HW 3 - CS754

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Q1

a) Define the restricted eigenvalue condition

$X : \mathbb{R}^{N\times p}$ and $N < p$, then $X^T X$'s rank would be at most N so some eigenvalues would be zero

For a function to be strongly convex at β^*,
$\frac{v^T \nabla^2 f(\beta) v}{||v||_2^2} \geq \gamma, \text{for all nonzero } v \in \mathbb{R}^p, \text{ for all } \beta \text{ in the neighbourhood of } \beta^*$

But as our cost function's second derivative is $\frac{X^T X}{N}$ so it is not strongly convex, but it is strongly convex in some subspace.

So our restricted eigenvalue condition: $\frac{v^T X^T X v}{N||v||_2^2} \geq \gamma, \text{for all nonzero } v \in C, \text{ for some } C \subset \mathbb{R}^p$

b) Why is $\mathbf{G(\hat{v}) \leq G(0)}$

$$G(v) = \frac{1}{2N}||y - X(\beta^* + v)||_2^2 + \lambda_N||\beta^* + v||_1$$
$$G(\hat{v}) = \frac{1}{2N}||y - X(\beta^* + \hat{\beta} - \beta^*)||_2^2 + \lambda_N||\beta^* + \hat{\beta} - \beta^*||_1$$
$$= \frac{1}{2N}||y - X(\hat{\beta})||_2^2 + \lambda_N||\hat{\beta}||_1 = J(\hat{\beta})$$
$$G(0) = \frac{1}{2N}||y - X(\beta^*)||_2^2 + \lambda_N||\beta^*||_1 = J(\beta^*)$$
$$J(\hat{\beta}) \leq J(\beta^*), \text{as } \hat{\beta} \text{ is a minimizer of J}$$
$$\therefore G(\hat{v}) \leq G(0)$$

c) Do the algebra to obtain equation 11.21

$G(\hat{v}) \leq G(0)$

$$y = X\beta^* + w$$
$$||y - X\beta^*||_2^2 = ||w||_2^2$$
$$||y - X(\beta^* + \hat{v})||_2^2 = ||w - X\hat{v}||_2^2 = (w - X\hat{v})^T(w - X\hat{v})$$
$$= w^T w + (\hat{v}X)^T X\hat{v} - w^T X\hat{v} - (X\hat{v})^T w$$
$$= ||w||_2^2 + ||X\hat{v}||_2^2 - 2w^T X\hat{v} \text{ (since all are scalars and scalar\^{}T = scalar)}$$

$$
\begin{aligned}
\frac{1}{2N}||y - X(\beta^* + \hat{v})||_2^2 + \lambda_N||\beta^* + \hat{v}||_1 &\leq \frac{1}{2N}||y - X\beta^*||_2^2 + \lambda_N||\beta^*||_1 \\
\frac{1}{2N}(||w||_2^2 + ||X\hat{v}||_2^2 - 2w^T X\hat{v}) &\leq \frac{||w||_2^2}{2N} + \lambda_N(||\beta^*||_1 - ||\beta^* + \hat{v}||_1) \\
\frac{||X\hat{v}||_2^2}{2N} &\leq \frac{w^T X\hat{v}}{N} + \lambda_N(||\beta^*||_1 - ||\beta^* + v||_1)
\end{aligned}
$$

d) Do the algebra in more detail to obtain equation 11.22

β is S sparse and the positions of non-zero elements are denoted by set s, s^* is complement of s.

For any vector u of same dimensions as that of β then u_s is the vector obtained by making the elements zero at position $p \in s^*$.

As $\beta_{\bar{s}}^* = 0$, $||\beta||_1 = ||\beta_s||_1$

$||\beta^* + \hat{v}||_1 = ||\beta_s^* + \hat{v}_s||_1 + ||v_{s^*}||_1$

By triangular inequality, $||u - v||_1 \geq ||u||_1 - ||v||_1$, as $||u||_1 = \sum |u_i|$ and $|x - y| \geq |x| - |y|$,

therefore, $\sum |u_i - v_i| \geq \sum |u_i| - \sum |v_i|$

$||\beta_s^* - (-\hat{v}_s)||_1 \geq ||\beta_s^*||_1 - || - \hat{v}_s||_1 = ||\beta_s^*||_1 - ||\hat{v}_s||_1$

So, $||\beta_s^* + \hat{v}_s)||_1 + ||v_{s^*}||_1 \geq ||\beta_s^*||_1 - ||\hat{v}_s||_1 + ||v_{s^*}||_1$

$-||\beta^* + \hat{v}||_1 \leq -||\beta_s^*||_1 + ||\hat{v}_s||_1 - ||v_{s^*}||_1$

Applying this to 11.21,

$\frac{||X\hat{v}||_2^2}{2N} \leq \frac{w^T X\hat{v}}{N} + \lambda_N(||\beta^*||_1 - ||\beta_s^*||_1 + ||\hat{v}_s||_1 - ||v_{s^*}||_1)$

$\frac{||X\hat{v}||_2^2}{2N} \leq \frac{w^T X\hat{v}}{N} + \lambda_N(||\hat{v}_s||_1 - ||v_{s^*}||_1)$

> Holder's inequality states $||fog||_1 \leq ||f||_p||g||_q$, given $p, q \in [1, \infty)$ and $1/p + 1/q = 1$
>
> So, $||AB||_1 = || < A^T, B > ||_1 \leq ||A^T||_p||B||_q$, given $p, q \in [1, \infty)$ and $1/p + 1/q = 1$

$w^T X\hat{v}$ is a scalar so $w^T X\hat{v} = ||w^T X\hat{v}||_1$

Here $f = (w^T X)^T = X^T w$, $g = \hat{v}$, $p \to \infty$, and $q = 1$

So, $w^T X\hat{v} \leq ||X^T w||_\infty||\hat{v}||_1$

Hence, $\frac{||X\hat{v}||_2^2}{2N} \leq \frac{||X^T w||_\infty}{N}||\hat{v}||_1 + \lambda_N(||\hat{v}_s||_1 - ||v_{s^*}||_1)$

e) Derive equation 11.23

We'll take $\frac{1}{N}||X^T w||_\infty \leq \frac{\lambda_N}{2}$

$$\frac{||X\hat{v}||_2^2}{2N} \leq \frac{\lambda_N}{2}||\hat{v}||_1 + \lambda_N(||\hat{v}_s||_1 - ||v_{s^*}||_1)$$
$$\leq \frac{\lambda_N}{2}(||\hat{v}_s||_1 + ||\hat{v}_{s^*}||_1) + \lambda_N(||\hat{v}_s||_1 - ||v_{s^*}||_1)$$
$$\leq \frac{3\lambda_N}{2}||\hat{v}_s||_1 - \frac{\lambda_N||v_{s^*}||_1}{2}$$
$$\leq \frac{3\lambda_N}{2}||\hat{v}_s||_1 \quad \text{(as the second term with negative sign is positive)}$$

> Cauchy Schwartz Inequality : $||v.w||_1 \leq ||v||_2||w||_2$
>
> $v = v.I$
>
> $||vI||_1 \leq ||v||_2||I||_2 = \sqrt{n}||v||_2$
>
> If v is k-sparse then $v = v.S$ where S is I with $I_{i,i} = 0$ if $v_i = 0$
>
> $||S||_2 = \sqrt{k}$
>
> So, $||v||_1 \leq \sqrt{k}||v||_2$ if v is k-sparse

$$\frac{||X\hat{v}||_2^2}{2N} \leq \frac{3\lambda_N}{2}||\hat{v}_s||_1 \leq \frac{3\lambda_N\sqrt{k}}{2}||\hat{v}_s||_2 \leq \frac{3\lambda_N\sqrt{k}}{2}||\hat{v}||_2 \text{ as } ||v||_2 \geq ||v_s||_2$$
$$\frac{||X\hat{v}||_2^2}{2N} \leq \frac{3\lambda_N\sqrt{k}}{2}||\hat{v}||_2$$

f) Complete the proof assuming Lemma 11.1 to be true

Assuming lemma 1 to be true, we can apply restricted eigenvalue condition

$$\frac{1}{N}\frac{||X\hat{v}||_2^2}{||\hat{v}||_2^2} \geq \gamma, \text{ where } \gamma \text{ is a positive constant, (as } v^TX^TXv = ||Xv||_2^2)$$
$$\frac{1}{N}||X\hat{v}||_2^2 \geq \gamma||\hat{v}||_2^2$$
$$\frac{\gamma||\hat{v}||_2^2}{2} \leq \frac{3}{2}\lambda_N\sqrt{k}||\hat{v}||_2, \text{ by } 11.23$$
$$||\hat{v}||_2 \leq \frac{3}{\gamma}\lambda_N\sqrt{k}$$
$$||\hat{\beta} - \beta^*||_2 \leq \frac{3}{\gamma}\lambda_N\sqrt{k}, \text{ equation } 11.14\text{b}$$

g) Where does bound on λ_N show up

While deriving 11.23 we took $\lambda_N \geq \frac{2}{N}||X^Tw||_\infty$, we assumed it to introduce conic constraint in $\hat{v}$, so as to apply γ-RE condition .

h) Why is cone constraint required

Cone constraint gives the γ-RE condition, using which we bounded the the LASSO L2-error. Without γ-RE error couldn't be bound so no guarantees of the estimator. We need the γ-RE condition so we require the cone constraint.

i) This Theorem v/s Theorem 3

- Theorem 3 uses Restricted Isometry Property, whereas this theorem uses Restricted Eigenvalue Conditon.
- In both the theorems sensing matrix doesn't need to be orthonormal.

- Both theorems handle noisy measurements.
- Theorem 3 give bounds for compressible signals (signals in which some values are very-very smaller than others), while this theorem only considers sparse signals.
- Restricted Eigenvalue Condition is less restrictive than the Restricted Isometry Property, so this theorem requires weaker assumptions than Theorem 3.
- This theorem is more obvious as it have $\frac{k}{N}$ term in the bound as it states no method can decay more quickly than $\frac{k}{N}$, while theorem 3 doesn't have any say about it in it's bound.
- This theorem states that this estimator gives near oracle performance ($\sqrt{log(n)}$ is additional) if σ is previously known or estimated on Gaussian noise.

j) What is the common thread between the bounds on the 'Dantzig selector' and the LASSO?

- Both set lower bound of parameters in terms of $||X^T w||_\infty$;
  $\text{Dantzig: } \lambda \geq ||X^T w||_\infty, \text{ Lasso: } \lambda_N \geq \frac{2}{N}||X^T w||_\infty.$
- In the case when $\hat{\beta} \in \sum_k$, so that $\sigma_k(\hat{\beta})_1 = 0$;
  $\text{Dantzig: } ||\hat{v}||_2 \leq C_1\sqrt{k}\lambda, \text{ Lasso: } ||\hat{v}||_2 \leq \frac{C_2}{\gamma}\sqrt{k}\lambda_N$, Both of them has the parameter and $\sqrt{k}$ in there bounds.
- When adapting both the theorems to Gaussian noise model, the bounds on $||\hat{v}||_2$ have $\sqrt{k\log(p)}$ term.

k) What is the advantage of the square-root LASSO over the LASSO?

- The lasso construction relies on knowing the standard deviation σ of the noise.
- The square-root lasso eliminates the need to know or pre-estimate σ.
- Despite taking the square-root of the least squares criterion function, the problem retains global convexity making the estimator computationally feasible.
- This method also doesn't rely on normality or sub-Gaussianity of noise.
- It matches the performance of lasso with known σ , i.e., achieving near-oracle performance.

Q2

Filtered Back Projection using the Ram-Lak filter

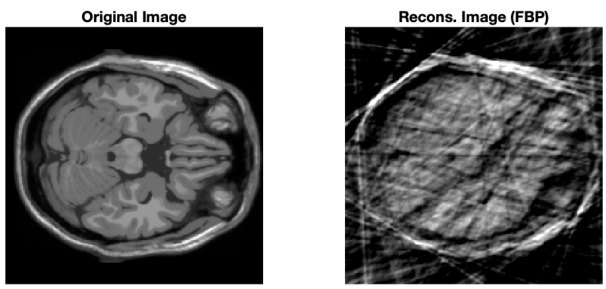

Fig 1. Reconstruction using filtered back projection using the Ram-Lak filter

Compression Sensing reconstruction (single slice)

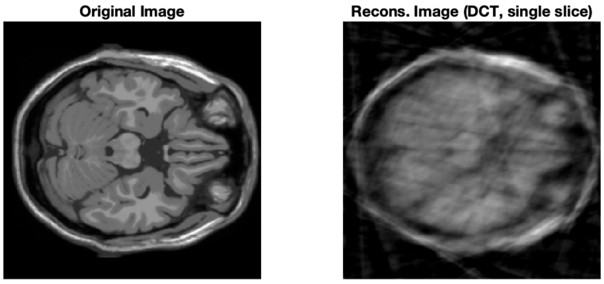

Fig 2. Reconstruction using Compressed Sensing on a single slice (2D-DCT basis).

Reconstruction using tow consecutive slices

$$E(\beta_1, \beta_2) = \left\| \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} - \begin{pmatrix} R_1U & 0 \\ R_2U & R_2U \end{pmatrix} \begin{pmatrix} \beta_1 \\ \Delta\beta_{21} \end{pmatrix} \right\|^2 + \lambda \left\| \begin{matrix} \beta_1 \\ \Delta\beta_{21} \end{matrix} \right\|_1$$

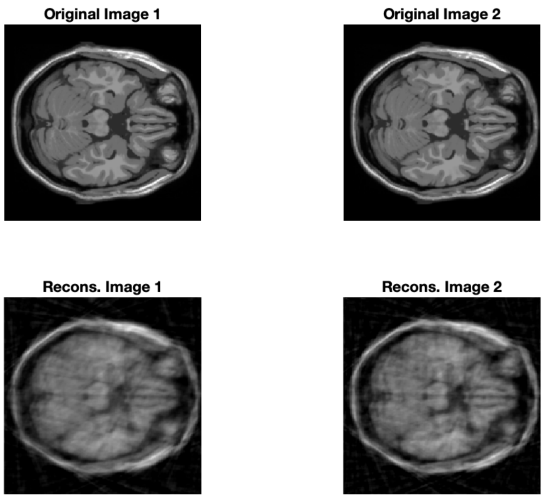

Fig 3. Reconstruction using CS on two consecutive slices (2D-DCT basis).

Reconstruction using three consecutive slices

$$E(\beta_1, \beta_2, \beta_3) = ||y_1 - R_1U\beta_1||^2 + ||y_2 - R_2U\beta_2||^2 + ||y_3 - R_3U\beta_3||^2 \\ + \lambda(||\beta_1||_1 + ||\beta_2 - \beta_1||_1 + ||\beta_3 - \beta_2||_1)$$

$$= ||y_1 - R_1 U \beta_1||^2 + ||y_2 - R_2 U(\beta_1 + \Delta\beta_{21})||^2 + ||y_3 - R_3 U(\beta_1 + \Delta\beta_{21} + \Delta\beta_{32})||^2$$
$$+ \lambda(||\beta_1||_1 + ||\Delta\beta_{21}||_1 + ||\Delta\beta_{32}||_1)$$

Final expression for reconstruction using 3 consecutive slices:

$$E(\beta_1, \beta_2, \beta_3) = \left\| \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} - \begin{pmatrix} R_1 U & 0 & 0 \\ R_2 U & R_2 U & 0 \\ R_3 U & R_3 U & R_3 U \end{pmatrix} \begin{pmatrix} \beta_1 \\ \Delta\beta_{21} \\ \Delta\beta_{32} \end{pmatrix} \right\|^2 + \lambda \left\| \begin{matrix} \beta_1 \\ \Delta\beta_{21} \\ \Delta\beta_{32} \end{matrix} \right\|_1$$

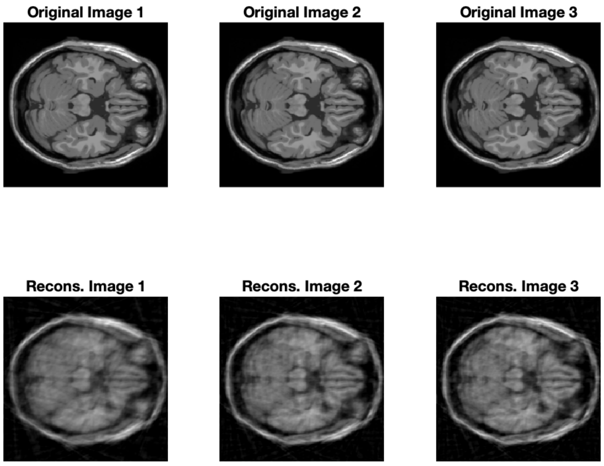

Fig 4. Reconstruction using CS on three consecutive slices (2D-DCT basis).

Q3

(a) Shifting :

$$R(g(x,y))(\rho,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x,y)\delta(x\cos\theta + y\sin\theta - \rho)dxdy$$
$$R(g(x-x_0,y-y_0))(\rho,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x-x_0,y-y_0)\delta(x\cos\theta + y\sin\theta - \rho)dxdy$$

With change of variable ($p = x - x_0, q = y - y_0$):

$$R(g(x',y'))(\rho,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x',y')\delta((x'+x_0)\cos\theta + (y'+y_0)\sin\theta - \rho)dx'dy'$$
$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x',y')\delta(x'\cos\theta + y'\cos\theta - (\rho - x_0\cos\theta - y_o\sin\theta))dx'dy'$$
$$= R(g(x,y))(\rho - x_0\cos\theta - y_0\cos\theta, \theta)$$

(b) Rotation :

$$g'(r,\psi) = g(r, \psi - \psi_0)$$

The graph represented by g is rotated by an angle ψ_0.

Polar equation of line $x\cos\theta + y\sin\theta = \rho$ will be $r\cos\theta\cos\psi + r\sin\theta\sin\psi - \rho$.

$$\begin{aligned} & r\cos\theta\cos\psi + r\sin\theta\sin\psi - \rho \\ & = rcos(\psi - \theta) - \rho \end{aligned}$$

Using these in the Radon transform, we get:

$$\begin{aligned} R(g')(\rho,\theta) &= \int_{-\infty}^{\infty}\int_{0}^{2\pi} g'(r,\psi)\delta(r\cos(\psi-\theta)-\rho)d\psi dr \\ &= \int_{-\infty}^{\infty}\int_{0}^{2\pi} g(r,\psi-\psi_0)\delta(r\cos(\psi-\theta)-\rho)d\psi dr \end{aligned}$$

With change of variable ($\psi' = \psi - \psi_0$), we get:

$$\begin{aligned} R(g')(\rho,\theta) &= \int_{-\infty}^{\infty}\int_{0}^{2\pi} g(r,\psi')\delta(r\cos(\psi'-(\theta-\psi_0))-\rho)d\psi' dr \\ &= R(g)(\rho,\psi_0-\theta) \end{aligned}$$

(c) Convolution :

$$(f*k)(x,y) := \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x-\tau,y-\varphi)k(\tau,\varphi)d\tau d\varphi$$

$$\begin{aligned} & LHS = R_\theta(f*k)(\rho) \\ = & \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x-\tau,y-\varphi)k(\tau,\varphi)\delta(x\cos\theta+y\sin\theta-\rho)d\tau d\varphi d\rho \end{aligned}$$

$$\begin{aligned} & RHS = R_\theta(f)*R_\theta(k) \\ & = \int_{-\infty}^{\infty} R_\theta(f)(\rho-\varrho)R_\theta(k)(\varrho)d\varrho \end{aligned}$$

Since,

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \delta(a-\rho+\varrho)\delta(a-\varrho)d\rho d\varrho = \int_{-\infty}^{\infty} \delta(a-\rho)d\rho$$

And, we can represent $f(x',y')$ as $f(x-\tau,y-\varphi)$ to have same integral (both from $-\infty \to \infty$). We get,

$$\begin{aligned} & \int_{-\infty}^{\infty} R_\theta(f)(\rho-\varrho)R_\theta(k)(\varrho)d\varrho \\ = & \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x-\tau,y-\varphi)k(\tau,\varphi)\delta(x\cos\theta+y\sin\theta-\rho)d\tau d\varphi d\rho \\ & \therefore LHS = RHS \end{aligned}$$

Q4

x is an s-sparse vector, and A is a unit normalised matrix.

$$||Ax||_2^2 = ||x^T A^T Ax||_2 = ||x_s^T A_s^T A_s x||_2$$

where A_s is obtained by stripping off the columns of A corresponding to zero-valued elements of x, like if $x_i = 0$ then A_s doesn't have A_i

Because $Ax = \sum A_i x_i$, so removing these doesn't alter our formula

$$||AB||_2 \leq ||A||_2 ||B||_2$$

$$\text{So, } ||Ax||_2^2 \leq ||x_s^T||_2 ||A_s^T A_s||_2 ||x_s||_2 = ||x||_2^2 ||A_s^T A_s||_2$$

The diagonal entries of $A_s^T A_s$ would be of the type $A_i^T A_i$, where A_i is the i^{th} column of A.

Since it is unit normalized, $A_i^T A_i = 1$

$$\mu = \max_{i,j,i\neq j} A_i^T A_j^T$$

By Gershgorin's theorum on a matrix B, for all eigenvalues of B, λ,

$B_{ii} - R_i \leq \lambda \leq B_{ii} + R_i$, where R_i is the absolute sum of offdiagonal values of row i, for all i

$$B = A_s^T A_s, \text{ so } B_{ii} = 1, \max_{i\neq j} B_{ij} \leq \mu$$

$R_i \leq (S-1)\mu$, as there are S-1 offdiagonal elements

$$||A_s^T A_s||_2 = \lambda_{max} \text{ of } A_s^T A_s$$

$$\text{So by Gershgorin, } \lambda_{max} \leq B_{ii} + R_i \leq 1 + (S-1)\mu$$

$$||A_s^T A_s||_2 ||x||_2^2 \leq (1 + (S-1)\mu) ||x||_2^2$$

$$||Ax||_2^2 \leq (1 + (S-1)\mu) ||x||_2^2$$

But by RIP, δ_s is the smallest constant such that $||Ax||_2^2 \leq (1+\delta_s)||x||_2^2$

$$\text{Therefore, } \delta_s \leq (S-1)\mu$$

Q5

- Radio Frequency Tomography for Tunnel Detection
- IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 48, NO. 3, MARCH 2010

The ground is modelled as a homogeneous medium with relative dielectric permittivity ϵ_D, conductivity σ_D, and permeability μ_0. The tunnels or voids are assumed to reside in the investigation domain D. We assume the relative dielectric permittivity profile $\epsilon_r(\mathbf{r}')$ and the conductivity profile $\sigma(\mathbf{r}')$ inside the investigation domain D as unknowns of the problem.

The sources are N electrically small dipoles (of length Δl^t) or loops (of area A^t) def with current I^t and located at position $\mathbf{r}_n^t$ and with dipole moment directed along the unit vector $\mathbf{a}_n^t$. For each transmitting antenna, the scattered field $\mathbf{E}^S$ is collected by M receivers, located at $\mathbf{r}_m^\tau$ points n space.

The inverse problem is recast in terms of the unknown dielectric permittivity constrast:

$$\epsilon_\delta(\mathbf{r}') = \epsilon_r(\mathbf{r}') - \epsilon_D + j\frac{\sigma(\mathbf{r}') - \sigma_D}{2\pi f \epsilon_0}$$

The wavenumber inside D can be expressed as:

$$
\begin{aligned}
k^2(\mathbf{r}^{'}) &= \omega^2\mu_0\epsilon_r(\mathbf{r}^{'}) + j\omega\mu_0\sigma(\mathbf{r}^{'}) \\
&= k_D^2 + k_0^2\epsilon_\delta(\mathbf{r}^{'}) \\
k_D &= \omega\sqrt{\mu_0\epsilon_0\epsilon_D + j\mu_0\sigma_D/\omega} \\
k_0 &= \omega\sqrt{\mu_0\epsilon_0}
\end{aligned}
$$

For each point in $\mathbf{r}^{'}$ in region D, the vector wave equation holds:

$$\nabla\times\nabla\times\mathbf{E}(\mathbf{r}^{'}) = [k_D^2 + k_0^2\epsilon_\delta(\mathbf{r}^{'})]\mathbf{E}(\mathbf{r}^{'})$$

Using Dyadic Green's function and Born approximation:

$$\mathbf{E}^S(\mathbf{r}) \approx k_0^2 \int\int_D\int \underline{\underline{\mathbf{G}}}(\mathbf{r},\mathbf{r}^{'}).\,\mathbf{E}^I(\mathbf{r}^{'})\epsilon_\delta(\mathbf{r}^{'})d\mathbf{r}^{'}$$

$\mathbf{E}(\mathbf{r}^{'})$ is the total field in the investigation domain D, given as superposition of the incident field $\mathbf{E}^I(\mathbf{r}^{'})$ and the field $\mathbf{E}^S(\mathbf{r})$ scattered by the targets.

$$
\begin{aligned}
\mathbf{E}^S(\mathbf{r}_n^t,\mathbf{r}_m^\tau) &= \mathbf{L}(\epsilon_\delta(\mathbf{r}^{'})) \\
&= Qk_0^2\int\int_D\int[\mathbf{a}_m^\tau.\,\underline{\underline{\mathbf{G}}}(\mathbf{r}_m^\tau,\mathbf{r}^{'})] \\
&\quad .\,[\underline{\underline{\mathbf{G}}}(\mathbf{r}^{'},\mathbf{r}_n^t).\,\mathbf{a}_n^t]\epsilon_\delta(\mathbf{r}^{'})d\mathbf{r}^{'}
\end{aligned}
$$

where $Q = j\omega\mu_0\Delta l^t I^t$ for electrically small dipole or $Q = -j\omega\mu_0 A^t I^t$ for an electrically small loop. The equation gives the field received by a dipole or loop with moment direction $\mathbf{a}_m^\tau$ positioned at $\mathbf{r}_m^\tau$ due to an equivalent current distribution defined inside the investigation domain D.

The problem of finding the dielectric profile is to compute the inverse of linear operator $\mathbf{L}$, connecting the unknown dielectric profile and the scattered field data.

The problem after discretization is:

$$\underline{E}^S = \underline{\underline{\mathbf{L}}}\underline{\epsilon}_\delta$$

where $\mathbf{L}$ is now a matrix with dimensions $NM\times K$ and $\underline{E}^S$, $\underline{\epsilon}_\delta$ are column vectors.

The paper present four inversion strategies :-

1. $Levenberg\text{-}Marquardt$ (LM) regularization procedure
2. $Truncated\ singular\text{-}value\ decomposition$ (TSVD)
3. $Back\text{-}propagation$ approach
4. $Fourier\text{-}Bojarski$ approach

LM Regularization procedure :

$$\underline{\hat{\epsilon}}_\delta(\beta) = (\underline{\underline{\mathbf{L}}}^H\underline{\underline{\mathbf{L}}} + \beta\mathbf{I})^{-1}\underline{\underline{\mathbf{L}}}^H\underline{E}^S$$

where $\mathbf{L}^H$ denotes the adjoint of $\mathbf{L}$ and β is the regularization parameter in the Tikhonov sense.