Minimizing the Impact of Thin Clouds on CO2 Measurements from an Intensity-Modulated Continuous-Wave Laser Absorption Spectrometer

F. Wallace Harrison[1], Jeremy Dobler[2], Bing Lin[1], Douglas McGregor[2], Edward Browell[1], Susan Kooi[3]

[1]NASA Langley Research Center, Hampton, Virginia 23681
[2]ITT Geospatial Systems, Fort Wayne, Indiana 46801
[3]Science System and Applications, Inc., Hampton, Virginia 23666

Langley Research Center

Introduction

Accurate understanding of carbon balance in the environment is critical to projections of the future evolution of the Earth's climate. Uncertainties in the modeling of carbon sources and sinks remain large due to the limited set of observations from the current network of in-situ and surface measurements. Global, spaceborne measurements of atmospheric CO_2 can reduce these uncertainties, and the National Research Council (NRC) Decadal Survey of Earth Science and Applications from Space identified Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) as an important mid-term (Tier II) mission. The active space remote XCO_2 measurement that is called for in the ASCENDS mission requires the simultaneous measurements of CO_2 and O_2 number density columns to derive the average CO_2 mixing ratio (XCO_2) column. The NRC recommendation calls for XCO_2 to be measured to a precision of less than 2 ppm and must be made with minimum biases from aerosols, dust, or clouds. This paper discusses algorithms for minimizing the impact of thin clouds on remote measurements of CO_2 obtained from an intensity-modulated (IM) continuous-wave (CW) laser absorption spectrometer (LAS) that is under development for the ASCENDS mission.

A prototype ASCENDS LAS measurement system, called the Multi-frequency Fiber Laser Lidar (MFLL) was tested during two flight campaigns in 2011 using an encoded intensity-modulated (IM) continuous-wave (CW) modulation scheme to minimize the impact of thin clouds on CO_2 measurements. MFLL has demonstrated the ability to simultaneously measure CO_2 and O_2 number density columns using wavelengths near 1.57 and 1.26 µm, respectively. The MFLL also simultaneously measures range to the surface. Ultimately, these three components are combined to produce a dry air equivalent column mixing ratio (XCO_2).

This paper describes the encoded thin cloud rejection modulation technique, presents preliminary flight test results for encoded modulation technique, and discusses algorithms for minimizing bias from thin clouds on CO_2 retrievals.

Measurement System Architecture

The Multi-frequency Fiber Laser Lidar (MFLL) measurement system is an Intensity Modulated-Continuous Wave (IM-CW) Laser Absorption Spectrometer (LAS)

The IM-CW LAS transmitter consists of a Distributed Feedback Diode (DFB) and modulator for each wavelength, λ_1 to λ_n.

Each wavelength is uniquely coded (modulated) with a range encoded signal.

Modulator outputs are combined before amplification by Fiber Amplifier (FA) gain modules.

FA outputs are not coupled, are continuously monitored, and are imaged in the far field.

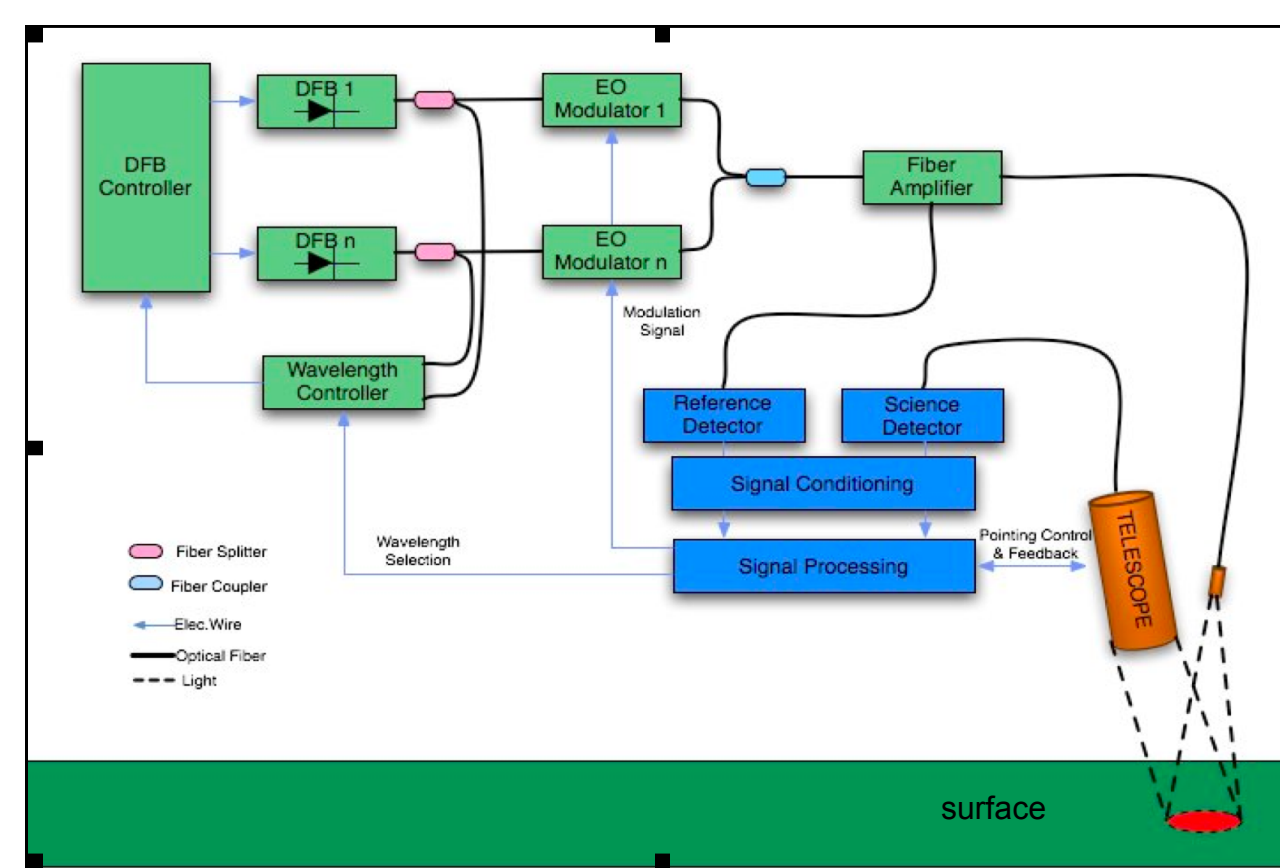Simplified Functional Diagram of the Multifunctional Fiber Laser Lidar

The LAS receiver consists of a distributed telescope, an optical bandpass filter, APD detector fabricated in HgCdTe and low noise amplifier.

Each wavelength, λ_1 to λ_n, is readily separated by demodulation of the electrical subcarriers in a common receiver.

Simultaneous transmission and detection of all wavelengths allows noise from the atmosphere, target and, sensor to be a common-mode term that is readily removed in signal processor during the calculation of differential absorption ratios ($\lambda_{on} / \lambda_{off}$).

Detection and signal processing of FA output provides provide a continuous measure of the LAS instrument response function.

For additional detail, see poster #154.

Limitations of "Pure" CW Measurements

Ground return at modulation frequency f provides expected signal from range R.

Cloud return, also at frequency f, provides interfering signal from range R-d.

Relative phases determined by difference in altitudes, d.

$$\phi \approx 2\pi \cdot d \cdot \left(\frac{2 \cdot f}{c}\right)$$

Combination of phase delayed signals causes cloud return to confuse or obscure the ground return (desired signal)

Worst case error is when d reults in phase cancellation of expected signal.

Note: Real clouds produce a "distributed return" and are unlikely to produce exact phase cancelation.

Range encoding of the modulation signal may permit differentiation between cloud return and ground return.

Encoding for Multi-Path Fading and Cloud/Aerosol Discrimination

During flight tests on the LaRC UC-12 aircraft in May-June of 2011, several approaches for range encoding on the MFLL signal were evaluated including Pseudo-Noise (PN) encoding, Stepped Frequency Modulation, and Swept Frequency Modulation.

In each of these methods, the intensity (amplitude) modulated CW transmitted signal is modulated with a range encoded signal. To remove aerosol/cloud bias, the MFLL must discriminate against signal return everywhere except at the surface S.

The Swept Frequency Modulation technique is similar to "intensity-modulated, stepped frequency cw lidar" demonstrated by Simpson/ORN; here, every wavelength is encoded with a 'Swept Sweep' modulation. The swept modulation signal is applied to each wavelength, but with a fixed delay in time. "Lock-in" performed for expected frequencies at time delay corresponding to range r = S.
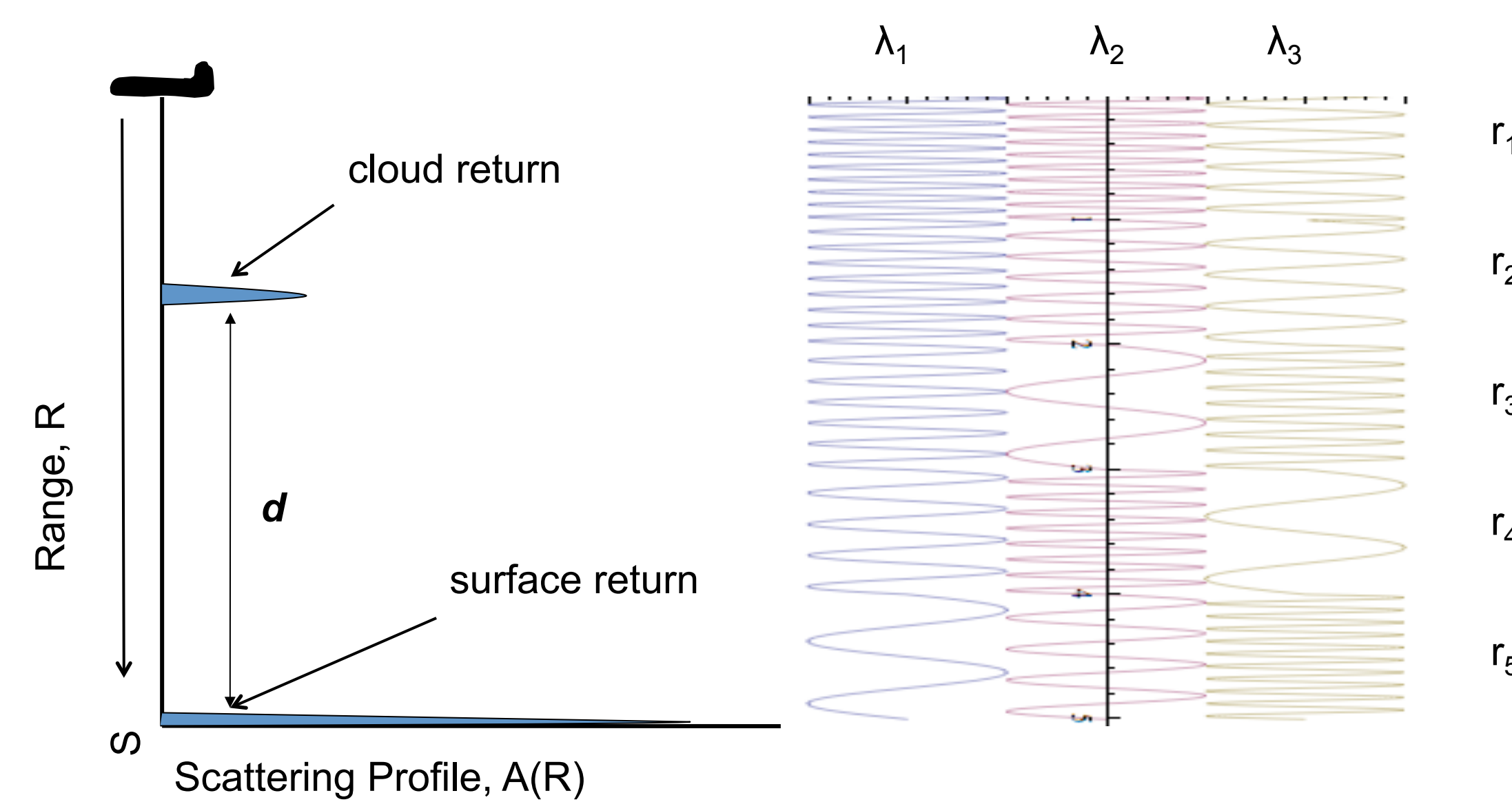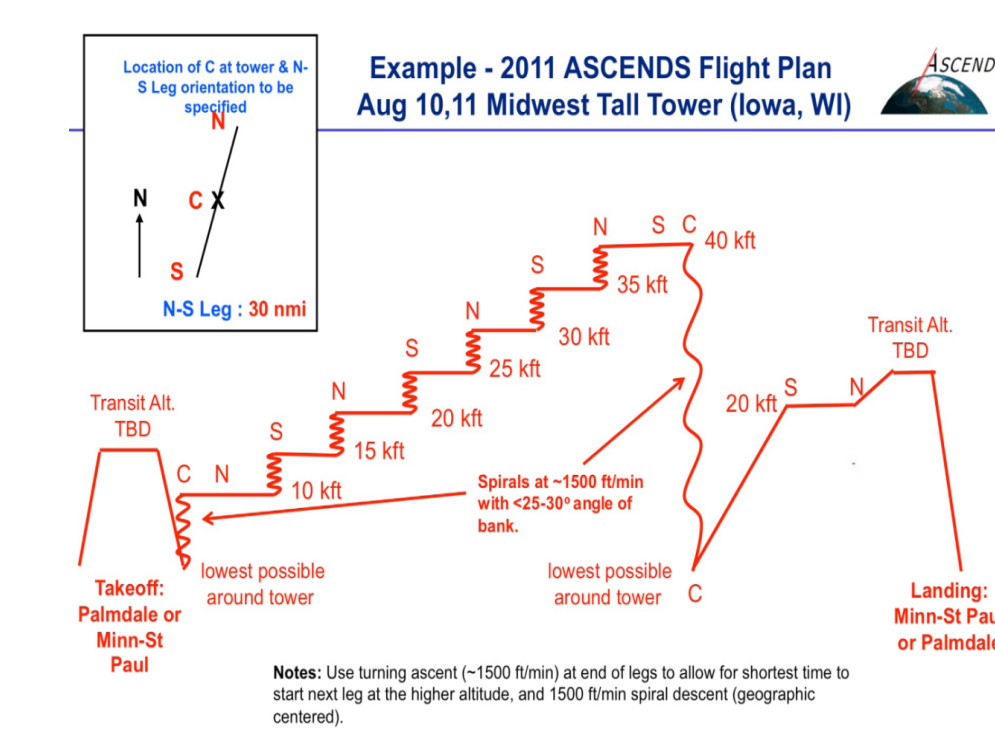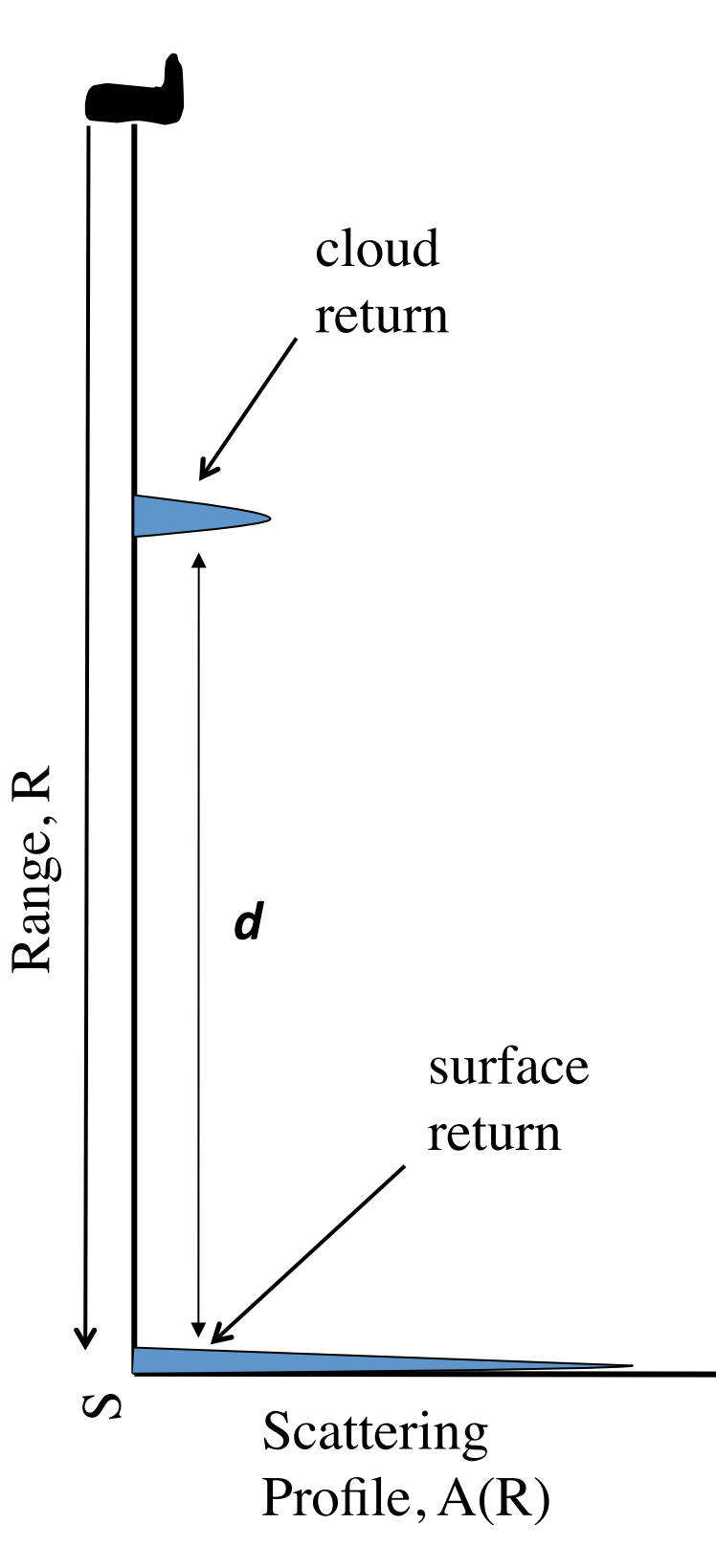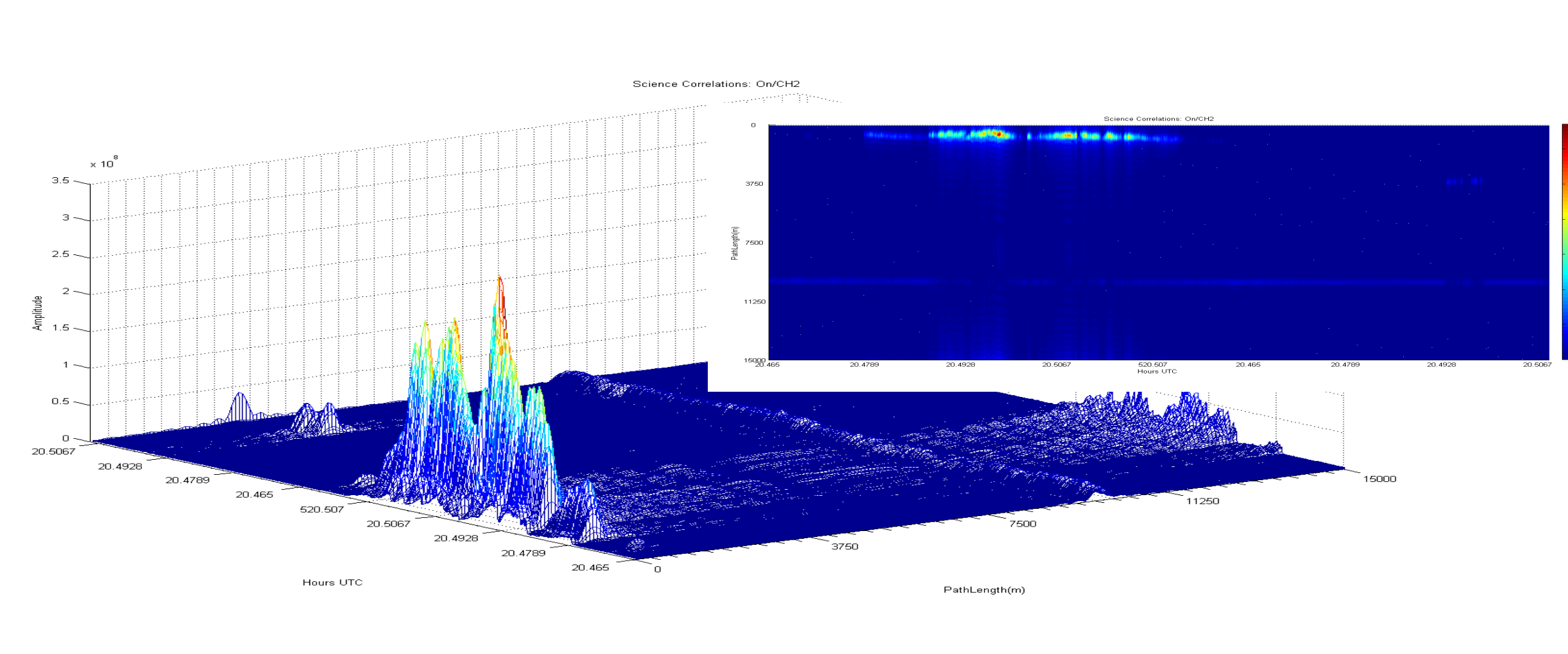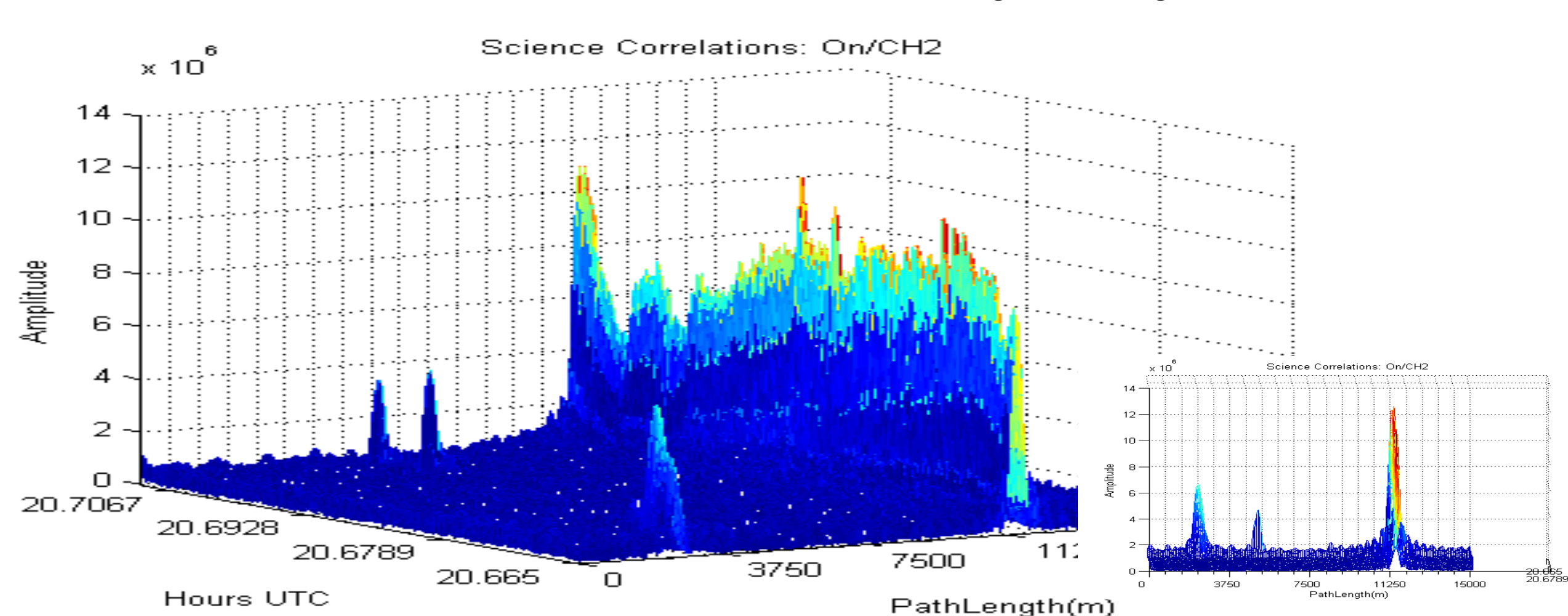

Measurement Validation

During 42 hours of flight tests on the LaRC DC-8 aircraft (left) in July-Aug of 2011, an extensive data set of CO_2 columns measurements were obtained. The MFLL instrument (right) used the Swept Frequency Modulation technique and measured CO_2 columns in clear air and cloudy conditions over a variety of surfaces including snow and ice.
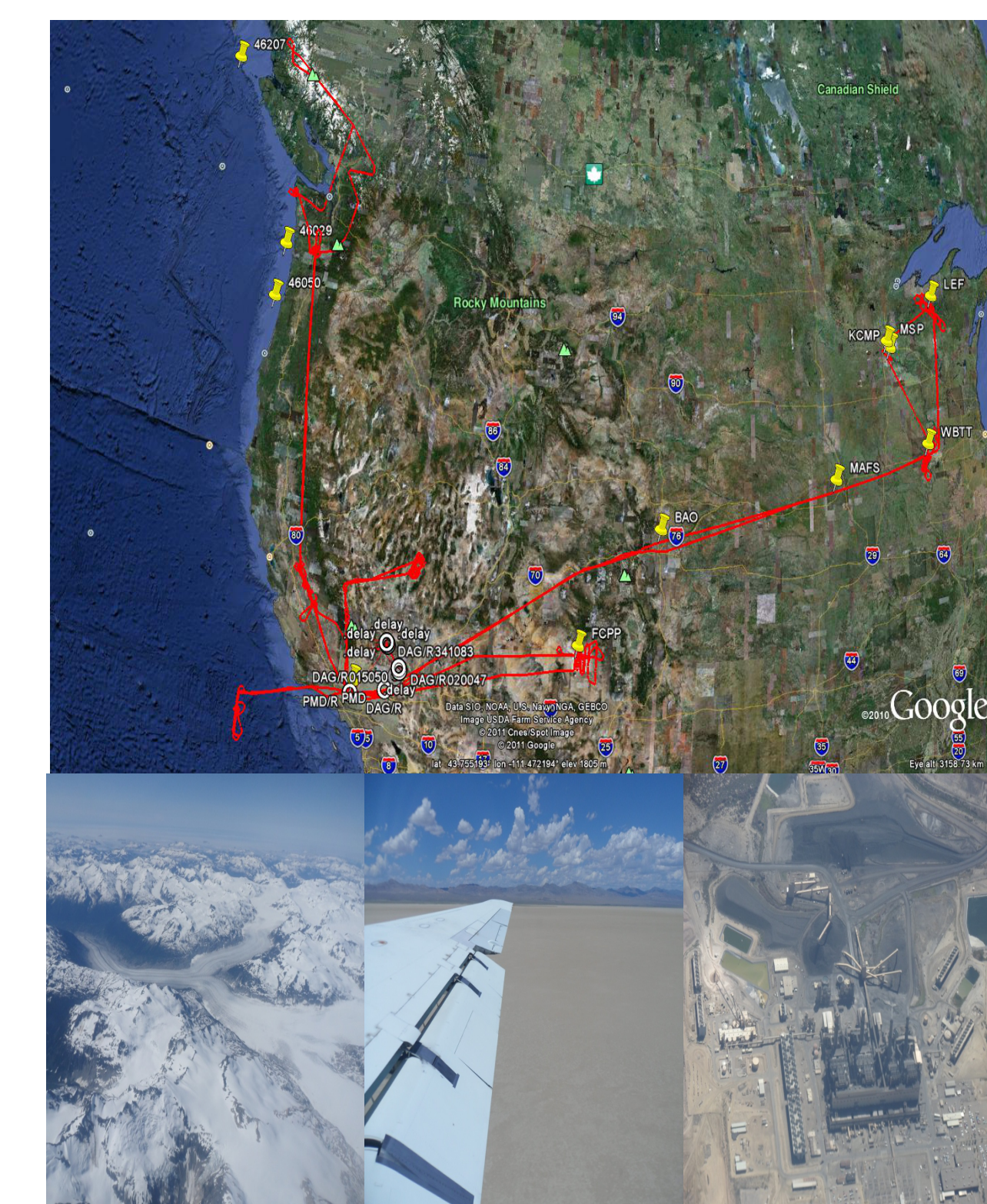
Eight flights were conducted on the DC-8 including
1. Engineering - Central Valley of California
2. Science 1 – Clear and smoke filled boundary layer near Sierra mountains (Central Valley of CA)
3. Science 2 – Pacific Ocean Stratus Clouds (off CA Coast)
4. Science 3 – Railroad Valley NV (plus scattered clouds and snow patches)
5. Science 4 – Snow & ice (northern WA & southern British Columbia)
6. Science 5 – Power Plant (Four Corners NM area)
7. Science 6 – CO_2 agriculture drawdown & CO_2 tower (Eastern IA)
8. Science 7 – Forested Area near the WLEF CO_2 tall tower (Park Falls, WI)

Typical flight profiles included measurements at altitudes from 3 to 13 km (in ~3 km steps) and spirals to near surface. High accuracy in-situ data, traceable to WMO standards, were obtained during spirals made as close as possible to the center of the track. The in-situ data is used to estimate the integrated column optical depth.

Range Measurements

Off-line returns obtained during science flight 5 on Aug 9, 2011 near Four Corners NM are shown Figure 1. The measurements were obtained from 17.355 – 17.365 UTC while the DC-8 was operating at 15-kft in clear air conditions.

The off-line return correlation power is displayed as a function of time and range from the aircraft. The peak of the return is ~3120 meters below the aircraft. Note the variations in return power due to changes in surface reflectivity.

Figure 1: Clear air returns over Four Corners, NM.

Figure 2 shows a single representative off-line return at a slice in time thru Figure 1. By "tracking" the position of the peak signal return, a measure of the range (pathlength) to the surface is obtained.

For these first demonstration of range discrimination and tracking techniques, the MFLL detector was digitized using a 2 mega samples/sec A/D converter. By fitting the instrument response function to output of the lock-in amplifier, the range resolution is enhanced over the 75 meter implicit resolution dictated by the sample rate. This demonstration used swept-frequency modulation with frequencies spanning 100 to 600 kHz.

Figure 2: Off-line return power.

The current MFLL implementation includes a pseudo-noise encoded altimeter for determining the path length to the surface. In Figure 3 the range measurements obtained from the PN altimeter are compared to the estimates obtained by tracking the CO_2 off-line return.

From 17.355 – 17.365 UTC, the surface elevation as measured by the PN altimeter changes ~100 meters. The range estimating using the encoded CO_2 signal compares well to the PN altimeter but with a small consistent bias.

Figure 3: Range estimated obtained from the off-line return and time coincident returns from the on-board PN altimeter.

Cloud Bias

Figure 4: Time history of on-line lock-in outputs.

Figure 5: Intensity map of lock-in output.

On-line lock-in returns obtained during science flight 3 on Aug 3, 2011 over Railroad Valley, NV are shown Figure 4. The measurements were obtained from 20.694 – 20.708 UTC while the DC-8 was operating at 40-kft.

In addition to the surface return from ~11500 meters, two optically thick clouds can be seen ~5000 meters below the DC-8 during 20.702 to 20.706 UTC. The ground return is significantly reduced when optically thick clouds are present as shown in Figure 5.
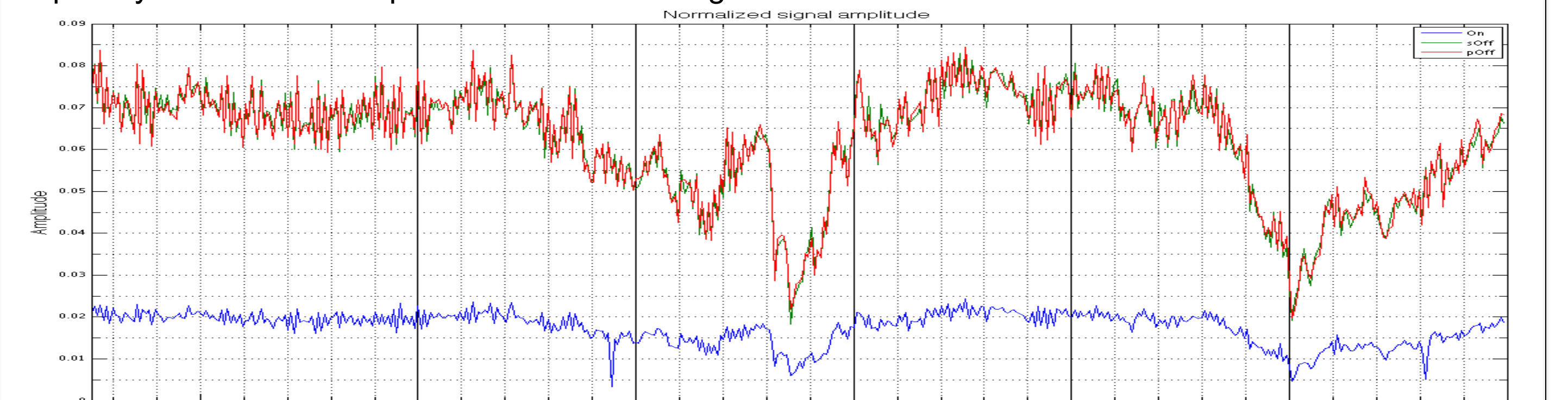
The normalized lock-in signals amplitudes, i.e. science/reference, are attenuated by optically thick clouds during the intervals after 20.6988, most significantly near 20.7014 and 20.706.
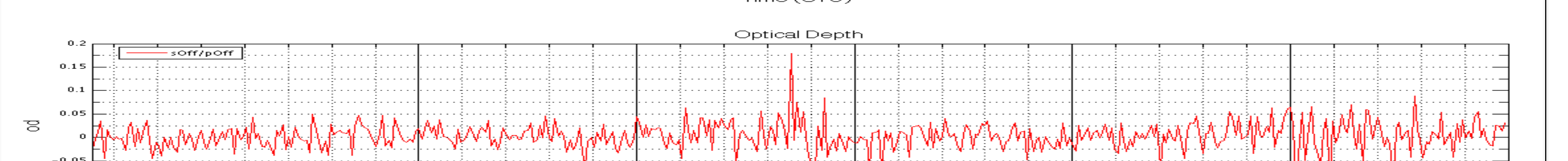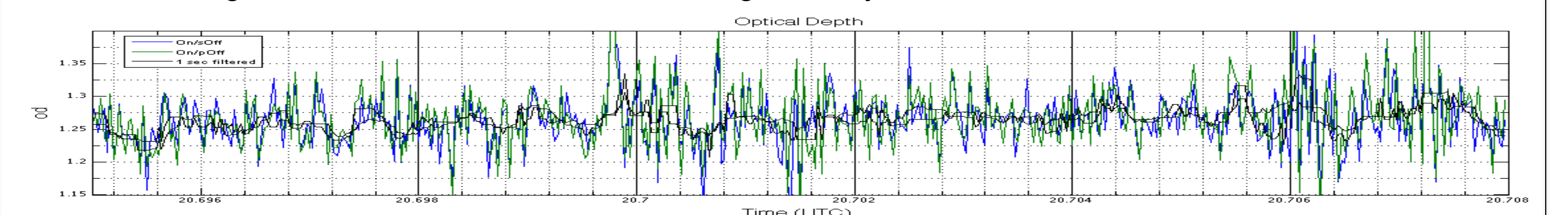
Mean optical depth shows little change in this cloudy region other than a reduction in signal to noise due to the attenuation of the signal.

Thin Cloud Error

Clouds introduce a bias in the standard "sinusoidal" lock-in approach due to phase cancellation from cloud returns. By adding encoded modulations that allow range discrimination, the desired return from the surface reflection of the transmitted signals can be obtained. The example here is MFLL data obtained during flights over Railroad Valley NV on August 3, 2011. The panels at left show MFLL returns obtained from an altitude of 12500m where a near-field cirrus cloud can be seen at ~20.67 UTC. The 2D insert shows the surface return at ~11300 and the near-field cirrus at ~2250 m. At ~20.7 UTC two more optically thick could can be seen at 4500 m below the aircraft. The panels of the left were obtained while the DC-8 was flying at 35k ft and show a near field cloud centered at 20.5 UTC. The 2D insert show that the ground signal is attenuated too sev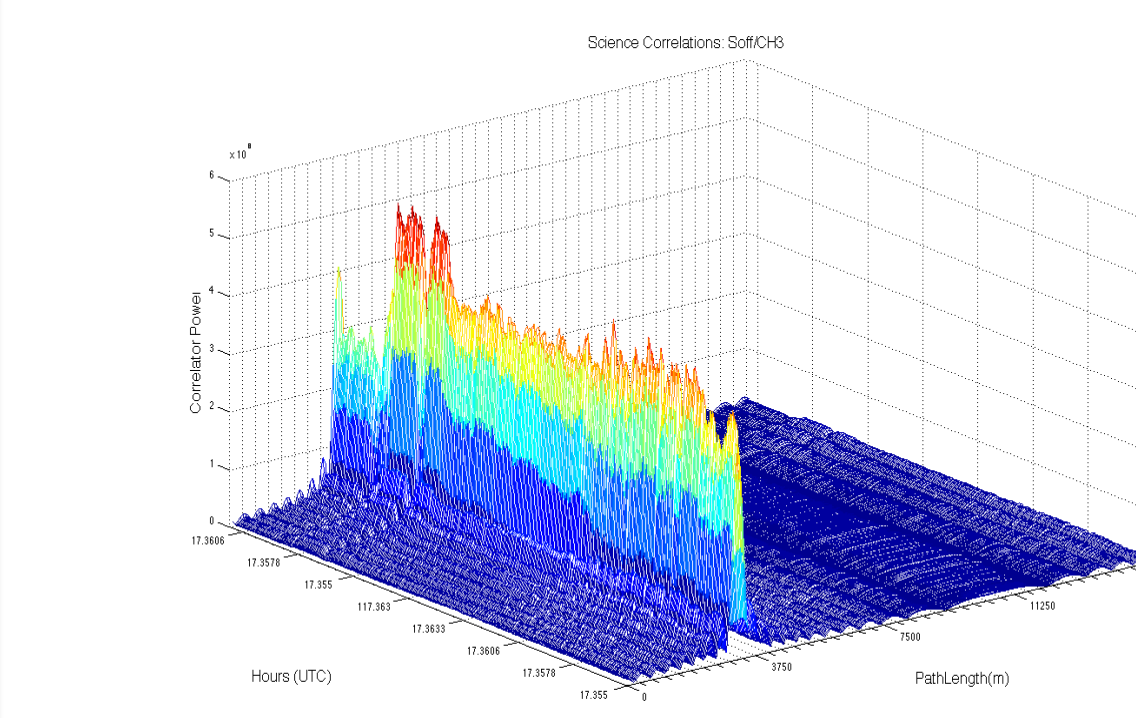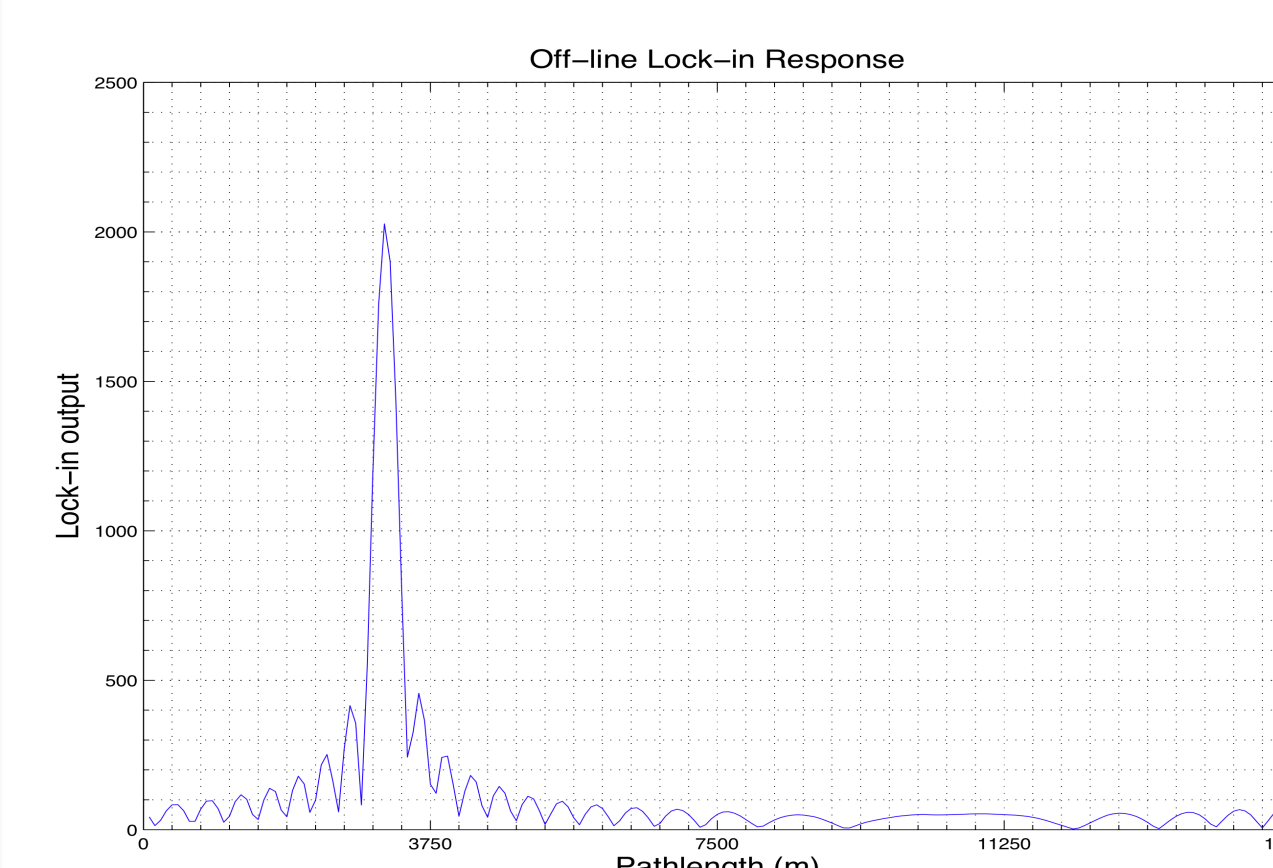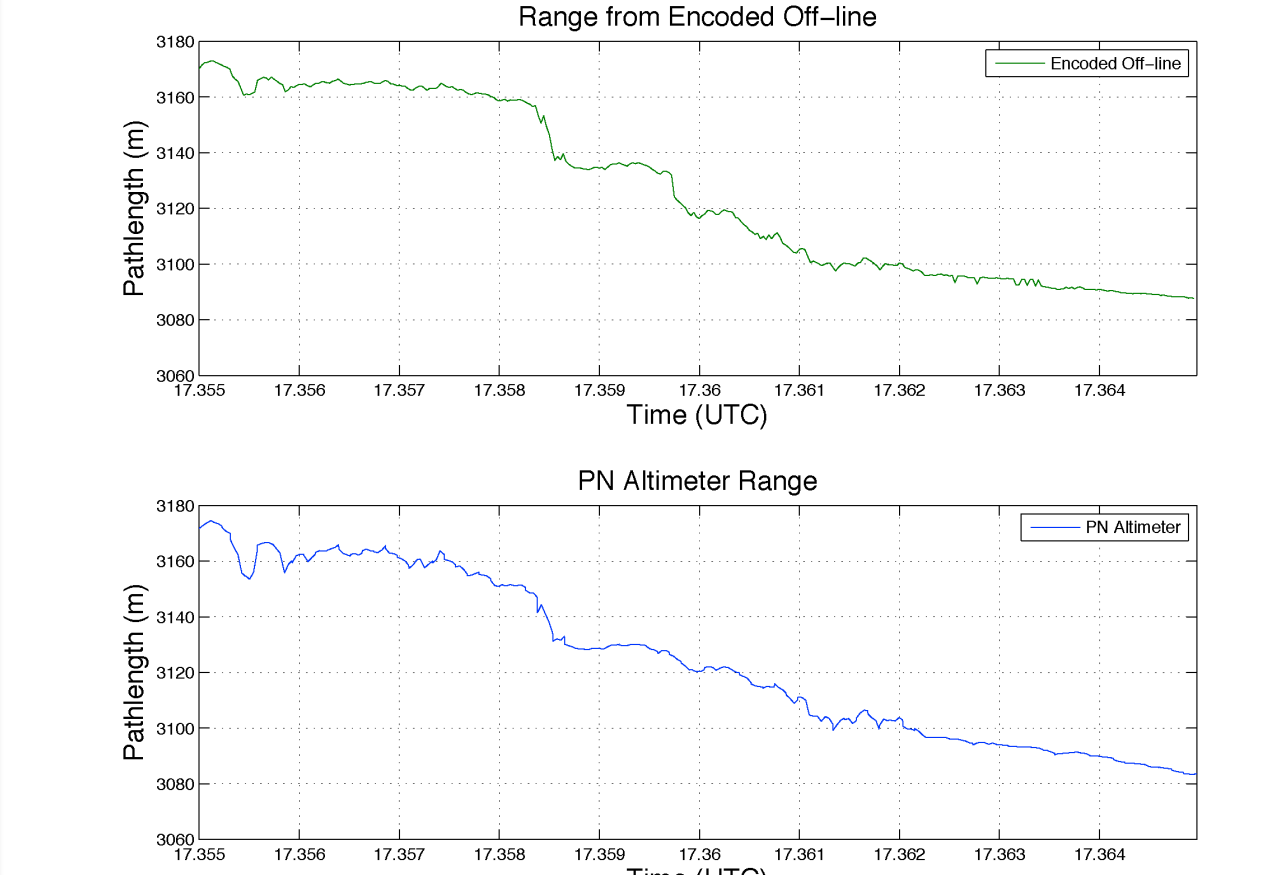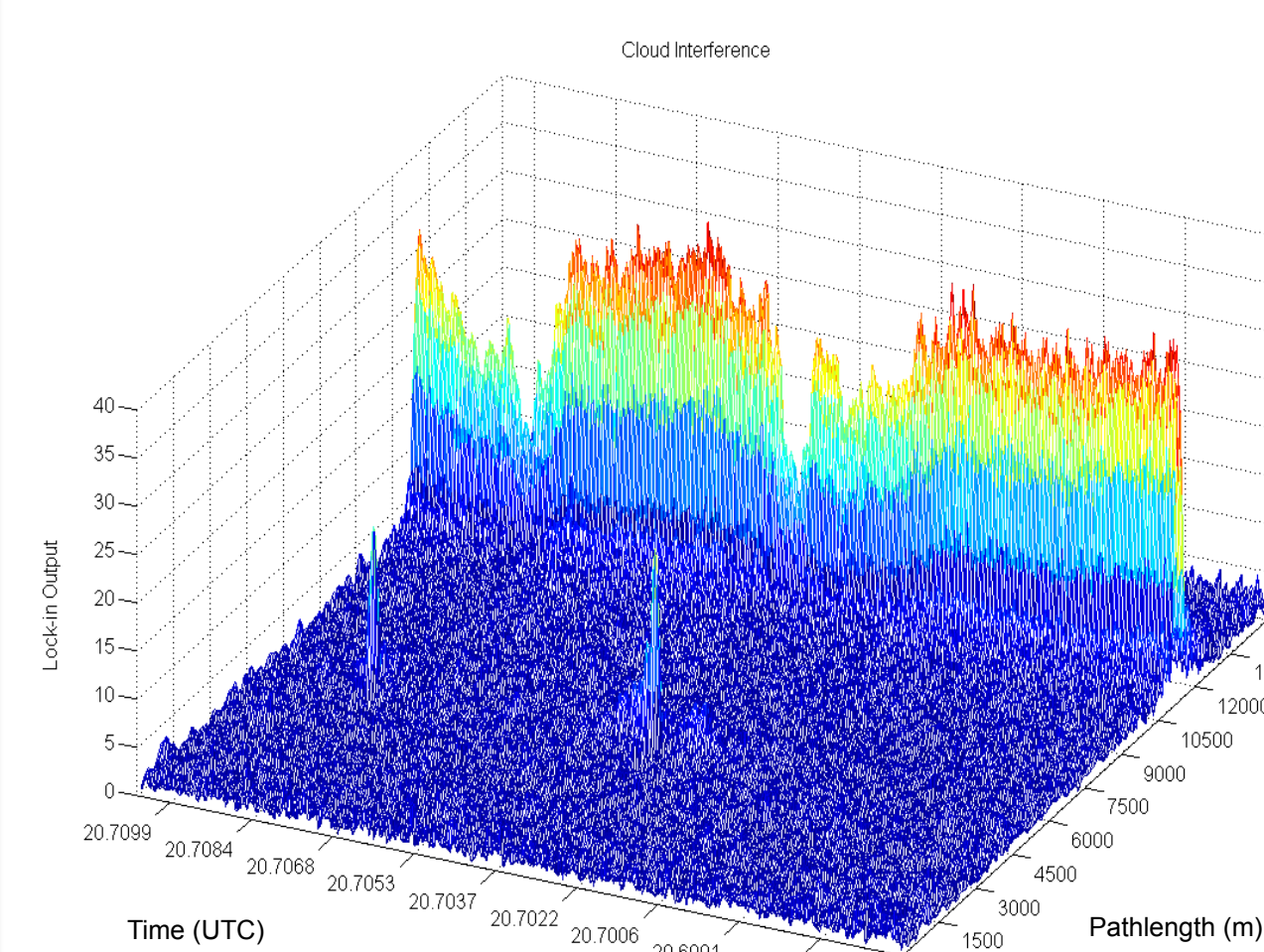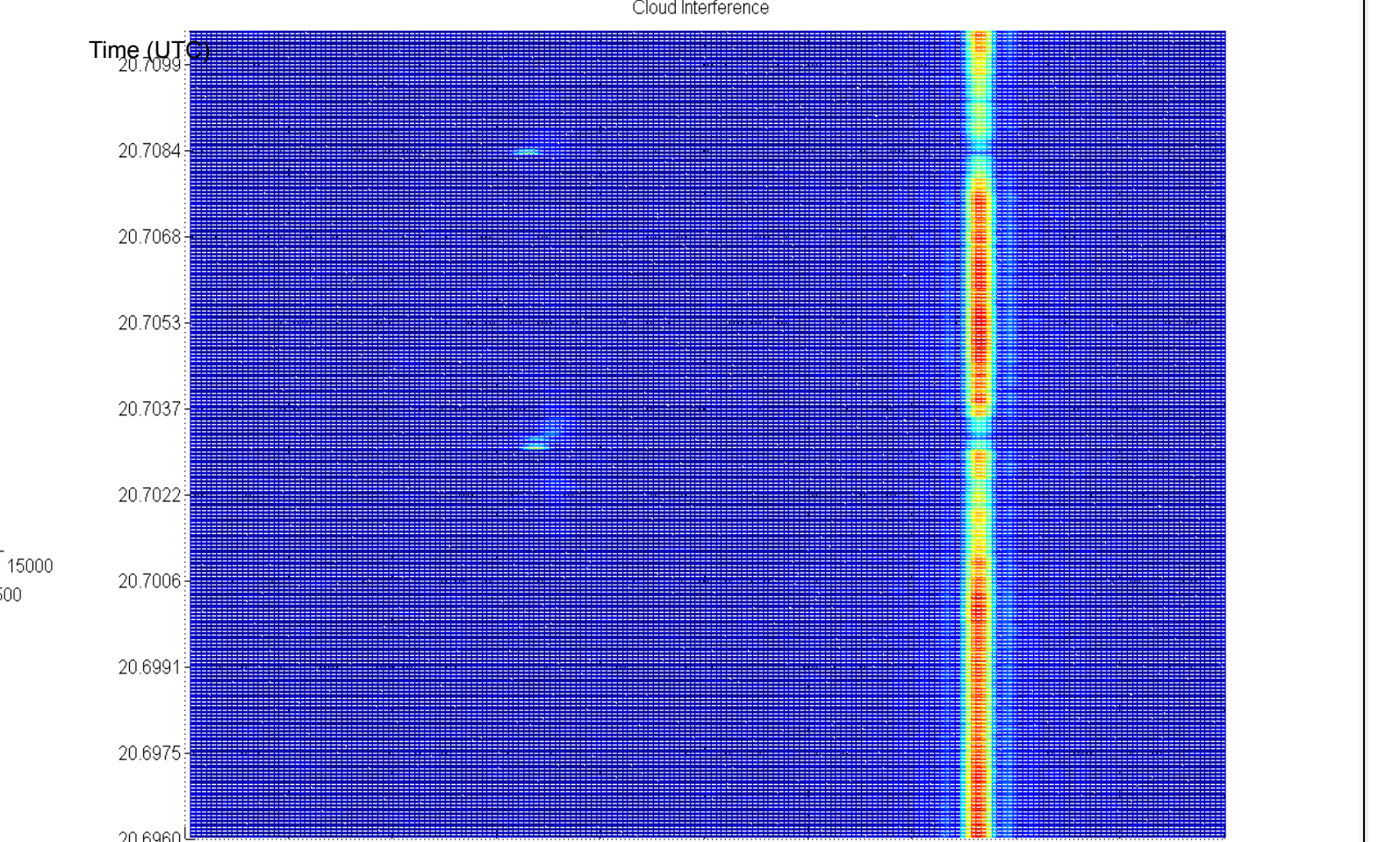erely for a viable measurement.