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HOW SMALL CAN AN HF RECEIVING DELTA LOOP BE? NUMERICAL ANALYSIS OF ANTENNA SIZE AND IMPEDANCE MATCHING

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ABSTRACT

Reducing the dimensions of a Delta Loop antenna is attractive to radio amateurs with limited installation space, but its consequences vary considerably across HF bands. This study evaluates 31 progressively reduced triangular loops, with upper-side lengths ranging from 14.00 to 3.01 m and a constant minimum height of 6 m. NEC2C simulations cover nine amateur bands between 3.5 and 29.7 MHz, producing 5,859 frequency solutions. Four ideal impedance transformations (1:1, 2:1, 4:1 and 9:1) are evaluated for a 50 Ω receiver. The minimum upper-side lengths satisfying a 3 dB modeled effective-gain criterion are 13.30 m for 40 m, 6.83 m for 20 m, and approximately 3.33-4.53 m for bands between 17 and 10 m. Reducing the upper side from 14.00 to 7.19 m produces a 16.80 dB deficit on 40 m when selecting the best of the four fixed ratios for each geometry. However, ideal conjugate matching reduces the difference to only 1.06 dB, demonstrating that impedance transfer, rather than a comparable deterioration in modeled hemispherical gain, accounts for most of the deficit. Practical recommendations distinguish full-size multiband loops from reduced loops intended primarily for higher HF bands. The results support antenna-size and matching decisions but do not directly predict received signal-to-noise ratio (SNR) or the performance of physical matching networks.

Keywords: Delta Loop; HF Receiving Antenna; NEC2C; Antenna Miniaturization; Impedance Matching; Effective Gain.

1 INTRODUCTION

Delta Loop antennas are attractive for amateur-radio HF reception because they can be constructed from inexpensive wire and installed using a limited number of supports. However, available space often prevents installation of a full-size loop.

Reducing the perimeter changes the antenna's electrical length, current distribution, input impedance and radiation pattern. Consequently, the power delivered to a receiver cannot be predicted from geometric dimensions alone [1-3].

A particularly important distinction concerns the antenna's modeled gain and the fraction of available signal power transferred to a receiving system. An antenna may retain favorable electromagnetic characteristics while presenting a highly reactive impedance that transfers little power to a conventional 50 Ω receiver.

This study investigates three practical questions:

- How small can a Delta Loop become before its modeled receiving performance deteriorates substantially?
- How much of that deterioration originates from changes in modeled gain rather than impedance mismatch?
- What antenna dimensions and matching arrangements should radio amateurs consider for different HF bands?

The analysis concentrates on antenna geometry and impedance transfer rather than a complete receiving-system SNR model.

This distinction is supported by a related study of HF antenna selection [4], which found that complete SNR modeling improved the simulated selection of a single fixed antenna by an average of only 0.1305 dB relative to a total-NEC2-gain-based selection rule, under the investigated scenarios. That result suggests that increasingly complex noise models do not necessarily produce materially better antenna-selection decisions.

However, the finding is conditional on the antenna candidates, propagation assumptions, receiver characteristics and modeled noise environments. It does not establish that SNR analysis is universally unnecessary, particularly where local noise, receiver noise or matching losses are significant.

The present work therefore addresses the more immediate engineering problem of selecting antenna dimensions and evaluating the limitations of simple impedance transformations.

2 MATERIALS AND METHODS

2.1 Antenna geometry

The reference antenna is an upright triangular Delta Loop modeled using NEC2C, with ground and excitation specifications following the NEC-2 documentation [5,6].

Its principal characteristics are:

- Upper horizontal side: 14.00 m.
- Approximate total perimeter: 42.6 m.
- Minimum height above ground: 6.00 m.
- Wire radius: 1 mm.

Lower horizontal feeding conductor: nominally 1.00 m in the original reference geometry.

Feed excitation: center segment of conductor GW4.

Ground: Sommerfeld-Norton real ground, with relative permittivity 13 and conductivity 0.005 S/m.

The antenna is progressively reduced using 31 geometries, with a nominal scaling factor of 0.95 between consecutive configurations.

The general scaling relationship is

$$L_n = 14(0.95)^n, \qquad n = 0, \ldots, 30$$

where L_n is the upper-side length in meters.

The smallest modeled upper side is approximately 3.005 m.

All antenna conductors, including the lower feeding conductor (GW4), were scaled proportionally by a factor of (0.95^n), while maintaining a minimum height of 6 m. Consequently, GW4 decreased from 1.00 m in the reference geometry to approximately 0.513 m and 0.215 m in the 7.19 m and 3.01 m configurations, respectively. The wire radius remained fixed at 1 mm, and GW4 retained three segments with excitation at its central segment throughout the simulations.

The 7.19 m configuration is selected as a representative approximately half-size antenna, rather than as a theoretically optimal design.

2.2 Electromagnetic simulations

Nine amateur-radio bands were investigated:

80, 60, 40, 30, 20, 17, 15, 12 and 10 m.

Each band was evaluated at 21 frequencies, giving

$$31 \times 9 \times 21 = 5859$$

electromagnetic solutions.

The NEC2C simulations supplied complex feed-point impedance and far-field gain patterns.

The gain patterns were sampled using 21 elevation points and 72 azimuth points.

The principal antenna-performance indicator is the linear-power mean gain over the upper hemisphere:

$$\overline{G}_H = \frac{1}{2\pi}\int_{\Omega_H} G\,(\theta,\phi)\,d\Omega$$

where $G(\theta,\phi)$ is the modeled linear gain and Ω_H denotes the upper hemisphere.

This metric summarizes the modeled gain distribution but does not represent the gain toward a particular transmitting station. It must not be interpreted directly as received SNR.

2.3 Impedance transformation

Four ideal lossless impedance ratios were considered:

$$r \in \{1,2,4,9\}$$

For a 50 Ω receiver, the corresponding antenna-side real load resistances are

$$R_L = 50r$$

giving 50, 100, 200 and 450 Ω.

For antenna impedance

$$Z_A = R_A + jX_A$$

the fraction of available power delivered to the equivalent resistive load is

$$\tau = \frac{4R_A R_L}{(R_A + R_L)^2 + X_A^2}$$

The modeled effective-gain indicator is

$$G_{\text{eff,dBi}} = 10\log_{10}\left(\overline{G}_H\right) + 10\log_{10}(\tau)$$

This expression separates two effects:

Changes in the modeled upper-hemisphere gain.

Changes in power transfer caused by the antenna impedance and selected load.

The transformations are mathematical and lossless. They do not represent measured baluns or ununs, and they do not cancel antenna reactance.

Physical transformer losses, feeder losses, common-mode currents and parasitic frequency responses are excluded.

2.4 Performance criteria

For each antenna size and frequency, effective gain was compared with the corresponding reference configuration.

Band means were calculated in decibels using logarithmic-frequency weighting. This represents a mean logarithmic performance criterion rather than the logarithm of average linear received power.

The 90th percentile (P90) of the paired frequency-by-frequency loss was also calculated to identify unfavorable portions of each sampled band.

Two engineering thresholds were adopted:

Maximum mean and P90 deficit of 3 dB.

Maximum mean and P90 deficit of 6 dB.

For the minimum-size analysis, each geometry was allowed to use its best band-mean result among the four ideal ratios. The reference was likewise allowed its best ratio.

These thresholds represent design criteria, not physical limits on intelligibility, SNR or communication range.

2.5 Electrical length and numerical verification

To help interpret the frequency dependence, the antenna perimeter may also be expressed as a fraction of wavelength:

$$\frac{P}{\lambda} = \frac{Pf}{c}$$

where P is antenna perimeter, f is frequency and c is the speed of light.

This normalized variable provides a physical reference for comparing antenna sizes across different frequencies. However, electrical length alone does not determine performance because ground interaction, feed geometry, conductor radius and impedance matching also matter.

The archived 279 antenna-band models were reproduced using NEC2C, with numerical arrays matching the original results.

A selective convergence test was also performed on the 7.19 m loop at 7.000, 7.150 and 7.300 MHz.

The three principal conductors were progressively refined, while the three-segment GW4 feeding conductor remained unchanged.

Between the two finest principal-wire meshes, the maximum relative complex-impedance difference was 0.091%, and the maximum effective-gain difference was below 0.004 dB.

These results support numerical stability with respect to principal-conductor segmentation at the tested frequencies. They do not independently establish convergence of the feeding-bar representation.

3 RESULTS

3.1 Minimum antenna dimensions by HF band

Table 1 presents the smallest tested upper-side length satisfying the selected effective-gain criteria.

Table 1: Minimum tested upper-side length satisfying the effective-gain criteria.

Band	Maximum deficit 3 dB (m)	Maximum deficit 6 dB (m)
80 m	12.00	9.78
60 m	12.63	10.83
40 m	13.30	12.00
30 m	8.38	7.57
20 m	6.83	6.16
17 m	4.53	4.09
15 m	4.53	4.09
12 m	3.33	≤3.01
10 m	3.33	≤3.01

Note: The thresholds refer to the specific antenna geometry, ground model, 6 m minimum height and four ideal impedance ratios. The smallest qualifying size is not necessarily followed by a continuous interval of qualifying larger sizes because the response can be non-monotonic. Values marked ≤3.01 m indicate that the lower boundary of the tested range qualified; smaller dimensions were not investigated.

The smallest qualifying modeled size depends strongly on the intended operating band.

On 40 m, the smallest tested upper-side length qualifying under the 3 dB criterion is 13.30 m.

On 20 m, the corresponding dimension falls to 6.83 m.

For 17-10 m, the smallest qualifying sizes are considerably shorter.

These results demonstrate that no single minimum Delta Loop size is appropriate for every HF band.

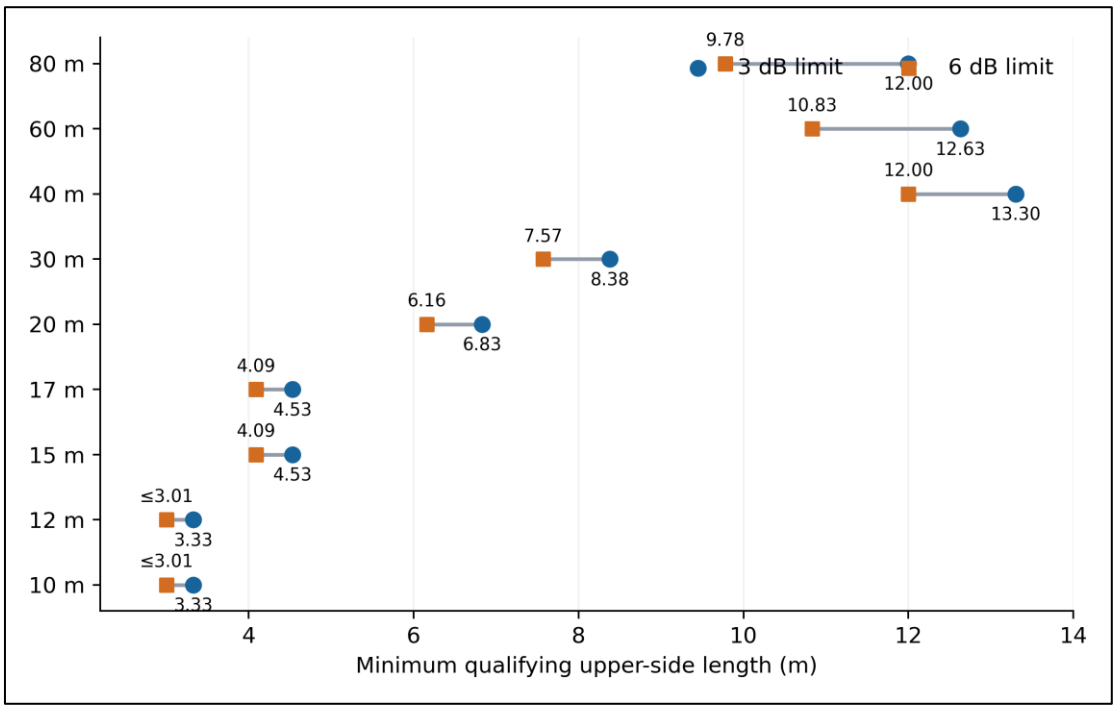

Figure 1: Minimum tested upper-side lengths meeting the joint mean and P90 effective-gain deficit criteria. The values are relative to the best 14 m reference among four ideal fixed impedance ratios; ≤3.01 m identifies the lower tested boundary.

3.2 Performance of the approximately half-size loop

Table 2 compares the 14.00 m reference with the 7.19 m configuration, using the best of the four ideal impedance ratios for each antenna.

Table 2: Best modeled band-mean effective gain among the four fixed impedance ratios.

Band	14 m (dBi)	7.19 m (dBi)	Difference (dB)	Best ratio at 7.19 m
80 m	−15.63	−24.97	−9.33	9:1
60 m	−7.88	−20.23	−12.35	9:1
40 m	+1.02	−15.78	−16.80	9:1
30 m	−2.29	−8.76	−6.47	9:1
20 m	+1.44	+1.15	−0.29	2:1
17 m	−3.61	−1.26	+2.35	9:1
15 m	+0.58	−1.69	−2.28	9:1
12 m	−3.29	−0.30	+2.99	9:1
10 m	+1.04	+0.69	−0.35	9:1

Note: Differences are calculated using the best tested fixed ratio for each geometry. Negative values indicate lower effective gain for the reduced loop. All impedance transformations are ideal and lossless.

The approximately half-size antenna performs comparatively well from 20 to 10 m.

On 20 m, its deficit is only 0.29 dB relative to the best tested reference configuration. On 17 and 12 m, it exceeds the reference under the investigated matching conditions.

However, its 40 m performance deteriorates substantially.

The 9:1 transformation gives the best result among the four evaluated ratios on eight of the nine bands for the 7.19 m loop. This does not establish that 9:1 is the optimum matching solution.

3.3 Why the reduced loop performs poorly on 40 m

The most important result concerns the separation between modeled gain and impedance transfer.

With a direct 1:1 connection, reducing the upper side from 14.00 to 7.19 m produces a 24.77 dB effective-gain deficit on 40 m.

This difference separates into:

$$\Delta G_{\text{eff}} = \Delta G_H + \Delta T$$

where

$$\Delta G_H = -1.06 \text{ dB}$$

and

$$\Delta T = -23.71 \text{ dB}$$

The large modeled deficit is therefore dominated by the impedance-transfer term (23.71 dB), whereas the change in upper-hemisphere NEC gain accounts for only 1.06 dB.

This distinction is particularly important for practical antenna design.

A reduced Delta Loop may retain a useful electromagnetic response while presenting an input impedance that is poorly suited to a conventional receiver connection.

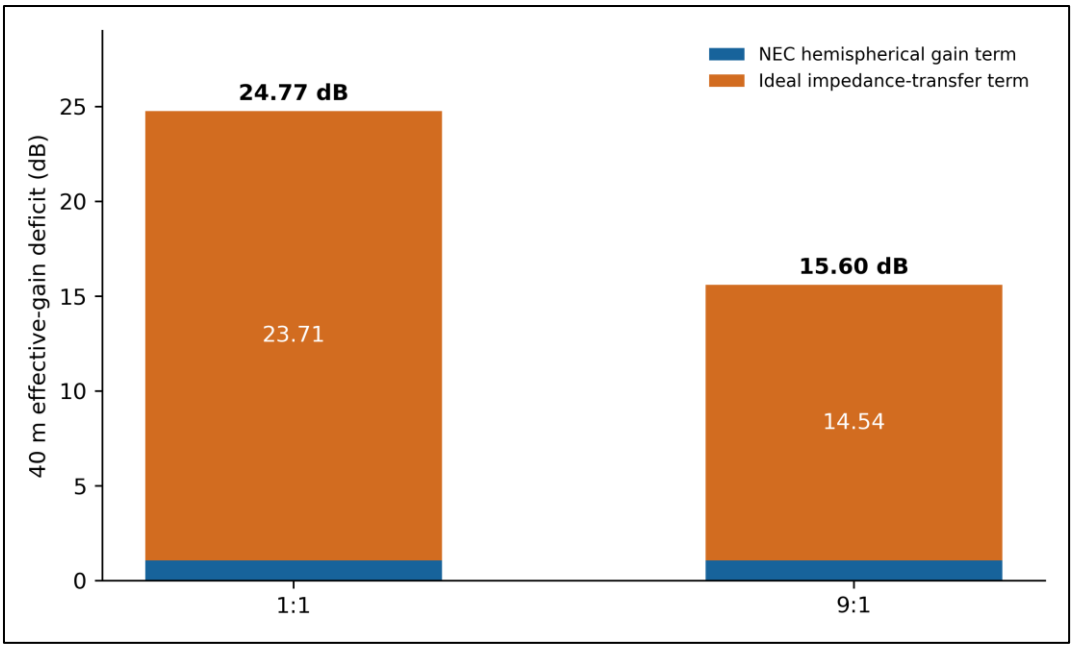

Figure 2: Decomposition of the 40 m receiving effective-gain deficit between the 14.00 and 7.19 m loops at a common ideal impedance ratio. Both components are differences in modeled indicators, not measured physical loss.

3.4 Fixed transformations versus ideal matching

The restricted set of four impedance ratios does not exhaust the possible matching solutions.

For a purely resistive load, the load maximizing the available-power transfer factor is

$$R_{L,\mathrm{opt}} = \sqrt{R_A^2 + X_A^2}$$

A conjugate load provides the theoretical maximum available-power transfer:

$$Z_L = Z_A^*$$

Table 3 compares the best fixed ratio with these ideal matching limits for the 40 m band.

Table 3: Modeled upper-hemisphere effective gain on 40 m under alternative ideal matching assumptions.

Matching condition	14 m loop (dBi)	7.19 m loop (dBi)	Difference (dB)
Best of four fixed ratios	+1.02	−15.78	−16.80
Frequency-dependent optimum resistive load	+1.11	−3.97	−5.08
Ideal conjugate matching	+1.92	+0.86	−1.06

The results show that the 16.80 dB deficit observed with the best fixed ratios falls to 5.08 dB under optimized resistive loading and to only 1.06 dB under ideal conjugate matching.

Thus, the large difference between the two antennas under the tested fixed-ratio arrangements should not be interpreted as an unavoidable geometric limitation.

Nevertheless, ideal conjugate matching is a theoretical bound. A physical network introduces losses and may not maintain the required impedance transformation over an entire amateur band.

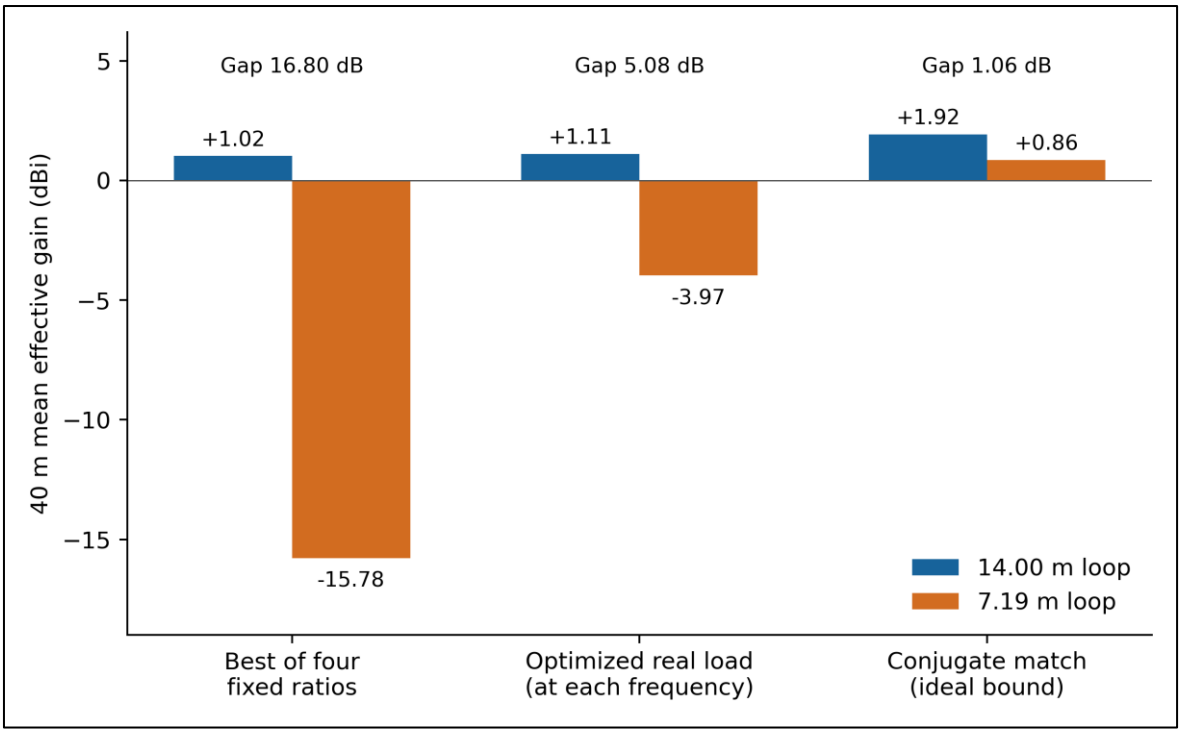

Figure 3: Forty-meter mean effective gain for the two loop sizes under three ideal loading assumptions. Optimized resistive and conjugate loads are frequency-dependent analytical bounds, not tested hardware.

3.5 Interpretation using electrical length

The large frequency dependence can be interpreted partly through the normalized perimeter P/λ.

The 14 m reference has a nominal perimeter of approximately 42.6 m, while the 7.19 m loop has a nominal perimeter of approximately 21.9 m.

At 7.15 MHz, the corresponding normalized perimeters are approximately

$$\left(\frac{P}{\lambda}\right)_{14\text{m}} \approx 1.02$$

and

$$\left(\frac{P}{\lambda}\right)_{7.19\text{m}} \approx 0.52$$

The reference is therefore close to one wavelength in perimeter, while the reduced antenna is close to half a wavelength.

These electrical lengths help explain why the two configurations exhibit substantially different input impedances on 40 m.

At approximately 14.2 MHz, the reduced loop approaches one wavelength in perimeter, consistent with its comparatively favorable 20 m behavior.

However, proximity to a nominal resonant electrical length does not by itself establish resonance, antiresonance or optimal reception. Those properties depend on the complete impedance response and geometry.

The observed non-monotonic behavior across the HF spectrum is consistent with changes in electrical length, current distribution and feed-point impedance as the antenna is scaled.

4 DISCUSSION

4.1 Practical antenna dimensions and matching recommendations

The simulations suggest three practical installation scenarios, depending on the intended HF bands and available antenna space.

4.1.1 Multiband Delta Loop including 40 m

A loop with an upper side close to 14 m is preferable when 40 m reception is important and sufficient installation space is available.

A 13.30 m upper side satisfies the selected 3 dB criterion on 40 m, while 12.00 m satisfies the 6 dB criterion.

For the 14 m reference, a 4:1 impedance transformation gives the highest modeled band-mean effective gain among the four tested ratios on both 40 and 20 m.

However, because the preferred transformation varies across HF bands, a balanced adjustable matching system is a reasonable practical alternative for multiband operation.

An open-wire feeder combined with an appropriate balanced tuner deserves consideration, although feeder lengths, losses and tuner performance were not simulated.

4.1.2 Reduced Delta Loop for 20-10 m

For operators with limited space, an upper side of approximately 7.2 m represents a useful compromise when reception is concentrated on 20 m and higher frequencies.

The modeled 20 m deficit relative to the 14 m reference is only 0.29 dB when the best tested fixed ratio is used for each antenna.

For this reduced configuration, the ideal 2:1 impedance ratio performs best on 20 m, while 9:1 gives the highest band-mean result among the investigated ratios on several other HF bands.

An adjustable matching system is consequently preferable when the operator intends to cover multiple bands and avoid dependence on one fixed transformation.

4.1.3 Reduced Delta Loop specifically for 40 m

A 7.2 m upper side is not recommended for 40 m when the antenna is connected through only one of the four tested fixed-ratio transformations.

The best modeled fixed-ratio configuration remains 16.80 dB below the reference.

Nevertheless, the substantially smaller deficit under theoretical conjugate matching suggests that a tuned reactive matching network may recover an important fraction of the modeled transfer loss.

Such a network should be designed from the measured complex feed impedance and evaluated for actual insertion loss, bandwidth and stability.

The present simulations do not establish the performance of any specific physical matching circuit.

4.2 Does lower effective gain necessarily mean worse SNR?

The preceding effective-gain differences should not be interpreted directly as equivalent differences in received SNR.

At HF, atmospheric, galactic and man-made noise often dominate the receiver's internal noise. The statistical characteristics of external radio noise are described in ITU-R P.372 [7].

When externally collected noise strongly dominates receiver noise, passive mismatch attenuation may reduce the desired signal and external noise together, yielding an SNR penalty smaller than the delivered-signal-power deficit. This does not apply automatically when receiver noise or matching-network loss is significant.

Conversely, when external noise becomes comparable to the receiver's internal noise, mismatch losses can substantially degrade SNR.

A related HF antenna-selection study [4] found that full SNR modeling improved the selection of a fixed antenna by only 0.1305 dB on average compared with a simpler NEC2-gain-based rule, under its simulated conditions.

That result supports using conventional electromagnetic modeling for initial antenna selection when more detailed noise information is unavailable.

It does not imply that impedance matching is unimportant, nor does it demonstrate that the large transfer losses identified here will have negligible consequences at every receiving station.

The practical significance of matching depends on the balance between external noise, internal receiver noise, feeder losses and antenna-specific noise coupling.

A complete SNR assessment would therefore require additional information about the actual receiving environment and system.

4.3 Limitations

This computational study lacks experimental validation, and its results depend on the modeled geometry, conductor properties, excitation, antenna height and ground conditions. Only four ideal fixed impedance ratios were evaluated; practical matching networks may introduce losses, parasitic reactance and bandwidth limitations.

The upper-hemisphere gain metric does not account for specific propagation directions, polarization or directional noise, and therefore cannot directly predict DX, NVIS or received SNR performance. Furthermore, the 21 frequency samples per band may miss narrow impedance extrema. Convergence tests confirmed principal-wire mesh stability on 40 m but did not independently validate the three-segment feeding conductor.

Future work should incorporate measured antenna impedances, practical matching networks, alternative ground conditions and direction-specific reception. Receiver-noise analysis would be particularly valuable for quiet locations or systems with significant matching and feeder losses.

5 CONCLUSION

The study demonstrates that the minimum useful size of an HF receiving Delta Loop depends strongly on the operating band and impedance-matching arrangement.

For the specific geometry and simulation conditions investigated, the smallest tested upper-side lengths satisfying a 3 dB effective-gain criterion are 13.30 m on 40 m, 6.83 m on 20 m, and approximately 3.33-4.53 m between 17 and 10 m.

A reduced Delta Loop with an upper side of approximately 7.2 m is therefore a reasonable space-saving option for radio amateurs primarily interested in 20-10 m reception.

The central finding concerns 40 m performance. The 7.19 m loop exhibits a 16.80 dB effective-gain deficit relative to the 14 m reference under the best tested fixed impedance ratios. This difference falls to only 1.06 dB under ideal, frequency-dependent conjugate matching. Thus, the large fixed-ratio deficit is primarily attributable to impedance transfer rather than an equivalent reduction in modeled hemispherical gain. The conjugate-matching result represents a theoretical limit, not experimentally demonstrated performance.

For practical installations, a near-full-size loop remains the more straightforward option when 40 m coverage is important. A smaller loop can be attractive on higher HF bands, preferably with adjustable impedance matching. Operation on 40 m with a substantially reduced loop warrants a specifically designed reactive matching network rather than reliance on a fixed-ratio transformer alone.

The practical conclusion is that Delta Loop dimensions and impedance matching must be selected together. Antenna size alone is insufficient to predict the power delivered to a receiver, while delivered-power differences must not be confused with equivalent differences in received SNR.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Acknowledgments

The study was conducted using open-source electromagnetic simulation and Python-based numerical analysis tools.

Disclosure of conflict of interest

The author declares no conflict of interest related to this research.

Data and code availability

The NEC2C antenna models, simulation results, analysis scripts, and numerical verification data supporting this study are available from the corresponding author upon reasonable request.

Declaration of AI assistance

AI-based tools assisted with manuscript drafting, technical review and editorial language. The author remains responsible for the numerical calculations, scientific interpretation, verification of results and approval of the final manuscript.

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