Preliminary comparisons of VHF radar maps of F-region irregularities with scintillations in the equatorial region

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Abstract—Multi-antenna 50 MHz radar backscatter maps of echo power from night-time F-region equatorial irregularities obtained at Jicamarca, Peru were compared with simultaneous VHF scintillation observations from Huancayo at 137 and 254 MHz during the period 20 November–12 December 1975. Saturation of VHF scintillations in excess of 20 dB was observed at both these frequencies during times when radar maps showed large intense plume structures rising into the topside ionosphere. On nights when only thin layers of bottomside irregularities were observed moderate to weak scintillations were recorded at VHF. Preliminary values of east–west horizontal irregularity drift velocities were obtained and compared with scintillation rate observations. Using the 1.5° and 4.5° longitudinal separation between the Jicamarca radar and ionospheric observation points of the two satellites from Huancayo, information was derived regarding large-scale east–west structure during the development phase of the irregularities.

INTRODUCTION

Radio star and satellite scintillation studies as well as VHF radar backscatter observations of night-time equatorial F-region irregularities have been carried out extensively over the past decade. The scintillation technique reveals the integrated effect on radio signals of propagation through the ionosphere and, as such, is of immense practical value for channel-modelling considerations. Radar backscatter and recent in situ observations have, however, been more fruitful in providing ideas regarding the detailed structure and origin of the irregularities causing scintillations. BASU and KELLEY (1977) have reviewed these recent developments and have pointed out that a better understanding of the scintillation phenomenon can be obtained if scintillation studies are coordinated with radar and in situ observations of equatorial irregularities. In this paper we shall present such a preliminary comparative study of high resolution radar backscatter maps of F-region irregularities made at Jicamarca, Peru, with scintillation observations made at Huancayo.

Recent improvements in observational and computing techniques at the Jicamarca Radar Observatory have provided new methods of studying equatorial irregularities. The first generation of programs using a new data processing system has yielded rather dramatic two-dimensional radar-time-intensity maps of night-time F-region irregularities (WOODMAN and LA HOZ, 1976). These maps have clarified many details of the behavior of the irregularities, which according to FARLEY et al. (1970), at least at the 3-m scale size to which the Jicamarca radar responds, are often of large amplitude (at least 70–80 dB above the incoherent scatter level) and often occur in relatively thick layers occasionally extending well into the topside ionosphere, to equatorial altitudes of at least 1000 km.

In a modification of the new radar mapping techniques, sets of three such high resolution maps have been obtained by using three independent radars to simultaneously probe three nearly adjacent volumes. The object of this new multi-antenna irregularity mapping technique is to add a new dimension to the
maps of Woodman and La Hoz in order to study the development and the east-west drift of the irregularities. Recent in situ observations have clarified the relationship between the drift of equatorial irregularities and the background plasma.

Data from the Atmosphere Explorer (AE-C) satellite (McClure et al., 1977) show that large-scale (10 to 200 km) irregular plasma convection is associated with equatorial irregularities. Plasma from the lower F-region, rich in molecular ions but having small total ion concentration $N_t$, drifts rapidly upward into the topside ionosphere. This phenomenon appears in the AE data on ion drifts (electric fields) and $N_t$ as moving plasma depletions of up to 3 decades (holes or 'bubbles') in the ionosphere. The observed velocities reach 150 m/sec or more, directed upward but also westward with respect to the background plasma. Similar upward motion was also observed during the combined rocket and radar study conducted by Kelley et al. (1976). Such motion must of course stop at some point, and the AE data show that most of the equatorial irregularities observed (i.e. most of the large $N_t$ depletions or bubbles and almost all of the smaller amplitude $N_t$ fluctuation) do in fact move with approximately the velocity of the background plasma. This has led McClure et al. (1977) to suggest that in some cases the east-west background ionospheric drift as well as the irregularity drift velocity could be obtained from multi-antenna radar maps of the type mentioned above.

In this comparative study it is our object to determine the association of VHF scintillation activity with radar backscatter intensity and thickness of scattering layer in an effort to explain some of the most important aspects of equatorial scintillation, such as, its rather abrupt and dramatic onset and saturation at the 20-dB level in the VHF-UHF range (Aarons, 1977). Also the scintillation fading rate which is of importance in fast data transmission systems, is found to vary considerably as a function of time from evening to post midnight hours. The concurrent east-west irregularity drifts provide clues regarding the rate variation.

Scintillation data at Huancayo were available from two satellites ATS-3 at 137 MHz and LES-6 at 254 MHz with ionospheric intersection points (at 350 km level) at 170 km and 450 km east of Jicamarca. The relative separation of the three radar beams and ionospheric intersection points to the two satellites are shown in Fig. 1. It is unfortunate that neither ray path is contained within the volume probed by the Jicamarca radar, but on the other hand the relatively large separation might be expected to yield in formation regarding large scale east-west structure and motions at the equator.

It is important to note that VHF scintillations are sensitive to irregularities of scale sizes of the order of 1 km (near their Fresnel dimension) whereas the radar is sensitive to irregularities smaller by over two orders of magnitude. However, as early as 1970, Farley et al., came to the conclusion that km scale irregularities are generally observed in conjunction with strong small scale radar irregularities. Analysis of recent rocket data (Costa and Kelley, 1976; Morse et al., 1977) and theoretical computations (Haerendel, 1974) have also confirmed this postulate. Thus it seems plausible to use the radar measurements of scattered power as tracers of the larger irregularities, although in some cases the two may vary independently.
Fig. 2. Multi antenna 50 MHz backscatter power maps of nighttime F-region irregularities obtained at Jicamarca on 10–11 December 1975.
Fig. 3. Backscatter power map using Antenna C, horizontal irregularity drifts derived from multiantenna radar maps, scintillation amplitude and fading rates at 137 MHz obtained on 10-11 December 1975.
Fig. 4. Multiantenna 50 MHz backscatter power maps of night-time F-region irregularities obtained at Jicamarca on 20-21 November 1975.
Fig. 5. Backscatter power map using Antenna C, horizontal irregularity drifts from multiantenna radar maps, scintillation amplitude and fading rates at 137 MHz obtained on 20–21 November 1975. Note the rapid growth of scintillation amplitude in conjunction with thickening of irregularity layer.
RESULTS AND DISCUSSIONS

Multiantenna 50 MHz radar backscatter maps of echo power from ionospheric irregularities were obtained at Jicamarca (dip 2°N) on 11 nights within the period 20 November to 12 December 1975 using a modification of techniques developed by Woodman and LaHoz (1976). Three independent radars were simultaneously used to probe three almost adjacent volumes of space separated in the east-west direction by 6% of the altitude. Scintillation data during this period were available at Huancayo (dip 2°N) from ATS-3 to LES-6. The radar data obtained on 10-11 December is shown in Fig. 2 where orientation of Antennae A, B, C are as shown in Fig. 1. The scale of echo power on this map is logarithmic and hence a large power range, close to 5 orders of magnitude, exists between the darkest (48 dB) and lightest tones representing the 3 m irregularities. The 0 dB reference level is larger than the measurement uncertainty which for the 20-sec integration time used is larger than the incoherent scatter level. The abscissa and ordinate on these maps have the same scale for an eastward drift of 125 m/sec which corresponds to a typical wind velocity for 2100 LT (Woodman, 1972). This means that the maps could be interpreted as looking southward toward an east-west vertical cut of the ionosphere. This interpretation would be valid for any structure that is rigid and unchanging with time and which moves eastward, with horizontal velocities of 125 m/sec. We shall see later from the 2-satellite scintillation and radar data that this assumption does not hold always over distances of the order of 100 km and hence this interpretation should not be extended over large distances or time scales longer than a few tens of minutes. An elementary resolution cell on these plots is 5 km in altitude and the integration period is 20 sec as mentioned earlier. The plots do not include distance squared or antenna pattern corrections.

Figure 2 shows a typical situation for days when irregularities are confined to the bottoms of the only. Although concurrent electron density profiles are not available from Jicamarca, a reference to the ionosonde data taken at Huancayo shows that the irregularities are observed on the bottoms of the layer. One particularly interesting aspect of this data is the appearance of patches of irregularities at altitudes of 500 and 700 km in the topside ionosphere, above the pre-existing thin layer near 0500 LT. It should be noted that in December this time is well past ionospheric sunrise at Jicamarca.

As indicated earlier, one object of the 3-map technique was to derive east-west horizontal drift velocities of irregularity patches in the F-region. This is done by identifying a specific signature of the irregularities on all 3 maps and measuring the relative time shift between them. The drift velocities presented in this paper should be considered preliminary with final values to be published later. We shall use the derived drift speeds as well as backscattering amplitude and layer thickness and try to relate them to ATS-3 scintillation amplitude and rates. Since Antenna C refers to a volume closest to the Huancayo ATS-3 observations, we shall compare the scintillation observations with this specific backscatter map.

Figure 3 shows the Antenna A and B panels of Fig. 2 replaced by the scintillation amplitude and fading rate at 137 MHz obtained by using ATS-3 transmissions and the horizontal irregularity drift velocities determined by the use of the Jicamarca radars. The backscatter echoes begin at 2005 while scintillations at Huancayo start at 2015. The thin layer of well developed irregularities gives rise to moderate VHF scintillations. Except for a 5-min period when 12 dB amplitude scintillation was observed, the activity was rather weak compared to the average night-time behaviour of scintillations during the December solstice under quiet magnetic conditions at Huancayo (Aaron, 1977). Thus it seems that the weak scintillations are probably due to a thin layer of km scale irregularities which are associated with the 3-m scale sizes.

Small increases in scintillation activity are correlated with the appearance of isolated structures in the radar data near 2200 hr, near midnight and also at 0500 hr. The east-west scale of generation of these irregularities appears to be at least about 200 km since they are observed near simultaneously at Jicamarca and Huancayo. This is the only occasion in 1975 when radar maps were obtained past ionospheric sunrise. However scintillation data is available for the entire period of these observations from 20 November to 12 December 1975 and 50% of the days show similar increase of scintillations near 0500 LT. The magnitude of the scintillation increase is sometimes as large as 6 dB at 137 MHz. This apparent intensification of irregularities after sunrise is an interesting subject for further study.

The average irregularity drift velocity derived from the radar data is approximately 100 m/sec eastwards in the pre-midnight hours. A reversal in the drift direction is seen past midnight. Earlier spaced receiver observations have also occasionally detected such reversals in the drift direction (Clemesha and Wright, 1966). Also, doppler velocity measurements at Jicamarca occasionally show such reversals (C. Calderon, private communication, 1976). The drift magnitude is less than or equal to 100 m/sec in the
post-midnight hours except for one data point derived from the new patch passing overhead near 0500 LT. However, this velocity measurement should be considered somewhat dubious because it was derived from the patch at 500 km altitude which was clearly changing as it drifted westward and downward.

The scintillation fading rates have been obtained by visual inspection. The relative scales for the drift velocity and fading rate have been so chosen that a Fresnel dimension of 1 km (which is appropriate for this frequency at 400 km height) when moving at a velocity of 100 m/sec would give rise to 6 fades/min. Thus for eastward velocities the two curves are expected to be close together if Fresnel filtering conditions apply. This is only true for weak scatter conditions as observed on this occasion. The fading rate is 14/min at 2200 LT and becomes as slow as 2/min in the post midnight and early morning hours. This is a characteristic feature of scintillations at Huancayo. The dashed line indicates unreliable fading rates because of the low amplitude of scintillations. Though a general association of drift velocity magnitudes and fading rates is noted, the agreement obviously is far from perfect, particularly around 2200 LT. It is to be pointed out however, that a reliable estimate of fading rates can only be obtained from power spectral analysis of scintillations. Unfortunately the present scintillation data were not recorded on magnetic tape and hence are unsuitable for such analysis. A further series of coordinated measurements planned for October 1976 will make such studies possible. It is interesting to note that the average behaviour of horizontal (doppler) drifts in the night-time F-region deduced from incoherent scatter measurements shows a maximum around 2100–2200 LT decreasing gradually in the post midnight hours until 0500 LT the direction reverse (Woodman, 1972, and unpublished results, 1976).

A dramatically different irregularity picture with the irregularities extending far into the topside is obtained on the night of 20–21 November as shown in Fig. 4. In this case also the irregularities exist as a thin layer on the bottomside when observations start at 1950 LT, but the height is approximately 100 km higher than that observed in Fig. 2. By 2010 LT the layer is observed to thicken and by 2020 LT the irregularity layer is from 200 to 400 km thick, the thickest layer being observed first on the westward Antenna A. Discrete upwellings are evident at time intervals of half hour to one hour and echoes are observed from heights up to 800 km. The irregularity intensity weakens considerably beyond 2200 hr (particularly on Antenna C) and in the post midnight hours both intensity and thickness are drastically reduced.

A time history of scintillation amplitude and rate as well as irregularity drift velocities are shown in Fig. 5 in conjunction with the radar map obtained with Antenna C. The remarkable aspect of the scintillation amplitude is its rapid development from 4 dB at 1955 LT to 20 dB at 2010 LT, that is, a 16-dB increase in 15 min. This explosive growth in scintillation amplitude is observed in association with the intensification and thickening of the 3-m irregularity layer observed at Jicamarca. Thus the near simultaneous growth of scintillation amplitude and backscatter amplitude could indicate a simultaneous production of large amplitude irregularities over three decades of scale lengths. It is interesting to note that this is one of the predictions of Haerendel’s (1974) work on the non-linear development of a hierarchy of irregularities.

Costa and Kelley (1976) have modelled the effect of one such upwelling structure or ‘plume’ on scintillations and showed that the power-law type irregularity spectrum with more power in the requisite wavenumber regime could indeed explain saturated scintillations at VHF and moderate scintillations at GHz even before the irregularity layer became a few hundred km thick. It is interesting to note that the scintillations do not lag behind the plume structures by 10 min or more as they would have if the irregularities observed by the Jicamarca radar had travelled rigidly in an eastward direction with the observed mean velocity of 200 m/sec. The near simultaneous onset of intense scintillations at Huancayo and plume development at Jicamarca probably indicates that the scale of generation is of the order of 200 km. This value is within the range of ‘bubble’ sizes (10 to over 200 km) observed by the AE-C in the night-time equatorial F-region (McClure et al., 1977).

In the later stages, it seems quite evident from the radar map that the intense VHF scintillations are caused by a thick irregularity layer of large amplitude extending over several hundred km in a region of high ambient density as discussed by Basu and Basu (1976). The $f_{o}F2$ was 9 MHz at 2000 LT before the onset of strong spread-$F$ made further readings impossible. Although the scintillation data is saturated at times, several distinct scintillation enhancements can still be associated with the plume-like structures. It would be interesting to make a similar comparative study with scintillations at GHz as it is probable that only such thick structures cause scintillations in that range.

The preliminary values of horizontal irregularity drift velocities observed before 2110 LT are larger
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Fig. 6. 50 MHz backscatter power map obtained on 28 September 1973 and scintillation index in dB obtained from ATS-3 and LES-6 at 137 MHz and 254 MHz respectively. Note the earlier onset of intense scintillation activity on LES-6.

than the expected background plasma drift of 100–150 m/sec and larger than those measured by the irregularity technique later this night and on the night of 10–11 December shown in Fig. 3. Much of the substructure within the first two plumes slopes upward with increasing time, whereas that of the last two plumes is more nearly horizontal. According to Woodman and La Hoz (1976) the doppler shifts to be expected from such upward sloping patches would be negative indicating upward drift corresponding approximately with the slope of the patch. Reliable horizontal irregularity drifts probably cannot be obtained from radar maps while such vertical motion exists. Also under these circumstances the horizontal irregularity and background plasma drifts are not identical (McClure et al., 1977). In the later two plumes the traces are much more nearly horizontal and the derived drift velocities are in the range 100–150 m/sec.

It is interesting to note that these plumes contain rather weak irregularities and are not associated with increases in scintillation amplitude. It is possible that these weak plumes may have formed west of Jicamarca and later drifted over the radar while the first two plumes could have formed locally.

The fading rates show clear increases with the increase in scintillation amplitude. The level of scintillations is such that the scattering conditions conform to the strong-scatter regime. Under such conditions the scale of the diffraction pattern becomes less than the Fresnel dimension by a factor which depends on the phase deviation suffered by the radio wave (Prokhorov et al., 1975). Thus it is quite reasonable to expect fading rates much greater than those to be expected from Fresnel filtering considerations in the weak-scatter regime. Beyond 2300 LT when the scintillation magnitude decreases, the fade rates decrease...
as well as the observed drift velocities. It was pointed out earlier that such slow scintillations are a characteristic feature of the decaying phase of scintillations.

Multiantenna maps were obtained on 11 nights in the November–December 1975 period. Of these, 5 nights showed plume-like structures generally similar to that shown in Fig. 3 while the other 6 were similar to the bottomside irregularity structure shown in Fig. 2. While a better understanding has been obtained regarding the generation of equatorial irregularities (Basu and Kelley, 1977, and references therein) it is not at all clear why there should be such great variability in irregularity behaviour from one night to another. Scintillations show saturation in excess of 20 dB level on nights with thick irregularity layers while the activity is much less severe when only a thin layer of bottomside irregularities is observed.

As mentioned before, scintillation data from LES-6 are also available at Huancayo. The satellite has some spin which makes the rate determination somewhat unreliable. Moreover, between 2100 and 2300 LT the signal level drops drastically on a regular basis so that scintillation amplitude cannot be measured. However, during the development phase of the irregularities particularly on evenings when saturated VHF scintillation is observed, the LES-6 intersection point usually shows an earlier onset in keeping with its more eastward location. This is best exhibited by Fig. 6 which is an enlarged backscatter map taken from Woodman and La Hoz (1976). While a 20 dB saturation level is observed on the ATS-3 raypath at 1945 LT in conjunction with a thick 3 m irregularity layer, LES-6 observations denote the same level as early as 1910. Thus it seems that one of the plume like structures developed near the LES-6 point approximately half hour before plumes appeared at the Jicamarca radar. The local time difference between Jicamarca and the LES-6 point is approximately 20 min. The concept of irregularities drifting rigidly eastward thus cannot be extended over distances of the order of a few hundred km in the developing phase as fresh generation is also taking place simultaneously.

CONCLUSIONS

This preliminary correlated study of 50 MHz backscatter radar maps of F-region irregularities and VHF scintillations has shown that intense long lasting equatorial scintillations are observed when large amplitude irregularities in a region of high ambient ionization are distributed over thick layers. The abrupt onset of intense scintillations in the evening hours is shown to be associated with the development of a plume-like irregularity structure extending into the topside. Weak scintillations, on the other hand, are caused by a thin layer of F-region irregularities. With the help of multisatellite scintillation and radar observations it has been shown that in the developing phase of irregularities, the concept of plumes drifting rigidly eastward cannot be extended over large distances as fresh generation is also taking place. The day-to-day variability of night-time irregularity occurrence and intensification of irregularity structures after ionospheric sunrise are problems deserving further attention.

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