An Array Feed Radial Basis Function Tracking System for NASA's Deep Space Network Antennas

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Outline

1. Introduction
    - 1.1 Antenna surface distortion
    - 1.2 The array feed compensation system
    - 1.3 Adaptive tracking and acquisition system

2. Acquisition and tracking in the presence of antenna distortions
    - 2.1 The acquisition problem
        - 2.1.1 RBF network
        - 2.1.2 Quadratic interpolated least squares
        - 2.1.3 Fuzzy interpolated least squares
        - 2.1.4 Results
        - 2.1.5 Observations
    - 2.2 The Tracking Problem
        - 2.2.1 RBF network
        - 2.2.2 Results
        - 2.2.3 Observations
3. Conclusions

1 Introduction

- NASA's 70-meter Deep Space Network antenna:
  - – Seeks to operate at Ka-band (32 GHz).
  - – ***Challenge:*** A pointing accuracy requirement of 0.8 millidegree or less.
  - – ***Why is this difficult?*** Time-varying deformation of antenna surface, or nonstationary antenna drift.

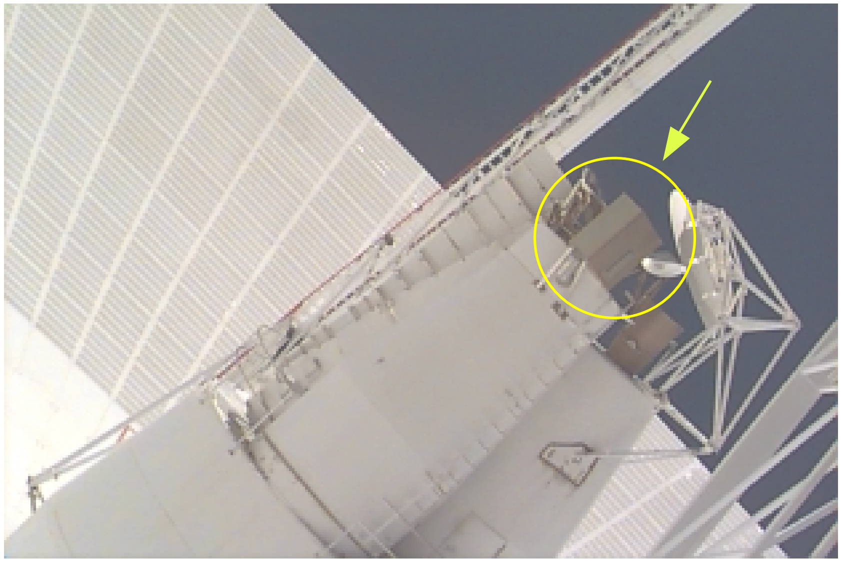
1.1 Antenna Surface Distortion

- Antenna surface distorts under its own weight.
- Small 2-3 mm distortions in the surface may produce significant changes in the received field at the focal plane of the horns.
- Surface distortion is a function of antenna elevation angle, wind, aging, temperature, and other factors.
- Distortions lead to unacceptably large ***pointing*** errors and signal-to-noise ratio (SNR) losses.
- Distortions also shift the peak of the signal distribution, and ***defocusing*** of the power distribution in the focal plane, causing a loss of power in the central channel.

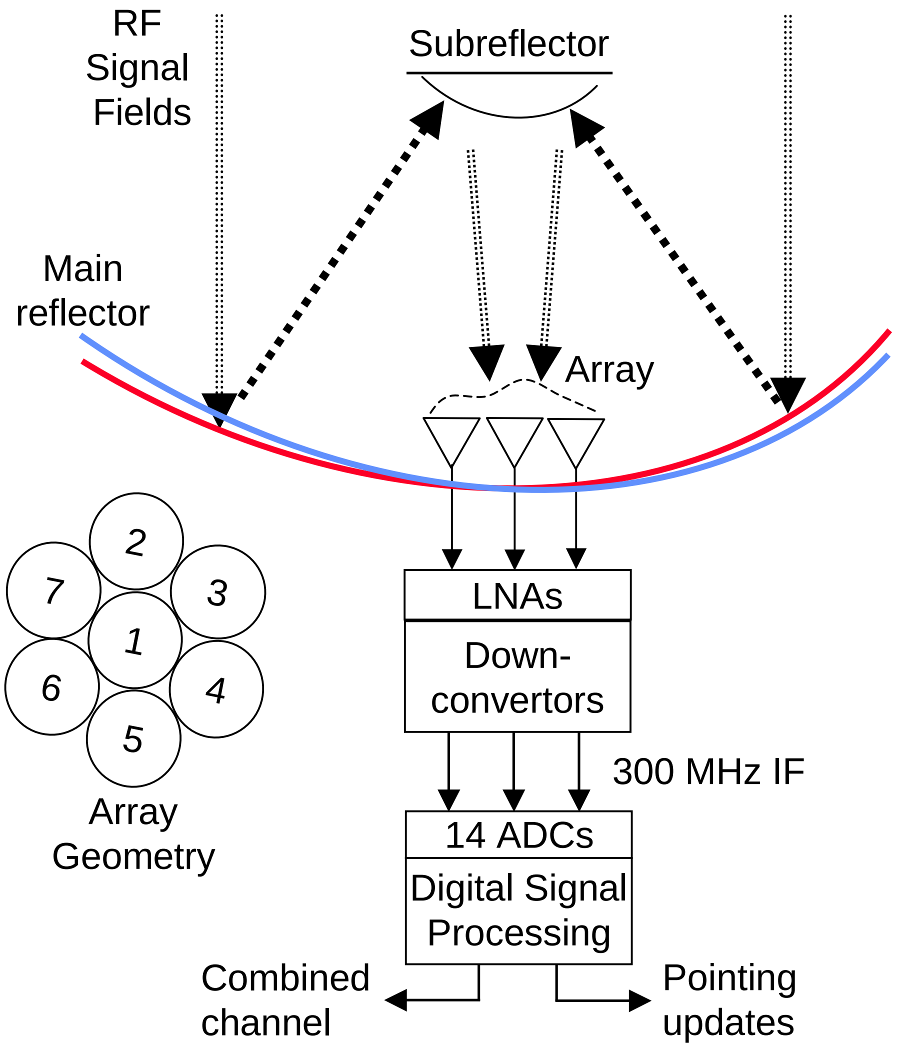
1.2 The Array Feed Compensation System

- The ***defocusing*** error is compensated by the *Array Feed Compensation System (AFCS),* which consists of 7 receiving horns:

  - Array's outer horn voltages are multiplied by complex weights matched to the instantaneous magnitude and phase of the signal in each channel, and combined.
  - This boosts the SNR almost to the level of an undistorted antenna operating under ideal conditions.



AFCS Block Diagram



1.3 Adaptive Tracking and Acquisition System

- But what about the ***pointing*** error (critical in initial signal **acquisition**, and subsequent signal **tracking**?)

- In the noiseless case, there exists a one-to-one mapping from the space of voltage vectors to antenna pointing offsets for any given antenna elevation.

- We will demonstrate that a properly trained RBF network or other adaptive compensation algorithms can exploit this mapping and
  - effectively remove the time-varying pointing offsets,
  - and keep the antenna pointed in the desired direction even in the presence of *significant* antenna distortions and other disturbances.

2 Acquisition and Tracking in the Presence of Antenna Distortions

- *Two distinct problems:*

1. **Acquisition:** Estimation of antenna pointing offsets over a *wide* range (≈ millidegrees) – performed on simulated data.

2. **Tracking:** After the initial *coarse* pointing above, the tracking algorithm must keep the antenna pointed on source despite possible slow drift in antenna pointing, by estimating *small or fine* pointing errors near the center of (XEL,EL) space (≈ tenths of millidegree) – performed on real data.

2.1 The Acquisition Problem

- Received spacecraft signals were simulated using an analytical antenna model:

1. **Compute the incident field at the focal plane of the antenna:** by assuming a plane wave incident on the main reflector surface, and tracing it back to the focal plane via the subreflector, using measured and interpolated antenna distortion data at various elevations.

2. **Compute the step response of each horn:** by the application of a unit voltage to the input of the horn, and calculated by a theoretical waveguide modal expansion.

3. **Convolve (1) and (2)** to calculate the final complex voltage.

Data Sets and Approaches

Training set (noiseless):

- Normalized horn voltages by the center horn output – resulting in 6 complex numbers and corresponding (XEL,EL) displacement vector.
- XEL and EL range: -7 to +7 mdeg in steps of 1 mdeg.
- Taken at three elevations: 15, 45, and 75 degrees.

Test set (with additive Gaussian noise):

- Central horn SNR range: 10 dB-Hz to 40 dB-Hz in steps of 5 dB-Hz.
- XEL and EL range: -4.67 to +4.67 mdeg in steps of 0.33 mdeg.
- Contains many points not used in training.

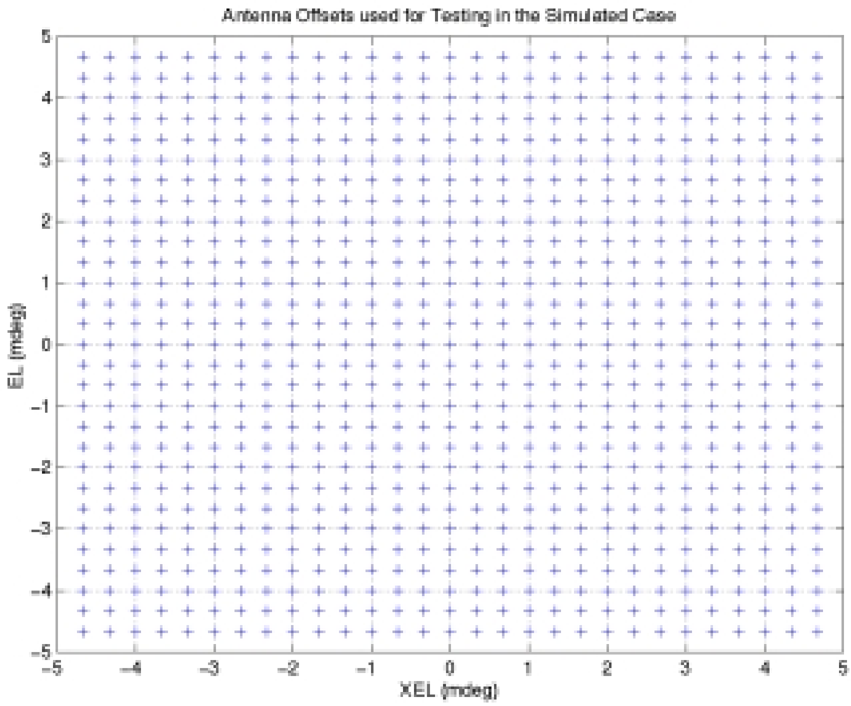
Approaches:

  - RBF Network
  - Quadratic Interpolated Least Squares
  - Fuzzy Interpolated Least Squares

Antenna Pointing Offsets

Training

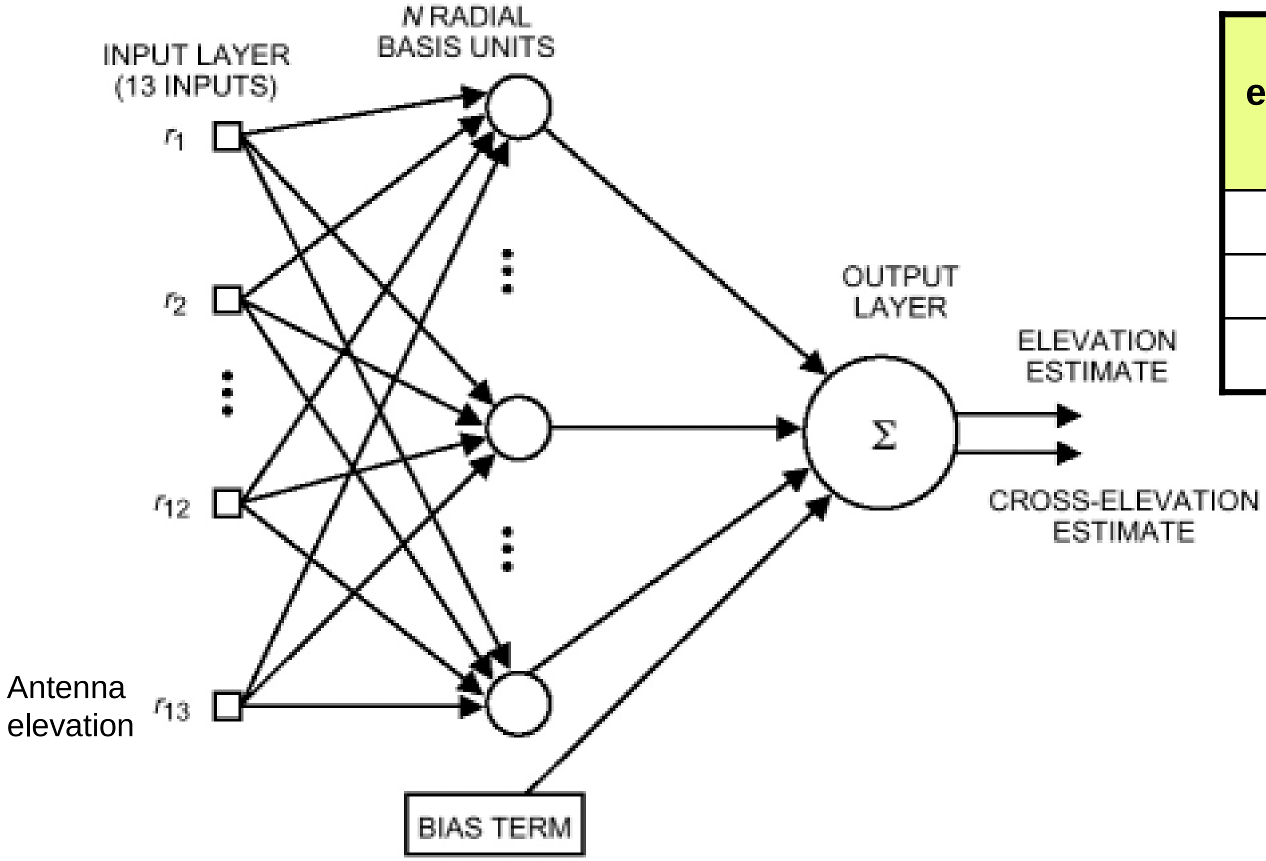
Testing



- Simulation of 1-second integration (no averaging)
- Simulation of 10-second integration (10 voltage vectors averaged)
  - Better noise resistance.

2.1.1 RBF Network

- Separate networks used for each of the three elevations.
- Trained using orthogonal least-squares learning (Chen, Cowan, and Grant, *IEEE Trans. Neural Networks*, vol.2, no. 2, March 1991).



Gross elevation (deg)	**RBF spread (mdeg)**	***N***
15	0.50	127
45	0.70	103
75	2.50	77

2.1.2 Quadratic Interpolated Least Squares

- Two Vector Spaces
  - Voltage: 12-dimensions
  - (XEL,EL): 2-dimensions

- The distance between 2 points in voltage space is approximated by a corresponding distance “d” in offset space:

$$d = \sqrt{a_1^2\left(XEL_{true} - XEL_{est}\right)^2 + a_2^2\left(EL_{true} - EL_{est}\right)^2}$$

- Now, for a given input voltage, we select the voltage vector closest to it, and the corresponding displacement vector: (XEL_{est},El_{est}).

- Next we take that point and the eight points which surround it in (XEL,EL) space, calculate d in voltage space for all of them, and do a best fit to the expression above and find XEL_{true} and EL_{true}.

2.1.3 Fuzzy Interpolated Least Squares

- Simpler interpolation strategy which does not require assumptions about the shape of the error surface.

- Obtain the same closest point in voltage space, and eight nearest neighbors in (XEL,EL) space as in the quadratic interpolated case.

- For each of these nine points, compute:

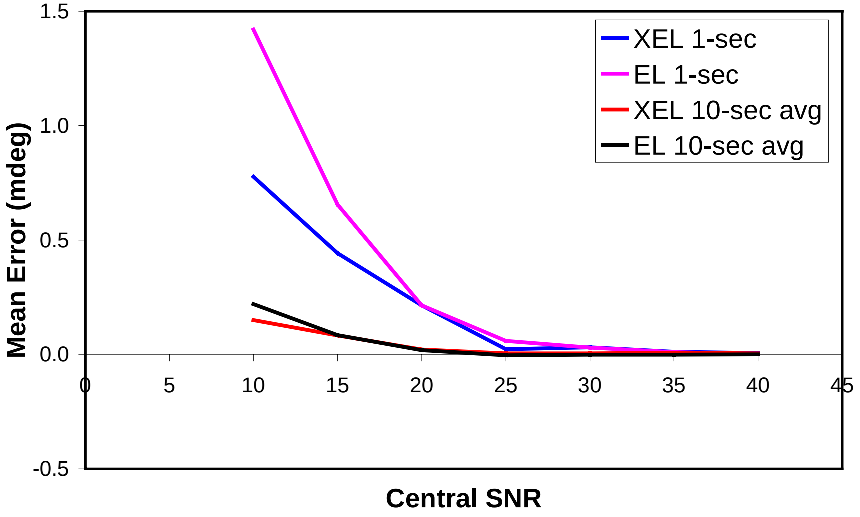
$$w_i = e^{-d_i}$$

- Let v_i be the ith antenna offset vector in the set of nine reference vectors chosen.

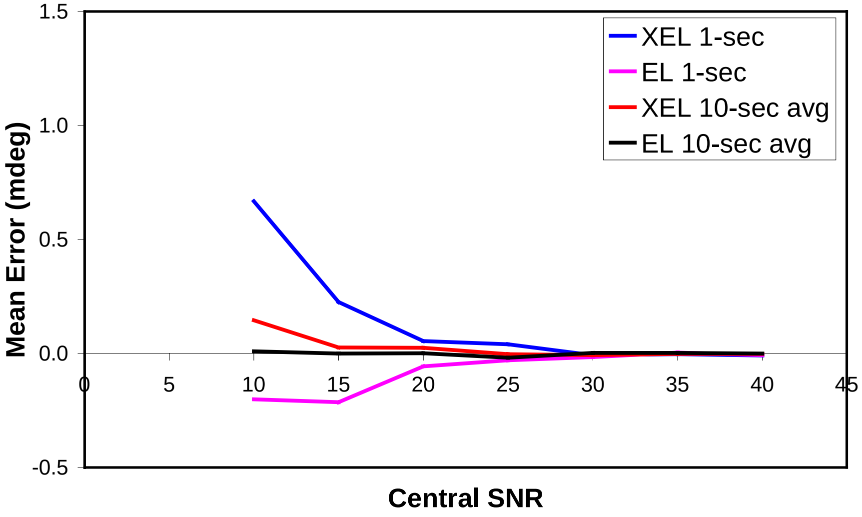
- The estimated pointing offset is given by: $v = \dfrac{\sum_{i=1}^{9} w_i v_i}{\sum_{i=1}^{9} w_i}$

2.1.4 Results

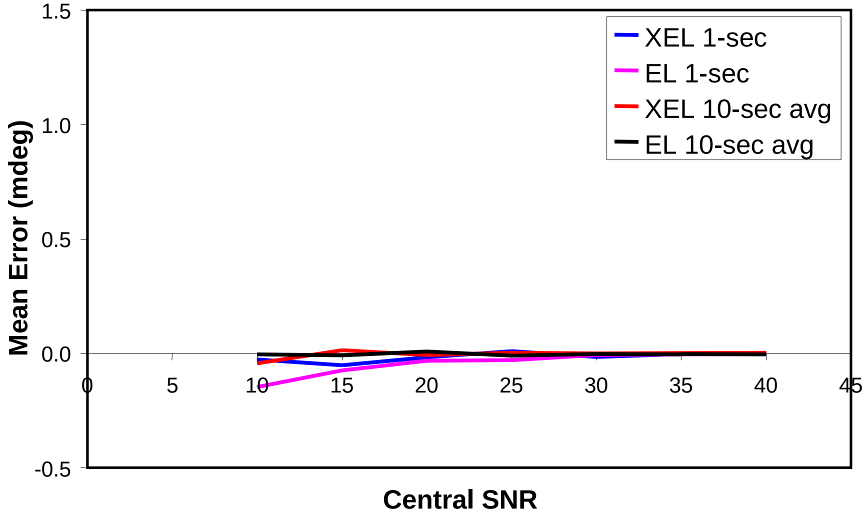
Neural Net: Mean Error at 15 degrees



Neural Net: Mean Error at 45 degrees

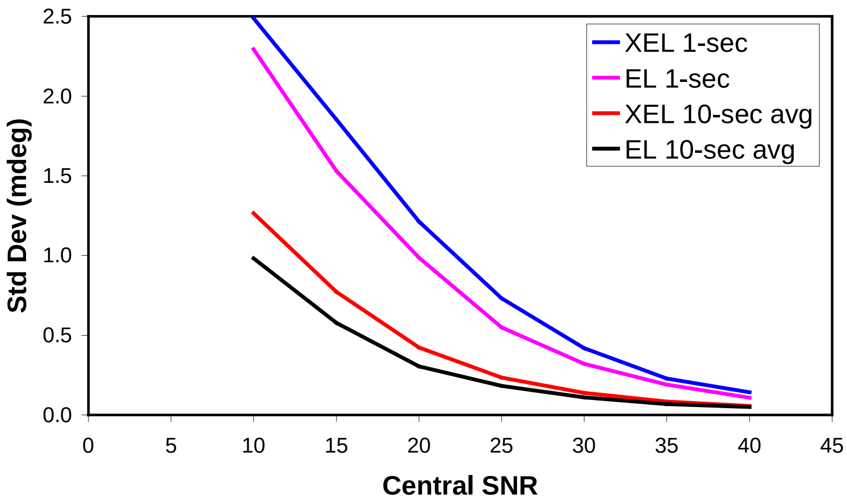


Neural Net: Mean Error at 75 degrees

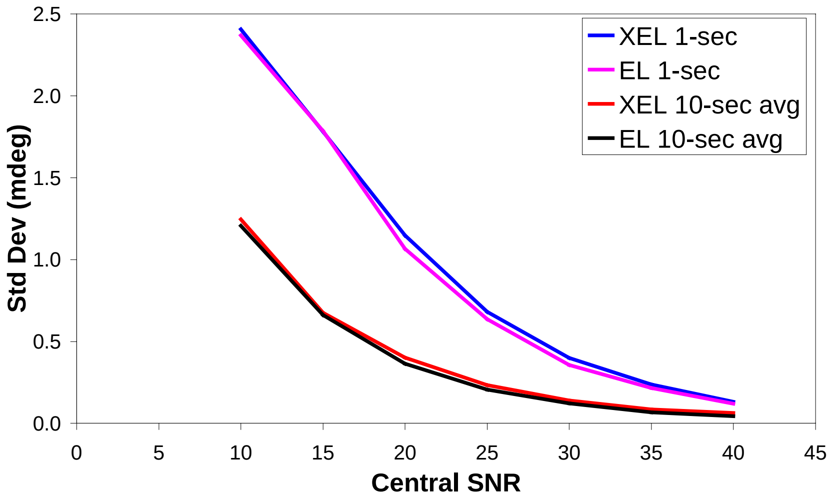


Results (cont'd)

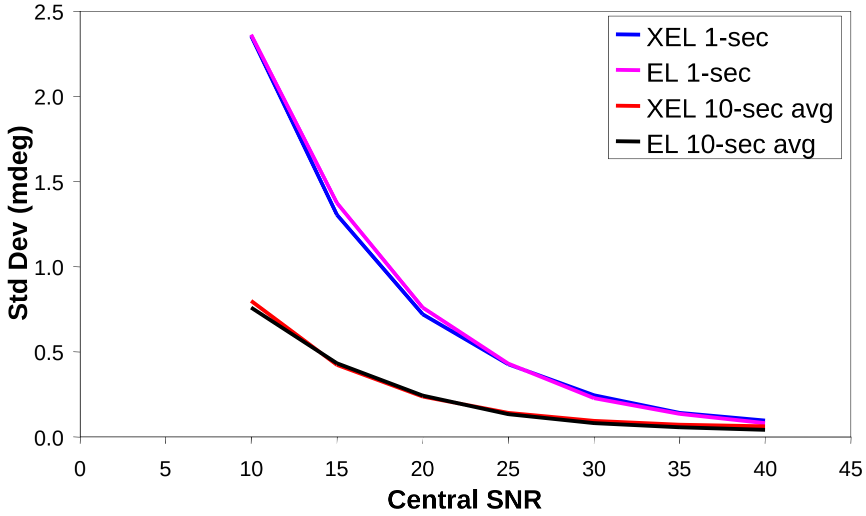
Neural Net Error Std Dev @ 15 degrees



Neural Net Error Std Dev @ 45 degrees

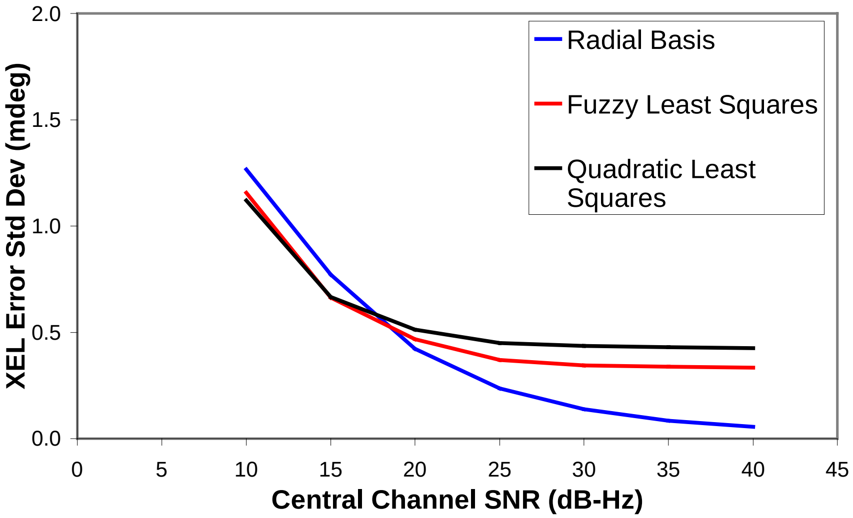


Neural Net Error
Std Dev @ 75 degrees

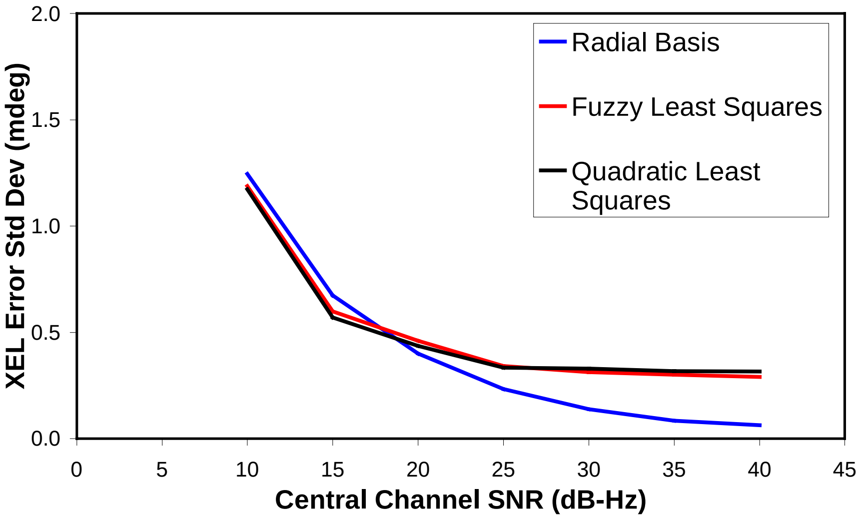


Results (cont'd)

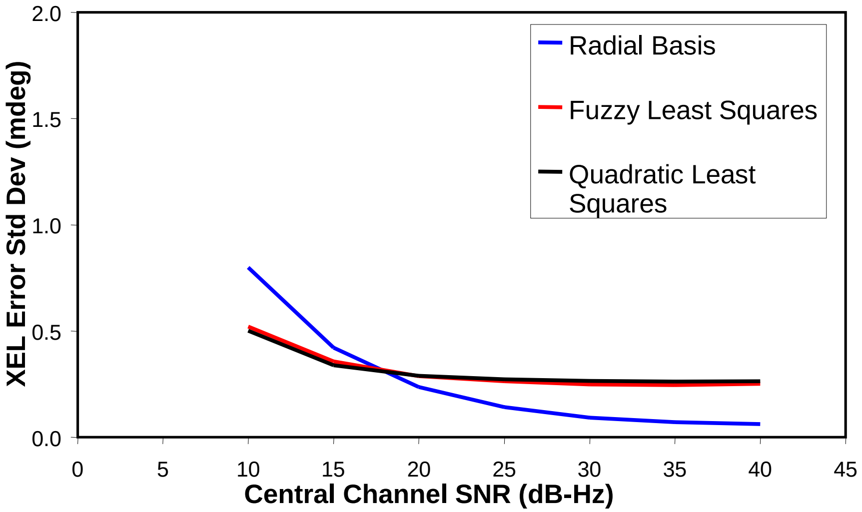
Comparison 15 deg XEL



Comparison 45 deg XEL

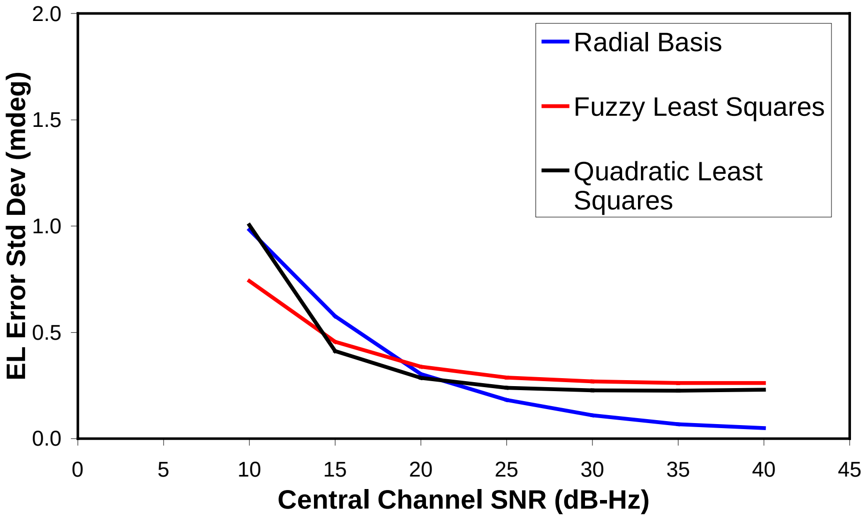


Comparison 75 deg XEL

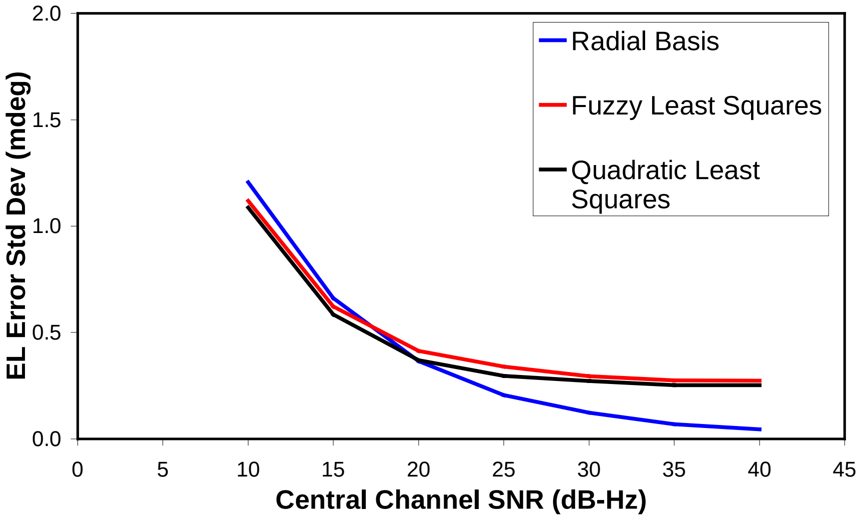


Results (cont'd)

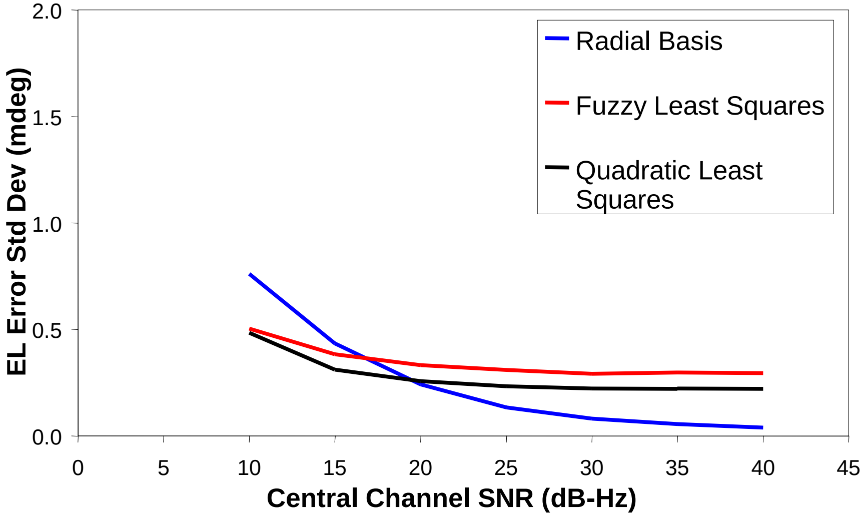
Comparison 15 deg EL



Comparison 45 deg EL



Comparison
75 deg EL



2.1.5 Observations

- For RBF networks with 10-s averaging, mean errors are less than 0.1 mdeg for SNRs above 15 dB-Hz.

- At low SNRs smaller mean errors were obtained at 75° than at 45° (less distortion) because at 75° more signal power is projected into the outer horns due to greater distortion, possibly providing better pointing information as the distorted patterns are scanned off-source.

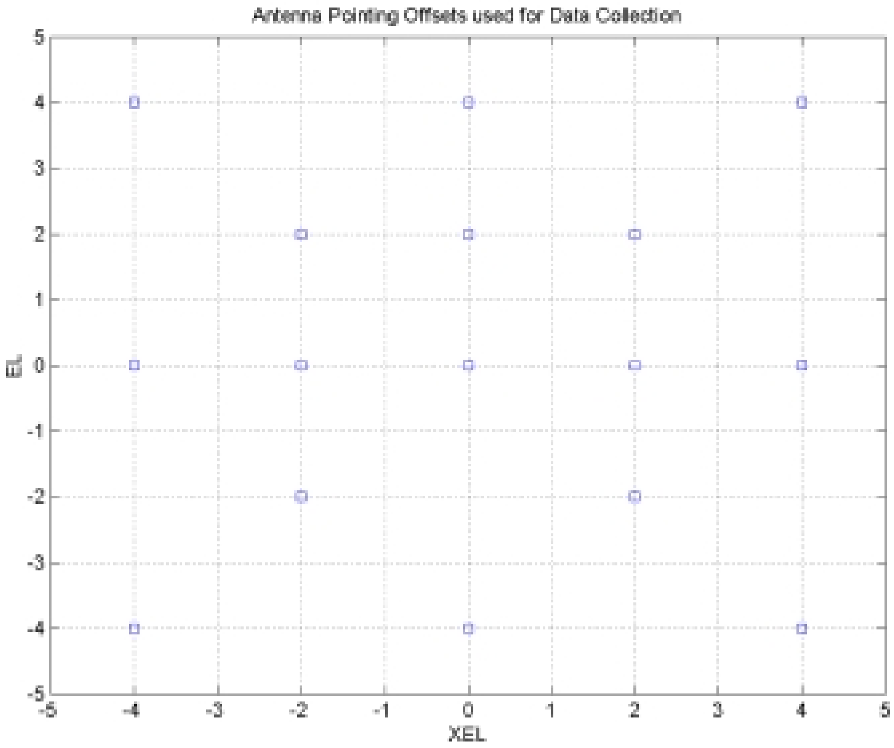
- 10-second integration results in significant improvements over 1-second integration, achieving a factor of 3+ decrease in standard deviation (a factor of 10 decrease in estimation variance).

- At medium-to-high SNR, the RBF network yields better performance than the 2 least squares algorithms, whereas for low SNR the least squares algorithm yield better performance – this suggests that RBF network generalization can be improved by training using noisy data.

2.2 The Tracking Problem

– Training uses real data taken at DSS-14 under a relatively narrow range of SNR conditions and 15 pointing offsets.

– Averaged over many days, in elevations from less than 10^{o} (near the horizon) to over 80^{o} (close to zenith).



– The test set voltage and elevation data were gathered at the same antenna pointing offsets as in the training set, with no averaging to reduce noise effects.

– Data gathered on two days

Day 29 (High SNR)

Day 38 (Lower SNR)

2.2.1 RBF Network

- The RBF widths were selected by examining the distances among input vectors in the training set, and by experimentation

- The best networks for day 38 (low SNR resulting in both poorer accuracy and greater difficulties in antenna tracking) were generally more complex than those for day 29 (high SNR).

- Notwithstanding, pointing errors even for low SNR data were ordinarily less than 1 millidegree for SNR greater than 20 dB–Hz.

Day	**Variable**	***N***	***Basis width***
38 (low SNR)	*XEL*	153	0.60
38	*EL*	77	0.58
29 (high SNR)	*XEL*	33	0.48
29	*EL*	23	0.68

2.2.2 Results

Day /	Gross	Gross	Mean	Std Dev	Mean	Std Dev	SNR	Direction of
Region	Elevation	Azimuth	XEL	XEL	EL	EL	(dB-Hz)	Gross EL
	(deg)	(deg)	(mdeg)	(mdeg)	(mdeg)	(mdeg)		
29 / 1	57.4 To 64.7	96.9 to 104.7	-0.0505	0.4207	0.0507	0.4147	30 to 40	Rising
29 / 1	57.4 To 64.7	96.9 to 104.7	0.1501	0.3152	-0.0204	0.2708	> 40	Rising
29 / 3	61.1 to 65.0	254.4 to 259.1	0.1318	0.4112	0.0419	0.4153	30 to 40	Falling
29 / 4	55.1 to 59.9	260.4 to 264.8	0.1262	0.6722	-0.1662	0.5116	30 to 40	Falling
29 / 4	55.1 to 59.9	260.4 to 264.8	0.2267	0.3488	-0.1797	0.3249	> 40	Falling
38 / 1	69.3 to 72.7	113.8 to 122.0	-0.1985	0.7383	0.0454	0.9468	20 to 30	Rising
38 / 4	77.3 to 79.6	142.0 to 191.9	-0.2711	0.6834	0.2703	0.6941	20 to 30	Rising
38 / 4	77.3 to 79.6	142.0 to 191.9	-1.1917	1.4167	-0.2350	1.1166	10 to 20	Rising

For very low SNR, error mean and standard deviations can exceed 1 millidegree. For medium-high SNR cases, errors are generally less than 0.5 millidegree, which exceeds the pointing accuracy requirement.

2.2.3 Observations

- Tracking is very close with errors generally well under 1 millidegree.

- The noisy output of the radial basis network could be smoothed by averaging, thus achieving even better performance when tracking near the center. Such averaging was not performed here. In a practical situation, where the objective is to keep the antenna centered on source, we can take advantage of averaging to significantly improve accuracy.

3 Conclusions

- Radial basis networks exhibit significant potential for keeping 70-meter deep space antennas pointed accurately on source.
- Currently being considered for implementation on the Deep Space Network antennas at Goldsone, CA.
- Using actual data gathered from such an antenna, it was possible to demonstrate that a radial basis network can track a source with errors less than 1 millidegree, and as good as 0.3 millidegree for a wide range of SNR values.
- Using simulated but realistic data, acquisition performance as good as 0.1 millidegree was demonstrated.
- Results can be further improved by fast averaging.