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Origin of short-period (30-300 s) Doppler frequency fluctuations of lower F region reflections in the equatorial electrojet region

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Measurements of phase path P of lower F region reflections at normal incidence at Kodaikanal (10° 14′N, 77° 28′E, dip 3.0° N) revealed the ubiquitous presence of 30-300 s quasi-sinusoidal variations in the time rate of change of phase path, $\dot{P}$ (Doppler frequency shift) during day time. A study is made of the influence of the irregularities in the equatorial electroject on the $\dot{P}$ fluctuations using simultaneous observations of F region phase path at Kodaikanal and of equatorial electrojet with the VHF backscatter radar at Thumba (08° 29′N, 76° 56′E, dip 0.9° S). It is shown that the spectral content of the Doppler fluctuations (quantified in terms of variance, σ^2 computed from $\dot{P}$ time series synthesized through FFT^{-1} (fast Fourier transfrom) in the chosen period bands, 30-300 s/30-120 s of the FFT of original $\dot{P}$ time series) bears a significant positive linear relationship to the horizontal phase velocity (Vp) of electrojet irregularities (3-m scale size)on a hourly basis. This result is in consonance with our earlier findings (Sastri et al., 1990) of a significant linear relationship of σ^2 to the electrojet strength (estimated from H field data) and a practical cessation of the $\dot{P}$ fluctuations at times of disappearance of Esq on ionograms (partial/complete counterelectrojet). The present work substantiates the interpretation that the short-period Doppler frequency fluctuations are due to phase path changes imposed on lower F region reflections by the refractive index variations associated with the convective motions of plasma density irregularities (type I and II) in the daytime equatorial electrojet.

INTRODUCTION

: ground-based HF phase path sounder or uivalent the Doppler sounder is a sensitive, :ceful, and inexpensive experimental tech- for probing the ionospheric plasma [Findlay, Ogawa, 1958; Watts and Davies, 1960]. It

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is traditionally used for investigating several aspects of ionospheric dynamics such as medium-scale traveling ionospheric disturbances (MSTIDS) [e.g., Georges, 1968; Pfister, 1971; Raghava Reddi and Rao, 1971; Butcher and Joyner, 1972; Schrader and Fraser, 1975; Wadlock and Jones, 1986; Jacobson and Carlos, 1989], ionospheric oscillations associated with geomagnetic micropulsations [e.g., Menk et al., 1983; Sutcliffe and Poole, 1984; Watermann, 1987; Yumoto et al., 1989] and energetic geophysical events like severe thunder storms and earthquakes [e.g., Georges, 1967, 1973; Baker and Davies, 1969; Davies and Jones, 1971, 1973; Prasad et al 1975; Raju et al., 1981; Tanaka et al., 1984; Okuzawa et al., 1986; Jacobson et al 1988]. It is also employed in recent times to derive information on ionospheric electric field disturbances and thermospheric wind vector [e.g., Tsutsui et al., 1984; Kikuchi and Araki, 1985; Kikuchi, 1986; Tsutsui et al., 1988).

We are operating a HF phase path sounder at Kodaikanal (10° 14'N, 77° 28'E, dip 3.0° N) to investigate ionospheric dynamics in the equatorial electrojet region. Topics of particular interest to us are MSTIDS, equatorial electric field and its temporal fine structure especially, signatures of penetration of magnetospheric electric fields during storm-time conditions (see, for example, Patel and Lagos [1985], Fejer [1986], and Earle and Kelley [1987]). The phase path sounder is well suited for the intended studies because phase path of ionospheric reflections at vertical incidence is highly responsive to changes in reflection height caused by vertical plasma drift, and such vertical EXB plasma drifts do commonly prevail in the vicinity of the dip equator as a result of the interaction of the large-scale east-west electric field (E) of dynamo origin with the nearly horizontal north-south geomagnetic field, B (see review of Fejer [1981]). The vertical EXB plasma drift, in fact, effectively governs the structure and dynamics of the equatorial ionosphere and is a vital experimental input for quantitative modeling of the low-latitude ionosphere [see Anderson, 1981; Sastri, 1990 and references therein]. It is to be borne in mind, however, that during day time an intense ribbonlike current termed the "equatorial electrojet" flows at E region altitudes in the proximity of the dip equator (see review of Forbes [1981]) and is usually turbulent with irregularities of sizes ranging from about a meter to a few kilometers generated by plasma instability processes (see reviews of Fejer and Kelley [1980] and Farley [1985]). Since the electrojet irregularities are semitransparent to reflections from higher altitudes in the HF band, measurements of phase path of F region echoes during daytime at electrojet locations (unlike those at stations outside the electrojet belt) could be influenced by the refractive index variations associated with the electrojet irregularities and their motion below the reflection level. Careful assessment of plausible electrojet modulation of F region phase path during daytime at electrojet locations must therefore be made to derive reliable information on the F region vertical plasma drift from HF phase path (Doppler) measurements.

Observations of phase path (P) of lower F region reflections (true height of reflection ~ 225 km) during day time at Kodaikanal indeed revealed the common presence of quasi-sinusoidal fluctuations in the time rate of change of phase path, $\dot{P}$ (or Doppler frequency shift $\Delta f = -f\dot{P}/c$, where f and c are the probing frequency and velocity of light, respectively) with periods in the range 30-600 s and peak-to-peak amplitudes of 6-30 ms^{-1} in $\dot{P}$ or 0.1-0.5 Hz in Δf [Sastri et al., 1988]. The ambient state of the electrojet and associated ionospheric conditions were found to influence the spectral content of the $\dot{P}$ fluctuations in that, while the longer-period segment of the oscillations (T > 300 s) persist almost all the time, the shorter-period components tend to cease at times of absence of Esq configuration on bottomside ionograms (signature of inhibition of gradient drift instabilities responsible for type II electrojet irregularities and Esq; see, for example, Balsley et al., [1976]). The view point that the entire regime (30-600 s) of $\dot{P}$ fluctuations are ionospheric manifestations of acoustic waves seemed unreasonable to us (though not yet disproved) because they are ubiquitous in our $\dot{P}$ data, while the experimental evidence reported to-date for acoustic waves signatures at F region heights consistently shows that they manifest without exception in association with only energetic events, both natural and man-made, like severe thunderstorms, nuclear explosions, and earthquakes [e.g., Georges, 1973; Baker and Davies, 1969; Davies and Jones, 1973; Prasad et al., 1975; Raju et al., 1981; Tanaka et al., 1984; Okuzawa et al., 1986]. Correlative studies of phase path data at Kodaikanal and ground level geomagnetic micropulsation data at Trivandrum (located ~200 km south of Kodaikanal in the electrojet belt) showed the absence of a systematic relationship of 30-600 s fluctuations in $\dot{P}$ with Pc4/Pc5 micropulsations, indicating that hydromagnetic (HM) waves are not the primary source of the Doppler oscillations. Keeping in view the facts that internal gravity waves are free of atmospheric absorption unlike acoustic waves and that the parameters of daytime F region over the dip equator respond to changes in the large-scale zonal electric field of dynamo origin [Sengupta and Krishnamurthy, 1973], we have attributed the longer-period (300 < T < 600 s) fluctuations in $\dot{P}$ at Kodaikanal to gravity waves related perturbations in the zonal electric field of the conjugate E region (the seat of the gravity wave field is to be at E region level because the Brunt-Väisälä period is 5.1 min at 110 km and increases to 11.6 min at 200 km; see Okuzawa et al., [1986]).

The theme of the present paper is the origin of the shorter-period (T < 300 s) segment of the F region Doppler variations at Kodaikanal. The morphology of these Doppler oscillations derived earlier by us [Sastri et al., 1988, 1991] from analysis of extensive data are as follows:

1. They are seen at all times during the day time with small peak-to-peak amplitudes of 6-18 ms^{-1} in $\dot{P}$ (0.1-0.3 Hz in Δf) and tend to practically disappear quite consistently (particularly variations with T < 180 s) when Esq is absent on ionograms, i.e., during partial/complete counterelectrojet conditions.
2. The spectral content of the fluctuations changes significantly not only from day to day at a given local time but also from hour to hour on a given day.
3. The level of wave activity in $\dot{P}$ in the period range 30-300 s (quantified in terms of variance computed at ~ 1-hour intervals) bears a significant linear relationship to the ambient strength of the equatorial electrojet estimated from ground-based magnetometer data.
4. $\dot{P}$ fluctuations in the range 30-120 s are most sensitive to changes in electrojet strength and dominate, in general, the spectral content of $\dot{P}$ in the range 30-300 s (variance of 30-120 s fluctuations constitutes, on the average, 65 percent of the variance of 30-300 s fluctuations).

Model calculations showed that for vertical soundings on 5.0 MHz at Kodaikanal the electrojet irregularities can produce appreciable changes in the phase path of F region reflections, even though the irregularities are located well below the reflection height [Sastri et al., 1991]. The model estimates of the net change in phase path ΔP ($<2\lambda$) have been found to be in good agreement with the peak-to-peak amplitudes of the 30-300 s fluctuations noticed in Kodaikanal $\dot{P}$ data. On the basis of these experimental and modeling results the short-period fluctuations in the Doppler frequency of lower F region echoes have been interpreted in terms of phase path changes imposed on F region echoes by the refractive index variations associated with the convective motions of electrojet irregularities.

In this paper we present the results of an effort made to assess the above interpretation of the origin of short-period Doppler fluctuations through a further quantitative study of their dependence on the characteristics of the electrojet irregularities using data from the VHF coherent backscatter radar at Thumba (08° 29′N, 76° 56′E, dip 0.9° S). The study confirms that the turbulent state of the equatorial electrojet is the basic cause of the commonly noticed short-period (30-300 s) Doppler frequency oscillations of lower F region echoes during day time at Kodaikanal in the electrojet belt.

EXPERIMENTAL DETAILS

The HF phase path sounder at Kodaikanal consists essentially of a broadband pulse transmitter, phase coherent receiver(s), a frequency synthesizer unit, timing and logic circuitry, and analog recording facilities. The system is rendered phase coherent by synthesizing all the frequencies required for transmitter and receiver injection and for various timing circuits from a single 10-MHz temperature-controlled crystal oscillator. The sounder is operated at vertical incidence on a frequency of 5.0 MHz, and its present configuration enables monitoring of phase path change to the limit equivalent of a total phase path change of a wavelength, λ (60 m) of the probing radio waves. The temporal and group height resolutions available are 6 s and 1.5 km, respectively. Details of the system design and hardware implementation of the same can be found elsewhere [Sastri et al., 1985].

The VHF backscatter radar at Thumba operates on a frequency of 54.95 MHz with a peak power of 12 kW. Yagi arrays are used both for transmission and reception. For each signal pulse received from the electrojet the phase quadrature components of the receiver outputs are low-pass filtered, digitized, and stored on magnetic tape. The Doppler power spectrum is computed from off-line processing of recorded data using a fast Fourier transform (FFT) algorithm. The horizontal phase velocity (Vp) of the electrojet irregularities is computed from the observed Doppler shift (f_D) using the relation

$$V_p^\theta = \frac{\lambda}{2} f_D$$

where λ is the radar wavelength and θ is the elevation angle of the radar beam. For type I spectra arising from two-stream plasma instability the Doppler frequency corresponding to the peak value of the spectrum is commonly used to compute Vp. In the case of type II spectra arising from gradient drift instability the mean Doppler frequency $\bar{f}_D$ is used as a measure of the mean phase velocity of the irregularities in the sampled volume. The value $\bar{f}_D$ is computed from

$$\bar{f}_D = \frac{\int f_D P(f_D) df_D}{\int P(f_D) df_D}$$

with the integration usually done from -200 to +200 Hz for f_D. The error in $\bar{f}_D$ so computed is typically $\pm$ 1 Hz which for the radar geometry at Thumba corresponds to an error of $\pm$ 2.7 ms^{-1} in Vp. The overall uncertainty in the absolute heights assigned to each range gate sampled spectrum is $\pm$ 1.5 km on average. Complete details of the system can be found elsewhere [Reddy et al., 1987].

RESULTS AND DISCUSSION

The present study is based on the same data as were used in our previous work [Sastri et al., 1991], namely, phase path recordings made on 116 days at Kodaikanal during the months May through October in 1983, 1984, and 1986 spanning the day time interval 0800-1600 hr (Indian Standard Time = UT + 5.5 hr). However, because of operational problems and absence of preplanning of observational schedules (at Kodaikanal and Thumba), simultaneous VHF radar data of Thumba have become available for only 7 days. The data span varied from 3 to 4 hours on individual days. The analysis of simultaneous data of F region phase path at Kodaikanal and of equatorial electrojet with the VHF radar at Thumba facilitates evaluation of the influence of electrojet irregularities on the short-period Doppler fluctuations of F region reflections over Kodaikanal, because the radar experiment provides direct and important information on the nature of the irregularities (type I/II or combination) and their horizontal phase velocities (Vp). It is to be noted that Kodaikanal (dip 3° N) is in the northern half of the electrojet belt, while Thumba (dip 0.9° S) is south of dip equator at a latitudinal separation of ~ 150 km from Kodaikanal. The comparative study of the F region phase path at Kodaikanal with that of equatorial electrojet at Thumba is, nevertheless, justified because the primary zonal electric field (Ey) of global wind dynamo origin as well as the secondary enhanced vertical polarization electric field (Ep) genarated by it and which is responsible for the electrojet current pervades the entire electrojet belt (Ep drops off rapidly only beyond 4° geomagnetic latitude; see Forbes [1981] and references therein). The close association between the parameters of daytime F region (height of constant electron density and semithickness) over Thumba and Ey (deduced from ground level H field data of Thumba) found by Sengupta and Krishnamurthy [1973] indicates, in fact, that the scale of Ey producing the changes in F region must be at least 10° in latitude, because the F region at Thumba would be linked to the dynamo region at a magnetic latitude of ~ 10° . The strength of the electrojet and the phase velocity (Vp) of electrojet irregularities depend on Ey. The characteristics of the electrojet irregularities at Kodaikanal will not therefore be substantially different from those at Thumba, both the stations being in the electrojet belt.

As the data sample available for the present study is rather limited in size, it is felt worthwhile and necessary to ascertain whether reliable conclusions can be drawn from analysis of the same. For this purpose, the dependence of the spectral content of the short-period Doppler fluctuations on the electrojet strength (the major finding of our previous study) is reevaluated and compared with that derived earlier from a large data sample. The salient features of the data analysis procedure adopted for the purpose are as follows. Since we are primarily interested in small-scale variations in phase path (P) which are swamped by the large and often rapid diurnal changes, the original P versus time record for each day is differentiated to yield a record of the time rate of change of phase path, $\dot{P}$. The $\dot{P}$ data are subjected to standard FFT for spectral features of the $\dot{P}$ variations. The Nyquist period (frequency) corresponding to the 6-s sampling interval of the data is 12 s (83 mHz). The electrojet strength is estimated from the published hourly H field data of Trivandrum (08° 29′N, 76° 56′E, dip 0.9° S) and Alibag (18° 38′N, 72° 52′E, dip 09° 26′N) through the parameter ΔSdI (see Kane [1976] for the procedure of calculating the parameter and its merit as an indicator of the electrojet strength). As the hourly averages of H field refer to time slots centered on half hours of UT (or full hours of IST; IST = UT + 5.5 hours), $\dot{P}$ data spanning 1-hour intervals centered on full hours of IST are taken up for correlative study with ΔSdI. A window of 51.2 min centered n the full hour of IST is in effect used with $\dot{P}$data o meet the requirement of 2^n data points for FFT $\Delta t = 6$ s, n = 512, T = 51.2 min). The omission f 8.8 min of data is felt not to vitiate the spectral estimates as we are primarily concerned here vith $\dot{P}$ fluctuations with periods 300 s. The level f wave activity in band 30-300 s is quantified by applying a unit gain rectangular filter in the chosen period range to the FFT spectra of original $\dot{P}$ data and then performing FFT^{-1} to retrieve the filtered $\dot{P}$ time series. The passband (30-300 s) chosen is considered wide enough to include the period regime (T<240 s) that is found to respond to ambient electrojet conditions and restrictive enough to minimize the contributions of noiselike components at the very high frequency end and spectral features attributable to internal gravity waves activity at the low-frequency end of the spectrum (Brunt-Väisälä periods at 110 and 200 km are 5.1 and 11.6 min respectively). The variance (σ^2) of the 51.2-min $\dot{P}$data segments thus synthesized is taken to represent the spectral content of the 30-300 s quasi-periodic oscillations for the central hour (in IST) of the data span. Simultaneous hourly values of σ^2 and ΔSdI are then collated and analyzed to assess the relationship, if any, between the parameters.

Figure. 1. depicts the dependence of the variance (σ^2) of the 30-120 s and 30-300 s fluctuations in $\dot{P}$ on the ambient electrojet strength, ΔSdI evidenced in the present data sample (N = 16). The lines of best fit to the mass plots and the correlation coefficients are also shown in the figure. Other results of the statistical analysis are given in Table 1. The $\sigma^2 - \Delta$SdI relationship is studied only for the 30-120 s subband because, as already mentioned, this period range was found earlier to respond very sensitively to changes in electrojet strength compared to the other two subbands (120-210 s and 210-300 s), and its variance contributes substantially to the variance of the entire band 30-300 s. The lines of best fit characterizing the $\sigma^2 - \Delta$SdI relationship evidenced in the large data sample (N = 281) of our previous study are also shown in Figure 1 to facilitate comparison. It is quite evident from Figure 1 that the linear relationship of σ^2 to ΔSdI holds good even in the data sample used here. In fact, the value of σ^2 for the 30-120 s oscillations calculated from the lines of best fit of the present data differs from that of the large data sample analyzed earlier by $\sim$ 13 percent at ΔSdI = 30 nT and by $\sim$ 3 percent at ΔSdI = 120 nT. The corresponding figures for

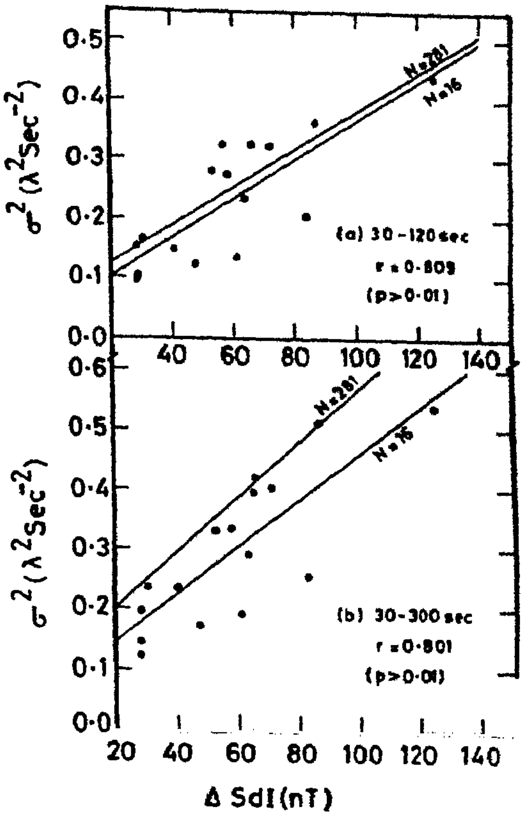

Fig. 1. Plot showing the relationship of the variance (σ^2) of 30-300 s and 30-120 s fluctuations in the time rate of change of phase path $\dot{P}$ (Doppler frequency shift) at Kodaikanal (dip 3.0° N) to the ambient strength of the equatorial electrojet ΔSdI (estimated from geomagnetic H field data). Each point represents the values of variance and ΔSdI corresponding to 1-hour data, and the solid line represents the line of best fit. The total number of hours (N) of data used and the correlation coefficient (r) with its significance (P) are also given. The line of best fit obtained with a large data sample (N=281) earlier is shown for comparison.

the 30-300 s band are $\sim$ 24 and 18 percent respectively. These numerical values show that the 7 day's observations analyzed here describe adequately the dependence of the short-period Doppler frequency fluctuations (particularly in the subband 30-120 s) on the electrojet conditions and hence form a suitable data base for further studies to understand the physical mechanism(s) responsible for the Doppler fluctuations.

Perusal of the original $\dot{P}$ data and the corresponding FFT spectra, the filtered time series of $\dot{P}$ and

Table 1. Statistical Relationship of the Variance of Quasi-Periodic Fluctuations

Parameters	Number of Data Points	Period Band 30-300 s			Period Band 30-120 s			Reference
		r	b	a	r	b	a	
σ^2 versus ΔSdI	281	0.689	4.596×10^{-3}	1.0772×10^{-1}	0.740	3.246×10^{-3}	5.822×10^{-2}	Sastri et al. [1991]
σ^2 versus ΔSdI	16	0.801	3.934×10^{-3}	6.729×10^{-2}	0.809	3.334×10^{-3}	3.473×10^{-2}	current work
σ^2 versus V_p (99 km)	16	0.766	3.743×10^{-3}	-6.088×10^{-2}	0.753	3.085×10^{-3}	-6.548×10^{-2}	current work
σ^2 versus V_p (104 km)	14*	0.829	1.887×10^{-3}	-2.303×10^{-2}	0.855	1.732×10^{-3}	-5.95×10^{-2}	current work

Details of the statistical relationship of the variance (σ^2) of quasi-periodic fluctuations (30-300 and 30-120 s) in the time rate of change of phase path, $\dot{P}$ (Doppler frequency shift) of lower F region reflections during daytime at Kodaikanal (dip 3° N) with the equatorial electrojet strength ΔSdI and the phase velocity (V_p) of electrojet irregularities measured with the VHF coherent backscatter radar at Thumba (dip 0.9° S).

Notes : r, correlation coefficient. All values of r significant > 99% level; a,b, Intercept and slope of the line of best fit.

* Intervals with type I spectra in radar data are excluded.

their variance (σ^2) levels in relation to the simultaneous data of phase velocities (Vp) of electrojet irregularities indicated the expected trend of a dependence of the spectral content of the short-period Doppler fluctuations on Vp and the type of irregularities regime. This behavior is illustrated in Figures 2 and 3, wherein the daytime variation of Vp at 99 and 104 km (based on 5-min interval VHF radar data) is shown along with the hourly values of the electrojet strength, ΔSdI, and levels of variance (σ^2) of the 30-120 s and 30-300 s $\dot{P}$ fluctuations for two successive days in October 1983 and two nearby days in October 1984, respectively. Since the relationship between σ^2 and ΔSdI is period dependent, the scales of ΔSdI (also Vp) and σ^2 in Figures 2 and 3 are arbitrarily chosen (for convenience in plotting the relevant data) and do not conform to the statistical relationships evidenced in the study between the parameters; see Figure 1 and Table 1 (the scales of ΔSdI and σ^2 are such that 20 nT corresponds to $0.1\lambda^2$ s^{-2} irrespective of period, while the corresponding value of σ^2 expected from the statistical relationships (N=16) is $0.0667\lambda^2$ s^{-2} for the 30-120 s band and $0.0787\lambda^2$ s^{-2} for the 30-300 s band). On October 12, 1983, a geomagnetically quiet day (Ap = 4), the normal buildup and decay of the electrojet strength was apparent during daytime. Strong electrojet conditions prevailed around noon as can be seen from the values of ΔSdI and Vp for the forenoon period presented in the bottom panel of Figure 2. In fact, type I spectra were seen in radar data at 104 km height from 1025 to 1130 IST, while at the lower height of 99 km Type I contamination was evident only for a short period from 1105 hrs to 1130 IST. It is to be recalled here that type I irregularities manifest under conditions of strong electrojet when the electric field that drives the electrojet renders the electron drift speed relative to the less mobile ions exceed the ion-acoustic speed in the electrojet. On the other hand, the type II irregularities occur even when the electrojet is weak (i.e., for electron drift speed ≥ 30 ms^{-1}) and are longer in wavelength compared to type I irregularities (see Figure 1 of Balsley [1977] for the concept of irregularities structure in the electrojet). Moreover, type II usually prevail at heights below 101 km although the height at which type I contribution begins to contaminate type II spectra significantly is rather variable from day to day. It is quite evident from Figure 2 that the level of variance (σ^2) of the short-period fluctuations in $\dot{P}$ closely followed the enhancement of the electrojet strength as well as Vp during the forenoon on October 12, and was high around noon when type I irregularities prevailed in the electrojet medium. Similar high values of σ^2 were also noticed on October 18, 1984 (Ap=43) when type I irregularities were seen at 104 km under strong electrojet conditions in the forenoon (1030-1230 IST) as may be seen from Figure 3. In contrast, on October 13, 1983, a day of moderate geomagnetic activity (Ap = 30), only weak electrojet conditions were evidenced dur-

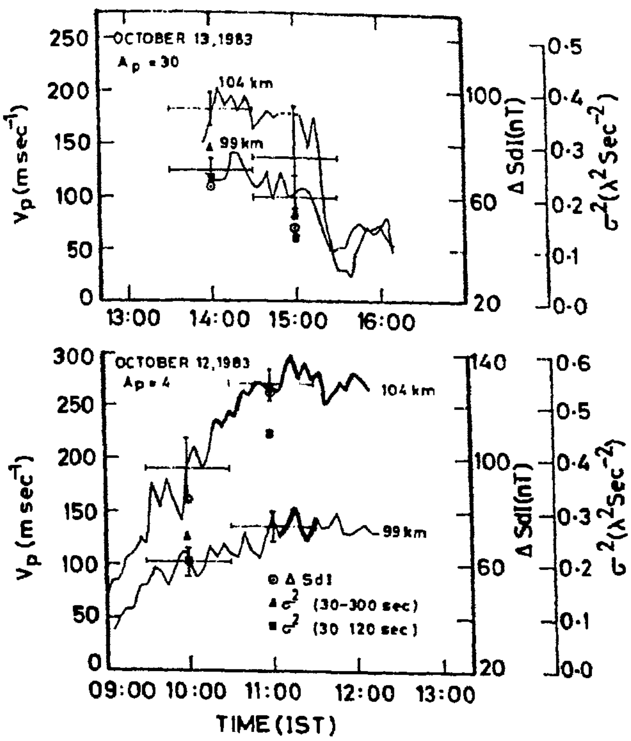

Fig. 2. Temporal variation of the phase velocity (Vp) of electrojet irregularities at 99 and 104 km deduced from VHF backscatter radar observations at Thumba (dip 0.9° S) on October 12, 1983 and October 13, 1983. The heavy line indicates the interval when type I spectra prevailed at 104 km. The average value of Vp and its standard deviation over 1-hour intervals centered on full hours of IST are shown by horizontal and vertical bars, respectively. The corresponding hourly values of the electrojet strength ΔSdI and variances (σ^2) of the 30-300 s and 30-120 s fluctuations in $\dot{P}$ at Kodaikanal are also shown. Note the systematic changes in the level of σ^2 with Vp as well as ΔSdI from hour to hour on the 2 days.

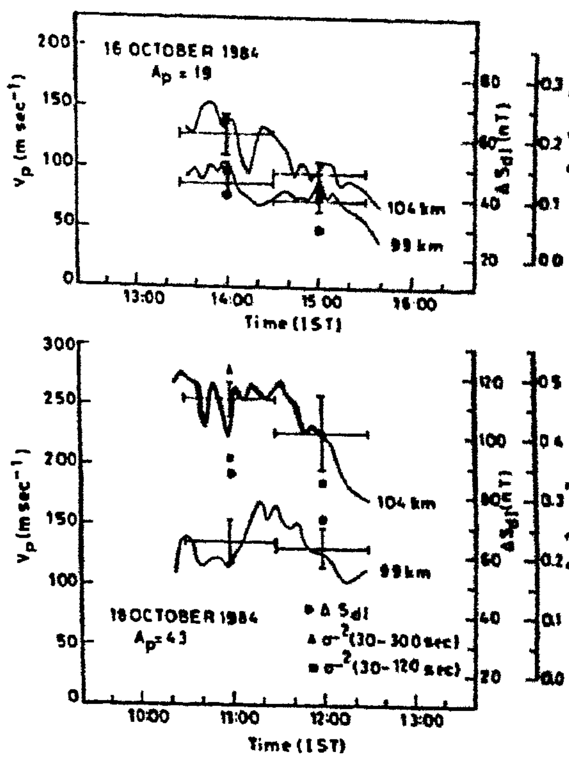

Fig. 3. Same as in Figure 2 but for October 16, 1984 and October 18, 1984.

ing the day, although the usual buildup and decay of the electrojet strength was seen. VHF radar data, in fact, showed the presence of only type II spectra both at 99 and 104 km. In response to this physical state of the electrojet medium the levels of variance (σ^2) of the short-period (30-300 and 30-120 s) fluctuations in $\dot{P}$ remained low and closely followed the decrease of the electrojet strength (ΔSdI) as well as Vp during the afternoon hours as can be seen from the data displayed in the top panel of Figure 2. A similar pattern of variation in Vp, ΔSdI, and σ^2 under weak electrojet conditions (type II spectra at both 99 and 104 km; ΔSdI $\leq$ 41 nT) was also evidenced in the afternoon (1330-1530 IST) on October 16, 1984 (Ap=19), as may be seen from Figure 3 (top panel). This type of well-correlated temporal variations in σ^2, ΔSdI, and Vp are seen in the 7 day's observations studied here. To establish this feature, hourly averages of Vp at 99 and 104 km are calculated and cross-correlation analysis of paired hourly values of σ^2 and average Vp is performed. It is to be mentioned here that the phase velocity of type I irregularities remains constant and gets saturated at the ion-acoustic velocity and is thus not proportional to the electron drift speed, while type II irregularities more or less move with the electron drift speed. Therefore the hourly data intervals when type I spectra were seen at 104 km are excluded in the correlation analysis. This limitation has reduced the number of paired values of σ^2 and average Vp (at 104 km) from 16 to 14. The results of the correlation analysis are displayed in Figure 4 and are also summarized in Table 1. It is quite evident that the variance levels of 30-300 s as well as 30-120 s fluctuations in $\dot{P}$ exhibit a statis-

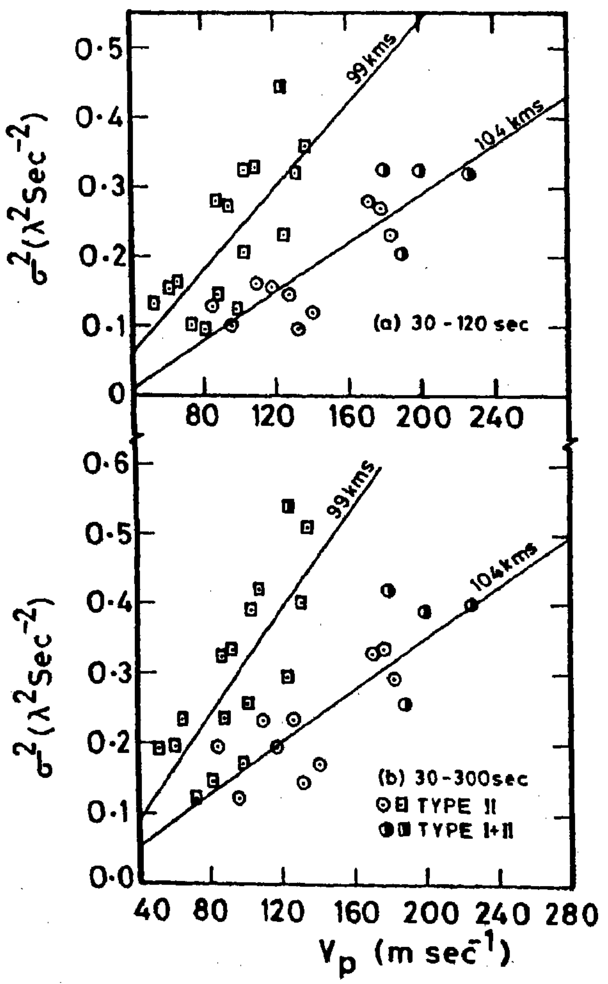

Fig. 4. Plots showing the dependence of the variance (σ^2) of 30-300 s and 30-120 s fluctuations in $\dot{P}$ at Kodaikanal on the phase velocity (Vp) of electrojet irregularities at 99 (squares with dots) and 104 km (circles with dots) measured with VHF coherent backscatter radar Thumba. The nature of the Doppler power spectrum (type II/combination of type I and II) from which Vp is deduced is also indicated.

tically significant linear relationship with Vp both at 99 and 104 km.

The principal experimental result that emerged from the present correlative study of simultaneous data from the HF phase path sounder at Kodaikanal and VHF backscatter radar at Thumba is that the phase velocities of the electrojet irregularities effectively modulate the spectral content of the short-period (30-300 s) Doppler frequency fluctuations of lower F region echoes during daytime in the electrojet belt. This finding further strengthens our interpretation that the convective motions of electrojet irregularities are the basic cause of the commonly noticed short-period Doppler frequency oscillations of F region echoes. The physical basis for the interpretation may be summarized as follows. It is well known from earlier work that under nonflare conditions and for normal incidence sounding, plasma motions near the reflection level are most effective in producing changes in phase path of ionospheric reflections, though the latter represent integrated effects along the entire path [e.g., Davies and Baker, 1966; Georges, 1967]. Similarly, electron density irregularities near the reflection level are found to cause marked changes in the phase path of radio waves reflected at vertical incidence due to the rapid variations in the refractive index (μ) near the reflection point [see Robinson and Dyson, 1975 and references therein]. The effect of irregularities depends on their location relative to the reflection level (for values of $X = f_N^2/f^2 \geq 0.9$, where f is the probing frequency and f_N is the plasma frequency corresponding to the peak of the irregularities), their strength ($\Delta n/n$), and the background ionization gradient. The model calculations of Robinson and Dyson [1975] in particular showed that for a given gradient of background ionization, substantial changes in phase path can be produced by irregularities of greater strength even if they are located farther below the reflection height (i.e., for values of $X < 0.9$).

The plasma frequency (f_N) corresponding to the seat of the equatorial electrojet irregularities (E region) lies in the range 3.3 to 4.0 MHz during daytime. For the F region phase path measurements on 5.0 MHz (f) discussed here, X varies over the range from 0.43 to 0.64, and these values of X are lower than those ($X \sim 0.9$) that are known to have significant effects on phase path [Robinson and Dyson, 1975]. It is to be noted, however, that the model calculations of Robinson and Dyson [1975] correspond to weak irregularities ($\Delta n/n$ 1-5 %), whereas the electrojet irregularities are much stronger ($\Delta n/n$ 5-15%) and, as already mentioned, irregularities of greater strength can produce significant phase path changes even if they are located below the reflection level. Moreover, though irregularities close to reflection level ($X \geq 0.9$) are in general have strong effect on the phase path, this influence is less prominent if the probing frequency (f) is well above the gyrofrequency (f_H) because then the refractive index (μ) just approaches $\sqrt{1-X}$. Now for vertical incidence soundings near the dip equator (as at Kodaikanal) where the geomagnetic field is horizontal, μ for the 0 ray is always described by $\sqrt{1-X}$ so that this mode will not show the sudden onset of an increase of μ as X approaches 1 even if f is not well above f_H. The sounding conditions at Kodaikanal also thus favor the possible modulation of F region phase path during daytime by the turbulent motions of the electrojet irregularities. Our model calculations based on the generalized approach of Robinson and Dyson [1975], in fact, showed that the electrojet irregularities (Δ n/n 5-15%; altitude extent 5 km; see Basu et al., [1977]) can produce appreciable changes in phase path (ΔP) of F region echoes on 5.0 MHz over Kodaikanal (dip 3° N, $f_H = 1$ MHz) even though they are located well below the reflection height. The model estimates of the net change in phase path, Δp ($< 2\lambda$) are in good agreement with the observed peak-to-peak amplitudes of the short-period fluctuations in $\dot{P}$. According to this assessment of the effect of electrojet irregularities on F region phase path then, as the electrojet strength increases the amplitude and frequency of the $\dot{P}$ fluctuations of F region echoes (i.e., level of variance) are to increase due to the increase in the drift speed and strength of the irregularities. The later is the net result of an enhancement in the electrojet strength as expected from the linear theory of plasma instabilities in the electrojet and VHF radar observations [see Reddy and Devasia, 1976; Farley, 1985]. A positive relationship between the level of variance of $\dot{P}$ fluctuations and horizontal phase velocity of electrojet irregularities is therefore to exist. Moreover, under strong electrojet conditions when type I irregularities are generated in the electrojet, the variance level of the shorter-period (30-120 s) segment of the $\dot{P}$ fluctuations is to be high because these irregularities are shorter in wavelength compared to type II irregularities and move with higher speed (though saturated at the ion-acoustic speed). Both of these features are clearly seen in the present study. The results of the present study are in consonance with those obtained by us recently as regards the dependence of the manifestation and spectral content of the $\dot{P}$ fluctuations on the ambient electrojet strength [Sastri et al., 1991] because the strength of the electrojet and the phase velocities (Vp) of electrojet irregularities are interrelated and depend on the global electric field of dynamo origin. Taken together our results thus validate the interpretation that the turbulent state of the equatorial electrojet plasma is the primary cause of the short-period (30-300 s) Doppler frequency fluctuations of lower F region echoes at electrojet locations during daytime.

Multifrequency measurements of phase path (preferably near simultaneous) are nevertheless needed to establish the interpretation because they enable verification of the dependence of the spectral content of the short-period Doppler fluctuations on the probing frequency (f). As the probing frequency is varied the relative locations of the irregularities and the reflection level vary such that the amplitude of the Doppler fluctuations is a maximum at frequencies corresponding to the plasma frequency of the seat of the irregularities ($\sim$ 3.5 MHz) and decreases as the sounding frequency is raised well beyond 5.0 MHz. The multifrequency phase path data will also help test the alternative interpretation of the $\dot{P}$ fluctuations in terms of vertically propagating acoustic waves which is discounted on logical grounds but not yet conclusively disproved. Efforts are in progress to upgrade the phase path sounder at Kodaikanal with multifrequency probing facility. The electrojet modulation of lower F region phase path variations at Kodaikanal, if confirmed by multifrequency phase path measurements, will find two important and immediate applications. First, because of their sensitivity to ambient electrojet conditions the high-frequency component of F region Doppler variations hold the promise of providing indirect information on the regime of the electrojet irregularities and their phase velocities. The later forms the primary data from which the equatorial electric field is estimated [see Reddy et al., 1987]. Campaign mode of observations are due to be conducted at Thumba and Kodaikanal to generate an extensive data base to develop and test emperical relationships between the variance level of 30-300 s /30-120 s Doppler fluctuations and V_p at different altitudes in the electrojet. Second, the HF Doppler data can be used to derive reliable and valuable data on F region vertical plasma drift (V_{zf}) at electrojet latitudes by adopting appropriate filtering techniques to minimize the contribution due to phase path changes caused by electrojet irregularities below the reflection level. This is warranted because the peak-to-peak amplitude of the Doppler variations due to electrojet irregularities (6-18 ms^{-1}) are comparable to those associated with the normal vertical plasma drifts (10-30 ms^{-1}) during daytime.

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