# United States Patent [19]

## Lewis et al.

#### [54] HIGH RESOLUTION, VERY SHORT PULSE, IONOSOUNDER

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   [58]
   Field of Search
   343/17.7, 114.5, 5 W;

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### [45] Apr. 29, 1975

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#### [57] ABSTRACT

A high resolution, super short pulse, VLF/LF ionosounder transmits signals which arrive at a distant receiver both by traveling over the earth's surface and by reflection from the ionosphere. There is radiated such short pulses that the groundwave, which arrives at the receiver first, has past before the arrival of the skywave signal, giving a clean separation between the ground and skywave signals thus making it possible to study uncontaminated individual skywave reflections and also making possible very high resolution. Amplitude and phase information may be recovered by frequency or time domain processing.

### 7 Claims, 8 Drawing Figures



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#### HIGH RESOLUTION, VERY SHORT PULSE, **IONOSOUNDER**

#### BACKGROUND OF THE INVENTION

lonospheric reflection data at long wavelengths is required for engineering purposes, and for attempts to understand the relationships between wave reflections and physical properties, such as electron density and collision frequency, in the lower ionosphere. The presat low, and very low, frequencies is primarily due to the practical difficulties in radiating suitable signals. If continuous waves are used, the direct wave (groundwave) and the reflected wave (skywave) overlap in space and indirectly by observing the interference pattern on the ground or by interpretation of the diurnal phase and amplitude changes. The ionosounder described here radiates a signal so brief in duration that the groundwave has passed beyond the receiver before the skywave arrives, thus allowing the ionospheric reflection properties to be observed directly. The time interval between the onsets of the groundwaves and skywaves were calculated geometrically for "day" (70 km) and "night" (90 km) reflector heights, for selected great circle distances from the transmitter, and are at a distance of 0 km during the day a delay of 467 µsec and during the night a delay of 600  $\mu$ sec; at 50 km during the day a delay of 329  $\mu$ sec and at night a delay of 456 30  $\mu$ sec; at 100 km during the day a delay of 241  $\mu$ sec and at night a delay of 284  $\mu$ sec; at 200 km during the day a delay of 150  $\mu$ sec, and at night 234  $\mu$ sec; and finally, at 250 km during the day a delay of 125  $\mu$ sec and at night a delay of 198  $\mu$ sec.

At a frequency of 15 kHz (period of 66.7  $\mu$ sec), for example, and near vertical incidence in the daytime, the transmitted pulse must be less than about 467  $\mu$ sec in duration to insure that the groundwaves and skywaves do not overlap; while for oblique incidence at a 40 distance of 200 km, the pulse should not be longer than about 150 µsec.

In earlier work VLF pulses were obtained by shockexciting a long vertical wire antenna, supported by a helicopter, but because of the tendency of the antenna 45 to ring at its natural frequency, the pulses were too long in duration to clearly display the reflected wave. For ionosounding, a refined version of this technique was developed to give much shorter radiation pulses, using either a balloon supported antenna of 1 to 2 kilometers 50in length or a fixed tower 100 to 200 meters tall.

In some respects the operation of this antenna system is more difficult than for an antenna consisting of wires laid on the ground, but the field radiated from the vertical antenna has aximuthal symmetry so that measure- 55 ments made simultaneously in different geomagnetic directions can be easily compared and interpreted. With the balloon, the effective position of the transmitting antenna changes slightly when the wind changes direction; for example, a displacement of 100 meters along the line of propagation changes the groundwave arrival time by about 0.3 microseconds. While this is readily observable at the receiver it is negligible with respect to the approximate 1  $\mu$ sec precision of measur-65 ing the skywave. The vertical antenna system is readily transportable, operates from a small area, and can even be used on a ship.

An essential feature of this oblique sounding technique is that the skywave measurements are made relative to the groundwave, which automatically tends to compensate for any variations in the transmitted waveform, or for differences in response of the receiving antenna and circuits. Since the receivers are remote from the transmitter, a common time base is provided by synchronized cesium beam frequency for synchronization purposes, or, a portable standard can be carried ent lack of comprehensive experimental reflection data 10 between sites. As an aid in extracting the received pulses from interfering signals, use is made of a time base which is slower (1 part in 400) than the standard time used by VLF communications transmitters.

It is noted that the present invention utilizes a special time, and reflection information can only be deduced 15 short pulse which is radiated by a vertical antenna. This allows for a clean time separation between the ground wave and ionospherically reflected pulses, making it possible to study uncontaminated individual skywave reflections. The high resolution can detect reflection 20 height changes as small as 200 meters. The high spectral content in the radiated pulse simultaneously provides over 100 frequencies in the VLF/VF range which are of sufficient amplitude for measurement. The vertical antenna provides an omnidirectional radiation pat-<sup>25</sup> tern which allows simultaneous measurements to be made along propagation paths in any azimuth. By utilizing a vertical antenna it is also possible to utilize the system aboard a ship. It is emphasized again that the present invention makes possible the clear observation of both normal and rotated skywave components with unparalleled precision and without groundwaveskywave interference. The data can be processed in either the time domain or frequency domain with resolution so great that split echo reflection can be observed 35

The ionosounder of this invention may be used in the study and prediction of upper atmosphere and lower ionosphere weather; in the study and prediction of ELF/VLF/VF radio propagation for long range communications; in the study and prediction of solar activity; in the remote sensing of natural and man-made terrain features; and in high accuracy time synchronization and navigation.

#### SUMMARY OF THE INVENTION

A high resolution, super short pulse, VLF/LF ionosounder is provided. Signals from a very low frequency (VLF) transmitter arrive at a distant receiver both by traveling over the earth's surface (groundwave) and by reflection from the ionosphere (skywave). These waves are ordinarily superimposed and difficult to separate and identify. The basic idea of this new ionosounding technique is to radiate such short pulses that the groundwave, which arrives at the receiver first, has passed before the arrival of the skywaves. The pulses are radiated from either a portable vertical antenna of about 1 kilometer long, balloon supported wire, or from a fixed tower approximately 200 meters high. The antenna is excited by a high voltage switching circuit which utilizes hydrogen thyratrons 60 and solid state diodes. This circuit provides pulses so short that groundwave-skywave separation can be obtained at distances out to several hundred kilometers. Each pulse has a broad spectral content, permitting useful reflection data to be obtained simultaneously at some 100 different frequencies from 6 to 50 kHz on both polarization components By allowing for antenna pattern, earth conductivity, etc., values for the plane

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wave reflection coefficients "R " and "R1 can be obtained.

Two methods are available for recovering amplitude and phase information. One is frequency domain processing and the other is time domain processing.

#### DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a simplified form of the VLF/LF super short pulse ionosounder of the present invention;

FIG. 2 shows the normal antenna signal;

FIG. 3 shows the rotated antenna signal;

FIG. 4 shows in schematic form the basic transmitter circuit;

FIG. 5 shows in block diagram form the receiver and associated apparatus for frequency domain processing; 15

FIG. 6 illustrates the radiated pulse observed at a distance of 15 km;

FIG. 7 illustrates a Fourier amplitude spectrum; and FIG. 8 shows in block diagram form at the receiver station apparatus for time domain processing.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Now referring to FIG. 1, there is shown at the transmitter station transmitter 10 and associated vertical an- 25 trated groundwave signal 15, normal skywave signal tenna 11. The transmitter uses in one instance, a 1.5 km vertical wire antenna supported by a balloon. In another instance, it may utilize a base insulated vertical antenna tower 100 to 200 meters tall for the associated vertical antenna. The balloon antenna system basically 30 consists of a helium filled polyethylene liner enclosed in a 6 meter diameter spherical shell of fiberglass reinforced nylon. It is emphasized the transmitter employs a vertical antenna of a predetermined length in accordance with and consistent with VLF/LF signal trans- 35 missions.

Transmitter 10 is of a single cycle type. The basic circuit is shown in FIG. 4. In reference thereto, there is shown 48 kv DC high voltage power supply 20 which 40 charges transmitting antenna 11 through the inductor and diode. The antenna acts somewhat like an openended section of a lossy transmission line, but the circuit may be understood by considering the antenna as a lumped capacitance C of about 6000 PF (for an antenna 1.5 km long). When a trigger voltage from trigger source 23 is applied to grid 24a of hydrogen thyratron 24, the charge flows from the antenna through inductance 25 (about 20 mk) for a time  $T = \pi \sqrt{LC} \approx 35$  $\mu$ sec. The capacitance C then has its maximum nega-50 tive charge, the thyratron ceases to conduct, and the charge flows back into the antenna through diode 22 for an additional 35  $\mu$ sec, at which time capacitance C is recharged positively. The system remains in this condition until the thyratron is triggered again. If the length or capacity of the antenna is reduced without changing inductance 25, the transmitter pulse is of shorter duration, and smaller amplitude. Trigger source 23 receives a timing pulse from clock 26 which is a conventional cesium beam frequency standard.

Because of inductance 21, the voltage in the antenna is about 25 percent higher than the supply voltage. With the antenna charged to 60 kv, each actuation of the thyratron circuit consumes about 2 joules. For a 1.5 km antenna, the total radiated energy is estimated at 65 0.35 jouleper actuation. When operated at 400 actuations per second, the total radiated power is 140 watts, with a power consumption of 1500 watts, resulting in

an overall efficiency of about 10 percent for the basic transmitter. Of the total power consumed 700 watts is used by the thyratron heaters and filter resistors. A more detailed description of the aforementioned transmitter may be found in U.S. Pat. application bearing Ser. No. 315,624, filed Dec. 15, 1972, entitled, "Single Cycle Transmitter". The transmitter may generate VLF/LF signals.

Referring again to FIG. 1, at the receiver station at 10 a predetermined distance from the transmitter station receiver 12 has two loop antennas 13 and 14 with horizontal axes. One loop is in the vertical plane through the transmitter, and responds to the magnetic fields of the groundwave and the unrotated component of the skywave (hereinafter referred to as the ' " -skywave'). The other loop perpendicular to the first, responds to the rotated component (the ' $\perp$ -skywave'). These resistively loaded loops were 1.5 m square, with 20 turns and electrostatic shielding.

It is noted that transmitter 10 and its associated antenna 11 radiates a signal so brief in duration that the groundwave has passed beyond the receiver before the skywave arrives, thus allowing the ionospheric reflection properties to be observed directly. There is illus-17.

Now referring to FIG. 2, there is shown in greater detail the normal signal received by antenna 13 in which the groundwave signal is clearly past before the arrival of the normal skywave signal.

FIG. 3 shows the rotated signal received by antenna 14 and being an abnormal skywave signal which is related in time to the above illustrated signals of FIG. 2.

Two methods are available for recovering amplitude and phase information: (1) frequency domain processing, and (2) time domain processing. The amplitude and phase information for selected frequencies can be obtained and recorded continuously by utilizing the receiver shown in FIG. 5 which permits frequency domain processing. The receiver of FIG. 5 is equivalent to that shown as simplified receiver 12 in FIG. 1.

Now referring in detail to FIG. 5, there is shown two loop antennas 13 and 14 with horizontal axes. Loop antenna 13 is in the vertical plane through the transmitter and responds to the magnetic fields of the groundwave signal and the unrotated component of the skywave signal. Other loop antenna 14 perpencicular to loop antenna 13 responds to the rotated component. Bandpass filter 30 and symmetrical clipper 31 pass the signals from antenna 13 through to normally open gating circuits 32 and 34. Bandpass filter 40 and symmetrical clipper 41 pass the signals from antenna 14 through to gating circuit 41. Clock 52 supplies a common time base. Clock 52 is conventional and like clock 26 of the transmitter is a cesium beam frequency standard. Clock 26 at the transmitter and clock 52 at the receiver are synchronized. This synchronization may be accomplished by a third identical clock that is alternately carried back and forth and utilized to time each of clocks 60 26 and 52. Synchronization may also be achieved by utilizing the received groundwave and adjusting clock 52 in relation thereto. Filters 30 and 40 limit the input bandwidth and in one instance covered a frequency range from 200 Hz to 100 KHz. Conventional symmetrical clippers 31 and 41 limit the noise.

The time separation between the received groundwave signals and skywave signals makes it possible to

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switch these pulses into separate channels without distortion. This is accomplished by analog gating circuits 32 and 34 precisely synchronized by the system's common time base, clock 52. To eliminate any vestiges of groundwave signal which may be picked up by loop antenna 14 receiving the rotated skywave signal, this skywave component is also gated. With gates having durations of approximately 200  $\mu$ sec and repeated every 2500  $\mu$ sec, about 92 percent of the background noise power is removed.

In the operation of normally open gating circuits 32, 34 and 42, thereinbefore mentioned clocks 26 and 52 have been synchronized with the timing of enabling pulses from clock 52 depending upon the distance between the transmitter and receiver wherein it is pre-15 cisely known the time required for a groundwave pulse to travel therebetween. The enabling pulse from clock 52 permits gating circuit 32 to close to permit the groundwave pulse to pass therethrough and then it opens. Thereupon an enabling pulse is received both by 20 gating circuits 34 and 42 to permit the normal and abnormal skywave signals, respectively, to pass therethrough. Thus, there is an alternate switching of the groundwave and skywave signals.

In each of the three channels the data consists of 25 pulses with a repetition rate of 400 per second, so that in the absence of noise the Fourier spectrum has discrete lines 400 Hz apart. For each series of pulses the envelope of this line spectrum has the same shape as the Fourier integral spectrum of an individual pulse.  $^{30}$ FIG. 7 shows the spectral lines of the pulse of FIG. 6. The amplitudes below 6 KHz, and around minima such as at 27 KHz, for example, are relatively weak, but in the band from 6-50 KHz, there are approximately 100 spectral lines of useful amplitude, all of which could in 35principle be observed simultaneously. For complete information at a single frequency three VLF tracking receivers 33, 53, and 43 are utilized, one for the groundwave signal, one for the normal skywave signal, and one for the abnormal skywave signal, respectively. The 40VLF tracking receivers are conventional and each provides phase and amplitude output signals. They may be of the type supplied by Tracor (VLF) tracking receivers.

The amplitude and phase information for each tracking receiver is recorded in analog form for immediate reference, and is also digitized and recorded for computer processing by conventional digital data logging system **54**. Digital data logging system may be such as model 140, manufactured by Hyperion. The digitized output in paper form from digital data logging system is received by conventional computer **55** which has been programmed for any aforementioned desired data analysis. Computer **55** may be such as the 6600 type manufactured by Control Data Corporation.<sup>55</sup>

The tracking receivers typically are operated with a time constant of 50 seconds so that, if the ionospheric reflection properties are changing, the indicated amplitudes and phases are really time averages.

Now referring to FIG. 8, there is shown receiving station for time domain processing. Receiving antennas 13a and 14a are identical to receiving antennas 13 and 14, respectively, of FIG. 5. There is also shown bandpass filters 30a and 40a which are identical to filters 30and 40, respectively, of FIG. 5. Also shown are symmetrical clippers 31a and 41a which are indentical to symmetrical clippers 31 and 41, respectively, of FIG. 5. The output signals of clippers 31a and 41a are fed to correlators 60 and 61, respectively. Correlators 60 and 61 are conventional and may be of the type known as "Ubiquitous", manufactured by Federal Scientific Corporation. Actually, components 60 and 61 provide signal enhancement by averaging a multiplicity of input pulses.

Because of the precise repetition of the pulses, the voltage at corresponding points on a succession of 10 waveforms can be observed for as many transmissions as desired. By averaging these observed voltages over a period of time, the contributions of noise tend to cancel out, giving an average value for the waveform amplitude at the particular sampling point.

This averaging (providing signal enhancement by components 60 and 61) is performed simultaneously for 256 equally spaced sampling points. These waveforms, which show both groundwaves and skywaves, clearly reveal the changes in pulse shape, duration, and polarity caused by the ionospheric reflection. Oscillograms can also be Fourier analyzed to obtain corresponding changes in amplitudes and phases as a function of frequency, or the outputs of components 60 and 61 can be digitized and then analyzed in a computer such as shown and described in FIG. 5.

What is claimed is:

1. A high resolution, very short pulse ionosounder having a transmitter station displaced a preselected distance from a receiver station comprising, at the transmitter station, very low frequency transmitting means generating signals in the form of single cycle pulses of a preselected very short duration at a preselected pulse repetition rate, vertical antenna means of preselected length in accordance with the signal frequency to be transmitted, said vertical antenna means transmitting said generated signals in the form of groundwave and skywave pulses, at the receiver station, first and second loop receiving antenna means with horizontal axis, said first loop receiving antenna means being in the vertical plane through said vertical antenna means and responding to the magnetic fields of the groundwave signal and the unrotated component of the skywave signal, said second loop receiving antenna means perpendicular to the first loop receiving antenna means and responding to the rotated component of the skywave signal, each of the transmitted pulses being so short in duration permitting the reception of the groundwave pulse at the receiver station distinctly prior in time to the reception of the skywave pulse, means to separate 50 the groundwave signal, the unrotated component of said skywave signal, and the rotated component of said skywave signal at predetermined times to provide first, second, and third signals, first, second, and third means to derive a separate phase and amplitude signal for each of said first, second, and third signals, respectively, said phase and amplitude signals being representative of ionospheric conditions, and means to synchronize said transmitter and receiver stations.

2. A high resolution very short pulse ionosounder as described in claim 1 further including means to digitize each of said phase and amplitude signals, and computer means to analyze the digitized signals.

3. A high resolution very short pulse ionosounder as described in claim 1 wherein said synchronizing means is comprised of first and second clocks, said first clock timing said transmitter means, and said second clock timing said separating means, said first and second clocks having a common time base with the timing of the enabling pulse from said second clock being dependent upon the preselected distance between said transmitter station and said receiver station.

4. A high resolution very short pulse ionosounder as 5 described in claim 3 wherein said separating means is comprised of first, second, and third gating circuits normally off, said first and second gating circuits receiving the output of said first receiving antenna means and said third the output of said second receiving antenna 10 means, said second clock enabling said first and second gating circuit to alternately pass said groundwave and skywave signal at a first and second predetermined time and also enabling said third gating circuit to pass said unrotated component at said second predeter- 15 mined time.

5. A high resolution very short pulse ionosounder as described in claim 4 wherein said first, second, and third means to derive phase and amplitude signals is

6. A high resolution very short pulse ionosounder having a transmitter station displaced a preselected distance from a receiver station comprising, at the transmitter station, very low frequency transmitting means generating signals in the form of single cycle pulses of 25 means to digitize the output of the first and second ava preselected very short duration at a preselected pulse repetition rate, vertical antenna means of preselected length in accordance with the signal frequency to be

transmitted, said vertical antenna means transmitting said generated signals in the form of groundwave and skywave pulses, at the receiver station, first and second loop receiving antenna means with horizontal axis, said first loop receiving antenna means being in the vertical plane through said vertical antenna means and responding to the magnetic fields of the groundwave signal and the unrotated component of the skywave signal, said second loop receiving antenna means perpendicular to the first loop receiving antenna means and responding to the rotated component of the skywave signal, each of the transmitted pulses being so short in duration permitting the reception of the groundwave pulse at the receiver station distinctly prior in time to the reception of the skywave pulse, first and second means receiving the output waveforms from said first and second receiving antenna means, respectively, and averaging said waveforms simultaneously for a multiplicity of equally spaced sampling points thus by avercomprised of first, second and third tracking receivers. 20 aging the contribution of noise cancel out giving an average value for the waveform amplitude at that particular sampling point.

7. A high resolution very short pulse ionosounder as described in claim 6 further including first and second eraging means and a computer to analyze the digitized signal to obtain ionospheric information.

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