JPL Carbon Dioxide Laser Absorption Spectrometer Data Processing Results for the 2010 Flight Campaign

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Summer 2010 Flight Campaign (I)

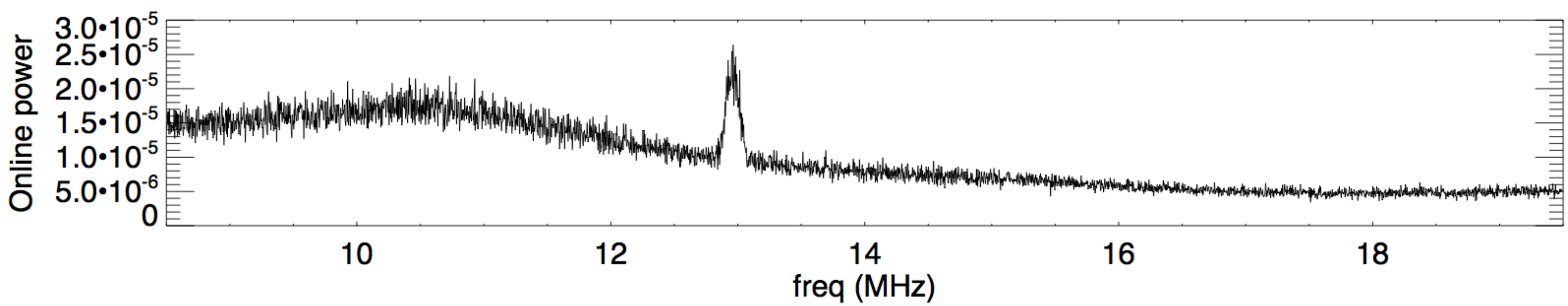
- 5 flights in July 2010 onboard NASA's DC-8 Airborne Laboratory
  - July 8: California Central Valley
  - July 9: California Mojave Desert / Needles
  - July 12: Nevada Railroad Valley
  - July 14: Pacific Ocean off California Coast
  - July 18: Oklahoma ARM site
- Stable overpasses at various altitudes between 8 KFt and 40 KFt

Summer 2010 Flight Campaign (II)

- Measure backscattered return in offline and online channels at 50 MHz rate
  - Data collection rate is ~ 0.5 TB / hour
- Inertial Navigation System (INS) / Global Positioning System (GPS)
  - Aircraft altitude, Aircraft attitude, Aircraft velocity
- DC-8 Research Environment for Vehicle-Embedded Analysis on Linux (REVEAL)
  - Aircraft altitude, Aircraft attitude, Aircraft velocity
  - Atmospheric conditions (temperature, pressure, relative humidity)
- Daily radiosonde launched by NASA Langley Research Center (LaRC) near center of flight path
  - Vertical profile of atmospheric conditions (temperature, pressure, relative humidity)
- In situ CO_2 sensor (Picarro) available for calibration

Ground Data Processing for Summer 2010 Flight Campaign (I)

- Frequency domain processing with 50 MHz samples
- 16K-point FFTs (320 μs time slice)
- Periodograms with ~3 KHz resolution
- Accumulate periodograms to desired integration time
- Detect return signal and estimate heterodyne frequency and power
- Heterodyne Intermediate Frequency signals appear in 8.5 - 19.5 MHz window
  - Based on aircraft ground speed and off-nadir point-ahead angle



Ground Data Processing for Summer 2010 Flight Campaign (I)

Need to carefully manage integration times.

The good: Long integration time improves signal to noise ratio

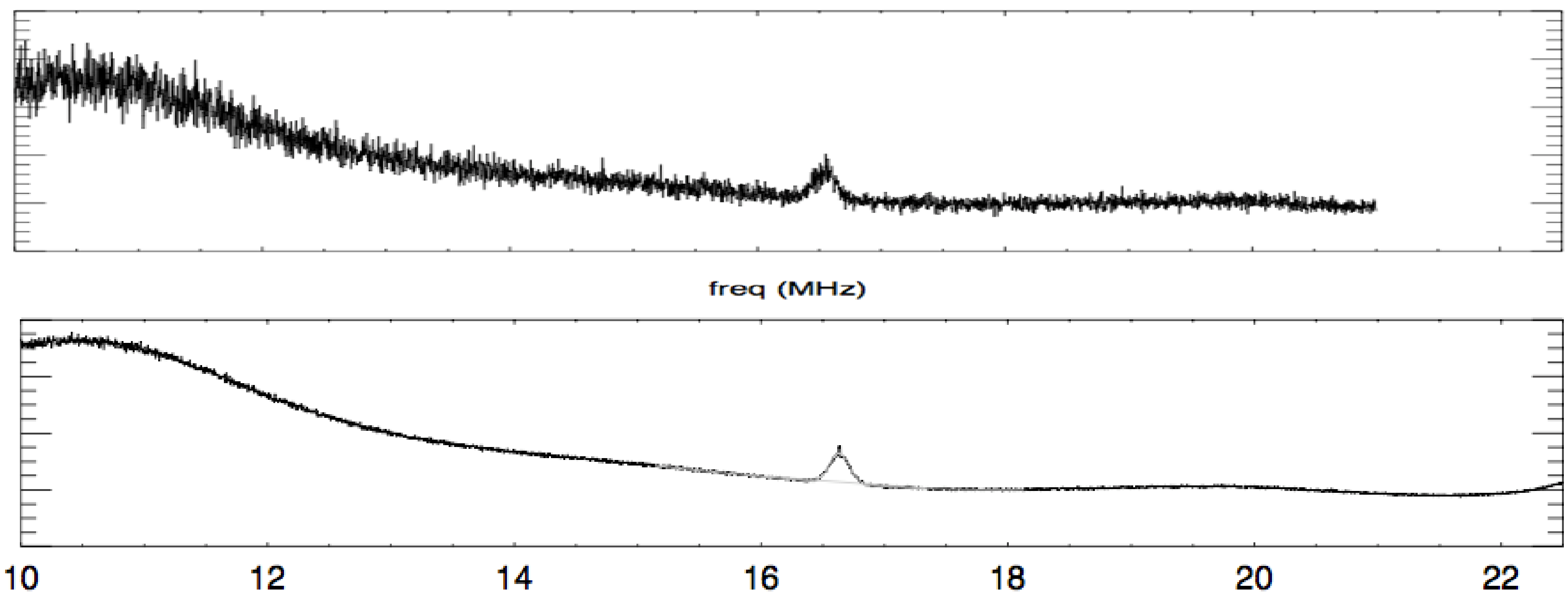
The bad: Long integration means more sensitivity to platform instability

•Aircraft altitude and attitude

•Atmospheric conditions (e.g., pressure, temperature, relative humidity)

•Ground elevation and reflectance

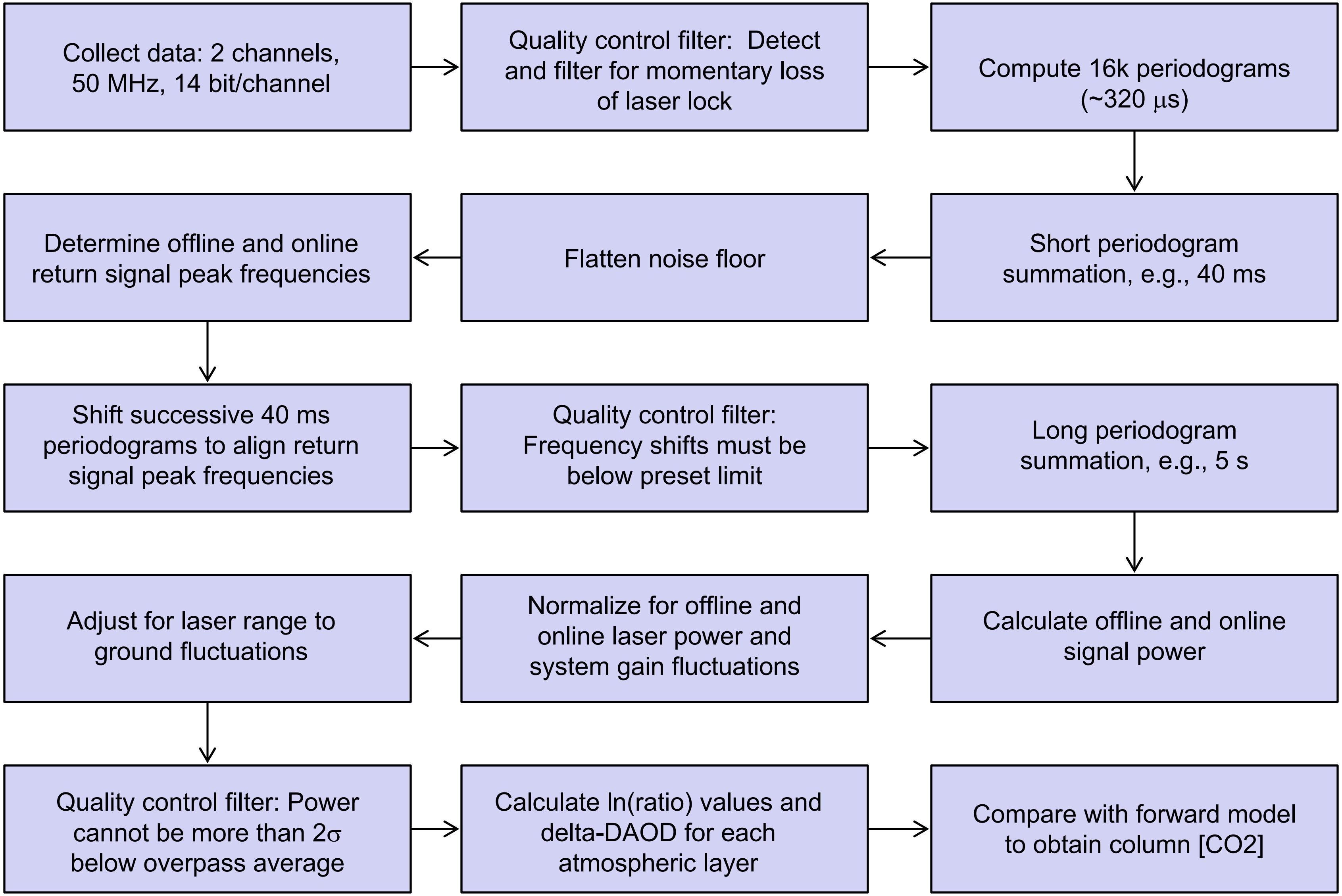
The ugly: Quality control filters used to detect and handle realistic flight conditions: clouds, excessive turbulence, instrument anomalies, etc.



Ground Data Processing for Summer 2010 Flight Campaign (II)

- Our algorithm uses both short and long integration times
  - Detect signal return and estimate heterodyne frequency over short time periods (e.g., 40 ms)
  - Estimate return power over longer time periods (e.g., 5 s)
  - Allows long integration times even during periods of aircraft attitude variability
- Laser range to ground correction compensates for aircraft attitude variability
- Quality control filters eliminate data segments that may introduce bias
- Clouds in the field of view
- Excessive turbulence
- Momentary loss of laser lock

Data Processing Flow

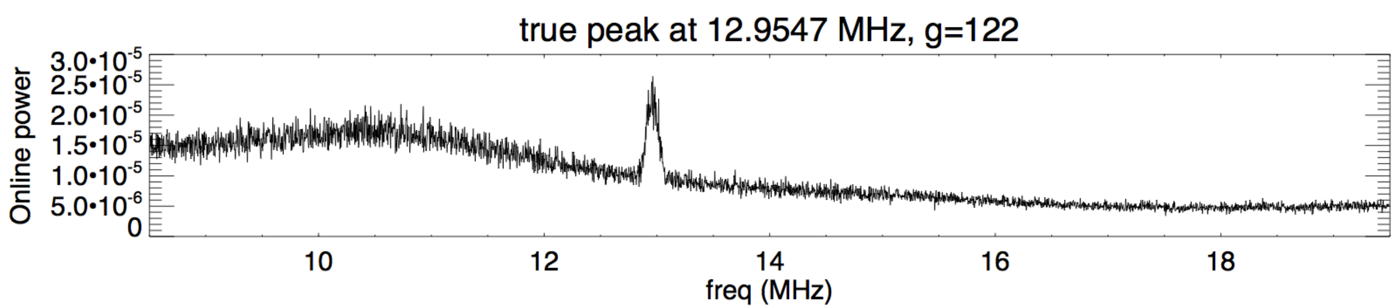


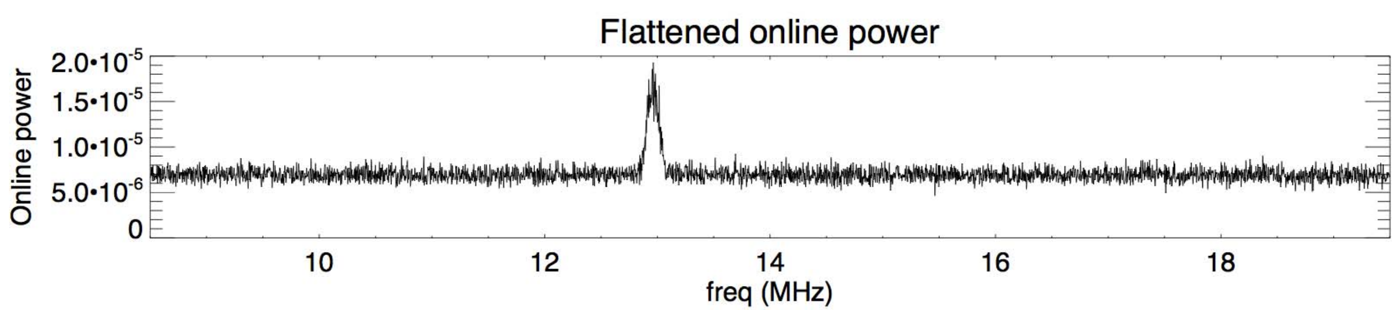
Periodogram Summation Strategy

- Use short integration times, e.g., 40 ms, for return signal peak detection and heterodyne frequency estimation
- Use long integration times, e.g., 5 s, for return power estimation
  - Compute enough (N) short periodogram summations to produce a long periodogram summation
  - Detect return signal peaks and estimate heterodyne frequency in each short periodogram summation
  - Compute the mean heterodyne frequency over the N short periodogram summations and shift them all so that their signal peaks align at the mean.
  - Add up the shifted and aligned short periodogram summations to produce a long periodogram summation

Noise Floor Flattening

- The 40 KFt altitude is processed to compute a noise floor for each channel
  - No significant signal return at this altitude
- Smooth and then jointly normalize noise floors so online value at 15 MHz = 1
- Remove noise floor component from a periodogram by dividing by the smoothed and normalized noise floor
  - Flattens the periodogram baseline
  - Makes noise level uniform across the spectrum





Peak Detection

- Automated matched filter peak detection
- Return signal expected in window from 8.5 MHz and 19.5 MHz
- Must distinguish noise spike from true peak
  - Especially important in low signal to noise conditions
- Matched filter detection
  - We know the typical signal width and shape
  - We search for a group of sample points that exceed a preset multiple of the root mean square noise level
  - Thresholds set based on known signal width and shape

Return Power Estimation

- Compute the long periodogram summation for each channel
- Flatten to remove noise floor
- Subtract baseline level (offset from 0)
- Compute area under the curve in the window from 8.5 MHz to 19.5 MHz
- Scale for laser power fluctuations as a function of time

Range to Ground Analysis (I)

- Aircraft latitude, longitude, altitude, attitude, and speed at 1 second intervals from REVEAL
- Calibrate pitch angle using Doppler equation
  - Depends on return signal frequency and aircraft speed
- Ground elevation relative to WGS-84 from 1 arc second resolution SRTM “finished” DEM (version 2.1)
  - No co-boresighted laser altimeter used

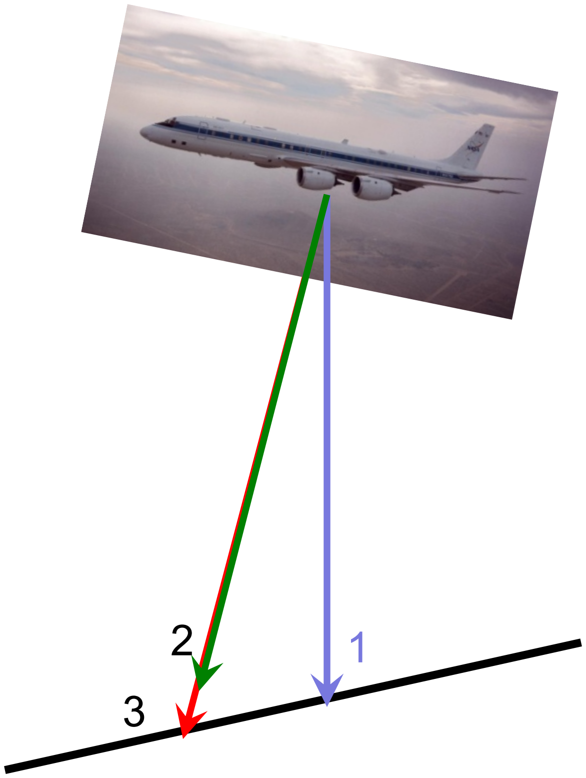
Range to Ground Analysis (II)

Slant path computation:

(1) Nadir vector from laser transmitter to ground

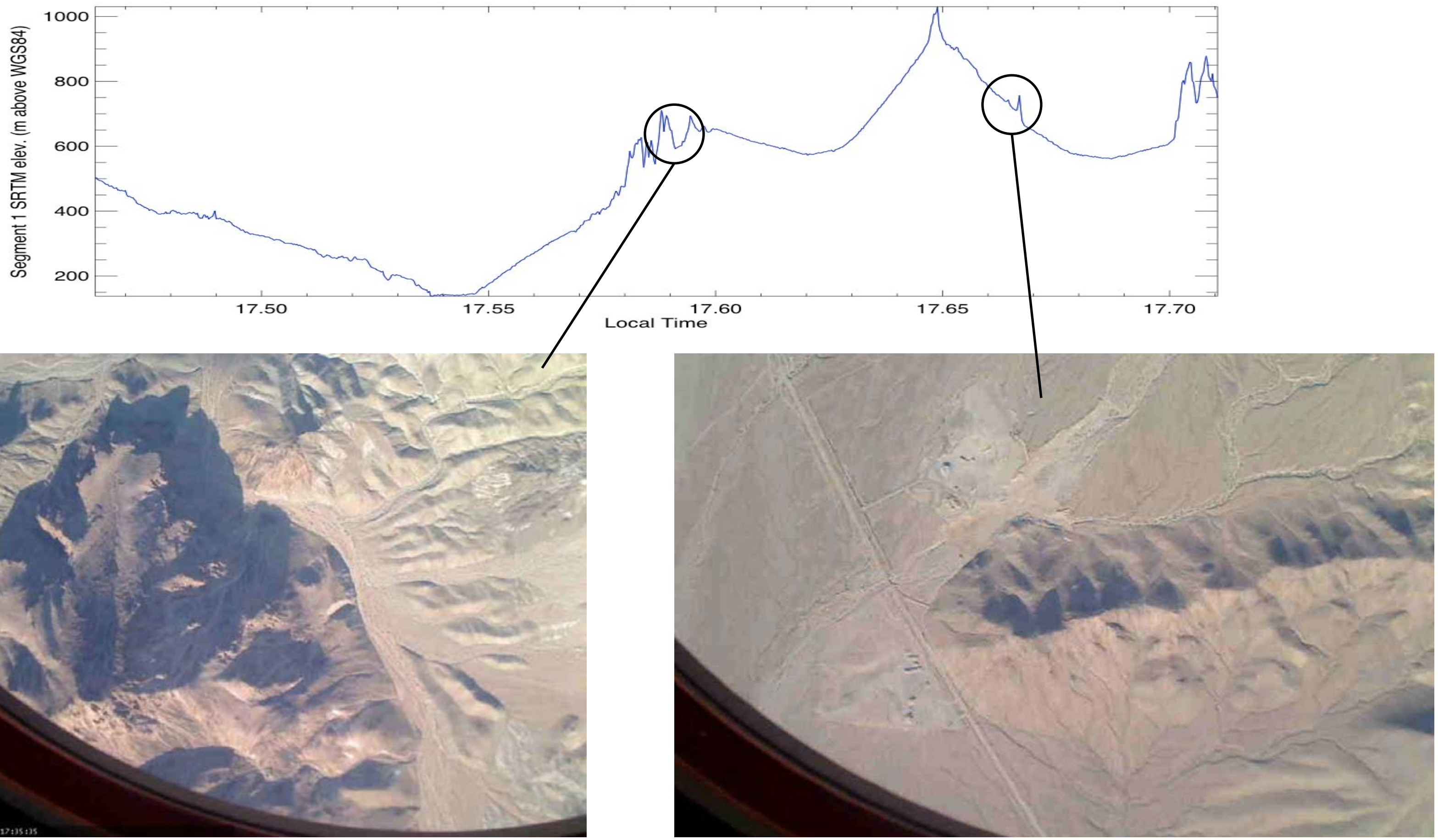
(2) Quaternion rotation based on aircraft attitude

(3) Extend rotated vector to intersect with SRTM topography



Range to Ground Analysis (III)

Mojave/Needles flight track had significant ground elevation variation, which was effectively handled by our algorithm:
<u>> 800 m elevation range!</u>



Quality Control Filters (I)

- We account for normal variations in:
  - Instrument
    - Laser power
  - Aircraft
    - Altitude
    - Attitude
    - Velocity
  - Atmosphere
    - Temperature
    - Pressure
    - Relative Humidity
  - Ground
    - Elevation
    - Reflectance
- Quality control filters discard short anomalous time periods due to, for example:
  - Clouds in the field of view
  - Excessive turbulence
  - Momentary instrument anomalies

Quality Control Filters (II)

- Laser power analyzed at ~10 ms resolution to automatically detect and discard time periods of momentary loss of laser lock
  - Detected by abnormally large values of the first derivative of laser power with respect to time
  - Can make it difficult or impossible to detect the online return signal
- Return signal analyzed on short time scales (e.g., 40 ms) to automatically detect and discard time periods when the heterodyne frequency drifts excessively (e.g., > 2 MHz) within a longer time period (e.g., 5 s).
- Return power analyzed on longer time scales (e.g., 5 s) to automatically detect and discard time periods when power in either channel drops more than 2 σ below the overpass average.

Forward Modelling

- AER's Line By Line Radiative Transfer Model (LBLRTM) used for forward modelling
  - Define up to 200 atmosphere layer boundaries
  - Pressure, temperature, and relative humidity from REVEAL or radiosondes assigned to each layer
- Spectroscopic line parameters modified from HITRAN
  - Incorporates updates to 1.57 and 2.05 micron bands based on OCO-supported spectroscopic studies by Geoffrey Toon and Linda Brown
  - New studies by Lance Christensen of the R(30) line profile using tunable semiconductor laser
    - Deviations from Voigt identified in the far wing region, including the band where the offline laser frequency is found.
    - Enables us to put an upper bound on any bias that may be due to imperfect line shape in the forward model.

Column CO_2 Retrieval

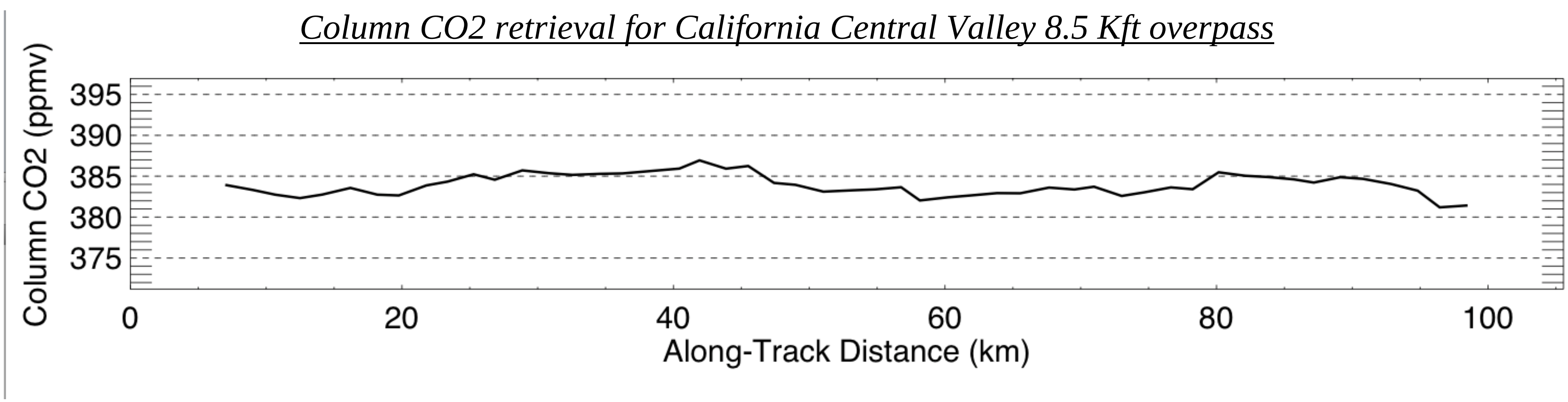
- Differential Absorption Optical Depth is related to both transmittance and return power:

$$DAOD = \ln(\tau_{off} / \tau_{on}) = \frac{1}{2} \ln(P_{off} / P_{on})$$

- If we assume a fixed column CO_2 density, D, in the forward model, then our column CO2 as a function of time for a CO2LAS overpass is:

$$CO_2(t) = D * \ln(P_{off} / P_{on}) / (2 * \ln(\tau_{off} / \tau_{on}))$$

- Convert to CO_2 as function of along track distance using aircraft velocity from REVEAL



Summary

- Data processing algorithm updated to accomplish consistent column CO2 retrieval from the Summer 2010 flight campaign
- We allow for integration times of arbitrary length to balance the need for:
  - High signal to noise ratio
  - Platform stability
- We correct for small but significant fluctuations in the laser power
- Range to ground analysis corrects for fluctuations in aircraft altitude, pitch, roll, true heading, and ground elevations
  - DEM from SRTM eliminates need for co-boresighted laser altimeter
- Quality control filters eliminate bias due to short-lived anomalous conditions
- Comparison with forward model (LBLRTM) to rapidly produce CO_2 time series for analysis.