Incoherent-Scatter Radar Estimates of Electron Density

The parameters involved in profile estimation of ionospheric electron density by incoherent-scatter radar (ISR) methods is best illustrated by the radar equation as it applies to ISRs, given as

$$N_e(R) = (C_s)\left(\frac{R^2}{P_t\tau}\right)(P_r(R))\left(\frac{(1+\alpha^2+T_r)(1+\alpha^2)}{2}\right)$$

where,

- the first bracket represents the numerical constants of the radar system, C_s, calibrated periodically through plasma line measurements and ionosondes (approximate percent error is about 5-10%).
- the second bracket contains variables that may change but are known for a particular experiment
    - R - range determined by a simple time delay (propagation speed is close to c_0 because of high frequency)
    - P_t - transmitted power (Watts) measured continuously (~1% error).
    - τ - transmitted pulse length (seconds) set by hardware considerations. For a given pulse length implies constant Ne over the scattering volume. Depending on the pulse width with respect to the structure in Ne, this can result in a reduction in peak value, broadening of actual Ne structure, and shifting in altitude of peak density structure.
- the third bracket contains variables directly measured
    - $P_r(R)$ - received power at range R (Watts), calibrated for instrument drift continuously. Because of it being an incoherent measurement, P_r is a random variable. The received power is often < the system noise power, so noise must be carefully estimated and accounted for. The system gain must also be known and stabilized so the power measurement represents an absolute number.
- the fourth bracket must be determined from the spectral measurements
    - T_r - electron-to-ion temperature ratio at range R is derived from the spectral shape of the incoherent-radar spectrum
    - $\alpha^2 = (kD)^2$ - Debye correction which for Sondrestrom is 13.94 x 10^6 (T_e/N_e) in MKS units. Also derived from spectra, however, this becomes further complicated by the fact that α^2 is itself a function of N_e. Thus, an iterative approach is required to properly estimate α^2 and, consequently, N_e.

Often a first step is to assume $\alpha^2 = 0$ and $T_r = 1$, giving what we call the raw electron density,

$$N_{raw} = (C_s)\left(\frac{R^2}{P_t\tau}\right)(P_r(R))$$

Now, once the receive signal is detected and noise and calibration pulses removed from the signal (and the radar system parameters calculated), the actual electron density can be derived from the expression,

$$N_e = N_{raw}\left(\frac{(1+\alpha^2+T_r)(1+\alpha^2)}{2}\right)$$

In this calculation, the radar spectrum or autocorrelation function (ACF) is of significant importance because information concerning the electron and ion temperatures are contained within the spectrum and are needed in determining the true density. A Debye correction (α) which is the ratio of the Debye length to the operating wavelength can also affect the spectra and the overall scattering cross section. In addition to reducing the overall scattered power, large α's result in extremely broad spectra. This spectral broadening ultimately limits the lowest densities that can be measured by a given ISR. An iterative approach involving nonlinear least squares fitting is used to arrive at estimates for the ion temperature, electron temperature and the actual electron density.

In discussing measurement accuracy, one needs to consider statistical uncertainties associated with the measurement of broadband signals in the presence of noise, and systematic errors associated with imperfect knowledge of the radar system and measurement inaccuracies. Here, we list a few key issues:

- Statistical uncertainty in $P_r(R)$, T_r, and T_e
- Range smearing due to finite pulse width
- Temporal smearing necessary to reduce statistical uncertainty
- Biases from changes in C_s (e.g. antenna shape deformation)
- Spatial smearing due to finite beamwidth and (more importantly) antenna motion
- Biases in T_e, T_r due to fitting of plasma parameters with inappropriate assumptions (e.g. spatial uniformity, Maxwellian plasma distribution, ion mass and composition, collision frequency, etc.)

Accounting for many of the tangible issues, the Sondrestrom radar was recently calibrated in Spring, 1999, Fall and Sprnig 2000 using plasma line measurements of electron density. This absolute measurement of electron density was compared with the estimate of electron density derived from the ion-line spectra (described above) using a system constant derived from plasma line measurements made in 1991. Only a 5% difference was found between plasma line and ion line electron density estimates. Equally good was the comparison with the local digisonde. More details are given below.

Plasma Line Measurements

A new plasma line data collection mode was implemented to, among other things, perform a radar system calibration of the ion line channel. Measurements were made of the F-region plasma line cutoff frequency during a period of quiet activity (good horizontal homogeneity) and high electron densities. The high densities are necessary for F-region plasma line detection at Sondrestrom due to the required resonant condition between photo-electrons and Langmiur waves at Sondrestrom's k vector. After correcting for electron temperature effects, the plasma line cutoff frequencies can be used to generate excellent estimates of the peak electron density in the radar's antenna beam. This can then be compared to ion line estimates of the peak as well as ionosonde estimates of foF2. The following figure shows such a comparison from 14 April 2000. That figure shows quite good agreement between the ion line and plasma line estimates, with a small bias apparent during the first portion of the measurements. The more or less constant bias when compared to the Digisonde estimates is most probably due to the fact that the ISR and Digisonde do not probe identical volumes and, as such, small horizontal gradients can be expected to result in differences. In any event, the electron density estimates from the three different methods agree to within better than 10%.