...ne Euro-Asia to Africa VHF Transequatorial Circuit During Solar Cycle

Part 2: Five-thousand-mile 2-meter circuits explained? Do the theories fit the observations? Where do we go from here?

By Ray Cracknell,* ZE2JV, Fred Anderson,** ZS6PW, and Costas Fimerelis,*** SV1DH

Part 1 of this article appeared in November 1981 *QST*. In that installment we provided the fundamental details of the propagation experiments and defined the kinds of equipment that were used in the tests. This installment concludes the discussion of the work done by the authors.

Doppler-Shift Measurements

Variations in the time taken for a signal to travel from the transmitter to the receiver indicate changes in the propagation medium. A mobile medium will produce changes in the frequency of the received signal, increasing it as the path shortens (a positive shift) or lowering it as the path lengthens (a negative shift). These changes, known as Doppler shifts, were measured by ZS6PW and SV1DH on 144 MHz. Both stations had access to

*13 Rowland Square, P. O. Belvedere, Salisbury, Zimbabwe
**101 van Niekerk St., Meyerspark 0184, near Pretoria, South Africa
***23 Elianou St., Athens 817, Greece

laboratory frequency counters of sufficient accuracy to determine the frequency of transmission and reception to within 10 Hz. They took frequent readings throughout several openings and reported them to each other via a 28-MHz ssb link.

The results varied in a random as well as in a systematic manner. Results of two evenings, when conditions were good enough for measurements to be made throughout the duration of the openings on 144 MHz, are illustrated in Fig. 12. Measurements made on other evenings are shown as dots, and they indicate random variations. Nevertheless, there seems to be a systematic variation where the Doppler shift starts slightly negative and swings to a small positive shift. Then it becomes progressively more negative with a shift of up to 200 Hz at the end of an opening.

The average shift recorded was about 100 Hz negative. This confirmed reports from Cyprus, Zimbabwe and South Africa of a downward Doppler shift on back-scattered signals received simultaneously with a weak ground-wave or tropospheric signal at 144 MHz. It would

appear that these systematic, random, short-term Doppler shifts are characteristic of TE on 144 MHz over the Euro-Asia to Africa circuit.

Back-scatter Observations

Although 144-MHz back-scatter reports are rare, available evidence points to a rising or retreating region of the ionosphere from which back scatter on 144 MHz occurs. This is consistent with the observed Doppler shift on such signals. Nowhere along the circuit are the 144-MHz signals observed to return to the earth with sufficient strength to scatter from there and to produce a detectable signal level back at the transmitting site.

By contrast, ZS6PW has observed ground back scatter of 50-MHz signals transmitted from his vicinity at times when multihop F-layer propagation was open to Europe. The regularity of back scatter on 28 MHz is remarkable. In these cases Doppler shift is not present, indicating that ionospheric height is relatively constant.

ZE2JV and ZS6PW, who are separated

Fig. 12 — Doppler-shift measurements on 144.9 MHz between ZS6PW in Pretoria and SV1DH in Athens.

Fig. 13 — Map of Southern Africa showing the locations of ZS6PW and ZE2JV and the optimum areas for back scatter between them on 10 meters. The locations of other 2-meter stations heard in the Mediterranean area are also shown.

by 600 miles (km = mi × 1.6093), have a back-scatter QSO almost every day of the year on ssb on 28,988 kHz at 5 P.M. local time. Their respective 10-meter beacons can be heard at each other's location from early morning until late at night, sometimes outlasting all other signals on the 10-meter band.

Surprisingly, it has been shown conclusively that this back scatter on 28 MHz comes mostly (and perhaps exclusively) from the ground and not, as might be expected, from the ionosphere. ZS6PW observed the pulses from the ZS6DN beacon located eight miles away, and measured the time delay between the ground-wave and back-scatter signals. He found a delay that varied between 16 and 20 milliseconds. This is equivalent to reflection from a distance of 1500-1900 miles, a typical one-hop F-layer range at 28 MHz. At such a distance the ionosphere is wholly below the radio horizon and can not act as the source of back scatter. These results were confirmed by beam-rotation tests between ZS6PW and ZE2JV.

The experiment showed that optimum back scatter was obtained from two areas equidistant from the two stations and within the range indicated. This system is illustrated in Fig. 13. Of the two, the area to the northwest is much more reliable, because it is near the high density area of the tropical ionosphere. Backscatter also comes from the north. The 600-mile difference in distance means that the area best illuminated by ZE2JV's signals does not coincide with the area best seen by ZS6PW's receiver. This leads to weaker and sometimes distorted ssb signals.

Angles of Arrival

Tests between Salisbury and Cyprus during the International Geophysical Year (IGY) revealed that at 50 MHz, Yagi beams tend to lose their directivity in a random manner. The loss of directivity was related to the southward spread of TE signal toward the southern end of Africa. Elevation tests conducted by SV1AB on

ZE2JV's 2-meter signals indicated similar random variations. The best signals were received sometimes with a nine-element Yagi elevated at 20 degrees and at others with it horizontal. Reports from 5B4WR indicate occasional preference for a beam heading 15 degrees to the west of the great circle bearing on 144 MHz. ZS6PW and SV1DH conducted tests on 6 meters at times of multipath propagation, as illustrated in Fig. 10 (see Part 1, November QST). These showed that turning beams to a more westerly bearing accentuated the longer-delayed pulses.

In these tests the propagation time of the first arriving pulse on 6 meters decreased steadily from about 8:30 P.M. to 9:30 P.M. local time. It disappeared when the delay became 24.3 ms. Fig. 8 (see Part 1, November QST) shows that the elevation angle of the wave was then 0 degrees. This means that the ionosphere at the distance concerned had then just dropped below the horizon for $2F_2$ propagation.

Nobody as yet has been able to follow a moving ionospheric target through the course of an opening on 144 MHz. Also, no one has reported a preference for a beam heading to the east of the great circle path. When an opening occurs on 144 MHz, there is an area of the ionosphere that becomes receptive to TE signals. Doppler shifts confirm that it is mobile. Beam tests indicate that the ionosphere target gets smaller with greater distance from the magnetic dip equator. At the

limit of the TE range (approximately 2500 miles from the dip equator) it presents a point target on the horizon.

Patterns of Fading and Frequency Spreading

TE signals have a characteristic sound often reported as being similar to signals reflected from aurora. The flutter-fading frequently present on late evening 28- and 50-MHz signals often appears to chop the signal to the extent that Morse signals may become unintelligible. From 70 to 144 MHz the flutter becomes increasingly rapid, giving the signal a raw, ac-sounding note. When frequency spreading is in evidence the signal becomes broad. At times no beat note can be obtained with the receiver BFO. Such a signal only makes an increase in the noise produced by the receiver, with perhaps an accompanying change in the quality of the noise. The signal is, therefore, rather difficult to detect by ear, especially when it is weak.

An assessment of the degree of frequency spreading is largely subjective. The spreading on 2-meter signals is believed to be as much as several hundred Hz. On occasion it is often less than this amount. Figs. 14, 15 and 16, which are sonograms of received signals, illustrate the various fading patterns. They give some indication of the degrees of frequency spreading that are encountered on the 10-, 6- and 2-meter bands over the southern Africa to Mediterranean TE circuit.
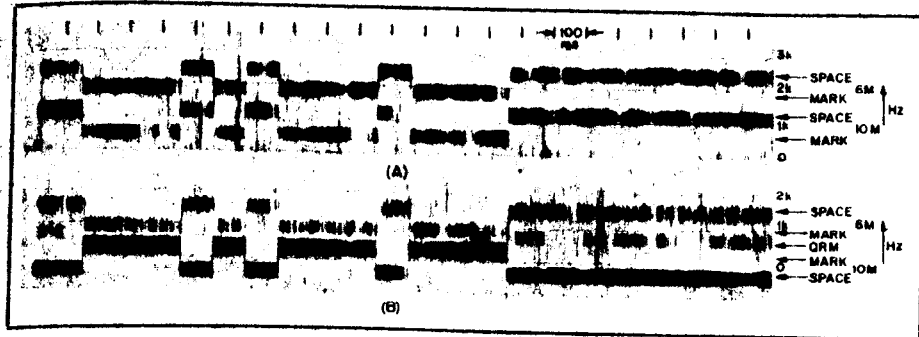
Fig. 14 — Sonograms of fsk signals on 10 and 6 meters from 5B4CY as received by ZS6PW showing (A) moderate amplitude flutter on both frequencies, and (B) a clear signal on 10 meters and severe flutter on 6 meters.
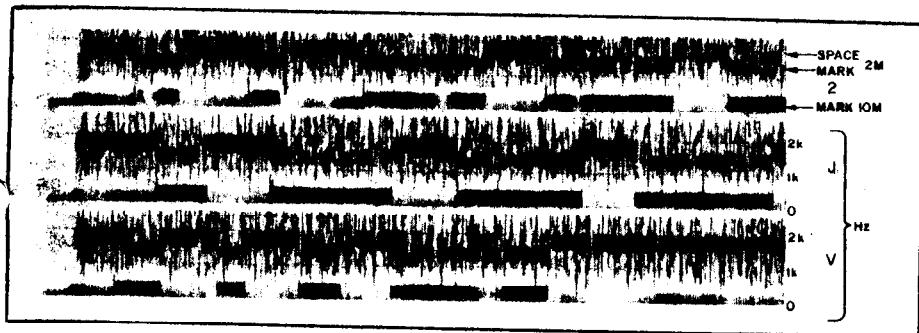

Fig. 15 — A sonogram of simultaneous fsk signals on 10 and 2 meters as received by SV1DH from ZE2JV showing slight flutter on 10 meters and severe flutter on 2 meters. The frequency spreading on 2 meters is not sufficient to make differentiation of the mark and space possible.
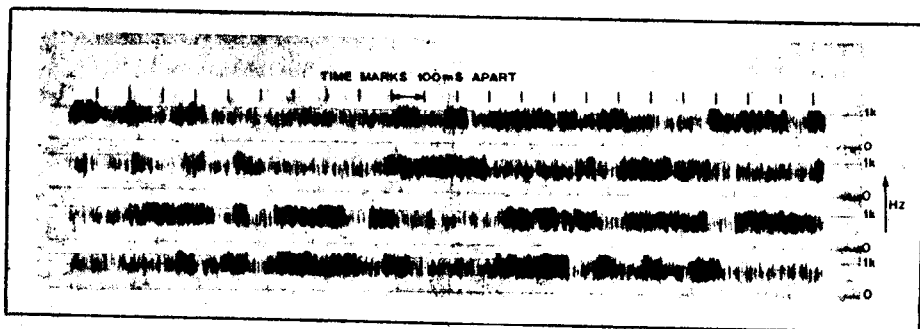

Fig. 16 — A sonogram of an A1 (cw) signal from ZS6DN as received at SV1DH. This signal produced no audible tone with the receiver BFO and was readable only as changes in the noise. It reads, bottom left to top right, FB Costas F.........

Under the best conditions, communication by ssb is marginally possible. A completely clear ssb signal has not yet been heard over the Africa TE circuit at 144 MHz. The rate of flutter and the degree of frequency spreading depend on the frequency of the signal. Variations in the quality of the signal, and the degree of fading and spreading, seem to be random. They do not correlate with loss of beam directivity. Strangely enough, sharpening the beam width does not reduce the degree of flutter and spread.

The Supporting Ionospheric Mechanism

TE is a mode that was not readily ex-

plainable by the knowledge of the tropical ionosphere available at the time of its discovery. This invited many unsubstantiated theories and explanations from academic, professional and amateur sources. These can be classified as theories of scattering from one or two areas, theories of tilts and gradients, and theories of ducting under, through or outside the ionosphere.

In 1960, ZE2JV[7] claimed to have isolated three distinct modes of propagation operative between 28 and 70 MHz from Salisbury to Cyprus. These were

'Notes appear on page 27.

two-hop F-layer, F-type TE and pure TE. He distinguished them by the characteristics of the signals, their propagation delays and times of occurrence. Two-hop F-layer and F-type TE were described as supported by the high density (HD) zones. HD zones tend to form some 10 to 15 degrees on either side of the magnetic dip equator from about midday. They persist until late at night.

Two-hop F layer ($2F_2$) up to frequencies well above 50 MHz supported circuits between Salisbury and Cyprus. Frequently chordal-hop F-type TE replaced $2F_2$ through the afternoon and early evening. Vhf signals "see" the HD zones as lenses; only half the bending is required for a chordal hop. Frequencies up to a maximum of 90 MHz could be propagated by this means. This mode depends on the horizontal density gradients on the equator side of the HD areas. It is sometimes referred to as "afternoon" or "early evening" type TE and sometimes as the FF mode. The mechanism and seasonal variations are generally thought to be understood and accepted. At that time many investigators thought TE resulted from the rise, breakup and descent of the tropical F region. After ionosphere sunset, "blobs" of ionization persisting in the HD areas scattered and deflected signals.

This late-night or pure TE was the first to be observed. Reports of "scatter" QSOs, back scatter and flutter-fading on transequatorial paths go back to the early 1930s. The name "TE scatter propagation" appeared in Amateur Radio literature until well into the 1960s. By that time, F-type TE became of importance because of the wonderful conditions it afforded on 50 MHz. It is a nuisance as a source of interference on the lower TV channels for four or five years out of every 11-year solar cycle. The strength of F-type TE signals is sometimes greater than the free-space signal strength over a comparable distance. This made the term "scatter" inappropriate, so it was dropped.

During solar cycle 21, pure TE has come back into prominence with record-breaking QSOs on 144 MHz. The possibility of repeating them on 432 MHz becomes apparent. No complete and totally satisfactory theory has yet been advanced. Many theorists tend to oversimplify down to a model that is related to mathematical analysis. This provides explanations for some, but not all, the phenomena that we observed. We have nevertheless consistently maintained that only a much greater knowledge of the morphology of the tropical ionosphere can provide the answers we seek. Without that knowledge, we are, to a large extent, guessing.

Some Recent Research and Proposals

Those who are interested in

theoretical approach to an intriguing propagation problem will find much of interest in the 50-MHz radar research of Woodman and La Hoz at Jicamarca.[8] They report "plumes" and "bubbles" of ionization depletions rising up to a height of 600 miles over the magnetic dip equator. This phenomenon gives rise to prolific 50-MHz backscatter echoes. Rastogi[9] has worked for many years on the tropical spread-F phenomenon. A critical frequency at vertical incidence is no longer apparent on vertical sounders, and diffused returns result. It seems to have a close association with TE regarding times of occurrence. It is present in that part of the ionosphere through which TE is propagated, namely up to 20 degrees either side of the magnetic dip equator.

Aarons and his coworkers[10] describe the dynamics of equatorial irregularity patch formation and decay. They postulate the formation of huge bridge-like structures, 1250 miles in length and a few hundred miles wide. These structures straddle the magnetic dip equator at right angles and align themselves along the magnetic field of the earth. These patches develop toward the west after the setting sun. Once formed, they break off and drift eastward with velocities ranging from 300 to 600 feet per second. They have a life of up to two and a half hours. Heron[11] used a mathematical model to explain the possibility of the depletion bubbles described by Woodman and La Hoz. He suggests they form ducts through the ionosphere, following the lines of the earth's magnetic field, and straddle the dip equator with "cones of acceptance" at each end. This allows for off-line propagation into gigantic natural waveguides. Woodman and La Hoz reported the easterly drift of the background ionosphere, which Aarons also observed. Heron uses this to explain Doppler shifts similar to those we observed. His concept of ducting is illustrated in Fig. 17, with the permission of the author.

Also writing in 1979, ZE2JV and 5B4WR[12] proposed a multiplicity of similar, but smaller, field-aligned ducts in a mobile and turbulent plasma. Small-scale irregularities in the lower levels of the F region also cause spread F. The effect is that of frosted glass. Some of the signal bounces and bends into the ducts, which are changing constantly.

In 1980 Tsunoda[13] published confirmation that the ducts exist. They pass right through the tropical-F region and align along the magnetic field of the earth. Radar on 155.5 MHz from the Pacific island of Kwajalein (magnetic dip latitude 4.3° N) showed depletions within these ducts of as much as 90% and greater than 750 miles in length. They are present in the nighttime tropical ionosphere.

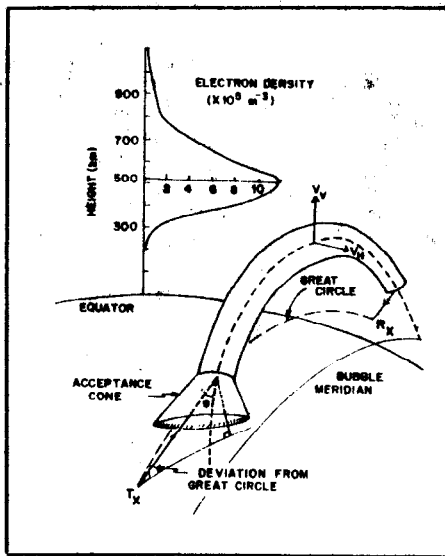### Discussion

Large transequatorial bridges of high-

Fig. 17 — The supporting mechanism for TE as suggested by M. L. Heron of James Cook University, Townsville, Australia (reproduced by permission of the author).

density irregularities, their growth, and subsequent drift and decay is to some extent supported by our observations of multipath propagation and Doppler-shift measurements. Several of these irregularity patches could be reached simultaneously. Aaron suggests that "several patches could be melded together." From this we can visualize various propagation paths, each with its own propagation time and Doppler shift. When the signals from the differing routes are combined, the resultant signal could carry the frequency-dependent rate of fading and the frequency spreading that characterize TE.

Although Heron discusses one discrete waveguide, he does not preclude the presence of several such structures. It is perhaps significant that workers in Australia and Africa came independently to the conclusion that only ducting, and not scattering, could account for the very wide band of frequencies propagated by pure TE. It seems that Aaron's findings and Heron's theoretical proposals could be combined to provide a plausible explanation. Both omit spread-F phenomena, and neither could explain the chopping and pulse-splitting action of flutter-fading. To explain these phenomena we envisage ducts that open and close as smaller-scale irregularities and bubbles shift and realign themselves within the larger structures.

Another interesting phenomenon not explained is that on many evenings around 7:30 P.M. local time, signals arriving by F-type TE on 50 MHz fade down or disappear, to be replaced soon afterward by pure TE signals. However, pure TE signals do not obey the usual rules, whereby lower frequencies appear first. Two meters often opens before the return

of the 50-MHz signals, which may be delayed up to an hour. The effect is presumably caused by the size of the ducts, the scattering irregularities or the greater penetrative power of higher frequencies. Whenever 144-MHz signals appear, however, pure TE also seems to be operative on lower frequencies later at night. The general rule of a hierarchial fade-out probably holds good although our observations on 432 MHz were too few to confirm this. Fifty- and 28-MHz signals last far too late into the night to be observed regularly.

There are also two major points of disagreement between our observations and the theories we have discussed.

1) The beam heading preference is toward the west rather than the east. Aarons and Heron proposed an easterly drift of the propagating medium. This should lead to a positive frequency shift when it approaches the direct line between stations, and a negative shift as it drifts away to the east. The average Doppler shift was observed to be about 100 Hz negative. This should lead to a preference for a beam heading to the east of the direct line. The opposite was in fact observed. Whenever a preference was noted, it was always to the west, as it would be if the propagating medium were retreating after the setting sun.

2) F-type TE has a longer propagation time than normal two-hop F-layer propagation.

This observation was first noted in 1960; the transponder propagation times reported then were confirmed by recent studies. A simple FF or chordal hop should take a similar or slightly shorter propagation time than two-hop F layer, according to its ray geometry. This is certainly not so, and the propagation times for F-type TE and pure TE are very similar. The question of whether both follow a very similar path has to be considered, but at present current theories can not explain this observation.

Conclusion

High density ionized zones exist 10 to 15 degrees north and south of the magnetic dip equator. These zones account for excellent transequatorial propagation in the 6- and 10-meter bands. Amateurs recently discovered that the ionosphere will support communications at 144 MHz, and at times, up to 432 MHz. These circuits can open between stations located up to 5000 miles apart. The stations must be spaced approximately equidistant from the dip equator, and the line joining them must be perpendicular to the equator. Amateurs situated in optimum areas have a unique opportunity to engage in pioneer research. We have the chance to investigate and to prove or disprove many interesting theories. Such opportunities are rare in radio today.

Our observations and experiments

provide many clues into the nature of this propagation. The final explanation must await the findings of basic research into the morphology of the nighttime tropical ionosphere. This will require resources far greater than those we employed. Ingenuity notwithstanding, the resources required may be beyond the limits of most amateurs. Time will tell.

APPENDIX

ZS6PW's pulses were derived from a 100-kHz oscillator locked to the 100-kHz modulation carried by the 'ZUO vhf link. This 100-kHz signal is of very high stability and is derived from a cesium frequency standard.

Dividing 100 kHz by 7990 gives pulses that are the required 79.9 ms apart. Their timing relative to UTC is set by starting the divider at the correct instant with reference to the UTC second, which is also obtained from 'ZUO.

The basic time interval of the Mediterranean Loran C system is 79.9 ms, and that of the UTC system is 1 second. It follows that 10,000 Loran C periods take precisely 799 seconds. Consequently, every 10,000th Loran C period coincides precisely with every 799th UTC second. Such moments (13 minutes, 19 seconds apart) are called "Times of Coincidence" (TOC).

The Lampedusa data, including tables of TOC, were kindly supplied by the U.S. Naval Observatory in Washington, DC.

Although the distance from Lampedusa to Pretoria is over 4400 miles, the 100-kHz signal can usually be received late at night, and this enabled the accuracy of ZS6PW's timing system to be checked by measuring the time of arrival of the Lampedusa pulse groups in Pretoria. The calculated and measured propagation times were found to correspond within 20 microseconds on most evenings. The application of this system is discussed in Part 1.

Notes

[1] R. G. Cracknell, "Transequatorial Propagation of VHF Radio Signals," *Proc. 1st Federal Science Congress,* Salisbury, 1960.

[2] R. F. Woodman and C. La Hoz, "Radar Observations of the F Region Equatorial Irregularities," *Jnl. Geophysical Research,* Aug. 1976, pp. 5447-5466.

[3] R. G. Rastogi, "Seasonal Variations on Equatorial Spread F in the American and Indian Zones," *Jnl. Geophysical Research* 85, A2, Feb. 1980, pp. 722-726.

[4] J. Aarons, J. P. Mullen, H. E. Whiting and E. M. Mackenzie, "The Dynamics of Equatorial Patch Formation, Motion and Decay," *Jnl. Geophysical Research* 85, A1, Jan. 1980, pp. 139-149.

[5] M. L. Heron, "Transequatorial Propagation Through Equatorial Plasma Bubbles — Discrete Events," *AGARD Conference Proc.,* No. 163, Nov. 1979.

[6] R. G. Cracknell and R. A. Whitney, "Twenty-one Years of TE," *Radio Communication,* 56, June/July 1980 (Part 1) and Aug. 1980 (Part II), RSGB, London.

[7] R. T. Tsunoda, "Magnetic-Field-Aligned Characteristics of Plasma Bubbles in the Night-Time Equatorial Ionosphere," *Journal of Atmospheric and Terrestrial Physics,* 42, Aug. 1980, pp. 743-752.