalies δg from Earth Gravitational Model 2008 (EGM2008)
- assuming small horizontal wind

$p_{k+1/2} = a_{k+1/2} + b_{k+1/2}\, p_{sfc}$, k=0,…,K.

$$\Phi = \int_0^z g dz$$

$$\Phi_{k+1/2} = \Phi_{k-1/2} - \int_{p_{k-1/2}}^{p_{k+1/2}} \frac{RT_V}{p} dp$$

$$\cong \Phi_{k-1/2} - RT_{V,k} \ln\left(\frac{p_{k+1/2}}{p_{k-1/2}}\right)$$

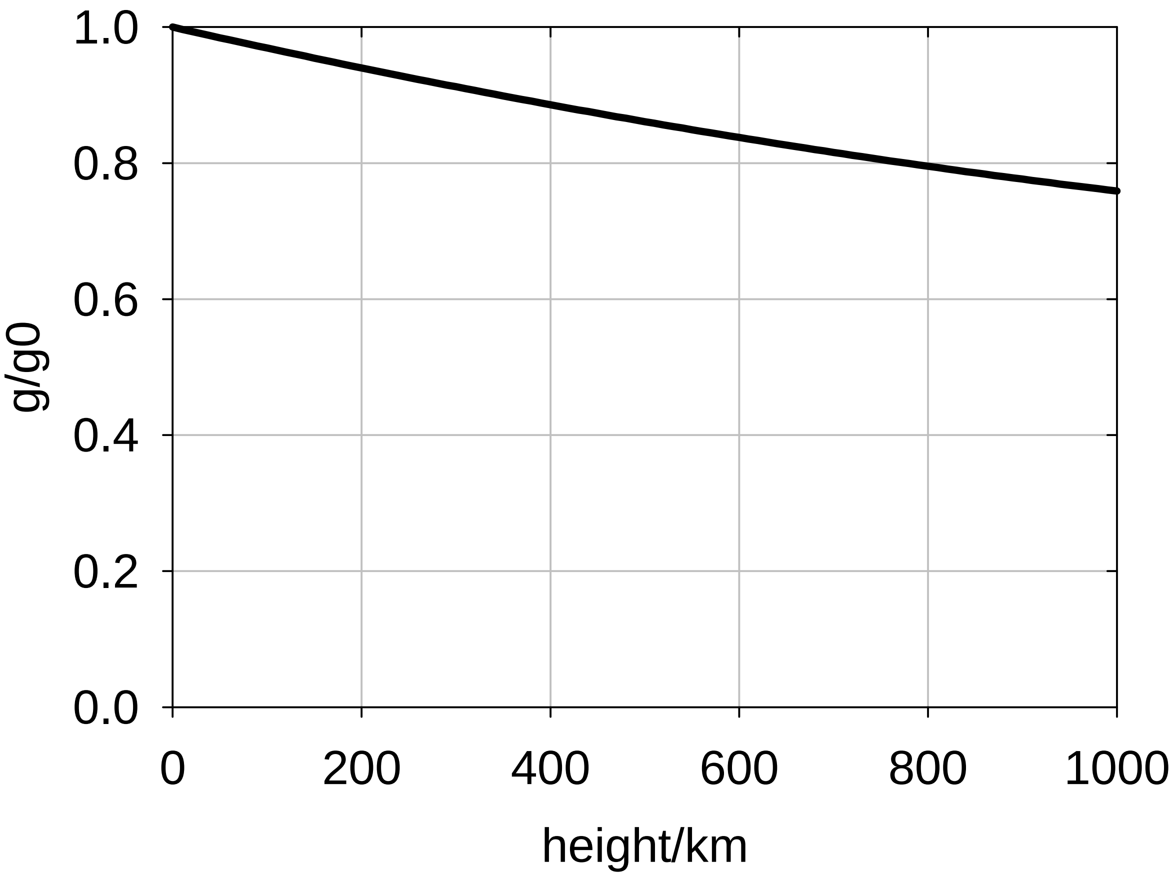
g= 9.80665 m s^{-2}
or
$g=\gamma_z(z,\phi)+ \delta g(\phi,\lambda)$

for $z < 13.5$ km: $\Delta g/g < 0.43\%$.

DLR

gravity varies due to the distance to Earth's center, Earth's rotation and local gravity anomalies from crust density variations

Gravity is altitude dependent



at FL 450,
13.7 km:

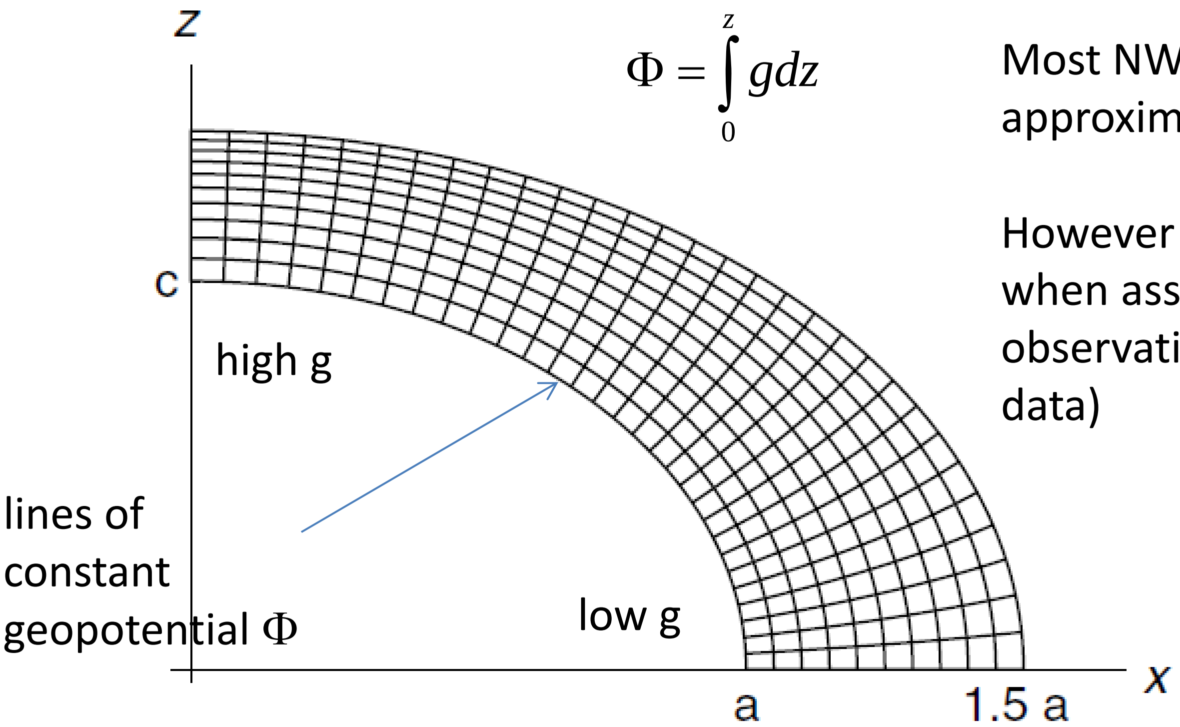
$\Delta g/g$=0.4 %

DLR

Deviation from sphere and rotation dependent gravity variability are connected

(Spheroidal and spherical geopotential approximations)

$$\Phi = \int_0^z g\,dz$$

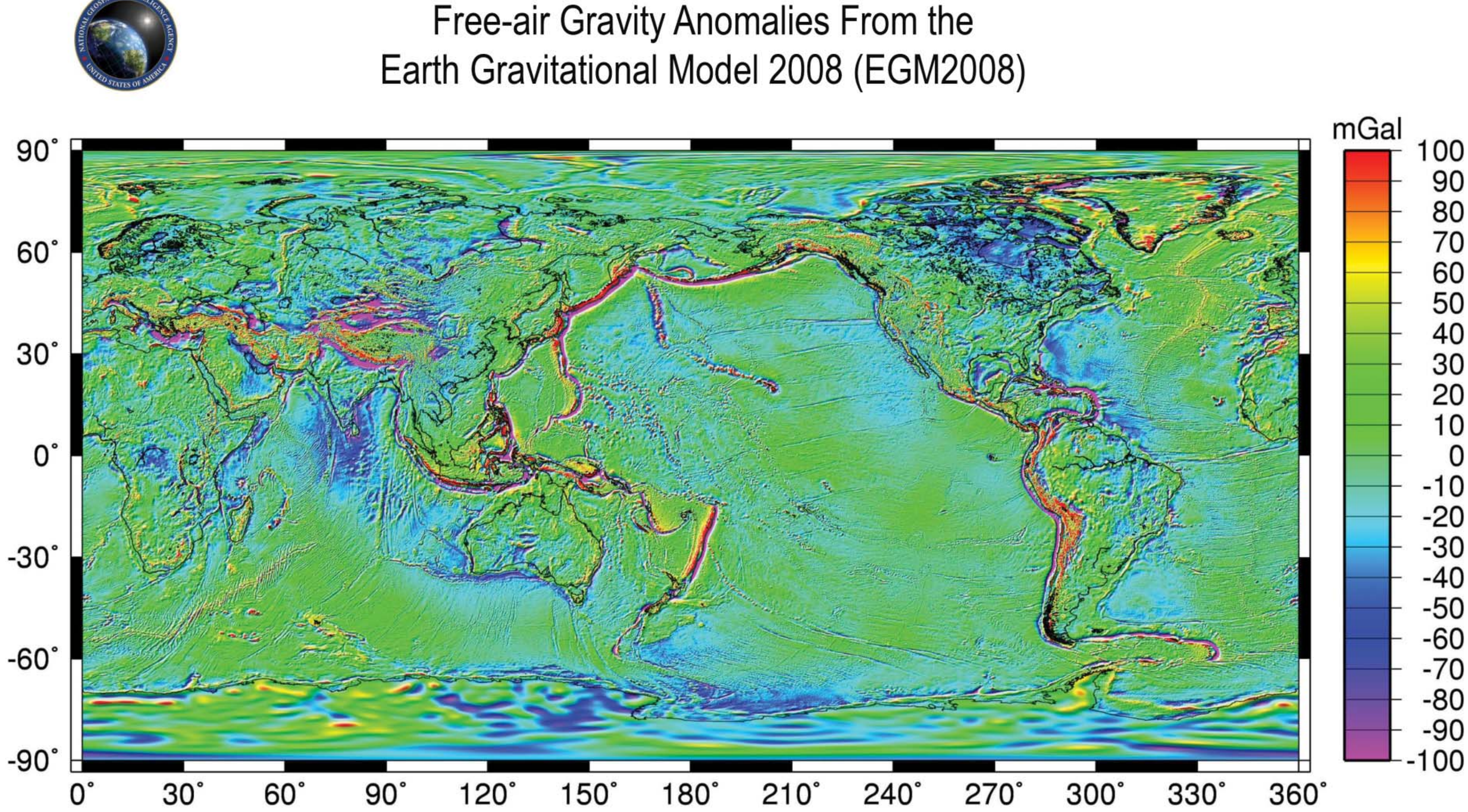


Most NWP models use the spherical approximation.

However ECMWF uses Φ for variable g when assimilating altitude dependent observations (e.g. GPS radio occultation data)

Bénard (QJRMS, 2014)
see also Staniforth (QJRMS, 2014)

Gravity is latitude and longitude dependent



Free-air gravity anomalies computed from EGM08, averaged over 5 arc-minute by 5 arc-minute cells on the surface of the Earth. A gravity anomaly is the difference of actual (observed) gravity from a nominal (theoretical) value. The unit is "milliGal" (denoted mGal, where 1 mGal = 10^{-5} ms^{-2}), which corresponds approximately to 1 part per million of the gravity acceleration sensed by an observer on the Earth's surface. Notice the numerous geophysical features that are revealed, such as oceanic trenches, ridges, subduction and fracture zones, and seamount chains.

DLR

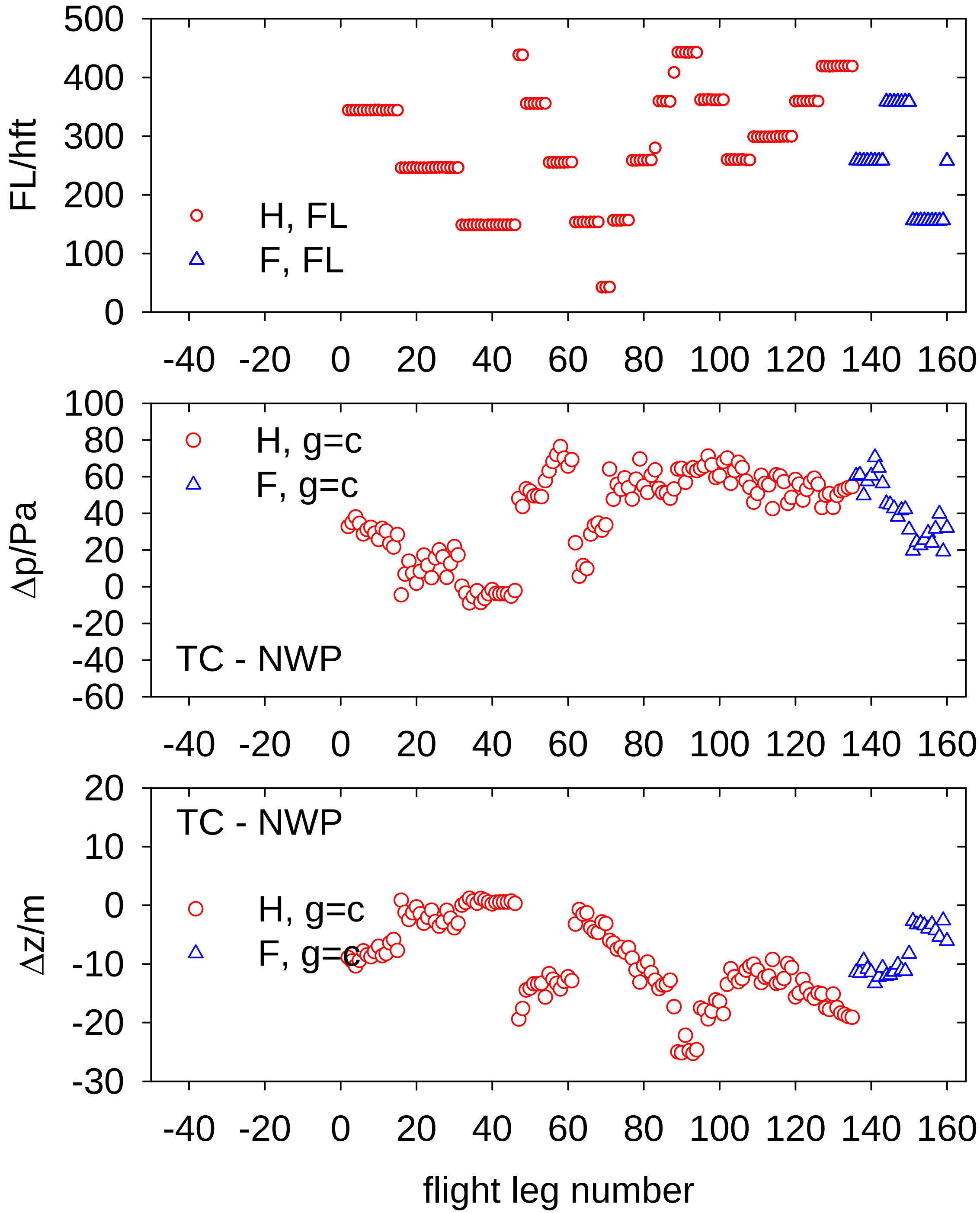
Pavlis et al. (JGR, 2012)

Results

159 test points from 6 days with 2 aircraft (Halo H and Falcon F) for FL 50 -430 hft

Δp, Δz computed for constant (g=c) gravity

Max deviations:
0.75 hPa, 27 m



DLR

Results

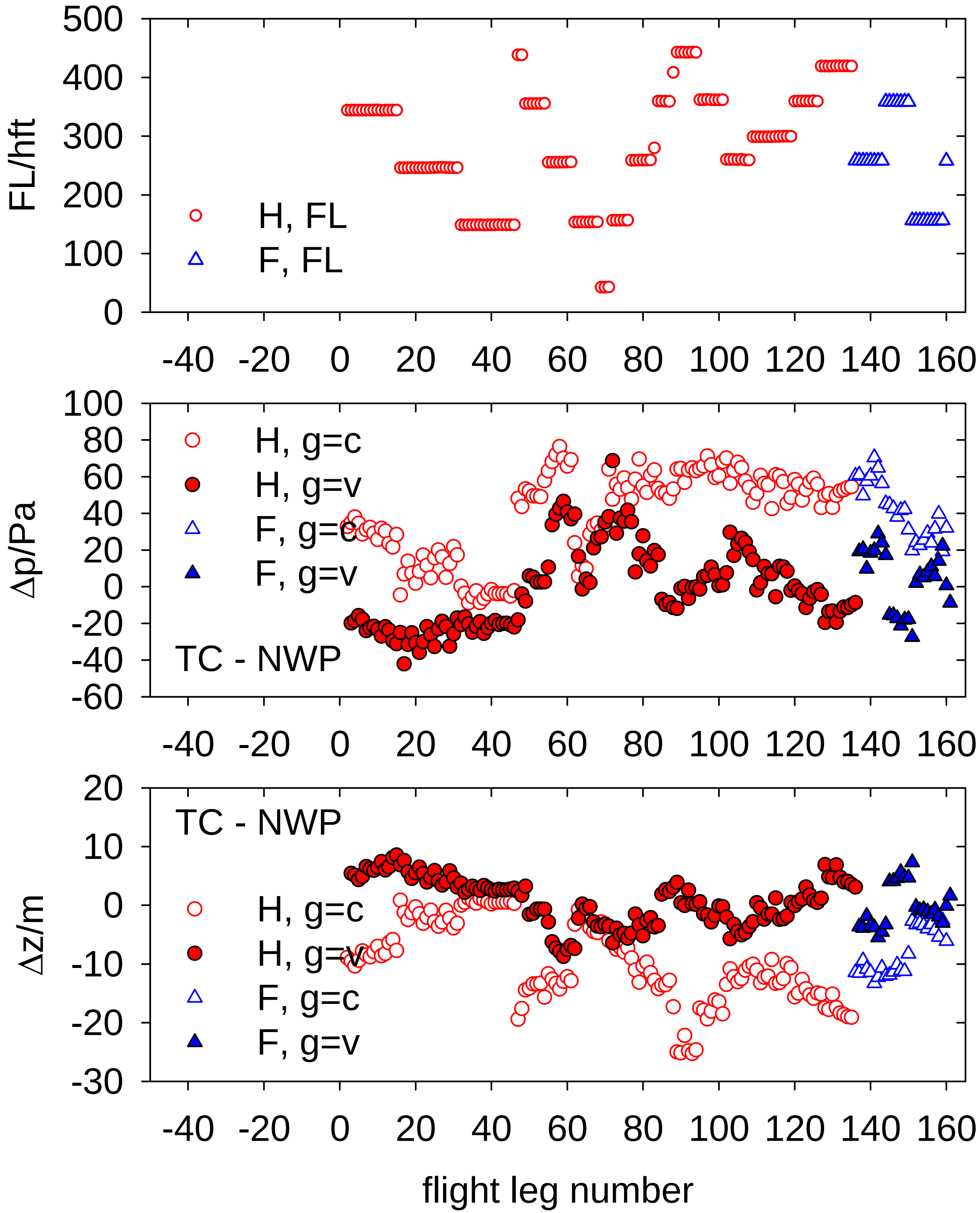
159 test points from 6 days with 2 aircraft (Halo H and Falcon F) for FL 50 -430 hft

Δp, Δz computed for constant (g=c) and variable (g=v) gravity

Max deviations:

(0.75 hPa, 27 m)

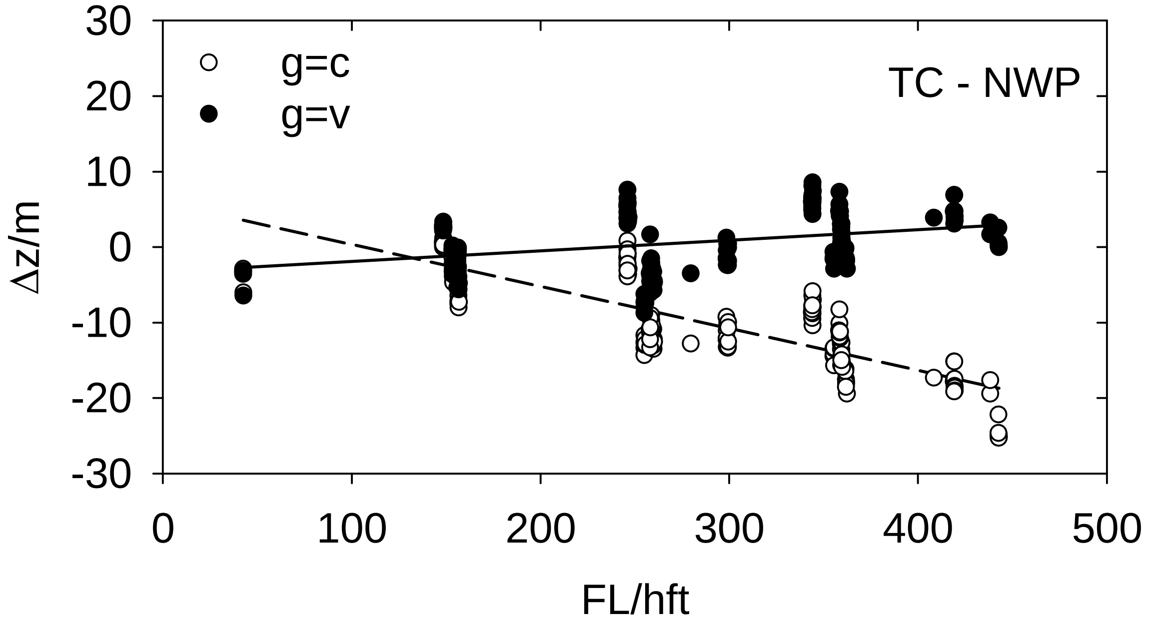
0.68 hPa, 9 m

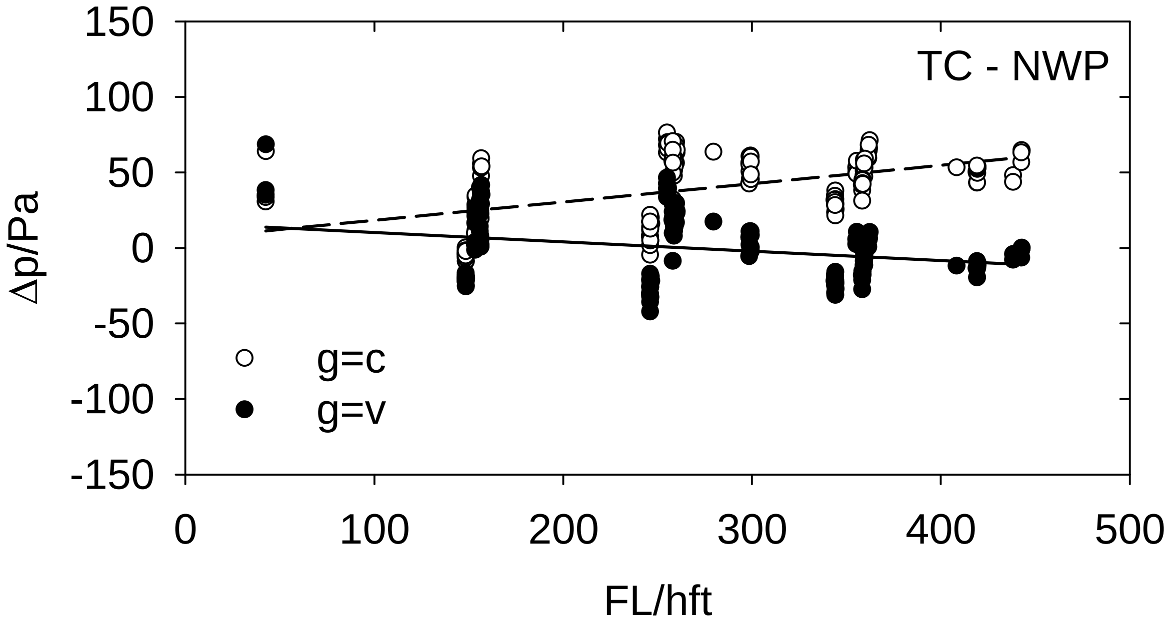


DLR

Flight level dependence:

Significantly smaller deviations of Δz and Δp for variable g than for constant g





DLR

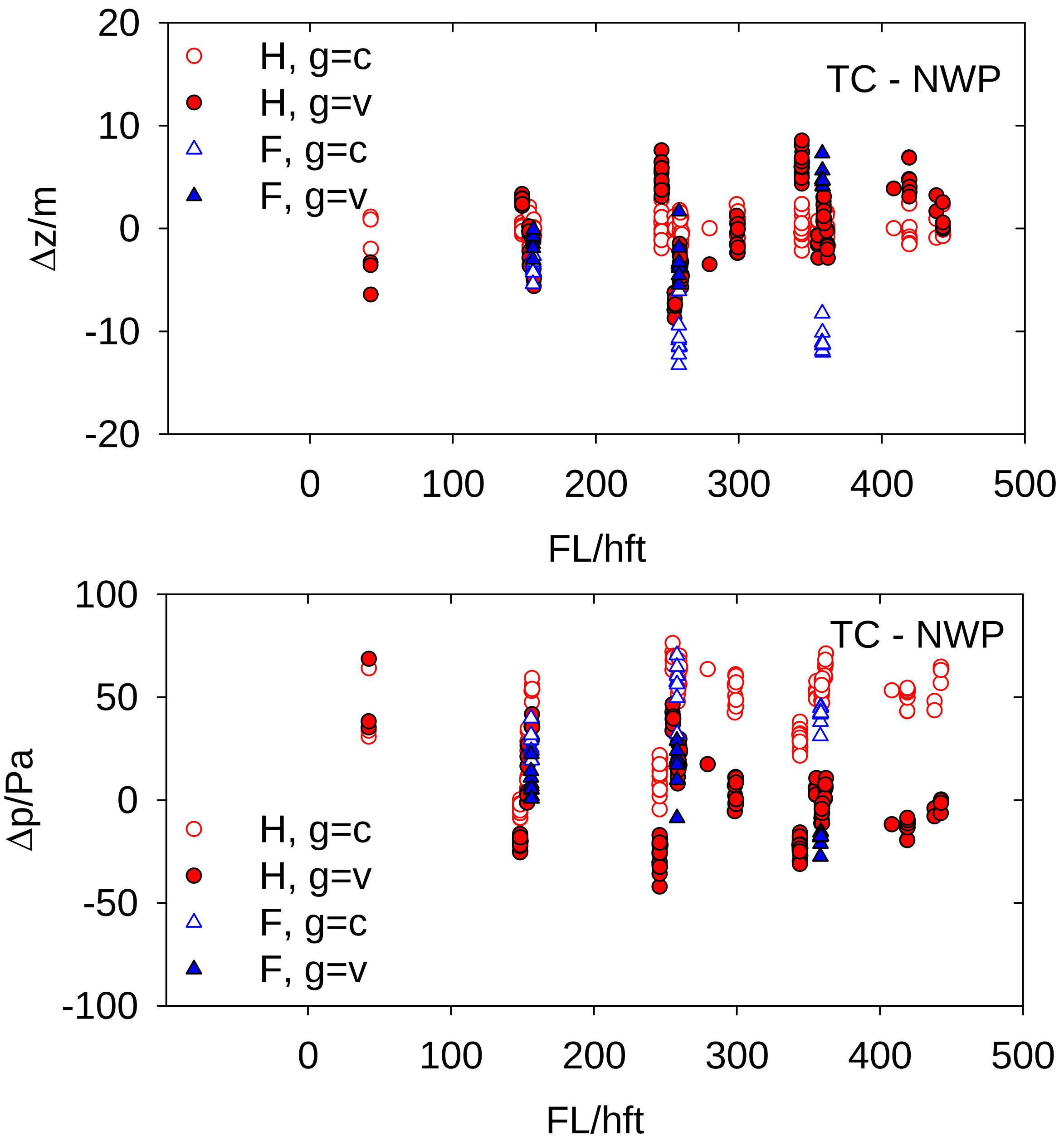
Mean deviations

gravity model	Δz/m	Δp/Pa
$g=9.80655$ m s^{-2}	-9.5±4.6	39.90±16.2
$g=\gamma_z(\phi,\lambda)+\Delta g$	0.6±2.8	-0.8±14.9

not only the mean errors but also the standard deviations are smaller for variable g than constant g!

DLR

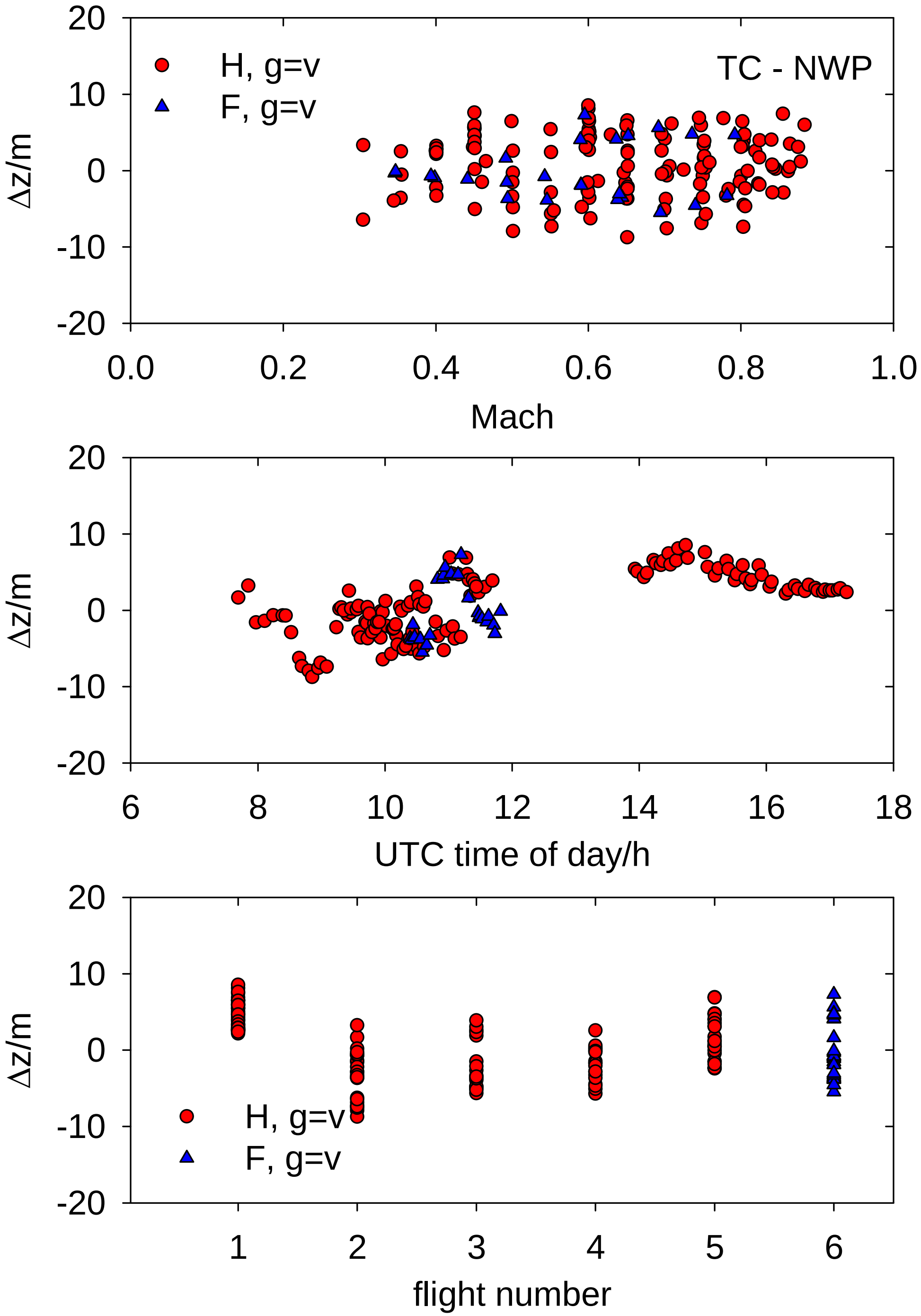
Low sensitivity to flight level, FL



Significantly smaller deviations for variable g than for constant g

DLR

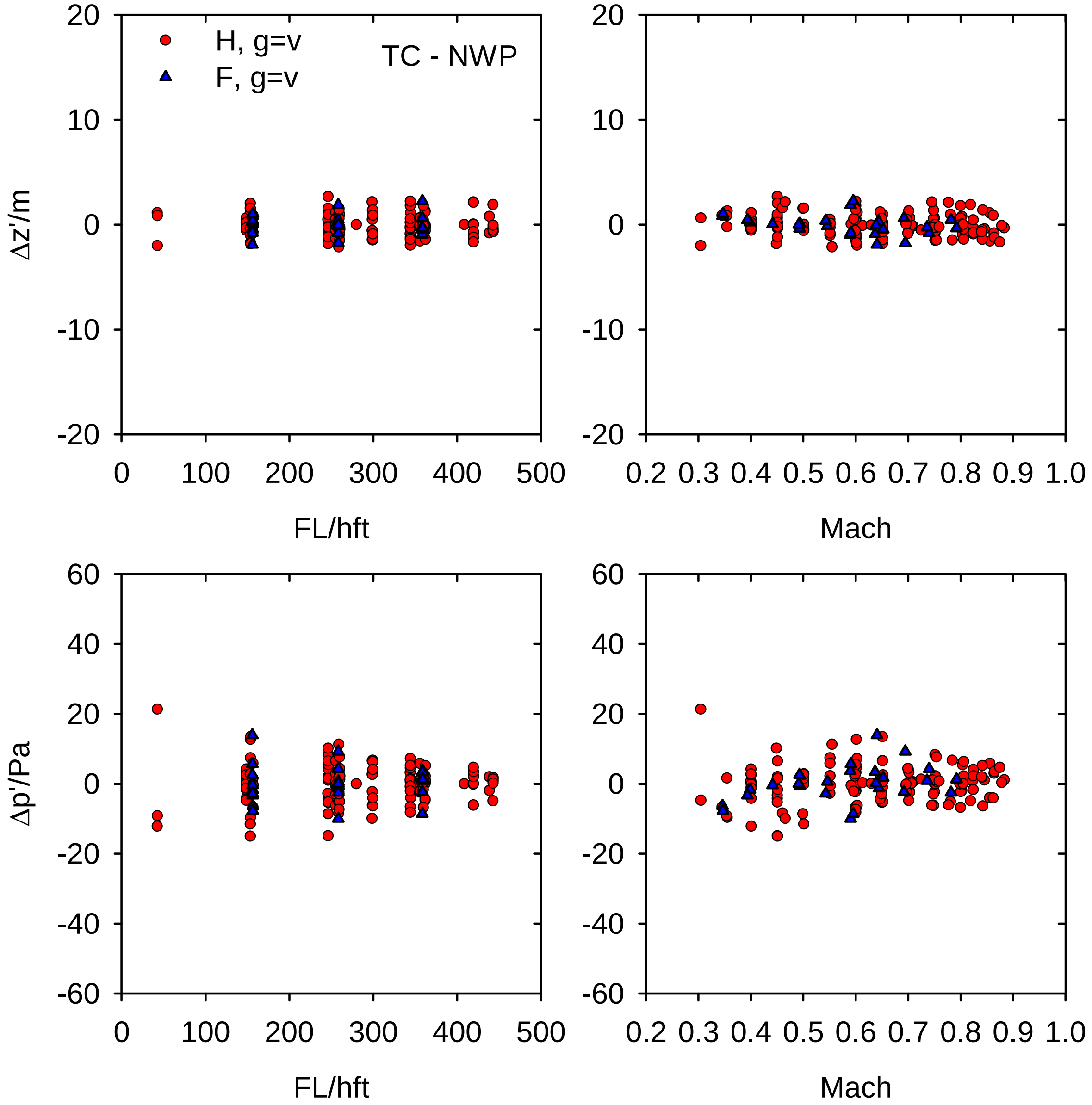
Low sensitivity to Mach number,
time of day,
number of flight,
and aircraft (H or F)



DLR

Low random errors (deviations of single values from average over all legs at constant FL)

$\Delta z' < 3$ m,
$\Delta p' < 20$ Pa



DLR

Random errors

(deviations of single values from average over all legs at constant FL)

Importance of gravity and DGPS/INU postprocessing

g model	$\sigma(\Delta p')$	$\sigma\ (\Delta z')$
	HALO	
$g=9.80665\ m\ s^{-2}$	5.63 Pa	1.10 m
$g=\gamma_z$	5.40 Pa	1.04 m
$g=\gamma_z+\Delta g$	5.33 Pa	1.02 m
online DGPS	6.98 Pa	1.49 m

DLR

Reminder: JAA Administrative & Guidance Material

Section One: General Part 3: Temporary Guidance Leaflets

LEAFLET NO 6: Revision 1 GUIDANCE MATERIAL ON THE APPROVAL OF AIRCRAFT AND OPERATORS FOR FLIGHT IN AIRSPACE ABOVE FLIGHT LEVEL 290 WHERE A 300M (1,000 FT) VERTICAL SEPARATION MINIMUM IS APPLIED

Altimetry System Error (ASE) The difference between the pressure altitude displayed to the flight crew when referenced to the International Standard Atmosphere ground pressure setting (1013.2 hPa /29.92 in.Hg) and free stream pressure altitude.

7.3.2 Assessment of ASE, whether based on measured or predicted data will need to consider sub-paragraphs (a) to (d) of 7.3.1. The effect of item (d) as a variable can be eliminated by evaluating ASE at the most adverse flight condition in an RVSM flight envelope.

7.3.3 The criteria to be met for the Basic envelope are:

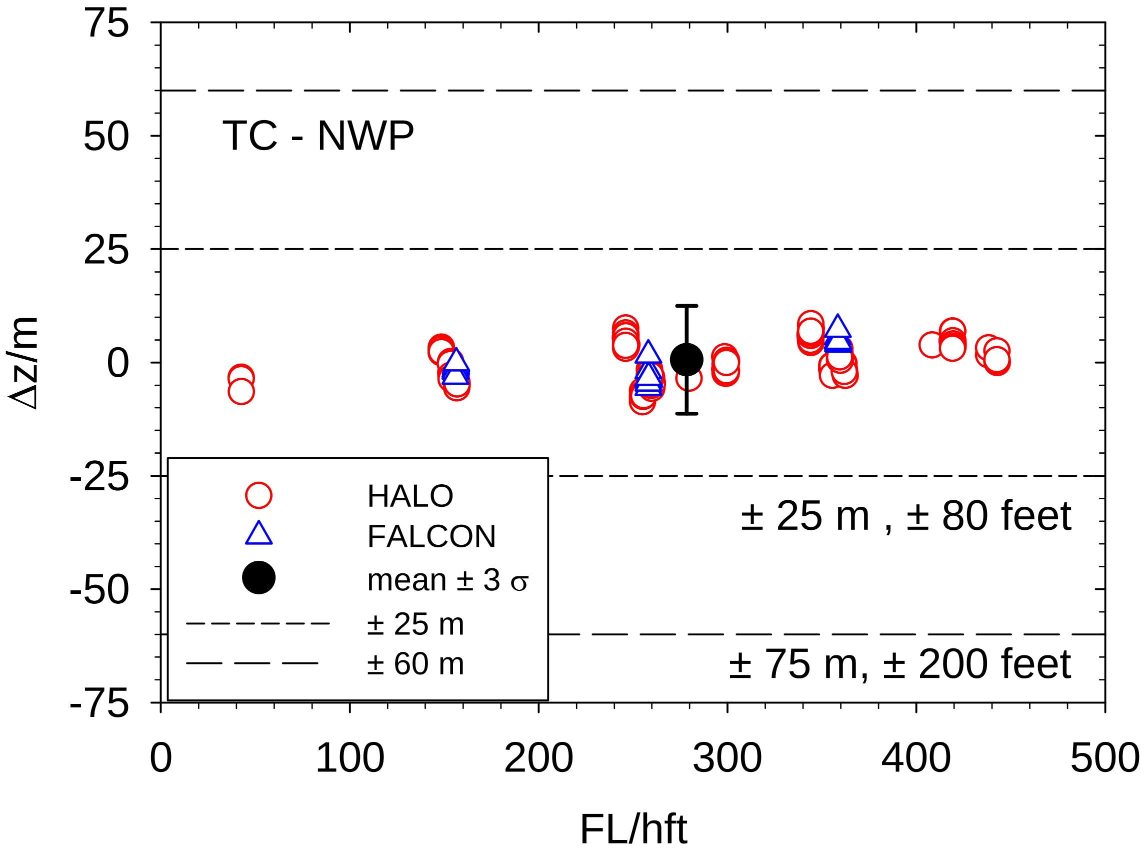
(a) At the point in the envelope where the mean ASE reaches its largest absolute value that value should not exceed 25 m (80 ft);

(b) At the point in the envelope where absolute mean ASE plus three standard deviations of ASE reaches its largest absolute value, the absolute value should not exceed 60 m (200 ft).

DLR

Results

Δz within the limits relevant for RVSM operation



DLR

Conclusions

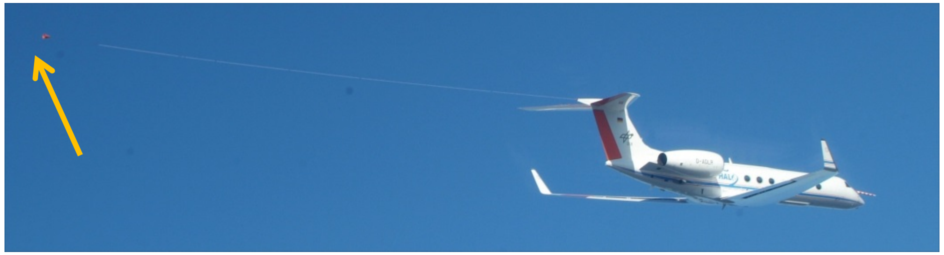
- Accuracy of static pressure and height assessed with TC pressure and DGPS altitude measurements and pressure/geopotential from ECMWF
- essential: post-processed DGPS altitude data and variable g
- $\Delta z < 9$ m for 159 data points from six flights
- Mean temperature error <0.1 K below flight levels.
- Agreement noteworthy for aviation and meteorology.
- Ellipsoidal geoid and variable gravity important also for NWP
- Geopotential is more sensitive to Δg than to Δhumidity in this test
- Open: prediction of most suitable test conditions, other NWP system data
- Further tests at DLR, Institute of Flight Systems, Braunschweig, tbp
- NWP data and the analysis method offer the potential for static pressure calibration and for control of the height keeping performance of aircraft during operation.

DLR

Acknowledgements

Acknowledgements

- Support from DLR Institute of Flight Systems in performing tower flybys with trailing cone measurements with the Falcon and position data post-processing.
- ECMWF data were provided within the ECMWF special project “Support Tool for HALO Missions”.
- Thanks to all supporting partners, in particular for support of FALCON and HALO operations
- Thanks to Martin Wirth and Oliver Brieger for helpful comments



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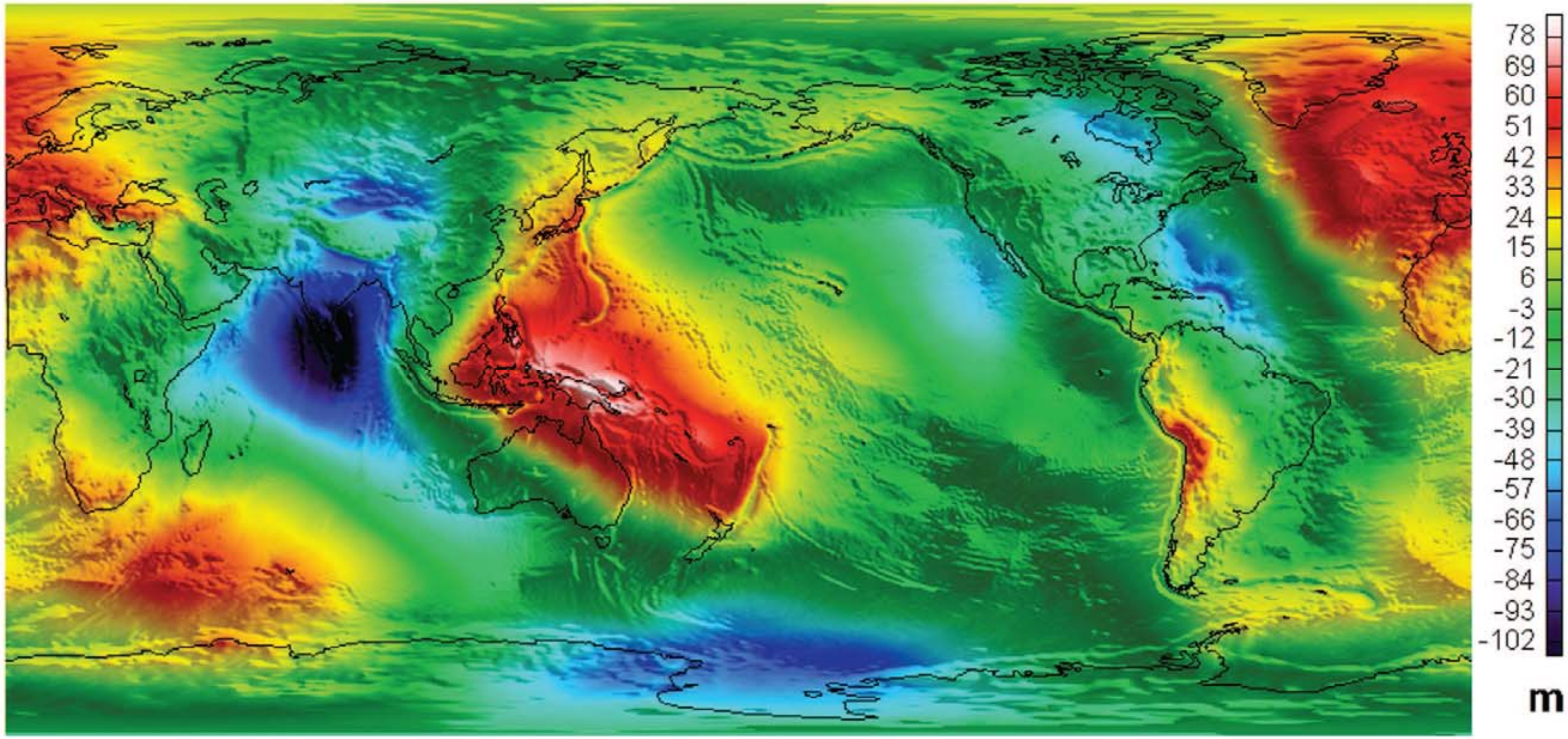
DLR

DGPS data corrected for Geoid undulation, N = h-z

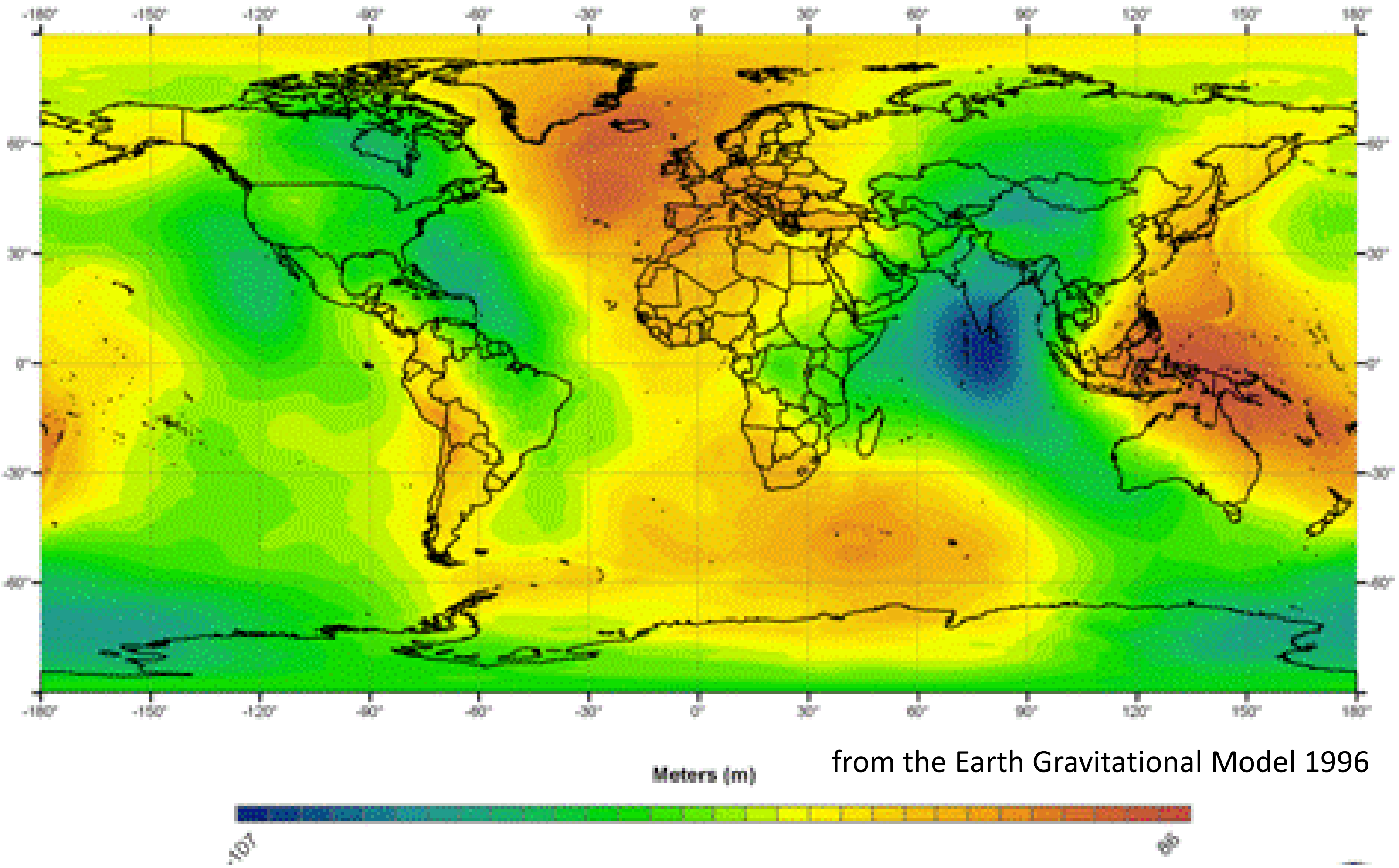
Difference between altitude h relative to WGS84 and height z above MSL.



Global geoid undulations (Lemoine et al., 1998).
The undulations range from −107 m to 85 m.

Geoid undulation

The height z above MSL differs from the altitude h relative to WGS84 by about 50 m over the European continent. The altitude difference is known as geoid undulation N, $N=h-z$.

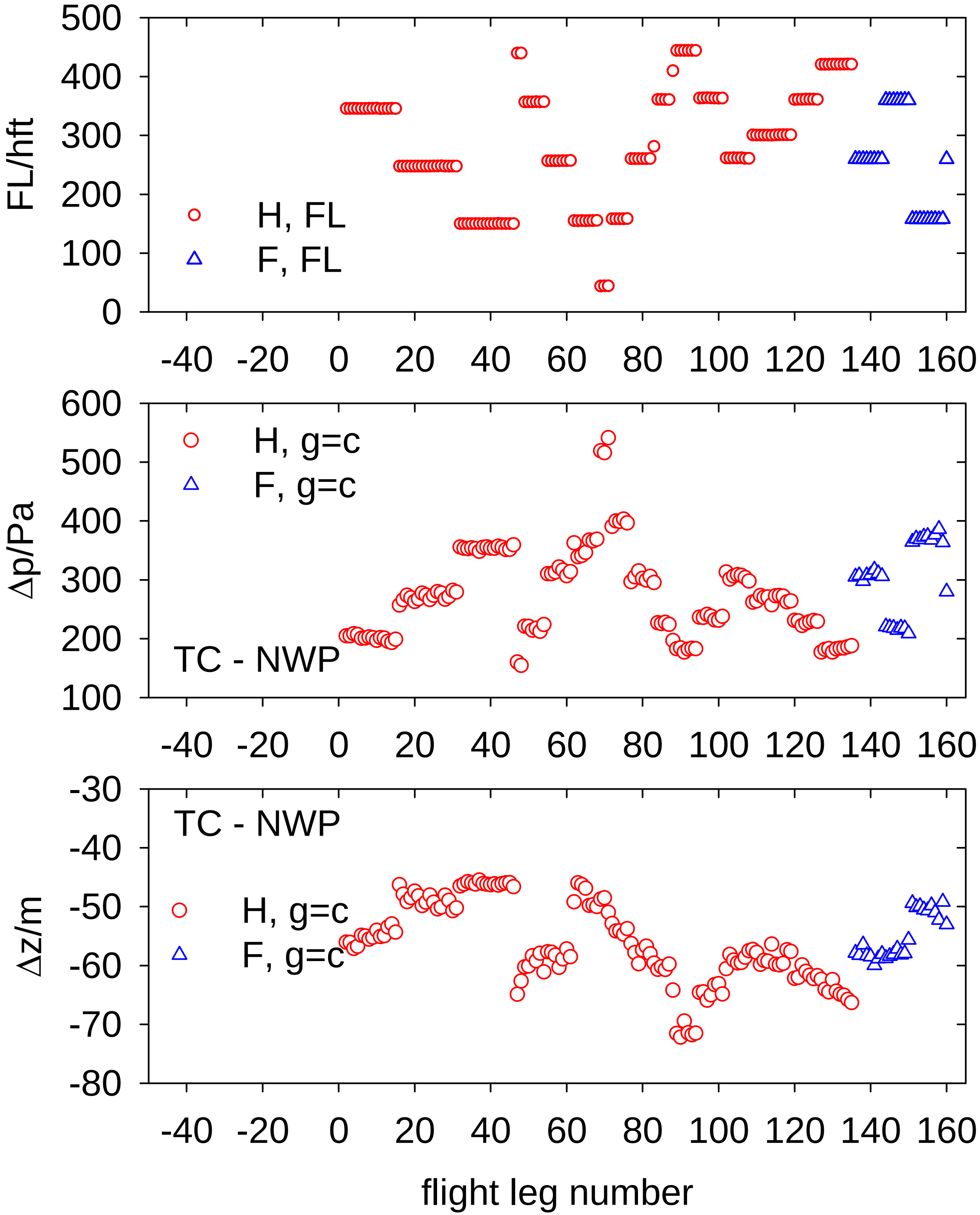


from the Earth Gravitational Model 1996

Results

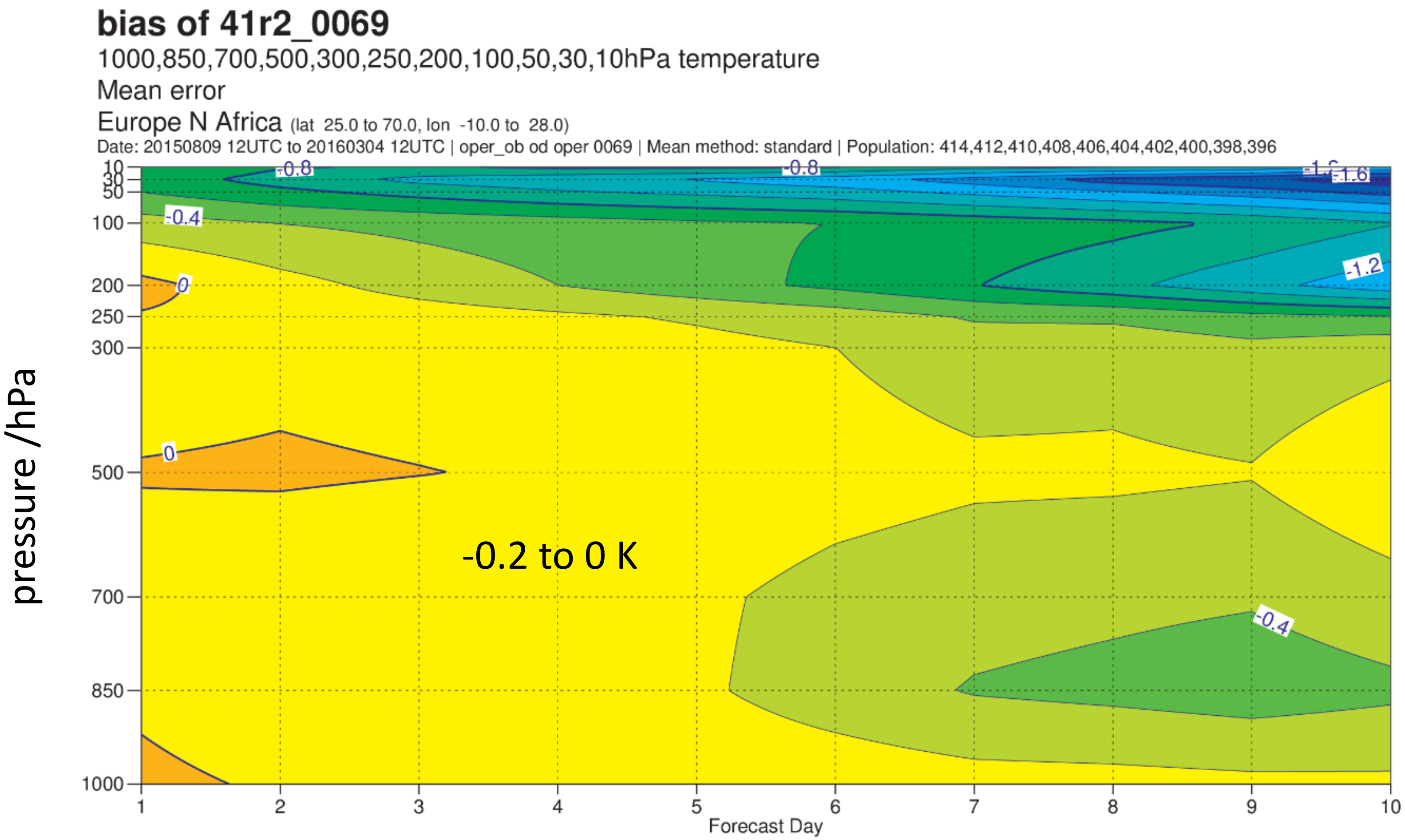
159 test points from
6 days with 2 aircraft
(Halo H and Falcon F)
for FL 50 -430 hft

unacceptable,
missing undulation
correction



DLR

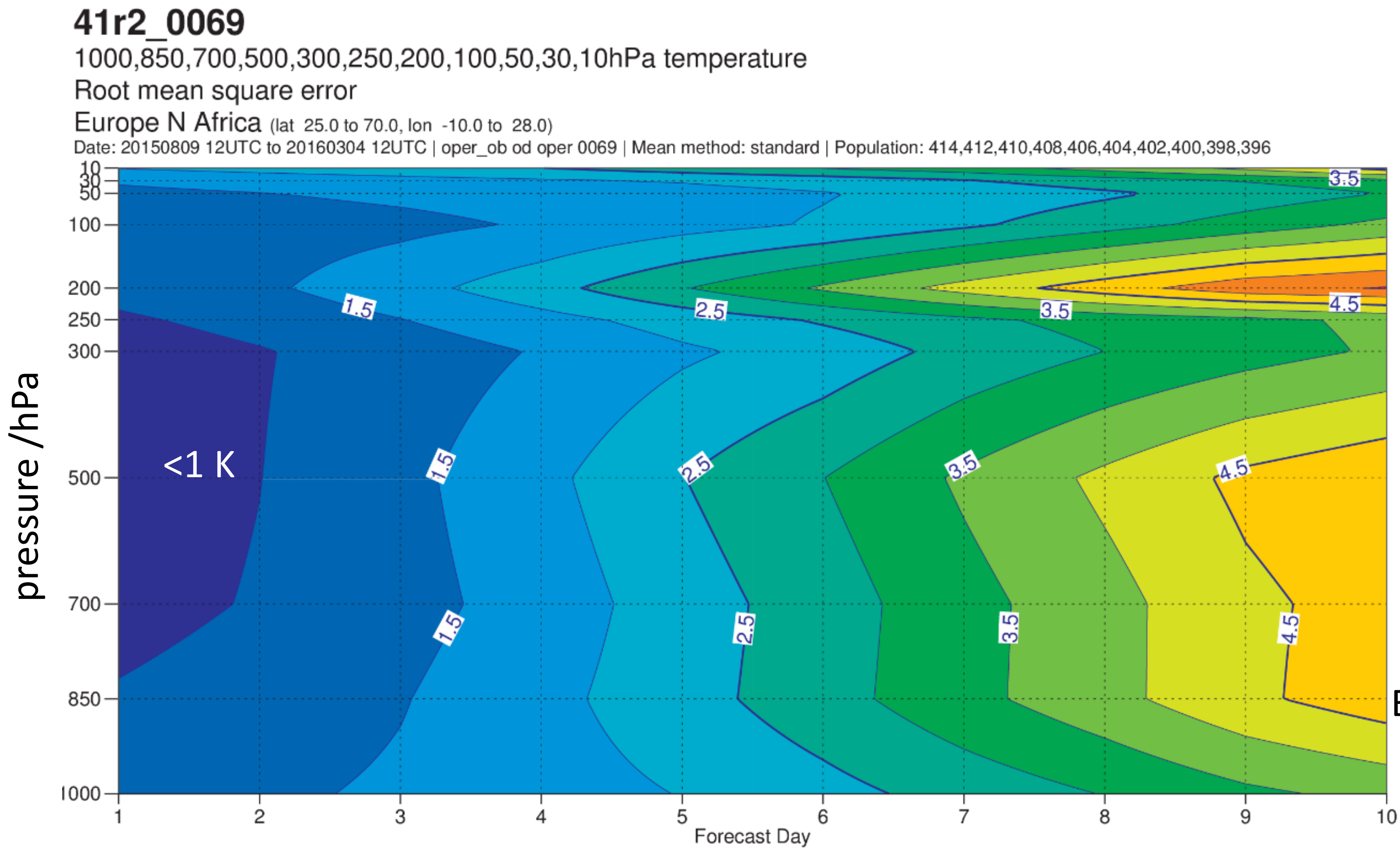
IFS Temperature bias compared to radiosondes
vs forecast time: < 0.2 K below 150 hPa



Thomas Haiden, ECMWF, pers. comm., 2016

Figure 1. Mean error (top) and RMSE (bottom) of the IFS temperature forecast over Europe, verified against uncorrected radiosonde data, as a function of height and forecast range. Verification period is 9 Aug 2015 – 4 March 2016. The model version verified is 41r2, which became operational in March 2016.

Temperature rms compared to radiosondes vs forecast time < 1 K



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time of day,
number of flight,
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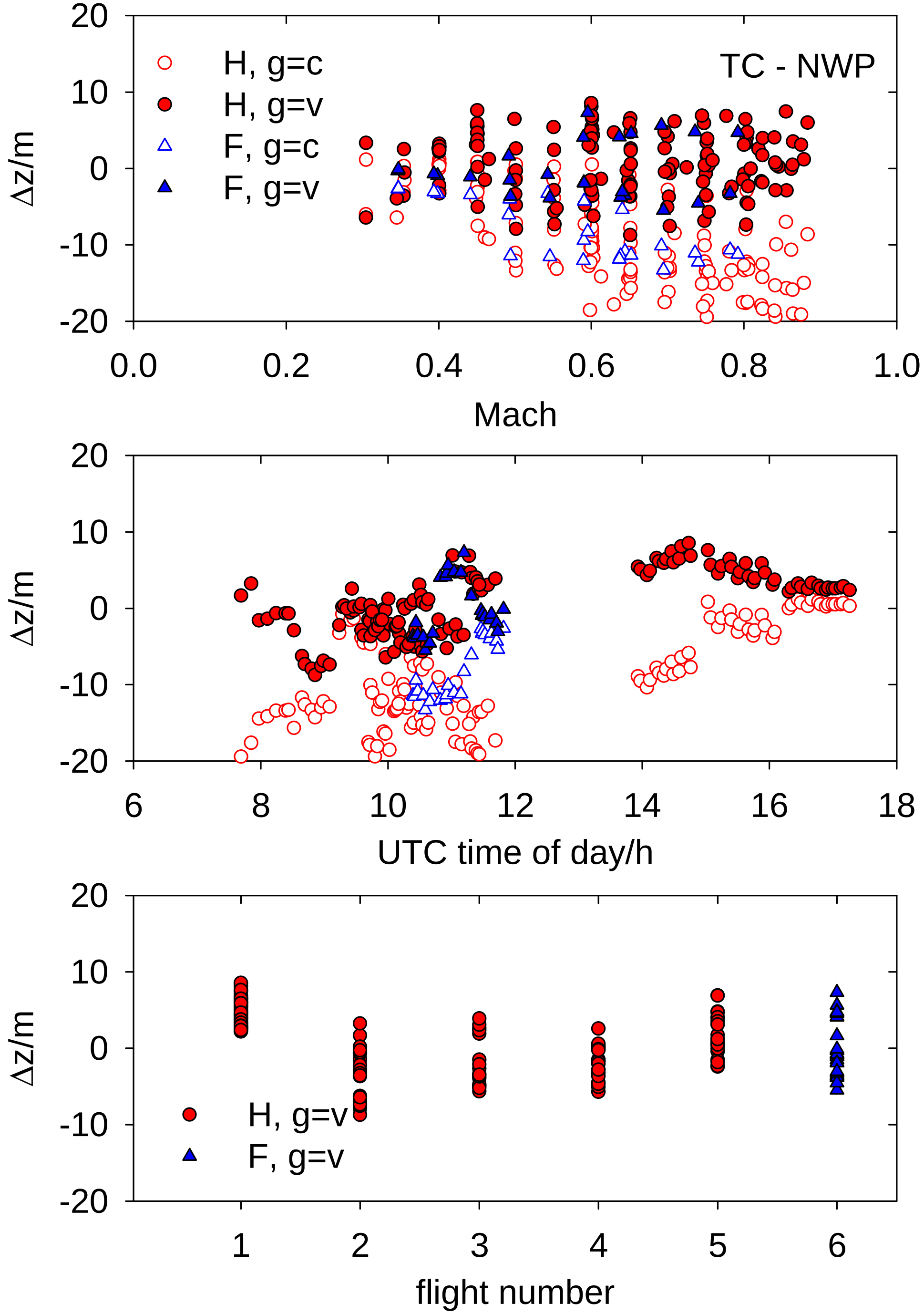
Smaller deviations for variable g than for constant g



DLR

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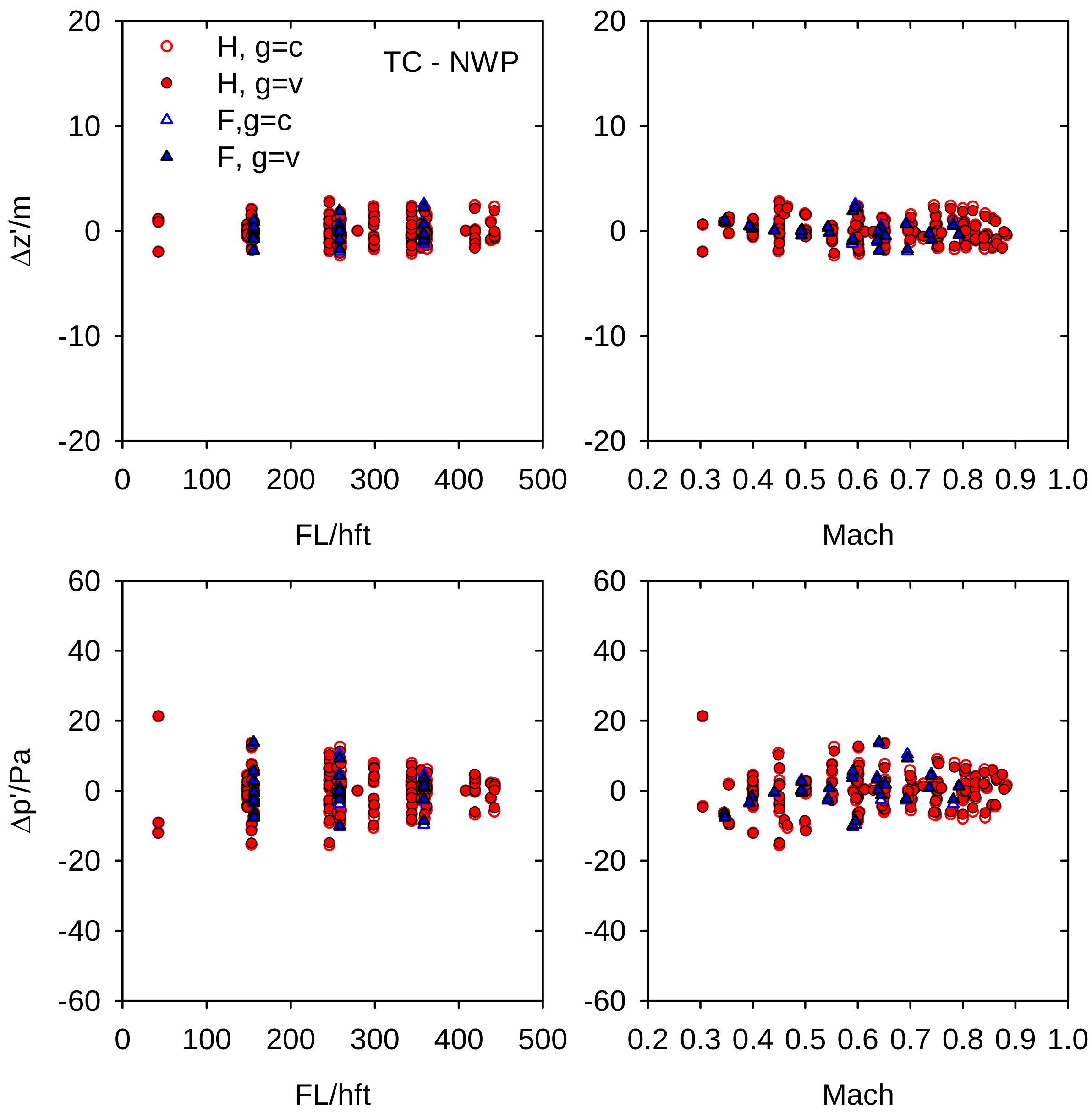
Δz’ < 3 m,

Δp’ < 20 Pa

Significantly smaller deviations for variable g than for constant g



DLR