DEEPWAVE workshop, Monterey, CA, Dec 2015

GV Sodium and Rayleigh Lidar Update:

Na Density and Wave Studies

Bifford P. Williams, Dave Fritts, Katrina Bossert

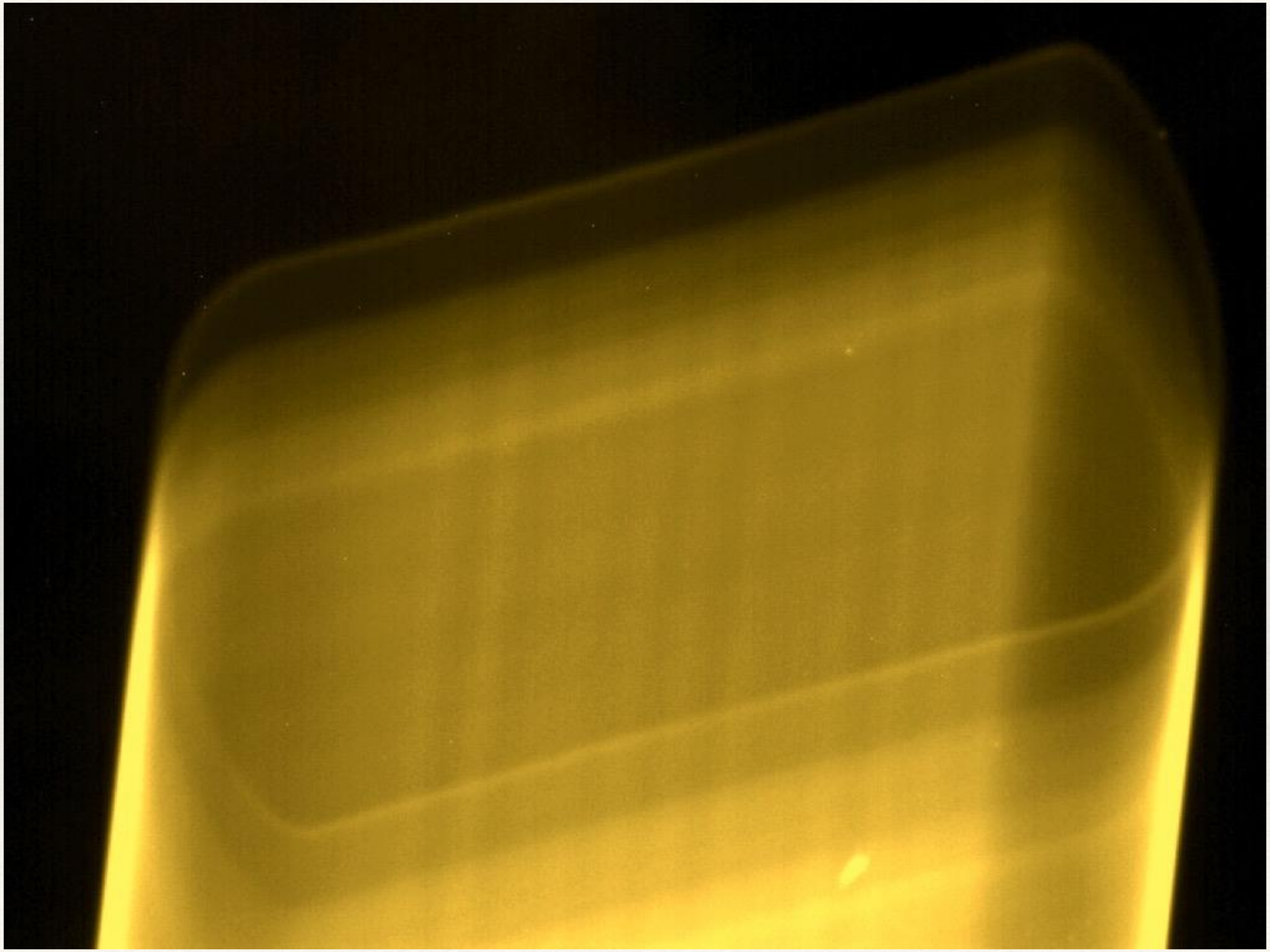
GATS, Inc. , Boulder, Colorado

Plus many collaborators at NCAR, USU, DLR, NRL, Yale, and other institutes and support from NSF AGS-1338646 and AGS-1261619

Outline

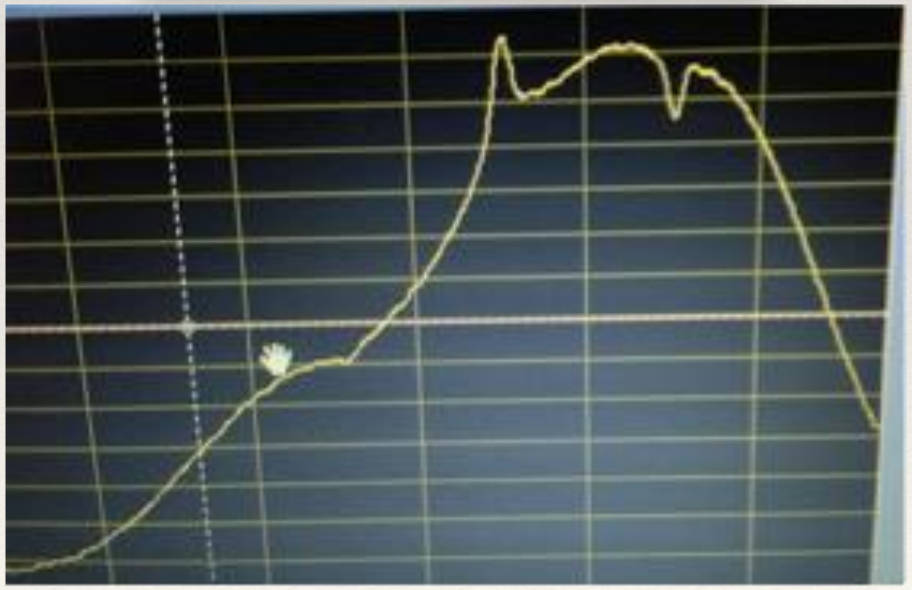
1. Technical update:
   - Scanning Na beam vs pulsed beam
2. Na density results:
   - Sodium density vs latitude (31° S to 64° S)
   - Sodium descending layers from mountain waves
   - Sodium layer descent due to trailing waves over ocean
3. Mountain waves
   1. RF26
   2. RF22
   3. RF04
4. Southern Ocean (if Andreas doesn’t show)
   1. Amplitudes during RF25

Section 1: Scanning vs Pulsed Na Measurements



GV Na Lidar: A High Spectral Resolution Lidar

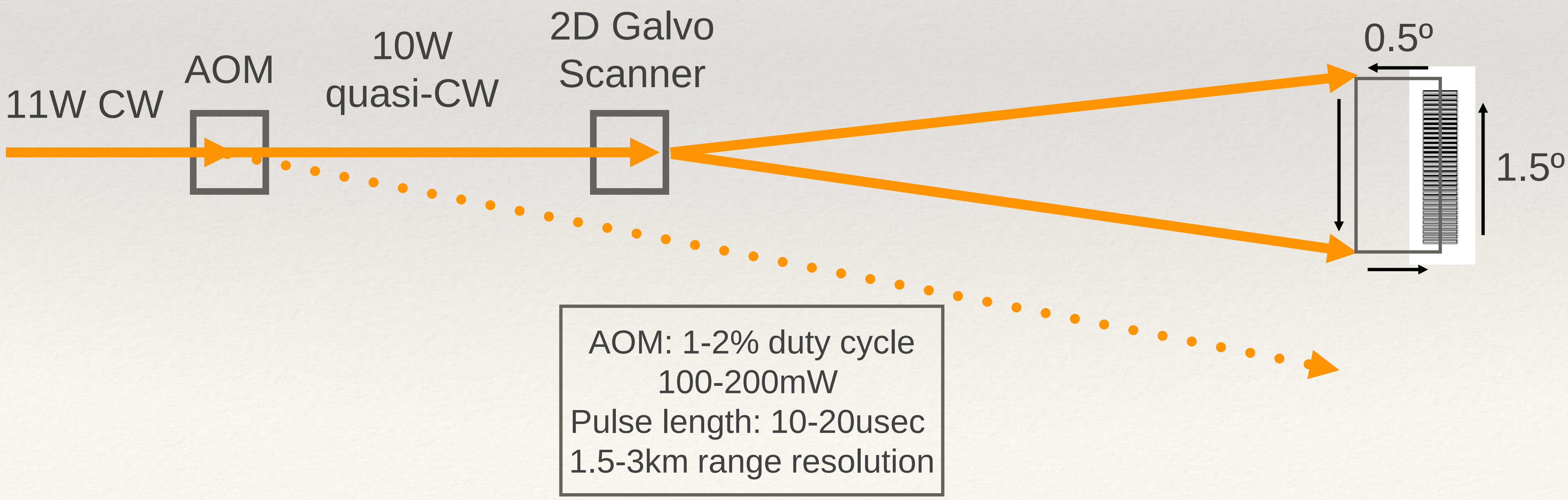
- The sodium laser (Toptica DL-RFA-SHG) produces 11W CW power at the Na D2 line at 589nm using a standard IR seeder, a new Raman fiber amplifier, and a standard doubling cavity
- Doppler-Free spectroscopy uses a Na vapor cell to lock output beam to 2 known frequencies
- Ratio of atmospheric Na scattering at two frequencies (D2a and crossover) is proportional to temperature – the two-frequency method used for any years at CSU
- System has AO frequency shifter to add 3rd frequency for winds, but not used during DEEPWAVE
- 10MHz line width (10x less than other Na systems)
- Laser can scan 10GHz/sec with no mode hops
- Laser only needs optical adjustment every ~3-6 months with little or no adjustment needed between flights
- Small, very efficient, can be automated in future, much easier to operate than current Na systems

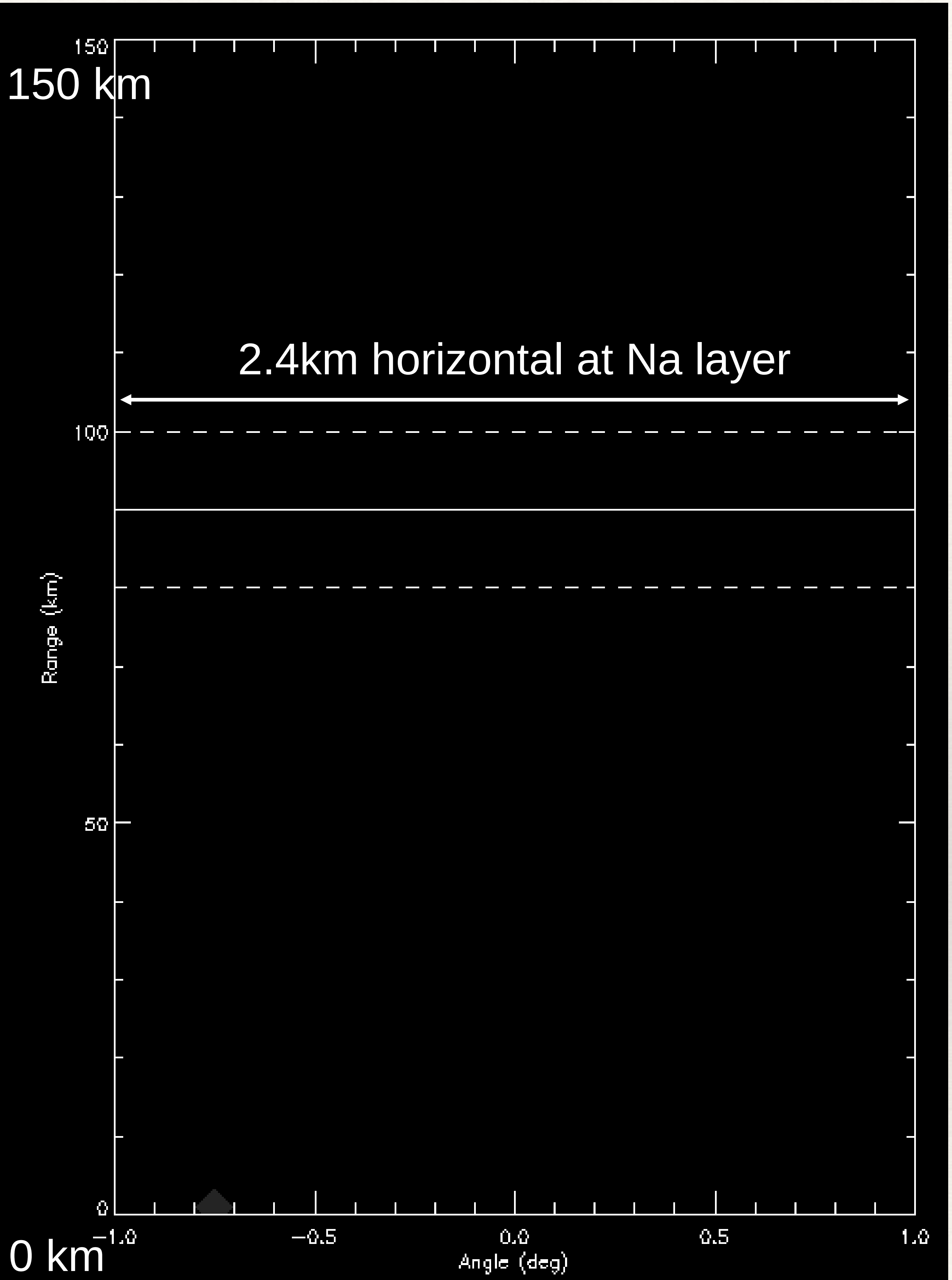


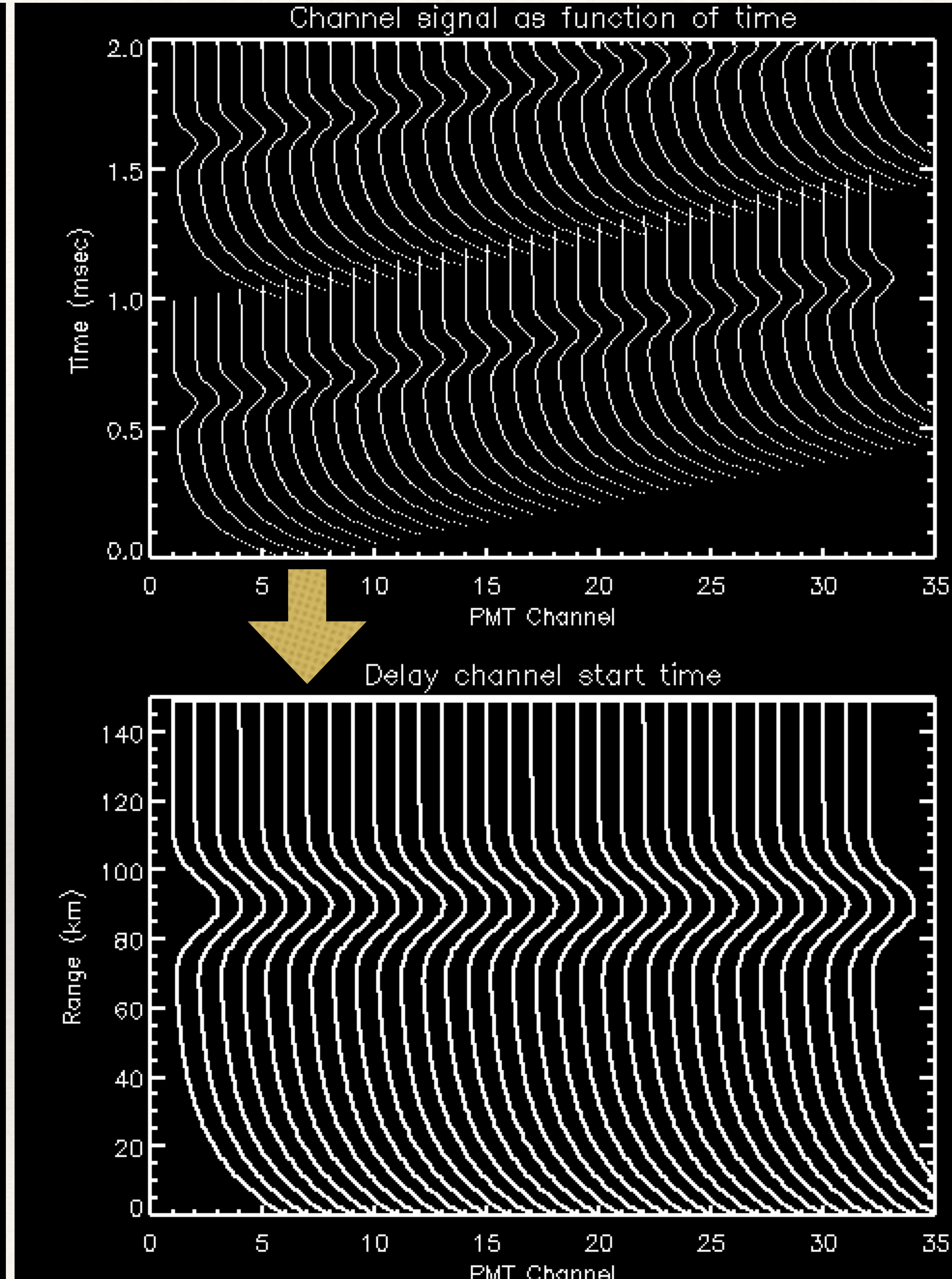
Na Doppler-Free spectrum in flight, 1 sec scan

Pulsed and Scanning Beams

- Na lidar uses two techniques to obtain range-resolution with a 11W CW laser:
  - Amplitude modulation with an acousto-optic crystal
  - Angle modulation via high speed scanner.
- 11W beam is divided into two beams:
  - Pulsed beam: Acousto-optic modulator makes a 150mW pulsed beam at 2% duty cycle and 1kHz pulse repetition rate. Full range 150km, range resolution: 3km (full width)
  - 10W beam scanned in 1.50º rectangle repeating at 1kHz, full range 150km, range resolution 3km (FWHM) using a commercial 70,000 point-per-second galvo scanner

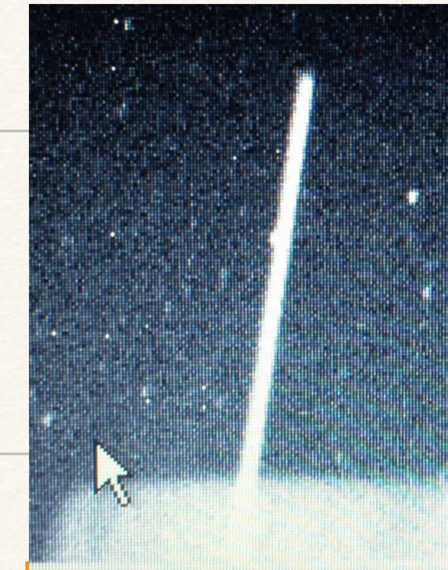




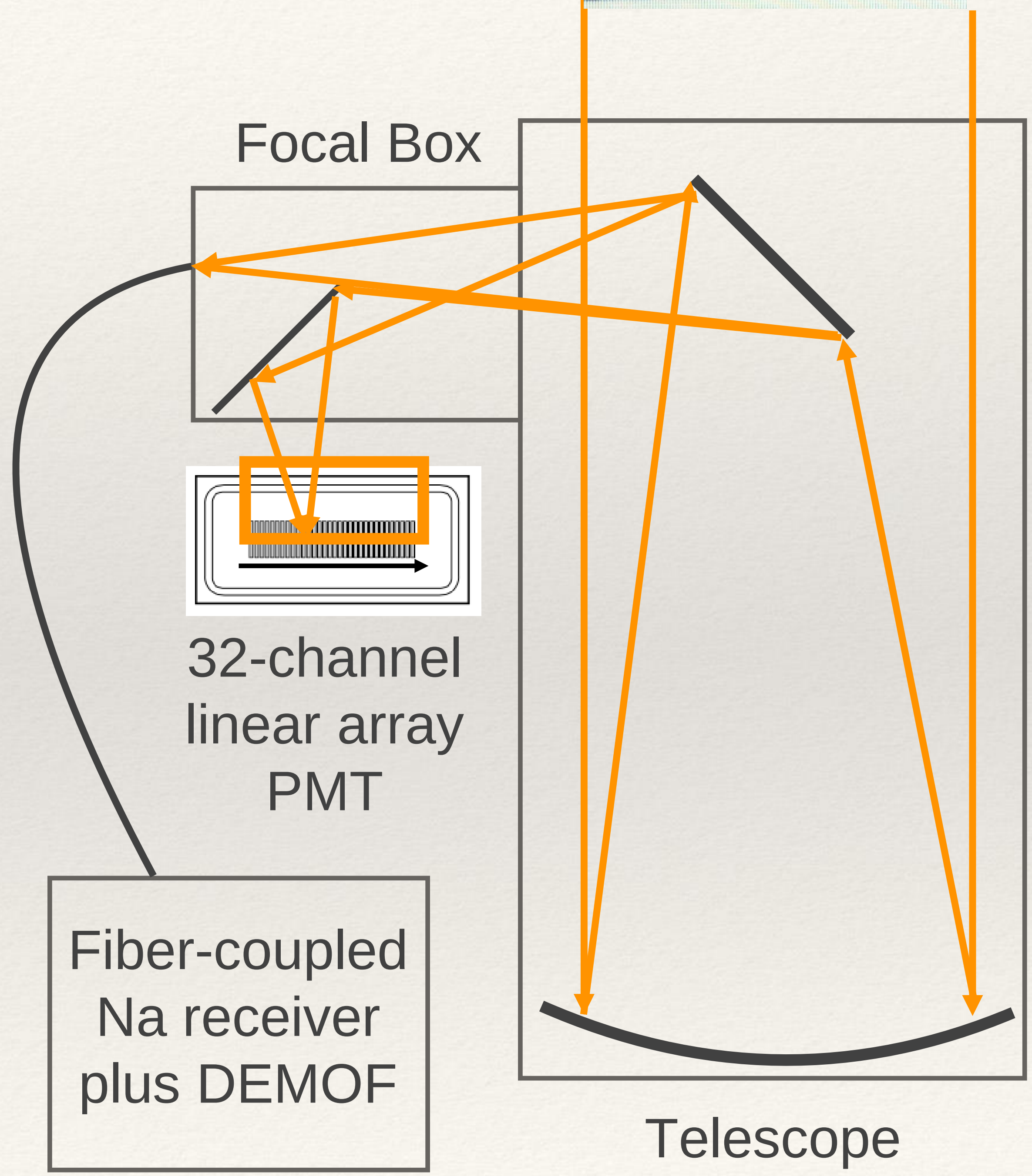


Scan direction

Na Receiver

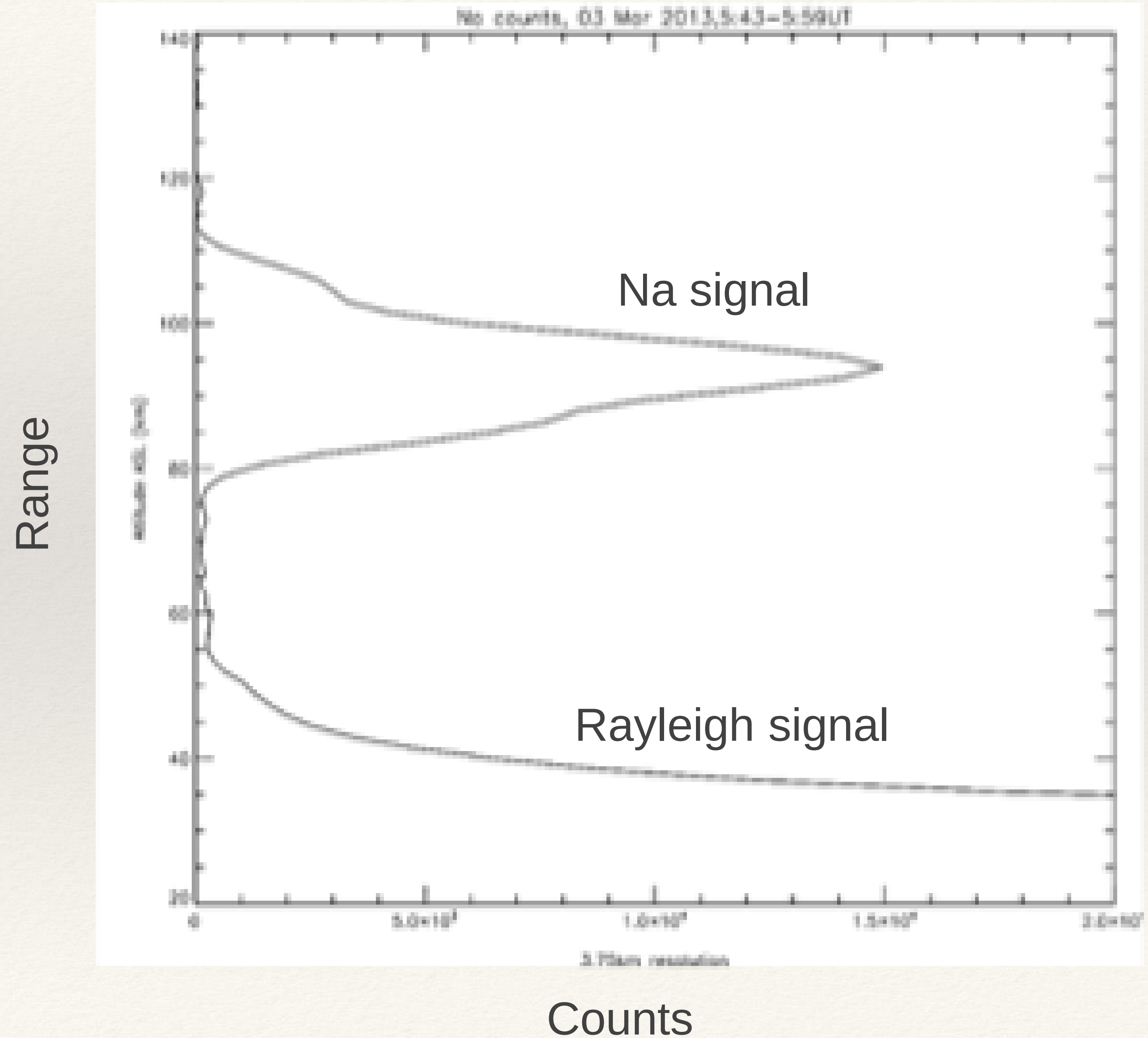


- 30cm diameter f/4 Newtonian telescope
- **Pulsed beam uses exact same fiber coupled receiver (40% PMT, filter) as some of the current Na lidars**
- Resolution: Raw data: 1 sec hor, 37m vert. binned to 20 sec, 3km
- Scanned beam: the forward scan edge is aligned with a new 32 channel PMT with an integrated 32 channel counter board
- Each of the 32 PMT channels sees a pulsed 150mW profile staggered in time
- On airplane: Add 32 profiles to get better SNR and time resolution

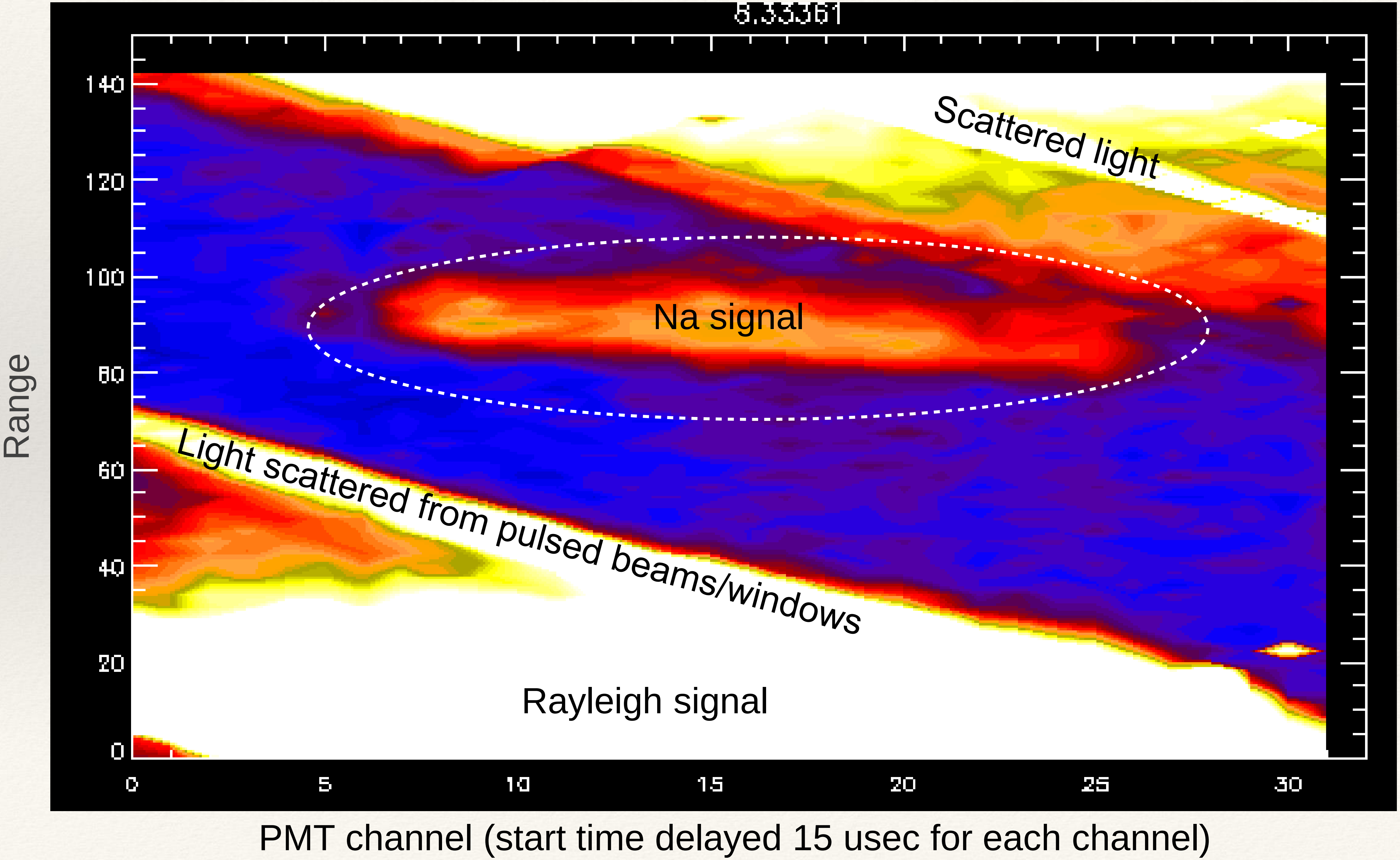


Example Pulsed Beam Profile

- Pulsed beam return profile is the same as normal Na lidar
- Flying at 12km:
  - $1/r^2$ advantage, especially in Rayleigh signal
  - very dark sky, reduced scattering from moon, stars, etc. into FOV
- Background about 3x higher than 30Hz ground based system

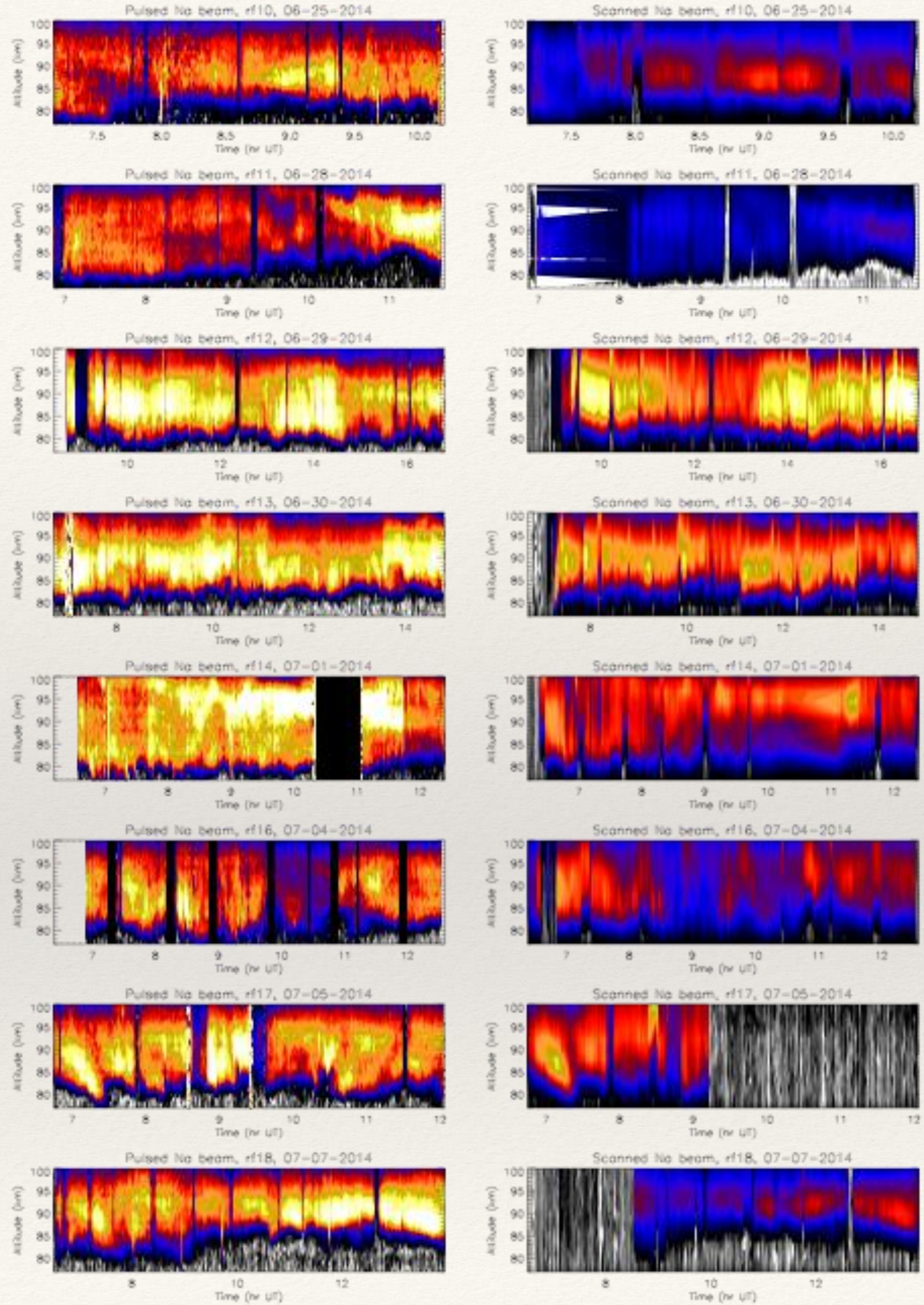


32 channel raw data: RF10, 3 sec integration

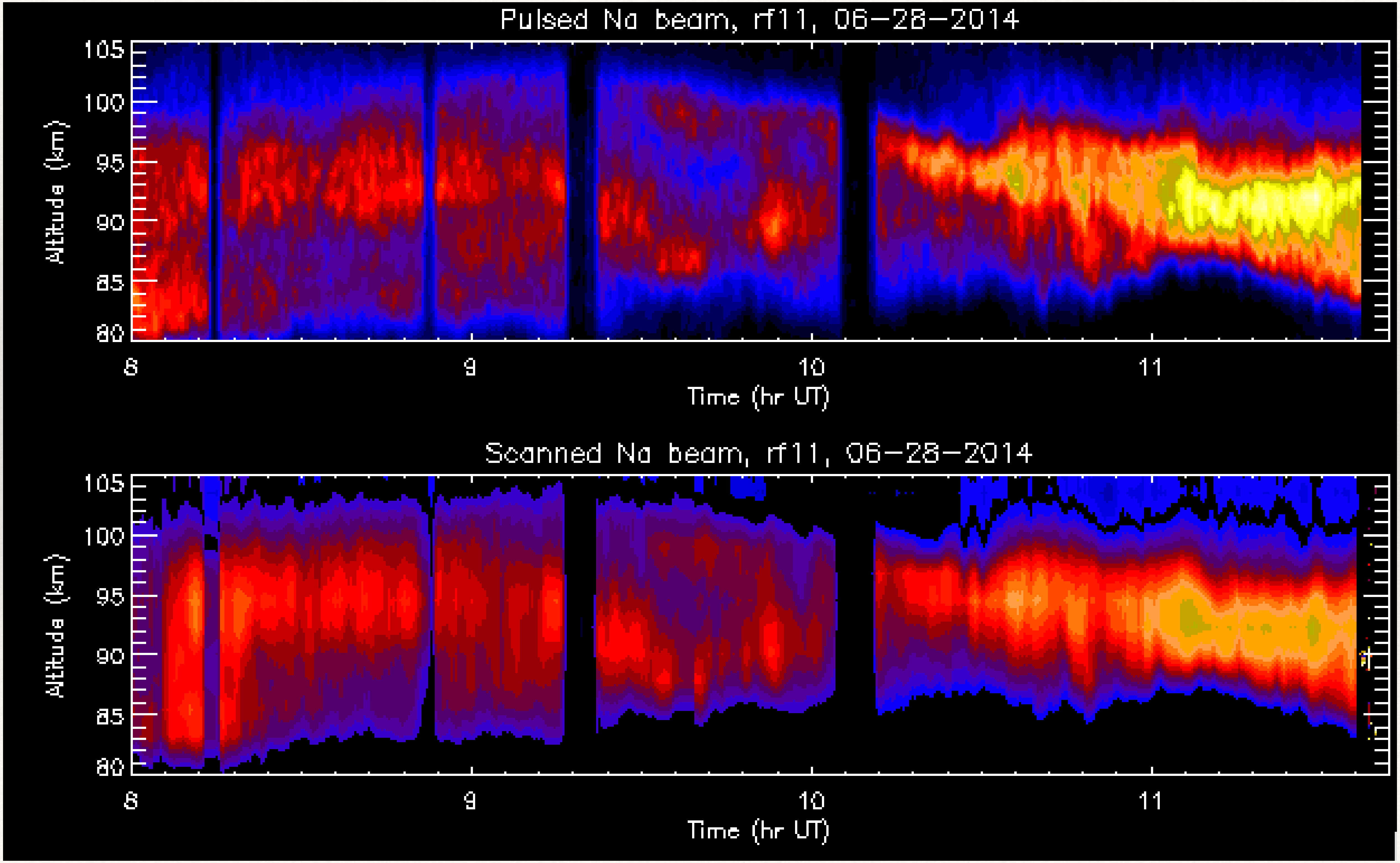


Pulsed (left) vs Scanned (right) RF10-RF18

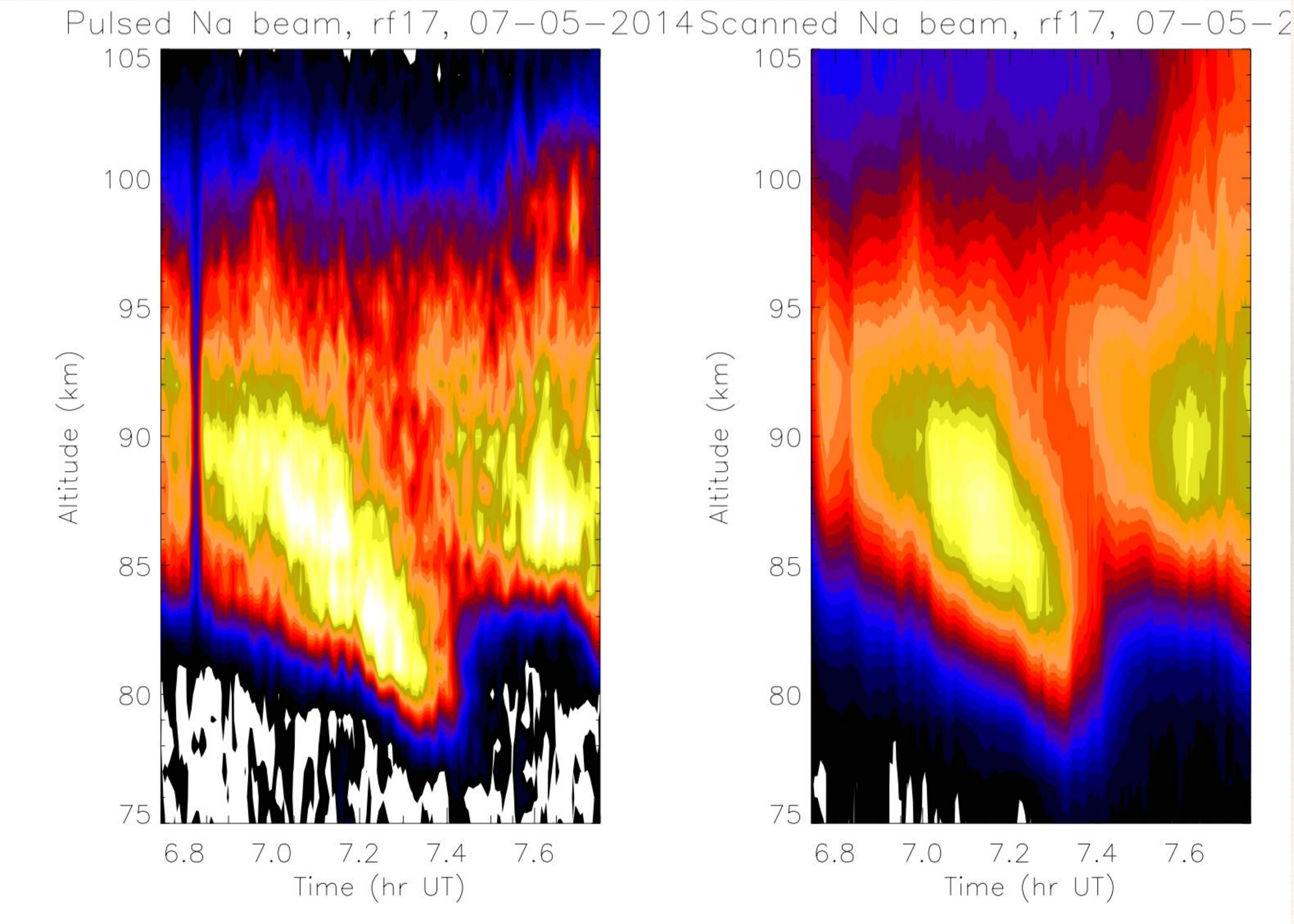
- Raw signal, not calibrated for Na density yet
- Scanned beam was 3rd priority for operator
  - Lost alignment more than pulsed beam
  - sometimes got aligned later than other beams
  - more signal variation
- Need to improve control software before next aircraft campaign



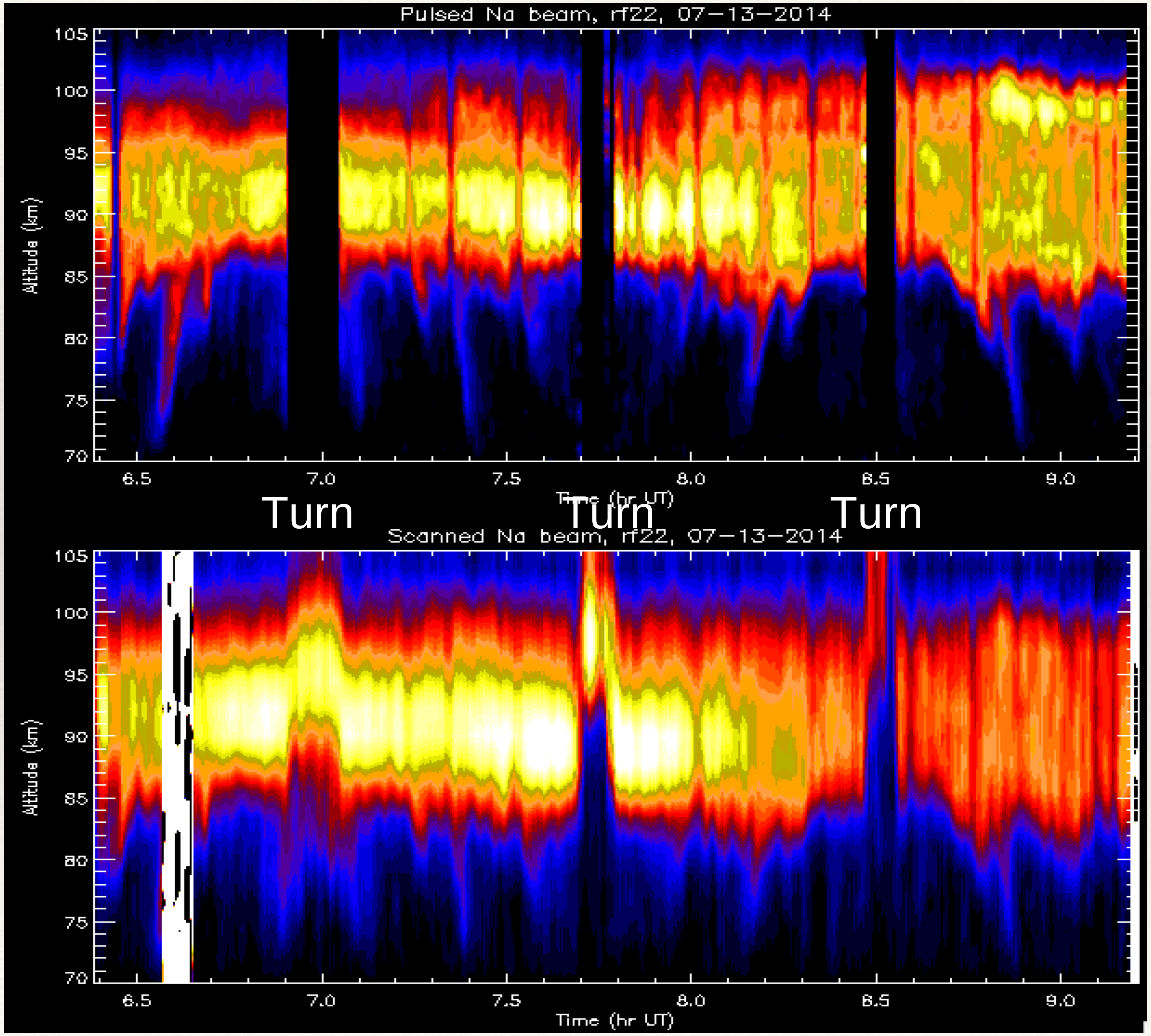
Pulsed vs. scanned, RF11



Pulsed vs. scanned, RF17



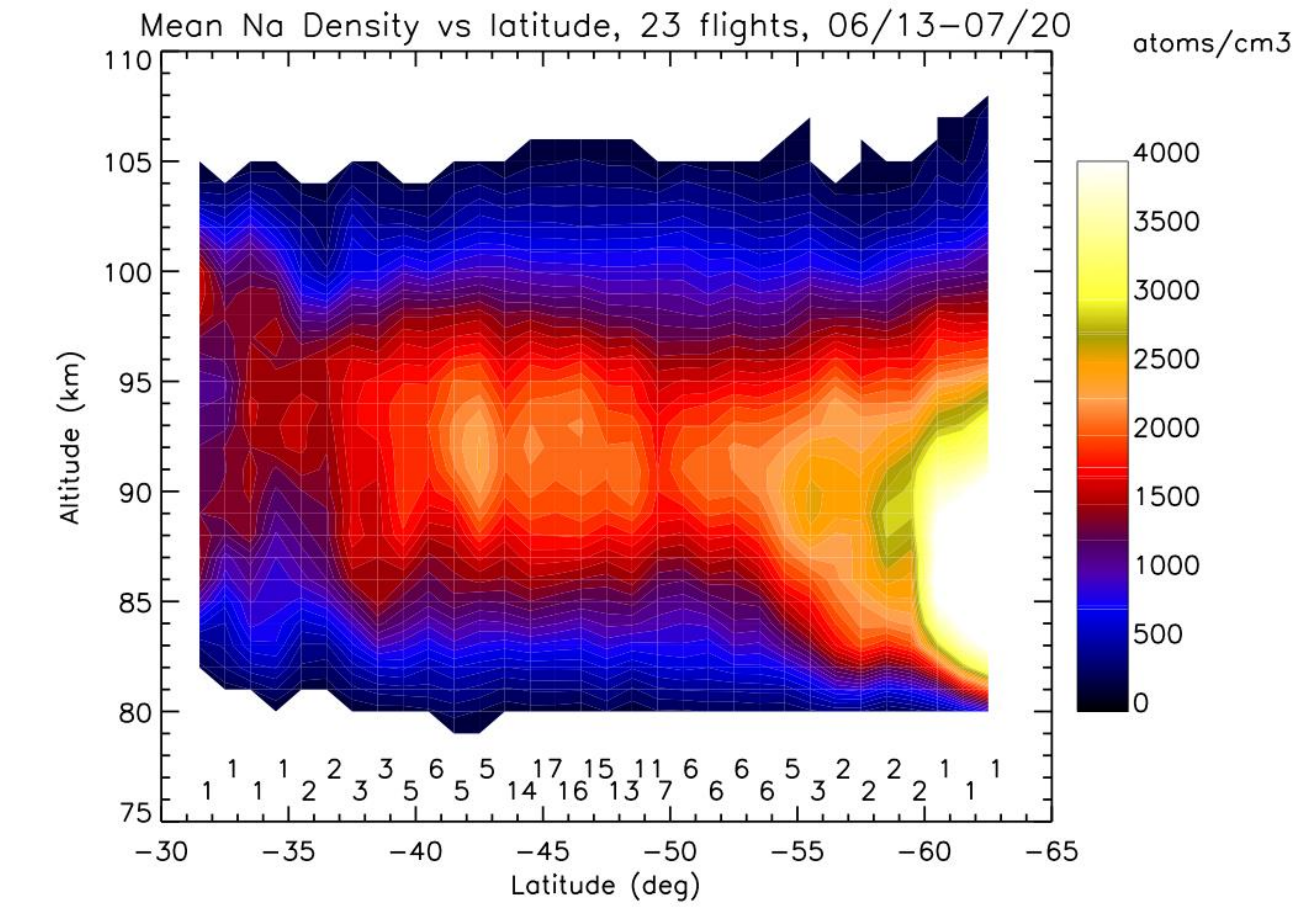
Pulsed vs. scanned, RF22



Scanning Na Conclusions

- Pulsed and scanned beams measured same Na layer shape and vertical motion
- When airplane rolls, the increased range to the Na layer is accurately measured
  - Scanned beam had slightly worse altitude resolution than pulsed, can be improved by adding more channels in the detector (about $1k/channel)
- When aligned well, the scanned beam received ~5 times more photons from sodium layer than pulsed beam with same altitude resolution
  - 50 times possible with better detector and better alignment
- This scanning technique can be used with any CW laser to add range resolution without adding significant size, weight or cost -> good for mobile platforms
  - CW lasers are usually much smaller, more efficient, and have ~10 times better spectral resolution and stability than pulsed lasers
  - High power CW lasers available for almost all frequencies in the IR, visible, and UV (with doubling, etc.)

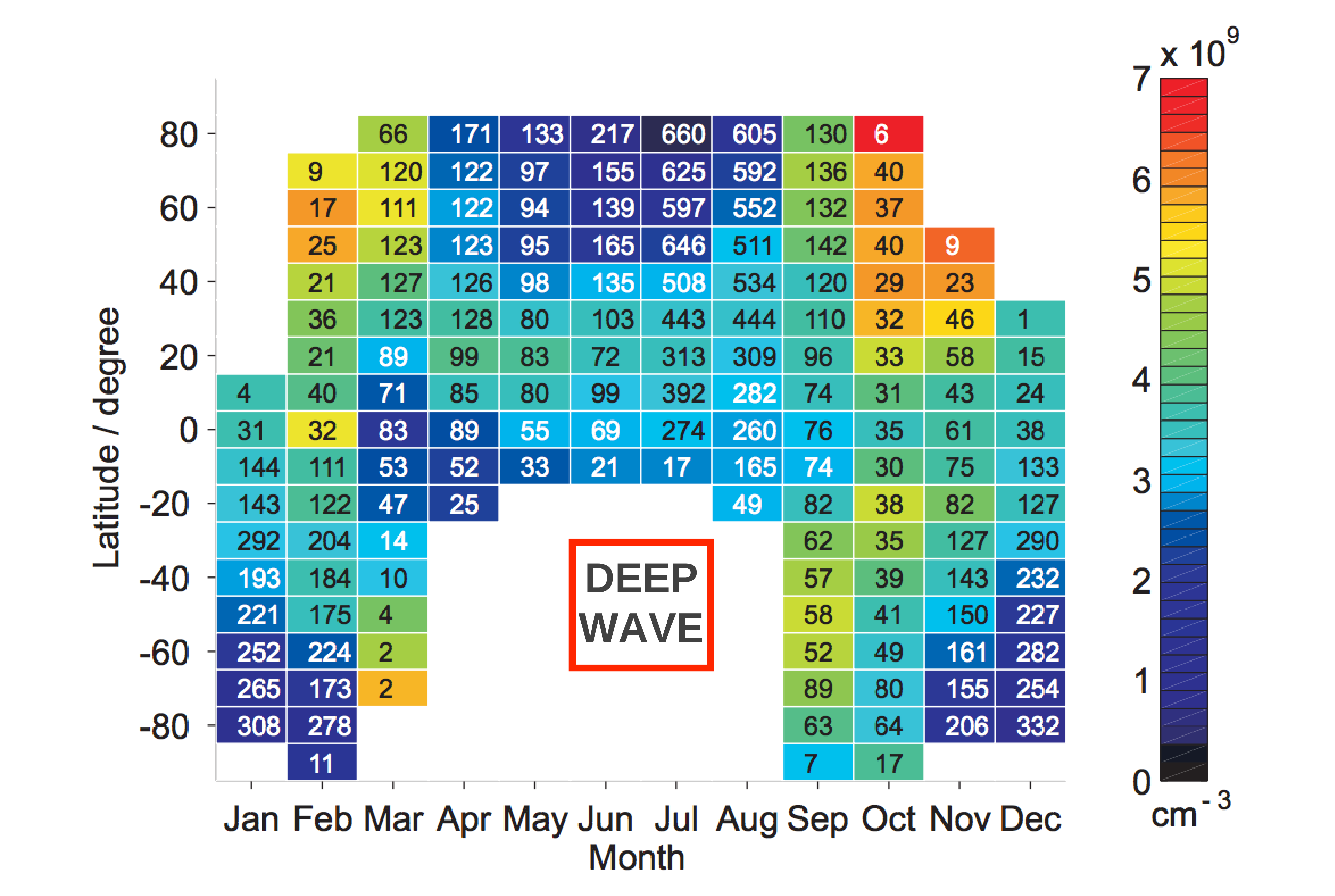
Section 2: Na Density Validation and Science Results



Prior Na Measurements in Southern Hemisphere

- São José dos Campos: 23° S, 46° W
- Andes Lidar Observatory: 30° S, 71° W
- **DEEPWAVE: 31° S to 63° S, 144° E to 184° E**
- Syowa Station: 69° S, 39° E
- South Pole Station: 90° S
- ODIN/OSIRIS: Almost global coverage except for southern hemisphere winter and smaller gap in NW winter
- SCIAMACHY satellite: global

ODIN/OSIRIS Na Abundance



SCIAMACHY Na Abundance

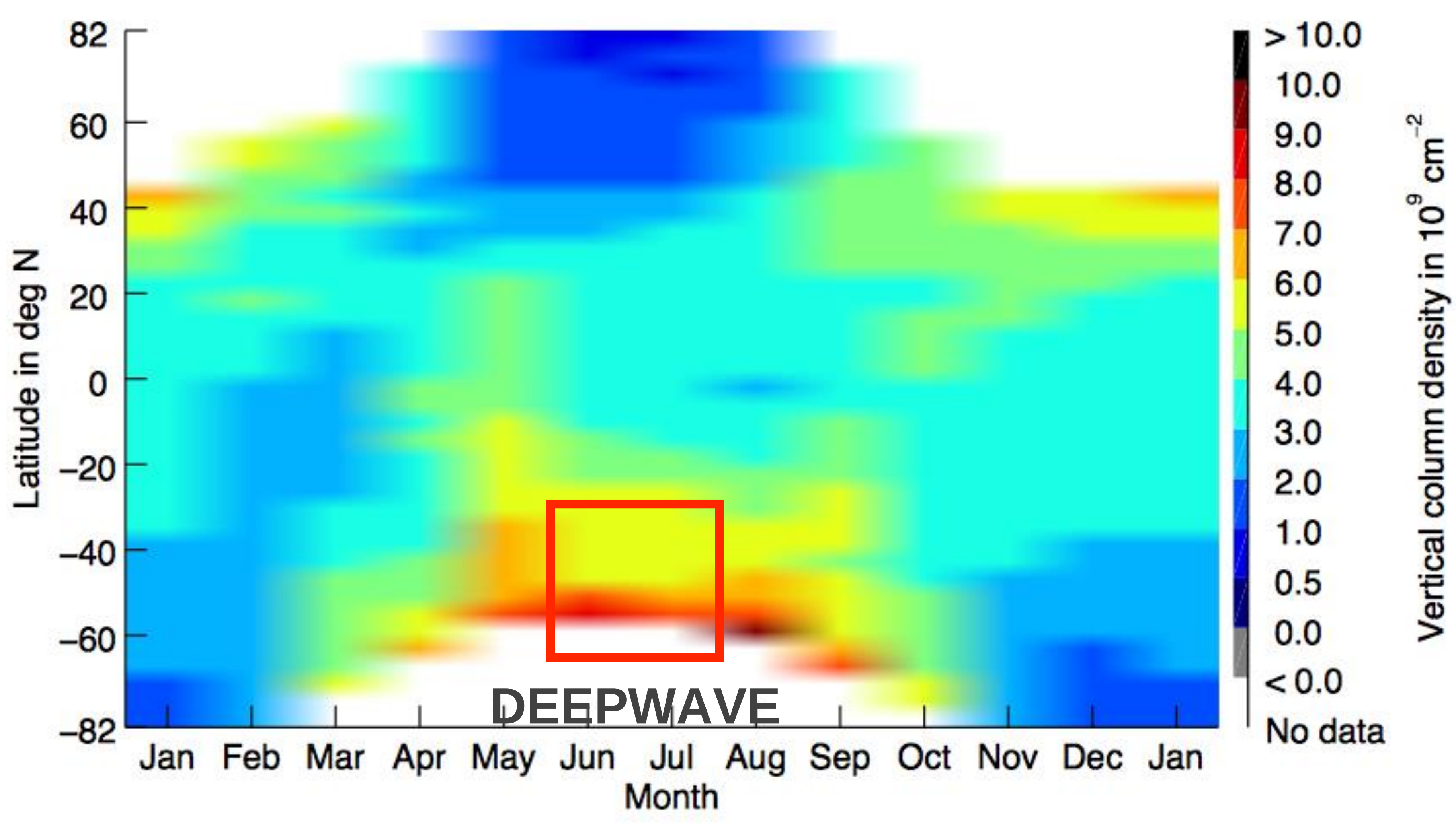
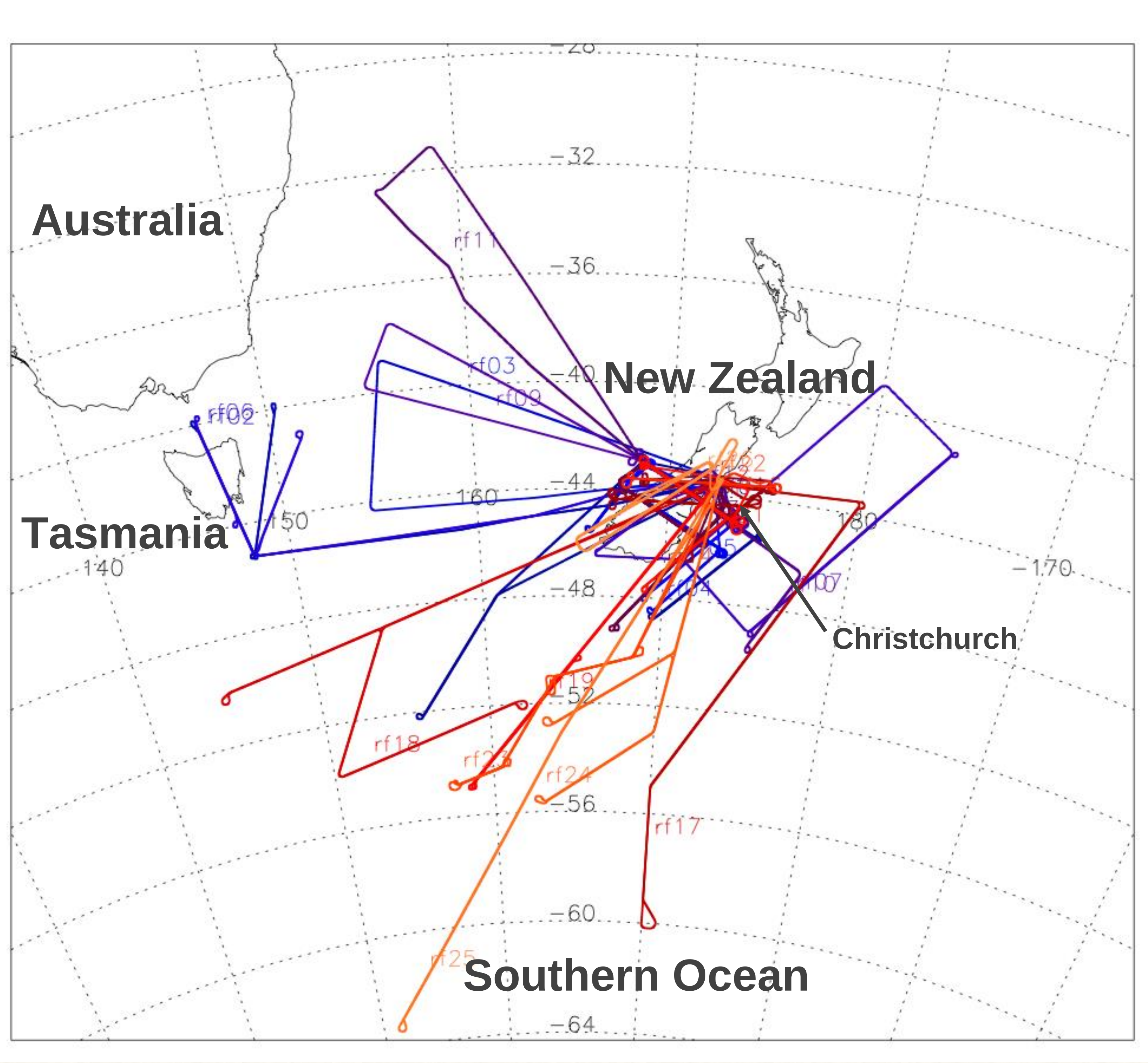
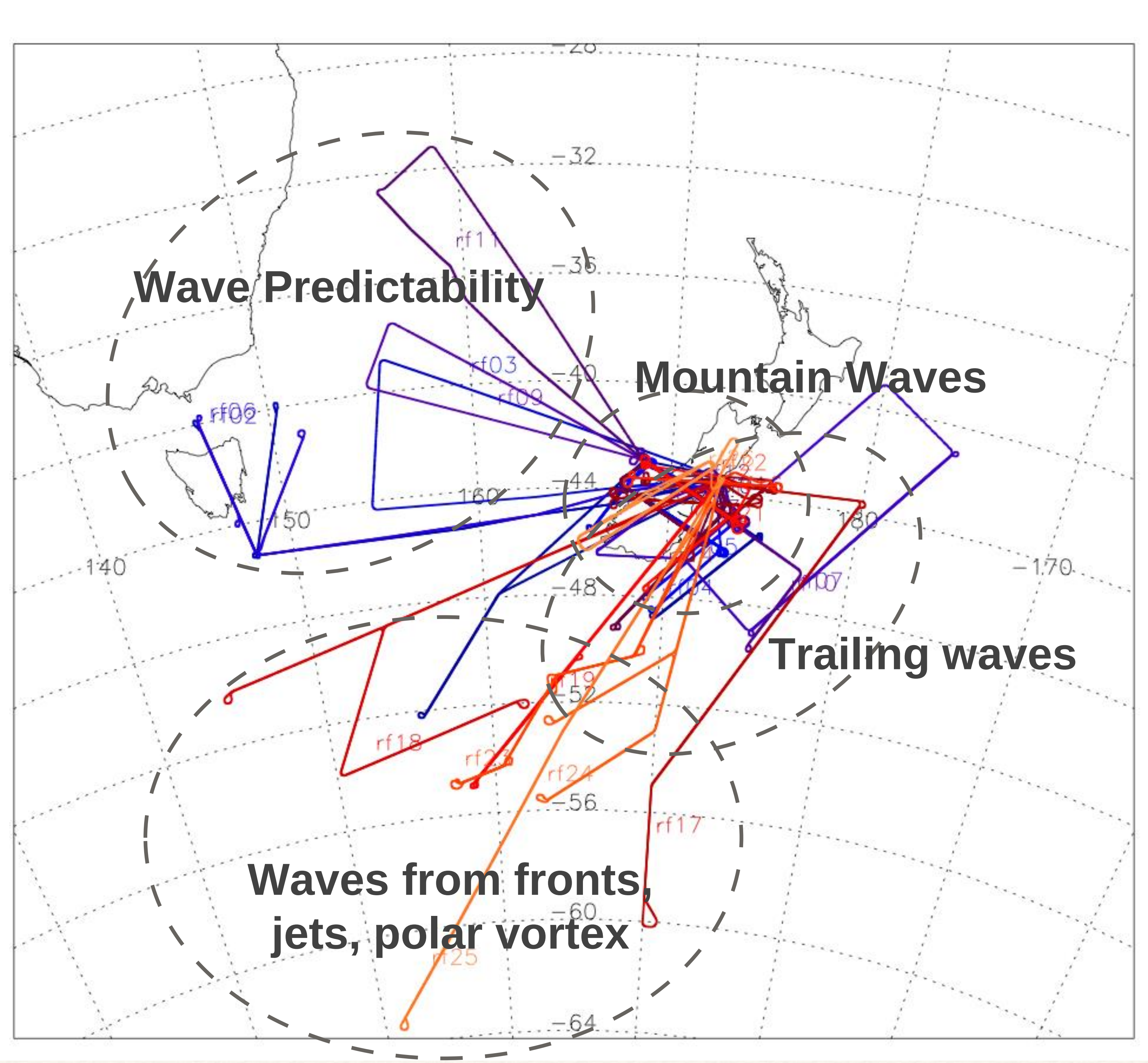


Figure 15. Seasonal variation of the vertical Na column densities (VCDs).

Geographic Coverage: Flight Paths

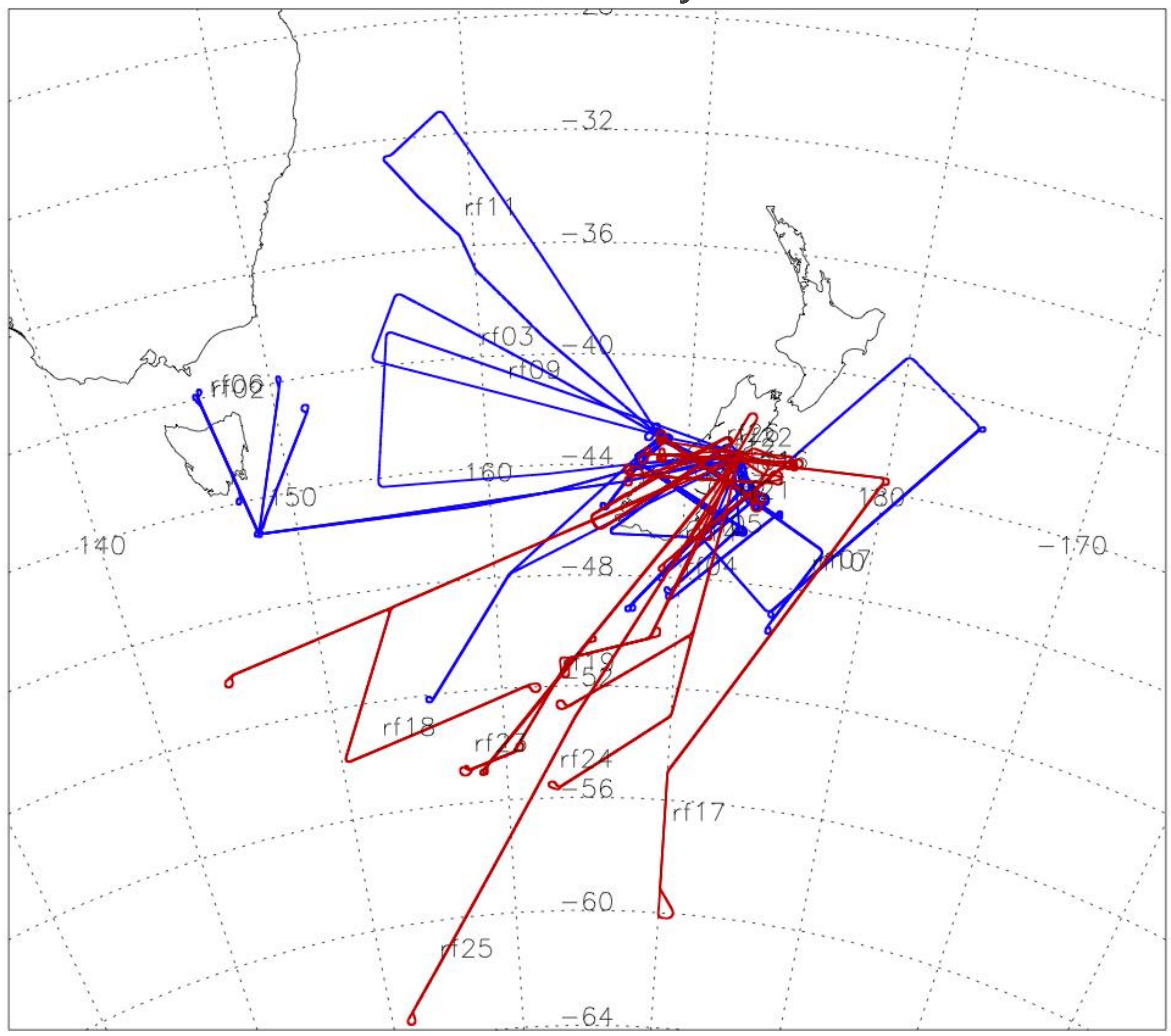


Geographic Coverage: Science Targets



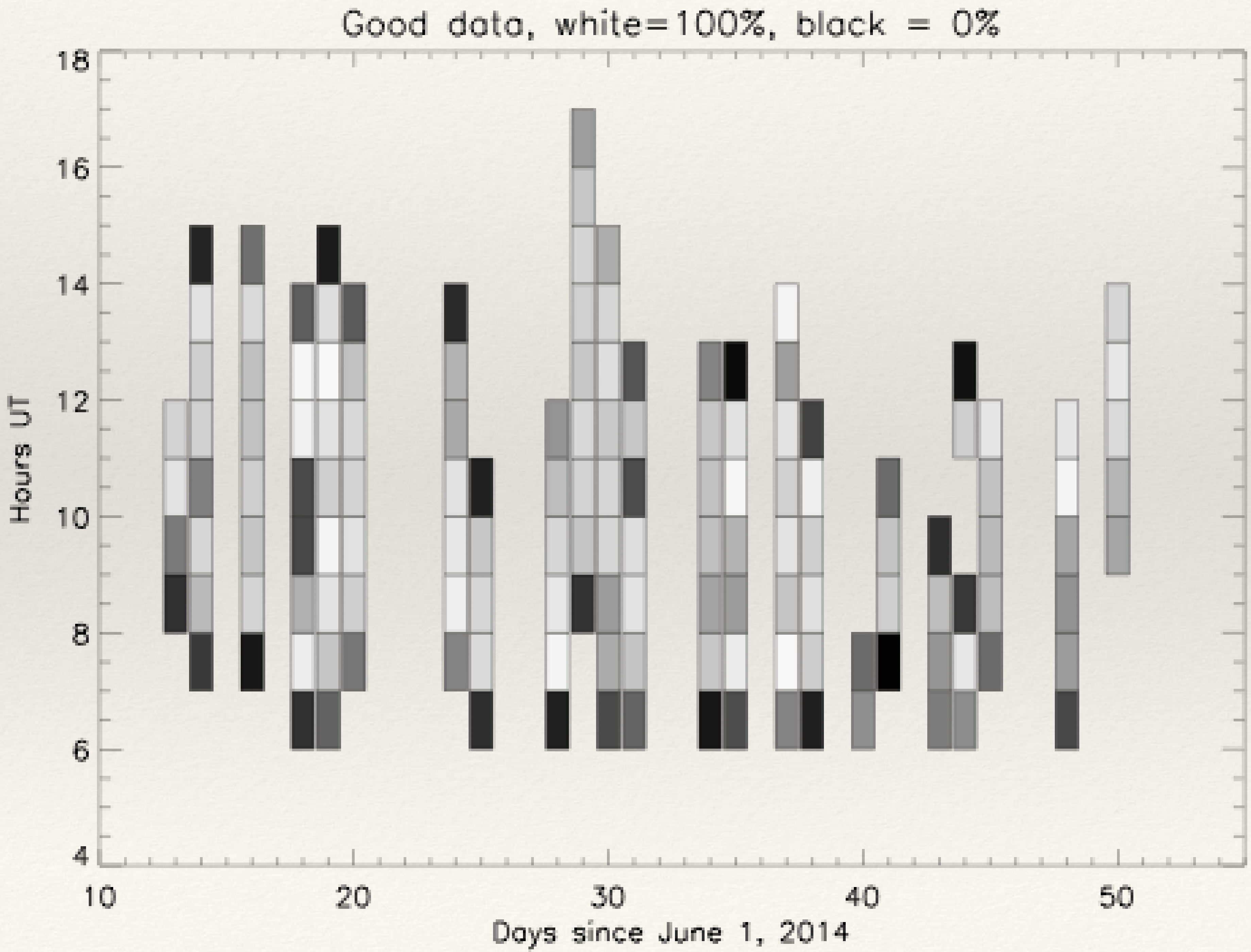
Geographic Coverage: June/July

June 2014: blue, July 2014: red

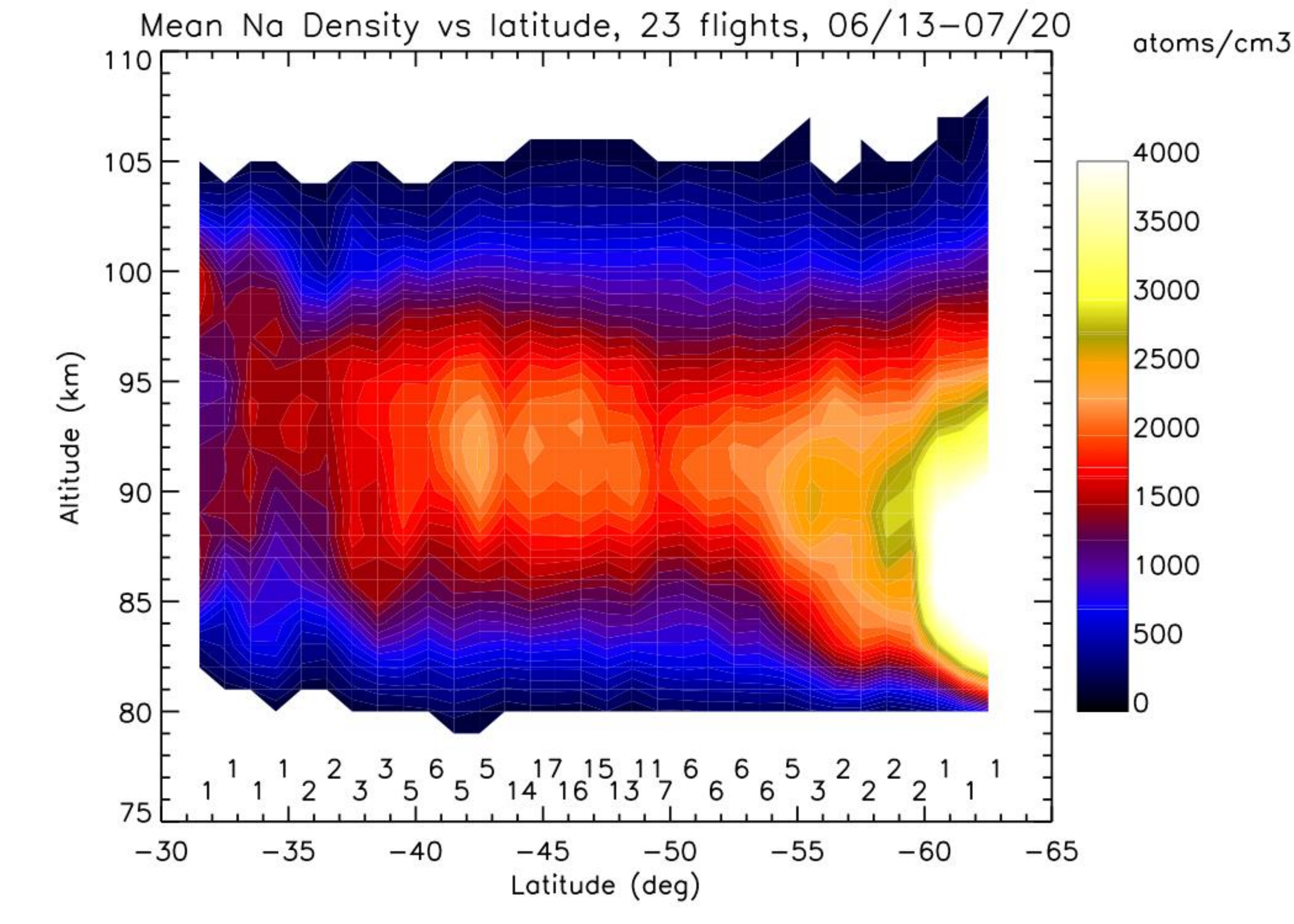


Seasonal/Time (UT) Coverage

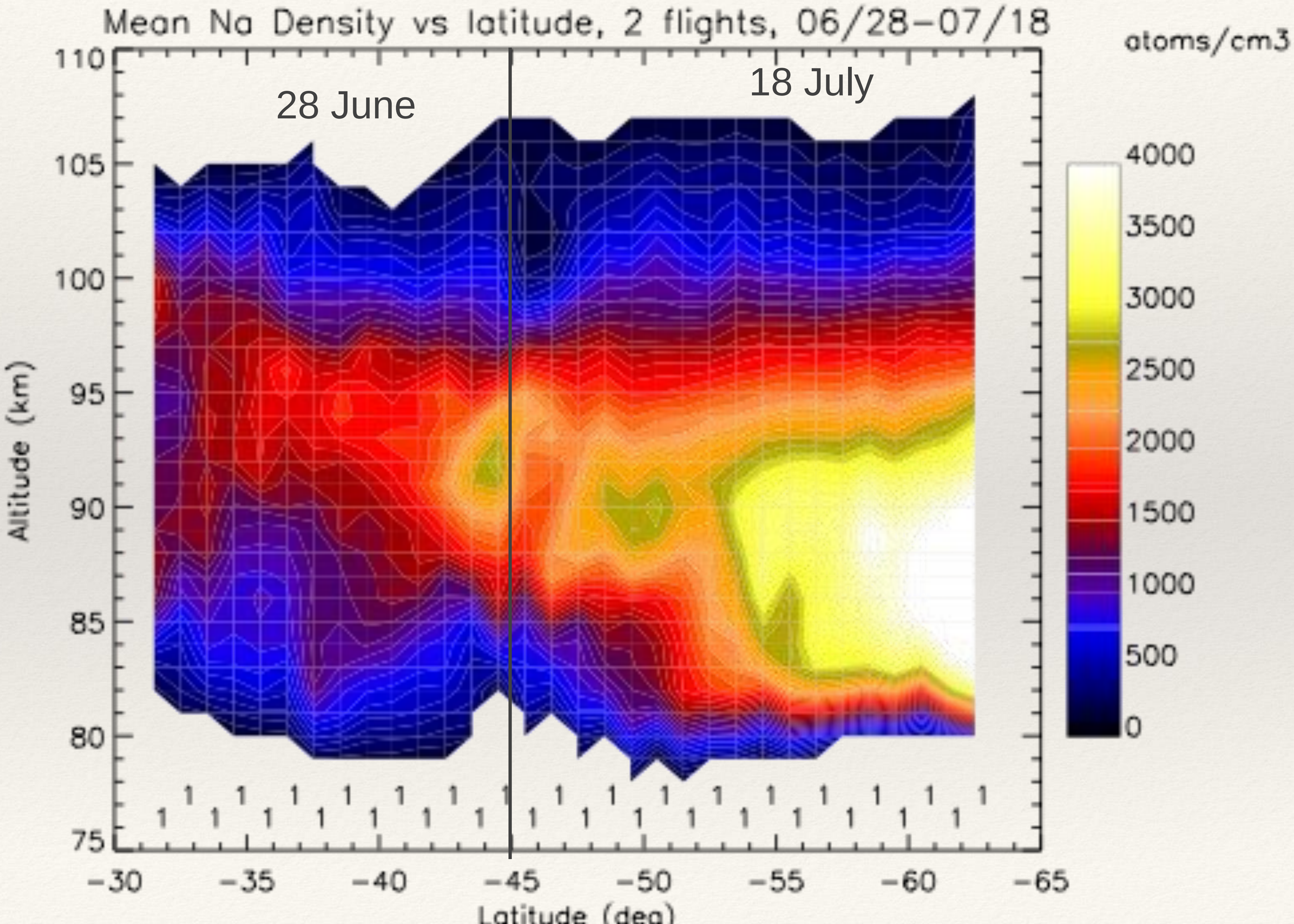
% coverage within each hour: 144 total hours, 130 hours with >40 profiles/hr



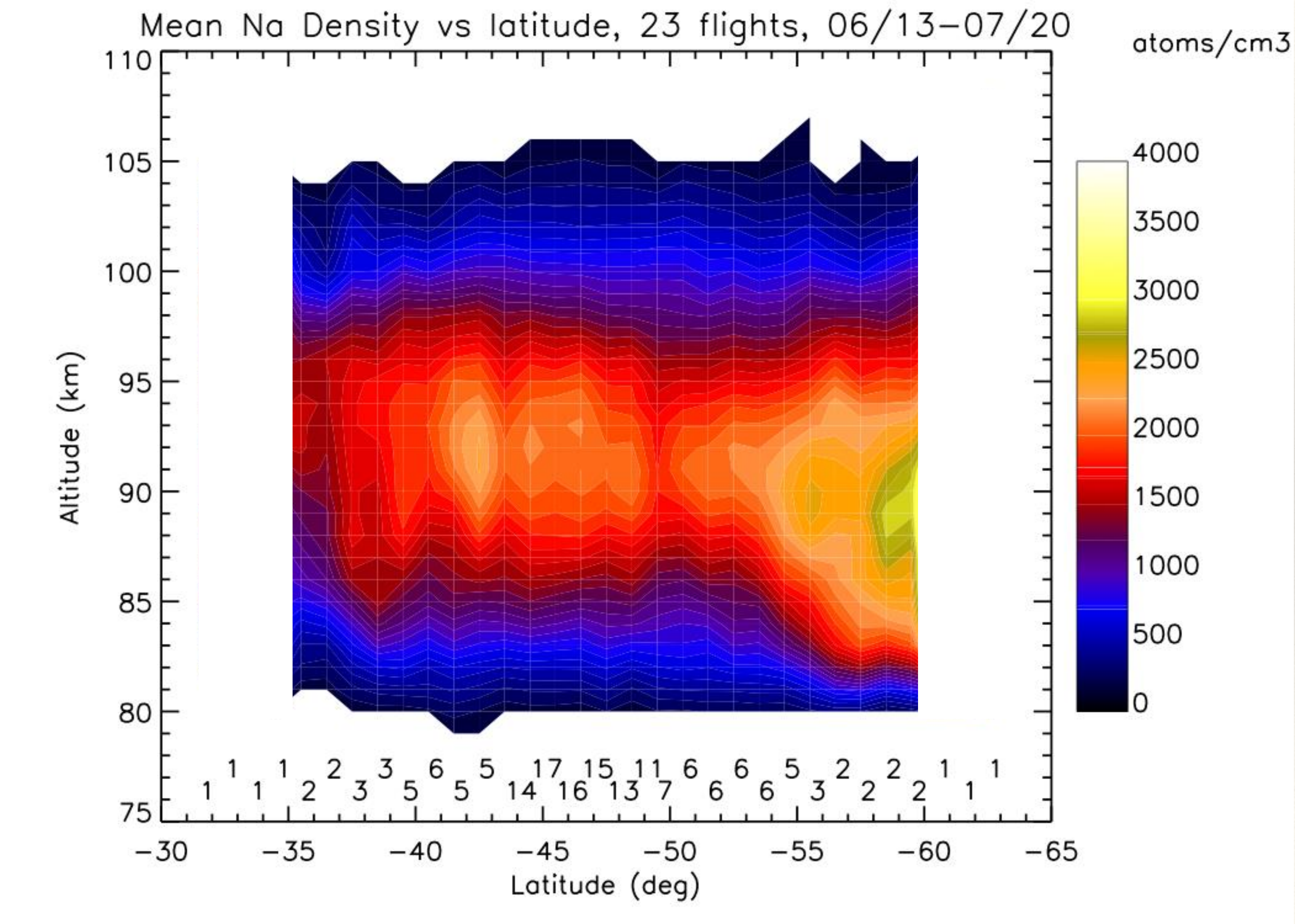
Na Density vs Latitude



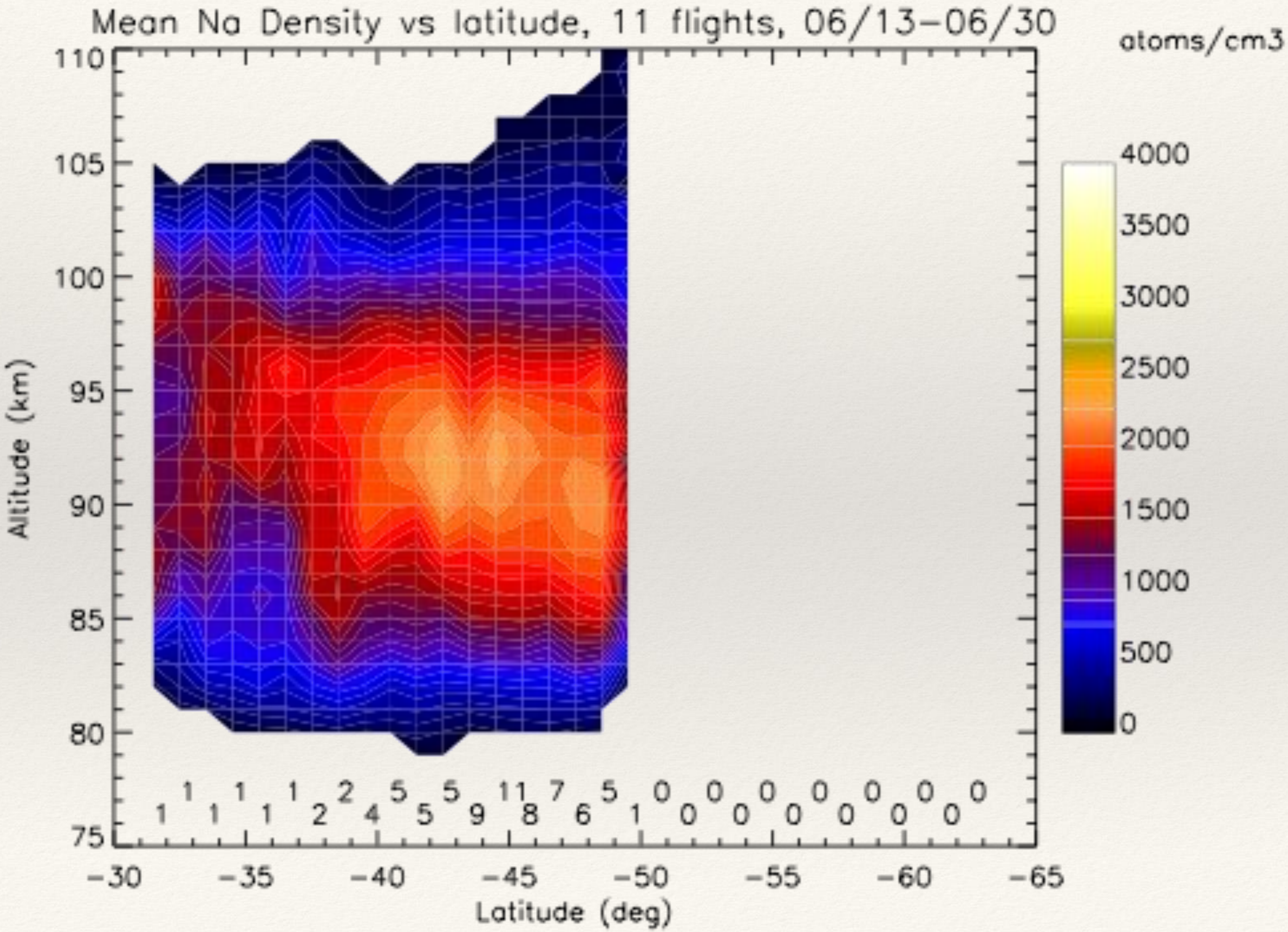
Na Density vs Latitude: two longest flights



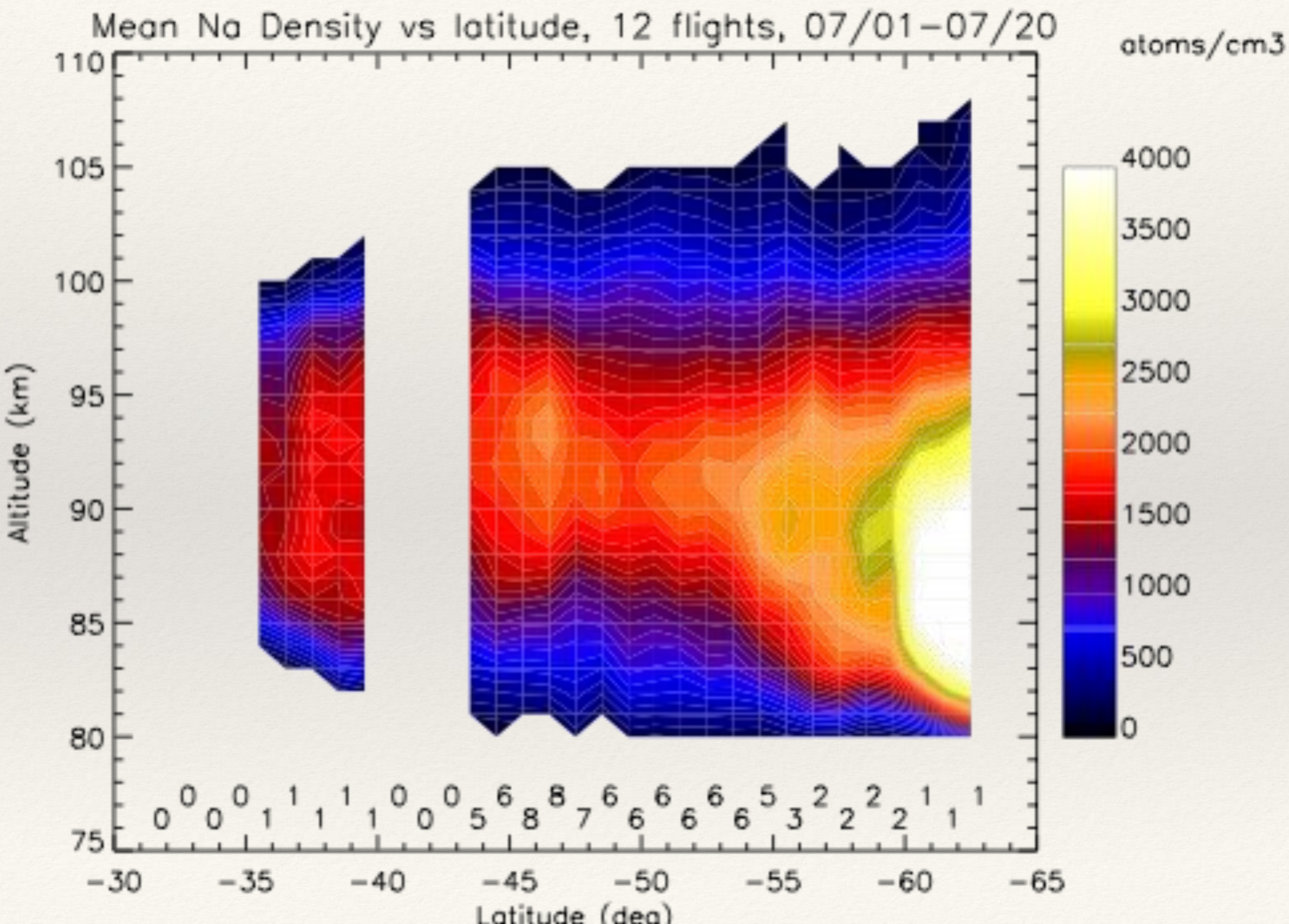
Na Density vs Latitude



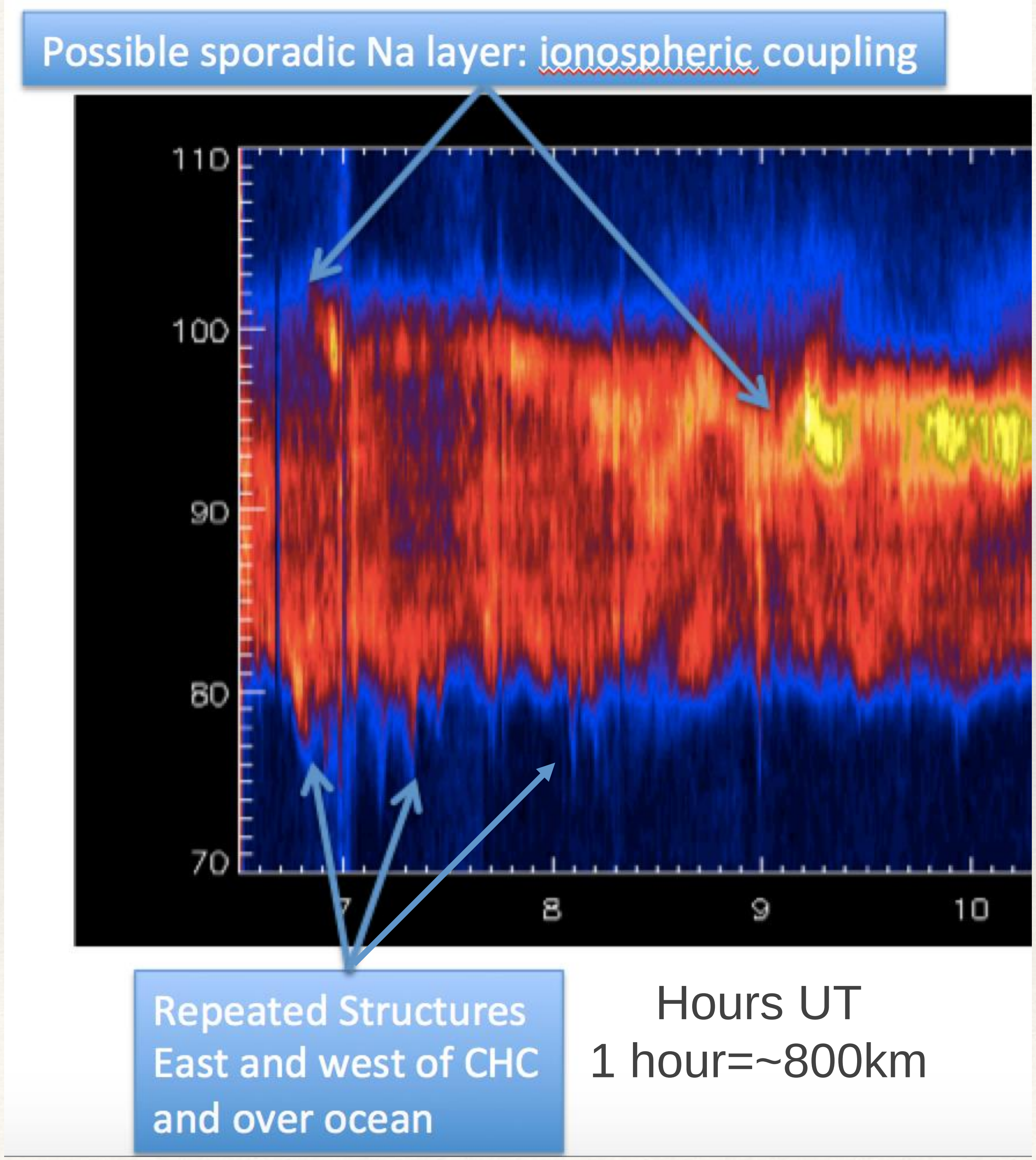
Na Density vs Latitude: June

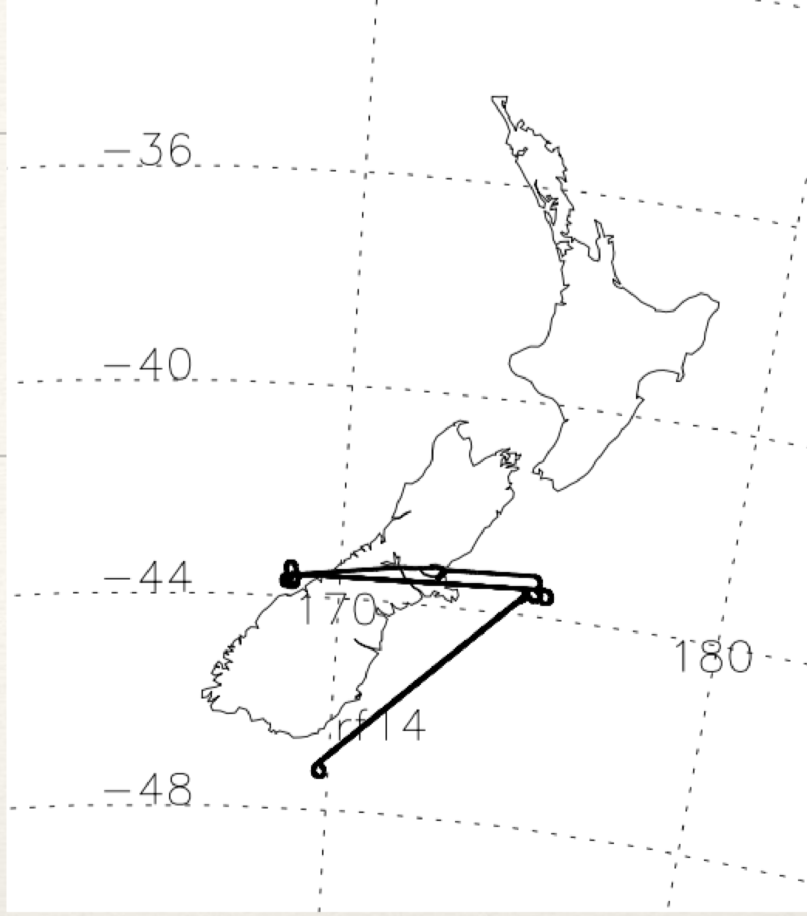


Na Density vs Latitude: July



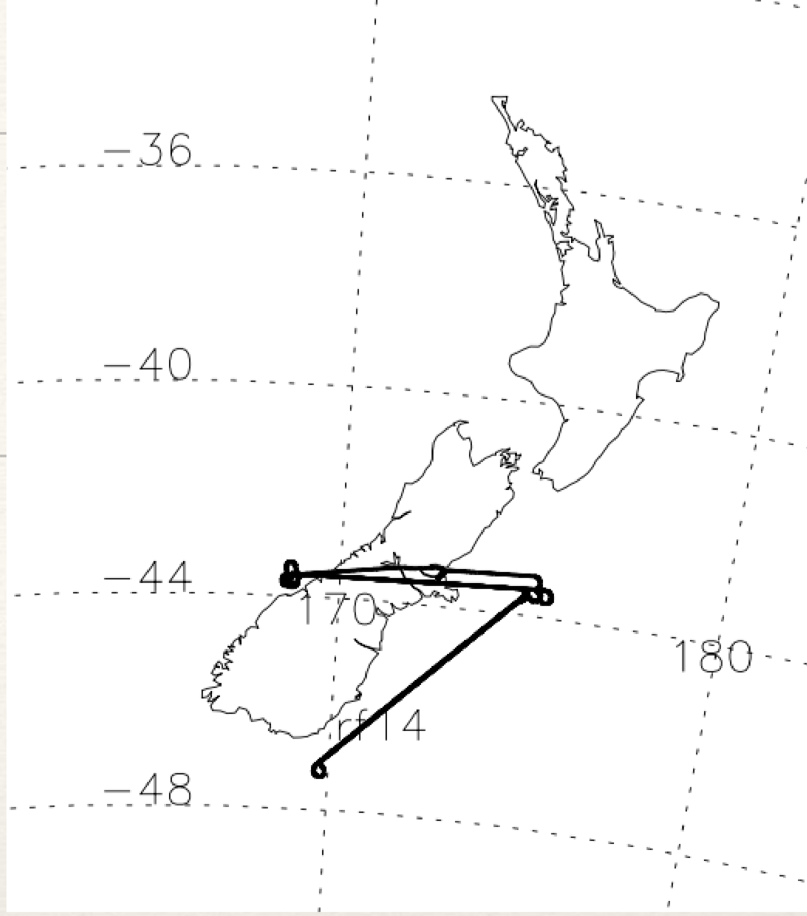
RF14, 01 July 2014: Sporadic Na layer





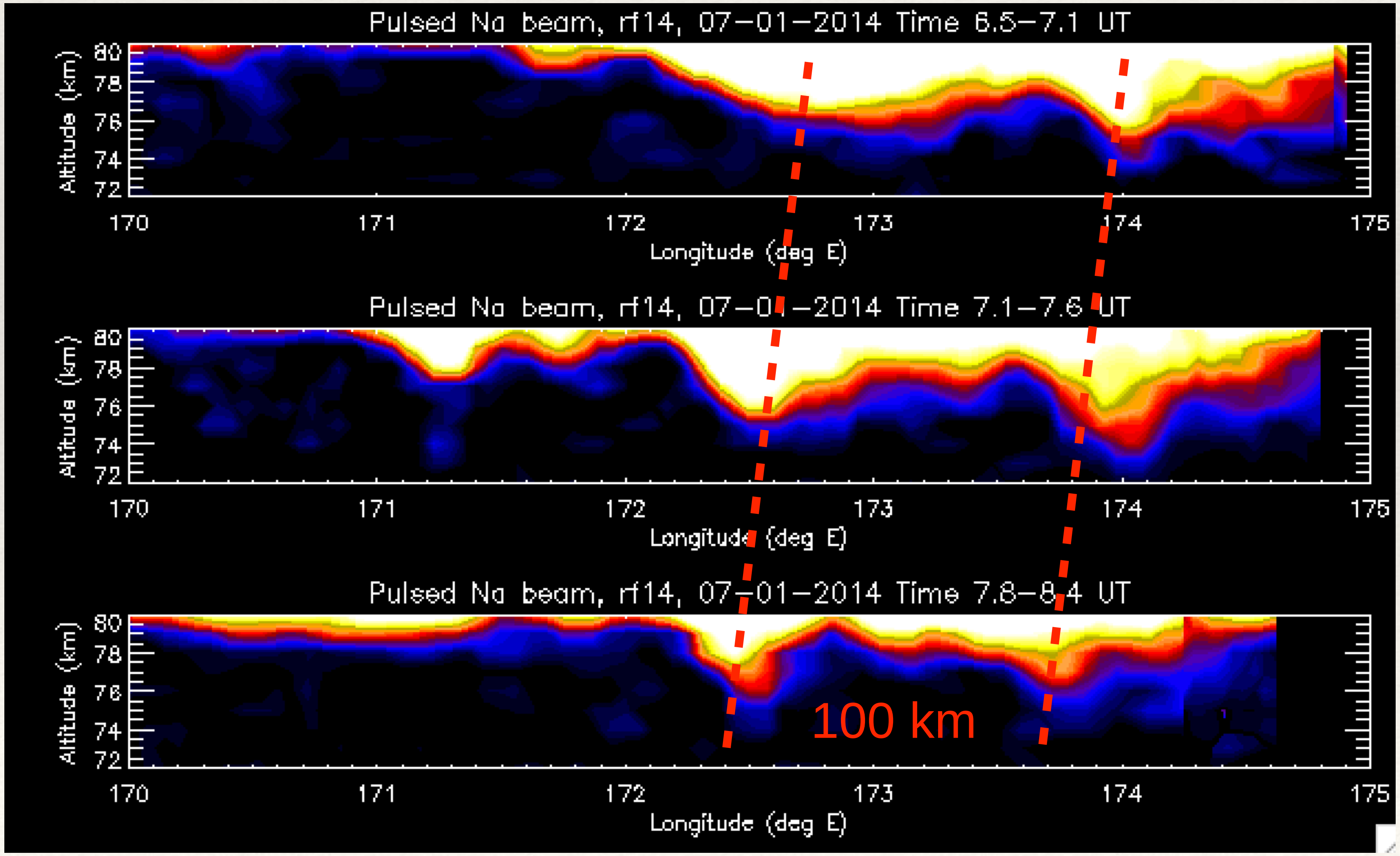
- Likely Sporadic Na layer at 100km then descending and spreading out
- A few potential sporadic Na layers during DEEPWAVE, but no large detached layers during 130 hours of operation

RF14, 01 July 2014: Na layers down to 73 km



- Repeating Na descending layers above and east of CHC
- ~100km east-west wavelength, moving west at ~6 m/s

Mountains CHC Ocean



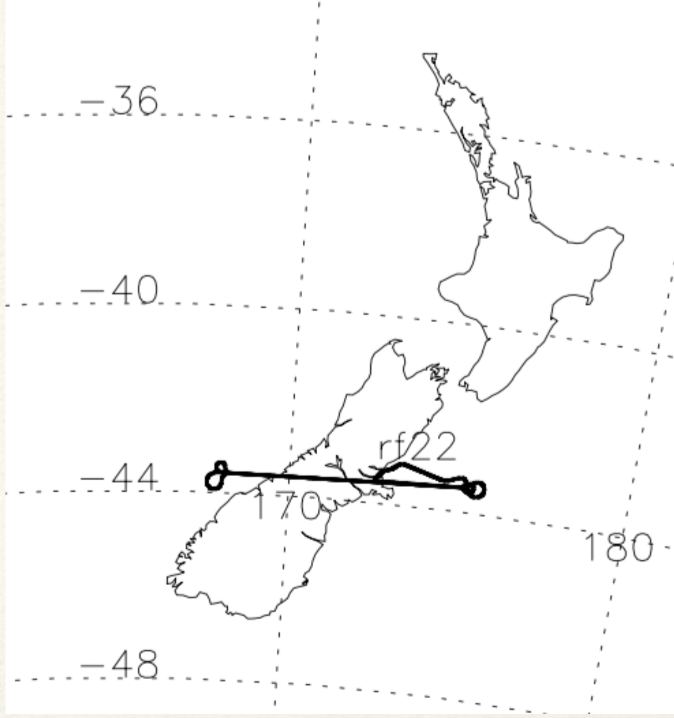
West to East Leg

East to West Leg

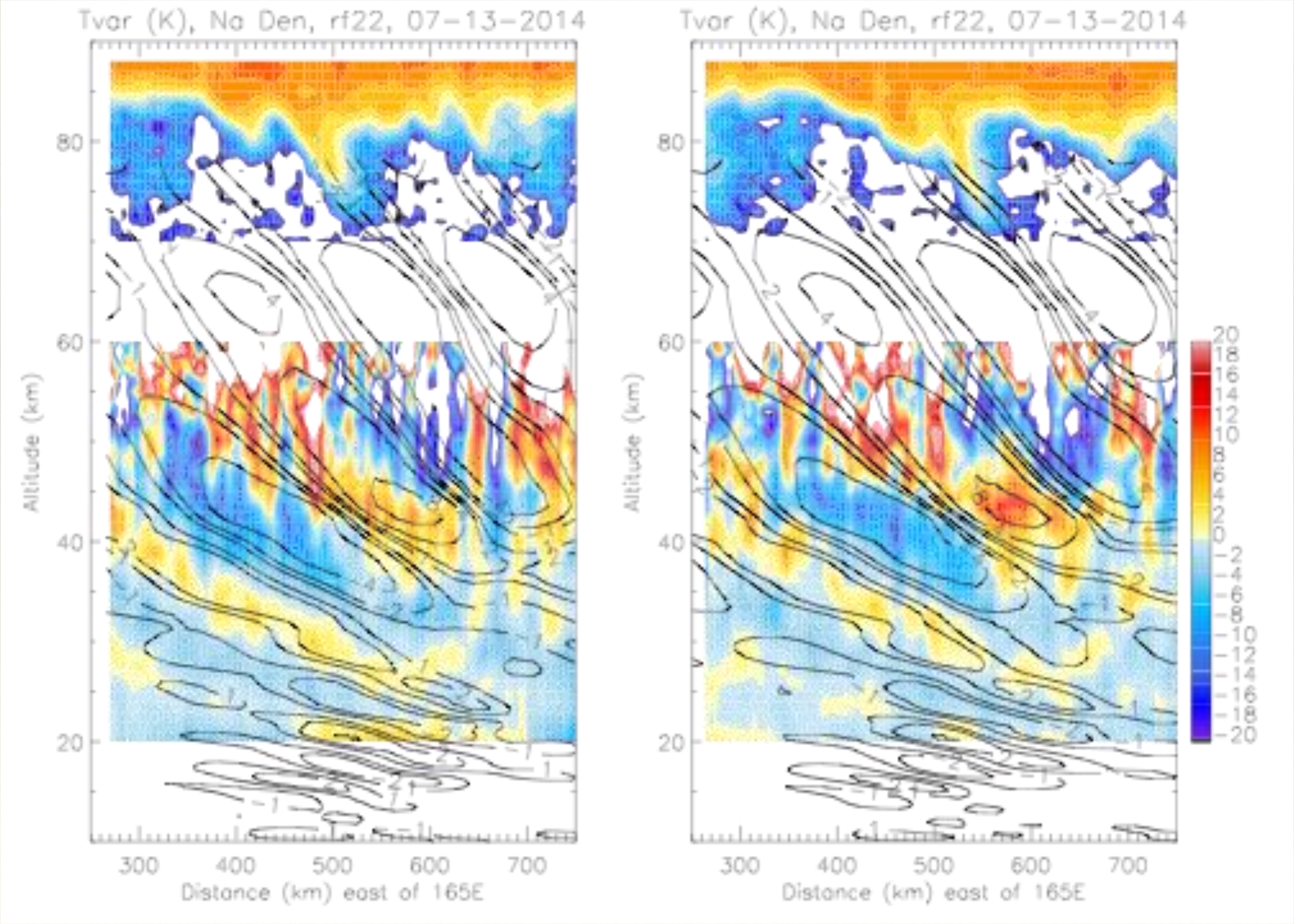
West to East Leg

390 km

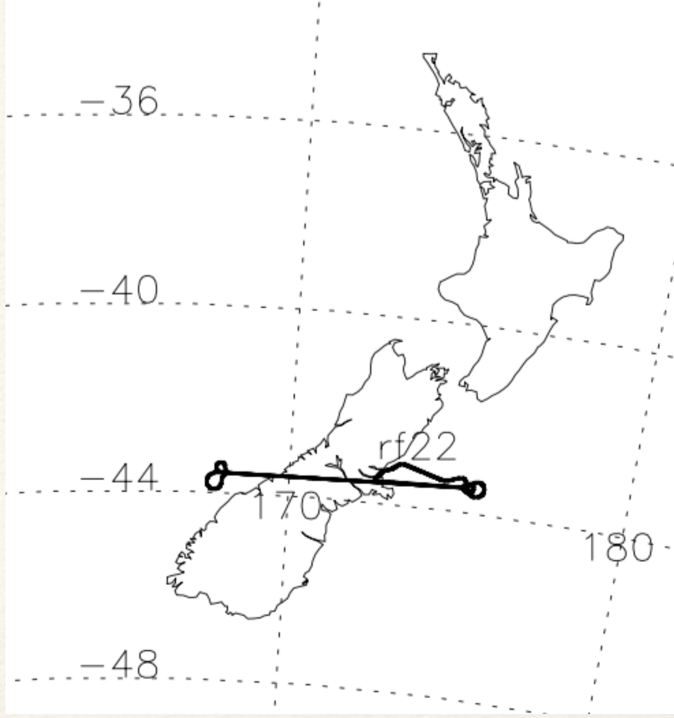
Mountain Wave - RF22
13 July 2014



- Weak forcing in troposphere, limited flight level response, flight cut off early after 4 passes over the mountains
- Middle and upper atmosphere: large mountain wave growing strongly with altitude in Rayleigh and sodium data
- ECMWF prediction (black contour lines) is very good.



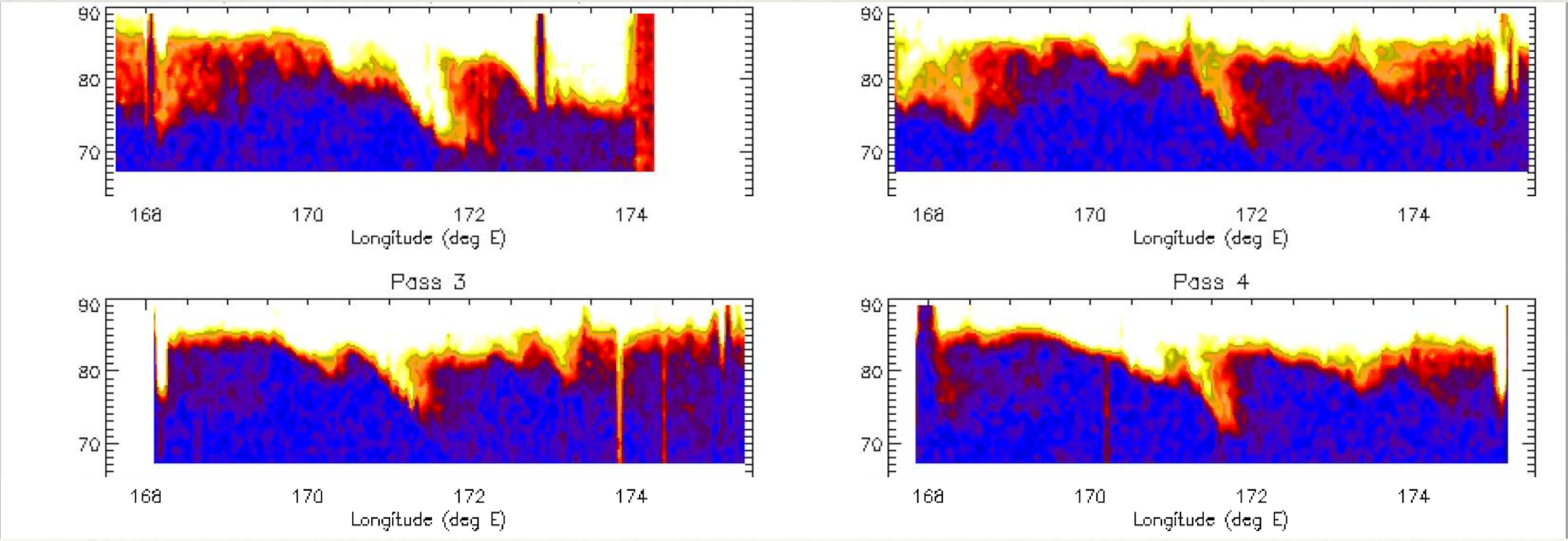
Mountain Wave - RF22
13 July 2014



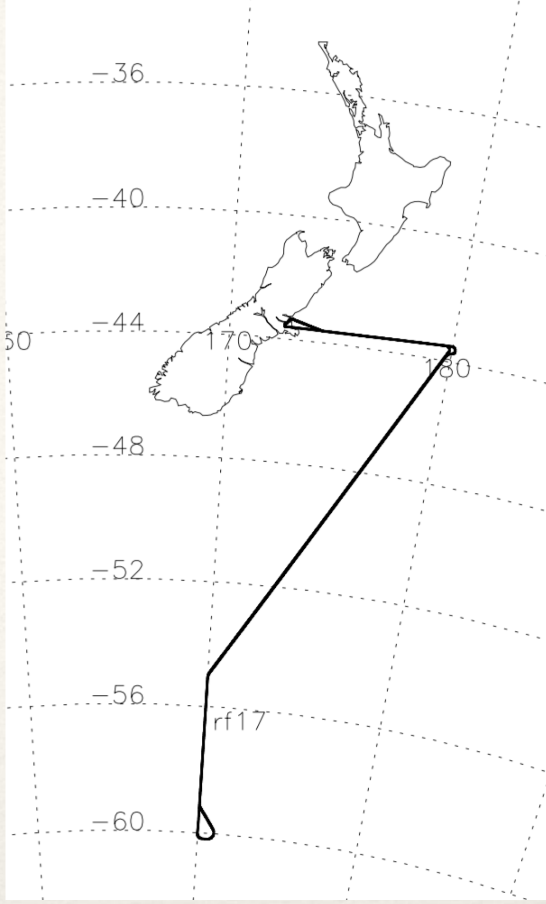
- Narrow layer at 171-172E descends down to ~70-72km just east of the mountains for 4 overpasses
- Layer position is stationary except for pass 3 which is slightly west
- Multiple small scale waves present including one that produces secondary layers in pass 3

Pass 1

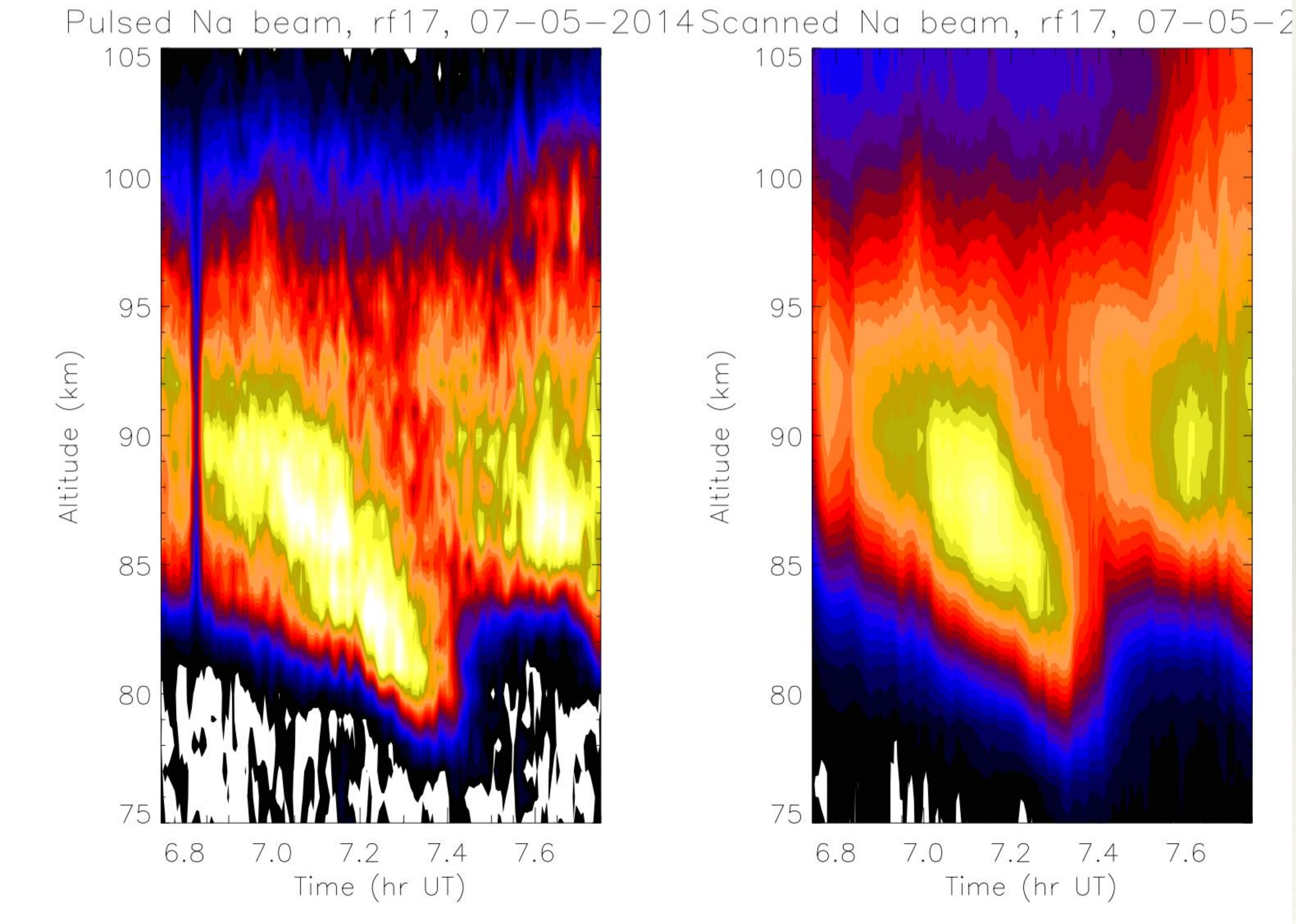
Pass 2



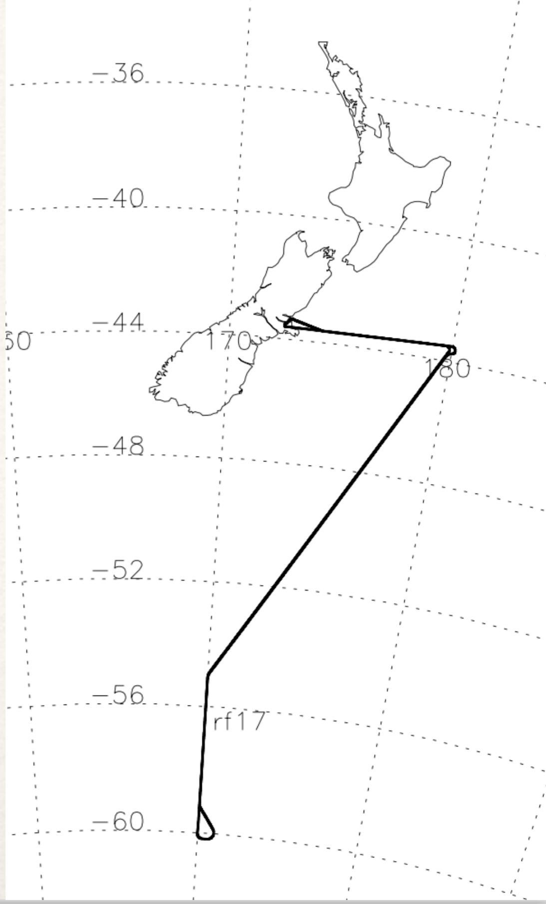
Na Layer descent over Ocean RF17, 5 Jul 2014



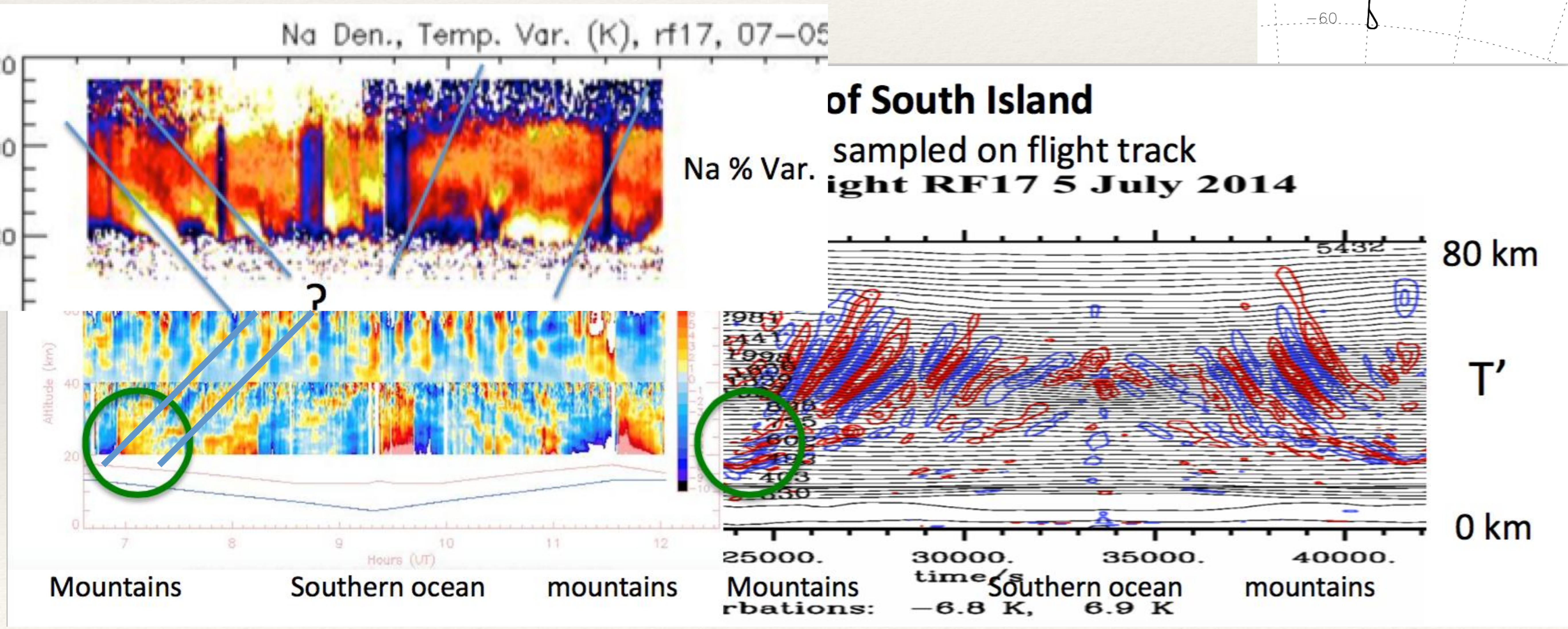
- Strong Na layer descent east of New Zealand



Na Layer descent over Ocean RF17, 5 Jul 2014



- Trailing wave predicted by ECMWF and measured in Rayleigh lidar data, but opposite phase tilt than waves in sodium data



Na Density Conclusions

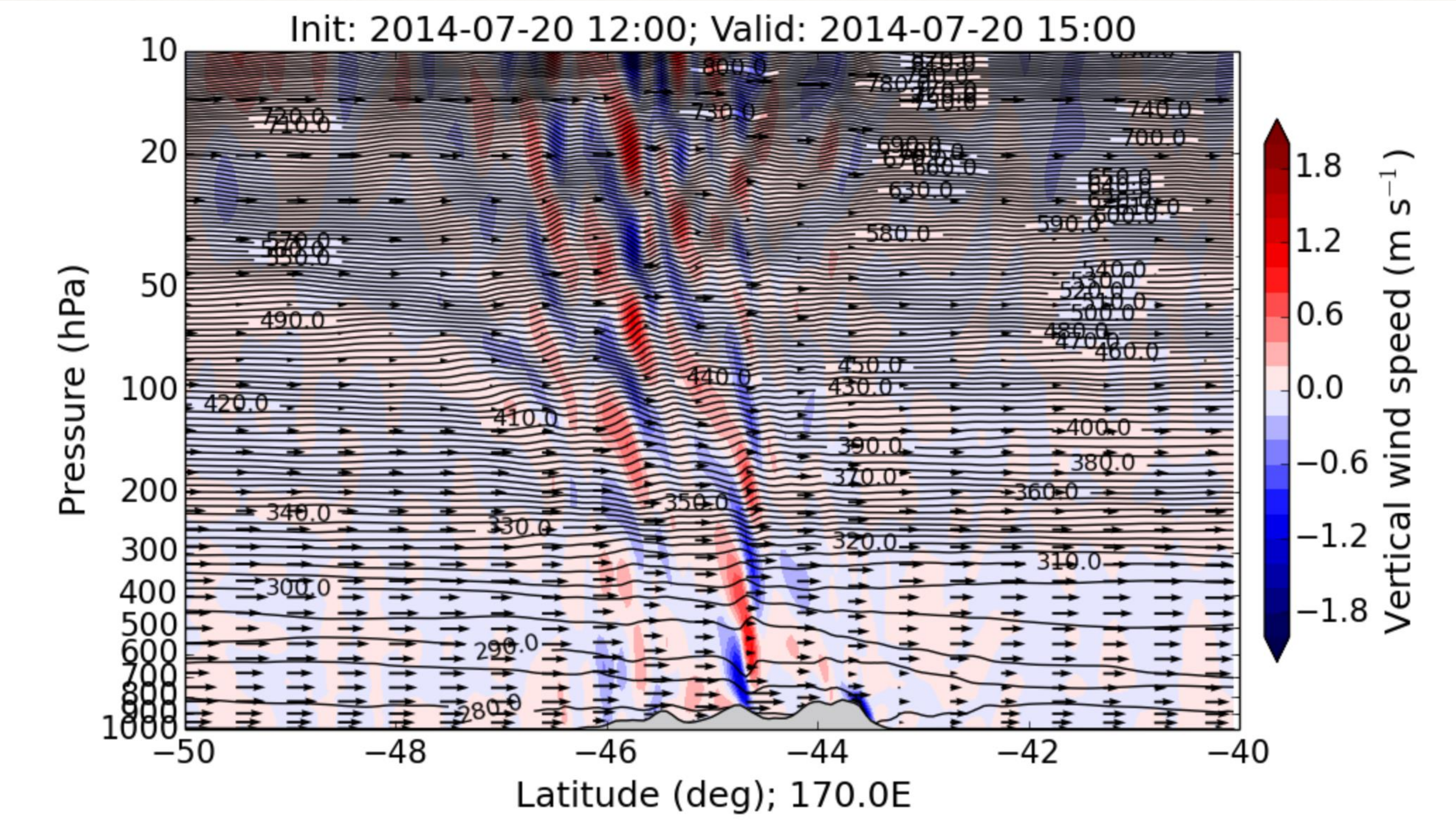
- Mean sodium density profile fairly uniform in height and peak density at (~2,000 atoms/cm^3)from 37S to 55S
- Validation: Need to compare with SCIAMACHY Na climatology, although different year (2008-2012) and local time (10am LT).
- One flight (18 July 2015) had much higher Na densities (~5,000/cm3 peak) increasing to the south and wider profile from 50-63S
- One flight to 31S had weaker, double peaked structure
- In general, the bottom side of the Na layer was extremely active due to wave perturbations
- But the top side was fairly quiet with few sporadic Na layers encountered in spite of covering wide swaths in latitude and longitude
- Repeated overpasses allow us to look at both time and spatial variation
- Bottom-side Na layers descended to ~71-73km over the New Zealand mountains (RF22, 13 July 2014) and east of mountains (RF14, 1 July 2014)
- Trailing wave over ocean (RF17, 5 July 2014): The Na layer maximum descended below 80km over the ocean east of New Zealand

Section 3: Lidar Wave Results

1. Mountain and Trailing waves
    1. RF26
    2. RF04
    3. RF07
    4. RF13
2. Southern Ocean
    1. Amplitudes during RF25
    2. Don’t forget similar RF19 and RF24

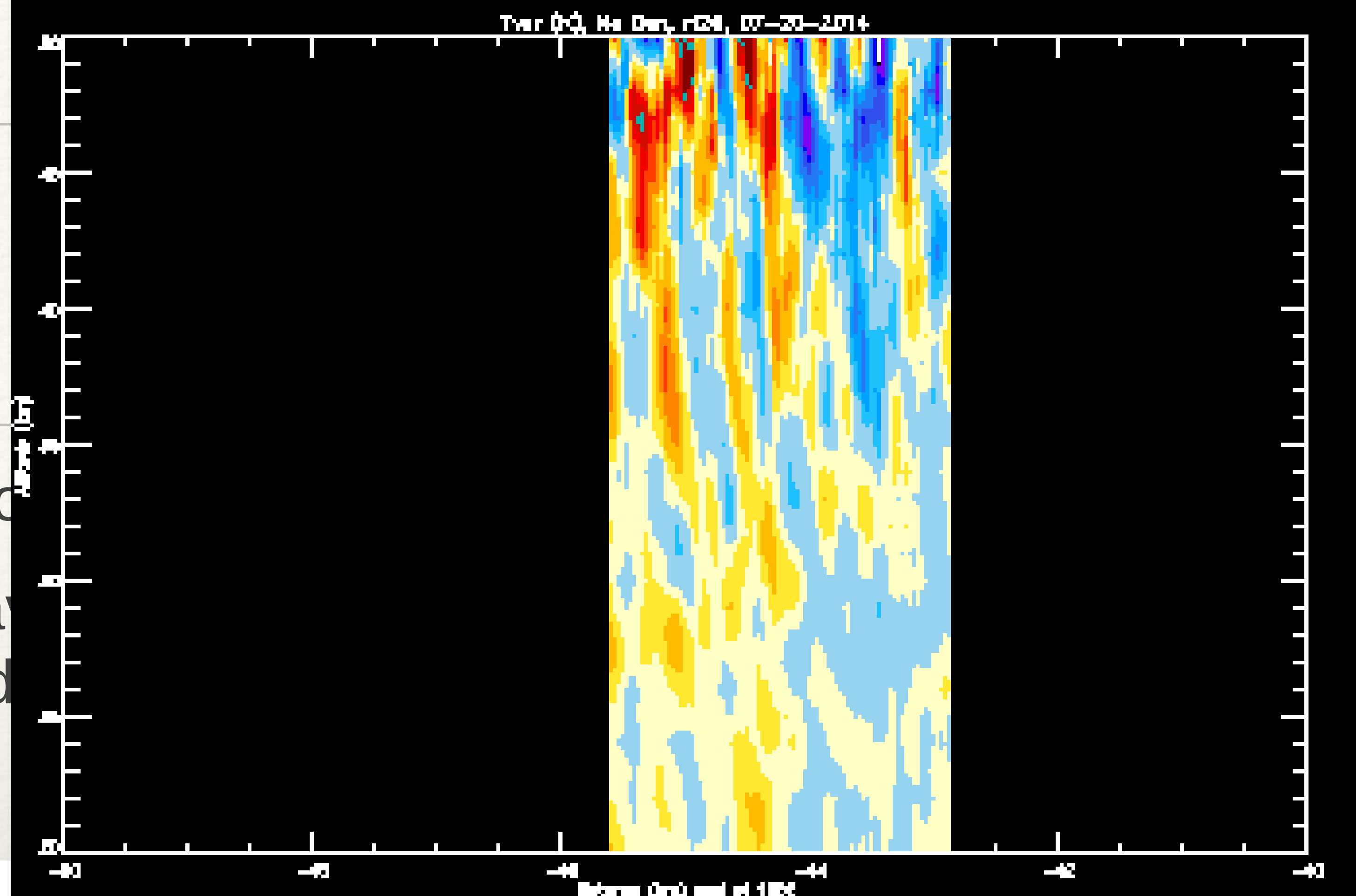
RF26 waves

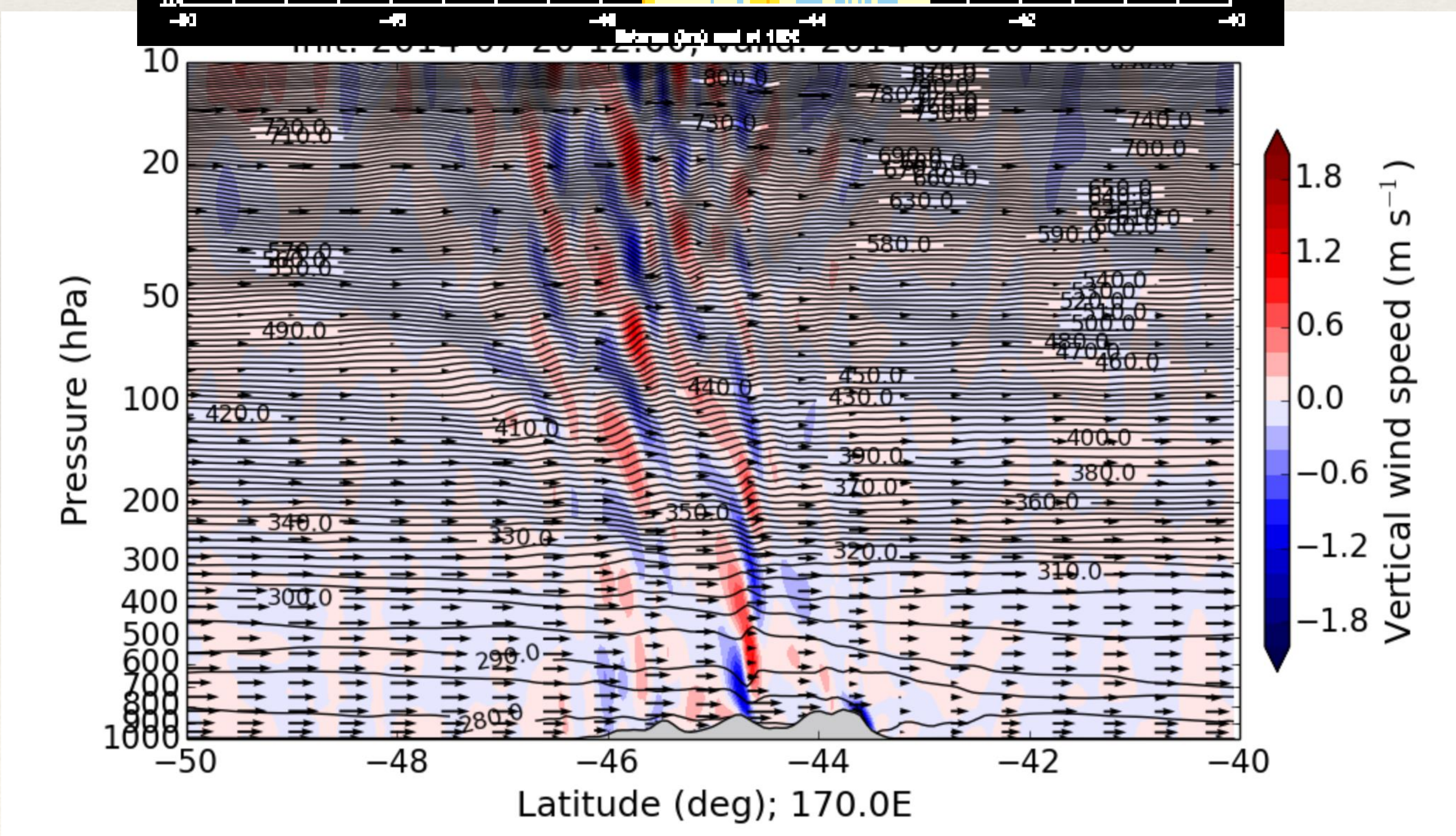
- Moderate forcing from SW
- multiple waves in WRF simulations (north-south cross section below), multiple waves in lidar data



Download model.WRF_UIBK_6km.201407201200.003_cross170_0E_vert.png

- Moderate fo
- multiple wa below), multiple waves in lid

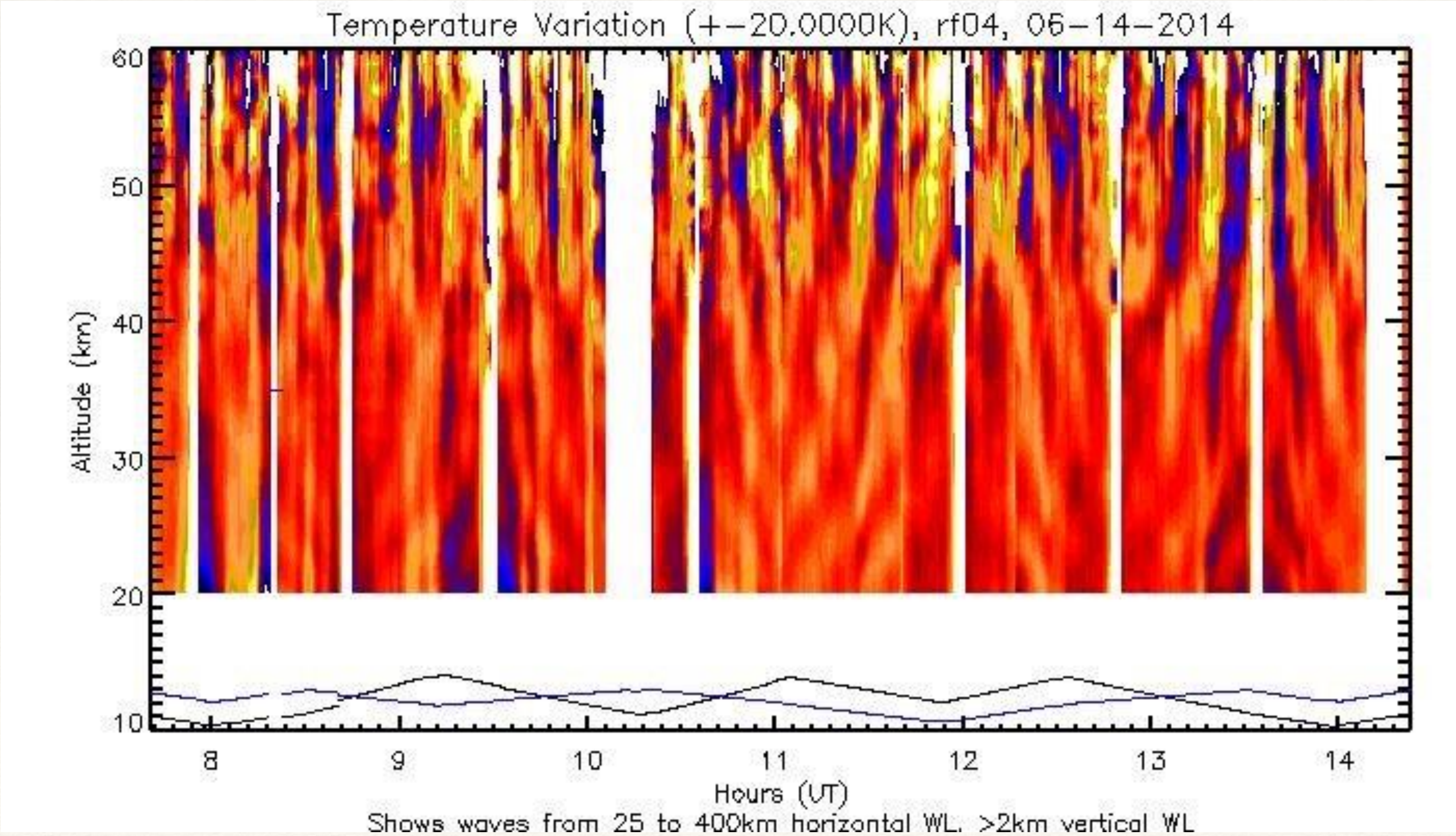




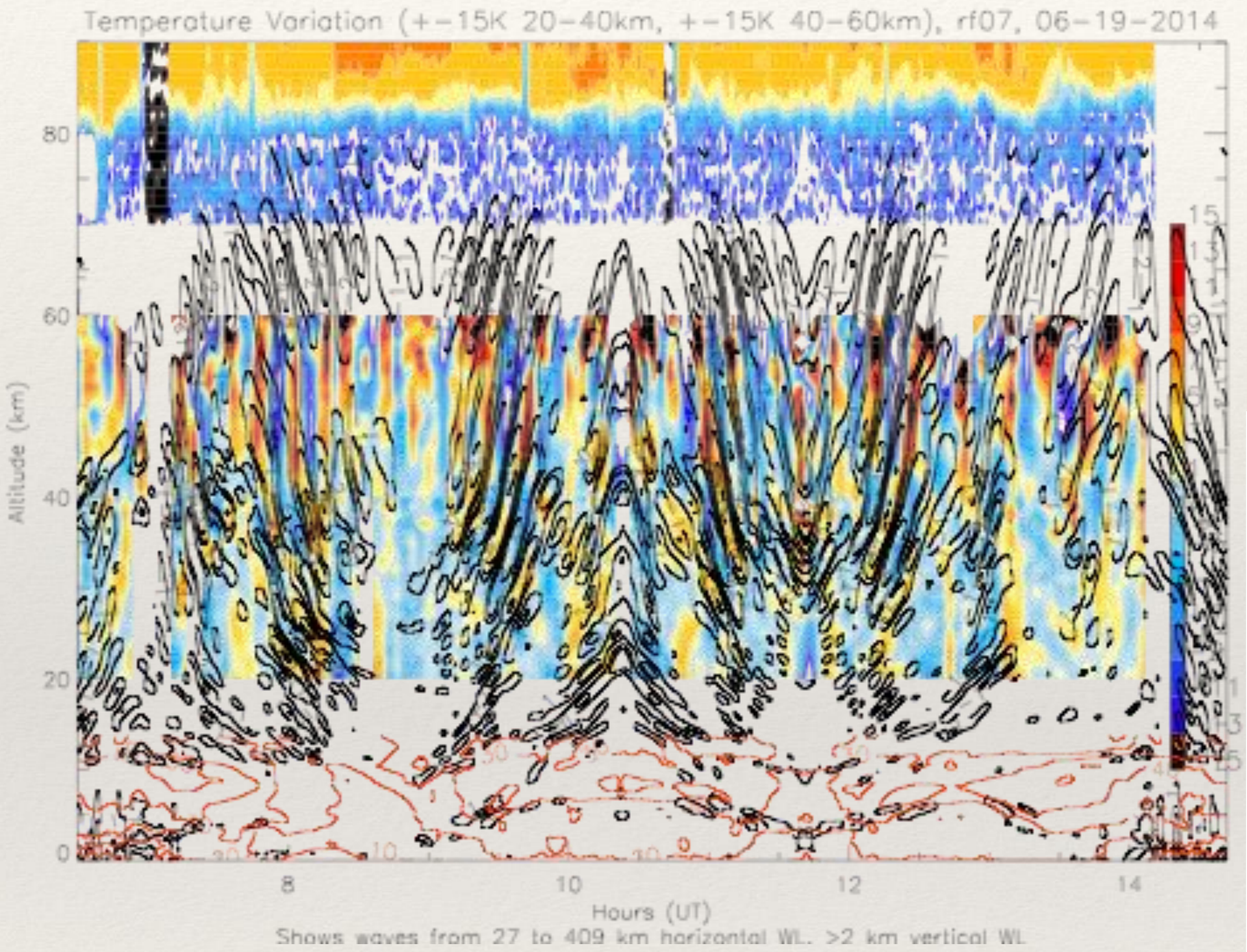
Download model.WRF_UIBK_6km.201407201200.003_cross170_0E_vert.png

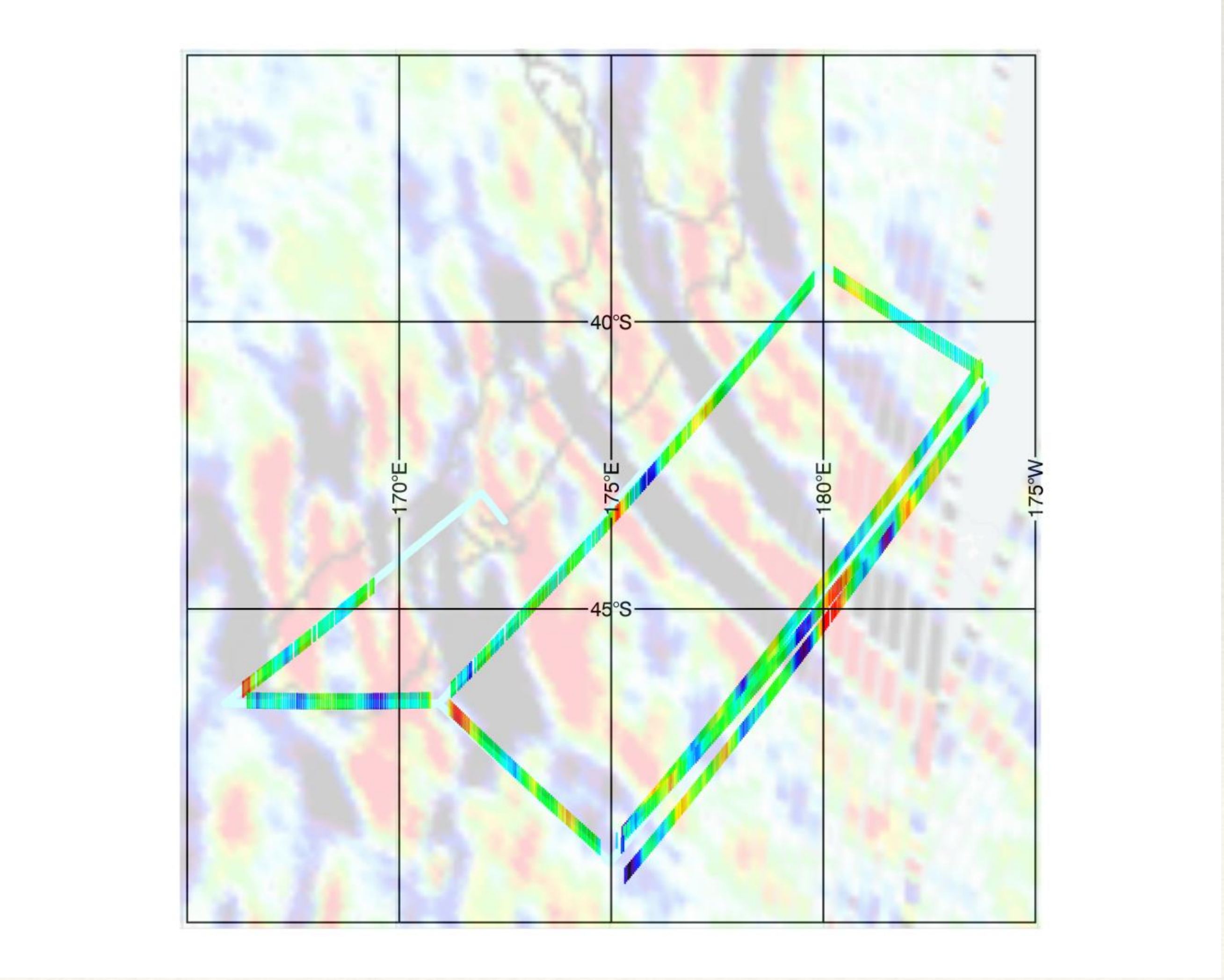
RF04 waves

- Weak forcing but strongly growing wave amplitudes with height to at least 60km
- Simon Vosper's mesoscale simulations of RF04 had scales similar to RF22, ranging from ~20 or 30 km to ~200-300 km scales

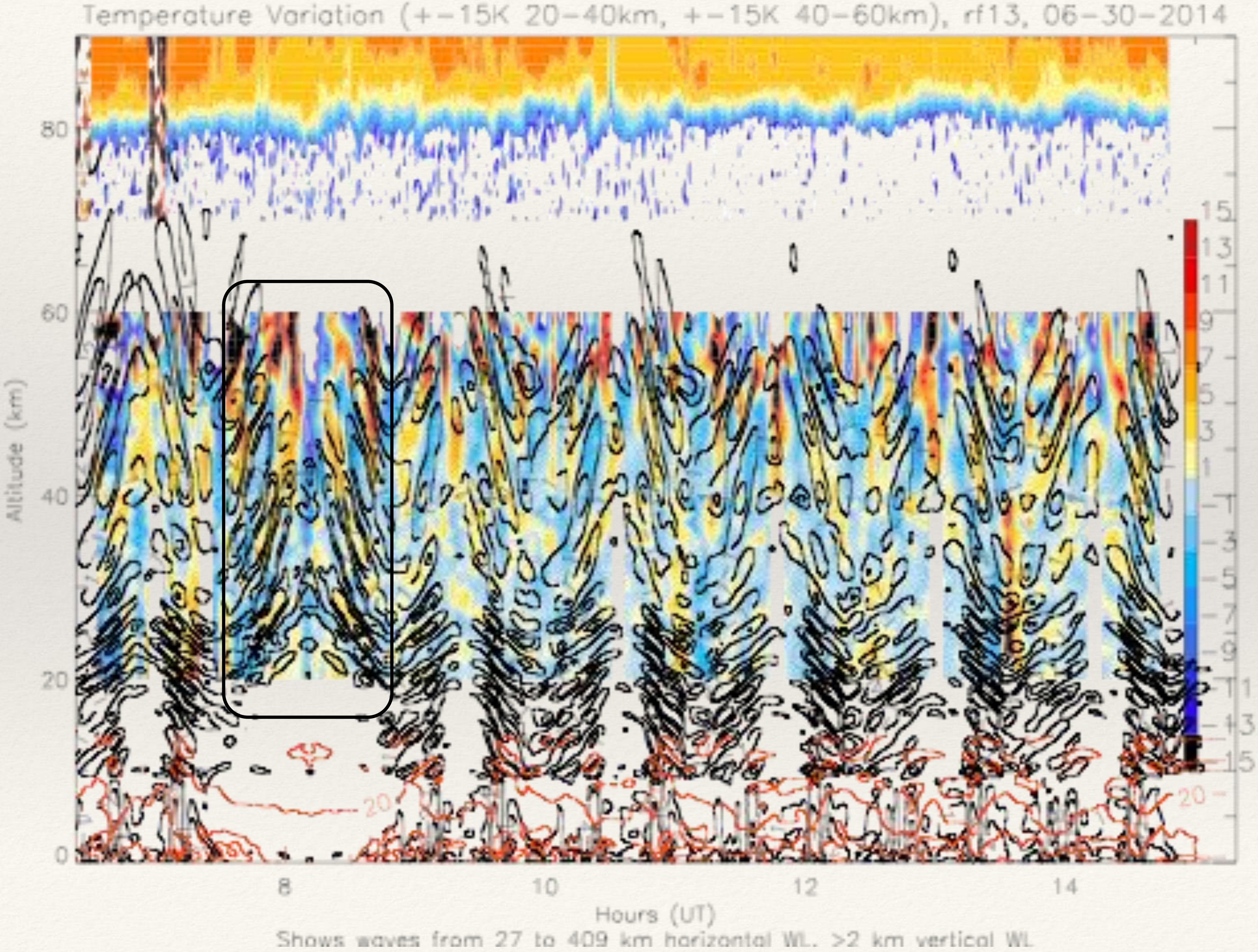


RF07 trailing waves





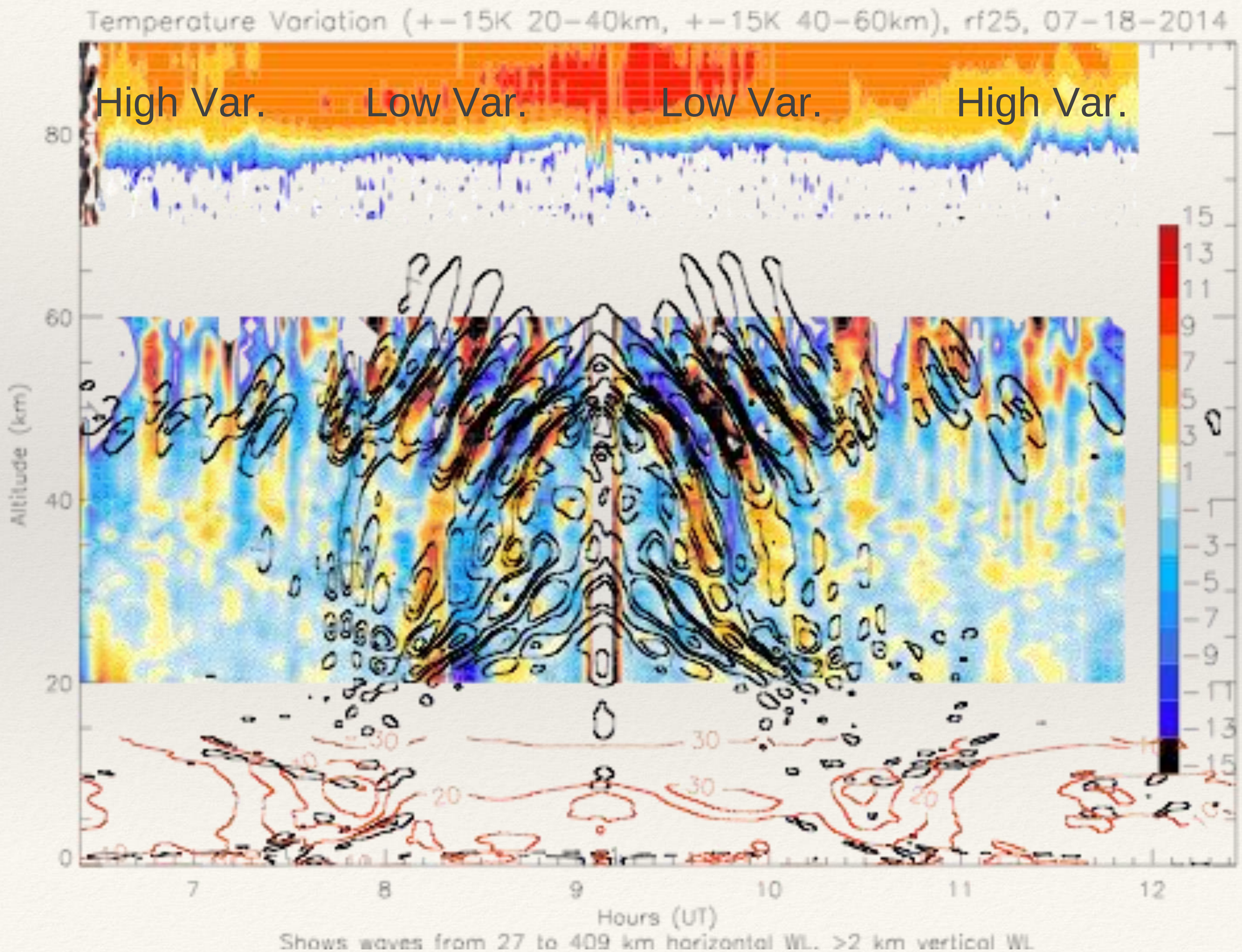
RF13 trailing waves



Southern Ocean

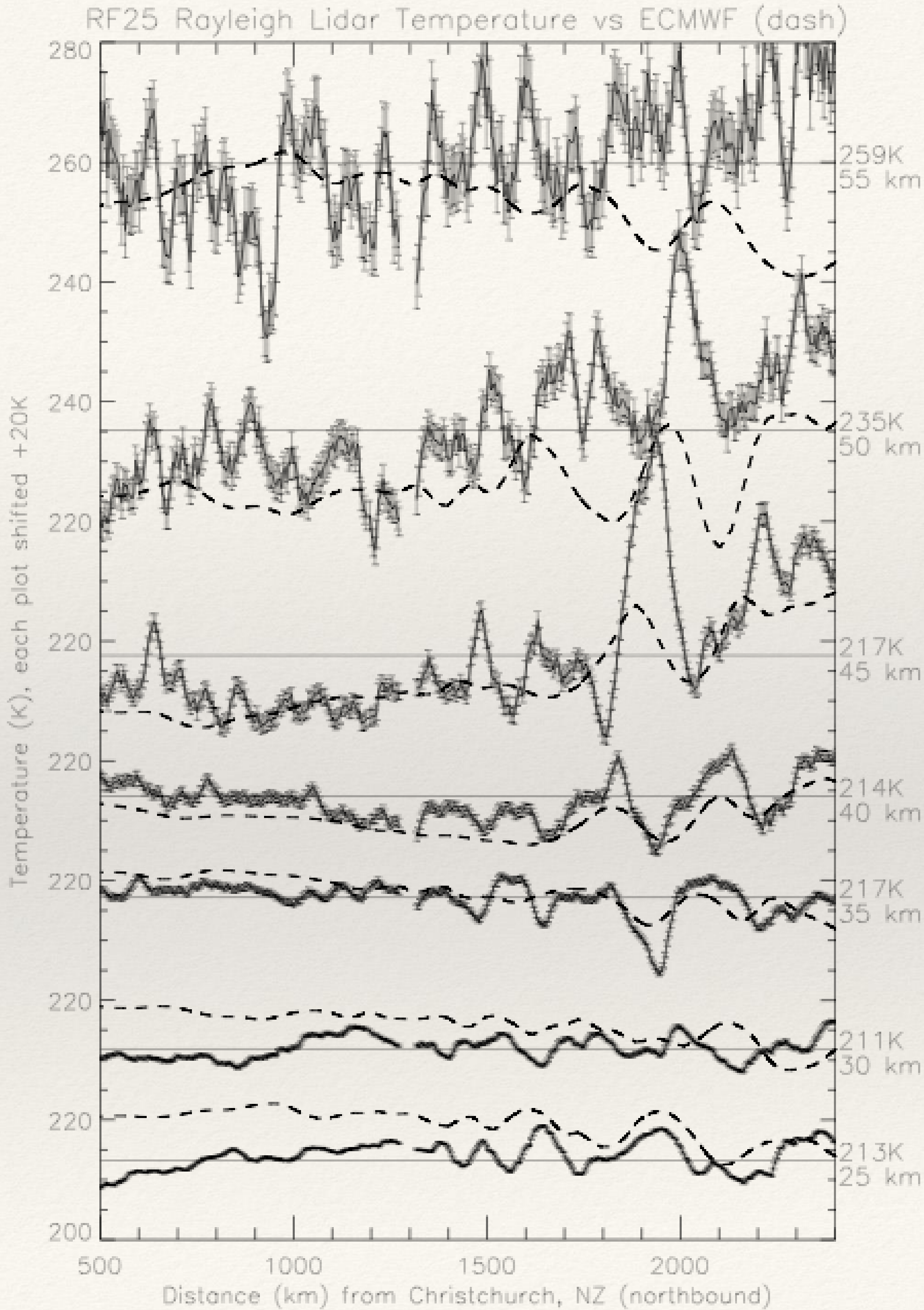
1. RF25: see Andreas paper
   1. RF26
   2. RF22
   3. RF04 and various
2. Southern Ocean (if Andreas doesn't show)
   1. Amplitudes during RF25

RF25

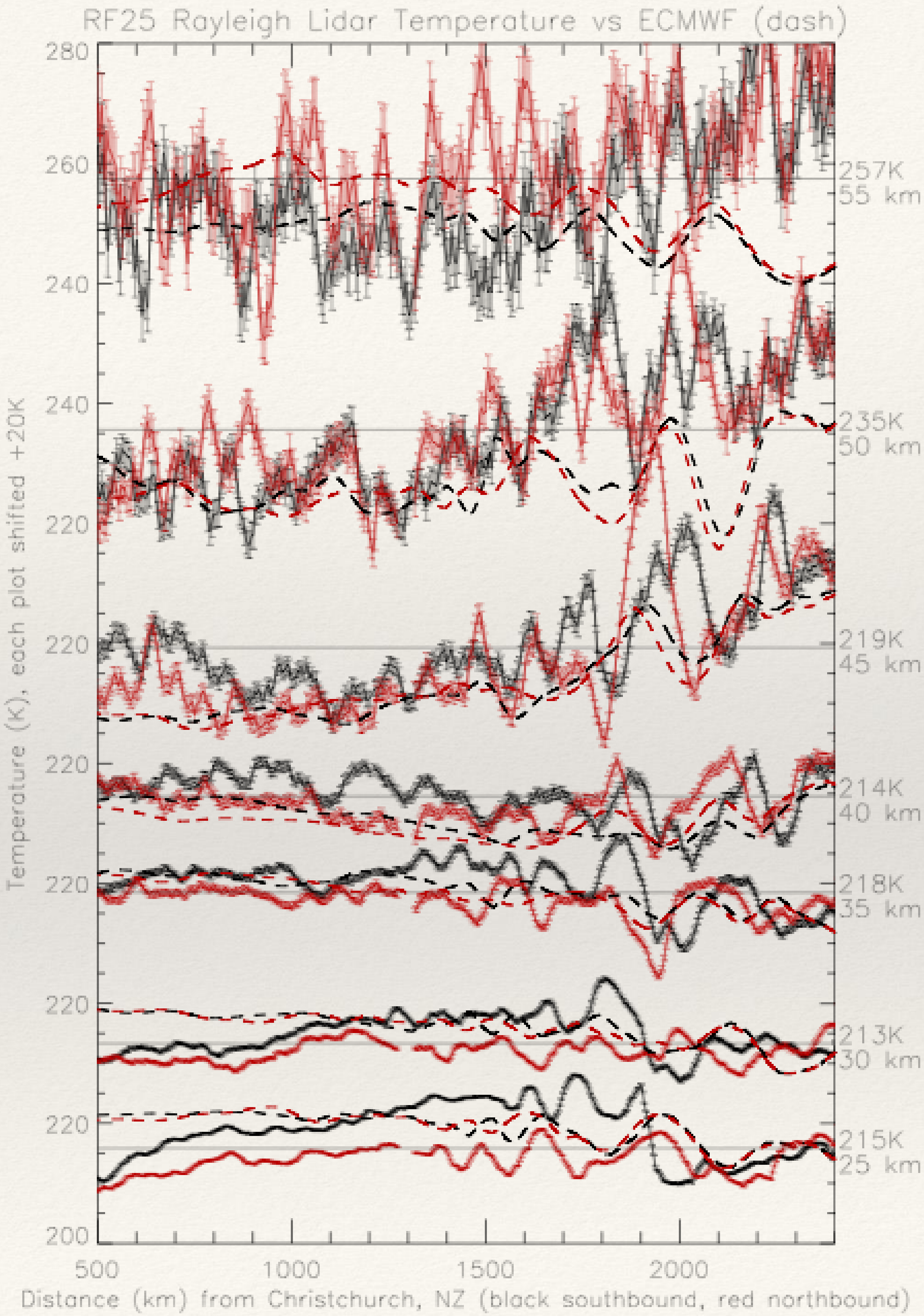


Temperature Variation (+-15K 20-40km, +-15K 40-60km), rf25, 07-18-2014
High Var.
Low Var.
Low Var.
High Var.
Altitude (km)
Hours (UT)
Shows waves from 27 to 409 km horizontal WL, >2 km vertical WL

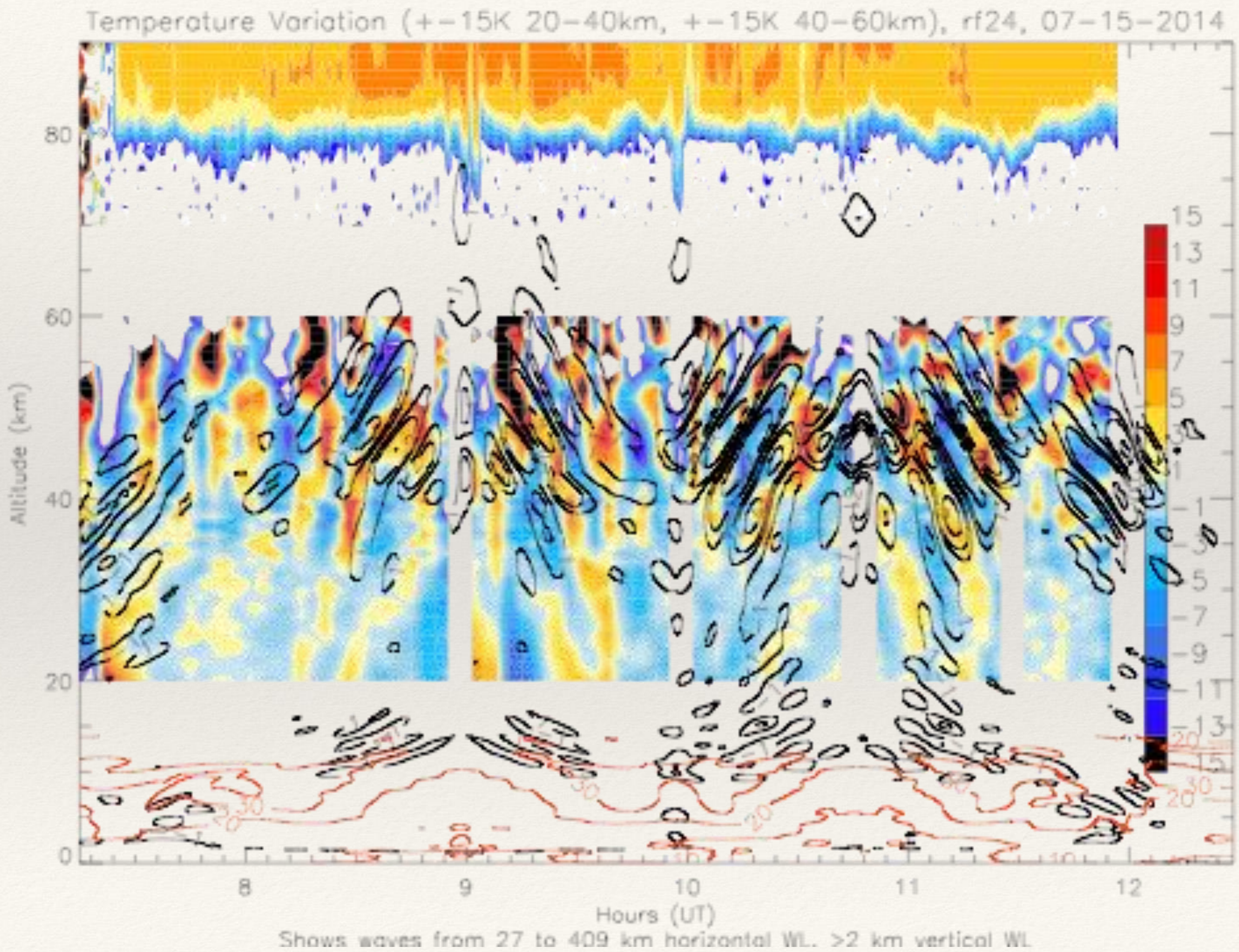
RF25 temperature time series



RF25 temperature time series



RF24



Temperature Variation (+-15K 20-40km, +-15K 40-60km), rf24, 07-15-2014
Altitude (km)
Hours (UT)
Shows waves from 27 to 409 km horizontal WL. >2 km vertical WL