Sporadic E— A Mystery Solved?

In Part 2 of this *QST* exclusive, Dr Whitehead examines mid-latitude sporadic E, the role of metal ions, some unresolved questions and an intriguing hypothesis.

By Dr David Whitehead

In spite of the theoretical problems associated with plasma instability, ordinary physics seems to offer reasonable explanations for the main features of equatorial and auroral sporadic E (E_S). The same is not true for sporadic E at mid-latitudes, which is the least understood of the three general types. Explaining even the major features of mid-latitude E_S has so far proved difficult, yet a great deal is known.

In its simplest form, *mid-latitude ES* consists of relatively thin layers of high density electrons and ions 1 or 2 kilometers thick, lying at a height of about 105 km (with a range of 95 to 150 km) on top of a much less dense but thicker E region. Unless the E_S layer is broken into clouds with gaps in between, it will prevent radio waves up to a certain frequency from penetrating through to the F region, hence it is known as *blanketing* E_S.

Ionized layers produced by radiation or energetic particles are always much thicker than sporadic E. The only way of producing the thin layers associated with E_S is to compress existing ionization. The most effective means of compression is by an east-west wind shear. A neutral wind blowing toward the east moves the ion wind both eastwards and upwards (the sideways ion motion discussed previously), but hardly moves the electrons at all. When there is an eastward wind at one height and a westward wind at a greater height, an east-west wind shear is created hence the name *wind shear theory* of sporadic E. Ions move upward from below and downward from above, and are thus compressed very effectively. See **Figure 6**.

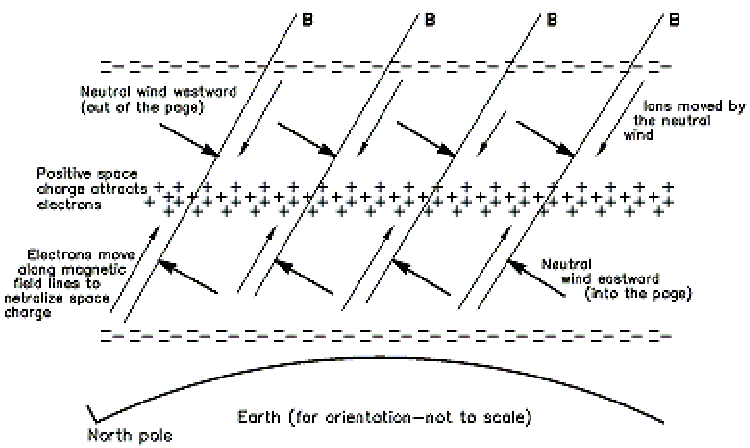


Figure 6—East-west wind shears moves ions eastward and upward as well as westward and downward. The result is a thin ion layer. Electrons then move along magnetic field lines to neutralize the space charge.

Electrons are then attracted by the positive charge of the compressed ions and move along the magnetic field lines to neutralize this charge. As a result of wind shear compression, ions move across the magnetic field lines and electrons move along the same field lines. Several rocket experiments designed to measure ionization density and wind velocity seem to confirm the general idea of wind shear compression, and most experts accept it as a satisfactory explanation.

The mechanism is most effective in the E region, but less effective above 150 km and below 95 km, where E_S is rarely seen. The east-west wind shear theory also seems at first sight to explain two important features of sporadic E. First, the theory predicts that the compression mechanism works best where the horizontal part of the Earth's magnetic field (B_h) is largest. B_h is indeed largest over Southeast Asia, where the most intense sporadic E of all places on the Earth occurs, and least over South Africa, where E_S is quite rare even in summer. Compare the world-wide magnitude of the horizontal component of the magnetic field and the occurrence of sporadic E in **Figure 7**.

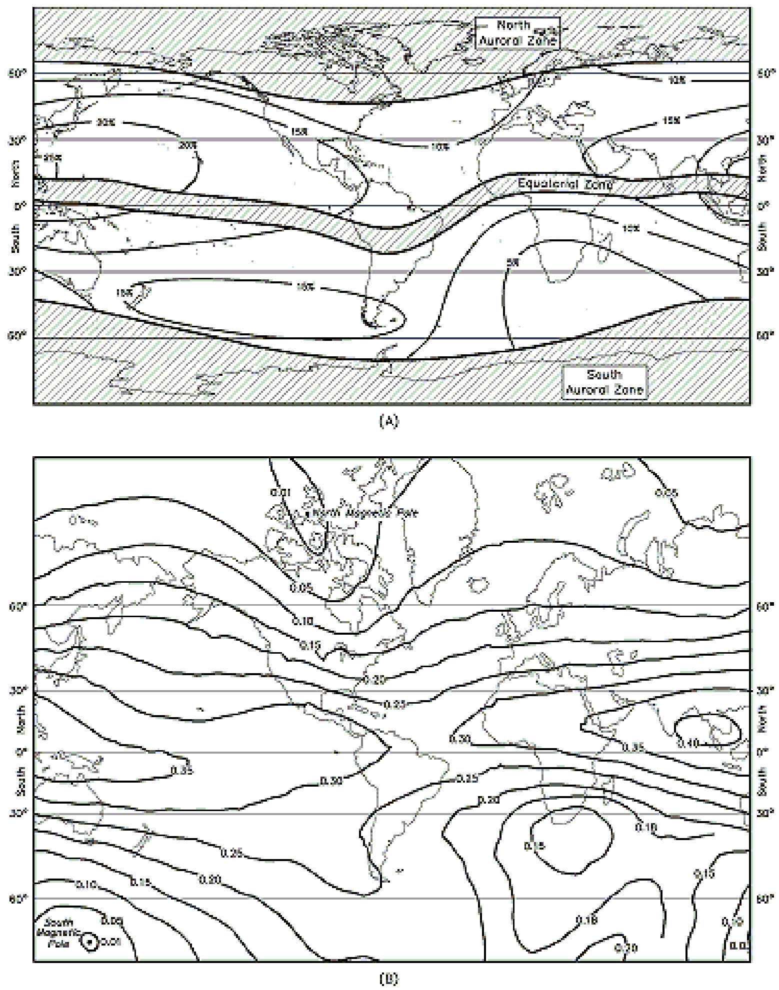


Figure 7—The occurrence of sporadic E roughly coincides with the intensity of the horizontal part of the Earth's magnetic field. Compare maps A and B. Map A—Sporadic-E occurrence is plotted as the percent of time ES critical frequency exceeds 5 MHz (equivalent to an MUF of about 27 MHz). Based on Smith (1957). Map B—Intensity of the horizontal component of the magnetic field, measured gauss. Based on Smith (1957).

The second prediction is that wind shear will not work near the magnetic equator, because electrons cannot move strictly along the magnetic field to neutralize the electric charge. This would prevent electron compression within a degree or two of the magnetic equator, where the field is horizontal. Indeed, there is a decrease in blanketing-type E_S near the equator. Equatorial plasma scatters radio waves, but cannot reflect radio waves. Some blanketing-type E_S seen right on the magnetic equator may be due to the wind not being exactly horizontal.

When these theories of compression were first put forward, most researchers thought that the normal E region ionization alone was being compressed by unusually strong wind shears. Typically, wind shear takes about 100 seconds to compress the ionization. Solar UV radiation produces ionization in the E region continuously during the day, but the ions and electrons recombine on average in just 10 seconds. If this is true, then rapid recombination would occur before ions could be compressed. This would have spelled the end of the wind shear theory, save for the discovery of another source of ions—gaseous metal atoms.

Role of Metallic Ions

The normal E region is composed mostly of oxygen and nitric oxide ions, but instruments carried through the E region on rockets also detected ions of magnesium and iron in thin layers. Metal ions are interesting because they do not disappear quickly. Left by themselves in the E region, they might last for days. Therefore, wind shear compression might not have to compete against the short life of the oxygen and nitric oxide ions, but rather against the tendency of metal ions to diffuse throughout the E region. In other words, diffusion limits the compression of the metal ions, not their lifetime. This discovery has important consequences.

Nevertheless, a significant shortcoming in the metallic ion explanation is that it fails completely to explain the summer maximum. Accepted theory requires that the MUF should be proportional to the square root of the total number of metal ions in a given volume of the E region and to the fourth root of the wind shear. This means that to double the MUF, there must be either four times as many metal ions or else sixteen times as much wind shear. Wind shear does not seem to vary much with the time of year, so there must be many more metal ions in summer than winter. The metal ions must be quite scarce during the equinoxes as well, since these are the seasons of least sporadic E. These huge hypothetical variations in metal ion content are both puzzling and difficult to explain.

A surprising result of incorporating metal ions into the wind shear model is that the theory predicts layers only about 100 meters thick, whereas the measured thickness is 10 to 20 times as great. This might be explained by turbulence, which would spread out the ionization to make a thicker layer, yet no turbulence is seen by rockets above about 115 km. Sporadic-E layers often form well above this level and slowly descend, becoming steadily thinner as they do without any sign of thickening. (Turbulence seen in rocket measurements at these lower altitudes may be partly generated by the rockets themselves.)

Another curious problem comes back to the abundance of E_S over Southeast Asia compared to its scarcity over South Africa. There is about 10 times more of it over Southeast Asia, where the magnetic field component B_h is about three times greater than in South Africa. This suggests that E_S varies roughly as the square of B_h, but the wind shear theory with metal ions predicts that it should really vary as the square root of B_h. There should only be about 70% more E_S over Southeast Asia as over South Africa! This contradiction also raises questions about the validity of the wind shear-metallic ion theory. So how do we get over all the problems associated with the wind shear theory? What happens to the metal ions at night for example? Where do they go after summer?

The ultimate source of the metal ions is presumably meteors, so it could be expected that there would be more E_S on or just after the dates of the annual meteor showers. Extensive studies over many years do not show this to be the case. In addition, ionosonde data at different stations a few thousand kilometers apart show E_S peaks on different dates of the year, further undermining a possible direct relationship between sporadic E and meteors.

Meteors almost certainly provide the ultimate source of the metal ions, but they might feed metals into some sort of reservoir. Let me use an analogy. The water behind the Hoover Dam has rain and snow as its ultimate source, yet the water level on any particular day is hardly affected by one day’s rainfall. Rather, the level behind the dam changes slowly based on rainfall and water usage over a long period of time. What is needed is an atmospheric reservoir that stores the metals, not as ions, but in some other form. Metal ions that emerge from this reservoir contribute to sporadic-E formation, but they are periodically removed by a sort of pumping process.

The pumping process depends on the structure of wind directions and velocities throughout the vertical extent of the atmosphere. The wind structure usually moves downward through the atmosphere. As the wind structure moves downward, any metal ion layers also move downward. To help visualize this, imagine holding a magnet under a piece of cardboard. Use some ball bearings on the top side of the cardboard to represent the ions. The magnet acts like the wind shear and the ball bearings are drawn over the magnet. Now move the magnet under the cardboard. This represents the movement of the wind pattern. Move it slowly and the ball bearings follow; move the magnet quickly, and the ball bearings are left behind, just as in the sporadic-E layers. Calculations show that the layers should descend to 90 km into D region. Here, in the more dense air, the metal ions can be made to lose their charge and recombine with electrons.

The descending wind pattern should carry the ions down to the place where the maximum downward velocity of the ions due to the wind just equals the speed of the wind pattern itself. This downward sweep of E_S layers is commonly seen on almost a daily basis at some places in summer. In the morning, a weak E_S appears as high as 150 km in the E region. During the day, it slowly descends down to about 105 km, becoming thinner and more dense as it does. Then it seems to park itself at this height, even though theory suggests it should continue its descent into D region. Weaker layers during the night descend into the D region, but during the day the layers are not carried as far down as they should be. So once again the wind shear theory looks more or less correct as a general description of what happens, but it fails on the details.

Recall that during wind shear compression, ions move across the magnetic field and the electrons along the field lines to preserve neutrality. This model could explain a uniform blanketing sporadic E with the same wind shear at the region of maximum electron density, but observations have revealed that E_S is often far from uniform. Narrow-beam steerable HF radar can be seen—the non-blanketing E_S. The calculated sizes of the sporadic-E clouds vary from hundreds of kilometers down to only a 100 meters or even smaller.

The larger clouds can probably be explained by changes in the wind from one place to the next. Suppose that there is an east-west wind shear as before, but now the neutral winds are confined to a small area of E region, such that 10 km away they are very small. This is depicted in **Figure 8**, which shows the ion wind in the plane of the paper at right angles to the magnetic field. The ions also move in the neutral wind direction. In the center of the wind pattern, the ions are compressed and electrons move along the field lines to neutralize the charge.

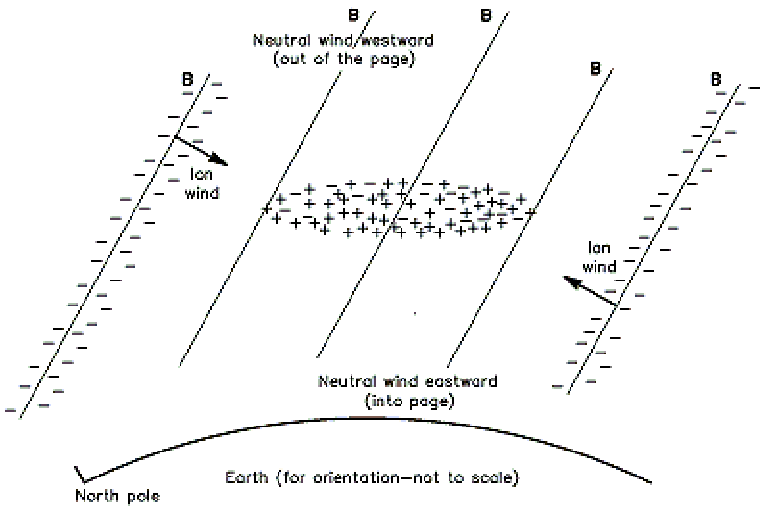


Figure 8—Ion motion when the east-west wind shear is restricted to a small area. The relative speed of the winds, which blow in and out of the page, suggested by the shaded contours. The highest speeds are toward the darker center and lighter winds are toward the edges. Wind-shear compression is effective only around the center magnetic field line. Ions are blown off the outer two magnetic field lines, leaving behind a net negative charge.

At the edges of the neutral wind pattern, the neutral wind moves the ions off certain magnetic field lines, leaving behind a net negative charge. Electron motion along the magnetic field lines cannot neutralize this charge. The electric field that results from the negative space charge attracts ions onto these field lines at all heights, not just where the neutral wind is strong. As a result, field-aligned structures are produced at the edges of all E_S clouds, as shown in **Figure 9**. During the day these field-aligned tails disappear quite rapidly, and are difficult to observe because of constant molecular ion production and recombination. The field-aligned tails could be expected at night, when there is little ion production. Japanese radar results suggest just such a structure. This effect may also account for the FAI formation in the early evening hours often observed by radio amateurs.

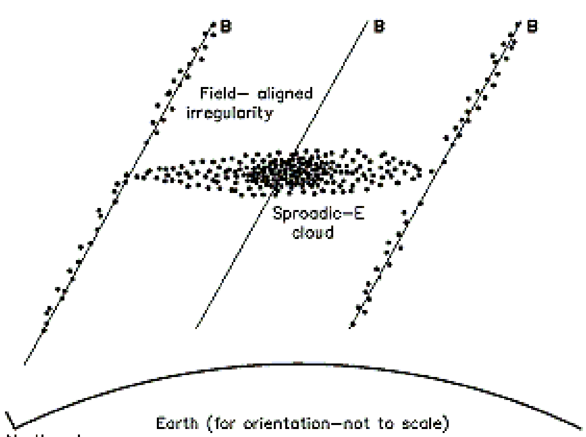


Figure 9—Sporadic-E clouds and adjacent field-aligned irregularities are shown in relation to magnetic field lines. Darker shading indicates greater ionization densities. Note that the field-aligned irregularities form at the edges of the central sporadic-E cloud.

Some E_S clouds are only 100 meters across and have critical frequencies over 30 MHz, yielding MUFs over 150 MHz. Such small intense clouds require much more compression both horizontally and vertically than can be produced by wind shear. The sharp gradients in ionization density may make the whole sporadic E layer break up in the way a stream of water from a hose breaks up. Sporadic E layers can be uniform one day and cover a whole continent, but the next day be broken into small clouds. The theory of yet another plasma instability, the *gradient drift instability*, has been suggested as the culprit. This instability tends to occur when there are sharp gradients in ionization and current flow, both of which occur in thin layer sporadic E. The irregularities that form are field aligned above and below the E_S layer.

Unresolved Questions

In spite of what seems to be a promising explanation, five major problems with the wind shear theory remain. The two most pressing are the intense summer maximum and the geographical distribution. For both of these, E_S varies much more than theory predicts. We might expect a summer maximum, for instance, because that is when the sun's radiation is strongest, but it should only be a modest increase, like the increase in the MUF for normal E region. Instead there is an enormous increase over what happens in the equinoxes. The higher than expected distribution over Southeast Asia than other parts of the world is also a puzzle.

E. K. Smith showed that this exaggerated behavior of E_S is even more marked for the occurrence of really strong E_S. The occurrence of a critical frequency greater than 10 MHz (corresponding to an MUF of about 54 MHz), for example, shows an even stronger summer maximum. What we need to explain both the summer maximum and the geographical distribution of E_S is a mechanism that produces even more metal ions when some already exist.

The third problem is the need for an ion reservoir to explain the lack of correlation between E_S and meteor showers. The reservoir for the metal ions cannot consist of free neutral metal atoms, because measurements show that there are fewer metal atoms than there are metal ions, not the reverse. Clumps of metal atoms or particles coated with metal atoms would fill the requirement, but they have never been observed. Perhaps this is because no one has ever looked for them!

The fourth problem is that the E_S layers descend only down to about 105 km. Theory says that metal ion layers should be carried down by the wind pattern to about 95 km. If the clumpy source of the metal ions were themselves ionized, the layers would not descend all the way into D region, but would break loose from the wind pattern much higher.

The fifth problem is the thickness of E_S layers. If ionized particles are being compressed, rather than the metal ions themselves, it would take as long as a day to compress the layer fully. The wind would have changed a lot by then. The net result is that ionized particles would be compressed into much thicker layers than metal ions alone.

Dust Hypothesis

These problems cannot be resolved by resorting to the previous review of what is generally known about atmospheric physics. Something else is required. Here is some speculation about a process involving dust particles that might help explain what we do not know. It might be possible to satisfy all the requirements of thickness, height, and time for compression if the E layer contained extremely small particles composed of only 100 or 1000 atoms, in addition to ions, electrons, and neutral molecules. At the same time, the summer maximum and geographical distribution might be explained.

These particles would not behave like the same material in a large lump. Since not much is known about such particles, we can speculate about them to our heart's content. One odd property I would like them to have is this. If such a particle is coated with a thin layer of metal, I would like a metal ion colliding with the particle to cause the ejection of an additional metal ion sometimes. But an air molecule or other non-metallic ion colliding with our particles must never cause an atom to be knocked off. Starting with such strange particles, let us see what we can make of this idea.

During the day, the few metal ions around would collide with the particles coated with metal and knock off a few additional ions. The number of metal ions will increase faster and faster, more so in summer than in winter because of higher levels of UV radiation. In summer, the E-layer may end up with 100 times more metal ions than in winter. So much for the seasonal change and the huge summer maximum, but what about the equinoxes? Even fewer ions are required. Perhaps the problem is not so much accounting for the minimum in the equinoxes, as explaining the small maximum in winter. The winter E region is electrically connected to the summer E region in the opposite hemisphere via the highly conducting magnetic field lines. I suggest this may have something to do with the winter maximum, although I do not know why.

The increased production of metal ions where more already exist may also explain the geographical distribution of E_S around the Earth. Over Southeast Asia, the wind pushes the ions and particles together more than over South Africa, because the horizontal component of the Earth's magnetic field is greater. The rate of metal ion production is thus greater over Southeast Asia and E_S production is greater. Again the effect of a few more ions initially can lead to more abundant E_S.

These hypothetical particles have other characteristics that can help resolve some of our problems. The particles themselves are ionized, contributing about half the total E_S ionization. This allows them to be compressed by the wind shear mechanism. The particles also contribute to forming thicker layers because they are much heavier than the ions alone. The pumping action of the descending wind pattern will act on the charged particles, but carry them down only to about 105 km, just as is observed for daytime descending layers.

The metal ions might descend further and leave the particles behind, but it is not clear what happens in the model. During the night, the ions would quietly disappear by attaching themselves to the particles and giving them a nice metal coating ready for the next day. The particles themselves would collect a few electrons and either have no charge or a negative charge when the sun is no longer shining on them. Only metal ions and their electron companions are left in the sporadic E layer and can now be carried down into D region.

The dust hypothesis also predicts much thinner layers at night, because they would be pure ion layers uncontaminated with particles, in contrast to the daytime layers. Even with modern ionosondes, it is difficult to measure the thickness of night-time layers, because they so often seem to be broken up, quite unlike the strong daytime layers. Perhaps the sharpness of the layer makes them unstable.

The dust hypothesis of sporadic E seems plausible, but it has yet to be modeled successfully on computer or confirmed in the real world. A rocket-borne instrument is needed that could detect tiny particles of 100 to 1000 atoms and measure metal atom densities more accurately than can now be done. Then we may get some answers that would further unravel the mystery of sporadic E.

Bibliography

Davies, Kenneth, *Ionospheric Radio*. London: Peter Peregrinus, 1990.

Hargreaves, J. K., The *Solar-Terrestrial Environment*. Cambridge: Cambridge University Press, 1992.

Smith, E. K. Jr, *Worldwide Occurrence of Sporadic E*. National Bureau of Standards Circular 582. 1957.

Smith, E. K. Jr, and Sadami Matsushita, eds. *Ionospheric Sporadic E*. London: Pergamon, 1962.

Whitehead, J. D., "Production and Prediction of Sporadic E." *Reviews of Geophysics and Space Physics* 8 (Feb. 1970), 65-144. Correction in *ibid*. 9 (May 1971), 445.

Whitehead, J. D., "Recent Work on Mid-Latitude and Equatorial Sporadic E". *Journal of Atmospheric and Terrestrial Physics* 51 (1989), 401-24.

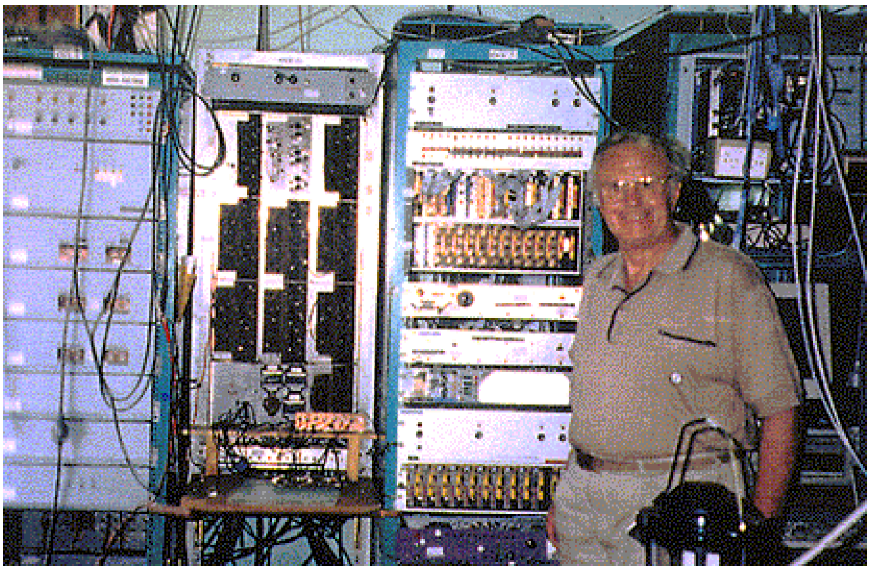
Probing the Ionosphere with Radio Signals

I have discussed the thickness of sporadic E and the way it often seems cloudy. How do we physicists know this? Over a period of more than 25 years, my colleagues and I at the University of Queensland in Australia have developed two instruments that have allowed us to find the answers.

The first instrument is a swept frequency sounder, which operates from 1.5 to 20 MHz and times the echo reflected directly back from the ionosphere. This ionosonde was unusual when we invented it, because it uses the phase of the echo to measure this time much more accurately. The time was accurate to within 1 microsecond, about 100 times better than the old style of sounders. The instrument is therefore known as a phase ionosonde. Nearly all the new generation of pulsed ionosondes are similar to this, but ours was the first and has been working for 25 years.

The other instrument was a high frequency radar working on frequencies near 2, 4, and 6 MHz pointing its beam upward into the ionosphere. The antenna arrays were in the form of a 1 × 1 km cross, one arm for transmitting and the other for receiving. The beam was 4° wide at 4 MHz and could be tilted in any direction using digital phase changers. The slope of the ionosphere could be measured to within about 0.2°. To give you some idea of how much the ionosphere does slope, on a quiet day the F region usually has slopes of about 2°. When sporadic E is steady over hundreds of kilometers, its slope averages only about 0.6°, the flattest thing in the ionosphere!

At other times sporadic E is broken up into clouds of ionization and you can see reflections from the edges of the clouds tilted as much as 60° away from the horizontal. The sporadic E clouds vary in size just like the ordinary clouds we see in the sky. A typical size horizontally is 10 km, but we have seen them from thousands of kilometers down to only a few hundred meters with indirect evidence of even smaller clouds. The radar echoes reveal that the undersides of clouds are often slightly wavy, and some of them look like upside down plates, concave downwards.



Dr David Whitehead with the electronics of the high-frequency radar he and his research group built and then used to probe the ionosphere, including sporadic-E clouds.