Profiling the atmosphere with the airborne RO technique using GPS signals recorded in open-loop mode

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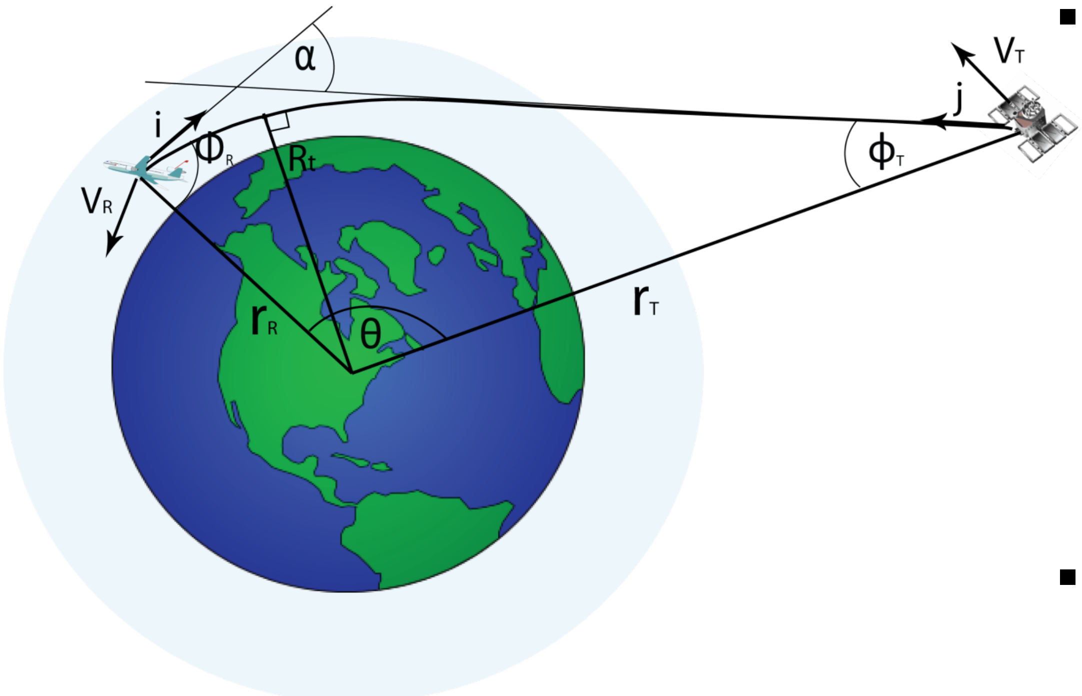
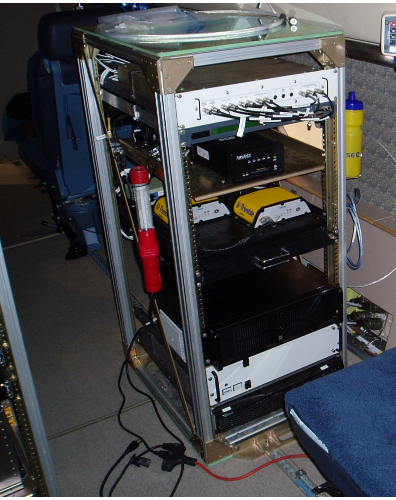
Airborne Radio Occultation (RO)

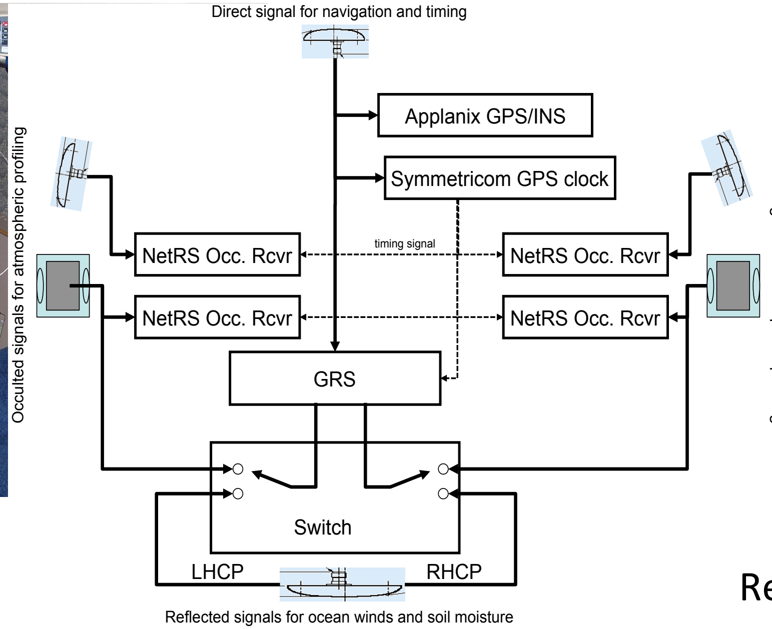


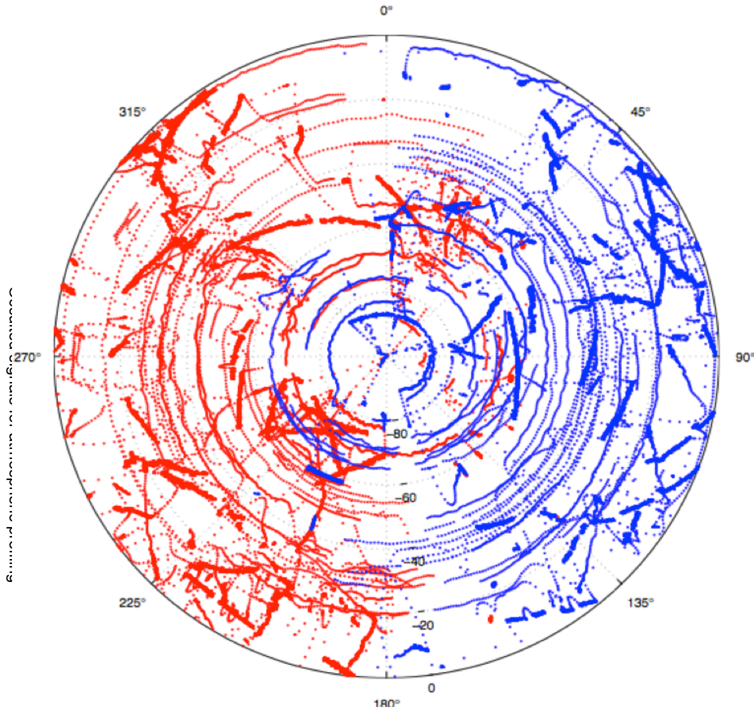
- Airborne RO measurements can contribute to understanding tropospheric moisture
  - Dense measurements of meteorological targets
  - Vertical resolution ~200m
  - Insensitive to clouds and precipitation
- Side-looking GPS antennas track setting and rising satellites
- GPS signal experiences refractive bending and delay

Problem: conventional closed loop tracking receivers have data gaps
Objective: evaluate the performance of open-loop tracking

GISMOS on HIAPER







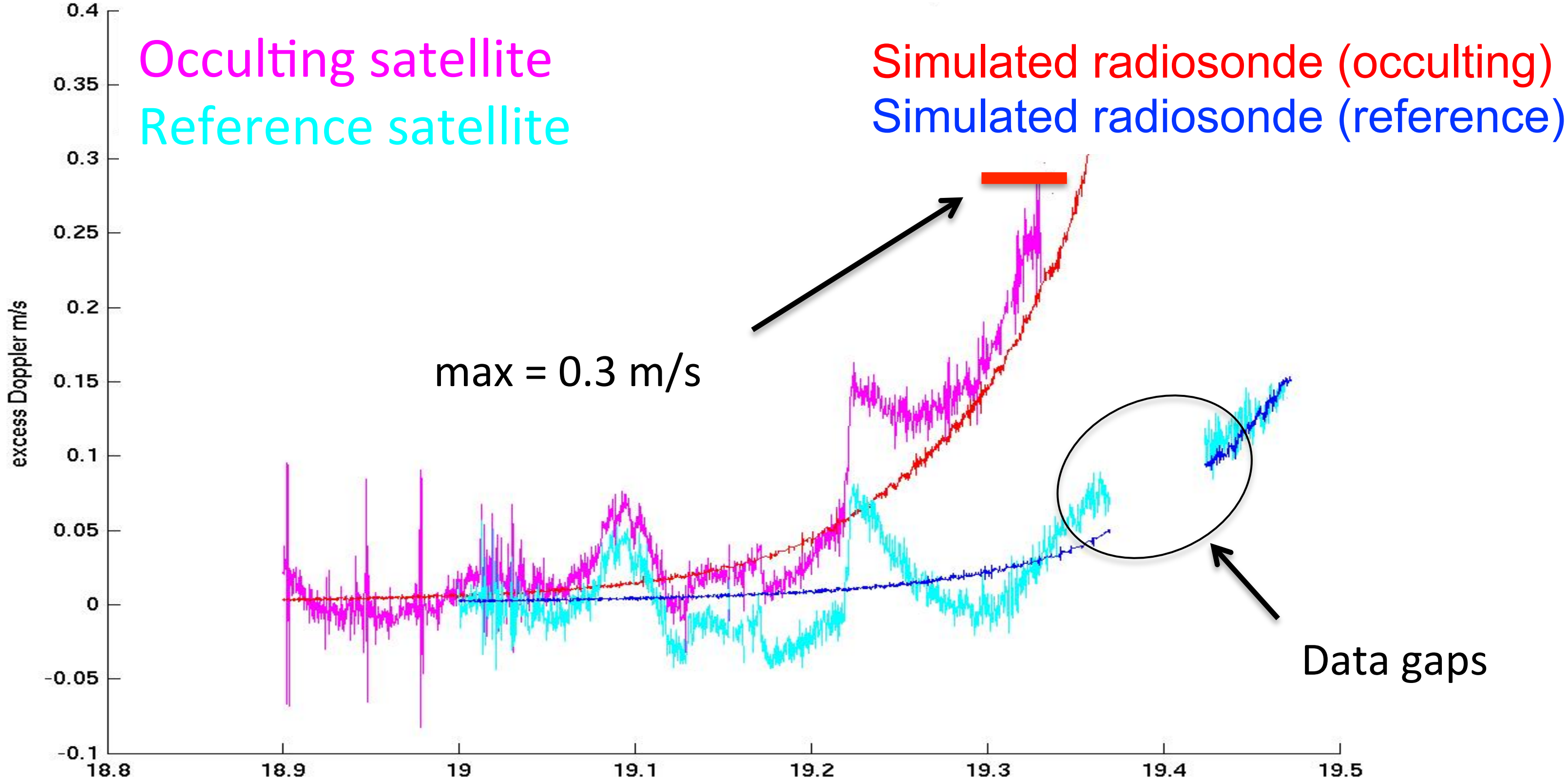
Red: Port antenna Blue: Starboard antenna

- 15.5 km maximum flight altitude
- High precision Applanix POS/AV 510 GPS/INS navigation system
- Dual-frequency geodetic quality receivers (NetRS)
- 10 MHz GNSS Recording System (GRS)

- High-gain narrow field of view antennas
- Peak Gain: 7.7 dbic L2
- 9.4 dbic L1
- Elevation: -3dB +/- 18°; -10dB +/- 30°
- Azimuth: -3dB +/- 25°; -10dB +/- 40°

Excess Doppler from NetRS Receivers

Satellite PRN12 on starboard high-gain antenna recorded with NetRS



Hours since 2008-02-22-00:00

- Limited by signal fading and multipath at low elevation angles causing the tracking loops in the conventional NetRS GPS receiver to lose lock
- Data gaps

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OL Tracking of Setting and Rising Occultations

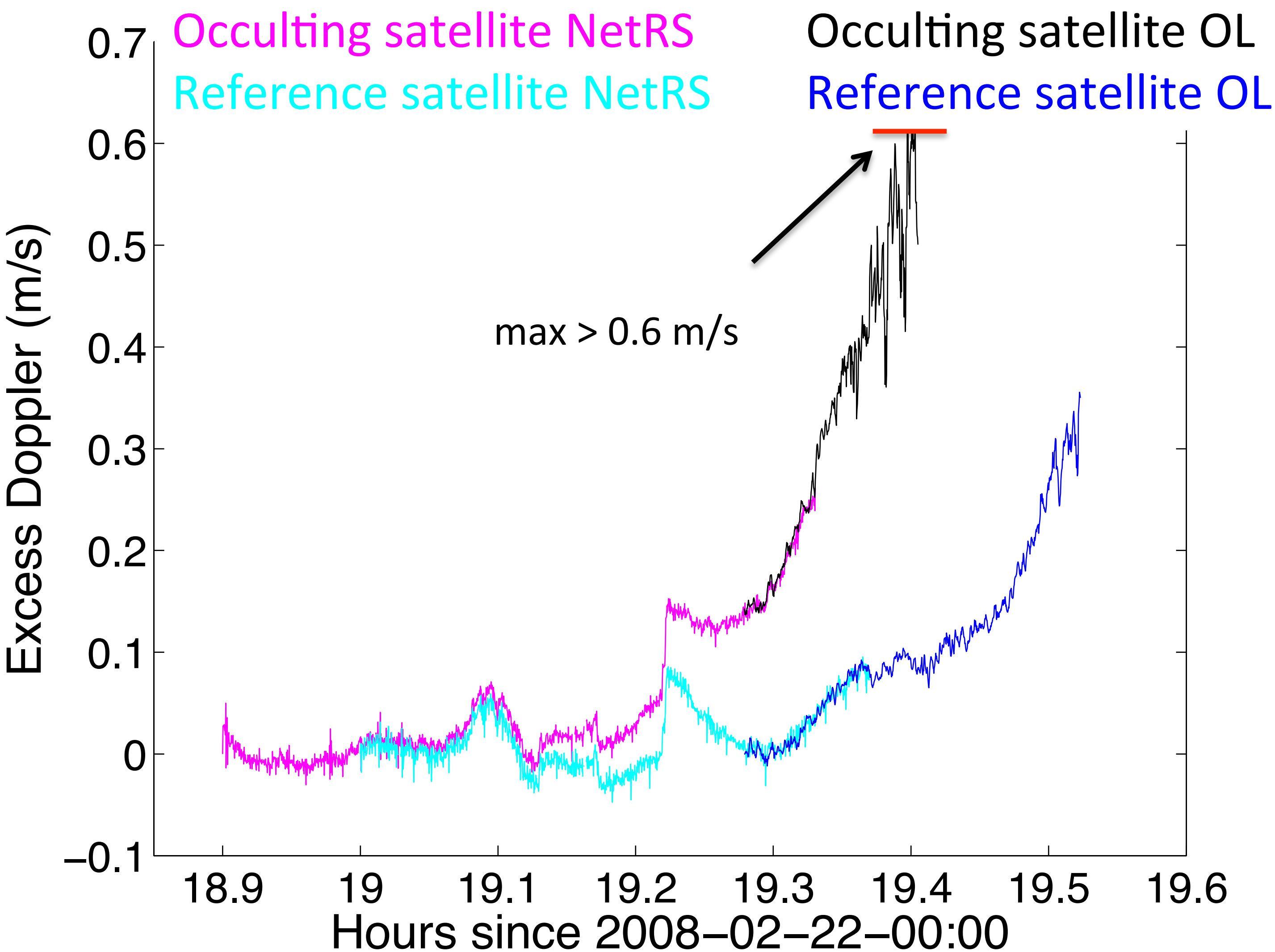
Determine the presence of signals and rough estimates of Doppler frequency → **Acquisition**

Generate a replica of the incoming signal.
Refine the rough estimates of code delay and Doppler from the acquisition → **CL tracking**

Code delay is initialized using that of obtained in CL.
Using a geometric Doppler model, steer the phase and frequency of the locally generated replica signal → **OL tracking**

- Need for navigation data bits: data bits (50Hz) modulated on the I&Q phase components
- Challenge for rising occultation: signal power is low in the beginning => cannot be acquired until satellite rises to some elevation
- "Backward OL tracking" (Acikoz 2011)
    - Rising satellite is acquired and tracked with CL tracking when signal power is high enough
    - OL tracking is initialized the same way as in setting occultation case but in reverse time

Closed-loop vs Open-loop (OL) Receiver



- Significant improvement over conventional receivers

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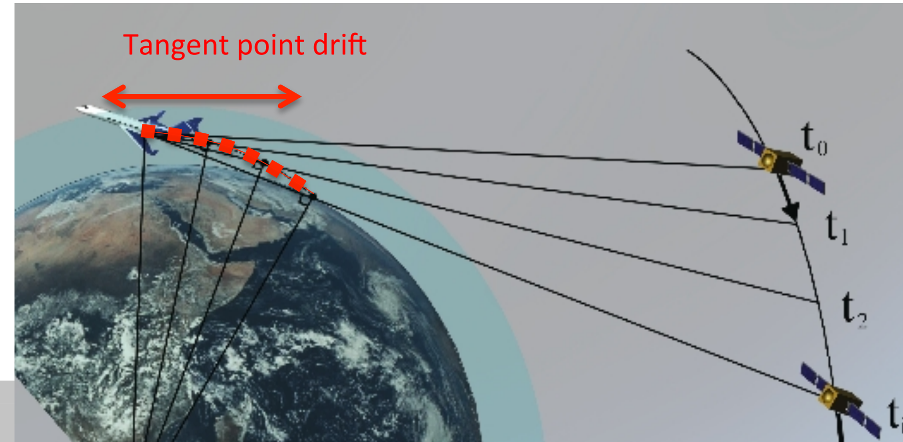
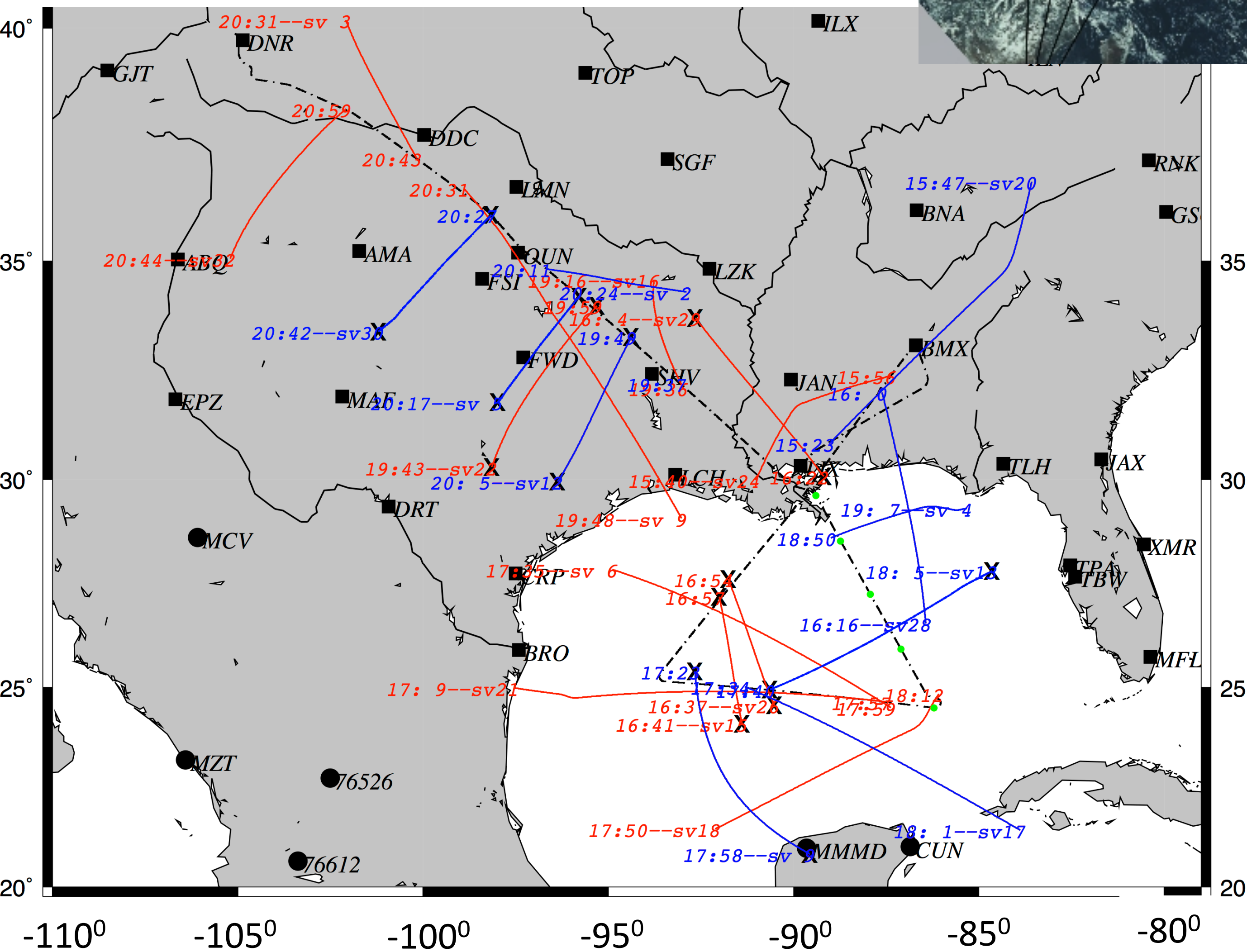
Occultation Geometry



15 FEBRUARY 2008 FLIGHT



- 5 hour flight
- 13.5 km altitude
- 19 occultations when aircraft was at flight level
  - 10 setting
  - 9 rising
- COSMIC:
- 5 occultations/5 hours

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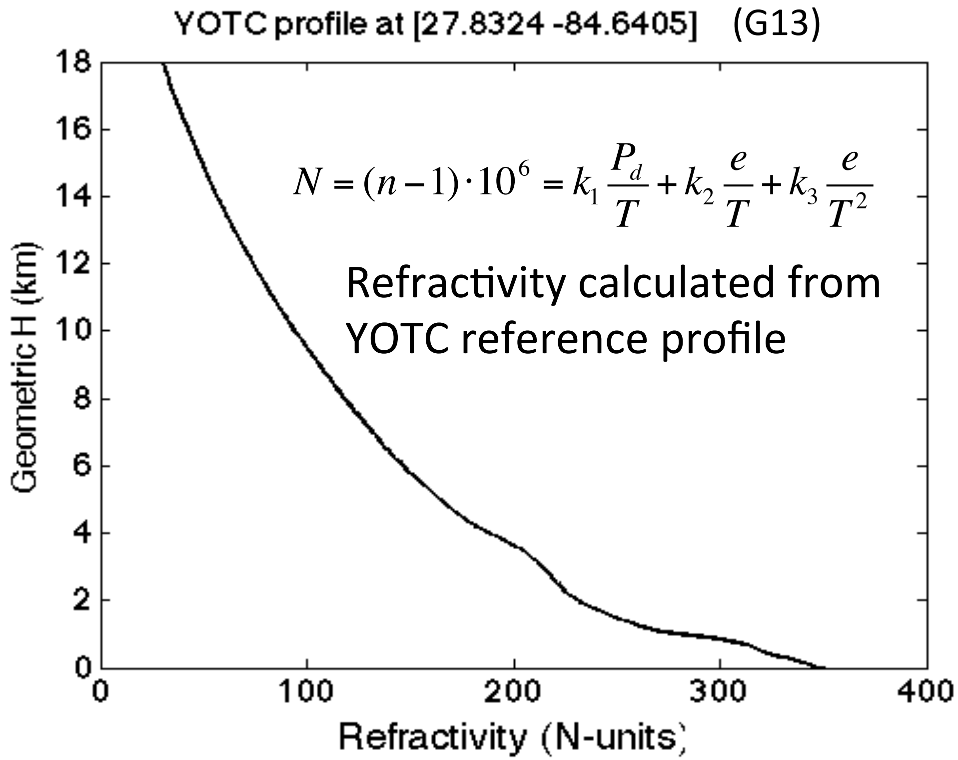
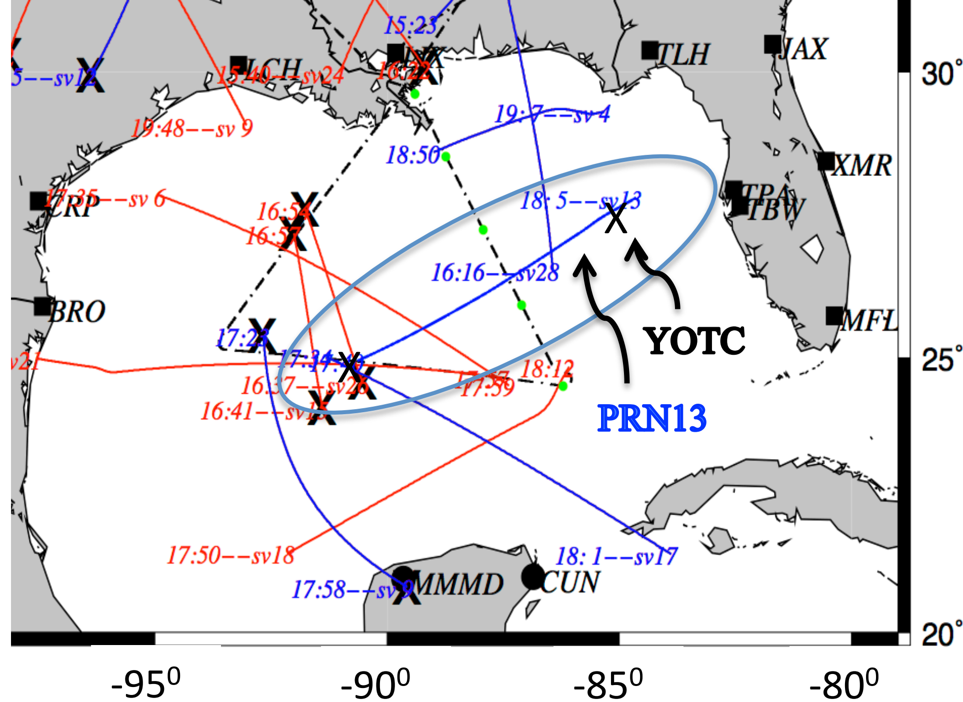
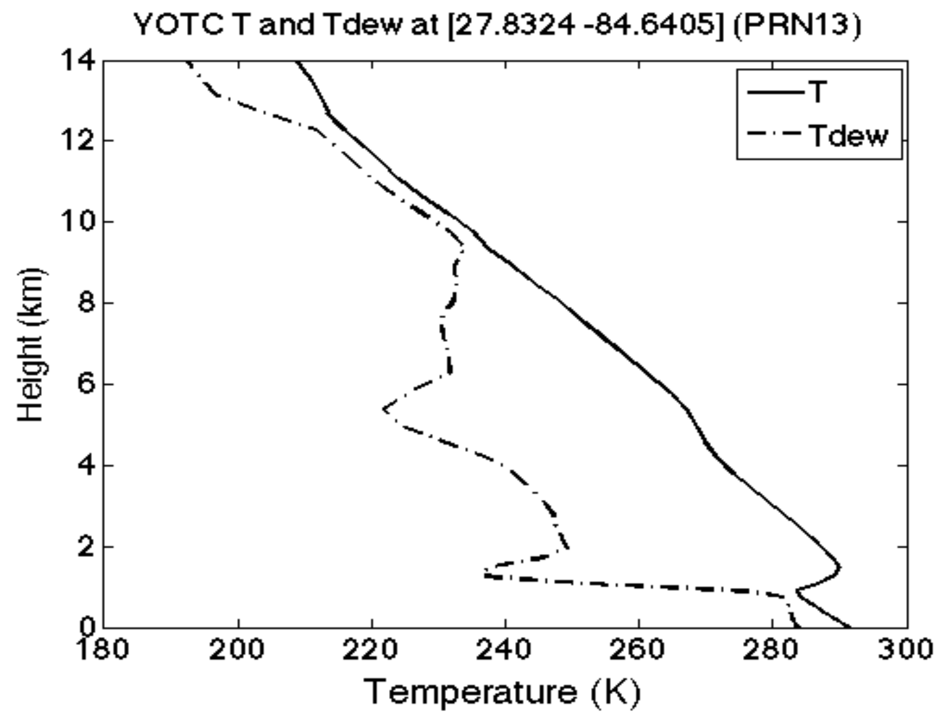






Reference profile for PRN13 is ECMWF

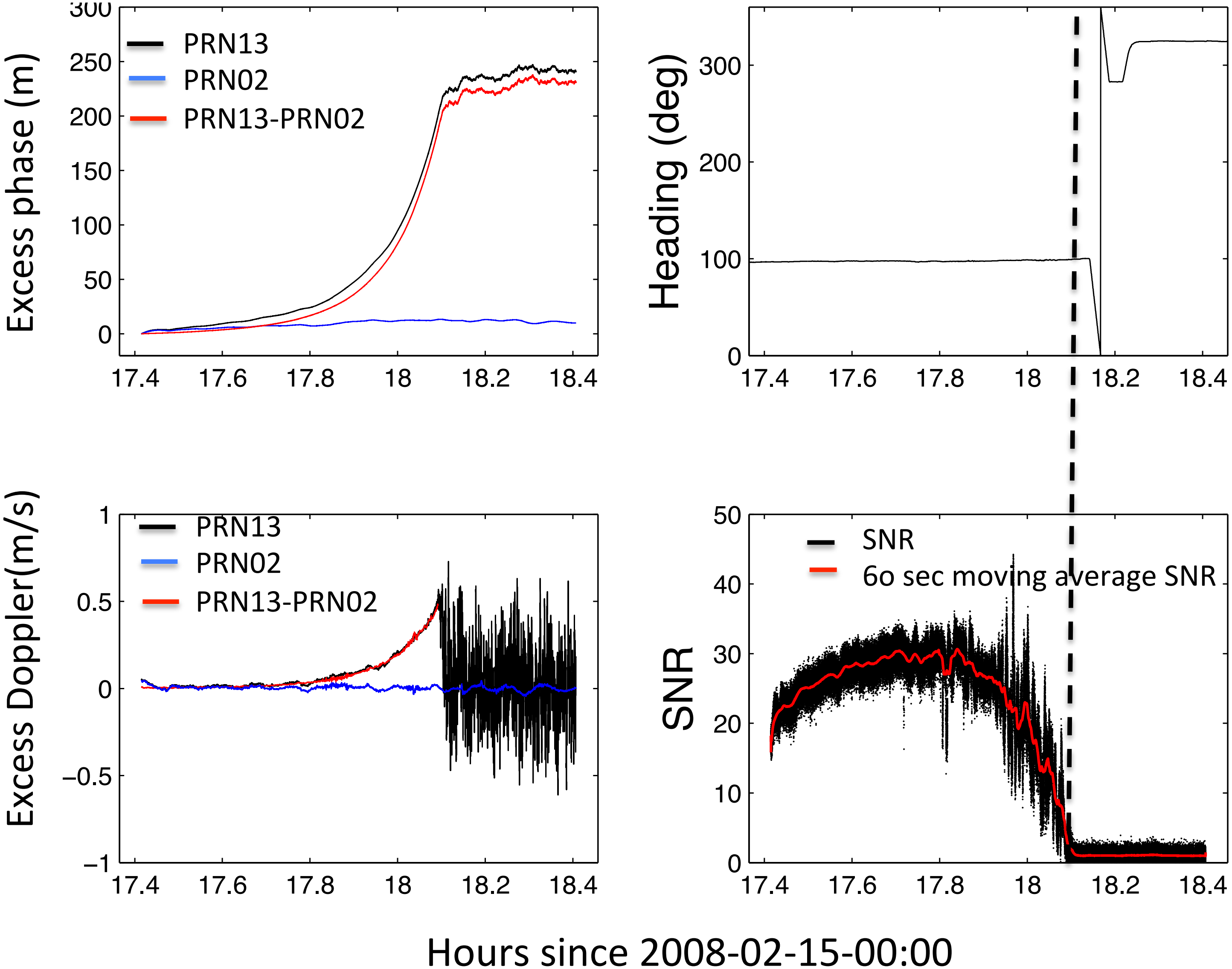
-Year of Tropical Convection (YOTC)

analysis profile at:

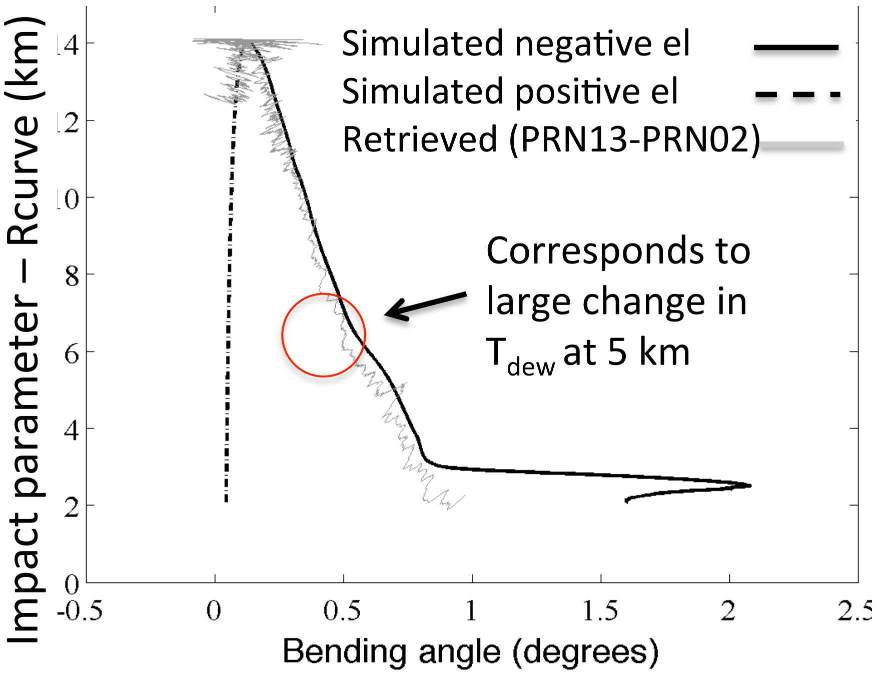
- ~25 km spatial resolution
- 91 levels
- Time 18:00 UTC
- Lat = [27.8324 27.7500]
- Lon = [-84.750 -84.6405]

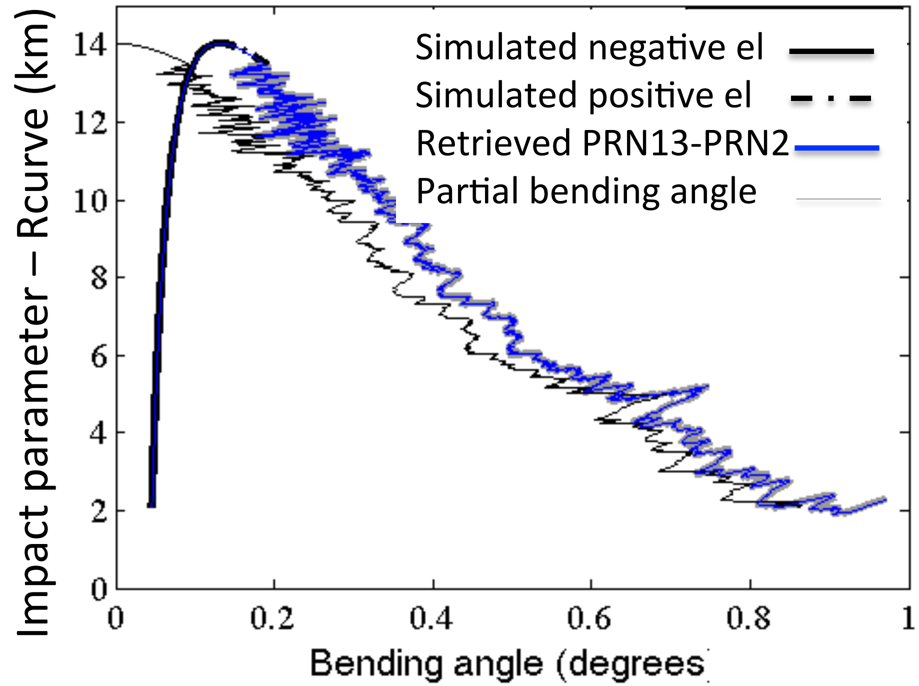
OL profiles: Setting occultation

15 February 2008 flight: Occulting GPS satellite PRN13 and high elevation satellite PRN02

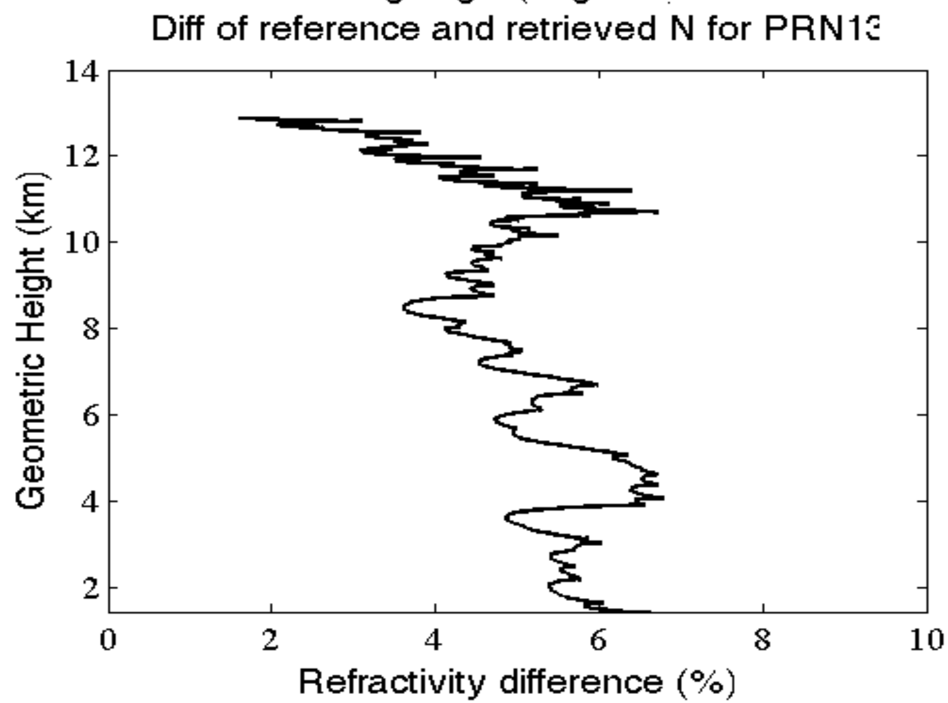


Rcurve = radius of local curvature = 6359.204 km





$$\alpha'(a) = \alpha_N(a) - \alpha_P(a) = -2a \int_{n_t R_t}^{n_R r_R} \frac{d \ln x}{dx} \frac{dx}{\sqrt{x^2 - a^2}}$$

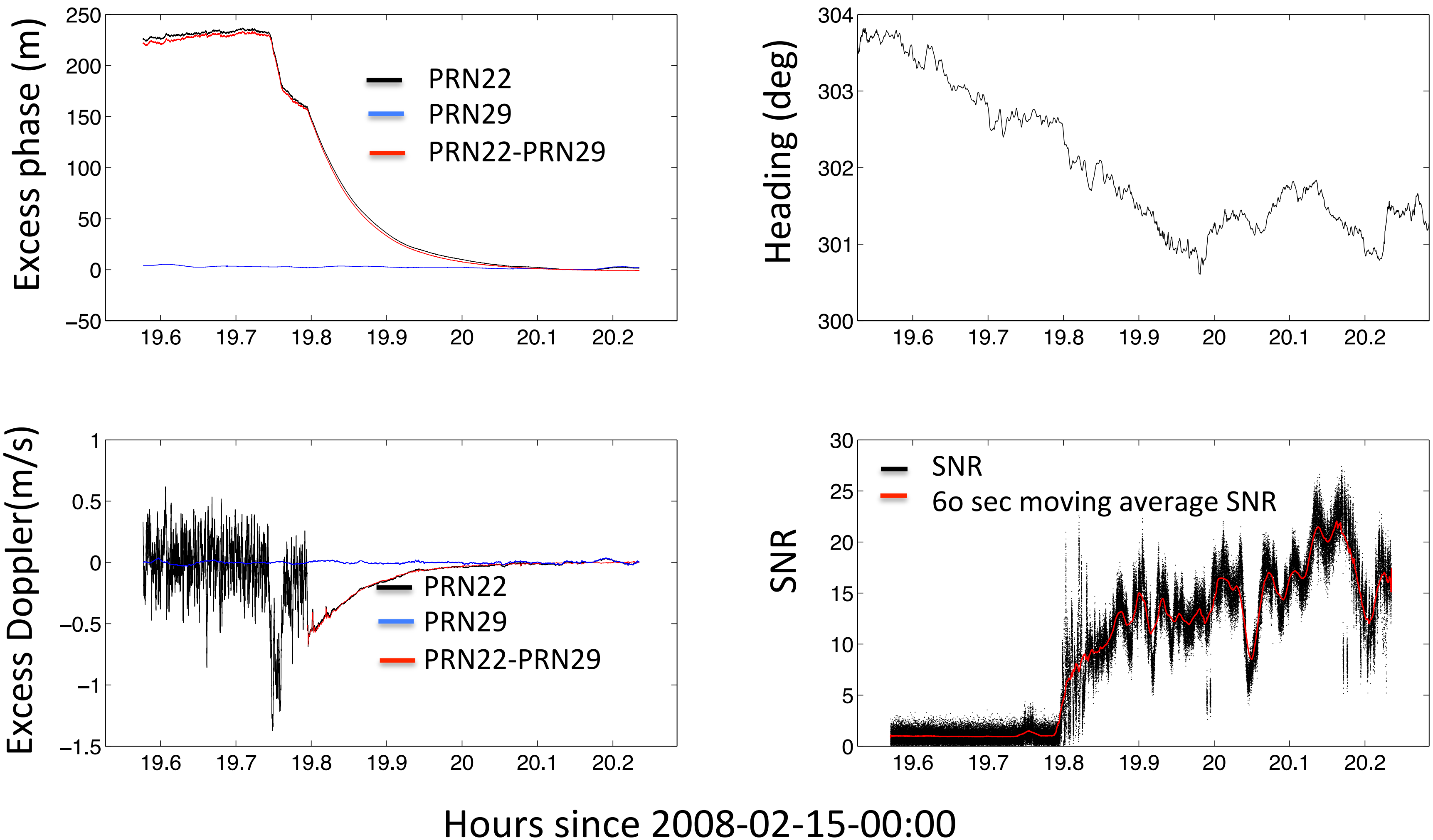


- Bias in bending angle maps into refractivity
- Bias wrt YOTC = 6% N
- Std wrt YOTC = 0.75% N from 1.5 to 11.5 km

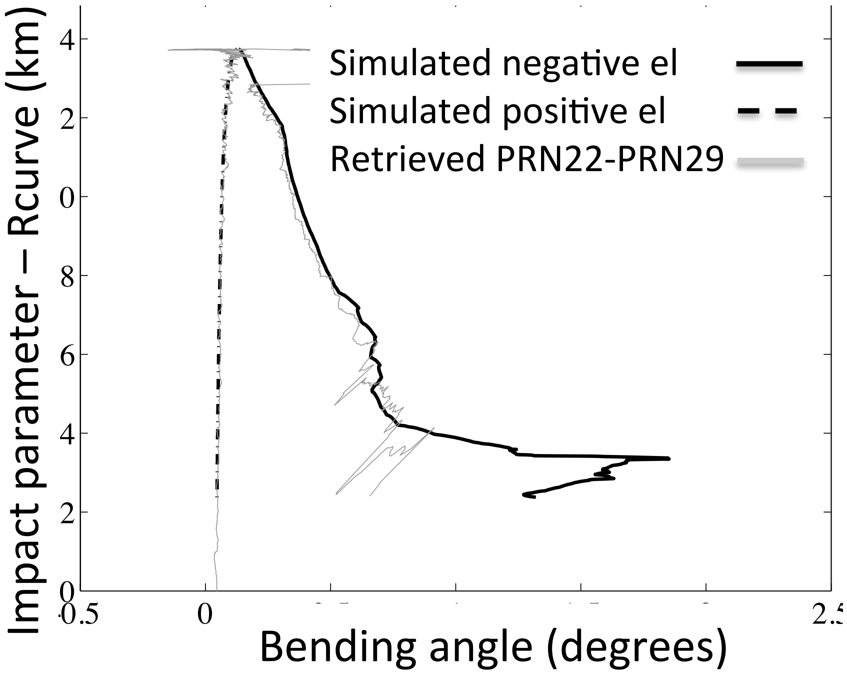
OL profiles: Rising occultation

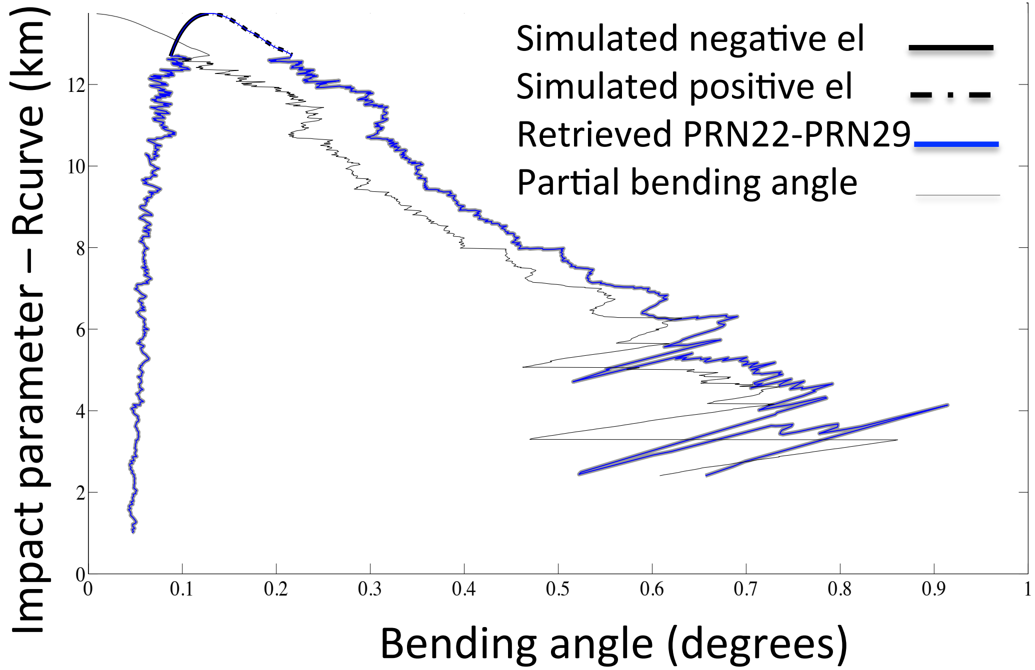
OL tracking has been implemented for rising occultations, with equivalent quality to setting occultations (Acikoz, 2011)

15 February 2008 flight: Rising GPS satellite PRN22 and high elevation satellite PRN29

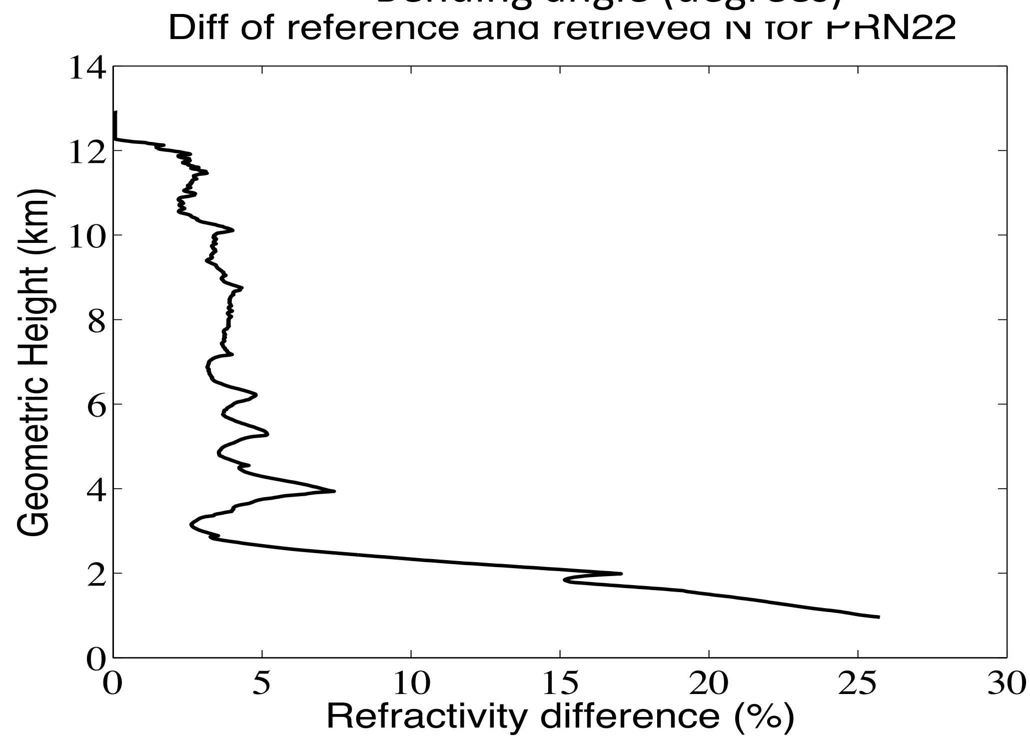


Rcurve = radius of local curvature = 6380.44 km





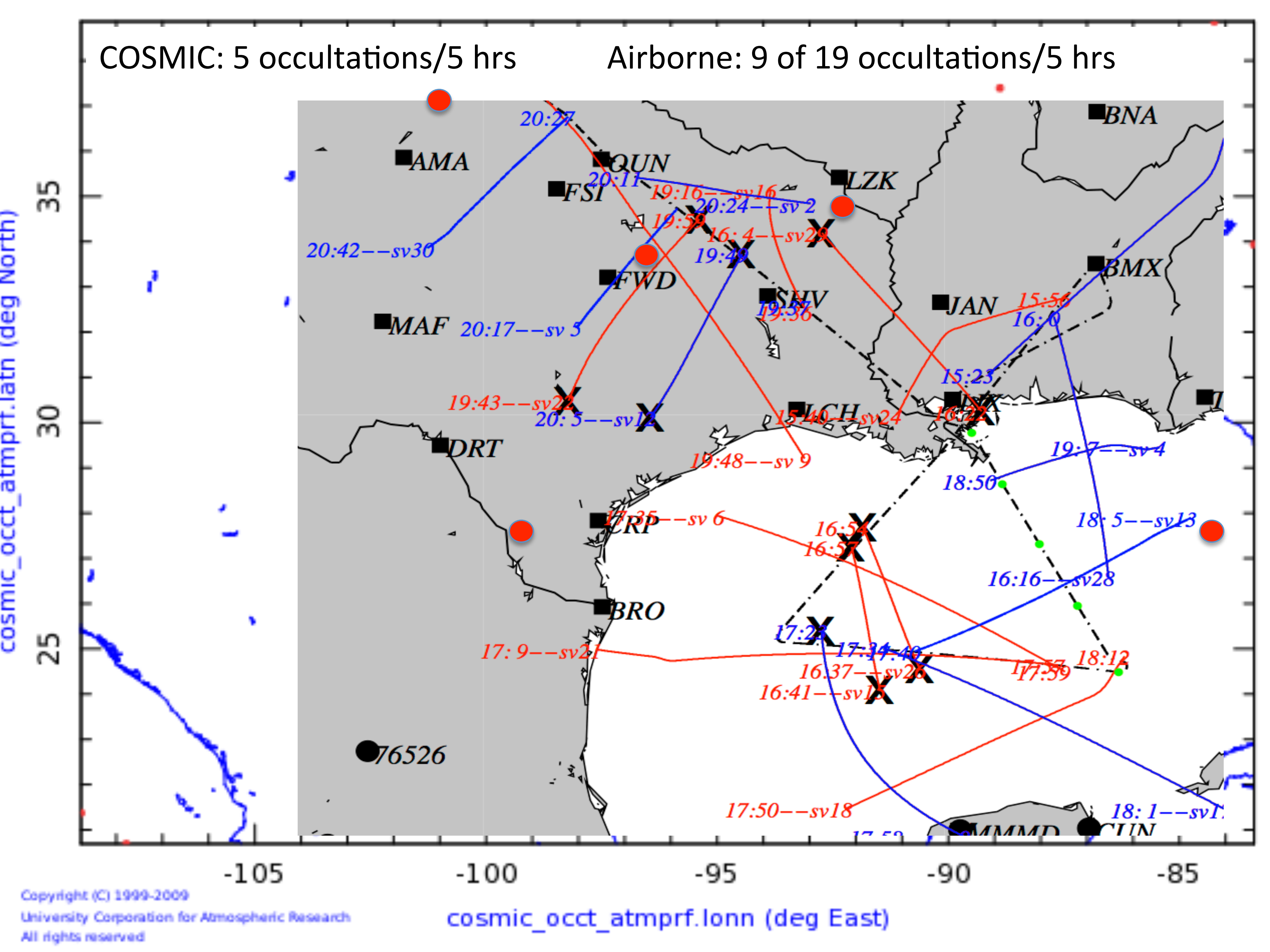
- Bias wrt YOTC = 5.5% N
- Std wrt YOTC = 1.5% N from 2.6 km to 13.5 km flight altitude



Summary for 9 occultations

PRN	Setting/ Rising	Port/ Starboard	Lowest Elevation (deg)	Lowest Geometric height (km)
05*	Setting	Port	-3.83	2.974
09	Setting	Starboard	-4.37	1.044
12	Setting	Port	-3.98	2.353
15	Rising	Port	-3.78	3.386
13	Setting	Port	-4.44	0.562
22	Rising	Port	-4.06	0.956
26	Rising	Port	-4.19	0.952
29	Rising	Starboard	-4.41	0.612
30	Setting	Port	-4.46	0.869

* Airplane turn truncated the profile early


COSMIC: 5 occultations/5 hrs
Airborne: 9 of 19 occultations/5 hrs
AMA
OUN
FSI
LZK
BNA
FWD
SHV
JAN
BMX
MAF
DRT
LCH
CRP
BRO
76526
20:27
20:11
19:16--sv16
20:24--sv 2
19:59
16: 4--sv29
19:49
20:42--sv30
20:17--sv 5
19:36
15:56
16: 0
15:23
19:43--sv22
20: 5--sv12
15:40--sv24
19:48--sv 9
19: 7--sv 4
18:50
17:35--sv 6
16:54
16:57
18: 5--sv13
16:16--sv28
17:28
17:34
17:40
16:37--sv26
16:41--sv15
17:57
17:59
18:12
17: 9--sv21
17:50--sv18
35
30
25
-105
-100
-95
-90
-85
cosmic_occt_atmprf.latn (deg North)
cosmic_occt_atmprf.lonn (deg East)
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Number predicted ≠ observed

Most important factors for missed occultations:

- Lack or poor quality of navigation data bits
  - 5 out of 19 occultations
  - Current global coverage is 99% (F. Zus 2011)
- Aircraft turns
  - 3 out of 19 occultations

- One occulting satellite was not acquired in CL tracking, which is required to align navigation data bits to initialize OL tracking
- One occultation was missed since GRS recording was stopped during the occultation

Conclusions

- Quality or absence of navigation data bits and the aircraft turns were the most important factors affecting the number of airborne RO profiles
- With an improved global network providing data bits, 2.8 occultations per hour can be achieved on a straight flight, majority to 1 km height, rising and setting.
- The retrieved refractivity profiles currently have a ~6% N bias and ≤ 1.5% STD relative to ECMWF YOTC reanalysis
- Fourier Spectral Inversion will be needed to improve results (F. Xie IROWG-2 poster presentation)
- B. Murphy will present results from the 2010 PREDICT campaign for investigating the initiation of tropical cyclones at the AMS conference on Hurricanes and Tropical Meteorology in April