Low Frequency Standards Transmissions

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The standard frequency broadcast services have required improvement at a rate of greater than one order increase in accuracy per decade since they were commenced by the National Bureau of Standards in 1923. The accuracy as transmitted is now ±1 part in 10^8 and may be increased to ±1 part in 10^9 or better by reference to the ephemeris second or by adoption of atomic frequency standards. An expanding science and technology requires higher accuracy and worldwide distribution of standards. The immediate problem is to distribute the basic standard of frequency with less loss of accuracy. Investigation has not uncovered a practical way of realizing an improvement in the high-frequency part of the radio spectrum; however, recent measurements in the USA, Europe, and New Zealand on 16 kc and 60 kc have shown that it is possible to operate at VLF and obtain a great improvement in received accuracy.

In the 1930's the NBS considered VLF before adoption of the plan to broadcast several high frequencies simultaneously. The principal reason for adopting the high-frequency system was the existence, at that time, of suitable receiving equipment in the hands of the public for the high frequencies and the lack of it for the low frequencies. It was recognized that the principal advantage of the low frequency would be freedom fron transmission vagaries and that two outstanding disadvantages would be high antenna cost and possible interference from natural noise.

VLF may now be used; the only disadvantage appears to be the initial expense of an efficient antenna. Natural noise is overcome by reduced bandwidth receivers, coherent detectors, and integration type measuring techniques. Receivers can be built for either VLF or HF at approximately the same cost.

The principal reasons for studying a VLF standard frequency service are to give the users an opportunity to obtain a quicker and more accurate frequency and phase-reference than is now possible and to make measurements versus a reference which may be reliably received throughout the world. In a document of the International Radio Consultative Committee[1], it is stated that, "practical experience has shown that the transmissions on 60 and 16 kc from Rugby are remarkable for their phase stability on reception." The receiving location was about 500 km from Rugby. At a distance of about 125 km, another document[2] has reported, measurements were made on 16 kc to a precision of 1 part in 10^{10} in a measuring time of 80 seconds. From still another document we find the following:[3]

<u>considering:</u>

a) that the bands allocated for standard frequency transmissions and time signals are at times made inoperable by ionospheric storms, which may last for a day or more,

b) that frequency comparisons to within 1 part in 10^9 against standard frequency transmissions operating in the allocated bands usually require a measurement period of 1 to 10 days,

c) that in communications, research, and industry there is an increasing need for high measurement accuracy in a shorter measurement time,

d) that frequency comparisons to within 1 part in 10^9 against standard frequency transmissions operating at 16 kc or 60 kc require a measurement period of about 10 minutes,

decides that the following question should be studied:

What can be recommended for the distribution of standard frequencies and time signals above 30 Mc and below 100 kc?

Professor J.A. Pierce at Cruft Laboratory has shown that 16 kc, after a 5000 km circuit over the North Atlantic, is still accurate to 3 parts in 10^9 at any time during the day and that measurements up to 1 part in 10^9 can be made in a few minutes. A precision exceeding 1 part in 10^{10} was consistently obtained by observations over a few hours. He has also given evidence that a single frequency, in the VLF band may be used to give worldwide service. At greater distances, up to 19,000 km, reports from New Zealand[4] indicate that instability in the transmission path causes maximum errors at 16 kc of 2 parts in 10^8; however, the errors do not exceed 4 parts in 10^9 during 17 hours of each day.

Frequency measurements which are accurate to 1 in 10^9 or 1 in 10^{10} using present WWV sky waves, require an integration time of one to ten days and somewhat specialized equipment at the receiving points. This is indicated in Figure 1, which is a 4-day photographic record of WWV time pulses made at the NBS Boulder Laboratories versus a high precision standard oscillator which controls the 0.001 s sweep of an oscilloscope. The leading edge of the received seconds pulse controlled the oscilloscope beam intensity. The photographic film was continuously moved across the oscilloscope screen. This type of record while relatively slow has many advantages in making highest precision comparisons. Unusual changes in the propagation path length and difficulties from local noise are easily discernible and may be omitted when scaling the record.

The VLF method of transferring the basic standard gives an accurate method of timing which may outweigh its value as an accurate frequency standard. This is because the actual transfer of atomic or crystal controlled clocks is not likely in many timing applications, e.g., in accurately synchronizing events at two or more locations which are separated by thousands of miles or, e.g., in the artificial earth satellite program where there is a need for more accurate timing and for reliable continuous time signals at numerous and widely spaced locations. At present the accuracy in setting a clock is generally limited to about 1 millisecond because of jitter in the received WWV signals. At VLF a two order or greater improvement can probably be realized, propagation would be supported at all hours and rather elaborate local quartz crystal clocks would not be required.

The high cost of establishing several local frequency standards, when the required accuracy is greater than that immediately received from WWV, led to the renewed study of possibly operating a low-frequency broadcast. A standard frequency broadcast at VLF appears to be far more practical and economical than establishing a high accuracy frequency standard at the hundreds and possibly thousands of locations where they are needed in science and industry. An alternative method might be used, e.g., numerous VHF stations on 100, 200 or 300 Mc. However, this also appears to be an even more expensive undertaking, particularly in first cost, operation, and maintenance.

A single, high-power (20 kw radiated) 10 kc standard-frequency station may be received throughout the world. A carrier frequency of ten kilocycles per second is being considered because: (a) it is a convenient number to use in measuring frequency and in the synthesis of other frequencies; (b) authority to use 10 kc may be more readily obtained; (c) less interference from other stations might be expected; (d) at distant receiving points the phase and amplitude of the carriers of higher frequencies is believed to be less stable. Moreover, at 10 kc the propagation is accomplished with lower attenuation; this and the required radiated power for worldwide reception at VLF is indicated in Figure 2. Dr. Pierce's considerations[5] have indicated that a field strength of 10 microvolts per meter at the receiver would be practical when specialized receivers and techniques are available. This field strength could be established at the antipode (approximately 19,000 km) with a radiated power of about 2 kilowatts at 10 kc. Dr. J.R. Wait[6] has calculated the power required to establish 100 microvolts per meter at 19,000 km. Results are shown in curve B of Figure 2.

In giving a standard frequency and time interval service the dual use of an existing VLF station was studied. It was found that existing VLF transmitters and antennas are not designed for highest phase stability, e.g., it is likely that changes in phase of the carrier because of heating of the different circuits of the transmitter, would at times cause frequency changes greater than 1 in 10^{10}. Such temperature changes would be more frequent and possibly greater if the transmitter were simultaneously used for telegraph communication and a standard frequency broadcast. VLF stations in operation use frequency shift as well as on-off keying; also the transmitters are switched to several different frequencies to avoid interference and to increase reliability at a particular time; these operating conditions would thus make these stations unsuitable for a continuous standard frequency broadcast which should be designed for maximum convenience to the user.

Reliability is most important to the majority of users whose requirements depend on continuity of a radio broadcast. Other factors to be considered are: (a) stability and accuracy which might be difficult to establish at existing stations; (b) the difficulty of providing continuity of service during the development and installation of improved control apparatus; (c) modification of the control equipment to automatically adjust the phase for changes caused by ground changes or atmospheric changes as the accuracy requirements are increased; (d) a nearby monitoring station and R&D laboratory for studying such changes and for engineering any modifications in the transmitting equipment.

In July 1956 an experimental standard frequency station was commenced on 60 kc at the NBS Boulder Laboratories. A view of the antenna is shown in Figure 3. It consists of a vertical, top-loaded, antenna 125 feet high. Radiated power is about 40 watts. The broadcast is from 1530 to 2000 universal time on each working day; it is cw except during the transmission of the call sign, KK2XEI, which is given each 20 minutes.

Results of measurements during the month of January 1957 are shown in Table 1. The standard deviation of changes which occurred in propagation was less than 1 part in 10^9.

REFERENCES

1. CCIR, Study Group VII, Document 179, France, March 13, 1956

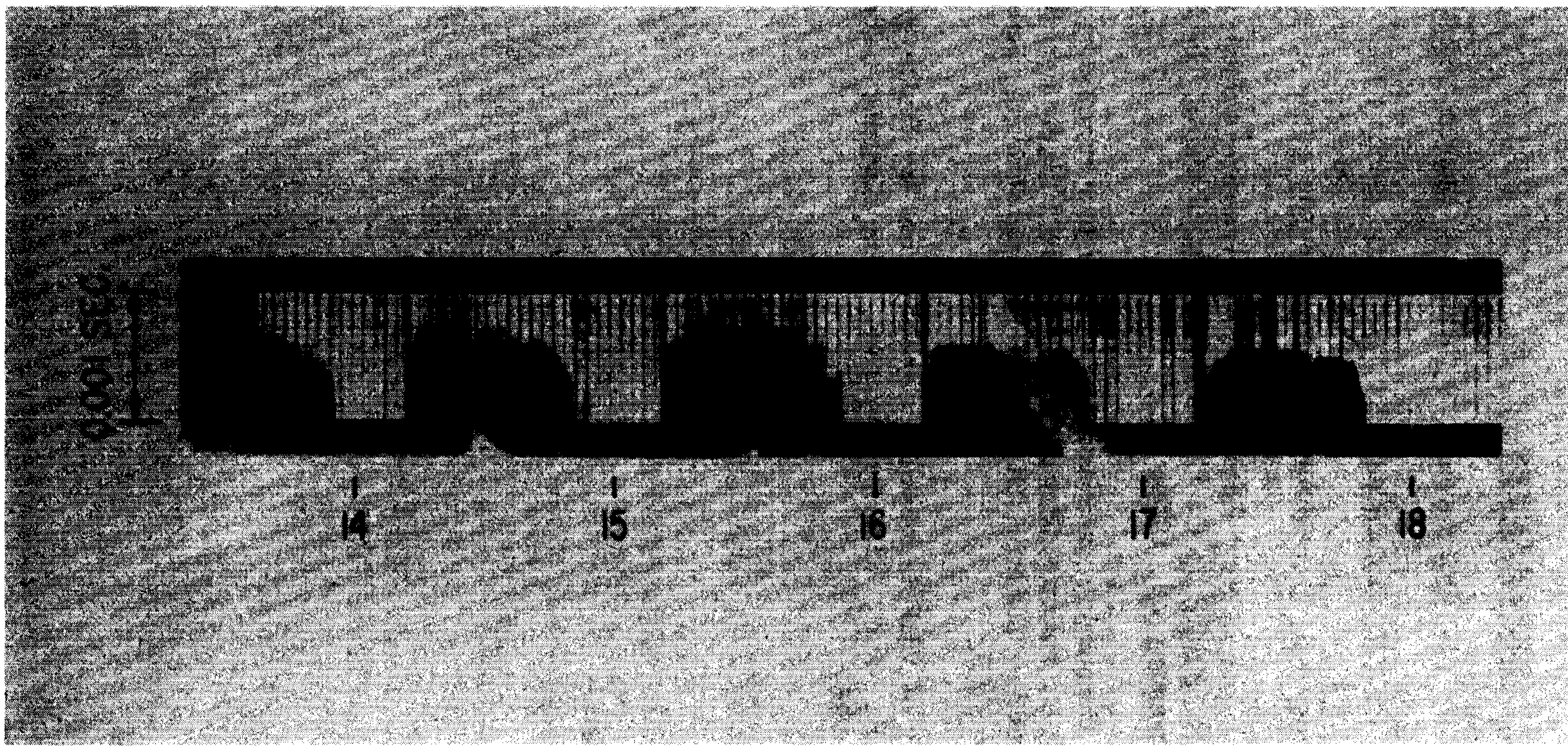
2. CCIR, Study Group VII, Document 151, UK, March 5, 1956

3. CCIR, Study Group VII, Document 703, IIth Plenary Assembly, Warsaw, August 30, 1956

4. Frequency variations in New Zealand of 16 kc transmissions from GBR Rugby, A.H. Allan, D.C. Crombie, W.A. Penton, Nature, 177, 178-179, January 28, 1956.

5. Intercontinental frequency comparison by very low frequency radio transmission, J.A. Pierce, Proceedings of the 10th Annual Symposium on Frequency Control, Signal Corps Engineering Laboratories, 15 - 16 - 17 May 1956.

6. The mode theory of VLF ionospheric propagation for finite ground conductivity, J.R. Wait, VLF Symposium, NBS Boulder Laboratories, January 23-25, 1957.



15 MC

WWV AT BOULDER, COLORADO

Fig. 1

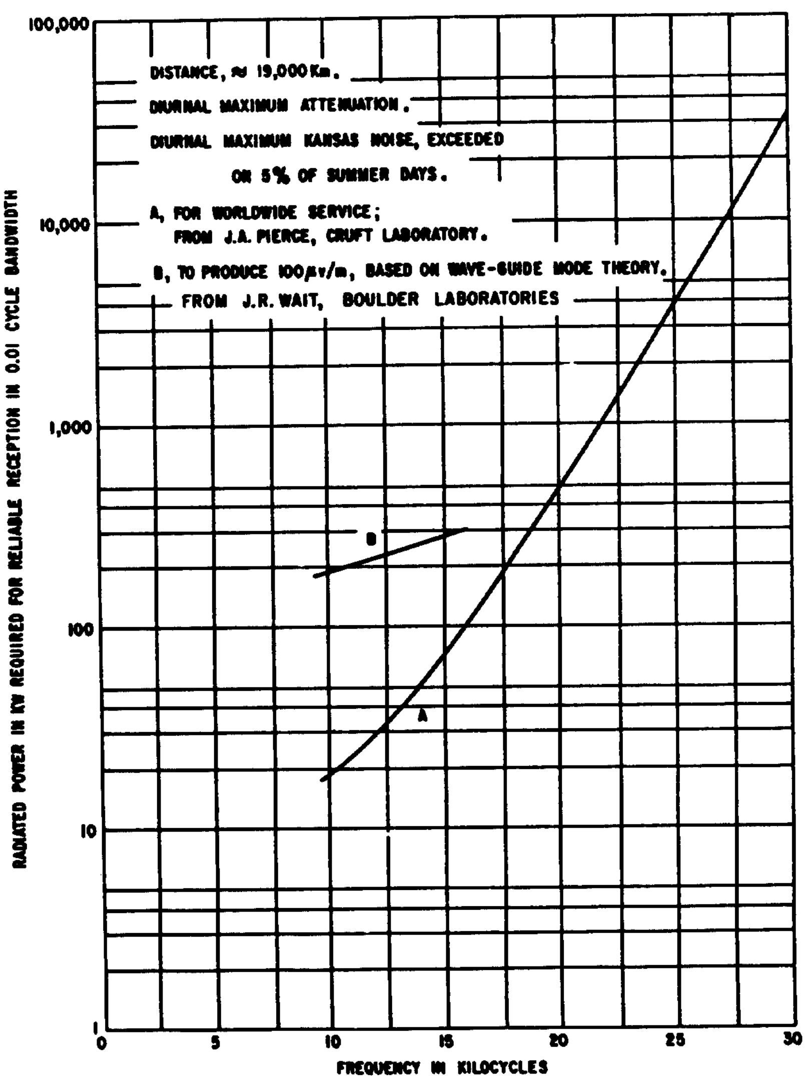

100,000
10,000
1,000
100
10
1
0
5
10
15
20
25
30
DISTANCE, ≈ 19,000 Km.
DIURNAL MAXIMUM ATTENUATION.
DIURNAL MAXIMUM KANSAS NOISE, EXCEEDED
ON 5% OF SUMMER DAYS.
A, FOR WORLDWIDE SERVICE;
FROM J.A. PIERCE, CRUFT LABORATORY.
B, TO PRODUCE 100μv/m, BASED ON WAVE-GUIDE MODE THEORY,
FROM J.R. WAIT, BOULDER LABORATORIES
B
A
RADIATED POWER IN KW REQUIRED FOR RELIABLE RECEPTION IN 0.01 CYCLE BANDWIDTH
FREQUENCY IN KILOCYCLES

Fig. 2

Comparisons of 60 kc Experimental Broadcast,
Station KK2XEI
(values given are parts in 10^9)

Jan. 1957	vs. NBS Standard at Boulder	vs GBR, measurements made at Cruft Lab.	vs WWV average value taken over 10 days as received at Boulder	vs WWV as received at Cruft Lab.
1				
2	-0.3	-1.4	+1.0	+2.2
3	+0.2	-2.1	+1.5	+2.2
4	+0.3	-2.3	+1.7	+0.7
5				
6				
7	+0.7		+2.3	
8	-0.1		+1.5	
9	-0.3	-3.7	+1.4	+0.4
10	+0.3		+2.1	
11	+0.5	-2.4	+2.3	-0.9
12				
13				
14	0	-1.8	+2.0	+1.0
15	+0.1	-1.4	+2.1	+1.6
16	0	-1.1	+2.2	+1.1
17	+0.1	-0.8	+2.4	+2.6
18	0	-1.5	+2.3	+2.8
19				
20				
21	+0.8	-1.4	+2.7	+2.6
22	+0.3	-0.5	+2.1	+1.7
23	+0.4	-0.3	+2.4	+2.4
24	+0.5	-0.9	+2.4	+2.9
25	+0.1	-1.8	+2.0	
26				
27				
28	-0.3	-2.4	+1.4	
29	+0.1	-1.9	+1.8	
30	-0.2	-2.9	+1.4	+1.7
31	-0.2	-2.4	+1.4	+1.2
Feb. 1	0	-2.6	+1.5	+1.7

Table 1

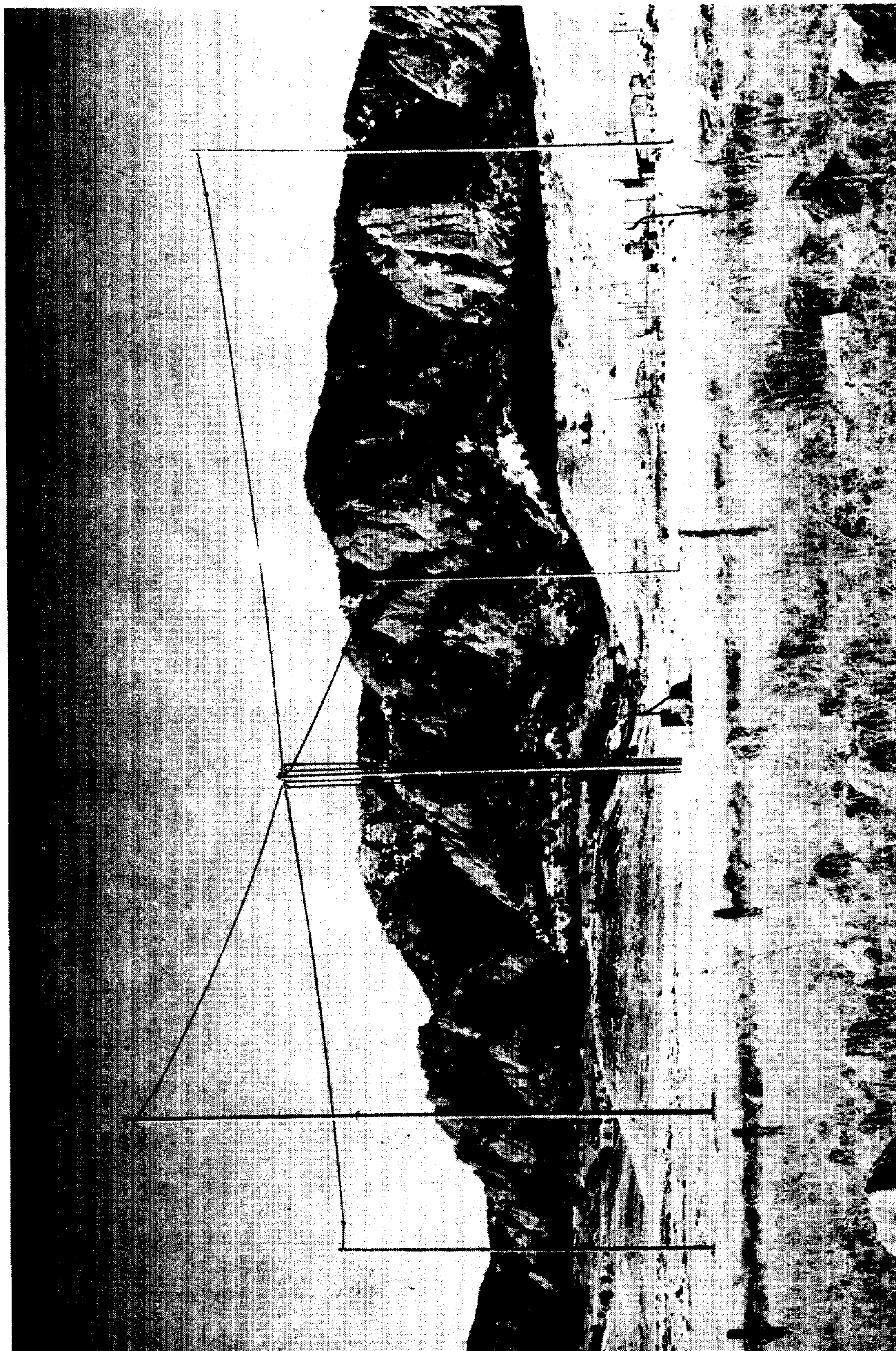


Fig. 3