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on

Conversion of Sunflower Multiband Radiometer Polarization Measurements to Polarization Parameters

prepared by

Larry L. Biehl
School of Electrical Engineering
Purdue University
West Lafayette, IN 47907

and

Dr. Vern C. Vanderbilt
MS 242-4
NASA Ames Research Center
Moffett Field, CA 94035

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The attached report is a copy of the information that is available via the World Wide Web (WWW). The URL for the information can be obtained from Larry Biehl or Vern Vanderbilt. Each section of the attached report represents a page that is available on the WWW. The sections in the report are:

Note: See Vern Vanderbilt or Larry Biehl for copies of the Appendices. These are very long.

Polarization Data Analysis

By Larry Biehl

revised 4-12-95

These hypertext pages summarize some of the analyses of the INRA Sunflower Polarization data collected in 1991.

Algorithm Development

Conversion to Stokes Parameters

The first step was to develop the algorithm to be used to convert the reflectance factors collected for each of nine different instrument channels and three polarizer angles to the I, Q, and U Stokes parameters for each of those nine instrument channels. If psi is the angle of the polarizer with respect to a common reference angle, the intensity, I, falling on the detector through the polarizer is given by:

```
I(psi) = ( I' + Q'cos(2psi) + U'sin(2psi) )/2

where I', Q', and U' represent the first 3 Stokes parameters.
```

The calibrated reflectance factor data in the Sunflower Polarization data base actually represent a ratio of two intensity values that fall on the detector - the response to the sunflower canopy divided by the response to the Barium Sulfate reflectance standard. Therefore the reflectance factors, RF, in the data base can be modeled as:

```
       ( Is' + Qs'cos(2psi) + Us'sin(2psi) )/2
RF = ----------------------------------------
       ( Ir' + Qr'cos(2psi) + Ur'sin(2psi) )/2

where:
  Is', Qs', Us' represent Stokes parameters for the Sunflowers
  Ir', Qr', Ur' represent Stokes parameters for the Barium Sulfate panel
```

If one assumes that the barium sulfate reference panel exhibits very little polarization affects, then Qr' and Ur' are 0. (Previous work indicates that barium sulfate reference panels do exhibit some polarization affects - less than 1% for zenith angles less than 50 degrees and up to 2% for view zenith angles of 80 degrees.) Assuming that Qr' and Ur' are 0, the refectance factor can then be modeled as:

```
       ( Is' + Qs'cos(2psi) + Us'sin(2psi) )/2
RF = ----------------------------------------
            Ir'/2

or

RF = Is'/Ir' + Qs'cos(2psi)/Ir' + Us'sin(2psi)/Ir'
```

The measurements for the three polarizer angles allow one to determine the three unknowns - Is'/Ir', Qs'/Ir' and Us'/Ir'. These parameters from now on will be labeled as I, Q, and U. The matrix setup for the three reflectance factor measurements at three polarizing angles (psi1, psi2 & psi3) is:

$$\begin{bmatrix} RF1 \\ RF2 \\ RF3 \end{bmatrix} = \begin{bmatrix} 1 & \cos(2*psi1) & \sin(2*psi1) \\ 1 & \cos(2*psi2) & \sin(2*psi2) \\ 1 & \cos(2*psi3) & \sin(2*psi3) \end{bmatrix} * \begin{bmatrix} I \\ Q \\ U \end{bmatrix}$$

The matrix setup for computing I, Q and U is:

$$\begin{bmatrix} I \\ Q \\ U \end{bmatrix} = INV \begin{bmatrix} 1 & \cos(2*psi1) & \sin(2*psi1) \\ 1 & \cos(2*psi2) & \sin(2*psi2) \\ 1 & \cos(2*psi3) & \sin(2*psi3) \end{bmatrix} * \begin{bmatrix} RF1 \\ RF2 \\ RF3 \end{bmatrix}$$

Also these three parameter allow one to compute three other parameters:

Degree of Polariation, PP = sqrt(Q*Q + U*U)/I * 100 (percent).

Angle Chi of the plane of polarization, X = arctan(U/Q)/2 (degrees).

Reflectance factor due to polarization, Rp = I * PP/100 (percent).

Procedure for averaging 1 degree FOV data

The algorithm used for averaging the 1 degree field of view data is a box car type average of the data along each view azimuth direction. The data are averaged so that the resulting measurement roughly simulates a 1 degree by 12 degree field of view that is sampled every two degrees. The first question that came to my mind was: do I average the original reflectance factor data or do I average the computed I, Q, and U parameters? I decided that it would be best to average the original reflectance factor data. Further analysis, however, indicated that it does not make any difference. The I, Q, and U parameters are computed as linear combinations of the original reflectance factor triplets.

The algorithm for averaging two sets of reflectance factor triplets and then computing I, Q and U is:

$$\begin{bmatrix} I \\ Q \\ U \end{bmatrix} = INVM * \begin{bmatrix} (RF1a + RF1b)/2 \\ (RF2a + RF2b)/2 \\ (RF3a + RF3b)/2 \end{bmatrix}$$

where INVM is the inverse matrix from above.

The algorithm for averaging after computing I, Q and U is:

$$\begin{bmatrix} I \\ Q \\ U \end{bmatrix} = \begin{bmatrix} INVM * \begin{bmatrix} RF1a \\ RF2a \\ RF3a \end{bmatrix} + INVM * \begin{bmatrix} RF1a \\ RF2a \\ RF3a \end{bmatrix} \end{bmatrix} * \frac{1}{2}$$

Note the above two equations are the same. Therefore it does not make any difference whether one averages the data before or after computing the I, Q and U parameters for a linear combination type of algorithm which the box car average is.

Another question does arise though concerning how to compute the percent polarization and chi angle of polarization for the simulated 1 degree by 12 degree field of view (FOV).

During the process of averaging the data into 2 degree bins, there were some bins which were empty. I decided to fill these bins with interpolated data from that available in the bins before and after. I interpolated the original reflectance factor triplets. I noticed that in some cases, the resulting calculated values for percent polarization and chi angle of polarization from the interpolated reflectance factor triplets were not the within the range of the respective values for the bins on either side.

This does make sense to me after thinking about it because the percent polarization (PP) and chi angle (X) of polarization are not a linear combinations of I, Q, and U. I plotted a series of measured data and interpolated data (mean of each view zenith pair for a view azimuth direction) which indicates that the computed PP and X parameters based on interpolated values can be quite different from that calculated from two measured values used for the interpolation. The affect is very apparent in the 1 degree field of view data and not so apparent in the 12 degree field of view data. This makes sense because the 1 degree field of view data are almost completely independent. The areas observed by a 12 degee FOV for a sequence of two samples separated by two degree is very nearly the same.

I decided that the proper procedure to simulate a 1 by 12 degree FOV is to average the original reflectance data (or I-Q-U parameters) and then compute PP and X. This process better estimates the polarization properties of the 1 by 12 degree FOV to compare to the Cimel 12 by 12 degree FOV.

Saying it in another way, averaging after computing the PP and X parameters will create a smoothed version of these 1 degree FOV parameters which will not necessarily be representative of larger FOV data. The percent polarization properties of smaller FOV data appear to always be larger than that for larger FOV data.

See figures comparing the two averaging techniques for computing 1x12 degree percent polarization data.

Data Processing

The July 25 data were selected as the first date of data to evaluate since this is the first date for which there are 12 degree FOV data available. The polarized data collected before this was collected with 1 degree field of views for both the Barnes and Cimel instruments. Beginning with July 25, the Cimel instruments had 12 degree field of view's. There is a lot of variation from one measurement to the next in one degree field of view data.

A data file was created that contains the obove six parameters for each observation. This data file, labeled as 'Single Observation Data', is available; see below.

A second data file was also created. A 'scan' of data for an azimuth direction consists of view zenith observations approximately every two degrees from 75 degrees to -75 degrees and back to 75 degrees. These data were averaged into two degree view zenith angle bins. Also for this data file, the Barnes data were averaged to simulate a 12 degree by 1 degree field of view that is sampled at every 2 degrees using a straight box car average to reduce the variation in the data. This data file, labeled as '2 Degree Bin Data', is also available; see below.

NOTE: Before downloading be sure to set your World Wide Web viewer so that these files will be downloaded to disk. (Otherwise the file, which is very large, will be displayed on the screen).

The data in the files are in a tab delimited format. The first row of data contains the titles for the columns. All view azimuth angles refer to the direction as measured from the target to the sensor. Relative azimuth refers to the above view azimuth angle minus the solar azimuth angle.

Changes (1/19/95):
Single Observation Data: Corrections were made in some Sky data view azimuth angle errors.

2 Degree Bin Data: Changes were made in some Sky view azimuth angles, view azimuth angles for all data and the procedure for the box car average. I found that the view azimuth angles in the '2 Degree Bin Data' generated in late November reflected the angle from the sensor to the scene not the scene to the sensor. This caused the relative azimuth angle to be off by 180 degrees.

Changes (1/26/95):
The data for July 11, 12, 15 and 16 were added.

Also some errors were found in the angles used for the polarizers for the Cimel Green, Red and IR bands in the July 25, 27 and 29 data. (The angles used were those for the Cimel radiometers with the 1 degree FOV's not the 12 degree FOV's as they should have been.) Also the reference polarizer angle is now taken into account for the polarizer angle 'triplets'. This affects the three Cimel bands and the MMR Blue and Red bands. The corrections cause changes in the July 25, 27 and 29 data for the Chi Angle of Polarization for the above bands and in the Percent of Polarization for only the Cimel Red band.

Polarizer Angles Used in Computations

List of Data Files Available

The Matlab M-files used to create the single observation data and 2-degree bin data are available.

Data Processing Results

The **I, Q, U** data represent the calculated I, Q and U Stokes parameters for the green, red and infrared bands of the Cimel and MMR multiband radiometers. Relative azimuth refers to the view azimuth angle minus the solar azimuth angle. Positive view zenith angle is in the direction represented by the relative azimuth angle. Negative view zenith angle is in the relative azimuth angle plus 180 degrees.

The **PP, X, Rp** data represent the calculated Percent Polarization, Chi angle of plane of polarization and the Reflectance factor due to polarization for the green, red and infrared bands of the Cimel and MMR multiband radiometers.

The **MMR Band 7** data plots represent the reflectance factor for MMR channel 7. There was one MMR channel 7 in each radiometer that did not have a polarizer. The field of view of this channel was 1 degree. These measurements can be used to compare the measurement from the 3 different instruments which were viewing slightly different scenes.

Some other pieces of information that are useful when analyzing the data are the relative sizes and locations of the field of views as a function of view zenith angle and the view zenith angle as a function of the plant row. This information is probably most useful for the 1-degree FOV data since this data represents only portions of a row width for a broad range of view zenith angles. The 12-degree FOV data represents the average of several row widths even for a view zenith angle of zero degrees.

Evaluation of Intermediate Reflectance Data

A key concern with the polarization data for this experiment is whether the one degree data represents more random scatter than real signal. Early evaluations of the one degree FOV data caused a concern that one may not be able to interpret this data because the variation in the data was quite high. This led to the change in the experiment whereby the FOV's of the Cimel instruments were changed to 12 degrees. The FOV's of the MMRs were left at 1 degree because one of the purposes of this experiment was to evaluate the polarization measurements of small areas.

The evaluation of the single observation reflectance factor data and I-Q-U processed data for the sky and the sunflowers indicate that the variation in the 1-degree data does represent 'real signal'. There is still some concern that some of the variation in the percent polarization and chi angle of polarization values for the 1-degree data may be due to the fact that the 3 radiometer channels (with 3 different polarizer angles) used to measure the polarization are not perfectly alligned. See the section on the evaluation of the single observation data for more information.

Comparison of Sky Data

The sky data were used as a verification tool to compare the data from the Cimel and MMR instruments. In most cases the sky represented a fairly uniform scene which makes comparisons of 1 degree and 12 degree field of view data easier. An item which probably compromises the comparisons is differences in shadowing of the polarizer material. Comparisons of the sky data were the reason for the changes made angles used for the polarizers in the data processed after January 26. (The Q and U parameters for the Cimel and MMR red bands processed before this date had almost opposite slopes.)

July 25, 1991

Set 1:Sunflowers (Solar Zenith: 53-50; Solar Azimuth: 98-101)

Plots of I, Q, U data:

Green band

Red Band

Infrared Band

Plots of PP, X, Rp data:

Green band

Red Band

Infrared Band

Plots of MMR Band 7 data

3D Plot of Percent Polarization

Some Observations: Note that the plots for the I Stokes parameter are very similar for the 3 measurements plotted in most cases. However, the plots for the Q and U parameters are not similar. The 12 x 1 degree FOV Barnes data have much more variation in them than the 12 degree FOV Cimel data. This represents the different amounts of polarization measured in the two different FOV's.

The Matlab M-files use to create the above plots are available.

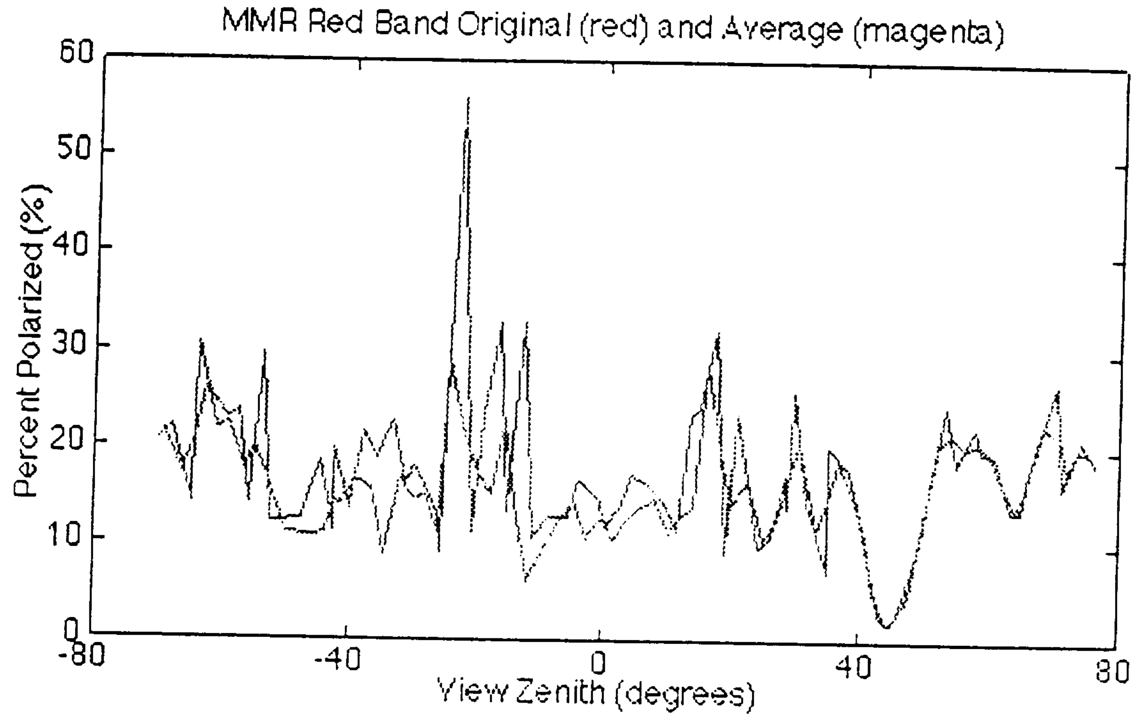
Comparison of Original and Average

The color codes for the lines in the plots are:

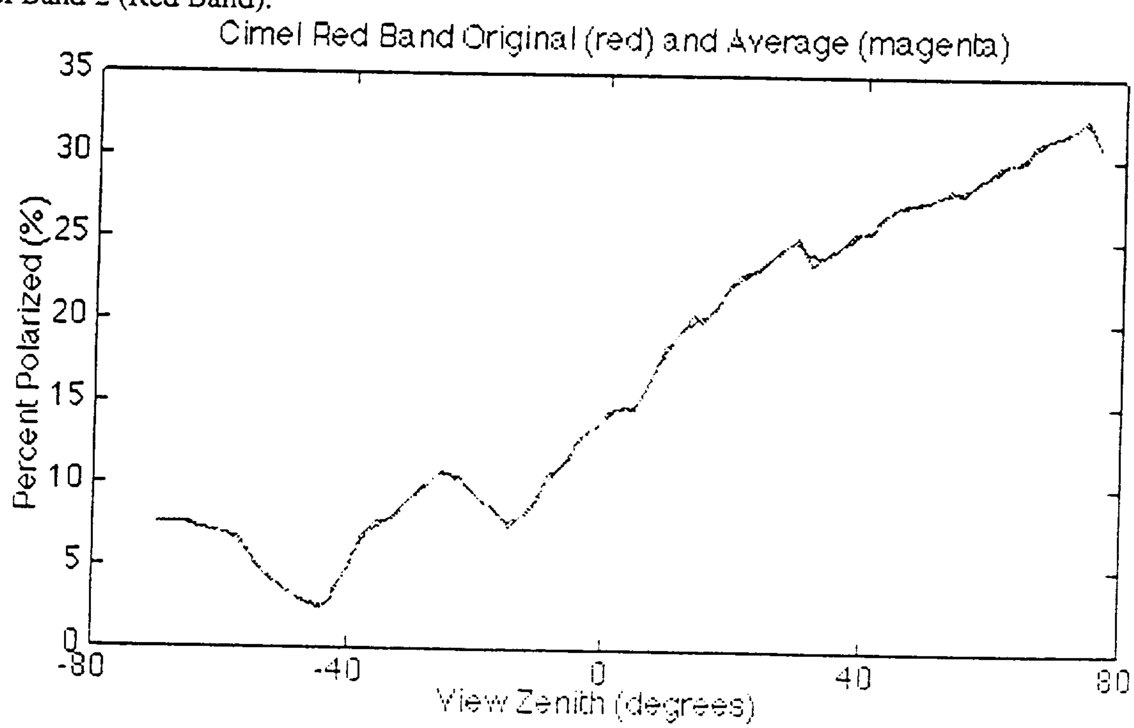
- Red - Original Data
- Magenta - Averaged Data

Percent Polarized

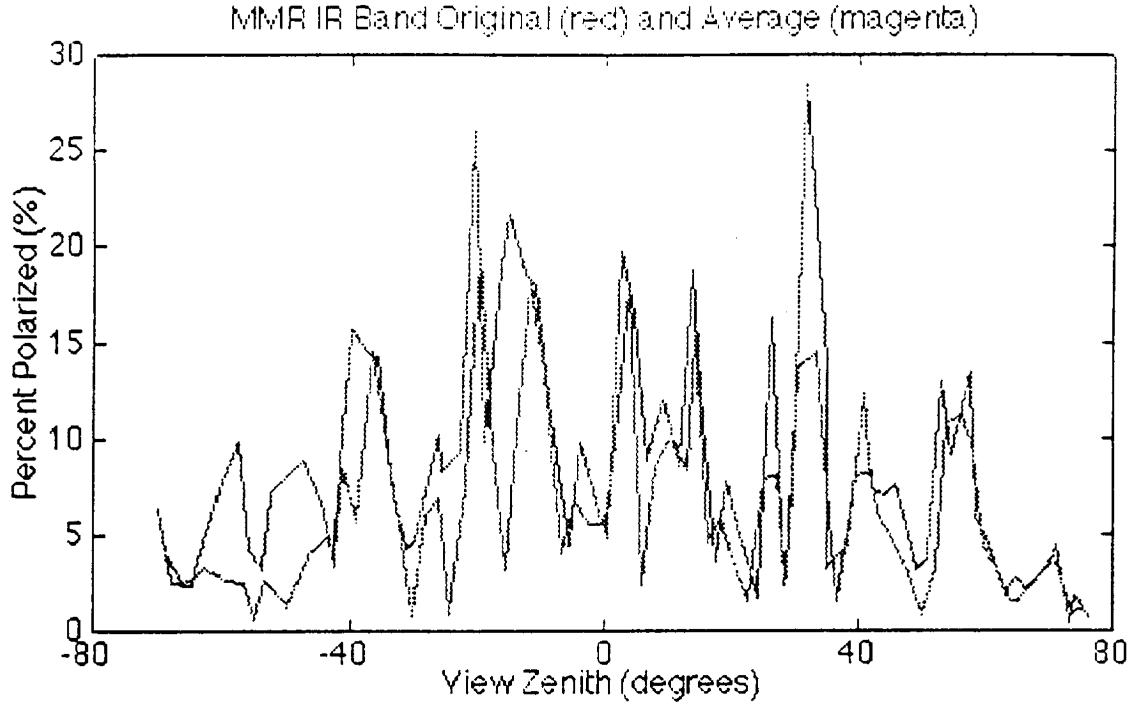
MMR Band 3 (Red Band).



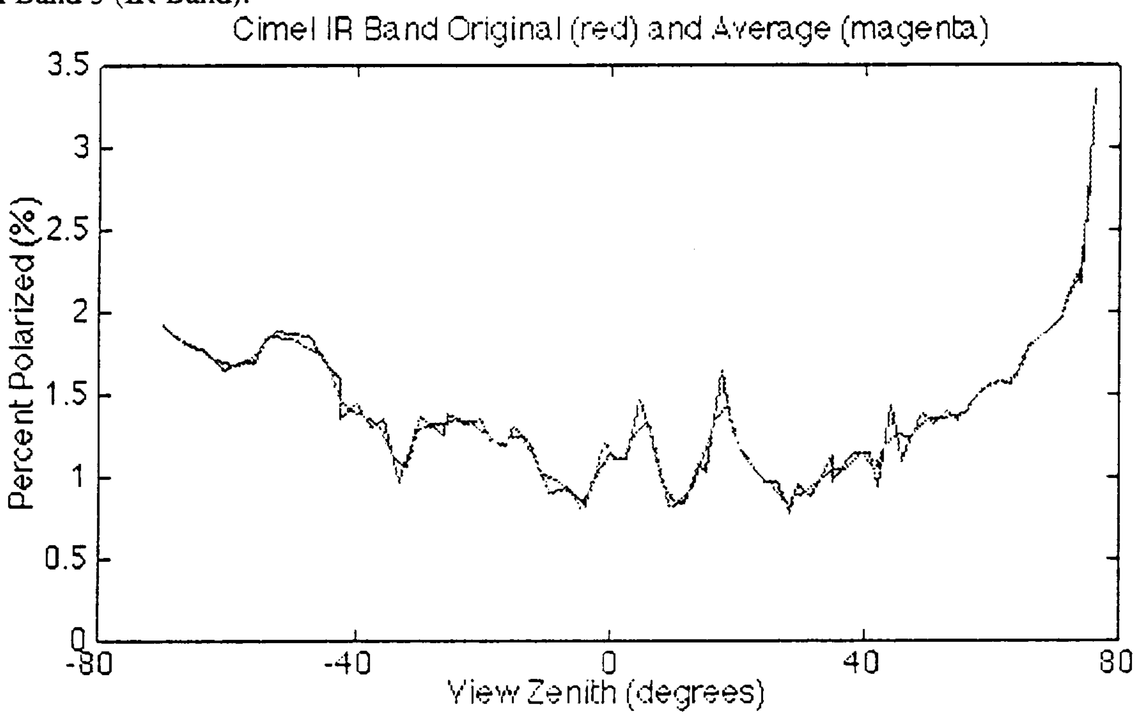
Cimel Band 2 (Red Band).



MMR Band 4 (IR Band).

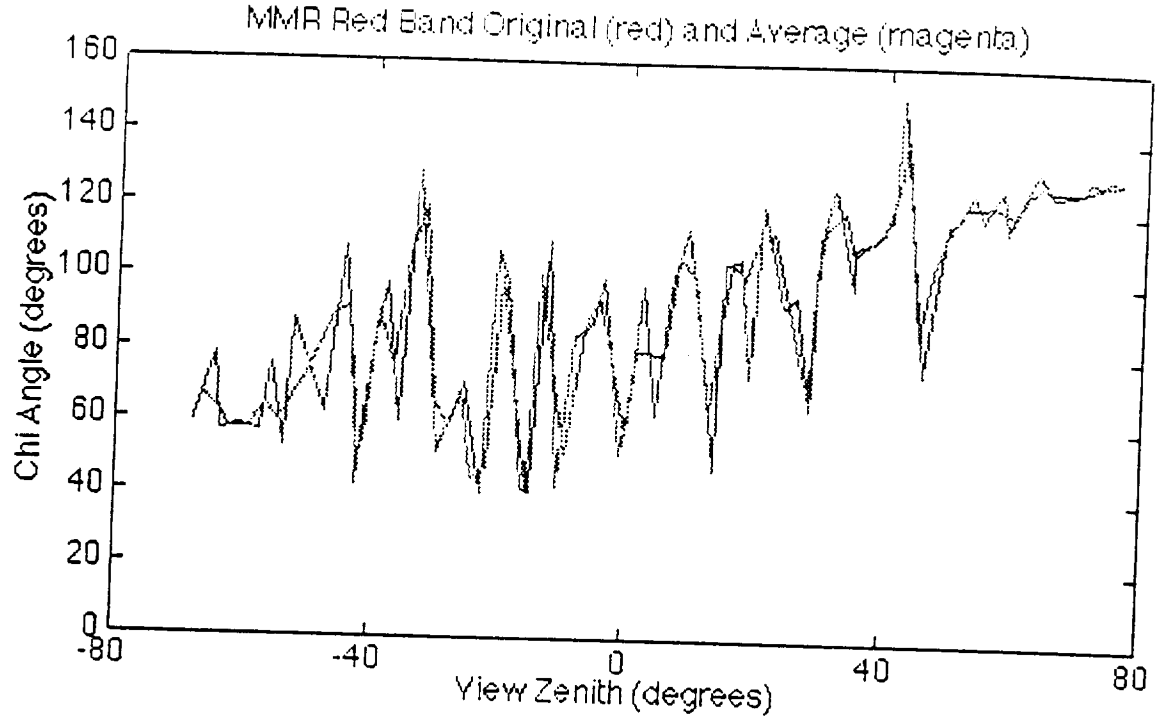


Cimel Band 3 (IR Band).

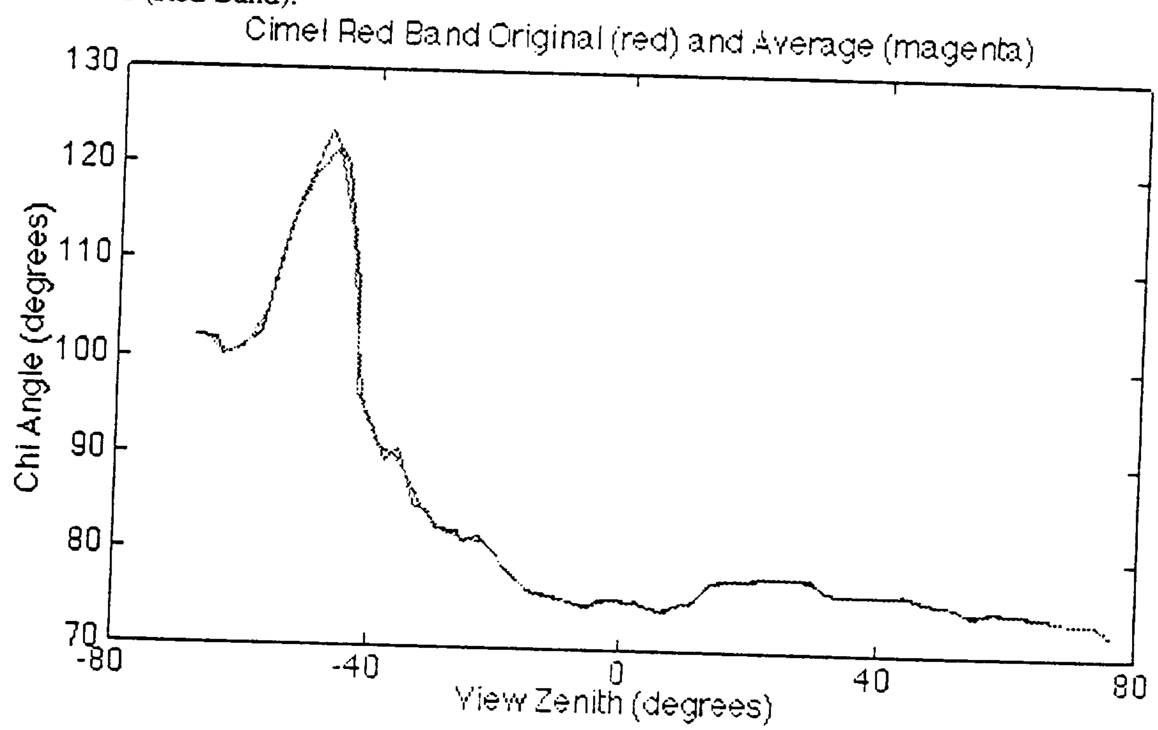


Chi Angle of Plane of Polarization

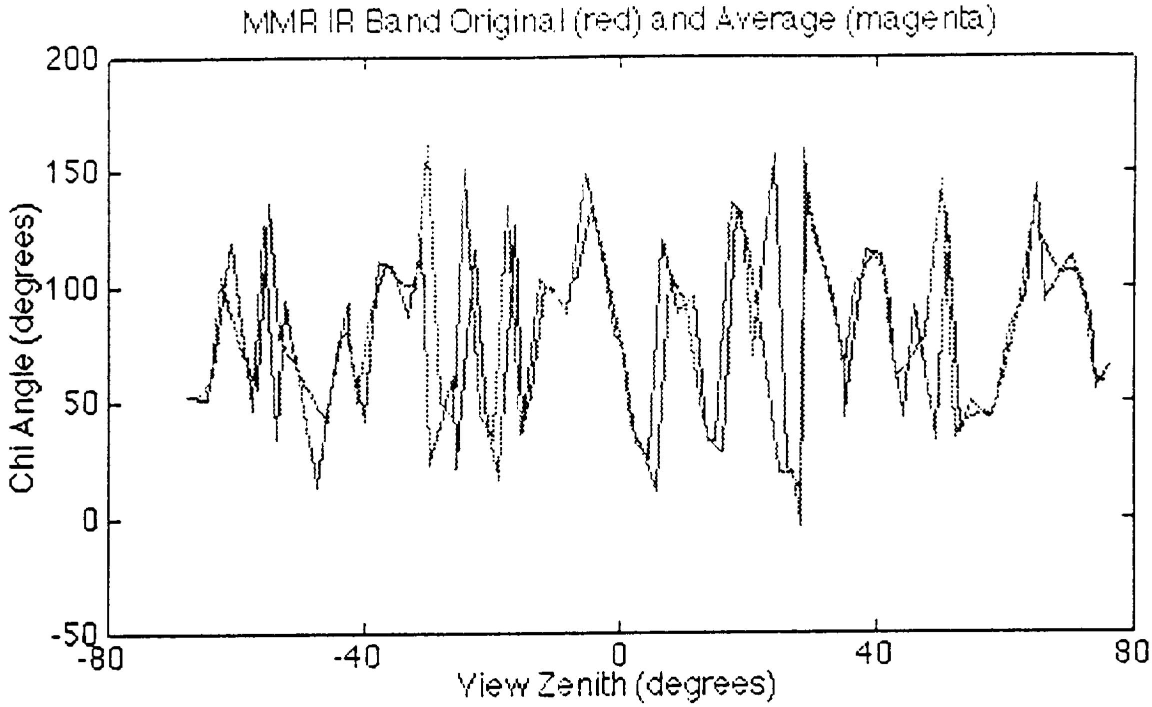
MMR Band 3 (Red Band).



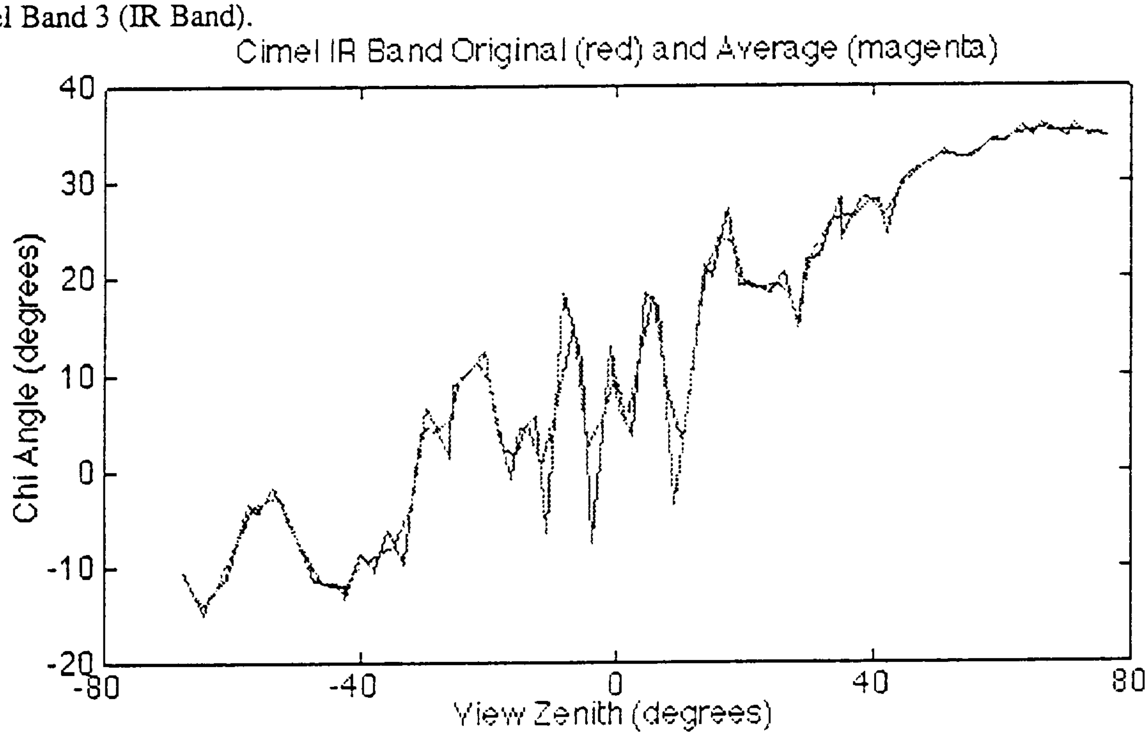
Cimel Band 2 (Red Band).



MMR Band 4 (IR Band).



Cimel Band 3 (IR Band).



Comparison of Two Averaging Techniques

The following plots compare two techniques to average the percent polarization parameter into a simulated 1x12 degree FOV. The 1x12 degree FOV data are plotted against the single observation (1-degree FOV) percent polarization data. The first averaging technique is labeled as 'Average of I-Q-U data'. The I-Q-U data are first averaged using a box car method to simulated 1x12 degree FOV data that is sample every 2 degrees. The percent polarization for the 1x12 degree FOV data is then computed from the averaged I-Q-U data. The second averaging technique is labeled as 'Average of Percent Polarization'. The percent polarization parameter is computed from the single observation I-Q-U data and then averaged to simulate 1x12 degree FOV data using the same box car technique described above.

Note in the plots that the average percent polarization based on I-Q-U is always less than or equal to the average of the single observation percent polarization data. The I-Q-U averaged based data is more similar to, but far from being the same as, the Cimel data which represent 12x12-degree FOV data.

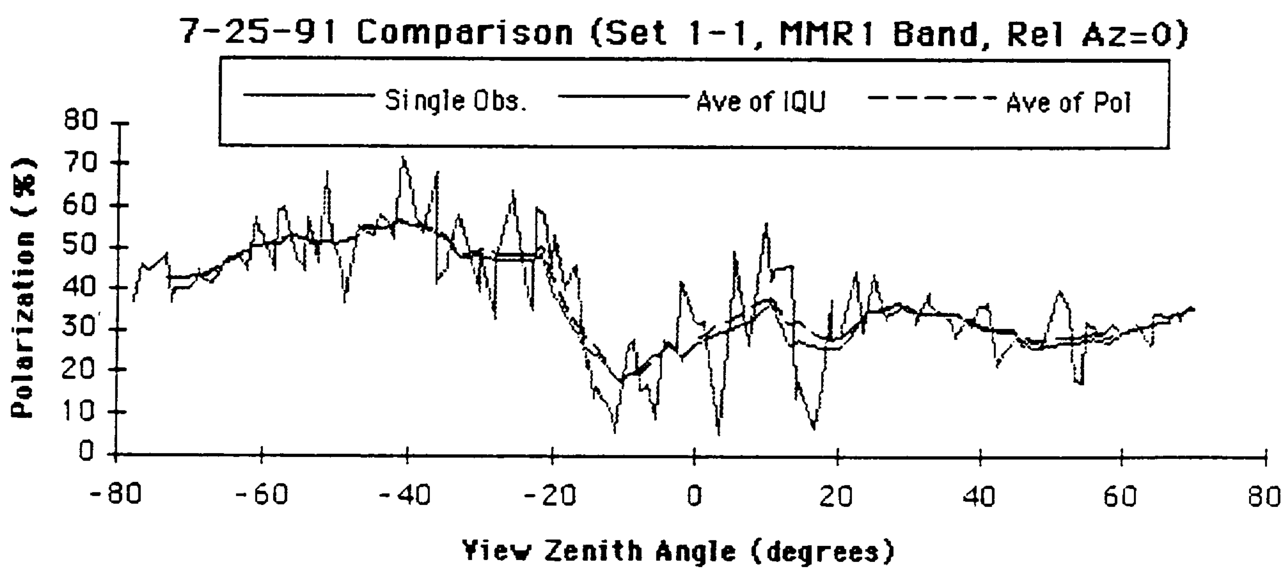
Also note that the two techniques produce the nearly the same results for the sky data. The sky represent a very uniform scene as compared to the sunflower canopy.

The color codes for the lines in the plots are:

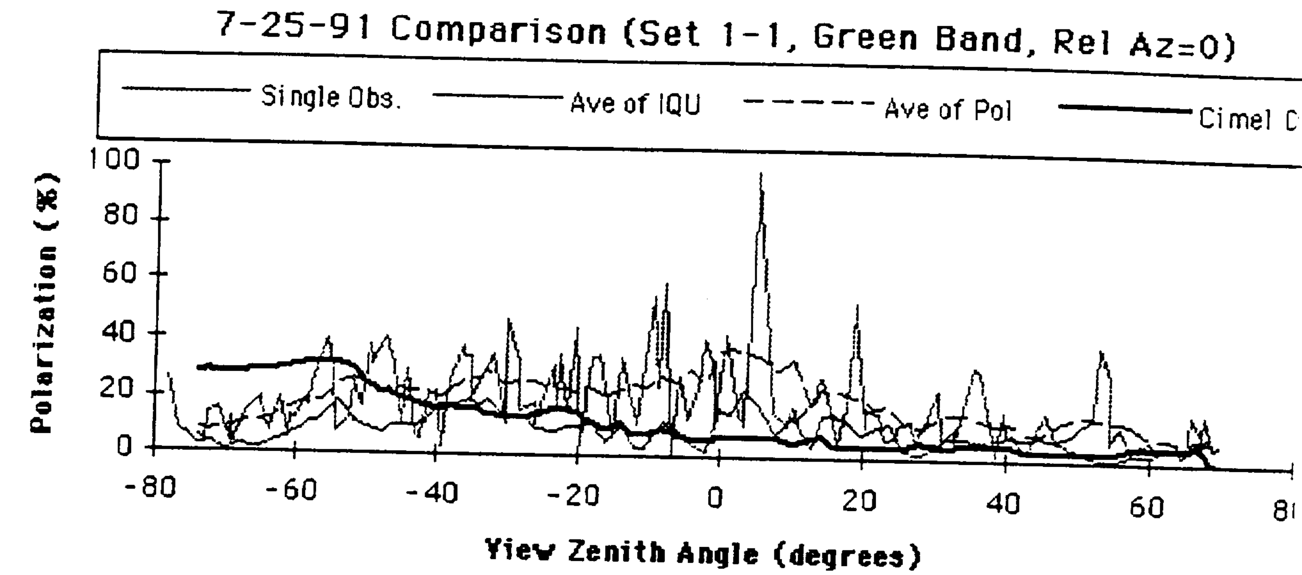
- Red - Single Observation data
- Green - Average of I-Q-U data
- Blue - Average of Percent Polarization
- Black - Equivalent Cimel Band (12-degree FOV)

7/25 Set 1,Rep 1, Relative View Azimuth = 0 (Sunflower Canopy)

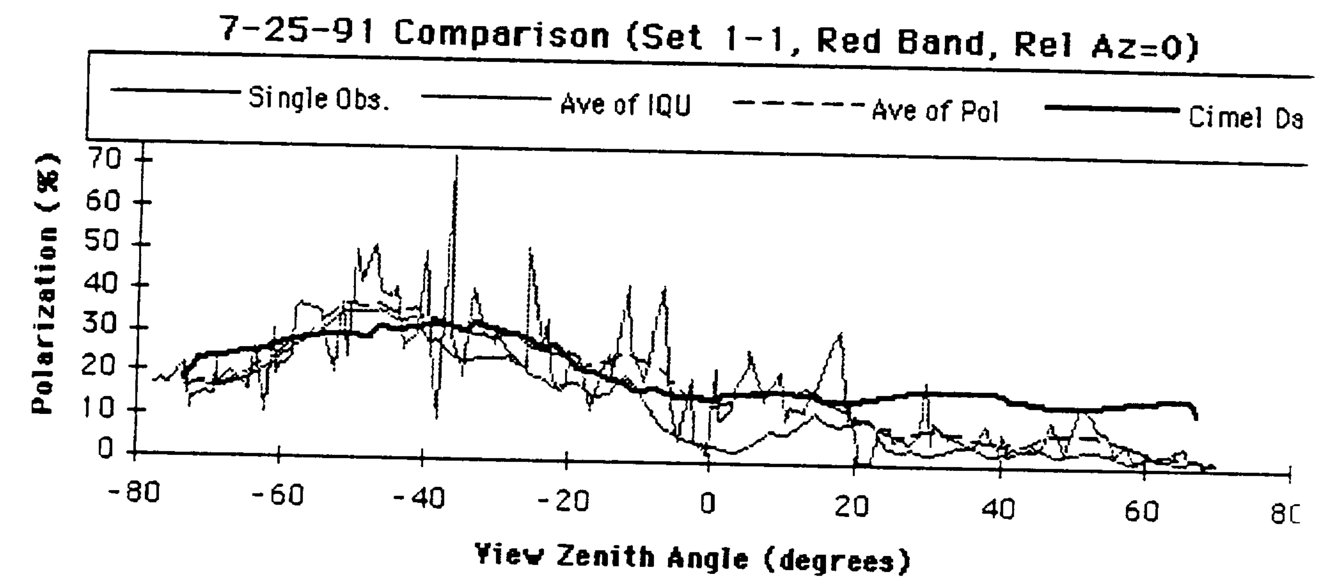
MMR Band 1 (blue band)



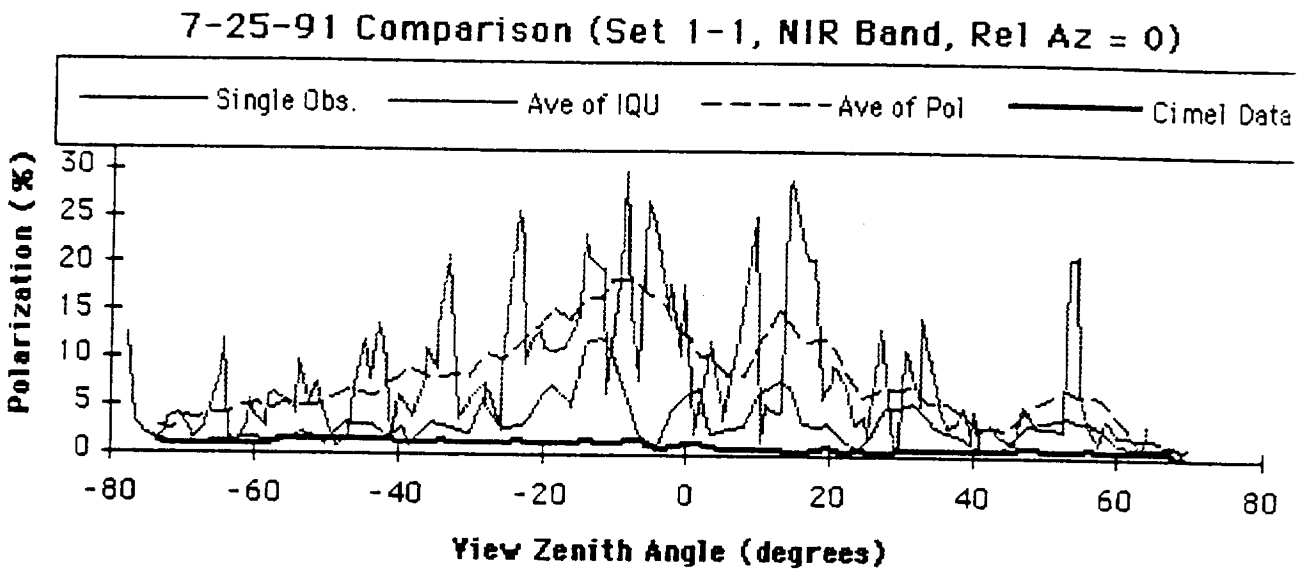
MMR Band 2 (green band)



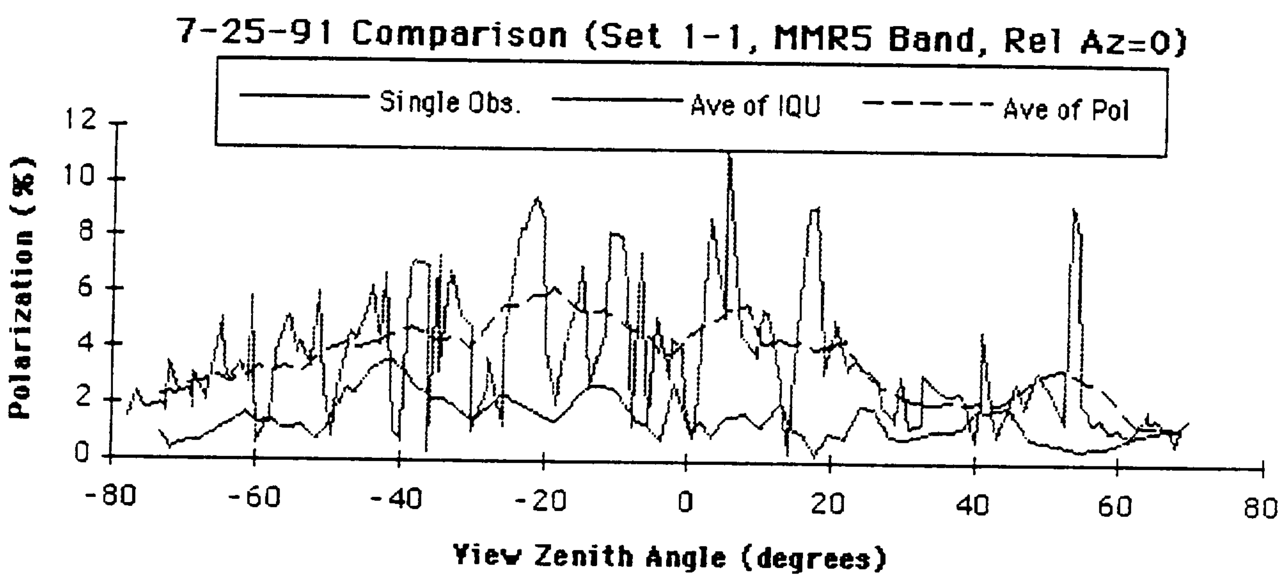
MMR Band 3 (red band)



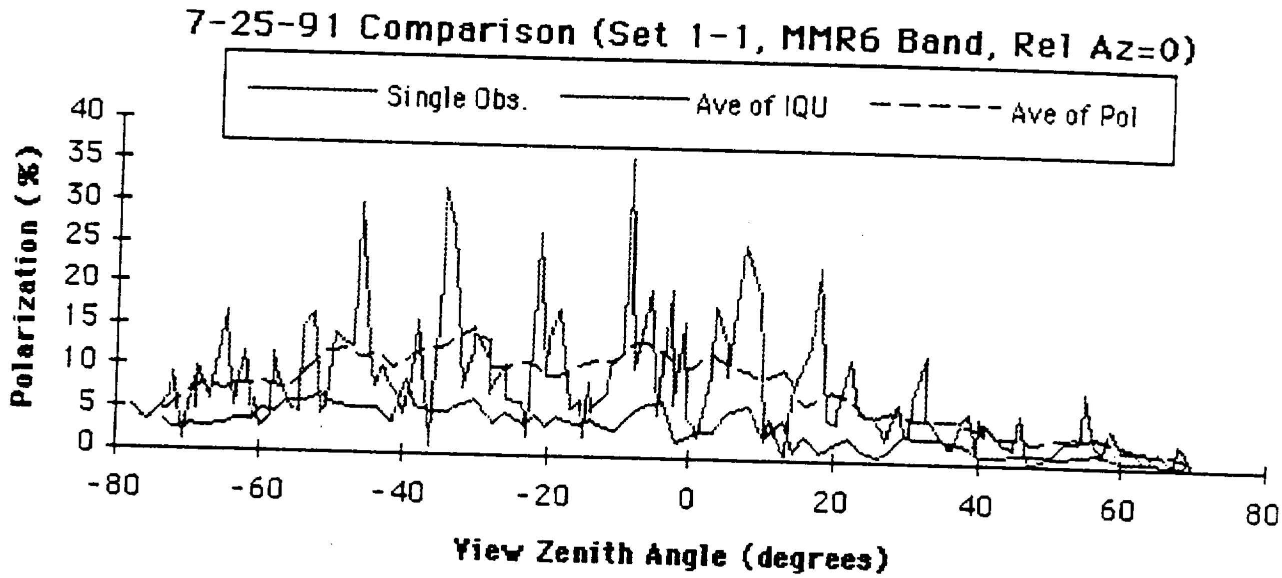
MMR Band 4 (NIR band)



MMR Band 5 (1.15-1.30 um)

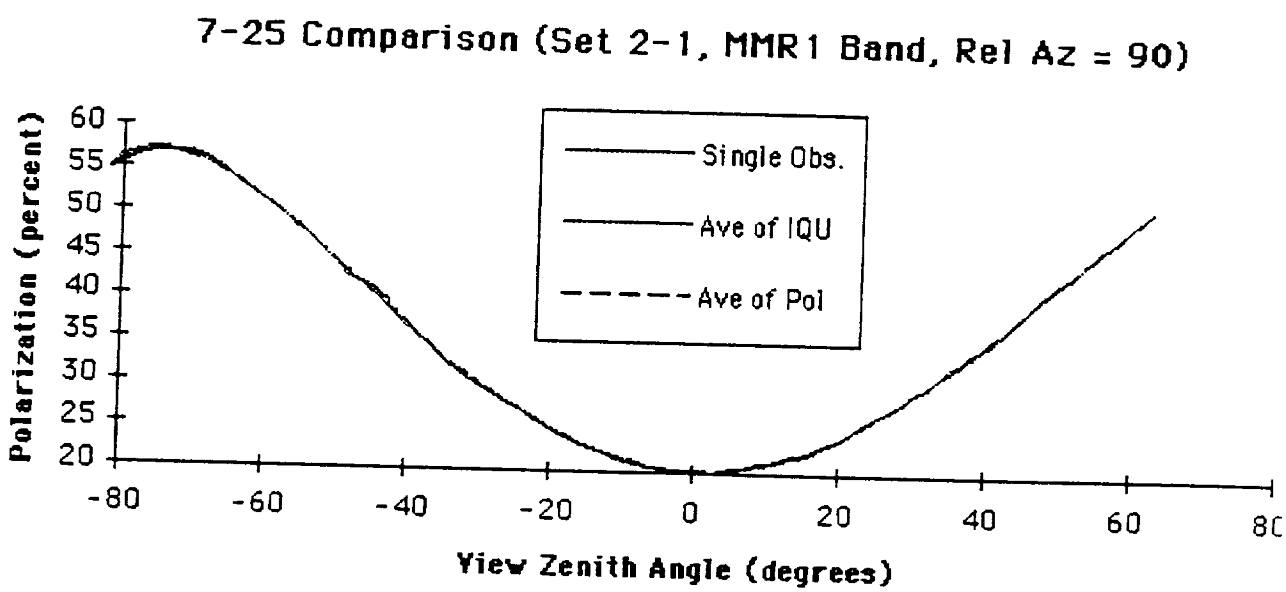


MMR Band 6 (1.55-1.75 um)

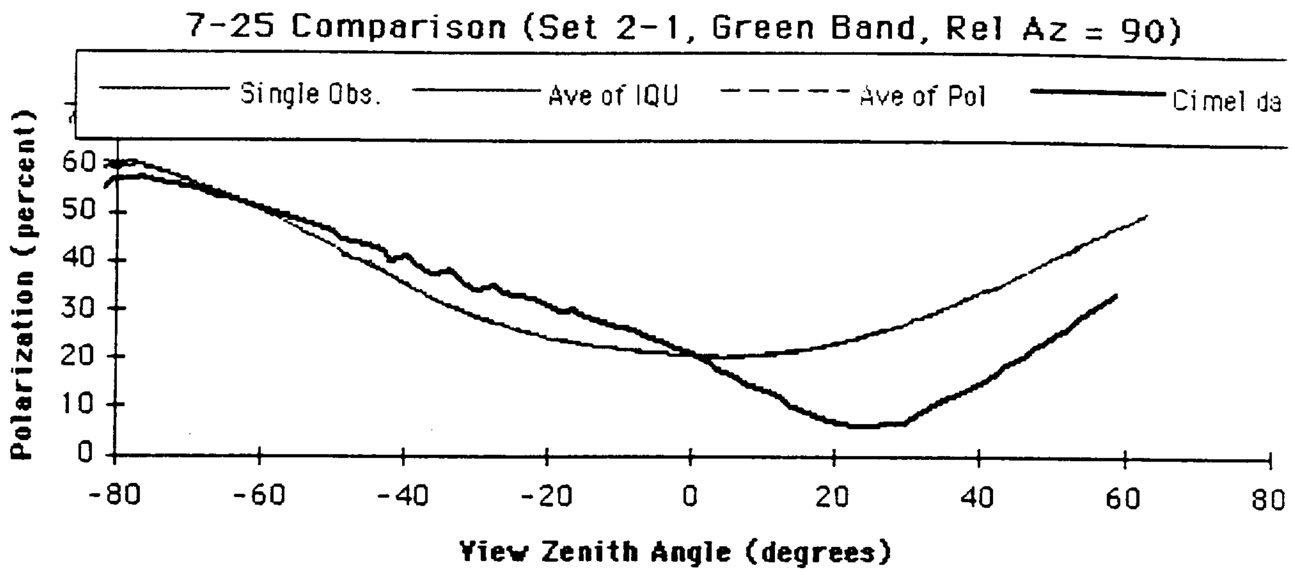


7/25 Set 2, Relative View Azimuth = 90 (Sky)

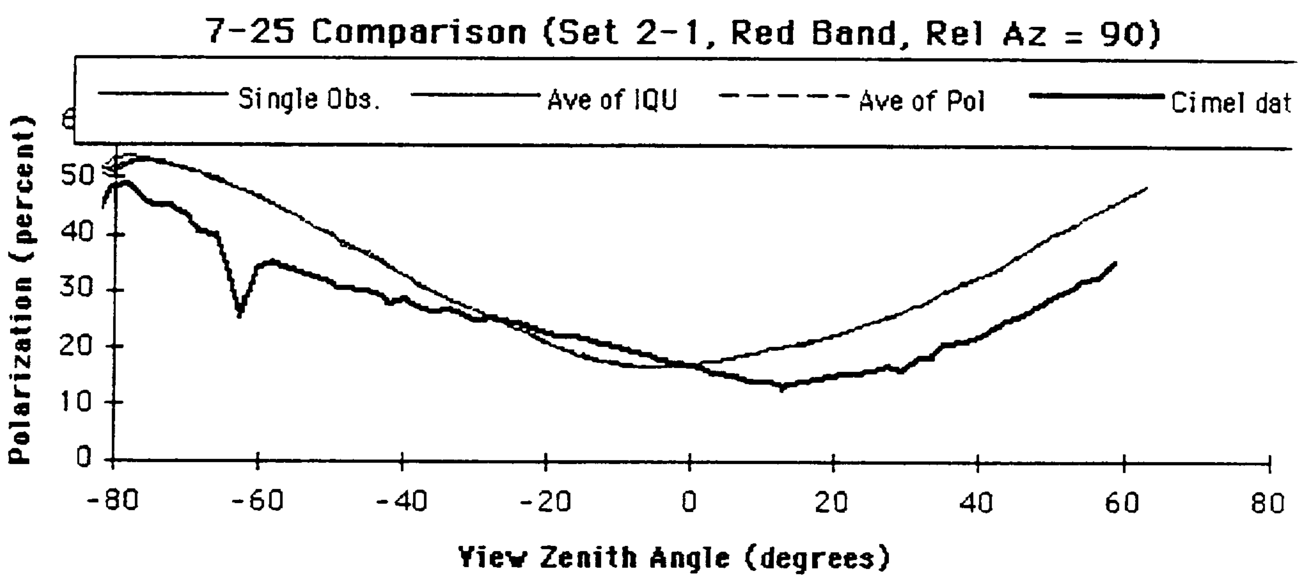
MMR Band 1 (blue band)



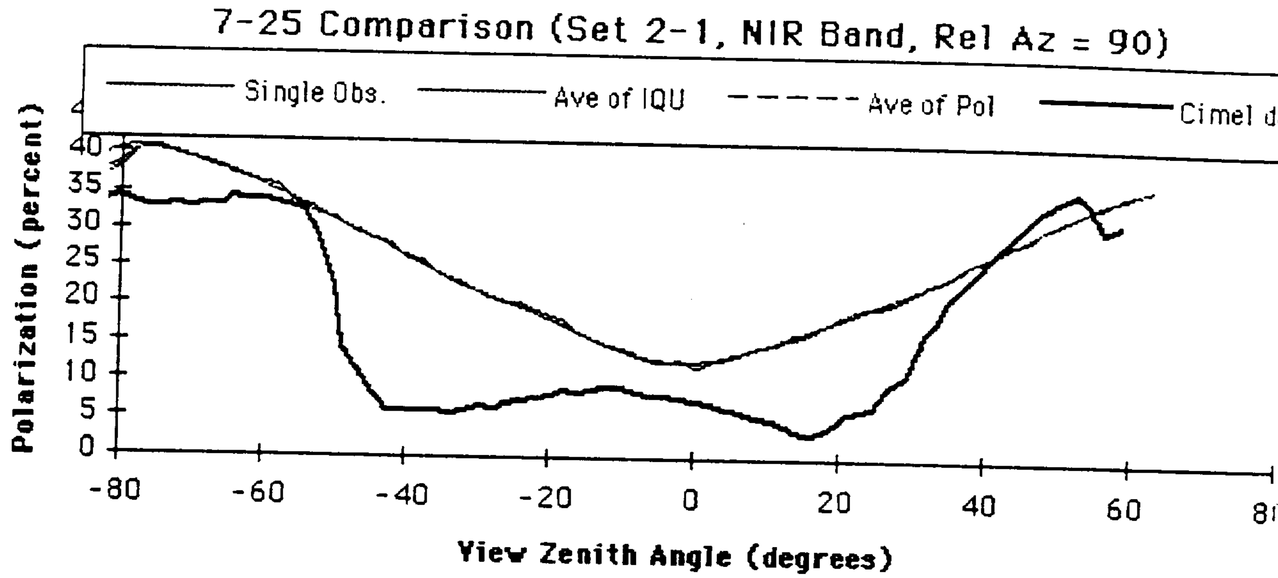
MMR Band 2 (green band)



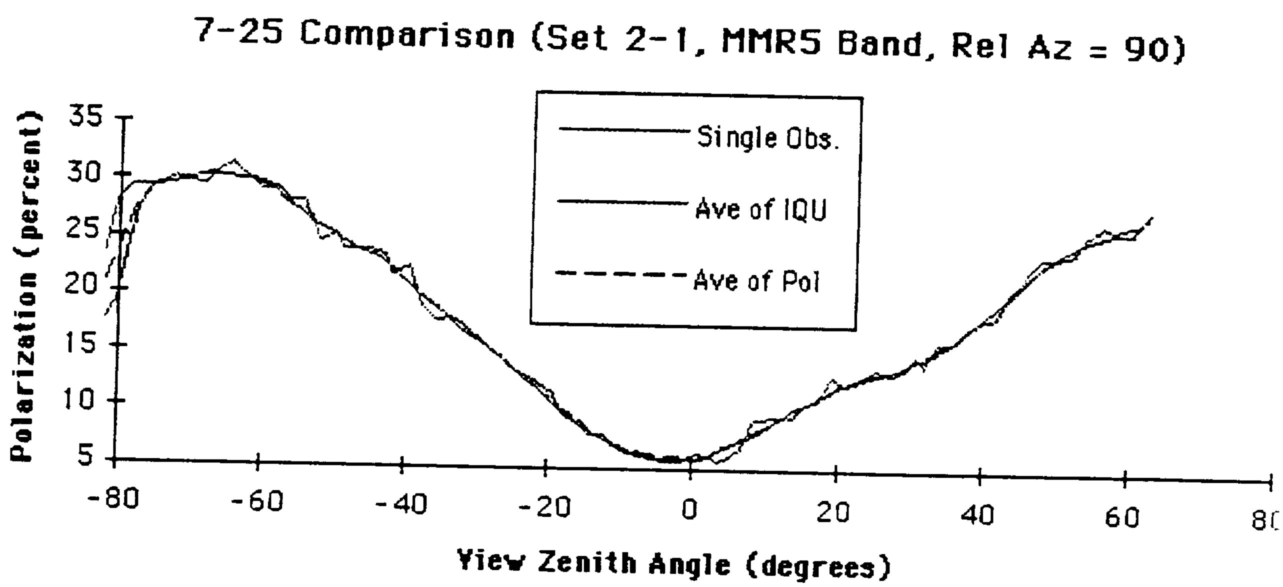
MMR Band 3 (red band)



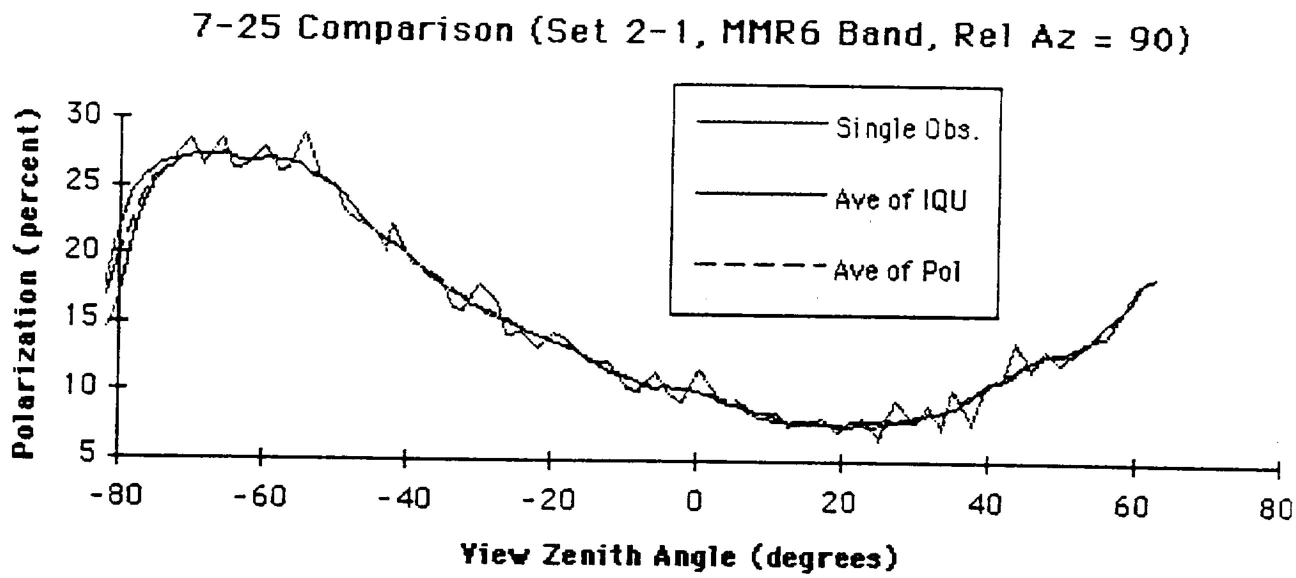
MMR Band 4 (NIR band)



MMR Band 5 (1.15-1.30 um)



MMR Band 6 (1.55-1.75 um)


7-25 Comparison (Set 2-1, MMR6 Band, Rel Az = 90)
Single Obs.
Ave of IQU
Ave of Pol
Polarization (percent)
30
25
20
15
10
5
-80
-60
-40
-20
0
20
40
60
80
View Zenith Angle (degrees)

Polarizer Angles

revised 1-27-95

The following polarizer angles come from two documents - a hand written document dated 8/1/91 titled 'Polarizer Results-Summary of Raw Data' and a printer output document titled 'Stokes Matrices used in the Avignon experiment, summer 91'.

For the calculations to determine I, Q and U, the Reference angle (REF) is subtracted from the 3 respective polarizer angles.

For data from July 11 thru July 16

Cimel - Green Band (Cimel-Quest)

Ch1: 123.308
Ch2: 342.266
Ch3: 80.697
Ref: 184.65

Cimel - Red Band (Cimel-Est)

Ch1: 81.618
Ch2: 121.136
Ch3: 31.609
Ref: 90.2

Cimel - Infrared Band (Cimel-Zenith)

Ch1: 83.972
Ch2: 118.719
Ch3: 167.245
Ref: 95.35

MMR - Blue Band (MMR-108)

Ch5: 357.127
Ch6: 43.061
Ch7: 87.537
Ref: 184.65

MMR - Green Band (MMR-104)

Ch1: 115.6
Ch2: 202.0
Ch3: 250.9
Ref: 181.6

MMR - Red Band (MMR-108)

Ch1: 178.729
Ch2: 222.001
Ch3: 269.525
Ref: 184.65

MMR - Infrared Band (MMR-105)

Ch1: 93.695

Ch2: 48.15
Ch3: 2.235
Ref: 0

MMR - Band 5 (MMR-105)

Ch5: 92.617
Ch6: 46.856
Ch7: 2.058
Ref: 0

MMR - Band 6 (MMR-104)

Ch5: 208.6
Ch6: 299.5
Ch7: 160.5
Ref: 95.35

For data from July 25 thru August 5

Cimel - Green Band (Cimel-Quest)

Ch1: 124.8
Ch2: 343.7
Ch3: 80.46
Ref: 2.5

Cimel - Red Band (Cimel-Est)

Ch1: 3.
Ch2: 40.8
Ch3: 92.7
Ref: 2.5

Cimel - Infrared Band (Cimel-Zenith)

Ch1: 343.614
Ch2: 21.377
Ch3: 78.979
Ref: 2.5

MMR - Blue Band (MMR-108)

Ch5: 357.127
Ch6: 43.061
Ch7: 87.537
Ref: 184.65

MMR - Green Band (MMR-104)

Ch1: 91.893
Ch2: 140.25
Ch3: 4.202
Ref: 0

MMR - Red Band (MMR-108)

Ch1: 178.729
Ch2: 222.001
Ch3: 269.525

Ref: 184.65

MMR - Infrared Band (MMR-105)

Ch1: 93.695
Ch2: 48.15
Ch3: 2.235
Ref: 0

MMR - Band 5 (MMR-105)

Ch5: 92.617
Ch6: 46.856
Ch7: 2.058
Ref: 0

MMR - Band 6 (MMR-104)

Ch5: 273.035
Ch6: 319.327
Ch7: 2.216
Ref: 0

List of Data Files Available:

July 11, 1994

Single Observation Data (1780k bytes)

2 Degree Bin Data (2000k bytes)

July 12, 1994

Single Observation Data (1000k bytes)

2 Degree Bin Data (970k bytes)

July 15, 1994

Single Observation Data (440k bytes)

2 Degree Bin Data (510k bytes)

July 16, 1994

Single Observation Data (2250k bytes)

2 Degree Bin Data (2460k bytes)

July 25, 1994

Single Observation Data (1660k bytes)

2 Degree Bin Data (1010k bytes)

July 26, 1994

Single Observation Data (380k bytes)

2 Degree Bin Data (220k bytes)

July 27, 1994

Single Observation Data (4350k bytes)

2 Degree Bin Data (2420k bytes)

July 29, 1994

Single Observation Data (270k bytes)

2 Degree Bin Data (160k bytes)

August 2, 1994

Single Observation Data (4350k bytes)

2 Degree Bin Data (2420k bytes)

August 5, 1994

Single Observation Data (4350k bytes)

2 Degree Bin Data (2420k bytes)

List of Matlab M-files Available:

M-files to Convert Reflectance Data to Single Observation I-Q-U data.
Process.m

M-files to Convert Reflectance Data to 2-Degree Bin data. The percent polarization and chi angle of polarization plane represents that computed from the 2-Degree Bin I-Q-U data.
ProcessToZenBinsR.m

M-files to Convert Reflectance Data to 2-Degree Bin data. The percent polarization and chi angle of polarization plane represents the average of the respective single observation parameters.
ProcessToZenBinsR2.m

Support M-files
- AddAllDataToBinsR.m
- AddAllDataToBinsR2.m
- AngOfPolarizedPlane.m
- ComputeAllBinDataR.m
- ComputeAllBinDataR2.m
- ComputeBinDataR.m
- ComputeBinDataR2.m
- DegOfPolarization.m
- GetObservation.m
- GetReformatDate.m
- InitInvStokseM.m
- InvStokesMatrix.m
- WriteAllDataToDisk.m

See Appendix A for File Listings
Vern Vanderbilt & Larry Biehl have copies.

Field of View Sizes as a Function of View Angles

The following two tables describe the physical sizes and locations of the field of views of the instruments as projected on the ground around the tower. The size of the plot was 100 meters by 100 meters and the row spacing beween plants was .43 meters in two perpendicular directions. Therefore, the maximum view zenith angle that should be considered valid is 68 degrees for the twelve degree FOV and 74 degrees for the one degree FOV. For a 0 degree view zenith angle, the FOV includes about 1/2 of a row width for the 1 degree FOV and 6-1/2 row widths for the 12 degree FOV.

One Degree Field of View

This field of view was used was used for the Barnes MMR instruments for all of the dates and for the Cimel instruments from July 11 through July 16.

View Zenith Angle (degrees)	Near Point (meters)	Mid Point (meters)	Far Point (meters)	FOV Length (meters)	FOV Width (meters)
0	-0.12	0.00	0.12	0.24	0.24
2	0.35	0.47	0.59	0.24	0.24
4	0.83	0.94	1.06	0.24	0.24
6	1.30	1.42	1.54	0.24	0.24
8	1.78	1.90	2.02	0.24	0.24
10	2.26	2.38	2.50	0.24	0.24
12	2.75	2.87	2.99	0.25	0.24
14	3.24	3.37	3.49	0.25	0.24
16	3.74	3.87	4.00	0.26	0.25
18	4.26	4.39	4.52	0.26	0.25
20	4.78	4.91	5.05	0.27	0.25
22	5.32	5.45	5.59	0.27	0.25
24	5.87	6.01	6.15	0.28	0.25
26	6.44	6.58	6.73	0.29	0.26
28	7.03	7.18	7.33	0.30	0.26
30	7.64	7.79	7.95	0.31	0.27
32	8.27	8.44	8.60	0.33	0.27
34	8.94	9.11	9.28	0.34	0.28
36	9.63	9.81	9.99	0.36	0.28
38	10.36	10.55	10.74	0.38	0.29
40	11.13	11.33	11.53	0.40	0.30
42	11.94	12.16	12.37	0.43	0.31
44	12.81	13.04	13.27	0.46	0.32
46	13.74	13.98	14.23	0.49	0.33
48	14.73	14.99	15.26	0.53	0.34
50	15.81	16.09	16.38	0.57	0.35
52	16.97	17.28	17.59	0.62	0.37
54	18.24	18.58	18.93	0.68	0.38
56	19.64	20.01	20.40	0.75	0.40
58	21.19	21.60	22.03	0.84	0.42
60	22.92	23.38	23.86	0.94	0.44
62	24.86	25.39	25.93	1.07	0.47
64	27.08	27.68	28.30	1.23	0.50
66	29.62	30.32	31.05	1.42	0.54
68	32.59	33.41	34.27	1.68	0.58
70	36.11	37.09	38.12	2.02	0.63
72	40.35	41.55	42.32	2.47	0.69

74	45.58	47.08	48.68	3.10	0.85
76	52.20	54.15	56.23	4.03	0.97
78	60.89	63.51	66.35	5.46	1.13
80	72.84	76.56	80.67	7.83	1.36

Twelve Degree Field of View

This field of view was used for the Cimel instruments from July 25 through August 5 .

View Zenith Angle	Near Point	Mid Point	Far Point	FOV Length	FOV Width
(degrees)	(meters)	(meters)	(meters)	(meters)	(meters)
0	-1.42	0.00	1.42	2.84	2.84
2	-0.94	0.47	1.90	2.84	2.84
4	-0.47	0.94	2.38	2.85	2.84
6	0.00	1.42	2.87	2.87	2.85
8	0.47	1.90	3.37	2.89	2.87
10	0.94	2.38	3.87	2.93	2.88
12	1.42	2.87	4.39	2.97	2.90
14	1.90	3.37	4.91	3.02	2.92
16	2.38	3.87	5.45	3.07	2.95
18	2.87	4.39	6.01	3.14	2.98
20	3.37	4.91	6.58	3.22	3.02
22	3.87	5.45	7.18	3.31	3.06
24	4.39	6.01	7.79	3.41	3.11
26	4.91	6.58	8.44	3.52	3.16
28	5.45	7.18	9.11	3.65	3.21
30	6.01	7.79	9.81	3.80	3.28
32	6.58	8.44	10.55	3.96	3.35
34	7.18	9.11	11.33	4.15	3.42
36	7.79	9.81	12.16	4.36	3.51
38	8.44	10.55	13.04	4.60	3.60
40	9.11	11.33	13.98	4.87	3.70
42	9.81	12.16	14.99	5.18	3.82
44	10.55	13.04	16.09	5.54	3.95
46	11.33	13.98	17.28	5.95	4.09
48	12.16	14.99	18.58	6.43	4.24
50	13.04	16.09	20.01	6.98	4.41
52	13.98	17.28	21.60	7.62	4.61
54	14.99	18.58	23.38	8.39	4.83
56	16.09	20.01	25.39	9.30	5.07
58	17.28	21.60	27.68	10.40	5.36
60	18.58	23.38	30.32	11.74	5.68
62	20.01	25.39	33.41	13.40	6.04
64	21.60	27.68	37.09	15.49	6.47
66	23.38	30.32	41.55	18.17	6.98
68	25.39	33.41	47.08	21.69	7.58
70	27.68	37.09	54.15	26.47	8.30
72	30.32	41.55	63.51	33.19	9.18
74	33.41	47.08	76.56	43.15	10.30
76	37.09	54.15	96.06	58.97	11.73
78	41.55	63.51	128.44	86.90	13.65
80	47.08	76.56	193.06	145.98	16.34

View Zenith Angles as a Function of Plant Row

The following table describes the view zenith angle for the each sunflower row in the plot. The sunflowers were planted in perpendicular rows spaced 0.43 meters apart in the E-W and N-S directions. This table assumes the view is towards the base of the plant in the row, i.e. at ground level. The column titled 'Perpendicular View Zenith Angle' represents the view zenith angle in the N, E, S and W azimuth directions. The column titled 'Diagonal View Zenith Angle' represents the view zenith angle in the NE, SE, SW and NW azimuth directions.

Row Number	Perpendicular View Zenith Angle (degrees)	Diagonal View Zenith Angle (degrees)
0	0.0	0.0
1	1.8	2.6
2	3.6	5.1
3	5.5	7.7
4	7.3	10.2
5	9.0	12.7
6	10.8	15.1
7	12.6	17.5
8	14.3	19.8
9	16.0	22.1
10	17.7	24.2
11	19.3	26.4
12	20.9	28.4
13	22.5	30.4
14	24.0	32.2
15	25.5	34.0
16	27.0	35.8
17	28.4	37.4
18	29.8	39.0
19	31.2	40.6
20	32.5	42.0
21	33.8	43.4
22	35.0	44.7
23	36.2	46.0
24	37.4	47.2
25	38.5	48.4
26	39.6	49.5
27	40.7	50.6
28	41.7	51.6
29	42.7	52.6
30	43.7	53.5
31	44.6	54.4
32	45.5	55.2
33	46.4	56.1
34	47.3	56.9
35	48.1	57.6
36	48.9	58.3
37	49.7	59.0
38	50.4	59.7
39	51.2	60.3
40	51.9	61.0
41	52.6	61.6
42	53.2	62.1

43	53.9	62.7
44	54.5	63.2
45	55.1	63.7
46	55.7	64.2
47	56.3	64.7
48	56.8	65.2
49	57.4	65.6
50	57.9	66.1
51	58.4	66.5
52	58.9	66.9
53	59.4	67.3
54	59.8	67.7
55	60.3	68.0
56	60.7	68.4
57	61.2	68.7
58	61.6	69.1
59	62.0	69.4
60	62.4	69.7
61	62.8	70.0
62	63.1	70.3
63	63.5	70.6
64	63.9	70.9
65	64.2	71.1
66	64.6	71.4
67	64.9	71.7
68	65.2	71.9
69	65.5	72.2
70	65.8	72.4
71	66.1	72.6
72	66.4	72.9
73	66.7	73.1
74	67.0	73.3
75	67.3	73.5
76	67.6	73.7
77	67.8	73.9
78	68.1	74.1
79	68.3	74.3
80	68.6	74.5
81	68.8	74.7
82	69.0	74.9
83	69.3	75.0
84	69.5	75.2
85	69.7	75.4
86	69.9	75.5
87	70.2	75.7
88	70.4	75.8
89	70.6	76.0
90	70.8	76.1

Evaluation of Single Observation Data

Comparison of the Two View Angle Scans (Reps)

A comparison was made of the reflectance factor data for the two scans of view zenith angle data over the sunflower canopy. The data were collected by starting a scan at a view zenith angle of 70 degrees to the left of nadir, rotating counter clockwise through nadir and to 70 degrees to the right of nadir (scan 1). Then the instrument was rotated clockwise back through nadir to 70 degrees to the left of nadir (scan 2). Observations were collected approximately every 2 degrees. The observations for the two scans represent two different samplings of a view zenith angle scan for a given view azimuth angle.

The data for the two scans in the figures are very similar. Even though there is a significant amount of variation in the 1-degree FOV data for the sunflowers, the variation is very similar for the two scans. This indicates that the variation is real and due to the sunflower canopy.

The correlation of two scans of the 1-degree FOV data for one of the bands was around 0.9. This analysis was done by matching up the nearest view zenith angles for the two scans.

The data in the figures represent all of the data collected on July 25 for Replication 1 of Set 1 with a relative view angle of 0 degrees.

Comparison of Polarizer Data Triplets

The single observation data were also evaluated by comparing the reflectance factor triplets (data from each of the three polarizer angles) for each band for one of the view angle scans. These data as indicated in the figures also track very well indicating again that the variation in the 1-degree FOV data is real.

The data also indicate that the FOV's for the band triplets are 'close', otherwise the variations in the data would not track very well. A key question though is, are the 1-degree FOV's close enough for an accurate determination of the polarizing properties of the canopy for 1-degree FOV data. The figures illustrate that there are significant changes in the reflectance factor of the 1-degree FOV data in some cases across just 2 degrees. If the alignment of the FOV's of the triplet bands are off by a few tenths of a degree in these cases, the resulting calculation of percent polarization could off by several percent of value.

The plots of the 1-degree FOV sky data also indicate that there is very little 'noise' in these data because the measurements are very smooth. The sky represents a very uniform scene - at least when there are no clouds.

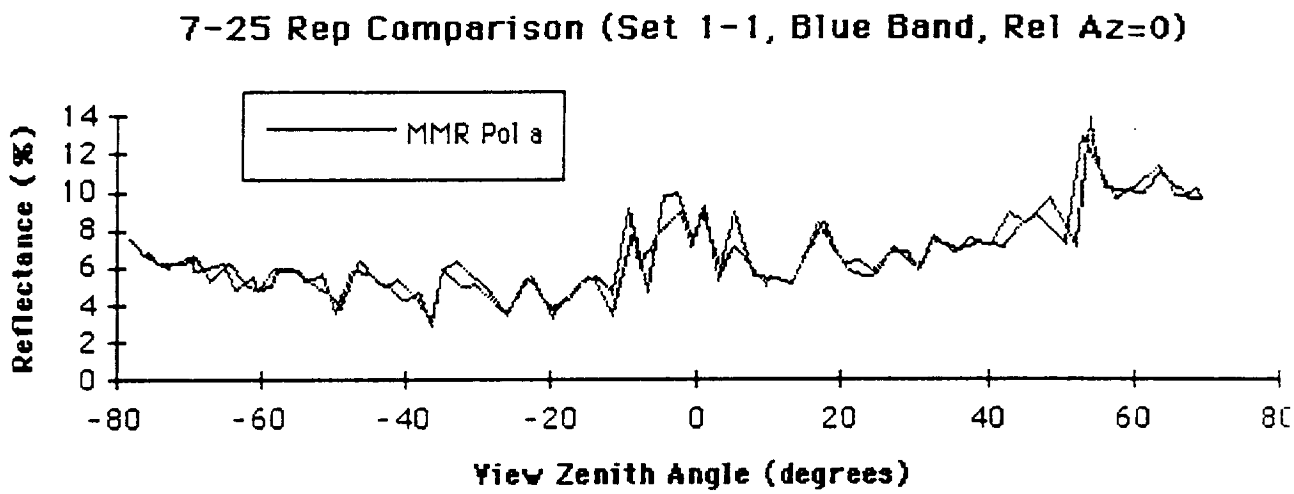
The figures represent the data collected for the red and near infrared bands on July 25 for Replication 1 of Set 1 for a relative view angle of 0 degrees (sunflower canopy) and Replication 2 for a relative view angle of 90 degrees (sky).

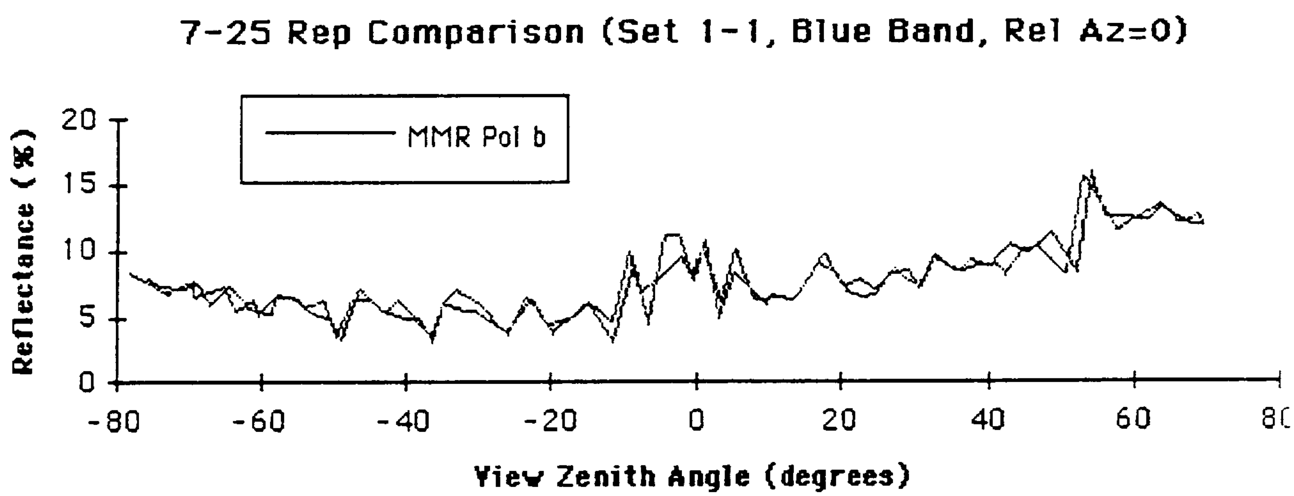
Figures of Two View Angle Scans

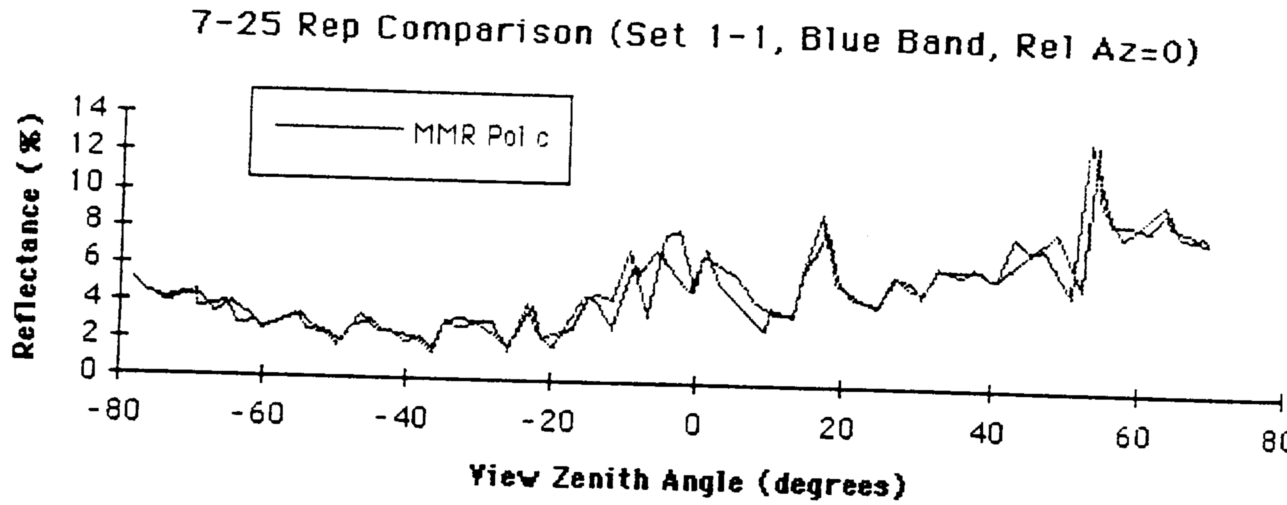
The following figures represent all of the data collected on July 25 for Replication 1 of Set 1 for a relative view angle of 0 degrees.

Sunflower Data (7/25, Set 1, Rep 1, Rel Az = 0 degrees)

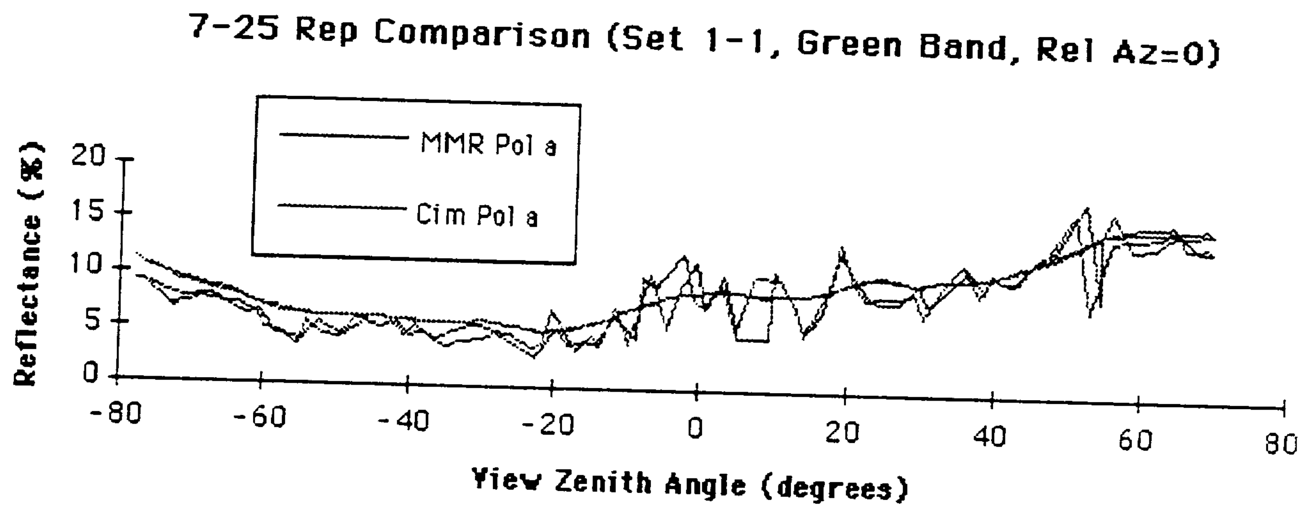
MMR1 (Blue) Band for polarizer angles a, b and c.

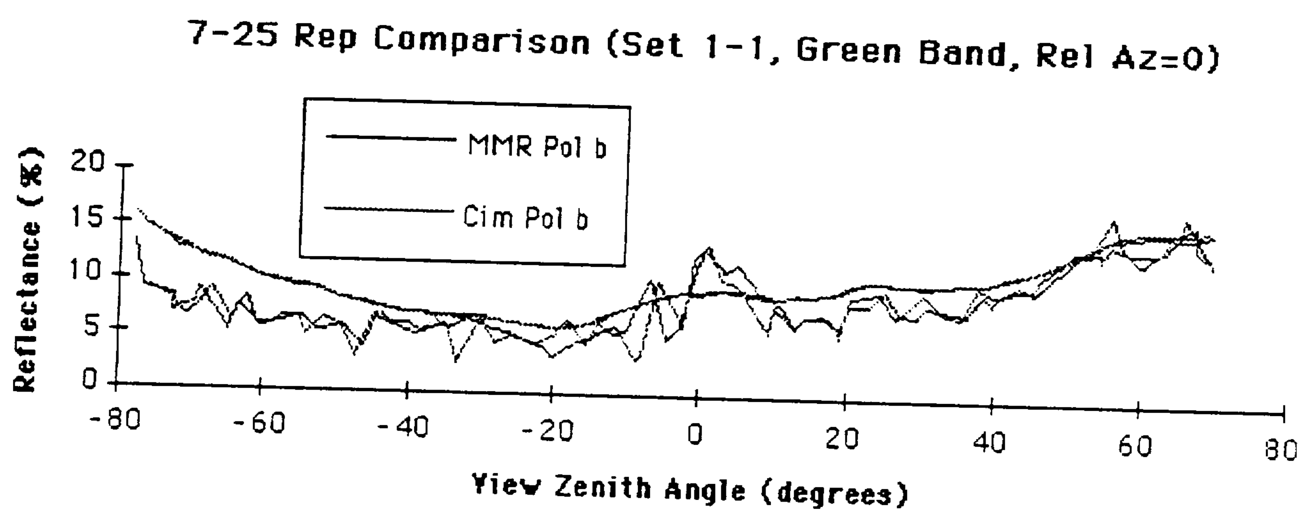


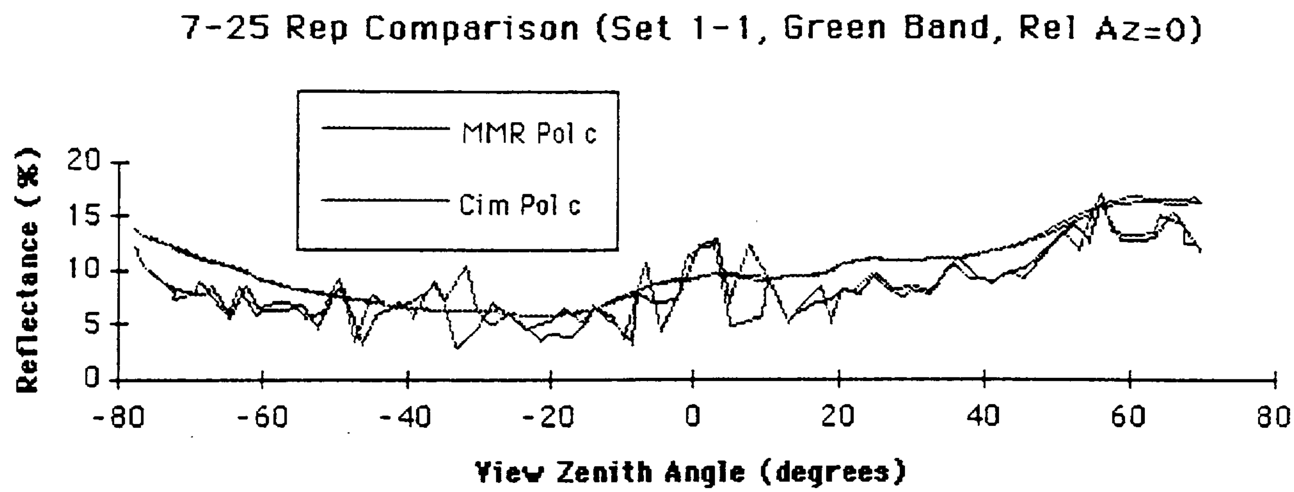




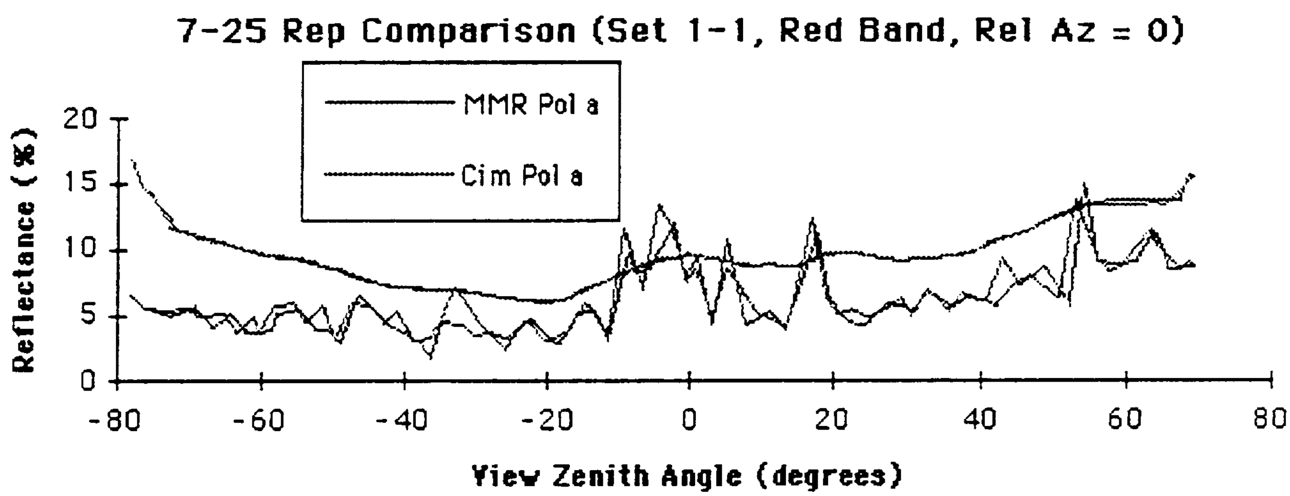
Green Band for polarizer angles a, b and c.

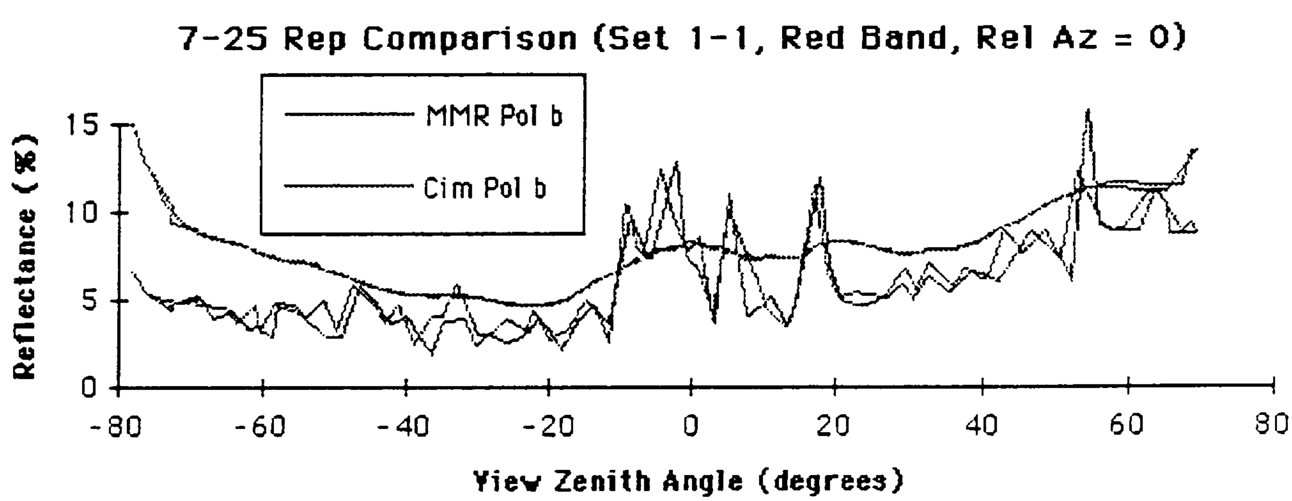


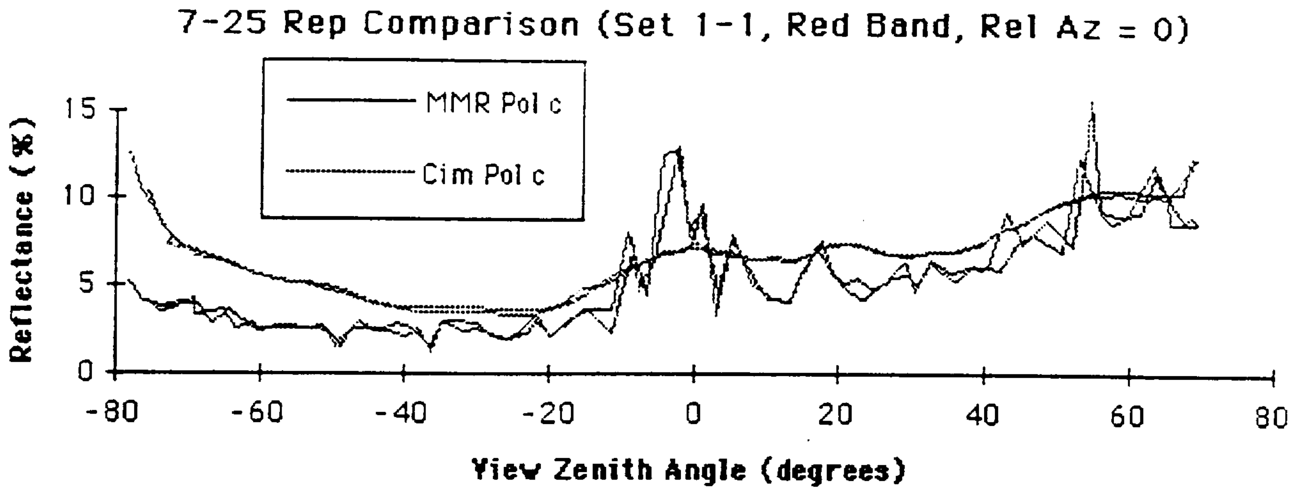




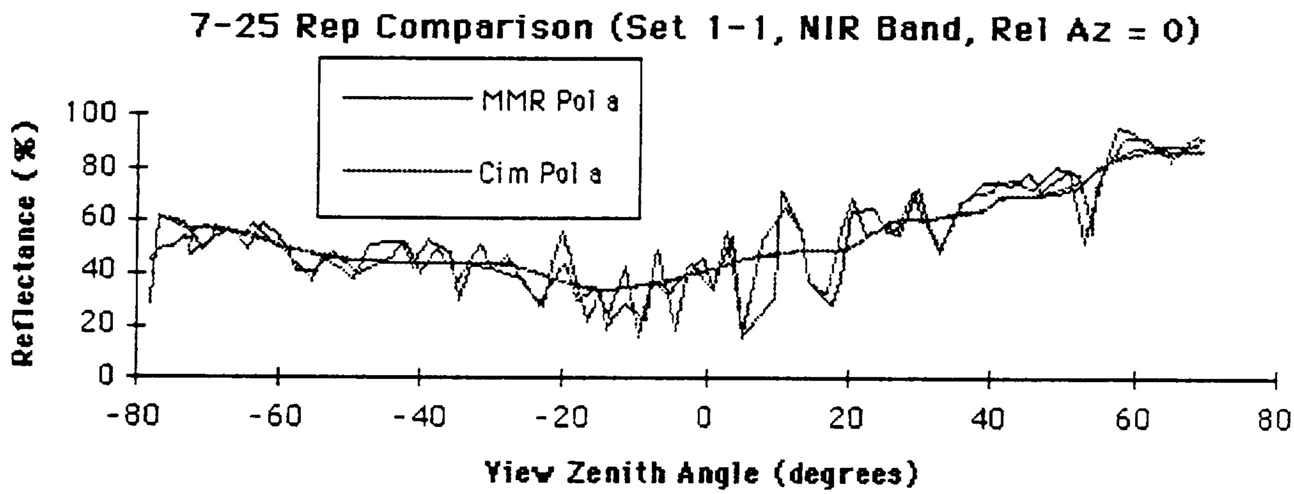
Red Band for polarizer angles a, b and c.

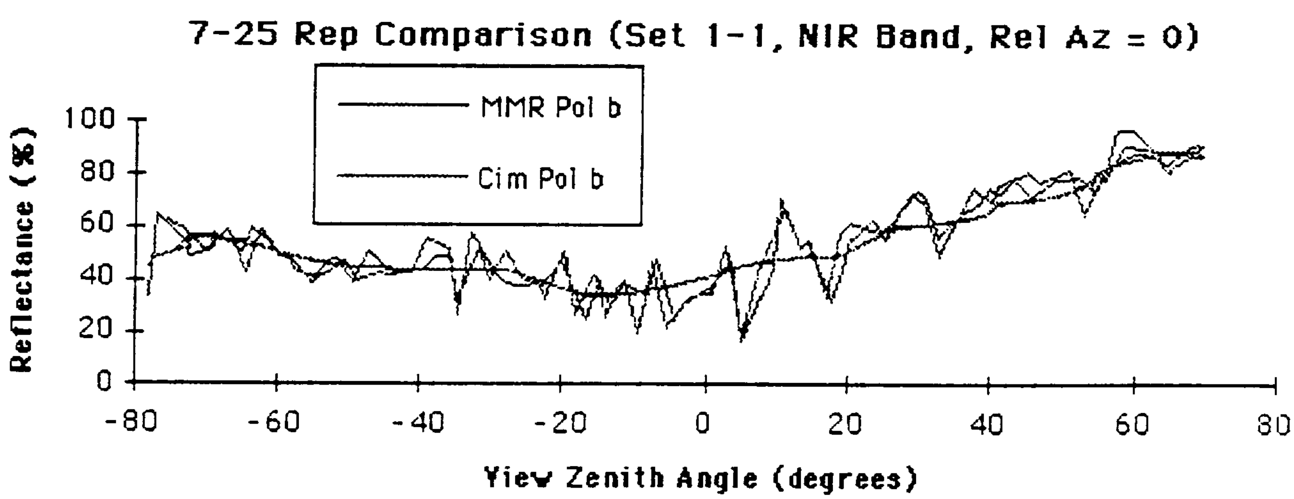




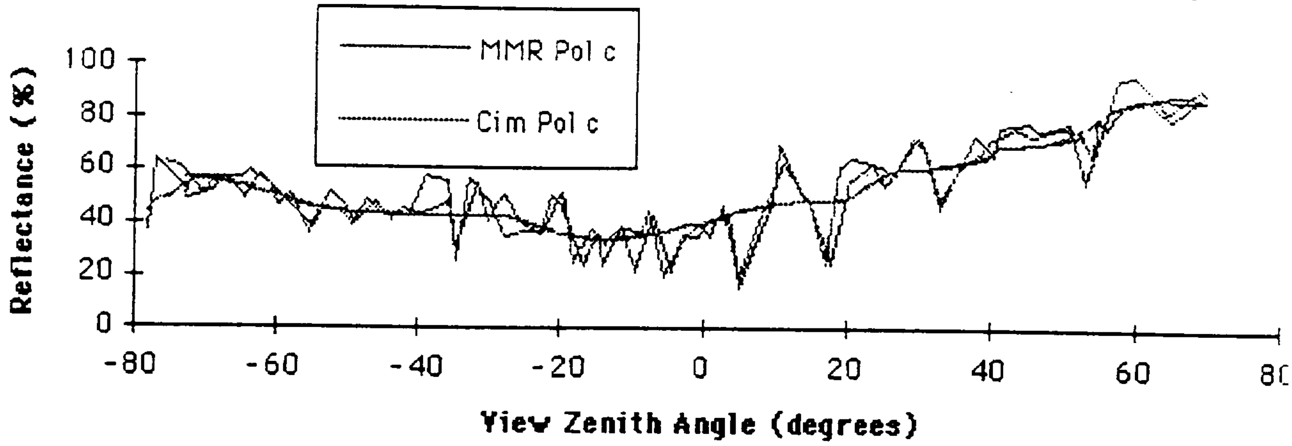


Near IR Band for polarizer angles a, b and c.



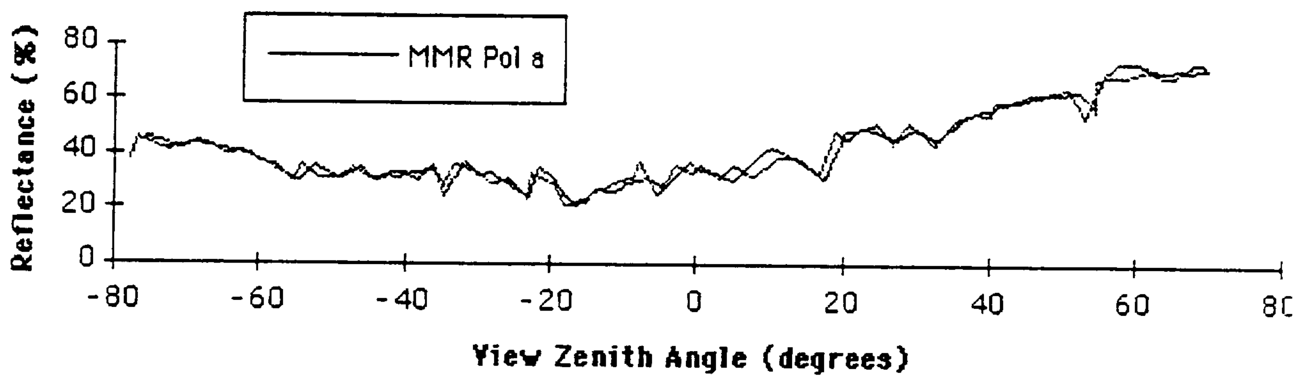


7-25 Rep Comparison (Set 1-1, NIR Band, Rel Az = 0)

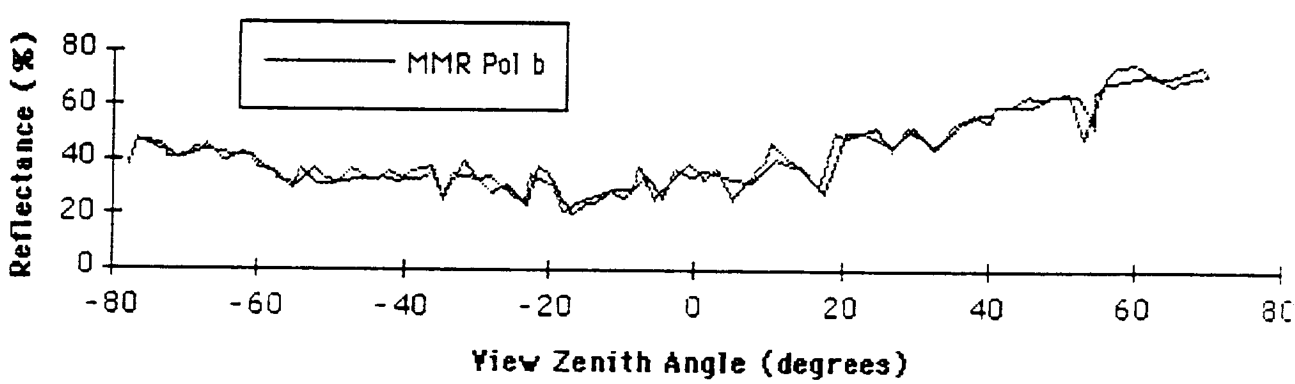


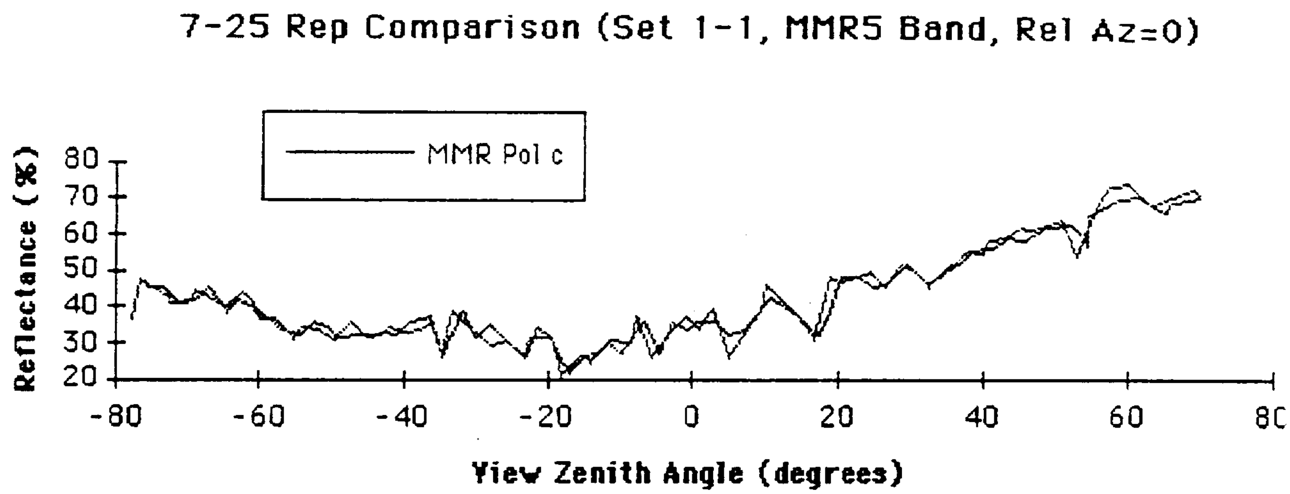
MMR5 Band for polarizer angles a, b and c.

7-25 Rep Comparison (Set 1-1, MMR5 Band, Rel Az=0)

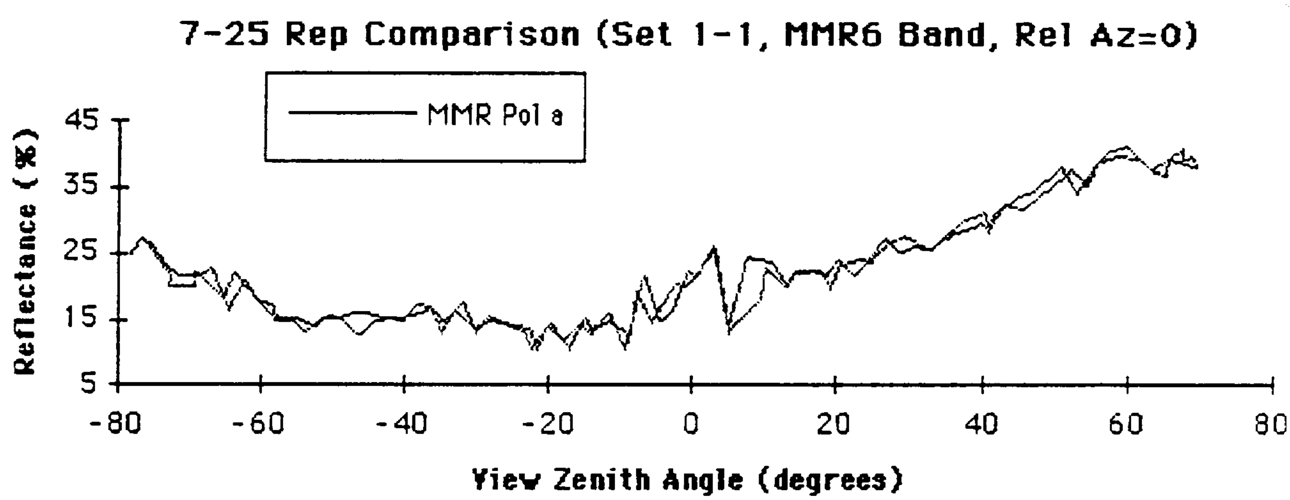


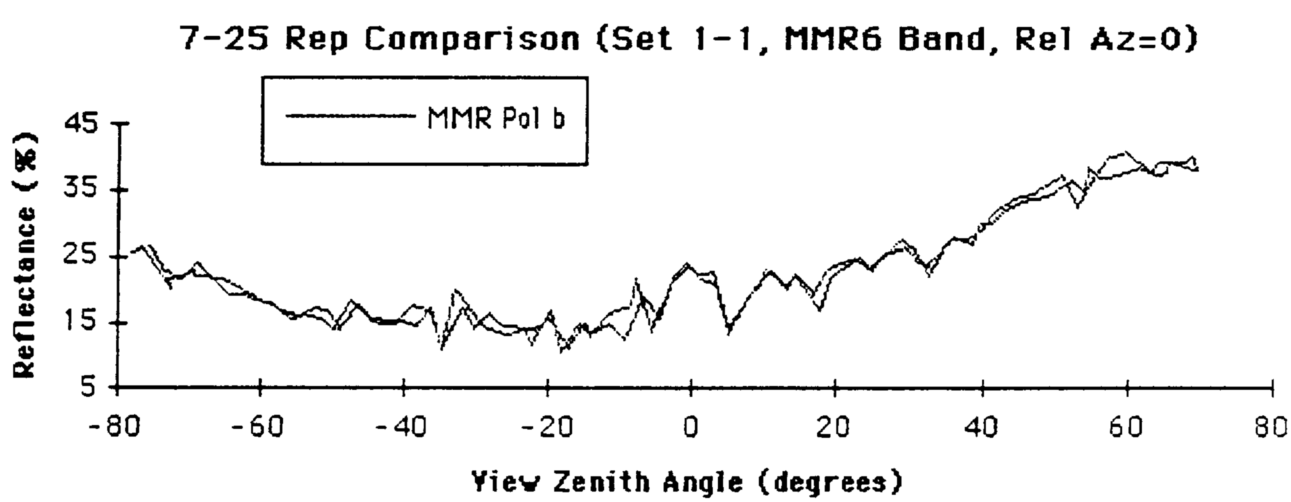
7-25 Rep Comparison (Set 1-1, MMR5 Band, Rel Az=0)

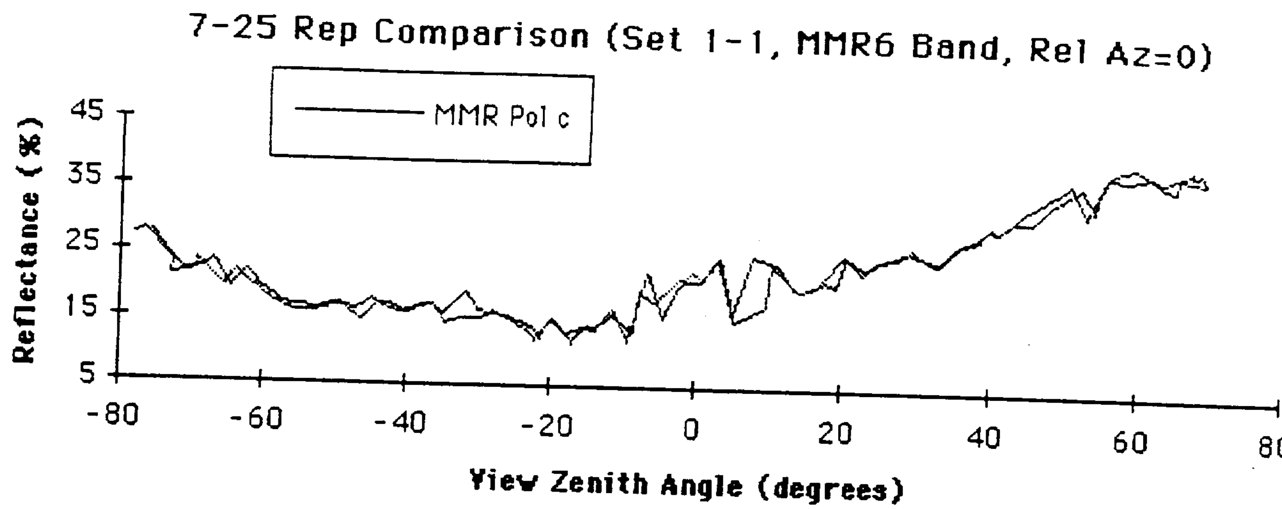




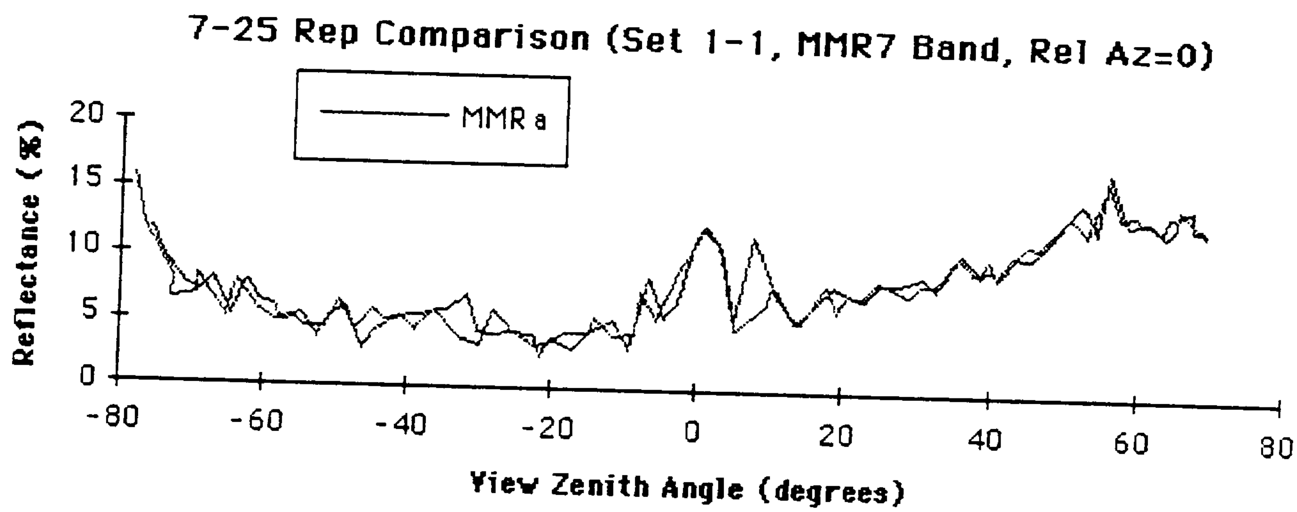
MMR6 Band for polarizer angles a, b and c.

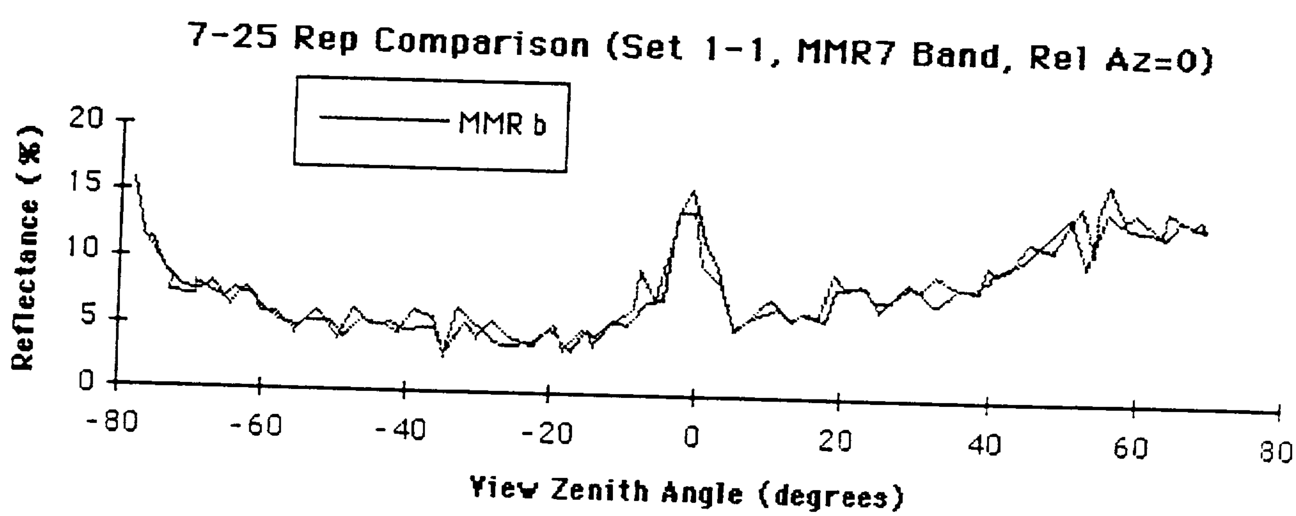


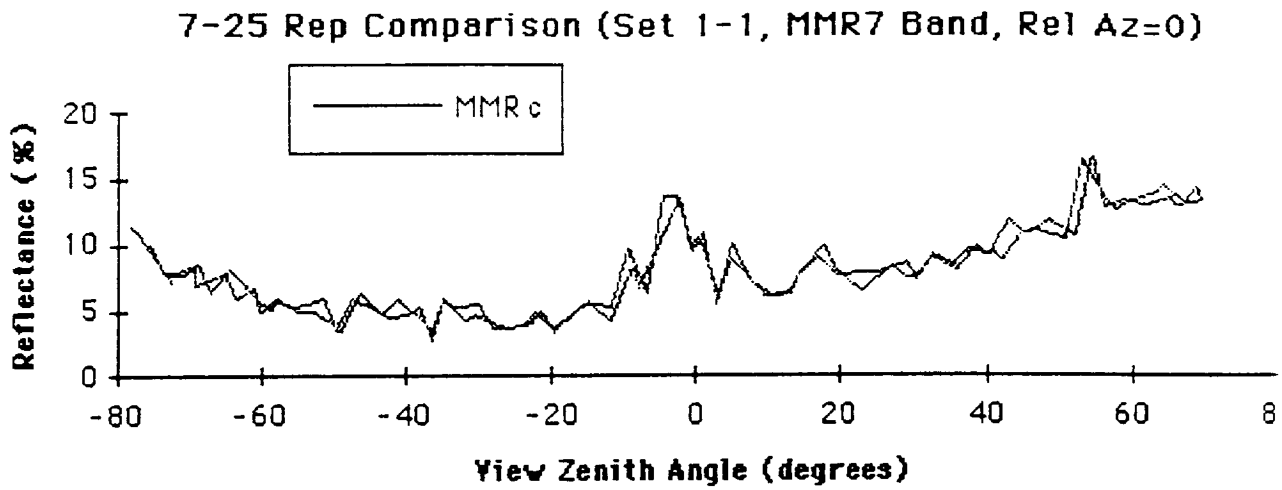




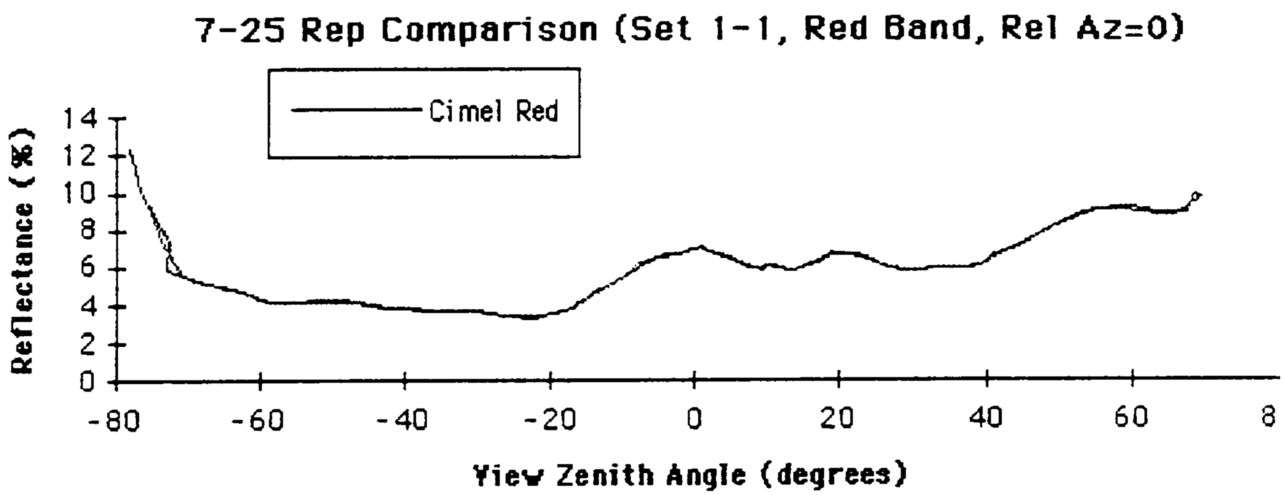
MMR7 Bands. There are no polarizers on these bands. There is one MMR channel 7 band on each of the three MMR's.

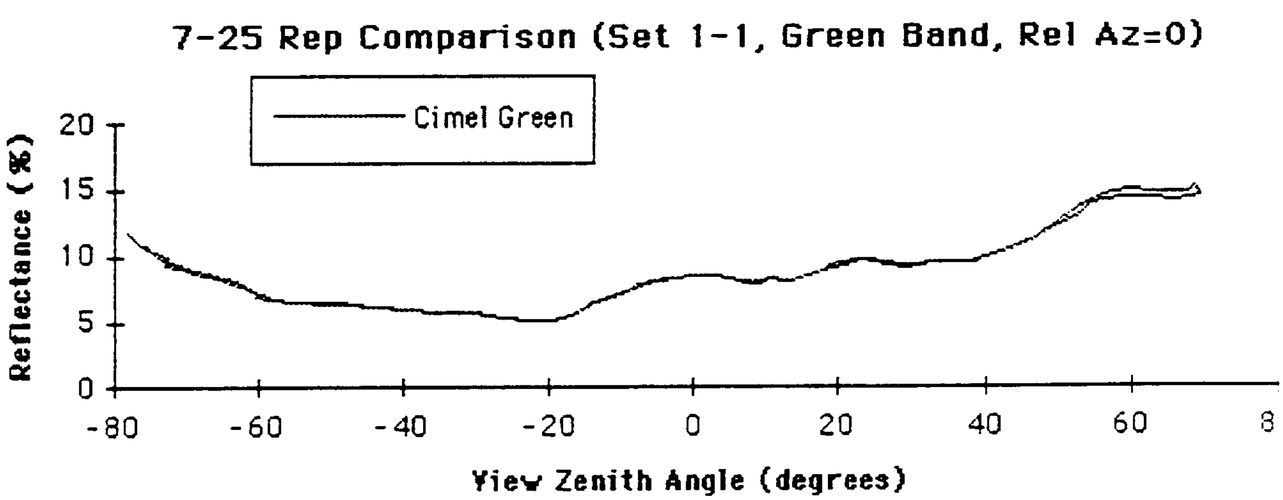


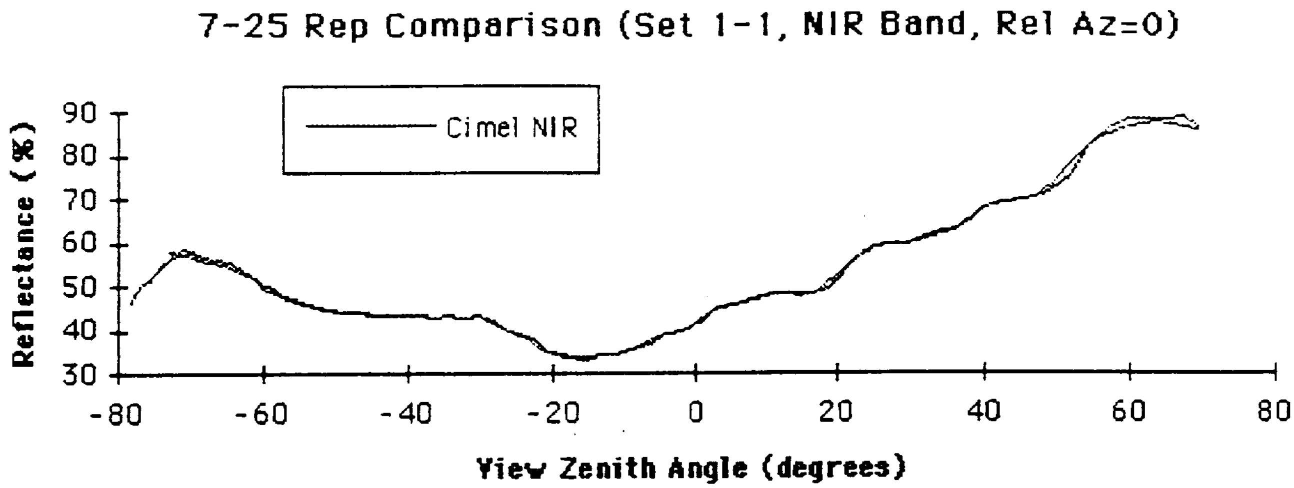




Cimel Bands with no polarizers.






7-25 Rep Comparison (Set 1-1, NIR Band, Rel Az=0)
Cimel NIR
Reflectance (%)
90
80
70
60
50
40
30
-80
-60
-40
-20
0
20
40
60
80
View Zenith Angle (degrees)

Comparison of Sky Data

revised 1-31-95

July 11, 1994 (There are no MMR Red Band data for this date.)

Set 2:Sky (Solar Zenith: 38-37; Solar Azimuth: 113-114)
Set 4:Sky (Solar Zenith: 28-28; Solar Azimuth: 134-135)
Set 6:Sky (Solar Zenith: 27-28; Solar Azimuth: 223-225)
Set 8:Sky (Solar Zenith: 49-50; Solar Azimuth: 262-263)

July 12, 1994

Set 2:Sky (Solar Zenith: 26-26; Solar Azimuth: 140-142)
Set 4:Sky (Solar Zenith: 37-39; Solar Azimuth: 246-249)

July 15, 1994

Set 2:Sky (Solar Zenith: 52-52; Solar Azimuth: 264-264)

July 16, 1994

Set 2:Sky (Solar Zenith: 34-34; Solar Azimuth: 121-122)
Set 4:Sky (Solar Zenith: 23-23; Solar Azimuth: 193-194)
Set 6:Sky (Solar Zenith: 28-28; Solar Azimuth: 223-225)
Set 8:Sky (Solar Zenith: 40-40; Solar Azimuth: 249-249)
Set 10:Sky (Solar Zenith: 52-53; Solar Azimuth: 264-265)

July 25, 1994

Set 2:Sky (Solar Zenith: 44-42; Solar Azimuth: 109-111)
Set 4:Sky (Solar Zenith: 32-32; Solar Azimuth: 130-131)

July 26, 1994 (No sky data)

July 27, 1994

Set 2:Sky (Solar Zenith: 44-44; Solar Azimuth: 110-110)
Set 4:Sky (Solar Zenith: 34-34; Solar Azimuth: 127-128)
Set 6:Sky (Solar Zenith: 27-26; Solar Azimuth: 154-154)
Set 8:Sky (Solar Zenith: 25-25; Solar Azimuth: 197-198)
Set 10:Sky (Solar Zenith: 47-47; Solar Azimuth: 254-255)

July 29, 1994 (No sky data)

August 2, 1994

Set 2:Sky (Solar Zenith: 36-36; Solar Azimuth: 127-128)
Set 4:Sky (Solar Zenith: 30-30; Solar Azimuth: 214-215)
Set 6:Sky (Solar Zenith: 39-39; Solar Azimuth: 239-239)
Set 8:Sky (Solar Zenith: 49-50; Solar Azimuth: 255-255)
Set 10:Sky (Solar Zenith: 70-71; Solar Azimuth: 276-277)

August 5, 1994

Set 2:Sky (Solar Zenith: 41-41; Solar Azimuth: 119-119)
Set 4:Sky (Solar Zenith: 32-32; Solar Azimuth: 141-142)
Set 6:Sky (Solar Zenith: 27-27; Solar Azimuth: 177-178)

Set 8:Sky (Solar Zenith: 30-30; Solar Azimuth: 213-213)
Set 10:Sky (Solar Zenith: 51-51; Solar Azimuth: 255-256)

See Appendix B for the Data Plots.

Vera Vanderbilt and Larry Biehl have copies.

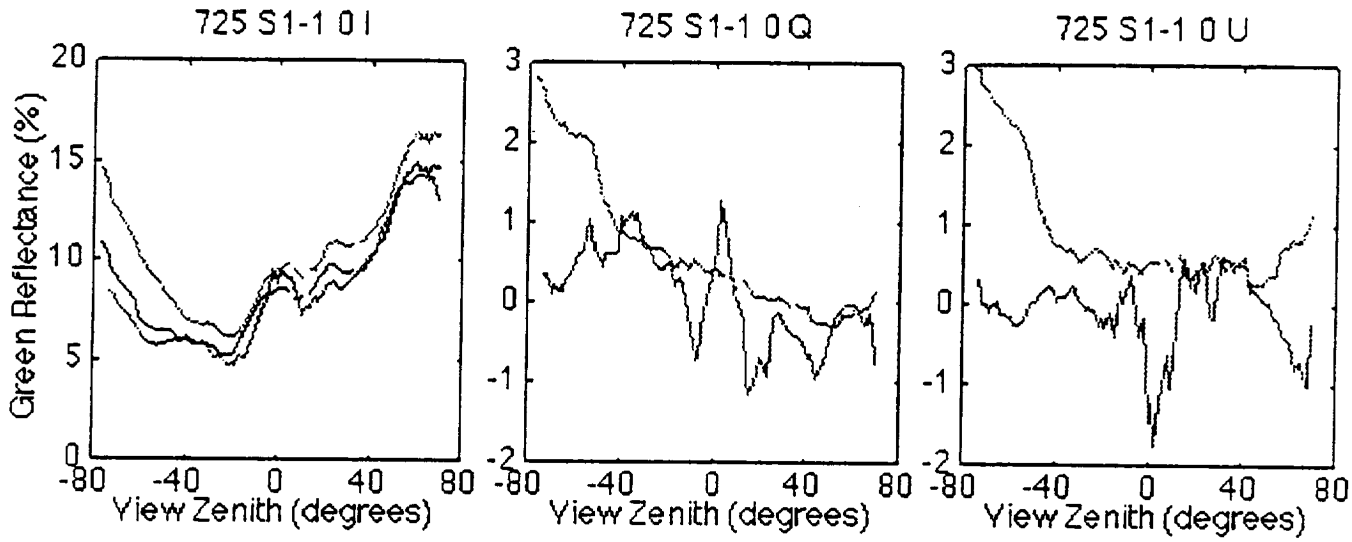
7/25 Set1-1 Green I Q U

revised 1-26-95

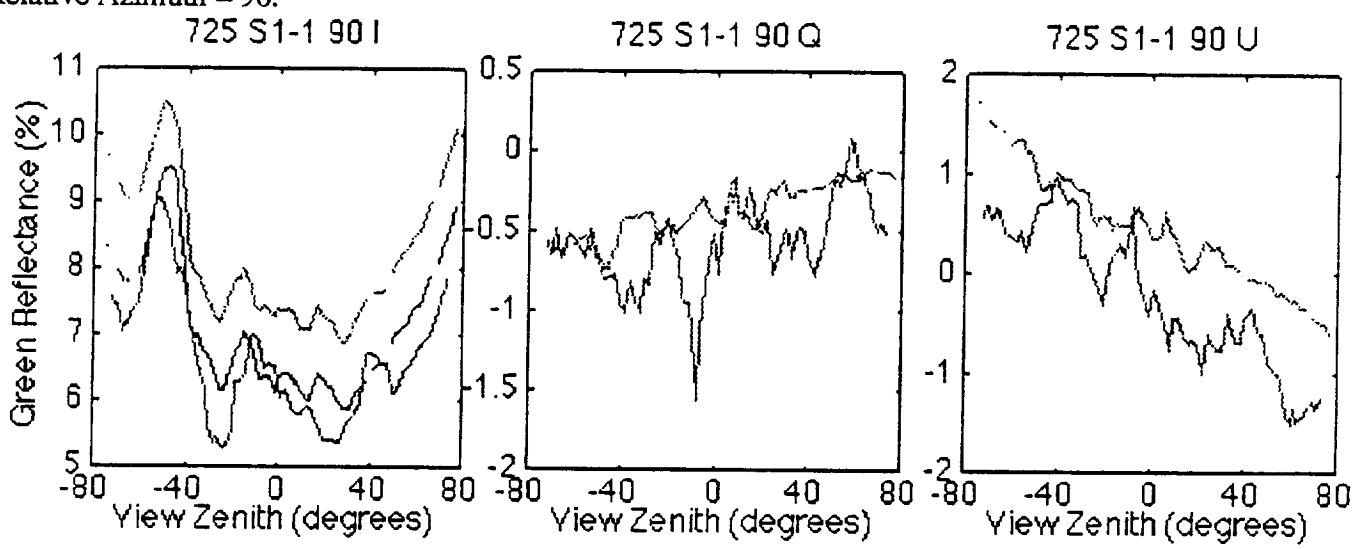
The color codes for the lines in the plots are:

- Red - MMR
- Magenta - Cimel
- Blue - Cimel with no polarizer (for I parameter only)

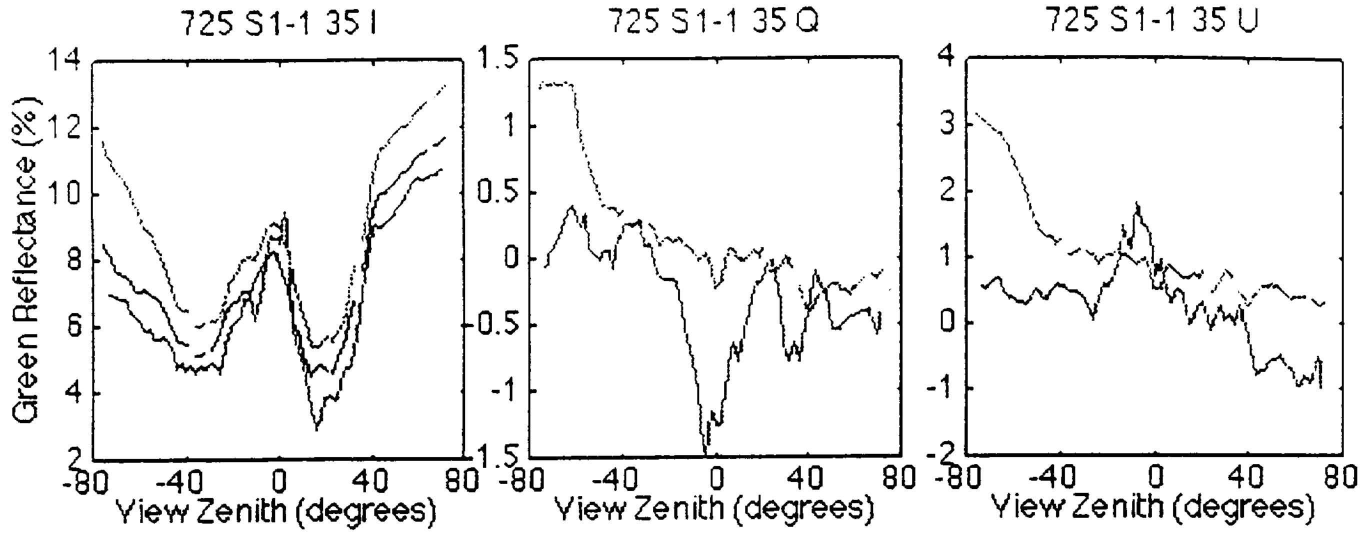
Relative Azimuth = 0.



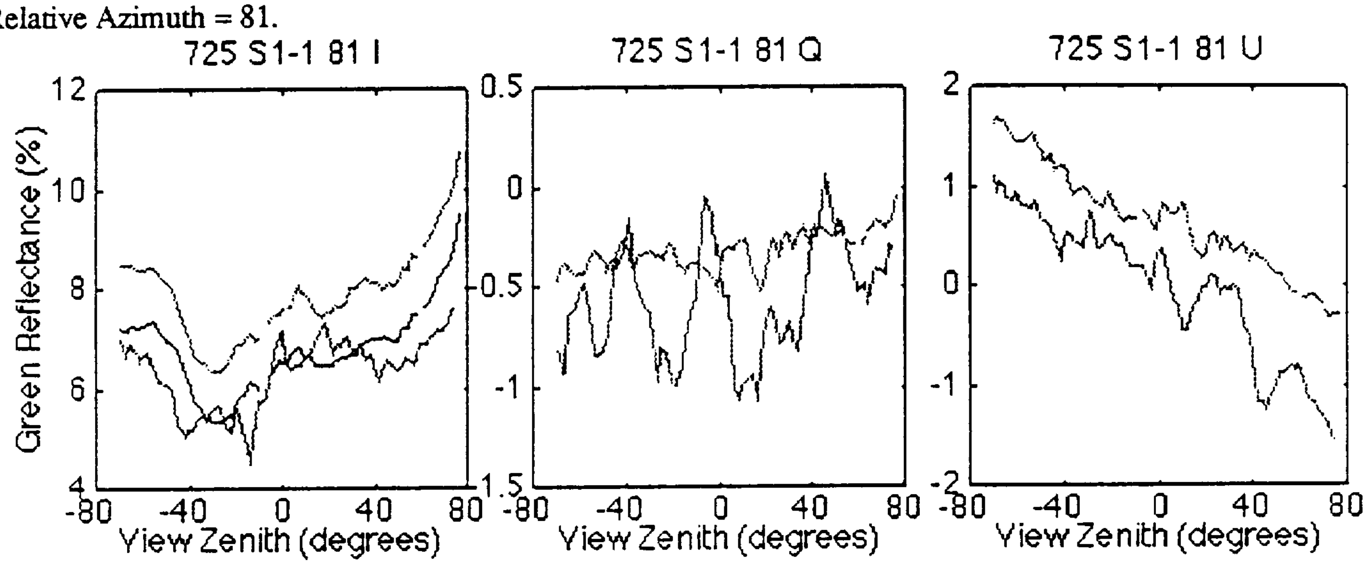
Relative Azimuth = 90.



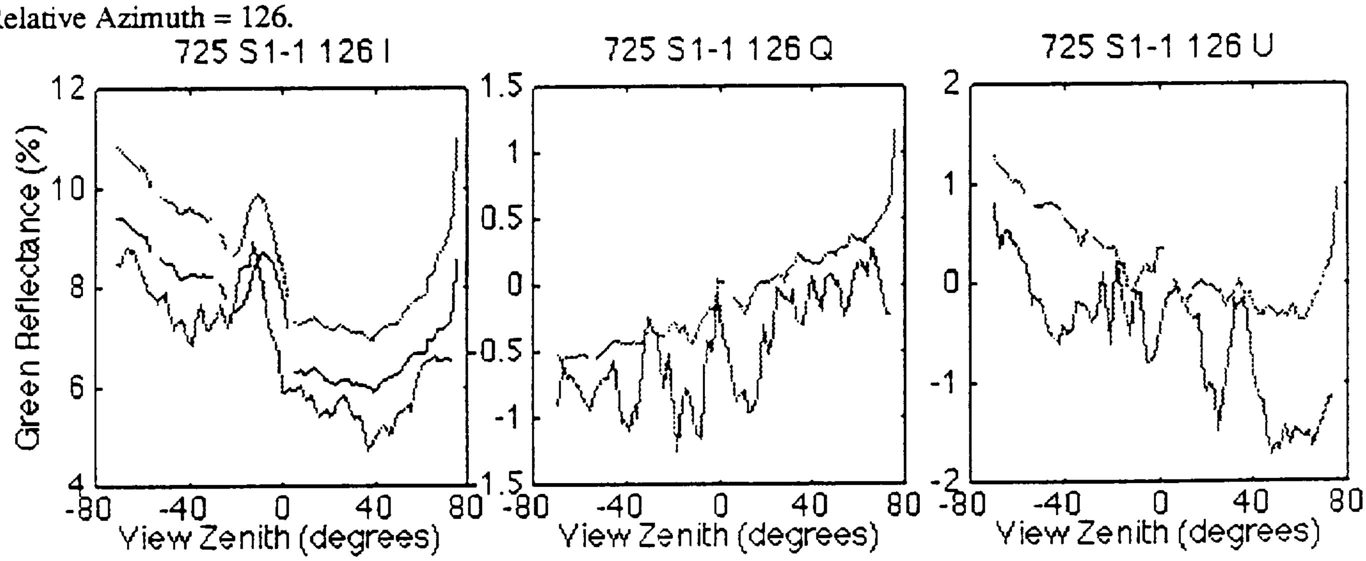
Relative Azimuth = 35.



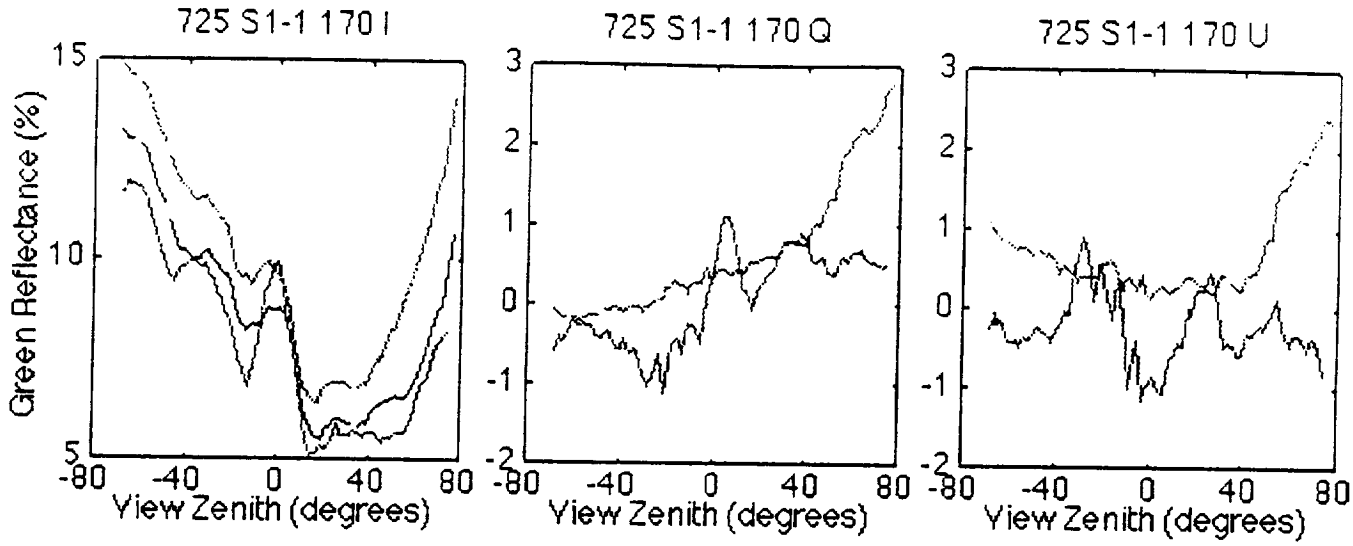
Relative Azimuth = 81.



Relative Azimuth = 126.



Relative Azimuth = 170.


725 S1-1 170 I
725 S1-1 170 Q
725 S1-1 170 U
Green Reflectance (%)
View Zenith (degrees)
15
10
5
3
2
1
0
-1
-2
-80
-40
0
40
80

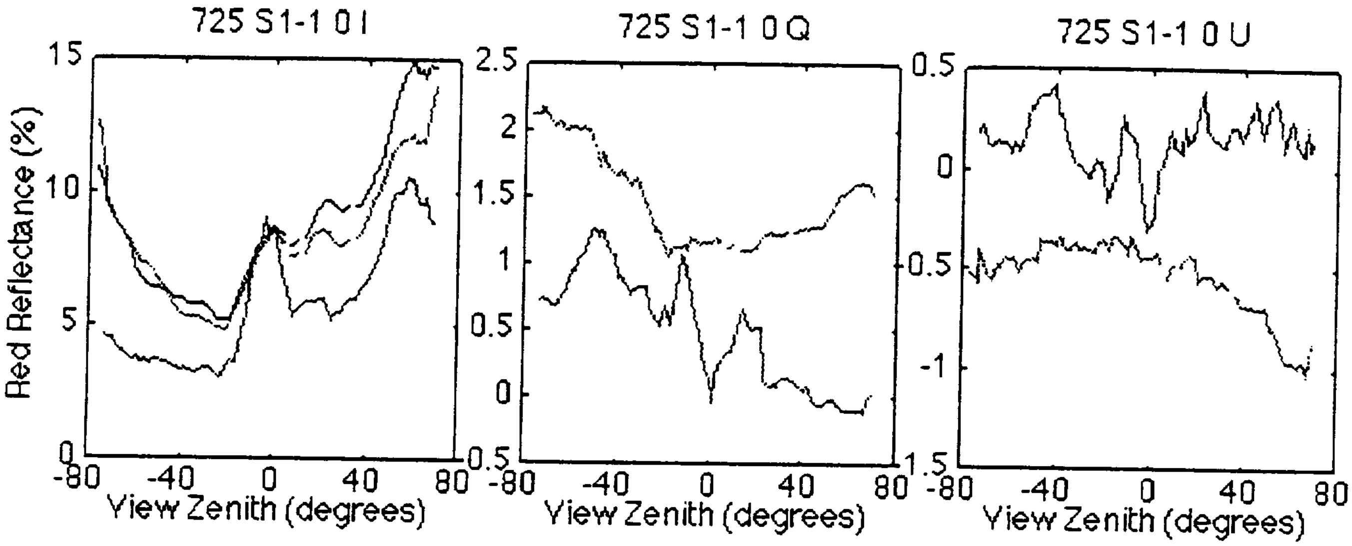
7/25 Set1-1 Red I Q U

revised 1-26-95

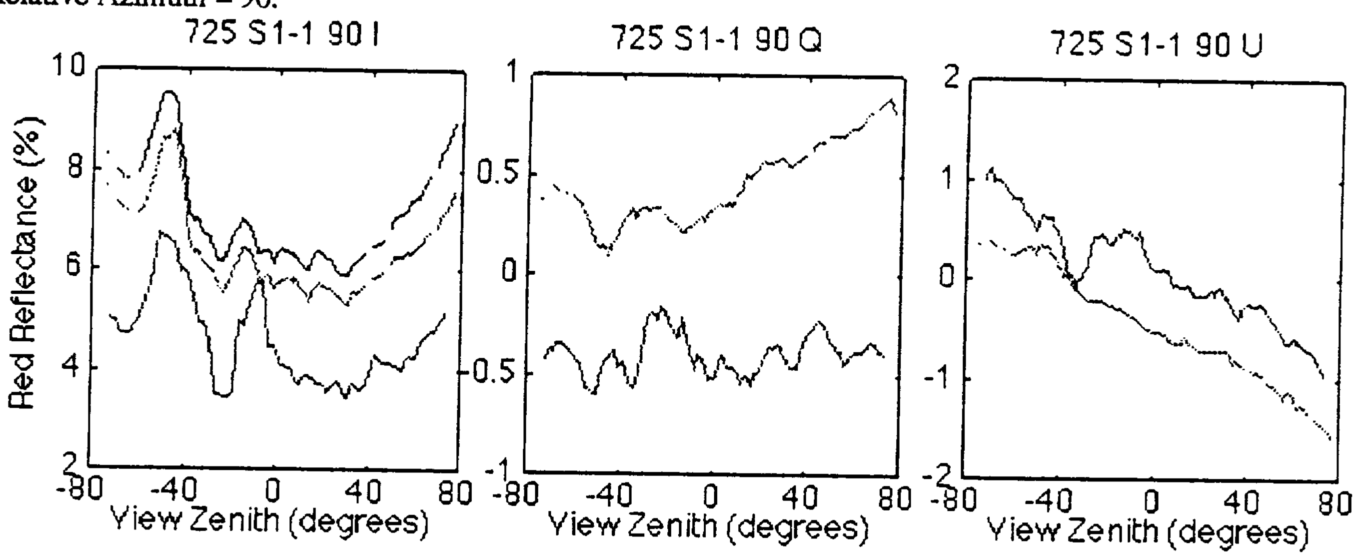
The color codes for the lines in the plots are:

- Red - MMR
- Magenta - Cimel
- Blue - Cimel with no polarizer (for I parameter only)

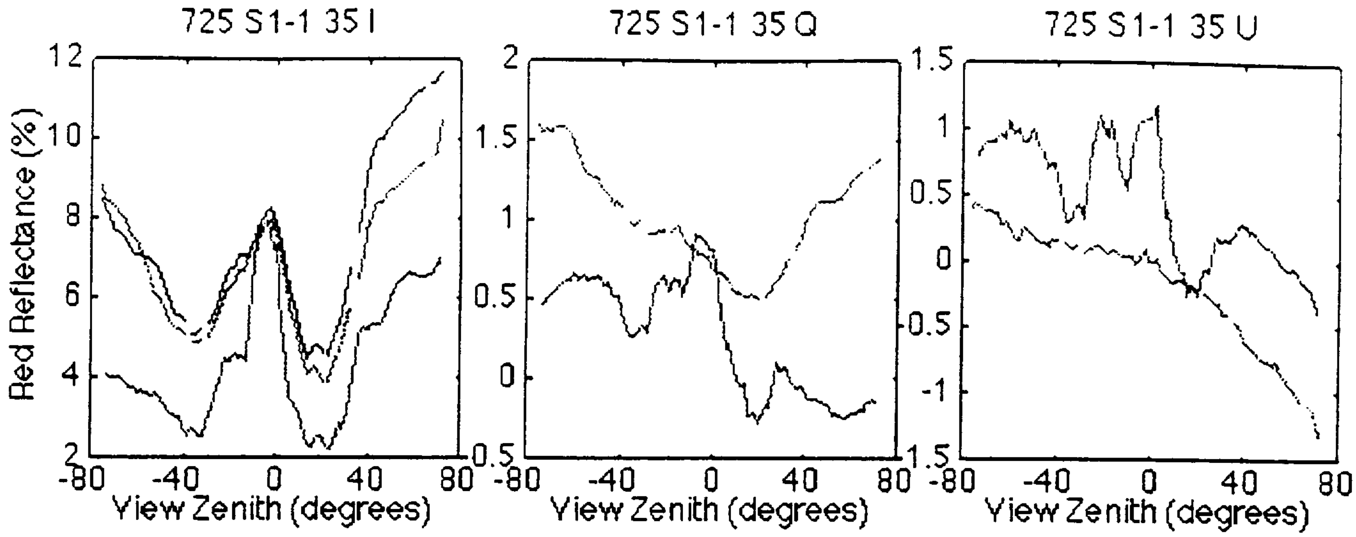
Relative Azimuth = 0.



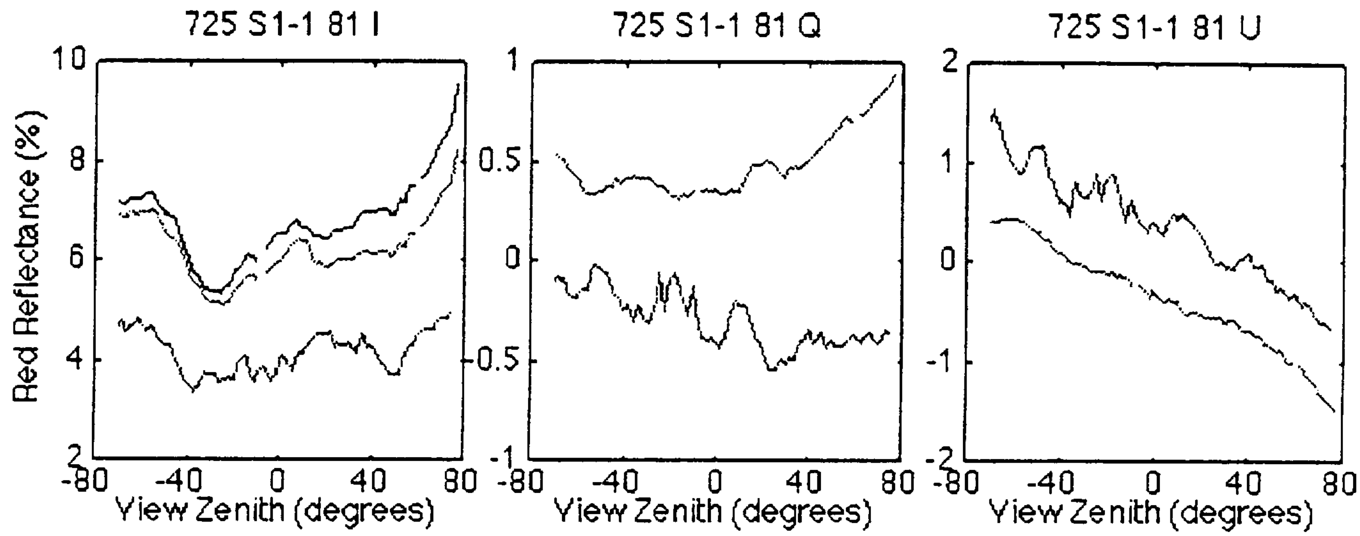
Relative Azimuth = 90.



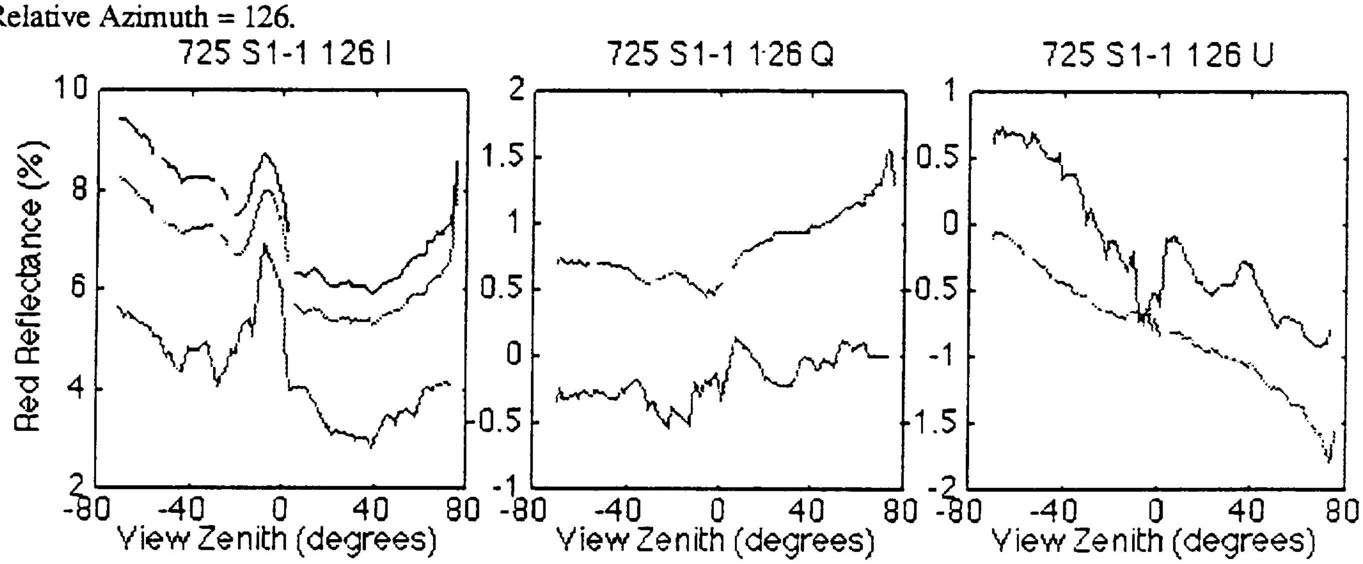
Relative Azimuth = 35.



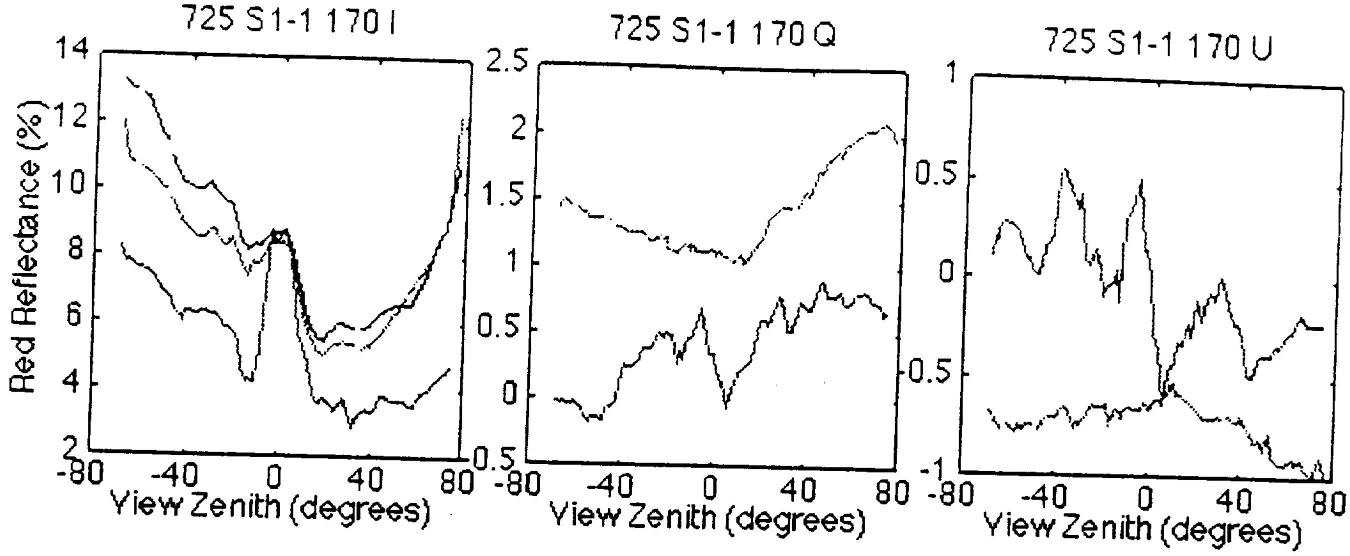
Relative Azimuth = 81.



Relative Azimuth = 126.



Relative Azimuth = 170.



725 S1-1 170 I
725 S1-1 170 Q
725 S1-1 170 U
Red Reflectance (%)
View Zenith (degrees)
View Zenith (degrees)
View Zenith (degrees)

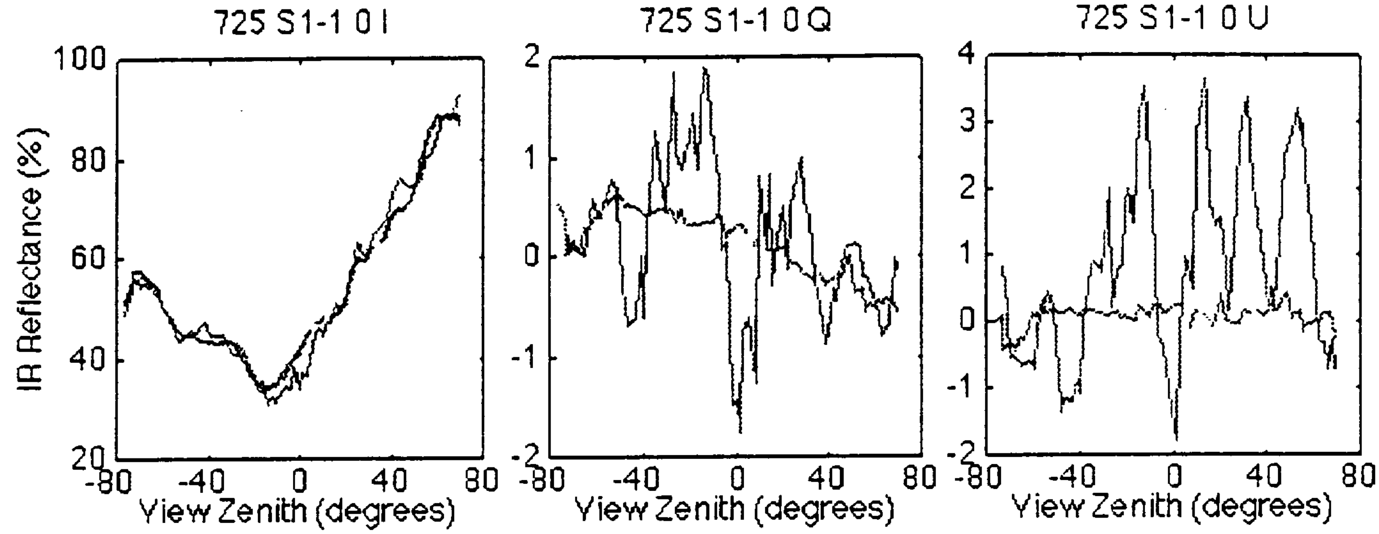
7/25 Set1-1 Infrared I Q U

revised 1-26-95

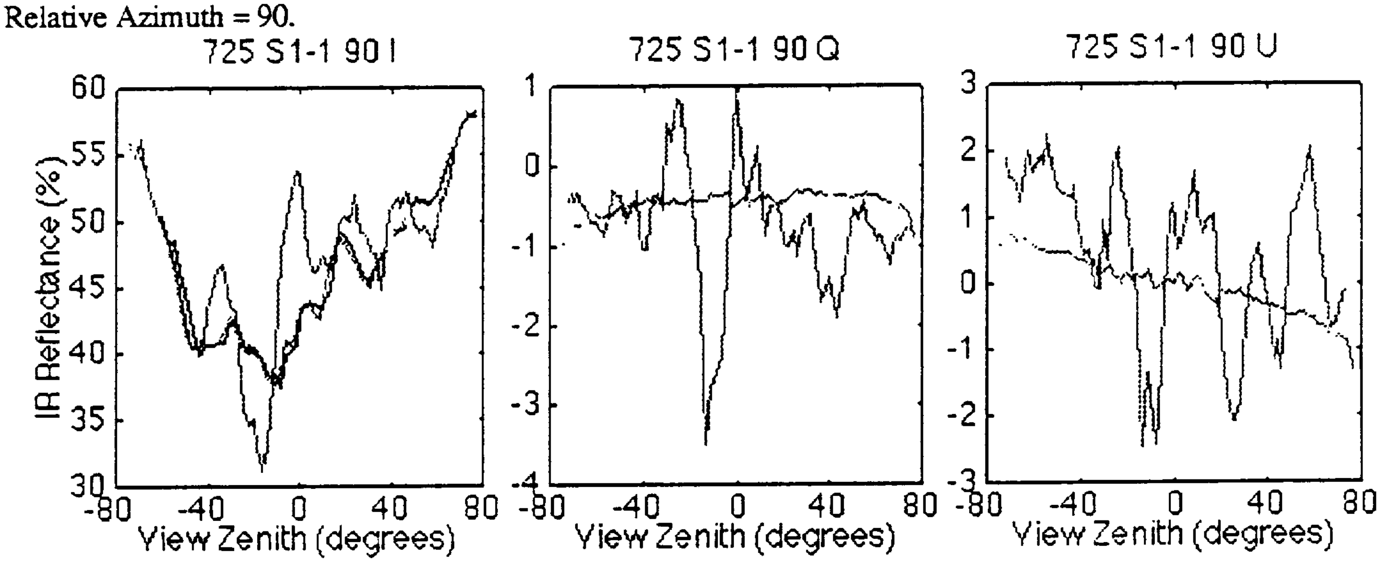
The color codes for the lines in the plots are:

- Red - MMR
- Magenta - Cimel
- Blue - Cimel with no polarizer (for I parameter only)

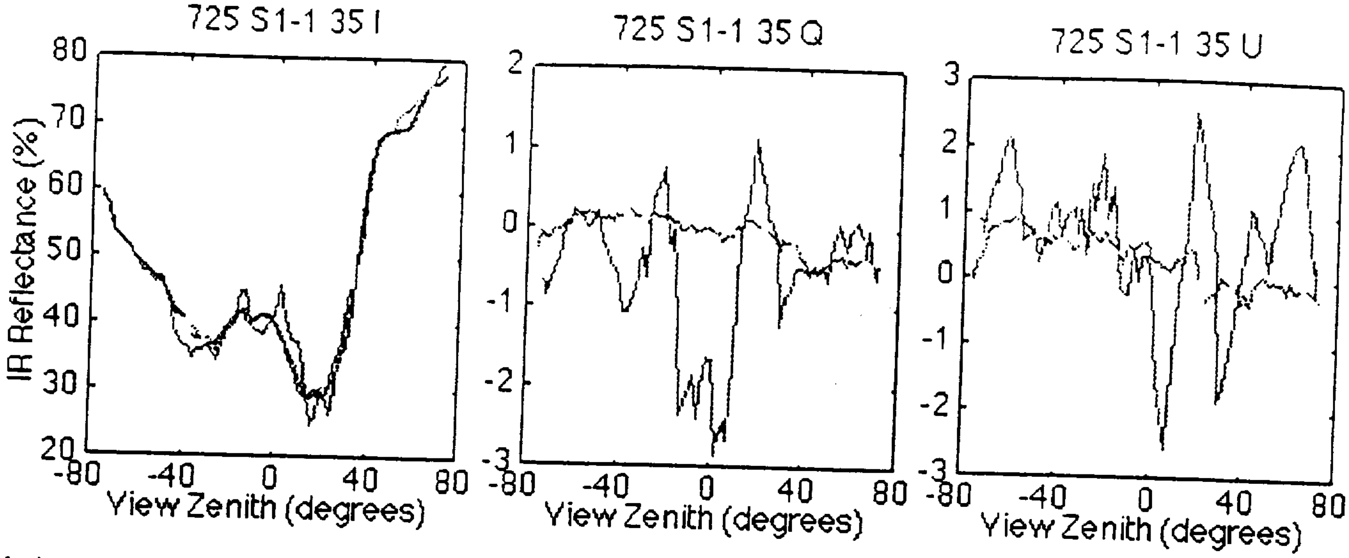
Relative Azimuth = 0.



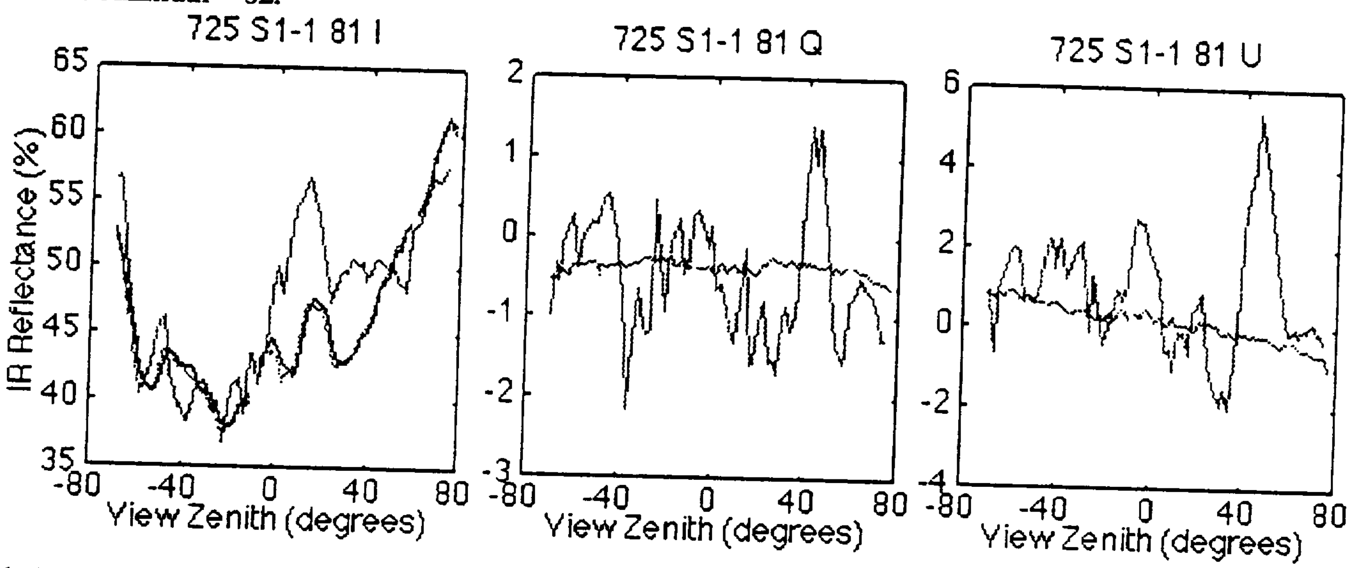
Relative Azimuth = 90.



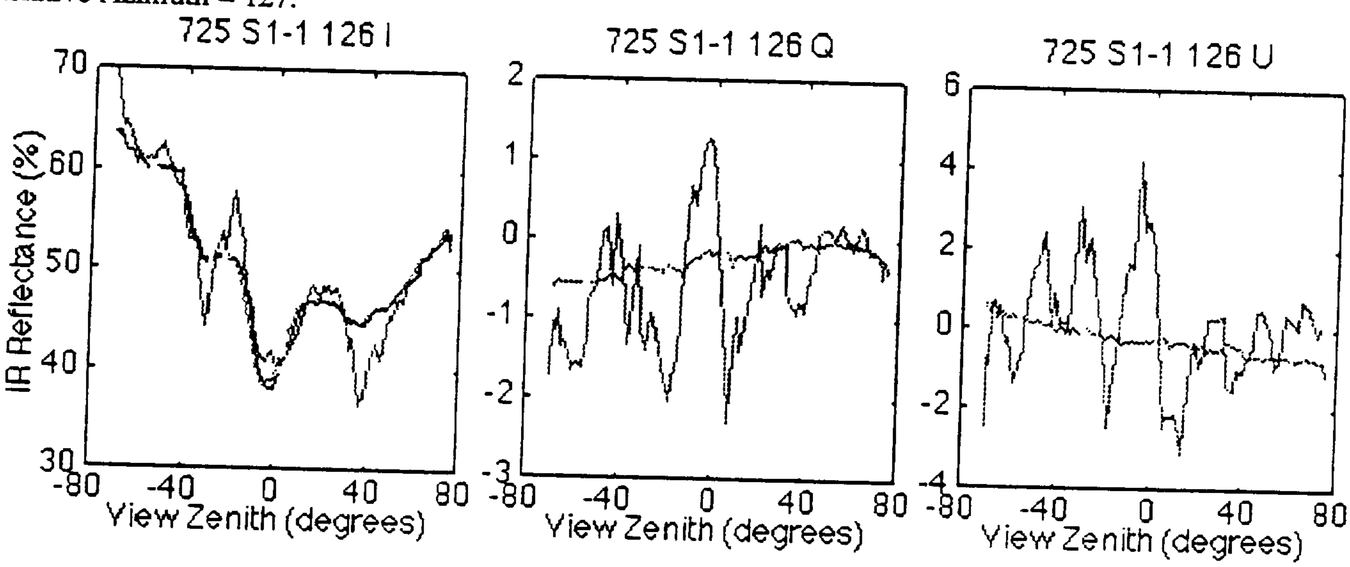
Relative Azimuth = 37.



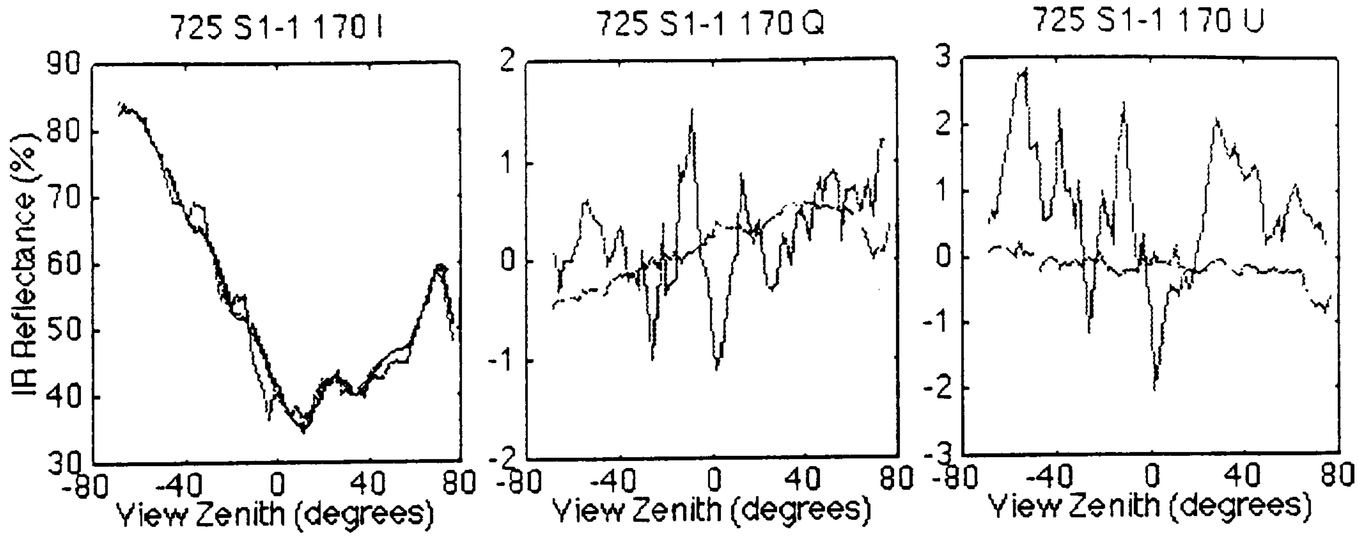
Relative Azimuth = 82.



Relative Azimuth = 127.



Relative Azimuth = 172.



725 S1-1 170 I
725 S1-1 170 Q
725 S1-1 170 U
IR Reflectance (%)
View Zenith (degrees)
View Zenith (degrees)
View Zenith (degrees)

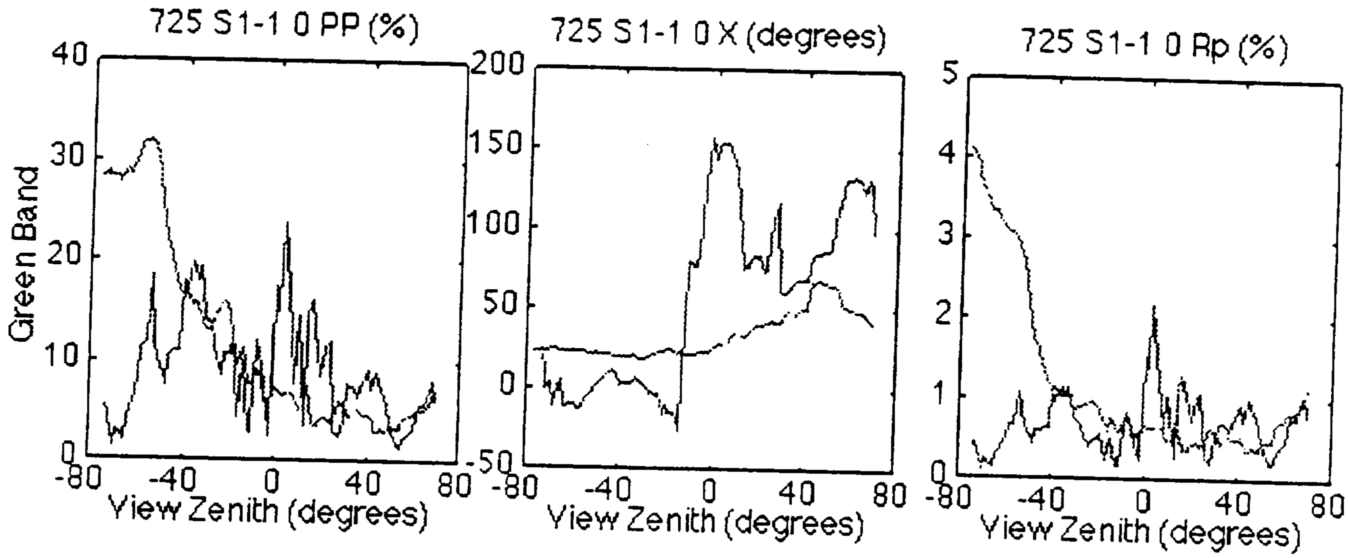
7/25 Set1-1 Green PP X Rp

revised 1-26-95

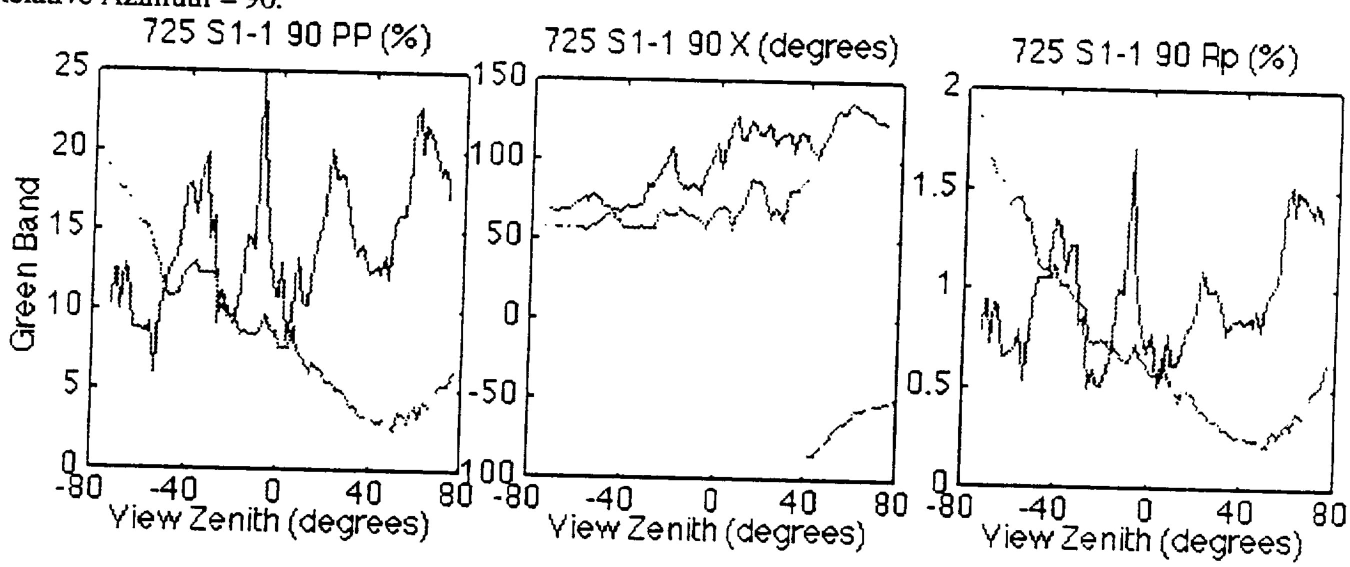
The color codes for the lines in the plots are:

- Red - MMR
- Magenta - Cimel

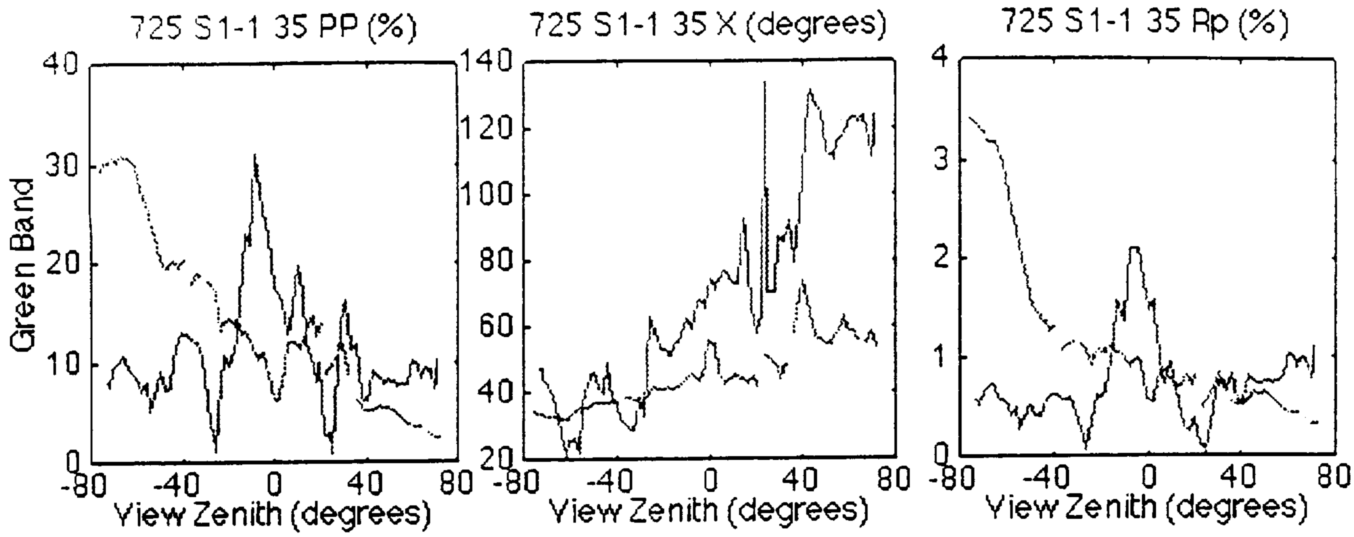
Relative Azimuth = 0.



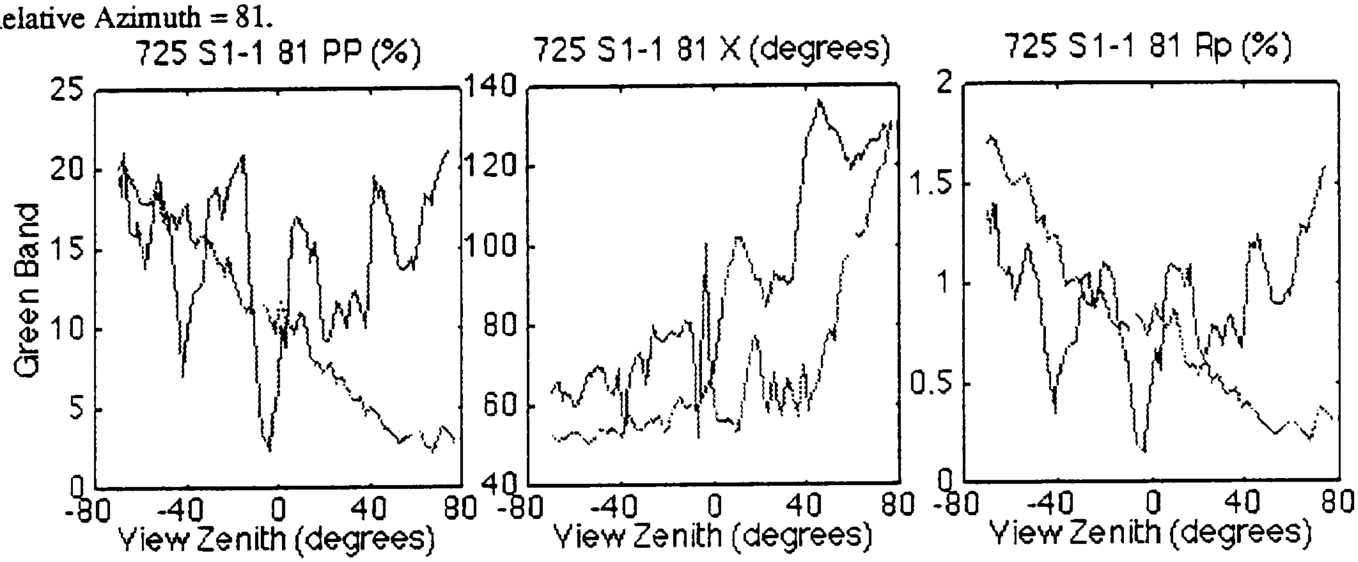
Relative Azimuth = 90.



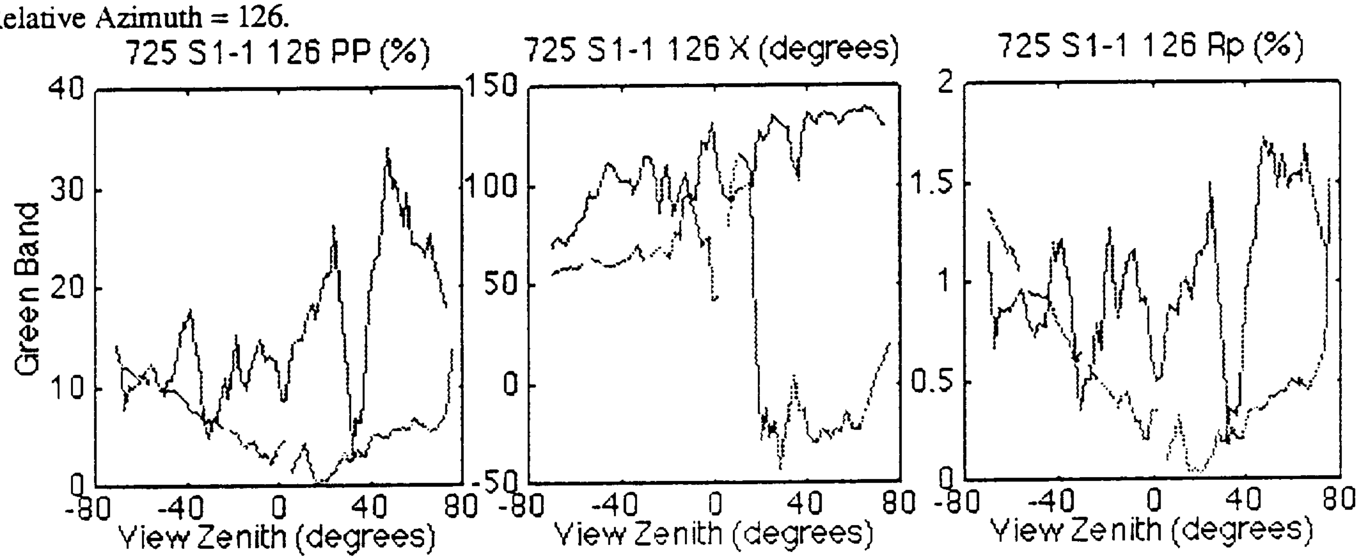
Relative Azimuth = 35.



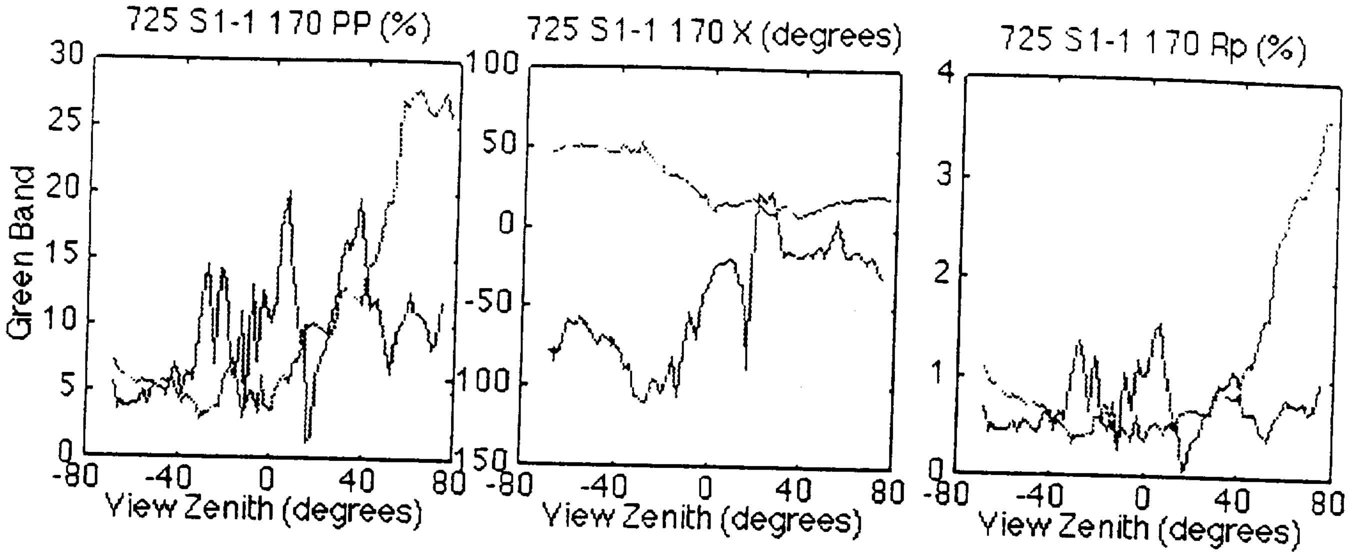
Relative Azimuth = 81.



Relative Azimuth = 126.



Relative Azimuth = 170.



725 S1-1 170 PP (%)
Green Band
30
25
20
15
10
5
0
-80
-40
0
40
80
View Zenith (degrees)
725 S1-1 170 X (degrees)
100
50
0
-50
-100
-150
-80
-40
0
40
80
View Zenith (degrees)
725 S1-1 170 Rp (%)
4
3
2
1
0
-80
-40
0
40
80
View Zenith (degrees)

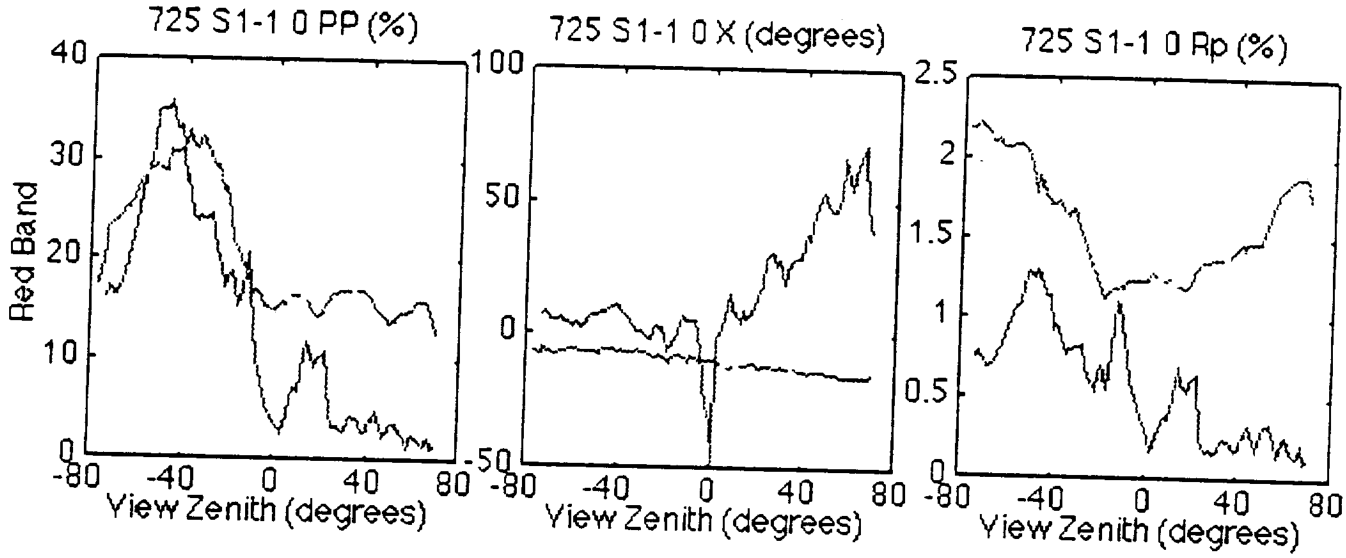
7/25 Set1-1 Red PP X Rp

revised 1-26-95

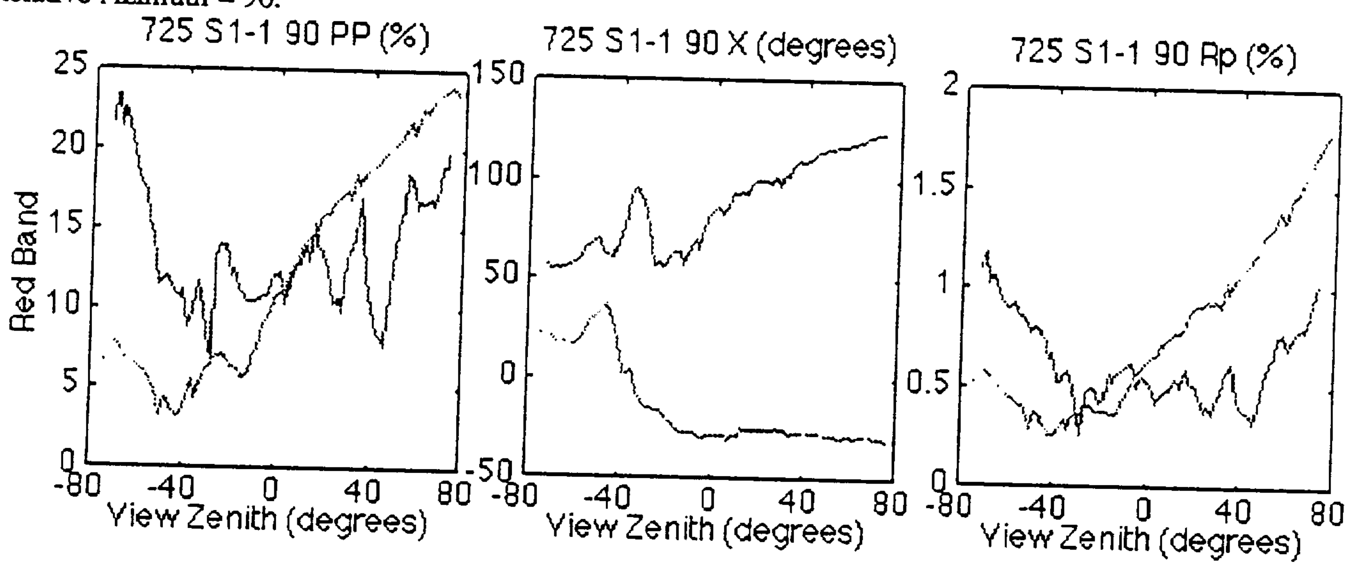
The color codes for the lines in the plots are:

- Red - MMR
- Magenta - Cimel

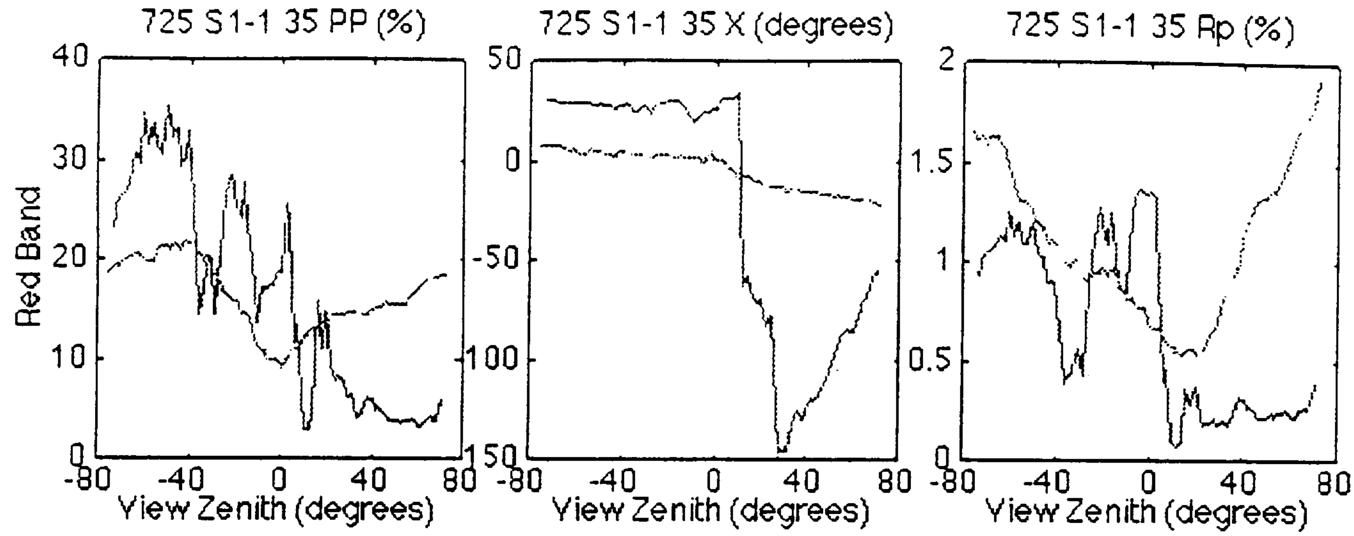
Relative Azimuth = 0.



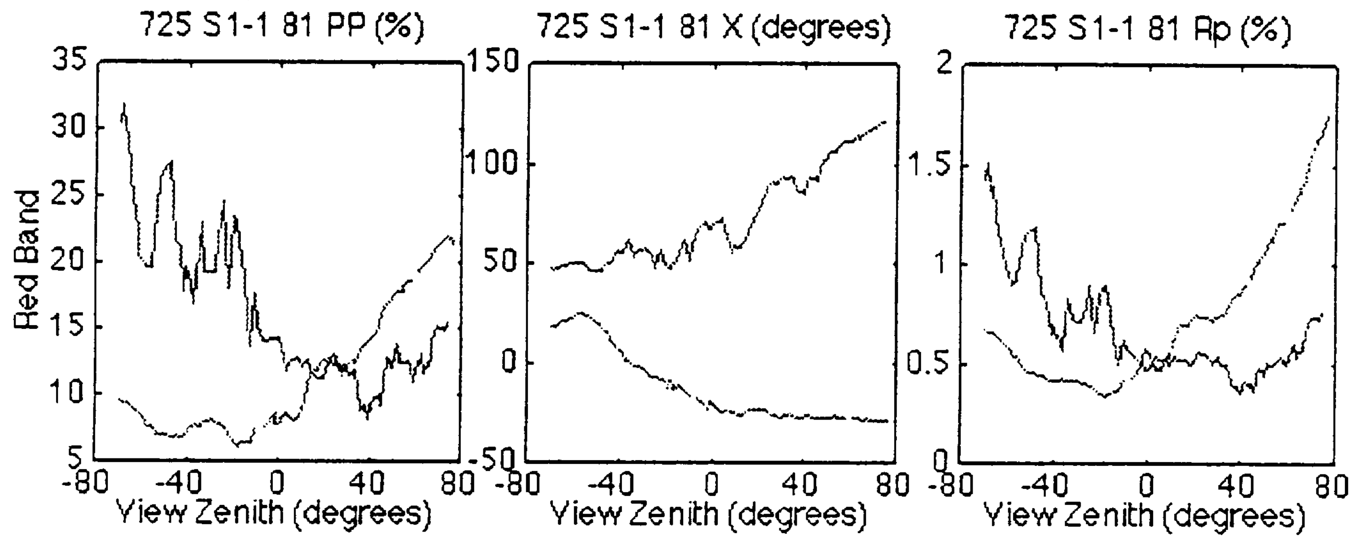
Relative Azimuth = 90.



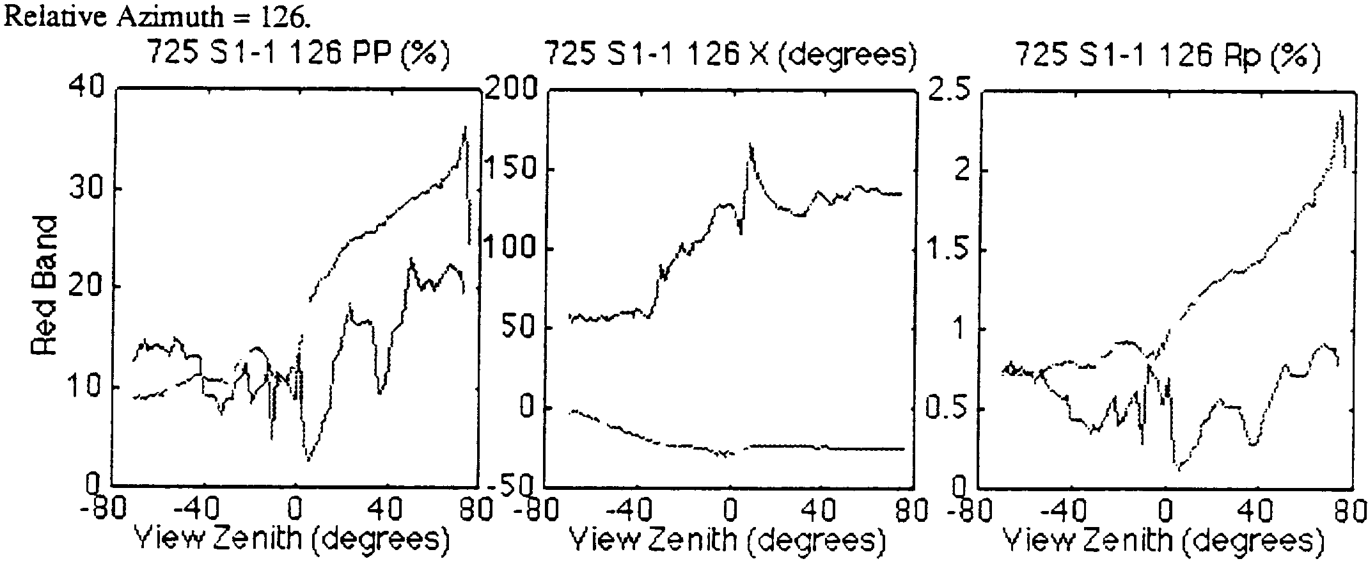
Relative Azimuth = 35.



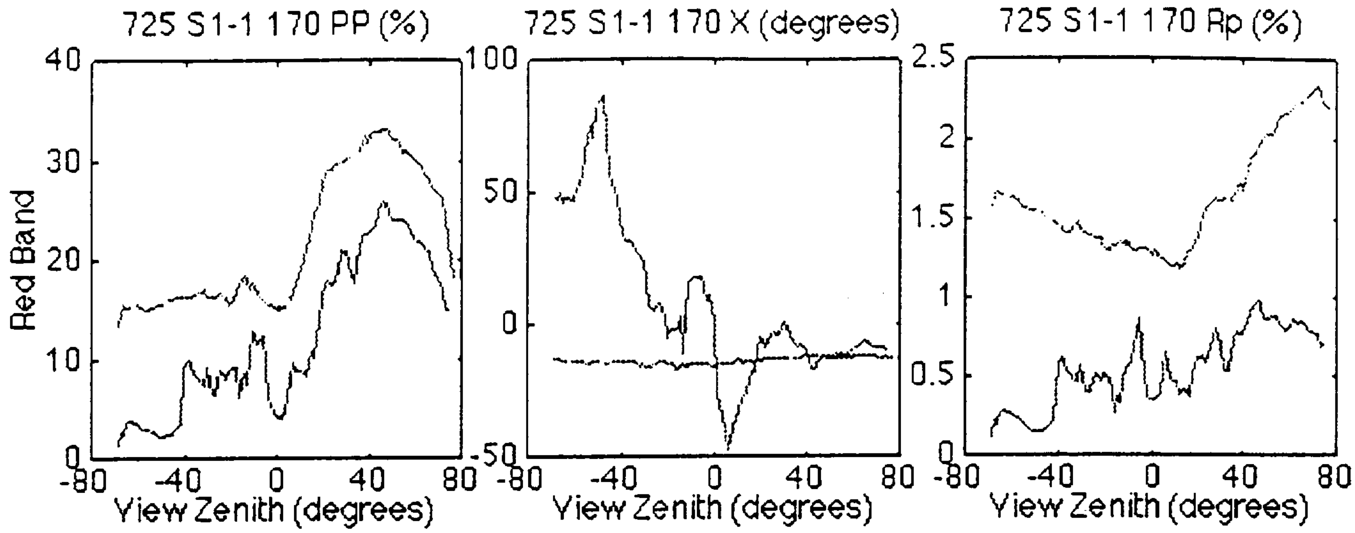
Relative Azimuth = 81.



Relative Azimuth = 126.



Relative Azimuth = 170.


725 S1-1 170 PP (%)
725 S1-1 170 X (degrees)
725 S1-1 170 Rp (%)
Red Band
View Zenith (degrees)
View Zenith (degrees)
View Zenith (degrees)

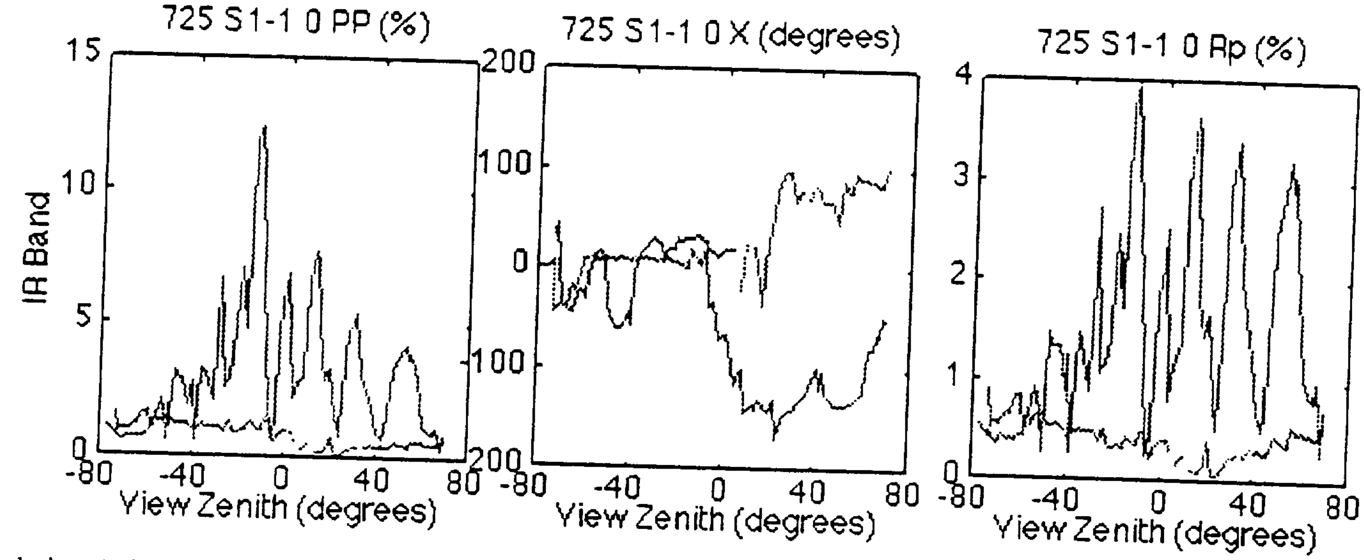
7/25 Set1-1 Infrared PP X Rp

revised 1-26-95

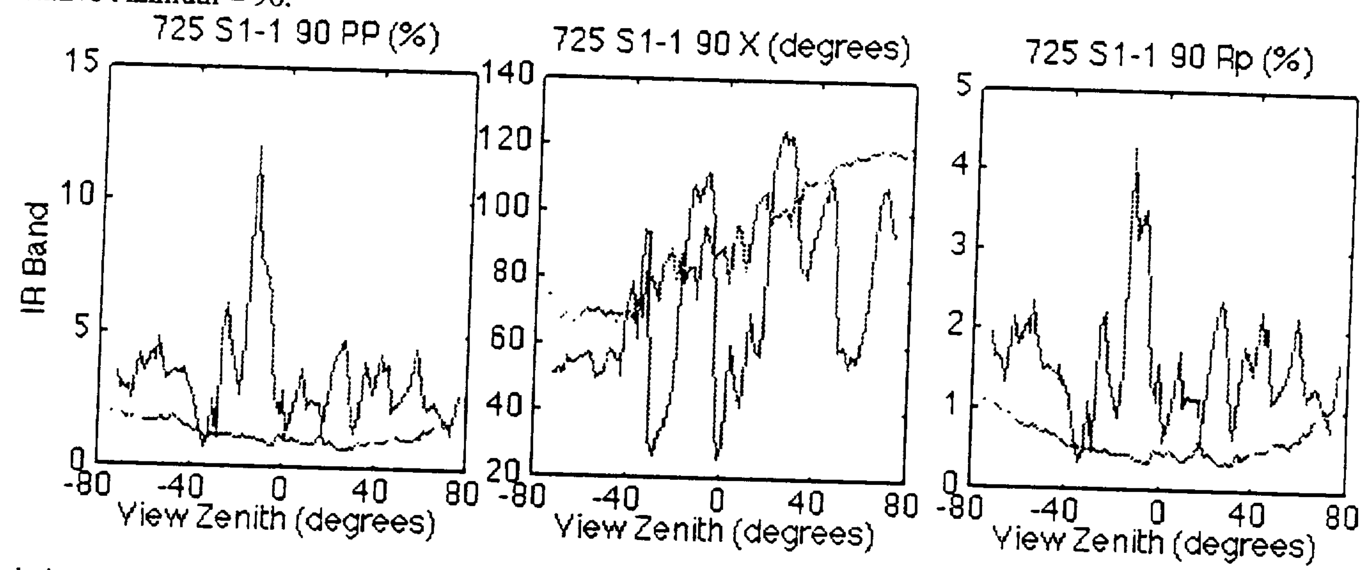
The color codes for the lines in the plots are:

- Red - MMR
- Magenta - Cimel

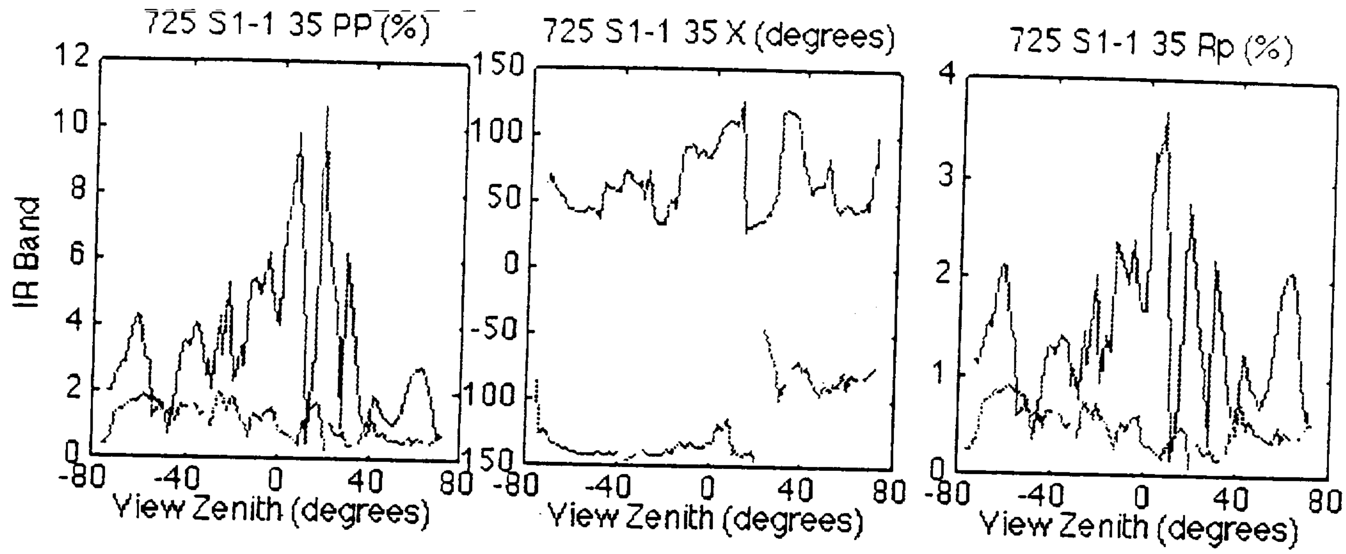
Relative Azimuth = 0.



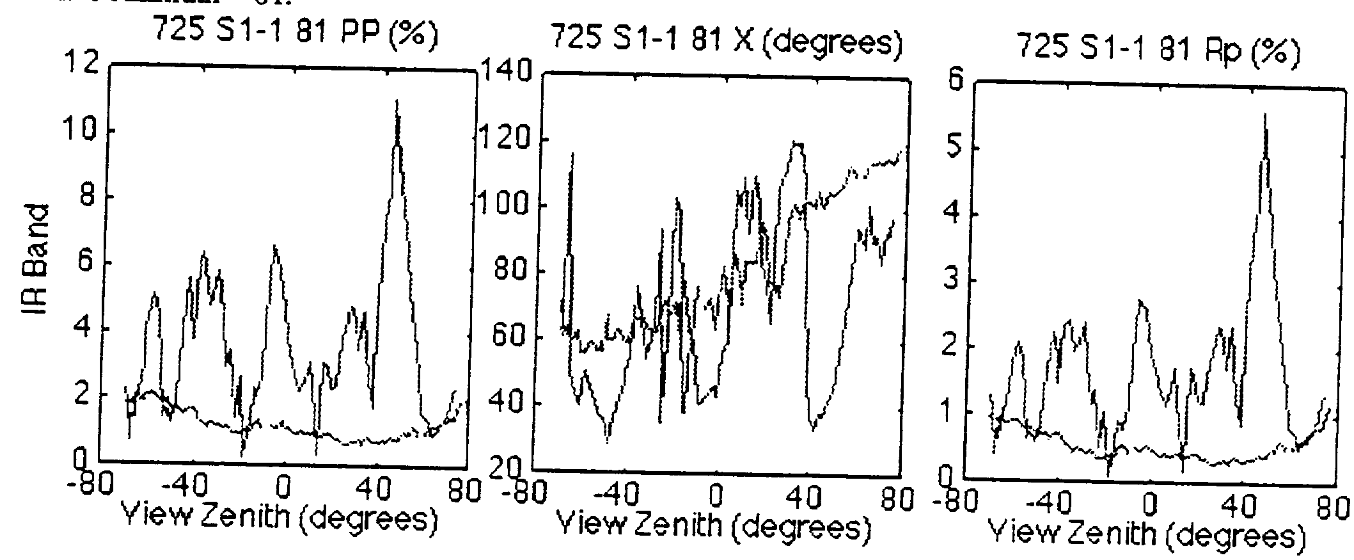
Relative Azimuth = 90.



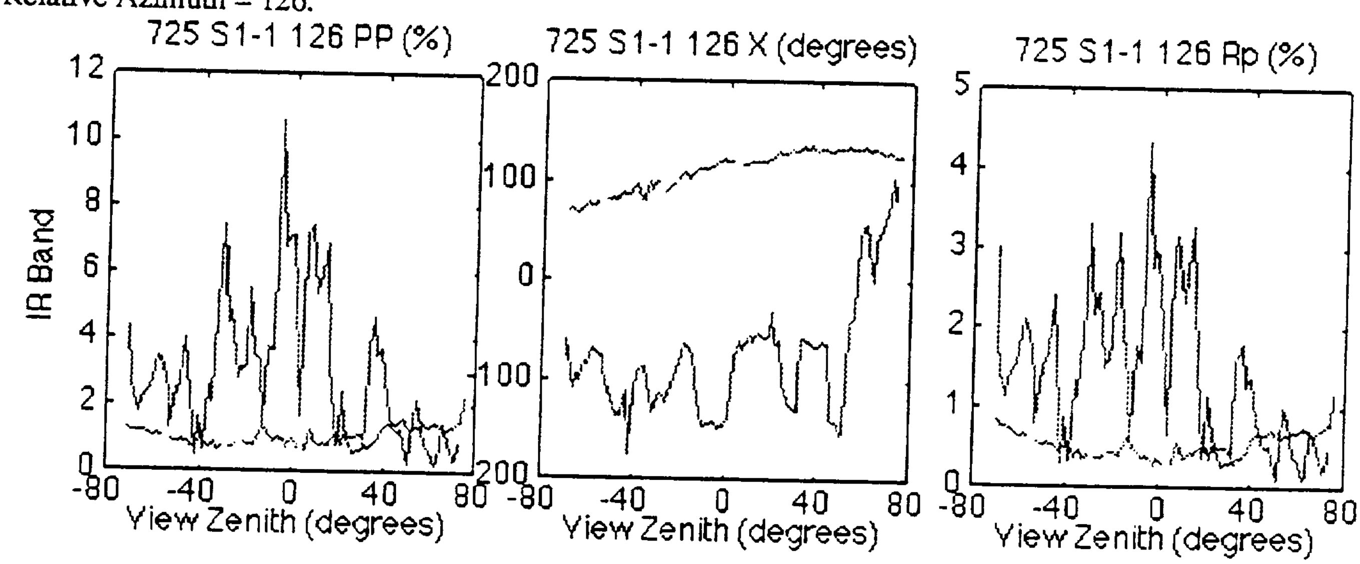
Relative Azimuth = 35.



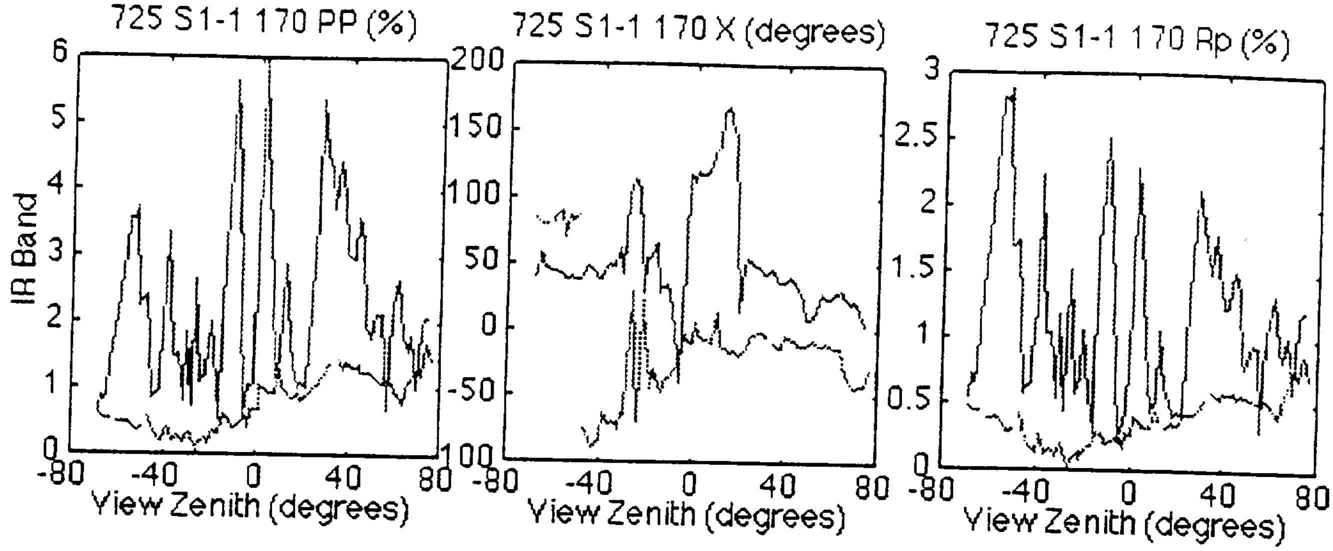
Relative Azimuth = 81.



Relative Azimuth = 126.



Relative Azimuth = 170.



725 S1-1 170 PP (%)
725 S1-1 170 X (degrees)
725 S1-1 170 Rp (%)
IR Band
View Zenith (degrees)
View Zenith (degrees)
View Zenith (degrees)

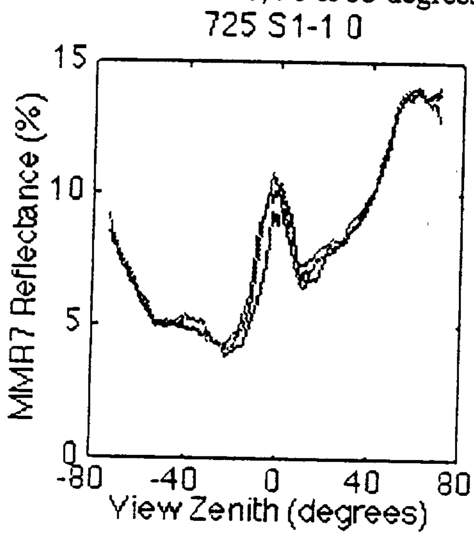
7/25 Set1-1 MMR Band 7

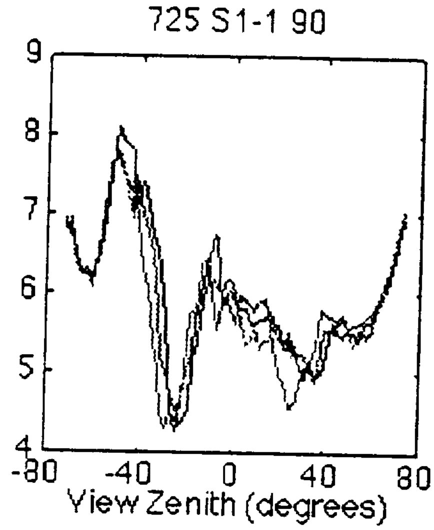
revised 1-26-95

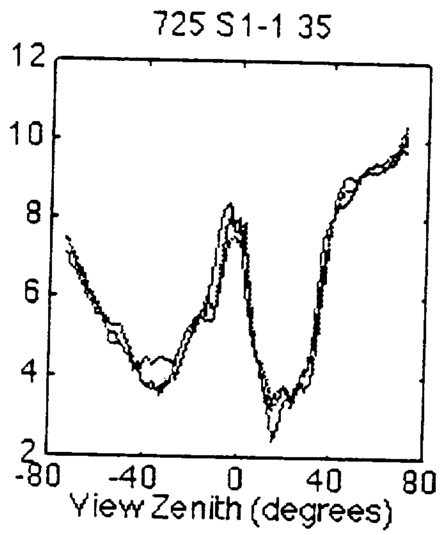
The color codes for the lines in the plots are:

- Red - MMR104
- Magenta - MMR105
- Blue - MMR108

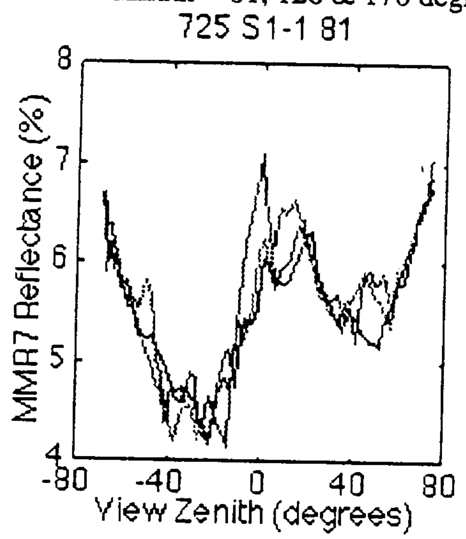
Relative Azimuth = 0, 90 & 35 degrees.

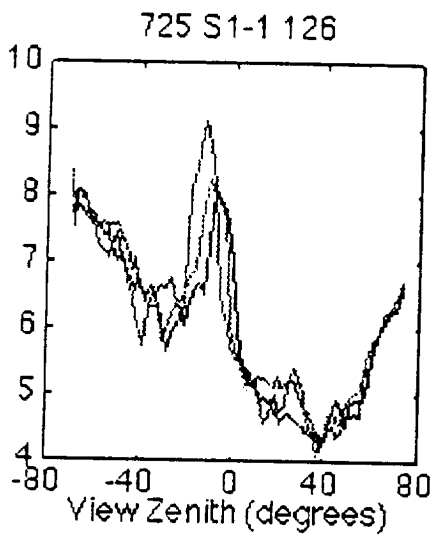


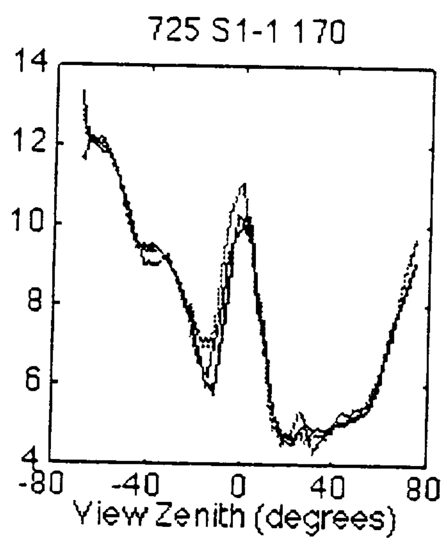




Relative Azimuth = 81, 126 & 170 degrees.





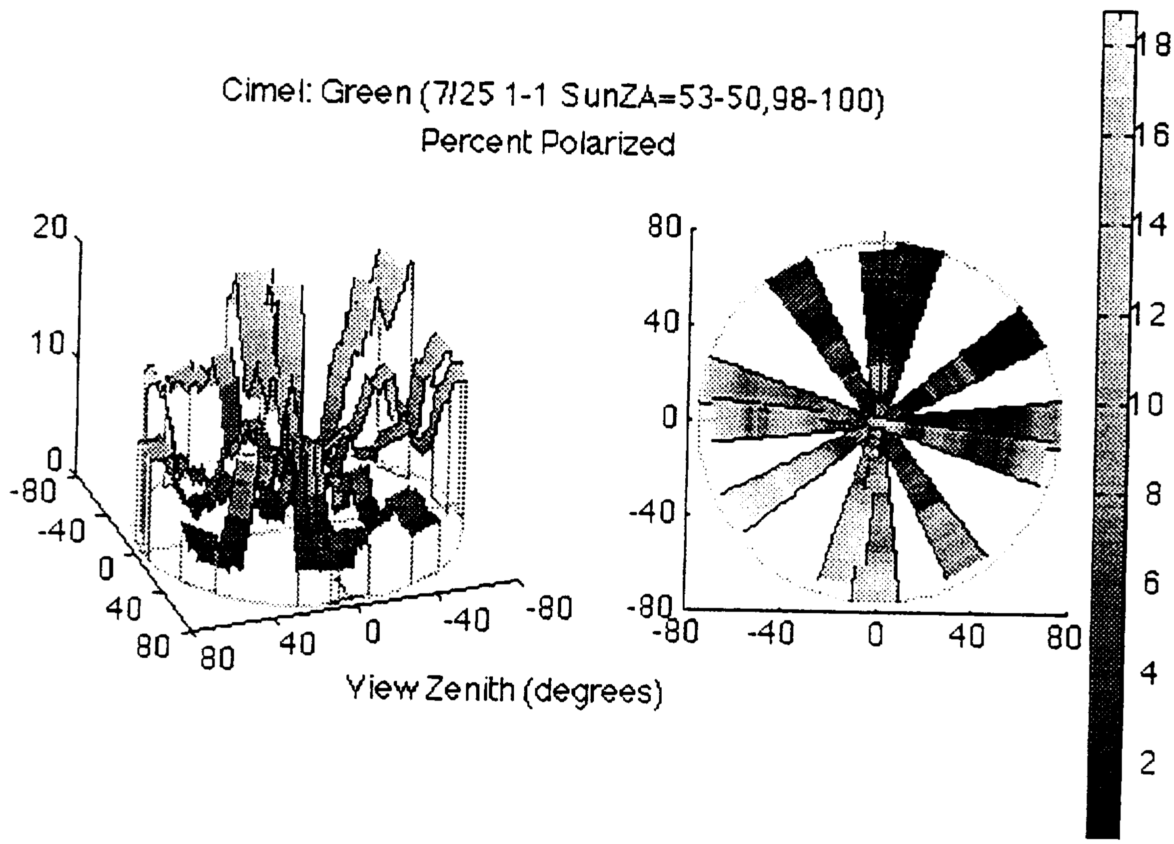


3D Plot of Percent Polarization

The left plot in the figure is a cylindrical plot of the percent polarization collected on July 25, 1991 for set 1 and replication 1. The radius of the cylinder represents view zenith angle, theta represents the relative view azimuth angle and the height represents percent polarization. The purple azimuth line represents a relative view azimuth of 0 degrees.

The right plot is a polar plot of same data that is in the cylindrical plot. The colors in both plots are related to the percent polarization according to the scale to the right side of the figure.

These data are for the Cimel green band. The width of the strips in the figures are related to the width of the FOV of the Cimel, i.e. 12 degrees.



Matlab Graph M-files:

M-files to create the triplet plot figures.
- GraphPLineData.m
- AdjustChiAngle.m
- Draw3LineGraph.m

M-files to create the 3D figure.
- GraphPData.m
- DrawGraph.m

See Appendix C for File listings.
Vara Vanderbilt and Larry Biehl have copies.