HF Sounder Signal Processing

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Introduction

HF sounders are radars that measure the virtual height (apparent range) of the ionosphere at a range of HF frequencies that reflect off the varying densities of the bottom-side ionosphere. Increasing frequencies penetrate deeper into the ionosphere up to a critical frequency, after which soundings penetrate the ionosphere completely with no return. This document briefly describes the processing for two sounder types, a linear-sweep sounder and an example pulsed sounder. Both require specifying the original transmitted frequencies in order to determine the time of flight and apparent range of the sounding signal as a function of transmission frequency.

Linear Sweep Sounder

Transmit Signal Description

A linear sweep sounder transmits a continuous wave that linearly increases frequency. This can be described by the following equation,

$$lss(t) = A \cdot \cos\left(2\pi \cdot \left(f_0 t + \frac{kt^2}{2}\right) + \phi_0\right),$$

Where t is time, A is an arbitrary signal amplitude, f_0 is the starting frequency, k is the frequency sweep rate, and ϕ_0 is an arbitrary initial phase. The instantaneous frequency of the transmitter, which we denote as $f_{tx}(t)$, is simply the derivative of the phase,

$$f_{tx}(t) = \frac{d\phi}{dt} = f_0 + kt.$$

More information about the linear sweep signal, otherwise known as a chirp can be found here.

Deriving Group Delay

As in any radar system, we are interested in the time it takes for that transmission to have traveled to the target (in our case the ionosphere) and back. For a linear sweep sounder, this delay conveniently manifests itself as a frequency shift relative to the transmit instantaneous frequency. To show this, consider a signal travel time of Δt. The $f_{tx}(t)$ of the transmit signal is time shifted by Δt and the instantaneous frequency of the reception is

$$f_{rx}(t) = \frac{d\phi}{dt} = f_0 + k(t - \Delta t).$$

By comparing the difference between the instantaneous transmit frequency and receive frequency at specific time t one gets the relationship,

$$f(t)_{tx} - f(t)_{rx} = k\Delta t.$$

This shows that a travel time Δt manifests itself as a frequency shift relative to the transmit signal at a time t. The time of travel Δt can be solved for the travel time as

$$\Delta t = \frac{f(t)_{tx} - f(t)_{rx}}{k}.$$

Therefore, with knowledge of the transmit linear sweep sounding signal (knowing the timing and the slope of the frequency sweep), one can derive the time of travel Δt by comparing the instantaneous frequency difference between the reception and the transmit signal at a specific time t.

In terms of signal processing, one calculates the spectrum of the reception centered by the transmit signal frequency to determine signal power at particular ranges. Calculating the spectrum centered by the transmit signal can be done by mixing the receive signal by the transmit signal, low-pass filtering, and then taking the spectrum of this down-converted signal. This basebands the receive signal relative to the transmit signal, and the spectrum of this basebanded signal will bin power by frequencies relative to the transmit frequency, corresponding to frequency differences between receive and transmit signals. By use of the relationship between the difference in transmit and receive frequency and Δt, power in particular frequency bins can be translated to Δt bins and, in turn, range bins. The range bins are simply defined as Δt times the speed of light divided by 2 (accounting for the two-way path to the target and back). For multiple reflection points off of the ionosphere (multihop, birefringence, ionospheric structure, etc.), multiple range bins will be populated with power. Keep in mind that noise and interferers will pollute range bins and degrade the signal-to-noise ratio (SNR).

Pulsed Sounder

While a linear sweep sounder is effective and mathematically convenient, it can be difficult to collocate the transmitted and receiver together, because the 100 percent duty cycle of the transmitter often saturates a receiver or requires a receiver with hard-to-achieve dynamic range that can handle both the direct reception of a high-power transmitter and reception off the ionosphere which is typically many several orders of magnitude weaker than the direct reception of a collocated transmitter. For single-site systems, pulsed sounders circumvent this potential collocation problem by transmitting for a short period of time and allow for the receiver to receive receptions off of a target when the transmitter is not transmitting. For ionospheric radars, this can be done at a few percent duty cycle typically with inter-pulse periods of 5 ms or more.

Pulse Transmit and Processing

Let's consider a simple short-duration pulse radar such as illustrated here. At a particular frequency, a short pulse is transmitted, and the receiver, tuned to the same frequency, listens for a short pulse reception off of a target. When the frequency channel is clear and void of noise or interferers, the short pulse method can detect target range. However, in practice, SNR is too low for moderate transmit power levels.

Pulse Compression

The shortcoming of a simple pulse system is remedied with pulse-compression for better SNR than a simple pulse with the same level of power. The keys are to use pulses with an autocorrelation most similar to a dirac delta (for improved SNR and precise range resolution). More about pulse compression can be found here.

16-Chip Complementary Phase Code Pair

While there are several methods for pulse-compression, we describe a complementary phase-coded pulse sequence that yields decent SNR and range resolution. A popular ionosonde, the Digisonde, uses 16-chip complementary phase-coded pulse pairs.

Consider the 16-chip Golay complementary phase code pair:

codeA = [+1, +1, -1, +1, +1, +1, +1, -1, -1, +1, +1, +1, -1, +1, -1, -1]
codeB = [-1, -1, +1, -1, -1, -1, -1, +1, -1, +1, +1, +1, -1, +1, -1, -1]

These phase code pairs have a property such that the sums of their autocorrelation is a dirac delta. More about complementary phase codes are found here.

Signal Processing 16-Chip Complementary Phase Code Pair

Generally speaking, the Digisonde, a popular pulsed ionosonde, transmits these 16-chip Golay complementary code pairs. More specifically, they transmit using 30 kHz baud that yields pulse widths of ~533 microseconds (16-chip x 1/30kHz). For Digisondes, the inter-pulse period (IPP) can be 5 or 10 milliseconds.

For signal processing:

1. Tune the reception to the ionosonde's transmit frequency.
2. Correlate the corresponding phase code to the reception per pulse period.
3. Sum up complementary pulse periods for improved range resolution and SNR.
4. For each time/range bin, discrete fourier transform across summed complementary pairs.

Step 3 resolves power in time/range bins. Step 4 integrates multiple complementary pair sums across time and subsequently bins power into Doppler bins. Because the ionosphere is coherent on time scales of the IPP, receptions off of the ionosphere will accumulate in a particular Doppler bin. For a non-moving ionosphere, power will accumulate in the zero-Doppler bin. Noise, on the other hand, is incoherent and statistically spreads evenly across Doppler bins. Hence, a discrete Fourier transform across repeated pulses yields improved SNR by coherent integration. After step 4, power is binned by both range and Doppler. It is up to the operator how to best use the binned power to determine best range estimates of the ionosphere. Simpler methods (but not necessarily the best practice) is to integrate across Doppler bins or to select the maximum power across Doppler bins in order to focus on power versus range. More details about signal processing of the Digisonde can be found here.

The key to extracting ionograms from pulsed sounder is to determine when exactly the sounder transmits and at what frequency (as it sounds through a range of frequencies). Upon understanding this, the signal processing is a matter of correlation and appropriate coherent integration.