AGU PUBLICATIONS

Radio Science

RESEARCH ARTICLE
10.1002/2015RS005799

Key Points:
- A quality factor for SSL estimates is proposed
- The quality factor is based on the frequency for optimum traffic (FOT) of the circuit
- Useful SSL results can be obtained if the elevation angle is at least 50% of that of the FOT

Supporting Information:
- Supporting Information S1
- Supporting Information S2

Correspondence to:
P. J. Coetzee,
hcoetzee@gew.co.za

Citation:
Coetzee, P. J., and W. P. du Plessis (2016), Definition of a quality factor for single site location estimates, *Radio Sci.*, *51*, 555–562, doi:10.1002/2015RS005799.

Received 18 AUG 2015
Accepted 13 FEB 2016
Accepted article online 18 FEB 2016
Published online 7 JUN 2016

Definition of a quality factor for single site location estimates

Petrus J. Coetzee[1] **and Warren P. du Plessis**[1]

[1]Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa

Abstract A technique to estimate the performance of single site location (SSL) based on high-frequency direction finding for reigning ionospheric propagation conditions is described. This technique is based on classic propagation information (maximum useable frequency, frequency for optimum traffic, optimum working frequency, highest possible frequency, lowest possible frequency, etc.) which can be deduced by ray tracing through an ionospheric model such as the International Reference Ionosphere. The correlation between the elevation angle measured by an interferometric direction finder and the angles corresponding to the propagation conditions is used to assign a quality factor to the calculated SSL ground range result.

1. Introduction

Reliable high frequency (HF) sky wave communications are highly dependent on utilizing the correct frequency for the applicable distance and on the reigning ionospheric conditions. It is also important that the antenna radiates adequate energy at the required wave angle (azimuth and elevation angles).

Single site location (also known as single station location) direction finding (simply referred to as SSL) is a technique to determine the origin (position) of a long-distance HF signal with the aid of a single, interferometric direction finder [*International Telecommunication Union* (*ITU*), 2011]. The elevation angle of the intercepted signal is used to calculate a ground range by modeling the path that the signal traveled through the ionosphere. The best results are obtained with the aid of ray tracing (sometimes referred to as ray retracing) techniques. With the measured direction (azimuth angle) and the calculated ground range it is possible to determine the origin of the HF transmission with useful accuracy. Position is usually determined by triangulating the azimuth results of multiple direction finders, so the requirement for only a single direction finder is a significant benefit of SSL.

Simply being able to intercept (monitor) a signal and determining the wave angle with the aid of an interferometric direction finder does not guarantee the quality of the calculated SSL ground range. The reigning propagation conditions for the communications circuit must also be taken into consideration for optimum results. However, computing the performance of an SSL system is a complex problem which requires accurate modeling of the ionospheric conditions and complex ray tracing techniques. To overcome this difficulty, a quality factor which only depends on the standard parameters for HF communication links is proposed. Measured results are presented to demonstrate that this quality factor is a useful indicator of SSL performance.

2. HF Propagation

Long-distance HF communications are possible due to the reflection and refraction of signals by the ionosphere [*Davies*, 1990]. The ionosphere is an extremely dynamic medium that is mostly influenced by solar activity [*Devoldere*, 2010]. Ionospheric models are used to describe and predict the behavior of the ionosphere and can also provide the data required for the analysis and prediction of the propagation of an HF signal.

Ray tracing techniques are used to model the propagation of an electromagnetic wave through a model of the ionosphere. It is thus possible to determine if a specified frequency propagates between two given positions at a certain time, date, elevation angle, and ionosphere.

In Figure 1 a simplified geometrical model is used to describe the aspects related to ionospheric propagation [*McNamara*, 1991]. For illustrative purposes use is made of a flat Earth and a flat ionosphere.

Conceptually, the radio waves in Figure 1 are emitted by the transmitter *T* at an elevation angle ϕ, travel a distance *D/*2 before being reflected back to Earth by the ionosphere at point *P* and finally arrive at the receiver *R*. In reality, the ray is not reflected at *P* but is continuously refracted or bent toward the ground,

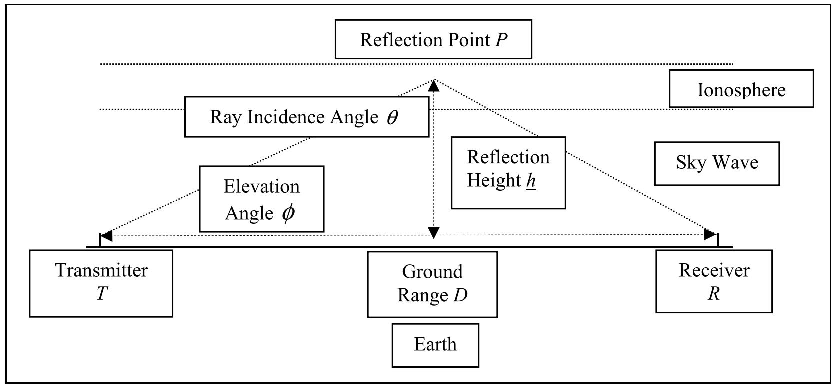

Figure 1. Simplified geometrical propagation model.

as it passes through the ionosphere [*Devoldere*, 2010]. The ionosphere at the conceptual point of reflection *P* is at a height *h* above the midpoint of the circuit. The distance along the ground between the transmitter *T* and the receiver *R* is called the ground range *D*.

One of the most important and most widely published quantities in HF communications is the maximum useable frequency (MUF), which is the maximum frequency that will be reflected by the ionosphere for a given circuit [*McNamara*, 1991]. The basic MUF is a median representation (statistical value) and not an individual value. The MUF depends on just two things, the critical frequency, f_c, of the ionosphere at the reflection point *P* and the geometry of the circuit. The MUF is given by the formula

$$\text{MUF} = fc\sec(\theta) \tag{1}$$

where θ is the ray incidence angle as depicted in Figure 1. Equation (1) is also known as the secant law [*Davies*, 1990].

For radio propagation purposes it is more convenient to work with the elevation angle ϕ, giving

$$\text{MUF} = \frac{fc}{\sin(\phi)}. \tag{2}$$

Since $\sin(\phi)$ can vary from 0 to 1, (2) indicates that the MUF is equal to the critical frequency of the ionosphere for vertical incidence as $\phi = 90°$ gives $\sin(\phi) = 1$. It also indicates that the MUF and ground range *D* are much higher for low elevation angles. In practice, the world is round, and the curvature of the surface prevents the elevation angle from getting too close to 0°, causing the MUF (and ground range) to reach a finite upper limit for a given ionosphere.

For propagation to be possible on a given circuit, the operating frequency f_o must be less than or equal to the MUF for the circuit. At frequencies higher than the MUF, the signals would simply penetrate the ionosphere. For communication purposes the MUF is calculated as a median frequency, defined as the highest frequency at which sky wave communication are possible 50% of the days in a month [*McNamara*, 1991]. Half the time, the actual MUF observed on any day will be higher than the median and half the time it will be lower. The highest possible frequency (HPF) is taken as 115% of the MUF and should support propagation 10% of the time [*Devoldere*, 2010]. The lowest useable frequency is the frequency at which communication with a required minimum signal-to-noise ratio (SNR) for a specified time period is possible 90% of the undisturbed days of the month and is normally determined by the amount of *D* layer absorption and the atmospheric noise level.

It is possible to use the MUF to determine an optimum working frequency (OWF) or frequency optimum de travail (FOT), generally referred to as the frequency for optimum traffic [*Hagn*, 1992]. The FOT is the frequency that is equal to the lower decile value of the thirty or thirty-one individual MUFs for the month. The OWF or FOT is the internationally agreed standard for the best or optimum frequency to use at a given hour on a given circuit. Its use will result in successful communications (at least as far as the correct choice of frequency is concerned) 90% of the time (27 days of the month) [*McNamara*, 1991]. It is possible to get an estimated value of the FOT by taking 85% of the median MUF [*Goodman*, 1992]. This is a convenient definition to calculate the FOT for a given circuit.

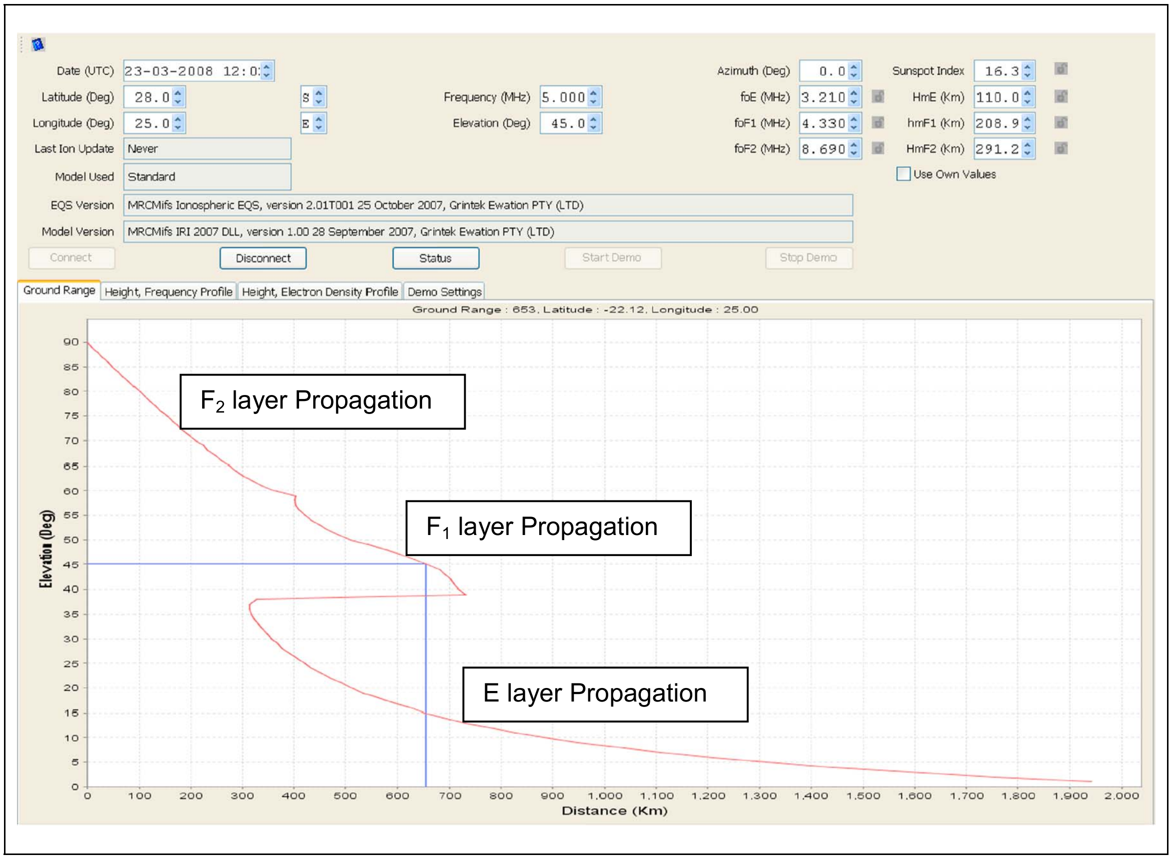

Figure 2. Calculated propagation of a 5 MHz signal through the International Reference Ionosphere model.

Under certain conditions a skip zone or dead zone may exist up to a certain distance from the transmitter. If the operating frequency is higher than the critical frequency (f_oF_2), reflection will only occur if the elevation angle is low enough to comply with (2). It will not be possible to communicate with stations within the skip zone unless the operating frequency is reduced to be less than or equal to the MUF for the required distance (backscatter modes and sporadic *E* may exist but are beyond the scope of this work). The skip zone for a given transmitter will depend on the operating frequency (getting larger as the frequency increases) and the critical frequency of the reflecting layer. The skip zone can be put to good effect if secure communications are required.

The propagation of HF signals through the ionosphere can be graphically illustrated by plotting the ground range for all elevation angles (0 to 90°) for a specific frequency, transmitter position, time of day, date, and ionosphere.

The International Reference Ionosphere (IRI) [*Bilitza*, 2001] ionospheric model was used to generate the ionospheric data required to calculate the ground range for all elevation angles as depicted in Figure 2. The time of the day was taken as noon UT, which is 14 h00 in South Africa. The season was toward the end of summer, and the position was taken as close to Pretoria. The solar activity was very low with a smoothed sunspot number of 16.3. A frequency of 5 MHz was chosen, as it can be seen to support successful communications for both very short distances (Near Vertical Incidence Signals, NVIS) and longer distances up to a few hundred kilometers under the above conditions. The peak layer parameters calculated by the IRI are displayed in the top, right-hand corner of Figure 2 as "*foE*", "*HmE*", "foF_1", "hmF_1", "foF_2", and "HmF_2," respectively.

Ray tracing techniques [*McKinnell*, 2002] were used to model the ray path through the ionosphere, and the red graph shows the elevation angle required for a specific ground range. The blue line is used to indicate a ground range for the elevation angle measured by an interferometric direction finder. Possible propagation via two ionospheric layers can be identified: *E* layer propagation for elevation angles between 0° and approximately 38° and *F* layer for higher elevation angles. The critical frequency of the *E* layer (f_oE) is 3.21 MHz according to Figure 2. As the operating frequency (5 MHz) is considerably higher than the critical frequency

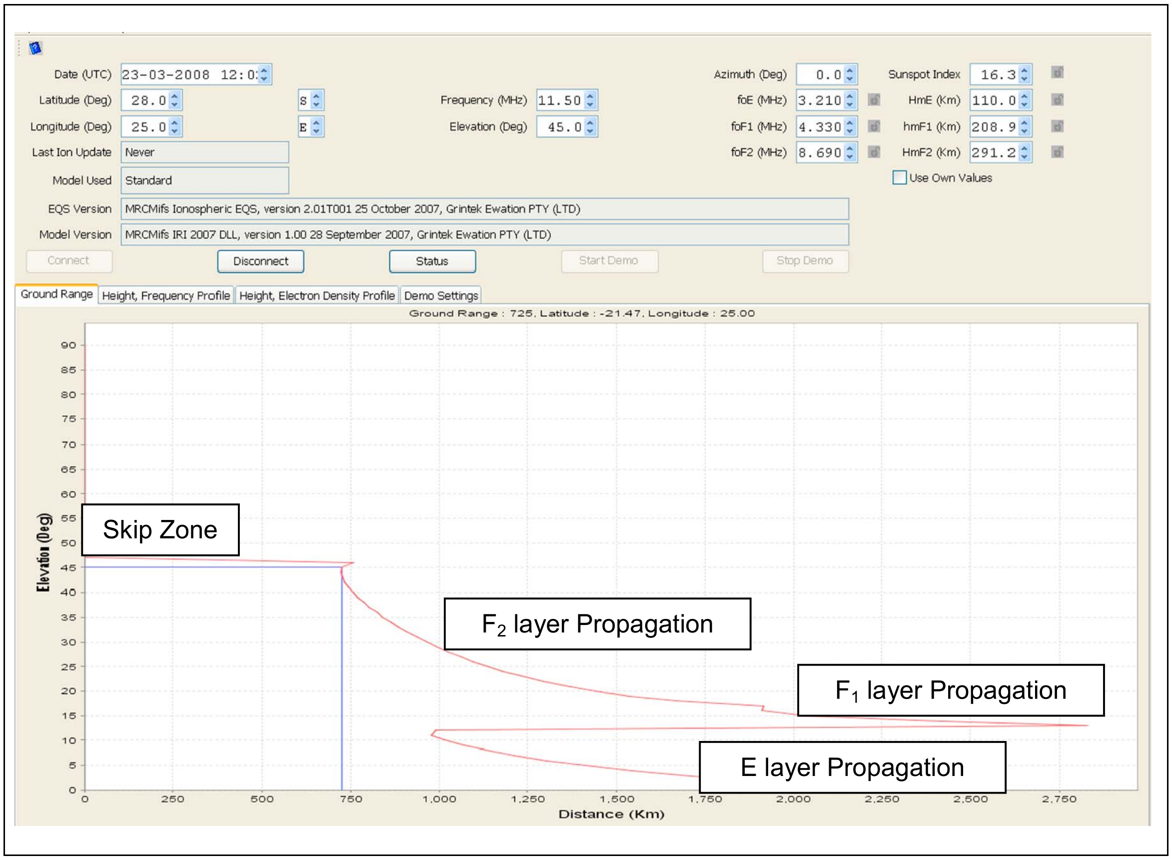

Figure 3. Calculated propagation of an 11.5 MHz signal through the International Reference Ionosphere.

of the E layer f_oE only low-angle signals will be reflected by the E layer. The situation is quite different for the F_2 layer, as f_oF_2 is 8.69 MHz with the result that all high-angle signals are reflected back to Earth by the F_2 layer. No skip or dead zone exists for 5 MHz under the conditions used to generate Figure 2, and sky wave communications from very close to the transmitter up to a distance of nearly 2000 km are possible dependent on the radiation angles of the antennas used.

Figure 3 uses the same parameters as Figure 2 at an operating frequency of 11.5 MHz, considerably higher than the critical frequency of any of the ionospheric layers. The E layer will support propagation for signals with elevation angles between 0° and approximately 13°. Above 13°, the F_1 and F_2 layers take over up to approximately 48°. For elevation angles higher than 48°, the 11.5 MHz signal cannot be refracted back to Earth by the ionosphere. Due to the fact that propagation is not possible for elevation angles higher than 48°, a skip zone of slightly less than 750 km exists. Communications over distances of between 0 and 750 km are thus not possible using sky wave propagation under the conditions depicted in Figure 3. It should be noted that short-range ground wave propagation and line of sight propagation exist, but these are beyond the scope of this work. Also, note that for distances between 1000 and 2000 km, propagation via both the E and F layers is possible (multipath propagation). If the antenna radiates most of the energy between 0 and 30°, considerable signal fading will be experienced due to the different path lengths. Multipath propagation should be avoided for reliable SSL results [*ITU*, 2011].

3. Assigning a Quality Factor to the Calculated SSL Distances

The elevation angle of the received signal as measured by an interferometric direction finder can be related back to the MUF, FOT, HPF, etc. for the reigning ionospheric conditions when ray tracing techniques are applied to the ionospheric data. The relevant ionospheric data may be provided by an ionosonde or obtained from an ionospheric model like the IRI as shown in Figure 4.

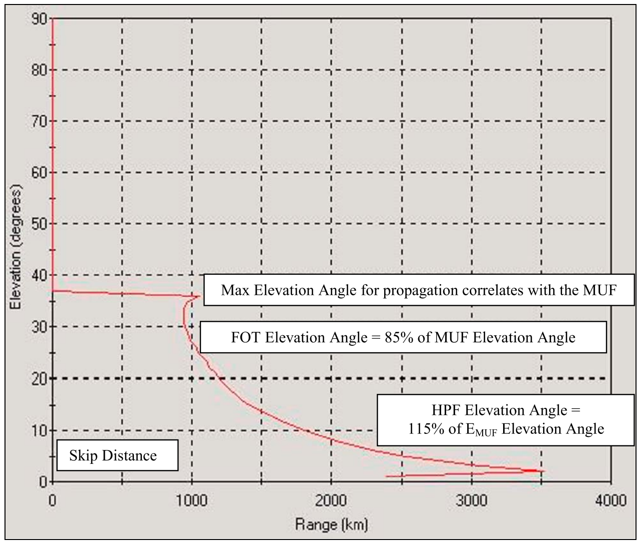

Figure 4. Relating elevation angle to propagation conditions using ray tracing techniques.

When an SSL is performed on an operating frequency above the FOT, the reliability of the result will suffer along with the reliability of the communications. In Figure 4, an intercepted elevation angle of approximately 31° (0.85 × 37°) corresponds to the FOT for the F_2 layer. Although it is statistically possible that a frequency above the MUF ($\phi > 37°$ in Figure 4) may propagate (HPF = 115% MUF), it will not be possible to calculate a SSL distance under the circumstances used to plot Figure 4.

The FOT is defined as having a reliability of 90% for a given circuit. If a SSL is performed under these near ideal conditions a quality factor of 0.9 (or 90%) can be assigned to the result. For stable ionospheric conditions an SSL accuracy of 90% can thus also be assumed or conversely a minimum distance (ground range) error of ±10% [*McNamara*, 1991; *Lai*, 2008].

When SSL is performed on a progressively lower elevation angle (corresponding to an operational frequency lower than the FOT), two factors influence the quality of the SSL result and thus ultimately the accuracy of the calculated distance to the transmitting station. First, while operating in the stable or linear region of the applicable layer, the reduction in SNR will reduce the accuracy of the calculated SSL ground range [*ITU*, 2011]. Second, when the elevation angle gets so low that the transition region between the *F* and *E* ionospheric layers is approached (elevation angle approximately 4° in Figure 4), the highest possible frequency (HPF) of the *E* layer will start to dominate the accuracy of the SSL result. Once this transition region is reached the SSL result will for all practical purposes become useless. A quality factor of 0.1 was used here, as the statistical nature of the parameters used to compute the relevant angle mean that useful results may still be possible under exceptional circumstances.

A nonlinear interpolation between the 90% reliability (quality factor of 0.9) result of a SSL calculation at the elevation angle corresponding to the FOT for a layer (e.g., the F_2 layer) and the 0.1 quality factor for the HPF for the next lower layer (e.g., the *E* layer) is proposed to provide an indication of the quality of SSL direction finding (DF) results. Based on observations, a quality factor of 0.7 is proposed if the elevation angle corresponds to 50% of the angle for the FOT. A quadratic polynomial function of the form

$$y = ax^2 + bx + c \quad (3)$$

was fitted to the three sets of data points corresponding to the ratios of the elevation angles relative to the elevation angle for the FOT as defined above (variable *x*). The coefficients were calculated as

$$a = -1.2222 \quad (4)$$

$$b = 2.23333 \quad (5)$$

$$c = -0.11111 \quad (6)$$

This result makes it possible to calculate a quality factor for any elevation angle where propagation is possible. This quality factor has the benefit that it can easily be computed from readily available ionospheric parameters (the MUF and HPF) while still providing valuable information about SSL accuracy as shown by the measurements in section 4.

4. Validation

The majority of South Africa's maritime HF traffic is handled by a station just outside Cape Town. This station makes use of high-power transmitters operating on multiple frequencies. A wideband interferometric

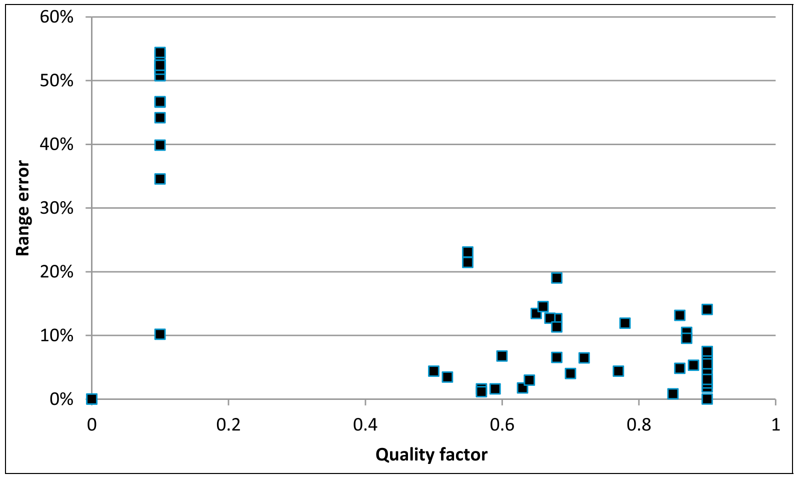

Figure 5. The calculated quality factor and the range error summarized for all the SSL measurements.

direction finder manufactured by GEW Technologies (Pretoria, South Africa) was deployed at Pretoria to measure the wave angles of the various transmissions over the 1300 km path. Measurements were performed at various frequencies and times that corresponded to both the FOT for the circuit as well as to nonideal (not near the FOT) combinations of frequencies and times. Figure 5 is a summary of the range error versus the calculated quality factor for all the measured SSL results.

The direction finder's graphical user interface is presented in Figure 6, demonstrating how the necessary information can be presented to a user in a real-world system. Figures 7 and 8 illustrate some of the SSL results obtained.

The calculated propagation of an 18.238 MHz signal is displayed in Figure 6 (top left-hand graph). It can be seen that the signal will not propagate at elevation angles above approximately 30° and that there is a skip zone of slightly less than 1200 km. When this measurement was performed, single-hop propagation was not possible over distances of more than approximately 3200 km, corresponding to an elevation angle of

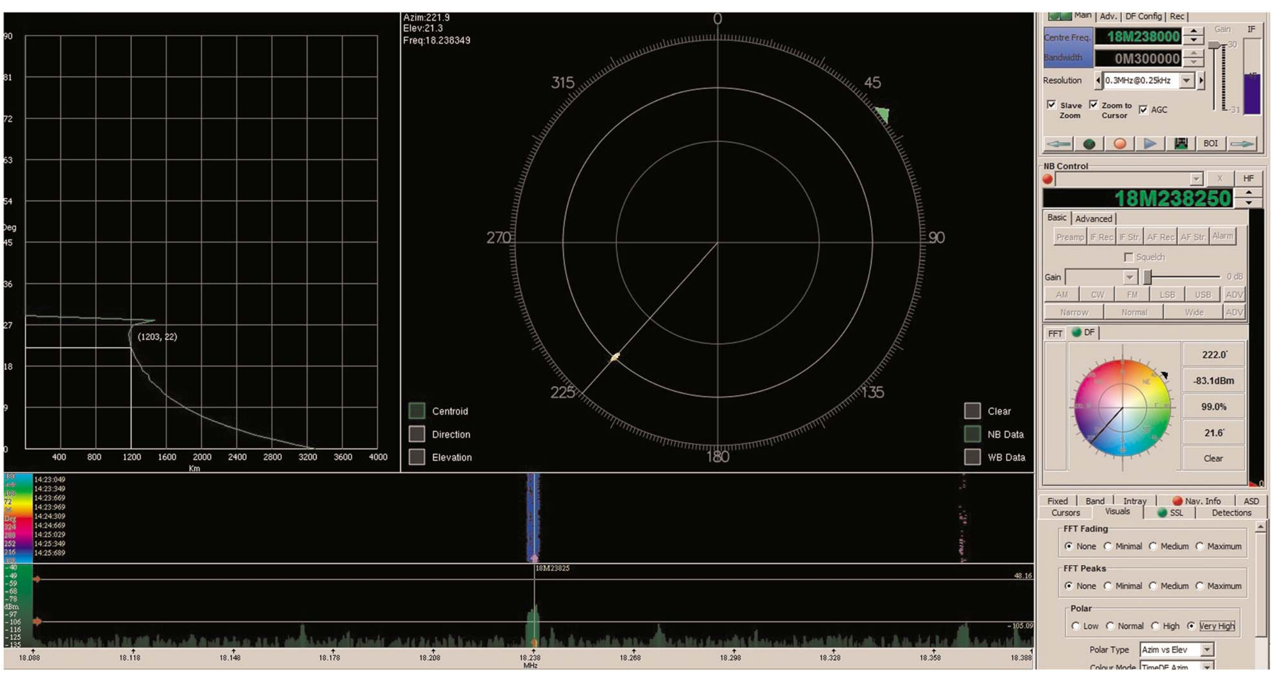

Figure 6. GEW Technologies wideband HF interferometric direction finder's graphical user interface.

10.1002/2015RS005799

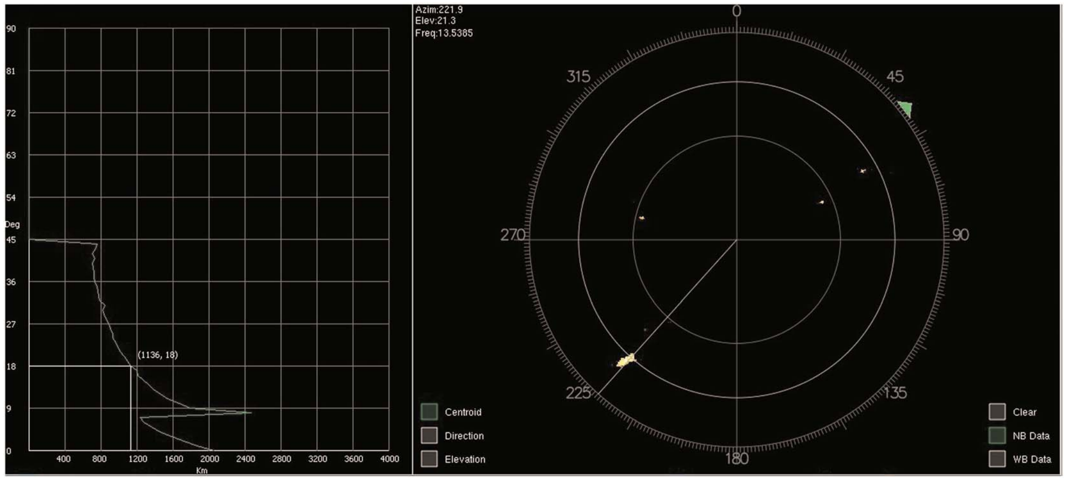

Figure 7. SSL result of a signal considerably below the FOT for the circuit.

approximately 0°. The intercepted transmission arrived at an elevation angle of 22°, corresponding to a ground range of 1203 km as indicated by the white lines and the white numerals. This elevation angle versus range graph is simply referred to as the SSL Graph.

The graph to the right of the SSL graph is the Polar Display. The Polar Display provides a line of bearing as well as indicating the elevation angle of the received signal. Signals arriving at low elevation angles are displayed toward the outside of the Polar Plot, while NVIS signals are displayed closer to the center. A signal arriving from directly overhead (90° elevation angle) will be displayed in the center of the Polar Plot. A persistence function implemented in software ensures that a visual histogram is formed, allowing the operator to judge the quality of the DF result. A stable DF result forms a small grouping, while unstable ionospheric conditions or multihop propagation cause the results to be more spread out leading to greater uncertainty regarding the correct wave angle of the target signal.

The direction finder's center frequency, bandwidth, resolution, and other radio frequency functions are set in the right-hand side panel. The DF result is displayed in the colored rosette near the bottom. In Figure 6 the measured bearing is 222°, and the signal level is −83.1 dBm.

Figure 6 (bottom graph) is a spectrum display showing amplitude over the selected 300 kHz bandwidth. The 18.238 MHz target frequency in the center of the display is also the strongest signal.

The graph above the spectrum display is a sonogram or history of the received energy that exceeds the selectable threshold level. Color is used to identify the direction of arrival of the signal, aiding an operator

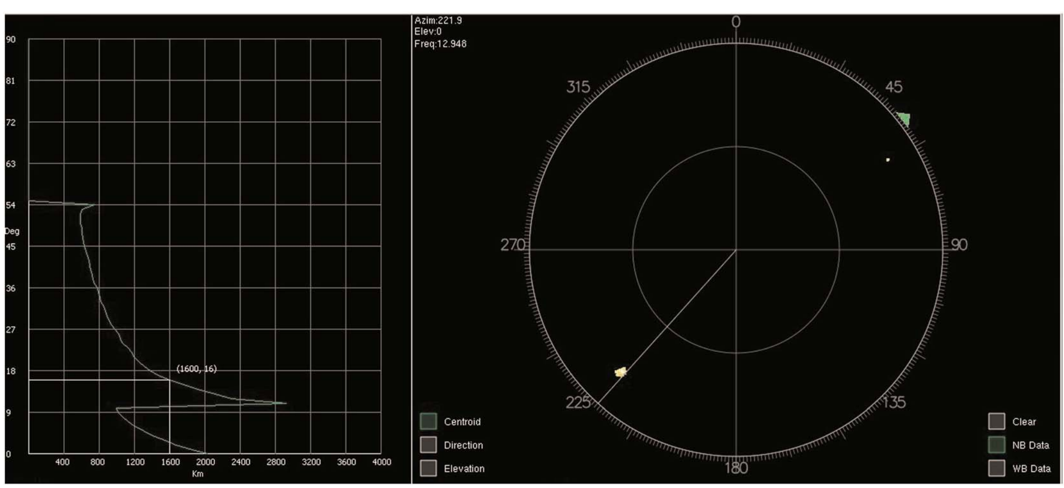

Figure 8. SSL result of a signal approaching the transition between ionospheric layers.

in immediately determining whether a signal originates from a specific target area. The dark blue of the 18.238 MHz signal corresponds to the DF result displayed on the small rosette to the right. A signal originating from the north will be displayed in red, for example. The homogenous color result of the target frequency indicates stable propagation as required by the *ITU* [2011] with no scatter modes present.

The measured elevation angle of 22° corresponds well with a calculated FOT angle of 25.5° (0.85 of the MUF angle of 30°). Using (3), (4), (5), and (6), a quality factor of 0.9 was calculated. The SSL distance estimate of 1203 km is better than 90% of the expected 1300 km.

The measured elevation angle of Figure 7 indicates that the 13.538 MHz transmission is 47% of the angle associated with the FOT (18° versus 38°) for the circuit at that moment in time. A quality factor of 0.67 is calculated for the SSL distance estimate of 1136 km (86% of the expected distance). Stable propagation conditions (indicated by a small grouping on the rosette) contribute to the operational usefulness of the result of Figure 7.

The 12.948 MHz signal of Figure 8 is well received with the correct bearing indicated, but the SSL performance is less spectacular (1600 km versus a true range of 1300 km). The signal is propagating too close to the transition of the E and F_2 layers (approaching the HPF of the E layer) with the expected nonideal result (calculated quality factor is 0.55).

The measurements of Figures 6–8 were performed during stable geomagnetic conditions to ensure that the results are applicable to the described technique [*ITU*, 2011].

In general, the SSL results were better (more stable and accurate) during the morning than the afternoons. From the test results it seems that the ionosphere is especially unstable in the afternoons, adding another dimension of uncertainty to the SSL results. To compensate for the instability of the ionosphere, multiple measurements over a longer time had to be taken, as recommended by the *ITU* [2011].

5. Discussion and Summary

The performance of SSL HF direction finding can be estimated by determining the correlation of the measured elevation angle with the angles associated with the FOT and the MUF of the circuit using ray tracing techniques.

When the measured elevation angle corresponds to the angle associated with the FOT, the SSL distance estimate is expected to be accurate. The expected distance accuracy will deteriorate, as the measured elevation angle approaches the angle associated with the HPF of the next lower layer (typically the E layer). However, if the measured elevation angle falls in the transition region of the E and F layers, the SSL distance is in principle undefined and the SSL result basically useless (very low quality).

Based on these observations, a quality factor for SSL range estimates was proposed based on widely available ionospheric propagation parameters (the MUF, FOT, and HPF). This quality factor was shown to be useful by comparing estimated performance to measurements.

Both the measurements and the quality factor show that useful SSL results can be obtained at elevation angles as low as 50% of that associated with the reigning FOT, on condition that the signal propagation was via a stable region of the ionosphere.

Acknowledgments
The authors wish to thank their colleague Wimpie van den Berg for the constructive discussion in the development of the above technique. This work is based on the research supported in part by the National Research Foundation of South Africa (NRF) (grant specific unique reference number (UID) 85845). The NRF Grantholder acknowledges that opinions, findings and conclusions, or recommendations expressed in any publication generated by the NRF supported research are that of the author (s) and that the NRF accepts no liability whatsoever in this regard. The data set to support this article is included in the supporting information as Data Set 1. Further requests for data can be directed via email to the corresponding author.

References

Bilitza, D. (2001), International Reference Ionosphere 2000, *Radio Sci.*, *36*(2), 261–275, doi:10.1029/2000RS002432.
Davies, K. (1990), *Ionospheric Radio*, Peter Peregrinus, London.
Devoldere, J. (2010), *ON4UN's Low-Band DXing*, 5th ed., The American Radio Relay League, Inc., Newington, Conn.
Goodman, J. M. (1992), *HF Communications Science and Technology*, Van Nostrand Reinhold, New York.
Hagn, G. H. (1992), MUFs and MOFs and LUFs and LOFs, stand on standards, *IEEE Antennas Propag. Mag.*, *34*(6), 68–73.
International Telecommunication Union (2011), *Handbook on Spectrum Monitoring*, ITU, Geneva, Switzerland.
Lai, K. (2008), A real-time HF single-station location system development, *Radar, 2008 International Conference on*, 307-310, 2–5 Sept., doi:10.1109/RADAR.2008.4653937.
McKinnell, L. A. (2002), A neural network based ionospheric model for the bottomside electron density profile over Grahamstown South Africa, PhD thesis of Rhodes Univ., Grahamstown, Republic of South Africa.
McNamara, L. F. (1991), *The Ionosphere: Communications, Surveillance, and Direction Finding*, Krieger Publ. Company, Malabar, Fla.