Radio backscatter studies in South Europe of the Midlatitude E Region Ionosphere

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Using a VHF radio Doppler system in Crete, Greece, and a large HF radar in south-east France, several experiments were performed in the last few years in order to study coherent backscatter from ionospheric *E* region plasma irregularities that occur in close relation with midlatitude sporadic *E* layers. Following a general introduction to the topic, the main observational findings obtained so far with these two radar experiments in South Europe are reviewed in an effort to document their physical significance and assess their advances in the present state of knowledge.

Background

The strongest radio wave scatter in the Earth's ionosphere occurs in the *E* region, mostly at the magnetic equator and the auroral zones and less frequently and intensely at midlatitude. These phenomena, which take place in the altitude range from about 95 to 115 km, can be detected only if the incident radio wave vector is perpendicular to the Earth's magnetic field. Note that in the weak scattering theory, e.g., see *Farley* [1971], coherent scatter occurs only if wavelike plasma density inhomogeneities propagate along the bisector of the scattering angle, that is, the angle Q between the incident and scattered radio wave vectors, and have a wavelength $l_{ir} = l_r / (2\sin Q/2)$, where l_r is the radar wavelength; for backscatter $Q = 180^o$, and thus $l_{ir} = l_r/2$. This means the scattering is caused by short-scale electron density fluctuations which are spatially coherent only in directions perpendicular to the magnetic field. The latter, known as magnetic aspect sensitivity, is a consequence of the strong electron magnetization which restricts electron motion perpendicular to the geomagnetic filed **B**, therefore allowing for plasma density wave generation and growth to occur only in directions close to perpendicularity because in these directions plasma diffusion is minimal.

On the other hand, the basic underlying physical reason for the strong backscatter to occur near the *E* region peak is the unique plasma properties at these heights which dictate different mobilities for the electrons and ions. There, the massive ions are unmagnetized because their motion is controlled by collisions with the much more numerous neutral particles, whereas the light electrons are strongly magnetized since their gyrofrequency W_e is much greater than the electron-neutral collision frequency n_e. This inherent plasma property leads to an electron-ion drift motion $\boldsymbol{V}_i - \boldsymbol{V}_e$ in the presence of an ambient electric field **E**, and therefore to an electric current. The *E* region currents, either alone or in combination with ambient gradients in electron density, provide the free energy that generates the aspect-sensitive electrostatic plasma waves, through plasma instability mechanisms and nonlinear interactions, that scatter HF and VHF radio waves.

After many years of intensive research, it is now established that the main instability mechanisms which operate in the *E* region plasma are the modified two stream, or Farley-Buneman, instability and the gradient drift instability (e.g., see classic review by *Fejer and Kelley* [1980]). As mentioned, the most intense *E* region scatter occurs at the magnetic equator and auroral zones. This is because of favorable magnetic field geometries and relatively large electric fields which combine to generate the strongest currents in the ionosphere, that is, the equatorial and auroral electrojets. Many studies show (e.g., see reviews by *Fejer and Kelley,* 1980 and *Haldoupis,* 1989) that in these regions the key role in plasma destabilization is played by the relatively large electric fields present, which means that the Farley-Buneman instability operates there routinely in generating meter-scale irregularities.

On the other hand, at midlatitude a key feature for instability generation is the close connection with E_s layers which are characterized by large abundance in heavy metallic ions and sharp vertical gradients in plasma density. Given that ambient electric fields at midlatitude are small, the destabilization of plasma irregularities is attributed to the gradient drift instability rather than the two stream instability.

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Figure 1 sketches the observing geometry for backscatter measurements at midlatitude in the presence of a sporadic *E* layer. As pointed out first by *Ecklund et al.* [1981], in this picture one would expect the generation of gradient drift irregularities near the top of E_s when the ambient electric field has a southward and downward component, and near the bottom of E_s if the electric field has a component pointing northward and upward. Although these irregularities propagate preferentially in the zonal direction, their wave energy may cascade through nonlinear wave-wave interactions to shorter scale secondary waves (e.g., *Sudan* [1983]). The latter, which presumably propagate in all directions perpendicular to the magnetic field, are believed to be responsible for the observed coherent radio wave backscatter at midlatitude.

Prior to 1990 nearly all *E* region backscatter research was conducted in equatorial and auroral latitudes, with very few radar studies made at midlatitudes. In the last few years, however, the situation has reversed and the interest in the midlatitude *E* region has grown remarkably. This trend actually started about 10 years ago with the deployment and operation of the large Middle and Upper atmosphere (MU) radar near Kyoto, Japan and the detection of some interesting range-time-intensity (RTI) radar signatures which came to be known in the literature as midlatitude Quasi-Periodic (QP) echoes (e.g., see *Yamamoto et al.* [1991]). Since then, several radar systems and experiments were put in operation at midlatitudes for the study of *E* region plasma instabilities and for investigating the physics of interaction between the motions of the neutral atmosphere and the *E* region plasma (e.g., see a recent paper by *Hysell and Burchmam* [2000] and references therein). The purpose of this report is to highlight the midlatitude *E* region backscatter findings contributed from the European sector with the SESCAT experiment in Crete, Greece and the SPOREX experiment in South France.

SESCAT: Experiment description and results

SESCAT, an acronym for Sporadic E SCATter experiment, is a continuous wave (CW) Doppler radar which started operation in 1992. As shown in Figure 2, the experiment is located along the northern coastline of Crete, Greece at about 35° N geographic latitude and 24° E geographic longitude, ~28° N geomagnetic latitude, and 50° magnetic dip angle. The system operates at 50.52 MHz with the transmitter and receiver arrays beaming northward to a region perpendicular to the Earth's magnetic field at *E* region peak electron density altitudes. As seen in Figure 3, which shows a view of the receiver site in western Crete, the antenna arrays consist of four 11-element Yagis antennas which give an array beamwidth of 8°. The intersection of the transmitting and receiving antenna array patterns defines an *E* region observing area of about 15x30 km^2 located in the central Aegean sea near 30.8° invariant geomagnetic latitude (*L* shell value = 1.35, magnetic dip *I* = 52.5°, magnetic declination D = 2.5°). As seen from Figure 2, the observing direction, which is along the bisector of the transmitter and receiver line-of-sights (wave vectors), points about 5.5° east of geomagnetic north and thus SESCAT observes nearly along the geomagnetic meridian. Although it cannot give range resolution, SESCAT has the advantage of providing excellent time and Doppler spectrum resolution. The data acquisition was based on a DSP (digital signal processor) unit and was fully automated to perform FFT (Fast Fourier Transform) analysis in real time and average the Doppler spectra, which had a 3.8 m/s Doppler velocity resolution, over ~ 5 s. More details about SESCAT are given by *Haldoupis and Schlegel* [1993].

Soon after its initial operation, SESCAT observations indicated that 50 MHz backscatter events with relative power of 10 to 25 dB and lifetimes of a few minutes to more than an hour do occur at midlatitudes, in accordance with

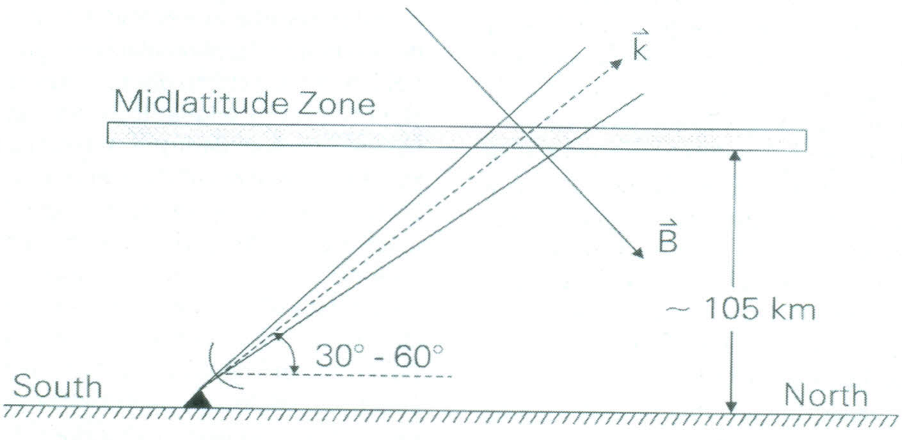

***Figure1.** Observing geometry for the detection of coherent radar backscatter from field-aligned irregularities in the midlatitude* E *region ionosphere*

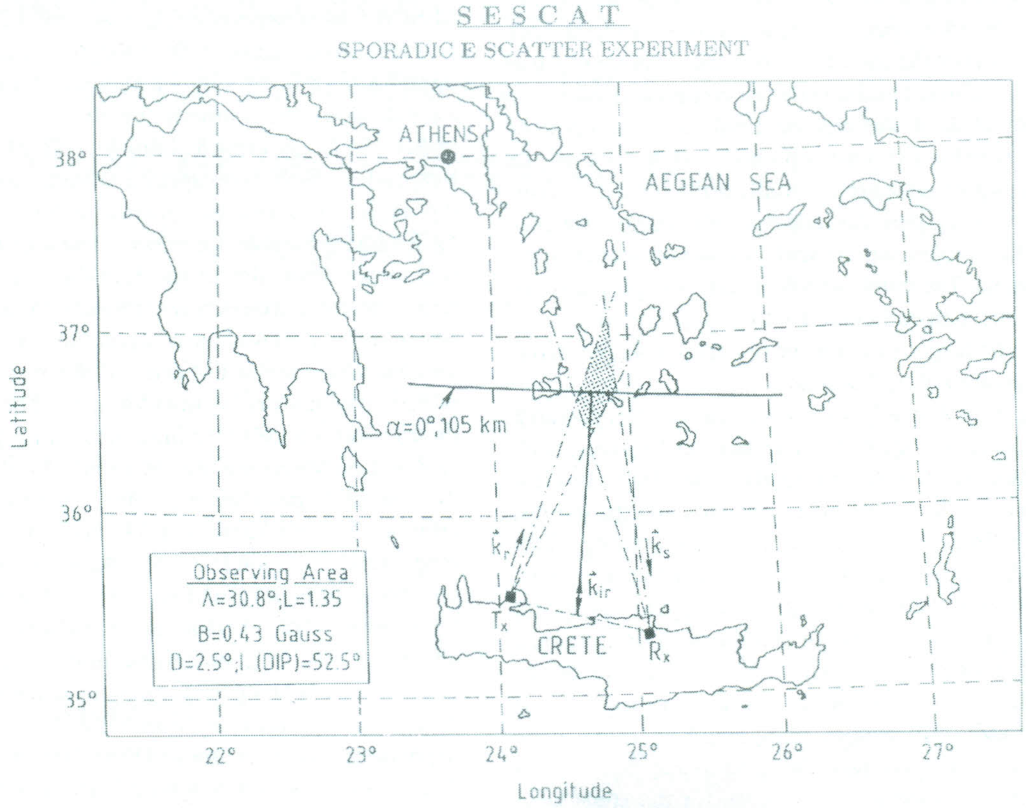

Figure 2. *Location and observing geometry of the Sporadic* E *Scatter experiment (SESCAT) in Crete, Greece.*

past experiments that related these echoes to sporadic *E* layers. The observed events, except for very few early afternoon cases, occurred during dark hours in the period between a few hours before and after local midnight. The backscatter was at times continuous but in many cases a quasi-periodic behavior was found with periods between 1 and 15 min. Backscatter is most often associated with symmetric Doppler spectra with mean velocities usually propagating northward and having magnitudes usually less than 100 m/s and mean spectral widths from 50 to 150 m/s. In terms of spectral width, the midlatitude *E* region echoes do not compare well with low velocity type 2 echoes from the equatorial and auroral electrojets where Doppler spectra are much broader and identify with secondary irregularities (e.g., see review papers by *Fejer and Kelley* [1980] and *Haldoupis* [1989]). On the basis of statistical evidence, it was concluded that 50-MHz midlatitude echoes are largely due to secondary irregularities generated during conditions of weak plasma turbulence.

Being an inexpensive experiment to run, SESCAT operated continuously for long periods of time and collected vast amounts of data which allowed detailed morphological and statistical studies [*Haldoupis and Schlegel*, 1996]. Based on one and a half years of continuous operation, a striking morphological pattern was established having a strong seasonal and diurnal character. The echoes, which showed no significant dependence on Kp index, appeared only during nighttime mostly in the pre-midnight local time sector. The absence of daytime echoes meant possibly that the gradient drift instability was inoperable during the day, probably because of electron density gradient smoothing due to strong solar photoionization production and electric field shortening effects due to conductivity enhancements. With respect to season, there was an abrupt rise in the number of echoes during the second half of May, followed by a broad maximum in the June-July period and a sharp decline in early September. Strong echoes were virtually nonexistent in the period from November to April. The seasonal echo occurrence follows exactly the seasonal morphology of strong E_s layers, a fact which reinforces the close relation believed to exist between the two phenomena. Finally, mean Doppler velocities were found to be larger in amplitude, but to vary approximately in phase with, both the ambient northward and upward **E** x **B** drifts and the neutral winds, as inferred from past incoherent scatter radar measurements and model predictions of the mean meridional wind, respectively.

We believe the most important contribution of SESCAT was the discovery of pure Farley-Buneman plasma waves in the midlatitude *E* region ionosphere. These are

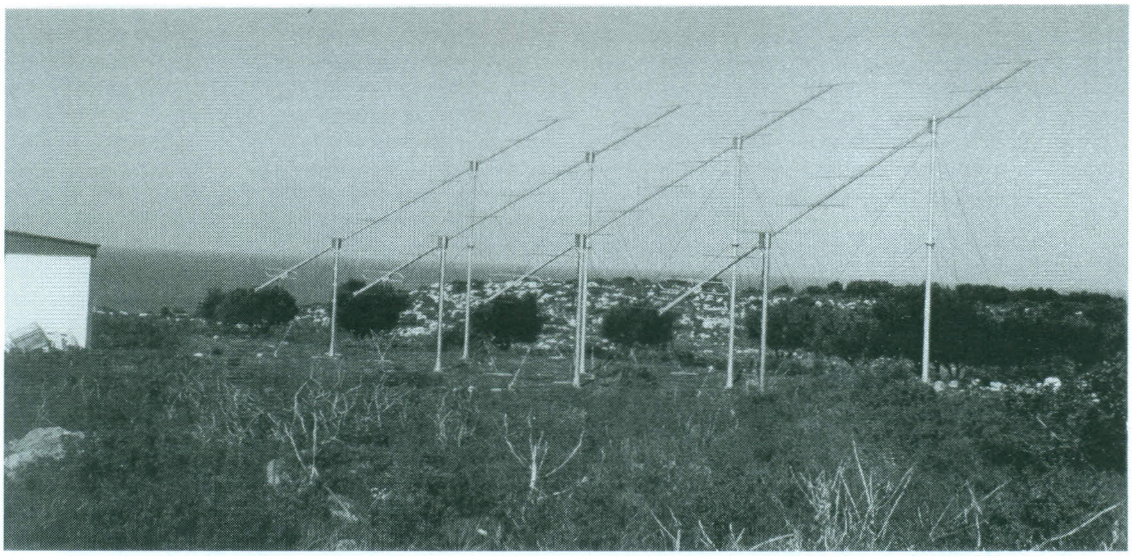

Figure 3. *A View of the SESCAT receiver array near the city of Chanea, west Crete*

identified with type 1 echoes that have relatively narrow Doppler spectra peaking at velocities near the plasma ion acoustic speed. Contrary to that anticipated, SESCAT showed that the Farley-Buneman instability can indeed operate for brief times in the midlatitude E region as well. The first clear evidence in favor of midlatitude type 1 irregularities was a single event presented and analyzed in detail by *Schlegel and Haldoupis* [1994]. *Haldoupis et al.* [1997] presented more evidence and statistics showing that type 1 echoes constituted a small but distinct subset of 50 MHz midlatitude coherent backscatter. These echoes were relatively rare and occurred sporadically in the summer nighttime. They lasted from several seconds to many minutes and had narrow Doppler spectral peaks corresponding to wave phase velocities from 250 to 350 m/s. On the average these values are about 20 % lower than nominal E region ion acoustic speed values, which represent the required threshold for instability. The measured lower type 1 velocities were probably because the instability occurred inside E_s layers where heavy metallic ions constitute the main ion population. This can lead to an increased mean ionic mass and thus to a reduced ion acoustic speed threshold. Figure 4, which is published here for first time, shows the longest lasting (for about half an hour) midlatitude type 1 echoes ever detected by SESCAT.

The midlatitude type 1 observations implied the existence of unexpectedly large electric fields; an order of magnitude higher than the prevailing ambient dynamo field on the average. To explain the origin of midlatitude type 1 echoes, *Haldoupis et al.* [1996a] proposed that the large fields required are simply polarization electric fields which can arise locally when nighttime sporadic E layer patches had the right geometry in relation to the magnetic field. They suggested that such fields could be generated by the same polarization process as at the magnetic equator, but with the geometry *turned on its side*. That is, they assumed that there were sharp horizontal conductivity gradients associated with patchy nighttime metallic ion layers that play the same role that vertical gradients play at the equator. In this mechanism, sharp gradients, particularly in the zonal direction, could lead to polarization fields more than an order of magnitude greater than the ambient dynamo fields. These polarization fields are sufficient to excite the Farley-Buneman instability in meridional directions, as implied by the SESCAT data.

The first simplified quantitative model of the proposed local polarization process was developed by *Shalimov et al.* [1998]. By including the effects of field aligned currents in the current continuity equation, they produced approximate analytical expressions which estimated the necessary conditions of the zonal versus meridional E layer extent and the ratio of the integrated Pedersen conductivity above and inside the layer for the generation of large zonal and meridional polarization fields. Their numerical results showed that the polarization process can account for elevated electric fields of several mV/m which were often implied from the SESCAT Doppler measurements. Moreover, it was shown that the polarization process could become more effective for dense and strongly elongated E_s layers under the action of an enhanced ambient electric field so that the resulting fields can become sufficiently large to excite the Farley-Buneman instability. According to the model by *Shalimov et al.* [1998], the stringent requirements for strongly elongated sporadic E layers with sharp boundaries, the low ionospheric Pedersen conductivities above the layer in relation to those inside, and the need for relatively enhanced ambient electric fields, would explain why type 1 echoes are so rare in midlatitude E region backscatter.

One of the least known observational parameters in the E region plasma instabilities is the irregularity k-spectrum dependence. To gain some knowledge on the wavelength dependence of coherent VHF echoes, a dual radar experiment was performed using a similar CW radar as SESCAT, but operating at 144 MHz. The 144 MHz radar was brought to Crete from the University of

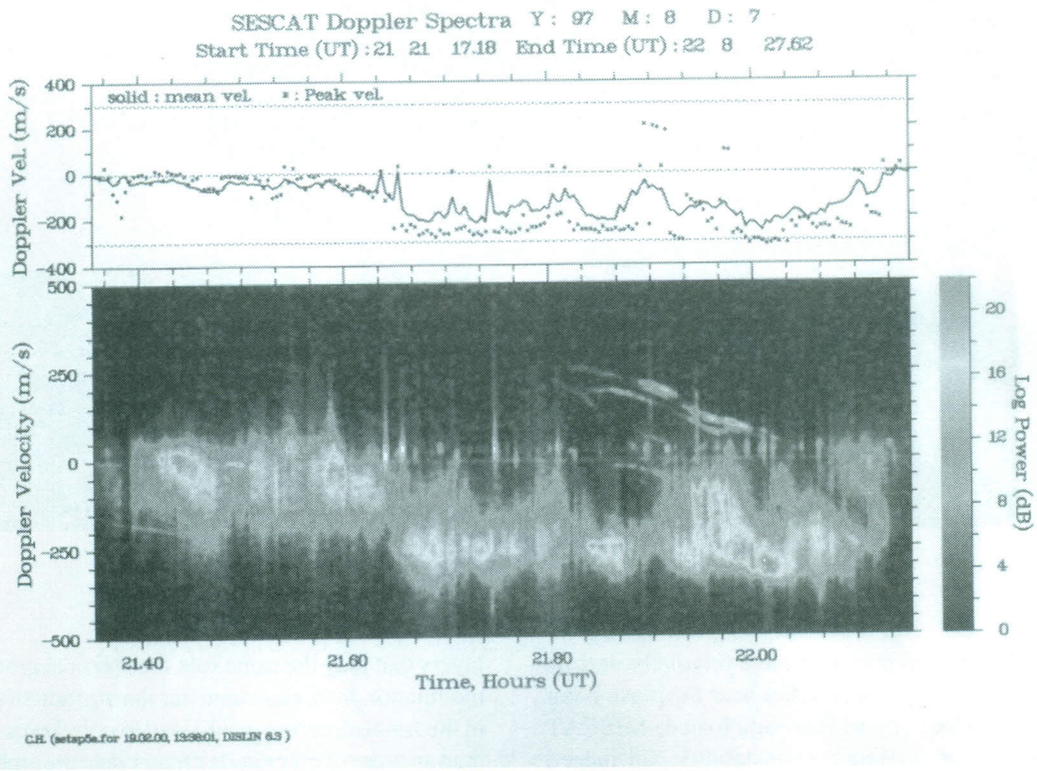

***Figure 4.** A SESCAT Doppler spectrogram showing the longest ever recorded interval of occurrence of type 1 irregularities (Farley-Buneman waves) at midlatitude. This implies that, in this event, electric fields exceeding 12 to 15 mV/m did prevail in the* E *region for about 25 min.*

Saskatchewan, Canada. The Canadian system used scaled antenna arrays at the SESCAT sites in order to observe the same *E* region volume as SESCAT. For the first time at midlatitudes, this made it possible to investigate simultaneous echoes from 3-m and 1-m irregularities in the same scattering volume. The observations demonstrated clearly the different character of type 1 and type 2 irregularities. The 144 MHz type 2 echoes were completely absent during times of weak to moderately strong 50 MHz backscatter activity and appeared only when the signal at 50 MHz was very strong with relative intensities exceeding 20 dB above noise. On the other hand and in sharp contrast to type 2 echoes, there was one to one correspondence in the occurrence of 50 MHz and 144 MHz type 1 echoes, even when the signal at 50 MHz was only a few dB above noise levels. By calibrating the measurements and assuming a power law *k*-dependence for the irregularity spatial spectrum, $I_k \mu k^{-b}$, the spectral slope *b* was found on the average to be about 1.0 and 2.8 for type 1 and type 2 irregularities, respectively. This suggested that the *k*-spectrum is nearly 3 times steeper for type 2 than type 1 waves in the meter wavelength range. The results of this dual frequency experiment are described in two papers by *Koehler et al.* [1997 and 1999].

SESCAT was operated for one summer with a Canadian Advanced Digital Ionosonde (CADI) which had been located in the island of Milos, almost beneath the SESCAT scattering volume. The purpose was to investigate in detail the relationship between VHF backscatter and midlatitude sporadic *E*. It was found that 50 MHz echoes occurred always in association with E_s. The statistical analysis indicated significant correlation between scatter power and E_s characteristics such as the layer's top frequency $f_t E_s$ (a measure of maximum E_s electron density) and the apparent E_s spread which results from range spreading due to oblique reflections from a non-uniform and horizontally inhomogeneous layer. The experiment confirmed that the presence of an E_s layer, which could provide destabilizing plasma density gradients perpendicular to the magnetic field, is necessary but not sufficient for the occurrence of 50 MHz backscatter. It was suggested that in addition there was need for a locally enhanced electric field to be present. This was in line with the observed correlation of backscatter with a dense but strongly inhomogeneous E_s layer and the proposed mechanism of strong polarization fields at midlatitude. For details about the SESCAT/CADI data comparison see *Hussey et al.* [1998].

In another study by *Voiculescu et al.* [1999], published as a highlight in *Geophysical Research Letters*, the large SESCAT data base was used to investigate the long term variability in echo occurrence. The backscatter was found to be dominated by quasi-periodic variations with periods in the range from about 2 days to 10 days, which persist for time intervals from about 10 to more than 20 days and have no relation to geomagnetic activity. The most commonly observed periods appeared in two preferential bands; that

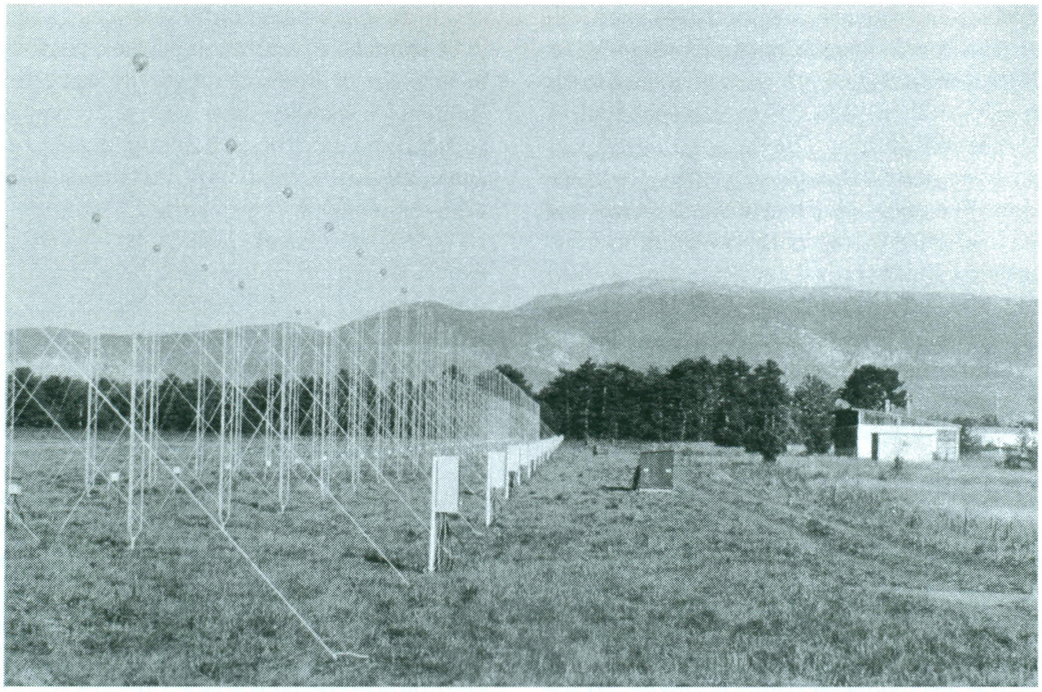

Figure 5. A view of the northward receiving array of the Valensole HF radar. The array consists of two rows of 48 vertical monopoles along a line of 560 m.

is, the 2 to 3 day and the 4 to 7 day band. Using concurrent ionosonde data, the variations in echo occurrence were found to be exactly in-phase with similar periodicities in the occurrence of relatively strong sporadic *E* layers. These findings constituted evidence in support of the possibility that planetary waves are responsible for the observed long-term periodicities in both E_s and echo occurrence, and suggested a close connection between the planetary wave morphology and the well known, but not well understood seasonal E_s dependence. This suggestion was taken up in a subsequent paper by *Shalimov et al.* [1999] who proposed a new mechanism for large-scale accumulation of metallic ions in the midlatitude *E* region driven by planetary waves in the lower thermosphere. In this process, the plasma is forced to converge horizontally and accumulate inside areas of positive vorticity set up by cyclonic neutral wind shears within a travelling planetary wave. Because of the long times required for ambipolar diffusion, the new mechanism can lead to significant plasma accumulation over large areas, thus acting as complementary to the vertical wind shear process so that dense E_s can form more efficiently and frequently. This new model provides the first physical base for understanding the long-period variations in occurrence and also the seasonal dependence of strong sporadic E layers at midlatitude. Finally, in a very recent paper by *Voiculescu et al.* [2000], the long-term periodicities in echo and E_s layer occurrence were compared directly with those in the neutral wind in the lower ionosphere (near 95 km) measured simultaneously from Collm, Germany. This comparison shows some reasonable agreement, which is the first direct indication in favor of a planetary wave role on the unstable midlatitude *E* region ionosphere.

SPOREX: Experiment description and results

SPOREX is an acronym for SPORadic E eXperiment, in which a large HF radar located near the town of Valensole in the south of France (43.8° N, 6.1° E geographic and 37.1° N, 82.2° geomagnetic) was used for midlatitude backscatter observations. This facility includes a monostatic oblique radar sounder and several large antenna arrays that cover the entire HF frequency band with 1 kHz resolution. It is a fully computerized multi-receiver system which can perform large azimuthal scans by using phased-array beam forming, to obtain in real time, full Doppler spectrum measurements over large regions of space. A unique characteristic of the system is its ability to operate in a multi-frequency mode by means of using a pulse-to-pulse frequency interlacing scheme within a given integration cycle. For transmission, the radar is equipped with two linear arrays of 16 broadband elements one beaming northward and the other westward. For reception, there are two large arrays made of vertical antenna elements. One is 1100 m long with a beamwidth of about 1° and covers east-west reception; the other is a 560 m long array with a beamwidth of 2° at 15 MHz and is used for northward or southward reception. Shown in Figure 5 is a view of the north-south receiving antenna array which was used for SPOREX experiments. The radar can be programmed to run under a variety of configurations. For more details on the radar system see [1995] and *Six et al.* [1996].

In SPOREX, the transmitter array was fixed and had a broad beamwidth, while the receiving array had a steering scheme which covered a large azimuthal sector extending from 26° east of north to about 58° west and the beamwidth was very narrow with a 2° angular resolution at 15 MHz. For SPOREX the transmitted waveform was adapted to the receiver bandwidth and consisted of Gaussian-shape pulses with pulse widths of 145 ms. The received signal was sampled every 18 km in 15 range gates extending between 100 and 370 km. The geographic location of the radar and the SPOREX field of view, which is centered near 37° invariant magnetic latitude (L ~ 1.7 and magnetic dip ~60°) are shown in Figure 6. Also shown across the field of view are the lines of zero magnetic aspect sensitivity at altitudes of 90, 100, 110 and 120~km. Finally, note that geographic and geomagnetic north are very close at Valensole because magnetic declination is only ~1°. SPOREX was run on a campaign basis for several weeks during consecutive summers from 1993 to 1998 using different multi-frequency and time averaging schemes, but keeping the same azimuthal coverage of about 84° over a 15-range times 42-azimuth grid. An example of azimuthal occurrence of Valensole backscatter is shown in Figure 7.

The first SPOREX paper by *Bourdillon et al.* [1995] was based on the 1993 summer campaign in which the experiment provided observations simultaneously at two frequencies of 9.0 and 14.8 MHz, which correspond to plasma backscatter wavelengths of from 16.7 and 10.1 m, respectively. The first results showed aspect-sensitive decameter-wavelength irregularities in the pre-midnight dark hours to have mean phase velocities less than 100 m/s and act as tracers of wavelike dynamic structures that drift westward with speeds in the 40 to 80 m/s range. These dynamic structures had characteristic lifetimes between 10 and 30 minutes and typical scale lengths between 40 and 90 km. In their interpretation these structures were considered to be sporadic E_s ionization patches, possibly affected by the passage of atmospheric gravity waves and/or Kelvin-Helmoltz instability shear waves, accompanied by both vertical and horizontal electron density gradients and enhanced electric fields which act to destabilize the plasma via the gradient drift instability.

In a subsequent paper by *Haldoupis et al.* [1996b], the dual frequency SPOREX-93 analysis showed that simultaneous Doppler velocities from largely shifted narrow spectra (presumably due to primary gradient drift decameter wavelength waves) were approximately equal for both 9.0 MHz (l_{ir} = 16.7 m) and 12.4 MHz (l_{ir} = 12.1 m) echoes. In a statistical treatment of the data, the velocity ratio $V_{12.1\,m}/V_{16.7\,m}$ was found to be somewhat less than 1.1; a ratio value well below the value of about 1.6 expected for the irregularity phase velocity ratio, if the widely-used assumption of wave velocity saturation at instability threshold is valid. On the other hand, the results of this study supported linear gradient drift theory predictions, that is, that the wave phase velocity of decameter waves should match closely the electron drift component along the direction of propagation (*Fejer and Kelley* [1980]). To gain more information on the geophysical conditions prevailing during HF backscatter events, a new experiment was performed in July 1994 which also included a vertical ionosonde beneath the scattering region. The results, presented by *Bourdillon et al.* [1997], showed evidence of modulation in the *F* region virtual height and Doppler velocity of the reflected signal during times of strong backscatter occurrence which displayed concurrent periodic-like range variations. These signatures were also accompanied by systematic changes

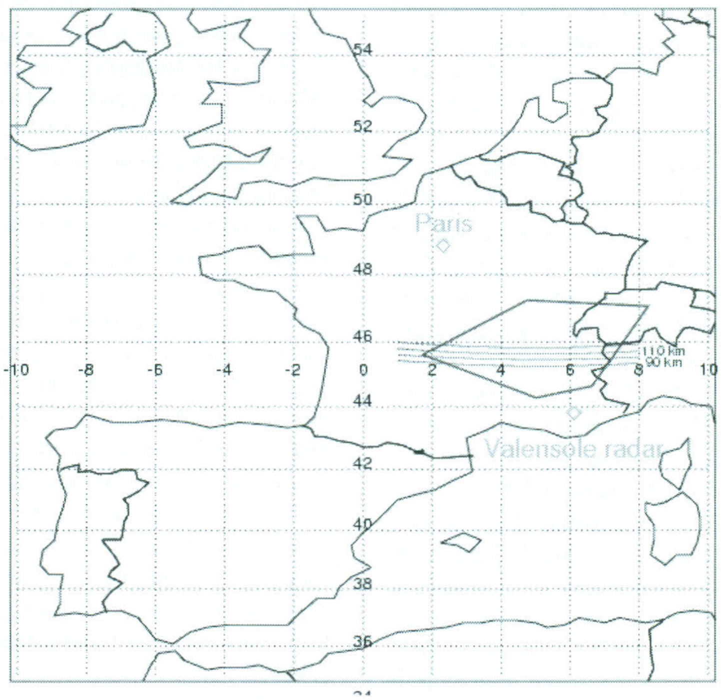

Figure 6. Location and viewing geometry of the SPOREX experiment for magnetic aspect sensitive backscatter observations.

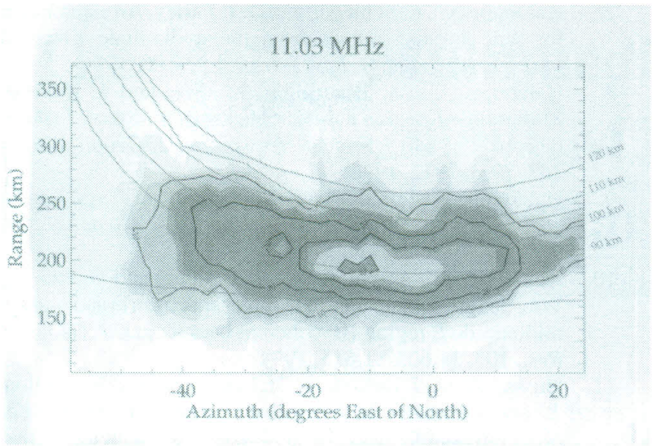

Figure 7. *Typical azimuthal occurrence of* E *region HF backscatter as observed by the Valensole HF radar. The expected line of sight field-aligned magnetic aspect curves are plotted for altitudes from 90 to 120 km. The southward displacement of the echoing regions, relative to the magnetic aspect angle curves of exact perpendicularity, is attributed to ionospheric refraction.*

in altitude of the sporadic *E* layer present, manifested by the vertical ionosonde time records. These wavelike variations in HF backscatter and ionosonde data were attributed to the passage and the modulatory effects of an atmospheric gravity wave.

To exploit the unique capability of the Valensole radar to perform multi-frequency probing of the plasma, a new experiment was performed in the summer of 1995 which allowed the measurement of *E* region backscatter Doppler spectra simultaneously at four different HF frequencies. As described by *Hussey et al.* [1997], the radar operated at the four frequencies of 9.23, 11.03, 12.71 and 16.09 MHz, which correspond to scatter from field aligned irregularities with wavelengths of 16.2, 13.6, 11.8, and 9.3 m, respectively. The data showed that lower-frequency echoes were stronger, more frequent, and more spatially extended than higher frequency ones, which is in general agreement with linear theory and rocket experiments. Using data from the same experiment, *Haldoupis et al.* [1998] studied the wavelength dependence of spectral broadening of decameter irregularities in the wavelength range measured by the radar. In their analysis they dealt with secondary irregularities, that is, type 2 echoes characterized by small mean Doppler velocities and mean spectral width to velocity ratios well above unity. The spectral width was found to increase monotonically with wavenumber k in the range from 0.38 to 0.67 m^{-1} covered by he experiment. By postulating that the width is determined mainly by the nonlinear growth rate of the secondary short-scale plasma turbulence, they compared their results to the theory by *Sudan* [1983]. Although there was some general agreement, on the average, the measured mean spectral width followed approximately a $k^{4/3}$ power law dependence which is considerably stronger than the theoretical $k^{2/3}$ dependence.

Finally, the multi-frequency Valensole measurements were used to study statistically the spatial occurrence of decameter midlatitude *E* region backscatter. The results were published recently by *Hussey et al.* [1999]. Based on the premise that scattering is fully aspect sensitive, statistics of spatial occurrence showed the aspect sensitive region to move toward the radar (southward) with respect to line of sight propagation calculations, with the lower frequency echoes being closer toward the radar than the higher frequency ones, in agreement with refraction theory predictions. Ray tracing inside nighttime midlatitude electron density profiles augmented with dense sporadic E_s layers was performed to calculate the expected echoing region, and good agreement was found. Another finding was the angular distribution of backscatter inside the wide azimuthal sector covered by the radar scan. The spatial distribution of echo occurrence had its maximum at small azimuths at and about geomagnetic north, suggesting that the meridional direction is strongly preferred for backscatter. Under the postulation that these are secondary waves, it was concluded that the observed angular anisotropy in spatial occurrence is at odds with the concept of strong isotropic plasma turbulence of *Sudan* [1983], but in general agreement with the two-step gradient drift instability theory of secondary wave generation process proposed earlier by *Sudan et al.* [1973].

Concluding Comments

In this report, the observations of midlatitude *E* region irregularities made during the last few years from the European sector independently with a 50 MHz continuous wave Doppler radar (SESCAT) in Greece and a multi-frequency HF radar (SPOREX) in France are reviewed. The studies undertaken with these two experiments had focused on a variety of research topics which included: 1) the morphological properties of backscatter and their relation to E_s layers, 2) the Doppler spectrum characteristics in relation with the predictions of the existing linear and nonlinear plasma instability models, 3) the *k*-spectrum dependence in the 1-m to 3-m and decameter irregularity wavelength ranges and comparison to theory, 4) the Farley-Buneman instability at midlatitude and the generation of strong polarization electric fields, 5) the azimuthal characteristics (including refraction effects) and spatial periodicities of HF echoes, and 6) the relationship between backscatter and large-scale neutral atmosphere wave motions, particularly planetary waves and their role in the formation of strong midlatitude sporadic *E* layers. Some of these investigations, for example those relating to the simultaneous multi-frequency observations in the VHF and HF band and the long-term variations detected in both backscatter and E_s occurrence, are quite unique in the sense that these studies were performed for the first time at midlatitude and only in the European sector. In this respect, several of the results here should be considered as complimentary to other findings made by midlatitude radar experiments in the Asian (Japan and Taiwan) and American sectors.

In concluding, we note that a substantial amount of experimental information was gathered from both these European ionospheric experiments. SESCAT and SPOREX have contributed new knowledge and a better understanding of the physics of midlatitude coherent radio backscatter phenomena and opened new dimensions in the long-going research of sporadic *E* layers. The discovery of pure Farley-Buneman waves in the unstable midlatitude *E* region ionosphere, which implied the presence at times of unexpectedly large electric fields (of about 15 mV/m or more), is one example. The detection of long-term variations, with periods in the ranges from 2 to 3 and 4 to 7 days, in both coherent backscatter and strong E_s occurrences (ionosonde observations) and the likely relation with planetary waves, is another example. These and several of our other findings emphasize the complexity of the physical processes in the unstable midlatitude *E* region of the Earth's ionosphere and the need for more research.

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