



Seasonal Polarimetric Measurements of Soil Moisture Using Tower-Based GPS Bistatic Radar

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Outline



- The results of GPS surface reflection measurements observed from the 300-m tall ETL Boulder Atmospheric Observatory (BAO) tower are described.
- In this experiment the first seasonal measurements of bare soil moisture from a stationary location using bistatic reflection were performed. Several receiving antennas offering various gain and polarization sensitivities were used.
- By observing from a fixed tower over low grass the roughness of the reflecting area remains constant, hence variations in the signal are uniquely related to changes in the dielectric permittivity, and therefore, to soil moisture.
- Seasonal retrievals of soil-moisture content from multi-polarization GPS reflection data is presented and compared with *in situ* soil moisture measurements.

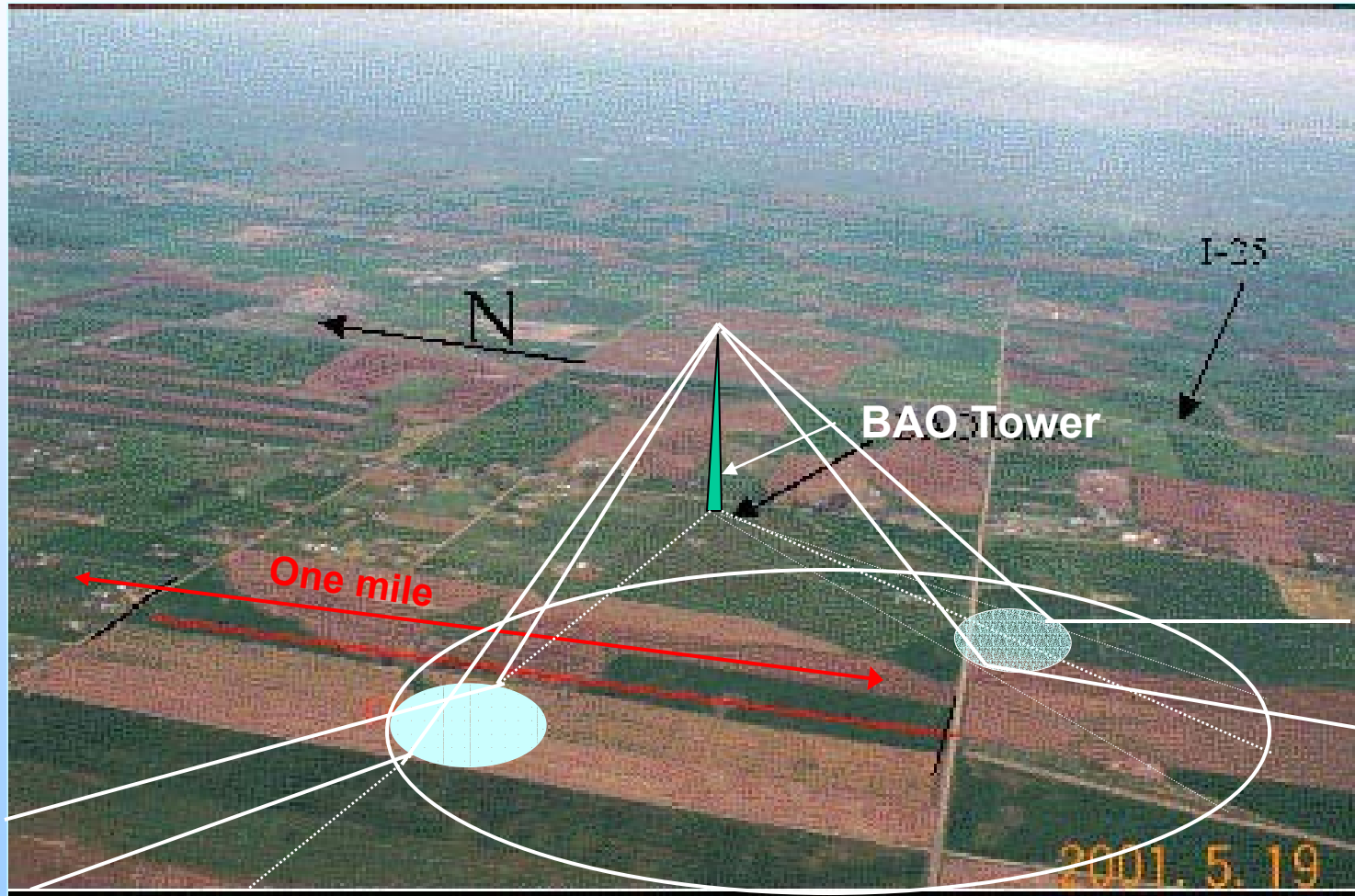


Introduction



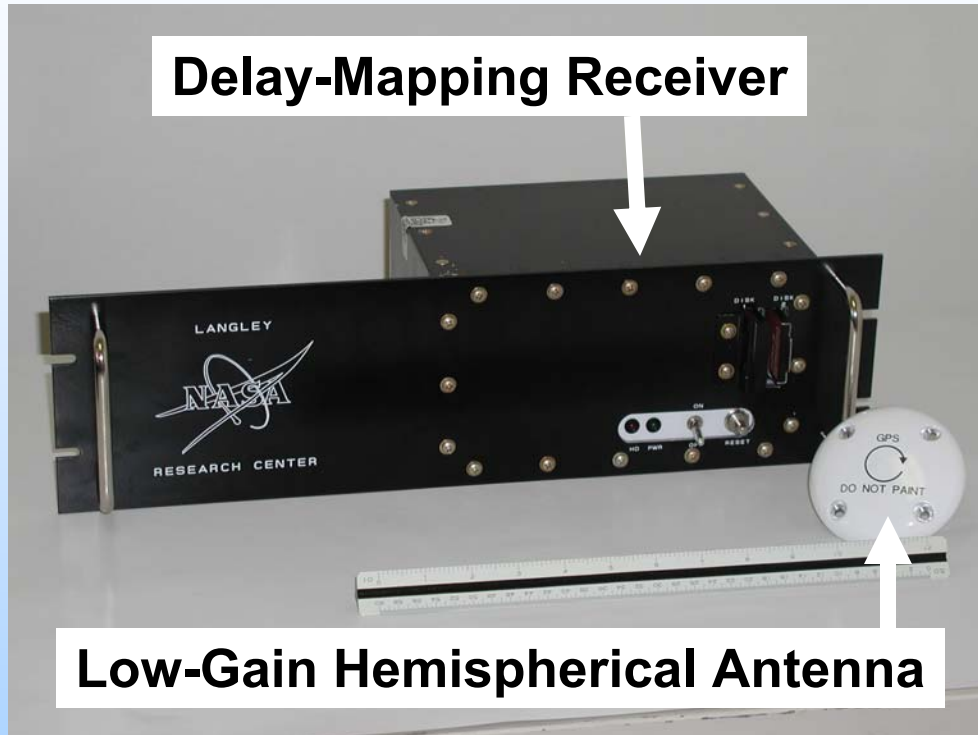
- Knowledge of soil moisture (SM) over wide areas is essential for many applications, e.g., crop yield expectation, prediction of potential flood hazards, air quality, and local weather forecasts.
- Remote sensing methods such as passive radiometers and active radar sensors are considered suitable for SM mapping because conventional *in situ* soil moisture measurement techniques are both localized and expensive.
- Attributes of using GPS signals of opportunity as a means of active airborne bistatic sensing of SM include:
 - The omnipresence of GPS signals during all weather conditions,
 - The low cost of GPS receiver technology compared to alternative remote sensing systems,
 - The civilian signal frequency of 1.575 GHz is also nearly optimal for SM sensing.

Geometry of the BAO Tower GPS Reflection Experiment





- A modified GPS navigation receiver was mounted on top of the 300-meter NOAA ETL Boulder Atmospheric Observatory (BAO) tower near Erie, CO ($40^{\circ}03'00.1''$ N, $105^{\circ}00'13.8''$ W).
- The stationary tower observation geometry facilitated seasonal measurements of GPS reflections from the same area of land, thus excluding signal variability due to changing roughness and vegetation cover scenes.



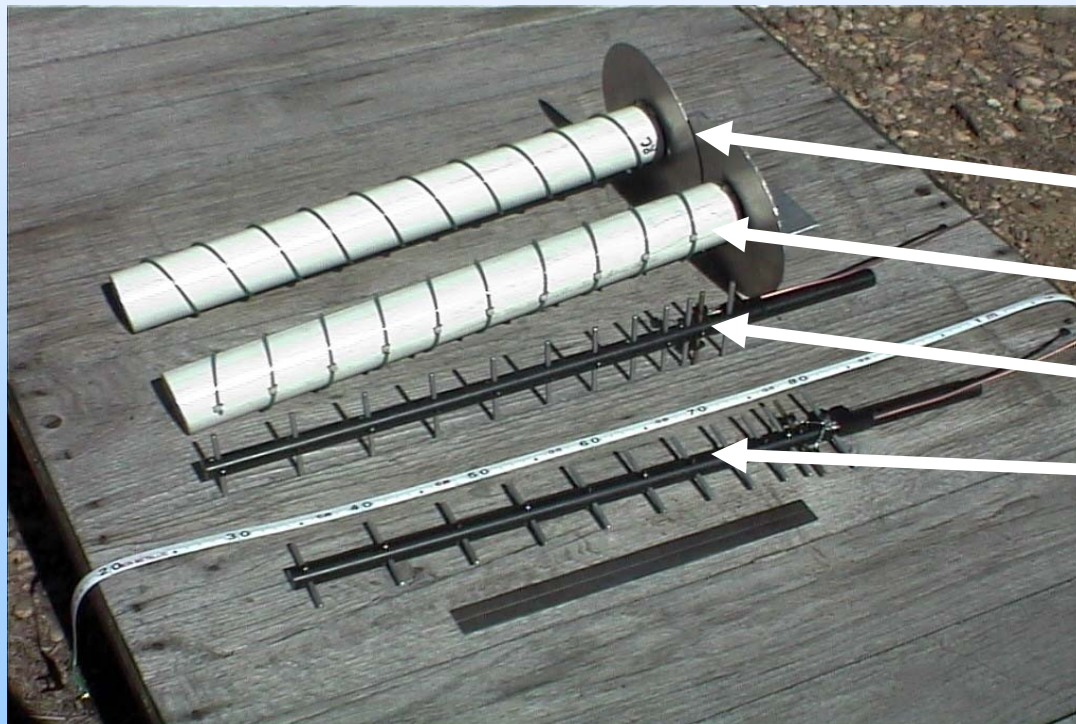
The receiver, provided by the NASA Langley Research Center, tracked the direct line of sight satellites using a low-gain zenith-oriented right hand circularly polarized (RHCP) antenna and recorded the cross correlation function of the reflected signals using an alternating series of surface-oriented antennas.

Instrumentation (cont'd)

The surface-oriented antennas consist of:

(a) a low-gain hemispherical left hand circularly polarized (LHCP) antenna;

(b) four endfire high gain (~ 12 dB) V, H, LHCP, and RHCP antennas



High gain antennas:

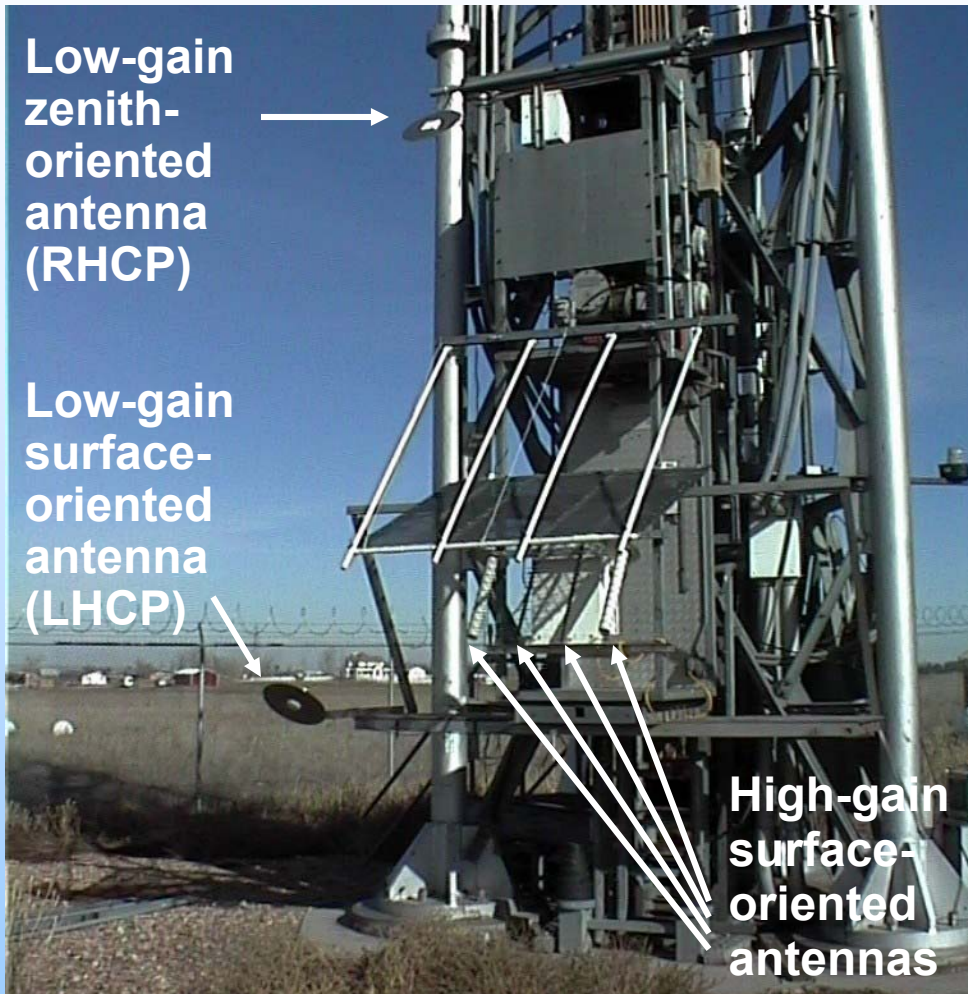
RHCP

LHCP

Vertical Pol.

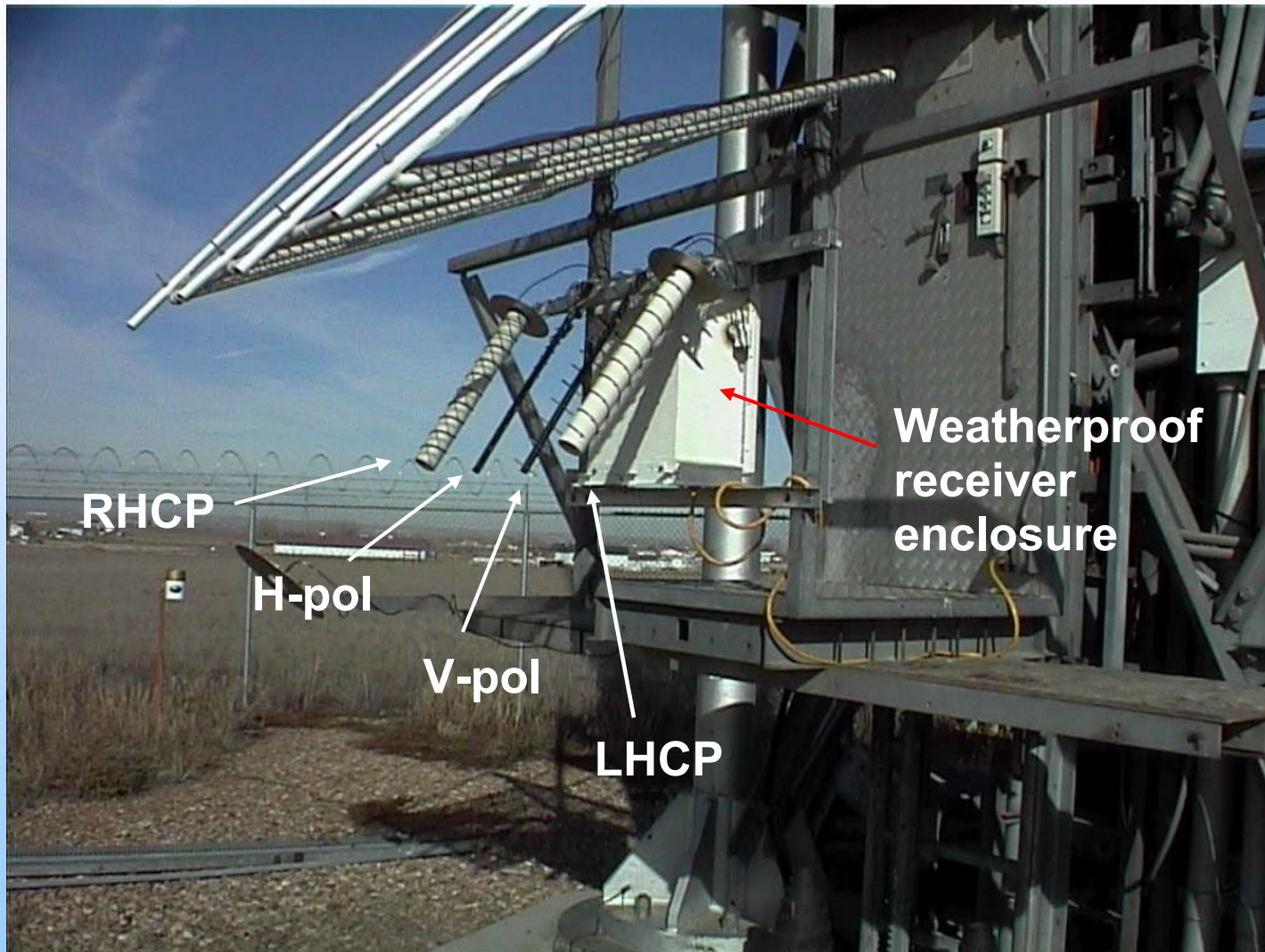
Horizontal Pol.

Instrumentation (cont'd)



The orientation of all surface-oriented antennas was 35° from nadir for the incident angle, and 245° for the azimuthal angle.

Instrumentation (cont'd)





Measurement Technique



- Each GPS satellite signal is coded with a unique pseudorandom noise (PRN) code designed to produce an autocorrelation function confined within ± 1 code bit transition, or code “chip.”
- Reflection of this incident signal from a rough dielectric surface will produce multiple delayed signals having amplitudes proportional to the power reflection coefficient at each specular point.
- The output of a typical GPS reflection receiver is a cross correlation between a receiver-generated replica of the PRN code and the PRN code of the reflected signal.
- The cross correlation function is generally both wider and lower than the autocorrelation of the direct signal, and carries information about the roughness and dielectric properties of the soil at the specular points.



Measurement Technique (cont'd)



- Cross correlation waveforms for single GPS satellites were continuously recorded in 21 quarter-chip bins for one satellite at a time.
- Accumulation of signals was performed in hardware for fundamental sampling intervals of 1 ms. Batches of length 0.1 s of the sum-square of the in-phase and quadrature waveform components were averaged prior to archival.
- Signals from the surface-looking antennas were sequentially selected using a microwave PIN switch which provided an 8 s total integration period for the low-gain LHCP antenna and a 2 s total integration period for the other antennas.
- To suppress high-frequency Rayleigh fading due to rough surface scattering an additional averaging of the reflected waveforms (after subtracting the noise floor) was performed over a 100-s moving window.

Zone of Reflection

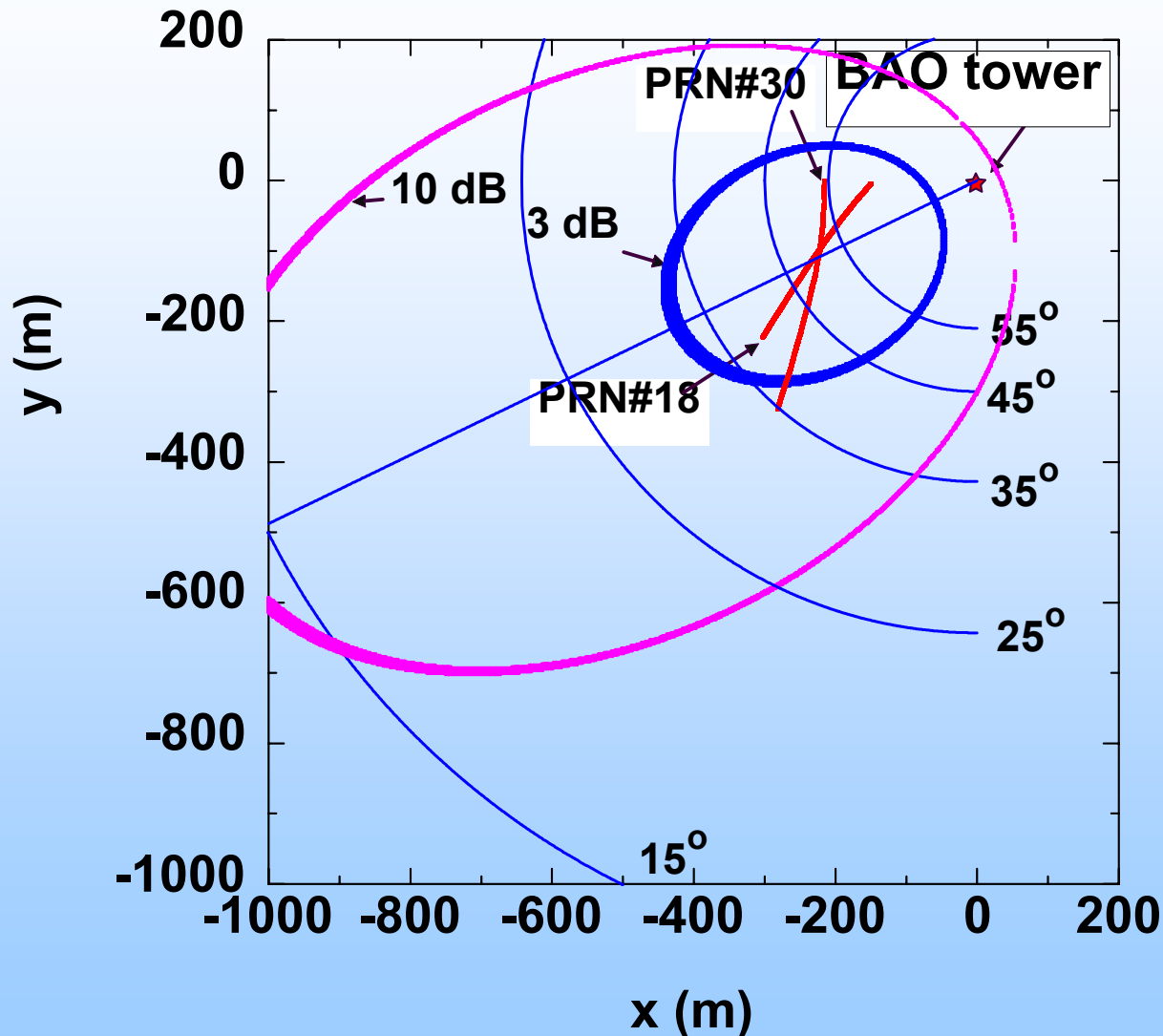


Variations in the signal are uniquely related to changes in the dielectric permittivity, and therefore, to soil moisture because roughness of the area with low grass remains constant.

Reflected signals were recorded only for satellites with reflection ground tracks passing through the high-gain antenna footprint of size $\sim 400 \text{ m} \times 350 \text{ m}$.

The gravimetric wetness of the soil was estimated at 6.0 cm depth using a Campbell Scientific CS-615 time-domain reflectometer. The soil in the uppermost 1.0 m layer at the BAO is heavy clay.

GPS Signal Reflection and Antenna Footprint Geometry



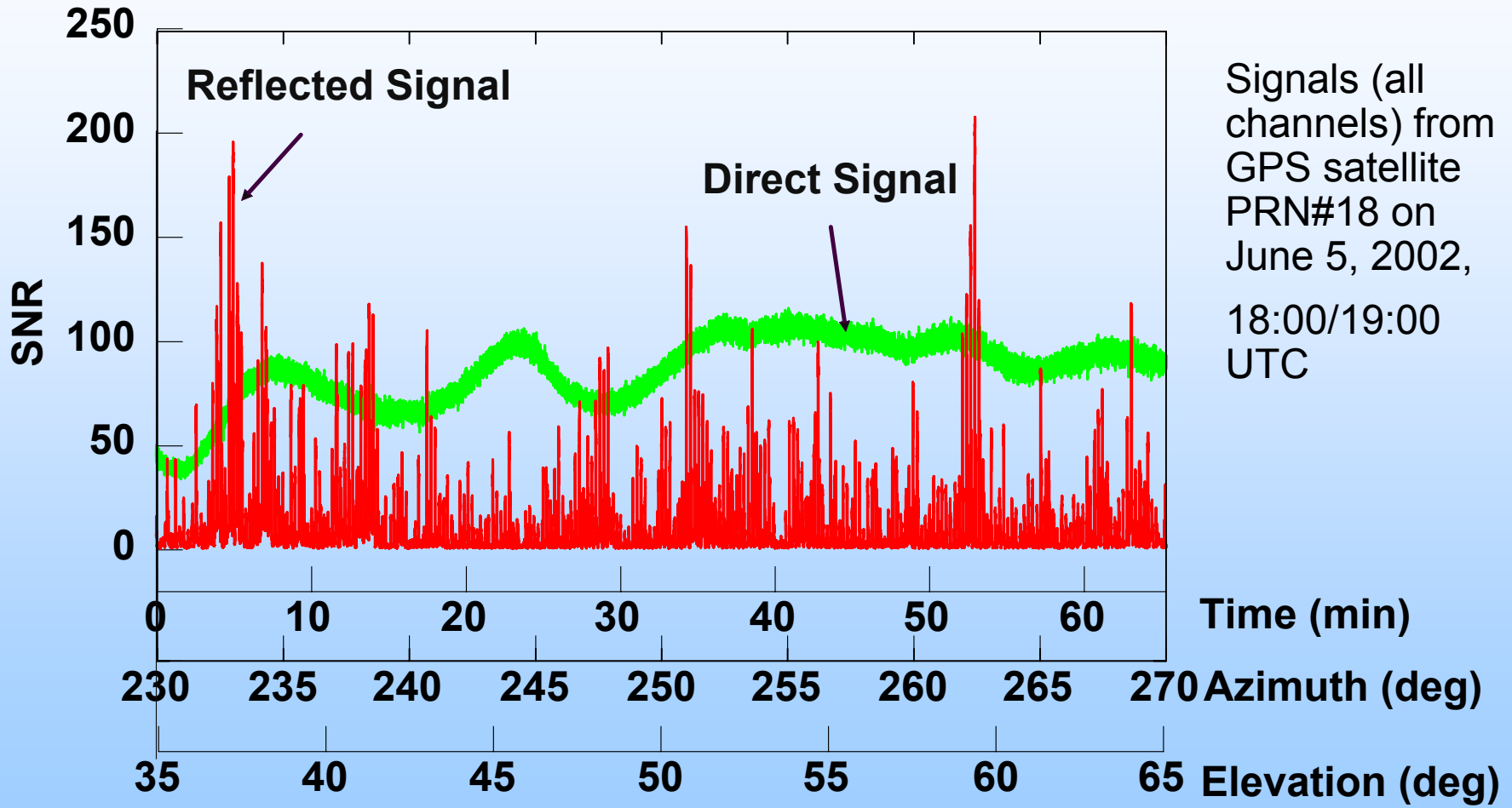
The specularly reflecting points on the land surface provided a set of diurnally repeatable ground tracks.

PRN#18 and PRN#30 were selected for analysis because their tracks passing through the center of the high-gain antenna footprint (3-dB and 10-dB contours shown).

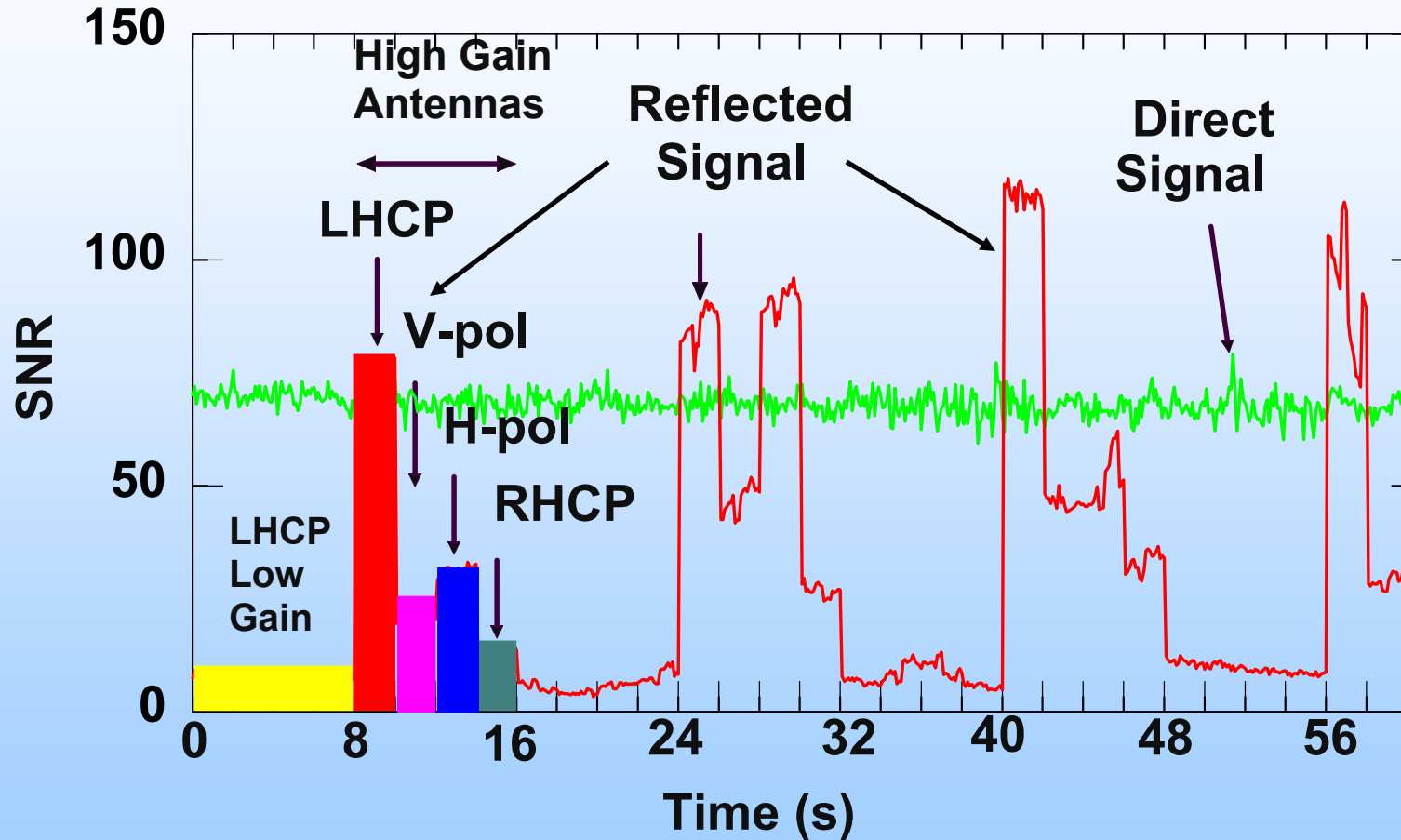
Their reflection tracks are shown for June 5, 2002.



Example of Raw Time Series for Reflected and Direct Signals

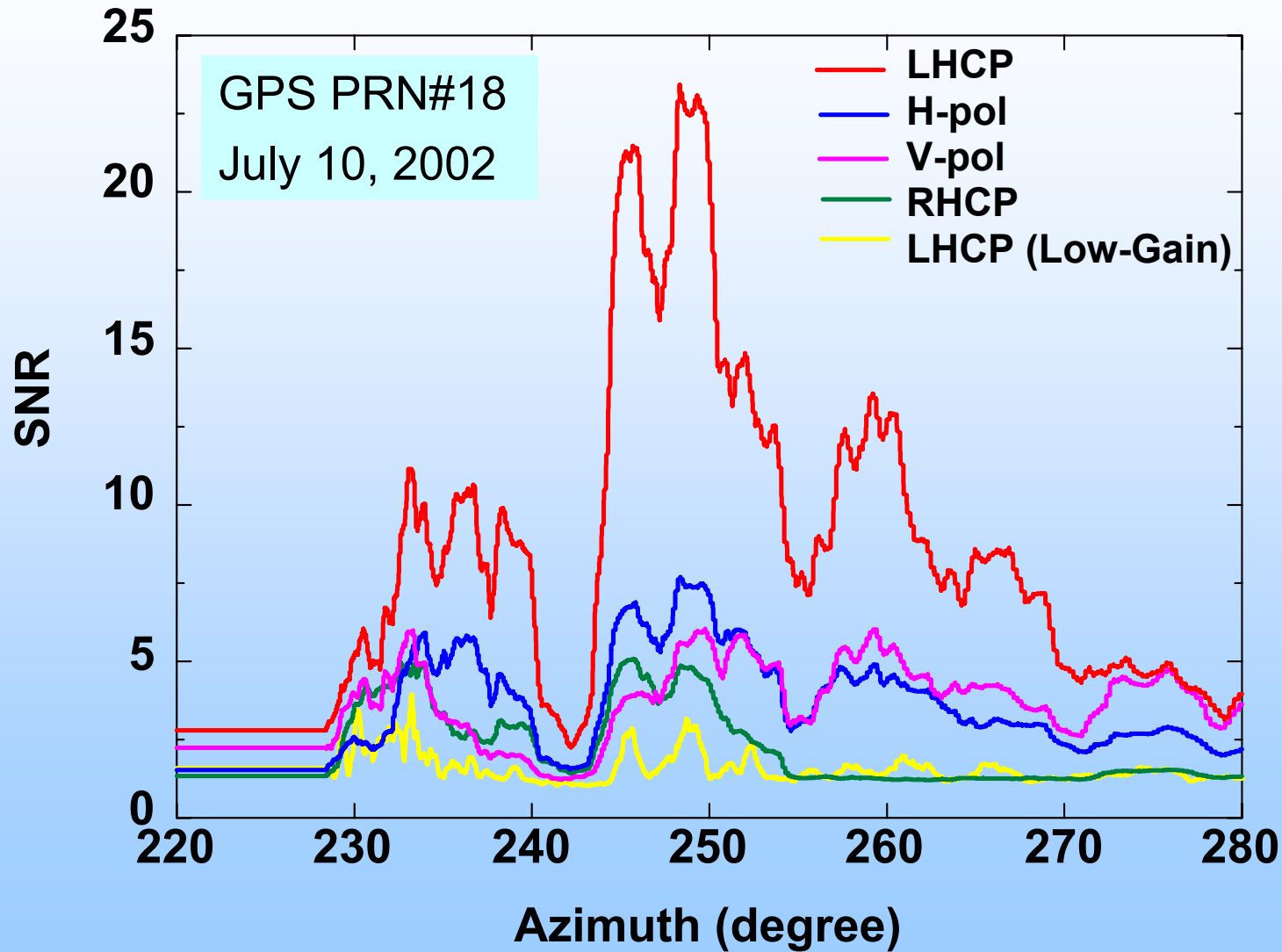


Fragment From the Previous Signal Time Series





Intercomparison Between Reflected Signals Obtained with All Antennas





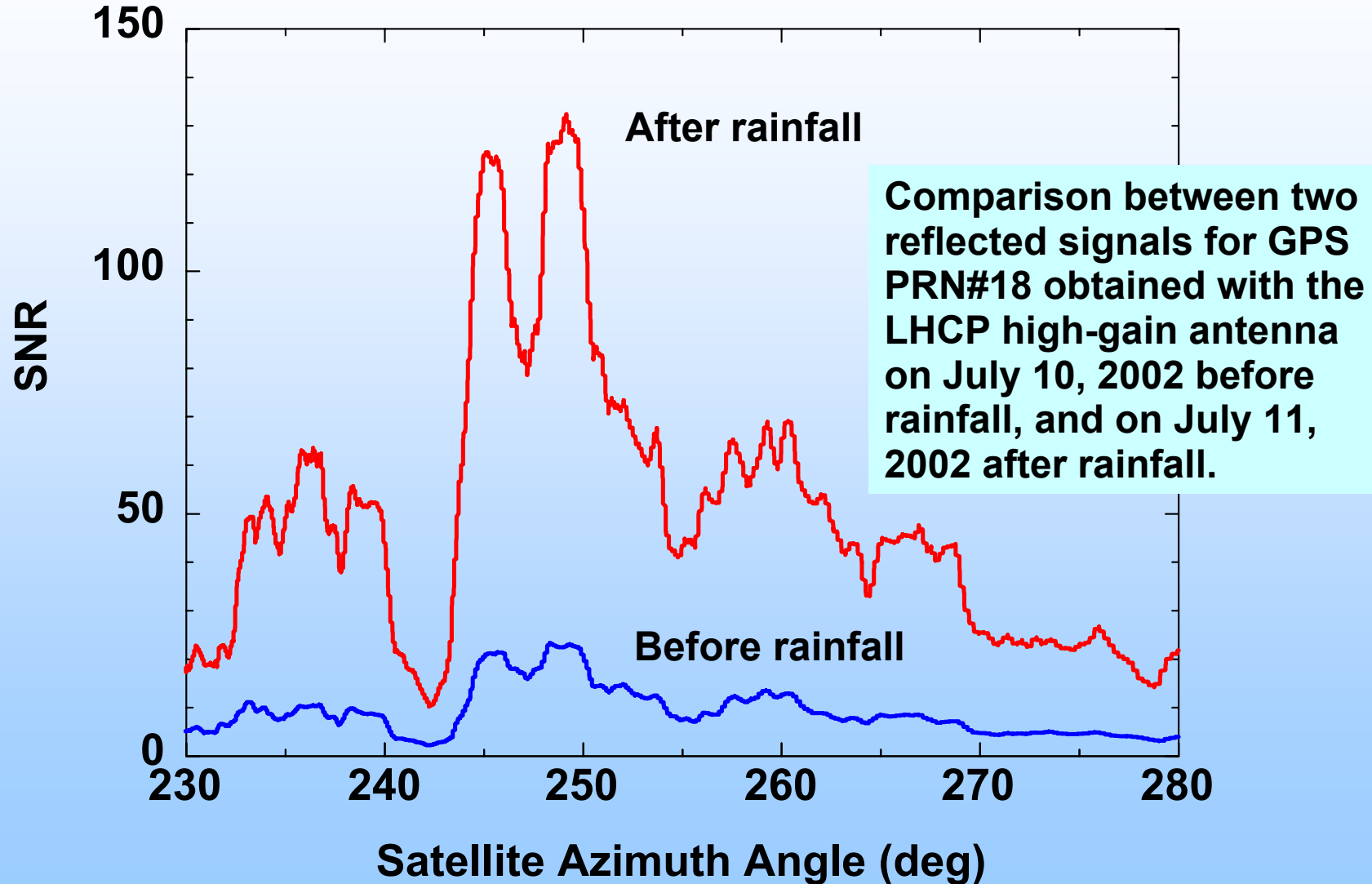
Data Analysis



- The reflected signals were analyzed for several days preceding four local rain events and immediately afterwards.
- An expected rise of the reflected signal power was observed after rain events and subsequent decreases during following dry periods.
- Analogous correlation with rain events was found for other polarization channels. The highest levels of reflected power were the result of a very wet top layer saturated with water or, in some instances, standing water.
- A correlation was found between reflected GPS signal power and *in situ* SM measurements made on days without rain events as water was absorbed by the soil.
- Examples of such data obtained from GPS satellites PRN#18 and PRN#30 using various antennas are presented in the following plots

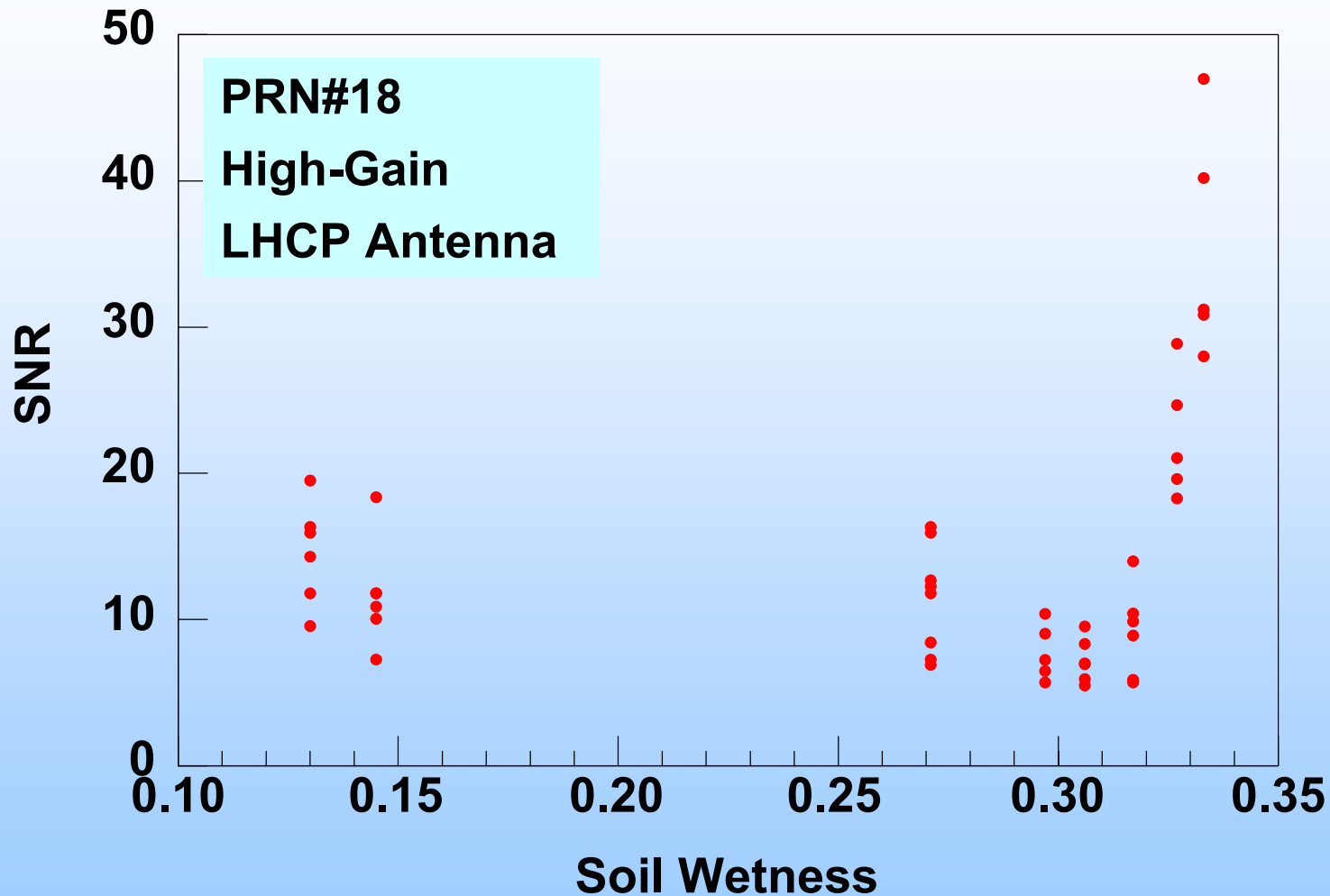


Effect of Rainfall on the Reflected Signal



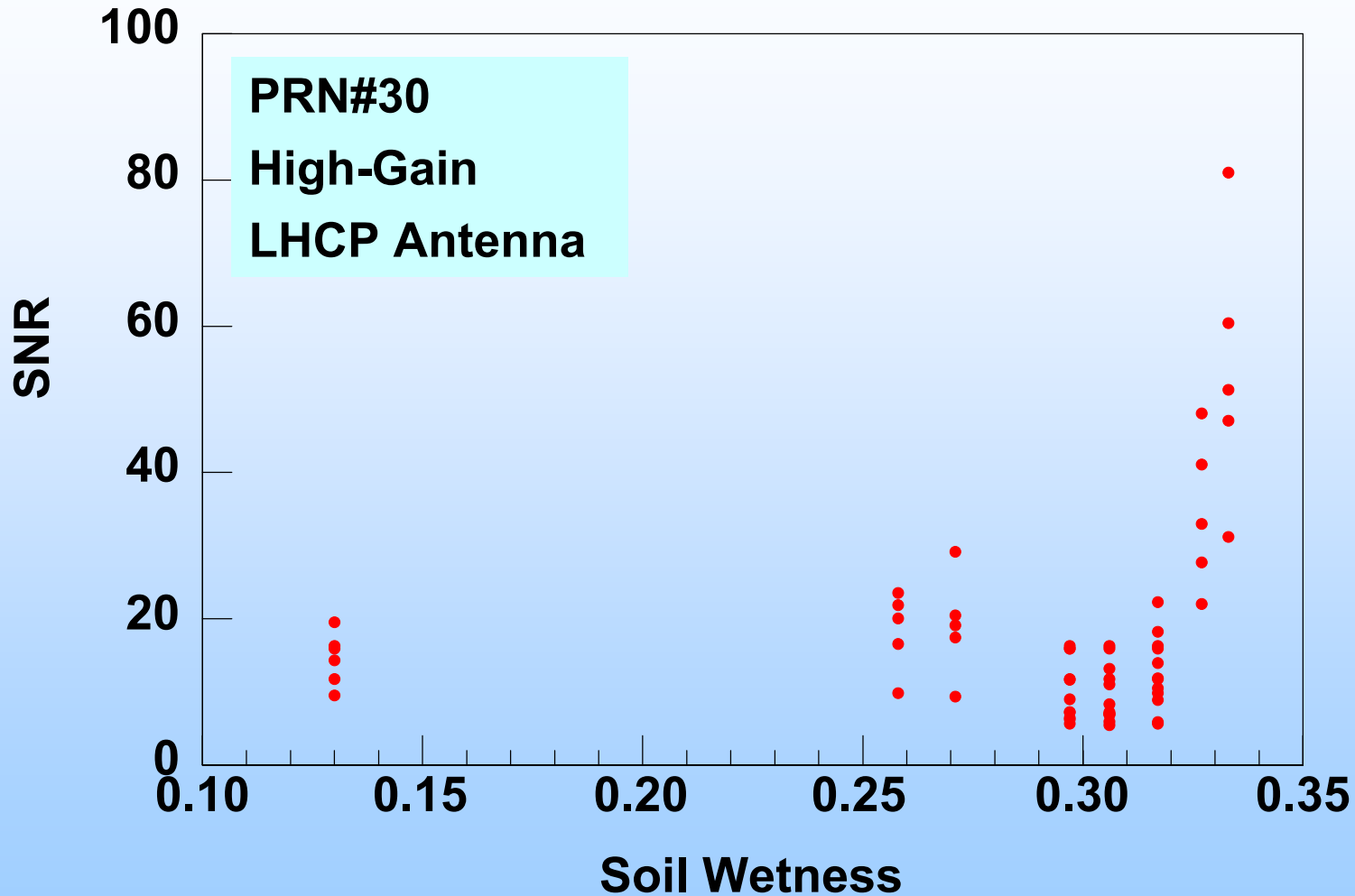


Comparison Between Reflected Signal and *in situ* Measured Soil Wetness (SW)



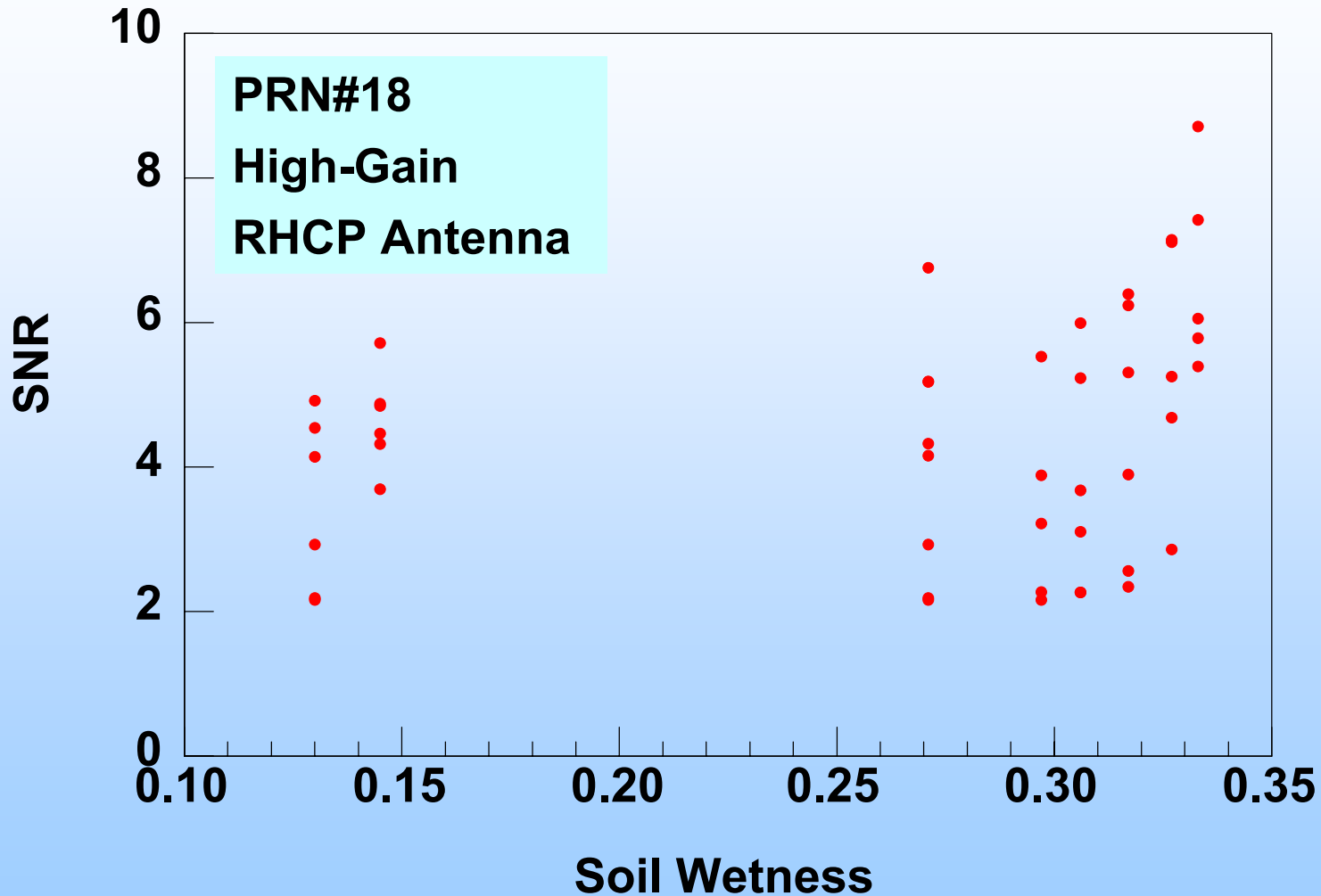


Comparison Between Reflected Signal and *in situ* Measured SW (cont'd)



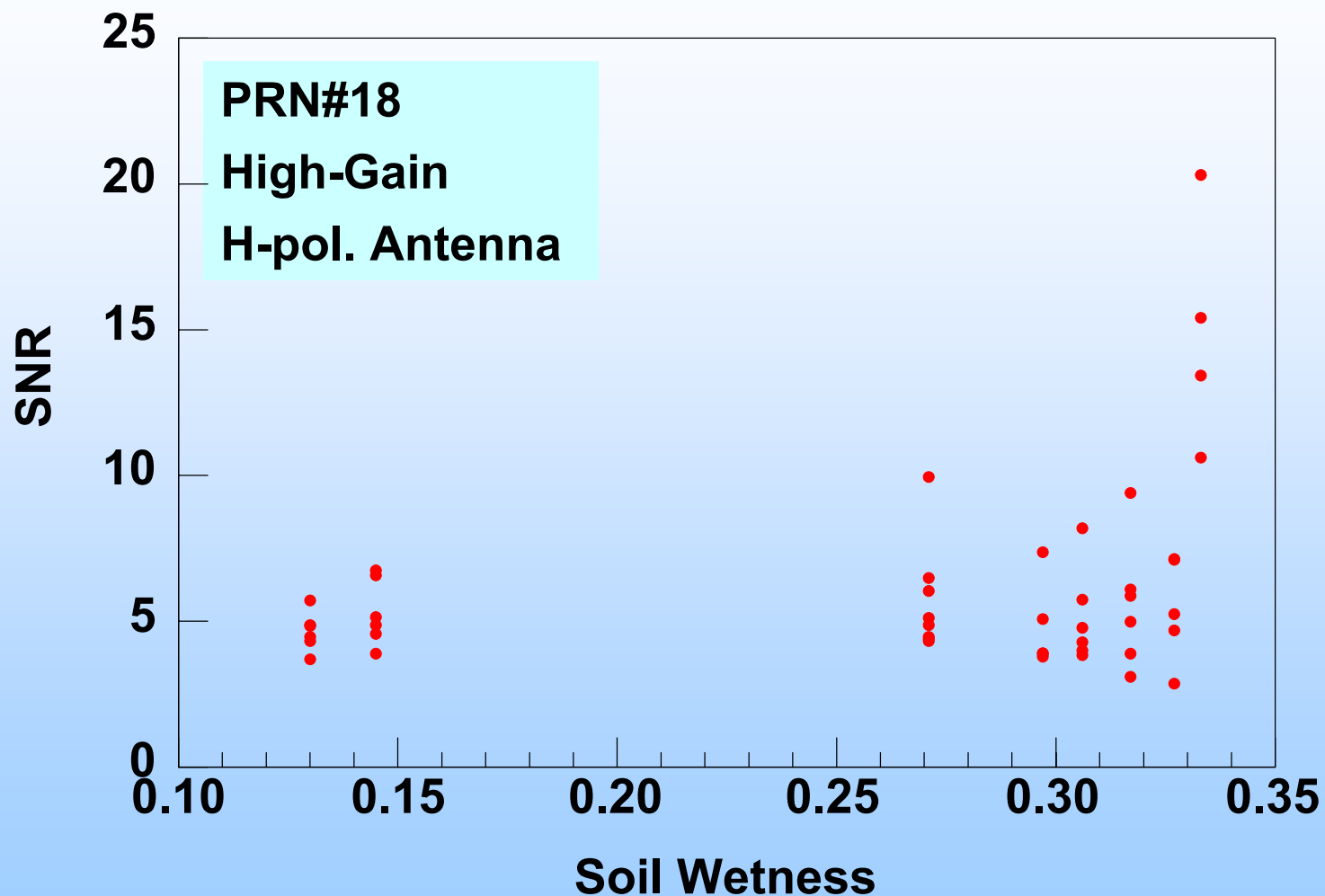


Comparison Between Reflected Signal and *in situ* Measured SW (cont'd)

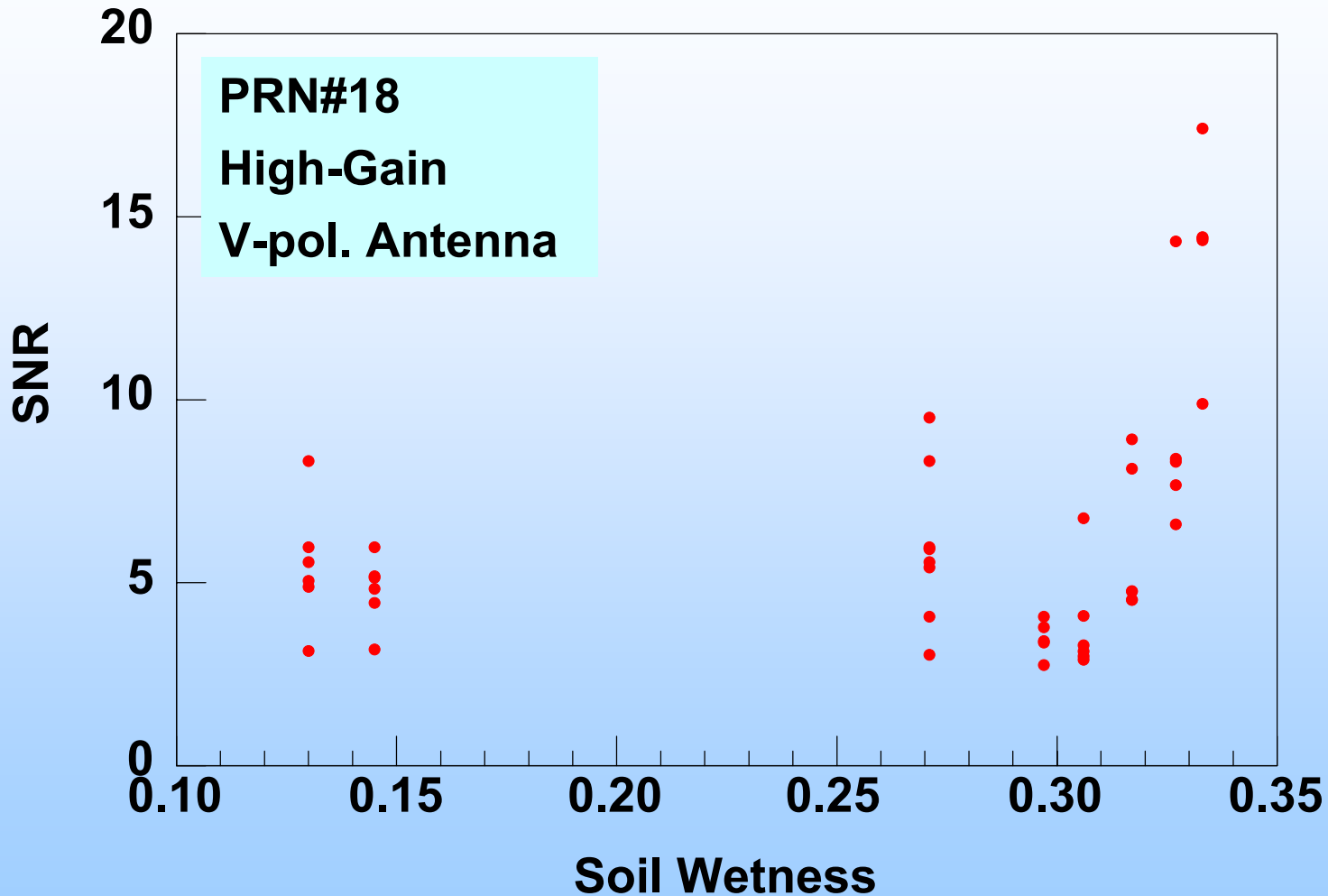




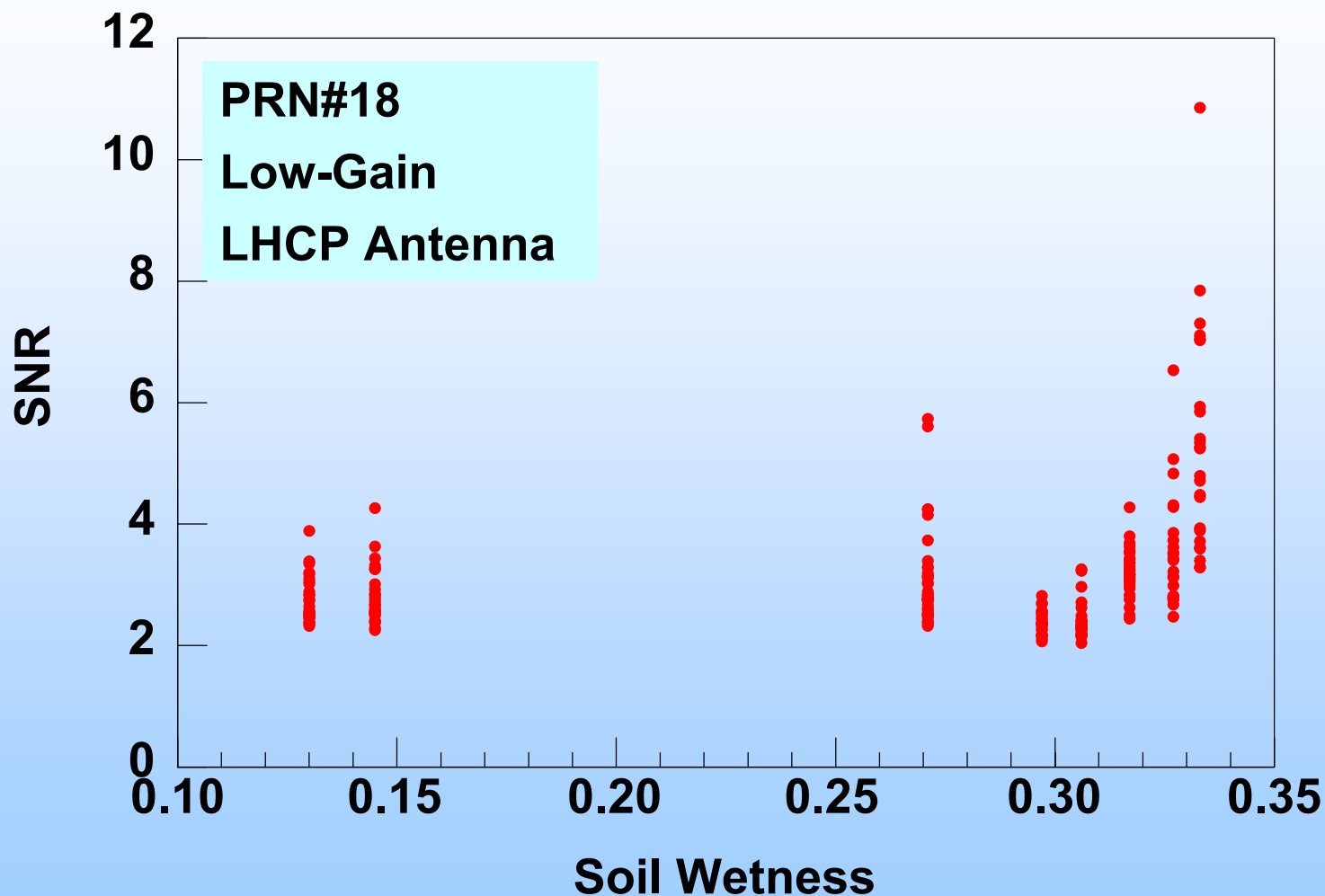
Comparison Between Reflected Signal and *in situ* Measured SW (cont'd)



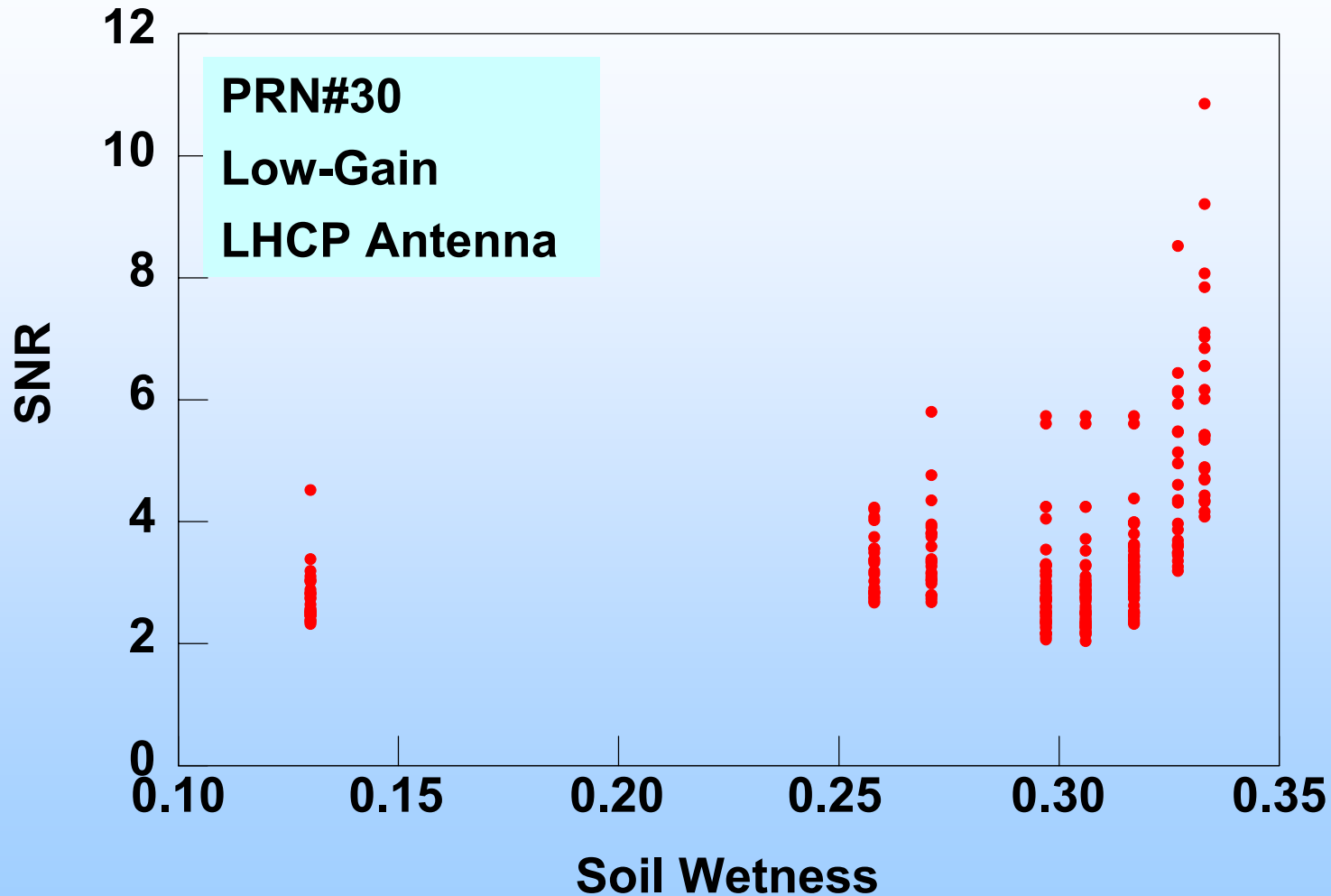
Comparison Between Reflected Signal and *in situ* Measured SW (cont'd)



Comparison Between Reflected Signal and *in situ* Measured SW (cont'd)



Comparison Between Reflected Signal and *in situ* Measured SW (cont'd)





Data Analysis: Summary



- The highest waveform SNR are for the high-gain LHCP antenna with the SNR reaching 50 for 0.33 soil wetness and leveling at 10-13 dB.
- A similar behavior is found for other polarization channels, however, at lower SNR levels.
- An encouraging result is obtained even the low-gain LHCP antenna despite the low gain and possible complications due to multipath.
- The SNR data do not show significant sensitivity to the measured wetness at lower levels of moisture.
- A possible explanation: The L-band waves can penetrate through the relatively thin and dry layer to deeper soil with larger reflectivity. It is thus suggested that the probe SM measurements at 6 cm are not representative for depths important for L-band radio wave propagation.



Conclusions



- An expected correlation between strong reflected signals and rain events has been observed.
- The high-gain antennas increased the receiver dynamic range and reduced surface multipath radio wave interference.
- A high level of correlation has been found between reflected signal power and *in situ* soil moisture measurements for high levels of moisture when the top layer of soil of about 6 cm of thickness was moist enough.
- For drier top layers the correlation between top-layer moisture and the reflected power is diminished due to deeper penetration of the L-band radio waves toward the more moist layers of soil.