Voyager 1979: Update to the Radial and Solar Cycle Variations in the Solar Wind Phase Fluctuation Spectral Index

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Of current interest is the value of, and possible variations in, the solar wind phase fluctuation spectral index. This article presents columnar spectral index information that has been extracted from a sizable volume of Voyager 1979 solar conjunction Doppler phase fluctuation data. The Voyager 1979 results, when compared to similar information derived from the 1976 Helios and Viking and 1978 Voyager solar conjunctions, lead to the following inferences: (1) there has been a significant change in the spectral index from 1976 to 1978/1979; (2) there is continuing evidence that favors a slight (positive) correlation between the spectral index and the solar (sunspot) cycle; (3) there is little or no evidence in support of a radial variation of the spectral index. Recently, it has been hypothesized that a flattening of the phase fluctuation spectrum occurs near the sun ($\lessdot 20r_\odot$); these data are at a variance with such a hypothesis.

I. Introduction

Of current interest are the possible variations in the solar wind phase fluctuation spectral index ($=K_0$, where the columnar phase spectral density variation with fluctuation frequency ν is ν^{-K_0}) with parameters such as radial distance, solar cycle, and fluctuation frequency regime. In a previous report (Ref. 1), the authors analyzed the parametric dependencies of the solar wind phase fluctuation spectral index as extracted from the solar conjunction Doppler data of the Helios (1976), Viking (1976), and Voyager (1978) spacecraft. Reference 1 found no evidence of a spectral index radial variation, and only inconclusive evidence pointing to a possible slight variation with solar cycle.

This article augments the previous spectral index data base with new information obtained from Voyager 1 Doppler data generated during the 1979 solar conjunction. These new data tend to confirm the results of Ref. 1. In addition, a hypothesized flattening of the phase fluctuation spectrum at close solar distances ($\lessdot 20r_\odot$, where $r_\odot$ = solar radius), currently in favor as, for instance, in Woo and Armstrong (Ref. 2) and Esposito et al. (Ref. 3), is not observed in these data.

II. Helios and Viking Spectral Index Data During 1976

Berman (Refs. 4 and 5) has analyzed a large volume of Doppler phase fluctuation data generated by the Deep Space Network (DSN) during the 1976 solar conjunctions of Helios and Viking. Analysis of the spectral index information derived from the Helios and Viking data yielded (Ref. 5) a mean value of 2.42 for the columnar (two-dimensional) spectral index and provided no indication of a spectral index radial dependence.

Figure 1 (from Ref. 5) presents the columnar spectral index, as computed from Viking Doppler phase fluctuation data, versus Sun-Earth-probe (SEP) angle. The absence of any significant spectral index radial dependence is obvious from inspection of Fig. 1.

III. Voyager Spectral Index Data During 1978

Doppler phase fluctuation data generated by the DSN during the 1978 Voyager solar conjunction were analyzed by the authors in Ref. 1. These data yielded a mean value of 2.67 for the columnar spectral index and provided little or no indication of a spectral index radial dependence.

Figure 2 (from Ref. 1) presents the spectral index, as computed from Voyager Doppler phase fluctuation data, versus Sun-Earth-probe (SEP) angle. Again, the absence of any significant spectral index radial dependence is obvious from inspection of Fig. 2.

IV. Voyager Spectral Index Data During 1979

In 1977, the DSN implemented a new capability to allow the convenient extraction of spectral index information from Doppler phase fluctuation data; this capability is described in detail in Refs. 5 and 6. Using this new capability, columnar spectral index information has been computed from the 1979 Voyager 1 Doppler phase fluctuation data. Very briefly, the spectral index extraction process is predicated on the following relationships (Ref. 6):

$$\phi^2(\nu) \propto \nu^{-K_0+1}$$

$$\nu \propto \tau_a^{-1}$$

$$\phi(\tau_a) \propto \tau_a \cdot \sigma_f(\tau_a)$$

where

ϕ = RMS Doppler phase fluctuation

τ_a = Doppler averaging time (sample interval)

σ_f = RMS Doppler frequency fluctuation

ν = fluctuation frequency

K_0 = columnar spectral index

The Voyager 1 two-way S-band Doppler phase fluctuation data were analyzed during the period July 24, 1979 to September 22, 1979. During this period, the SEP varied between 1.3 degrees and 22.2 degrees. The approximate fluctuation frequency (ν) range for which the columnar spectral index was computed for the Voyager 1 data was:

$$2.8 \times 10^{-4} \text{ Hz} < \nu < 2.8 \times 10^{-3} \text{ Hz}$$

The spectral index information determined from the Voyager 1 Doppler phase fluctuation data is presented in Figs. 3 and 4. Figure 3 presents the spectral index vs day of year (DOY), while Fig. 4 presents the spectral index vs SEP.

The mean value of the spectral index as computed from the Voyager 1 1979 Doppler data is K_0 = 2.60. Again, inspection of Fig. 4 indicates no significant spectral index radial dependence. In Fig. 5, all Viking 1976, Voyager 1978, and Voyager 1979 data have been plotted as a function of signal path closest approach distance. Although a casual look at Fig. 5 might leave the impression of a spectral index radial dependence, what is really in evidence is a significant steepening of the spectral index between solar cycle minimum data (1976) and solar cycle maximum data (1978-1979), in combination with different spans of data closest approach distance.

V. Spectral Index Variations With Solar Cycle

Reference 1 inferred a possible slight variation of the spectral index with solar cycle. What trends exist point to a positive correlation with solar cycle; i.e., the fluctuation spectrum appears to be *steeper* during solar cycle (sunspot) maximum. In this regard, the Voyager 1979 data are consistent with earlier results presented in Ref. 1.

Table 1 presents the results of ten experimental determinations of the spectral index during Solar Cycles 20 and 21. The mean value of the ten experiments listed in Table 1 is K_0 = 2.50 and the standard deviation is $1\sigma = 0.13$. It is, therefore, suggested that a mean model for the solar wind phase fluctuation spectrum (P_ϕ) be adopted as follows:

$$P_\phi(\nu) \propto \nu^{-2.5 \pm 0.2}$$

where the spectrum is more likely to be *flatter* during solar cycle minimum and *steeper* during solar cycle maximum.

In Fig. 6, the various spectral index determinations have been plotted as a function of solar cycle. As already noted, there appears to be a slight steepening of the spectral index with solar cycle maximum; however, it is clear that a much greater volume of data will be required before any solar cycle dependence can be claimed with certainty.

VI. Radial Variations in the Spectral Index

Many investigators have claimed a radial variation in the spectral index; examples are Woo and Armstrong (Ref. 2), Esposito et al. (Ref. 3), and Coles et al. (Ref. 7). In particular, Woo and Armstrong claim that at approximately $20r_{\odot}$, the phase fluctuation columnar spectral index changes from approximately 2.65 ($\gtrsim 20r_{\odot}$) to approximately 2.1 ($\lesssim 20r_{\odot}$). Review of the data in Figs. 1, 2, and 4 does not provide any evidence of such a flattening of the near-Sun phase fluctuation spectrum.

Of course, the results derived from closed-loop Doppler data presented here are very low frequency (2.8×10^{-4} Hz $< \nu < 2.8 \times 10^{-2}$ Hz) and it is conceivable that such a flattening exists in a different fluctuation frequency regime; nonetheless, the claims of near-Sun spectrum flattening can be considered as speculative at this time.

VII. Summary and Discussion

A new DSN capability has been utilized to obtain a sizeable volume of spectral index information during the Voyager 1979 solar conjunction. Major conclusions derived from a comparative study of these data with similar data obtained during 1976 solar conjunctions of Helios and Viking and the 1978 solar conjunction of Voyager are:

(1) There has been a significant change in the spectral index from solar cycle minimum (1976; $K_0 = 2.42$) to (near) solar cycle maximum (1978/1979; $K_0 = 2.64$).

(2) There continues to be evidence for a slight (positive) correlation between spectral index and solar (sunspot) cycle.

(3) There continues to be little or no evidence for a significant variation of spectral index with radial distance. In particular, there is no evidence to support a currently hypothesized near-Sun phase fluctuation spectrum flattening.

The exercise of this new DSN capability is expected to be continued in future years to derive columnar spectral index information from Voyager solar conjunction Doppler phase fluctuation data, and hence to allow the continued monitoring of spectral index variations during the remainder of Solar Cycle 21.

References

1. Berman, A. L., and Conteas, A. D., "Radial and Solar Cycle Variations in the Solar Wind Phase Fluctuation Spectral Index as Determined From Voyager 1978 Solar Conjunction Data," in *The Deep Space Network Progress Report 42-48*, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1978.

2. Woo, R., and Armstrong, J. W., "Spacecraft Radio Scattering Observations of the Power Spectrum of Electron Density Fluctuations in the Solar Wind," *Journal of Geophysical Research* (in press).

3. Esposito, P. B., et al., "Helios Data Analysis Results," EM 315-90, Aug. 22, 1979 (JPL Internal Document).

4. Berman, A. L., "A Comprehensive Two-Way Doppler Noise Model for Near-Real-Time Validation of Doppler Data," in *The Deep Space Network Progress Report 42-37*, Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1977.

5. Berman, A. L., "Phase Fluctuation Spectra: New Radio Science Information to Become Available in the DSN Tracking System Mark III-77," in *The Deep Space Network Progress Report 42-40*, Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1977.

6. Berman, A. L., and Conteas, A. D., "A Solar Wind Turbulence Event During the Voyager 1978 Solar Conjunction Profiled via a New DSN Radio Science Capability," in *The Deep Space Network Progress Report 42-48*, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1978.

7. Coles, W. A., Rickett, B. J., and Scott, S. L., "Scintillation Observations Near the Sun," in *A Close-up of the Sun*, edited by Neugebauer, M., and Davies, R. W., JPL Publication 78-70, Jet Propulsion Laboratory, Pasadena, Calif., Sept. 1, 1978.

8. Chang, H., *Analysis of Dual-Frequency Observations of Interplanetary Scintillations Taken by the Pioneer 9 Spacecraft*, Doctoral Dissertation, Department of Electrical Engineering, Stanford University, May 1976.

9. Woo, R., Yang, F., Yip, W. K., and Kendall, W. B., "Measurements of Large Scale Density Fluctuations in the Solar Wind Using Dual Frequency Phase Scintillations," *The Astrophysical Journal*, Vol. 210, No. 2, Part 1, Dec. 1, 1976.

10. Unti, T. W. J., Neugebauer, M., and Goldstein, B. E., "Direct Measurements of Solar Wind Fluctuations Between 0.0048 and 13.3 Hz," *The Astrophysical Journal*, Vol. 180, March 1, 1973.

11. Goldstein, B., and Sisco, G. L., "Spectra and Cross Spectra of Solar Wind Parameters from Mariner 5," in *Solar Wind*, edited by Sonett, C. P., Coleman, P. J., Jr., and Wilcox, J. M., National Aeronautics and Space Administration, Washington, D. C., 1972.

12. Intriligator, D. S., and Wolfe, J. H., "Preliminary Power Spectra of the Interplanetary Plasma," *The Astrophysical Journal, Letters*, Vol. 162, Dec. 1970.

Table 1. Solar wind columnar phase fluctuation spectral index measurements

Source	Year	K_0	Type of measurement	Reference
Berman	1979	2.60	Voyager Doppler Phase Fluctuation	
Berman	1978	2.67	Voyager Doppler Phase Fluctuation	1
Woo	1976/ 1977	2.65	Viking Doppler Spectra	2
Berman	1976	2.41	Viking Doppler Phase Fluctuation	4
Berman	1976	2.43	Helios Doppler Phase Fluctuation	4
Chang	1972/ 1975	2.5	Pioneer 9 Intensity Scintillation	8
Woo	1974	2.55	Mariner Venus Mercury Dual-Frequency Doppler	9
Unti	1968	2.55	OGO 5 in-situ	10
Goldstein	1967	2.3	Mariner Mars in-situ	11
Intriligator	1965	2.3	Pioneer in-situ	12

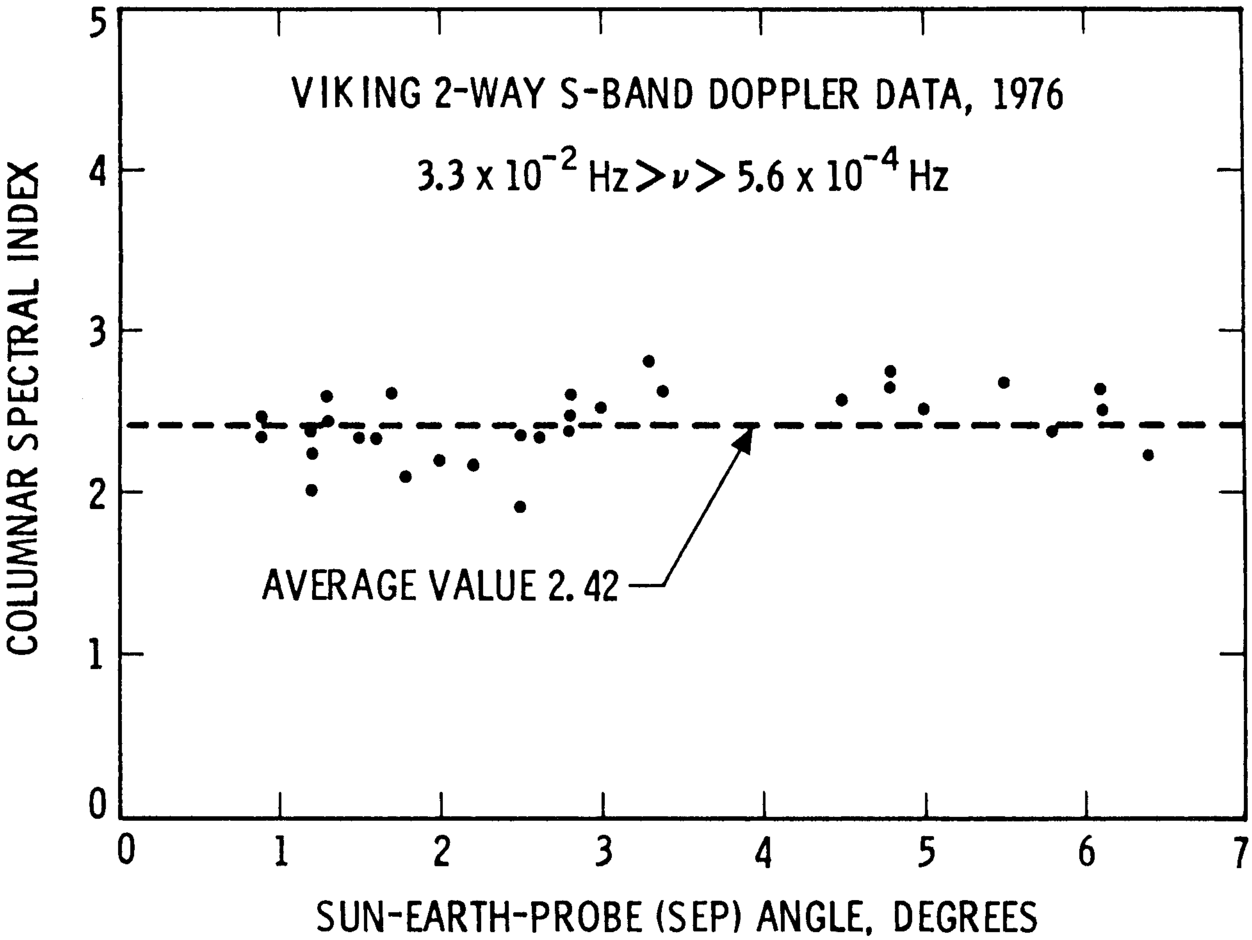

Fig. 1. Columnar solar wind phase fluctuation spectral index versus Sun-Earth-probe angle, 1976

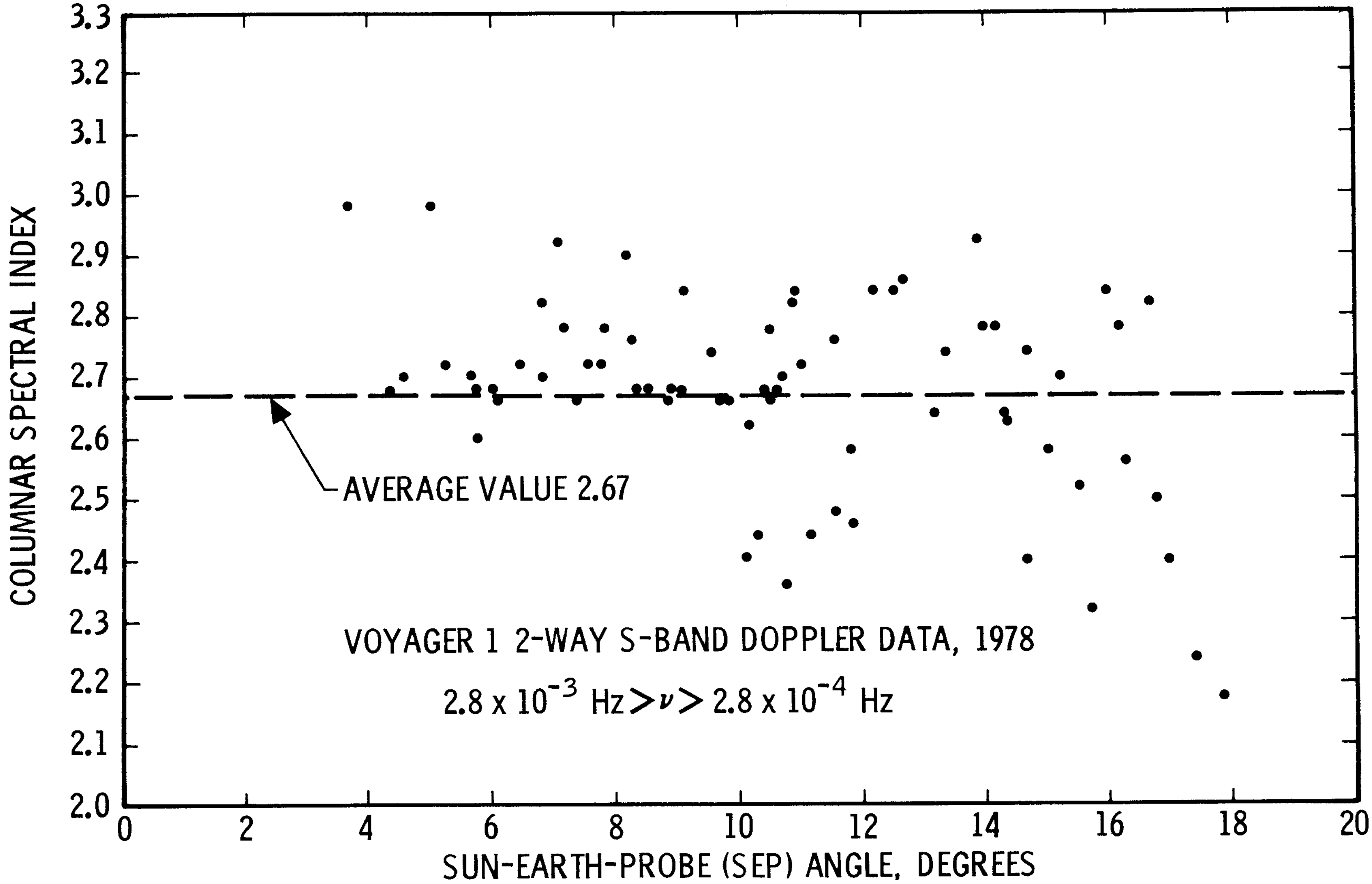

Fig. 2. Columnar solar wind phase fluctuation spectral index versus Sun-Earth-probe angle, 1978

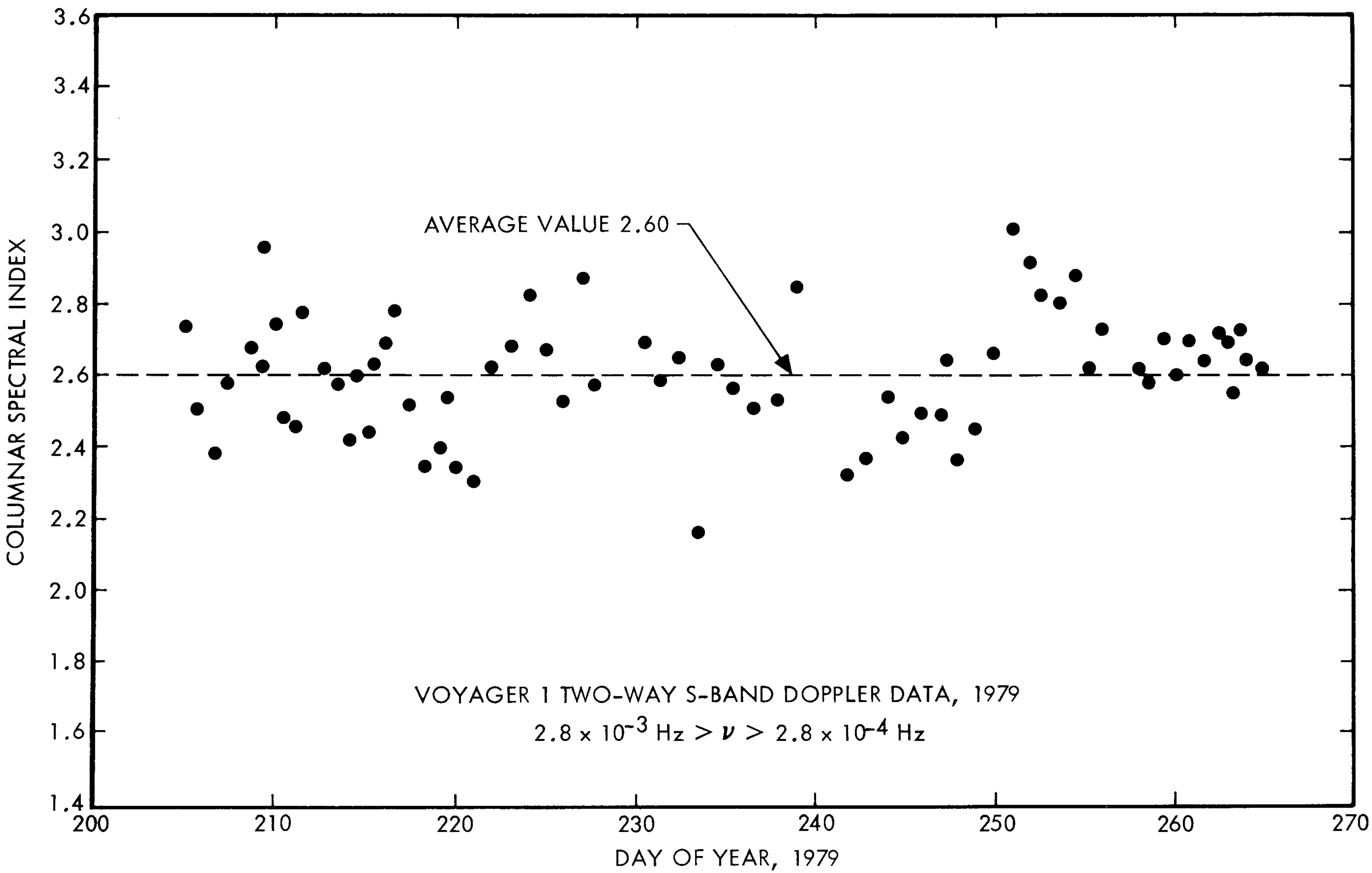

Fig. 3. Columnar solar wind phase fluctuation spectral index versus day of year, 1979

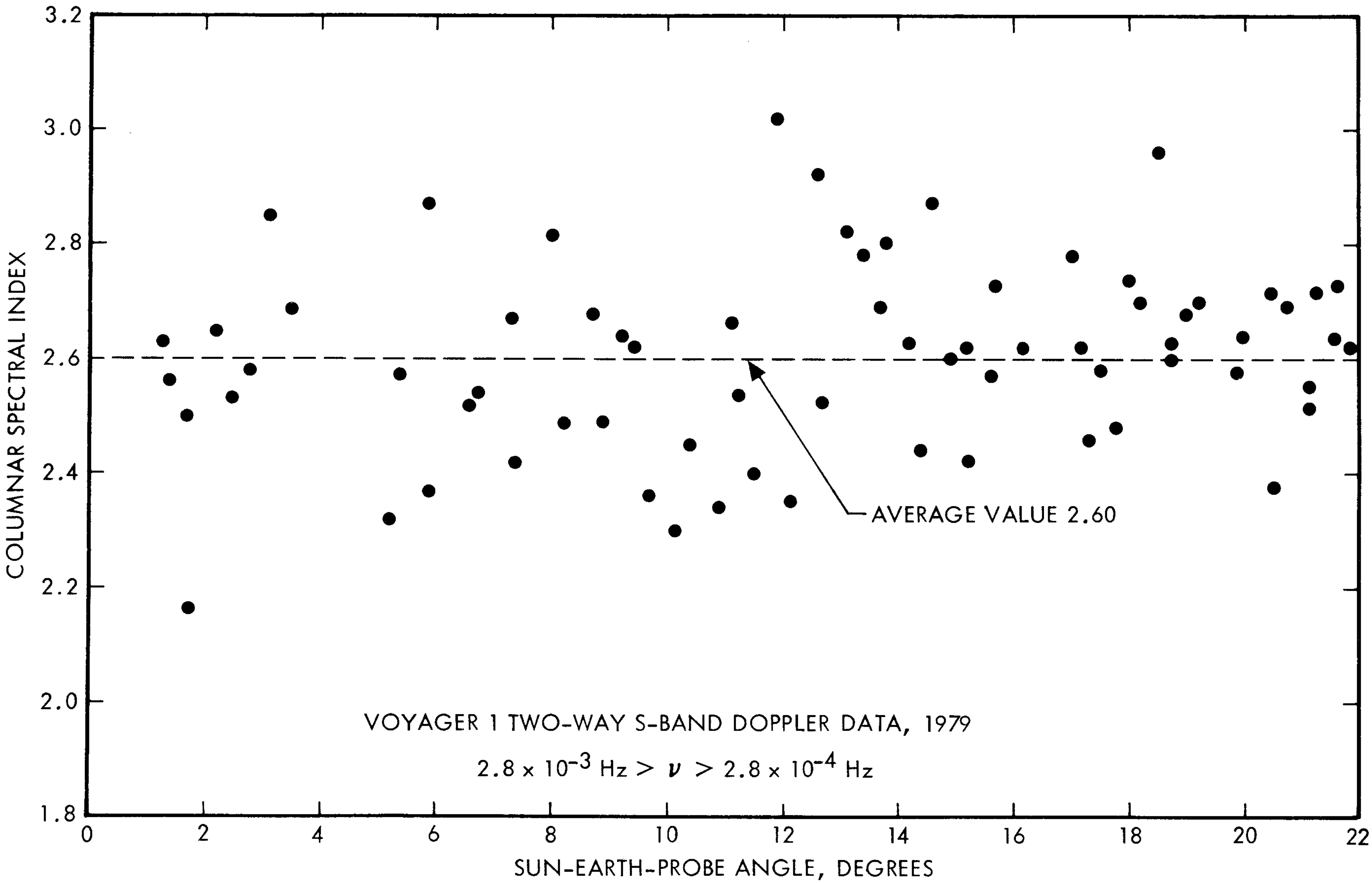

Fig. 4. Columnar solar wind phase fluctuation spectral index versus Sun-Earth-probe angle, 1979

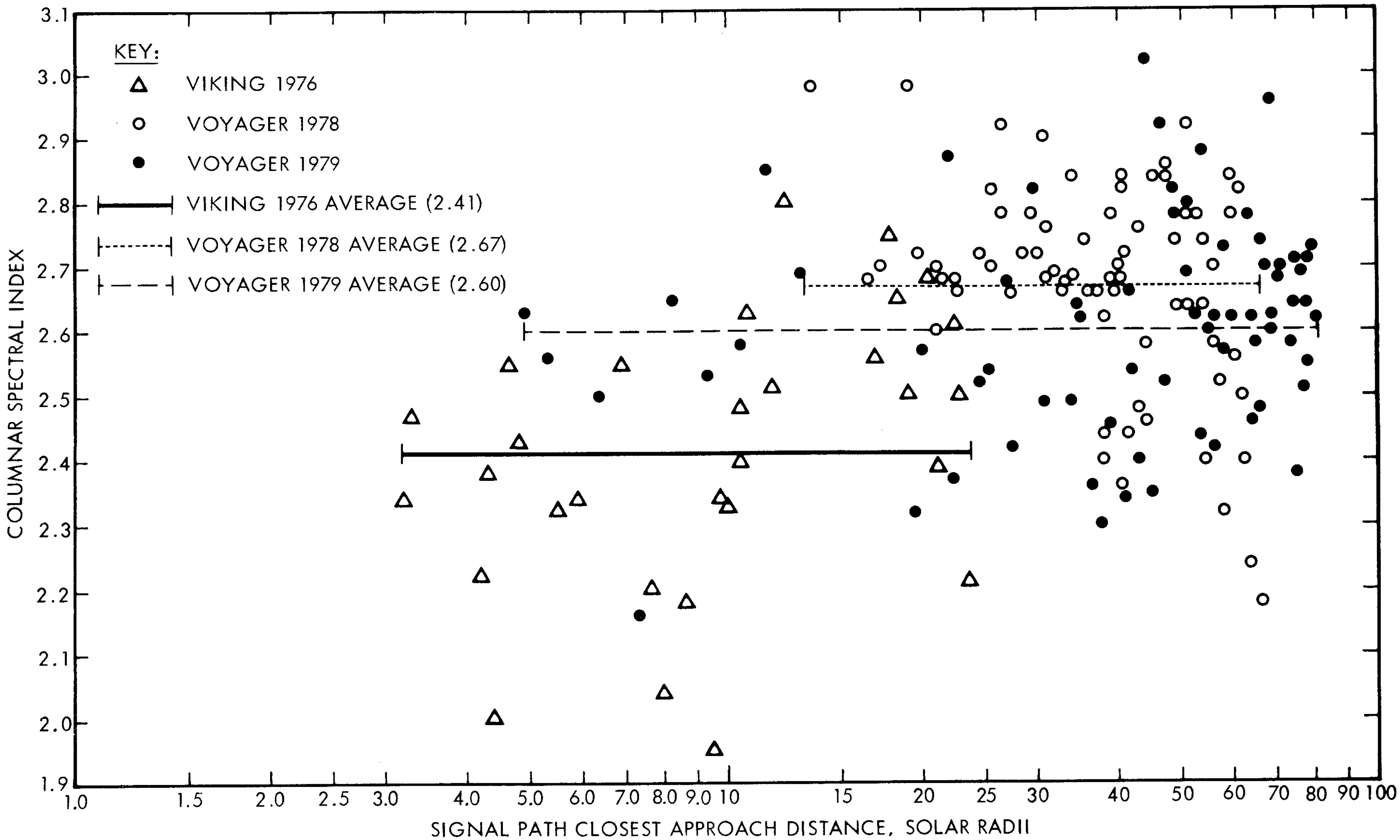

Fig. 5. Columnar solar wind phase fluctuation spectral index versus signal path closest approach distance

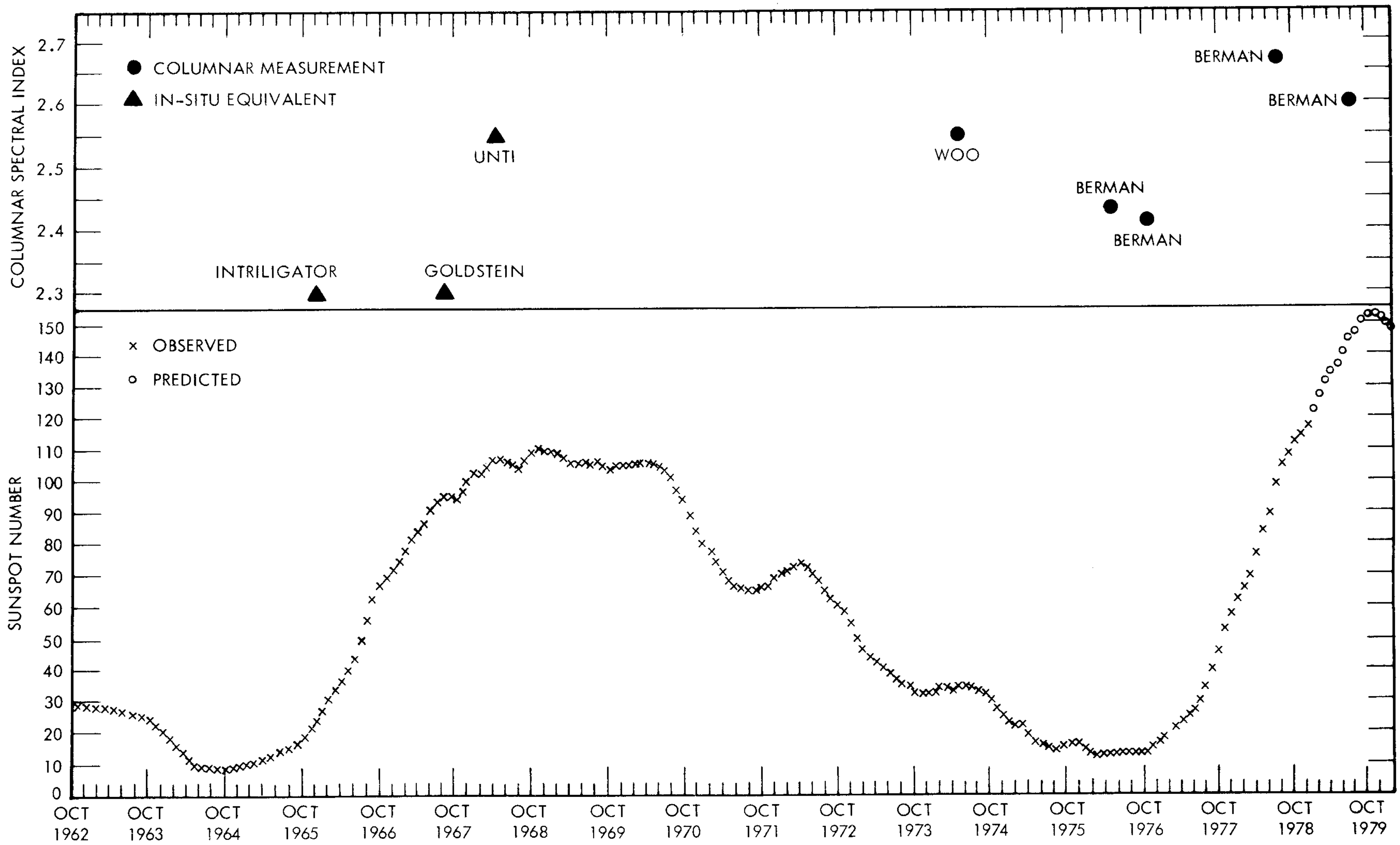

Fig. 6. Columnar solar wind phase fluctuation spectral index versus solar (sunspot) cycle