Elevation Estimation in 3D Radar by an Ensemble Regression Model for Surveillance Applications

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AI for Radar

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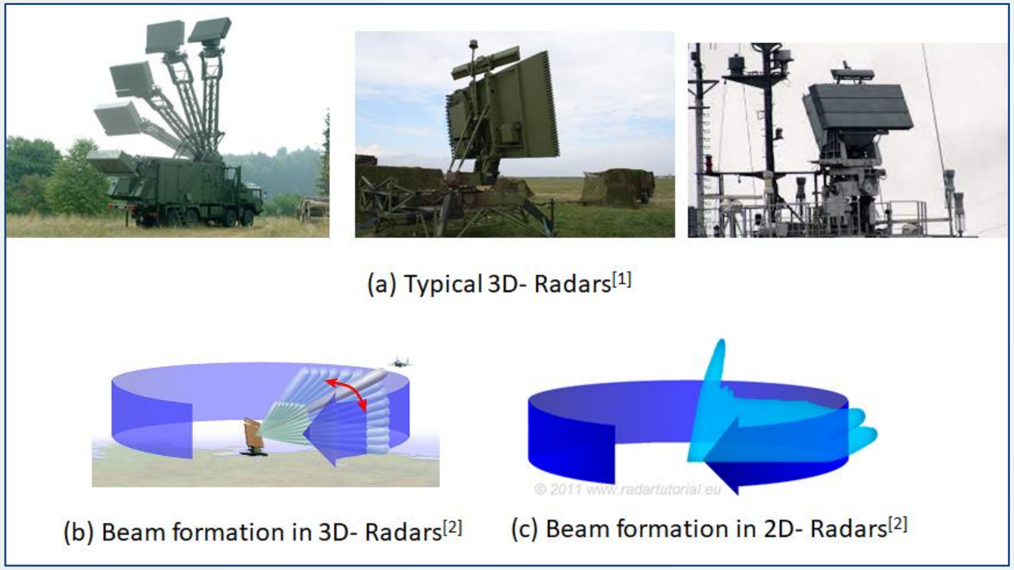
Agenda

- Existing challenges in the elevation estimation of aerial targets in 3D surveillance radars
- Motivation to use the AI in elevation estimation techniques
- Implementation & testing of the proposed elevation estimation techniques using MATLAB tools
- Performance improvement using AI techniques

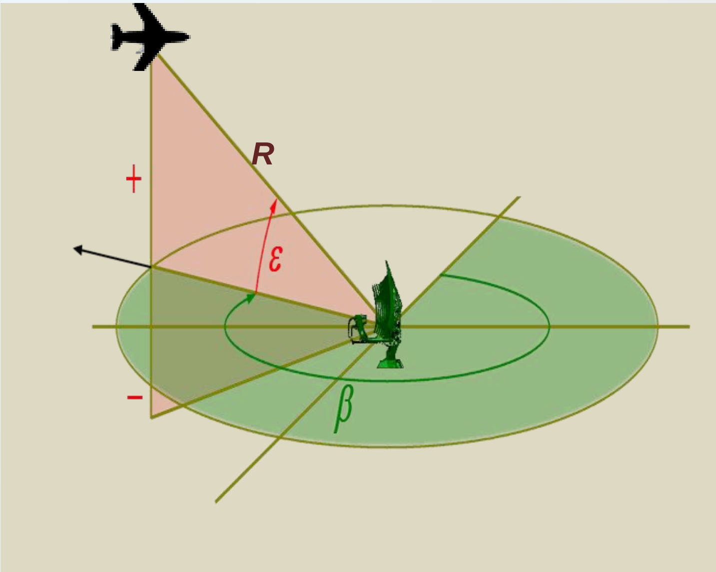
Introduction: 3D Surveillance Radars

- 3D surveillance radars determine three main parameters: *Range*, *Azimuth*, and *Elevation* of the aerial target.



(a) Typical 3D-Radar, (b) Beam formation in 3D Radar, (c) Beam formation in 2D Radar

[1]: https://radartutorial.org, https://Wikimedia.org, https://drdo.gov.in [2]: https://radartutorial.org



R: Target Range; ε : Elevation Angle ; β : Azimuth

Basics of Elevation Angle Estimation

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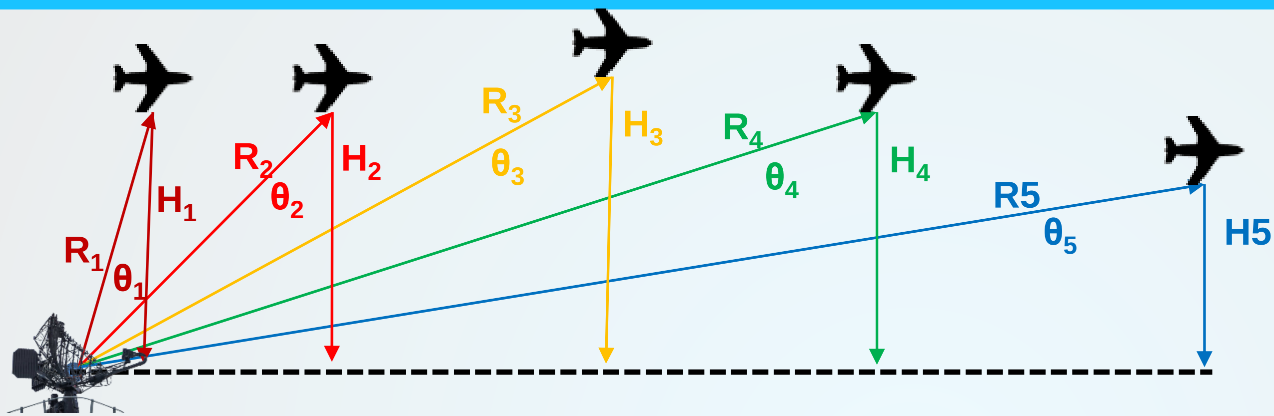
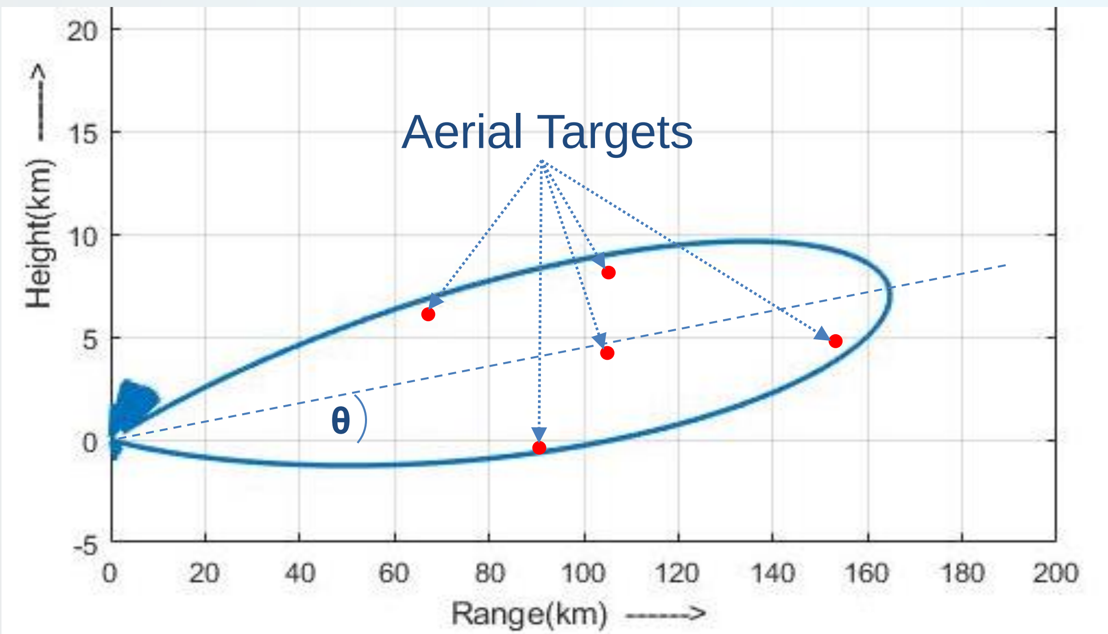
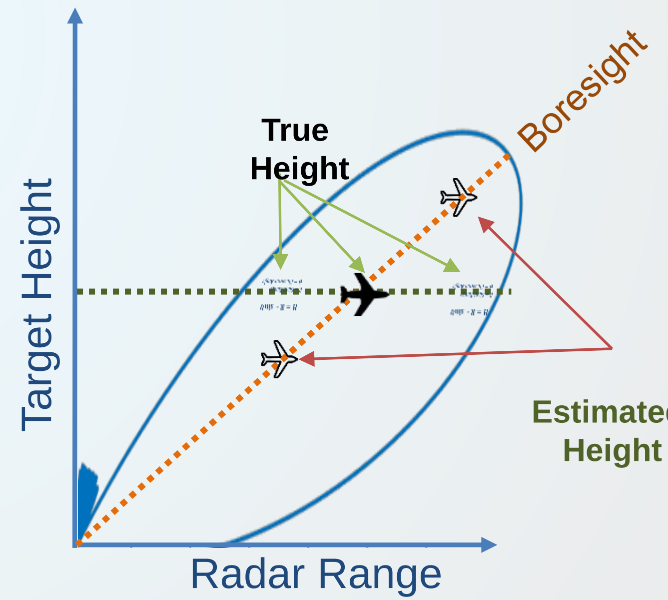


$$H = R * \sin\theta$$

R = Slant Range
Θ = Elevation Angle





Limitation of elevation estimation with single broad beam in surveillance application

3D Surveillance Radars

3D Surveillance Radars Jointly developed by BEL & LRDE

3DTCR

3DCAR

REVATHI

ASLESHA MK-I

ASLESHA MK-II

MPR

History of Elevation Estimation

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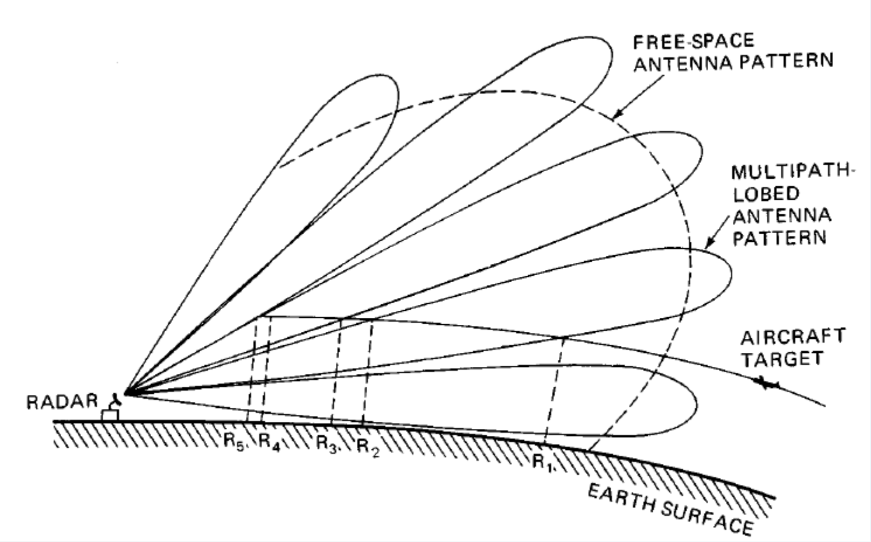
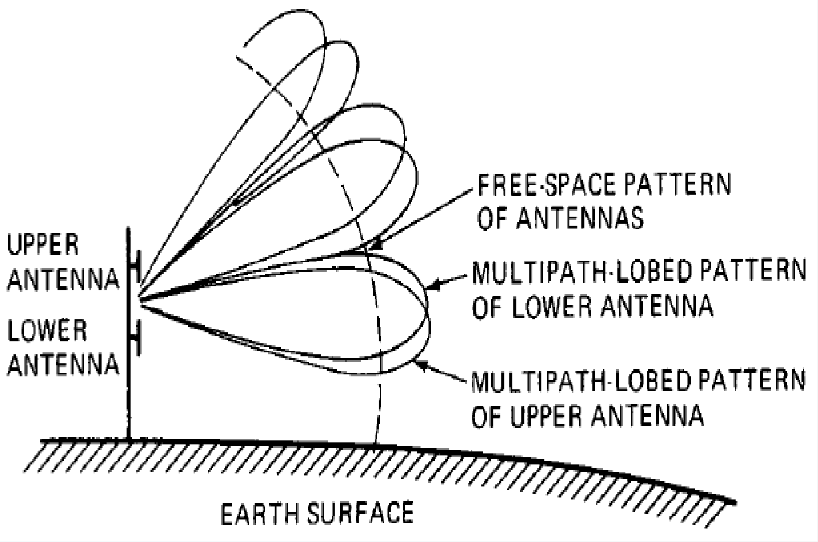
Early radar height finding techniques.



Method of multipath nulls



Amplitude comparison using multipath lobes

U.S. Naval research laboratory (1939):

Estimate the height of the target by the range of its very first detection with the **prior knowledge** of the **shape of antenna pattern due to multipath reflection**.

Traditional Techniques for estimating Elevation angle

- Traditional methods of calculating elevation angle in 3D Radars.

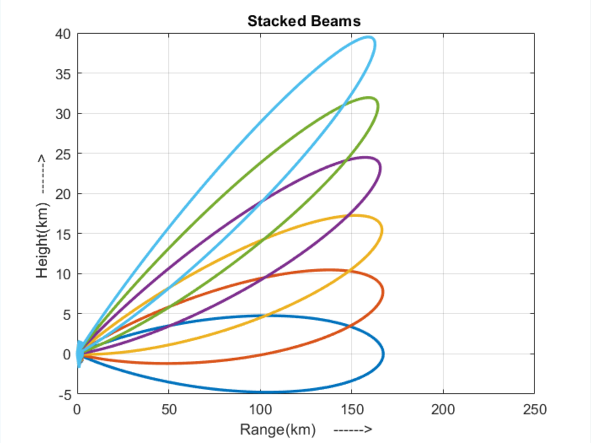
  a) **Elevation scanning through pencil beam,**

  b) **Stacked Beams,**

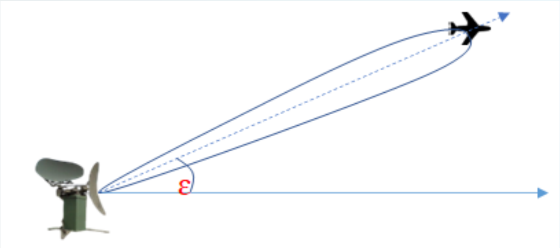
  c) **Sequential Lobing,**

  d) **Conical Scanning,**

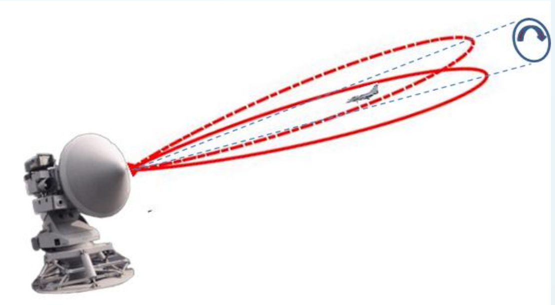
  e) **Mono-Pulse.**



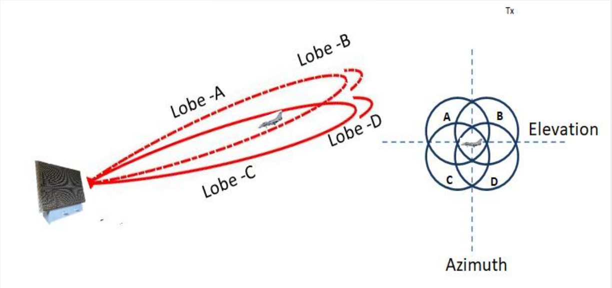
(b)



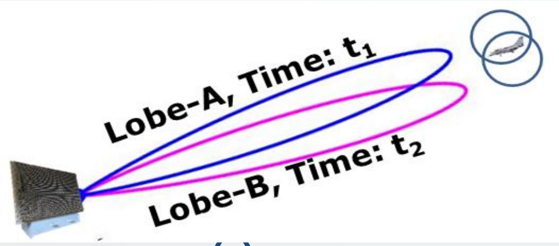
(a)



(d)



(e)



(c)

Challenges of Elevation Estimation

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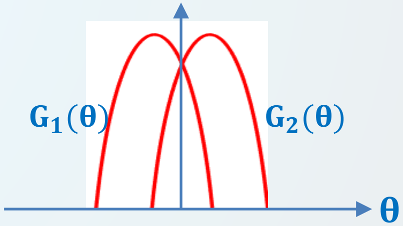
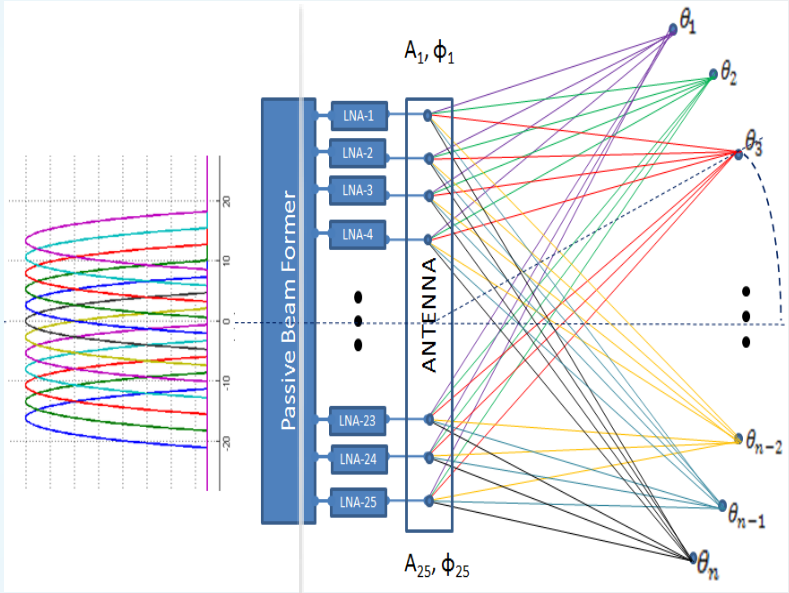
- Mono-pulse technique used for elevation and azimuth estimation in tracking radar applications.
- Multiple stacked elevation beams to simultaneously estimate the elevation angle of targets present in a particular azimuth.
- Target must be present in at least two elevation beams for elevation estimation
- Fundamental accuracy (rmse) of elevation estimation given as $\left[E(\hat{\theta}-\theta)^2\right]^{1/2} = \frac{1}{|\dot{f}|}\left(\frac{1+f^2}{2*SNR}\right)^{1/2}$; $where\ f = f(\theta) = \frac{G_2(\theta)}{G_1(\theta)}$; $f^{\cdot} = \frac{df(\theta)}{d\theta}$



- Accuracy of elevation extraction depends upon the presence of ***thermal noise***, ***antenna pattern error***, ***channel mismatch error***, ***platform orientation***, ***platform stabilization***, ***jamming and clutter***, ***multipath reflection***, ***target fluctuation***, ***thresholding effect, channel combining effect***, ***beam pointing errors , SNR of each beam*** etc.

Simulation of Multiple Stacked Beams using Antenna Array Factor

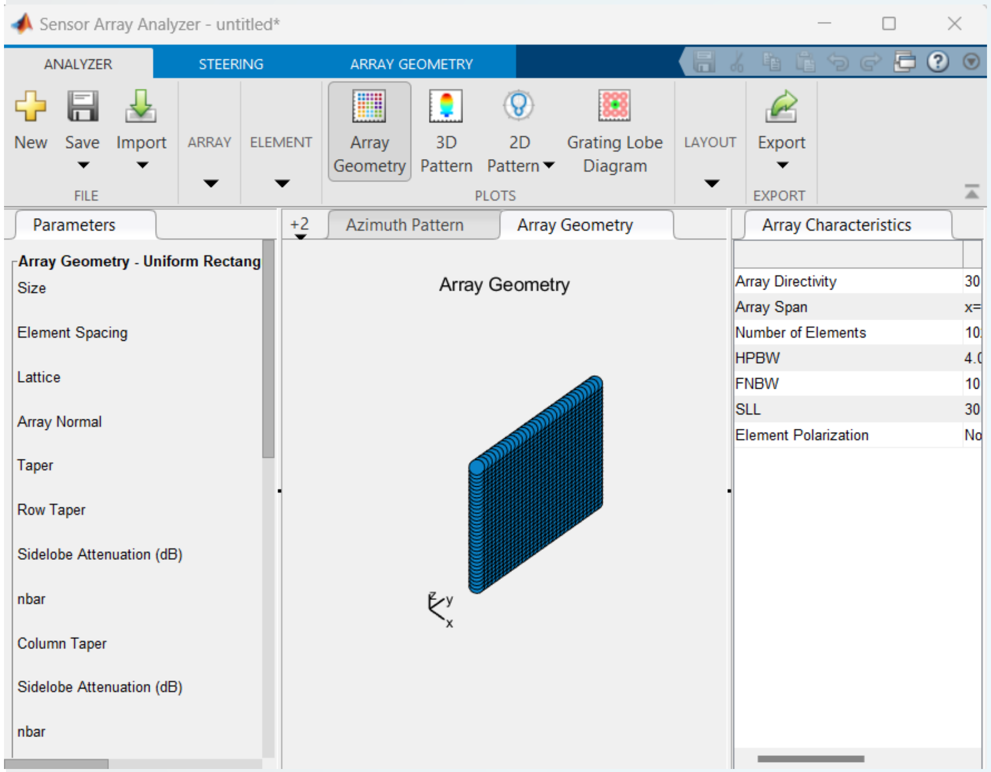
$$Beam\_m = \sum_{\theta_n=-30}^{\theta_n=+30} \sum_{n=1}^{N} A_n . \exp\left[j.\left(\varphi_n + \left(\frac{2\pi d}{\lambda}\right)\left(n - \frac{N}{2} - 0.5\right)\sin(\theta_n)\right)\right]$$

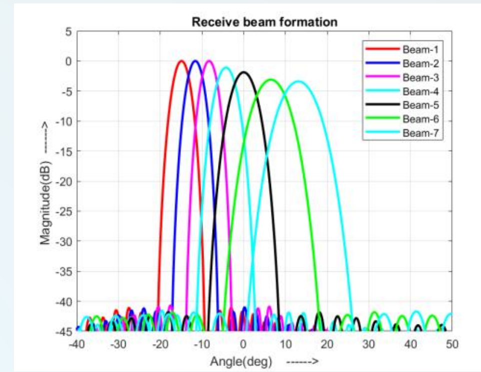


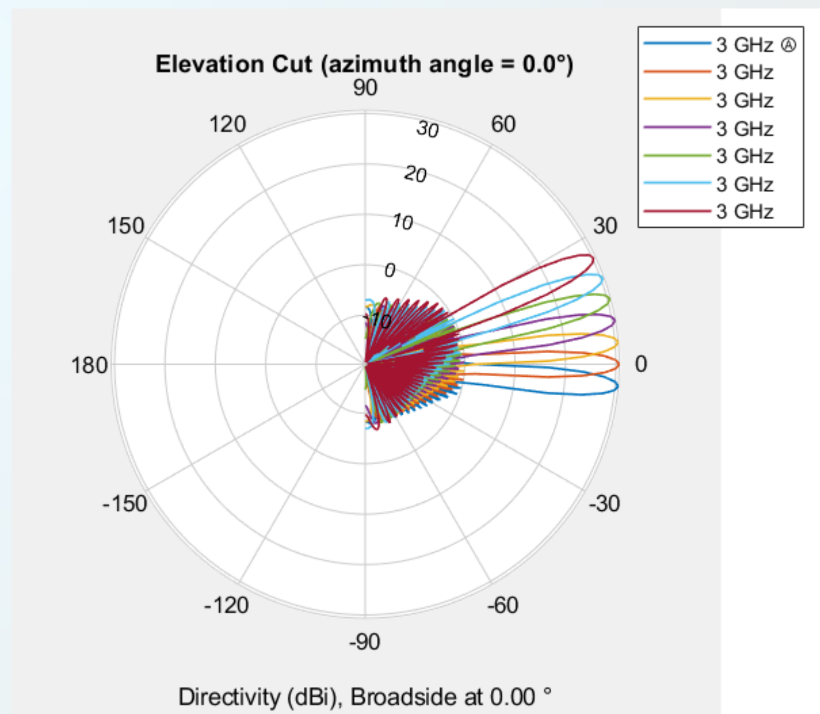

```
lambda_mm = lambda * 1000;
k =2*pi/lambda_mm;
d=65.6;
N1=32;n1=1:N1; d1=(n1-N1/2-0.5)*d;
N2=32;n1=1:N2; d2=(n1-N2/2-0.5)*d;
N3=32;n1=1:N3; d3=(n1-N3/2-0.5)*d;
N4=25;n4=1:N4; d4=(n4-N4/2-0.5)*d;
N5=21;n5=1:N5; d5=(n5-N5/2-0.5)*d;
N6=16;n6=1:N6; d6=(n6-N6/2-0.5)*d;
N7=15;n7=1:N7; d7=(n7-N7/2-0.5)*d;
count_rbf=1;
elev_range = -60:0.1:60;

 for theta_elev = elev_range
    elev=(theta_elev)*pi/180;
     far_field_beam1(count_rbf)=(amp_port_1).*exp(1i*ph_port_1)*(exp(1i*k*d1*sin(elev))');
     far_field_beam2(count_rbf)=(amp_port_2).*exp(1i*ph_port_2)*(exp(1i*k*d2*sin(elev))');
     far_field_beam3(count_rbf)=(amp_port_3).*exp(1i*ph_port_3)*(exp(1i*k*d3*sin(elev))');
     far_field_beam4(count_rbf)=(amp_port_4).*exp(1i*ph_port_4)*(exp(1i*k*d4*sin(elev))');
     far_field_beam5(count_rbf)=(amp_port_5).*exp(1i*ph_port_5)*(exp(1i*k*d5*sin(elev))');
     far_field_beam6(count_rbf)=(amp_port_6).*exp(1i*ph_port_6)*(exp(1i*k*d6*sin(elev))');
     far_field_beam7(count_rbf)=(amp_port_7).*exp(1i*ph_port_7)*(exp(1i*k*d7*sin(elev))');
  count_rbf=count_rbf+1;
 end
```

Simulation of Multiple Stacked Beams

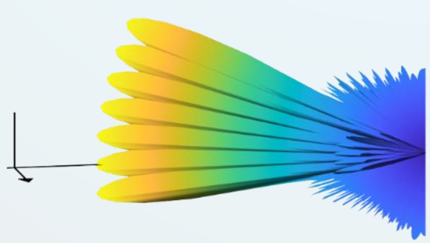




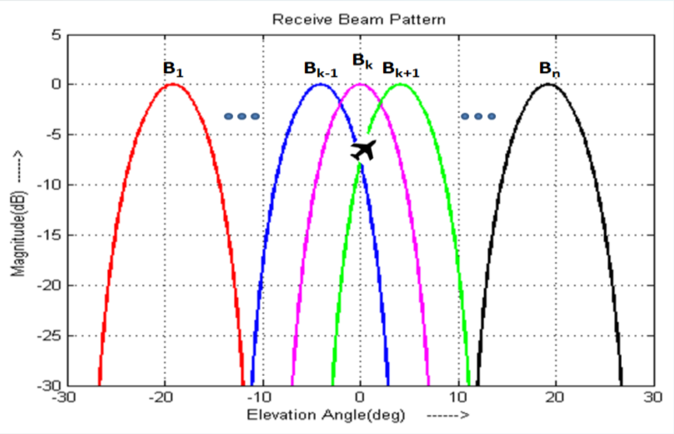


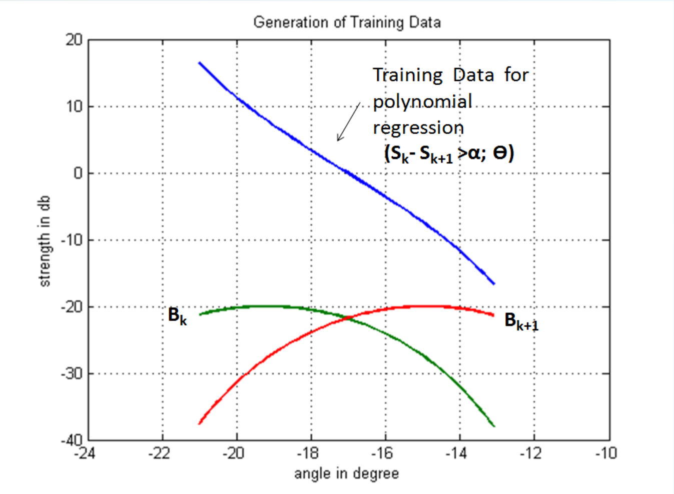
Elevation Stacked beam formation

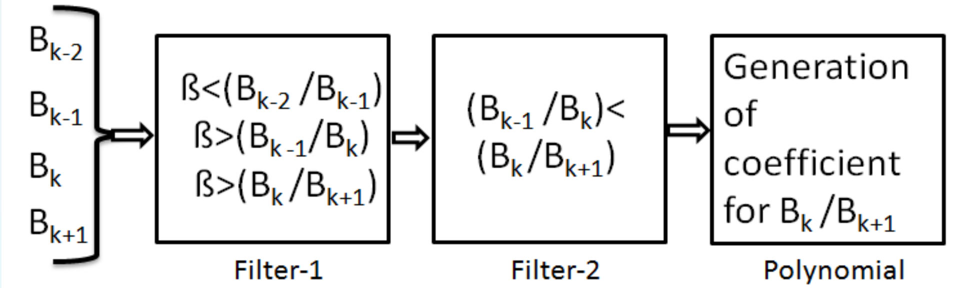
MATLAB
Phased Array Toolbox
Sensor Array Analyzer App



Estimating Target Elevation Angle in Multiple Stacked Beams

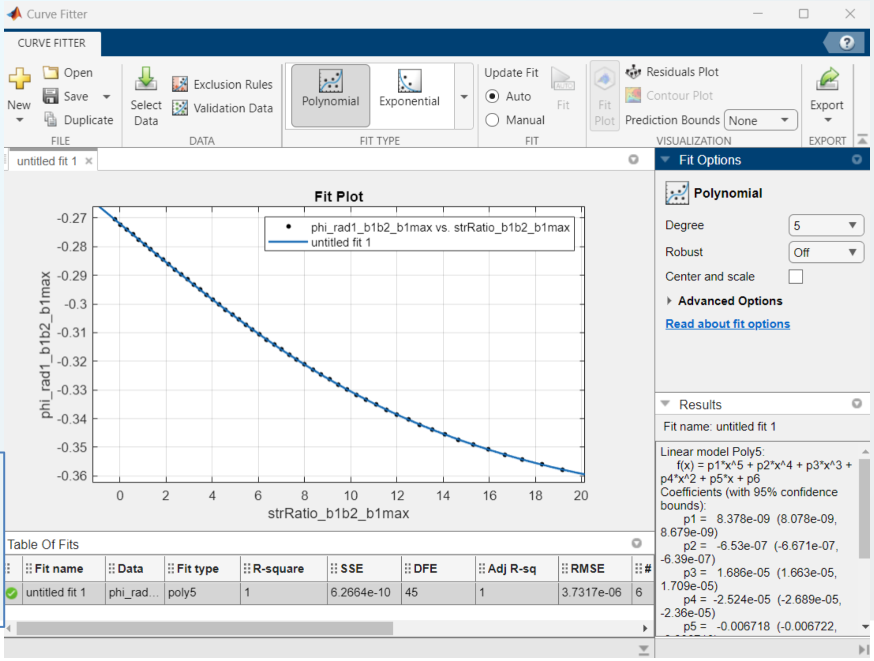






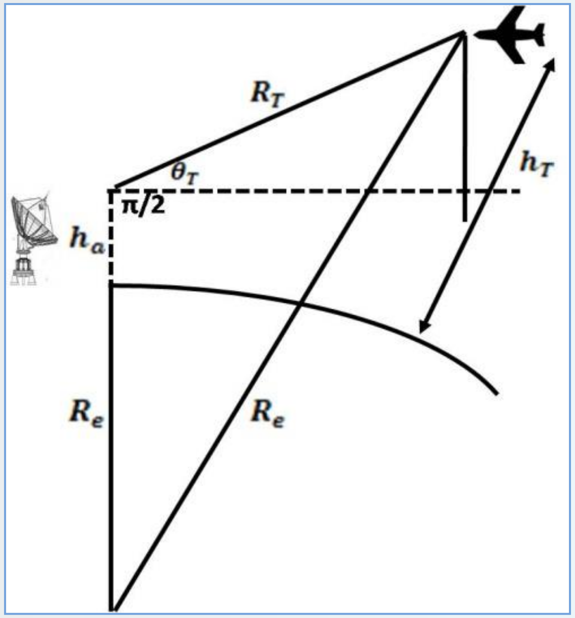
$$\hat{\theta} = C_n(\gamma)^n + C_{n-1}(\gamma)^{n-1} + \cdots C_2(\gamma)^2 + C_1(\gamma) + C_0$$

Where, $\gamma = S_k - S_{k+1}(in\ db\ Scale)$ and $\hat{\theta}$ is in Rad. $C_n, C_{n-1}, \ldots, C_2, C_1, C_0$ are the coefficient of the nth degree polynomial.



MATLAB
Curve Fitting Toolbox
Curve Fitter App

Target Height from Estimated Elevation Angle



Spherical Earth Geometry

By Using Cosine Rule,

$$h_T = \sqrt{(kR_e + h_a)^2 + {R_T}^2 + 2\,R_T(kR_e + h_a)\sin\theta_T} - kR_e$$

Where,

θ_T = Estimated target elevation angle.

R_e= Earth radius,

h_a= Antenna Height from ground,

R_T= Target range,

h_T = Target height above sea level,

k = Refractivity factor (for standard atmospheric condition $\boldsymbol{k = 4/3}$),

kR_e= Effective earth radius.

Finding the value of K:

Given N (refractivity) = -39 /km

$$\frac{dn}{dh} = \frac{dN/dh}{10^6} = -39\,X\,10^{-6}/km$$

Substituting $\frac{dn}{dh}$ in above equation, we get

$$k = \frac{1}{1 - 6370.88(39\,X10^{-6})} = 1.33 = 4/3$$

MATLAB function:

tgtht = el2height(el,anht,R)

Calibration Methods for Target Height Accuracy

Radar Calibration Pre Condition

- Clear weather condition.
- Radar should not have Jamming and heavy clutter condition.
- No variation in gain of multiple beams.
- Antenna tilts must be constant during measurement.
- Absence or very least effect of Multipath.
- Target must lie in clear line of site.

Reference Target Height:

- Measured aircraft height by its own instrument and communicated to radar.
- Measured barometric aircraft height communicated to radar in response to IFF interrogation.
- By GPS method (Duel GPS).

Measurement Methods for Target Height Accuracy

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Percentage Height Accuracy

Table-2
Experimental Data for Percentage Height Accuracy

No. of Scans	True Target Height (Km) (H)	Radar Estimated Height (Km) ($\hat{H}$)	Measurement Error	
			$\lvert H - \hat{H} \rvert$ (meters)	Pass/ Fail
1	10.67	10.78	106	✓
2	10.67	11.20	530	×
3	10.67	10.44	234	✓
4	10.67	10.88	210	✓
5	10.67	10.31	364	✓
6	10.67	10.84	170	✓
7	10.67	10.51	159	✓
8	10.67	10.82	148	✓
9	10.67	10.79	125	✓
10	10.67	10.12	550	×

$$\%\ Height\ Accuracy = \frac{Total\ Accepted\ Scans}{Total\ observed\ Scans}$$

$$Height\ Accuracy = \frac{17}{20} = 85\ \%$$

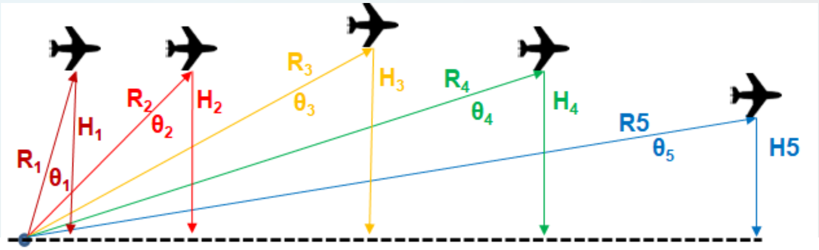
RMSE (Root Mean Square Error)

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(H_i - \widehat{H_i})^2}{n}}$$

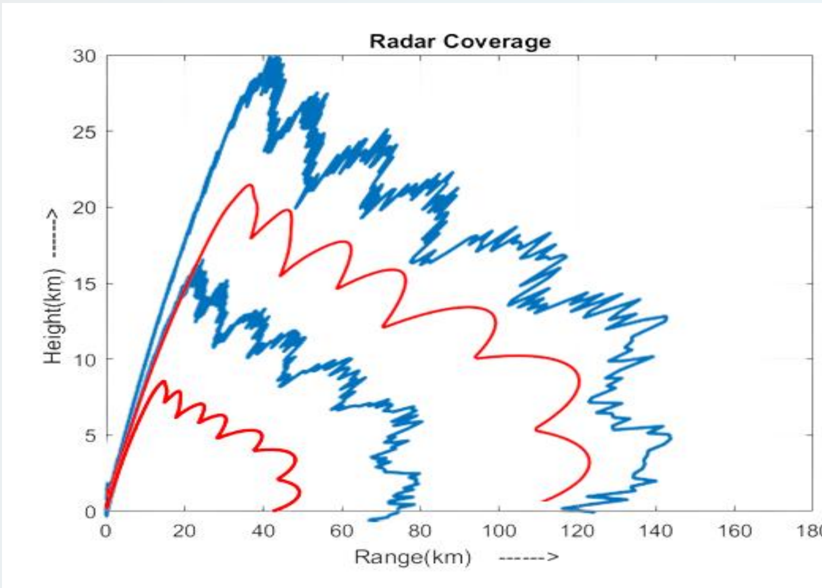
Where Hi = True Target Height, $\widehat{H_i}$ =Radar Estimated Target Height, n = Total number of observed scans.

RMSE value calculated from Table-2 is 286.85 meter which is less than Target Height Accuracy specified (500 meter).

MATLAB
Phased Array Toolbox
Radar Toolbox



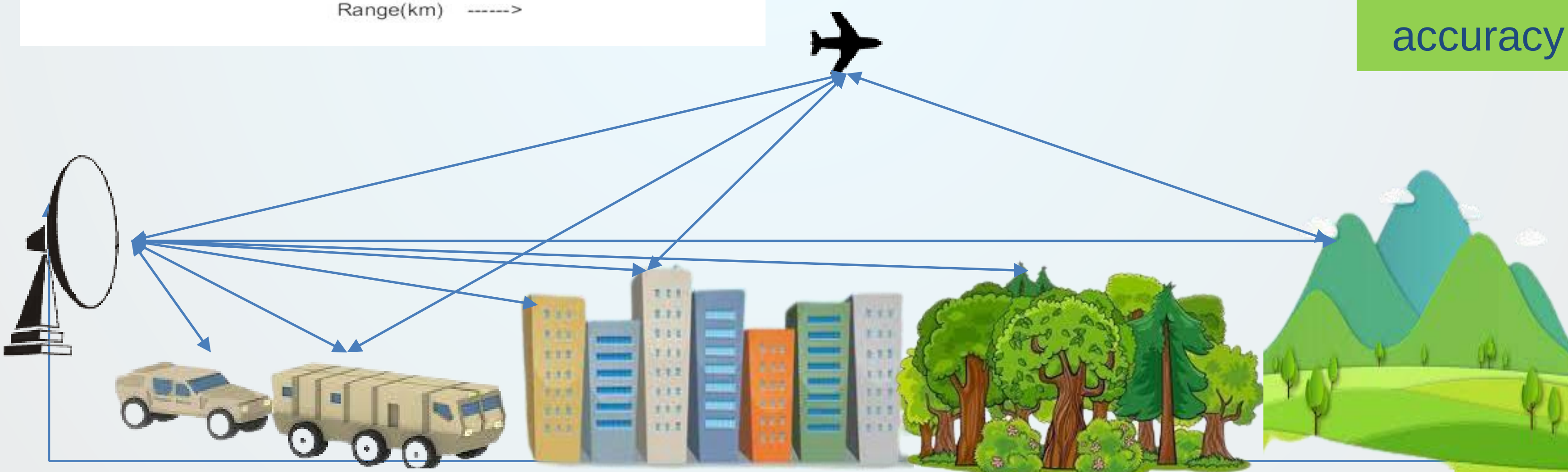
Multipath Effects in Height Estimation



Ground Reflection (Multipath)

High Reflection → Poor Elevation Estimation accuracy

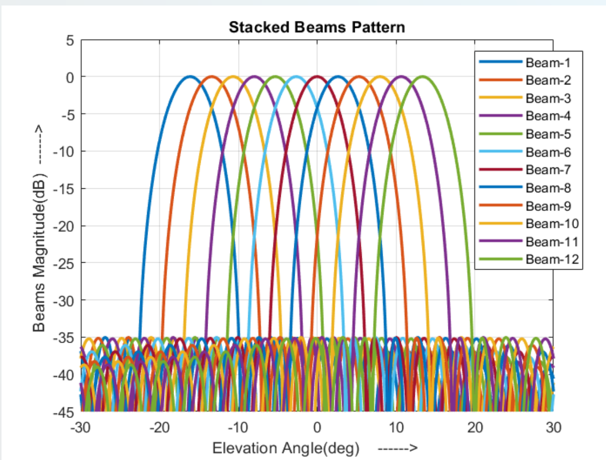
Low Reflection → Good Elevation Estimation accuracy



Unpredictable Radar environment

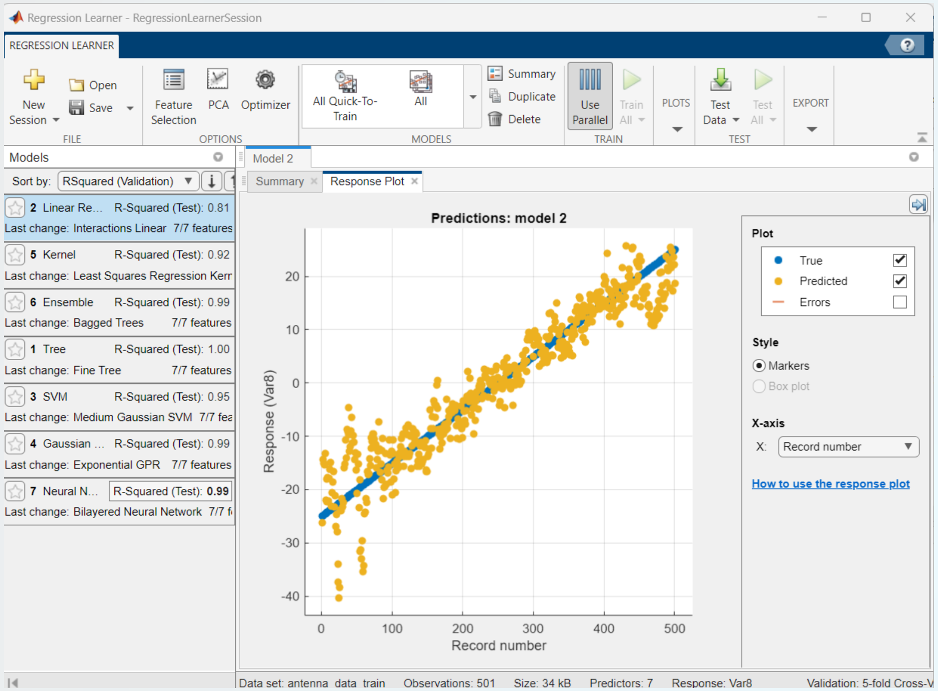
Elevation Angle Estimation Using AI

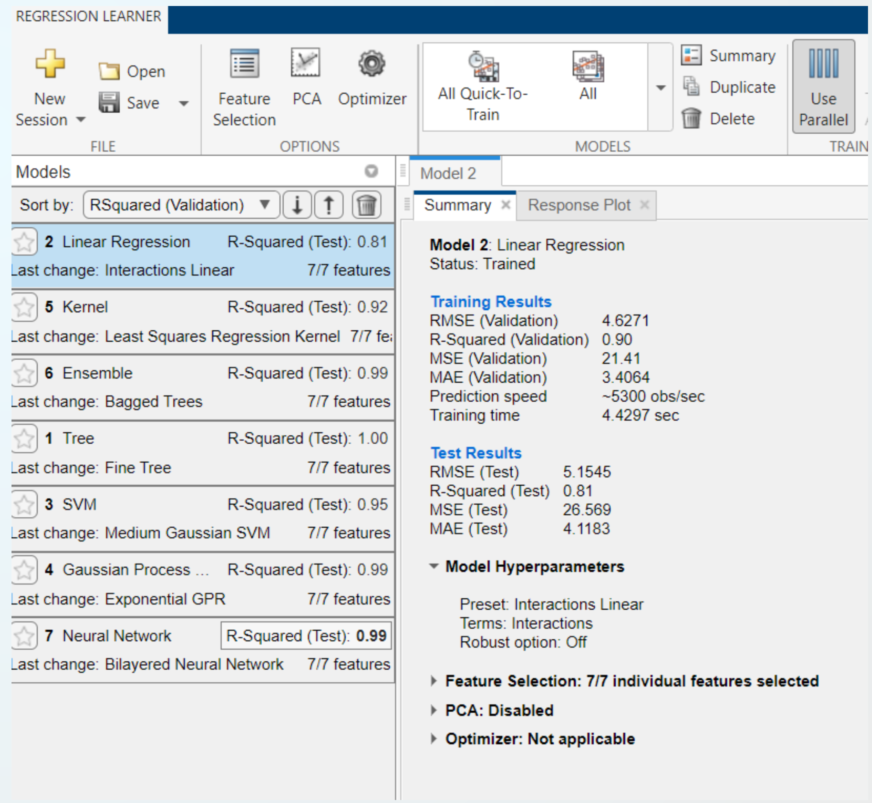
- AI techniques can overcome Antenna pattern error, channel mismatch error, platform orientation, platform stabilization, jamming and clutter, multipath reflection, target fluctuation, etc.
- AI techniques for elevation estimation make more robust and less susceptible to environmental noise and other variations.
- Various regression techniques have been investigated using the *Regression Learning App (in MATLAB).*



Beam 1	Beam 2	Beam 3	Beam 4	Beam 5	Beam 6	Beam 7	Beam 8	Beam 9	Beam 10	Elevation Angle
-19.6088	2.9340	24.4296	29.9205	26.9463	12.5378	-6.1245	-5.2309	-6.2498	-18.3524	-7.6000
-27.3690	1.0578	24.0273	29.8726	27.2160	13.4670	-5.6308	-5.0948	-6.7057	-22.4366	-7.5000
-34.5199	-1.1077	23.6071	29.8135	27.4719	14.3457	-5.2971	-5.0400	-7.2598	-30.5848	-7.4000
-21.9929	-3.6928	23.1683	29.7430	27.7144	15.1786	-5.1223	-5.0669	-7.9263	-35.5360	-7.3000
-17.1620	-6.9518	22.7103	29.6612	27.9437	15.9699	-5.1135	-5.1776	-8.7249	-24.0157	-7.2000
-14.1717	-11.4972	22.2321	29.5679	28.1601	16.7228	-5.2866	-5.3758	-9.6834	-19.2597	-7.1000
-12.0458	-19.6614	21.7329	29.4630	28.3636	17.4404	-5.6702	-5.6675	-10.8430	-16.2420	-7
-10.4322	-28.3792	21.2118	29.3465	28.5546	18.1252	-6.3121	-6.0611	-12.2677	-14.0505	-6.9000
-9.1634	-15.8700	20.6676	29.2182	28.7332	18.7792	-7.2942	-6.5685	-14.0645	-12.3497	-6.8000
-8.1469	-11.5298	20.0992	29.0780	28.8995	19.4046	-8.7654	-7.2066	-16.4333	-10.9785	-6.7000
-7.3261	-9.0732	19.5053	28.9258	29.0536	20.0029	-11.0358	-7.9989	-19.8188	-9.8470	-6.6000
-6.6642	-7.4976	18.8843	28.7614	29.1959	20.5756	-14.9270	-8.9803	-25.6095	-8.9002	-6.5000
-6.1362	-6.4471	18.2346	28.5848	29.3262	21.1240	-24.5000	-10.2033	-53.4934	-8.1023	-6.4000
-5.7244	-5.7555	17.5542	28.3956	29.4448	21.6495	-21.9960	-11.7537	-26.3012	-7.4285	-6.3000
-5.4164	-5.3332	16.8410	28.1938	29.5517	22.1530	-12.4467	-13.7830	-20.1101	-6.8614	-6.2000
-5.2032	-5.1283	16.0924	27.9791	29.6471	22.6354	-7.5645	-16.6015	-16.5681	-6.3883	-6.1000
-5.0787	-5.1097	15.3055	27.7513	29.7310	23.0977	-4.1504	-21.0219	-14.1048	-5.9998	-6
-5.0388	-5.2597	14.4769	27.5102	29.8034	23.5407	-1.4744	-30.9869	-12.2396	-5.6890	-5.9000
-5.0813	-5.5703	13.6027	27.2555	29.8644	23.9650	0.7519	-29.5034	-10.7611	-5.4511	-5.8000
-5.2057	-6.0415	12.6781	26.9869	29.9141	24.3714	2.6725	-20.3979	-9.5574	-5.2826	-5.7000
-5.4131	-6.6813	11.6972	26.7042	29.9525	24.7604	4.3698	-16.0744	-8.5626	-5.1811	-5.6000
-5.7063	-7.5070	10.6531	26.4070	29.9796	25.1325	5.8959	-13.2497	-7.7348	-5.1457	-5.5000

Finding Suitable Regression Methods



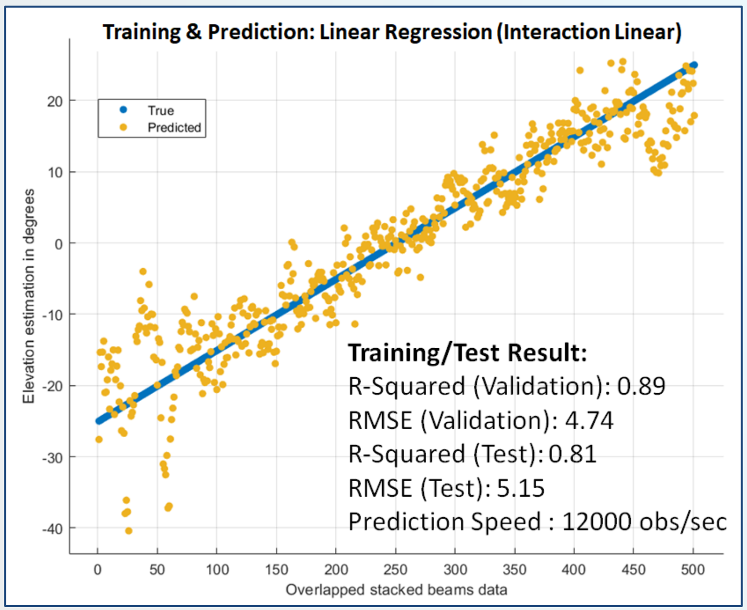


MATLAB
Statistics & Machine
Leaning Toolbox
Regression Learner App

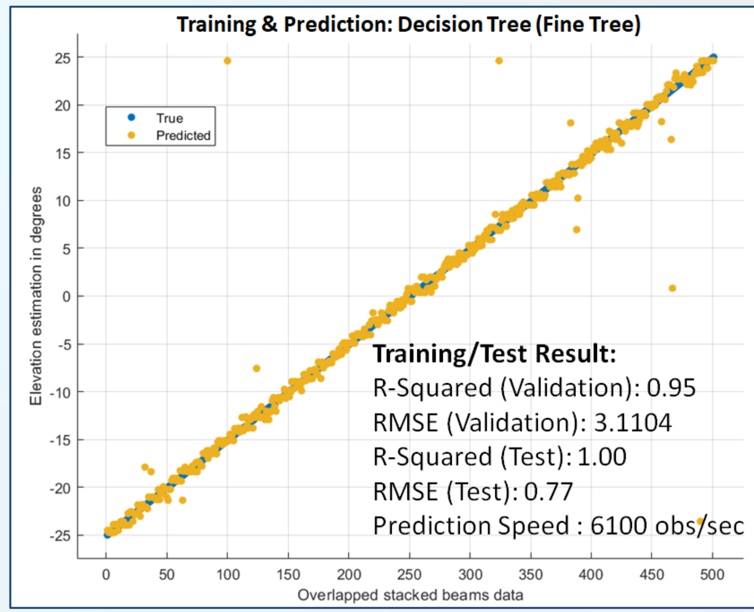
Evaluation of Various Regression Methods cont…

Linear Regression Block	R-Squared (Validation)
Robust Linear	0.58
Linear	0.62
Stepwise Linear	0.89
Interaction Linear	0.89

Decision Tree Regression Block	R-Squared (Validation)
Coarse Tree	0.87
Medium Tree	0.93
Fine Tree	0.95



Training & Prediction Result of **Interaction Linear**

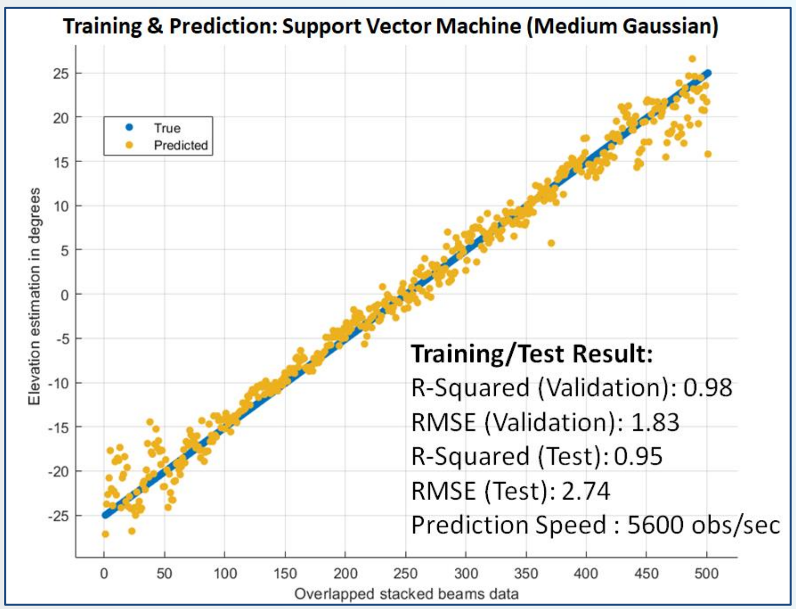


Training & Prediction Result of **Decision Tree (Fine Tree)**

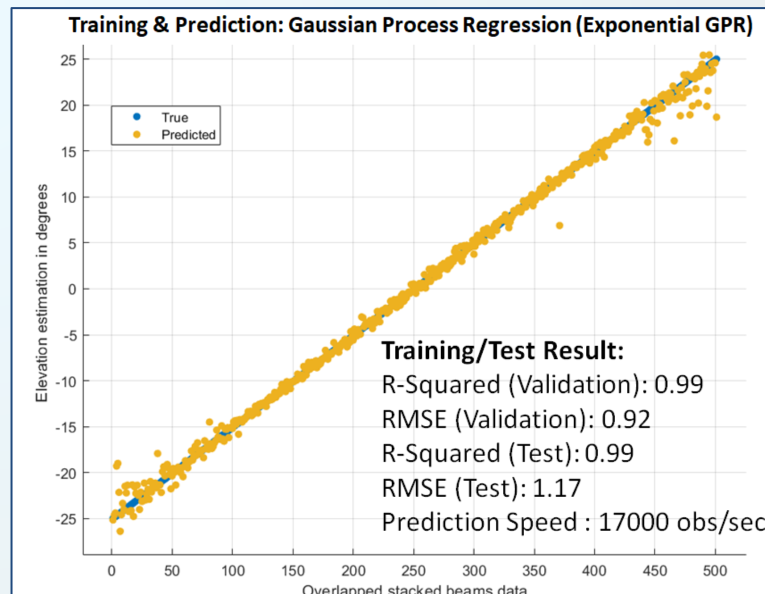
Evaluation of various regression methods cont…

Support Vector Machine (SVM) Regression Block	R-Squared (Validation)
Linear SVM	0.60
Coarse Gaussian SVM	0.67
Quadratic SVM	0.89
Cubic SVM	0.97
Fine Gaussian SVM	0.97
Medium Gaussian SVM	0.98

Gaussian Process Regression (GPR) Block	R-Squared (Validation)
Rational Quadratic GPR	0.97
Matern 5/2 GPR	0.97
Exponential GPR	0.99



Training & Prediction Result of **SVM (Medium Gaussian)**



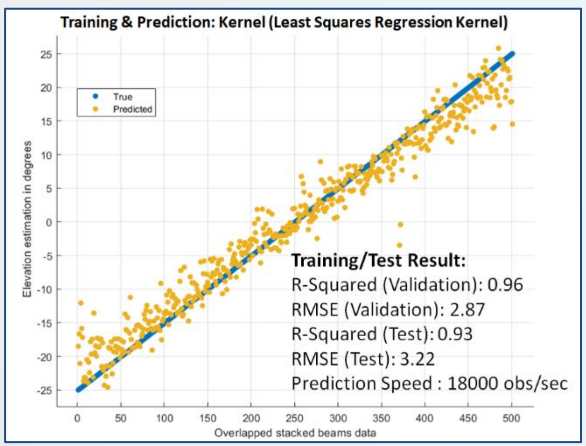
Training & Prediction Result of **Exponential GPR**

Evaluation of Regression methods cont...

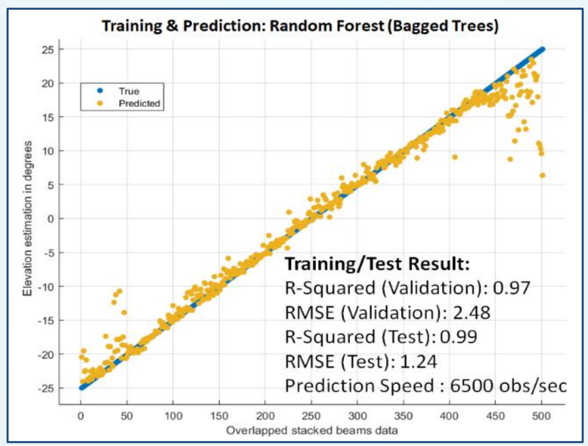
Kernel Regression Block	R-Squared (Validation)
SVM Kernel	0.78
Least Squares Regression Kernel	0.96

Random Forest Regression Model	R-Squared (Validation)
Boosted Trees	0.96
Bagged Trees	0.97

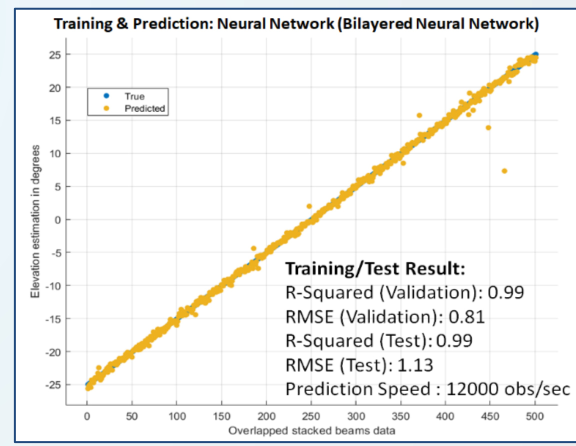
Neural Network Regression Model	R-Squared (Validation)
Narrow Neural Network	0.96
Medium Neural Network	0.96
Wide Neural Network	0.97
Bilayered Neural Network	0.98
Trilayered Neural Network	0.98



Training & Prediction Result of
Least Squares Regression Kernel

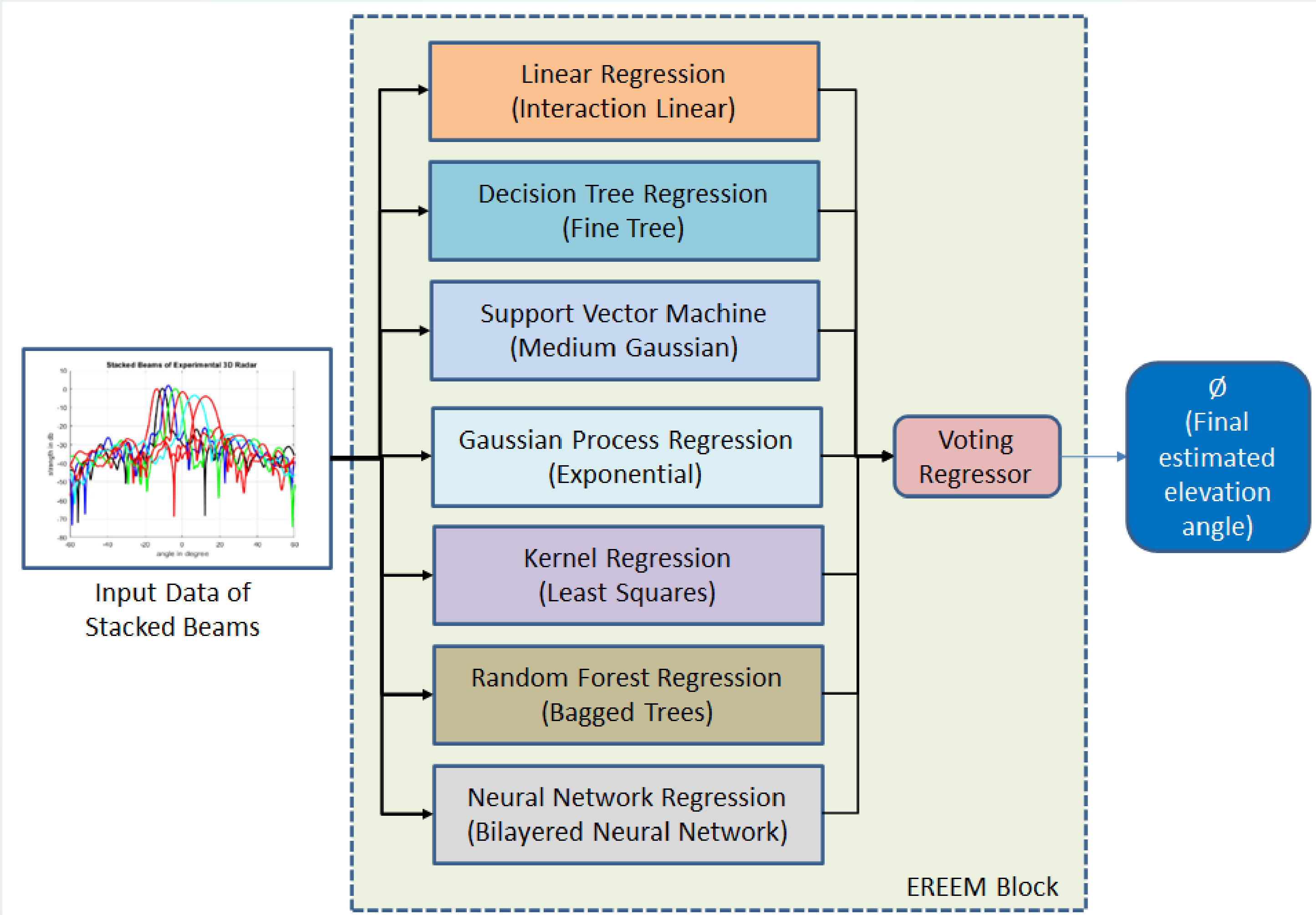


Training & Prediction Result of
Random Forest (Bagged Tree)

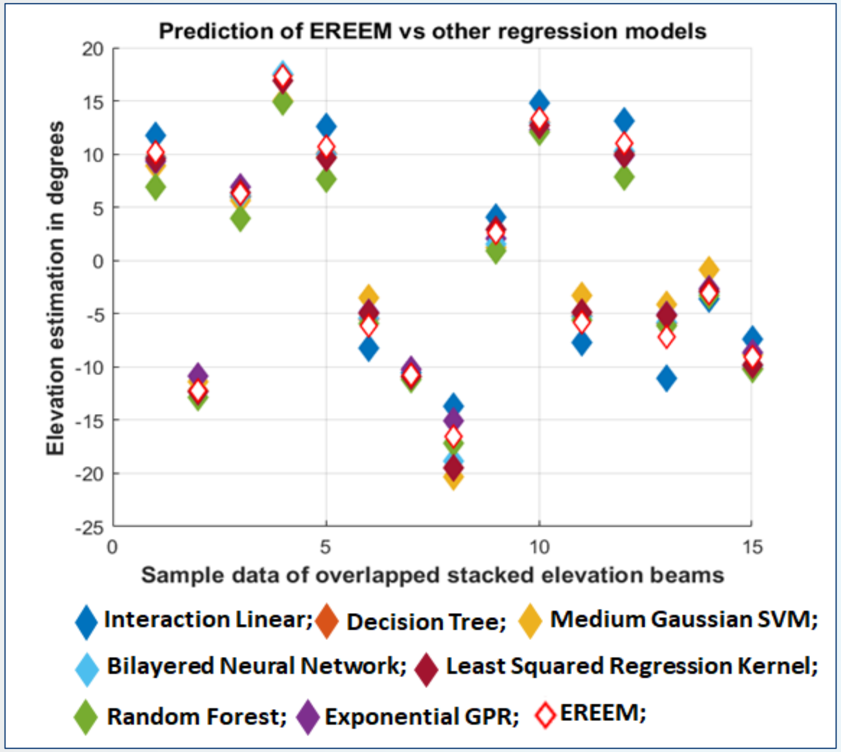


Training & Prediction Result of
Bilayered Neural Network

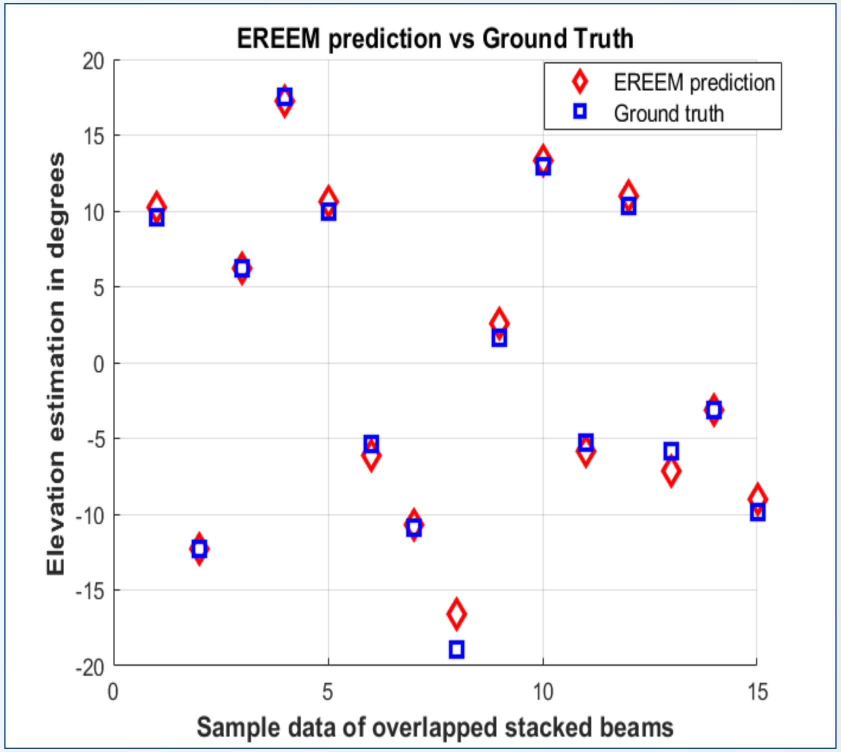
EREEM for Elevation Estimation with Selected Regression Model.



Simulation Results of Ensemble Regression Model



Prediction of EREEM vs other regression models



EREEM prediction vs Ground Truth

Summary

- ❑ Elevation estimation is difficult due to external factors, including radar variations
- ❑ The EREEM model can overcome the challenges of elevation estimation
- ❑ Model testing and performance analysis over various datasets
- ❑ Usage of Radar, ML and DL tools for dataset generation and analyzing radar data.

Future Scope of Work

- ❑ Deployment of EREEM model in radar system.

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Thank You