

ON ASYMPTOTICS OF EIGENVECTORS OF LARGE SAMPLE COVARIANCE MATRIX

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Let $\{X_{ij}\}$, $i, j = \dots$, be a double array of i.i.d. complex random variables with $EX_{11} = 0$, $E|X_{11}|^2 = 1$ and $E|X_{11}|^4 < \infty$, and let $A_n = \frac{1}{N}T_n^{1/2}X_nX_n^*T_n^{1/2}$, where $T_n^{1/2}$ is the square root of a nonnegative definite matrix T_n and X_n is the $n \times N$ matrix of the upper-left corner of the double array. The matrix A_n can be considered as a sample covariance matrix of an i.i.d. sample from a population with mean zero and covariance matrix T_n , or as a multivariate F matrix if T_n is the inverse of another sample covariance matrix. To investigate the limiting behavior of the eigenvectors of A_n , a new form of empirical spectral distribution is defined with weights defined by eigenvectors and it is then shown that this has the same limiting spectral distribution as the empirical spectral distribution defined by equal weights. Moreover, if $\{X_{ij}\}$ and T_n are either real or complex and some additional moment assumptions are made then linear spectral statistics defined by the eigenvectors of A_n are proved to have Gaussian limits, which suggests that the eigenvector matrix of A_n is nearly Haar distributed when T_n is a multiple of the identity matrix, an easy consequence for a Wishart matrix.

1. Introduction. Let $X_n = (X_{ij})$ be an $n \times N$ matrix of i.i.d. complex random variables and let T_n be an $n \times n$ nonnegative definite Hermitian matrix with a square root $T_n^{1/2}$. In this paper, we shall consider the matrix $A_n = \frac{1}{N}T_n^{1/2}X_nX_n^*T_n^{1/2}$. If T_n is nonrandom, then A_n can be considered as a sample covariance matrix of a sample drawn from a population with the same distribution as $T_n^{1/2}\mathbf{X}_{\cdot,1}$, where $\mathbf{X}_{\cdot,1} = (X_{11}, \dots, X_{n1})'$. If T_n is an inverse of another sample covariance matrix, then the multivariate F matrix can be considered as a special case of the matrix A_n .

In this paper, we consider the case where both dimension n and sample size N are large. Bai and Silverstein [7] gave an example demonstrating the considerable

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difference between the case where n is fixed and that where n increases with N proportionally. When $T_n = I$, A_n reduces to the usual sample covariance matrix of N n -dimensional random vectors with mean 0 and covariance matrix I . An important statistic in multivariate analysis is

$$W_n = \ln(\det A_n) = \sum_{j=1}^N \ln(\lambda_j),$$

where λ_j , $j = 1, \dots, n$, are the eigenvalues of A_n . When n is fixed, by taking a Taylor expression of $\ln(1+x)$, one can easily prove that

$$\sqrt{\frac{N}{n}} W_n \xrightarrow{D} N(0, EX_{11}^4 - 1).$$

It appears that when n is fixed, this distribution can be used to test the hypothesis of variance homogeneity. However, it is not the case when n increases as $[cN]$ (the integer part of cN) with $c \in (0, 1)$. Using results of the limiting spectral distribution of A_n (see [12] or [1]), one can show that with probability one that

$$\frac{1}{n} W_n \rightarrow \frac{c-1}{c} \ln(1-c) - 1 \equiv d(c) < 0,$$

which implies that

$$\sqrt{\frac{N}{n}} W_n \sim d(c) \sqrt{Nn} \rightarrow -\infty.$$

More precisely, the distribution of W_n shifts to left quickly when n increases as $n \sim cN$. Figure 1 gives the kernel density estimates using 1000 realizations of W_n for $N = 20, 100, 200$ and 500 with $n = 0.2N$. Figures 2 and 3 give the kernel density estimates of $\sqrt{\frac{N}{n}} W_n$ for the cases $n = 5$ and $n = 10$ with $N = 50$. These figures clearly show that the distribution of W_n cannot be approximated by a centered normal distribution even if the ratio c is as small as 0.1.

This phenomenon motivates the development of the theory of spectral analysis of large-dimensional random matrices which is simply called random matrix theory (RMT). In this theory, for a square matrix A of real eigenvalues, its empirical spectral distribution (ESD) F^A is defined as the empirical distribution generated by its eigenvalues. The limiting properties of the ESD of sample covariance matrices have been intensively investigated in the literature and the reader is referred to [1, 17, 5–7, 11–13, 20, 21, 23].

An important mathematical tool in RMT is the *Stieltjes transform*, which is defined by

$$m_G(z) = \int \frac{1}{\lambda - z} dG(\lambda), \quad z \in \mathbb{C}^+ \equiv \{z \in \mathbb{C}, \Im z > 0\},$$

for any distribution function $G(x)$. It is well known that $G_n \xrightarrow{v} G$ if and only if

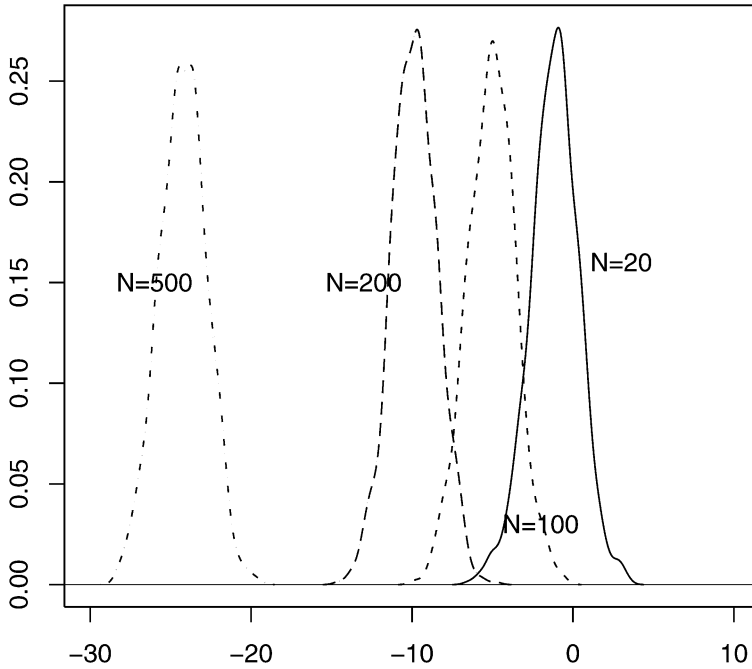


FIG. 1. Density of W_n under different sample sizes, $c = 0.2$.

$m_{G_n}(z) \rightarrow m_G(z)$, for all $z \in \mathbb{C}^+$.

In [13], it is assumed that:

- (i) for all n, i, j , X_{ij} are independently and identically distributed with $EX_{ij} = 0$ and $E|X_{ij}|^2 = 1$;
- (ii) $F^{T_n} \xrightarrow{D} H$, a proper distribution function;
- (iii) $\frac{n}{N} \rightarrow c > 0$ as $n \rightarrow \infty$.

It is then proved that, with probability 1, F^{A_n} converges to a nonrandom distribution function $F^{c,H}$ whose Stieltjes transform $m(z) = m_{F^{c,H}}(z)$, for each $z \in \mathbb{C}^+$, is the unique solution in \mathbb{C}^+ of the equation

$$(1.1) \quad m(z) = \int \frac{1}{t(1 - c - czm) - z} dH(t).$$

Let $\underline{A}_n = \frac{1}{N} X_n^* T_n X_N$. The spectrum of A_n differs from that of \underline{A}_n only by $|n - N|$ zero eigenvalues. Hence, we have

$$F^{A_n} = \left(1 - \frac{n}{N}\right) I_{[0,\infty)} + \frac{n}{N} F^{A_n}.$$

It then follows that

$$(1.2) \quad \underline{m}_n(z) = m_{F^{A_n}}(z) = -\frac{1 - n/N}{z} + \frac{n}{N} m_{F^{A_n}}(z)$$

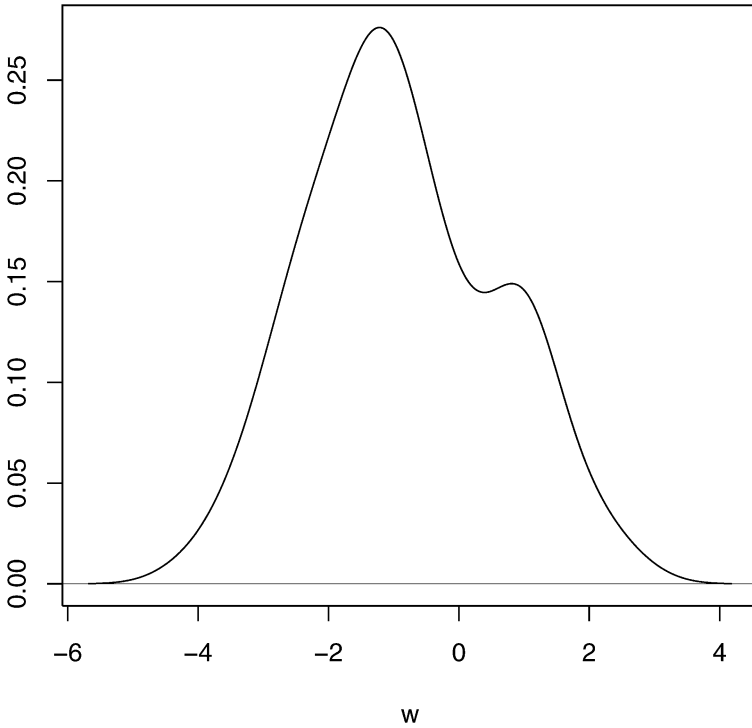


FIG. 2. Probability density of $\sqrt{\frac{N}{n}}W_n$ ($n = 5, N = 50$).

and, correspondingly for their limits,

$$(1.3) \quad \underline{m}(z) = m_{\underline{F}^{c,H}}(z) = -\frac{1-c}{z} + cm(z),$$

where $\underline{F}^{c,H}$ is the limiting empirical distribution function of \underline{A}_n .

Using this notation, equation (1.1) can be converted to equation (1.4) for $\underline{m}(z)$. That is, $\underline{m}(z)$ is the unique solution in \mathbb{C}^+ of the equation

$$(1.4) \quad \underline{m} = -\left(z - c \int \frac{t dH(t)}{1 + t\underline{m}}\right)^{-1}.$$

From this equation, the inverse function has the explicit form

$$(1.5) \quad z = -\frac{1}{\underline{m}} + c \int \frac{t dH(t)}{1 + t\underline{m}}.$$

The limiting properties of the eigenvalues of A_n have been intensively investigated in the literature. Among others, we shall now briefly mention some remarkable ones. Yin, Bai and Krishnaiah [22] established the limiting value of the largest eigenvalue, while Bai and Yin [2] employed a unified approach to obtain the limiting value for the smallest and largest eigenvalues of A_n when $T_N = I$. A breakthrough on the convergence rate of the ESD of a sample covariance matrix was

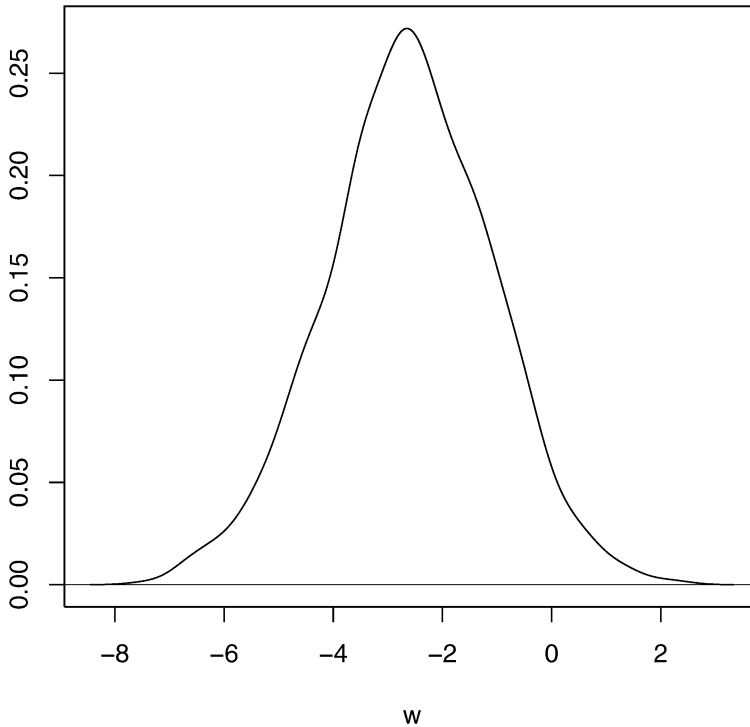


FIG. 3. Probability density of $\sqrt{\frac{N}{n}}W_n$ ($n = 10, N = 50$).

made in [3] and [4]. In [5], it is shown that, with probability 1, no eigenvalues of A_n appear in any interval $[a, b]$ which is contained in an open interval outside the supports of F^{c_n, H_n} for all large N under the condition of finite 4th moment (here, $c_n = n/N$ and H_n is the ESD of T_n).

However, relatively less work has been done on the limiting behavior of eigenvectors of A_n . Some results on this aspect can be found in [14–16]. That more attention has been paid to the ESD of the sample covariance matrix may be due to the origins of RMT, which lie with quantum mechanics (QM), where the eigenvalues of large-dimensional random matrices are used to describe energy levels of particles. With the application of RMT to many other areas, such as statistics, wireless communications,—for example, the CDMA (code division multiple access) systems and MIMO (multiple input multiple output) systems, finance and economics, and so on, the importance of the limiting behavior of eigenvectors has been gradually recognized. For example, in signal processing, for signals received by linearly spaced sensors, the estimates of the directions of arrivals (DOA) are based on the noise eigenspace. In principal component analysis or factor analysis, the directions of the principal components are the eigenvectors corresponding to the largest eigenvalues.

Now, let us consider another example of the application of eigenvectors of a large covariance matrix A_n which is important in wireless communications. Consider transmission methods in wireless systems. In a direct sequence CDMA system, the discrete-time model for a synchronous systems is formulated as

$$\mathbf{r} = \sum_{k=1}^K b_k \mathbf{s}_k + \mathbf{w},$$

where $b_k (\in \mathbb{C})$ and $\mathbf{s}_k (\in \mathbb{C}^N)$ are the transmitted data symbols and signature sequence of the user k , respectively, and \mathbf{w} is an N -dimensional background Gaussian noise of i.i.d. variables with mean zero and variance σ^2 . The goal is to demodulate the transmitted b_k for each user. In this case, the performance measure is defined as the signal-to-interference ratio (SIR) of the estimates. In a large network, since the number of users is very large, it is reasonable to assume that K is proportional to N . That is, one can assume that their ratio remains constant when both K and N tend to infinity. Thus, it is feasible to apply the theory of large-dimensional random matrices to wireless communications and, indeed, there has already accumulated a fruitful literature in this direction (see, e.g., [18] and [19], among others). Eldar and Chen [10] derived an expression of SIR for the decorrelator receiver in terms of eigenvectors and eigenvalues of random matrices and then analyzed the asymptotics of the SIR (see [10] for details).

Our research is motivated by the fact that the matrix of eigenvectors (eigenmatrix for short) of the Wishart matrix has the Haar distribution, that is, the uniform distribution over the group of unitary matrices (or orthogonal matrices in the real case). It is conceivable that the eigenmatrix of a large sample covariance matrix should be “asymptotically Haar distributed.” However, we are facing a problem on how to formulate the terminology “asymptotically Haar distributed” because the dimensions of the eigenmatrices are increasing. In this paper, we shall adopt the method of Silverstein [14, 15]. If U has a Haar measure over the orthogonal matrices, then for any unit vector $\mathbf{x} \in \mathbb{R}^n$, $\mathbf{y} = U\mathbf{x} = (y_1, \dots, y_n)'$ has a uniform distribution over the unit sphere $S_n = \{\mathbf{x} \in \mathbb{R}^n; \|\mathbf{x}\| = 1\}$. If $\mathbf{z} = (z_1, \dots, z_n)' \sim N(0, I_n)$, then \mathbf{y} has the same distribution as $\mathbf{z}/\|\mathbf{z}\|$.

Now, define a stochastic process $Y_n(t)$ in the space $D(0, 1)$ by

$$(1.6) \quad \begin{aligned} Y_n(t) &= \sqrt{\frac{n}{2}} \sum_{i=1}^{[nt]} \left(|y_i|^2 - \frac{1}{n} \right) \\ &\stackrel{d}{=} \sqrt{\frac{n}{2}} \frac{1}{\|\mathbf{z}\|^2} \sum_{i=1}^{[nt]} \left(|z_i|^2 - \frac{\|\mathbf{z}\|^2}{n} \right), \end{aligned}$$

where $[a]$ denotes the greatest integer $\leq a$. From the second equality, it is easy to see that $Y_n(t)$ converges to a Brownian bridge (BB) $B(t)$ when n converges to infinity. Thus we are interested in whether the same is true for general sample covariance matrices.

Let $U_n \Lambda_n U_n^*$ denote the spectral decomposition of A_n , where $\Lambda_n = \text{diag}(\lambda_1, \lambda_2, \dots, \lambda_n)$ and $U_n = (u_{ij})$ is a unitary matrix consisting of the orthonormal eigenvectors of A_n . Assume that $\mathbf{x}_n \in \mathbb{C}^n$, $\|\mathbf{x}_n\| = 1$, is an arbitrary nonrandom unit vector and that $\mathbf{y} = (y_1, y_2, \dots, y_n)^* = U_n^* \mathbf{x}_n$. We define a stochastic process by way of (1.6). If U_n is ‘‘asymptotically Haar distributed,’’ then \mathbf{y} should be ‘‘asymptotically uniformly distributed’’ over the unit sphere and $Y_n(t)$ should tend to a BB. Our main goal is to examine the limiting properties of the vector \mathbf{y} through the stochastic process $Y_n(t)$.

For ease of application of RMT, we make a time transformation in $Y_n(t)$,

$$X_n(x) = Y_n(F^{A_n}(x)),$$

where F^{A_n} is the ESD of the matrix A_n . If the distribution of U_n is close to Haar, then $X_n(x)$ should approximate $B(F^{c,H}(x))$, where $F^{c,H}$ is the limiting spectral distribution of A_n .

We define a new empirical distribution function based on eigenvectors and eigenvalues:

$$(1.7) \quad F_1^{A_n}(x) = \sum_{i=1}^n |y_i|^2 I(\lambda_i \leq x).$$

Recall that the ESD of A_n is

$$F^{A_n}(x) = \frac{1}{n} \sum_{i=1}^n I(\lambda_i \leq x).$$

It then follows that

$$X_n(x) = \sqrt{\frac{n}{2}} (F_1^{A_n}(x) - F^{A_n}(x)).$$

The investigation of $Y_n(t)$ is then converted to one concerning the difference $F_1^{A_n}(x) - F^{A_n}(x)$ of the two empirical distributions.

It is obvious that $F_1^{A_n}(x)$ is a random probability distribution function and that its Stieltjes transform is given by

$$(1.8) \quad m_{F_1^{A_n}}(z) = \mathbf{x}_n^* (A_n - zI)^{-1} \mathbf{x}_n.$$

As we have seen, the difference between $F_1^{A_n}(x)$ and $F^{A_n}(x)$ is only in their different weights on the eigenvalues of A_n . However, it will be proven that although these two empirical distributions have different weights, they have the same limit; this is included in Theorem 1.1 below.

To investigate the convergence of $X_n(x)$, we consider its linear functional, which is defined as

$$\hat{X}_n(g) = \int g(x) dX_n(x),$$

where g is a bounded continuous function. It turns out that

$$\begin{aligned}\hat{X}_n(g) &= \sqrt{\frac{n}{2}} \left[\sum_{j=1}^n |y_j|^2 g(\lambda_j) - \frac{1}{n} \sum_{j=1}^n g(\lambda_j) \right] \\ &= \sqrt{\frac{n}{2}} \left[\int g(x) dF_1^{A_n}(x) - \int g(x) dF^{A_n}(x) \right].\end{aligned}$$

Proving the convergence of $\hat{X}_n(g)$ under general conditions is difficult. Following an idea of [7], we shall prove the central limit theorem (CLT) for those g which are analytic over the support of the limiting spectral distribution of A_n . To this end, let

$$G_n(x) = \sqrt{N} (F_1^{A_n}(x) - F^{c_n, H_n}(x)),$$

where $c_n = \frac{n}{N}$ and where $F^{c_n, H_n}(x)$ denotes the limiting distribution by substituting c_n for c and H_n for H in $F^{c, H}$.

The main results of this paper are formulated in the following three theorems.

THEOREM 1. *Suppose that:*

(1) *for each n , $X_{ij} = X_{ij}^n$, $i, j = 1, 2, \dots$, are i.i.d. complex random variables with $EX_{11} = 0$, $E|X_{11}|^2 = 1$ and $E|X_{11}|^4 < \infty$;*

(2) *$\mathbf{x}_n \in \mathbb{C}_1^n = \{\mathbf{x} \in \mathbb{C}^n, \|\mathbf{x}\| = 1\}$ and $\lim_{n \rightarrow \infty} \frac{n}{N} = c \in (0, \infty)$;*

(3) *T_n is nonrandom Hermitian nonnegative definite with its spectral norm bounded in n , with $H_n = F^{T_n} \xrightarrow{\mathcal{D}} H$ a proper distribution function and with $\mathbf{x}_n^* (T_n - zI)^{-1} \mathbf{x}_n \rightarrow m_{FH}(z)$, where $m_{FH}(z)$ denotes the Stieltjes transform of $H(t)$. It then follows that*

$$F_1^{A_n}(x) \rightarrow F^{c, H}(x) \quad \text{a.s.}$$

REMARK 1. The condition $\mathbf{x}_n^* (T_n - zI)^{-1} \mathbf{x}_n \rightarrow m_{FH}(z)$ is critical for our Theorem 1 as well as for the main theorems which we give later. At first, we indicate that if $T_n = bI$ for some positive constant b or, more generally, $\lambda_{\max}(T_n) - \lambda_{\min}(T_n) \rightarrow 0$, then the condition $\mathbf{x}_n^* (T_n - zI)^{-1} \mathbf{x}_n \rightarrow m_{FH}(z)$ holds uniformly for all $\mathbf{x}_n \in \mathbb{C}_1^n$.

We also note that this condition does not require T_n to be a multiple of an identity. As an application of this remark, one sees that the eigenmatrix of a sample covariance matrix transforms \mathbf{x}_n to a unit vector whose entries' absolute values are close to $1/\sqrt{N}$. Consequently, the condition $\mathbf{x}_n^* (T_n - zI)^{-1} \mathbf{x}_n \rightarrow m_{FH}(z)$ holds when T_n is the inverse of another sample covariance matrix which is independent of X_n . Therefore, the multivariate F matrix satisfies Theorem 1.

In general, the condition may not hold for all $\mathbf{x}_n \in \mathbb{C}_1^n$. However, there always exist some $\mathbf{x}_n \in \mathbb{C}_1^n$ such that this condition holds, say $\mathbf{x}_n = (\mathbf{u}_1 + \dots + \mathbf{u}_n)/\sqrt{n}$, where $\mathbf{u}_1, \dots, \mathbf{u}_n$ are the orthonormal eigenvectors of the spectral decomposition of T_n .

Applying Theorem 1, we get the following interesting results.

COROLLARY 1. *Let $(A_n^m)_{ii}, m = 1, 2, \dots$, denote the i th diagonal elements of matrices A_n^m . Under the conditions of Theorem 1 for $\mathbf{x}_n = \mathbf{e}_{ni}$, it follows that for any fixed m ,*

$$\lim_{n \rightarrow \infty} \left| (A_n^m)_{ii} - \int x^m dF^{c,H}(x) \right| \rightarrow 0 \quad a.s.,$$

where \mathbf{e}_{ni} is the n -vector with i th element 1 and all others 0.

REMARK 2. If $T_n = bI$ for some positive constant b or, more generally, $\lambda_{\max}(T_n) - \lambda_{\min}(T_n) \rightarrow 0$, then there is a better result, that is,

$$(1.9) \quad \lim_{n \rightarrow \infty} \max_i \left| (A_n^m)_{ii} - \int x^m dF^{c,H}(x) \right| \rightarrow 0 \quad a.s.$$

[The corollary follows easily from Theorem 1. The uniform convergence of (1.9) follows from the uniform convergence of condition (3) of Theorem 1 and by careful checking of the proof of Theorem 1.]

More generally, we have the following:

COROLLARY 2. *If $f(x)$ is a bounded function and the assumptions of Theorem 1 are satisfied, then*

$$\sum_{j=1}^n |y_j^2| f(\lambda_j) - \frac{1}{n} \sum_{j=1}^n f(\lambda_j) \rightarrow 0 \quad a.s.$$

REMARK 3. The proof of the above corollaries are immediate. Applying Corollary 2, Theorem 1 of [10] can be extended to a more general case without difficulty.

THEOREM 2. *In addition to the conditions of Theorem 1, we further assume that:*

(4) g_1, \dots, g_k are defined and analytic on an open region \mathcal{D} of the complex plane which contains the real interval

$$(1.10) \quad \left[\liminf_n \lambda_{\min}^{T_n} I_{(0,1)}(c)(1 - \sqrt{c})^2, \limsup_n \lambda_{\max}^{T_n} (1 + \sqrt{c})^2 \right]$$

and

(5)

$$\sup_z \sqrt{N} \left| x_n^* (\underline{m}_{F^{c_n, H_n}}(z) T_n + I)^{-1} x_n - \int \frac{1}{\underline{m}_{F^{c_n, H_n}}(z)t + 1} dH_n(t) \right| \rightarrow 0$$

as $n \rightarrow \infty$.

Then the following conclusions hold:

(a) The random vectors

$$(1.11) \quad \left(\int g_1(x) dG_n(x), \dots, \int g_k(x) dG_n(x) \right)$$

form a tight sequence.

(b) If X_{11} and T_n are real and $EX_{11}^4 = 3$, then the above random vector converges weakly to a Gaussian vector X_{g_1}, \dots, X_{g_k} with mean zero and covariance function

$$(1.12) \quad \begin{aligned} & \text{Cov}(X_{g_1}, X_{g_2}) \\ &= -\frac{1}{2\pi^2} \int_{\mathcal{C}_1} \int_{\mathcal{C}_2} g_1(z_1)g_2(z_2) \\ & \quad \times \frac{(z_2\underline{m}(z_2) - z_1\underline{m}(z_1))^2}{c^2 z_1 z_2 (z_2 - z_1)(\underline{m}(z_2) - \underline{m}(z_1))} dz_1 dz_2. \end{aligned}$$

The contours \mathcal{C}_1 and \mathcal{C}_2 in the above equation are disjoint, are both contained in the analytic region for the functions (g_1, \dots, g_k) and both enclose the support of F^{c_n, H_n} for all large n .

(c) If X_{11} is complex with $EX_{11}^2 = 0$ and $E|X_{11}|^4 = 2$, then the conclusions (a) and (b) still hold, but the covariance function reduces to half of the quantity given in (1.12).

REMARK 4. If $T_n = bI$ for some positive constant b or, more generally, $\sqrt{n}(\lambda_{\max}(T_n) - \lambda_{\min}(T_n)) \rightarrow 0$, then condition (5) holds uniformly for all $\mathbf{x}_n \in \mathbb{C}_1^n$.

REMARK 5. Indeed, we can also establish the central limit theorem for $\hat{X}_n(g)$ according to Theorem 1.1 of [7] and Theorem 2. Beside Theorem 2, which holds for more general functions $g(x)$, the following theorem reveals more similarities between the process $Y_n(t)$ and the BB.

THEOREM 3. Beside the assumptions of Theorem 2, if $H(x)$ satisfies

$$(1.13) \quad \int \frac{dH(t)}{(1 + t\underline{m}(z_1))(1 + t\underline{m}(z_2))} - \int \frac{dH(t)}{(1 + t\underline{m}(z_1))} \int \frac{dH(t)}{(1 + t\underline{m}(z_2))} = 0,$$

then all results of Theorem 2 remain true. Moreover, formula (1.12) can be simplified to

$$(1.14) \quad \begin{aligned} \text{Cov}(X_{g_1}, X_{g_2}) &= \frac{2}{c} \left(\int g_1(x)g_2(x) dF^{c,H}(x) \right. \\ & \quad \left. - \int g_1(x_1) dF^{c,H}(x_1) \int g_2(x_2) dF^{c,H}(x_2) \right). \end{aligned}$$

REMARK 6. Obviously, (1.13) holds when $T_n = bI$. Actually, (1.13) holds if and only if $H(x)$ is a degenerate distribution. To see this, one need only choose z_2 to be the complex conjugate of z_1 .

REMARK 7. Theorem 3 extends the theorem of Silverstein [15]. First, one sees that the r th moment of $F_1^{A_n}(x)$ is $x_n^* A_n^r x_n$, which is a special case with $g(x) = x^r$. Then applying Theorem 3 with $T_n = bI$ and combining with Theorem 1.1 of [7], one can obtain the sufficient part of (a) in the theorem of Silverstein [15]. Actually, for $T_n = I$, formula (1.12) can be simplified to

$$(1.15) \quad \text{Cov}(X_{g_1}, X_{g_2}) = \frac{2}{c} \left(\int g_1(x)g_2(x) dF_c(x) - \int g_1(x_1) dF_c(x_1) \int g_2(x_2) dF_c(x_2) \right),$$

where $F_c(x)$ is a special case of $F^{c,H}(x)$, as $T_n = I$.

The organization of the rest of the paper is as follows. In the next section, we complete the proof of Theorem 1. The proof of Theorem 2 is converted to an intermediate Lemma 2, given in Section 3. Sections 4 and 5 contain the proof of Lemma 2. Theorem 3 and some comparisons with the results of [15] are given in Section 6. A truncation lemma (Lemma 4) is postponed to Section 7.

2. Proof of Theorem 1. Without loss of generality, we assume that $\|T_n\| \leq 1$, where $\|\cdot\|$ denotes the spectral norm on the matrices, that is, their largest singular values. Throughout this paper, K denotes a universal constant which may take different values at different appearances.

LEMMA 1. (Lemma 2.7 in [5]). *Let $X = (X_1, \dots, X_n)$, where X_j 's are i.i.d. complex random variables with zero mean and unit variance. Let B be a deterministic $n \times n$ complex matrix. Then for any $p \geq 2$, we have*

$$E|X^*BX - \text{tr} B|^p \leq K_p((E|X_1|^4 \text{tr} BB^*)^{p/2} + E|X_1|^{2p} \text{tr}(BB^*)^{p/2}).$$

For $K > 0$, let $\tilde{X}_{ij} = X_{ij}I(|X_{ij}| \leq K) - EX_{ij}I(|X_{ij}| \leq K)$ and $\tilde{A}_n = \frac{1}{N}T_n^{1/2}\tilde{X}_n\tilde{X}_n^*T_n^{1/2}$, where $\tilde{X}_n = (\tilde{X}_{ij})$. Let $v = \Im z > 0$. Since $X_{ij} - \tilde{X}_{ij} = X_{ij}I(|X_{ij}| > K) - EX_{ij}I(|X_{ij}| > K)$ and $\|(A_n - zI)^{-1}\|$ is bounded by $\frac{1}{v}$, by Theorem 3.1 in [22], we have

$$\begin{aligned} & |x_n^*(A_n - zI)^{-1}x_n - x_n^*(\tilde{A}_n - zI)^{-1}x_n| \\ & \leq \|(A_n - zI)^{-1} - (\tilde{A}_n - zI)^{-1}\| \\ & \leq \|(A_n - zI)^{-1}\| \|(A_n - \tilde{A}_n)\| \|(\tilde{A}_n - zI)^{-1}\| \end{aligned}$$

$$\begin{aligned} &\leq \frac{1}{Nv^2}(\|X_n - \tilde{X}_n\| \|X_n^*\| + \|\tilde{X}_n\| \|X_n^* - \tilde{X}_n^*\|) \\ &\rightarrow \frac{(1 + \sqrt{c})^2}{v^2} [E^{1/2}|X_{11} - \tilde{X}_{11}|^2 (E^{1/2}|\tilde{X}_{11}|^2 + E^{1/2}|X_{11}|^2)] \quad \text{a.s.} \\ &\leq \frac{2(1 + \sqrt{c})^2}{v^2} E^{1/2}|X_{11}|^2 I(|X_{11}| > K). \end{aligned}$$

The above bound can be made arbitrarily small by choosing K sufficiently large. Since $\lim_{n \rightarrow \infty} E|\tilde{X}_{11}|^2 = 1$, the rescaling of \tilde{X}_{ij} can be dealt with similarly. Hence, in the sequel, it is enough to assume that $|X_{ij}| \leq K$, $EX_{11} = 0$ and $E|X_{11}|^2 = 1$ (for simplicity, suppressing all super- and subscripts on the variables X_{ij}).

Next, we will show that

$$(2.1) \quad \mathbf{x}_n^*(A_n - zI)^{-1}\mathbf{x}_n - \mathbf{x}_n^*E(A_n - zI)^{-1}\mathbf{x}_n \rightarrow 0 \quad \text{a.s.}$$

Let \mathbf{s}_j denote the j th column of $\frac{1}{\sqrt{N}}T_n^{1/2}X_n$, $A(z) = A_n - zI$, $A_j(z) = A(z) - \mathbf{s}_j\mathbf{s}_j^*$,

$$\begin{aligned} \alpha_j(z) &= \mathbf{s}_j^*A_j^{-1}(z)\mathbf{x}_n\mathbf{x}_n^*(E\underline{m}_n(z)T_n + I)^{-1}\mathbf{s}_j \\ &\quad - \frac{1}{N}\mathbf{x}_n^*(E\underline{m}_n(z)T_n + I)^{-1}T_nA_j^{-1}(z)\mathbf{x}_n, \\ \xi_j(z) &= \mathbf{s}_j^*A_j^{-1}(z)\mathbf{s}_j - \frac{1}{N}\text{tr}T_nA_j^{-1}(z), \\ \gamma_j &= \mathbf{s}_j^*A_j^{-1}(z)\mathbf{x}_n\mathbf{x}_n^*A_j^{-1}(z)\mathbf{s}_j - \frac{1}{N}\mathbf{x}_n^*A_j^{-1}(z)T_nA_j^{-1}(z)\mathbf{x}_n \end{aligned}$$

and

$$\beta_j(z) = \frac{1}{1 + \mathbf{s}_j^*A_j^{-1}(z)\mathbf{s}_j}, \quad b_j(z) = \frac{1}{1 + N^{-1}\text{tr}T_nA_j^{-1}(z)}.$$

Noting that $|\beta_j(z)| \leq |z|/v$ and $\|A_j^{-1}(z)\| \leq 1/v$, by Lemma 1, we have

$$(2.2) \quad E|\mathbf{s}_j^*A_j^{-1}(z)\mathbf{x}_n\mathbf{x}_n^*A_j^{-1}(z)\mathbf{s}_j|^r = O\left(\frac{1}{N^r}\right), \quad E|\xi_j(z)|^r = O\left(\frac{1}{N^{r/2}}\right).$$

Define the σ -field $\mathcal{F}_j = \sigma(\mathbf{s}_1, \dots, \mathbf{s}_j)$, let $E_j(\cdot)$ denote conditional expectation given the σ -field \mathcal{F}_j and let $E_0(\cdot)$ denote the unconditional expectation. Note that

$$\begin{aligned} &\mathbf{x}_n^*(A_n - zI)^{-1}\mathbf{x}_n - \mathbf{x}_n^*E(A_n - zI)^{-1}\mathbf{x}_n \\ &= \sum_{j=1}^N \mathbf{x}_n^*E_jA^{-1}(z)\mathbf{x}_n - \mathbf{x}_n^*E_{j-1}A^{-1}(z)\mathbf{x}_n \end{aligned} \tag{2.3}$$

$$\begin{aligned}
 &= \sum_{j=1}^N \mathbf{x}_n^* E_j (A^{-1}(z) - A_j^{-1}(z)) \mathbf{x}_n - \mathbf{x}_n^* E_{j-1} (A^{-1}(z) - A_j^{-1}(z)) \mathbf{x}_n \\
 &= - \sum_{j=1}^N (E_j - E_{j-1}) \beta_j(z) \mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j \\
 &= - \sum_{j=1}^N E_j b_j(z) \gamma_j(z) \\
 &\quad - (E_j - E_{j-1}) \mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j \beta_j(z) b_j(z) \xi_j(z).
 \end{aligned}$$

By the fact that $|\frac{1}{1+\mathbf{s}_j^* A_j^{-1}(z) \mathbf{s}_j}| \leq \frac{|z|}{v}$ and use of the Burkholder inequality, (2.2) and the martingale expression (2.3), we have

$$\begin{aligned}
 &E |\mathbf{x}_n^* (A_n - zI)^{-1} \mathbf{x}_n - \mathbf{x}_n^* E (A_n - zI)^{-1} \mathbf{x}_n|^r \\
 &\leq E \left[\sum_{j=1}^N E_{j-1} |(E_j - E_{j-1}) \beta_j(z) \mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j|^2 \right]^{r/2} \\
 &\quad + E \sum_{j=1}^N |(E_j - E_{j-1}) \beta_j(z) \mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j|^r \\
 &\leq E \left[\sum_{j=1}^N \frac{K|z|^2}{v^2} E_{j-1} |\gamma_j(z)|^2 + E_{j-1} |\mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j \xi_j(z)|^2 \right]^{r/2} \\
 &\quad + \sum_{j=1}^N \frac{K|z|^r}{v^r} E |\mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j|^r \\
 &\leq K [N^{-r/2} + N^{-r+1}].
 \end{aligned}$$

Thus (2.1) follows from Borel–Cantelli lemma, by taking $r > 2$.

Write

$$A(z) - (-z E \underline{m}_n(z) T_n - zI) = \sum_{j=1}^N \mathbf{s}_j \mathbf{s}_j^* - (-z E \underline{m}_n(z)) T_n.$$

Using the identities

$$\mathbf{s}_j^* A^{-1}(z) = \beta_j(z) \mathbf{s}_j^* A_j^{-1}(z)$$

and

$$(2.4) \quad \underline{m}_n(z) = -\frac{1}{zN} \sum_{j=1}^N \beta_j(z)$$

(see (2.2) of [13]), we obtain

$$\begin{aligned} & EA^{-1}(z) - (-zE\underline{m}_n(z)T_n - zI)^{-1} \\ &= (zE\underline{m}_n(z)T_n + zI)^{-1} E \left[\sum_{j=1}^N \mathbf{s}_j \mathbf{s}_j^* - (-zE\underline{m}_n(z))T_n A^{-1}(z) \right] \\ &= \frac{1}{z} \sum_{j=1}^N E\beta_j(z) \left[(E\underline{m}_n(z)T_n + I)^{-1} \mathbf{s}_j \mathbf{s}_j^* A_j^{-1}(z) \right. \\ &\quad \left. - \frac{1}{N} (E\underline{m}_n(z)T_n + I)^{-1} T_n EA^{-1}(z) \right]. \end{aligned}$$

Multiplying by \mathbf{x}_n^* on the left and \mathbf{x}_n on the right, we have

$$\begin{aligned} & \mathbf{x}_n^* EA^{-1}(z)\mathbf{x}_n - \mathbf{x}_n^* (-zE\underline{m}_n(z)T_n - zI)^{-1} \mathbf{x}_n \\ &= N \frac{1}{z} E\beta_1(z) \left[\mathbf{s}_1^* A_1^{-1}(z)\mathbf{x}_n \mathbf{x}_n^* (E\underline{m}_n(z)T_n + I)^{-1} \mathbf{s}_1 \right. \\ (2.5) \quad & \left. - \frac{1}{N} \mathbf{x}_n^* (E\underline{m}_n(z)T_n + I)^{-1} T_n EA^{-1}(z)\mathbf{x}_n \right] \\ & \triangleq \delta_1 + \delta_2 + \delta_3, \end{aligned}$$

where

$$\begin{aligned} \delta_1 &= \frac{N}{z} E\beta_1(z)\alpha_1(z), \\ \delta_2 &= \frac{1}{z} E\beta_1(z)\mathbf{x}_n^* (E\underline{m}_n(z)T_n + I)^{-1} T_n (A_1^{-1}(z) - A^{-1}(z))\mathbf{x}_n, \\ \delta_3 &= \frac{1}{z} E\beta_1(z)\mathbf{x}_n^* (E\underline{m}_n(z)T_n + I)^{-1} T_n (A^{-1}(z) - EA^{-1}(z))\mathbf{x}_n. \end{aligned}$$

Similar to (2.2), by Lemma 1, for $r \geq 2$, we have

$$E|\alpha_j(z)|^r = O\left(\frac{1}{N^r}\right).$$

Therefore,

$$(2.6) \quad \delta_1 = -\frac{N}{z} Eb_1(z)\beta_1(z)\xi_1(z)\alpha_1(z) = O(N^{-3/2}).$$

It follows that

$$\begin{aligned} & |\delta_2| = \frac{1}{|z|} \left| E\beta_1^2(z)\mathbf{x}_n^* (E\underline{m}_n(z)T_n + I)^{-1} T_n A_1^{-1}(z)\mathbf{s}_1 \mathbf{s}_1^* A_1^{-1}(z)\mathbf{x}_n \right| \\ (2.7) \quad & \leq K \left(|E|\mathbf{x}_n^* (E\underline{m}_n(z)T_n + I)^{-1} T_n A_1^{-1}(z)\mathbf{s}_1|^2 E|\mathbf{s}_1^* A_1^{-1}(z)\mathbf{x}_n|^2 \right)^{1/2} \\ & = O(N^{-1}) \end{aligned}$$

and

$$\begin{aligned}
 |\delta_3| &= \frac{1}{|z|} |E\beta_1(z)b_1(z)\xi_1(z)\mathbf{x}_n^*(E\underline{m}_n(z)T_n + I)^{-1} \\
 &\quad \times T_n(A^{-1}(z) - EA^{-1}(z))\mathbf{x}_n| \\
 (2.8) \quad &\leq K(E|\xi_1(z)|^2 E|\mathbf{x}_n^*(E\underline{m}_n(z)T_n + I)^{-1} \\
 &\quad \times T_n(A^{-1}(z) - EA^{-1}(z))\mathbf{x}_n|^2)^{1/2} \\
 &= o(N^{-1/2}),
 \end{aligned}$$

where to estimate the second factor, we need to use the martingale decomposition of $A^{-1}(z) - EA^{-1}(z)$.

Combining the above three results and (2.5), we conclude that

$$(2.9) \quad \mathbf{x}_n^*EA^{-1}(z)\mathbf{x}_n - \mathbf{x}_n^*(-zE\underline{m}_n(z)T_n - zI)^{-1}\mathbf{x}_n \rightarrow 0.$$

In [13], it is proved that, under the conditions of Theorem 1, $E\underline{m}_n(z) \rightarrow \underline{m}(z)$, which is the solution of equation (1.2), and we then conclude that

$$\mathbf{x}_n^*EA^{-1}(z)\mathbf{x}_n - \mathbf{x}_n^*(-z\underline{m}(z)T_n - zI)^{-1}\mathbf{x}_n \rightarrow 0.$$

By condition (3) of Theorem 1, we finally obtain that

$$\mathbf{x}_n^*EA^{-1}(z)\mathbf{x}_n \rightarrow \int \frac{dH(t)}{-z\underline{m}t - z},$$

which completes the proof of Theorem 1.

3. An intermediate lemma. In the sequel, we will follow the work of Bai and Silverstein [7]. To complete the proof of Theorem 2, we need an intermediate lemma.

Write

$$M_n(z) = \sqrt{N}(m_{F_1^{A_n}}(z) - m_{F^{c_n, H_n}}(z)),$$

which is defined on a contour \mathcal{C} in the complex plane, described as follows. Let u_r be a number which is greater than the right endpoint of interval (1.10) and let u_l be a negative number if the left endpoint of interval (1.10) is zero, otherwise let $u_l \in (0, \liminf_n \lambda_{\min}^{T_n} I_{(0,1)}(c)(1 - \sqrt{c})^2)$. Let $v_0 > 0$ be arbitrary. Define

$$\mathcal{C}_u = \{u + iv_0 : u \in [u_l, u_r]\}.$$

Then the contour

$$\begin{aligned}
 \mathcal{C} &= \mathcal{C}_u \cup \{u_l + iv : v \in [0, v_0]\} \cup \{u_r + iv : v \in [0, v_0]\} \\
 &\quad \cup \{\text{their symmetric parts below the real axis}\}.
 \end{aligned}$$

Under the conditions of Theorem 2, for later use, we may select the contour \mathcal{C} in the region on which the functions g are analytic.

As in [7], due to technical difficulties, we will consider $M_n^*(z)$, a truncated version of $M_n(z)$. Choose a sequence of positive numbers $\{\delta_n\}$ such that for $0 < \rho < 1$,

$$(3.1) \quad \delta_n \downarrow 0, \quad \delta_n \geq n^{-\rho}.$$

Write

$$\mathcal{C}_l = \begin{cases} \{u_l + iv : v \in [n^{-1}\delta_n, v_0]\}, & \text{if } u_l > 0, \\ \{u_l + iv : v \in [0, v_0]\}, & \text{if } u_l < 0, \end{cases}$$

and

$$\mathcal{C}_r = \{u_r + iv : v \in [n^{-1}\delta_n, v_0]\}.$$

Let $\mathcal{C}_0 = \mathcal{C}_u \cup \mathcal{C}_l \cup \mathcal{C}_r$. Now, for $z = u + iv$, we can define the process

$$M_n^*(z) = \begin{cases} M_n(z), & \text{if } z \in \mathcal{C}_0 \cup \bar{\mathcal{C}}_0, \\ \frac{nv + \delta_n}{2\delta_n} M_n(u_r + in^{-1}\delta_n) + \frac{\delta_n - nv}{2\delta_n} M_n(u_r - in^{-1}\delta_n), & \text{if } u = u_r, v \in [-n^{-1}\delta_n, n^{-1}\delta_n], \\ \frac{nv + \delta_n}{2\delta_n} M_n(u_l + in^{-1}\delta_n) + \frac{\delta_n - nv}{2\delta_n} M_n(u_l - in^{-1}\delta_n), & \text{if } u = u_l > 0, v \in [-n^{-1}\delta_n, n^{-1}\delta_n]. \end{cases}$$

$M_n^*(z)$ can be viewed as a random element in the metric space $C(\mathcal{C}, \mathbb{R}^2)$ of continuous functions from \mathcal{C} to \mathbb{R}^2 . We shall prove the following lemma.

LEMMA 2. *Under the assumptions of Theorem 1 and assumptions (4) and (5) of Theorem 2, $M_n^*(z)$ forms a tight sequence on \mathcal{C} . Furthermore, when the conditions in (b) and (c) of Theorem 2 on X_{11} hold, for $z \in \mathcal{C}$, $M_n^*(z)$ converges to a Gaussian process $M(\cdot)$ with zero mean and for $z_1, z_2 \in \mathcal{C}$, under the assumptions in (b),*

$$(3.2) \quad \text{Cov}(M(z_1), M(z_2)) = \frac{2(z_2 \underline{m}(z_2) - z_1 \underline{m}(z_1))^2}{c^2 z_1 z_2 (z_2 - z_1) (\underline{m}(z_2) - \underline{m}(z_1))},$$

while under the assumptions in (c), the covariance function similar to (3.2) is the half of the value of (3.2).

Similar to the approach of [7], to prove Theorem 2, it suffices to prove Lemma 2. Before proceeding with the detailed proof of the lemma, we need to truncate, re-centralize and renormalize the variables X_{ij} . However, those procedures are purely

technical (and tedious), thus we shall postpone then to the last section of the paper. Now, according to Lemma 4, we further assume that the underlying variables satisfy the following additional conditions:

$$|X_{ij}| \leq \varepsilon_n n^{1/4}, \quad EX_{11} = 0, \quad E|X_{11}|^2 = 1, \quad E|X_{11}|^4 < \infty$$

and

$$\begin{cases} E|X_{11}|^4 = 3 + o(1), \\ \text{if assumption (b) of Theorem 2 is satisfied,} \\ EX_{11}^2 = o(n^{-1/2}), \quad E|X_{11}|^4 = 2 + o(1), \\ \text{if assumption (c) of Theorem 2 is satisfied.} \end{cases}$$

Here, ε_n is a sequence of positive numbers which converges to zero.

The proof of Lemma 2 will be given in the next two sections.

4. Convergence in finite dimensions. For $z \in \mathbb{C}_0$, let

$$M_n^1(z) = \sqrt{N}(m_{F_1^{A_n}}(z) - Em_{F_1^{A_n}}(z))$$

and

$$M_n^2(z) = \sqrt{N}(Em_{F_1^{A_n}}(z) - m_{F^{c_n, H_n}}(z)).$$

Then

$$M_n(z) = M_n^1(z) + M_n^2(z).$$

In this section for any positive integer r and complex numbers a_1, \dots, a_r , we will show that

$$\sum_{i=1}^r a_i M_n^1(z_i) \quad (\Im z_i \neq 0)$$

converges in distribution to a Gaussian random variable and will derive the covariance function (3.2). To this end, we employ the notation introduced in Section 2.

Before proceeding with the proofs, we first recall some known facts and results.

1. (See [7].) Let $Y = (Y_1, \dots, Y_n)$, where Y_i 's are i.i.d. complex random variables with mean zero and variance 1. Let $A = (a_{ij})_{n \times n}$ and $B = (b_{ij})_{n \times n}$ be complex matrices. Then the following identity holds:

$$\begin{aligned} (4.1) \quad & E(Y^*AY - \text{tr } A)(Y^*BY - \text{tr } B) \\ &= (E|Y_1|^4 - |EY_1^2|^2 - 2) \sum_{i=1}^n a_{ii}b_{ii} + |EY_1^2|^2 \text{tr } AB^T + \text{tr } AB. \end{aligned}$$

2. (See Theorem 35.12 of [9].)

LEMMA 3. Suppose that for each n , $Y_{n1}, Y_{n2}, \dots, Y_{nr_n}$ is a real martingale difference sequence with respect to the increasing σ -field $\{\mathcal{F}_{nj}\}$ having second moments. If, as $n \rightarrow \infty$, we have

$$(i) \quad \sum_{j=1}^{r_n} E(Y_{nj}^2 | \mathcal{F}_{n,j-1}) \xrightarrow{i.p.} \sigma^2,$$

where σ^2 is a positive constant and for each $\varepsilon > 0$,

$$(ii) \quad \sum_{j=1}^{r_n} E(Y_{nj}^2 I_{(|Y_{nj}| \geq \varepsilon)}) \rightarrow 0,$$

then

$$\sum_{j=1}^{r_n} Y_{nj} \xrightarrow{\mathcal{D}} N(0, \sigma^2).$$

3. Some simple results follow by using the truncation and centralization steps described in Lemma 4 given in the Appendix:

$$(4.2) \quad \begin{aligned} E|\mathbf{s}_1^* C \mathbf{s}_1 - N^{-1} \text{tr } T_n C|^p &\leq K_p \|C\|^p (\varepsilon_n^{2p-4} N^{-p/2} + N^{-p/2}) \\ &\leq K_p \|C\|^p N^{-p/2}, \end{aligned}$$

$$(4.3) \quad E|\mathbf{s}_1^* C \mathbf{x}_n \mathbf{x}_n^* D \mathbf{s}_1 - N^{-1} \mathbf{x}_n^* D T_n C \mathbf{x}_n|^p \leq K_p \|C\|^p \|D\|^p \varepsilon_n^{2p-4} N^{-p/2-1},$$

$$(4.4) \quad E|\mathbf{s}_1^* C \mathbf{x}_n \mathbf{x}_n^* D \mathbf{s}_1|^p \leq K_p \|C\|^p \|D\|^p \varepsilon_n^{2p-4} N^{-p/2-1}.$$

Let $v = \Im z$. To facilitate the analysis, we will assume that $v > 0$. By (2.3), we have

$$\begin{aligned} &\sqrt{N}(m_{F_1^{A_n}}(z) - Em_{F_1^{A_n}}(z)) \\ &= -\sqrt{N} \sum_{j=1}^N (E_j - E_{j-1}) \beta_j(z) \mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j. \end{aligned}$$

Since

$$\beta_j(z) = b_j(z) - \beta_j(z) b_j(z) \xi_j(z) = b_j(z) - b_j^2(z) \xi_j(z) + b_j^2(z) \beta_j(z) \xi_j^2(z),$$

we get

$$\begin{aligned} &(E_j - E_{j-1}) \beta_j(z) \mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j \\ &= E_j b_j(z) \gamma_j(z) - E_j \left(b_j^2(z) \xi_j(z) \frac{1}{N} \mathbf{x}_n^* A_j^{-1}(z) T_n A_j^{-1}(z) \mathbf{x}_n \right) \\ &\quad + (E_j - E_{j-1}) (b_j^2(z) \beta_j(z) \xi_j^2(z) \mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j \\ &\quad \quad \quad - b_j^2(z) \xi_j(z) \gamma_j(z)). \end{aligned}$$

Applying (4.2), we obtain

$$\begin{aligned} & E \left| \sqrt{N} \sum_{j=1}^N E_j \left(b_j^2(z) \xi_j(z) \frac{1}{N} \mathbf{x}_n^* A_j^{-1}(z) T_n A_j^{-1}(z) \mathbf{x}_n \right) \right|^2 \\ &= \frac{1}{N} \sum_{j=1}^N E |E_j(b_j^2(z) \xi_j(z) \mathbf{x}_n^* A_j^{-1}(z) T_n A_j^{-1}(z) \mathbf{x}_n)|^2 \\ &\leq K \frac{|z|^4}{v^8} E |\xi_1(z)|^2 = O(N^{-1}), \end{aligned}$$

which implies that $\sqrt{N} \sum_{j=1}^N E_j(b_j^2(z) \xi_j(z) \frac{1}{N} \mathbf{x}_n^* A_j^{-1}(z) T_n A_j^{-1}(z) \mathbf{x}_n) \xrightarrow{i.p.} 0$.

By (4.2), (4.4) and Hölder’s inequality, we have

$$\begin{aligned} & E \left| \sqrt{N} \sum_{j=1}^N (E_j - E_{j-1}) b_j^2(z) \beta_j(z) \xi_j^2(z) \mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j \right|^2 \\ &\leq K \left(\frac{|z|}{v} \right)^6 N^2 \left(E |\xi_1^4(z)| |\gamma_1^2(z)| + \frac{1}{N^2} E |\xi_1^4(z)| |\mathbf{x}_n^* A_1^{-1}(z) T_n A_1^{-1}(z) \mathbf{x}_n|^2 \right) \\ &= O(N^{-3/2}), \end{aligned}$$

which implies that

$$\sqrt{N} \sum_{j=1}^N (E_j - E_{j-1}) b_j^2(z) \beta_j(z) \xi_j^2(z) \mathbf{s}_j^* A_j^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z) \mathbf{s}_j \xrightarrow{i.p.} 0.$$

Using a similar argument, we have

$$\sqrt{N} \sum_{j=1}^N (E_j - E_{j-1}) b_j^2(z) \xi_j(z) \gamma_j(z) \xrightarrow{i.p.} 0.$$

The estimate above (4.3) of [5], (2.17) of [7] and (4.3) collectively yield that

$$\begin{aligned} & E |(b_j(z) + z \underline{m}(z)) \gamma_j(z)|^2 \\ &= E [E(|(b_j(z) + z \underline{m}(z)) \gamma_j(z)|^2 | \sigma(\mathbf{s}_i, i \neq j))] \\ &= E [|(b_j(z) + z \underline{m}(z))|^2 E(|\gamma_j(z)|^2 | \sigma(\mathbf{s}_i, i \neq j))] = o(N^{-2}), \end{aligned}$$

which gives

$$\sqrt{N} \sum_{j=1}^N E_j [(b_j(z) + z \underline{m}(z)) \gamma_j(z)] \xrightarrow{i.p.} 0.$$

Note that the above results also hold when $\Im z \leq -v_0$, by symmetry. Hence for finite-dimensional convergence, we need only consider the sum

$$\sum_{i=1}^r a_i \sum_{j=1}^N Y_j(z_i) = \sum_{j=1}^N \sum_{i=1}^r a_i Y_j(z_i),$$

where $Y_j(z_i) = -\sqrt{N} z_i \underline{m}(z_i) E_j \gamma_j(z_i)$. Since

$$E|Y_j(z_i)|^4 = O(\varepsilon_n^4 N^{-1}),$$

we have

$$\sum_{j=1}^N E \left(\left| \sum_{i=1}^r a_i Y_j(z_i) \right|^2 I \left(\left| \sum_{i=1}^r a_i Y_j(z_i) \right| \geq \varepsilon \right) \right) \leq \frac{1}{\varepsilon^2} \sum_{j=1}^N E \left| \sum_{i=1}^r a_i Y_j(z_i) \right|^4 = O(\varepsilon_n^4).$$

Thus condition (ii) of Lemma 3 is satisfied.

Now, we only need to show that for $z_1, z_2 \in \mathbb{C} \setminus \mathbb{R}$,

$$(4.5) \quad \sum_{j=1}^N E_{j-1}(Y_j(z_1)Y_j(z_2))$$

converges in probability to a constant under the assumptions in (b) or (c). It is easy to verify that

$$(4.6) \quad |\text{tr} E_j(A_j^{-1}(z_1)\mathbf{x}_n\mathbf{x}_n^*A_j^{-1}(z_1))T_n E_j(A_j^{-1}(z_2)\mathbf{x}_n\mathbf{x}_n^*A_j^{-1}(z_2))T_n| \leq \frac{1}{|v_1 v_2|^2},$$

where $v_1 = \Im(z_1)$ and $v_2 = \Im(z_2)$. It follows that, for the complex case, applying (4.1), (4.5) now becomes

$$(4.7) \quad \begin{aligned} & z_1 z_2 \underline{m}(z_1)\underline{m}(z_2) \frac{1}{N} \sum_{j=1}^N E_{j-1} \text{tr} E_j(A_j^{-1}(z_1)\mathbf{x}_n\mathbf{x}_n^*A_j^{-1}(z_1))T_n \\ & \quad \times E_j(A_j^{-1}(z_2)\mathbf{x}_n\mathbf{x}_n^*A_j^{-1}(z_2))T_n + o_p(1) \\ & = z_1 z_2 \underline{m}(z_1)\underline{m}(z_2) \frac{1}{N} \sum_{j=1}^N E_{j-1}(\mathbf{x}_n^* A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n) \\ & \quad \times (\mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n A_j^{-1}(z_1) \mathbf{x}_n) + o_p(1), \end{aligned}$$

where $\check{A}_j^{-1}(z_2)$ is defined similarly as $A_j^{-1}(z_2)$ by $(\mathbf{s}_1, \dots, \mathbf{s}_{j-1}, \check{\mathbf{s}}_{j+1}, \dots, \check{\mathbf{s}}_N)$ and where $\check{\mathbf{s}}_{j+1}, \dots, \check{\mathbf{s}}_N$ are i.i.d. copies of $\mathbf{s}_{j+1}, \dots, \mathbf{s}_N$.

For the real case, (4.5) will be twice the magnitude of (4.7).

Write

$$\begin{aligned}
 (4.8) \quad & \mathbf{x}_n^*(A_j^{-1}(z_1) - E_{j-1}A_j^{-1}(z_1))T_n\check{A}_j^{-1}(z_2)\mathbf{x}_n \\
 & = \sum_{t=j}^N \mathbf{x}_n^*(E_tA_j^{-1}(z_1) - E_{t-1}A_j^{-1}(z_1))T_n\check{A}_j^{-1}(z_2)\mathbf{x}_n.
 \end{aligned}$$

From (4.8), we note that

$$\begin{aligned}
 (4.9) \quad & E_{j-1}(\mathbf{x}_n^*A_j^{-1}(z_1)T_n\check{A}_j^{-1}(z_2)\mathbf{x}_n)(\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_nA_j^{-1}(z_1)\mathbf{x}_n) \\
 & = \sum_{t=j}^N E_{j-1}\mathbf{x}_n^*(E_tA_j^{-1}(z_1) - E_{t-1}A_j^{-1}(z_1))T_n\check{A}_j^{-1}(z_2)\mathbf{x}_n\mathbf{x}_n^*\check{A}_j^{-1}(z_2) \\
 & \quad \times T_n(E_tA_j^{-1}(z_1) - E_{t-1}A_j^{-1}(z_1))\mathbf{x}_n \\
 & \quad + E_{j-1}(\mathbf{x}_n^*(E_{j-1}A_j^{-1}(z_1)T_n)\check{A}_j^{-1}(z_2)\mathbf{x}_n) \\
 & \quad \times (\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_n(E_{j-1}A_j^{-1}(z_1))\mathbf{x}_n) \\
 & = E_{j-1}(\mathbf{x}_n^*(E_{j-1}A_j^{-1}(z_1)T_n)\check{A}_j^{-1}(z_2)\mathbf{x}_n) \\
 & \quad \times (\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_n(E_{j-1}A_j^{-1}(z_1))\mathbf{x}_n) + O(N^{-1}),
 \end{aligned}$$

where we have used the fact that

$$\begin{aligned}
 & |E_{j-1}\mathbf{x}_n^*(E_tA_j^{-1}(z_1) - E_{t-1}A_j^{-1}(z_1)) \\
 & \quad \times T_n\check{A}_j^{-1}(z_2)\mathbf{x}_n\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_n(E_tA_j^{-1}(z_1) - E_{t-1}A_j^{-1}(z_1))\mathbf{x}_n| \\
 & \leq 4(|E_{j-1}|\beta_{tj}(z_1)\mathbf{x}_n^*(A_{tj}^{-1}(z_1)\mathbf{s}_t\mathbf{s}_t^*(A_{tj}^{-1}(z_1)T_n\check{A}_j^{-1}(z_2)\mathbf{x}_n)|^2 \\
 & \quad \times E_{j-1}|\beta_{tj}(z_1)\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_n(A_{tj}^{-1}(z_1)\mathbf{s}_t\mathbf{s}_t^*(A_{tj}^{-1}(z_1))\mathbf{x}_n|^2)^{1/2} = O(N^{-2}).
 \end{aligned}$$

Similarly, one can prove that

$$\begin{aligned}
 & E_{j-1}(\mathbf{x}_n^*(E_{j-1}A_j^{-1}(z_1)T_n)\check{A}_j^{-1}(z_2)\mathbf{x}_n)(\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_n(E_{j-1}A_j^{-1}(z_1))\mathbf{x}_n) \\
 & = E_{j-1}(\mathbf{x}_n^*A_j^{-1}(z_1)T_n\check{A}_j^{-1}(z_2)\mathbf{x}_n) \\
 & \quad \times E_{j-1}(\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_nA_j^{-1}(z_1)\mathbf{x}_n) + O(N^{-1}).
 \end{aligned}$$

Define

$$\begin{aligned}
 A_{ij}(z) & = A(z) - \mathbf{s}_i\mathbf{s}_i^* - \mathbf{s}_j\mathbf{s}_j^*, \quad T^{-1}(z_1) = \left(z_1I - \frac{N-1}{N}b_{n1}(z_1)T_n \right)^{-1}, \\
 \beta_{ij}(z) & = \frac{1}{1 + \mathbf{s}_i^*A_{ij}^{-1}(z)\mathbf{s}_i} \quad \text{and} \quad b_{n1}(z) = \frac{1}{1 + N^{-1}E \operatorname{tr} T_nA_{12}^{-1}(z)}.
 \end{aligned}$$

Then (see (2.9) in [7])

$$(4.10) \quad A_j(z_1) = -T^{-1}(z_1) + b_{n1}(z_1)B_j(z_1) + C_j(z_1) + D_j(z_1),$$

where $B_1(z_1) = B_{j1}(z_1) + B_{j2}(z_1)$,

$$B_{j1}(z_1) = \sum_{i>j} T^{-1}(z_1)(\mathbf{s}_i \mathbf{s}_i^* - N^{-1}T_n)A_{ij}^{-1}(z_1),$$

$$B_{j2}(z_1) = \sum_{i<j} T^{-1}(z_1)(\mathbf{s}_i \mathbf{s}_i^* - N^{-1}T_n)A_{ij}^{-1}(z_1),$$

$$C_j(z_1) = \sum_{i \neq j} (\beta_{ij}(z_1) - b_{n1}(z_1))T^{-1}(z_1)\mathbf{s}_i \mathbf{s}_i^* A_{ij}^{-1}(z_1)$$

and

$$D_j(z_1) = N^{-1}b_{n1}(z_1)T^{-1}(z_1)T_n \sum_{i \neq j} (A_{ij}^{-1}(z_1) - A_j(z_1)).$$

It follows that

$$(4.11) \quad \begin{aligned} & E_{j-1}(\mathbf{x}_n^* A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n) E_{j-1}(\mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n A_j^{-1}(z_1) \mathbf{x}_n) \\ &= -E_{j-1}(\mathbf{x}_n^* A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n) \\ & \quad \times E_{j-1}(\mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n T^{-1}(z_1) T_n \mathbf{x}_n) \\ & \quad + B(z_1, z_2) + C(z_1, z_2) + D(z_1, z_2), \end{aligned}$$

where

$$\begin{aligned} B(z_1, z_2) &= b_{n1}(z_1) E_{j-1}(\mathbf{x}_n^* A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n) \\ & \quad \times E_{j-1}(\mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n B_{j2}(z_1) \mathbf{x}_n), \\ C(z_1, z_2) &= E_{j-1}(\mathbf{x}_n^* A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n) \\ & \quad \times E_{j-1}(\mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n C_j(z_1) \mathbf{x}_n) \end{aligned}$$

and

$$D(z_1, z_2) = E_{j-1}(\mathbf{x}_n^* A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n) (\mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n D_j(z_1) \mathbf{x}_n).$$

We then prove that

$$(4.12) \quad E|C(z_1, z_2)| = o(1) \quad \text{and} \quad E|D(z_1, z_2)| = o(1).$$

Note that although C and D depend on j implicitly, $E|C(z_1, z_2)|$ and $E|D(z_1, z_2)|$ are independent of j since the entries of X_n are i.i.d.

We then have

$$\begin{aligned}
 E|C(z_1, z_2)| &\leq \frac{1}{|v_1 v_2|} E|\mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n C_j(z_1) \mathbf{x}_n| \\
 &\leq \frac{1}{|v_1 v_2|} \sum_{i \neq j} (E|\beta_{ij}(z_1) - b_{n1}(z_1)|^2 \\
 &\quad \times E|\mathbf{s}_i^* A_{ij}^{-1}(z_1) \mathbf{x}_n \mathbf{x}_n^* (\check{A}_j^{-1}(z_2)) T_n T^{-1}(z_1) \mathbf{s}_i|^2)^{1/2}.
 \end{aligned}$$

When $i > j$, \mathbf{s}_i is independent of $\check{A}_j^{-1}(z_2)$. As in the proof of (2.2), we have

$$(4.13) \quad E|\mathbf{s}_i^* A_{ij}^{-1}(z_1) \mathbf{x}_n \mathbf{x}_n^* (\check{A}_j^{-1}(z_2)) T_n T^{-1}(z_1) \mathbf{s}_i|^2 = O(N^{-2}).$$

When $i < j$, by substituting $\check{A}_j^{-1}(z_2)$ for $\check{A}_{ij}^{-1}(z_2) - \check{\beta}_{ij}(z_2) \check{A}_{ij}^{-1}(z_2) \mathbf{s}_i \mathbf{s}_i^* \times \check{A}_{ij}^{-1}(z_2)$, we can also obtain the above inequality. Noting that

$$(4.14) \quad E|\beta_{ij}(z_1) - b_{n1}(z_1)|^2 = E|\beta_{ij}(z_1) b_{n1}(z_1) \xi_{ij}|^2 = O(n^{-1}),$$

where $\xi_{ij}(z) = \mathbf{s}_i^* A_{ij}^{-1}(z) \mathbf{s}_i - \frac{1}{N} \text{tr} A_{ij}^{-1}(z)$ and $\check{\beta}_{ij}(z_2)$ is defined similarly to $\beta_{ij}(z_2)$, and combining (4.13)–(4.14), we conclude that

$$E|C(z_1, z_2)| = o(1).$$

The argument for $D(z_1, z_2)$ is similar to that of $C(z_1, z_2)$, only simpler, and is therefore omitted. Hence, (4.12) holds.

Next, write

$$(4.15) \quad B(z_1, z_2) = B_1(z_1, z_2) + B_2(z_1, z_2) + B_3(z_1, z_2),$$

where

$$\begin{aligned}
 B_1(z_1, z_2) &= \sum_{i < j} b_{n1}(z_1) E_{j-1} \mathbf{x}_n^* \beta_{ij}(z_1) A_{ij}^{-1}(z_1) \mathbf{s}_i \mathbf{s}_i^* A_{ij}^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n \\
 &\quad \times E_{j-1} \mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n T^{-1}(z_1) (\mathbf{s}_i \mathbf{s}_i^* - N^{-1} T_n) A_{ij}^{-1}(z_1) \mathbf{x}_n, \\
 B_2(z_1, z_2) &= \sum_{i < j} b_{n1}(z_1) E_{j-1} \mathbf{x}_n^* A_{ij}^{-1}(z_1) T_n \check{A}_{ij}^{-1}(z_2) \mathbf{s}_i \mathbf{s}_i^* \check{A}_{ij}^{-1}(z_2) \check{\beta}_{ij}(z_2) \mathbf{x}_n \\
 &\quad \times E_{j-1} \mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n T^{-1}(z_1) (\mathbf{s}_i \mathbf{s}_i^* - N^{-1} T_n) A_{ij}^{-1}(z_1) \mathbf{x}_n
 \end{aligned}$$

and

$$\begin{aligned}
 B_3(z_1, z_2) &= \sum_{i < j} b_{n1}(z_1) E_{j-1} \mathbf{x}_n^* A_{ij}^{-1}(z_1) T_n \check{A}_{ij}^{-1}(z_2) \mathbf{x}_n \\
 &\quad \times E_{j-1} \mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n T^{-1}(z_1) (\mathbf{s}_i \mathbf{s}_i^* - N^{-1} T_n) A_{ij}^{-1}(z_1) \mathbf{x}_n.
 \end{aligned}$$

Splitting $\check{A}_j^{-1}(z_2)$ into the sum of $\check{A}_{ij}^{-1}(z_2)$ and $-\check{\beta}_{ij}(z_2)\check{A}_{ij}^{-1}(z_2)\mathbf{s}_i\mathbf{s}_i^*\check{A}_{ij}^{-1}(z_2)$, as in the proof of (4.14), one can show that

$$\begin{aligned} E|B_1(z_1, z_2)| &\leq \sum_{i < j} |b_{n1}(z_1)| (E|\mathbf{x}_n^* \beta_{ij}(z_1) A_{ij}^{-1}(z_1) \mathbf{s}_i \mathbf{s}_i^* A_{ij}^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n|^2 \\ &\quad \times E|\mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n T^{-1}(z_1) (\mathbf{s}_i \mathbf{s}_i^* - N^{-1} T_n) A_{ij}^{-1}(z_1) \mathbf{x}_n|^2)^{1/2} \\ &= O(N^{-1/2}). \end{aligned}$$

By the same argument, we have

$$E|B_2(z_1, z_2)| = O(N^{-1}).$$

To deal with $B_3(z_1, z_2)$, we again split $\check{A}_j^{-1}(z_2)$ into the sum of $\check{A}_{ij}^{-1}(z_2)$ and $-\check{\beta}_{ij}(z_2)\check{A}_{ij}^{-1}(z_2)\mathbf{s}_i\mathbf{s}_i^*\check{A}_{ij}^{-1}(z_2)$. We first show that

$$\begin{aligned} B_{31}(z_1, z_2) &= \sum_{i < j} b_{n1}(z_1) E_{j-1} \mathbf{x}_n^* A_{ij}^{-1}(z_1) T_n \check{A}_{ij}^{-1}(z_2) \mathbf{x}_n \\ (4.16) \quad &\quad \times E_{j-1} \mathbf{x}_n^* \check{A}_{ij}^{-1}(z_2) T_n T^{-1}(z_1) (\mathbf{s}_i \mathbf{s}_i^* - N^{-1} T_n) A_{ij}^{-1}(z_1) \mathbf{x}_n \\ &= o_p(1). \end{aligned}$$

We have

$$\begin{aligned} E|B_{31}(z_1, z_2)|^2 &= \sum_{i_1, i_2 < j} |b_{n1}(z_1)|^2 E E_{j-1} \mathbf{x}_n^* A_{i_1 j}^{-1}(z_1) T_n \check{A}_{i_1 j}^{-1}(z_2) \mathbf{x}_n \\ &\quad \times E_{j-1} \mathbf{x}_n^* A_{i_2 j}^{-1}(\bar{z}_1) T_n \check{A}_{i_2 j}^{-1}(\bar{z}_2) \mathbf{x}_n \\ &\quad \times E_{j-1} \mathbf{x}_n^* \check{A}_{i_1 j}^{-1}(z_2) T_n T^{-1}(z_1) \\ &\quad \times (\mathbf{s}_{i_1} \mathbf{s}_{i_1}^* - N^{-1} T_n) A_{i_1 j}^{-1}(z_1) \mathbf{x}_n \mathbf{x}_n^* \check{A}_{i_2 j}^{-1}(\bar{z}_2) \\ &\quad \times T_n T^{-1}(\bar{z}_1) (\mathbf{s}_{i_2} \mathbf{s}_{i_2}^* - N^{-1} T_n) A_{i_2 j}^{-1}(\bar{z}_1) \mathbf{x}_n. \end{aligned}$$

When $i_1 = i_2$, the term in the above expression is bounded by

$$K E|\mathbf{x}_n^* \check{A}_{i_1 j}^{-1}(z_2) T_n T^{-1}(z_1) (\mathbf{s}_{i_1} \mathbf{s}_{i_1}^* - N^{-1} T_n) A_{i_1 j}^{-1}(z_1) \mathbf{x}_n|^2 = O(N^{-2}).$$

For $i_1 \neq i_2 < j$, define

$$\begin{aligned} \beta_{i_1 i_2 j}(z_1) &= \frac{1}{1 + \mathbf{s}_{i_2}^* A_{i_1 i_2 j}^{-1}(z_1) \mathbf{s}_{i_2}}, \\ A_{i_1 i_2 j}(z_1) &= A(z_1) - \mathbf{s}_{i_1} \mathbf{s}_{i_1}^* - \mathbf{s}_{i_2} \mathbf{s}_{i_2}^* - \mathbf{s}_j \mathbf{s}_j^* \end{aligned}$$

and similarly define $\check{\beta}_{i_1, i_2, j}(z_2)$ and $\check{A}_{i_1 i_2 j}(z_2)$.

We have

$$\begin{aligned}
 & |EE_{j-1}\mathbf{x}_n^*A_{i_1,i_2,j}^{-1}(z_1)\mathbf{s}_{i_2}\mathbf{s}_{i_2}^*A_{i_1,i_2,j}^{-1}(z_1)\beta_{i_1,i_2,j}(z_1)T_n\check{A}_{i_1j}^{-1}(z_2) \\
 & \times \mathbf{x}_nE_{j-1}\mathbf{x}_n^*A_{i_2j}^{-1}(\bar{z}_1)T_n\check{A}_{i_2j}^{-1}(\bar{z}_2)\mathbf{x}_n \\
 & \times E_{j-1}\mathbf{x}_n^*\check{A}_{i_1j}^{-1}(z_2)T_nT^{-1}(z_1)(\mathbf{s}_{i_1}\mathbf{s}_{i_1}^* - N^{-1}T_n)A_{i_1j}^{-1}(z_1)\mathbf{x}_n \\
 & \quad \times \mathbf{x}_n^*\check{A}_{i_2j}^{-1}(\bar{z}_2)T_nT^{-1}(\bar{z}_1)(\mathbf{s}_{i_2}\mathbf{s}_{i_2}^* - N^{-1}T_n)A_{i_2j}^{-1}(\bar{z}_1)\mathbf{x}_n| \\
 & \leq K(E|\mathbf{x}_n^*A_{i_1,i_2,j}^{-1}(z_1)\mathbf{s}_{i_2}\mathbf{s}_{i_2}^*A_{i_1,i_2,j}^{-1}(z_1)\beta_{i_1,i_2,j}(z_1)T_n\check{A}_{i_1j}^{-1}(z_2)\mathbf{x}_n|^2)^{1/2} \\
 & \quad \times (E|\mathbf{x}_n^*\check{A}_{i_1j}^{-1}(z_2)T_nT^{-1}(z_1)(\mathbf{s}_{i_1}\mathbf{s}_{i_1}^* - N^{-1}T_n)A_{i_1j}^{-1}(z_1)\mathbf{x}_n|^4)^{1/4} \\
 & \quad \times (E|\mathbf{x}_n^*\check{A}_{i_2j}^{-1}(z_2)T_nT^{-1}(z_1)(\mathbf{s}_{i_2}\mathbf{s}_{i_2}^* - N^{-1}T_n)A_{i_2j}^{-1}(z_1)\mathbf{x}_n|^4)^{1/4} \\
 & = O(N^{-5/2}),
 \end{aligned}$$

$$\begin{aligned}
 & |EE_{j-1}\mathbf{x}_n^*A_{i_1,i_2,j}^{-1}(z_1)T_n\check{A}_{i_1,i_2,j}^{-1}(z_2)\mathbf{s}_{i_2}\mathbf{s}_{i_2}^*\check{A}_{i_1,i_2,j}^{-1}(z_2)\check{\beta}_{i_1,i_2,j}(z_2)\mathbf{x}_n \\
 & \times E_{j-1}\mathbf{x}_n^*A_{i_2j}^{-1}(\bar{z}_1)T_n\check{A}_{i_2j}^{-1}(\bar{z}_2)\mathbf{x}_n \\
 & \times E_{j-1}\mathbf{x}_n^*\check{A}_{i_1j}^{-1}(z_2)T_nT^{-1}(z_1)(\mathbf{s}_{i_1}\mathbf{s}_{i_1}^* - N^{-1}T_n)A_{i_1j}^{-1}(z_1)\mathbf{x}_n \\
 & \quad \times \mathbf{x}_n^*\check{A}_{i_2j}^{-1}(\bar{z}_2)T_nT^{-1}(\bar{z}_1)(\mathbf{s}_{i_2}\mathbf{s}_{i_2}^* - N^{-1}T_n)A_{i_2j}^{-1}(\bar{z}_1)\mathbf{x}_n| \\
 & \leq K(E|\mathbf{x}_n^*A_{i_1,i_2,j}^{-1}(z_1)T_n\check{A}_{i_1,i_2,j}^{-1}(z_2)\mathbf{s}_{i_2}\mathbf{s}_{i_2}^*\check{A}_{i_1,i_2,j}^{-1}(z_2)\check{\beta}_{i_1,i_2,j}(z_2)\mathbf{x}_n|^2)^{1/2} \\
 & \quad \times (E|\mathbf{x}_n^*\check{A}_{i_1j}^{-1}(z_2)T_nT^{-1}(z_1)(\mathbf{s}_{i_1}\mathbf{s}_{i_1}^* - N^{-1}T_n)A_{i_1j}^{-1}(z_1)\mathbf{x}_n|^4)^{1/4} \\
 & \quad \times (E|\mathbf{x}_n^*\check{A}_{i_2j}^{-1}(z_2)T_nT^{-1}(z_1)(\mathbf{s}_{i_2}\mathbf{s}_{i_2}^* - N^{-1}T_n)A_{i_2j}^{-1}(z_1)\mathbf{x}_n|^4)^{1/4} \\
 & = O(N^{-5/2})
 \end{aligned}$$

and, by (4.1),

$$\begin{aligned}
 & |EE_{j-1}\mathbf{x}_n^*A_{i_1,i_2,j}^{-1}(z_1)T_n\check{A}_{i_1,i_2,j}^{-1}(z_2)\mathbf{x}_nE_{j-1}\mathbf{x}_n^*A_{i_2j}^{-1}(\bar{z}_1)T_n\check{A}_{i_2j}^{-1}(\bar{z}_2)\mathbf{x}_n \\
 & \times E_{j-1}\mathbf{x}_n^*\check{A}_{i_1,i_2,j}^{-1}(z_2)\mathbf{s}_{i_2}\mathbf{s}_{i_2}^*\check{A}_{i_1,i_2,j}^{-1}(z_2)\check{\beta}_{i_1,i_2,j}(z_2)T_nT^{-1}(z_1) \\
 & \times (\mathbf{s}_{i_1}\mathbf{s}_{i_1}^* - N^{-1}T_n) \\
 & \quad \times A_{i_1j}^{-1}(z_1)\mathbf{x}_n\mathbf{x}_n^*\check{A}_{i_2j}^{-1}(\bar{z}_2)T_nT^{-1}(\bar{z}_1)(\mathbf{s}_{i_2}\mathbf{s}_{i_2}^* - N^{-1}T_n)A_{i_2j}^{-1}(\bar{z}_1)\mathbf{x}_n| \\
 & \leq K(E|\mathbf{x}_n^*\check{A}_{i_1,i_2,j}^{-1}(z_2)\mathbf{s}_{i_2}\mathbf{s}_{i_2}^*\check{A}_{i_1,i_2,j}^{-1}(z_2)\check{\beta}_{i_1,i_2,j}(z_2)T_nT^{-1}(z_1) \\
 & \quad \times (\mathbf{s}_{i_1}\mathbf{s}_{i_1}^* - N^{-1}T_n)A_{i_1j}^{-1}(z_1)\mathbf{x}_n|^2)^{1/2} \\
 & \quad \times (E|\mathbf{x}_n^*\check{A}_{i_2j}^{-1}(z_2)T_nT^{-1}(z_1)(\mathbf{s}_{i_2}\mathbf{s}_{i_2}^* - N^{-1}T_n)A_{i_2j}^{-1}(z_1)\mathbf{x}_n|^2)^{1/2}
 \end{aligned}$$

$$\begin{aligned}
&\leq K(E|\mathbf{x}_n^* \check{A}_{i_1, i_2, j}^{-1}(z_2) \mathbf{s}_{i_2} \mathbf{s}_{i_2}^* \check{A}_{i_1, i_2, j}^{-1}(z_2) T_n T^{-1}(z_1) \\
&\quad \times (\mathbf{s}_{i_1} \mathbf{s}_{i_1}^* - N^{-1} T_n) A_{i_1, j}^{-1}(z_1) \mathbf{x}_n|^2)^{1/2} \times O(N^{-1}) \\
&\leq K(E \mathbf{x}_n^* \check{A}_{i_1, i_2, j}^{-1}(z_2) \mathbf{s}_{i_2} \mathbf{s}_{i_2}^* \check{A}_{i_1, i_2, j}^{-1}(z_2) T_n T^{-1}(z_1) T_n T^{-1}(\bar{z}_1) T_n \\
&\quad \times \check{A}_{i_1, i_2, j}^{-1}(\bar{z}_2) \mathbf{s}_{i_2} \mathbf{s}_{i_2}^* \check{A}_{i_1, i_2, j}^{-1}(\bar{z}_2) \mathbf{x}_n \mathbf{x}_n^* A_{i_1, j}^{-1}(\bar{z}_1) T_n A_{i_1, j}^{-1}(z_1) \mathbf{x}_n)^{1/2} \\
&\quad \times O(N^{-2}) \\
&\leq K(E|\mathbf{x}_n^* \check{A}_{i_1, i_2, j}^{-1}(z_2) \mathbf{s}_{i_2} \mathbf{s}_{i_2}^* \check{A}_{i_1, i_2, j}^{-1}(\bar{z}_2) \mathbf{x}_n|^2)^{1/4} \\
&\quad \times (E|\mathbf{s}_{i_2}^* \check{A}_{i_1, i_2, j}^{-1}(z_2) T_n T^{-1}(z_1) T_n T^{-1}(\bar{z}_1) T_n \check{A}_{i_1, i_2, j}^{-1}(\bar{z}_2) \mathbf{s}_{i_2}^2)^{1/4} \\
&\quad \times O(N^{-2}) \\
&= O(N^{-9/4}).
\end{aligned}$$

The conclusion (4.16) then follows from the above three estimates.

Therefore,

$$\begin{aligned}
B_3(z_1, z_2) &= B_{32}(z_1, z_2) + o_p(1), \\
B_{32}(z_1, z_2) &= - \sum_{i < j} b_{n1}(z_1) E_{j-1} \mathbf{x}_n^* A_{ij}^{-1}(z_1) T_n \check{A}_{ij}^{-1}(z_2) \mathbf{x}_n \\
&\quad \times E_{j-1} \mathbf{x}_n^* \check{A}_{ij}^{-1}(z_2) \mathbf{s}_i \mathbf{s}_i^* \check{A}_{ij}^{-1}(z_2) \check{\beta}_{ij}(z_2) T_n T^{-1}(z_1) \\
&\quad \times (\mathbf{s}_i \mathbf{s}_i^* - N^{-1} T_n) A_{ij}^{-1}(z_1) \mathbf{x}_n \\
&= - \sum_{i < j} b_{n1}(z_1) E_{j-1} \mathbf{x}_n^* A_{ij}^{-1}(z_1) T_n \check{A}_{ij}^{-1}(z_2) \mathbf{x}_n \\
&\quad \times E_{j-1} \mathbf{x}_n^* \check{A}_{ij}^{-1}(z_2) \mathbf{s}_i \mathbf{s}_i^* \check{A}_{ij}^{-1}(z_2) \check{\beta}_{ij}(z_2) T_n T^{-1}(z_1) \\
&\quad \times \mathbf{s}_i \mathbf{s}_i^* A_{ij}^{-1}(z_1) \mathbf{x}_n + o_p(1).
\end{aligned}$$

By (4.3) of [5], (4.2) and (4.4), for $i < j$, we have

$$\begin{aligned}
(4.17) \quad &E|\mathbf{x}_n^* \check{A}_{ij}^{-1}(z_2) \mathbf{s}_i \mathbf{s}_i^* A_{ij}^{-1}(z_1) \mathbf{x}_n (\mathbf{s}_i^* \check{A}_{ij}^{-1}(z_2) \check{\beta}_{ij}(z_2) T_n T^{-1}(z_1) \mathbf{s}_i \\
&\quad - N^{-1} b_{n1}(z_2) \operatorname{tr} T_n \check{A}_{ij}^{-1}(z_2) T_n T^{-1}(z_1))| \\
&\leq (E|\mathbf{x}_n^* \check{A}_{ij}^{-1}(z_2) \mathbf{s}_i \mathbf{s}_i^* A_{ij}^{-1}(z_1) \mathbf{x}_n^2)^{1/2} \\
&\quad \times [(E|\check{\beta}_{ij}(z_2)|^2 |\mathbf{s}_i^* \check{A}_{ij}^{-1}(z_2) T_n T^{-1}(z_1) \mathbf{s}_i \\
&\quad - N^{-1} \operatorname{tr} T_n \check{A}_{ij}^{-1}(z_2) T_n T^{-1}(z_1)|^2)^{1/2} \\
&\quad + (E|\check{\beta}_{ij}(z_2) - b_{n1}(z_2)|^2 |N^{-1} \operatorname{tr} T_n \check{A}_{ij}^{-1}(z_2) T_n T^{-1}(z_1)|^2)^{1/2}] \\
&= O(N^{-3/2}).
\end{aligned}$$

Collecting the proofs from (4.10) to (4.17), we have proved that

$$\begin{aligned}
 B(z_1, z_2) &= -b_{n1}(z_1)b_{n1}(z_2) \\
 &\quad \times \sum_{i < j} E_{j-1} \mathbf{x}_n^* A_{ij}^{-1}(z_1) T_n \check{A}_{ij}^{-1}(z_2) \mathbf{x}_n E_{j-1} \\
 &\quad \times (\mathbf{x}_n^* \check{A}_{ij}^{-1}(z_2) \mathbf{s}_i \mathbf{s}_i^* A_{ij}^{-1}(z_1) \mathbf{x}_n N^{-1} \text{tr } T_n \text{tr } T_n \check{A}_{ij}^{-1}(z_2) T_n T^{-1}(z_1)) \\
 &\quad + o_p(1).
 \end{aligned}$$

Similarly to the proof of (4.16), we may further replace $\mathbf{s}_i \mathbf{s}_i^*$ in the above expression by $N^{-1} T_n$, that is,

$$\begin{aligned}
 B(z_1, z_2) &= -b_{n1}(z_1)b_{n1}(z_2) N^{-2} \\
 &\quad \times \sum_{i < j} E_{j-1} \mathbf{x}_n^* A_{ij}^{-1}(z_1) T_n \check{A}_{ij}^{-1}(z_2) \mathbf{x}_n E_{j-1} \\
 &\quad \times (\mathbf{x}_n^* \check{A}_{ij}^{-1}(z_2) T_n A_{ij}^{-1}(z_1) \mathbf{x}_n \text{tr } T_n \check{A}_{ij}^{-1}(z_2) T_n T^{-1}(z_1)) + o_p(1).
 \end{aligned}$$

Reversing the above procedure, one finds that we may also replace $A_{ij}^{-1}(z_1)$ and $\check{A}_{ij}^{-1}(z_2)$ in $B(z_1, z_2)$ by $A_j^{-1}(z_1)$ and $A_j^{-1}(z_2)$, respectively. That is,

$$\begin{aligned}
 B(z_1, z_2) &= -\frac{b_{n1}(z_1)b_{n1}(z_2)(j-1)}{N^2} E_{j-1} \mathbf{x}_n^* A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n E_{j-1} \\
 &\quad \times (\mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n A_j^{-1}(z_1) \mathbf{x}_n \text{tr } T_n \check{A}_j^{-1}(z_2) T_n T^{-1}(z_1)) + o_p(1).
 \end{aligned}$$

Using the martingale decomposition (4.8), one can further show that

$$\begin{aligned}
 B(z_1, z_2) &= -\frac{b_{n1}(z_1)b_{n1}(z_2)(j-1)}{N^2} E_{j-1} \mathbf{x}_n^* A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n \\
 &\quad \times E_{j-1} \mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n A_j^{-1}(z_1) \mathbf{x}_n E_{j-1} \text{tr } T_n \check{A}_j^{-1}(z_2) T_n T^{-1}(z_1) \\
 &\quad + o_p(1).
 \end{aligned}$$

It is easy to verify that

$$N^{-1} \text{tr}(T_n M(z_2) T_n T^{-1}(z_1)) = o_p(1)$$

when $M(z_2)$ takes the value $\check{B}_j(z_2)$, $\check{C}_j(z_2)$ or $\check{D}_j(z_2)$. Thus, substituting the decomposition (4.10) for $\check{A}_j^{-1}(z_2)$ in the above approximation for $B(z_1, z_2)$, one finds that

$$\begin{aligned}
 (4.18) \quad B(z_1, z_2) &= \frac{b_{n1}(z_1)b_{n1}(z_2)(j-1)}{N^2} E_{j-1} \mathbf{x}_n^* A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) \mathbf{x}_n \\
 &\quad \times E_{j-1} \mathbf{x}_n^* \check{A}_j^{-1}(z_2) T_n A_j^{-1}(z_1) \mathbf{x}_n \\
 &\quad \times E_{j-1} \text{tr } T_n T^{-1}(z_2) T_n T^{-1}(z_1) + o_p(1).
 \end{aligned}$$

Finally, let us consider the first term of (4.11). Using the expression for $A_j^{-1}(z_1)$ in (4.10), we obtain

$$(4.19) \quad \begin{aligned} & -E_{j-1}\mathbf{x}_n^*A_j^{-1}(z_1)T_n\check{A}_j^{-1}(z_2)\mathbf{x}_nE_{j-1}\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_nT^{-1}(z_1)\mathbf{x}_n \\ & = W_1(z_1, z_2) + W_2(z_1, z_2) + W_3(z_1, z_2) + W_4(z_1, z_2), \end{aligned}$$

where

$$W_1(z_1, z_2) = E_{j-1}\mathbf{x}_n^*T^{-1}(z_1)T_n\check{A}_j^{-1}(z_2)\mathbf{x}_nE_{j-1}\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_nT^{-1}(z_1)\mathbf{x}_n,$$

$$\begin{aligned} W_2(z_1, z_2) & = -b_{n1}(z_1)E_{j-1}\mathbf{x}_n^*B_{j2}^{-1}(z_1)T_n\check{A}_j^{-1}(z_2)\mathbf{x}_n \\ & \quad \times E_{j-1}\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_nT^{-1}(z_1)\mathbf{x}_n, \end{aligned}$$

$$W_3(z_1, z_2) = -E_{j-1}\mathbf{x}_n^*C_j^{-1}(z_1)T_n\check{A}_j^{-1}(z_2)\mathbf{x}_nE_{j-1}\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_nT^{-1}(z_1)\mathbf{x}_n$$

and

$$W_4(z_1, z_2) = -E_{j-1}\mathbf{x}_n^*D_j^{-1}(z_1)T_n\check{A}_j^{-1}(z_2)\mathbf{x}_nE_{j-1}\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_nT^{-1}(z_1)\mathbf{x}_n.$$

By the same argument as (4.12), one can obtain

$$(4.20) \quad E|W_3(z_1, z_2)| = o(1) \quad \text{and} \quad E|W_4(z_1, z_2)| = o(1).$$

Furthermore, as in dealing with $B(z_1, z_2)$, the first $\check{A}_j^{-1}(z_2)$ in $W_2(z_1, z_2)$ can be replaced by $-b_{n1}(z_2)\check{A}_{ij}^{-1}(z_2)\mathbf{s}_i\mathbf{s}_i^*\check{A}_{ij}^{-1}(z_2)$, that is,

$$\begin{aligned} & W_2(z_1, z_2) \\ & = b_{n1}(z_1)b_{n1}(z_2) \\ & \quad \times \sum_{i < j} E_{j-1}\mathbf{x}_n^*T^{-1}(z_1)(\mathbf{s}_i\mathbf{s}_i^* - N^{-1}T_n)A_{ij}^{-1}(z_1)T_n \\ & \quad \quad \times \check{A}_{ij}^{-1}(z_2)\mathbf{s}_i\mathbf{s}_i^*\check{A}_{ij}^{-1}(z_2)\mathbf{x}_nE_{j-1}\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_nT^{-1}(z_1)\mathbf{x}_n + o_p(1) \\ & = b_{n1}(z_1)b_{n1}(z_2) \\ & \quad \times \sum_{i < j} E_{j-1}\mathbf{x}_n^*T^{-1}(z_1)\mathbf{s}_i\mathbf{s}_i^*A_{ij}^{-1}(z_1)T_n \\ & \quad \quad \times \check{A}_{ij}^{-1}(z_2)\mathbf{s}_i\mathbf{s}_i^*\check{A}_{ij}^{-1}(z_2)\mathbf{x}_nE_{j-1}\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_nT^{-1}(z_1)\mathbf{x}_n + o_p(1) \\ & = \frac{b_{n1}(z_1)b_{n1}(z_2)(j-1)}{N^2} \\ & \quad \times E_{j-1}(\mathbf{x}_n^*T^{-1}(z_1)T_n\check{A}_j^{-1}(z_2)\mathbf{x}_n \operatorname{tr} T_n A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2)) \\ & \quad \times E_{j-1}\mathbf{x}_n^*\check{A}_j^{-1}(z_2)T_nT^{-1}(z_1)\mathbf{x}_n + o_p(1). \end{aligned}$$

It can also be verified that

$$\mathbf{x}_n^*M(z_2)T_nT^{-1}(z_1)\mathbf{x}_n = o_p(1),$$

when $M(z_2)$ takes the value $\check{B}_j(z_2)$, $\check{C}_j(z_2)$ or $\check{D}_j(z_2)$. Therefore, $W_2(z_1, z_2)$ can be further approximated by

$$(4.21) \quad W_2(z_1, z_2) = \frac{b_{n1}(z_1)b_{n1}(z_2)(j-1)}{N^2} (\mathbf{x}_n^* T^{-1}(z_1) T_n T^{-1}(z_2) \mathbf{x}_n)^2 \\ \times E_{j-1} \operatorname{tr}(T_n A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2)) + o_p(1).$$

In (2.18) of [7], it is proved that

$$E_{j-1} \operatorname{tr}(T_n A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2)) \\ = \frac{\operatorname{tr}(T_n T^{-1}(z_1) T_n T^{-1}(z_2)) + o_p(1)}{1 - (j-1)/N^2 z_1 z_2 \underline{m}(z_1) \underline{m}(z_2) \operatorname{tr}(T_n T^{-1}(z_1) T_n T^{-1}(z_2))}.$$

By the same method, $W_1(z_1, z_2)$ can be approximated by

$$(4.22) \quad W_1(z_1, z_2) = \mathbf{x}_n^* T^{-1}(z_1) T_n T^{-1}(z_2) \mathbf{x}_n \mathbf{x}_n^* T^{-1}(z_2) T_n T^{-1}(z_1) \mathbf{x}_n + o_p(1).$$

Consequently, from (4.11)–(4.22), we obtain

$$(4.23) \quad E_{j-1} \mathbf{x}_n^* A_j^{-1}(z_1) T_n \check{E}_j(A_j^{-1}(z_2) \mathbf{x}_n E_{j-1} \mathbf{x}_n^* \check{A}_j^{-1}(z_2)) T_n A_j^{-1}(z_1) \mathbf{x}_n \\ \times \left[1 - \frac{j-1}{N} b_{n1}(z_1) b_{n1}(z_2) \frac{1}{N} \operatorname{tr} T^{-1}(z_2) T_n T^{-1}(z_1) T_n \right] \\ = \mathbf{x}_n^* T^{-1}(z_1) T_n T^{-1}(z_2) \mathbf{x}_n \mathbf{x}_n^* T^{-1}(z_2) T_n T^{-1}(z_1) \mathbf{x}_n \\ \times \left(1 + \frac{j-1}{N} b_{n1}(z_1) b_{n1}(z_2) \frac{1}{N} E_{j-1} \operatorname{tr}(A_j^{-1}(z_1) T_n \check{A}_j^{-1}(z_2) T_n) \right) \\ + o_p(1).$$

Recall that $b_{n1}(z) \rightarrow -z \underline{m}(z)$ and $F^{T_n} \rightarrow H$. Hence,

$$(4.24) \quad d(z_1, z_2) := \lim b_{n1}(z_1) b_{n1}(z_2) \frac{1}{N} \operatorname{tr}(T^{-1}(z_1) T_n T^{-1}(z_2) T_n) \\ = \int \frac{ct^2 \underline{m}(z_1) \underline{m}(z_2)}{(1 + t \underline{m}(z_1))(1 + t \underline{m}(z_2))} dH(t) \\ = 1 + \frac{\underline{m}(z_1) \underline{m}(z_2) (z_1 - z_2)}{\underline{m}(z_2) - \underline{m}(z_1)}.$$

By the conditions of Theorem 2,

$$(4.25) \quad h(z_1, z_2) = \lim z_1 z_2 \underline{m}(z_1) \underline{m}(z_2) \mathbf{x}_n^* T^{-1}(z_1) T_n T^{-1}(z_2) \mathbf{x}_n \\ \times \mathbf{x}_n^* T^{-1}(z_2) T_n T^{-1}(z_1) \mathbf{x}_n \\ = \frac{\underline{m}(z_1) \underline{m}(z_2)}{z_1 z_2} \left(\int \frac{t^2 \underline{m}(z_1) \underline{m}(z_2)}{(1 + t \underline{m}(z_1))(1 + t \underline{m}(z_2))} dH(t) \right)^2$$

$$\begin{aligned} &= \frac{\underline{m}(z_1)\underline{m}(z_2)}{z_1z_2} \left(\int \frac{t dH(t)}{(1+t\underline{m}(z_1))(1+t\underline{m}(z_2))} \right)^2 \\ &= \frac{\underline{m}(z_1)\underline{m}(z_2)}{z_1z_2} \left(\frac{z_1\underline{m}(z_1) - z_2\underline{m}(z_2)}{(\underline{m}(z_2) - \underline{m}(z_1))} \right)^2. \end{aligned}$$

From (4.10), (4.24) and (4.25), we get

$$\begin{aligned} (4.7) \xrightarrow{i.p.} h(z_1, z_2) &\left(\int_0^1 \frac{1}{(1 - td(z_1, z_2))} dt + \int_0^1 \frac{td(z_1, z_2)}{(1 - td(z_1, z_2))^2} dt \right) \\ &= \frac{h(z_1, z_2)}{1 - d(z_1, z_2)} = \frac{(z_2\underline{m}(z_2) - z_1\underline{m}(z_1))^2}{c^2 z_1 z_2 (z_2 - z_1)(\underline{m}(z_2) - \underline{m}(z_1))}. \end{aligned}$$

5. Tightness of $M_n^1(z)$ and convergence of $M_n^2(z)$. First, we proceed to the proof of the tightness of $M_n^1(z)$. By (4.3), we obtain

$$E \left| \sum_{i=1}^r a_i \sum_{j=1}^N Y_j(z_i) \right|^2 = \sum_{j=1}^N E \left| \sum_{i=1}^r a_i Y_j(z_i) \right|^2 \leq K.$$

Thus, as pointed out in [7], condition (i) of Theorem 12.3 of [8] is satisfied. Therefore, to complete the proof of tightness, we only need verify that

$$(5.1) \quad E \frac{|M_n^1(z_1) - M_n^1(z_2)|^2}{|z_1 - z_2|^2} \leq K \quad \text{if } z_1, z_2 \in \mathcal{C}.$$

Write

$$Q(z_1, z_2) = \sqrt{N} \mathbf{x}_n (A_n - z_1 I)^{-1} (A_n - z_2 I)^{-1} \mathbf{x}_n.$$

Recalling the definition of M_n^1 , we have

$$\begin{aligned} &\frac{|M_n^1(z_1) - M_n^1(z_2)|}{|z_1 - z_2|} \\ &\leq \begin{cases} |Q(z_1, z_2) - EQ(z_1, z_2)|, & \text{if } z_1, z_2 \in \mathcal{C}_0 \cup \bar{\mathcal{C}}_0, \\ |Q(z_1, z_{2+}) - EQ(z_1, z_{2+})| + |Q(z_1, z_{2-}) - EQ(z_1, z_{2-})|, & \text{if } z_1 \in \mathcal{C}_0 \cup \bar{\mathcal{C}}_0 \text{ only,} \\ |Q(z_+, z_-) - EQ(z_+, z_-)|, & \text{otherwise,} \end{cases} \end{aligned}$$

where $\Re(z_{2\pm}) = \Re z_2$, $\Im(z_{2\pm}) = \pm \delta_n n^{-1}$, $\Im(z_{\pm}) = \pm \delta_n n^{-1}$ and $\Re(z_{\pm}) = u_l$ or u_r . Thus we need only to show (5.1) when $z_1, z_2 \in \mathcal{C}_0 \cup \bar{\mathcal{C}}_0$.

From the identity above (3.7) in [7], we obtain

$$\begin{aligned} (5.2) \quad \frac{M_n^1(z_1) - M_n^1(z_2)}{z_1 - z_2} &= \sqrt{N} \sum_{j=1}^N (E_j - E_{j-1}) \mathbf{x}_n^* A^{-1}(z_1) A^{-1}(z_2) \mathbf{x}_n \\ &= V_1(z_1, z_2) + V_2(z_1, z_2) + V_3(z_1, z_2), \end{aligned}$$

where

$$\begin{aligned}
 V_1(z_1, z_2) &= \sqrt{N} \sum_{j=1}^N (E_j - E_{j-1}) \beta_j(z_1) \beta_j(z_2) \mathbf{s}_j^* A_j^{-1}(z_1) A_j^{-1}(z_2) \mathbf{s}_j \mathbf{s}_j^* \\
 &\quad \times A_j^{-1}(z_2) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z_1) \mathbf{s}_j, \\
 V_2(z_1, z_2) &= \sqrt{N} \sum_{j=1}^N (E_j - E_{j-1}) \beta_j(z_1) \mathbf{s}_j^* A_j^{-1}(z_1) A_j^{-1}(z_2) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z_1) \mathbf{s}_j
 \end{aligned}$$

and

$$V_3(z_1, z_2) = \sqrt{N} \sum_{j=1}^N (E_j - E_{j-1}) \beta_j(z_2) \mathbf{s}_j^* A_j^{-1}(z_2) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z_1) A_j^{-1}(z_2) \mathbf{s}_j.$$

Applying (3.1) and the bounds for $\beta_j(z)$ and $\mathbf{s}_j^* A_j^{-1}(z_1) A_j^{-1}(z_2) \mathbf{s}_j$ given in the remark concerning (3.2) in [7], we obtain

$$\begin{aligned}
 E|V_1(z_1, z_2)|^2 &= N \sum_{j=1}^N E|(E_j - E_{j-1}) \beta_j(z_1) \beta_j(z_2) \mathbf{s}_j^* A_j^{-1}(z_1) \\
 &\quad \times A_j^{-1}(z_2) \mathbf{s}_j \mathbf{s}_j^* A_j^{-1}(z_2) \mathbf{x}_n \mathbf{x}_n^* \times A_j^{-1}(z_1) \mathbf{s}_j|^2 \\
 (5.3) \quad &\leq KN^2 (E|\mathbf{s}_j^* A_j^{-1}(z_2) \mathbf{x}_n \mathbf{x}_n^* A_j^{-1}(z_1) \mathbf{s}_j|^2 \\
 &\quad + v^{-12} n^2 P(\|A_1\| > u_r \text{ or } \lambda_{\min}^{A(1)} < u_l)) \\
 &\leq K,
 \end{aligned}$$

where (1.9a) and (1.9b) in [7] are also employed. It is easy to see that (1.9a) and (1.9b) in [7] also hold under our truncation case. Similarly, the above argument can also be used to treat $V_2(z_1, z_2)$ and $V_3(z_1, z_2)$. Therefore, we have completed the proof of (5.1).

Next, we will consider the convergence of $M_n^2(z)$. Note that

$$(5.4) \quad m_{F^{cn}, H_n}(z) = -\frac{1}{z} \int \frac{1}{1 + t \underline{m}_{F^{cn}, H_n}(z)} dH_n(t).$$

Substituting (2.5) into (5.4), we obtain that

$$\begin{aligned}
 &z\sqrt{N}((\mathbf{x}_n^* E(A^{-1})(z) \mathbf{x}_n - m_{F^{cn}, H_n}(z))) \\
 (5.5) \quad &= \sqrt{N} \left(\mathbf{x}_n^* (-E \underline{m}_n(z) T_n - I)^{-1} \mathbf{x}_n + \int \frac{1}{1 + t \underline{m}_{F^{cn}, H_n}(z)} dH_n(t) \right) \\
 &\quad + \sqrt{N} z (\delta_1 + \delta_2 + \delta_3).
 \end{aligned}$$

Applying (2.6)–(2.8), we have

$$\sqrt{N}z(\delta_1 + \delta_2 + \delta_3) = o(1).$$

On the other hand, in Section 4 of [7], it is proved that

$$(5.6) \quad \sup_z \sqrt{N}(\underline{m}_{Fc_n, H_n}(z) - E\underline{m}_n(z)) \rightarrow 0.$$

Following a similar line to (4.3) of [7], along with (4.2) of [7], we can obtain

$$\sup_{n, z \in \mathcal{C}_0} \|(\underline{m}_{Fc_n, H_n}(z)T_n + I)^{-1}\| < \infty.$$

It follows, via (4.3) of [7] and the assumption of Theorem 2, that

$$(5.7) \quad \sup_{n, z \in \mathcal{C}_0} \int \frac{t}{(1 + t\underline{m}_{Fc_n, H_n}(z))(tE\underline{m}_n(z) + 1)} dH_n(t) < \infty.$$

Appealing to (4.1), (4.3) in [7], (5.6) and (5.7), we conclude that

$$\begin{aligned} & \sqrt{N} \left(\mathbf{x}_n^* (E\underline{m}_n(z)T_n + I)^{-1} \mathbf{x}_n - \int \frac{1}{E\underline{m}_n(z)t + 1} dH_n(t) \right) \\ &= \sqrt{N} \left(\mathbf{x}_n^* (\underline{m}_{Fc_n, H_n}(z)T_n + I)^{-1} \mathbf{x}_n - \int \frac{1}{\underline{m}_{Fc_n, H_n}(z)t + 1} dH_n(t) \right) + o(1). \end{aligned}$$

Using (5.6) and (5.7), we also have

$$\begin{aligned} & \sqrt{N} \left(\int \frac{1}{E\underline{m}_n(z)t + 1} dH_n(t) - \int \frac{1}{1 + t\underline{m}_{Fc_n, H_n}(z)} dH_n(t) \right) \\ &= \sqrt{N} (\underline{m}_{Fc_n, H_n}(z) - E\underline{m}_n(z)) \int \frac{t}{(1 + t\underline{m}_{Fc_n, H_n}(z))(tE\underline{m}_n(z) + 1)} dH_n(t) \\ &= o(1). \end{aligned}$$

Combining the above arguments, we can conclude that

$$(5.5) \rightarrow 0.$$

6. Proof of Theorem 3 and supplement to Remark 7. In this section, when $T_n = I$, we will show that formula (1.12) includes (1.2) of [15] as a special case and we will also present a proof of (1.14).

First, one can easily verify that (1.15) reduces to (1.2) of [15] when $g(x) = x^r$. Next, our goal is to prove that (1.12) implies (1.14) under the condition of Theorem 3.

Write

$$(6.1) \quad \begin{aligned} (z_2\underline{m}(z_2) - z_1\underline{m}(z_1))^2 &= z_1z_2(\underline{m}(z_1) - \underline{m}(z_2))^2 + \underline{m}(z_1)\underline{m}(z_2)(z_2 - z_1)^2 \\ &+ z_2\underline{m}(z_2)(z_2 - z_1)(\underline{m}(z_2) - \underline{m}(z_1)) \\ &+ z_1\underline{m}(z_1)(z_2 - z_1)(\underline{m}(z_2) - \underline{m}(z_1)). \end{aligned}$$

Recall that

$$(6.2) \quad z = -\frac{1}{\underline{m}(z)} + c \int \frac{t}{1 + t\underline{m}(z)} dH(t),$$

from which [together with assumption (1.13)] we obtain

$$\begin{aligned} \frac{\underline{m}(z_1)\underline{m}(z_2)(z_2 - z_1)}{\underline{m}(z_2) - \underline{m}(z_1)} &= 1 - c \int \frac{t^2 \underline{m}(z_1)\underline{m}(z_2) dH(t)}{(1 + t\underline{m}(z_1))(1 + t\underline{m}(z_2))} \\ &= 1 - c \int \frac{t\underline{m}(z_1)}{1 + t\underline{m}(z_1)} dH(t) \int \frac{t\underline{m}(z_2)}{1 + t\underline{m}(z_2)} dH(t) \\ &= 1 - c^{-1}(1 + z_1\underline{m}(z_1))(1 + z_2\underline{m}(z_2)). \end{aligned}$$

Replacing one copy of $z_2 - z_1$ by this in the second term on the right-hand side of (6.1), we obtain

$$(6.3) \quad \begin{aligned} &(z_2\underline{m}(z_2) - z_1\underline{m}(z_1))^2 \\ &= z_1z_2(\underline{m}(z_1) - \underline{m}(z_2))^2 \\ &\quad + (z_2 - z_1)(\underline{m}(z_2) - \underline{m}(z_1))[(1 - c^{-1})(1 + z_1\underline{m}(z_1) + z_2\underline{m}(z_2)) \\ &\quad \quad \quad - c^{-1}z_1z_2\underline{m}(z_1)\underline{m}(z_2)]. \end{aligned}$$

Using this and the facts that (1), (2), (3), we obtain RHS

$$\begin{aligned} \frac{1}{2\pi i} \oint_{\mathcal{C}} z^{-1} g(z) dz &= \begin{cases} g(0), & \text{if } \mathcal{C} \text{ encloses the origin,} \\ 0, & \text{otherwise,} \end{cases} \\ \frac{1}{2\pi i} \oint_{\mathcal{C}} \underline{m}(z)g(z) dz &= - \int g(x) d\underline{F}^{c,H}(x), \end{aligned}$$

$$- \frac{1}{4\pi^2} \oint_{\mathcal{C}_1} \oint_{\mathcal{C}_2} \frac{\underline{m}(z_2) - \underline{m}(z_1)}{z_2 - z_1} g_1(z_1)g_2(z_2) dz_1 dz_2 = \int g_1(x)g_2(x) d\underline{F}^{c,H}(x),$$

when \mathcal{C}_j enclose the origin, we obtain

RHS of (1.12)

$$\begin{aligned} &= \frac{2}{c^2} \int g_1(x)g_2(x) d\underline{F}^{c,H}(x) \\ &\quad + \frac{2(c-1)}{c^3} \left(g_1(0)g_2(0) - g_1(0) \int g_2(x) d\underline{F}^{c,H}(x) \right. \\ &\quad \quad \quad \left. - g_2(0) \int g_1(x) d\underline{F}^{c,H}(x) \right) \\ &\quad - \frac{2}{c^3} \int g_1(x) d\underline{F}^{c,H}(x) \int g_2(x) d\underline{F}^{c,H}(x) \\ &= \frac{2}{c} \left(\int g_1(x)g_2(x) d\underline{F}^{c,H}(x) - \int g_1(x) d\underline{F}^{c,H}(x) \int g_2(x) d\underline{F}^{c,H}(x) \right). \end{aligned}$$

The same we can obtain when \mathcal{C}_j does not enclose the origin, we can obtain the same result even more easily.

Thus the result is proved.

7. Truncation, recentralization and renormalization of X_{ij} . In this section, to facilitate the analysis in the other sections, the underlying random variables need to be truncated, recentralized and renormalized. Since the argument for (1.8) in [7] can be carried directly over to the present case, we can then select ε_n such that

$$(7.1) \quad \varepsilon_n \rightarrow 0 \quad \text{and} \quad \varepsilon_n^{-4} \int_{\{|X_{11}| \geq \varepsilon_n n^{1/4}\}} |X_{11}|^4 \rightarrow 0.$$

Let $\hat{X}_{ij} = X_{ij}I(|X_{ij}| \leq \varepsilon_n n^{1/4}) - EX_{ij}I(|X_{ij}| \leq \varepsilon_n n^{1/4})$, $\tilde{X}_n = X_n - \hat{X}_n$, and $\hat{A}_n = \frac{1}{N}T_n^{1/2}\hat{X}_n\hat{X}_n^*T_n^{1/2}$, where $\hat{X}_n = (\hat{X}_{ij})$. Let $\sigma_n^2 = E|\hat{X}_{11}|^2$ and $\check{A}_n = \frac{1}{N\sigma_n^2}T_n^{1/2}\hat{X}_n\hat{X}_n^*T_n^{1/2}$. Write $A^{-1}(z) = (A_n - zI)^{-1}$ and $\check{A}^{-1}(z) = (\check{A}_n - zI)^{-1}$.

LEMMA 4. *Suppose that $X_{ij} \in \mathcal{C}$, $i = 1, \dots, n, j = 1, \dots, N$, are i.i.d. with $EX_{11} = 0, E|X_{11}|^2 = 1$ and $E|X_{11}|^4 < \infty$. For $z \in \mathcal{C}_0$, we then have*

$$(7.2) \quad \sqrt{N}\mathbf{x}_n^*(\check{A}^{-1}(z)\mathbf{x}_n - \mathbf{x}_n^*A^{-1}(z)\mathbf{x}_n) \xrightarrow{i.p.} 0.$$

PROOF. Corresponding to the truncated and renormalized variables, we similarly define $\hat{\mathbf{s}}_j, \tilde{\mathbf{s}}_j, \hat{A}^{-1}(z), \hat{A}_j^{-1}(z), \hat{\beta}_j(z), \hat{\beta}_{j_1j_2}(z)$ and $\hat{\beta}_{j_2j_1}(z)$.

We then have

$$(7.3) \quad \begin{aligned} & \sqrt{N}(\mathbf{x}_n^*\hat{A}^{-1}(z)\mathbf{x}_n - \mathbf{x}_n^*A^{-1}(z)\mathbf{x}_n) \\ &= \frac{1}{\sqrt{N}}(\mathbf{x}_n^*\hat{A}^{-1}(z)T_n^{1/2}(X_n - \hat{X}_n)X_n^*T_n^{1/2}A^{-1}(z)\mathbf{x}_n \\ & \quad + \mathbf{x}_n^*\hat{A}^{-1}(z)T_n^{1/2}\hat{X}_n(X_n^* - \hat{X}_n^*)T_n^{1/2}A^{-1}(z)\mathbf{x}_n) \\ &= \sqrt{N} \sum_{j=1}^N \mathbf{x}_n^*\hat{A}^{-1}(z)\tilde{\mathbf{s}}_j\mathbf{s}_j^*A^{-1}(z)\mathbf{x}_n + \sqrt{N} \sum_{j=1}^N \mathbf{x}_n^*\hat{A}^{-1}(z)\hat{\mathbf{s}}_j\tilde{\mathbf{s}}_j^*A^{-1}(z)\mathbf{x}_n \\ &= \sqrt{N} \sum_{j=1}^N \beta_j(z)\mathbf{x}_n^*\hat{A}^{-1}(z)\tilde{\mathbf{s}}_j\mathbf{s}_j^*A_j^{-1}(z)\mathbf{x}_n \\ & \quad + \sqrt{N} \sum_{j=1}^N \hat{\beta}_j(z)\mathbf{x}_n^*\hat{A}_j^{-1}(z)\hat{\mathbf{s}}_j\tilde{\mathbf{s}}_j^*A^{-1}(z)\mathbf{x}_n \end{aligned}$$

$$\triangleq \omega_1 + \omega_2.$$

Consider first the term ω_1 .

$$\begin{aligned}
 E|\omega_1|^2 &\leq N \sum_{j=1}^N E|\beta_j(z)\mathbf{x}_n^* \hat{A}^{-1}(z)\tilde{\mathbf{s}}_j \mathbf{s}_j^* A_j^{-1}(z)\mathbf{x}_n|^2 \\
 &\quad + N \sum_{j_1 \neq j_2} |E\beta_{j_1}(z)\mathbf{x}_n^* \hat{A}^{-1}(z)\tilde{\mathbf{s}}_{j_1} \mathbf{s}_{j_1}^* A_{j_1}^{-1}(z)\mathbf{x}_n \\
 &\quad \quad \quad \times \beta_{j_2}(\bar{z})\mathbf{x}_n^* A_{j_2}^{-1}(\bar{z})\tilde{\mathbf{s}}_{j_2} \mathbf{s}_{j_2}^* \hat{A}^{-1}(\bar{z})\mathbf{x}_n| \\
 (7.4) \quad &\triangleq \omega_{11} + \omega_{12},
 \end{aligned}$$

where $\beta_{j_2}(\bar{z})$ is the complex conjugate of $\beta_{j_2}(z)$.

Our next goal is to show that the above two terms converge to zero for all $z \in \mathcal{C}_u$ and $z \in \mathcal{C}_l$ when $u_l < 0$.

In this case, $\beta_j(z)$ is bounded. It is straightforward to verify that

$$\begin{aligned}
 &E|\beta_j(z)\mathbf{x}_n^* \hat{A}_j^{-1}(z)\tilde{\mathbf{s}}_j \mathbf{s}_j^* A_j^{-1}(z)\mathbf{x}_n|^2 \\
 &\leq KE|\mathbf{s}_j^* A_j^{-1}(z)\mathbf{x}_n \mathbf{x}_n^* \hat{A}_j^{-1}(z)\tilde{\mathbf{s}}_j|^2 = o(N^{-2}), \\
 (7.5) \quad &E|\hat{\mathbf{s}}_j^* \hat{A}_j^{-1}(z)\tilde{\mathbf{s}}_j - E(\hat{X}_{11}\tilde{X}_{11}^*)N^{-1} \text{tr} \hat{A}_j^{-1}(z)T_n|^4 = o(N^{-2}), \\
 &E|\mathbf{s}_j^* A_j^{-1}(z)\mathbf{x}_n \mathbf{x}_n^* \hat{A}_j^{-1}(z)\hat{\mathbf{s}}_j|^4 = O(N^{-3}).
 \end{aligned}$$

Therefore,

$$\begin{aligned}
 &E|\beta_j(z)\hat{\beta}_j(z)\mathbf{x}_n^* \hat{A}_j^{-1}(z)\hat{\mathbf{s}}_j \mathbf{s}_j^* \hat{A}_j^{-1}(z)\tilde{\mathbf{s}}_j \mathbf{s}_j^* A_j^{-1}(z)\mathbf{x}_n|^2 \\
 &\leq K(E|\hat{\mathbf{s}}_j^* \hat{A}_j^{-1}(z)\tilde{\mathbf{s}}_j - E(\hat{X}_{11}\tilde{X}_{11}^*)N^{-1} \text{tr} \hat{A}_j^{-1}(z)T_n|^4)^{1/2} \\
 &\quad \times (E|\mathbf{s}_j^* A_j^{-1}(z)\mathbf{x}_n \mathbf{x}_n^* \hat{A}_j^{-1}(z)\hat{\mathbf{s}}_j|^4)^{1/2} \\
 &\quad + E|X_{11}|^2 I(|X_{11}| \geq \varepsilon_n n^{1/4}) E|\mathbf{s}_j^* A_j^{-1}(z)\mathbf{x}_n \mathbf{x}_n^* \hat{A}_j^{-1}(z)\hat{\mathbf{s}}_j|^2 = o(N^{-2}).
 \end{aligned}$$

It then follows that

$$\begin{aligned}
 \omega_{11} &\leq KN \sum_{j=1}^N (E|\beta_j(z)\hat{\beta}_j(z)\mathbf{x}_n^* \hat{A}_j^{-1}(z)\hat{\mathbf{s}}_j \mathbf{s}_j^* \hat{A}_j^{-1}(z)\tilde{\mathbf{s}}_j \mathbf{s}_j^* A_j^{-1}(z)\mathbf{x}_n|^2 \\
 (7.6) \quad &\quad \quad + E|\beta_j(z)\mathbf{x}_n^* \hat{A}_j^{-1}(z)\tilde{\mathbf{s}}_j \mathbf{s}_j^* A_j^{-1}(z)\mathbf{x}_n|^2) \\
 &= o(1).
 \end{aligned}$$

Now consider the term ω_{12} . We have

$$\begin{aligned}
 &E\beta_{j_1}(z)\beta_{j_2}(\bar{z})\mathbf{s}_{j_1}^* A_{j_1}^{-1}(z)\mathbf{x}_n \mathbf{x}_n^* A_{j_2}^{-1}(\bar{z})\mathbf{s}_{j_2} \tilde{\mathbf{s}}_{j_2}^* \hat{A}^{-1}(\bar{z})\mathbf{x}_n \mathbf{x}_n^* \hat{A}^{-1}(z)\tilde{\mathbf{s}}_{j_1} \\
 &= \Delta_1 + \Delta_2 + \Delta_3 + \Delta_4,
 \end{aligned}$$

where

$$\begin{aligned}\Delta_1 &= E\beta_{j_1}(z)\beta_{j_2}(\bar{z})\hat{\beta}_{j_1}(z)\hat{\beta}_{j_2}(\bar{z})\mathbf{s}_{j_1}^* A_{j_1}^{-1}(z)\mathbf{x}_n\mathbf{x}_n^* A_{j_2}^{-1}(\bar{z})\mathbf{s}_{j_2}\tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_2} \\ &\quad \times \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_2}^{-1}(\bar{z})\mathbf{x}_n\mathbf{x}_n^* \hat{A}_{j_1}^{-1}(z)\hat{\mathbf{s}}_{j_1}\hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1}^{-1}(z)\tilde{\mathbf{s}}_{j_1}, \\ \Delta_2 &= -E\beta_{j_1}(z)\beta_{j_2}(\bar{z})\hat{\beta}_{j_2}(z)\mathbf{s}_{j_1}^* A_{j_1}^{-1}(z)\mathbf{x}_n\mathbf{x}_n^* A_{j_2}^{-1}(\bar{z})\mathbf{s}_{j_2} \\ &\quad \times \tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_2}\hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_2}^{-1}(\bar{z})\mathbf{x}_n\mathbf{x}_n^* \hat{A}_{j_1}^{-1}(z)\tilde{\mathbf{s}}_{j_1}, \\ \Delta_3 &= -E\beta_{j_1}(z)\beta_{j_2}(\bar{z})\hat{\beta}_{j_1}(z)\mathbf{s}_{j_1}^* A_{j_1}^{-1}(z)\mathbf{x}_n\mathbf{x}_n^* A_{j_2}^{-1}(\bar{z})\mathbf{s}_{j_2}\tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_2}^{-1}(\bar{z})\mathbf{x}_n \\ &\quad \times \mathbf{x}_n^* \hat{A}_{j_1}^{-1}(z)\hat{\mathbf{s}}_{j_1}\hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1}^{-1}(z)\tilde{\mathbf{s}}_{j_1}, \\ \Delta_4 &= E\beta_{j_1}(z)\beta_{j_2}(\bar{z})\mathbf{s}_{j_1}^* A_{j_1}^{-1}(z)\mathbf{x}_n\mathbf{x}_n^* A_{j_2}^{-1}(\bar{z})\mathbf{s}_{j_2}\tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_2}^{-1}(\bar{z})\mathbf{x}_n\mathbf{x}_n^* \hat{A}_{j_1}^{-1}(z)\tilde{\mathbf{s}}_{j_1}.\end{aligned}$$

In the sequel, Δ_1 will be further decomposed. However, since the expansions of Δ_1 are rather complicated, as an illustration, we only present estimates for some typical terms; other terms can be estimated similarly. The main technique is to extract the j_1 th and j_2 th column, respectively, from $T_n^{1/2}\hat{X}_n$ of $A_{j_2}^{-1}(z)$ and $A_{j_1}^{-1}(z)$, and so on. We will evaluate the following terms of Δ_1 :

$$\Delta_{11}, \Delta_{12}, \Delta_{13}, \Delta_{14}.$$

Their definitions will be given below, when the corresponding terms are evaluated.

Define

$$\begin{aligned}V_1 &= \mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(z)\mathbf{x}_n\mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z})\mathbf{s}_{j_2}, \\ V_3 &= \tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_2} - E(\hat{X}_{11}\tilde{X}_{11}^*)N^{-1}\text{tr}\hat{A}_{j_1 j_2}^{-1}(\bar{z})T_n, \\ V_2 &= \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\mathbf{x}_n\mathbf{x}_n^* \hat{A}_{j_1 j_2}^{-1}(z)\hat{\mathbf{s}}_{j_1}, \\ V_4 &= \hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(z)\tilde{\mathbf{s}}_{j_1} - E(\hat{X}_{11}\tilde{X}_{11}^*)N^{-1}\text{tr}\hat{A}_{j_1 j_2}^{-1}(z)T_n.\end{aligned}$$

One can then easily prove that

$$(7.7) \quad \begin{aligned}E|V_3|^2 &= o(N^{-1}), & E|V_4|^2 &= o(N^{-1}), \\ E|V_1|^4 &= O(N^{-4}) & \text{and} & E|V_2|^4 = O(N^{-4}).\end{aligned}$$

Using (7.7) and (7.1), we obtain

$$\begin{aligned}|\Delta_{11}| &= |E[\beta_{j_1}(z)\beta_{j_2}(\bar{z})\hat{\beta}_{j_1}(z)\hat{\beta}_{j_2}(\bar{z})\mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(z)\mathbf{x}_n\mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z})\mathbf{s}_{j_2} \\ &\quad \times \tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_2}\hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\mathbf{x}_n\mathbf{x}_n^* \hat{A}_{j_1 j_2}^{-1}(z)\hat{\mathbf{s}}_{j_1}\hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(z)\tilde{\mathbf{s}}_{j_1}]| \\ &\leq K[E|V_1|^4]^{1/4}[E|V_2|^4]^{1/4}[E|V_3V_4|^2]^{1/2} \\ &\quad + KE|X_{11}|^2 I(|X_{11}| \geq \varepsilon_n n^{1/4})[E|V_1|^4]^{1/4}[E|V_2|^4]^{1/4}[E|V_3|^2]^{1/2}\end{aligned}$$

$$\begin{aligned}
 &+ KE|X_{11}|^2 I(|X_{11}| \geq \varepsilon_n n^{1/4}) [E|V_1|^4]^{1/4} [E|V_2|^4]^{1/4} [E|V_4|^2]^{1/2} \\
 &+ K(E|X_{11}|^2 I(|X_{11}| \geq \varepsilon_n n^{1/4}))^2 \\
 &\quad \times [E|\mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* \hat{A}_{j_1 j_2}^{-1}(z) \hat{\mathbf{s}}_{j_1}|^2]^{1/2} \\
 &\quad \times [E|\hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z}) \mathbf{x}_n \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z}) \mathbf{s}_{j_2}|^2]^{1/2} \\
 &= o(N^{-3}),
 \end{aligned}$$

where we make use of the independence between $\tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z}) \hat{\mathbf{s}}_{j_2}$ and $\hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(z) \tilde{\mathbf{s}}_{j_1}$ when $\hat{A}_{j_1 j_2}^{-1}(\bar{z})$ is given.

Let

$$V_5 = \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z}) \mathbf{x}_n \mathbf{x}_n^* \hat{A}_{j_1 j_2}^{-1}(z) \hat{\mathbf{s}}_{j_1} \mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(z) \mathbf{s}_{j_2}.$$

Similarly, we have

$$\begin{aligned}
 E|\mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(z) \mathbf{s}_{j_2}^*|^4 &= O(N^{-2}), \\
 E|V_5|^4 &= O(N^{-4}), \\
 E|\mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z}) \mathbf{s}_{j_2}|^2 &= O(N^{-2}).
 \end{aligned}
 \tag{7.8}$$

Consequently, by (7.5), (7.7), (7.8) and (7.1), we have

$$\begin{aligned}
 |\Delta_{12}| &= |E[\beta_{j_1}(z) \beta_{j_2}(\bar{z}) \beta_{j_2 j_1}(z) \hat{\beta}_{j_1}(z) \hat{\beta}_{j_2}(\bar{z}) \mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(z) \mathbf{s}_{j_2} \mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(z) \mathbf{x}_n \\
 &\quad \times \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z}) \mathbf{s}_{j_2} \tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z}) \hat{\mathbf{s}}_{j_2} \\
 &\quad \times \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* \hat{A}_{j_1 j_2}^{-1}(z) \hat{\mathbf{s}}_{j_1} \hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(z) \tilde{\mathbf{s}}_{j_1}]| \\
 &\leq K[E|\mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z}) \mathbf{s}_{j_2}|^2]^{1/2} \times [E|V_3 V_4|^4]^{1/4} \times [E|V_5|^4]^{1/4} \\
 &\quad + KE|X_{11}|^2 I(|X_{11}| \geq \varepsilon_n n^{1/4}) [E|\mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z}) \mathbf{s}_{j_2}|^2]^{1/2} \\
 &\quad \times [E|V_4|^4]^{1/4} [E|V_5|^4]^{1/4} \\
 &\quad + KE|X_{11}|^2 I(|X_{11}| \geq \varepsilon_n n^{1/4}) [E|\mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z}) \mathbf{s}_{j_2}|^2]^{1/2} \\
 &\quad \times [E|V_3|^4]^{1/4} [E|V_5|^4]^{1/4} \\
 &\quad + K(E|X_{11}|^2 I(|X_{11}| \geq \varepsilon_n n^{1/4}))^2 [E|\mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z}) \mathbf{s}_{j_2}|^2]^{1/2} \\
 &\quad \times [E|V_2|^4]^{1/4} [E|\mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(z) \mathbf{s}_{j_2}^*|^4]^{1/4} \\
 &= o(N^{-3}).
 \end{aligned}$$

Let $V_6 = \mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(z) \mathbf{x}_n \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z}) \mathbf{s}_{j_1} \mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(\bar{z}) \mathbf{s}_{j_2}$. By Lemma 1, one can ob-

tain $E|V_6|^2 = O(N^{-3})$. Hence,

$$\begin{aligned} |\Delta_{13}| &= |E[\beta_{j_1}(z)\beta_{j_2}(\bar{z})\beta_{j_1j_2}(\bar{z})\beta_{j_2j_1}(z)\hat{\beta}_{j_1}(z)\hat{\beta}_{j_2}(\bar{z})\mathbf{s}_{j_1}^*A_{j_1j_2}^{-1}(z)\mathbf{s}_{j_2} \\ &\quad \times \mathbf{s}_{j_2}^*A_{j_1j_2}^{-1}(z)\mathbf{x}_n\mathbf{x}_n^*A_{j_1j_2}^{-1}(\bar{z})\mathbf{s}_{j_1}\mathbf{s}_{j_1}^*A_{j_1j_2}^{-1}(\bar{z})\mathbf{s}_{j_2}\hat{\mathbf{s}}_{j_2}^*\hat{A}_{j_1j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_2} \\ &\quad \times \hat{\mathbf{s}}_{j_2}^*\hat{A}_{j_1j_2}^{-1}(\bar{z})\mathbf{x}_n\mathbf{x}_n^*\hat{A}_{j_1j_2}^{-1}(z)\hat{\mathbf{s}}_{j_1}\hat{\mathbf{s}}_{j_1}^*\hat{A}_{j_1j_2}^{-1}(z)\hat{\mathbf{s}}_{j_1}]| \\ &\leq K[E|V_6|^2]^{1/2}[E|V_3V_4|^4]^{1/4} \times [E|V_5|^4]^{1/4} \\ &\quad + KE|X_{11}|^2I(|X_{11}| \geq \varepsilon_n n^{1/4})K[E|V_6|^2]^{1/2}[E|V_4|^4]^{1/4} \times [E|V_5|^4]^{1/4} \\ &\quad + KE|X_{11}|^2I(|X_{11}| \geq \varepsilon_n n^{1/4})[E|V_6|^2]^{1/2}[E|V_3|^4]^{1/4} \times [E|V_5|^4]^{1/4} \\ &\quad + K(E|X_{11}|^2I(|X_{11}| \geq \varepsilon_n n^{1/4}))^2 \\ &\quad \times [E|V_6|^2]^{1/2}[E|V_2|^4]^{1/4}[E|\mathbf{s}_{j_1}^*A_{j_1j_2}^{-1}(z)\mathbf{s}_{j_2}^*|^4]^{1/4} \\ &= o(N^{-3}). \end{aligned}$$

Before proceeding, we need the following estimate:

$$(7.9) \quad E|\mathbf{s}_p^*A_{pq}^{-1}(z)\mathbf{s}_q\hat{\mathbf{s}}_p^*\hat{A}_{pq}^{-1}(\bar{z})\mathbf{x}_n\mathbf{x}_n^*\hat{A}_{pq}^{-1}(z)\hat{\mathbf{s}}_q\hat{\mathbf{s}}_q^*\hat{A}_{pq}^{-1}(\bar{z})\hat{\mathbf{s}}_p|^4 = O(N^{-4}).$$

For $p \neq q$, write

$$\begin{aligned} T_n^{1/2}A_{pq}^{-1}(z)T_n^{1/2} &= (a_{uv}), \\ T_n^{1/2}\hat{A}_{pq}^{-1}(\bar{z})\mathbf{x}_n\mathbf{x}_n^*\hat{A}_{pq}^{-1}(z)T_n^{1/2} &= (b_{ml}), \\ T_n^{1/2}\hat{A}_{pq}^{-1}(\bar{z})T_n^{1/2} &= (c_{ij}). \end{aligned}$$

Then

$$\begin{aligned} &E|\mathbf{s}_p^*A_{pq}^{-1}(z)\mathbf{s}_q\hat{\mathbf{s}}_p^*\hat{A}_{pq}^{-1}(\bar{z})\mathbf{x}_n\mathbf{x}_n^*\hat{A}_{pq}^{-1}(z)\hat{\mathbf{s}}_q\hat{\mathbf{s}}_q^*\hat{A}_{pq}^{-1}(\bar{z})\hat{\mathbf{s}}_p|^4 \\ &= \frac{1}{N^{12}} \sum E a_{u_1v_1} a_{u_2v_2} a_{u_3v_3} a_{u_4v_4} \\ &\quad \times X_{u_1p}^* X_{u_2p} X_{u_3p}^* X_{u_4p} X_{v_1q} X_{v_2q}^* X_{v_3q} X_{v_4q}^* \\ (7.10) \quad &\quad \times b_{m_1l_1} b_{m_2l_2} b_{m_3l_3} b_{m_4l_4} \\ &\quad \times \hat{X}_{m_1p}^* \hat{X}_{m_2p} \hat{X}_{m_3p}^* \hat{X}_{m_4p} \hat{X}_{l_1q} \hat{X}_{l_2q}^* \hat{X}_{l_3q} \hat{X}_{l_4q}^* \\ &\quad \times c_{i_1j_1} c_{i_2j_2} c_{i_3j_3} c_{i_4j_4} \\ &\quad \times \hat{X}_{i_1p} \hat{X}_{i_2p}^* \hat{X}_{i_3p} \hat{X}_{i_4p}^* \hat{X}_{j_1q} \hat{X}_{j_2q} \hat{X}_{j_3q}^* \hat{X}_{j_4q}, \end{aligned}$$

where the summations run over all indices except p and q , and where $\hat{X}_{u_1p}^*$ denotes the complex conjugate and transpose of \hat{X}_{u_1p} , that is, the intercrossed element of the u_1 th row and p th column of matrix X_n . Observe that:

(1) none of the indices of the above twenty-four random variables appear alone, otherwise the expectation is zero,

(2) $\text{tr}(\hat{A}_j^{-1}(z)T_n\hat{A}_{pq}^{-1}(\bar{z})T_n) = O(N)$ and $|\hat{X}_{\cdot p}| \leq \varepsilon_n n^{1/4}$;

(3) $|\mathbf{x}_n^* \hat{A}_{pq}^{-1}(z)T_n\hat{A}_{pq}^{-1}(\bar{z})\mathbf{x}_n|$ is bounded. Combining the above, we obtain (7.9).

Similarly to (7.9), one can also verify that

$$(7.11) \quad \begin{aligned} E|\hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_1} \mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(z)\mathbf{x}_n \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z})\mathbf{s}_{j_1} \hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_2}|^4 &= O(N^{-4}), \\ E|\tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_1} \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(z)\tilde{\mathbf{s}}_{j_1}|^4 &= o(N^{-2}) \end{aligned}$$

and that

$$(7.12) \quad E|\mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(\bar{z})\mathbf{s}_{j_2} \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_1}|^4 = O(N^{-2}).$$

It follows that

$$\begin{aligned} |\Delta_{14}| &= |E[\beta_{j_1}(z)\beta_{j_2}(\bar{z})\beta_{j_1 j_2}(\bar{z})\beta_{j_2 j_1}(z)\hat{\beta}_{j_1}(z)\hat{\beta}_{j_2}(\bar{z})(\hat{\beta}_{j_1 j_2}(\bar{z}))^2(\hat{\beta}_{j_2 j_1}(z))^2 \\ &\quad \times \mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(z)\mathbf{s}_{j_2} \mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(z)\mathbf{x}_n \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z})\mathbf{s}_{j_1} \mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(\bar{z}) \\ &\quad \times \mathbf{s}_{j_2} \tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_1} \hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_2} \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_1} \hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\mathbf{x}_n \\ &\quad \times \mathbf{x}_n^* \hat{A}_{j_1 j_2}^{-1}(z)\hat{\mathbf{s}}_{j_2} \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(z)\hat{\mathbf{s}}_{j_1} \hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(z)\hat{\mathbf{s}}_{j_2} \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(z)\tilde{\mathbf{s}}_{j_1}]| \\ &\leq K[E|\mathbf{s}_{j_1}^* A_{j_1 j_2}^{-1}(z)\mathbf{s}_{j_2} \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\mathbf{x}_n \mathbf{x}_n^* \hat{A}_{j_1 j_2}^{-1}(z)\hat{\mathbf{s}}_{j_2} \hat{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_1}|^4]^{1/4} \\ &\quad \times [E|\hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_2} \mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(z)\mathbf{x}_n \mathbf{x}_n^* A_{j_1 j_2}^{-1}(\bar{z})\mathbf{s}_{j_1} \hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_2}|^4]^{1/4} \\ &\quad \times [E|\hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(z)\hat{\mathbf{s}}_{j_2} \mathbf{s}_{j_2}^* A_{j_1 j_2}^{-1}(\bar{z})\mathbf{s}_{j_2}|^4]^{1/4} \\ &\quad \times [E|\tilde{\mathbf{s}}_{j_2}^* \hat{A}_{j_1 j_2}^{-1}(\bar{z})\hat{\mathbf{s}}_{j_1} \hat{\mathbf{s}}_{j_1}^* \hat{A}_{j_1 j_2}^{-1}(z)\tilde{\mathbf{s}}_{j_1}|^4]^{1/4} \\ &= o(N^{-3}). \end{aligned}$$

All other terms of Δ_1 can be dealt with in a similar manner. Hence, combining the above arguments, one can conclude that

$$n \sum_{j_1 \neq j_2} \Delta_1 \rightarrow 0.$$

Similarly, one can also prove that $n \sum_{j_1 \neq j_2} \Delta_2$, $n \sum_{j_1 \neq j_2} \Delta_3$ and $n \sum_{j_1 \neq j_2} \Delta_4$ converge to zero. Hence, $\omega_{12} \rightarrow 0$. Combining this with (7.6), we have

$$\omega_1 \xrightarrow{i.p.} 0.$$

Using the same method, one can prove that ω_2 converges to zero in probability. Hence, we complete the truncation and centralization of X_{ij} . The rescaling of random variables X_{ij} can be completed in a similar way. By Theorem 1 in [2], we have

$$\liminf_{n \rightarrow \infty} \min(u_r - \lambda_{\max}^{\hat{A}_n}, \lambda_{\min}^{\hat{A}_n} - u_l) > 0 \quad \text{a.s.}$$

and

$$\liminf_{n \rightarrow \infty} \min(u_r - \lambda_{\max}^{A_n}, \lambda_{\min}^{A_n} - u_l) > 0 \quad \text{a.s.}$$

Hence, for $z \in \mathcal{C}_l$, $u_l > 0$ or $z \in \mathcal{C}_r$, we can also proceed with the truncation, centralization and rescaling of X_{ij} by the above method. Thus the proof is complete. \square

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