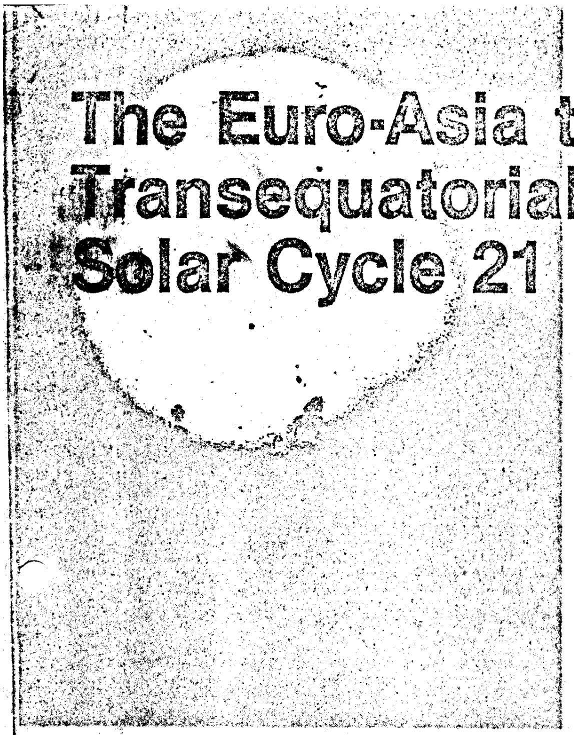

The Euro-Asia to Africa VHF Transequatorial Circuit During Solar Cycle 21

Part 1: "VHFers" have long suspected that Transequatorial Propagation would support 2-meter contacts over great distances. In 1978 that suspicion became reality. This is a two-part report on research conducted since then.

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

The current world long-distance record for a 144-MHz two-way QSO via the ionosphere, a distance of 4475 miles (kilometers = mi × 1.6093), is held by SV1AB and ZS6LW. The longest distance over which 144-MHz signals have been heard and recorded is from ZS3B in Luderitz (26°38′ S, 15°10′ E) to I4EAT in Faenza (44°17′ N, 11°48′ E), a great circle distance of 4930 miles.

Transequatorial Propagation

Countries bordering on the Mediterranean in Europe and Asia, as well as the coastal strip of North Africa, are ideally situated to enjoy optimum vhf and uhf transequatorial propagation (TE) into a belt of Africa stretching from somewhere north of Zambesi to the Orange River (approximately 15-30° S). Following is an account of the use made of these opportunities by a group of amateurs in Cyprus, Greece, South Africa and Zimbabwe during the high solar activity of Solar Cycle 21.

Twenty-two years ago, during solar cycle 19, amateurs in these areas explored the possibilities of TE at 50 and 70 MHz[1] with encouragement from The ARRL Propagation Research Project.[2] When solar-cycle 21 promised to produce peaks of solar activity almost as high as those experienced in solar-cycle 19, and propagation at 144 MHz was found possible,[3] old friends of the Africa circuit[4] got together with several new ones to take up the investigation again.

As the basic method of investigation, we monitored continuous transmissions from ZE2JV in Salisbury, Zimbabwe, on 29, 144 and 432 MHz; ZS6DN, near Pretoria, South Africa, on 28 and 144 MHz; and ZS6PW, in the suburbs of Pretoria, on 28, 50 and 144 MHz. Stations 5B4WR, 5B4AZ and 5B4HY in Limassol, Cyprus, and SV1DH and SV1AB in Athens, Greece, were on the monitoring end. We resumed propagation time measurements with much improved techniques. We successfully obtained Doppler-shift measurements between ZS6PW and SV1DH at 144 MHz. We looked at angles of arrival and again found they vary considerably. The characteristics of the signals, especially the flutter-fading and frequency spreading, were compared at various frequencies.

The Experiments

Our experiments this time concentrated on the 144-MHz band, but not exclusively. Communications at 432 MHz over the 3750-mile circuits proved to be possible, and we made detailed observations of the 10- and 6-meter transmissions and propagation times as well as those for 4 meters. As a result we were able to say, without fear of contradiction, that propagation on all these frequencies did indeed occur across the equator via the ionosphere. At times, particularly at night in years of high solar activity, the tropical ionosphere is capable of supporting propagation between optimum areas over a wide band of frequencies including the whole of the vhf and the lower portion of the uhf spectrum.

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[1]Notes appear on page 36.

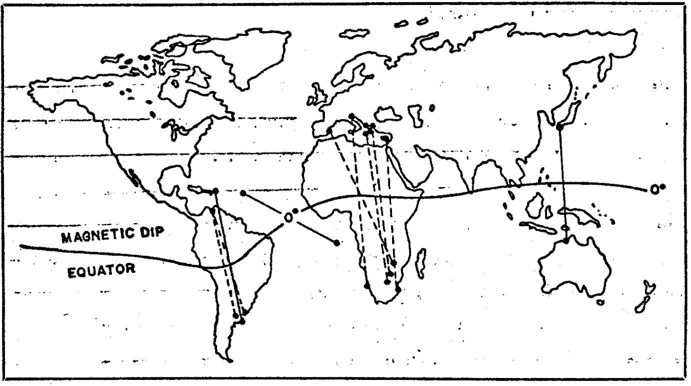

Fig. 1 — TE paths worked by amateurs on 144 MHz, showing the symmetrical distribution of stations with respect to the magnetic dip equator drawn on a map of magnetic inclination or dip, published by the U.S. Defense Mapping Agency Hydrographic Center.

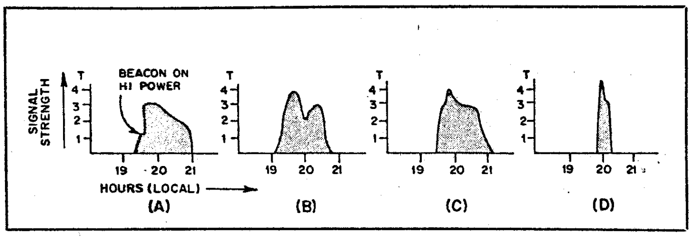

Fig. 2 — Typical signal strengths and duration of openings on 144 MHz: at A, ZE2JV at 5B4WR October 10, 1978; at B, ZE2JV at 5B4WR March 14, 1979; at C, ZE2JV at SV1DH March 25, 1980; and at D, ZS6DN at SV1DH March 25, 1980.

We found that as the signal frequency increased, the zones became more restricted to those equidistant from and perpendicular to the magnetic dip equator (Fig. 1). The duration of openings tended to be shorter and closer to 8 P.M. local time. We also found that the rate of flutter-fading and the degree of frequency spreading, both of which tend to characterize pure TE signals, likewise increased with signal frequency.

At lower frequencies (below 70 MHz) two-hop F-layer and F-type TE, which are supported by the high-density belts of the ionosphere forming on each side of the magnetic dip equator, may provide very strong signals during the afternoon and early evening. Later at night and sometimes in the early morning as well, only the weak and watery type of propagation we call pure TE was likely to be operative on frequencies of 50 MHz and above. In this two-part series we concentrate on pure TE, describe our experiments, detail the results achieved, and discuss modern theories and research relevant to the tropical ionosphere.

The Early Contacts

The initial contacts on 144 MHz occurred later over the African circuit than over Central/South American circuits. The strong signals reported by YV5ZZ[3] were not at any time in evidence. The first signals received in Cyprus by 5B4AZ from ZE2JV on April 8, 1978, and then by 5B4WR, SV1AB and SV1DH, were very weak, diffuse and difficult to copy because of rapid flutter-fading and frequency spreading. We were excited and thrilled because these QSOs arose, not from a chance hearing, but from careful preparation, and only after weeks of unsuccessful monitoring. Conditions improved thereafter, but the excitement died down, only to be revived by the appearance later in 1978 of ZS6DN's 144-MHz signal in Athens, and of ZE2JV's 432-MHz transmission in Athens and Cyprus in March and May 1979.

The geographical distribution of the TE paths worked by amateurs on 144 MHz is illustrated (Fig. 1) on a map of magnetic inclination, as published by the U.S. Defense Agency. TE paths are all between stations spaced more or less at equal distances from the magnetic dip equator and on paths that cross it at right angles. The greatest deviation experienced at 144 MHz is EA6FB on the Island of Ibiza, hearing ZE2JV's signal and ZD8DT on Ascension Island hearing KP4EOR.

Reliability and Seasonal Variation

After the excitement of the first QSOs, stations in Cyprus and Athens concentrated on monitoring beacon transmissions and plotting the daily and seasonal variations in reliability. SV1DH had spent 2500 hours monitoring by the end of December 1980. A comparable effort was maintained in Cyprus. Because of the low signal strengths encountered, the wide frequency spectrum to be covered and the number of stations to be monitored, mechanical means were not feasible. The combined efforts of our stations represent the only known systematic investigation so far made of the TE phenomenon above 100 MHz.

We first conducted tests on a 24-hour basis. Although some short, early-morning openings were recorded, no other daytime signals were heard. It soon became apparent that at 144 MHz the most significant openings were confined to a period of a little over two hours after the setting of the sun on the ionosphere. 5B4WR plotted graphs of every evening reception of ZE2JV's signals from April 1978 to December 1979. The results of two good evenings (October 10, 1978, and March 14, 1979) are illustrated in Fig. 2, together with SV1DH's reception of ZE2JV and ZS6DN on March 25, 1980. The Salisbury-to-Cyprus path proved to be the most reliable and provided, by a small margin, the strongest signals. It is remarkable that the South African stations were heard rarely in Cyprus, and when they were, they were very weak.

The monthly reliability of occurrence of propagation at 144 MHz over three circuits (Pretoria-Athens, Salisbury-Athens and Salisbury-Limassol) is illustrated in Fig. 3 for the period from March 1978 to December 1980. The three monthly running means are illustrated in Fig. 4. From these, the seasonal dependence, with maxima shortly after the equinoxes and minima at the summer and winter solstices, is clearly apparent. These results can be compared with the smoothed monthly value of solar flux and the average monthly values of geomagnetic activity that are illustrated in Fig. 5.

Complex Relationship

The relationship is complex. In general, it may be said that the high level of ionization that results from high solar flux is essential for TE at 144 MHz, and that magnetic disturbances disrupt it. However, when the solar flux is below about 180, and as the seasons near the summer and winter solstices, ionization is pushed high enough only for propagation at 144 MHz to occur in the period immediately following a solar outburst and before the arrival of the associated disrupting magnetic disturbance. Hence, prior to mid-1979, the reliability curves tend to follow the geomagnetic activity curve. After that time, when the magnetic index decreased, the curves follow the solar-flux curves much more closely. These conclusions are confirmed when our results and solar data are compared on a daily basis.

Signal strengths at 144 MHz were generally low. At SV1DH the strongest signal received via 144-MHz TE was from ZS6DN. This produced 0.6 microvolt across the 50-ohm input to the receiver. It represents a propagation loss of 43 dB, relative to free-space attenuation over a comparable propagation distance. Signals from ZE2JV were weaker, but lasted longer with a minimum propagation loss of 47 dB compared with free space. The strongest signals were received over the Salisbury-Cyprus (ZE2JV and 5B4WR) circuit with a minimum propagation loss of 40 dB, relative to free space being recorded.

Receivers

A good receiver with a front-end noise figure of 2 dB or less is essential for TE work at 144 MHz. As with other modes of ionospheric propagation, the noise level rises when the band opens; efforts to reduce the noise figure below 2 dB may not pay off. Above that figure many openings may be missed. Variable selectivity is desirable, but when the signal is broad because of frequency spreading, narrowing the selectivity excessively is not helpful.

Weak signals, received with flutter-fading, frequency spreading and poor notes caused by the propagation medium, are not suitable for RST code reporting. We reported with a simple T code in which T1 stood for signal present and

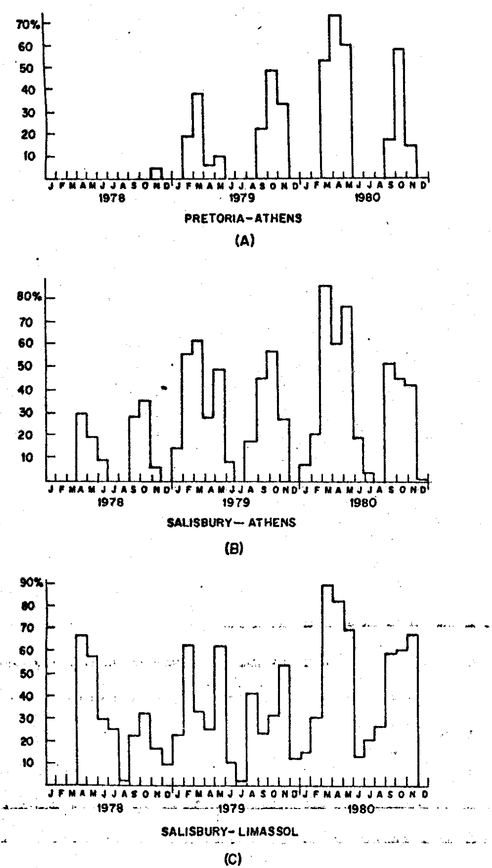

Fig. 3 — Reliability of occurrence of 144-MHz signals: at A, Pretoria-Athens; at B, Salisbury-Athens; and at C, Salisbury-Limassol.

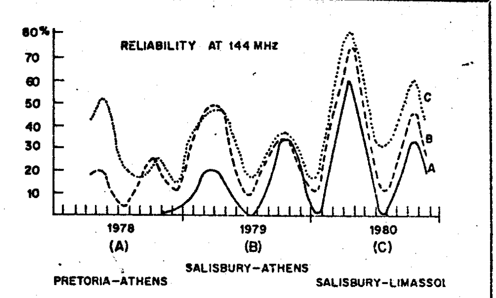

Fig. 4 — Smoothed reliability of occurrence curves for three circuits.

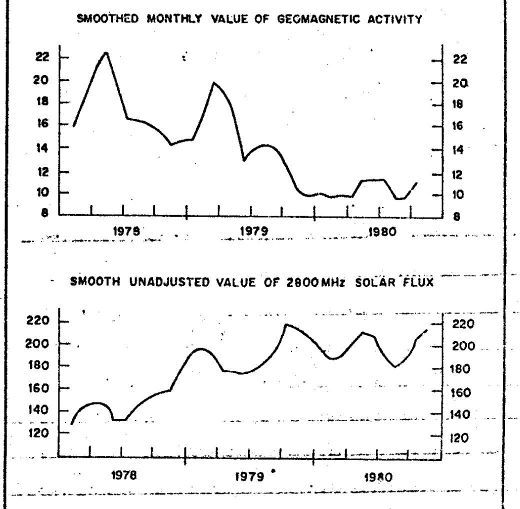

Fig. 5 — Smoothed monthly value of 2800-MHz solar flux and average monthly value of geomagnetic activity based on data extracted from the solar Geophysical Reports published by the National Oceanic and Atmospheric Administration (NOAA), Department of Commerce, USA.

recognizable, T2 for signal copied 50%, and T3 for signal copied 100%. For initial and record-breaking QSOs, we employed the RST code. Reports such as 317F (the report given by ZE2JV to 5B4WR on the first TE 144-MHz QSO over the Africa circuit) seemed to be a poor reward for the effort involved.

Transmitters

Under the best conditions, low-power transmitters (10 to 50 watts output) have been heard across the TE circuit. A power of at least 100 watts into a well-matched antenna proved necessary for comprehensive TE work. The effect of increasing power from the 40-watt, 24-hour beacon to 200 watts for the evening test period is illustrated in Fig. 2A. This resulted in a jump from a T1 (just recognizable) to a T3 (fully readable) signal. Below the 100-watt level the duration of openings is considerably reduced. Above that level, increased power improves the received signal proportionately without extending the length of openings to any appreciable extent.

Crystal oscillators, although quite satisfactory for working QSOs, present drift problems. Stabilization against a frequency standard is necessary when sophisticated measurements are attempted.

Cw (A1) was used for most transmissions, although ZE2JV used fsk (F1) to avoid TVI problems. Fsk has the advantage that casual listeners are less likely to tune through an F1 signal without hearing it. Against this, many operators find it difficult to copy, and more heat has to be dissipated in the PA than when using A1. Two-hundred watts of output on fsk was about as much as ZE2JV's Johnson Thunderbolt (two 4CX250Bs) could manage when running continuously in hot weather. ZS6DN used 100 watts (A1) into a high-gain antenna system on an excellent site. ZS6PW transmitted 150 watts, also on A1.

Between call signs, pulses were applied to these transmitters and used extensively for time-delay measurements. These pulses were in fact a series of dots. It would have been of great advantage to use pulses with much higher peak power, but this was not permissible because of licensing restrictions.

Antennas

We have avoided the term erp (effective radiated power) when discussing power. When working a mode of propagation involving multipath, off-line transmission and variable vertical angles, obtaining the optimum cone of radiation is difficult. Clearly, sharpening the beam directivity below the optimum will not increase the *effective* radiated power. This may even cause the signal to be lost.

An efficiently coupled antenna system is, however, essential for successful TE work. Time spent in optimizing a beam for maximum forward gain usually will be rewarded amply. The aim has to be the maximum transfer of power into or from space. Deficiencies in this respect cannot be compensated for by adding more elements to an array, once the optimum condition has been reached.

Many stations with large stacked beams were unable to work TE. We conducted tests at 432 MHz from ZE5JJ, a well-known moonbounce station, using 1 kW of rf into a 20-ft (meters = feet × 0.3048) parabolic dish, which could be aimed right down to the horizon. The installation produced signals in Athens that were no better, if as good, as ZE2JV's 40-watt one into a pair of horizontally spaced 8-element quagis. Stations farther out from the magnetic dip equator will likely have an ionospheric target low on the horizon. They will seldom be far off a direct great circle line from station to station. They may well benefit from big stacked arrays. ZS6DN used an array of four 16-element Yagis. ZS3B and I4EAT also used big arrays very successfully. Closer in, however, in Cyprus, Athens and Zimbabwe, single Yagis of 10 to 16 elements seem to provide the most reliable results at 144 MHz.

The Transponder System

The first TE propagation time measurements were devised some 21 years ago to prove or disprove a suggestion by Professor Obayashi[6] that TE signals traveled through field-aligned ducts outside the ionosphere. The method used was to transmit a series of dots on cw (A1) to the far end of the TE circuit, where a receiver in the cw mode produced a train of audio pulses. These audio pulses were then applied as modulation and transmitted back to the originating station. The returned pulses and a sample of the original outgoing pulses were displayed on an oscilloscope. Time markers were also applied. This represented the time taken by the signal to cover the distance between stations twice, plus equipment delays. The latter were found readily by repeating the experiment between stations that were a short, known distance apart and that used similar equipment.

Crude as it was, this method demonstrated that TE propagation times were slightly longer than normal two-hop F-layer propagation time. They were never long enough to indicate that any extraordinary path outside the ionosphere was being followed by either the 28- or 50-MHz signals.

The Relative Time Delay System

The suggestion that propagation at 144 MHz was an entirely new mode of propagation led to renewed interest in propagation times. Different modes would be associated with different time delays over the circuit. A transponder system would not be satisfactory because of the poor signal-to-noise ratio, flutter-fading and

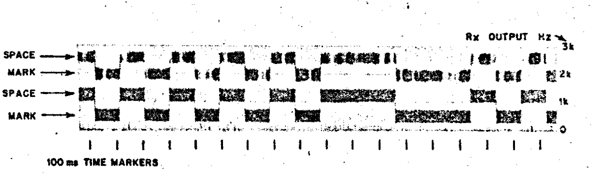

Fig. 6 — Spectrogram of simultaneous 28- and 50-MHz transmissions from 5B4CY in Limassol, Cyprus, as received by ZS6PW in Pretoria, South Africa.

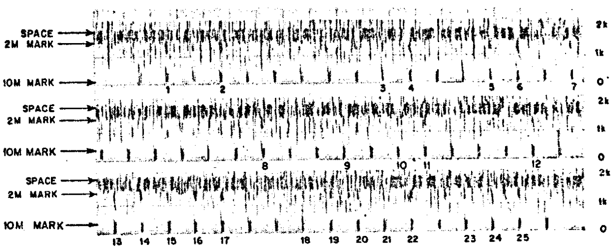

Fig. 7 — Spectogram of simultaneous fsk pulses on 28 and 144 MHz as received by SV1DH in Athens from ZE2JV in Salisbury.

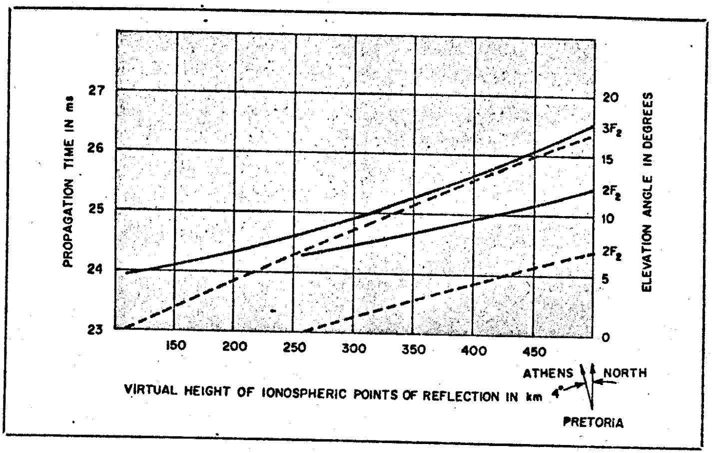

Fig. 8 — Propagation time and angles of arrival of normal multi-hop, F_2-layer propagation between Pretoria, South Africa, and Athens, Greece.

frequency spreading experienced on 2 meters. Also, we knew from the original tests that multipath propagation takes place on 10 meters, the band that would have had to be used for the retransmission back to the originating station. The resulting oscilloscope display would have been completely unintelligible.

The interest lay, however, in determining whether signals on one band had traveled over a longer or shorter path than those on another band. The measurement of *relative* propagation times would provide the required information.

We therefore conducted a series of tests in which the call sign 5B4CY was keyed simultaneously on the Cyprus 28- and 50-MHz beacons. The ZE2JV beacons were arranged to transmit call sign and pulses simultaneously on 28 and 144 MHz. At the receiving end of the TE circuit we adjusted two receivers, operating in the cw mode, to produce different audio notes, which were summed and recorded on tape. We subsequently analyzed the tape recordings on a sonograph. This is a device that provides a running display of the audio spectrum over several seconds.

Some results of these tests are shown in Figs. 6 and 7. In Fig. 6, the "5B" of the call sign 5B4CY is shown as received simultaneously on 50.498 and 28.220 MHz by ZS6PW. It can be seen that any difference in the time of arrival of the transitions from mark to space, or vice versa, is less than the resolution of the system — some 2 milliseconds in this case. Band conditions at the time were typical for evening propagation with slight, slow fading on 10 meters and moderate flutter-fading on 6 meters. Note the excellent signal-to-noise ratio presented in Fig. 6.

Fig. 7 shows a series of pulses that were received simultaneously by SV1DH from ZE2JV on 144.160 and 29.266 MHz. Band conditions were typical, with slight QSB on 10 meters and severe flutter-fading on 2 meters. Owing to the poor signal-to-noise ratio, not all the 2-meter pulses are visible. The best 25 have been marked, and none appear to occur at times that are not coincident with those at which the 10-meter pulses were received.

Although this system showed that there were no significant differences in the propagation times on 10, 6 and 2 meters, its limitations are fundamental. It is cumbersome and places great demands on the operator to adjust two receivers to produce the optimum audio notes. Furthermore, the bandpass of the analyzing filter has to be narrow to resolve the limited frequency shift of the F1 signals. This severely limits the time resolution. There is, of course, no measurement of the actual time taken by either signal.

A System for Measuring Absolute Propagation Times

Consider the transequatorial circuit involved, the probable virtual height of the ionosphere and the propagation modes that could be in operation. A little geometry plus a few simplifying assumptions lead to Fig. 8. The range of values to be expected for the propagation time over the Pretoria-to-Athens circuit for the two normal propagation modes would be some 2 or 3 milliseconds. Hence, a system providing a time resolution of 0.1 millisecond would be very useful in estimating the propagation parameters involved. The 2-ms resolution of the previous systems only indicated broad trends.

These considerations, as well as the drawbacks to the relative time measurements mentioned above, led to the decision to set up an entirely new one-way measuring system, based on Universal Coordinated Time (UTC). UTC was available with great accuracy at both ends of the Pretoria-to-Athens circuit. In Pretoria at ZS6PW, it is only a short ground-wave path to the vhf transmitter of ZUO, the South African equivalent of WWV. In Athens at SV1DH, UTC was available from the Lampedusa station of the Mediterranean Loran C navigation system operating on 100 kHz. Over both these paths the propagation times are constant and can be calculated with great accuracy.

The system used is based on the transmission by ZS6PW of pulses having the same repetition period as the Mediterranean Loran C eight-pulse groups, namely 79.9 ms. The first pulse of each group as received by SV1DH from Lampedusa triggers a two-channel oscilloscope. In the oscillogram reproduced in Fig. 9, the last

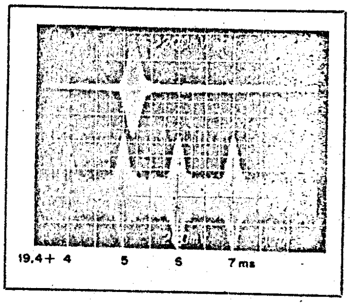

Fig. 9 — Oscillogram of propagation delay photographed by SV1DH, displaying a pulse received from ZS6PW on 28.270 MHz on the upper trace, and Loran C timing pulses on the lower trace. The actual delay is 19.4 plus the 5.2 milliseconds read from the oscillogram.

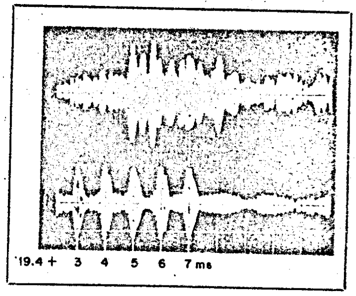

Fig. 10 — Multipath propagation from ZS6PW on 28.270 MHz photographed by SV1DH. There are 10 received pulses from the one transmitted pulse, with time delays from 24.3 to 27.5 milliseconds.

four of the set of eight pulses, which are spaced by 1 millisecond, are displayed on the bottom trace, while a pulse received from ZS6PW is shown on the top trace. From the very convenient Loran C markers the time of arrival can be read off once all delays have been accounted for. These are the offsets from UTC of both pulse systems and the transit time from Lampedusa to Athens. Inherent delays in receivers used for these two signals cancel, provided they have similar band-pass filters and time measurements are taken at corresponding points on the two pulse envelopes, such as at the peaks in Fig. 9. In our system a total of 19.4 ms has to be added, so that the 5.2-ms delay shown in Fig. 9 represents a propagation time between Pretoria and Athens of 24.6 ms. Keeping in mind the distance, time of day and operating frequency, a delay of 24.6 ms is a realistic figure. Propagation was probably by two hops, with the virtual height of the F layer at 210 miles.

Fig. 9 represents almost ideal propagation on 10 meters. The signal-to-noise ratio was very good, the pulse shape well preserved and no multipath propagation could be detected. By way of contrast Fig. 10 shows extreme multipath propagation with numerous pulses arriving between 24.3 and 27.5 ms for every pulse transmitted by ZS6PW. The signal-to-noise ratio is much poorer than in Fig. 9.

Examples of the received pulses are illustrated in Fig. 11 for which much wider (1.8 ms) pulses were used to improve the chances of detection on 2 meters. Fig. 11A shows elongation of a 10-meter pulse to 3.9 ms, its beginning occurring at 24.9 ms. This is an example of severe multipath propagation. Fig. 11B shows a relatively undistorted 6-meter pulse received under typical F-type TE conditions; the propagation time can be read as 25.1 ms. By way of contrast, Figs. 11C and 11D show how typical pure TE propagation causes severe elongation on 6 meters, but rather less on 2 meters. The propagation times were 25.0 and 25.8 ms, respectively.

In February 1980, ZS6PW commenced transmitting these Loran-synchronized pulses simultaneously on the 10-, 6- and 2-meter bands. SV1DH made routine measurements of the propagation time under various propagation conditions.

Of main interest was the measurement of propagation times when the three transmissions of ZS6PW could be heard simultaneously by SV1DH. This normally occurred within the period 7:30 to 8:30 P.M. local time. During the 1980 March and September equinoxes there were 10 evenings when all of these signals were strong enough to make such measurements possible. Their combined results are listed in Table 1. In the case of multiple or elongated pulses the propagation time was logged as the time indicated by the first-arriving peak.

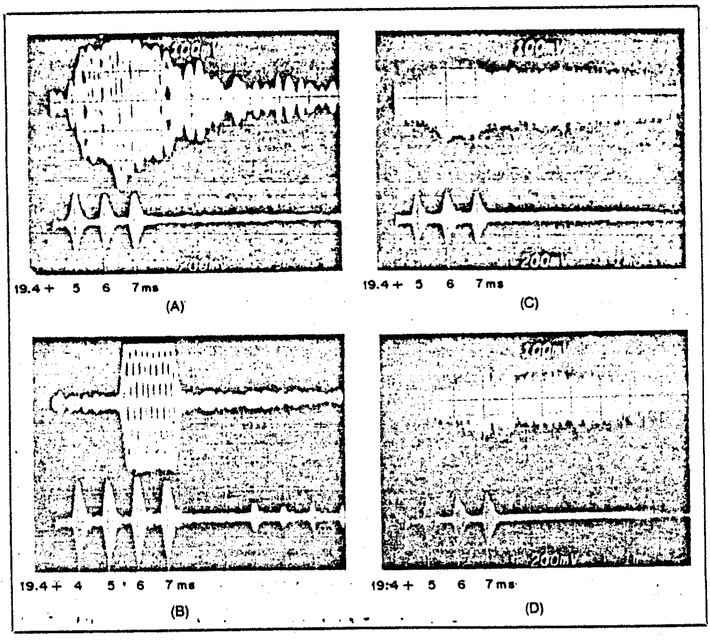

Fig. 11 — Recordings of propagation time between Pretoria and Athens. Pulse width in all cases = 1.8 ms: at A, an elongated pulse on 10 meters (24.8 ms); at B, an undistorted 50-MHz pulse (25.1 ms); at C, pure TE on 50 MHz at 8 P.M. March 18, 1980 (25.0 ms); at D, TE on 144 MHz at 7:45 P.M. on the same evening (25.8 ms).

Table 1

Variations in Propagation Time by Band

Frequency	*Avg. Propagation Time*	*Standard Deviation*
28.270 MHz	24.6 ms	0.2 ms
50.029 MHz	25.2 ms	0.3 ms
144.90 MHz	26.0 ms	0.2 ms

Propagation time recorded between ZS6PW in Pretoria and SV1DH in Athens using the 10-, 6- and 2-meter amateur bands.

There are significant differences in propagation times at the three frequencies, with a slightly longer time being taken at higher frequencies. The differences are within the limits of error possible in the relative propagation-time tests. The absolute time system, like the transponder system, indicates different modes of propagation are operative on the lower frequencies.

At 28 MHz, measurements were taken during the day as well as during the evening. The dominant mode (the first to arrive) was almost certainly two-hop F-layer propagation. It is occasionally present at 50 MHz and never present at 144 MHz.

At 50 MHz, the dominant mode is likely to be F-type TE, which exhibits a slightly longer propagation time than two-hop F layer. As two-hop F-layer and pure TE are also operative at times on 50 MHz, this frequency shows the greatest variation in propagation time.

At 144 MHz, the only mode that has been observed is pure TE. Even so, there remained considerable variability, and this is a matter of great interest.

In the concluding Part 2 of this article, we will discuss Doppler-shift measurements, backscatter observations, angles of arrival, patterns of fading and the support mechanism. We also include an appendix explaining our propagation time measuring system.

[Editor's Note: The references cited in this article provide excellent background information. Reference 5 is particularly germane and should be readily available to most readers.]

Notes

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