

ZHANG Wenao, WANG Junyi, CAI Yihui, DING Feng, HÄGGSTRÖM Ingemar, YUE Xin'an. Simulation and Experimental Validation of a Combined Ion Line and Plasma Line Inversion Method for Incoherent Scatter Radar. *Chinese Journal of Space Science*, 2026, **46**(5): 1448–1458. CSTR:32142.14.cjss.2026-0006. DOI:10.11728/cjss2026.05.2026-0006

Simulation and Experimental Validation of a Combined Ion Line and Plasma Line Inversion Method for Incoherent Scatter Radar*

ZHANG Wenao^{1,2} WANG Junyi¹ CAI Yihui¹
DING Feng^{1,2} HÄGGSTRÖM Ingemar³ YUE Xin'an^{1,2}

1(Key Laboratory of Planetary Science and Frontier Technology/Beijing National Observatory of Space Environment,
Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029)

2(College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049)

3(EISCAT Scientific Association, Kiruna, SE-981 92)

Abstract In the ionospheric monitoring, one of the key techniques is the Incoherent Scatter Radar (ISR), which usually uses the so called ion line spectra resulted from the ion acoustic wave to derive multiple plasma parameters including electron density, electron and ion temperature, and ion velocity and composition. In addition to the ion line, ISR could also measure the so called plasma line spectra due to the existence of Langmuir wave, the dispersion relation of which is associated with the electron density and temperature. In the conventional ion line inversions, the Temperature-Ion Composition Ambiguity (TICA) and the systematic bias hinder the accuracy of retrieved parameters. To address these issues, here we propose an improved method by incorporating the information of plasma line into the ion line fitting process. We expect that the retrieval accuracy could be enhanced with the independent constraint on electron density and electron temperature obtained from the plasma line. Simulations based on the International Reference Ionosphere demonstrate that the combined ion line-plasma line method significantly reduces deviations in electron density and temperature, and it can improve the impact of the TICA effect to a certain extent. The comparison of the experimental results of Sanya Incoherent Scatter Radar with the ionosonde data on 6 June 2022 shows that this method has a certain effect on improving the electron density. This study establishes the feasibility of combined inversion for ISR data analysis, enabling more accurate and calibration-free ionospheric parameter retrievals in the future.

Key words Incoherent Scatter Radar (ISR), Plasma line, Combined inversion, Ion line inversion

Classified index P353

0 Introduction

Incoherent Scatter Radar (ISR) is a highly effective

ground-based tool for ionospheric detection. The electromagnetic waves transmitting toward the ionosphere excite the Thomson scattering of electrons^[1]. The received

* Supported by the National Natural Science Foundation of China (42425403), B-type Strategic Priority Program of the Chinese Academy of Sciences (XDB0780000), and the Project of Stable Support for Youth Team in Basic Research Field, CAS (YSBR-018)

Received January 8, 2026. Revised August 25, 2026

©The Author(s) 2026. This is an open access article under the CC-BY 4.0 License (<https://creativecommons.org/licenses/by/4.0/>)

incoherent scatter spectrum includes mainly two frequency components^[2]. One corresponds to ion-acoustic waves and appears as bimodal spectral lines centered around the zero frequency, commonly referred to as the ion line. Another is the plasma line component corresponding to Langmuir waves, which appears as a pair of sharp peaks with up- and down-shifted frequency. As the basis of ISR measurements, the ion line spectra enable estimation of multiple plasma parameters, particularly the electron density and temperature, ion temperature and velocity, and ion composition^[3], supporting the ionosphere science. By analyzing these parameters, we can further derive other useful ionospheric parameters such as the electric field, wind field^[4], and even neutral temperature. The plasma line was first observed by Yngvesson *et al.*^[5]. It can be used for the study of electron density profiles and photoelectron fluxes^[6]. The plasma line is usually difficult to detect, owing to the typically weak power of its backscattered signal. However, photoelectrons enhancements during daytime substantially increase the backscattered power of the plasma line, enable its observability by high power radar^[7]. This provides the possibility for the combined measurements of ion line and plasma line by ISR. Recent observations from Sanya Incoherent Scatter Radar (SYISR; 109.6°E, 18.3°N)^[8,9] demonstrate that the plasma lines can be observed throughout the daytime^[10].

In the standard ion line inversion, ion composition is not included in the fitting process while other ionospheric parameters are derived using least-squares fitting^[11]. Based on the preconfigured value from such as the International Reference Ionosphere (IRI) model, four key parameters—electron density (N_e), electron temperature (T_e), ion temperature (T_i), and ion velocity (V_i)—are obtained for each range gate and used as initial guesses to calculate the theoretical ion line spectrum. By iterating the input values of the four parameters through a least-squares algorithm, the theoretical Auto-correlation Function (ACF) is fitted to the measured ACF, yielding the optimal values for the four basic ionospheric parameters. The width of the ion line spectrum depends on the ion thermal velocity, which is the square root of the ratio of ion temperature to ion mass (T_i/m_i). This means that ISR primarily allow for accurate detection of T_i/m_i ^[12]. During the inversion process, it is usu-

ally assumed that the ion composition is perfectly provided by the model. Variations in initial guesses of ion composition directly affect the ion line morphology. Consequently, the initial guess of ion composition significantly impacts the temperature estimation. Different combinations of ion composition and temperature can yield same T_i/m_i values, a phenomenon known as the Temperature-Ion Composition Ambiguity (TICA)^[13]. Since the ion composition is given by the model and remains unchanged in the inversion, inaccuracies in the fitted ion temperatures may result from the TICA effect. Various methods have been proposed for correcting estimates of electron density, electron temperature, and ion temperature as ion composition changes^[14]. Some researchers have tried to address TICA effect by accurately modeling the ion composition of the F-region^[15]. An accurate ion composition model does can effectively avoid ambiguity and improve the accuracy of ion temperature inversion results. However, the ion composition model is often inaccurate when the ionosphere is disturbed^[16]. Other ways to mitigate the TICA effect include using plasma data to provide prior information^[17], the usage of which is restricted by the plasma data availability. Furthermore, in ion-line inversions, the electron density is typically proportional to the Signal-to-Noise Ratio (SNR) of the radar echoes^[18]. Since the SNR is influenced by both system noise and environmental noise, frequent calibration is required to ensure accurate electron density estimates. Traditionally, calibration of radar system parameters is performed by comparing the F-layer peak density obtained from ISR measurements with the critical frequency measured by a co-located ionosonde^[19], or by using electron densities derived from ISR plasma lines to calibrate the ISR ion line measurements^[10].

The inversion method proposed in this study fully incorporates plasma line information into the ion line fitting process. In ion line theory, T_e is intrinsically coupled to T_i , and T_i is further coupled to m_i , resultig in parameter ambiguities during inversion. The plasma line frequency offset, however, is governed mainly by N_e and T_e provides an additional constraint that is largely independent of ion composition. The inclusion of plasma line observations therefore helps disentangle the coupled inversion parameters. As a result, N_e and T_e are

jointly constrained by both ion line and plasma line measurements, significantly alleviating the TICA effect and enhancing parameter retrieval accuracy. Due to the inclusion of plasma line information, parameters such as ion composition and ion-neutral collision frequency can be extracted more accurately^[20,21]. Moreover, the inclusion of plasma line data allows for more accurate determination of electron density during fitting, eliminating the need for additional calibration procedures. In this study, we employ an approach of simulation-based observational system and SYISR measurements to validate the feasibility of the combined inversion method and to assess its improvement on multi-parameter retrievals.

1 Methodology

1.1 Ion Line and Plasma Line Combined Inversion

The general expression of ISR spectrum formula applicable to the non-magnetized case is as follows^[22]:

$$\frac{S(\theta_0) w_0}{N_e \sigma_0} d\theta_0 = \frac{|y_e|^2 \sum_i \eta_i R_e[y_i] + \left| \sum_i u_i y_i + i k^2 \lambda_D^2 \right|^2 R_e[y_e]}{\left| y_e + \sum_i u_i y_i + i k^2 \lambda_D^2 \right|^2} \frac{d\theta_0}{\pi \theta_0}, \quad (1)$$

where $\theta_0 = w/w_0$.

The admittances are given by

$$y_s(\theta_s - i\psi_s) = i + \theta_s \frac{J(\theta_s)}{1 - \psi_s J(\theta_s)}, \quad J = -iG;$$

$$\theta_s = \frac{w}{w_s}, \quad w_s = k \sqrt{\frac{2kT_s}{m_s}}, \quad \psi_s = \frac{v_s}{w_s},$$

$$\psi_i = \psi_0, \quad \psi_e = 0.357\psi_0, \quad \psi_0 = \frac{v_{in}}{w_0};$$

$$G(z) = i\sqrt{\pi}e^{-z^2} + 2e^{-z^2} \int_0^z e^{t^2} dt;$$

$$\eta_i = \frac{N_i}{N_e}, \quad u_i = \frac{N_i}{N_e} \frac{T_e}{T_i}, \quad \gamma_i = \sqrt{\frac{T_0}{T_i} \frac{m_i}{m_0}};$$

$$\lambda_D = \sqrt{\frac{\epsilon_0 T_e k_B}{e^2 N_e}}.$$

Here v_{in} is the ion-neutral collision frequency, $G(z)$ is the plasma dispersion function, m_i is the ion mass, N_i is the ion density, N_e is the electron density, T_i is the ion temperature, T_e is the electron temperature, m_0 and T_0

is the reference parameters, ϵ_0 is the vacuum permittivity, k_B is the Boltzmann constant, e is the elementary charge.

The ion line spectrum and the ACF are Fourier transform pairs, and the conversion from the theoretical ion line spectrum to the theoretical ACF is achieved using the Fast Fourier Transform method^[23].

The plasma-line frequency offset depends on the plasma density and the electron temperature. Under the conditions considered in this study, the contribution of the magnetic field strength is sufficiently small to be neglected, and the frequency offset can therefore be expressed as follows^[24]:

$$v_v = \left(\frac{N_e e^2}{m\pi} + \frac{12kT_e}{m\lambda^2} \right)^{1/2}, \quad (2)$$

where v_v is the frequency offset of plasma line, N_e and T_e represent the electron density and temperature, respectively, e is the elementary charge, m is the electron mass, k is the Boltzmann constant and λ is the wavelength.

We use the objective function proposed by Bjørnå & Kirkwood^[20], in which the weight is determined by the reciprocal of the variance of the ion line and the plasma line, and the dimension can be eliminated for numerical calculations. The objective function of the inversion is defined as follows^[20]:

$$Q = \sum_i \left[\hat{R}(i) - R(i) \right]^2 W(i) + (\hat{v}_v - v_v)^2 W_r, \quad (3)$$

where $\hat{R}(i)$ and $R(i)$ are the measured and theoretical ion line ACFs at different lag i within a range gate, respectively. $\hat{v}_v$ and v_v are the measured and theoretical plasma line frequency offset at the same range gate. The $W(i)$ and W_r are the inverse of the variance calculated for the ACF and plasma line frequency offset measurement. Specifically, the variance estimate of the ACF at each lag is calculated using the method in GUIDAP^[25] and the variance of plasma line frequency offset mainly depends on the frequency resolution of the spectrum. The formula is as follows^[20]:

$$W_r = \frac{1}{12\tau^2}, \quad (4)$$

where τ is the pulse width. During the fitting process, the optimal parameter estimates were obtained by minimizing the objective function with a damped least-squares algorithm. The initial damping coefficient was

set to 0.001 and subsequently updated at each iteration according to the residual sum of squares. The initial parameter guesses were provided by the IRI model version 2016^[26] corresponding to the same time and location. At each iteration, parameter updates were determined from the Jacobian matrix. When the magnitude of an update fell below a predefined threshold, the corresponding parameter was regarded as sufficiently close to its true value, and the resulting estimate was taken as the inversion output.

1.2 Simulation Configuration

The IRI model provides an empirical standard of the ionosphere using comprehensive data sources. For a given location, time, and date, IRI offers monthly averages of electron density, electron temperature, ion temperature, and ion composition across the ionospheric altitude range. In this study, we used the IRI model values over Sanya on 2 April 2022 as the true values, employing these to calculate the corresponding ACF spectrum for simulation purposes.

We first obtained the parameter (N_e , T_e , T_i) according to the altitude of gate from the IRI model. Only four ion composition were considered in the calculation of the ISR spectrum, O_2^+ , NO^+ , O^+ , and H^+ . The ion masses m_i were set to 30.5 (25% O_2^+ and 75% NO^+), 16 (O^+), and 1 (H^+). These parameters are substituted into Eq.(1) to calculate the theoretical ISR spectrum. The Gaussian random white noises with zero means were added as the interference. The noise amplitude is determined by the SNR specified in the simulation, and the calculation formula is

$$P_{\text{noise}} = \frac{1}{1 + R_{\text{sn}}} \times 100\%, \quad (5)$$

where P_{noise} is the noise ratio and R_{sn} is the signal-to-noise ratio. Meanwhile, N_e and T_e are substituted into Eq.(2) to calculate the theoretical plasma line frequency offset, and then the simulated measured frequency deviation

is obtained in the same way as described above. The added noise amplitude will fluctuate between $-P_{\text{noise}}$ and P_{noise} .

We conducted simulations for four cases. Case 1 is ion line inversion. In Case 2, the electron density N_e is extracted directly from the measured plasma line frequency offset, as described above. The electron temperature T_e is obtained from the IRI model with error, and the perturbed T_e is then substituted into Eq.(2) to solve for N_e . The resulting N_e is subsequently used as a priori information in the ion line fitting process to derive the multi-parameter inversion results. Case 3 follows the same procedure, except that T_e is used as the a priori constraint. In case 4, the combined ion line/plasma line inversion method described in Section 1.1 is applied, in which plasma line information is incorporated into the ion line fitting process to obtain multi-parameters. In the simulations, three initial parameter deviations of 10%, 30%, and 50% were applied to N_e , T_e and T_i ; the results shown here correspond to the 10% deviation case. Based on observations from one experimental period, the ion line SNR was estimated to range from 5 dB to 25 dB depending on altitude. In the simulations, fixed SNR values of 13 dB and 17 dB were used, and the case with SNR = 13 dB is presented here. The plasma line SNR exhibited a similar trend: after denoising, it typically ranged from 3 dB to 10 dB. In the simulations, SNR values of 5 dB and 9 dB were adopted, and the results for SNR = 9 dB are shown here. The configurations for the simulations are detailed in Table 1. In Case 2–4, plasma line has been incorporated into the inversion.

1.3 SYISR Experimental Configuration

The experiment was conducted using the SYISR^[8,9], with the radar beam directed at an azimuth of 358° and an elevation of 77°. Observations were made from 00:05:00 LT to 23:55:00 LT on 6 June 2022. Complete plasma line data were obtained between approximately 06:00:00 LT and 11:00:00 LT, when the frequency off-

Table 1 Parameter configuration of the simulation experiments

	Fitting setup	Initial guessed deviation/(%)	SNR of ion line /dB	SNR of plasma line /dB
Case 1	Ion line fitting	10	13	—
Case 2	N_e used as priori	10	13	9
Case 3	T_e used as priori	10	13	9
Case 4	Combined ion line/plasma line	10	13	9

sets remained within the receiver bandwidth. After 11:00:00 LT, the maximum plasma line frequency offset exceeded the available bandwidth, resulting in incomplete plasma line coverage. Considering both the SNR of the ion lines and the frequency resolution of the plasma lines, a long-pulse waveform with a pulse width of 330 μs was transmitted, and the integration time was set to 1 min. The Pulse Repetition Time (PRT) was 7000 μs , and the transmitting frequency was 440 MHz. Three receiving channels were used, centered at 440, 444, 448 MHz, each with a bandwidth of 4 MHz, providing a total bandwidth of 12 MHz for sampling both the ion line and the plasma line simultaneously. The raw data were off-line downsampled to 0.1 MHz for the ion line measurements by mean filtering. Due to limitations imposed by beam pointing and the PRT, the maximum detectable altitude is approximately 730 km. Accordingly, during data processing, spectra above 700 km were regarded as background noise, as the plasma line signal at these altitudes is negligible. The average spectral amplitude above 700 km was subtracted from spectra at lower altitudes to suppress noise. In addition, since plasma lines are absent at night, the nighttime spectra were averaged and used to normalize the daytime spectra, thereby enhancing the plasma line SNR.

Due to the use of long-pulse waveforms, the plasma lines in the spectra appear broadened. To obtain

more accurate estimates of the plasma line frequency offset, Gaussian fitting was applied to the spectra at each altitude. The frequency offset corresponding to the maximum amplitude in the denoised spectrum (excluding zero frequency) was used as the initial guess for the Gaussian fitting. A Gaussian curve was then fitted at each altitude to determine the optimal frequency offset. For altitudes where the fitting failed, spline interpolation was applied to recover the missing values, yielding a continuous plasma line profile.

2 Simulation Result

Figure 1 presents the parameter values versus altitude and local time from the IRI model during the whole day, which are treated as the known true values in the simulation. Figure 2 shows an example of the simulated ion line ACF amplitudes and plasma line frequency offsets as functions of altitude. Since the true values of all parameters are known in the simulation, the relative deviation for each parameter is calculated using the following formula:

$$R = \frac{P_{\text{fitting}} - P_{\text{true}}}{P_{\text{true}}}, \quad (6)$$

where R is the relative deviation of each parameter, P_{true} is the true value of each parameter and P_{fitting} is the fitting value of each parameter. Figure 3 shows the in-

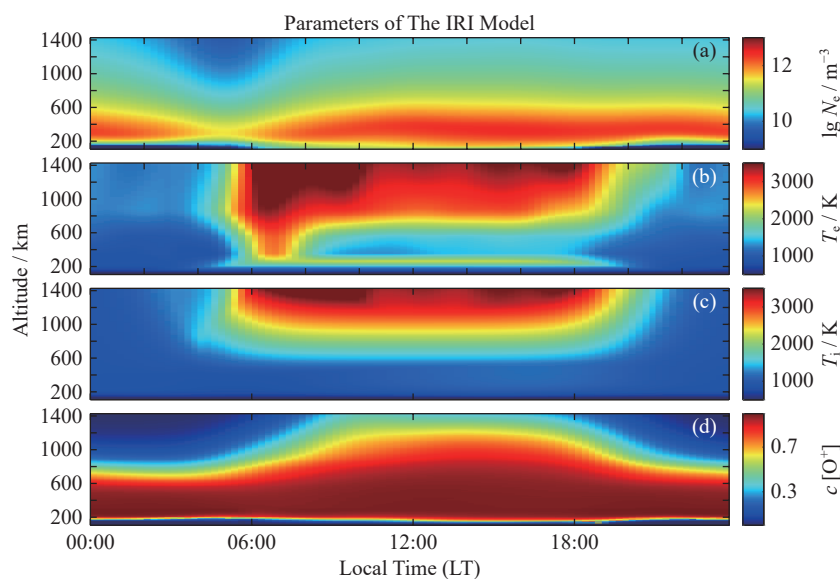


Fig. 1 Local Time (LT) and altitude variations of electron density (a), electron temperature (b), ion temperature (c) and oxygen ion ratio (d) used in the simulation calculated by the IRI model

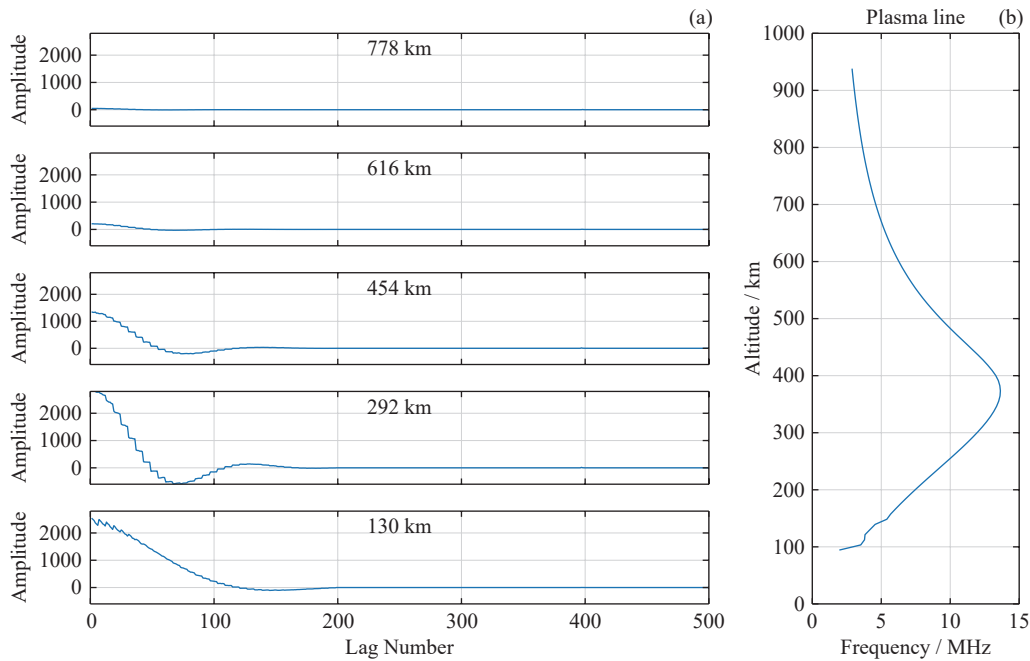


Fig. 2 Simulated ACF amplitude versus lag number for five selected altitudes (a) and plasma line frequency offset for the whole profile in the simulation (b) at 11:45 LT

verted results for all four cases, while Figure 4 is the corresponding relative deviation of the inversion in comparison with the simulated truth.

As shown in Figures 3 and 4, direct ion-line fitting (Figure 3a, 4a) yields stable multi-parameter estimates; however, it exhibits relatively large deviations among the tested cases. In particular, compared with Case 2 (Figure 3b, 4b) and Case 4 (Figure 3d, 4d), the deviations in electron density, electron temperature, and ion temperature are more pronounced. When N_e is incorporated as a priori information (Figure 3b, 4b), the electron density retrieval is further improved, with the overall deviation becoming nearly negligible. This case provides the most accurate electron density estimates among all tested scenarios and also yields moderate improvements in the electron temperature results. In contrast, using T_e as a priori information (Figure 3c, 4c) does not lead to the expected improvement. This is because, as indicated by Eq.(2), the contribution of electron temperature to the plasma line frequency offset is relatively smaller compared with that of electron density. Moreover, in the presence of noise, the retrieved electron temperature becomes less accurate, particularly when the plasma-line SNR is low. By contrast, the combined inversion of plasma and ion lines (Figure 3d, 4d)

produces the most significant overall improvement. The deviations in electron density, electron temperature, and oxygen ion concentration are substantially reduced. Although the improvement in electron density is not as pronounced as in Case 2, the accuracy of both electron temperature and ion temperature is the best among all tested cases, especially at higher altitudes.

The residuals shown in the bottom row of Figure 3 are generally largest below 600 km altitude, coinciding with the region of enhanced electron density. This behavior can be attributed to the fact that the spectral power is directly proportional to electron density, causing regions with higher electron density to contribute more strongly to the overall fitting residual. Consequently, the residual magnitude is particularly sensitive to the accuracy of the electron density estimation. Among the four methods, Case 2 produces the smallest overall residuals, indicating the closest agreement between the modeled and observed spectra. This result is primarily due to its superior retrieval of electron density, which dominates the spectral power and therefore has the greatest influence on the residual magnitude. Case 4, which combines ion-line and plasma-line information in a joint inversion framework, yields slightly larger residuals than Case 2 but still performs better than Cases 1 and 3. It is

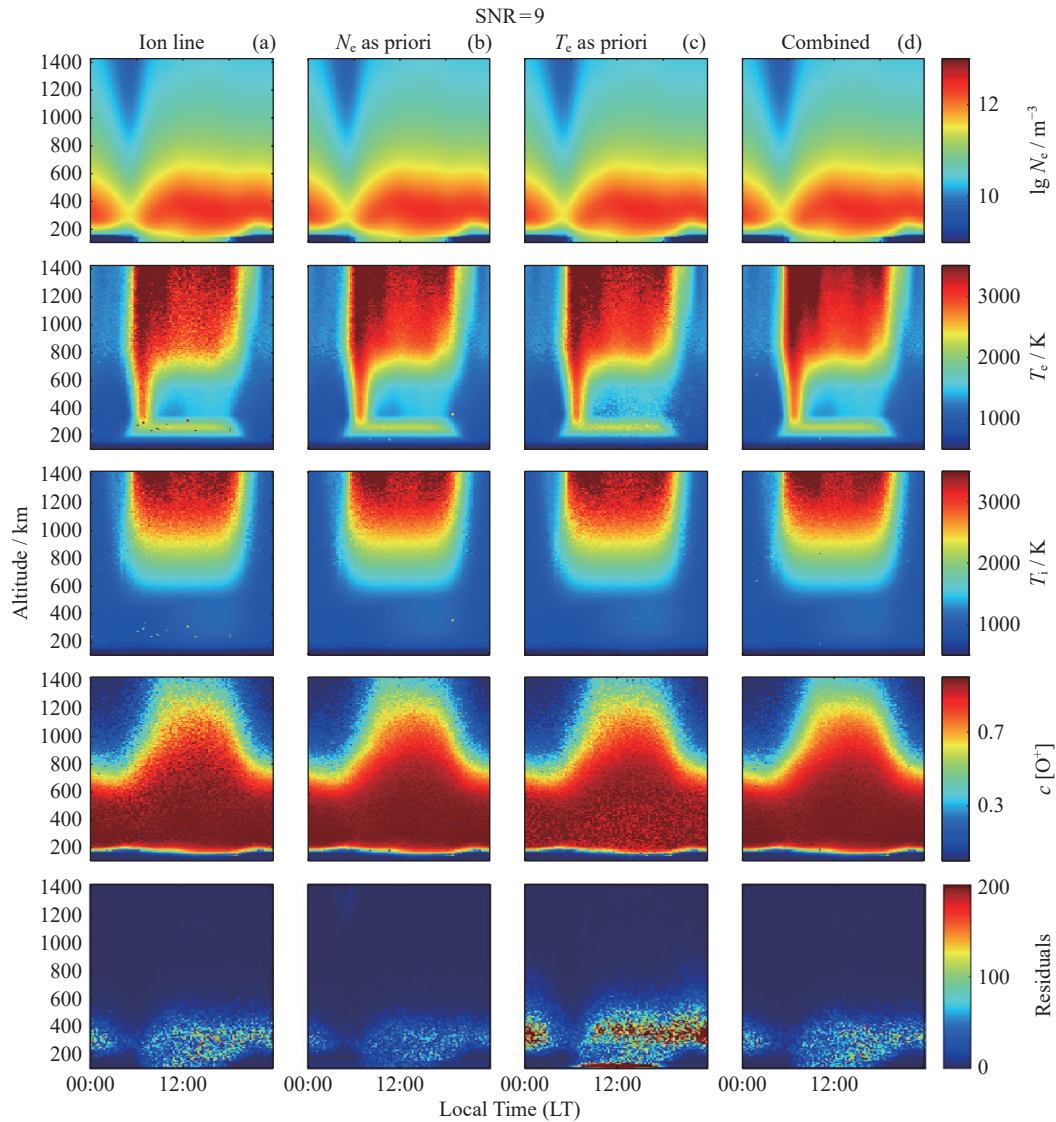


Fig. 3 Retrieved results in the simulation. From the left to the right are for four cases listed in Table 1 and from the top to the bottom are results of electron density, electron temperature, ion temperature, oxygen ion ratio and residuals

important to note that the residuals mainly reflect the agreement between the modeled and observed spectra and are strongly weighted by electron density. Therefore, a smaller residual does not necessarily correspond to the most accurate retrieval of all plasma parameters. Although Case 2 achieves the lowest residuals through a more accurate estimation of electron density, Case 4 provides more accurate estimates of electron temperature, ion temperature, and ion composition. The incorporation of plasma-line constraints effectively reduces parameter ambiguities and leads to a more physically consistent overall solution.

3 Measurement Result

Figure 5 presents the example ion line and plasma line spectra observed at 09:30 LT on 6 June 2022 by SYISR. Owing to the long-pulse coding, the retrieved plasma lines exhibit noticeable vertical broadening; therefore, Gaussian fitting was applied to the spectra to obtain more accurate estimates of the plasma line frequency offset. The extracted plasma lines span altitudes from 122 km to 510 km and are relatively smooth. These plasma line data were fully incorporated into the combined inversion procedure, and the resulting multi-parameter inversion for the full profile at that time is shown in Fig-

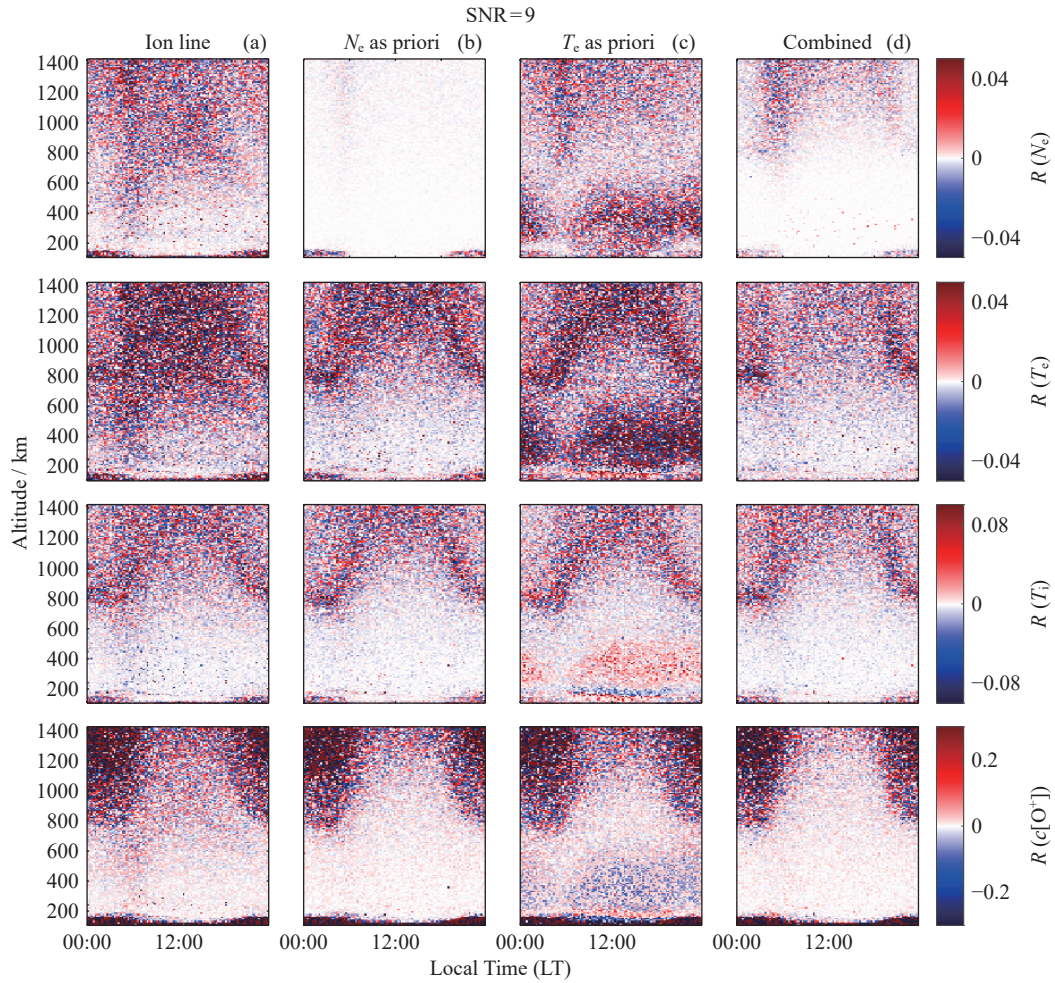


Fig. 4 Relative deviations of the retrieved results from that of the simulated truth (Explanation same as Figure 3)

ure 6.

Figure 6 (a) displays the electron density profile; the black curve denotes ionosonde measurements from Danzhou (109.1°E, 19.5°N), located approximately 140 km from SYISR, with a Chapman fit used to extend densities above the F-region peak. The electron density retrieved by the combined inversion agrees well in magnitude with the ionosonde results, while morphological differences likely arise from the spatial separation between two sites. We compared the electron density profiles obtained from the inversion results with those measured by this ionosonde between 07:00 LT and 11:00 LT, as shown in statistical results in Figure 7. For the combined inversion method, the average difference across all profiles was $-6.62 \times 10^{10} \text{ m}^{-3}$, with a root-mean-square error of $1.35 \times 10^{11} \text{ m}^{-3}$. In contrast, the ion-line-only inversion yielded an average difference of

$-4.15 \times 10^{11} \text{ m}^{-3}$ and a root-mean-square error of $4.37 \times 10^{11} \text{ m}^{-3}$. The electron density from the ion line inversion presents a similar time variation but differs substantially in magnitude, indicating that additional calibration would be required in practical applications. The middle and right panels of Figure 6 show the electron and ion temperature profiles, respectively. Above 250 km, both inversion methods produce consistent temperature estimates. Below 250 km, however, the combined inversion yields lower electron temperatures and higher ion temperatures compared with the ion line inversion. This discrepancy is likely associated with the TICA effect in the compositional transition region^[14] (130–220 km), where the dominant ion species change from molecular to atomic, and the biases arise from inaccuracies in the initial ion composition provided by the IRI model. The inclusion of plasma line data in the in-

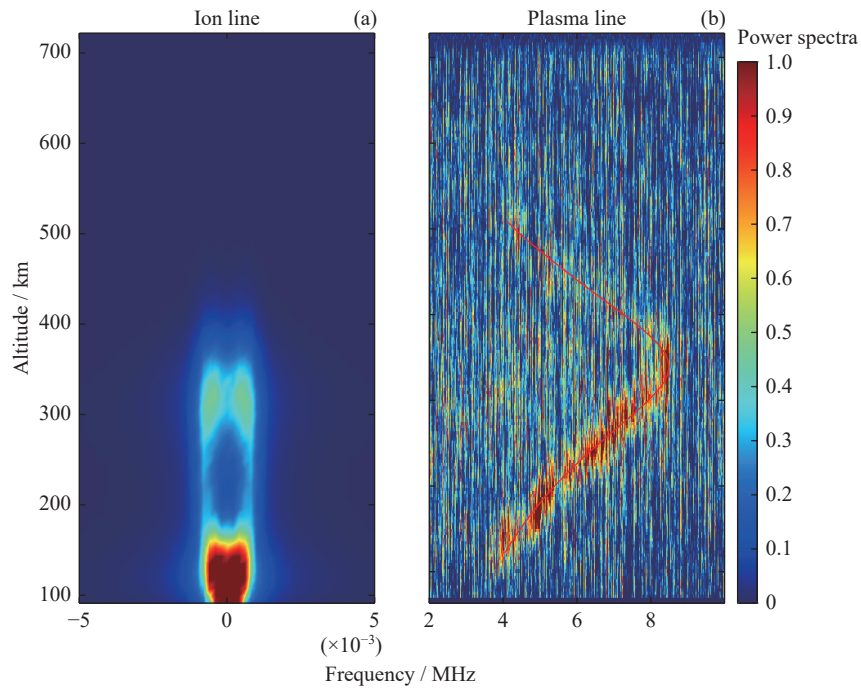


Fig. 5 (a) Altitude variation of measured ion line power spectra by SYISR on 6 June 2022 morning at 09:30 LT. (b) The simultaneous plasma line frequency offset spectrum corresponding to (a), the zero frequency of the spectrum corresponds to the radar transmitting frequency (440 MHz), and the red line is the plasma line extracted after Gaussian fitting

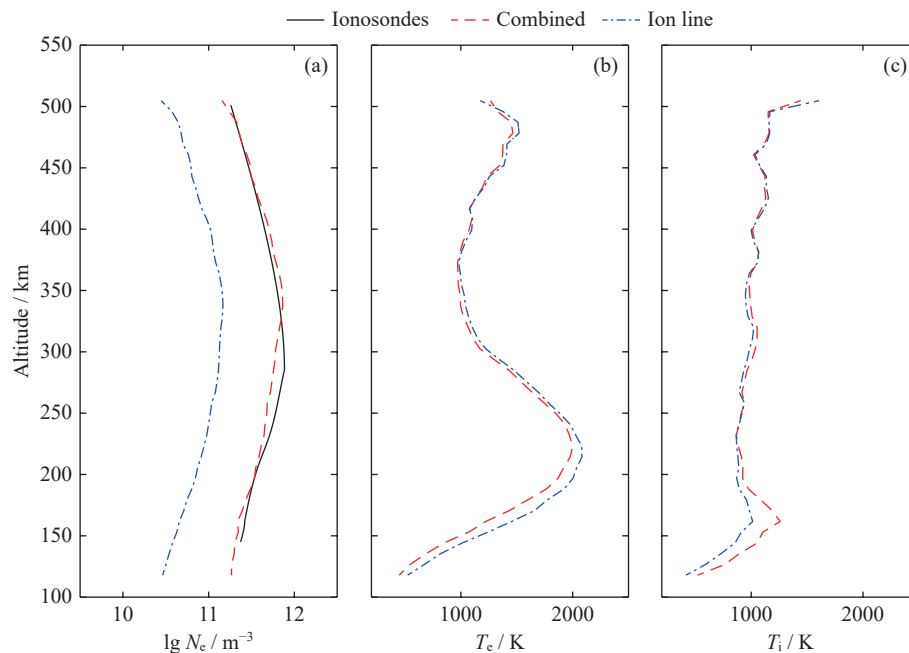


Fig. 6 Comparison between the traditional ion line inversion (blue dotted line) and combined plasma/ion line inversion (red dotted line) for electron density (a), electron temperature (b), and ion temperature (c) for realistic SYISR measurements at 09:30 LT on 6 June 2022. Also embedded in (a) is the electron density profile measured by a co-located ionosonde

version appears to mitigate these biases, limiting anomalous temperature features and improving overall re-

trieval performance.

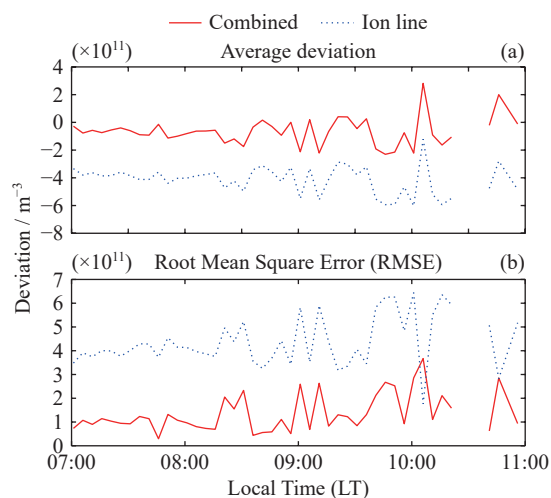


Fig. 7 Deviation of electron density measured by different inversion methods from 07:00 LT to 11:00 LT to ionosonde

4 Summary and Conclusion

In this study, we investigated an inversion method that combines both ion line and plasma line information from incoherent scatter radar observations to improve the retrieval of key ionospheric parameters. The methodology incorporates plasma line frequency offsets into the ion line fitting process, thereby constraining electron density and electron temperature simultaneously. This approach addresses the TICA effect and enhances the accuracy of multi-parameter estimation.

Simulation experiments were carried out under four scenarios: ion line inversion only; ion line inversion with electron density as a priori information; ion line inversion with electron temperature as a priori information, and the combined ion line and plasma line inversion. Results demonstrated that while direct ion line inversion yields reasonable parameter estimates, the combined inversion achieves the smallest relative deviations in both electron density and temperature. Notably, using electron density as a priori information improves inversion stability, whereas applying electron temperature constraints alone does not yield comparable benefits due to its weaker contribution to plasma line frequency offsets.

Observational validation was performed using data from the SYISR on 6 June 2022. Plasma line frequency offsets were extracted through Gaussian fitting and integrated into the combined inversion. Comparisons with ionosonde measurements confirmed that the combined

method retrieves electron densities that are more consistent in magnitude with independent observations, while also mitigating biases in electron and ion temperature retrievals within the compositional transition region.

Overall, the results highlight the significant advantages of incorporating plasma line data into ISR inversions. The combined inversion method effectively reduces the need for external calibration, enhances parameter accuracy, and provides more physically reliable retrievals of ionospheric electron density, electron temperature, and ion temperature. This study thus demonstrates the feasibility and superiority of combined ion line and plasma line inversion, offering a more robust framework for multi-parameter ionospheric research. This method needs more experimental verification in the future when we have more simultaneous ion line and plasma line measurements.

Future work will focus on several aspects to further improve the proposed inversion framework. First, global optimization techniques will be explored to reduce the possibility of convergence to local minima during the inversion process and to improve the robustness of parameter retrievals. Second, instead of using only the plasma-line frequency offsets, the complete plasma-line spectral function will be incorporated into the joint inversion procedure. This approach is expected to provide additional physical constraints and enhance the theoretical rigor of the inversion framework. Finally, image-recognition-based techniques will be investigated for the automatic identification and extraction of plasma-line signatures from target regions, enabling a more efficient and reliable implementation of ion-line and plasma-line combined inversion.

Acknowledgments The authors acknowledge the data usage of the Chinese Meridian Project.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of Interests The authors declare that there is no conflict of interests.

References

- [1] GORDON W E. Incoherent scattering of radio waves by free

- electrons with applications to space exploration by radar[J]. *Proceedings of the IRE*, 1958, **46**(11): 1824-1829
- [2] SALPETER E E. Electron density fluctuations in a plasma[J]. *Physical Review*, 1960, **120**(5): 1528-1535
- [3] GORDON W E. *F* region and magnetosphere, backscatter results[J]. *Reviews of Geophysics*, 1967, **5**(2): 191-205
- [4] ZHANG N, YUE X A, WANG J Y, *et al.* Calculation and evaluation of neutral winds in the lower thermosphere based on SY-ISR observations[J]. *Journal of Geophysical Research: Space Physics*, 2024, **129**(11): e2024JA032994
- [5] YNGVESSON K O, PERKINS F W. Radar Thomson scatter studies of photoelectrons in the ionosphere and Landau damping[J]. *Journal of Geophysical Research*, 1968, **73**(1): 97-110
- [6] HAGFORS T. Incoherent scatter radar observations of the plasma line with a chirped pulse system[J]. *Radio Science*, 1982, **17**(3): 727-734
- [7] PERKINS F W, SALPETER E E, YNGVESSON K O. Incoherent scatter from plasma oscillations in the ionosphere[J]. *Physical Review Letters*, 1965, **14**(15): 579-581
- [8] YUE X A, WAN W X, NING B Q, *et al.* Development of the Sanya incoherent scatter radar and preliminary results[J]. *Journal of Geophysical Research: Space Physics*, 2022, **127**(8): e2022JA030451
- [9] YUE X A, NING B Q, JIN L, *et al.* A tristatic phased array radar system in China[J]. *Nature Astronomy*, 2024, **8**(5): 673
- [10] YUE X A, LIU F Y, WANG J Y, *et al.* On the ion line calibration by plasma line in ISR measurements[J]. *Remote Sensing*, 2023, **15**(6): 1553
- [11] WU L L, ZHOU Q H, CHEN T J, *et al.* Application of particle swarm optimization method to incoherent scatter radar measurement of ionosphere parameters[J]. *Journal of Geophysical Research: Space Physics*, 2015, **120**(9): 8096-8110
- [12] BLELLY P L, ALCAYDÉ D, VAN EYKEN A P. A new analysis method for determining polar ionosphere and upper atmosphere characteristics from ESR data: illustration with IPY period[J]. *Journal of Geophysical Research: Space Physics*, 2010, **115**(A9): A09322
- [13] VALLINKOSKI M. Statistics of incoherent scatter multiparameter fits[J]. *Journal of Atmospheric and Terrestrial Physics*, 1988, **50**(9): 839-851
- [14] WALDTEUFEL P. Combined incoherent-scatter *F*₁-region observations[J]. *Journal of Geophysical Research*, 1971, **76**(28): 6995-6999
- [15] ZETTERGREN M, SEMETER J, HEINSELMAN C, *et al.* Incoherent scatter radar estimation of *F* region ionospheric composition during frictional heating events[J]. *Journal of Geophysical Research: Space Physics*, 2011, **116**(A1): A01318
- [16] LATHUILLÈRE C, KOFMAN W. A short review on the *F*₁-region ion composition in the auroral and polar ionosphere[J]. *Advances in Space Research*, 2006, **37**(5): 913-918
- [17] APONTE N, SULZER M P, NICOLLS M J, *et al.* Molecular ion composition measurements in the *F*₁ region at Arecibo[J]. *Journal of Geophysical Research: Space Physics*, 2007, **112**(A6): A06322
- [18] LEHTINEN M S. Statistical theory of incoherent scatter radar measurements[D]. Helsinki: University of Helsinki, 1986
- [19] KIRKWOOD S, COLLIS P N, SCHMIDT W. Calibration of electron densities for the EISCAT UHF radar[J]. *Journal of Atmospheric and Terrestrial Physics*, 1986, **48**(9/10): 773-775
- [20] BJØRNÅ N, KIRKWOOD S. Derivation of ion composition from a combined ion line/plasma line incoherent scatter experiment[J]. *Journal of Geophysical Research: Space Physics*, 1988, **93**(A6): 5787-5793
- [21] BJØRNÅ N. Derivation of ion-neutral collision frequencies from a combined ion line/plasma line incoherent scatter experiment[J]. *Journal of Geophysical Research: Space Physics*, 1989, **94**(A4): 3799-3804
- [22] VICKREY J F, SWARTZ W E, FARLEY D T. Incoherent scatter measurements of ion counterstreaming[J]. *Geophysical Research Letters*, 1976, **3**(4): 217-220
- [23] SWARTZ W E, FARLEY D T. A theory of incoherent scattering of radio waves by a plasma, 5. The use of the Nyquist Theorem in general quasi-equilibrium situations[J]. *Journal of Geophysical Research: Space Physics*, 1979, **84**(A5): 1930-1932
- [24] PERKINS F, SALPETER E E. Enhancement of plasma density fluctuations by nonthermal electrons[J]. *Physical Review*, 1965, **139**(1A): A55-A62
- [25] LEHTINEN M S, HUUSKONEN A. General incoherent scatter analysis and GUISDAP[J]. *Journal of Atmospheric and Terrestrial Physics*, 1996, **58**(1/2/3/4): 435-452
- [26] BILITZA D, ALTADILL D, TRUHLIK V, *et al.* International Reference ionosphere 2016: from ionospheric climate to real-time weather predictions[J]. *Space Weather*, 2017, **15**(2): 418-429

Author Biography



ZHANG Wenao was born in Sanming, Fujian Province, China, in July 2000. He is currently a Ph.D. candidate at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). His research interests include ionospheric physics, incoherent scatter radar (ISR) signal processing, and data processing.
E-mail: wazhang@mail.iggcas.ac.cn



YUE Xin'an (Corresponding author) was born in Hubei Province, China, in January 1980. He is currently a Professor and Ph.D. supervisor at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). His research interests include incoherent scatter radar (ISR) techniques, ionospheric physics, ionospheric numerical modeling, and data assimilation.
E-mail: yuexinan@mail.iggcas.ac.cn