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CALIBRATION OF THE NIMBUS-7 SMMR: II POLARIZATION MIXING CORRECTIONS

Per Gloersen

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Goddard Space Flight Center
Greenbelt, Maryland 20771

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II POLARIZATION MIXING CORRECTIONS

Per Gloersen
Goddard Laboratory for Atmospheric Sciences
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

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Abstract

Averaged radiance data obtained over the oceans from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) are used to produce an empirical correction algorithm for the polarization mixing which is inherent to the SMMR because of its fixed multichannel receiving horn and its scanning antenna dish. The algorithm, developed without the use of an ocean/atmosphere radiance model, also properly accounts for off-center and scan-independent polarization mixing, which were discovered after launch as a result of analyzing the aforementioned data. The radiance averaging consisted of collecting data for each beam position of each of the ten radiance channels of SMMR (nominal horizontal and vertical polarizations of the five SMMR wavelengths, 0.81, 1.4, 1.7, 2.8, and 4.6 cm) for about 300 orbits, subdividing the global ocean radiance data into 10° latitude bands and ascending (daytime) and descending (nighttime) orbits. This served to smooth out atmospheric and ocean surface variations in order to perform the polarization mixing analysis. Four different time periods were studied: November 1978, December 1978, March 1979, and June 1979. Two of the channels (vertical polarizations of 2.8 and 4.6 cm) were found to require a latitude-dependent correction, which, however, is independent of season. The algorithm was found to flatten the averaged cross-track beam position data for all seasons and locations studied to within the standard deviation of the curve-fitted data, which ranged from 0.2 kelvins at 4.6 cm to 1 kelvin at 0.81 cm.

Introduction

In order to accommodate spacecraft weight and volume constraints, the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) (Gloersen & Barath 1977) was designed with an antenna system consisting of a fixed multispectral receiving horn and a scanning off-axis parabolic dish. As a result, the polarizations at each wavelength become mixed, nominally as the dish scans away from the center beam position. Ideally, this polarization mixing is predictable and a correction scheme is derivable from a simple optical model (Gloersen et al. 1980). Such a theoretical correction algorithm was not successful, probably because of polarization switch leakage and mixing in the antenna structure, and resulted in the investigation to be described in this paper. A number of other authors (Njoku et al. 1980, Gloersen et al. 1980, 1981a, and 1981b) have addressed this problem earlier, based on models of the instrument and/or of the ocean/atmosphere radiating system. In this paper, an entirely empirical approach is used to determine the scan angle phase-shifts at each wavelength for the center of the polarization mixing, and the adjustments to the amplitude of the mixing corrections necessitated by an angle-independent polarization mixing component. In this way, problems with the earlier results being model-dependent are circumvented.

The SMMR data are averaged by integrate-and-dump circuits during the continuous oscillatory scanning of the antenna dish to produce beam spots along the arc of observations on the earth. The number of such spots is 14 at the 4.6 cm wavelength, 28 at 1.4 - 2.8 cm, and 56 at 0.81 cm. The technique to be described here utilizes averaged ocean data collected for each of these beam spots for the purpose of obtaining the coefficients for the polarization mixing correction algorithm. Next, the data in the individual beam spots for each channel are fitted by a curve of assumed functional form, justified by the excellence of fit at widely different times and places. Then, the analytical form used for the fit is interpreted in terms of an optical polarizer. Finally, the regression coefficients from the fitted curve are used to construct the polarization mixing correction algorithm. To check the consistency of the results, the coefficients obtained from one time period and earth location are used to correct data from other times and places, and the success of the correction is measured.

The prelaunch radiance calibration constants (Gloersen et al. 1982a) were used to provide the radiances for this study. While these were found to be result in values different from model predictions over various earth targets and are therefore in question, the technique described here does not require absolute radiances. Indeed, an appropriate way to calibrate the SMMR is to apply the polarization mixing correction as described here first, and then adjust the observed radiances to agree with a reasonable ocean/atmosphere radiation model (Gloersen et al. 1982b).

Observations

For the purposes of this analysis, the global oceans were divided into 10° latitude bands from which major land effects were excluded by manual selection of the latitude band boundaries. These bands were further subdivided into ascending and descending orbital node passes to permit discerning any day/night differences that might be present, and into four different time periods of approximately one month duration (about 300 orbits) in order to determine any seasonal effects. These time periods occured during November 1978, December 1978, March 1979, and June 1979. Thus, data were averaged into each of the SMMR beam spots for each channel for each of these subdivisions. Multiple linear regression analysis was then used to fit curves to all of the beam spots of a given channel at a given time and location.

The functional form used for the regression analysis is as follows:

$$P = P0 + P1*\cos(2*A) + P2*\sin(2*A)$$

$$S = S0 + S1*\cos(2*A) + S2*\sin(2*A) \quad (1)$$

where P and S refer to the observations at a scan angle A with the horizontal and vertical polarization channels, respectively, at a given wavelength. The variables used in the multiple linear regressions are:

$$x1 = \cos(2*A)$$

$$x2 = \sin(2*A)$$

$$y = P \text{ or } S$$

The functional forms used in Equations (1) are certainly not arbitrarily selected, nor are they claimed to be a unique best-fit. The origin of these forms is not important for the present discussion, since their use is justified on the basis of an excellent fit to the data, but they had been utilized earlier in a different analysis (Gloersen et al. 1982).

The standard deviation (sigma) of the fits represented by Equations (1) are shown in Figures 1a - 1f for three of the four different seasons and each of the channels. Generally speaking, the best fits are for December 1978 and the worst are for June 1979, daytime Southern Hemisphere data (not shown). The sigmas are larger than the values expected on the basis of averaged instrument noise and stability (Gloersen and Barath 1978) and are attributed to geophysical variability. On the other hand, the sigmas for a given channel are usually the order of the instrument noise in individual beam spot observations, so that the subject correction scheme based on these averaged observations is meaningful.

The large sigmas in the June (and March) data have been clearly shown to be due to sunglint off the surface of the ocean (Gloersen 1982d). December data, on the other hand, have proved to have the least problems with occasional earth mislocations and other bad data problems that were discovered in the raw data set used in this study. (These problems have since been corrected and the data set has been redone for archiving.) It should be mentioned that the results shown in Figure 1 are from the second of two passes on the data set. Initial values of sigma and the mean radiance in each beam spot were obtained from the first pass. Then, in order to minimize contributions of severe weather disturbances and/or a very bad data point (keeping in mind that we are dealing with averaged data), an upper limit of the first-pass mean plus one-half of the sigma for a given channel was applied to the data averaged into each beam spot of each channel. If an observation exceeded this limit, then data from the entire scan were discarded for the second-pass regression fit. Typically, there were about 400 observations in each of the beam spots for each channel on the first pass, and about half that for the second pass. While the sigma of the second pass was also about half that of the first, there were only slight differences in the coefficients found for Equations 1 for the two passes.

Analysis

Equations (1) have extrema at the following four values of the scan angle A:

DH = (1/2)*ATN(P2/P1), DH' = DH + 90°

DV = (1/2)*ATN((S2/S1), DV' = DV + 90° -- ~~(2)~~

Equations (2) lead to the following relations:

$$\cos(2*DH) = +/- P1/sqr(P1^2 + P2^2)$$

$$\sin(2*DH) = +/- P2/sqr(P1^2 + P2^2)$$

$$\cos(2*DV) = +/- S1/sqr(S1^2 + S2^2)$$

$$\sin(2*DV) = +/- S2/sqr(S1^2 + S2^2) \quad (3)$$

where the + refers to the maximum and the - tc the minimum in the fitted curves. The maximum for the P-curve and the minimum for the S-curve fall outside of the normal range of scan angle A values of +/- 25°. Recall that the ideal value for DH and DV is 0°. The observed values vary with the channel, with a high value of about 10° being observed for the vertical channel at a wavelength of 1.4 cm (see Table I).

The observed maximum and minimum values can be obtained from the regression coefficients by substituting the values of A given by Equations (3) into Equations (1) with the following result:

$$Pmin = P0 - sqr(P1^2 + P2^2)$$

$$Smax = S0 + sqr(S1^2 + S2^2) \qquad (4)$$

Finally, with the use of some trigonometric relations after applying Equations (3) to eliminate P1, P2, S1, and S2 from Equations (1), an equivalent and more useful form of Equations (1) can be found and is as follows:

$$P = Pmin + 2*sqr(P1^2 + P2^2)*sin^2(A - DH)$$

$$S = Smax - 2*sqr(S1^2 + S2^2)*sin^2(A - DV) \quad (5)$$

It is interesting to note that the amplitude of the oscillations represented by Equations (5) can be interpreted on the basis of an optical polarization analyzer as the polarization difference (V - H) of the ocean/atmosphere radiator. Thus, each polarization channel gives an independent measurement of (V - H) which, in turn, ideally should agree with (Smax - Pmin). The fact that they do not agree (see Table II) indicates polarization mixing independent of scan angle and/or different changes from the prelaunch values of gain for the P and S channels.

The Correction Algorithm

It is desirable to construct a polarization mixing correction algorithm which uses observed radiances which may not necessarily have correct absolute values, i.e. require subsequent adjustments for gain and offset. Such an algorithm would provide, once and for all, a flat cross-track instrument response which could then subsequently be adjusted for gain and offset, and readily fine-tuned after that, if necessary. If the true horizontal and vertical polarizations of the multispectral microwave radiation from the pseudo-isometric earth surface are designated by H and V, respectively, and the corresponding flattened instrument responses from the P and S channels as HP and VS, then the gain and offset adjustments described can be represented as follows:

$$H = ah + bh*HP$$

$$V = av + bv*VS \quad (6)$$

For a given wavelength, the desired correction algorithm will then have the form:

$$HP = P - (S - P)*fP(A,P0,P1,P2,S0,S1,S2)$$

$$VS = S + (S - P)*fS(A,P0,P1,P2,S0,S1,S2) \quad (7)$$

Thus, the correction algorithm uses as input only the prelaunch values of the radiometer response, the coefficients determined from the regression analysis of the pseudo-isometric global ocean radiator, and the scan angle.

Rather than displaying the tedious algebra of the intermediate steps, the procedure for obtaining the functions fP and fS in Equations (7) is instead outlined as follows:

1. Find an expression for (S - P) from Equations (5) by taking the difference.
2. Factor out from the above expression first $2*sqr(P1^2 + P2^2)$, then factor out from the same expression $2*sqr(S1^2 + S2^2)$. This results in two additional forms of the same expression for (S - P).
3. Solve the two additional expressions from Step 2. for the two different factored sqr terms and substitute them for the corresponding sqr terms in Equations (5).
4. Recognize that for the averaged ocean surface HP and Pmin, and VS and Smax, are equal; make that substitution in Equations (5).
5. Solve the results of Step 4. for HP and VS. This gives the following values for the correction coefficients in Equations (7):

$$fP = BP/(AP - BP - BS/G)$$

$$fS = BS/(AS - BS - BP*G) \quad (8)$$

where

$$BP = \sin^2(A - DH)$$

$$BS = \sin^2(A - DV)$$

$$AP = (Smax - Pmin)/2*sqr(P1^2 + P2^2)$$

$$AS = (Smax - Pmin)/2*sqr(S1^2 + S2^2)$$

$$G = sqr(P1^2 + P2^2)/sqr(S1^2 + S2^2)$$

and A, DH, and DV have been defined earlier.

If the calibration adjustments for the P and S channels at a given wavelength were the same and if there were no angle-independent polarization mixing, then the ratios AP, AS, and G would all be unity, since the numerators and denominators are all independent observations of the same quantity, (V - H), as mentioned earlier. Since this is obviously not the case (see Table I), one could hope that the ratios would be at least independent of time and latitude. As it turns out, this is true for all but the 4.6V and 2.8V channels, which require a slight adjustment for latitude.

The adjustments required for AS and DV in the 2.8 and 4.6 cm channels can be approximated by piecewise linear fits to the data. For AS, two cycles are required; for DV, only one. Curiously, the cycle intervals are the same at both wavelengths. The latitudinal variation in AS and DV is illustrated in Figure 2. Only the curves are shown, but the maximum deviation of the points used to determine them is about 0.2 degrees of scan angle, representing at most a cross-track error of +/-0.2 K. This adjustment appears to be independent of season, within the errors of the determination.

Discussion and Summary

The polarization mixing correction algorithm constants shown in Table I were determined from the averaged ocean radiances constructed for the 30 - 40S latitude band, December 1978 daytime data. December data were chosen since they displayed the best fit (sigma) to the analytic form of Equations (1). The particular time and location were chosen since those data were the closest to mean values for December, and since using averaged values for the constants was feared to destroy the self-consistency between the various constants in the algorithm.

The algorithm was tested at other locations and times by using the following procedure to save computer time and analysis effort: Since Equations (1) represents an excellent fit to all of the averaged data (except in the presence of sunglint), it was used in conjunction with the regression coefficients P0 ,P1, P2, S0, S1, and S2 which had been generated for all of the averaged radiance data from all times and locations to calculate radiances (P and S) for the individual beam spots. These calculated values were then used in Equations (7) to obtain values of HP and VS for all beam spots, times, and locations. As would obviously be expected, the results for the December 1978, 30 - 40S latitude band daytime data were perfect, i.e. the HP and VS values were, respectively, the same for each beam spot. For the other 79 ascending/descending latitude bands studied (20 for each month), the degree of flatness across the swath of beam spots was within the sigmas of the curve fits (see Figure 1).

Another test of the correction algorithm, principally for the 4.6 V channel, was to generate a one-year set of sea surface temperatures for each month, broken into ascending and descending orbital node data, since the launch of Nimbus-7 (end of October 1978) using a simplified retrieval algorithm (Gloersen 1982) to check for cross-track bias in the retrievals. The results were a significant improvement over those shown earlier (Gloersen 1981); the earlier cross-track bias observed on the images with 1°C temperature resolution is no longer discernable.

The approach of this analysis is deliberately empirical, in order to avoid having controversial interpretation of the observations obscure the validity of the correction procedure. A number of explanations for these observations, however, is possible. While a detailed discussion of the probable mechanisms is beyond the scope of this paper, there are at least two likely sources of polarization mixing in the SMMR. One is the mixing of the H and V polarization components in the antenna dish/receiving horn assembly, e.g. due to short focal lengths and support struts, and the other is due to leakage in the rf switches used to alternate the useage of the common radiometers for the 1.4 - 4.6 cm wavelengths between the horizontal and vertical polarization ports of the receiving horn. The former source of mixing is the only reasonable one at the 0.81 cm wavelength since there are separate radiometers for the two polarizations; indeed, the degree of mixing and phase shifts observed at that wavelength is commensurate with prelaunch measurements of cross-polarization of the dish and horn assembly. Unfortunately, the full significance of polarization switch leakages was not realized until after launch, and cross-polarization tests of the assembled system were not carried out prior to launch. Component test results are available, but not in sufficient detail for a meaningful analysis. Incidentally, subsequent limited testing of the SMMR engineering model mounted so as to scan a local large body of water has also shown polarization mixing effects, but with different mixing constants.

In conclusion, the algorithm described here successfuly corrects for the polarization mixing inherent to the SMMR on Nimbus-7 on a global and time-independent basis, at least for the four time periods studied which include the two soltices and therefore extremes in any diurnal effects that might occur. Based on the differences between the correction coefficients for Nimbus-7 and engineering model SMMRs, it would be necessary to generate a separate set of coefficients in order to apply similar corrections to the Seasat-A SMMR data.

Acknowledgement

The author wishes to cite the skill of Mr. Hugh W. Powell in implementing the correction algorithm on the Goddard computers, and also in producing the results used to check the validity of the algorithm.

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TABLE I

CHANNEL	DH or DV	AP or AS	G
4.6 H	4.7°	1.08	0.88
4.6 V	-1.9 to -3.8°*	0.92 - 1.04*	0.88
2.8 H	1.5°	1.09	0.88
2.8 V	-0.1 to +1.0°*	0.92 - 1.04*	0.88
1.7 H	-2.4°	1.05	0.89
1.7 V	1.4°	0.91	0.89
1.4 H	-3.6°	0.86	0.87
1.4 V	10.8°	0.75	0.87
0.8 H	0.7°	1.27	0.96
0.8 V	-0.2°	1.22	0.96

*See Figure 2 for variation with location.

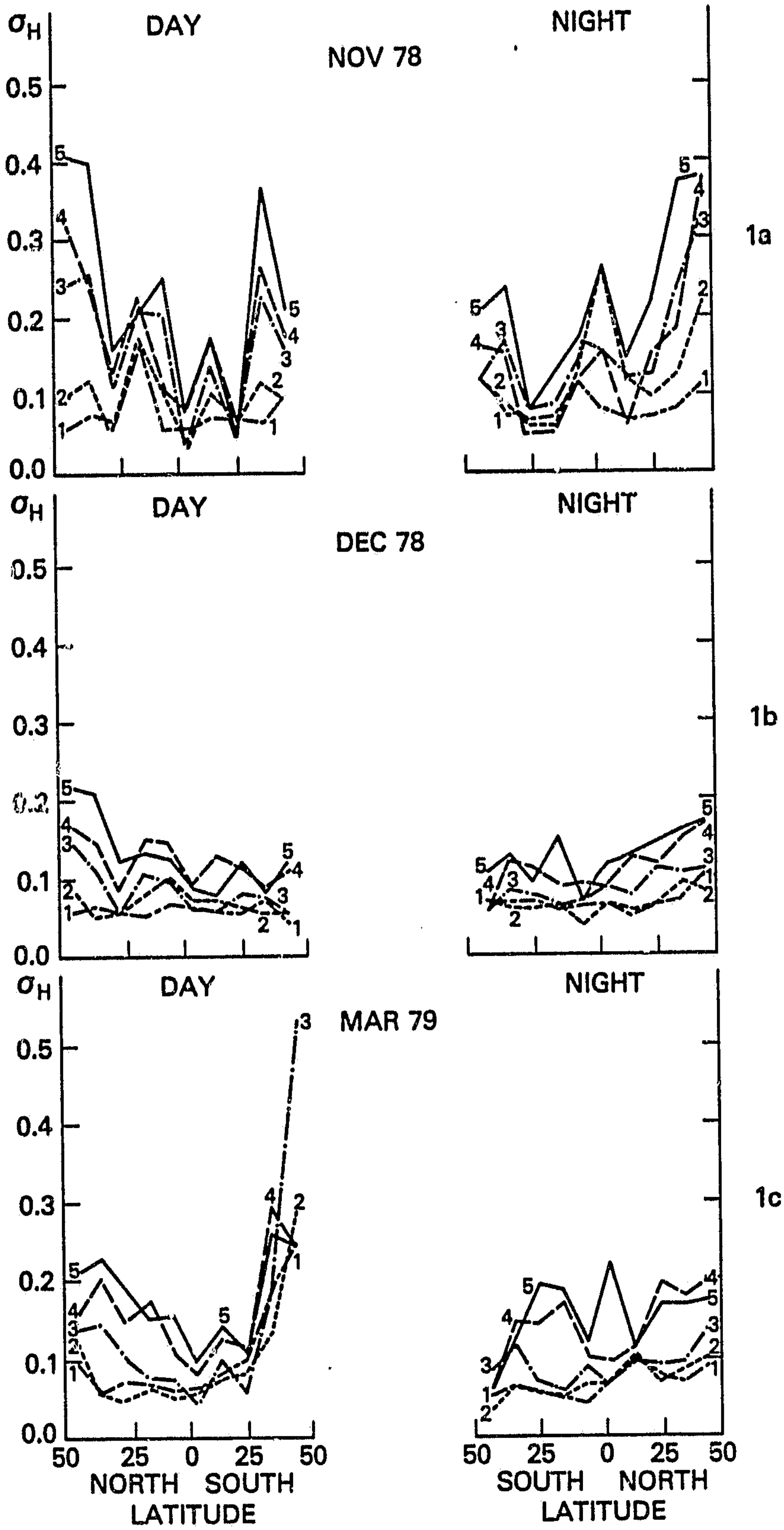
TABLE II

WAVELENGTH	4.6 cm	2.8 cm	1.7 cm	1.4 cm	0.8 cm
2*sqr(P1^2+P2^2)	51.0 K	54.0 K	49.8 K	42.8 K	46.3 K
Smax-Pmin	54.9	58.7	52.1	36.6	62.6
2*sqr(S1^2+S2^2)	58.1	61.3	57.1	49.2	51.5

FIGURE CAPTIONS

Figure 1. Standard deviations (in degrees Kelvin) of the averaged SMMR radiance data from the curves given by Equations (1) vs. orbital position. The numbers 1-5 refer to the wavelengths 4.6, 2.8, 1.7, 1.4, and 0.8 cm respectively. Solid curves are daytime data; dashed are nighttime. a. - c.: Horizontal channels for November 1978, December 1978, and March 1979, respectively. d. - f.: Same, except for vertical channels. The large deviations in March for 40-50S, daytime data, are the result of sunglint appearing in the right-hand portion of the scan.

Figure 2. Variation of the quantity AS in Equations (8) and the polarization mixing phase angle, DV (Equations (2)), with orbital position. Such variation was observed only for the two channels shown and is the same for both channels. Note that while the amplitudes of the two channels shown differ, their phases are the same. Again, the other channels did not show such variation.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NIGHT
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1a
DEC 78
1b
MAR 79
1c
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0.1
0.2
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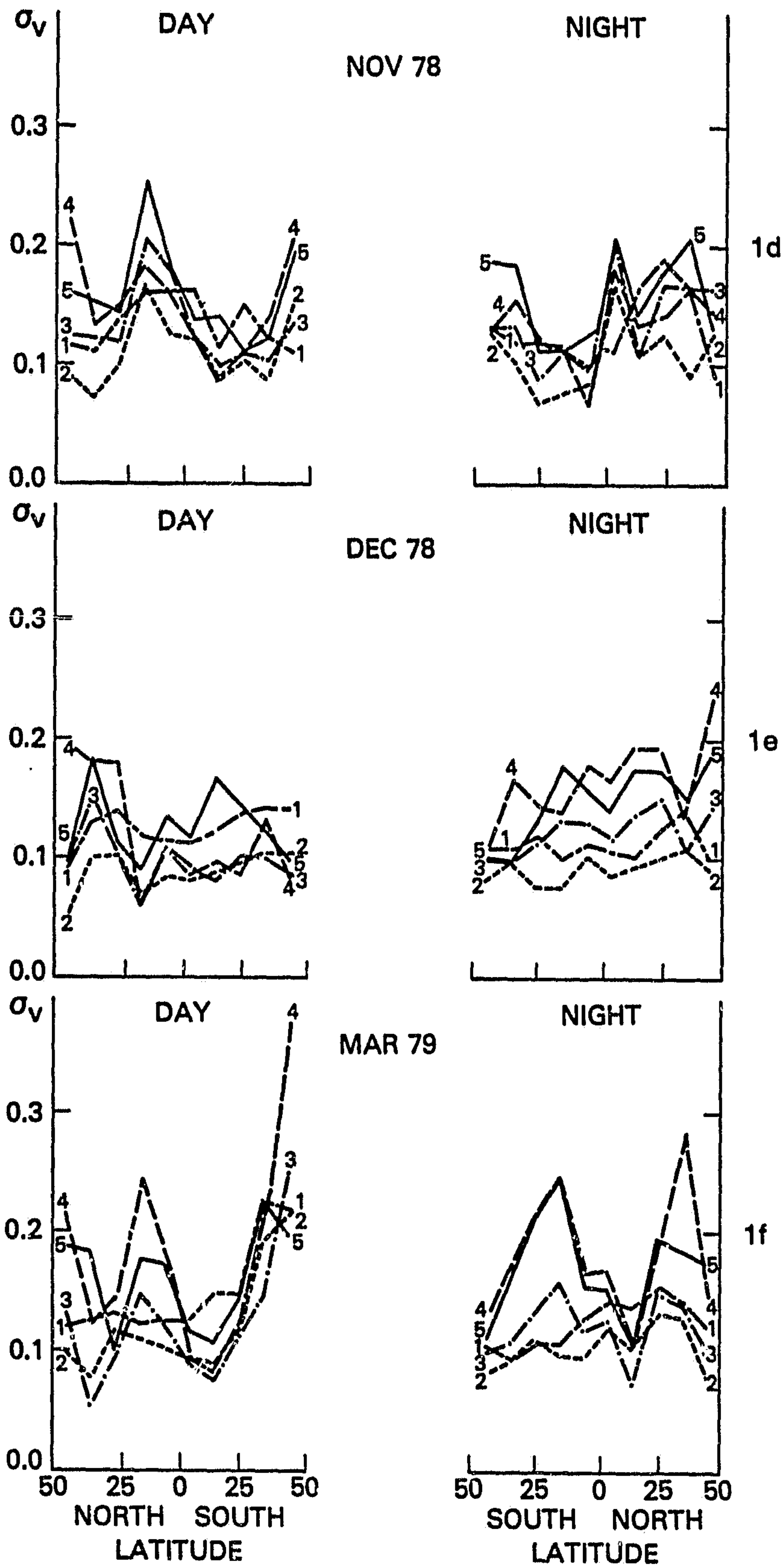

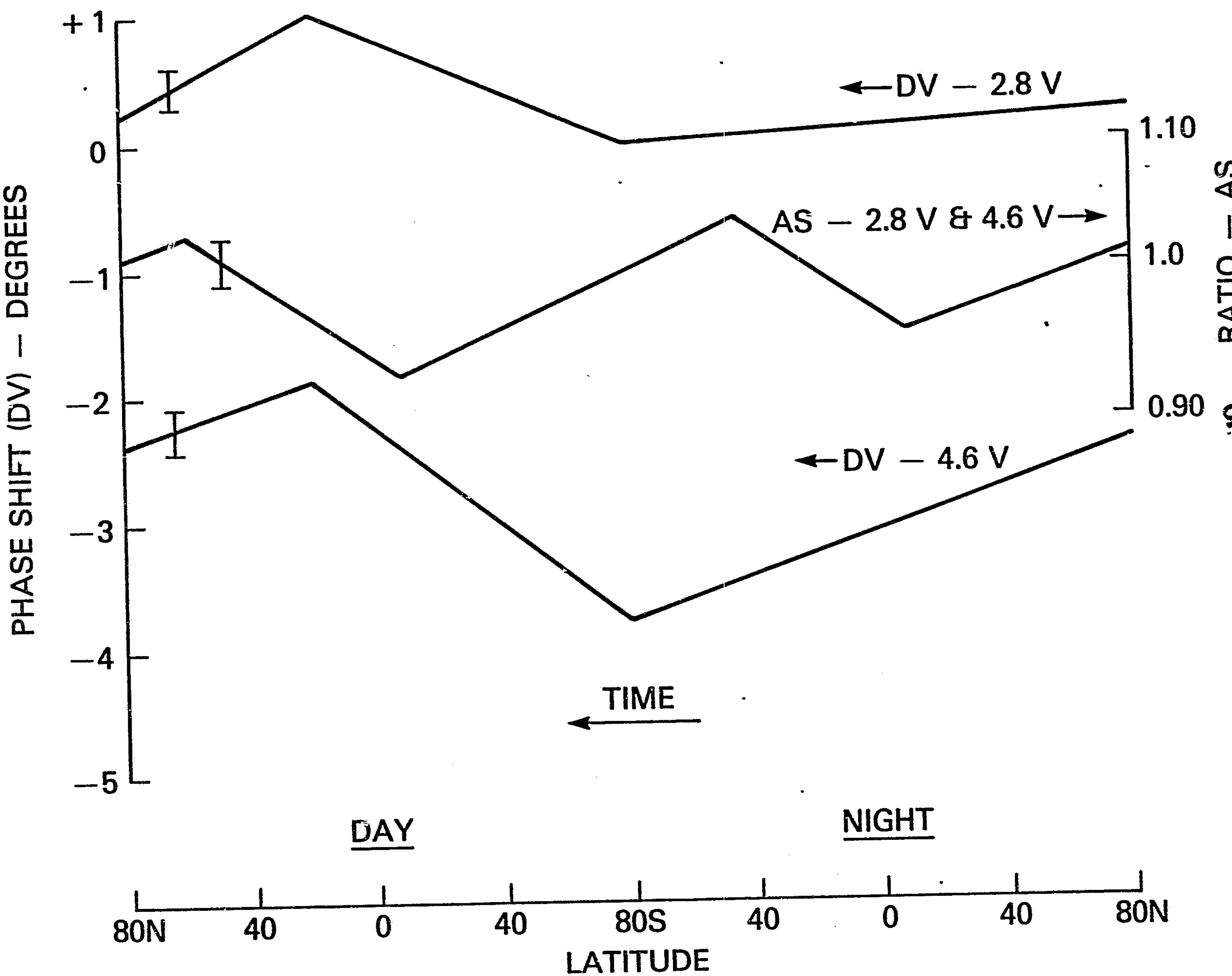

+1
0
−1
−2
−3
−4
−5
PHASE SHIFT (DV) — DEGREES
←DV — 2.8 V
AS — 2.8 V & 4.6 V→
←DV — 4.6 V
1.10
1.0
0.90
RATIO — AS
TIME
DAY
NIGHT
80N
40
0
40
80S
40
0
40
80N
LATITUDE