ADAPTIVE INTEGRATION TECHNIQUES FOR TOPSIDE INCOHERENT SCATTER USING THE MIDAS-W SOFTWARE RADAR SYSTEM

Philip J. Erickson(1), **Frank D. Lind**(2)

(1)*Atmospheric Sciences Group, MIT Haystack Observatory, Westford, MA 01886, USA; E-mail pje@haystack.mit.edu*
(2)*As (1) above, but E-mail: flind@haystack.mit.edu*

ABSTRACT

Observations of topside ionospheric parameters present unique challenges for incoherent scatter radar systems with moderate power-aperture products. We present investigations of algorithms specifically targeted at optimal topside ionospheric measurements using the mid-latitude Millstone Hill MIDAS-W software radar system. The MIDAS-W multicast gigabit ethernet data transmission backbone allows access to pulse-level receiver signal information, and enables adaptive selection of both spatial and temporal integration resolution based on observed signal parameters. We present initial results using playback of recorded raw receiver voltages, which allow exploration of appropriate adaptive signal metrics as well as easy comparisons with standard fixed-resolution measurements.

INTRODUCTION

Observations of topside ionospheric parameters present unique challenges for incoherent scatter radar (ISR) systems with moderate power-aperture products. The topside ionosphere is geophysically important due to its role as the interface between the oxygen ion dominated F region and the overlying helium and hydrogen ion-dominated plasmasphere. Exchanges of plasma along field lines are common, whether comprised of normal diurnal and seasonal flows or more intense heavy ion outflows and polar wind changes following geomagnetic disturbances. These flows impact total electron content and can drastically change relative ion concentration at fixed altitudes. Study of this region has taken place over more than 40 years [1], yet many topside physical processes such as the formation of helium ion layers between 500 and 1000 km altitude [2], the relative importance of cross-field transport and field-aligned ambipolar diffusion, and the dynamics of oxygen-hydrogen charge exchange remain poorly understood and modelled. This is especially true at mid-latitudes where several moderate power-aperture product incoherent scatter radar systems are located.

Mid-latitude ISR systems have measurement difficulties in the near topside (below $\sim$ 1500 km) due to the large changes in scale height of O+, H+, and He+ as the lighter ions become dominant and are held up against gravity by the ambipolar diffusion electric field. The lighter ion species increase the observed incoherent scatter spectral width proportionately, forcing wider receiver bandwidths with correspondingly higher noise levels. These effects combine with smaller incident power levels (due to range falloff) to keep topside signal-to-noise levels at or below unity. Furthermore, the region of maximum composition change with respect to altitude often occurs precisely where signals become difficult to measure, especially at night. Careful selection of sampling bandwidths and transmitted waveforms are therefore essential for optimal measurement. This selection must be an adaptive one as well, for light ion fractions vary as functions of altitude, local time, season, and solar cycle.

ADAPTIVE PROCESSING AND THE SOFTWARE RADAR CONCEPT AT MILLSTONE HILL

Real-time adaptive integration techniques provide a solution well suited to making optimal signal processing parameter selections for topside observations. Recent advances in hardware and software have made these methods feasible through a Software Radar architecture, in which the received incoherent scatter waveform is digitized after as few analog operations as possible. Subsequently, all signal manipulations (filtering, downconversion, clutter subtraction, and correlation) are completed wholly in the digital domain. The approach is flexible and reliable, but most significantly enables dynamic reconfiguration of the receiver signal processing chain in response to changing ionospheric conditions. Current computer speeds allow a majority of processing to be completed in general-purpose computing hardware, using standard compiled and scripted programming languages such as C and Python.

We are currently investigating algorithms specifically targeted at optimal topside ionospheric measurements using the mid-latitude Millstone Hill MIDAS-W Software Radar system [3]. For the Millstone Hill observations (42.6° N latitude, 288.5° E longitude, 55° invariant latitude) described here, we use a 68 meter zenith antenna coupled to a 440 MHz, 2.5 megawatt peak power, 6 percent duty cycle transmitter. The MIDAS-W Software Radar employs a multicast gigabit ethernet data transmission backbone to distribute receiver samples at an intermediate frequency (IF) of 12.25 MHz and 500 kHz bandwidth. We apply multiple 128 tap digital filters simultaneously to these samples using several computing elements connected to the gigabit backbone. These filters produce outputs at varying bandwidths, which after software downconversion and decimation become in-phase and quadrature complex baseband samples. These samples are correlated and the resulting autocorrelation functions (ACFs) are fit using standard incoherent scatter least-squares fitting theory [4] to produce final physical parameters. We performed initial investigations in a development mode, where software recorders captured the 500 kHz IF samples to disk. Subsequent rebroadcast of these samples effectively replayed the experiment allowing several different adaptive signal metrics to be explored. In the future, we will implement a standard topside processing module using the knowledge gained to perform real-time adaptive processing.

CONSTANT STATISTICAL ACCURACY: CHARACTERISTIC CURVES

We briefly explore two simple variations on a topside adaptive metric. Since accuracy becomes essential in the near topside as signal falls off, a metric can be defined which aims to maintain constant statistical accuracy for power measurements as a function of altitude. Statistical estimation theory [5] defines the variance of signal power measurements in the presence of noise (and with SNR approximately 1 or less) as

$$\delta_S^2 = \frac{(S+N)^2}{K_{S+N}} + \frac{N^2}{K_N} \tag{1}$$

where δ_S is the power estimate variance, S is the signal power, N is noise power, K_{S+N} is the number of independent estimates of signal plus noise, and K_N is the number of estimates of noise. The assumption that many more noise samples are taken compared to signal plus noise allows the last term to be neglected. Following Farley [6], therefore, examining the relative fractional error δ_S/S leads to the metric definition

$$K_{S+N} \propto (1 + \frac{N}{S})^2 \tag{2}$$

defining the number of independent samples required to maintain constant statistical accuracy as a function of altitude.

For clarity, we limit the discussion here to simple single pulse transmission modes. With this restriction, a characteristic relative sample number curve results for a given radar's transmitter power, antenna gain, and receiver sensitivity, as well as for a given transmitted pulse length and receiver bandwidth. Figure 1 plots two of these characteristic relative curves for a medium length pulse (300 usec or 45 km long; blue) and a long pulse (2000 usec or 300 km long; red) from 5 minute averaged data taken using the MIDAS-W system at Millstone Hill at 1700 UT on 11 April 2002 ($f_0F2 = 12$ MHz). As altitude increases, the number of independent samples required over that necessary in the F region quickly becomes substantial as SNR falls off. For example, at 600 km, 10 minutes of integration time would be necessary using the 300 usec pulse for the same statistical accuracy as 1 minute integration at F region altitudes.

The medium and long pulse curves use a 50 kHz receiver bandwidth which is ideal at Millstone's 440 MHz transmitter frequency for oxygen ion dominated altitudes. However, as altitude increases, a wider receiver bandwidth is necessary to avoid removing significant energy arising from wider hydrogen ion spectra. To show the effects of this, a third curve in Figure 1 (green) uses a receiver bandwidth of 100 kHz with a 2000 usec pulse mode. The larger noise level admitted by the wider filter leads to increased integration time at a given altitude when compared with the narrower filter.

OPTIMIZING FOR INDIVIDUAL ION SPECIES

The curves of Figure 1 give relative sample counts necessary to achieve a constant accuracy metric. The sample counts can be achieved either by increased integration time, increased height averaging, or a combination of both. Increasing the

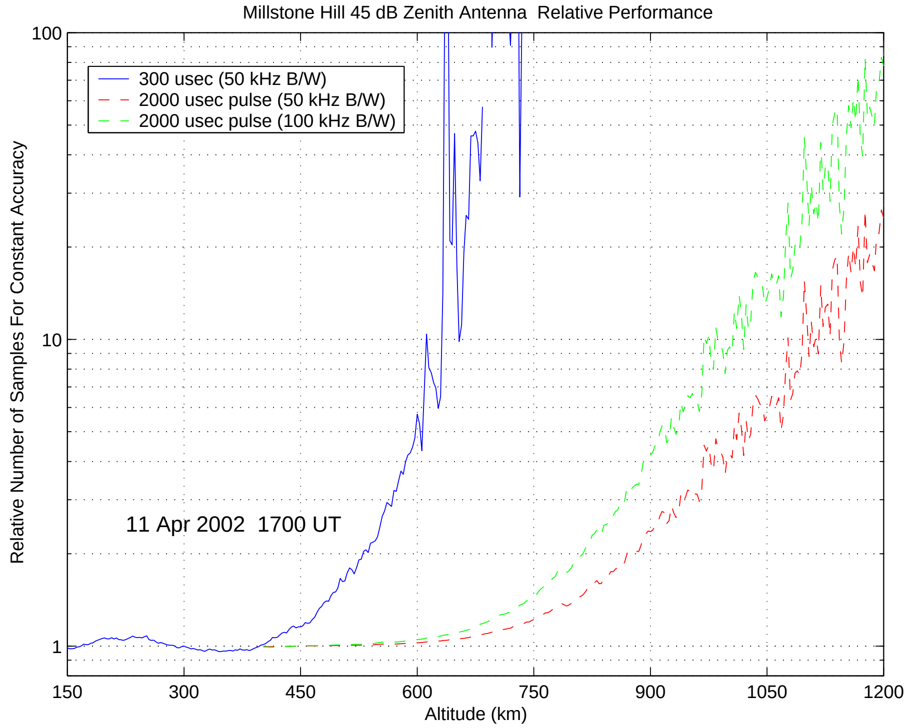

Figure 1. Number of samples required to maintain constant accuracy as a function of altitude for Millstone Hill zenith 5 minute integrated observations on 11 April 2002 at 1700 UT.

number of samples averaged in height (i.e. decreasing final altitude resolution), however, only yields gains if the average does not extend beyond scales where significant changes occur in the geophysical parameters being measured. To model this, we constructed a simple two-ion (O+ and H+) diffusive equilibrium density model using an ambipolar diffusion electric field [7] for a L=3 flux tube characteristic of mid-latitudes at 1700 UT. The model yields diffusive scale heights for each ion as a function of altitude.

We now define our measurement objective as the resolution of density variations on the order of the scale height, typically 100 to 200 km for O+ and 200 to over 1000 km for H+. Factoring in the pulse length, the amount of height averaging permissible as a function of altitude is determined, which decouples the integration time from the total relative sample count factor. Figure 2's top panel plots the results for the medium length (300 usec) pulse assuming alternately that the O+ and H+ density variation is the desired observation parameter, with the vertical axis now determining relative integration time alone. For this case, although significant height averaging can be done (typically between 2 and 3 pulse lengths worth), the steep rise in necessary samples must be accomplished primarily by increasing integration time. In contrast, Figure 2's bottom panel plots the results for the long pulse (2000 usec) when H+ density variation is the target parameter. The very large scale height ($>$ 1000 km) of H+ in the topside above 900 km allows enough altitude averaging that the relative integration curve now approaches unity above 1050 km. These results overestimate actual gains since the altitude averaging is assumed to contain fully independent samples.

CONCLUSION

The simple metrics we have explored here demonstrate that straightforward criteria concerning measurement accuracy and targeted parameters lead to well-defined choices concerning incoherent scatter signal processing parameters such as integration time and height average size. We are exploring other topside metrics with the MIDAS-W Software Radar system and the Millstone Hill UHF incoherent scatter radar facility, and we intend to implement the most promising candidates as real-time adaptive modules for optimal topside experiments. Such flexible processing maximizes the utility and scientific productivity of the powerful incoherent scatter radar technique.

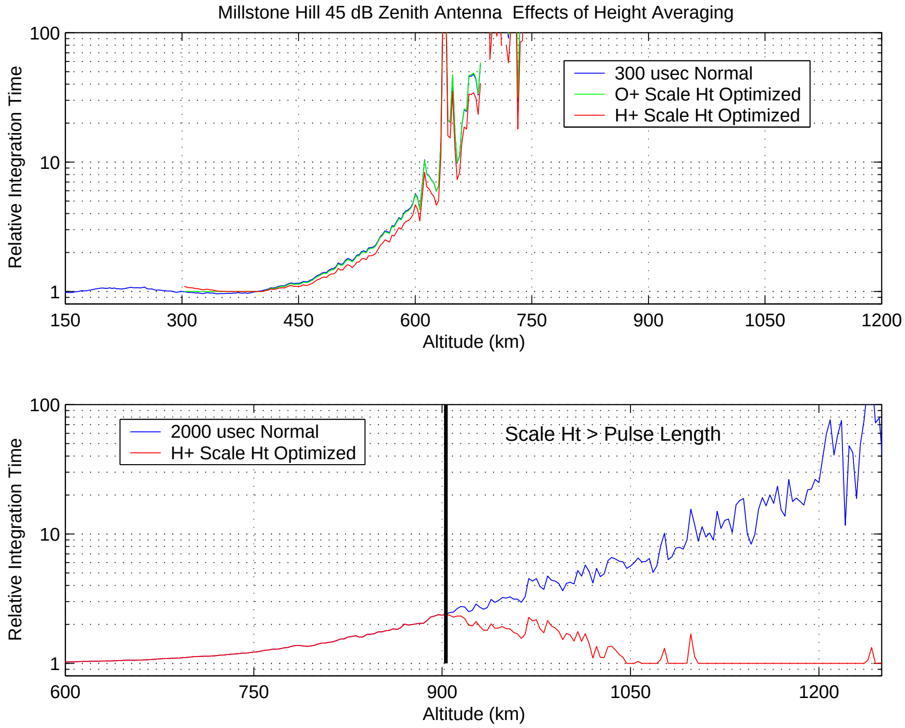

Figure 2. Relative integration time required to maintain constant accuracy for O+ and H+ targeted topside observations, using the same data as Figure 1. See text for details.

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