REDUCTION AND ANALYSIS OF TWO SETS OF ELECTRON CONTENT MEASUREMENTS PERMITTING THE INFERENCE OF ELECTRON DENSITY IN THE SOLAR WIND

by

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Abstract

A large body of data has been acquired from five sun-orbiting spacecraft and from four earth satellites in geostationary orbits. By radio propagation means we have obtained measurements of the electron content from earth to each of these craft, at various times in various sequences spread continuously over the past 5.3 years. Through processing and analysis it is possible to infer the electron content of the solar wind along the radio path above the orbit of the geostationary craft, effectively removing the influence of the earth's ionosphere and magnetosphere from the derived result. Dividing the interplanetary content by the spacecraft distance yields the average free electron number density of the solar wind along the radio path.

The density thus observed is of great potential scientific value, both in the study of short unusual events and in the derivation of long-term statistical properties of the wind. For the latter purpose, it is important to obtain a body of "clean" data and, in the case of these data, the primary source of contamination can be traced back through the processes and attributed to inaccuracy in our estimation of the ionospheric electron content along the line of sight to the deep space probes. We have devised methods to improve these estimations and have trained personnel and written computer programs which implement the known processes. The running of the programs and the associated manual and mental processing was still under way at the conclusion of this project, as further data is still being obtained from deep space.

We have derived some solar wind statistics by inexpensive interim processes which are relatively inaccurate, and we can see trends. Clearly we will only derive the full scientific benefit of these data when the data processing and analysis are completed.

It is shown herein that the specific processing and analysis are having a direct payoff in scientific terms. Two statistical measurements are shown in their present form and it can be seen that cleaner data will permit the derivation of trends indicating, among other things:

1. The variation of solar wind density with respect to the 11-year solar cycle.

2. The variation of density as a function of distance from the sun, which now appears to differ from the $1/r^2$ variation predicted by the most simplified theory.

3. The variation of density with sector structure, which has been measured during times of the quiet sun but not during the active period of our investigations.

Introduction

On Pioneers 6, 7, 8, and 9 and on Mariner 5, we have placed similar dual-frequency receivers designed to provide measures of the solar wind density. Because of the availability of many spacecraft, it has been possible to obtain these data almost daily since December 1965. To perform measurements, phase-modulated signals at 49.8 and 423.3 MHz are transmitted from a 150 foot paraboloid antenna located near Stanford and beamed toward the selected spacecraft. There the spacecraft receiver and its associated processors measure the relative phase delay and group delay of the signals for subsequent telemetry back to earth. The delay differences are interpreted as a measure of the columnar content of electrons along the line of sight and thus solar wind structural details are revealed.

A portion of the measured content is attributable to electrons in the earth's ionosphere and magnetosphere. The sum of these two contents is referred to here as "ionospheric content". This has been monitored continuously by measuring the Faraday rotation of the polarization plane of the signal from various geostationary earth satellites. Additionally, in 1966, sparse data points were derived from observations of the passage of orbiting Ionosphere Beacon satellites. A large proportion of the data processing effort will be devoted to the use of these observations to deduce the most likely ionospheric content versus time along the line of sight to the sun-orbiting spacecraft, continuously during all hours of operation. After the ionospheric portion of the content is subtracted, the remaining interplanetary content may be divided by spacecraft distance to yield the spatial average of free electron number density along the radio path in the solar wind.

These data are by themselves useful as an indicator of the solar wind density and morphology. However, a linear column content is inherently ambiguous in the sense that one cannot determine how the density varies along the path. Consequently, these data are most useful when combined with other indicators, particularly with measures of density and other wind characteristics flown on the same and on other spacecraft. Therefore, we conduct liaison with other spacecraft experimenters, with the objective of enhancing the utility of both their data and our dual-frequency data through cooperative analysis.

Spatial Coverage of the Data

All participating spacecraft have been near the ecliptic plane, staying within 0.3 A.U. of the earth's orbit. Most of this region has been explored by the experiment, largely by virtue of the fact that the prime derived measurement is a spatial average of the density along the entire path from earth to each spacecraft. Figure 1 shows the trajectories of the five probes; note that Pioneer 9 recently passed behind the sun and, as a consequence, we obtained measurements along the line of sight which goes much nearer the sun than any man-made hardware has ever reached. (When this path was about 23 solar radii from the sun, the experiment was rendered inoperative by the effects of scintillation attributed to the outer corona.) The region within 1/2 A.U. of the earth has been under relatively constant surveillance since early 1966. The earlier spacecraft, Mariner 5 and Pioneers 6 and 7, were not capable of locking onto our radio signals beyond about 0.7 to 1 A.U., but Pioneers 8 and 9 can work all the way around their trajectories to the farthest points beyond the sun.

Although not shown on the figure, Pioneer 6 has nearly completed its first circuit of the sun and is once again within operating range; at the time of this writing it is roughly at the location of the "8" in the "Pioneer 8" label on Fig. 1, headed toward the earth. It works well despite its relatively old age of 5.2 years. Consequently there will be three paths under surveillance until mid-1972, those from earth to Pioneers 6, 8 and 9.

Time Periods Covered by Data

The on-board spacecraft data storage capability was not often used for gathering this "cruise" data, and so the measurements have been taken only when there was simultaneous transmission from Stanford and reception

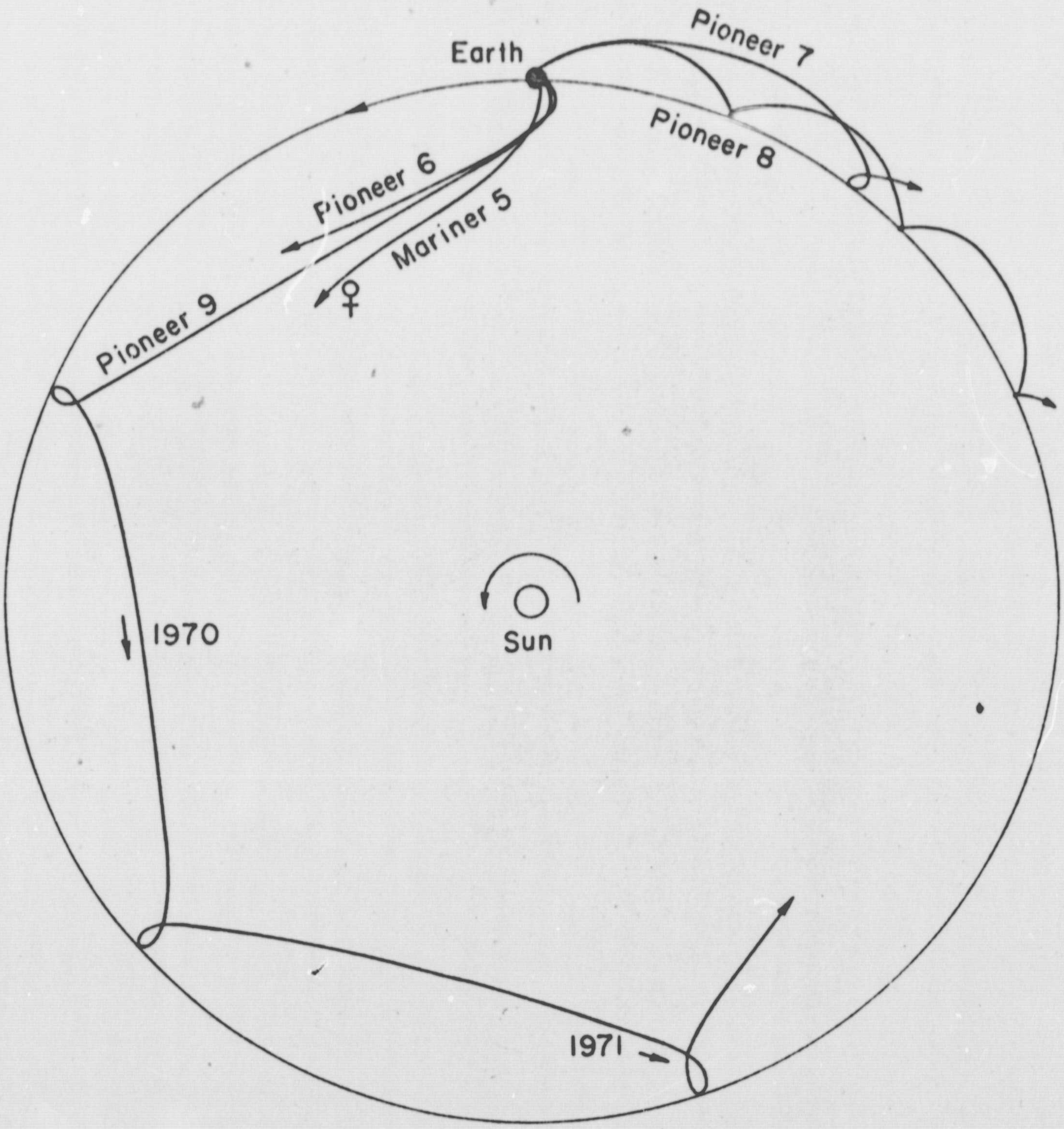

Earth
Pioneer 7
Pioneer 8
Pioneer 6
Mariner 5
♀
Pioneer 9
1970
Sun
1971

Figure 1

by some station in the Deep Space Network. The content is measured along the Stanford line of sight and is unaffected by the content along the line of sight from the spacecraft to the earthbound telemetry receivers.

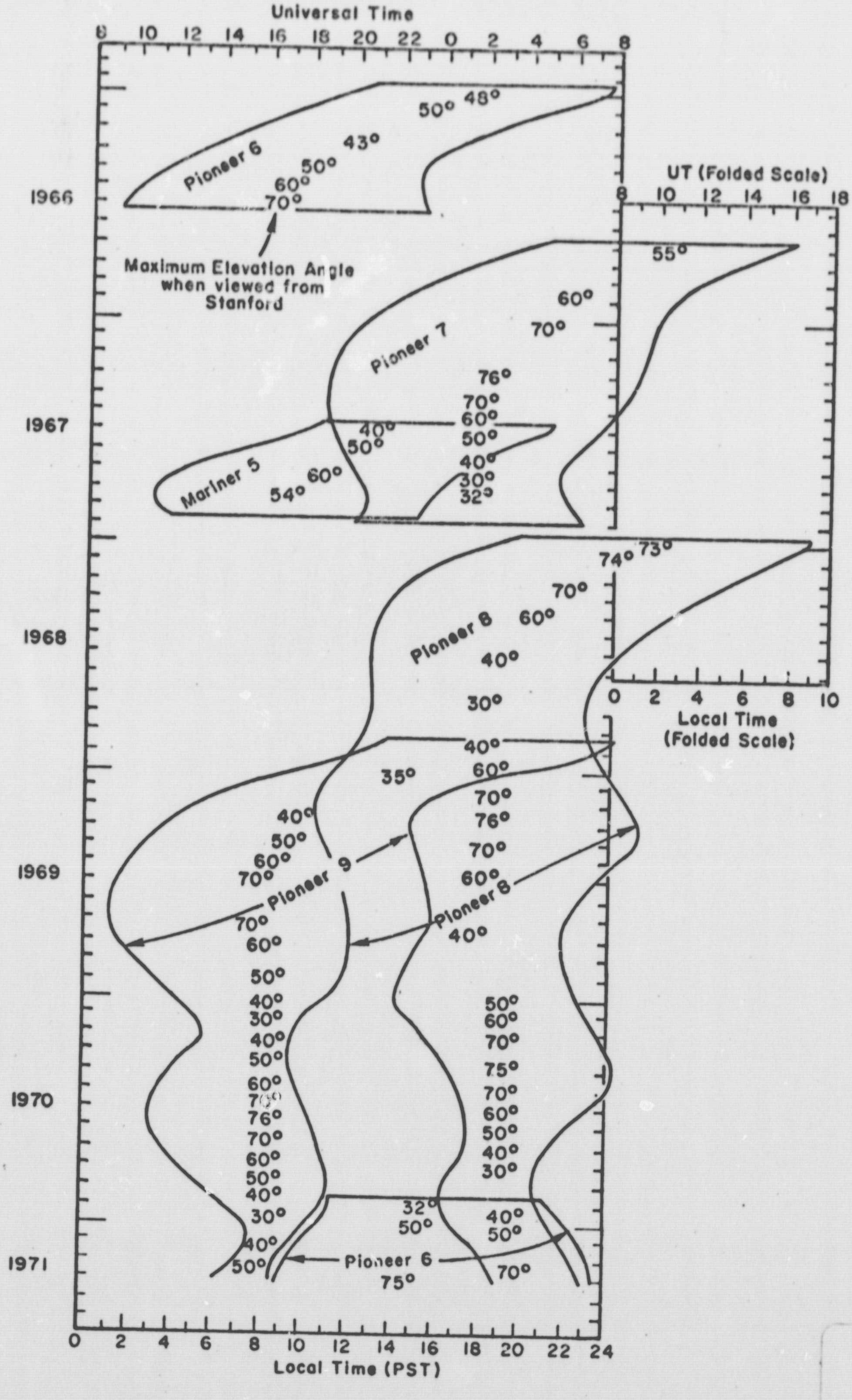
The times and places of interest have been summarized in Fig. 2. Each spacecraft is near the plane of the ecliptic, so that each follows a path in the sky (as seen from the Stanford transmitter) which is much like that of the sun, but at a different apparent "season" and "time of day". The time interval from spacecraft rise till set varies from about 10 to 14 hours per day, for exactly the same reason as does the length of the day vary with the season.

Data are not available for all the time periods drawn on Fig. 2 since the receivers or transmitters have often been inactive due to conflicting schedules or to budgetary limitations. Nevertheless, the data available do provide a good sampling of all the indicated areas of the figure.

Figure 3 shows the relation of these data to the current solar cycle. It can be seen that the data provide good indications of the solar wind behavior when the sun is active and that the change from quiet to active and back toward quiet has been continuously monitored. However, the quiet solar wind has not yet been observed by this technique since the sunspot number has been above 40 during all but a brief portion of the Pioneer 6 observations. (The earliest 3 months' data are difficult to interpret because of error incurred in subtracting the ionospheric content from the measured total. This is a particularly severe problem in relation to Pioneer 6 because the ionospheric content monitoring was comparatively crude in 1966.)

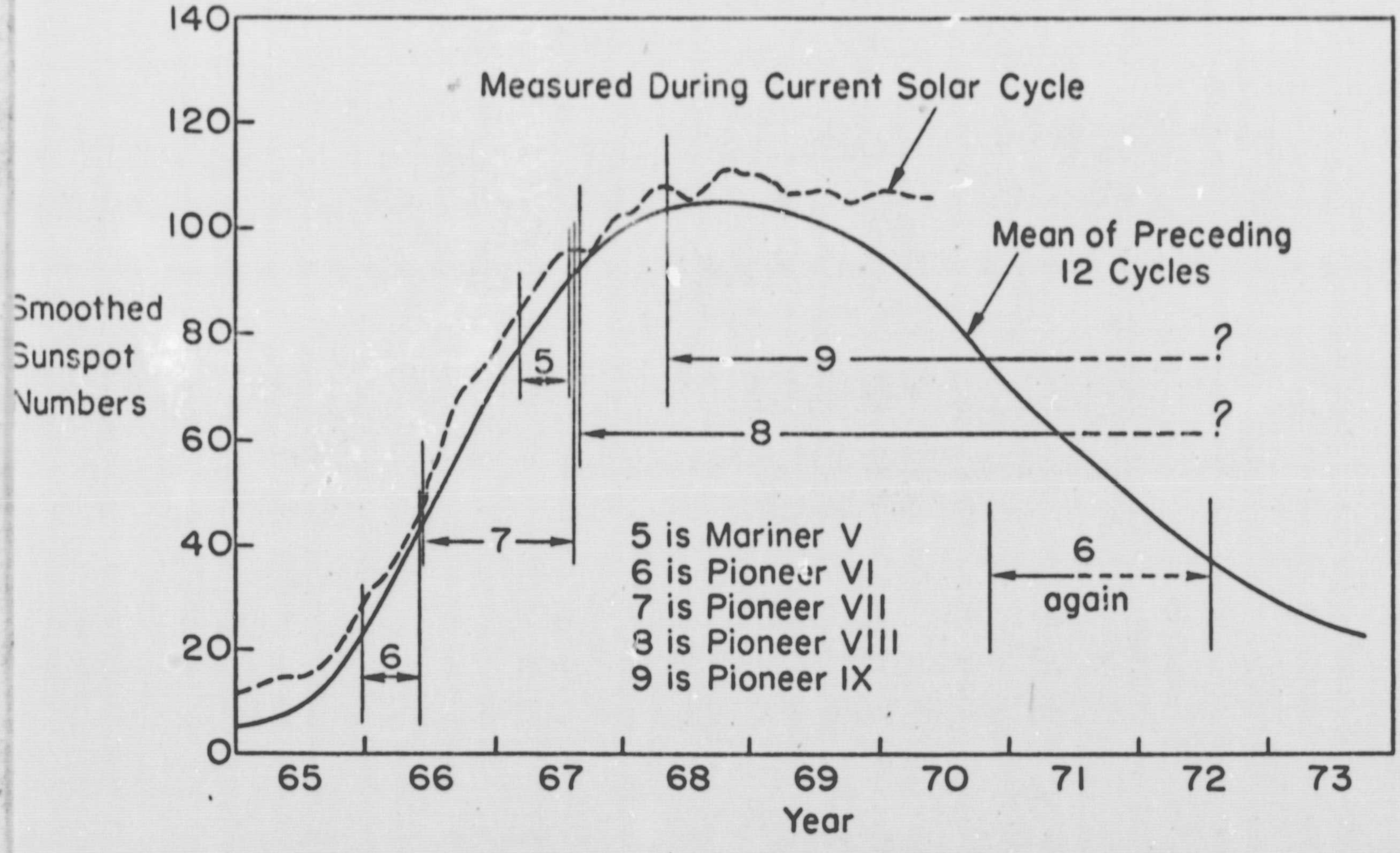
Specific Events vs Statistics of All Measures

With data of this type, two different types of study are feasible: (1) examination of isolated, unusual events, and (2) derivation of the statistics of the ensemble. In practice, the statistical results are the most difficult to extract because they are typically the end result



Universal Time
8 10 12 14 16 18 20 22 0 2 4 6 8
UT (Folded Scale)
8 10 12 14 16 18
Pioneer 6
Pioneer 7
Mariner 5
Pioneer 8
Pioneer 9
Maximum Elevation Angle when viewed from Stanford
1966
1967
1968
1969
1970
1971
0 2 4 6 8 10
Local Time (Folded Scale)
0 2 4 6 8 10 12 14 16 18 20 22 24
Local Time (PST)

Figure 2



Measured During Current Solar Cycle
Mean of Preceding 12 Cycles
Smoothed Sunspot Numbers
140
120
100
80
60
40
20
0
65
66
67
68
69
70
71
72
73
Year
5
6
7
8
9
6 again
?
5 is Mariner V
6 is Pioneer VI
7 is Pioneer VII
8 is Pioneer VIII
9 is Pioneer IX

Figure 3

of a complex data reduction process which must be carried out with all the data. The logistic task of reaching this end is at the limit of the capability of the personnel, since the group has been assembled for just this purpose and thus is not overequipped. In contrast, the study of isolated events is easy, once the events have been identified as "unusual". The duration of each event is typically less than a day, so the data can be processed in short order.

At the present time, budgetary limitations make it impractical for us to carry out our reduction processing with the ensemble because, if we did this work, there would be insufficient funds remaining for us to analyze the isolated events: The output of the experiment would then cease. This is a trap easily fallen into; many past experiments have foundered in the data reduction stage, and if we devoted our available resources to processing, then it seems likely that this experiment might similarly founder. There are many aspects of the observational data which can be studied in isolated events, and some gross statistics of the ensemble are being derived from data processing by comparatively inexpensive interim processes. Nevertheless it is clear that many statistical measures can only be extracted from the ensemble after completion of the processing which is now curtailed.

The Ionospheric Portion of Content

In a sense, the operation of this experiment is much like the operation of a very large optical telescope: that is, we are able to resolve smaller detail than that exhibited by the measurable data. The limit on angular resolution of optical telescopes is imposed by intervening atmospheric turbulence. The limit on our ability to resolve detail in the solar wind content is imposed by the intervening ionosphere which has a content comparable to the wind and which is in a constant state of change. The Pioneer/Mariner measurement is unavoidably the sum of the ionospheric plus the interplanetary contents, and it is necessary to obtain an independent measure of the ionospheric portion so that it may be subtracted to yield the desired difference. There are imperfections in the acquired ionospheric data and in the processes used to derive the correct value for subtraction, so that the difference contains "noise" which masks detail; thus, there is loss of resolving power.

In order to obtain ionospheric content, we have made much use of the signals from Syncom and from three Applied Technology Satellites (ATS), observing the rotation of the plane of polarization which is roughly proportional to the electron content along the line of sight. Several ground stations have been used, in order to sample the ionosphere over a wide geographic area. Conventional techniques are being used to convert this Faraday rotation into ionospheric electron content and improved techniques are under study. Newly devised methods are used to translate this value to the line of sight to the Pioneer or Mariner spacecraft in use. It has been found that these techniques work fairly well when both lines of sight are at elevation angles higher than about fifteen degrees from the horizontal. However, more subtle analysis and conversion techniques are apparently needed when low angles of observation occur. This need can be identified because of the evidence of a diurnal component remaining in the data after subtraction of the ionosphere. There should be no diurnal variation in a true measure of the interplanetary content alone. When the spacecraft are within roughly 0.5 A.U. and are at elevation angles which are near the horizontal as seen from Stanford, the ionospheric component of the total content is so large that the derived interplanetary component becomes marginally accurate. Of course this source of error is inherently additive, so that the percentage degradation depends on the magnitude of the interplanetary content. When the spacecraft are new and still near the earth, the length of each line of sight is so short that the interplanetary content is at times only a few percent of the measured total.

Computer-Assisted Extraction of the Columnar Content from Telemetered Data

While the dual-frequency data provide a measure of the columnar electron content, there are nevertheless 3 sources of difficulty which arise in any effort to extract a simple "content vs time" tabulation from the telemetered data returning from the sun orbiters. These 3 features of the data will be illustrated by example, and the optimum solution to the difficulties will be described.

There is actually no problem in overcoming these barriers if one wishes to deal with only a small portion of the data, since manual techniques have already been found to work well (with some computer assistance). The problem arises when we contemplate the task of deriving the single-valued function of content versus time for the entire body of data covering over 5 years. The manual process would then be impractically cumbersome.

The three main sources of difficulty are:

1. The fine structural detail of the content is contained in the phase path measurement, for which we have only a discontinuous and sometimes faulty measure of the derivative. This is an unavoidable disadvantage of such a phase path measure, which is actually derived from a precise comparison of the two radio frequencies arriving at the spacecraft.

2. The content magnitude is determined from the group path measurement, in which our spacecraft instrument response curve is discontinuous and subject to variability as the signal level varies. It has not been possible to remove all these vagaries by computer, and some human intervention and checking is needed before final tabular results can be trusted.

3. Nonlinearities occur, principally in the earth's ionosphere. They cause the phase and group path measures to lose their simple proportional relation to the electron content.

An example which shows all 3 of these features of the data is given on Fig. 4 which consists of two plots of the same data at successive stages of data processing. For this example we have selected an extreme case of group path difficulty. This example is the first day of operation of Mariner V, and it was rendered especially difficult because the

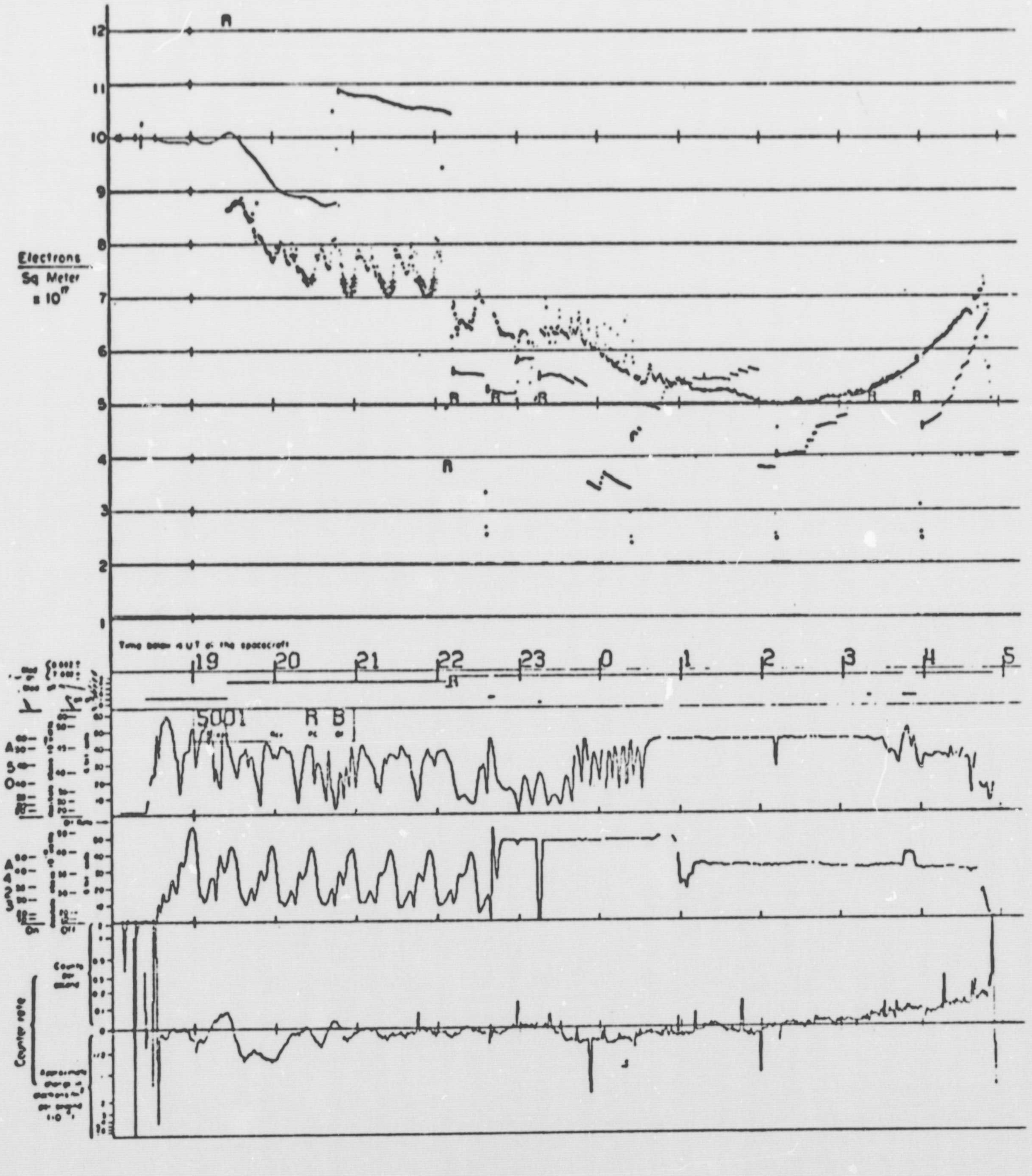
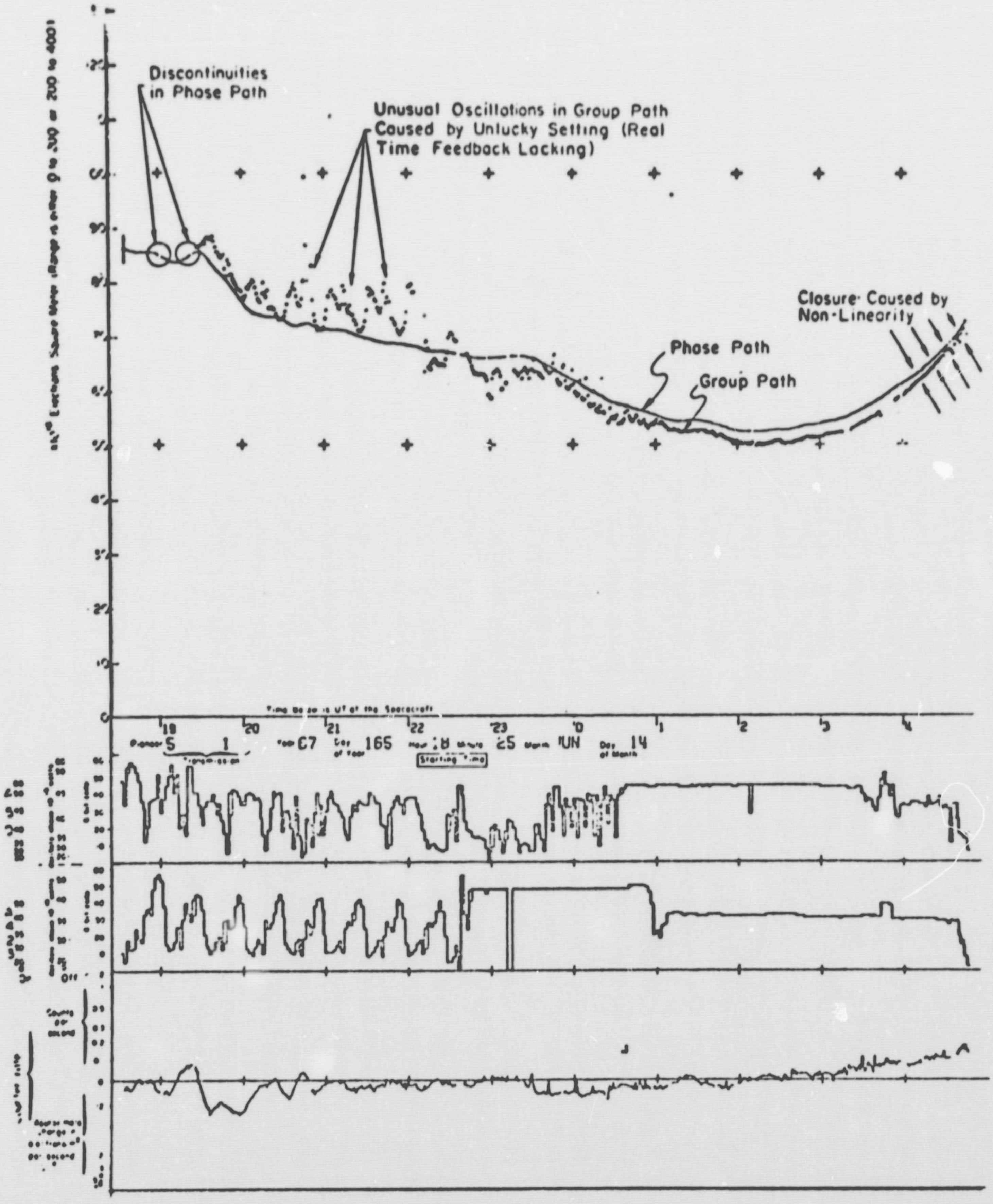

Electrons
Sq Meter
x 10^17
Time below 4 UT at the spacecraft
Counter rate

Figure 4(a)



Discontinuities
in Phase Path
Unusual Oscillations in Group Path
Caused by Unlucky Setting (Real
Time Feedback Locking)
Closure Caused by
Non-Linearity
Phase Path
Group Path

Figure 4(b)

real-time teletype link to our transmitter was inoperable in the first hours of the mission so that it was necessary to run "blind". This means that the transmitter personnel could not monitor the total content in real time, as is usually done, and so they could not adjust the modulation phase in the usual manner which places the signal at the spacecraft in an optimum condition for group path measurement. Consequently the transmitter personnel had to guess, and they had the worst possible luck! The group path measure oscillated up and down from about 19:30 till midnight as can be seen by the oscillation of the dotted curve on Fig. 4a. The oscillation is readily explained if one examines the instrument response as a function of both modulation phase and signal strength. The situation can be avoided when real-time data are available (as is usual) and even in this worst case the correct content can be inferred after appropriate consideration.

The intermittent nature of the phase path measurement is illustrated by the discontinuous line segments on Fig. 4a. These discontinuities disappear when the derivative is optimally integrated, as has been done in Fig. 4b. As long as the gaps in these data are short, one can interpolate across the gaps without accumulating much error. In this example the gaps are very short, but when signals are weaker late in the mission, the receiver readily unlocks and the gaps tend to be longer. Furthermore, the phase path data tend to contain errors which are difficult to identify when the signal is weak. This is usually caused by the fact that we are counting the occurrence of wavefront arrivals at the two transmitted frequencies, and sometimes the spacecraft counter goes out of lock. There is no foolproof way to eliminate all the out-of-lock data by computer, but a human can delete most of it by inspection of the plots. This is tedious work, however. A few such bad points are shown on the bottom "rate plot" of Fig. 4a, and they have been manually removed in Fig. 4b.

Finally, the nonlinear effect shows up toward the end of the day at about 04:00. This is seen as a closure of the two curves on Fig. 4b. If delay were linearly related to electron content, then both curves would be proportional to the content and the two curves would be coincident except for constant vertical displacement attributable to the unknown constant of integration. It can be seen on the figure that the group and phase curves could be thus matched from 01:00 (when the group oscillations cease) only until 04:00. Thereafter, the nonlinearity changes the relative shape of the curves, decreasing the apparent content of the phase path measure and increasing the content of the group path measure. The best measure of content would be derived by translating the phase path down to produce a best fit between 01:00 and 04:00.

The 3 kinds of difficulty mentioned relative to Fig. 4 are manifested to some extent on each day's data. Usually, the nonlinearity is worse than that illustrated, but the group path is better. The phase path plots often have large gaps, and then each segment of each phase path curve must be manually positioned for a best fit within the array of group path data points. This has been done with small amounts of data but has not been accomplished with all of the 5 years' observations. The bad rate points are most frequent on the Mariner data where they are attributed to telemetry errors; there was not as much parity redundancy built into the Mariner telemetry as there was in the Pioneer system. In Pioneer, such bad points are less frequent and are almost all attributable to the dual-frequency counter going into and out of lock, producing data which just barely pass through the logical self-consistency tests which have been built into our major computer data reduction program.

The solution to these problems demands participation by a trained person--the indications of erroneous data are too subtle (and often unexpected) to be built into a computer program. Therefore we use the "displayer" program which incorporates an optimal integration of the phase path rate. The operator fits the resulting curve to the group path. We have added features which permit the operator to make corrections or deletions to compensate for the 3 areas of difficulty cited above. This task consists mainly of the deletion of the bad rate points, fitting by observation of the group path and understanding its significance, and the directed location of the optimum content curve at times when the nonlinearity appears.

Results of Studies of Isolated Events

Generally, analyses of these data have fallen into one of two classes: studies of the nature of specific plasma events, and inference from trends in long-term data.

An example of a specific plasma event study has recently been completed by J. A. Landt and T. A. Croft using the data from Pioneer 6. Just when that spacecraft was at the limit of our operational range (106 million km for that particular craft), there occurred one of the largest and best-documented solar events, on July 9, 1966. The disturbance in the solar wind on this and on neighboring days has been the subject of many scientific papers, and was even the subject of a special symposium which resulted in a special issue (volume 3) of the Annals of the IQSY.

When we first reduced our data, it appeared that the SNR was inadequate to permit us to deduce the content on that day. However, a later, more refined data reduction process revealed hints of the existence of a pulse in the plasma stream so large that its appearance had misled the earlier investigator into believing that the rapid changes in the data were a manifestation of noise. Still later, careful manual data analysis has shown an extremely large plasma pulse, and this content integral was used, together with local solar wind density measurements of other investigators, to determine the shape of the plasma cloud passing through our radio path. A paper has been published on the work (Journal of Geophysical Research, Sept. 1, 1970). This new data reduction technique subsequently served a valuable operational purpose during the solar occultation of Pioneer 9.

We see plasma pulses quite often (once a week, more or less, depending on how one defines a "pulse") and can learn much about the sun from trends in the occurrence and shape of these disturbances. We are in liaison with other investigators who have local density measurements from space, hoping to glean pulse structural information from a comparison of the line integral and spot densities, velocities, etc. Mr. Landt is working on his doctoral dissertation in this area.

The statistics of pulses will shed light, for example, on the hypothesis of Ballif and Jones (JGR, July 1969) that Forbush decreases and geomagnetic storms are actually caused by interplanetary streams rather than by individual solar flares. Each of our pulses is caused by passage through the line of sight of a stream such as Ballif and Jones discuss or of a shell ejected by a flare. From morphology studies and from studies of the coincidence with storms and Forbush decreases, we should derive a good data base for testing this hypothesis.

Interim Data Processing to Recover Ensemble Properties

Because of limited funds, we have devised a number of inexpensive methods for continuing the study of the long-term properties of the interplanetary medium. Generally these fall into a single class; we examine the reduced group delay data and then obtain samples at some low rate. The stress has been on Pioneers 8 and 9 since their data are "cleaner". The differences among the three methods in use stem primarily from their different sampling rate.

The lowest sampling rate is about 1/day, comprised of one interplanetary content value hand-selected from the real-time plots produced by the transmitter operating crew. This particular data form is useful as a gross aid in spotting major trends in the solar wind; the increasing density as Pioneer 9 approaches occultation is the most obvious trend in these data; relative noisiness among spacecraft and 27-day repetition effects are also clear. There is some hint in the last few months before occultation that the solar wind may spread as, say $R^{-1.9}$ rather than as R^{-2} but a better measure of this possibility has been derived from hourly data (described next) and it clearly points to the need for full data processing if the true exponent (or other functional relationship) is to be derived from these data.

The next more detailed body of data has also been obtained from manual inspection of the group path plots produced in real time by the transmitter crew. Hourly points have been selected in such a manner that linear interpolation between the points will most closely match the indicated content-time curve. Furthermore, some obvious ionospheric effects have been removed by appropriate corrections to these hourly points. Six pages of such data are plotted on Fig. 5. For six solar rotations following 20 October 1968, there was a paucity of data due to the launch of Pioneer 9 and the preferential coverage of that spacecraft by the tracking network. Until it became quite distant (.4 A.U.), we could not achieve reasonable accuracy in this interim data form because the error in the ionospheric determination was so large relative to the interplanetary content. When we can afford to complete the processing of these data, we should rescue one or more rotations' measurements from this gap in time. As an interim measure, we simply ignore periods like this when spacecraft are near the earth.

One of the goals of our future efforts will be the recovery of these data which are effectively "lost" at the present time. The object of the planned processing and analysis is the production of clean data points for each minute. All statistical inferences drawn from these data should be much less contaminated by error if the data base is of the high quality that we wish to produce.

There are a number of visible defects in Fig. 5 and a few examples will be pointed out: (a) Consistent daily trends in Pioneer 9 in April 1969 are surely ionospheric, as are similar trends in Pioneer 8 for September 1970. Other similar errors abound but these cited examples are readily seen because they persist from day to day. (b) Rapid fluctuations are not well resolved, and yet trends at the beginning and end of each short data string are needed to deduce what happened in the gaps. See mid-May 1969 and late January 1970 for examples. (c) Data strings which endure for only an hour or so are poorly represented by only one or two points; the trends would be useful if they could be more adequately resolved. Some days' runs are represented by a single point which provides no indication of trends during these short runs. A careful study of the 1968 data led to the judgment that the trends are a useful guide to interpolation across data gaps, even when data strings are quite short.

These defects have led us to search for a means of achieving higher time resolution (more points than one per hour) at low cost and to this end we have begun to generate "Group Only" (GO) cards, the third interim

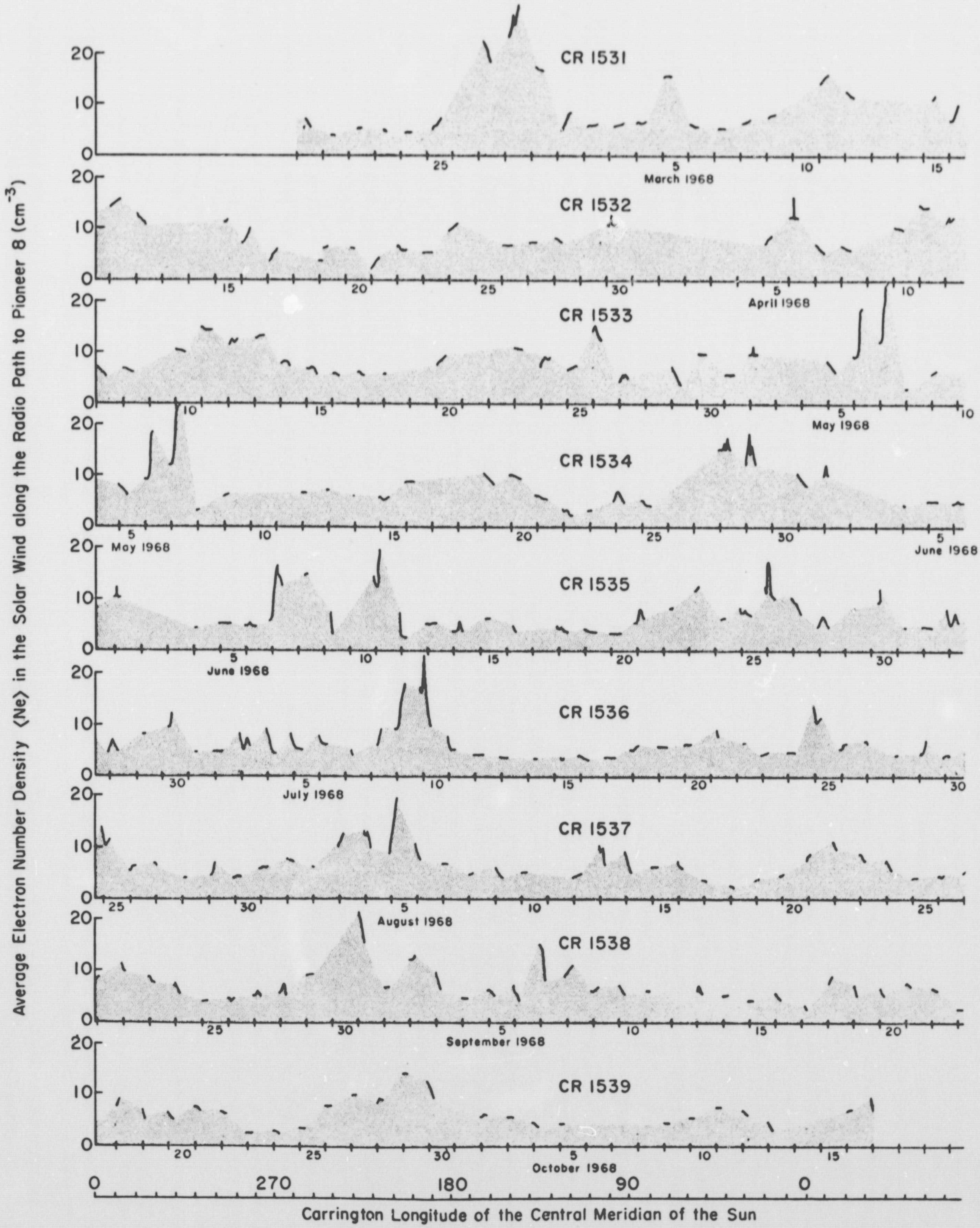

Average Electron Number Density ⟨Ne⟩ in the Solar Wind along the Radio Path to Pioneer 8 (cm^-3)
CR 1531
March 1968
CR 1532
April 1968
CR 1533
May 1968
CR 1534
May 1968
June 1968
CR 1535
June 1968
CR 1536
July 1968
CR 1537
August 1968
CR 1538
September 1968
CR 1539
October 1968
0 270 180 90 0
Carrington Longitude of the Central Meridian of the Sun

Figure 5(a)

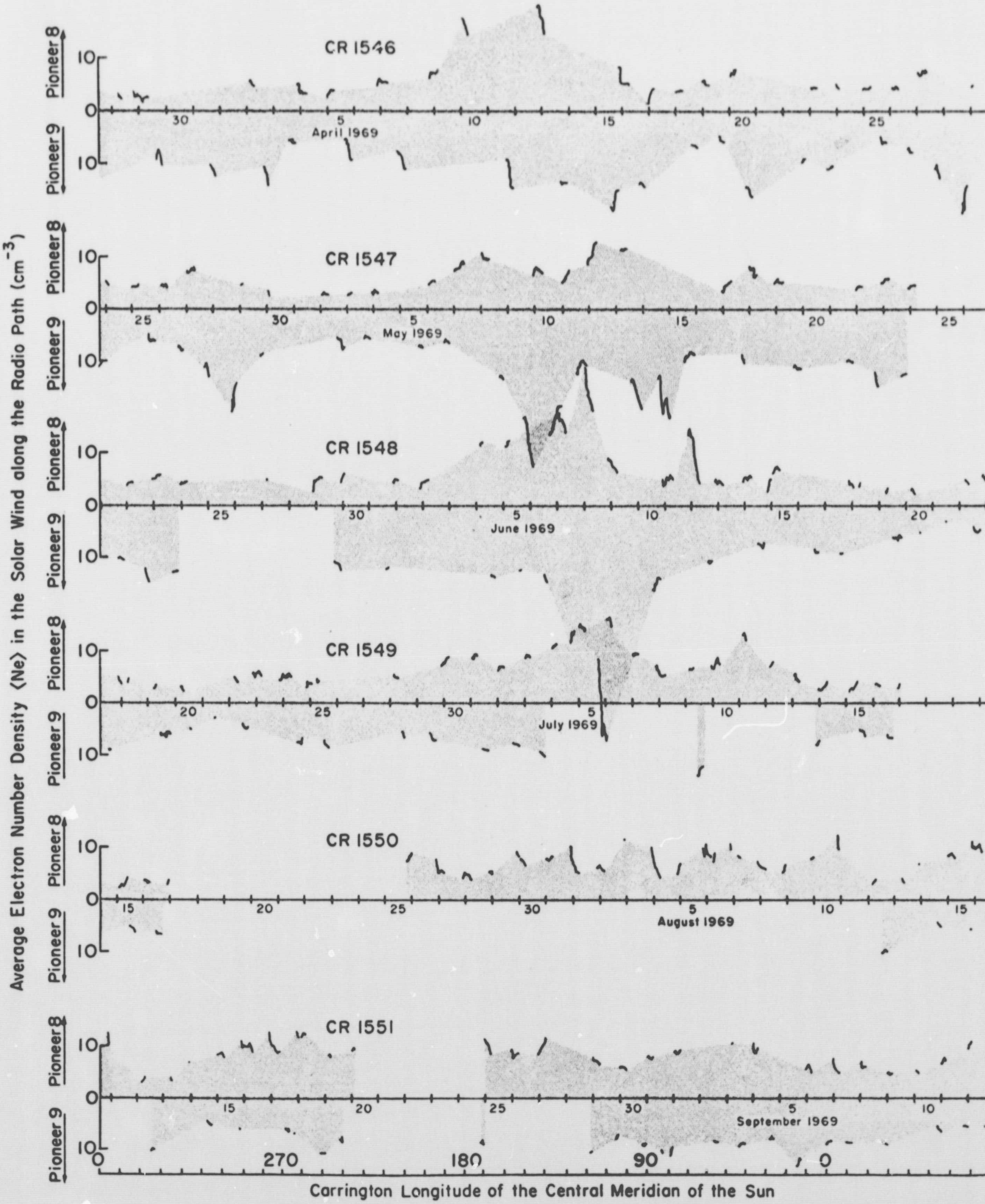
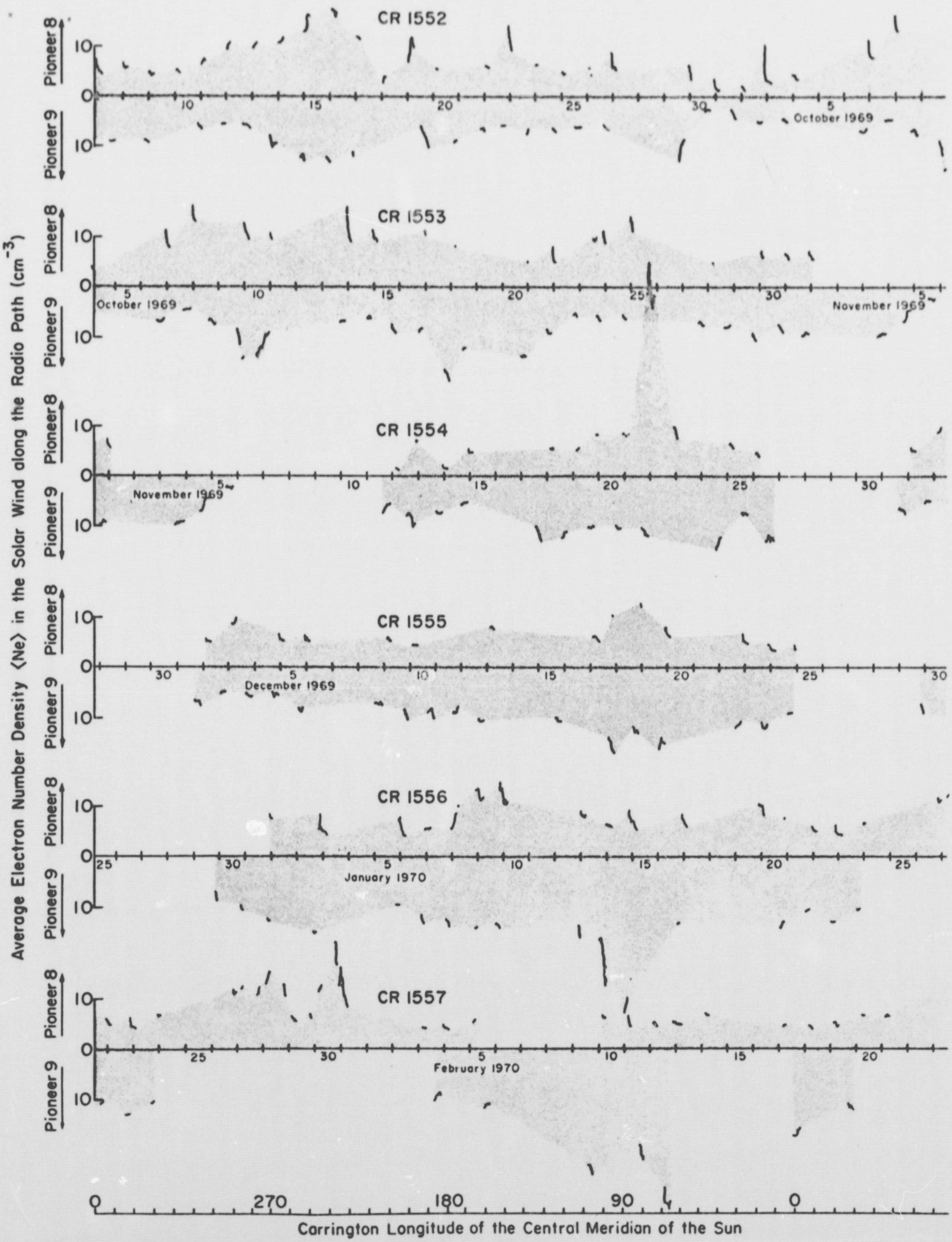

Average Electron Number Density ⟨Ne⟩ in the Solar Wind along the Radio Path (cm^{-3})
CR 1546
April 1969
CR 1547
May 1969
CR 1548
June 1969
CR 1549
July 1969
CR 1550
August 1969
CR 1551
September 1969
Pioneer 8
Pioneer 9
270
180
90
0
Carrington Longitude of the Central Meridian of the Sun

Figure 5(b)



Average Electron Number Density ⟨Ne⟩ in the Solar Wind along the Radio Path (cm^{-3})
CR 1552
October 1969
CR 1553
October 1969
November 1969
CR 1554
November 1969
CR 1555
December 1969
CR 1556
January 1970
CR 1557
February 1970
Pioneer 8
Pioneer 9
0
270
180
90
0
Carrington Longitude of the Central Meridian of the Sun

Figure 5(c)

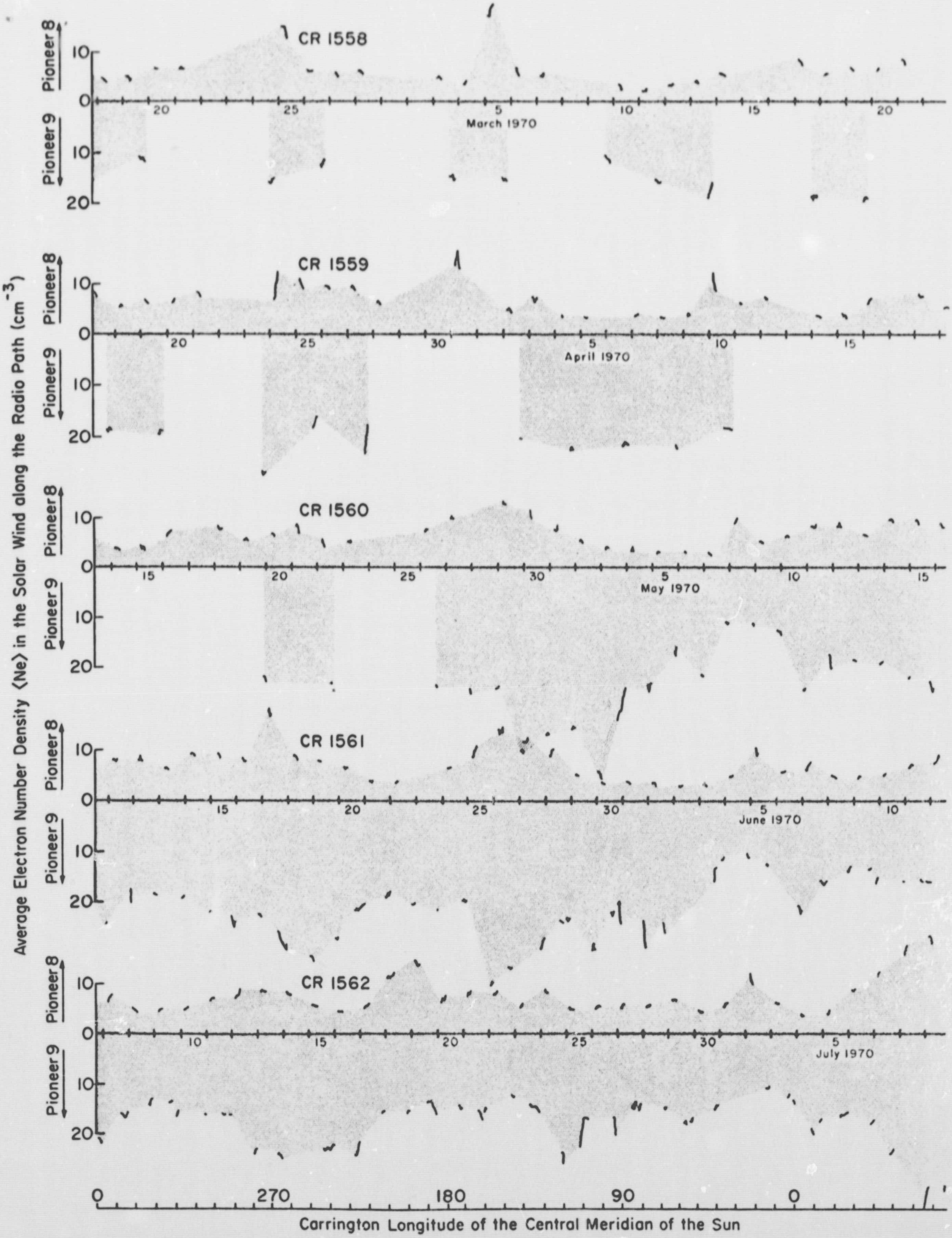
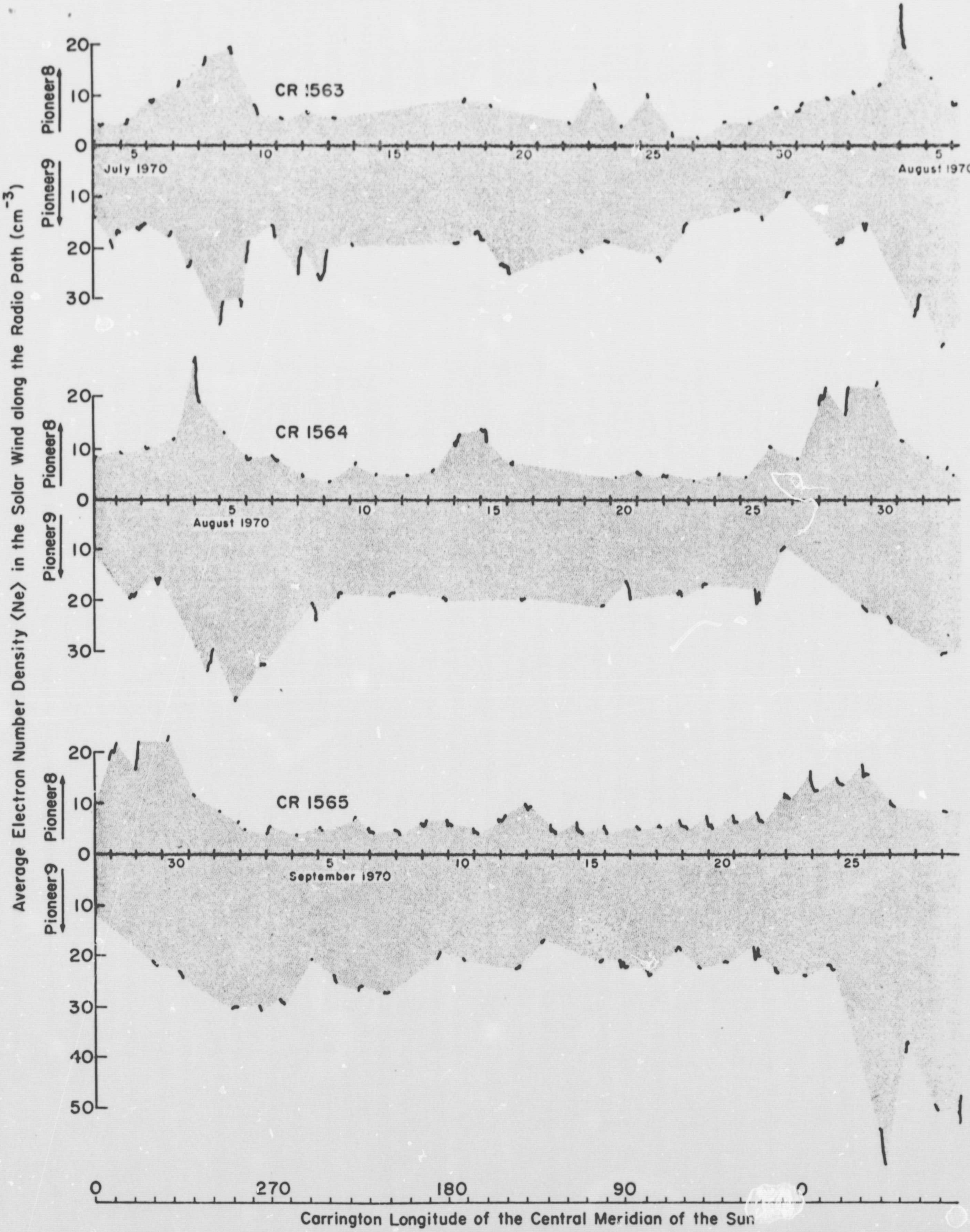

Average Electron Number Density ⟨Ne⟩ in the Solar Wind along the Radio Path (cm^{-3})
Pioneer 8
Pioneer 9
CR 1558
March 1970
CR 1559
April 1970
CR 1560
May 1970
CR 1561
June 1970
CR 1562
July 1970
Carrington Longitude of the Central Meridian of the Sun

Figure 5(c)



Average Electron Number Density ⟨Ne⟩ in the Solar Wind along the Radio Path (cm⁻³)
CR 1563
Pioneer 8
Pioneer 9
July 1970
August 1970
CR 1564
August 1970
CR 1565
September 1970
0
270
180
90
0
Carrington Longitude of the Central Meridian of the Sun

Figure 5(e)

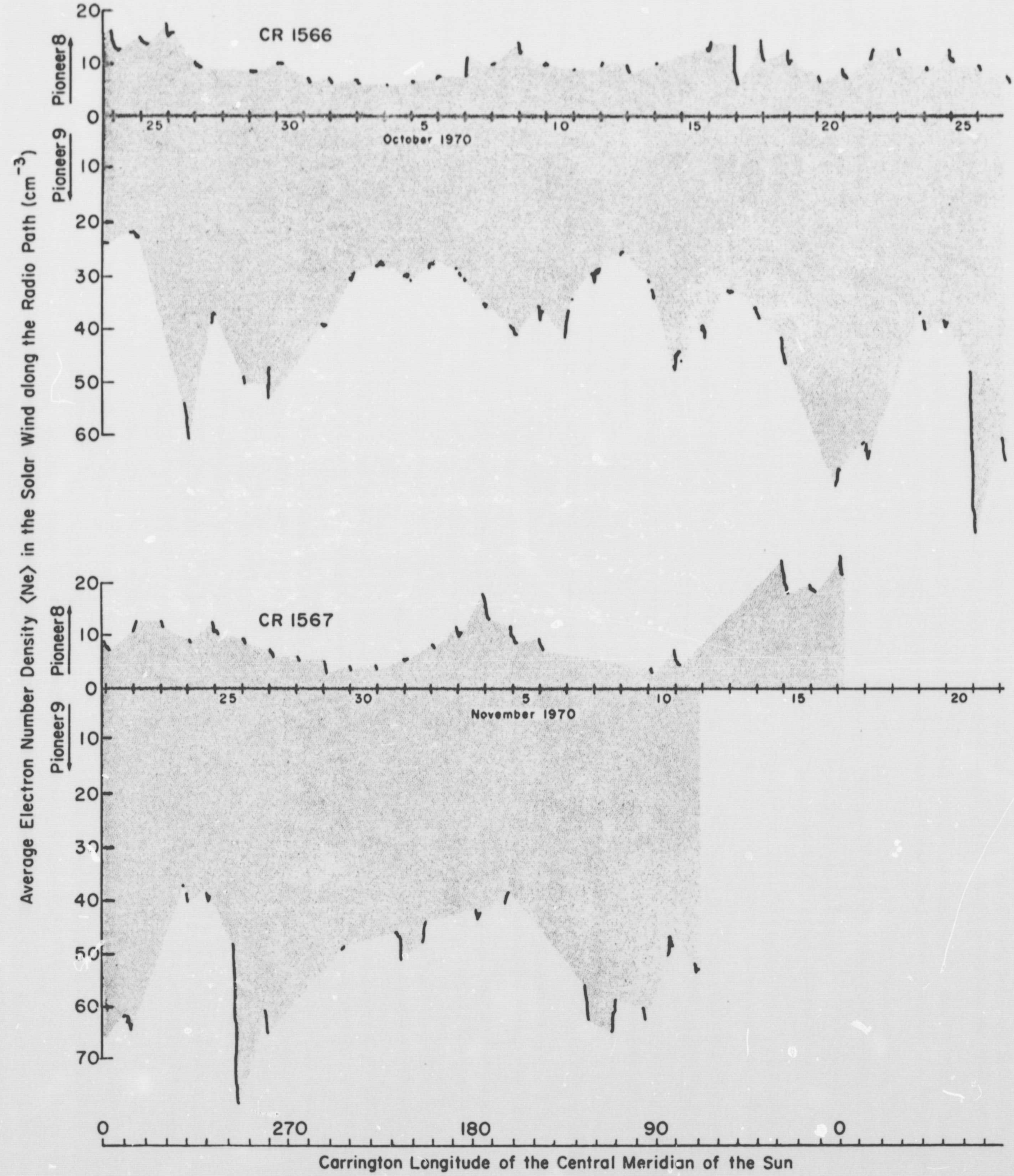

CR 1566
Pioneer 8
Pioneer 9
October 1970
CR 1567
November 1970
Average Electron Number Density ⟨Ne⟩ in the Solar Wind along the Radio Path (cm^{-3})
0
270
180
90
0
Carrington Longitude of the Central Meridian of the Sun

Figure 5(f)

data form. By computer, we average the group path measurement for each four minutes and subtract the ionosphere to produce an interplanetary content value once each 4 minutes. Fifteen such points fit onto one card (one hour's data) and thus one can store approximately a year's data in a single box of cards. This not only eases the logistic cost and effort but reduces the cost of computation too. The GO cards suffer primarily from the continued presence of ionospheric errors because of lack of analysis. Also, the group delay suffers from nonlinearity in the ionosphere to a greater degree than does the phase delay. Finally, the GO cards are somewhat inferior to the hourly points due to the absence of human intervention which permitted recognition and rejection of obvious errors in the hourly data. Nevertheless the high-rate trends are more fully represented by GO cards.

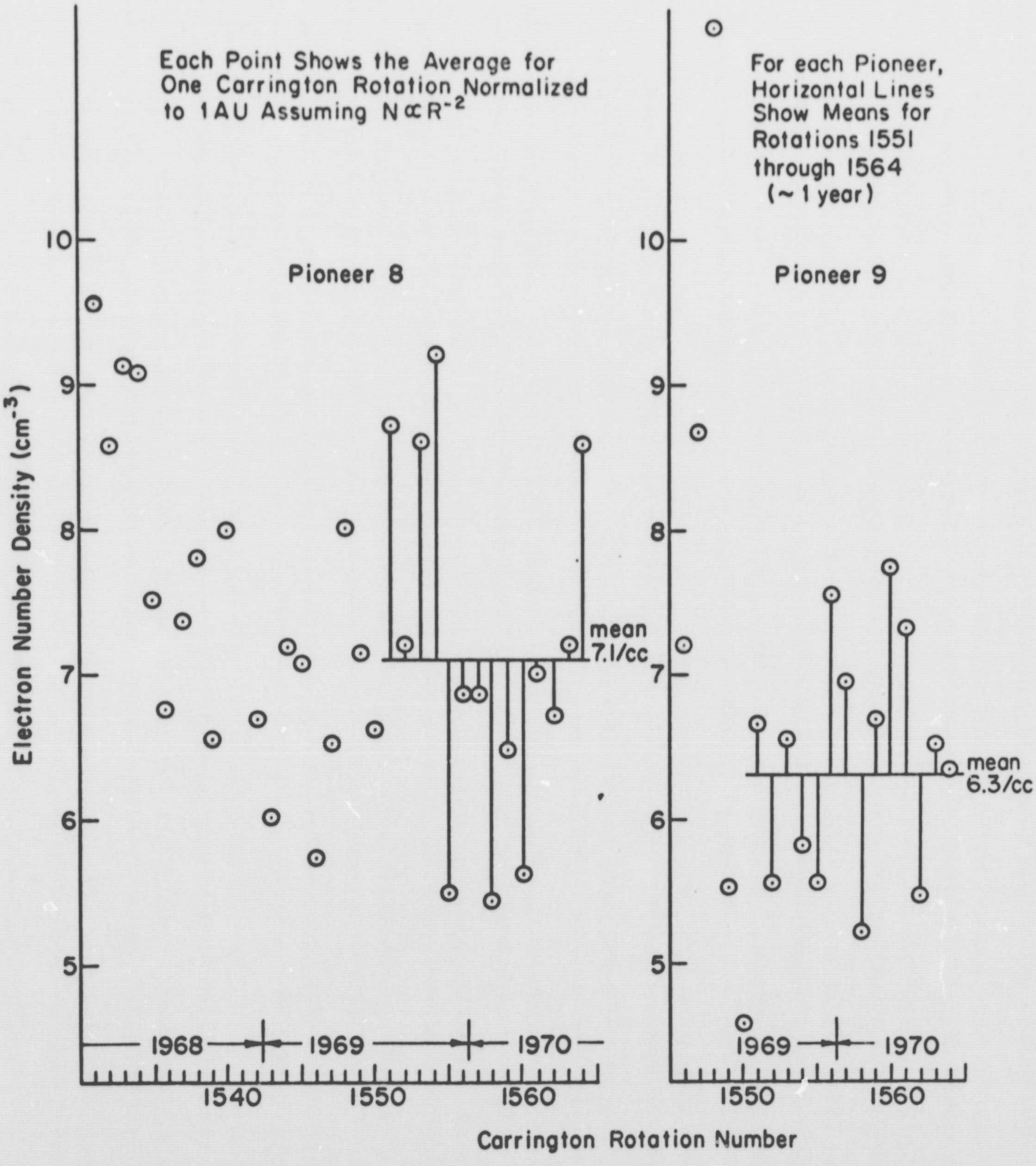
As described above, three interim data forms are serving as a basis for study of long term trends. The full processing is currently reserved for a few days of special interest, because of fund limitations. Next we will describe results derived and results expected, pointing out from time to time those aspects of the studies where the faults inherent in these interim forms are serving to limit the use of the data or to prevent its use altogether.

Applications of These Observations

The stress in this section is on examples of physical reasoning which are based upon the measurements illustrating why it is important that we resume the processing of the data. Only a few examples are given, selected largely on the basis of their adaptability to representation in a short description or in a single figure. We have studied many other, different aspects of our data not described here and we consistently find that a primary limitation is the lack of full analysis of the past data. In particular, the ionospheric error causes artificial systematic trends that are difficult to work with.

Using the hourly density points we have averaged over complete solar rotations to minimize the effect of density variations due to corotating structures which are so apparent in Fig. 5. This concept of averaging deserves some comment, since it is a temporal average of a spatial average and is thus doubly averaged. Such a process is needed if we are to study the mean density of the solar wind because the density is so variable that a single point measurement is of little use as a guide to the mean. Even the time average of measurements taken at a point in space would not be as good as these data. For example, if our radio path is taken to a Pioneer that is at 1 A.U. from both the earth and from the sun (so that the earth-sun-spacecraft triangle is equilateral), then the measurement that we take at any moment is averaged much as if it had been derived from point density averaged for over 4 days. Therefore, when we take the time average of our spatial average, we have a near optimum representation of the mean. We believe that most of the "noise" left in such data is attributable to the fact that we have not cleaned up our data through adequate analysis.

A series of 1-rotation averages are plotted in Fig. 6 for two spacecraft over the last 2.5 years during the period of declining solar activity. Notice that there appears to be a decline in the averaged averages from a value of perhaps 8/cm^3 down to a present value of roughly 7/cm^3. This trend is weak, however, because the variance is significant relative to this variation in the mean. When we do this same plot using fully analyzed data, it should be possible to discern the way in which the mean varies with solar activity. Similarly notice the 1-year averages shown by horizontal lines. The Pioneer 9 value is 0.8 electrons/cm^3 less than the Pioneer 8 value in the same year. Since the Pioneer 9 path was much closer to the sun during this period, we suspect that perhaps the density falls off less rapidly than $1/R^2$ and in fact our preliminary analysis indicates that an exponent of 1.9 would roughly equalize these means. Physically this may be an indication that, over the long run, the solar wind slows down as it recedes from the sun or, alternatively, there is some trend for the wind to converge away from pure radial



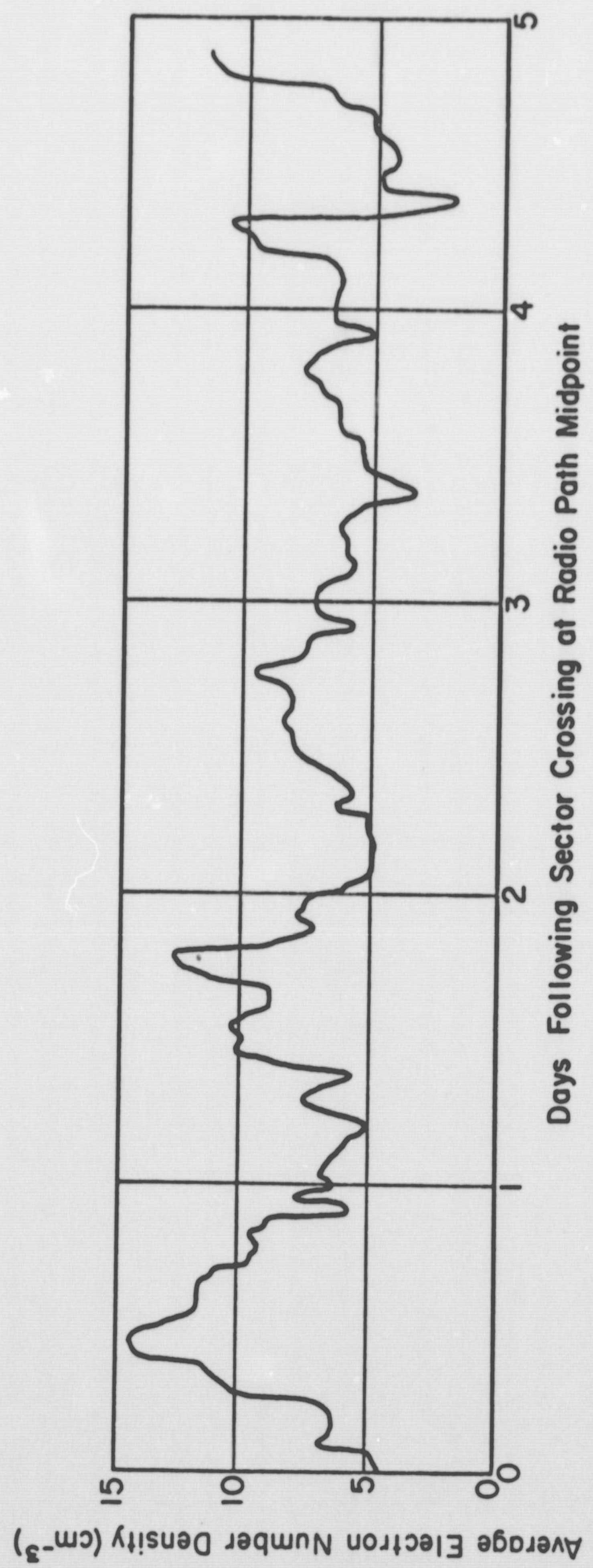
Each Point Shows the Average for
One Carrington Rotation Normalized
to 1AU Assuming N ∝ R⁻²
For each Pioneer,
Horizontal Lines
Show Means for
Rotations 1551
through 1564
(~1 year)
Pioneer 8
Pioneer 9
Electron Number Density (cm⁻³)
10
9
8
7
6
5
mean
7.1/cc
mean
6.3/cc
1968
1969
1970
1540
1550
1560
Carrington Rotation Number

Figure 6

flow in the direction of the solar equator. If we clean up these data through better analysis such as we hope to conduct, we may be able to determine the functional relation between density and heliocentric distance and thus discriminate between various hypotheses as to the cause of these differing means. Until we can reduce the variance, however, it is clear that the difference between 6.3 and 7.1/cm^3 is not a convincing indication of a trend.

Numerous investigators, notably J. M. Wilcox, have found trends for greater activity in the solar wind just after passage of a sector boundary. Through private communication with Wilcox we are attempting to find correlations between wind density and sector structure; one aspect of our work in progress is shown in Fig. 7 which shows a superposed epoch analysis of the type which has become conventional in this work. There is, indeed, seen to be an increase in density following the sector crossing and, in other similar data not included here, we have found that the insertion of random timing errors will destroy the correlation. Thus we suspect that the high peak seen 0.5 day after the sector crossing is a positive sign of the suspected relationship. However, we cannot claim to provide a useful measurement of the size of this effect because we are using unanalyzed data which are clearly inadequate. Notice that the density actually undergoes a 24-hour oscillation with subsidiary peaks at about 1.5 and 2.5 days. This is not reasonable since no known solar wind phenomenon exhibits a 24-hour period; the ionosphere does, though, and so it is thought that these large variations in the derived averages on Fig. 7 are caused by erroneous estimation of the ionospheric component which has been subtracted from the Pioneer-measured total content prior to this superposed epoch analysis. Thus we see another scientific application of the data hindered by the incomplete processing.

It would be interesting to run auto- and cross-correlation studies of our data to determine the period of revolution of the solar wind over a time of several years. Similar studies by Wilcox (and also, at Stanford, by Professor R. N. Bracewell) have shown that the 10th or 20th harmonic of the 27-day period seems to settle to a single value regardless

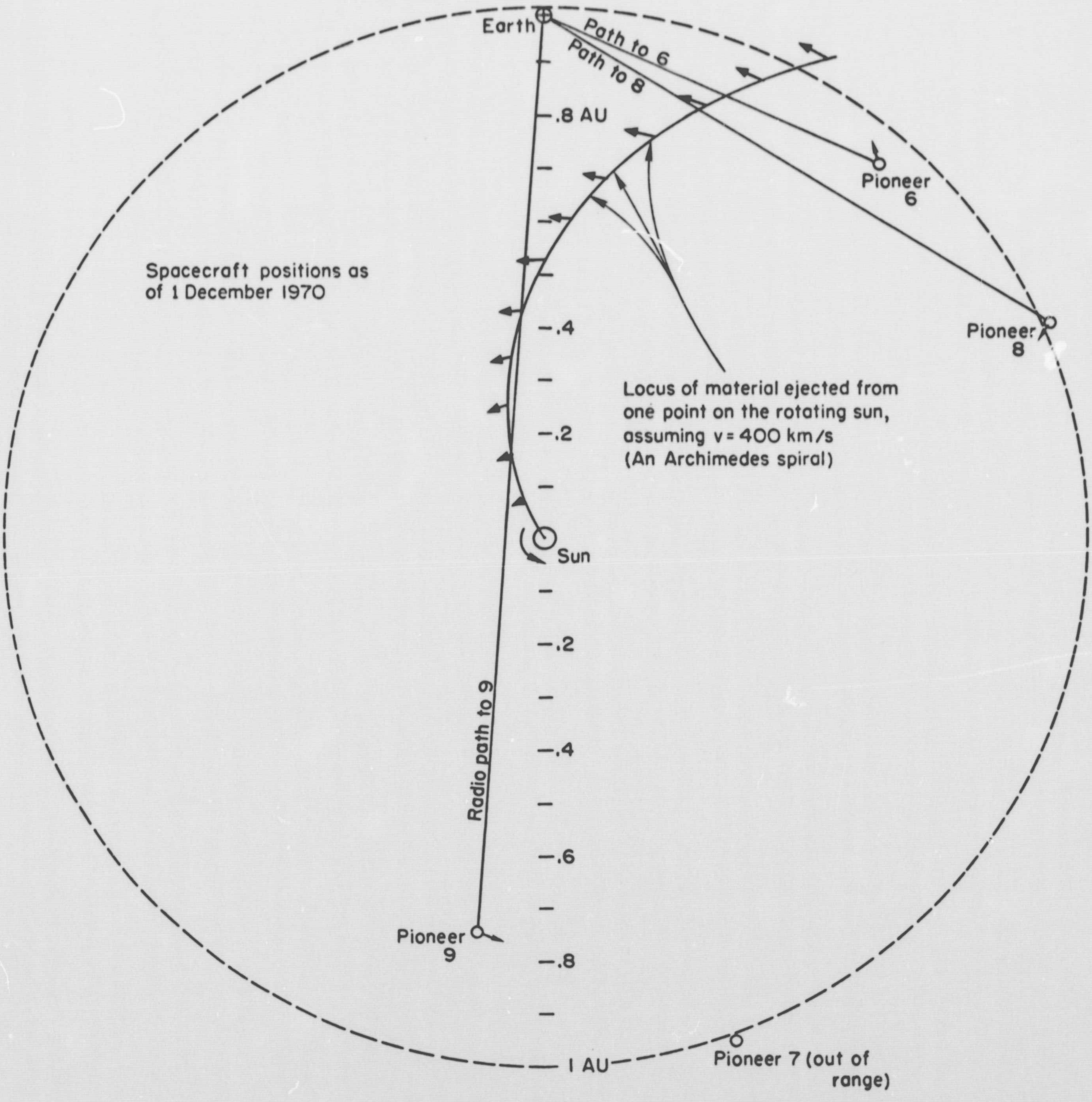


Days Following Sector Crossing at Radio Path Midpoint
0
1
2
3
4
5
Average Electron Number Density (cm^{-3})
0
5
10
15

Figure 7

of how one chooses to select the data. Shorter-term observations show variations as, for example, Wilcox's data show differential rotation when the data are selected from different solar latitudes. These unexpected trends are thought to indicate the presence of an underlying solar structure that rotates as a rigid body at the rate indicated by the high harmonics. Discontinuities deep within the sun may then convect upward from the rigid core and in the process acquire different statistics in their character over the short term. So far the only data which we have in the needed quantity are the hourly data. There is seen in this data much evidence of corotating patterns but there is such large error that, so far, we have not felt that the required correlation calculations were sufficiently likely to produce results that we could risk spending the funds to do the computations. If the data were fully processed, however, it would clearly be worthwhile to run the correlation calculations.

Because our measurement is a spatial average, it is possible to determine whether the larger content fluctuations in our observations are caused by spatial or temporal variations in the solar wind. In practice the judgment cannot always be made, partly because of contaminating ionospheric error, partly because of the intermittent nature of our measurement, and partly because some variations can be attributed to either cause with equal credibility. In the cases where we can determine the flow patterns, however, it appears that our data offer unique evidence of the gross overall flow patterns of the wind. This kind of reasoning has been described by Croft (Radio Science, January 1971) and will only briefly be summarized here. Consider Fig. 8 which shows the positions of the three operating Pioneers in late 1970, together with an Archimedes spiral of a steady flow at 400 km/s. If we hypothesize that there is a steady source of plasma on the sun ejecting a narrow stream, then the flow pattern would appear to be the spiral revolving at a 27-day rate. Its effect on our measurement would be proportional to the product of the stream density and the distance along our path within the stream. Imagining such a rotating spiral, one can see that the stream would enter the path to Pioneers 6 or 8 and cause the content to increase, staying high for the time required for the spiral to reach



Earth
Path to 6
Path to 8
.8 AU
Pioneer 6
Spacecraft positions as of 1 December 1970
Pioneer 8
−.4
Locus of material ejected from one point on the rotating sun, assuming v = 400 km/s (An Archimedes spiral)
−.2
Sun
−.2
Radio path to 9
−.4
−.6
Pioneer 9
−.8
1 AU
Pioneer 7 (out of range)

Figure 8

the earth. This increase would be relatively uneventful; careful calculations show that the content would start high and then gradually and steadily diminish to a lower value as the stream approaches earth. However, with Pioneer 9 the situation is qualitatively different; the first encounter of the stream is broadside so that the length of the path in the stream is initially very large. After a short period the enclosed path length decreases rapidly until the stream encounters the earth. After that, the content stays low for many days while the stream rotates around to hit Pioneer 9. Consequently we would find the density to be very impulsive for Pioneer 9, but less so for Pioneers 6 and 8. This conclusion would not follow if one assumed instead that the predominant flow pattern is outwardly expanding spherical clouds of increased plasma density. Neither would it follow if one assumed that irregular shapeless "blobs" of plasma are the dominant travelling forms. From such arguments, quantified, we can deduce the general flow patterns. This effort, too, will be much more fruitful after the basic data are finally analyzed.

Other potential work of scientific value could be cited, but it can be seen from the above examples that much remains to be gained from a continuation of analysis of the existing data and from continued reduction of raw data from the Pioneers.

Submission of Data to the NSSDC Data Bank

We have provided to the NSSDC a complete history of all the Pioneer results (for Pioneers 6, 7, 8 and 9) up to date in December 1968 and we provided two complete revisions up to date in February 1969 and in September 1969. These include hourly samples of the total content measured over the duration of the flights of all Pioneer spacecraft while they are in range of our transmitter. These data provide NSSDC users with a good picture of the events in space, together with a comprehensive summary of the times and places where further data are available.

In November 1970, we prepared a revised version of these data which contain the latest runs from Pioneers 8 and 9. We have set up a system with the data bank whereby these revisions can be easily accommodated, since it is expected that new data will be continually arriving for some time to come, and since we expect to make gradual small improvements in our interpretation of the older data.

The November 1970 submission to the bank was much more fully processed than the earlier content data; we had subtracted the ionospheric portion of the measurement, and then divided the interplanetary content by the earth-spacecraft distance to yield average path density. It was felt that bank users would probably not have accurate spacecraft trajectories readily available, so in addition we normalized all average densities to 1 A.U., assuming for the purpose that the wind spreads as $1/R^2$. Thus the user of the data bank can discern the significance of our data even if he only has a rough idea of the spacecraft locations at various past times.

Summation

Analysis of these data advances man's knowledge in four broad areas:

1. It leads to a better understanding of the sun, through insight into the outflow of solar plasma and the relationship of flow characteristics to other solar features observed either via spacecraft or from earthbound observations.

2. Since the solar wind is the medium through which the sun affects the earth in diverse ways, analysis of these data will lead to more knowledge of the action mechanisms. Similarly, these studies will better our understanding of how the wind affects the other bodies in the solar system.

3. It is already apparent that solar wind observations have given a great impetus to plasma physics studies, since the wind serves in effect as an excellent "laboratory" wherein phenomena occur that could hardly be reproduced in any man-made laboratory. In this indirect manner solar wind studies benefit many realms of astronomy and other areas of application

of plasma physics knowledge, some of which show promise of being of great practical value to man (e.g., fusion).

4. The decrease of group velocity and the increase of phase velocity through the action of free electrons in the solar wind provide the mechanism through which we make these measurements. They also affect S and X radio signals in the same manner and we have measured wind fluctuations that would seriously degrade spacecraft tracking accuracy. Insight gleaned from these data will provide (and are providing) impetus to implement systems and procedures for tracking outer-planet probes that will alleviate this problem. Such efforts can be optimized only if we understand the character of the actual propagation medium, and our data are the best in existence for the study of this problem.

Publications List

Publication	Pioneers 6	7	8	9
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Howard, H. T., Koehler, R. L., Interplanetary Electron Concentration and Variability Measurements with Pioneer VI and VII, URSI, Spring Meeting, Commission V, Ottawa, Canada, May 22-25, 1967.	X	X		
Merritt, R. P., Baron, M. J., Ionospheric Integrated Electron Content for Use with Pioneer Interplanetary Spacecraft, URSI, Spring Meeting, Commission III, Ottawa, Canada, May 22-25, 1967.	X	X		
Howard, H. T., Koehler, R. L., Interplanetary Electron Concentration and Variability Measurements with Pioneer VI and VII, Zodiacal Light in the Interplanetary Medium Conference, January 30-February 2, 1967, Honolulu, Hawaii	X	X		
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Lusignan, B. B., Density Measurement with Radio Wave Occultation Techniques, COSPAR (Communications on Space Research), Tokyo, 9-21 May 1968.		X		
Eshleman, V. R., Bistatic Radar Astronomy, American Astronomical Society, vol. 24, 1969.	X	X	X	X
Croft, T. A., Corotating regions in the solar wind, evident in number density measured by a radio-propagation technique, Radio Science, January 1971.			X	X
Landt, J. A., T. A. Croft, Shape of a solar-wind disturbance on 9 July 1966 inferred from radio signal delay to Pioneer 6, JGR, 73, 25, September 1970.	X			
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Croft, T. A., Evidence of Temporal Fluctuation in the Solar Wind, AGU, San Francisco, 7-10 December 1970.			X	X
Pomalaza-Diaz, J.C., Measurement of the Lunar Ionosphere by Occultation of the Pioneer VII Spacecraft, SU-SEL-67-095, 1967.		X		

	6	7	8	9
Koehler, R. L., A Phase Locked Dual Channel, Spacecraft Receiver for Phase and Group Path Measurements, SU-SEL-67-007, February 1965	X	X	X	X

Figure Captions

Page

5 Fig. 1 Paths of five spacecraft carrying the special dual frequency receiver, projected onto the ecliptic plane and shown in the frame that rotates with the earth.

7 Fig. 2 Times available for measurement, when the spacecraft are in range and above our horizon.

8 Fig. 3 Relationship of the spacecraft data intervals to the current solar cycle. (Sunspot numbers were obtained from the NOAA Solar-Geophysical Data, volume 317, number 1.)

12 Fig.4a A "compressor plot" showing all available data points for pass 1 of Mariner V. (Plot produced by a computer program which subsequently "compresses" the data into a compact, convenient form.) Top: Electron content vs. time, in which the dots are derived from group path measurement and the line segments are derived from integration of the phase path rate measurement. Middle: Modulation history and A50, A423 which are the amplitudes of the 2 frequencies as measured at the spacecraft. Bottom: The phase path rate, i.e., the slope of the line segments shown in the top portion of the figure.

13 Fig.4b A display of the compressed data after partial manual processing. Notice that many erroneous spikes in the rate have been removed.

19 Fig.5a Average density of the solar wind along the line from earth to Pioneer 8. Short line segments show average interplanetary electron number density along the path to Pioneer 8. To obtain this, the ionospheric content was subtracted from the measured total content and the remaining interplanetary content was divided by the distance from earth to the spacecraft. Shading between line segments is provided to aid visual pattern perception. One point per hour is plotted.

20 Fig.5b On this and the succeeding 4 pages is shown density averaged concurrently along two paths in the solar wind: The density from earth to Pioneer 8 is plotted upward, and the density from earth to Pioneer 9 is plotted downward.

21 Fig.5c

22 Fig.5d

23 Fig.5e

24 Fig.5f

Figure Captions (continued)

Page

27 Fig. 6 Solar wind density averaged in space over the radio path and in time over a complete solar rotation for each plotted point. Density is normalized to 1 A.U. assuming that it varies as $1/R^2$, in order to minimize the largest source of long-term variation. Notice that the density seems to be decreasing since 1968 as the sun becomes quiet. Also the 1-year average is 7.1 for Pioneer 8 and only 6.3 for Pioneer 9. This inequality is under study; it has been noted that normalization assuming density varies as $1/R^{1.9}$ leads to nearly equal averages, and such a governing relation has many implications of scientific importance.

29 Fig. 7 Density vs. Time after sector crossing as found by superposed epoch analysis, showing the largest peak at 0.5 day in agreement with other observations (1968 observations). This work is in progress in a joint effort with J.M. Wilcox. Some refinement of the analysis will improve this result slightly, but contamination by ionospheric error must be minimized before trends can be clarified to any significant degree. (Notice the 24-hour periodicity which is probably a consequence of ionospheric error.)

31 Fig. 8 Spacecraft positions in late 1970 just after loss of content with Pioneer 9 due to interplanetary scintillation in the solar corona. Because of the relative locations of Pioneers 6 and 8, it has been possible to subtract the 6 content from the 8 content to obtain the content along the line between 6 and 8, well away from earth.