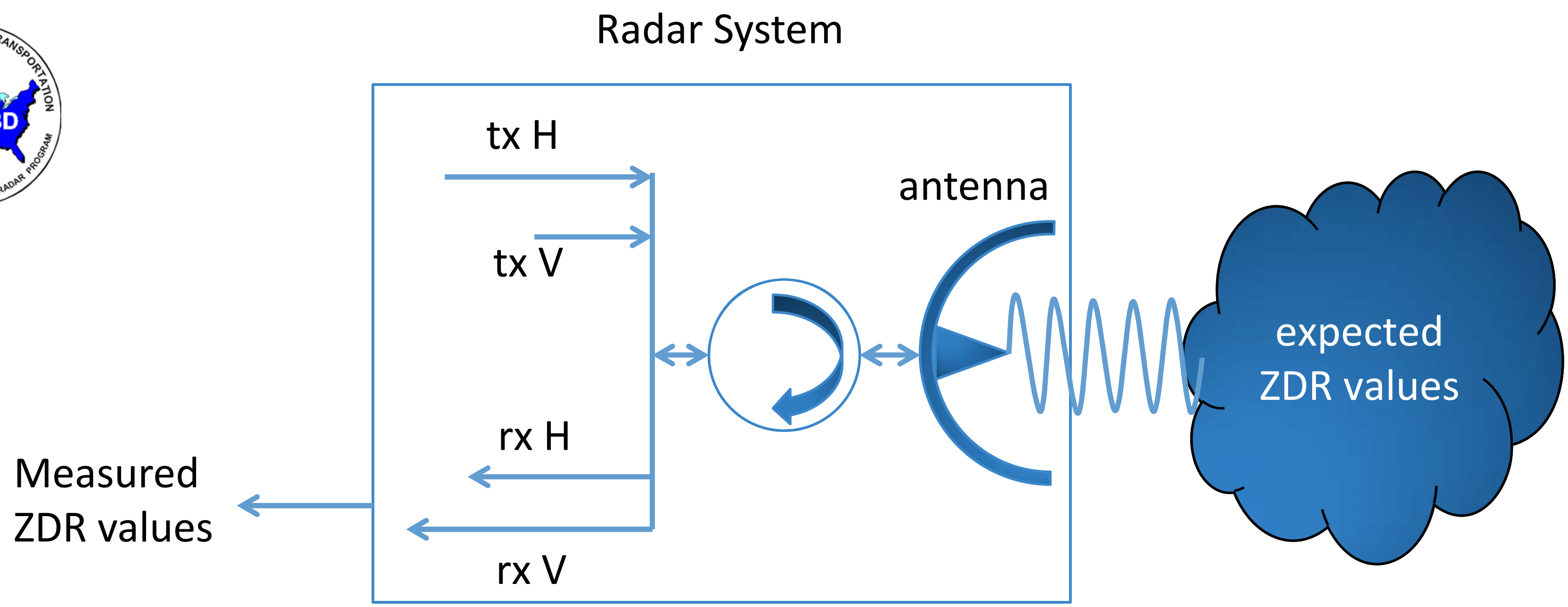
Status
of the
Cross-Polarization Power Technique
for
Validating Zdr Calibration

Technical Advisory Committee Meeting
1 March 2012
Darcy Saxion

Overview

- Review the Zdr calibration issue
- Review the Engineering Calibration
- Summarize the Zdr Calibration Validation Efforts
- Provide an overview of the cross-polarization power method for validating Zdr calibration
- Provide a status of the cross-polarization power method

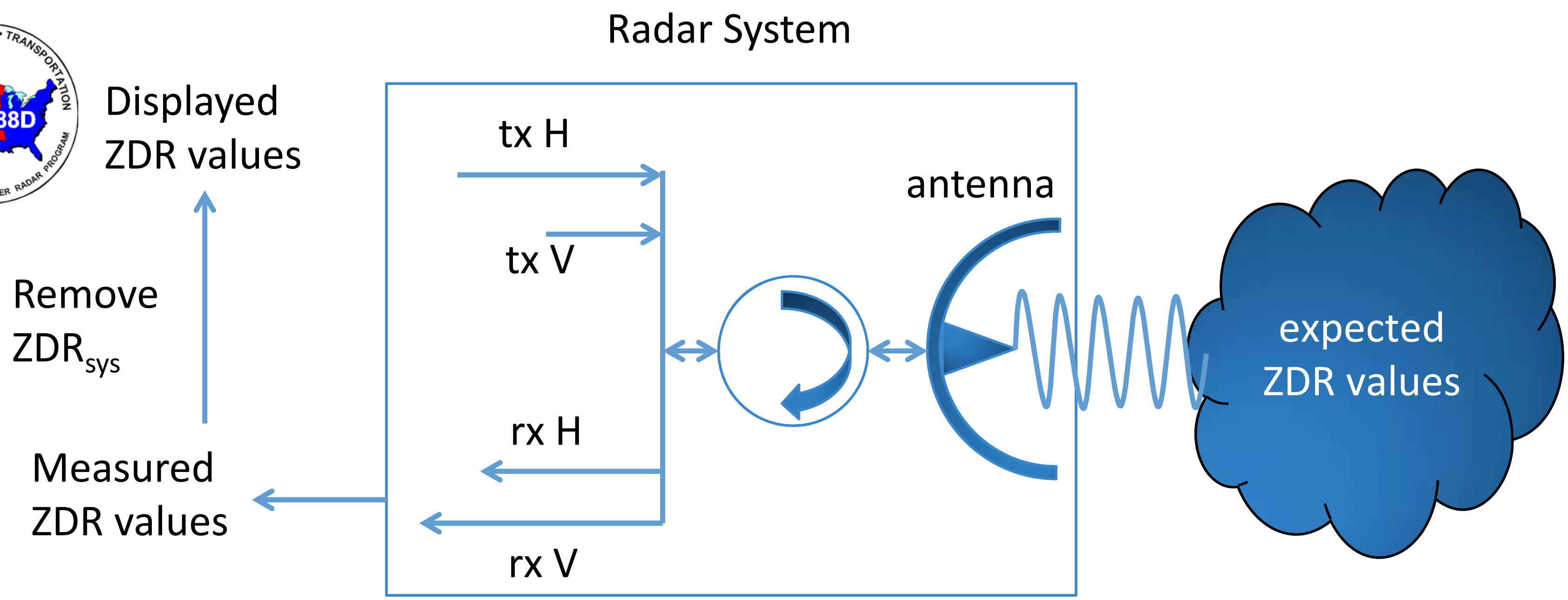
Review of the Zdr Calibration Issue



We can only ‘see’ what the radar measures.

We know what ZDR values we expect to see.*

* Since we don’t really know what the true ZDR values are, we make well educated guesses about what we expect to see in ‘known’ precipitation types.

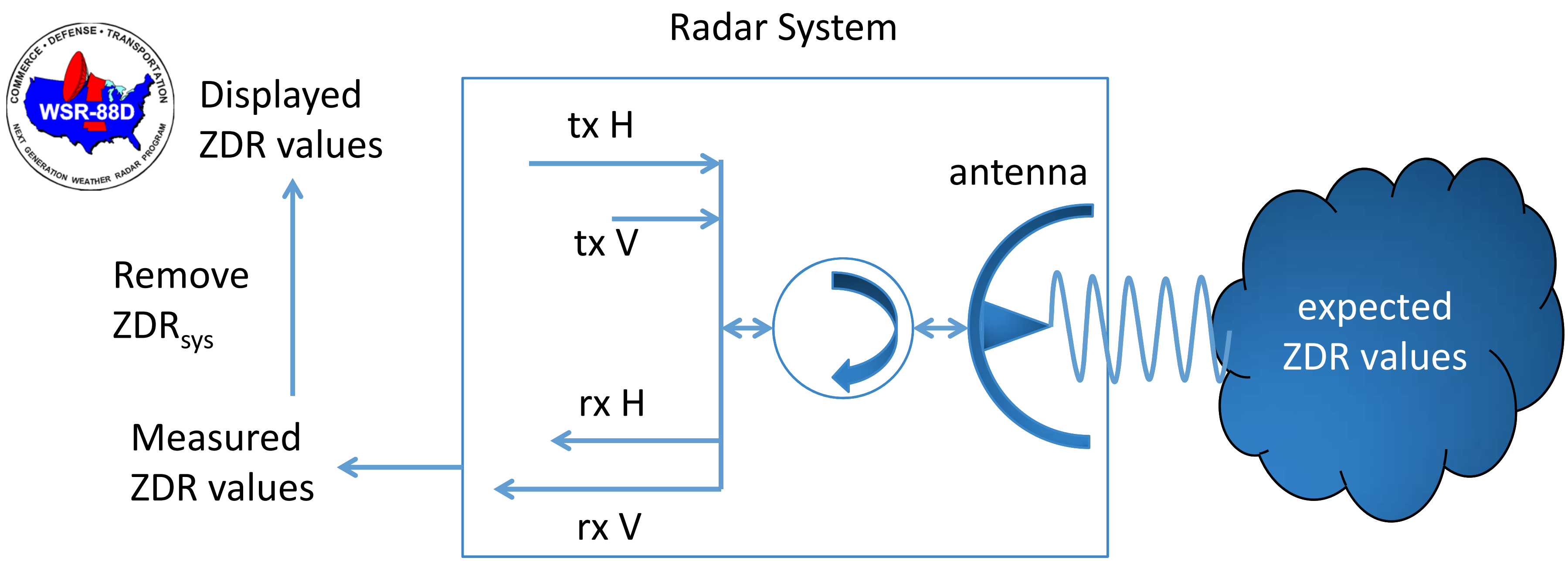


Displayed ZDR values (ZDR) are intended to match expected ZDR (ZDR_{exp})

$$ZDR_{exp} \cong ZDR = ZDR_{measured} - ZDR_{sys}$$

Where:

- **System differential reflectivity (ZDR_{sys})** – differential reflectivity introduced by the system
- **ZDR** – differential reflectivity displayed by the system
- **Expected ZDR (ZDR_{exp})** – expected ZDR values for known precipitation types
- **ZDR error** – difference in expected ZDR values (ZDR_{exp}) and ZDR values

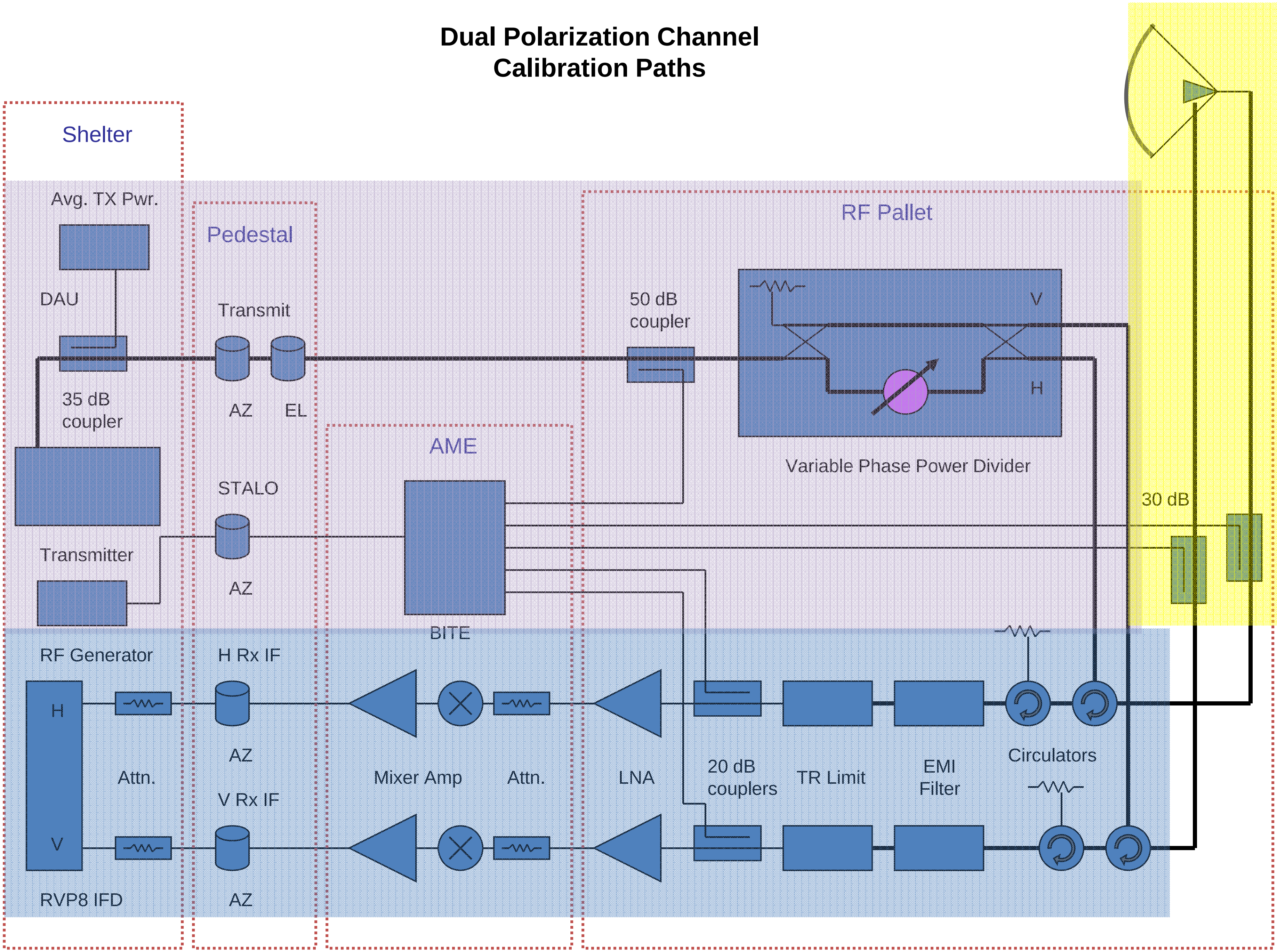


Requirement:

Provide a technique to calibrate Zdr within ± 0.1db accuracy (at a 95% confidence level) that is executable by a field technician with the level of training as described in the WSR-88D Integrated Logistics Support Plan (ILSP).

Engineering Calibration Overview

Dual Polarization Channel Calibration Paths



Engineering Calibration Overview

- Calibration Equation:

$$ZDR_{sys} = (2 * ZDR_{ant}) + ZDR_{tx} + ZDR_{rx}$$

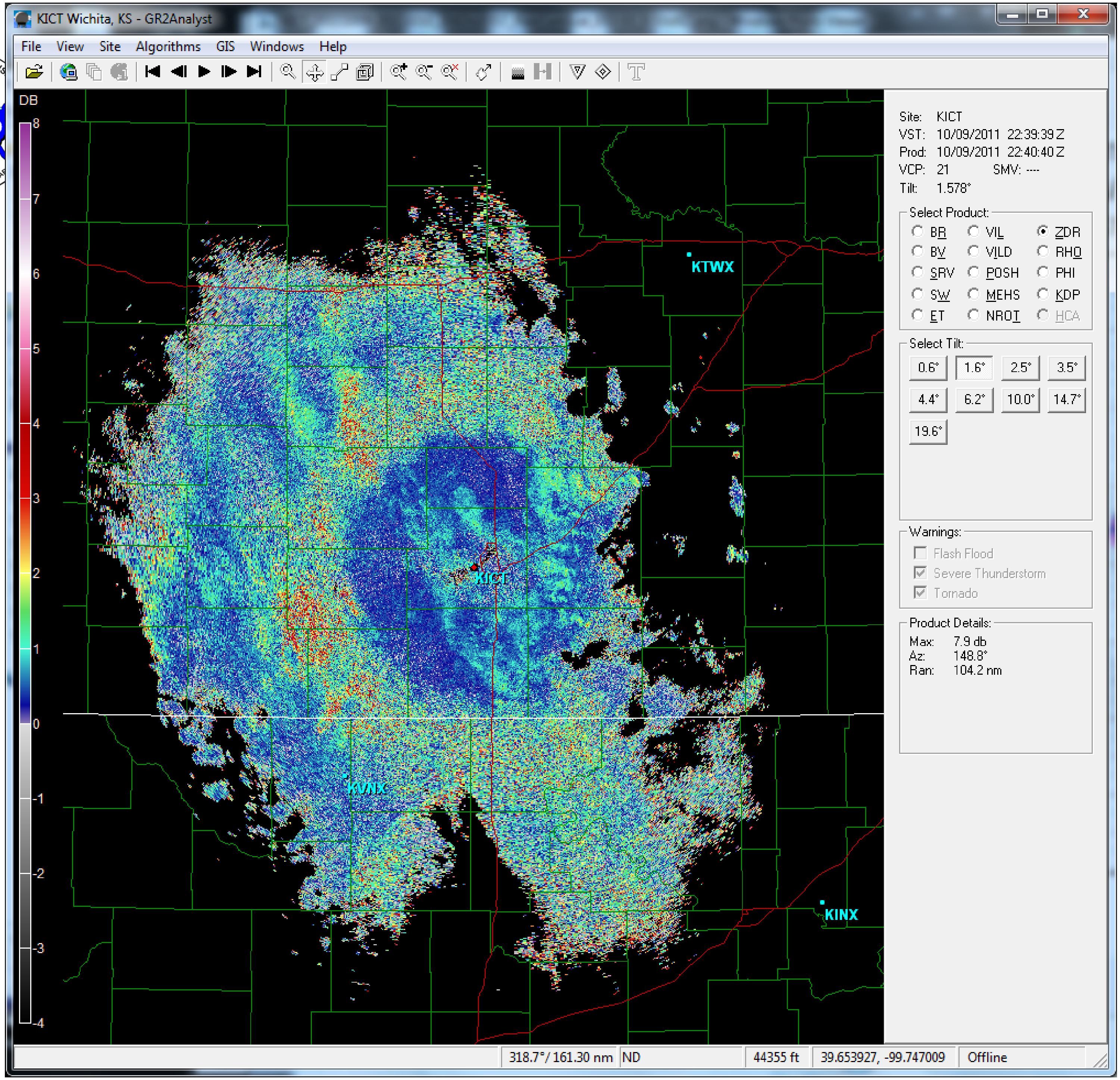
- ZDR_{ant} from offline calibration
- ZDR_{tx} from offline calibration and monitored in performance checks (usually every 8 hours)
- ZDR_{rx} from offline calibration and monitored on retrace (every VCP)

Engineering Calibration Overview

- Engineering calibration is the method used for calibration with deployment
  - Provided by L-3/Baron as part of the upgrade
  - Calibrates reflectivity and differential reflectivity
    - System differential phase is determined separately
- L-3/Baron provided analysis of the engineering method on 9 August, 2011
  - "Zdr Calibration Accuracy Analysis; BS-2000-000-107"
    - "L-3 submits that the NEXRAD DP Upgrade and calibration procedure meets the Statement of Objectives (SOO) requirement of +-0.1 dB Zdr calibration accuracy"
  - The Government concurred, the deployment decision based on this

Zdr Base Data Examples

- The next four slides are Zdr images (Level II) from different radars. All events are light rain. This is an example of what is currently being observed across the fleet.
- Keep in mind the many things that can affect these images
  - Zdr calibration
  - Weather regime
  - Height of the Melting Layer


KICT Wichita, KS - GR2Analyst
File View Site Algorithms GIS Windows Help
DB
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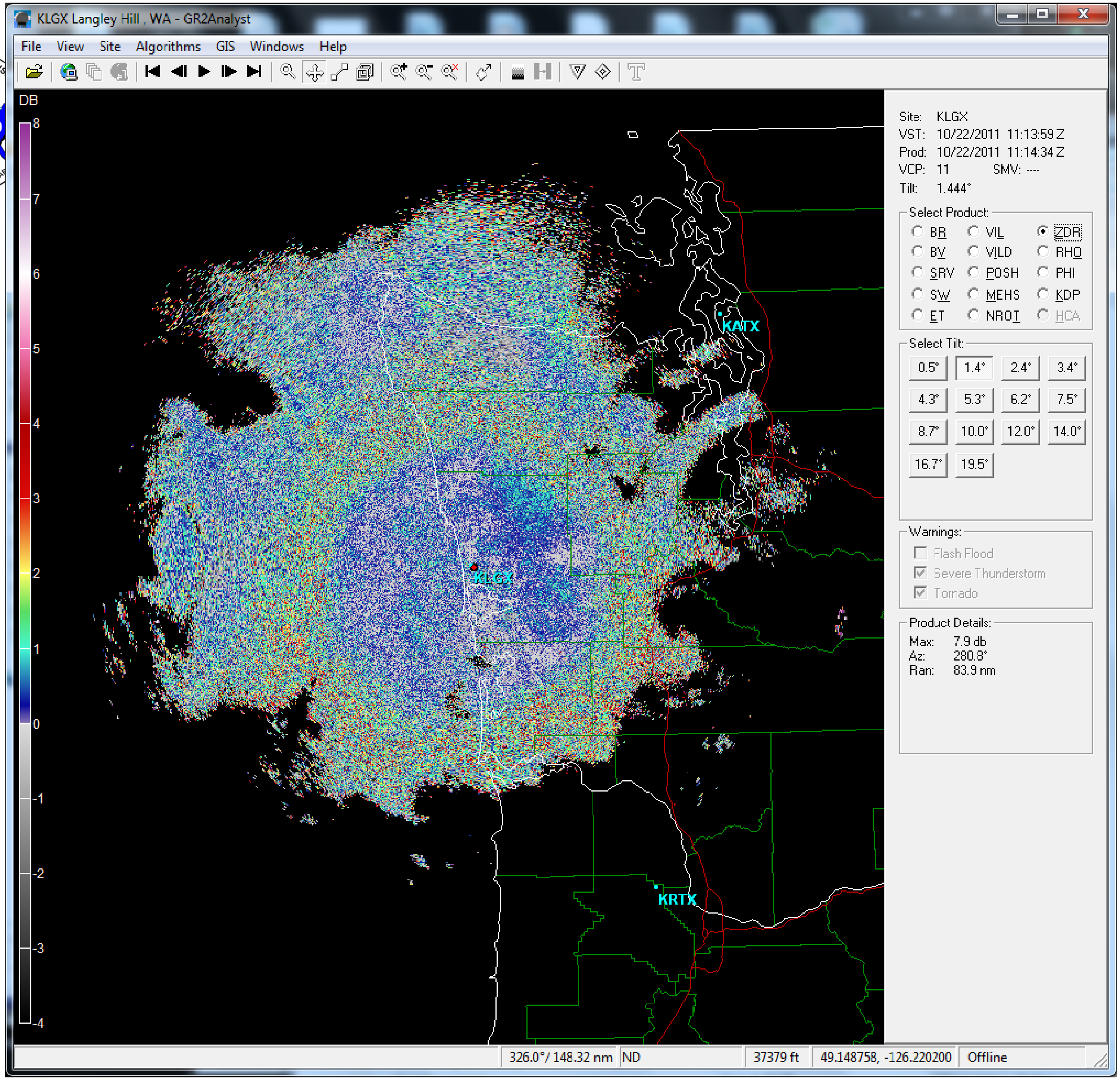
0
-1
-2
-3
-4
KTWX
KICT
KVNX
KINX
Site: KICT
VST: 10/09/2011 22:39:39 Z
Prod: 10/09/2011 22:40:40 Z
VCP: 21 SMV: ---
Tilt: 1.578°
Select Product:
BR VIL ZDR
BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
Select Tilt:
0.6° 1.6° 2.5° 3.5°
4.4° 6.2° 10.0° 14.7°
19.6°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Max: 7.9 db
Az: 148.8°
Ran: 104.2 nm
318.7°/ 161.30 nm ND
44355 ft
39.653927, -99.747009
Offline


KLGX Langley Hill , WA - GR2Analyst
File View Site Algorithms GIS Windows Help
DB
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KATX
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KRTX
Site: KLGX
VST: 10/22/2011 11:13:59 Z
Prod: 10/22/2011 11:14:34 Z
VCP: 11 SMV: ---
Tilt: 1.444°
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BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
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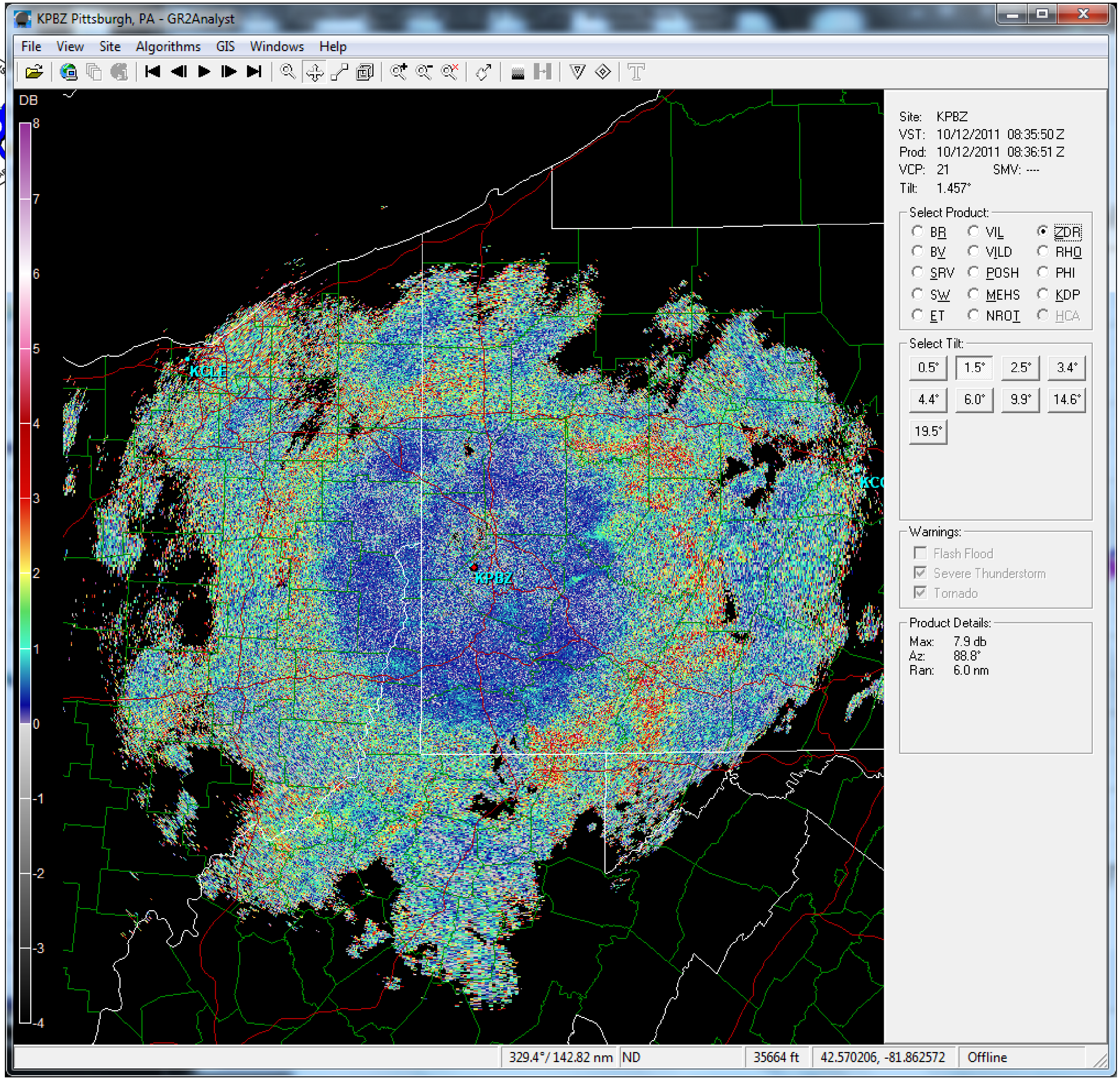
4.3° 5.3° 6.2° 7.5°
8.7° 10.0° 12.0° 14.0°
16.7° 19.5°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Max: 7.9 db
Az: 280.8°
Ran: 83.9 nm
326.0°/ 148.32 nm
ND
37379 ft
49.148758, -126.220200
Offline


KPBZ Pittsburgh, PA - GR2Analyst
File View Site Algorithms GIS Windows Help
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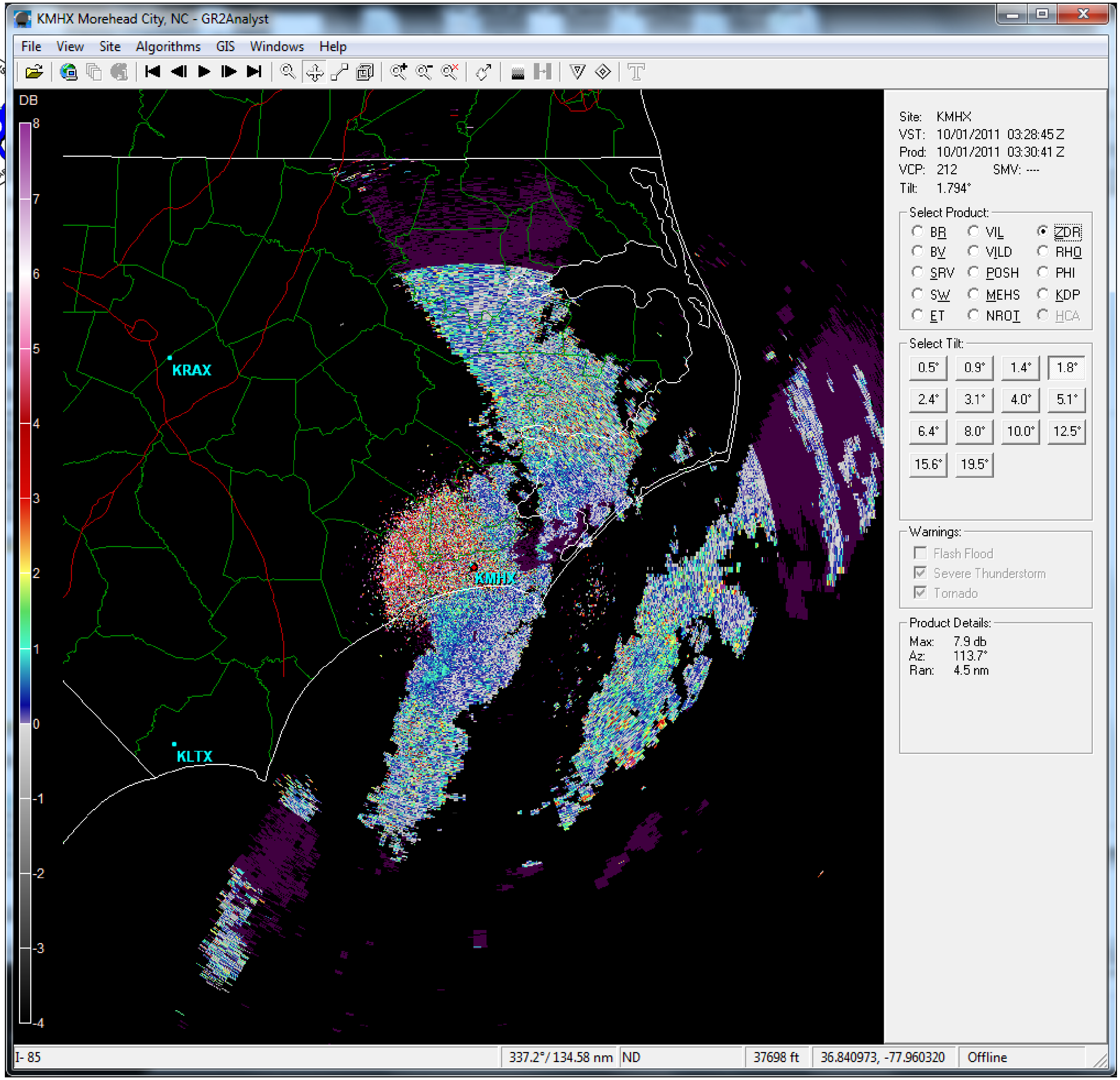
KCLE
KPBZ
Site: KPBZ
VST: 10/12/2011 08:35:50 Z
Prod: 10/12/2011 08:36:51 Z
VCP: 21 SMV: ---
Tilt: 1.457°
Select Product:
BR VIL ZDR
BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
Select Tilt:
0.5° 1.5° 2.5° 3.4°
4.4° 6.0° 9.9° 14.6°
19.5°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Max: 7.9 db
Az: 88.8°
Ran: 6.0 nm
329.4° / 142.82 nm ND
35664 ft
42.570206, -81.862572
Offline



KMHX Morehead City, NC - GR2Analyst
File View Site Algorithms GIS Windows Help
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KRAX
KMHX
KLTX
Site: KMHX
VST: 10/01/2011 03:28:45 Z
Prod: 10/01/2011 03:30:41 Z
VCP: 212 SMV: ---
Tilt: 1.794°
Select Product:
BR VIL ZDR
BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
Select Tilt:
0.5° 0.9° 1.4° 1.8°
2.4° 3.1° 4.0° 5.1°
6.4° 8.0° 10.0° 12.5°
15.6° 19.5°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Max: 7.9 db
Az: 113.7°
Ran: 4.5 nm
I- 85
337.2°/ 134.58 nm
ND
37698 ft
36.840973, -77.960320
Offline

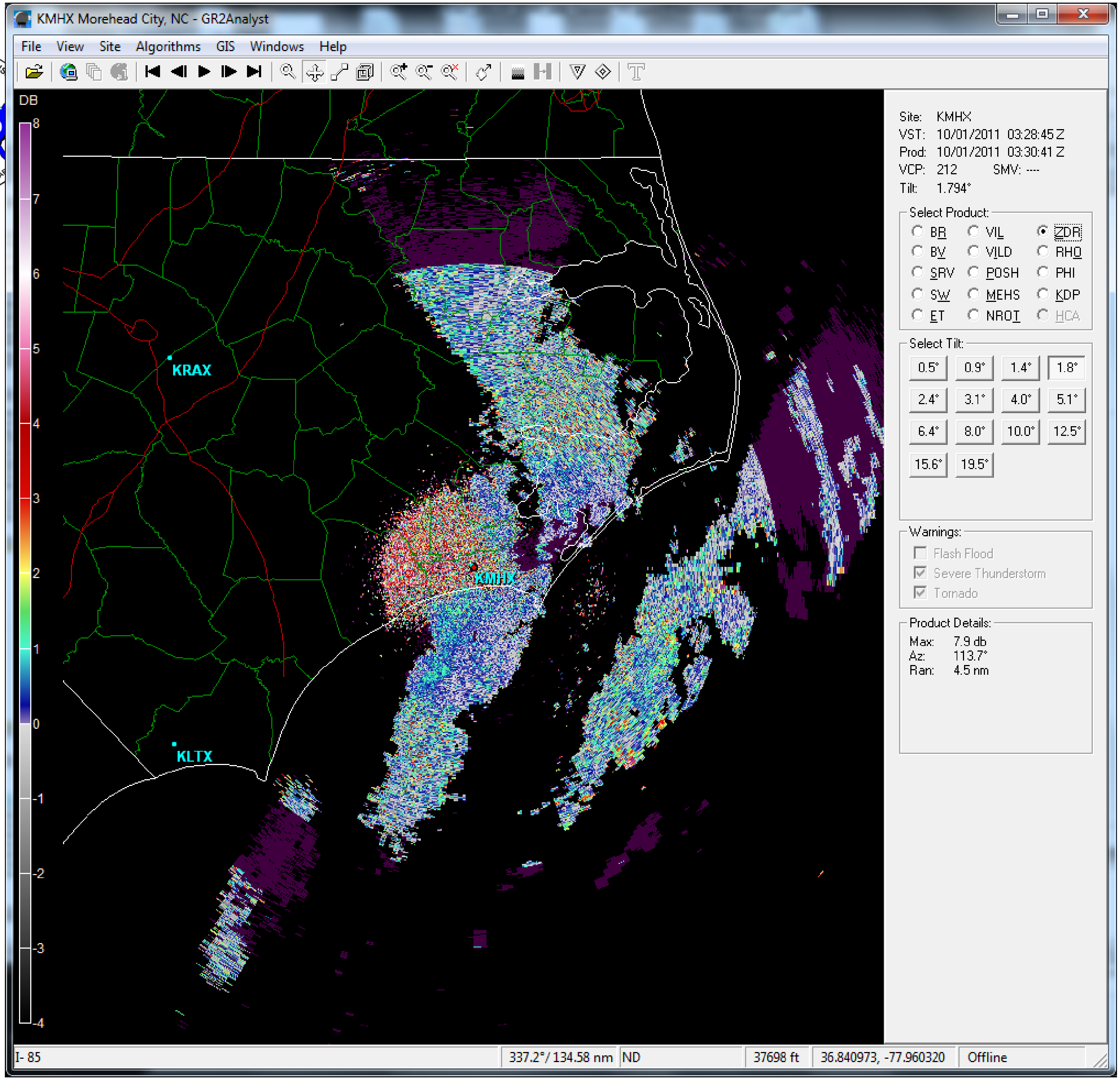
Zdr Calibration Validation Efforts

- DQDP Subcommittee worked to find an independent means for validating stability and accuracy
- Stability:
  - Reviewed loops of data – no visible changes of Zdr values over time (except when heavy rain passed over the radome)
  - Monitored Performance Maintenance Data
- Accuracy:
  - Began with subjective evaluation of regions of Zdr values from radar data vs. expected Zdr of drizzle and dry aggregated snow, too much variation in the process
  - Better approach: Z/Zdr scatterplots of liquid water
  - Meanwhile, Cross-polarization Power Technique was being developed

Z/Zdr Scatterplot Summary

- Evaluating seven sites, the five Beta Sites, KOUN, and KLGX
- Select bins containing only liquid water
  - Below the melting layer, use knowledge of the weather event and range information
  - CC > 0.98 ensures all liquid, no mixed phase
  - SNR > 20 dB
  - Expect Zdr value of 0.23 dB at 20-22 dBz (Ryzhkov), and curve asymptotically approach 0.0 dB for low reflectivity values (Chandra)
  - Still saw variance on the order of 0.2-0.3 dB
- Refined data selection based on reflectivity values, % Weak
  - 11.0 dBz < Z < 30.0 dBz defined as weak
  - 30.0 dBz < Z < max dBz defines as strong
  - The weak criteria helps to ensures stratiform conditions
  - Results are converging to within 0.2 dB

KMHX Example


KMHX Morehead City, NC - GR2Analyst
File View Site Algorithms GIS Windows Help
DB
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-3
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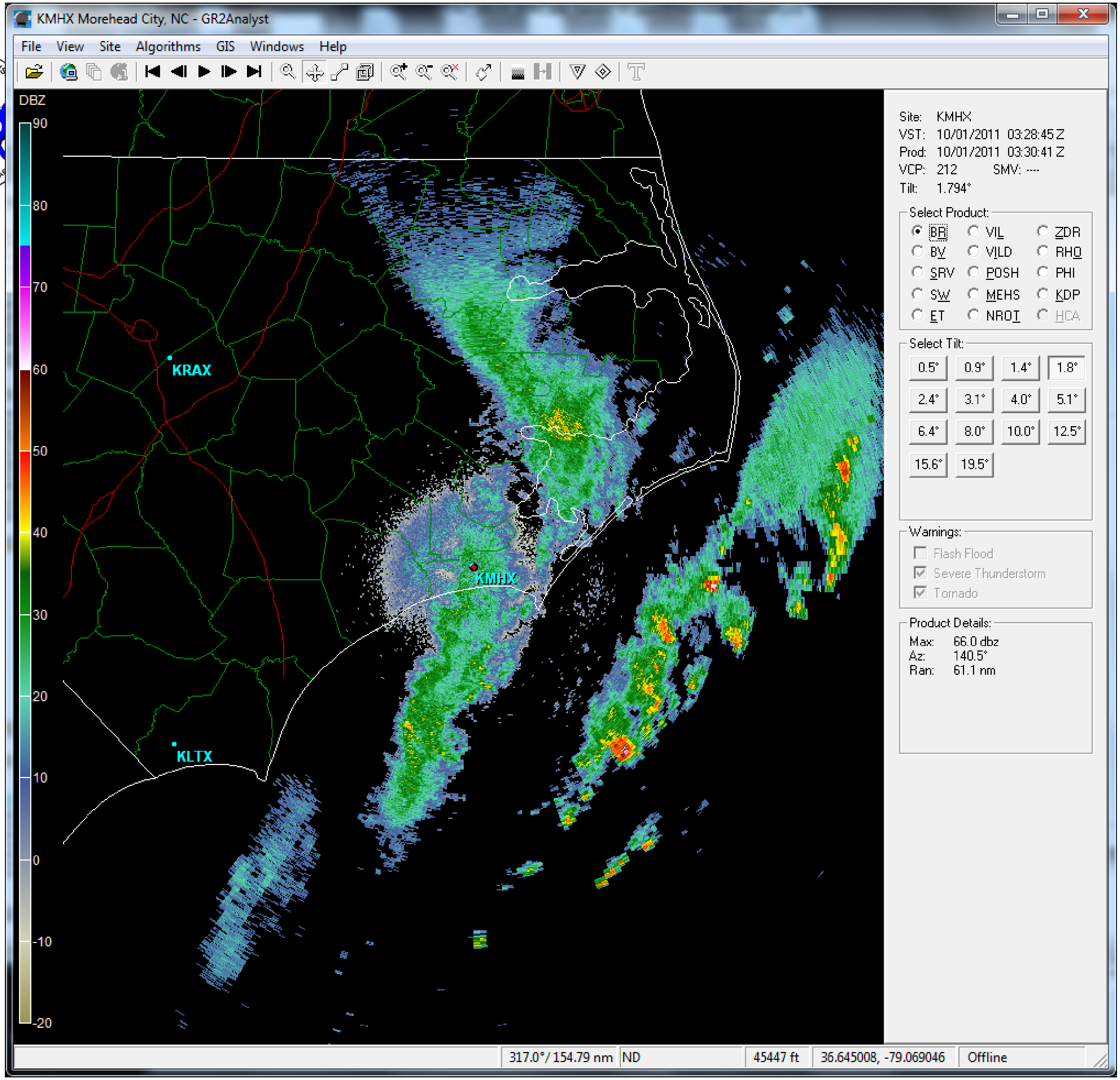
KRAX
KMHX
KLTX
Site: KMHX
VST: 10/01/2011 03:28:45 Z
Prod: 10/01/2011 03:30:41 Z
VCP: 212 SMV: ---
Tilt: 1.794°
Select Product:
BR VIL ZDR
BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
Select Tilt:
0.5° 0.9° 1.4° 1.8°
2.4° 3.1° 4.0° 5.1°
6.4° 8.0° 10.0° 12.5°
15.6° 19.5°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Max: 7.9 db
Az: 113.7°
Ran: 4.5 nm
I- 85
337.2°/ 134.58 nm ND
37698 ft
36.840973, -77.960320
Offline


KMHX Morehead City, NC - GR2Analyst
File View Site Algorithms GIS Windows Help
DBZ
90
80
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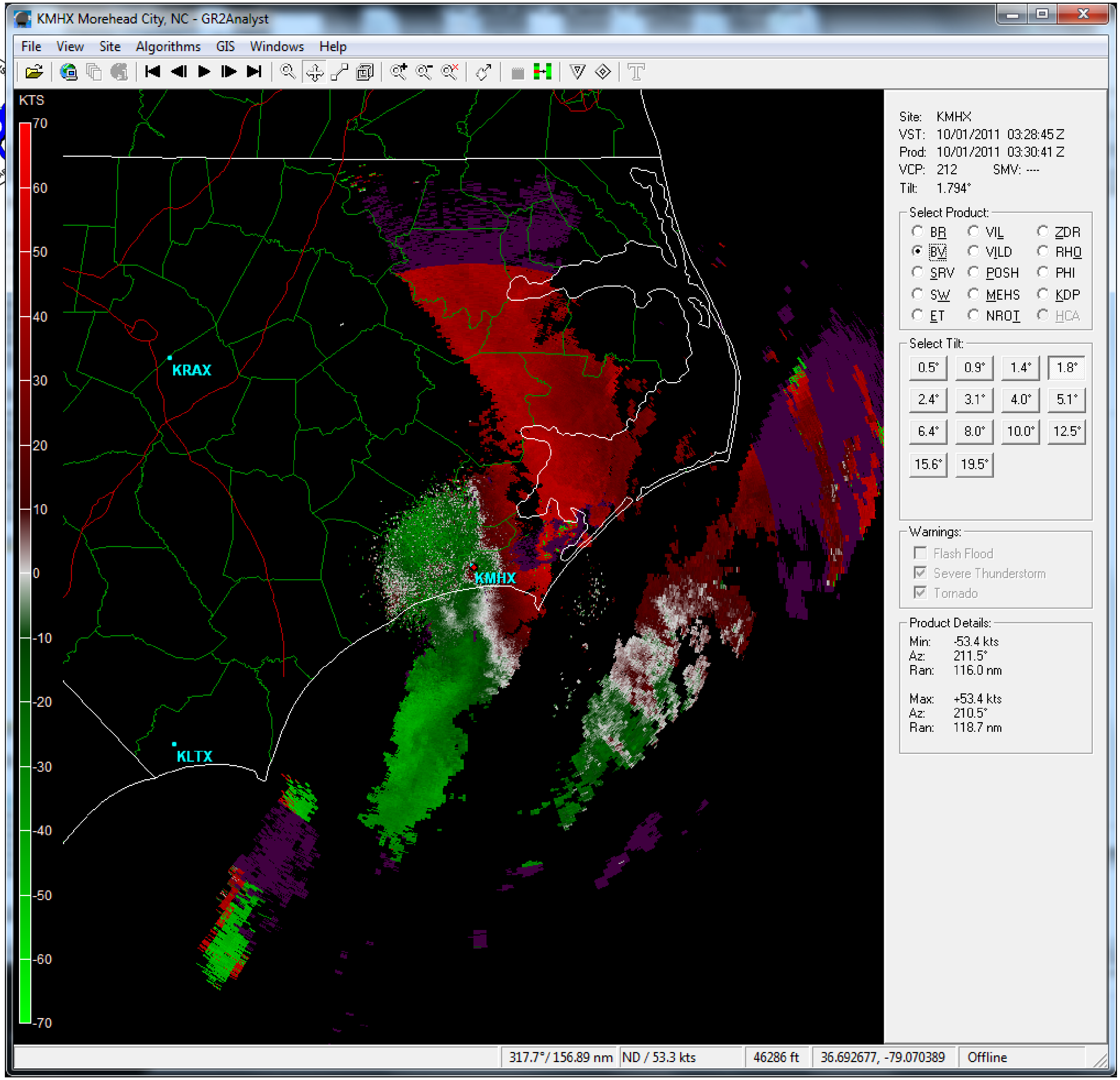
-10
-20
KRAX
KMHX
KLTX
Site: KMHX
VST: 10/01/2011 03:28:45 Z
Prod: 10/01/2011 03:30:41 Z
VCP: 212 SMV: ---
Tilt: 1.794°
Select Product:
BR VIL ZDR
BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
Select Tilt:
0.5° 0.9° 1.4° 1.8°
2.4° 3.1° 4.0° 5.1°
6.4° 8.0° 10.0° 12.5°
15.6° 19.5°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Max: 66.0 dbz
Az: 140.5°
Ran: 61.1 nm
317.0°/ 154.79 nm ND
45447 ft
36.645008, -79.069046
Offline


KMHX Morehead City, NC - GR2Analyst
File View Site Algorithms GIS Windows Help
KTS
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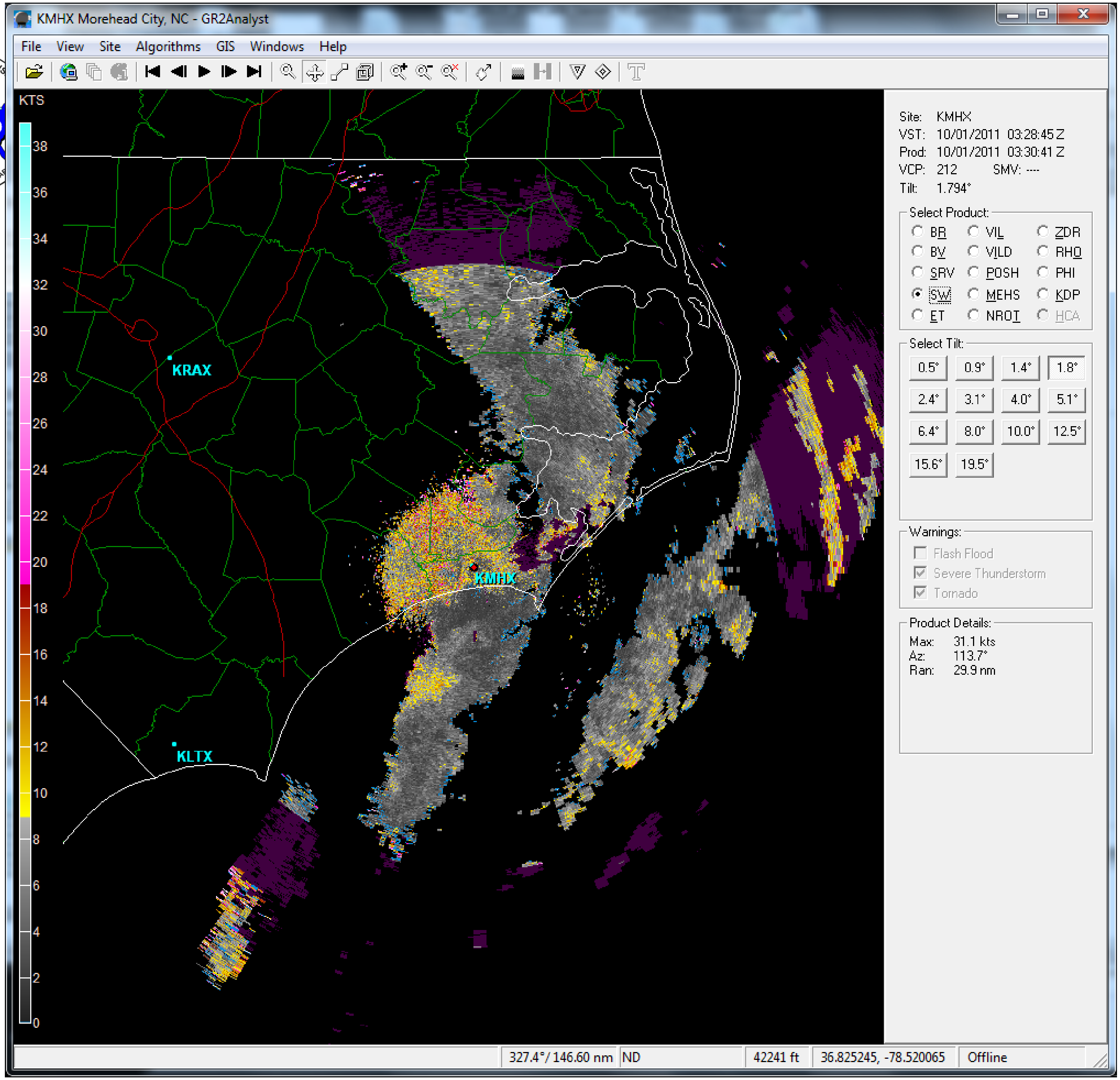
-50
-60
-70
KRAX
KMHX
KLTX
Site: KMHX
VST: 10/01/2011 03:28:45 Z
Prod: 10/01/2011 03:30:41 Z
VCP: 212 SMV: ---
Tilt: 1.794°
Select Product:
BR VIL ZDR
BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
Select Tilt:
0.5° 0.9° 1.4° 1.8°
2.4° 3.1° 4.0° 5.1°
6.4° 8.0° 10.0° 12.5°
15.6° 19.5°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Min: -53.4 kts
Az: 211.5°
Ran: 116.0 nm
Max: +53.4 kts
Az: 210.5°
Ran: 118.7 nm
317.7°/ 156.89 nm
ND / 53.3 kts
46286 ft
36.692677, -79.070389
Offline



KMHX Morehead City, NC - GR2Analyst
File View Site Algorithms GIS Windows Help
KTS
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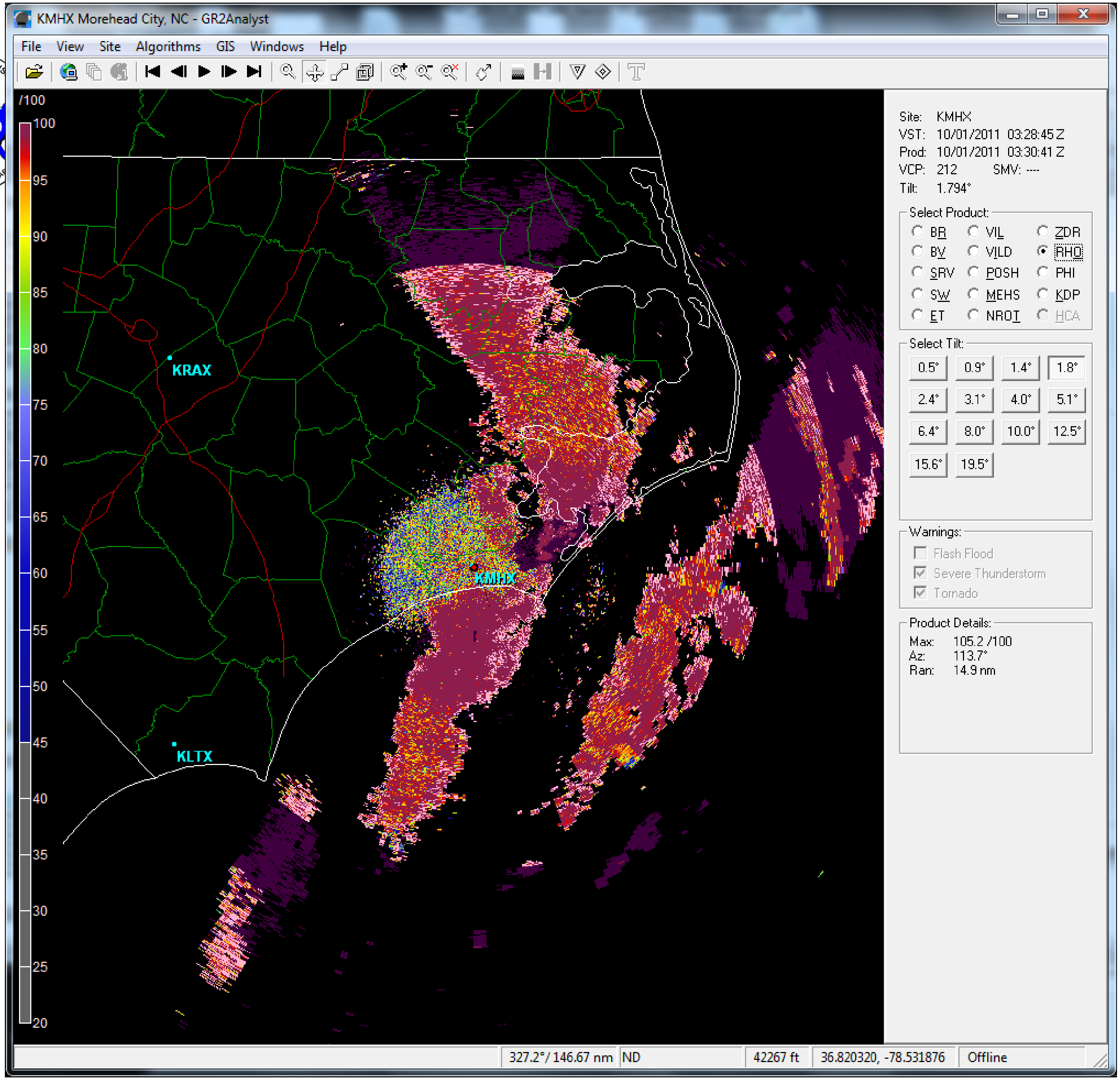
KRAX
KMHX
KLTX
Site: KMHX
VST: 10/01/2011 03:28:45 Z
Prod: 10/01/2011 03:30:41 Z
VCP: 212 SMV: ---
Tilt: 1.794°
Select Product:
BR VIL ZDR
BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
Select Tilt:
0.5° 0.9° 1.4° 1.8°
2.4° 3.1° 4.0° 5.1°
6.4° 8.0° 10.0° 12.5°
15.6° 19.5°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Max: 31.1 kts
Az: 113.7°
Ran: 29.9 nm
327.4° / 146.60 nm ND
42241 ft
36.825245, -78.520065
Offline


KMHX Morehead City, NC - GR2Analyst
File View Site Algorithms GIS Windows Help
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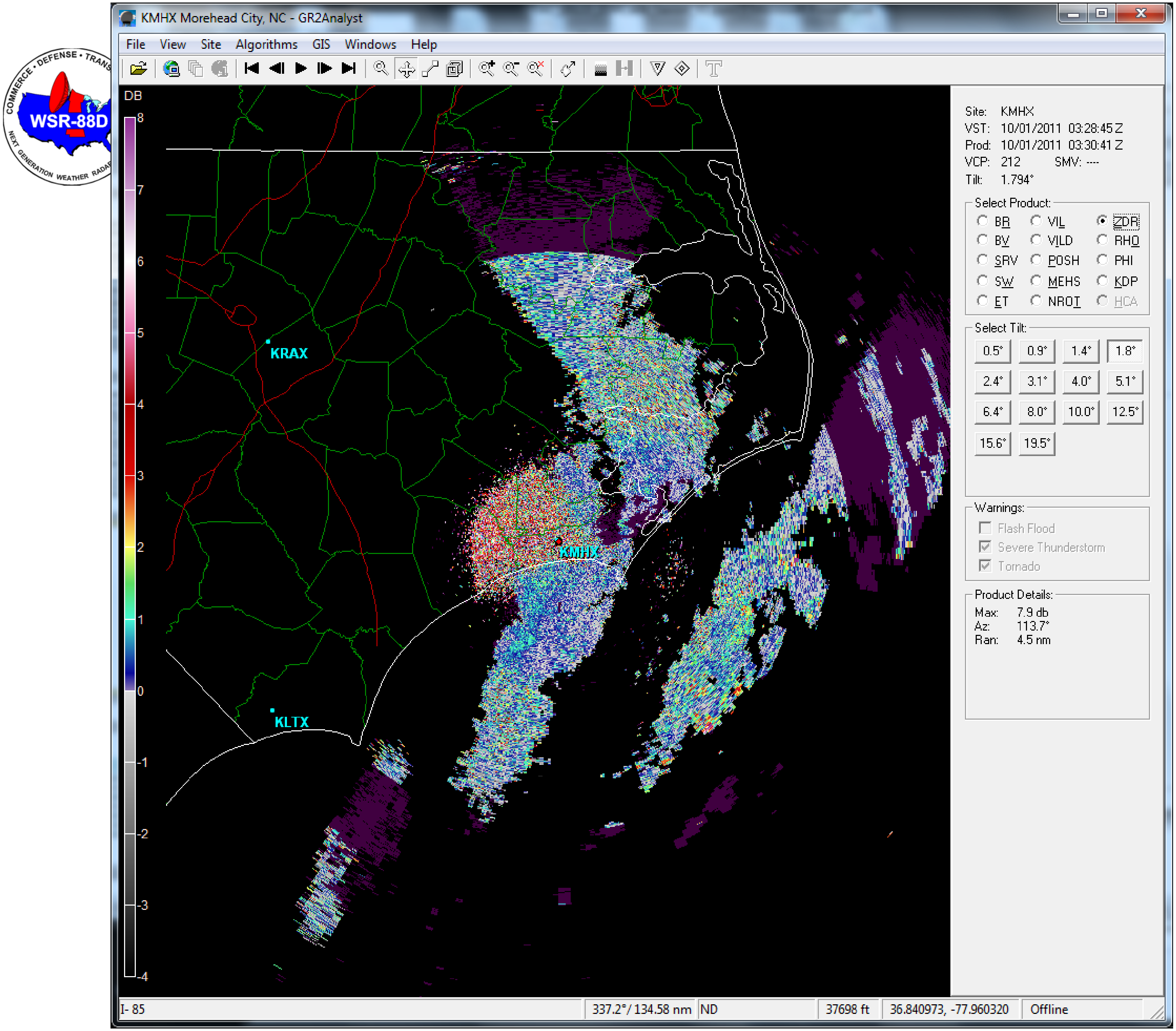
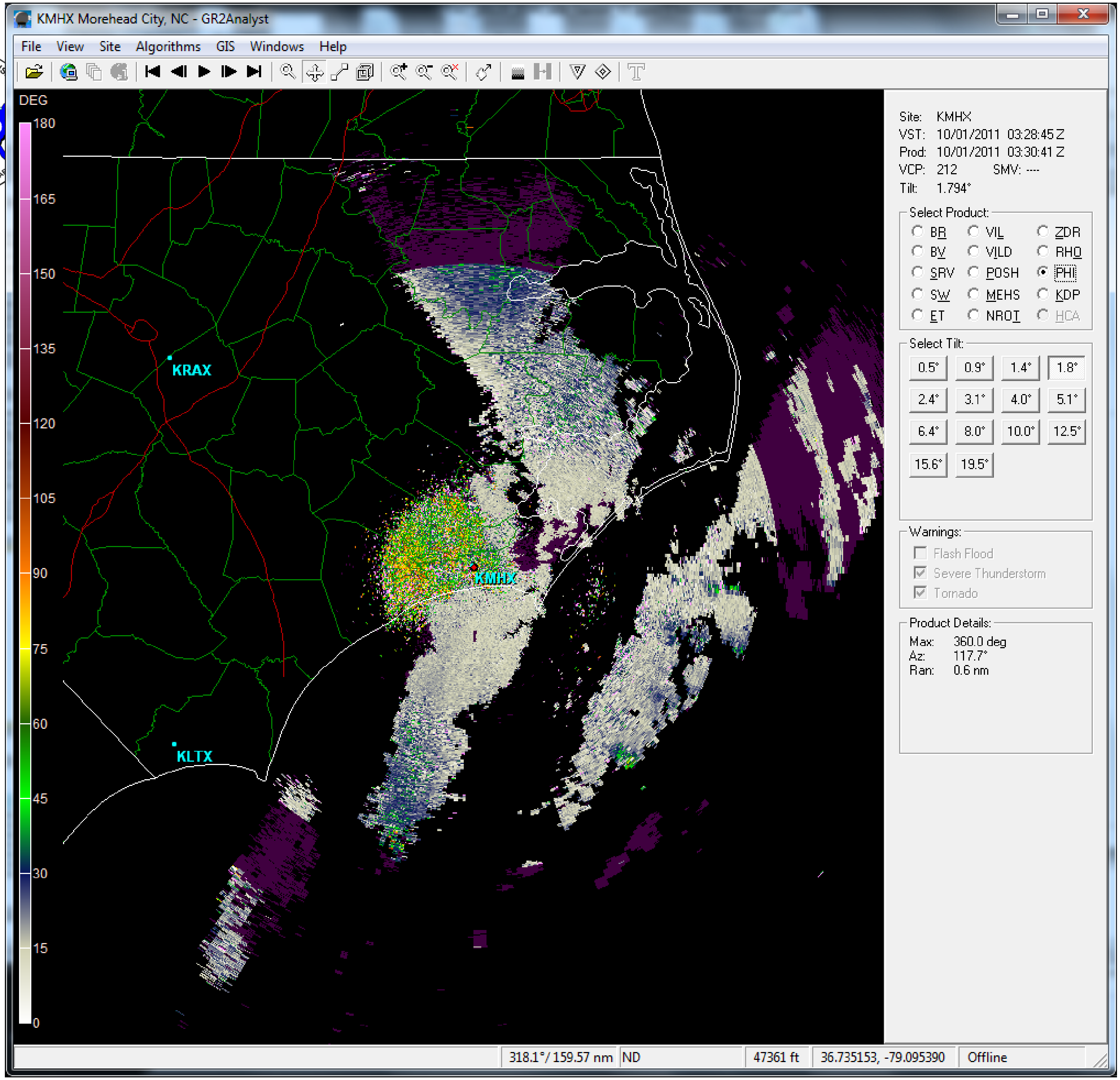
KRAX
KMHX
KLTX
Site: KMHX
VST: 10/01/2011 03:28:45 Z
Prod: 10/01/2011 03:30:41 Z
VCP: 212 SMV: ---
Tilt: 1.794°
Select Product:
BR VIL ZDR
BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
Select Tilt:
0.5° 0.9° 1.4° 1.8°
2.4° 3.1° 4.0° 5.1°
6.4° 8.0° 10.0° 12.5°
15.6° 19.5°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Max: 105.2 /100
Az: 113.7°
Ran: 14.9 nm
327.2°/ 146.67 nm ND
42267 ft
36.820320, -78.531876
Offline



WSR-88D
COMMERCE • DEFENSE • TRANS
NEXT GENERATION WEATHER RADAR
KMHX Morehead City, NC - GR2Analyst
File View Site Algorithms GIS Windows Help
DB
KRAX
KMHX
KLTX
Site: KMHX
VST: 10/01/2011 03:28:45 Z
Prod: 10/01/2011 03:30:41 Z
VCP: 212 SMV: ---
Tilt: 1.794°
Select Product:
BR VIL ZDR
BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
Select Tilt:
0.5° 0.9° 1.4° 1.8°
2.4° 3.1° 4.0° 5.1°
6.4° 8.0° 10.0° 12.5°
15.6° 19.5°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Max: 7.9 db
Az: 113.7°
Ran: 4.5 nm
I- 85
337.2°/ 134.58 nm ND
37698 ft
36.840973, -77.960320
Offline


KMHX Morehead City, NC - GR2Analyst
File View Site Algorithms GIS Windows Help
DEG
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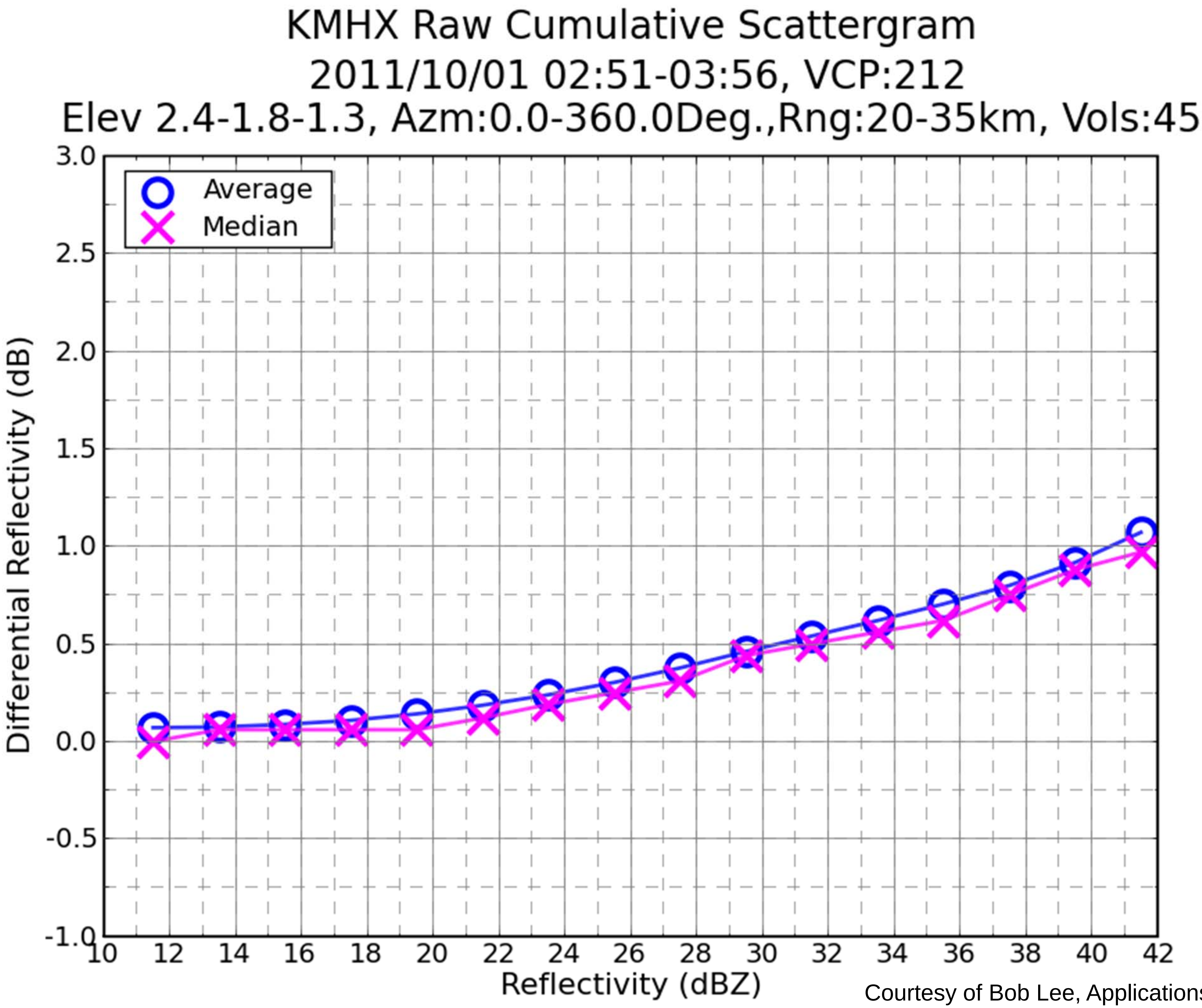
KRAX
KMHX
KLTX
Site: KMHX
VST: 10/01/2011 03:28:45 Z
Prod: 10/01/2011 03:30:41 Z
VCP: 212 SMV: ---
Tilt: 1.794°
Select Product:
BR VIL ZDR
BV VILD RHO
SRV POSH PHI
SW MEHS KDP
ET NROT HCA
Select Tilt:
0.5° 0.9° 1.4° 1.8°
2.4° 3.1° 4.0° 5.1°
6.4° 8.0° 10.0° 12.5°
15.6° 19.5°
Warnings:
Flash Flood
Severe Thunderstorm
Tornado
Product Details:
Max: 360.0 deg
Az: 117.7°
Ran: 0.6 nm
318.1°/ 159.57 nm ND
47361 ft
36.735153, -79.095390
Offline



Courtesy of Bob Lee, Applications Branch

Z/Zdr Scatterplot Summary

Courtesy of Bob Lee, Applications Branch

Site	# Vols	ZDR dB at 20 dBz	ZDR - Expected dB
KOUN (After 11 Aug)	461	.35	.12
KVNX (After 10 Aug)	1030	.40	.17
KIWA (After 19 Aug)	155	.38	.15
KMHX (After 14 Aug)	1170	.14 / .11	-.09/ -.12
KPBZ (After 14 Aug)	2100	.34	.11
KICT (After 10 Aug)	510	.43	.20
KLGX (After 26 Sep)	458	-.03	-.26

Z/Zdr Scatterplot Conclusions

Courtesy of Bob Lee, Applications Branch

- It is critical to use data from only stratiform rain
- Encouraging trends in the results
  - For all but one site, Zdr error is less than 0.2 dB
    - Coastal sites show negative Zdr error (-0.09 to -0.29 dB)
    - Land-based sites show slightly higher than expected Zdr error (0.11 to 0.2 dB)
  - With greater number of data cases, variance is reduced
    - **Seven sites and over 5000 volumes of data analyzed**
  - Observed errors could be due to our process for validation, specifically, using weather
- Applications Branch will continue to analyze data

Cross-Polarization Power Technique Overview

Basic Overview

- Cross-Polarization Power Technique (cross-pol) is built on the principle of radar reciprocity of cross-polarization power in dual polarization radars
  - Specifically, the two cross-polar members of the radar scattering matrix are equal; i.e., $S_{hv} = S_{vh}$
- The technique consists of two main steps
  - Measure the combined antenna and receiver bias by scanning the sun
  - Measure the cross-polar biases in the system by scanning ground clutter in two ways to measure receiver bias
    - Transmit all H, receive V
    - Transmit all V, receive H
- To achieve the accuracy required, it is critical to accumulate enough data to minimize variance
  - This currently takes two hours during sun-up, still being investigated

Basic Overview

- The main equation for Cross-polarization Power Technique is:

$$Zdr_{true} = \frac{S_{hh}}{S_{vv}} = Zdr_{meas} * \frac{CP_{xv}}{CP_{xh}} * (Sun)^2$$

  - Where
    - S_{hh} is the transmit/receive H during normal operations
    - S_{vv} is the transmit/receive V during normal operation
    - Zdr_{meas} is the measured Zdr that includes any bias introduced by the radar system
    - CP_{xv} is the clutter scan of transmit H, receive V
    - CP_{xh} is the clutter scan of transmit V, receive H
    - *Sun* is the measured sun bias which is equal for the co-polar and cross-polar measurements
- This equation is expanded and explained in seven slides which are hidden. The best reference is the NCAR provided AEL.

Basic Overview

- Assumptions of the basic algorithm
  - The transmit powers are equal in the H and V channels
  - The transmit powers during the clutter scan for the H and V channels are equal to the transmit powers during operations
  - The receiver bias does not change over time
- NCAR designed S-Pol to meet these assumptions
- Cross-pol needs to be adapted to L-3/Baron design

Differences: S-Pol and L-3/Baron Design (KOUN)

- Antenna
  - S-Pol does not have a radome
  - Not expected to have a large impact
- Receive Path
  - S-Pol: LNA is in a temperature controlled engineering shelter
  - KOUN: temperature compensating LNA is in the radome
- Transmit Path
  - S-Pol: The total power transmitted for the H/V channel is the same for both cross-pol data collection and normal operations
  - KOUN:
    - During cross-pol data collection, 100% power is transmitted for H, then 100% for V
    - During normal operations, 50% power is transmitted for H and V

Current Status

- NCAR submitted a status report, 27 November 2011
  - Compares three calibration techniques using S-Pol
    - Vertical pointing (VP)
    - Fast-Alternating Cross-pol
    - Simultaneous Cross-pol (simulated)
  - Fast-Alternating Cross-pol results are within 0.02 dB of vertical pointing results
  - Simultaneous Cross-pol results are not as consistently accurate, but show promise
    - Four cases
      - One was within 0.105 dB of VP, results are not understood
      - Two are within 0.025 dB of VP
      - One was within 0.088 dB of VP, possibly due to weather in the second trip

Current Status

- ROC Efforts
  - Cross-polarization power technique is implemented non-operationally in Build 13
  - KOUN Data Collection on 08/30/2011 – 09/05/2011 (continuously)
    - Except for 09/01/2011 when there was a full calibration
    - NCAR evaluated the data
      - Too much variance in results, but are still encouraging
        - » Over five days, results changed by as much as 0.165 dB
        - » Standard deviation for each day is low (0.05 dB), this is encouraging
      - Results from the sun scan data are noisy
      - Identified the receiver bias issues, L-3/Baron identified behavior as similar to that seen when a cable is loose
    - There was too much variance in the cross-pol results to compare to the engineering calibration method

Current Status

- ROC
  - KOUN Data Collection on 12/28/2011 – 01/02/2012
    - Computed sun scan results were noisy
      - Issue is identified and fixed, included in the Cross-pol implementation for Build 13
      - The time series data collected is good
    - Receiver bias measurements have too much variance
      - Investigation ongoing
    - There was too much variance in the cross-pol results to compare to the engineering calibration method

Factors Affecting Past Progress

- Radar Resources
  - When dual pol began, ROC provided L-3/Baron with Build 10 CM software
    - L-3/Baron developed dual pol as Build 12
    - In parallel, the ROC developed Build 11, single pol CMD
    - Each of the parallel builds require testing, thus doubling test-bed demands
  - Mid-summer of 2012, the parallel builds will be merged
- Engineering Resources
  - Build 13 was necessarily a higher priority (CMD, HSW)
- NCAR DYNAMO project
  - S-Pol was unavailable for testing while being shipped to the Maldives

Future Plans

- Phase I Efforts:
  - Finalize cross-pol for simultaneous transmit and L-3/Baron design (NCAR)
  - Determine most efficient data collection scheme (NCAR/ROC)
  - Validate ROC's implementation (ROC/NCAR)
- Phase II Efforts:
  - Rigorous comparison to engineering calibration and weather observations
  - Define operational usage of cross-pol
    - Refinement of engineering calibration, not a replacement
  - Requires test-bed radar time

Future Plans

- Phase III Efforts
  - Determine impacts of different clutter regimes
    - Regions with little ground clutter
    - Regions with very strong clutter, i.e., mountains
    - Regions with sea clutter
  - Determine impacts of different locations
    - Northern regions where the sun is at a lower elevation
    - Different atmospheric conditions
  - Field tests needed to accomplish this
    - Cross-pol in Build 13 facilitates this
- If Cross-pol is proven to be viable, the ROC will target operational use for the earliest release possible

Factors Affecting Future Progress

- Cross-polarization Power Technique has not been fully proven on the L-3/Baron dual polarization radar design
- Radar and Engineering resources
- Budget constraints
  - Field test travel limitations
  - NCAR support

Summary

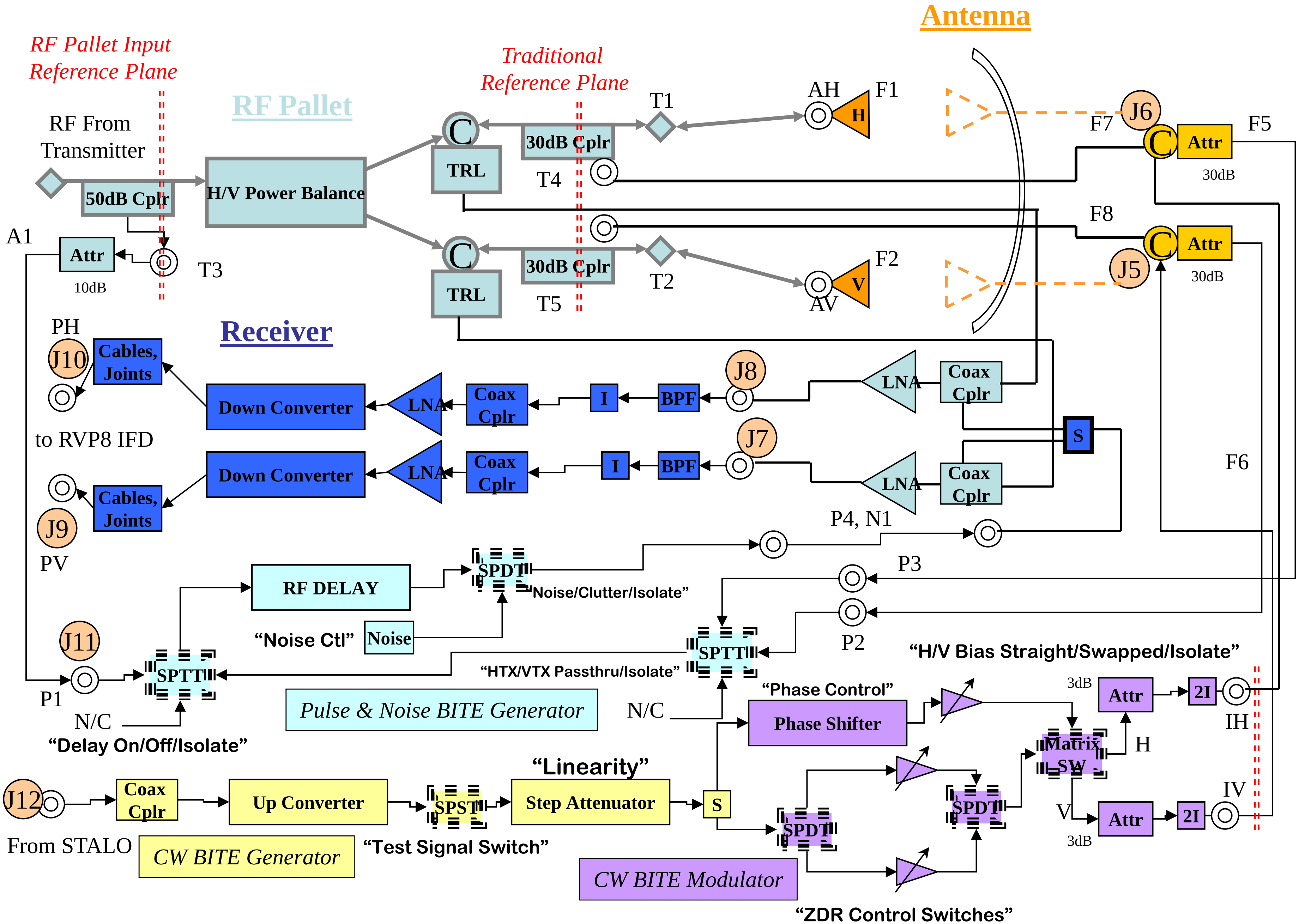
- L-3/Baron Zdr Calibration Accuracy Analysis showed Zdr Calibration to be accurate to within 0.1 dB
- Z/Zdr scatterplot analyses indicate no significant issue with Zdr calibration accuracy
- Cross-polarization Power Technique for validating Zdr calibration is nearly adapted to the L-3/Baron design
  - Implemented non-operationally in Build 13
  - Once complete, Zdr calibration validation may begin on test bed radars
  - Operational use needs to be determined
    - Depends on collecting enough data to reduce variance
    - Will be a refinement to the engineering calibration

Thank you!

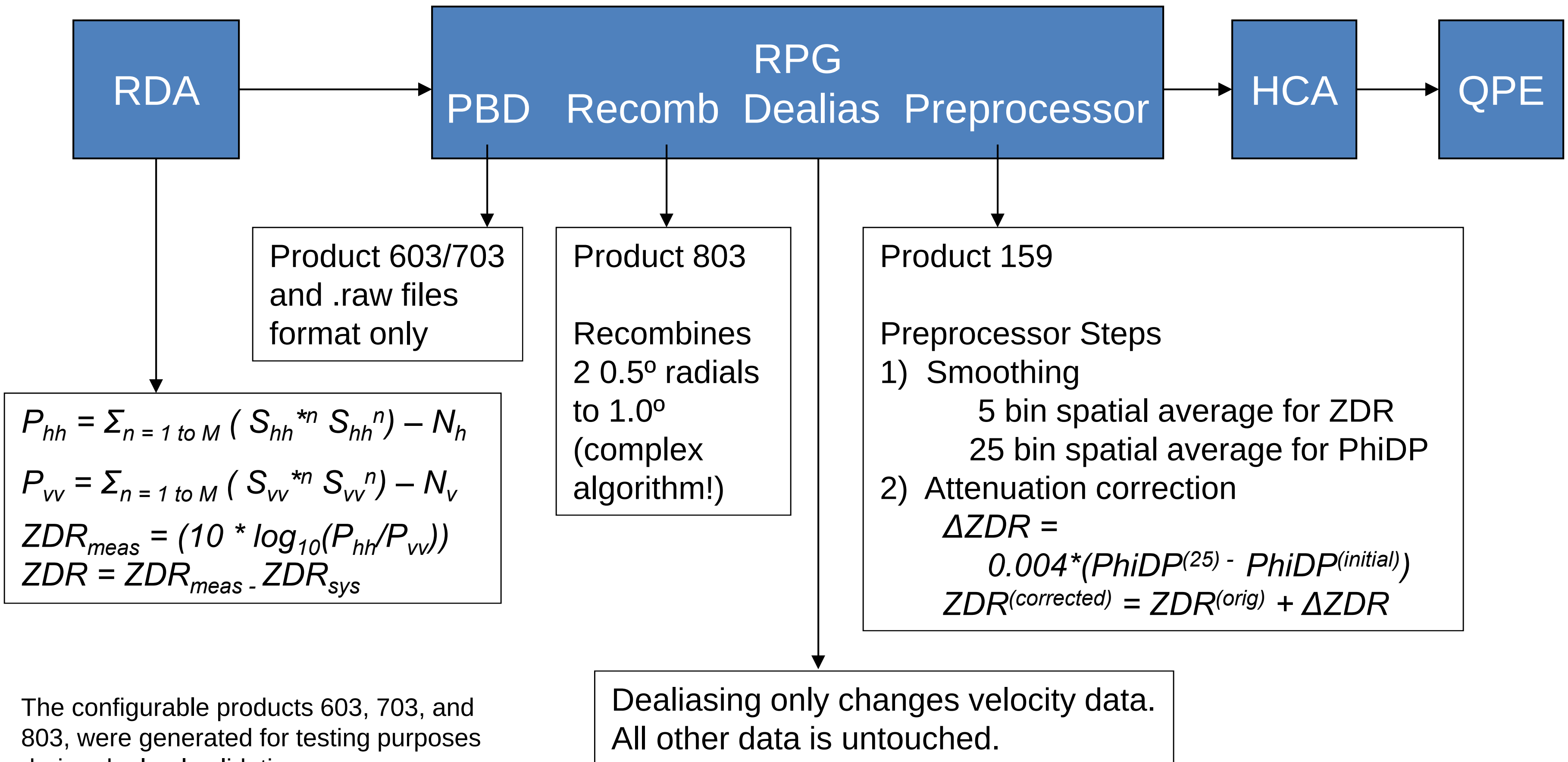
Questions?

Backup Slides

Calibration Measurement Paths (adapted from F. Pratte, 12/16/2008)



Simplified
ZDR Process Flow Diagram



The configurable products 603, 703, and 803, were generated for testing purposes during dual pol validation

Cross-Pol Math Overview
Goal of Cross-pol

Differential Reflectivity (ZDR_{meas}):

Reflectivity for the H channel (Z_h) equals the transmit power (T), times the gains in the transmit path (G_{th}), times the gains in the receive path (G_{rh}), times the power received from the backscatterer (S_{hh}) :

$$Z_h = TG_{th}G_{rh}S_{hh}$$

Similarly, Z_v for the V channel equals the transmit power (T), times the gains in the transmit path (G_{TV}), times the gains in the receive path (G_{rv}), times the power received from the backscatterer (S_{vv}) :

$$Z_v = TG_{tv}G_{rv}S_{vv}$$

ZDR is the ratio of the Z_H and Z_V, so our *measured* ZDR values are:

$$\frac{Z_h}{Z_v} = \frac{TG_{th}G_{rh}P_{hh}}{TG_{tv}G_{rv}P_{vv}}$$

Canceling common terms yields (assumes transmit power ratio does not change):

$$Zdr_{meas} = \frac{Z_h}{Z_v} = \frac{G_{th}G_{rh}P_{hh}}{G_{tv}G_{rv}P_{vv}}$$

The highlighted part is Zdr introduced by the system (Zdr_{sys}). We want to account for and remove this!

Cross-Pol Math Overview

- The main equation for Cross-polarization Power Technique is:

$$Zdr_{true} = \frac{S_{hh}}{S_{vv}} = Zdr_{meas} * \frac{CP_{xv}}{CP_{xh}} * (Sun)^2$$

  - Where
    - S_{hh} is the transmit/receive H during normal operations
    - S_{vv} is the transmit/receive V during normal operation
    - Zdr_{meas} is the measured Zdr that includes any bias introduced by the radar system
    - CP_{xv} is the clutter scan of transmit H, receive V ??
    - CP_{xh} is the clutter scan of transmit V, receive H ??
    - *Sun* is the measured sun bias which is equal for the co-polar and cross-polar measurements

Cross-Pol Math Overview

- The main equation for Cross-polarization Power Technique is:

$$Zdr_{true} = \frac{S_{hh}}{S_{vv}} = Zdr_{meas} * \frac{CP_{xv}}{CP_{xh}} * (Sun)^2$$

- From the cross-polar power technique, the measured Zdr is corrected by:

$$C = S^2 \frac{CP_{xh}}{CP_{xv}}$$

- Therefore C should equal ZDR_{sys} from the engineering calibration process,

$$Zdr_{sys} = C$$

Cross-Pol Math Overview Step 1

- Measured Zdr – this includes the system differential reflectivity
  - Calculate Reflectivity for H and V channels
    - Z_h = Transmit * $Gain_{th}$ * $Gain_{rh}$ * S_{hh}
    - Z_v = Transmit * $Gain_{tv}$ * $Gain_{rv}$ * S_{vv}
  - Zdr_{meas} is the ratio

$$Zdr_{meas} = \frac{Z_h}{Z_v} = \frac{\cancelto{1}{Transmit} * Gain_{th} * Gain_{rh} * S_{hh}}{\cancel{Transmit} * Gain_{tv} * Gain_{rv} * S_{vv}}$$

Cross-Pol Math Overview Step 2

- Cross-Polar Power
  - Scan ground clutter with all H
  - Measure (receive) ONLY the cross-polar power, V
    - CP_{xv} = Transmit * $Gain_{th}$ * $Gain_{rv}$ * S_{vh}
  - Scan ground clutter with all V, measure H
    - CP_{xh} = Transmit * $Gain_{tv}$ * $Gain_{rh}$ * S_{hv}
  - Calculate differential cross-pol power by taking the ratio

$$\frac{CP_{xv}}{CP_{xh}} = \frac{\cancel{Transmit} * Gain_{th} * Gain_{rv} * \cancel{S_{vh}}}{\cancel{Transmit} * Gain_{tv} * Gain_{rh} * \cancel{S_{hv}}}$$

Equal by Reciprocity

Cross-Pol Math Overview Step 3

- Sun Scan
  - Scan the sun
    - It has equal H/V power and H/V polarization
  - No Transmit, only receive
    - $Sun_h = Gain_{rh}\ S_h$
    - $Sun_v = Gain_{rv}\ S_v$
  - The sun scan measures both cross-polar and copolar receiver biases, which are equal, therefore this is squared

$$\frac{Sun_v}{Sun_h} * \frac{Sun_v}{Sun_h} = \left(\frac{Gain_{rv}\cancel{S_v}}{Gain_{rh}\cancel{S_h}}\right)\left(\frac{Gain_{rv}\cancel{S_v}}{Gain_{rh}\cancel{S_h}}\right)$$

Power received by the sun is equal in H and V

Previously, we had:

$$Zdr_{meas} = \frac{Z_h}{Z_v} = \frac{Gain_{th}}{Gain_{tv}} * \frac{Gain_{rh}}{Gain_{rv}} * \frac{S_{hh}}{S_{vv}}$$

$$\frac{CP_{xv}}{CP_{xh}} = \frac{Gain_{tv}}{Gain_{th}} * \frac{Gain_{rh}}{Gain_{rv}}$$

$$\left(\frac{Sun_v}{Sun_h}\right)^2 = \left(\frac{Gain_{rv}}{Gain_{rh}}\right)\left(\frac{Gain_{rv}}{Gain_{rh}}\right)$$

Combining using the main equation for Cross-polarization Power Technique:

$$Zdr_{meas} * \frac{CP_{xv}}{CP_{xh}} * (Sun)^2 = \left(\frac{Z_h}{Z_v}\right)\left(\frac{CP_{xv}}{CP_{xh}}\right)\left(\frac{Sun_v}{Sun_h}\right)^2$$

$$= \left(\frac{\cancel{Gain_{th}} * \cancel{Gain_{rh}} * S_{hh}}{\cancel{Gain_{tv}} * \cancel{Gain_{rv}} * S_{vv}}\right)\left(\frac{\cancel{Gain_{tv}} * \cancel{Gain_{rh}}}{\cancel{Gain_{th}} * \cancel{Gain_{rv}}}\right)\left(\left(\frac{\cancel{Gain_{rv}}}{\cancel{Gain_{rh}}}\right)\left(\frac{\cancel{Gain_{rv}}}{\cancel{Gain_{rh}}}\right)\right)$$

$$= \frac{S_{hh}}{S_{vv}} = Zdr_{true}$$

Essentially, the sun scan information about the received path allows us to compare measured Zdr and measured crosspolar power by removing the repeated receiver information from measured ZDR and crosspolar power. It can be thought of as a conversion factor.