Simultaneous \textit{Pc} 1 observations by the synchronous satellite ATS-1 and ground stations: implications concerning IPDP generation mechanisms

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Abstract—Simultaneous observations of \textit{Pc} 1 pulsations were made at the synchronous ATS-1 satellite and 2 Canadian ground stations. Both in space and on the ground the \textit{Pc} 1 activity studied followed substorm expansion phase onsets and occurred most frequently at dusk. \textit{Pc} 1 activity was detected at the Tungsten, N.W.T. ground station 88\% of the time \textit{Pc} 1 activity was detected at ATS-1. \textit{Pc} 1 activity was detected at ATS-1 only 47\% of the time such waves were observed on the ground. \textit{Pc} 1 waves in the ground records have a broader frequency spectrum than waves at ATS-1 observed simultaneously. Dynamic spectra of waves observed at Tungsten and Ralston, Alberta show these waves generally increase in frequency with time, a characteristic of IPDP type wave activity. Simultaneous wave observations at ATS-1 do not increase in frequency with time during the event. Of three possible mechanisms proposed to explain IPDP generation, one requiring a rapid increase in magnetic field is shown to be inconsistent with ATS-1 observations. Two other IPDP source mechanisms are shown to be equally plausible to explain IPDP generation.

INTRODUCTION

Of all magnetic pulsation phenomena, \textit{Pc} 1 are of particular interest because there is an accepted theoretical generation mechanism based upon ion cyclotron resonance of ring current protons (Heacock, 1967; McPherron et al., 1968; Fukunishi, 1969; Gulyel’emi et al., 1970; Gendrin, 1970). Two types of \textit{Pc} 1 activity are thought to originate as a result of ion cyclotron resonance of energetic protons. One type, pearls, are thought to be generated by ring current protons inside the plasmapause (Cornwall, 1965; Obayashi, 1965; Jacobs and Watanabe, 1964). Another type, Intervals of Pulsations Diminishing by Period (IPDP) are thought to be generated when substorm injected energetic protons drift into the dusk sector and encounter the plasmapause or regions of detached cold plasma (Heacock, 1967; Fukunishi, 1969; Gendrin, 1970; Heacock, 1971; Fukunishi, 1973). If the IPDP generation mechanism were well understood, it might be possible to infer information about the generation region from ground observations alone.

Numerous ground observations of \textit{Pc} 1 activity have been the foundation for theoretical work on \textit{Pc} 1 generation. Auroral zone observations of pearls or \textit{pPc} 1 activity have established the generation region for pearl pulsations is inside the plasmapause. Ground observations of IPDP have shown the relationship of IPDP to the substorm process and other magnetic pulsation activity (Heacock, 1967; Fukunishi, 1969; Heacock, 1971; Fukunishi, 1973).

Fewer observations of \textit{Pc} 1 pulsations have been made \textit{in situ} than on the ground (Heppner et al., 1969; Dward, 1971; McPherron et al., 1972; Fredericks and Russell, 1973). \textit{In situ} observations can differ noticeably from ground observations of the same phenomena as wave properties are undistorted by propagation through the ionosphere (Field and Greifinger, 1965; Greifinger and Greifinger, 1965). As shown by Bosseen et al. (1975), \textit{Pc} 1 are a common occurrence at synchronous orbit; where 187 intervals of \textit{Pc} 1 activity were observed in 3 years of instrument observation.

Simultaneous observations of \textit{Pc} 1 activity were made from 1967–1969 at ATS-1 and 2 Canadian observatories, Tungsten N.W.T. and Ralston, Alberta during the same period of time. It is the purpose of this paper to examine the properties of \textit{Pc} 1 activity observed simultaneously at ATS-1 and ground stations. These simultaneous observations suggest of 3 mechanisms previously suggested to explain IPDP generation (Fukunishi, 1969; Roxburgh, 1970; Gulyel’emi et al., 1970; Peraut et al., 1973), only 2 mechanisms utilizing drift of energetic plasma in a near constant magnetic field are plausible.

SATELLITE OBSERVATIONS

A visual search of high resolution microfilm plots of 1969 ATS-1 magnetometer data was made for
\textbf{Pc 1} magnetic pulsation events, producing 21 intervals of \textbf{Pc 1} activity. Data recorded for each event included an average wave period, the maximum peak-to-peak amplitude and the beginning and ending time of the event. These events were required to have observed wave frequencies from 0.1 to 1 Hz and wave amplitude 1 gamma above background signals. As an example, the Pc 1 event of 0044–0047 UT 24 June 1969 is shown in Fig. 1. The magnetometer signal in Fig. 1 shows a waveform of 3–5 sec period. The amplitude of the wave varies in this data segment from 1 to 5 gammas peak to peak. The three curves are the three components of the ATS-1 fluxgate magnetometer measured in GSE coordinates (McPherron, 1972). Thus, the Z-axis is parallel to the satellite spin axis, approximately parallel to the Earth's rotation axis. The X-axis lies in a plane defined by the Z-axis and the satellite sun vector; the Y-axis completes a right handed system. A complete description of the ATS-1 magnetometer is given in Barry and Snare (1966) and Snare and Spellman (1967).

The maximum peak-to-peak amplitude was established for each event for the wave cycle in which the sinusoidal magnetic field variation was the largest, and was measured to the nearest one gamma. \textbf{Pc 1} wave activity was typically transverse to the background field. Maximum peak-to-peak amplitudes ranged from 2 to 8 gammas, with most events displaying maximum amplitudes of 4 gammas. Root mean square power for these intervals was considerably less, about 0.2 gamma. An average period was calculated for each interval of \textbf{Pc 1} activity. Ten wave cycles were chosen to include the cycle of maximum peak-to-peak amplitude and allowed an average period to be calculated for that interval of wave activity. Most events occurred with a wave period of 3 sec. Spurious instrumentation signals were carefully eliminated by using both visual inspection and power spectra.

Almost all ATS-1 events followed within 1.5 hr of a substorm expansion phase onset, as determined by a visual examination of mid-latitude and auroral zone magnetograms. Judgement of substorm expansion onsets was made on the basis of their latitudinal extent and structure. When there existed more than one expansion onset both preceding and following the beginning of \textbf{Pc 1} activity, onset times directly preceding the event were chosen.

\section*{GROUND OBSERVATIONS}

Low resolution plots of the north-south component of the Tungsten, N.W.T. search coil magnetometer were scanned for \textbf{Pc 1} enhancements.
During magnetically quiet times the Tungsten observatory has been shown to be 80 miles west southwest of the foot of the field line near ATS-1 (K. Pfitzer, private communication). Tungsten \( Pc \) 1 wave enhancements were required to have a signal strength greater than 0.2 gammas/sec and to last at least 10 min. An example of a Tungsten \( Pc \) 1 event on 10 December 1969 is shown in Fig. 2. The Tungsten search coil magnetometer is aligned with axes along the north–south and east–west directions with respect to the local geomagnetic field. A description of both the Tungsten fluxgate and search coil magnetometer instrumentation is given in Snare et al. (1973). The vertical axis in Fig. 2 is the amplitude output of the search coil in gammas/sec at the scale of 0.5 gamma/sec/division and the horizontal axis of Fig. 2 is UT. Because the Tungsten data are plotted to such low resolution, no visual determination of period was made for Tungsten \( Pc \) 1 events, but intervals of activity were chosen which had obvious frequency enhancements within the \( Pc \) 1 range; the intervals were later checked by power spectral analysis.

**SIMULTANEOUS GROUND AND SATELLITE OBSERVATIONS**

Figure 3 is a schematic of the data coverage at ATS-1 and Tungsten for 1969. This Venn diagram shows the total amount of data available from the ATS-1 and Tungsten magnetometers where the data coverage is proportionately represented by sections on the diagram. There were 106 days during which some data was available at the synchronous satellite. For 145 days data were also available at the Tungsten ground observatory. The 20 days when there were \( Pc \) 1 events at ATS-1 are
Fig. 3. Histogram of the number of occurrences of Pc 1 waves versus local time for observations by the Tungsten, N.W.T. search coil magnetometer and the ATS-1 fluxgate magnetometer in 1969.

divided into three groups. In the first group, 12 events occurred when no data were available from Tungsten because the instrumentation was inoperative. In the second group, indicated with cross-hatched shading, there were seven simultaneous ATS-1 and Tungsten events. In the third group, only one ATS-1 event did not appear in the simultaneous data at the conjugate point. All simultaneous observations were checked in both the time and frequency of occurrence. As noted by Arthur et al. (1973) for simultaneous ground-satellite observations of Pc 3 and Pi 1 micropulsations, the Tungsten and ATS-1 observatories rarely had simultaneous micropulsation activities during disturbed magnetic period. Thus, it appears that ionospheric propagation of Pc 1 must be very favorable for semi-structured Pc 1 in view of the high proportion of simultaneous events when the Tungsten and ATS-1 instrumentation were both operational. In contrast, Pc 1 activity was often observed at the Tungsten station without simultaneous observations of Pc 1 activity at ATS-1. It is probable that events which are only seen at the Tungsten ground observatory and not at ATS-1 have originated in a spatial volume distinct from that of ATS-1. There were 8 events which were not seen in the satellite observations but were observed at the Tungsten ground station.

Figure 4 is the distribution of Pc 1 events for both ATS-1 and Tungsten observatories as a function of local time. For both Tungsten and ATS-1 observations, the majority of events were seen in the afternoon sector, principally in the hours 1400-1700 LT. Given statistical fluctuations imposed by a small ATS-1 data sample, the local time distributions for Tungsten and ATS-1 are similar to the local time profile of afternoon-dusk sector Pc 1 events previously described by Bosser et al. (1975). In that paper, the 1967 data sample examined in a statistical study of Pc 1 events included a variety of semi-structured Pc 1 activities which were shown to have peak-to-peak amplitudes, relation to substorm onsets, local time and event duration disturbances identical to the 1969 Pc 1 events described in this paper.

GROUND SATELLITE CORRELATIONS

(1) ATS and Tungsten

Pc 1 events visually selected from the low-resolution magnetograms had power spectral analysis performed on 1 sec average field values. Power spectral plots were created for the east–west and north–south components of the field at Tungsten and for the full 3×3 spectral matrix at ATS-1. Data segments of 4096 points or 68 minutes were used for construction of the power spectral matrix and calculation of wave ellipticity and polarization; see McPherron et al. (1972) for a complete description of this technique. The three graphs of Fig. 5 are the results of power spectral and coherency analyses for an ATS-1 event simultaneously observed at Tungsten from 0000–0108 UT 24 June
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Pc1 MICROPULSATIONS
UCLA Fluxgate Magnetometer
ATS-1
0000–0108 UT JUNE 24, 1969

Fig. 5. Power spectrum of a Pc 1 event observed at ATS-1 on 24 June 1969. Wave polarization and ellipticity are plotted to the same frequency scale as the upper power spectral plot. For details of the power spectral analysis and eigenanalysis of the spectral matrix, refer to McPherron et al. (1972).

1969. In the upper right hand plot the range of frequency values in which there is a power enhancement, approximately 0.2 to 0.32 Hz, is shown by dashed lines. In this frequency band the waves are predominantly of negative ellipticity or left handed rotation with respect to the main field. The percent polarization, or coherent power in the principal plane, is 80% or greater in this frequency range.

Figure 6 is a similar series of power spectral plots constructed for the Tungsten search coil magnetometer for the data interval 0000–0108 UT on 24 June 1969. The data sampling interval, plot construction and spectral analysis techniques are identical to that used for the ATS-1 spectral plots. There is a power enhancement observed at Tungsten from approximately 0.07 to 0.32 Hz. The values of wave ellipticity range from positive to negative for different values of wave wave frequency in this event.

Comparing Figs. 5 and 6, some power and coherency properties are evident. The range of frequencies in which there is a power enhancement observed at Tungsten is larger than but includes that seen at ATS-1. This characteristic has been seen for all the simultaneous events in the 1969 data file for ATS-1 and Tungsten. In the range of frequencies with wave power enhancement the ellipticity is not identical for both ATS-1 and Tungsten although the percent polarization is similarly high for both. As an example, in the frequency band from 0.25 to 0.3 Hz, the ellipticity is negative at ATS-1 and positive at Tungsten. Thus, a transition in wave ellipticity has taken place as a consequence of some effect of space-to-ground propagation.

Pc 1 wave power is always greater at the satellite than in ground measurements. The ratio of maximum power in one frequency band at ATS-1 relative to that at Tungsten was examined for 7 simultaneous events. This ratio of powers varied
from 8–1 to 100–1 where an average value was 48–1. Signal to noise ratios were similar for both Tungsten and ATS-1 Pc 1 activity. At the maximum wave power in one frequency band, the ratio of wave power to background noise power was 30–1 for most events.

Tungsten and ATS-1 dynamic spectra on 24 June 1969 are shown in Fig. 7. Both ATS-1 and Tungsten dynamic spectra are created from 1 sec averages such that spectral estimates are computed every 32 sec over 43 frequency bands of 0.012 Hz each. The upper ATS-1 dynamic spectrum was computed for the V and D components of the field; the lower Tungsten dynamic spectrum was computed for the east–west and north–south components.

For the ATS-1 dynamic spectral plot, wave activity ranges from 0.17 to 0.32 Hz, as indicated by the lower and upper frequency limits of the lightest shaded contour. The lightest shaded contour represents a power level of $1\gamma^2/(\text{Hz-s}^2)$. This power level was chosen to be the lowest level which did not display numerous random frequency enhancements on the dynamic spectral plot.

The lower Tungsten dynamic spectral plot was constructed similarly to that of ATS-1. The Tungsten dynamic spectrum has power enhancement in a range of frequencies from 0.1 to 0.35 Hz in a characteristic upward sweeping form denoted IPDP in ground observations. The Tungsten IPDP event has power enhancement at lower frequencies not seen in the ATS-1 dynamic spectrum, although there is a remarkable similarity in the power enhancement in the range of frequencies from 0.17 to 0.32 Hz between the ATS-1 and Tungsten spectra. As is commonly observed in Tungsten dynamic spectra, low frequency Pc 1 activity continues after the upward sweep of the IPDP event while no activity was present in the ATS-1 dynamic spectrum.
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Fig. 7. Two digital dynamic spectra of the simultaneously observed $P_c$ 1 event of Figs. 5 and 6 on 24 June 1969.
(2) ATS and Ralston

Dynamic spectra from Ralston, Alberta and ATS-1 for 18 March 1967 are shown in Fig. 8. The ATS-1 dynamic spectrum was constructed from the $V$ and $D$ field components. Superimposed upon the ATS-1 spectrum are fractions 0.05 to 0.2 of the local in gyrofrequency generated from 2.5 min values of the background magnetic field at ATS-1. Four separate wave bursts are seen in the interval 0420–0700 UT when each event is identified by a $1\gamma^2$/Hz-sec$^2$ minimum power level.

**SIMULTANEOUS Pc1 EVENT MARCH 18, 1967**

![Graph showing Pc1 event on March 18, 1967](image)

**Fig. 8.** Two sonagrams of a simultaneously observed Pc 1 event on 18 March 1967. The upper portion of the figure is a digital dynamic spectrum of the Pc 1 event at ATS-1. Four horizontal lines corresponding to $0.2f_p$ to $0.5f_p$ (ion gyrofrequency) are superimposed upon the spectrum to show the slightly decreasing nature of the magnetic field during Pc 1 activity. The lower portion is an analog sonagram of the Pc 1 event recorded at Ralston, Alberta by ROKBURGH (1970).
The lower portion of Fig. 8 is a ground sonagram from Ralston, Alberta (Roxburgh, 1970). \( \text{Pc} 1 \) activity clearly starts at Ralston prior to the start at ATS-1. The ground IPDP event is of longer duration and has a larger range of frequencies than the ATS-1 \( \text{Pc} 1 \) event. It is probable that field-aligned propagation of \( \text{Pc} 1 \) waves gives rise to a similar power enhancement in the frequency range of 0.1–0.27 Hz.

Curves superimposed upon the ATS-1 dynamic spectrum show after the onset of \( \text{Pc} 1 \) activity at 0420 the background magnetic field decreased slightly. Thus, during the latter portion of the Ralston IPDP event, when the frequency of ground wave activity increased, the field in space decreased. Constant or slightly decreasing magnetic field behavior is typical of \( \text{Pc} 1 \) events observed at ATS-1 with simultaneous IPDP events at Ralston.

**DISCUSSION**

The contour map in Fig. 9 summarizes the relation of 1967 \( \text{Pc} 1 \) events to the total background magnetic field. The frequency of \( \text{Pc} 1 \) events is shown as a function of magnetic field where contours represent an equal density of events. Included within the shaded area of this figure are 70% of all the events. The shaded region is of limited extent because the magnetic field does not vary outside these values in the dusk sector. Most of the events in the shaded region are included within the area between the two curves marked 0.1\( f_p \) and 0.2\( f_p \) or 10–20% of the proton gyrofrequency. A more complete discussion of the relation of ATS-1 \( \text{Pc} 1 \) activity to background magnetic field is given in Bossen et al. (1975).

The energy necessary for protons of a cold plasma density \( N_b \) to resonate with left-handed ion cyclotron waves of frequency \( \omega \) is given by the cold plasma energy relation (Cornwall, 1965; Kennel and Petschek, 1966). The cold plasma energy relation is given in the upper portion of Fig. 8, where

\[
N_b = \text{cold background plasma density} \\
E_p = \text{ion resonant parallel energy} \\
B = \text{background magnetic field} \\
\omega = \text{visually observed wave frequency} \\
\Omega_i = \text{ion gyrofrequency}. 
\]

Curved lines passing through the contours of Fig. 9 represent curves of constant values of the product of background plasma density, \( N_b \), and resonant particle parallel energy, \( E_p \), as predicted by the cold plasma energy relation. Thus the majority of events correspond to a product, \( N_bE_p \), of 1000 keV/cm\(^3\).

During a particular \( \text{Pc} 1 \) event, \( \omega/\Omega_i \) remained constant, within 10% of its initial value, for 40% of all \( \text{Pc} 1 \) events and decreased in 43%. Thus the

**Frequency of \text{Pc1} Micropulsations as a Function of Total Magnetic Field at ATS-1 and Expected Energy-Density Product for Cyclotron Resonance**

![Fig. 9. Contour map of occurrence of \( \text{Pc} 1 \) activity plotted upon a grid of observed wave frequencies versus total magnetic field values for 1967. Seventy percent of the events are included within the shaded area, varying from 10 to 135 gammas. Curved lines passing through the contours represent values of \( N_bE_p \) derived from the cold plasma energy relation. For further details see the discussion section.](image-url)
product $N_B E_i$ remained constant or decreased during a given event for 83% of 1967 $Pc$ 1 activity.

Several theories have been advanced regarding the generation mechanism for IPDP. Of these, three likely source mechanisms suggested for IPDP are illustrated schematically in the lower portion of Fig. 10. One mechanism requires the equatorial magnetic field to increase rapidly ($dB/dt > 0$) (Roxburgh, 1970). The mechanism would produce a rise in frequency at observation points in space and on the ground. A second mechanism suggests that ring current protons of successively lower energies azimuthally gradient-drift through a given point in space. The cold plasma energy relation given at the top of Fig. 8 then requires that successively higher frequencies be generated as a function of time. This mechanism produces IPDP frequency increases which are more rapid at observatories located later in local time on the ground. Satellite observations of the energetic proton distribution would show a successive decrease in the energy of resonant particles through the event (Fukunishi, 1969; Gulve, et al., 1970; Heacock, 1971). A third mechanism combines radial E cross B drift and gradient drift of energetic protons. Thus protons injected in the dusk to midnight quadrant radially drift inward as they are gradient drifting. For each of the latter two mechanisms a satellite observes wave activity generated in the local region of space, with field strength nearly constant, and a narrow range of wave frequencies from 10 to 15% of the proton gyrofrequency. A conjugate ground station observes signals which originate in a spatial volume larger than but inclusive of the satellite with increasing frequency IPDP structure (Perraut et al., 1973).

The first two mechanisms are shown schematically in the top panel of Fig. 10. As shown by the horizontal arrow, an IPDP event could occur from the cyclotron resonance of ring current protons when the background field changed during the event by an amount $\Delta B$ between constant frequency curves 0.2 and 0.5 Hz. An IPDP could also occur when resonant energy product $N_B E_i$ changed by an amount $\Delta E$ between constant frequency curves 0.2 and 0.5 Hz, as shown by the vertical arrow in Fig. 10. A change in resonant energy product $N_B E_i$ could independently be due to either a change in density as particles drifted into regions of higher density, or a change in the population of resonant energetic protons, or both. For observations of $Pc$ 1 magnetic pulsations at the synchronous satellite ATS-1, the magnetic field and hence product of cold plasma density and resonant particle energy were constant or decreased. Thus, ATS-1 observations are inconsistent with any theory which requires the equatorial magnetic field to increase.

**SUMMARY AND CONCLUSIONS**

Simultaneous observations of $Pc$ 1 magnetic pulsations were made at the geosynchronous ATS-1 satellite and 2 Canadian ground stations. For 88% of the observations at ATS-1, simultaneous observations were made at the ATS-1 conjugate point ground station at Tungsten, N.W.T. The power spectra of ATS-1 events show the waves are left hand elliptically polarized. Power spectra of simultaneous Tungsten pulsation events show ground $Pc$ 1 waves have both left and right hand elliptical structure, and have a broader frequency spectrum than waves observed at ATS-1. The ratio of power of waves observed at ATS-1 to power of Tungsten waves was approximately 50:1.

Dynamic spectra of waves at both Tungsten and Ralston ground stations are that of IPDP type $Pc$ 1; the wave frequency increases during the event. Simultaneous ATS-1 dynamic spectra show wave activity does not increase in frequency during the event. The background field at ATS-1 remained
constant or decreased slightly during 83% of all
intervals of $Pc$ 1 activity.

Three source mechanisms have been suggested to
explain IPDP generation. One mechanism requires
a rapid increase in the equatorial magnetic field to
produce IPDP. Our dynamic spectra and magnetic
field observations are inconsistent with this theory.
Either purely azimuthal or a combination of
azimuthal and radial inward drift of energetic reso-
nant protons is an equally plausible mechanism
to explain IPDP generation. Since our observations
have been made at a single satellite moving in
space without information on the energy spectra of
energetic protons or background plasma density, no
conclusions can be drawn as to the appropriateness
of one single ion drift mechanism. For both of two
possible ion drift mechanisms, the satellite observes
wave activity generated only in the local region of
space, with constant or decreasing field strength,
and a narrow range of wave frequencies from 10 to
20% of the proton gyrofrequency. A conjugate
ground station observes a signal with power en-
hancement in a frequency band larger than but
including the range of frequencies observed at
ATS-1.

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REFERENCES

Arthur C. W., McPherron R. L. and
Coiman P. J., JR.
BARRY J. D. and Snare R. C.
Bossen M. D., McPherron R. L. and
Rus settle C. T.
Cornwall J. M.
Dwarkin M. L., Zmuda A. J. and
Radford W. E.
Field E. C. and Greifinger C.
Greifinger C. and Greifinger P.
Fredrick R. W. and Russett C. T.
Fukunishi H.
Fukunishi H.
Gendrin R.
Gulyel'mi A. V., Mal'tseva N. F. and
Trotskaya V. A.

1965 J. geophys. Res. 70, 4885.
1965 J. geophys. Res. 70, 2217.
1967 On the role of hydromagnetic pulsations of the IPDP
type in forming of asymmetric ring current, paper
presented at the International Symposium on
Solar-Terrestrial Physics, Moscow.
1973 IAGA bull. 34, 392.
1968 J. geophys. Res. 73, 1697.
1965 J. geophys. Res. 70, 1069.
1973 Digital data acquisition from a remote magnetic
1967 Digital offset field generator for spacecraft mag-
netometers, paper presented at the symposium on
space magnetic exploration and technology,
Reno, Nevada.
1973 IPDP's a typical ULF manifestation of magnetos-
pheric substorms, preprint, Groupe de Recherches
Ionospheriques, CNET.
1970 A theory for the generation of "Intervals of Pulsation
of British Columbia, Department of Geophysics,
Vancouver, Canada.