Solar-Terrestrial Physics. 2024. Vol. 10. Iss. 1. P. 63–67. DOI: 10.12737/stp-101202409. © 2024
V.P. Tashlykov, S.S. Alsatkin, A.V. Medvedev, K.G. Ratovsky. Published by INFRA-M Academic Publishing House

UDC 550.380
DOI: 10.12737/stp-101202409

Received November 12, 2022
Accepted December 18, 2023

EFFECTIVE SUBTRACTION TECHNIQUE: IMPLEMENTATION FOR IRKUTSK INCOHERENT SCATTER RADAR

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Abstract. For incoherent scatter measurements, the effective subtraction technique is to alternate the duration of amplitude-modulated signals between a pair of consequently radiated pulses. The resulting gain of spatial resolution enables us to steadily assess the electron density profile by the Faraday rotation method. The paper describes the electron density measurement technique, which involves analyzing narrow-band signals from Irkutsk Incoherent Scatter Radar, and proposes an automated method of determining the electron density for the problem in which the convolution of the radiated signal waveform with backscatter signal cannot be neglected. The inverse problem of electron density recovery is considered as a standard nonlinear optimization problem, which is solved using the algorithms for global and local optimization applied consequently. We compare the electron density profiles obtained by analyzing different pulse waveforms and from Irkutsk ionosonde data.

Keywords: Irkutsk Incoherent Scatter Radar, effective subtraction technique, plasma density recovery, Faraday effect, optimization algorithms.

INTRODUCTION

Incoherent scatter (IS) experimental observations necessitate considering a number of conditions that determine which ionospheric plasma parameters can be recovered by analyzing a received signal and what accuracy and resolution they can have. Most of these conditions are specified as early as at the IS radar design stage. For instance, location and design of the antenna system define a spatial configuration of the experiment. Other important parameters, viz. spatial and spectral resolutions, depend on the transmitted signal waveform and can be intended for a specific purpose. For a simple pulse waveform, we have to find a compromise between the two types of resolution. There are pulse code techniques [Farley, 1972; Lehtinen, Haggstrom, 1987] that enable us to preserve sufficiently high spectral and spatial resolutions by adding some complexity to signal analysis. Similar characteristics can be obtained by altering sounding pulse duration from one transmit-receive cycle to another and then analyzing the corresponding lag profiles. Proposed in [Berngardt, Kushnarev, 2013], this method has been named the effective subtraction technique (EST). For its implementation for Irkutsk Incoherent Scatter Radar (IISR) [Potekhin et al., 2009], a special mode has been introduced which consists of alternating three different sounding signals:

- a phase-shift Barker-code signal with a total duration of ~200 ms (code length depends on seasonal level of electron density);
- a successive amplitude modulated pulse ~700 ms in duration radiated at a slightly different frequency (with a difference of 300 kHz): due to IISR's frequency scanning operating principle, the main lobes are directed differently;
- an amplitude modulated pulse ~ 900 ms in duration radiated at the next radiation cycle.

A phase-shift signal, which we term as wideband signal, is used for power profile analysis. By match filtering, this signal has a high spatial resolution, which makes it possible to estimate the electron density profile by the Faraday rotation method [Alsatkin et al., 2020]. It is significant that the IISR operating frequency band 154–162 MHz is nearly optimal for mid-latitude Faraday measurements of the electron density [Farley, 1969]. Amplitude-modulated pulses (narrowband signals) are used to analyze lag profiles and estimate ionospheric plasma temperatures. However, the EST allows us to obtain a power profile with improved spatial resolution and hence to evaluate the electron density profile as well.

To represent the idea of the EST, let us look at the integrated lagged product of the received signal

$$\overline{x(t)x^*(t+\tau)}, \tag{1}$$

where t is the start time of the receiving gate whose form is identical to that of the transmitted single pulse. The product of the envelope function of the transmitted pulse and its copy, shifted by τ, refers to the ambiguity function term.

$$W(r,t,\tau)=Q(t-rc/2)Q^*(t-rc/2+\tau), \tag{2}$$

where $Q(t)$ *is* the sounding signal waveform; c is the speed of light; r is the radar range. If we assume the receiver pulse response as delta function (IISR receiver frequency band is 250 KHz), the resulting radar equation for the lag profile is as follows:

$$\overline{x(t)x^*(t+\tau)} \simeq \sum_r P_0(r) W(t,\tau)\sigma(r,\tau), \quad (3)$$

where $P_0(r)$ is the antenna pattern and signal propagation effects including Faraday rotation of the polarization plane; $\sigma(r, \tau)$ is the plasma scatter correlation function that depends on N_e, T_e, and T_i profiles for a first approximation. According to [Shpynev, 2001], the radar equation for the power profile can be represented as

$$|x(t)|^2 \simeq \sum_r 1/r^2 Q^2(t-rc/2)\cos\Omega(r) N_e(r) / \\ /(1+T_e(r)/T_i(r)), \quad (4)$$

where $\Omega(r)$ is the rotation velocity of the polarization plane proportional to the electron density integral along the radar main beam; N_e is the electron density; T_e is the electron temperature; T_i is the ion temperature.

Technically, ambiguity function (2) provides estimation of the lag extent and spatial resolution. Figure 1 exhibits a pattern of one IS-radar transmission-reception cycle for a single pulse experiment and a principle behind the ambiguity function for the single pulse and EST. Transmitted at t=0, two 700 and 900 ms pulses provide sufficient spectral resolution, but low spatial resolution (for the 700 ms pulse, it is 105 km). The EST lag profile can be obtained by subtracting the lag profile for the 700 ms pulse from that for the 900 ms pulse. At the same time, we consider the ionosphere to be stationary throughout the integration time. Selecting only zero lag from this lag profile yields a subtractive power profile with a spatial resolution of 30 km, which corresponds to the 200 ms pulse duration, whereas the signal-to-noise ratio is constant for all lag extents of a shorter pulse. A significant drawback of the EST is the measurement accuracy deterioration, i.e. it can hardly be implemented for the data with a low signal-to-noise ratio.

Nevertheless, the EST has great potential for IISR in terms of its technical specificity. Its antenna system can transmit and receive a signal of strictly linear polarization but its antenna can detect only one of two orthogonal signals. This leaves the possibility open to recover the absolute electron density profile, but significantly complicates the analysis of plasma temperatures. For IISR, the main advantage of the EST is the fact that the accuracy of electron density and plasma temperature measurements is the same provided of course that the signal-to-noise ratio is high enough. Thus, we can obtain electron density profiles independently from wideband and narrowband signal data and then compare their key characteristics with the data from the Irkutsk ionosonde [Alsatkin et al., 2020]. The method of plasma temperature recovery is currently under development, but all the deductions inferred for the EST in terms of the electron density are also valid for the electron and ion temperatures.

1. METHOD

Assuming that there are no effects of signal depolarization during scattering in a medium, the location of Faraday fadings on the signal time-base provides all information necessary to recover the electron density. To solve this problem, we fit the received power profile, using the least squares method. The model power profile, which is fitted to the experimental one, is modeled by the electron density profile (see (4)). To find the optimal Chapman parameters, a complete search is carried out when analyzing wideband signals. Although the factor $Q(t–rc/2)$ in (4) also takes place for wideband

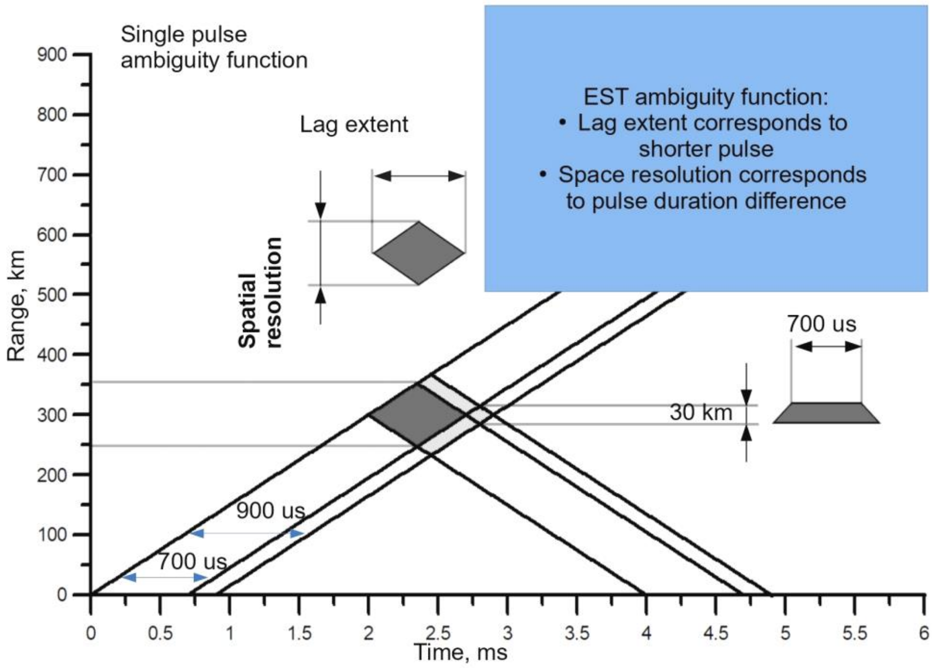

Figure 1. Scheme of IS experiment in case of alteration of pulse duration from one sounding cycle to another

signals, the power convolution with signal waveform can be neglected due to its short duration (from 15 to 40 ms for one Barker-code element). However, in the case of the EST (200 ms duration) the convolution effect cannot be counted out and hence the high computational cost does not allow us to use the complete search method. Furthermore, a potential complication of setting of the direct problem, for example, by increasing the number of model parameters, necessitates a search for faster algorithms for solving the inverse problem. In this paper, we describe an approach based on global and local optimization algorithms (NLopt nonlinear-optimization package, [http://github.com/stevengj/nlopt]).

Signal processing and ensuing analysis are carried out as follows. After accumulation of lag profiles, the entire set of data (daily measurements) obtained can be divided into independent data sets, each processed by a certain thread. The global optimization algorithm is applied to each first power profile in such a data set in order to ensure global convergence to problem solving. Then, for each subsequent profile, a local optimization algorithm searches for a solution starting from the initial values obtained as a solution at the previous step. In the case of a twofold increase in the optimal value of the objective function, the global optimization algorithm for the current profile is restarted. This approach ensures the temporal continuity of the results and allows us to find a compromise between the time spent on calculations and the search for a solution to the problem.

2. EXPERIMENTAL DATA PROCESSING

Compared to the complete search algorithm, the technique we propose requires 1000-fold less iterations for the global optimization algorithm and 10000-fold less iterations for the local optimization algorithm. It is important to account for the slightly higher calculation complexity of the EST because of the necessity to include convolution to the radar equation. We have used Improved Stochastic Ranking Evolution Strategy [Runarsson, Yao, 2000, 2005] as a global optimization algorithm, and Constrained Optimization By Linear Approximations (COBYLA [Powell, 1994, 1998]) as a local optimization algorithm. Both approaches are proved to be effective for a large variety of nonlinear optimization problems requiring constraints on search in parameter space. Linear constraints on optimal Chapman parameters are determined empirically. The choice of the aforementioned algorithms is also due to the possibility to set constraints in the form of nonlinear equalities and inequalities, which is important for the problems of plasma temperature or electron density recovery for the E and F1 layers of the ionosphere. The above method can well be scaled and adjusted for these problems. Figure 2 compares experimental and model power profiles for the EST for different time points during the day and different SNR levels. In all the cases, the recovered power profile describes the obtained data adequately.

Figure 3 (two top panels) compares subtractive power profiles (narrowband signals) and model profiles recovered due to the fitting algorithm. We use the data on June 5, 2015; the accumulation time is 5 min. The proposed algorithm is stable even in the presence of space object clutter (for instance, at ~8 and 16 UT). In this case, the clutter signal highly overrides the dynamic range for the desired signal, so heights containing clutter were excluded from the fitting process (marked in white).

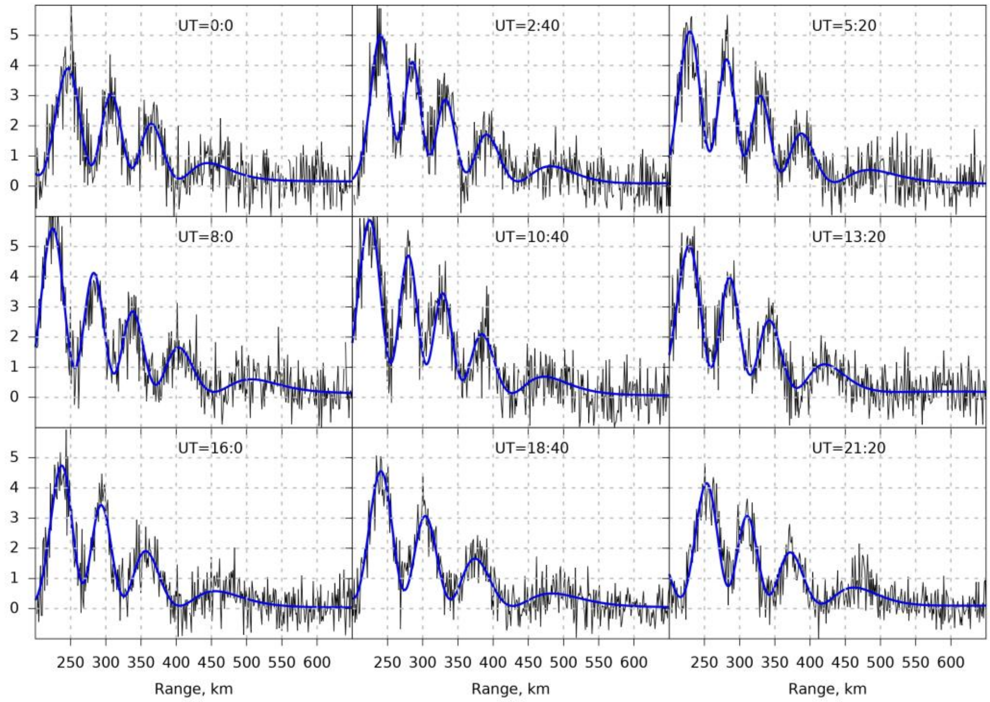

Figure 2. Comparison of experimental subtractive power profiles (black [rel. units]) with model power profiles (blue [rel.units]) obtained by the least squares method for June 05, 2015

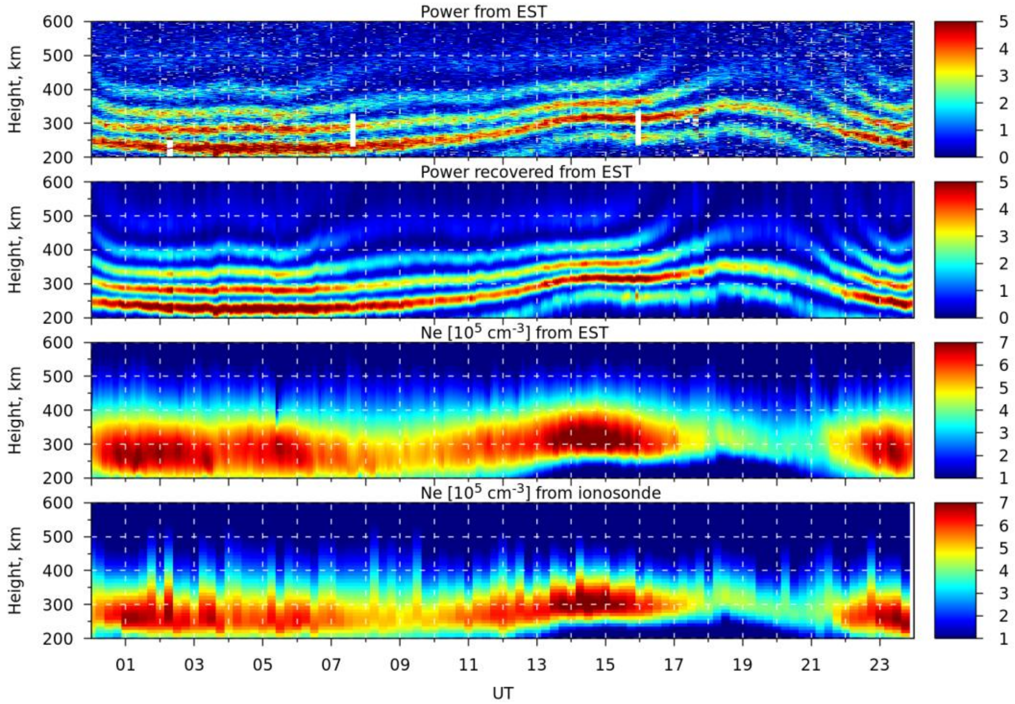

Figure 3. From top to bottom: EST power obtained by subtracting the power of narrowband signals (with pulse durations of 900 and 700 ms); model power recovered due to the fitting algorithm; electron density according to IISR data; electron density according to Irkutsk ionosonde data

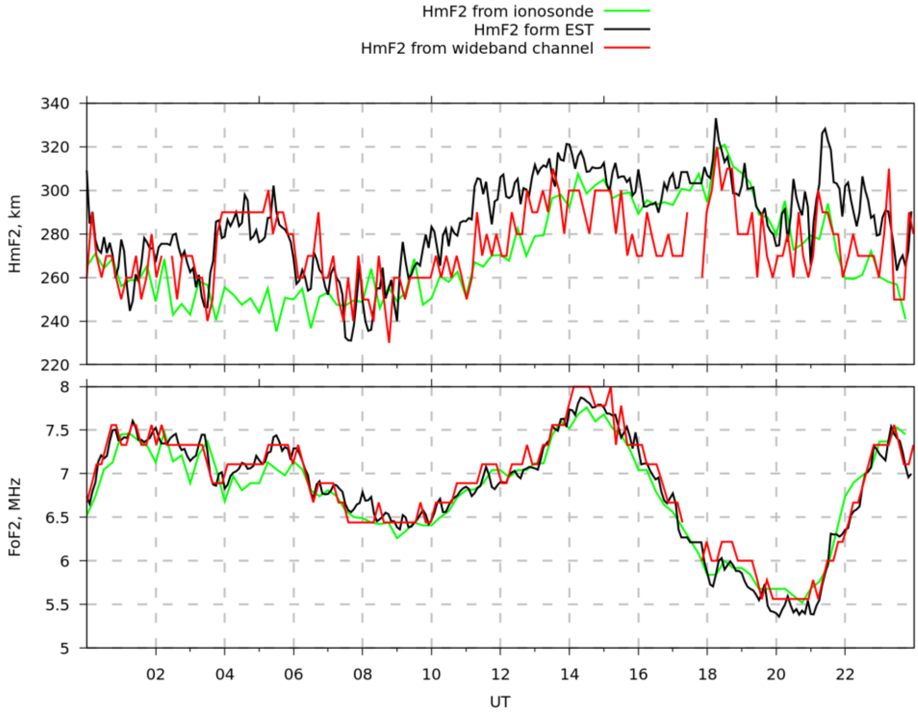

Figure 4. Comparison of key parameters of electron density profiles obtained from IISR data (by analyzing narrowband and wideband signals independently) with those from Irkutsk ionosonde data

The algorithm demonstrates sufficient stability to describe the time dynamics of the electron density with each power profile analyzed independently. In the two bottom panels of Figure 3, the electron density obtained by the EST is compared with that from the Irkutsk ionosonde data. Although ionograms cannot provide information about plasma at heights above the F2-layer maximum, the resulting electron density profiles are extrapolated by the Chapman layer. The presented comparison provides a qualitative agreement between IISR and Irkutsk ionosonde data. For a quantitative comparison, turn to Figure 4. It shows two key parameters: the height of the F2-layer maximum and its value on the scale of plasma frequency. Narrowband and wideband signals were analyzed independently, using different approaches to signal processing and inverse problem solving.

CONCLUSION

The effective subtraction technique employed for IISR provides sufficient spatial resolution to recover the electron density profile by the Faraday rotation method for signals with a pulse duration over 700 ms. Joint analysis for narrowband and wideband signals can give a considerable amount of information necessary to recover the electron density and to increase the accuracy of its estimate. Despite the significantly lower signal-to-noise ratio for the power difference profile, the global optimization algorithms we use can find solutions providing qualitative agreement with the Irkutsk ionosonde data and the IISR data obtained independently in another receiving channel. By appropriately alternating pulse durations, the statistical accuracy of measurements can be improved, thereby maintaining the integration time.

The optimization algorithms we use are stable and reliable for solving the inverse problem of recovering the electron density, especially in the case of high ambiguity, which applies to any signals (including codes) with a relatively long duration. They are also applicable for the problems with a large number of parameters if a more accurate estimation of ionospheric plasma parameters is required. The proposed approach to solving the inverse problem can also be used in the problem of determining electron and ion temperatures, where nonlinear constraints on the search for optimal parameters are needed. The algorithm for the joint analysis of various plasma parameters by the full-profile fitting is currently under development.

The work was financially supported by the Russian Science Foundation (Grant No. 22-17-00146 [https://rscf.ru/project/22-17-00146/]) in terms of developing the data processing method and analyzing the results and by the Ministry of Science and Higher Education of the Russian Federation in terms of observations. We have used measurement data from the Unique Research Facility "Irkutsk Incoherent Scatter Radar" [http://ckp-rf.ru/usu/77733/].

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Original Russian version: Tashlykov V.P., Alsatkin S.S., Medvedev A.V., Ratovsky K.G., published in Solnechno-zemnaya fizika. 2024. Vol. 10. Iss. 1. P. 68–73. DOI: 10.12737/szf-101202409.

How to cite this article

Tashlykov V.P., Alsatkin S.S., Medvedev A.V., Ratovsky K.G. Effective subtraction technique: implementation for Irkutsk Incoherent Scatter Radar. *Solar-Terrestrial Physics*. 2024. Vol. 10. Iss. 1. P. 63–67. DOI: 10.12737/stp-101202409.