shieldeval: reconstruction and modernisation of the legacy shield-evaluation tool

Project C — transfer impedance and screening attenuation from triaxial and line-injection measurements

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Contents

1 Purpose and the ground rules of a legacy rewrite

An in-house program, several versions old, turns the raw output of the shield measurement into the two numbers the laboratory reports: the transfer impedance Z_T of the cable shield at low frequency and its screening attenuation a_S at high frequency. The physics behind those numbers is fiddly. The measurement fixture — a tube around the cable, or an injection wire above it — behaves as an electrically short loop below a certain frequency and as a resonant transmission line above it, so the software has to know which regime it is in, trace the envelope of a standing-wave pattern in the second regime, normalise the result to a reference condition, and subtract a calibration run. The old program does all of that, with constants typed in by people who have since left, and nobody dares to touch it because its results are in ten years of reports.

The rules this project follows are the ones any responsible rewrite of such a tool has to follow:

1. **Reconstruct before changing.** The legacy behaviour is re-implemented step by step, each step named, its quirk documented, and the whole reproduced *byte for byte* on the archived data (six samples, six result files) before a single number is improved. The compatibility mode stays available, so an old report can always be regenerated.
2. **Change only with a reason and a number.** Every modernisation is tied to a documented quirk, and its effect on the archived samples is quantified (Section 6).
3. **Extend by data, not by code.** The newer fixtures the laboratory has acquired (a 1 m tube, a line-injection set-up, a connector fixture) are profiles in TOML files that carry the fixture's physics; the evaluation code is the same for all of them.

One thing must be stated plainly. The laboratory's legacy program and its archive are confidential and were not available to this project. The "legacy tool" here — `legacy/shieldeval_v3.py`, 150 lines in the style of a 2016 script — was *written for this project* as a stand-in, with the kinds of quirks such tools really have, and the "archive" was produced by running it on synthetic raw files generated from the physics of Section 2. The method is therefore demonstrated end to end, but the reproduction of a stand-in is not evidence about the real program; on the real one the same procedure applies, starting with the characterisation tests of Section 4.

2 Physics of the measurement

2.1 Circuit and coupling function

The cable under test is the *inner* circuit: a line of characteristic impedance Z_1 and propagation constant γ_1, driven at $z = 0$ by a generator of source impedance R_1 and terminated in R_1 at $z = L_c$, so that $I_1(z) = I_0 e^{-\gamma_1 z}$ with $I_0 = V_{\mathrm{gen}}/(2R_1)$. The *outer* circuit is formed by the outside of the shield and the tube (triaxial method, IEC 62153-4-3 (IEC 2013) and -4-4 (IEC 2015)) or the injection wire (line injection, IEC 62153-4-6 (IEC 2017)): a second line of impedance Z_2 and propagation constant γ_2, connected to the receiver R_2 at $z = 0$ and short-circuited (triaxial) or terminated in R_2 (line injection) at $z = L_c$.

The transfer impedance $Z_T(f)$ of the shield (Vance 1978) acts as a distributed series EMF in the outer circuit, $\mathrm{d}E = Z_T I_1(z)\,\mathrm{d}z$. By superposition, the receiver voltage is

$$V_2 = R_2 \int_0^{L_c} \frac{Z_T\, I_1(z)\, T(z)}{Z_{\mathrm{near}}(z) + Z_{\mathrm{far}}(z)}\,\mathrm{d}z,$$

where $Z_{\mathrm{near}}(z) = Z_2 \dfrac{R_2 + Z_2 \tanh \gamma_2 z}{Z_2 + R_2 \tanh \gamma_2 z}$ is the impedance seen from z toward the receiver, $Z_{\mathrm{far}}(z)$ the impedance toward the far end ($Z_2 \tanh \gamma_2 (L_c - z)$ for a short, the matched-line expression for line injection), and $T(z) = 1/(\cosh \gamma_2 z + (R_2/Z_2) \sinh \gamma_2 z)$ the current transfer from z to the receiver. With a Z_T that is uniform along the sample the measured transmission factorises,

$$S_{21}(f) = \frac{2V_2}{V_{\text{gen}}} = Z_T(f)\,K(f),$$

into the shield property and a **coupling function** $K(f)$ that depends only on the fixture (Z_2, γ_2, L_c, R_1, R_2, far-end condition) and on the inner line's γ_1. In the electrically short limit $K \to L_c/R_1$ for the short-circuited tube and $L_c/(2R_1)$ for the matched injection line (the EMF then drives two terminations in series), which gives the textbook formulas $Z_T = R_1|S_{21}|/L_c$ and $Z_T = 2R_1|S_{21}|/L_c$ — the IEC form $Z_T = (R_1 + R_2)|S_{21}|/(2L_c)$ coincides with them for $R_1 = R_2 = 50\ \Omega$. Both limits are unit tests of `physics.coupling_function`.

2.2 Transfer impedance of a braid (synthetic data)

For the synthetic archive the shield is a braid with the classical model (Vance 1978; Tyni 1976)

$$Z_T(f) = R_{\text{dc}}\,\frac{(1+j)\,d/\delta}{\sinh\left((1+j)\,d/\delta\right)} + j\omega M_T, \qquad \delta = \sqrt{\frac{2\rho}{\omega\mu_0}},$$

with d the strand diameter, δ the skin depth and $M_T = L_{\text{hole}} - L_{\text{braid}}$ the net coupling inductance, which is negative for optimised braids. The diffusion term falls, the inductive term rises, and the magnitude has the well-known minimum around 1 MHz. Six shields (single, optimised, braid + foil, loose, thin-strand and double braid) span two decades of Z_T; three more samples were "measured" on the newer fixtures. The analyser export is emulated exactly: 401 log-spaced points from 100 kHz to 1 GHz, attenuation with two decimals, phase with one, a calibration run on a coarser 101-point grid, and receiver noise at −110 dB.

3 The legacy tool and its quirk register

`legacy/shieldeval_v3.py` reads the raw file, subtracts the calibration run, splits the band at a fixed cut-off, computes Z_T below it and the envelope-based a_S above it, and writes 61 result lines plus a verdict. Its re-implementation `shieldeval.legacy` keeps the arithmetic in the same order so that the floating-point results are identical, and documents nine quirks:

	legacy behaviour	why it is questionable	modern behaviour
Q1	fixture table hard-coded: TUBE500 only, $L_c = 0.5$ m, $Z_2 = 100\ \Omega$, $f_{\text{cut}} = 30$ MHz	new fixtures cannot be used; the cut-off is a typed-in number	fixture profiles in TOML; transition from the coupling function
Q2	calibration interpolated linearly *in linear frequency* from the 101-point cal grid, subtracted in dB	the sweeps are logarithmic; the interpolation over-estimates the loss by up to 0.02 dB below 1 MHz	interpolation in log frequency
Q3	first sweep point dropped ("DC glitch")	hides a data problem instead of flagging it	all points kept; noise-floor flag

	legacy behaviour	why it is questionable	modern behaviour
Q4	envelope = sliding minimum of attenuation over $N = \lfloor n/40 \rfloor + 1$ points, forward-looking window $[i, i + N)$	shifted toward lower frequency by up to N points (1.5 dB error in a_S on the rising part); N depends on the number of sweep points, not on the physics	centred window of one resonance spacing $v_2/(2L_c)$, applied only where a standing wave is present
Q5	output on 61 fixed frequencies by nearest neighbour	the reported frequency is not the measured one; interpolation error up to 3 % in Z_T	full-resolution curves; summary values interpolated in log–log
Q6	10^{-12} added to Z_T	a log guard that outlived its purpose	removed
Q7	$a_S = a_{\text{env}} + 10 \log_{10}(300/Z_2)$	$k_{\text{norm}} = 2$ and $Z_s = 150\ \Omega$ baked into a literal	both in the fixture profile, with provenance
Q8	"Z_T at 10 MHz" = last raw point at or below 10 MHz	systematically low by 2–3 % because Z_T rises with f	log–log interpolation at exactly 10 MHz
Q9	Z_T with 3 decimals, a_S with 1 decimal, "–" where not applicable	format only	JSON with full precision; HTML report

And one behaviour that is not a formatting quirk but a wrong answer: the legacy tool reports a number for Z_T whatever the signal level, so a very good shield whose coupling is at the receiver noise floor gets a flattering, fictitious Z_T (the double braid: 0.388 mΩ/m reported, 0.625 true, both below the floor). The modern tool reports an *upper bound* instead.

4 Equivalence proof

`shieldeval compare archive/` runs the compatibility mode on every raw file of the archive and compares the output text with the archived result:

```
S01_single_braid          IDENTICAL
S02_optimised_braid       IDENTICAL
S03_braid_foil            IDENTICAL
S04_loose_braid           IDENTICAL
S05_thin_strands          IDENTICAL
S06_double_braid          IDENTICAL
6/6 archived results reproduced byte for byte
```

`tests/test_legacy_equivalence.py` makes this a permanent characterisation test, and a second test runs the *original* script and compares its bytes as well, so that the archive cannot drift either. Byte identity, not "within tolerance", is the right criterion here: the moment a rewrite is allowed to differ by 0.001, every later difference has to be argued about.

5 The modern evaluation

`shieldeval.core.evaluate` performs, for any fixture profile:

1. **Calibration** in log frequency and a noise-floor flag from the instrument specification (105 dB, lowered if the raw trace is visibly at the floor), with a 10 dB margin.
2. **Regime detection.** The *model* transition f_t is the frequency at which $|K(f)|$ has fallen 1 dB below L_c/R_1 — where the textbook formula starts to be wrong by that amount (25 MHz for the 0.5 m tube, 14 MHz for the 1 m tube, 36 MHz for the injection line); the *data* cross-checks are the position of the first standing-wave maximum and the spacing of the pattern, compared with the fixture model's first resonance and $v_2/(2L_c)$. A measurement evaluated with the wrong profile (the 1 m tube's data with the 0.5 m profile) is flagged (`test_fixture_mismatch_is_flagged`).
3. **Transfer impedance** by dividing the complex S_{21} by the full coupling function, $Z_T = S_{21}/K$, valid up to the first zero of K and masked where $|K| < 0.25|K(0)|$ or the signal is within 10 dB of the noise floor. This is the substantive extension: on the 0.5 m tube the usable range grows from 30 MHz (legacy) to 630 MHz with a median error of 0.05 dB and a 90th percentile of 0.5 dB against the generating model (Table 1), and on the injection line — where the legacy formula would be 6 dB wrong even at low frequency, because the far end is matched — the model-based value is right to 0.1 dB (Figure 2).
4. **Screening attenuation** from the centred-window envelope, $a_S = a_{\text{env}} + 10\log_{10}(k_{\text{norm}} Z_s / Z_2)$ with k_{norm} and Z_s in the profile (values transcribed from the public standard text; the profile carries a verify-against-controlled-copy note, as in Project A).
5. **Summary and verdict**: Z_T at 1, 10 and 30 MHz (log–log interpolation, never bridging a masked region), the upper bound at 10 MHz when the reading is at the floor, a_S, min and where it occurs, the transition frequencies, and PASS / FAIL / INCONCLUSIVE against the profile's limit class. A shield below the floor *passes* if the floor itself is inside the limit, and is INCONCLUSIVE otherwise — the honest version of what the legacy tool silently did.

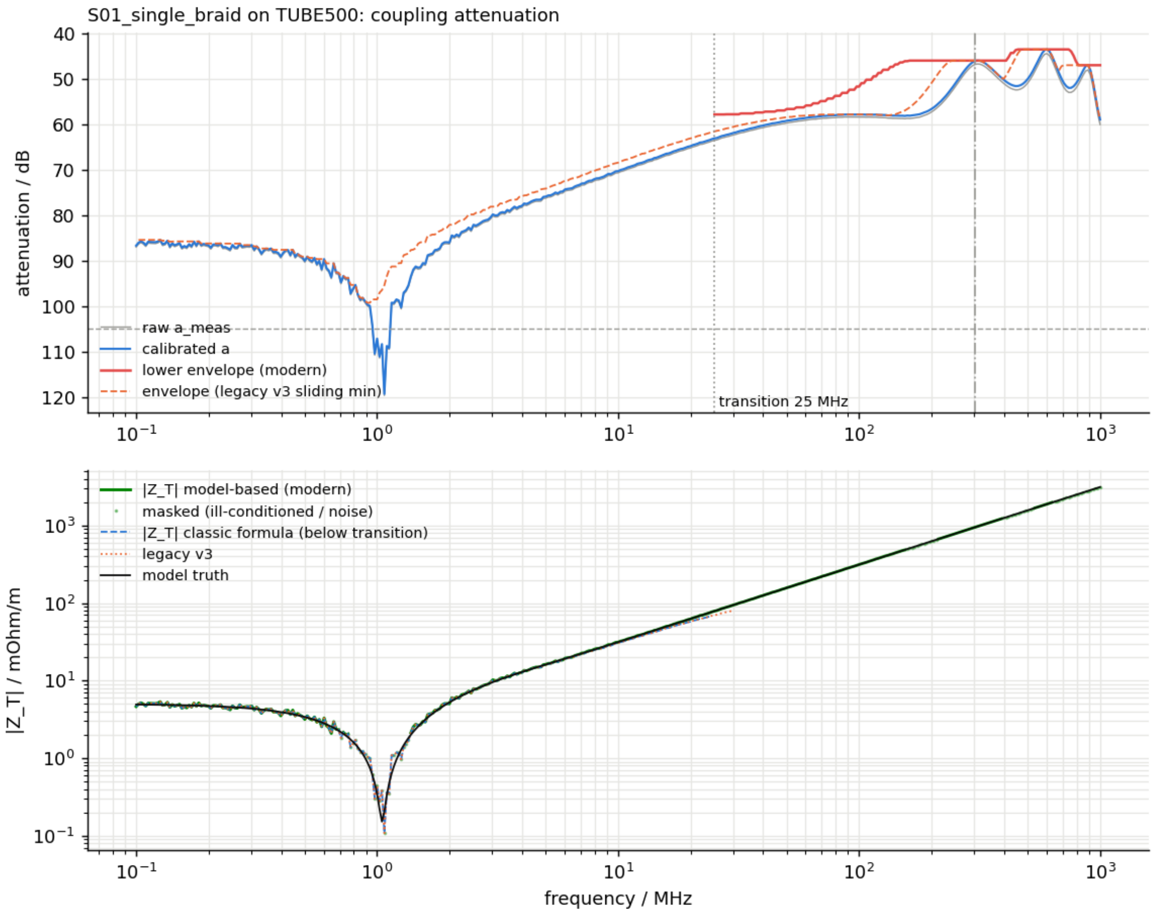

Figure 1: `S01_single_braid` on the 0.5 m tube: raw and calibrated attenuation with the modern envelope (red) and the lagging legacy envelope (orange, dashed); below, $|Z_T|$ from the model-based division (green) against the generating model (black), with the legacy result (dotted) ending at its 30 MHz cut-off.

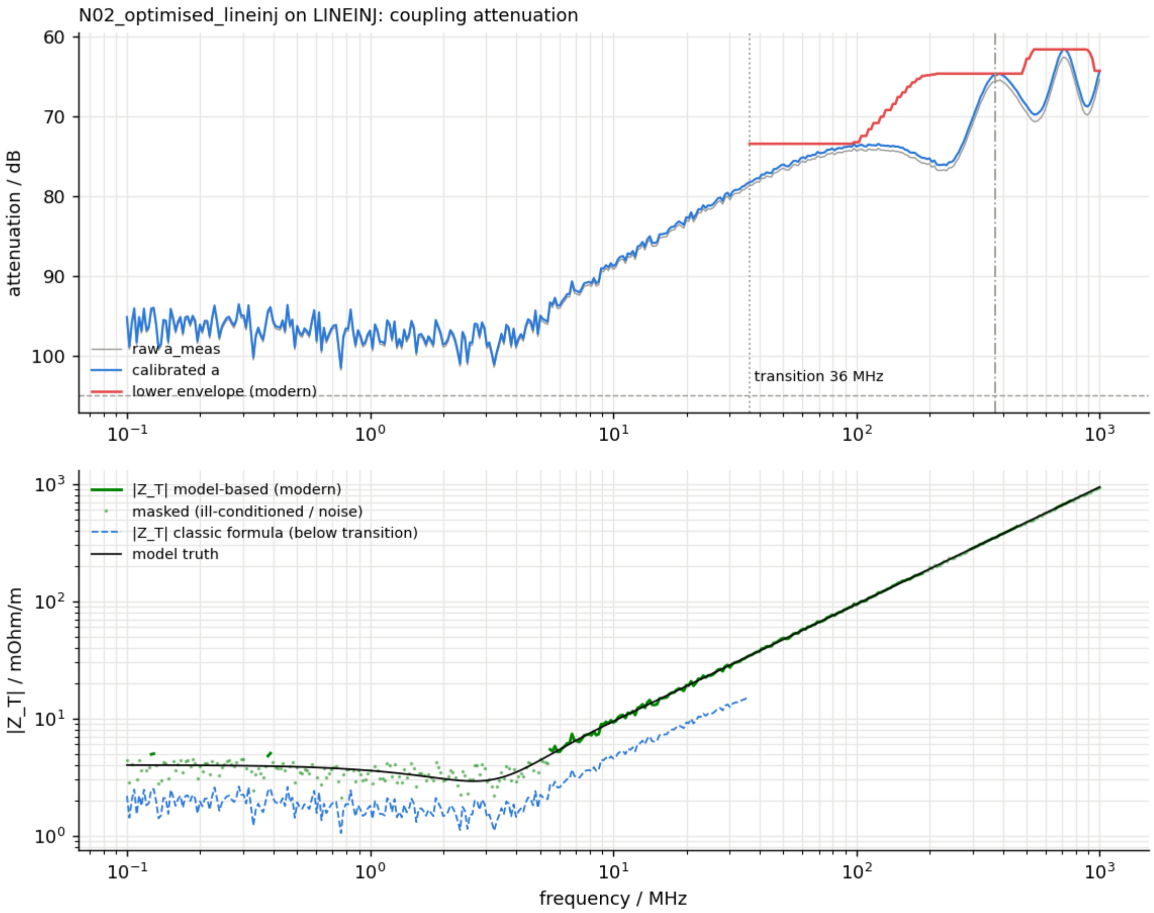

Figure 2: `N02_optimised_lineinj` on the line-injection fixture: the classic formula (blue, dashed) is 6 dB low because the matched far end halves the coupled current; the model-based Z_T (green) follows the truth. Below 4 MHz the measurement is at the noise floor and correctly masked.

6 Validation against the generating model

sample	fixture	Z_T(10 MHz) true	legacy v3	modern	modern err median / 90 % (dB), valid to	classic err median / 90 % below f_cut	a_S,min legacy / modern	verdict legacy / modern
S01_single_braid	TUBE500	31.407	30.549	31.314	0.05 / 0.52, 631 MHz	0.28 / 0.87	48.3 / 48.3	FAIL / FAIL
S02_optimised_braid	TUBE500	9.432	9.322	9.555	0.14 / 0.69, 631 MHz	0.40 / 0.97	58.7 / 58.7	PASS / PASS
S03_braid_foil	TUBE500	2.036	1.858	1.904	0.33 / 1.12, 631 MHz	0.62 / 1.48	72.7 / 72.7	PASS / PASS
S04_loose_braid	TUBE500	157.070	153.638	157.483	0.01 / 0.31, 631 MHz	0.16 / 0.72	34.3 / 34.3	FAIL / FAIL
S05_thin_strands	TUBE500	50.080	48.473	49.686	0.04 / 0.25, 631 MHz	0.17 / 0.55	44.2 / 44.2	FAIL / FAIL
S06_double_braid	TUBE500	0.625	0.388	< 1.904 (floor)	0.37 / 1.55, 631 MHz	0.68 / 1.99	82.4 / 82.4	PASS / PASS
N01_single_braid_tube1000	TUBE1000	31.407	nan	31.331	0.03 / 0.26, 316 MHz	0.20 / 0.62	nan / 49.0	– / FAIL
N02_optimised_lineinj	LINEINJ	9.432	nan	9.208	0.12 / 0.82, 759 MHz	6.19 / 6.95	nan / 64.6	– / PASS

sample	fixture	Z_T(10 MHz) true	legacy v3	modern	modern err median / 90 % (dB), valid to	classic err median / 90 % below f_cut	a_S,min legacy / modern	verdict legacy / modern
N03_connector	CONN	125.628	nan	125.531	0.01 / 0.10, 1000 MHz	0.03 / 0.33	nan / 23.7	– / FAIL

Table 1: Z_T at 10 MHz in mΩ/m (mΩ for the connector); errors are $|20\log_{10}(Z_{T,\text{eval}}/Z_{T,\text{true}})|$ over the valid points.

Three observations. The legacy Z_T at 10 MHz is 2–3 % low on every sample (Q8), the modern one within 0.5 %. The legacy and modern $a_{S,\text{min}}$ agree to 0.05 dB on the 0.5 m tube because both find the same global minimum of the standing-wave pattern — the envelopes differ elsewhere, which matters when a limit line rather than a single minimum is applied. And the newer fixtures work without any code change: the 1 m tube (usable Z_T range to 316 MHz, resonance spacing halved), the injection line (usable to 760 MHz), and the connector fixture, whose results are absolute ohms over the 50 mm coupling length.

7 Limitations

- The stand-in nature of the legacy tool and archive (Section 1). The procedure — characterisation tests first, byte-exact compatibility mode, quirk register with numbers, then extension by profiles — is the deliverable; the real program will have its own quirks.
- The coupling function assumes a uniform Z_T along the sample and neglects the transfer admittance (capacitive leakage), which is the standard assumption for braids with good optical coverage in a low-impedance outer circuit; for leaky braids or foils with drain wires the IEC methods themselves are approximate.
- The screening-attenuation normalisation constants (k_{norm}, Z_s) and the limit values are transcribed from public material and flagged for verification against the controlled standards.
- Above the first zero of K the transfer impedance is not recoverable from a single fixture length; the standards' answer (a second, shorter sample) is a second fixture profile here.

8 Appendix: the legacy result format (S01)

```
# SHIELDEVAL v3.2 RESULT
# SAMPLE=S01_single_braid
# FIXTURE=TUBE500 LC=0.500 Z2=100.0 FCUT=30000000
# CAL=cal_20210412.cal
# N_ENV=11 NPOINTS=400
# ZT_10MHZ=30.549 mOhm/m  AS_MIN=48.3 dB  VERDICT=FAIL
f[Hz]  ZT[mOhm/m]  aS[dB]  f_raw[Hz]
1.000000e+06  0.440  -  1.000000e+06
1.120000e+06  0.348  -  1.122018e+06
1.260000e+06  0.969  -  1.258925e+06
1.410000e+06  2.523  -  1.412538e+06
1.580000e+06  2.924  -  1.584893e+06
1.780000e+06  4.188  -  1.778279e+06
2.000000e+06  5.009  -  1.995262e+06
2.240000e+06  6.539  -  2.238721e+06
2.510000e+06  7.861  -  2.511886e+06
2.820000e+06  8.821  -  2.818383e+06
3.160000e+06  9.994  -  3.162278e+06
3.550000e+06  11.105  -  3.548134e+06
3.980000e+06  12.647  -  3.981072e+06
4.470000e+06  14.575  -  4.466836e+06
5.010000e+06  16.051  -  5.011872e+06
5.620000e+06  17.418  -  5.623413e+06
6.310000e+06  19.656  -  6.309573e+06
7.080000e+06  22.387  -  7.079458e+06
7.940000e+06  24.889  -  7.943282e+06
8.910000e+06  27.534  -  8.912509e+06
1.000000e+07  30.549  -  1.000000e+07
1.120000e+07  34.207  -  1.122018e+07
1.260000e+07  37.888  -  1.258925e+07
1.410000e+07  42.596  -  1.412538e+07
1.580000e+07  47.534  -  1.584893e+07
1.780000e+07  52.541  -  1.778279e+07
2.000000e+07  57.510  -  1.995262e+07
2.240000e+07  63.460  -  2.238721e+07
2.510000e+07  70.065  -  2.511886e+07
2.820000e+07  76.669  -  2.818383e+07
3.160000e+07  -  65.1  3.162278e+07
3.550000e+07  -  64.5  3.548134e+07
3.980000e+07  -  64.0  3.981072e+07
4.470000e+07  -  63.6  4.466836e+07
5.010000e+07  -  63.2  5.011872e+07
5.620000e+07  -  62.9  5.623413e+07
6.310000e+07  -  62.8  6.309573e+07
7.080000e+07  -  62.6  7.079458e+07
7.940000e+07  -  62.6  7.943282e+07
8.910000e+07  -  62.6  8.912509e+07
1.000000e+08  -  62.6  1.000000e+08
1.120000e+08  -  62.6  1.122018e+08
1.260000e+08  -  62.7  1.258925e+08
1.410000e+08  -  62.6  1.412538e+08
1.580000e+08  -  61.4  1.584893e+08
1.780000e+08  -  59.1  1.778279e+08
2.000000e+08  -  55.7  1.995262e+08
2.240000e+08  -  52.1  2.238721e+08
2.510000e+08  -  50.8  2.511886e+08
2.820000e+08  -  50.8  2.818383e+08
3.160000e+08  -  50.8  3.162278e+08
3.550000e+08  -  52.5  3.548134e+08
3.980000e+08  -  54.8  3.981072e+08
4.470000e+08  -  50.0  4.466836e+08
5.010000e+08  -  48.3  5.011872e+08
5.620000e+08  -  48.3  5.623413e+08
6.310000e+08  -  49.7  6.309573e+08
7.080000e+08  -  51.8  7.079458e+08
7.940000e+08  -  51.8  7.943282e+08
8.910000e+08  -  51.8  8.912509e+08
```

```
1.000000e+09  -  63.7  1.000000e+09
```

9 References

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