Assimilation of GNSS Radio Occultation data

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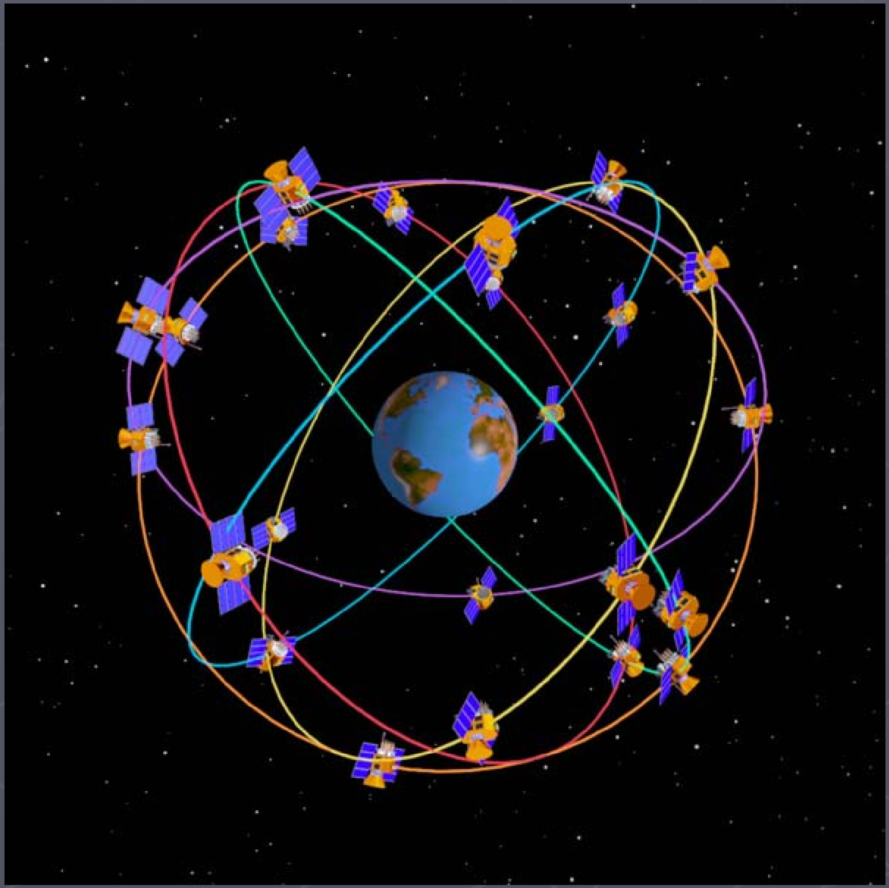
What is GNSS ?

- Global Navigation Satellite System
- Ensemble of satellite systems intended to provide “PNT” services
  - Positioning
  - Navigation
  - Timing
- Global Positioning System (GPS)
- GLONASS
- GALILEO
- WAAS, EGNOS, MSAS, QZSS, Beidou



What is GNSS ?

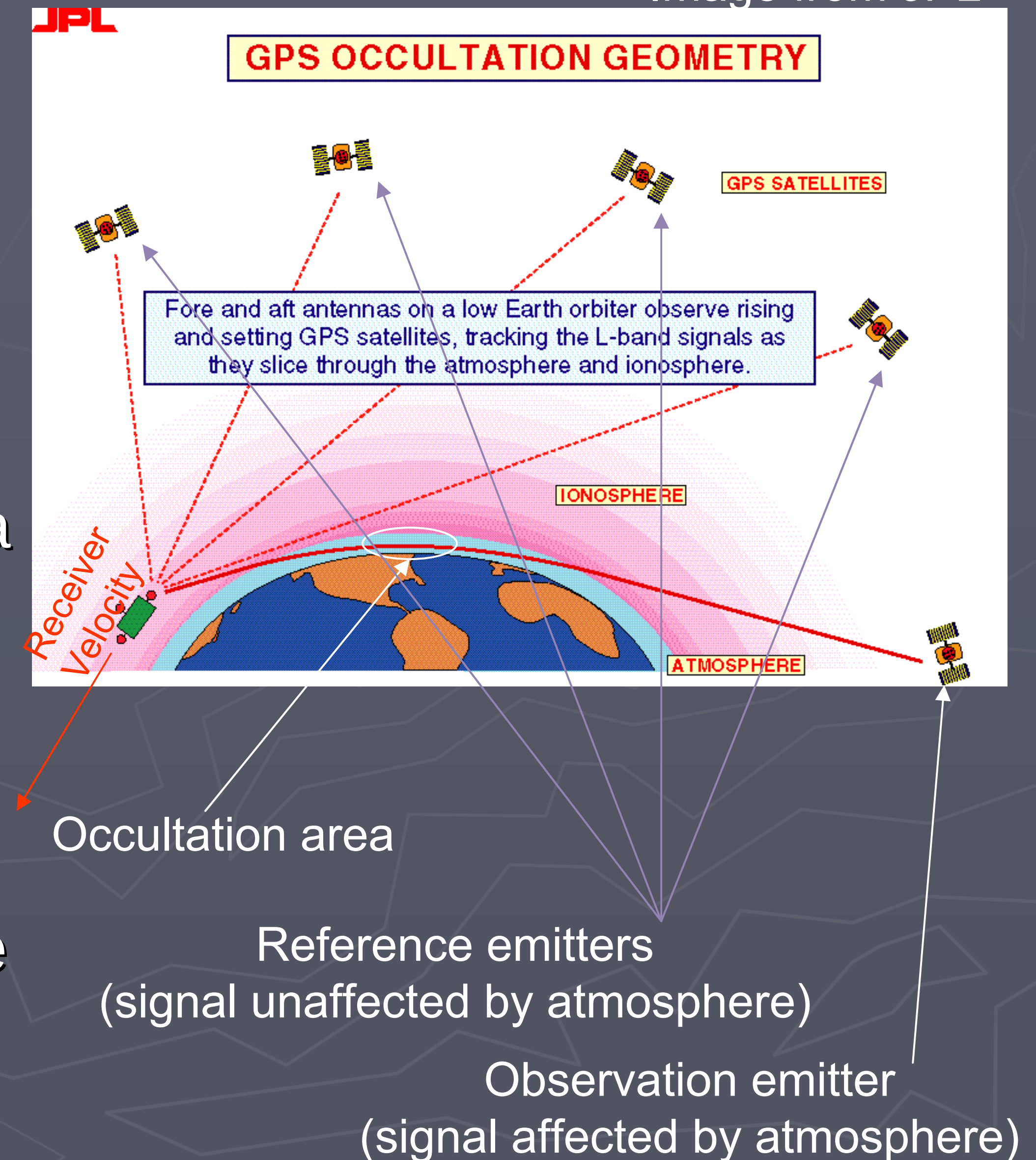
- Constellations of orbiting atomic clocks
- Signal emitted is an encoding of clock tick marks
- Signal stable to ~10 ps (10 light-ps=3mm)
- But many things distort signal more than 10 ps
  - Distance to us: delay ~ 0.01s
  - Refraction by e^- in ionosphere: ~0.1 μs
  - Refraction in the atmosphere: delay ~1 μs
  - Weather variability: ~ +/- 0.1 μs

- "Some people's noise is other people's signal"
  - Distance to us is fundamental measure for PNT
  - Weather is noise of PNT applications
- 5 orders of magnitude left to measure weather

GNSS Radio Occultation

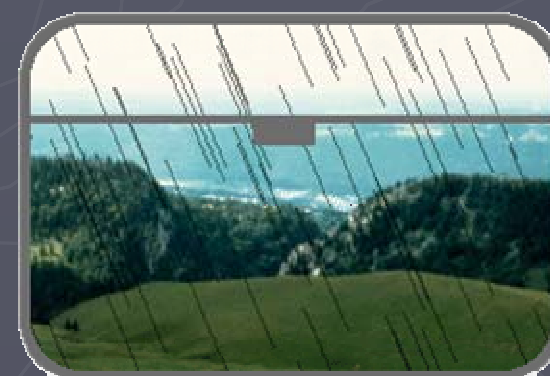
- From a LEO, GNSS satellites appear and disappear through the Earth's limb (=occultation, ~500 events/receiver/day).
- During each event we get a vertical scan of the atmospheric delay (from 0 at high altitudes to ~300m at the surface)
- Each scan of delay can be inverted to a vertical profile of refraction index.

Image from JPL



The observation

- Raw: As the satellite sets at the horizon, follow the evolution of the excess delay in arrival of the signal
- Signal trajectory in the atmosphere is bent. But this angle is small and difficult to measure, but we can measure the speed aberration
- Excess Doppler: Time derivative of the delay, is the speed aberration
- Bending angle: From Doppler
- Refraction index: From bending + simple geometry



The GNSS Radio Occultation

- Limb-looking observation with vertical scan
- Active technology (from artificial L-band sources)
- Passive receiver satellites
  - emitters are preexisting radionavigation satellites (GNSS, ex. GPS)
- Observations are sensitive to refraction index of air

$$n(P_{Air}, P_{WV}, T)$$

- Grosso modo:
  - In dry air (eg stratosphere, poles): ~measure of temperature
  - In wet air (eg low troposphere): ~measure of vapor moisture
- Sensitive to water vapor, but not liquid water
- Horizontal representativity ~300km
- Vertical resolution ~500m
- Polar LEO orbits lead to
  - global coverage
  - Particularly dense coverage in polar regions
- All-weather. Signal traverses clouds, rain

Orbiting Emitters & Receivers

- Currently ~30 emitters (GPS) and 2 orbiting receivers (CHAMP, SAC-C): 300 profiles/day
- Other emitters (future missions may also consider them)
  - GLONASS (~30, but currently only ~10 operational)
  - GALILEO (~30, first emitter just launched, system will be operational in 2008)
  - Others (~10)
- All current projects are focused on GPS only

Name	Number	Launched	In oper.	Launch date	Oper. commitmnt
GPS/MET	1	yes	no	1995	no
OERSTED	1	yes	not the RO rcvr	1999	no
SAC-C	1	yes	yes	2000	no
CHAMP	1	yes	yes	2000	no
GRACE	2	yes	yes	2002	no
COSMIC	6	no		~2006	Demonstr.
METOP	1-3	no		~2006	Fully oper.
NPOESS	1	no		~2008	Cancelled
CHINOOK	1	no		~2010	TBD
COSMIC II	6-12	no		~2010 TBD	Fully oper.

RO vs other data sources

- RO:
  - Profile of high vertical resolution.
  - 1 measured magnitude.
  - Global well distributed.
  - Non-recurrent sampling, but continuous operation
  - All weather.
- RS:
  - Profile of high vertical resolution.
  - 4 major magnitudes (winds, T, q).
  - Distribution very uneven.
  - Recurrent sampling, but sparse in time (most sites every 12h).
  - All weather.
- Radiometric profilers:
  - Low vertical resolution.
  - Can measure T, q, and even liquid water
  - Global coverage, but may omit large areas (some channels useful over sea only, others only cloud-free)
  - Non-recurrent, but coverage in time is good.
  - Limited by weather.

- GPSRO fills gaps from other technologies.

Distribution of profiles

- Typical distribution for 1 day of COSMIC data (green dots)
- Dense, very uniform worldwide coverage
- Geographically well distributed
- Large density at high latitudes
- Land & ocean, all weather

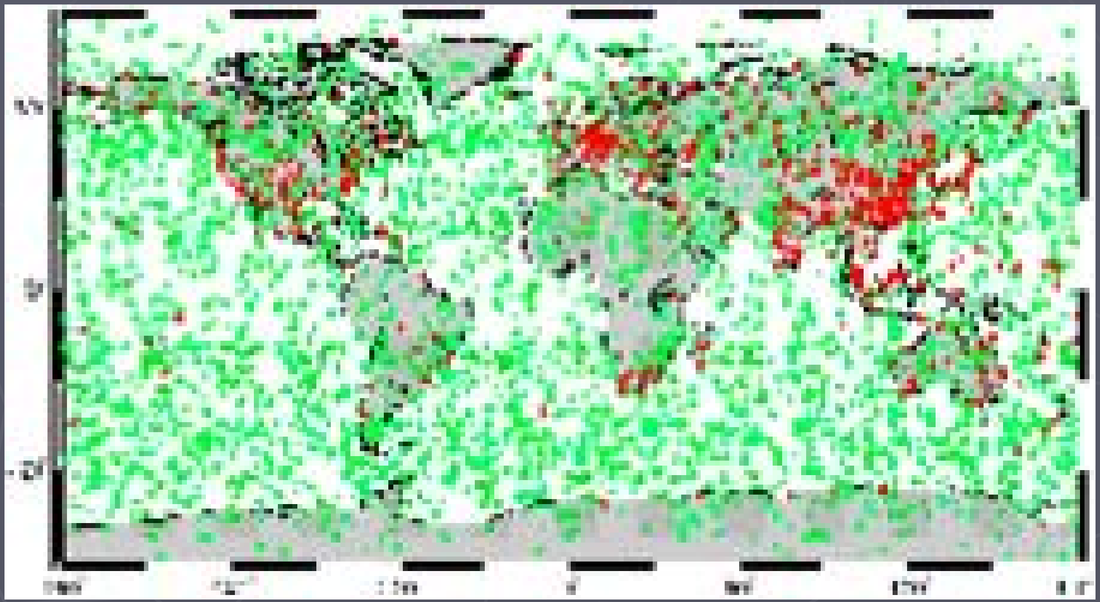


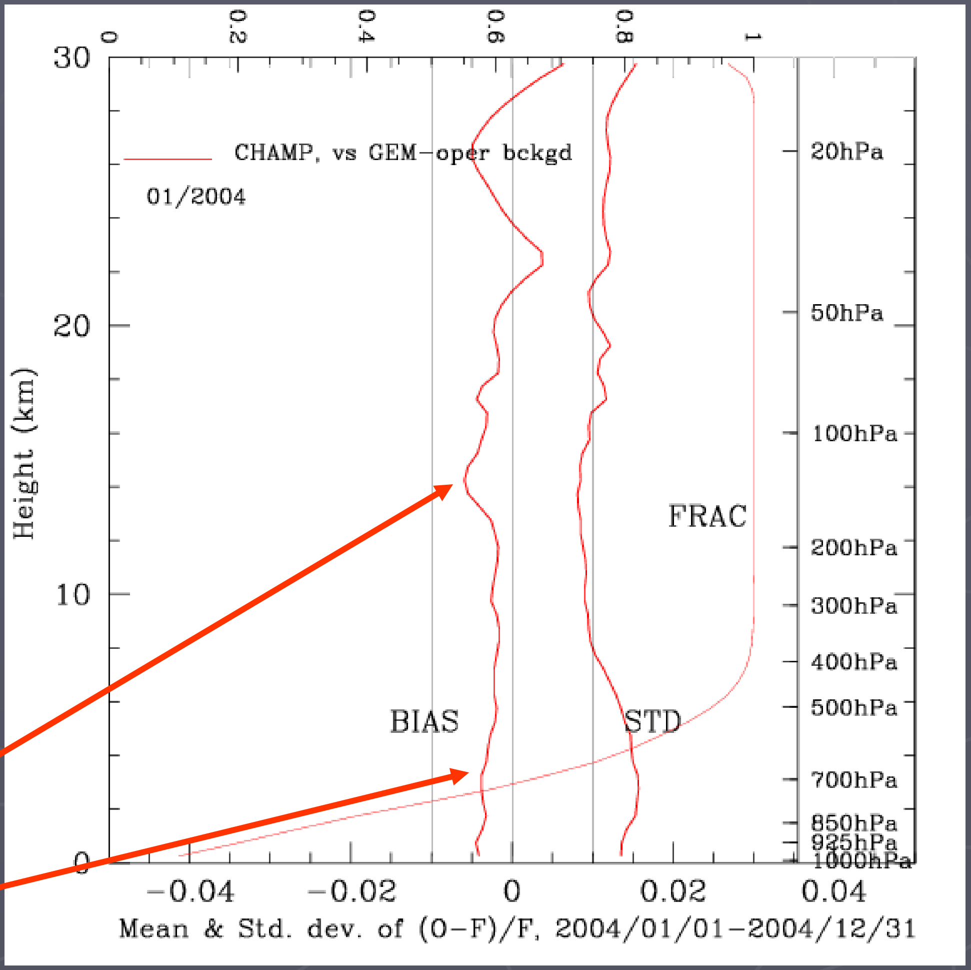
Image by COSMIC team
GREEN: Sample 1-day COSMIC soundings
RED: Radiosondes

Why we expect it to be relevant for NWP...

- Operational NWP: Good complement to existing data
  - Good vertical resolution
  - Uniform worldwide sampling (including poles)
  - All weather
  - Greatly improve southern hemisphere data
  - Particularly near tropopause
- Climate: Technique is based on fundamental physics (speed of light)
  - Few sources of observation bias
  - Good option for long-term climate studies
- The data distribution suggests that we should find improvements forecasting
  - The southern hemisphere
  - The tropopause
- Preliminary tests at UKMO & ECMWF (S. Healy) suggest that this is the case

The observation

- Obs-6h Forecast show seasonal variations
- Obs varies vertically by ~2 orders of magnitude.
- Shown (O-F)/F
- Likely means part of the climate is not yet represented by model
- In any case bias<0.5%
- STD 1-1.5%
- Two systematic biases
  - Around tropopause
  - Low troposphere



12 months data: 2004/01-2004/12
UCAR inversion vs GEM (global oper)

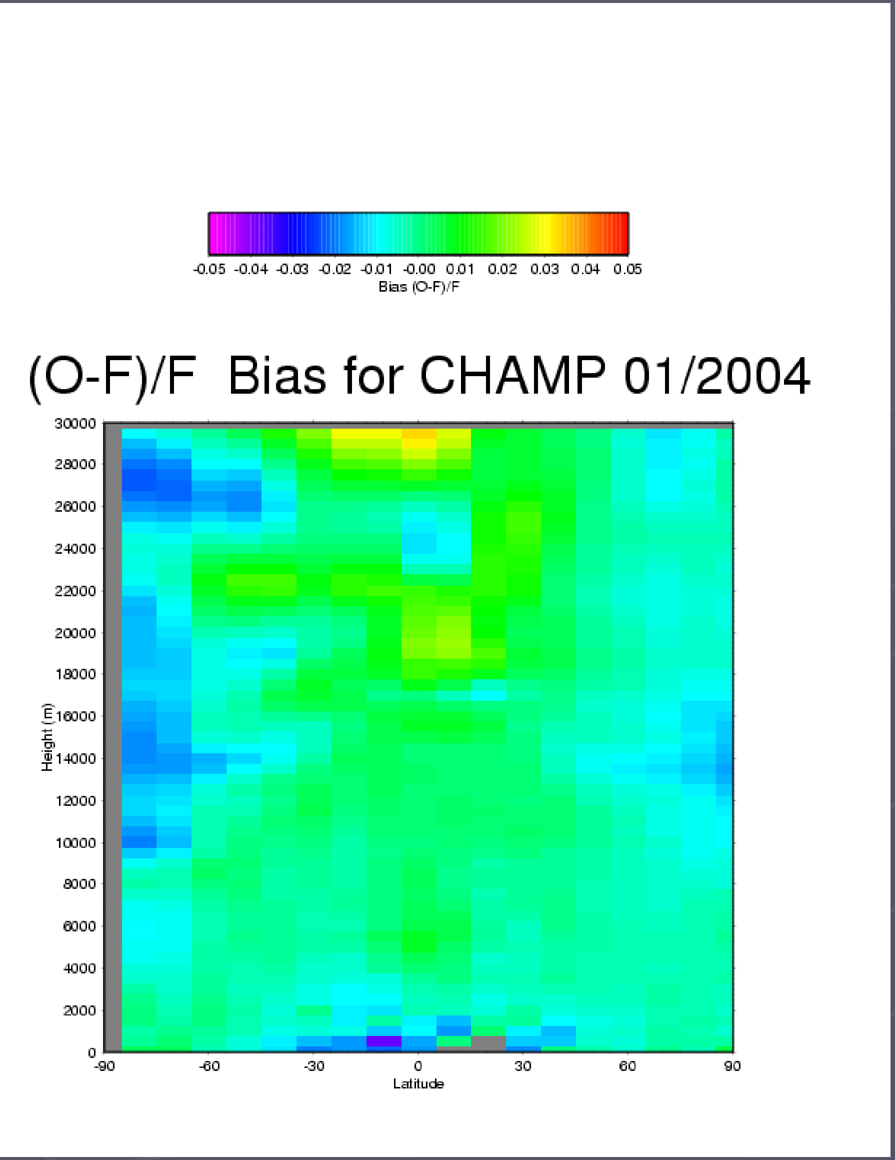
Wasn't it bias-free?

- It is quite low, actually
  - Lower than 0.5% of the refractivity
  - Lower than 1/3 of the (O-F) STD
- Low tropo bias is in part sampling bias
  - signal is lost in very wet situations
  - averaged cases tend to be the dryer ones
- Tropopause bias is a modeling problem
  - Model is discrete (~1 km vertical resolution)
  - Tropopause finer structure is not modeled
  - Temp structure always concave in tropopause
  - Systematic discretization error (bias)

$$\frac{d^2T}{dh^2} > 0$$

Some comments

- The above O-F suggests that this kind of data has good properties to perform tests and validations.
- There is much potential, but let's just focus on one example
  - O-F showed a correlation with topography
  - Zonal averages showed some bias in the Antarctica

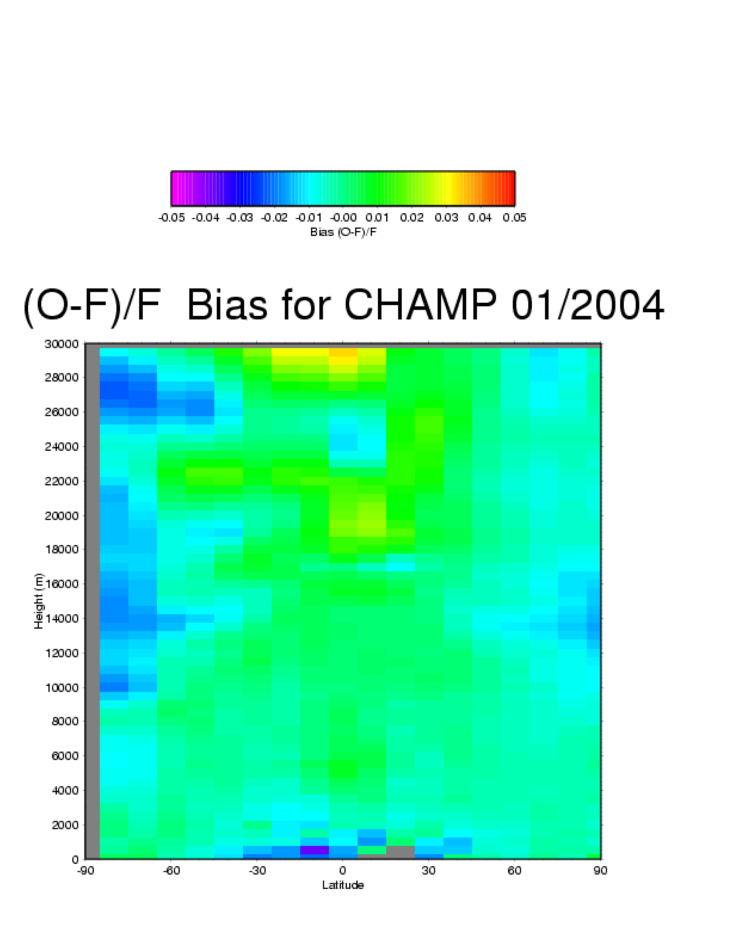


Topography

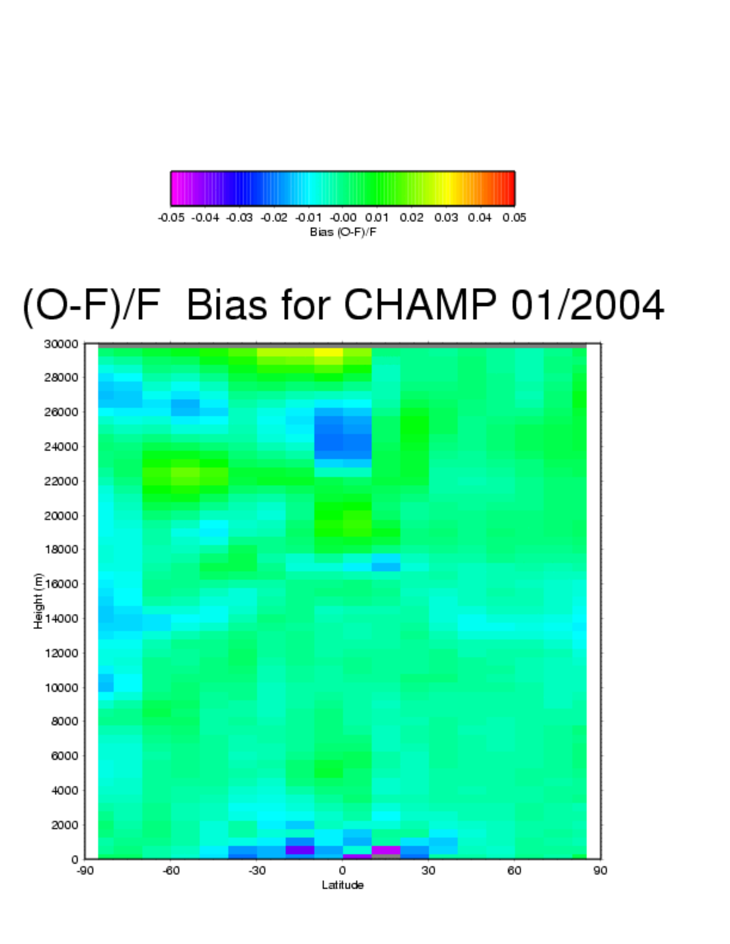
- The topography and the Antarctica seemed related...
- Gem topography
  - Relevant variable is not height, but surface geopotential
  - Geopotential related to local gravity acceleration
  - Standard: $z=g_0*h$ (J/kg or m^2/s^2)
  - but g is not uniform (latitude & altitude)
- A test was made to see the impact
  - New topography
  - Recalculate surface z with non-uniform g

Topography remap: Bias

Zonal statistics, each frame averaged over 1 month (~5000 occultations/frame)



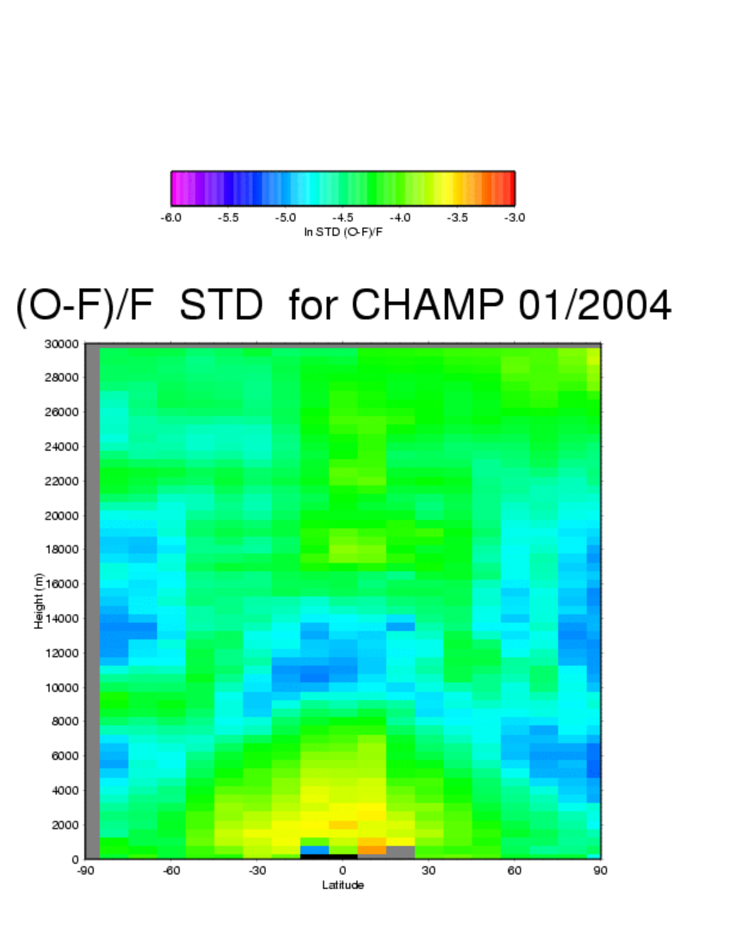
Standard topography



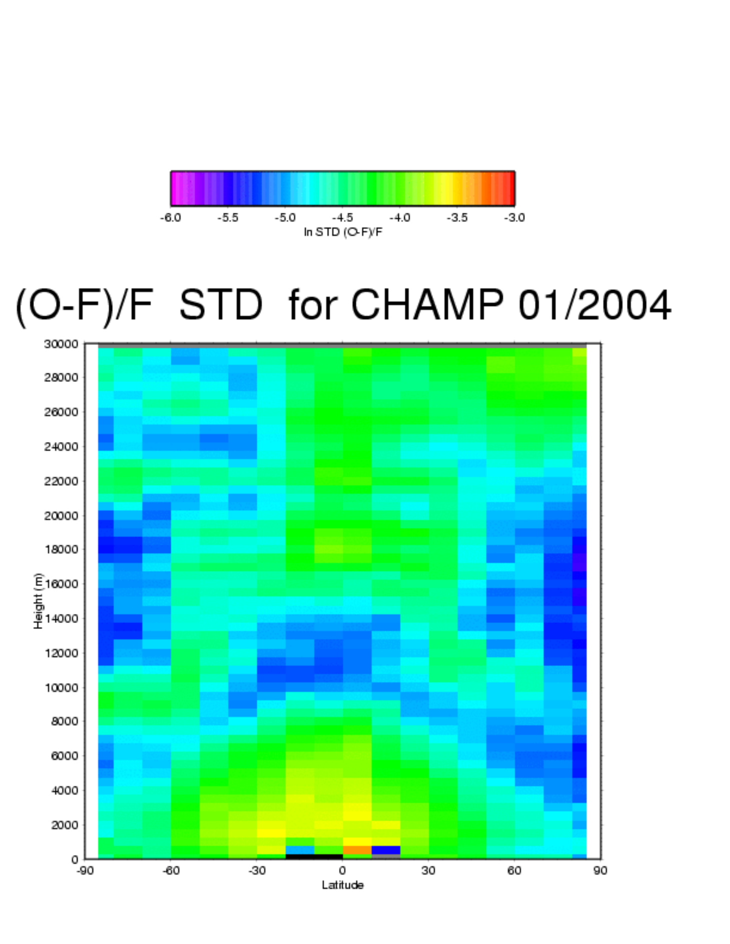
Variable-g topography

Topography remap: STD

Zonal statistics, each frame averaged over 1 month (~5000 occultations/frame)



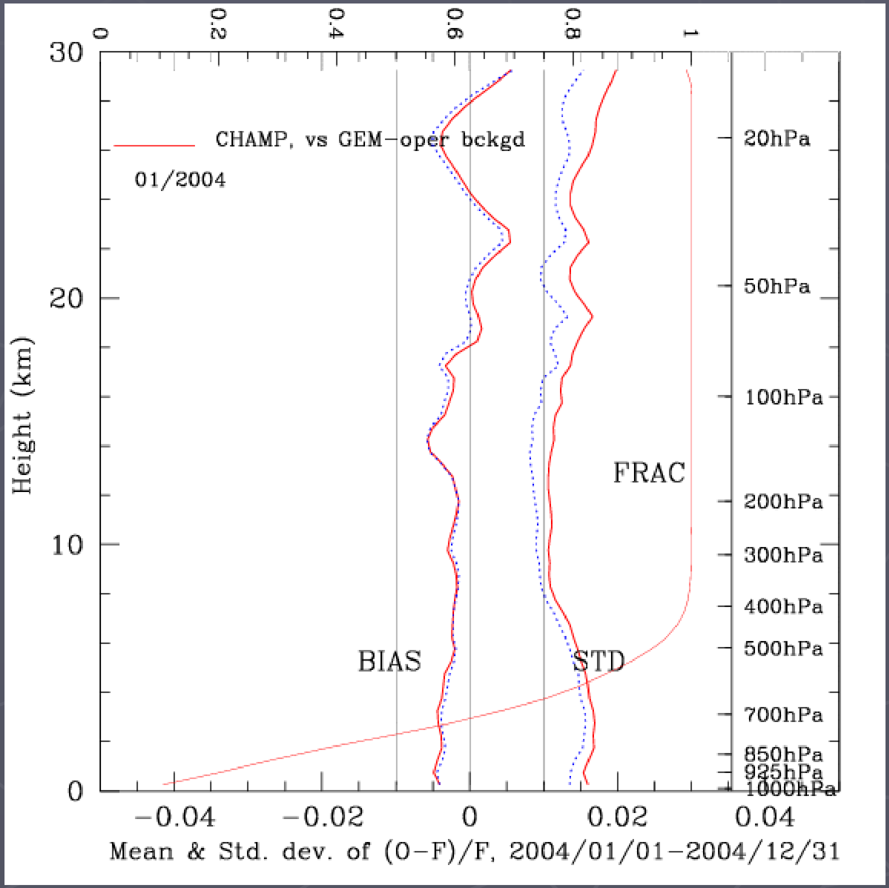
Standard topography



Variable-g topography

Conclusions of Topography test

- Worldwide average also shows better behavior, specially STD
- Accounting for variable gravity acceleration substantially improves O-F agreement
- No assimilation yet
- Validation mode



Red: Standard geopotential topography
Blue: Variable-g geopotential topography

Comments on O-F

- O-F shows
  - Bias in general < 0.5%
  - STD always < 2%, outside low tropo ~ 1%
  - |Bias| / STD < 1/3
  - H vs latitude STD presents features that suggest tropopause-related discrepancies (i.e. model tropopause would not be accurate)
    - Probably related to vertical discretization: A discontinuity in T gradient is difficult to represent discretely.
  - If so, model should improve tropopause if GPSRO is assimilated.
  - Observations sensitive to non-uniform gravity

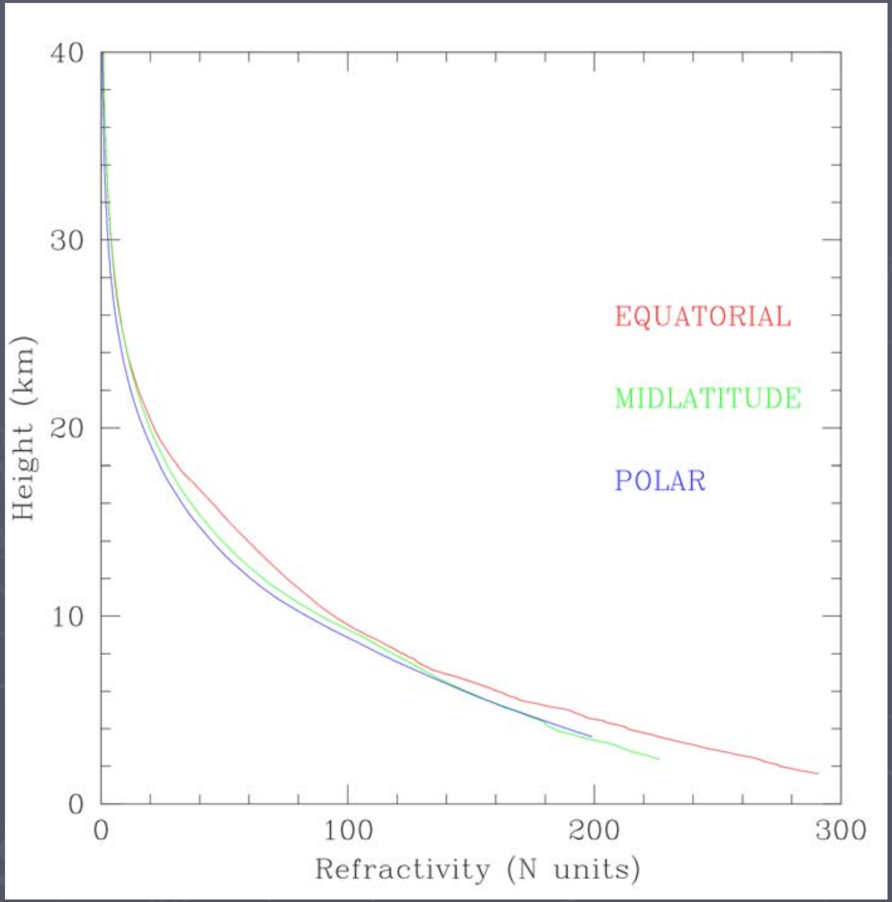
The RO profiles

- Main observable: refractivity N(h).
  - Where moisture is very small, N is proportional to density (ex stratosphere)

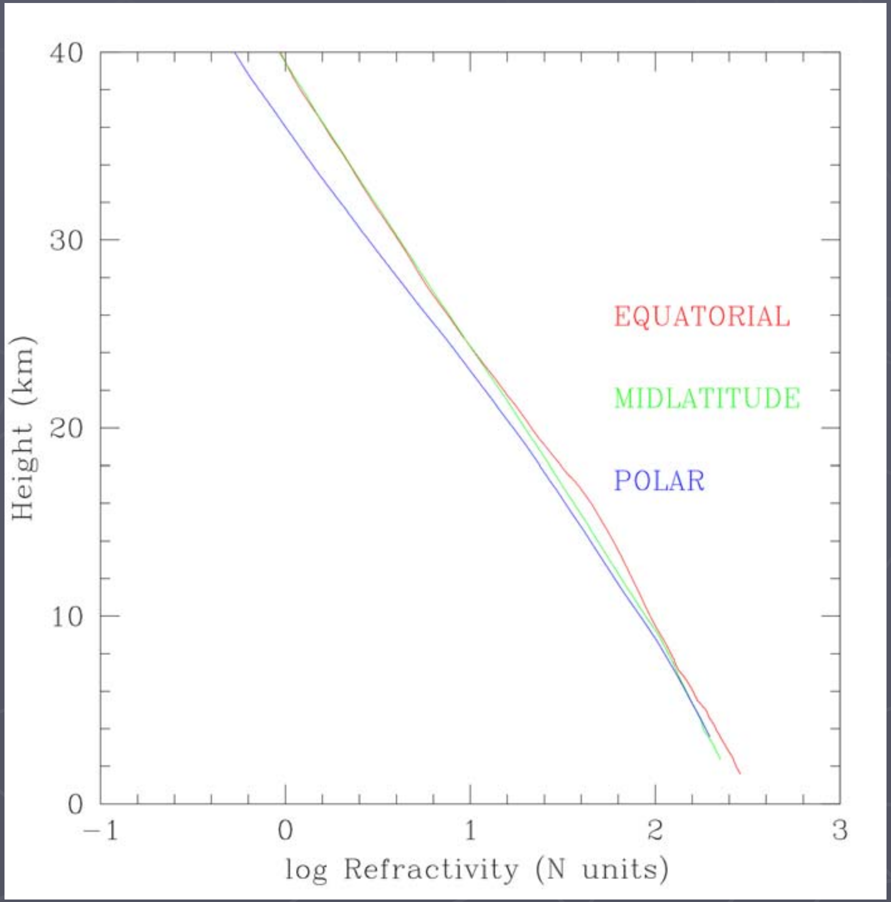
$$N = A\frac{P}{T} + B\frac{P_W}{T} + C\frac{P_W}{T^2}$$

  - A~77 N/K·hPa
  - B~68 N/K·hPa
  - C~370000 N/K^2·hPa
- Density + hydrostatic + Eq. State-> P, T profiles
  - These P,T are called “dry” profiles, and are a good approximation to real P,T above the point where a substantial fraction of the refractivity is from WV (i.e. significantly wrong only in medium & low tropo, sp tropics)
- $N \rightarrow \rho_{Dry} \rightarrow P_{Dry} \rightarrow T_{Dry}$
- In the tropopause & above T_{Dry} is a good approx to T

Profiles I

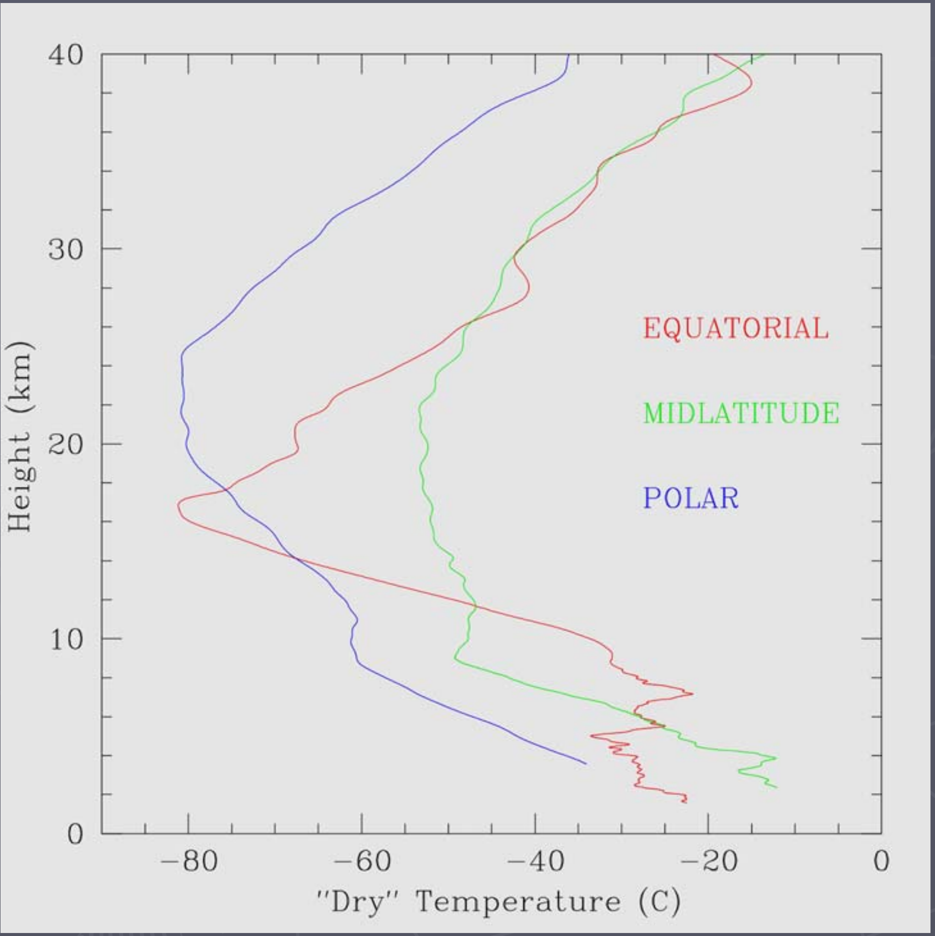


40
30
20
10
0
Height (km)
0
100
200
300
Refractivity (N units)
EQUATORIAL
MIDLATITUDE
POLAR



40
30
20
10
0
Height (km)
−1
0
1
2
3
log Refractivity (N units)
EQUATORIAL
MIDLATITUDE
POLAR

Profiles II



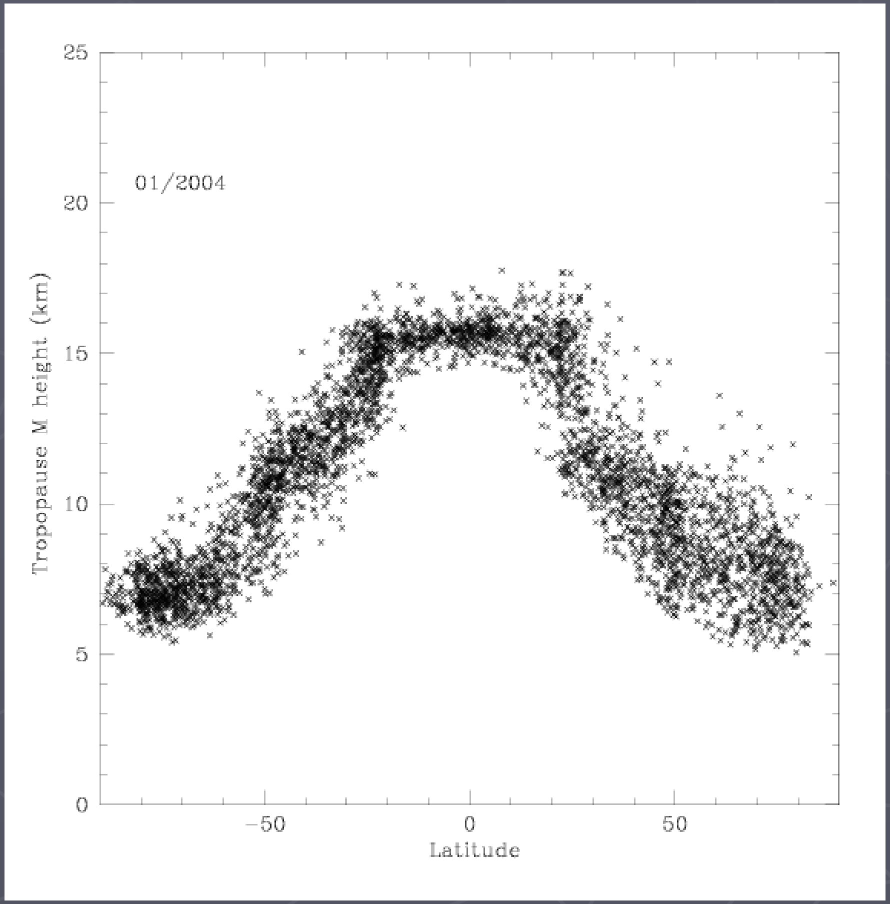
- The dry temperatures show the structure of the tropopause
- The mid & low troposphere shows that dry T do not represent well the real T there
- Having T(h) with a resolution ~500m we can apply any algorithm that describes the tropopause
  - LRT (Lapse Rate Trop.)
  - CPT (Cold Point Trop.)
  - ULR (Upper Lapse Rate boundary)

Some comments

- RO provides info from surface to ~40km
- We have info on mid & low tropo, but resolving into T, q is complex there
- Around tropopause & above RO is an accurate direct measure of T (~0.5 K)

Is it the tropopause?

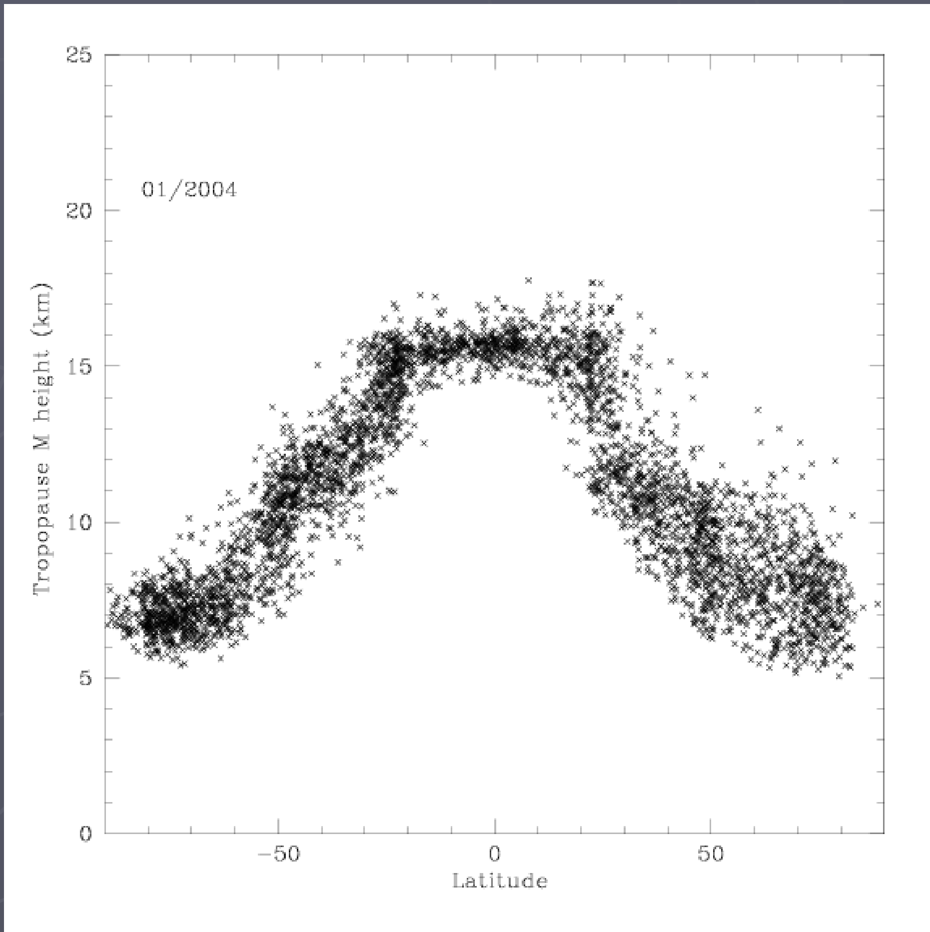
- H vs lat STD showed a feature resembling the mean tropopause.
- We have GPS profiles. We can apply several algorithms to find the T/P, mimicking several definitions of T/P.
  - LRT
  - CPT
  - etc



LRT-finding algorithm

Examples I

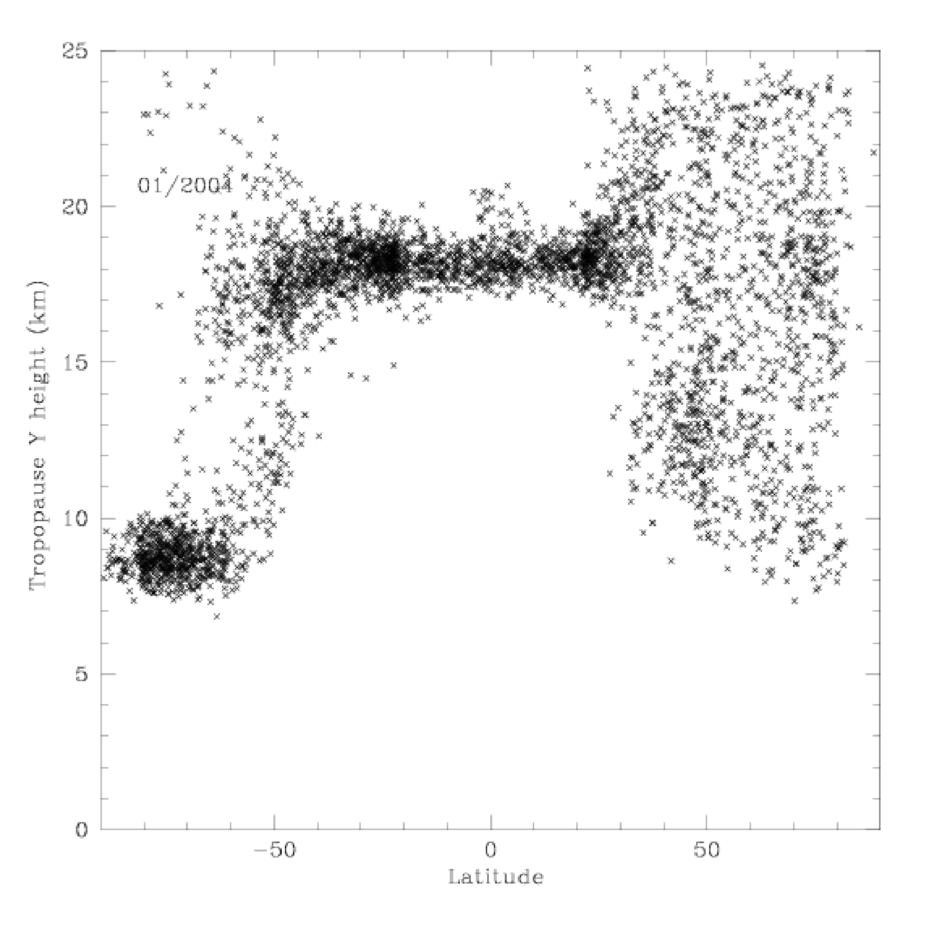
- M Point: Largest area triangle in the T(h) profile
- ~ Lapse Rate T/P
- Dichotomic behavior (equatorial vs elsewhere)
- Annual frequencies evident
- N-S annual movement of equatorial band
- Some frequencies that we may naively believe semiannual are annual
  - See equatorial band



LRT-finding algorithm

Examples II

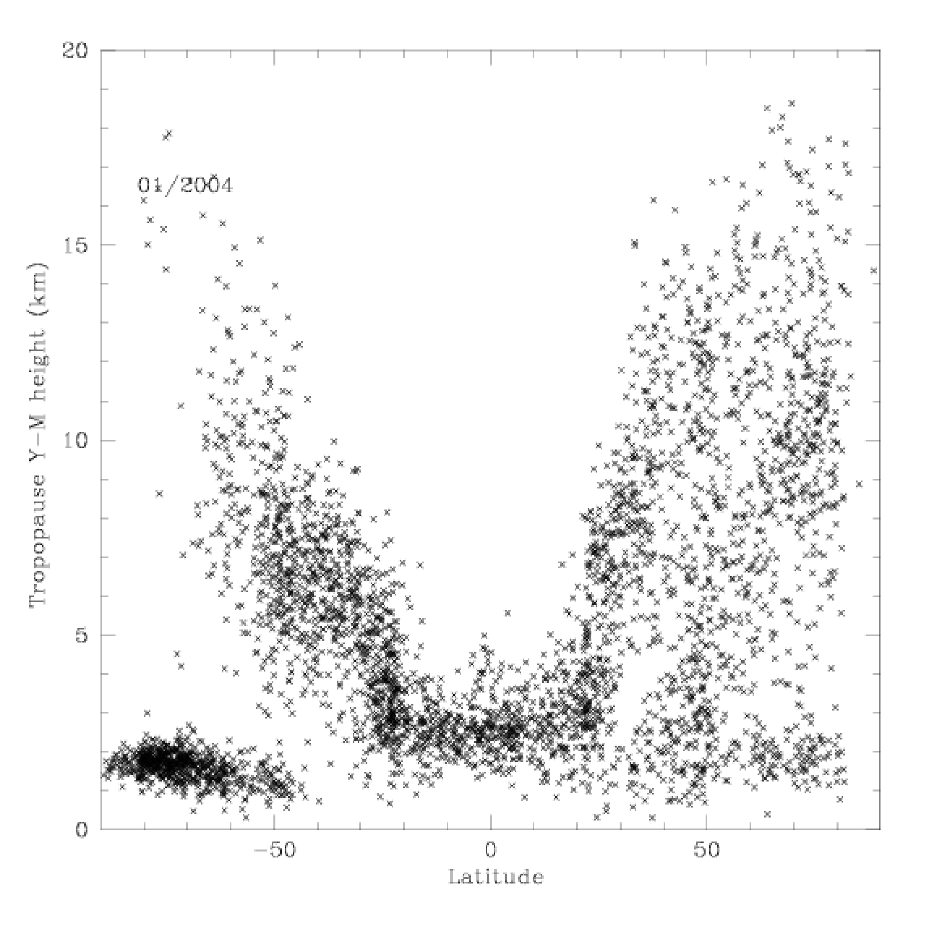
- Y Point: Largest triangle above M point
- ~ Top of T/P transition
- Again dichothomic
- Annual & semiannual frequencies
- Again equatorial band behaves annually



ULR-finding algorithm

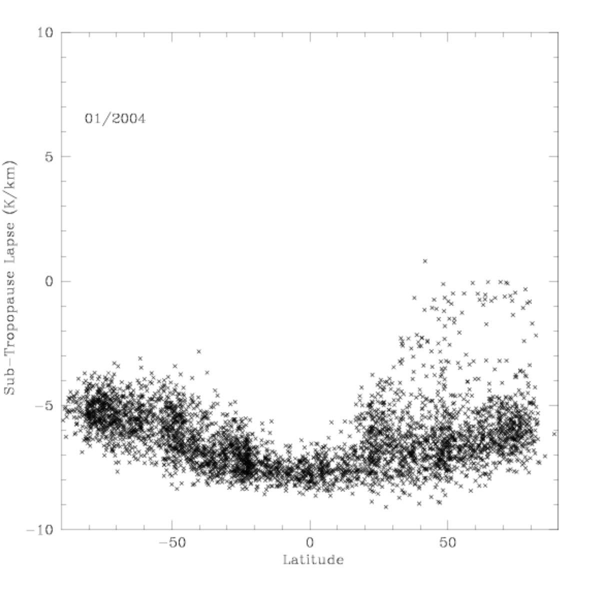
Examples III

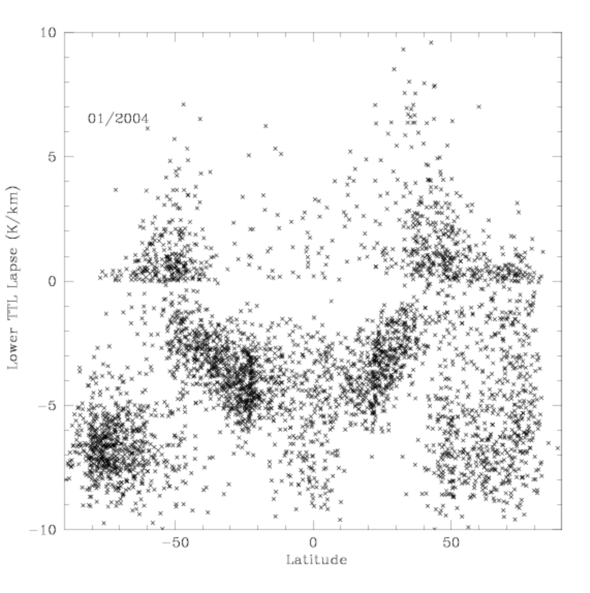
- Y-M Distance (~depth of T/P)
- Obviously dichotomic
- Thin T/P that is only strongly defined in midlat & polar summers (1-2 km)
- Equatorial T/P ~ 3 km smoothly transitions to thick extratropical T/P

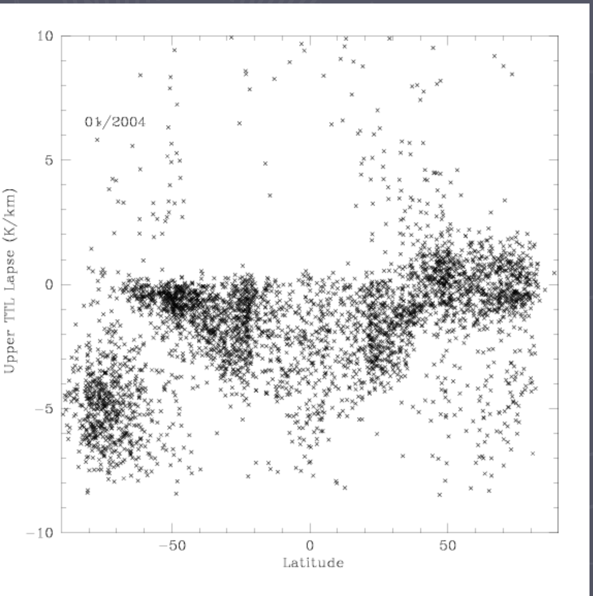


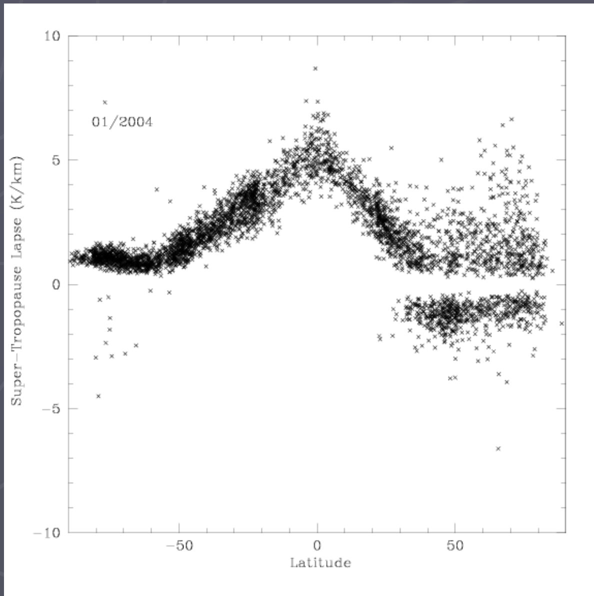
Examples IV

- Slopes (Dry T gradient)
  - Below the LRT
  - Low T/P
  - Upper T/P
  - Above the upper boundary
- Lower and upper T/P seem to differ
- See annual vs semiannual above T/P in equatorial band
- Empty bands near 0 gradient are artificial (system unable to lock an i/f when there is little gradient)



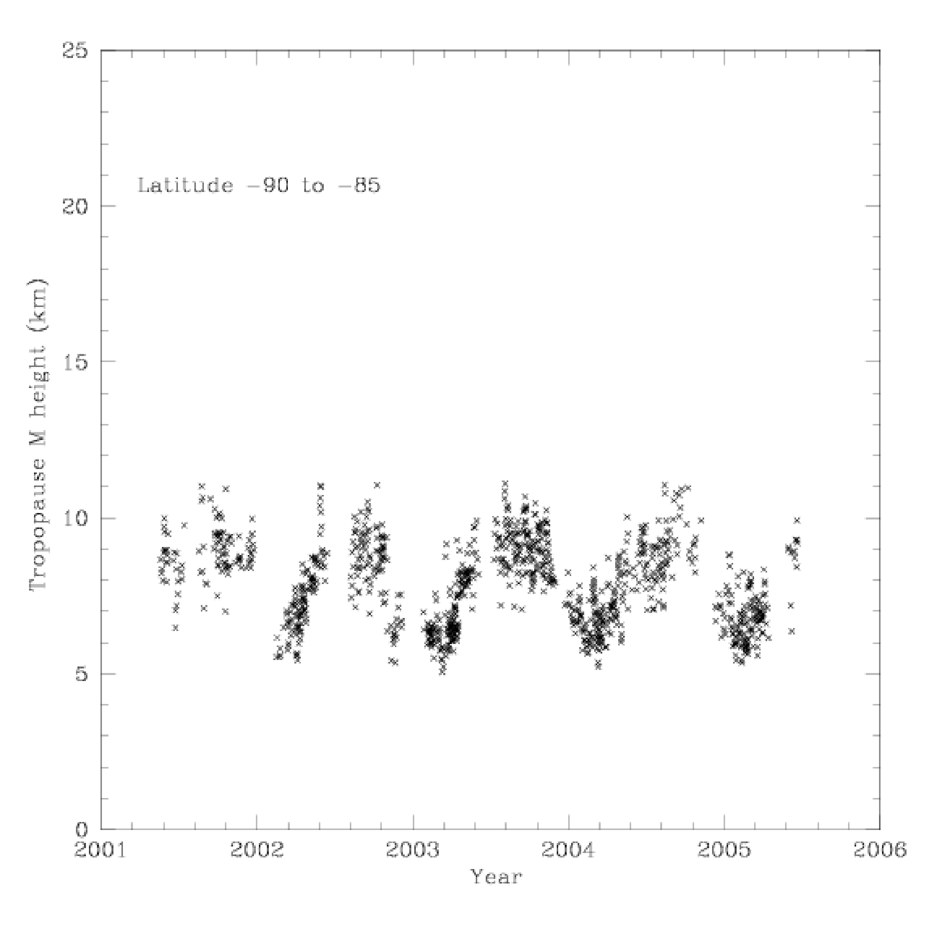






Long term

- Video by latitude band on a multiyear series
- Lack of N/S symmetry (related to annual vs semiannual issue)
- Little evidence without numeric mining of QBO



Conclusions

- RO provides an excellent direct measure of T/P profiles of T
- Large quantities of data now available (essentially continuous since 2001)
- Systematic algorithm definitions of CPT, LRT, etc have been tested.
    - More refined algorithms are of course possible.
    - Input welcome.
- Some interesting issues identified
    - Annual vs semiannual frequencies
    - Dichotomic behavior of T/P (equatorial vs elsewhere)
- Figures intended only to show the potential

Assimilation

- Former viewgraphs oriented to show the potential to learn about the atmosphere and as verification tool
- Are these data useful to NWP?
- Performed 2 experimental cycles comparing
  - Standard 3DVar
  - Standard 3DVar + Radio Occultation
- Cycles:
  - 1 Jan 2004 – 15 Feb 2004
  - 1 Jun 2004 – 15 Jul 2004

Comments on the Assimilation

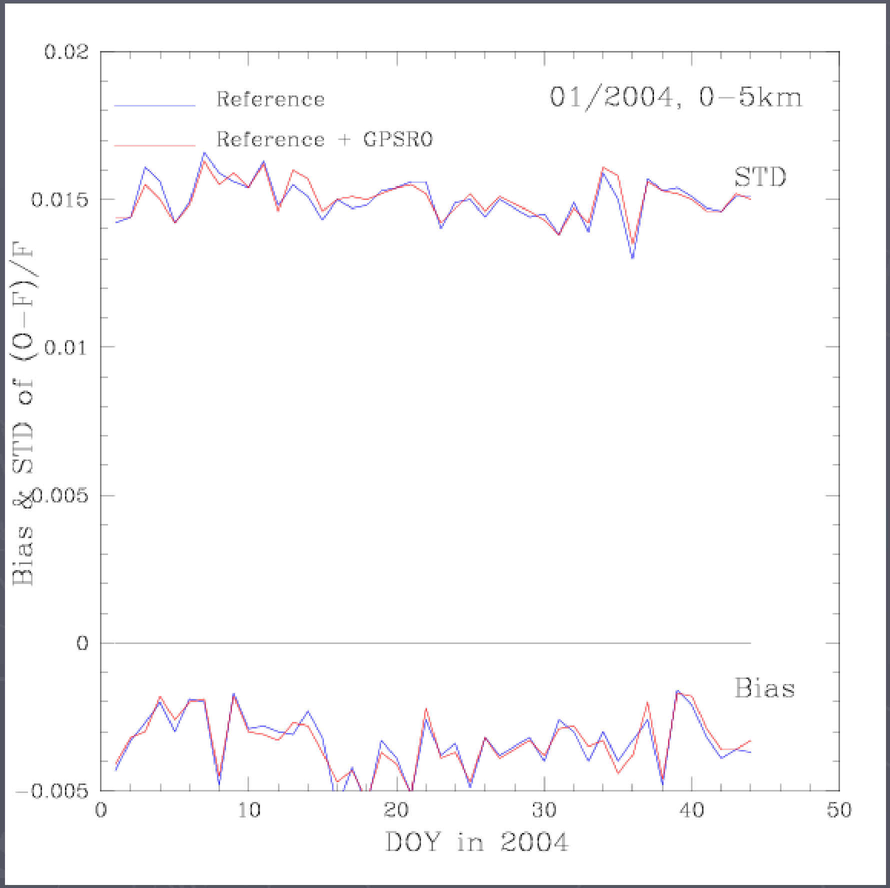
- 2 satellites in operation (CHAMP & SAC-C)
  - CHAMP-only in this experiment
  - SAC-C data still to be reprocessed with latest generation software
  - Non-NRT
  - Setting-only occultations
  - GPS-only occultations
  - Low troposphere often lost
- COSMIC to be launched early April 2006.
  - 6 satellites
  - NRT
  - Rising & Setting occultations
  - 12 times more occultations (6x2) expected later this year
  - COSMIC receivers improved wrt CHAMP & SAC-C
  - Profiles to reach low troposphere more often
  - Expected impact ~ proportionally larger

What we can assimilate

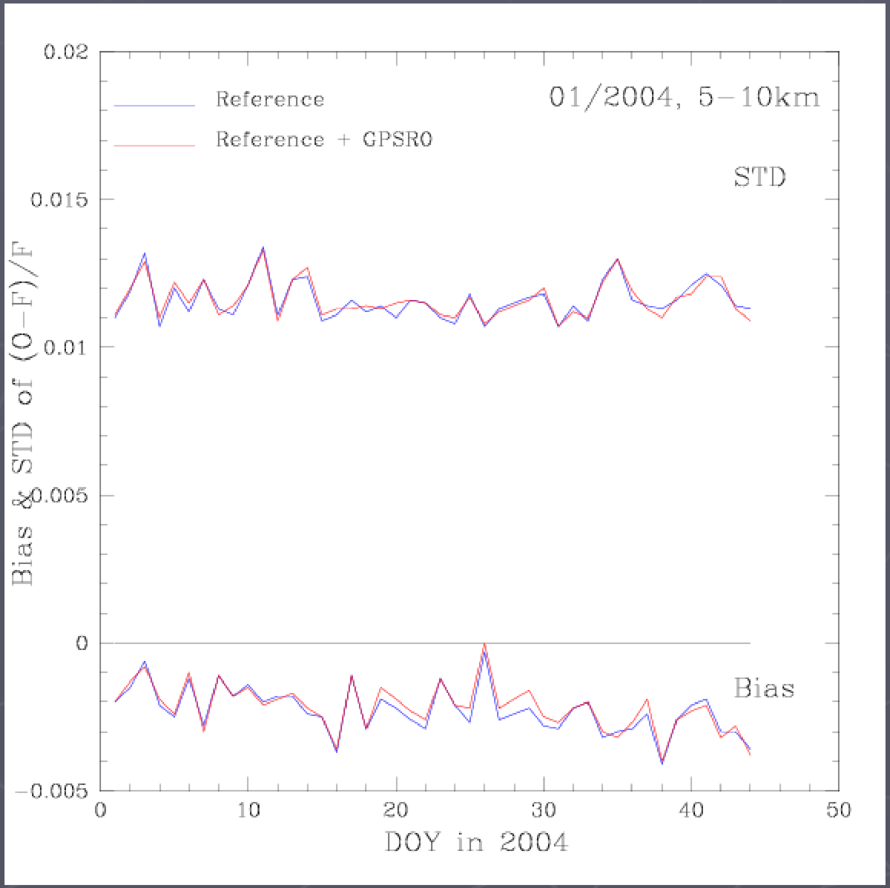
- Bending angle vs height: Less processed, but difficult to model. GEM has a low lid (10 hPa). Atmosphere above also has weight.
- Refraction index vs height: More processed but very practical. No problem with lid. Useful data from the surface to GEM lid.
- Temperature vs height or vs pressure: Refraction index is an accurate measure of T & P only above all water vapor (say, tropopause & above)

- We choose Refraction index vs height

Evolution of O-F(6h) over the experiment (Jan-Feb 2004)

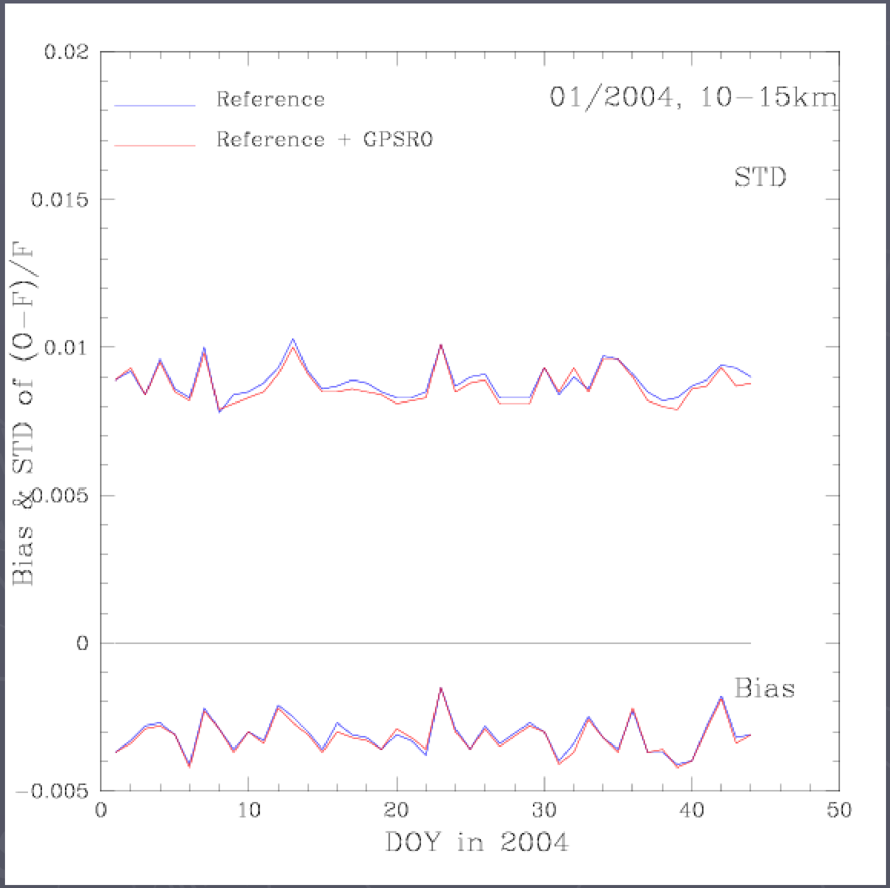


0-5km Height

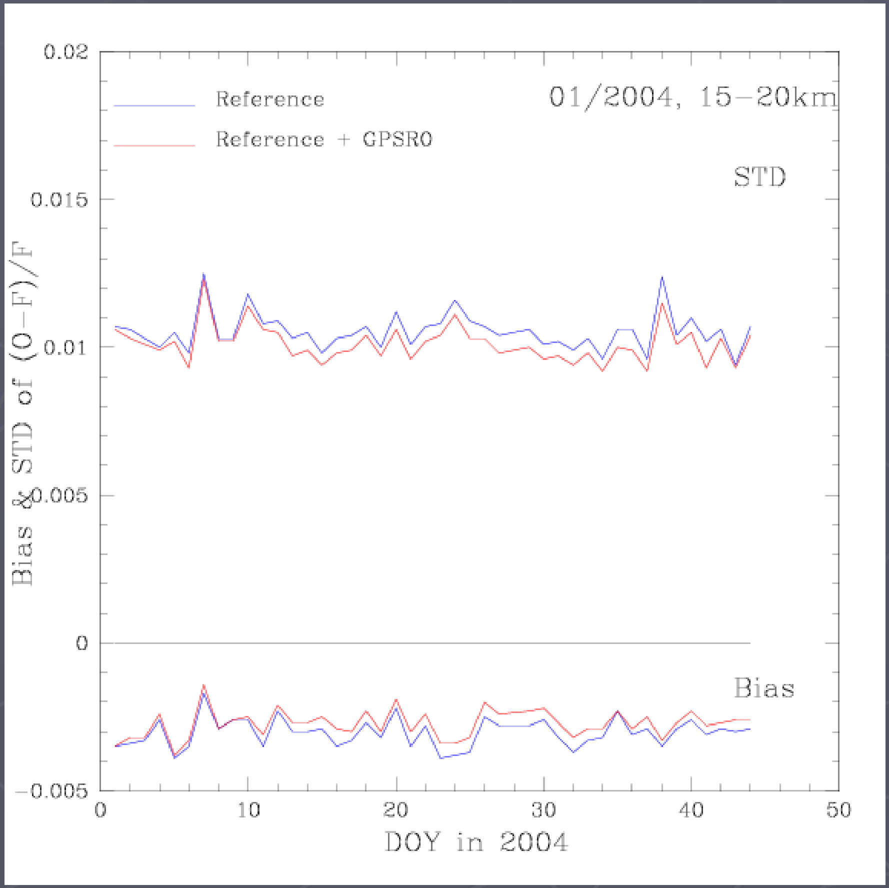


5-10km Height

Evolution of O-F(6h) over the experiment (Jan-Feb 2004)

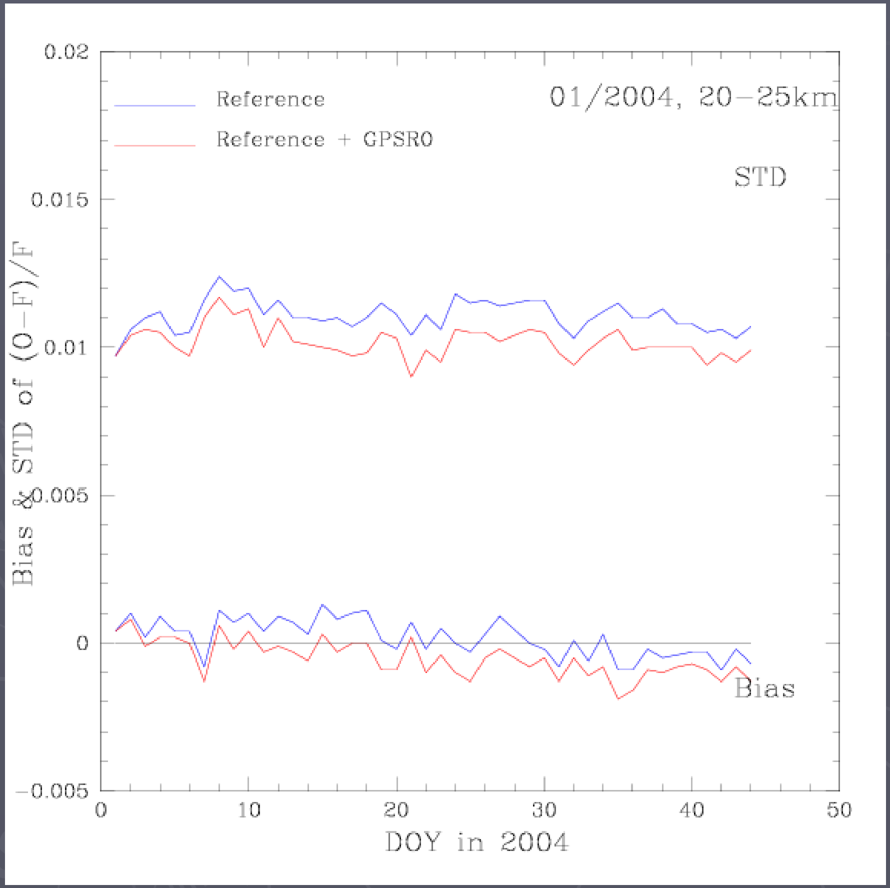


10-15km Height

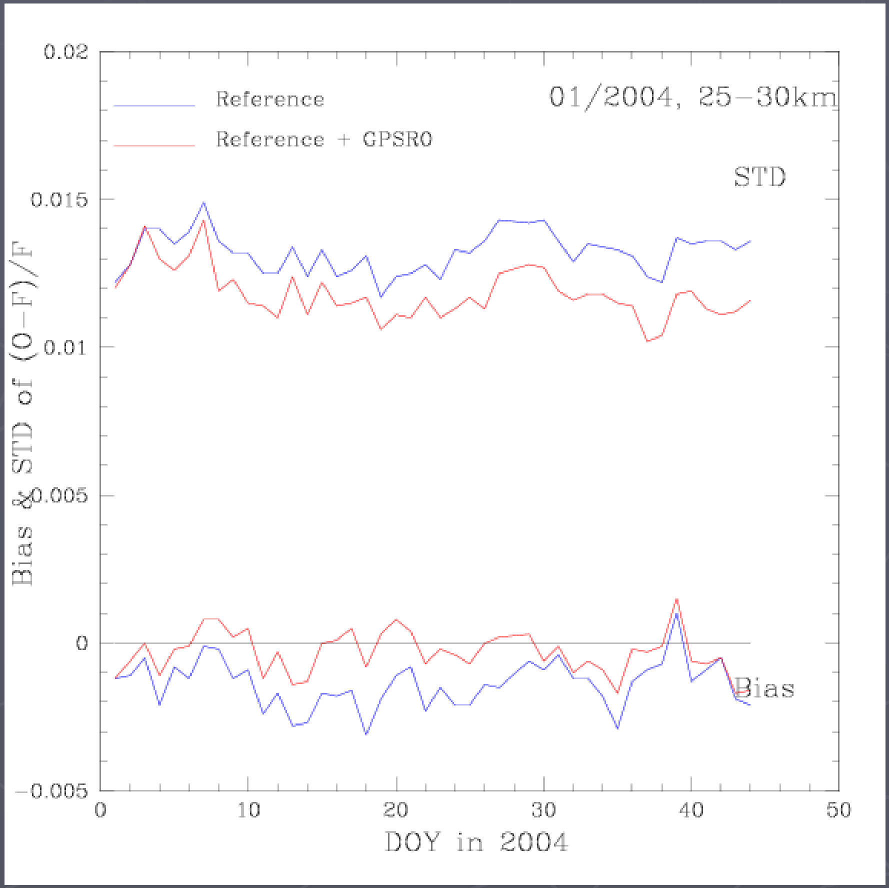


15-20km Height

Evolution of O-F(6h) over the experiment (Jan-Feb 2004)

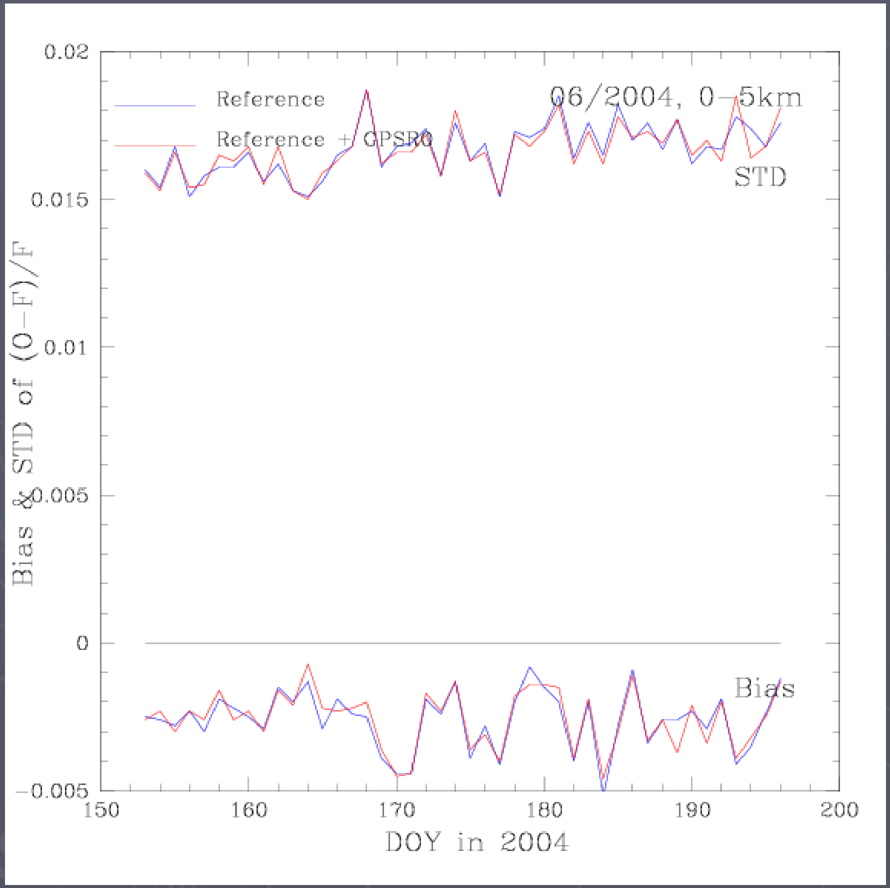


20-25km Height

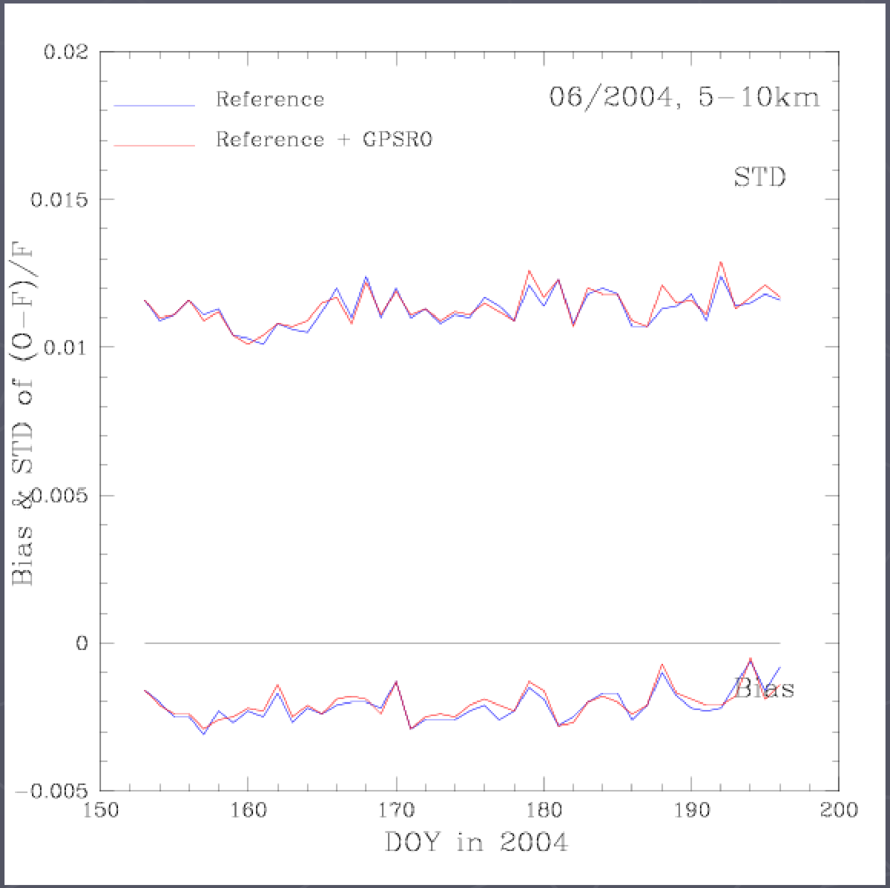


25-30km Height

Evolution of O-F(6h) over the experiment (Jun-Jul 2004)

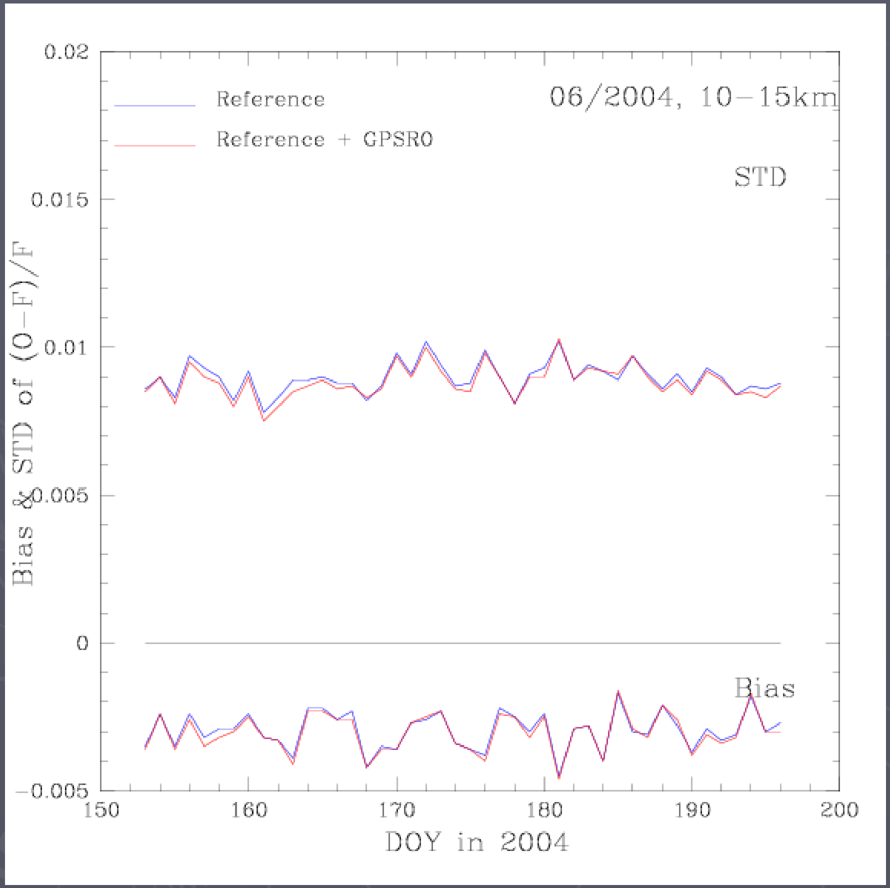


0-5km Height

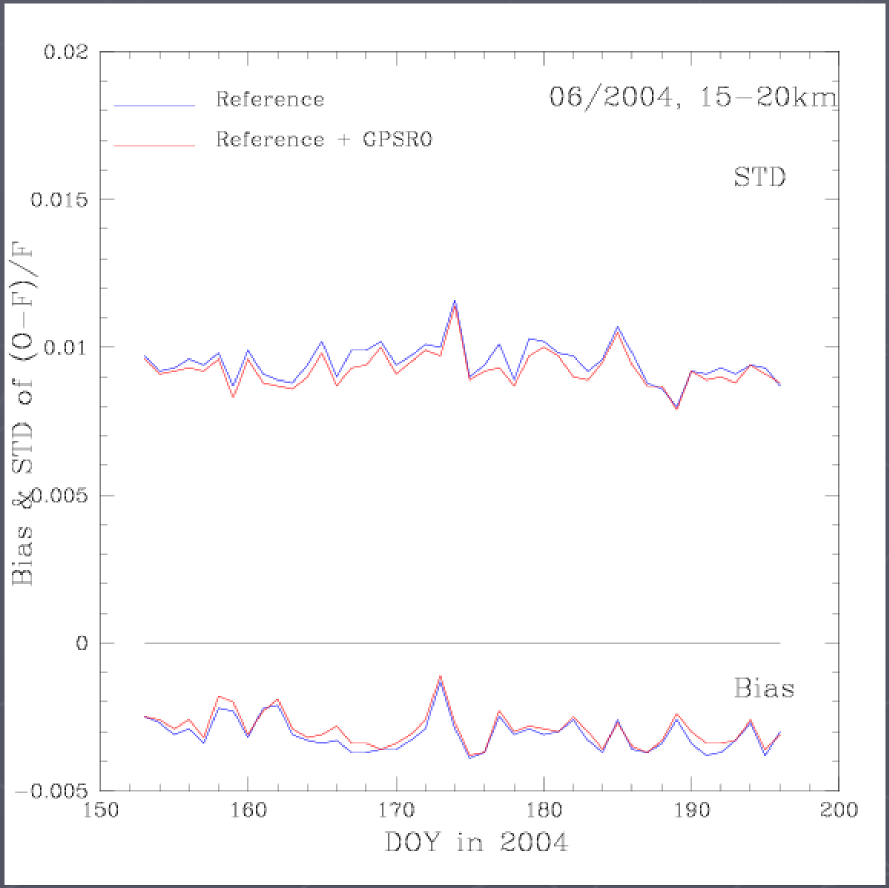


5-10km Height

Evolution of O-F(6h) over the experiment (Jun-Jul 2004)

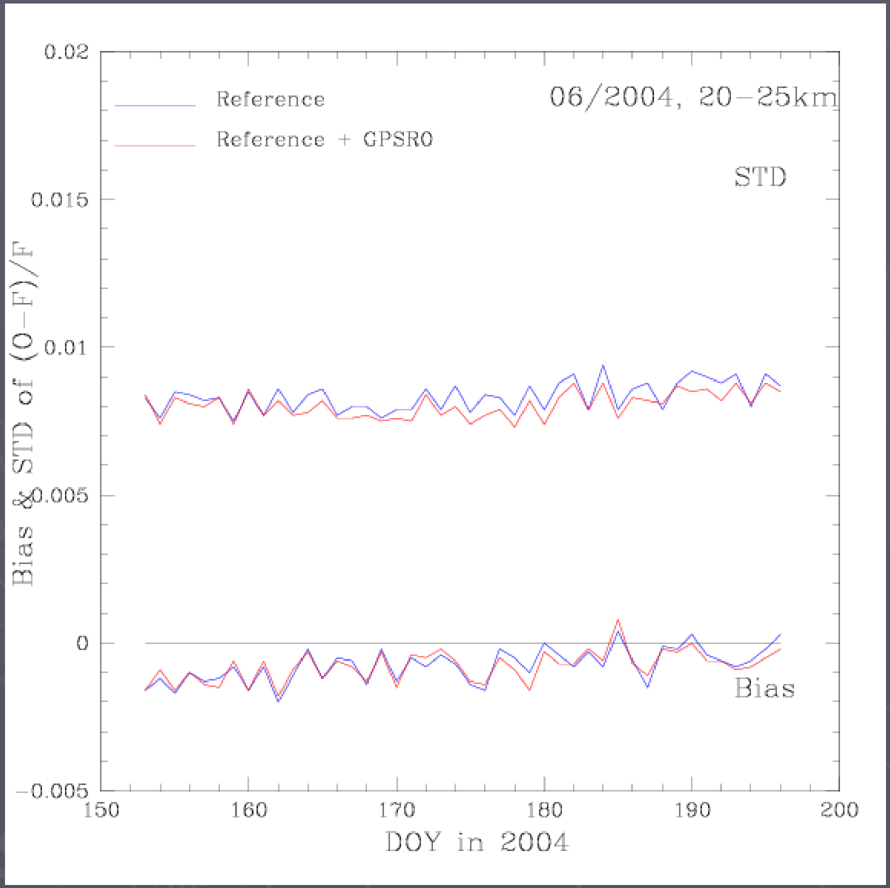


10-15km Height

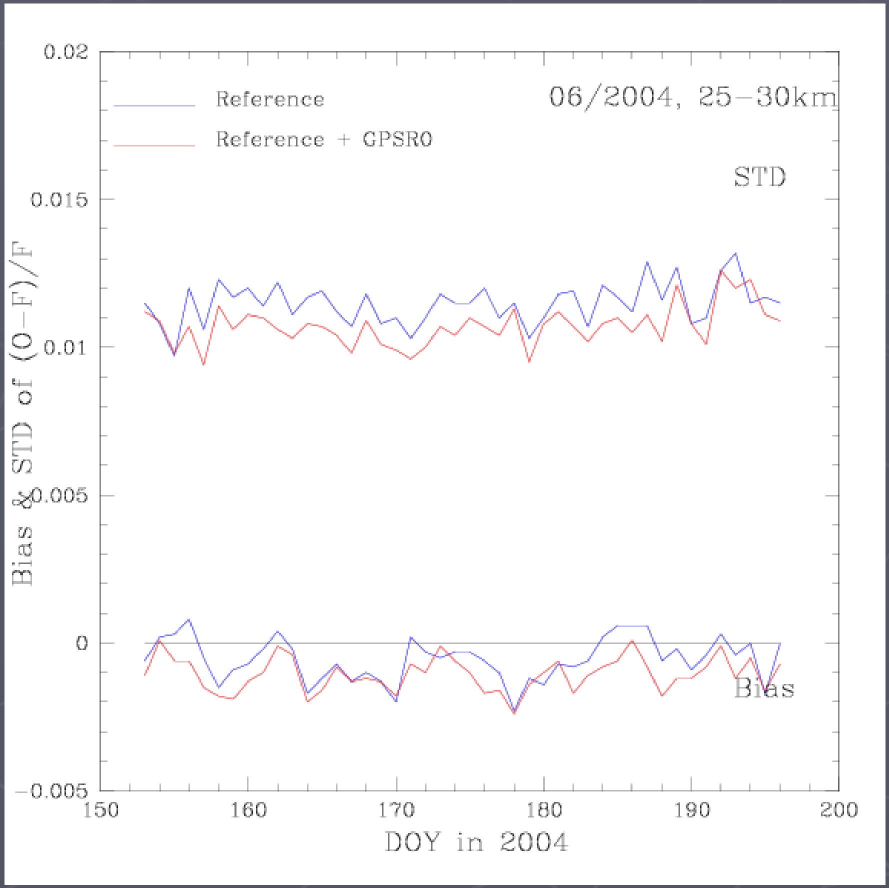


15-20km Height

Evolution of O-F(6h) over the experiment (Jun-Jul 2004)



20-25km Height

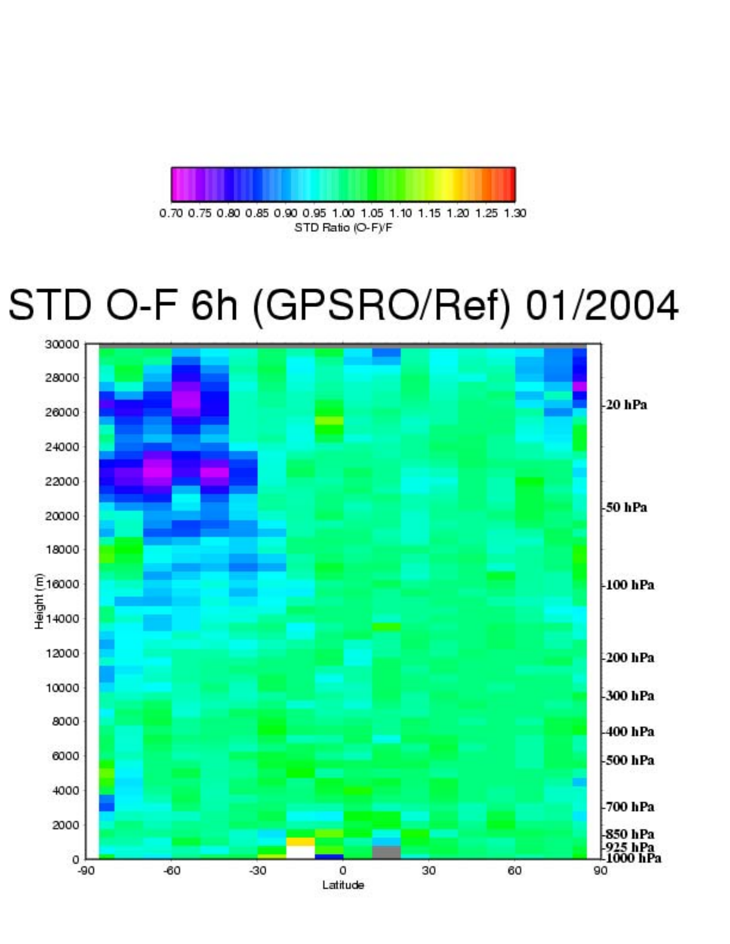


25-30km Height

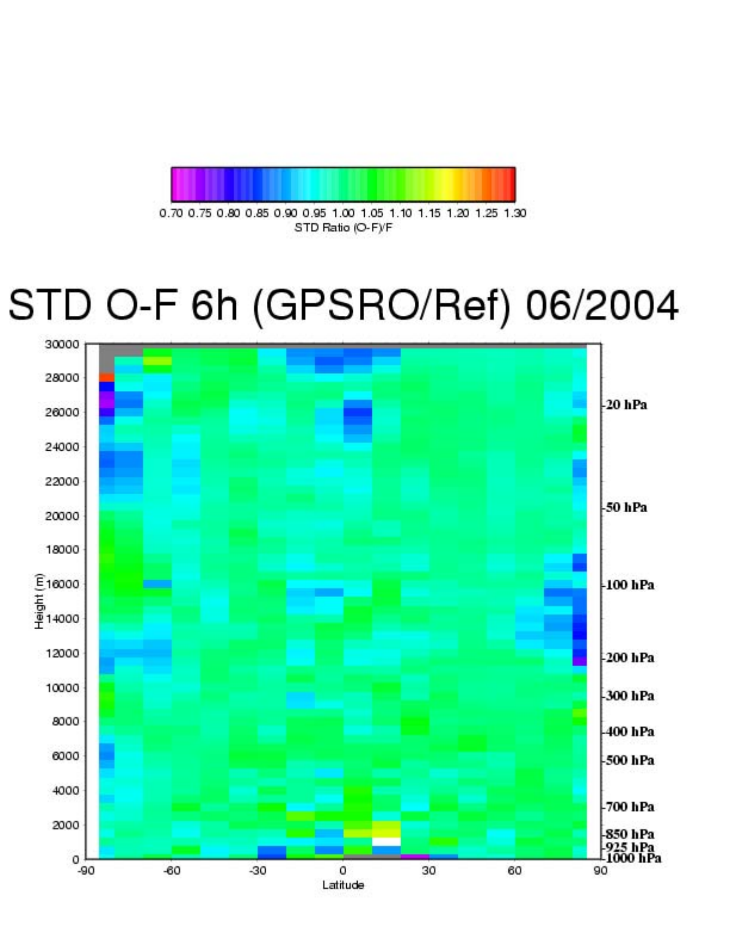
Comments on the evolution

- Positive impact
  - STD reduced nearly systematically
  - Bias reduced in general
  - In the winter exp, bias reduces to ~0 in the upper layers
  - RO only data effective in driving upper layers?
- Larger impact at higher layers
- Transient period ~ 1 week
  - Later grand averages will ignore first 2 weeks

Evaluation I: RO



CYCLE: 2004/01/01-2004/02/15
AVG: 2004/01/15-2004/02/15



CYCLE: 2004/06/01-2004/07/15
AVG: 2004/06/15-2004/07/15

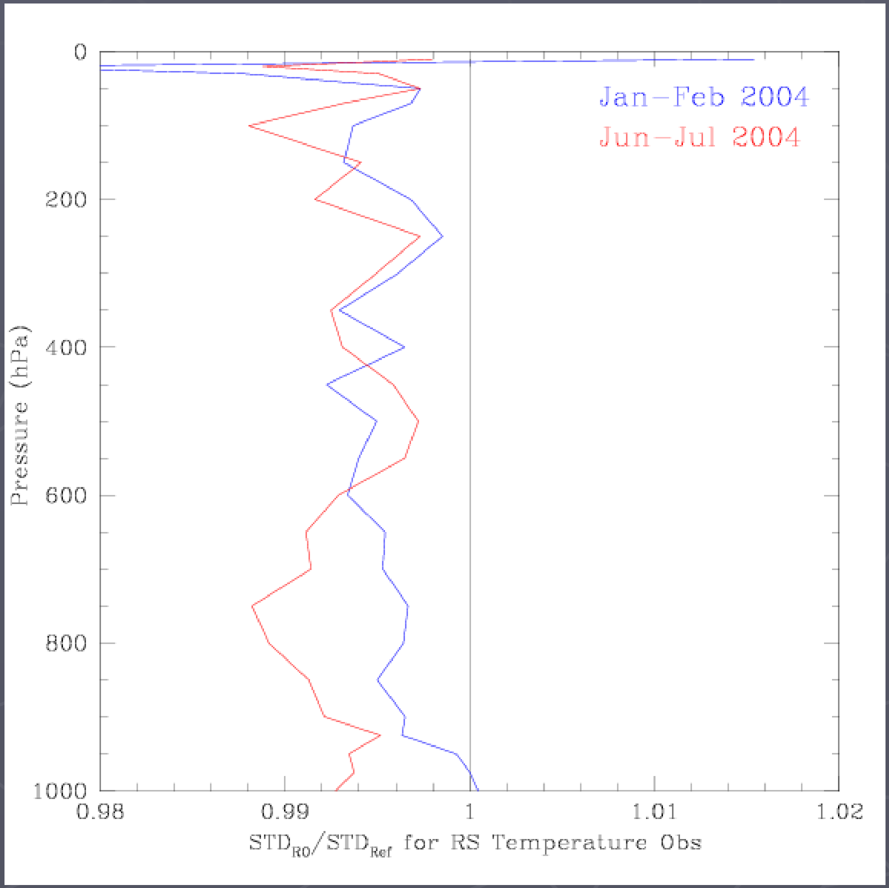
Comments to the Global RO evaluation

- The winter exp shows a large improvement in all southern stratosphere ~25-30%
- A small improvement everywhere (~5%)
- No major area with negative effects

- Summer exp shows major improvements in only scattered areas (southern pole, equatorial stratosphere)
- Small improvement everywhere (~5%)
- No major are with negative effects

Evaluation RS

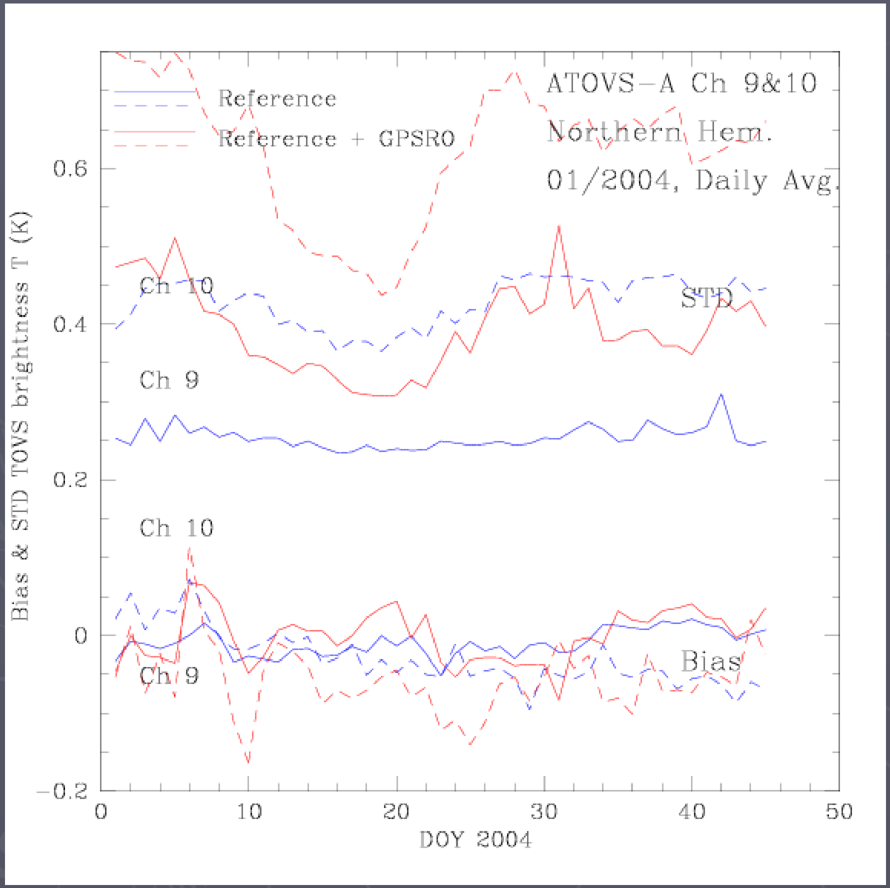
- A positive impact is observed
- However, it is smaller than for RO
- Distribution of RS is very uneven
  - Large concentration of obs where there is little improvement
  - Few RS where improvement is larger
- Normal behavior for a source of data that is filling gaps
- 0.5-1% reduction in STD of the 6h forecast of T

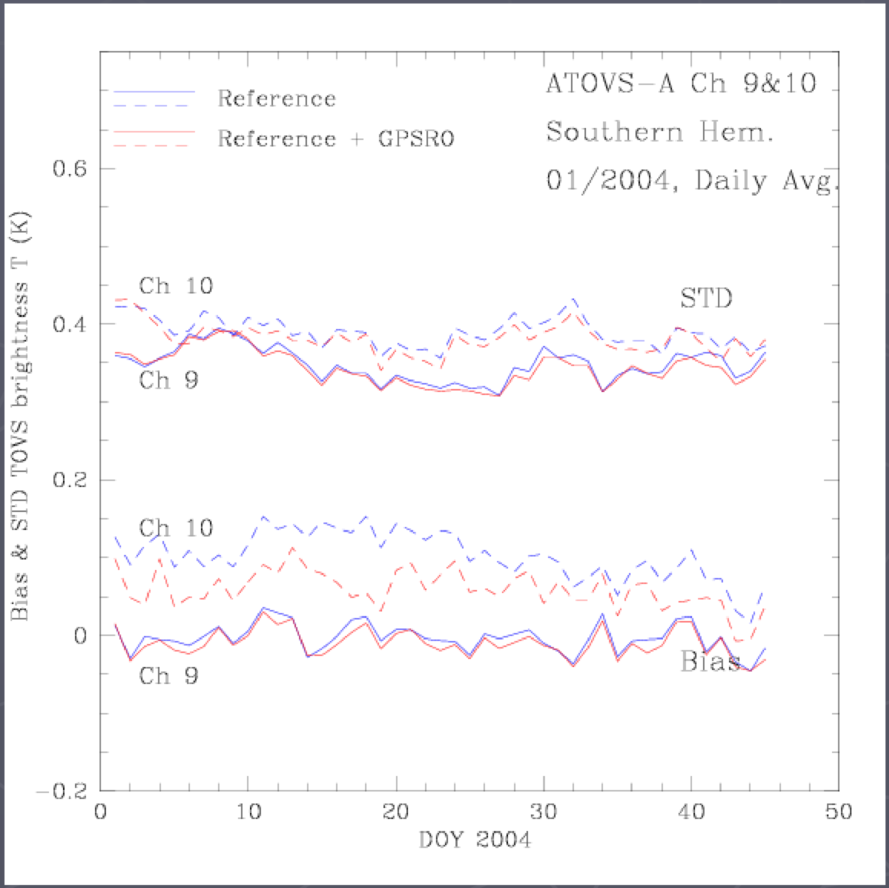


Evaluation TOVS

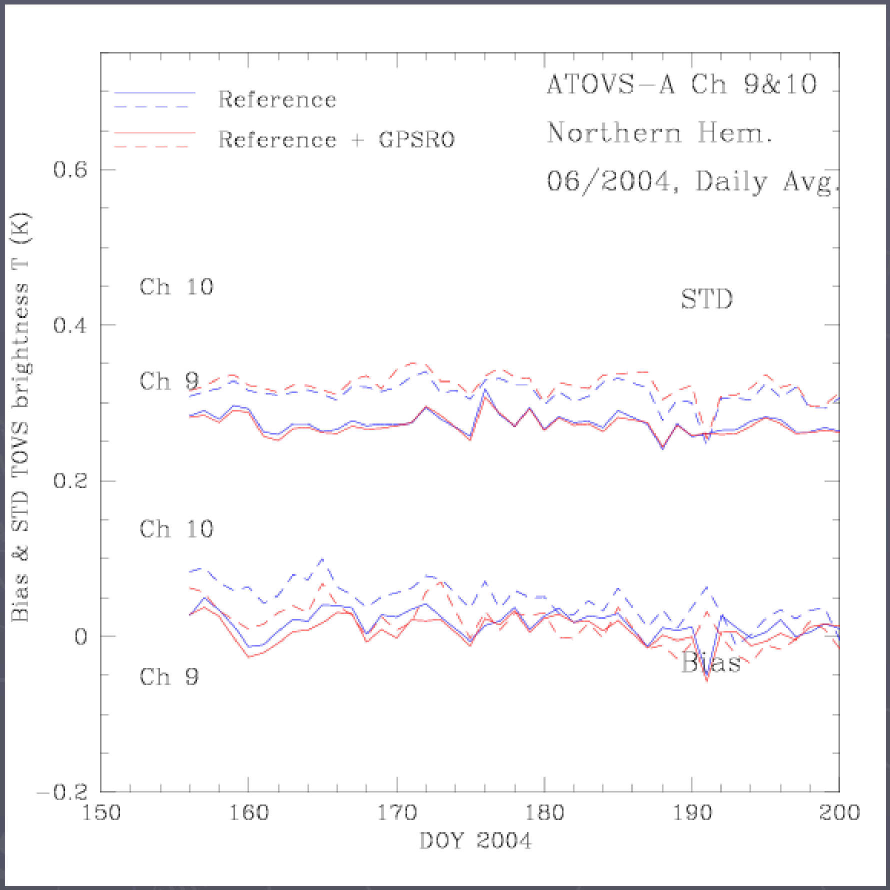
- TOVS observations have better geographical distribution than RS
- Better chances to observe impact
- RO Evaluation suggested looking at the stratosphere, specially southern hemisphere
- Weight of channels 9 & 10 peak at the stratosphere

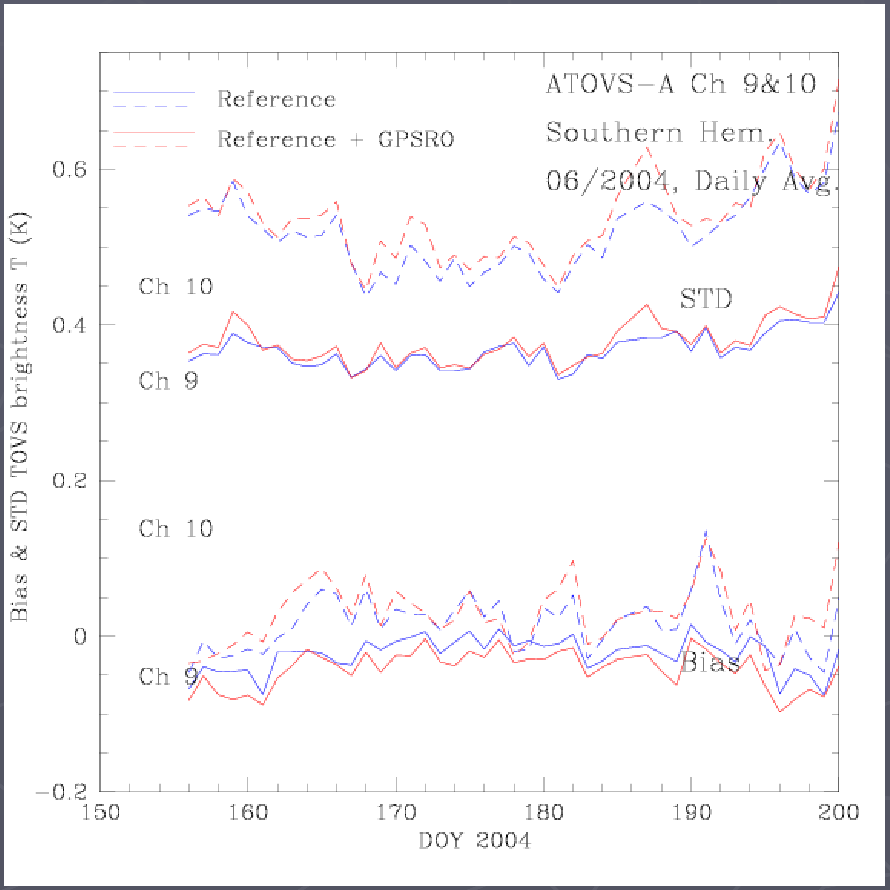
Evaluation TOVS Jan-Feb 2004





Evaluation TOVS Jun-Jul 2004





Evaluation TOVS

- Results for hemisphere in summer better
- Specially good in southern summer
- Take with caution
  - Amount of data in NH < than SH
  - Data is geographically selected. Specially important in NH

Evaluation conclusions

- Most results are positive
- RO shows significant positive results
  - RO is global and uniform
- RS shows positive results
  - Only slight improvement
  - RS are dense where little improvement is expected
- TOVS shows mixed results
  - Good in summer weather, bad in winter weather
  - The substantial improvement in southern summer can be clearly traced with TOVS (Ch 9 & 10)

To finish

- Ability to assimilate RO data reached
- COSMIC mission to be launched Apr/2006
- As a global, continuous, uniform and vertically well resolved source, RO data useful for assimilation and verification
- Many assimilation stats are positive
- Some issues still to be clarified (upper TOVS channels in winter weather)