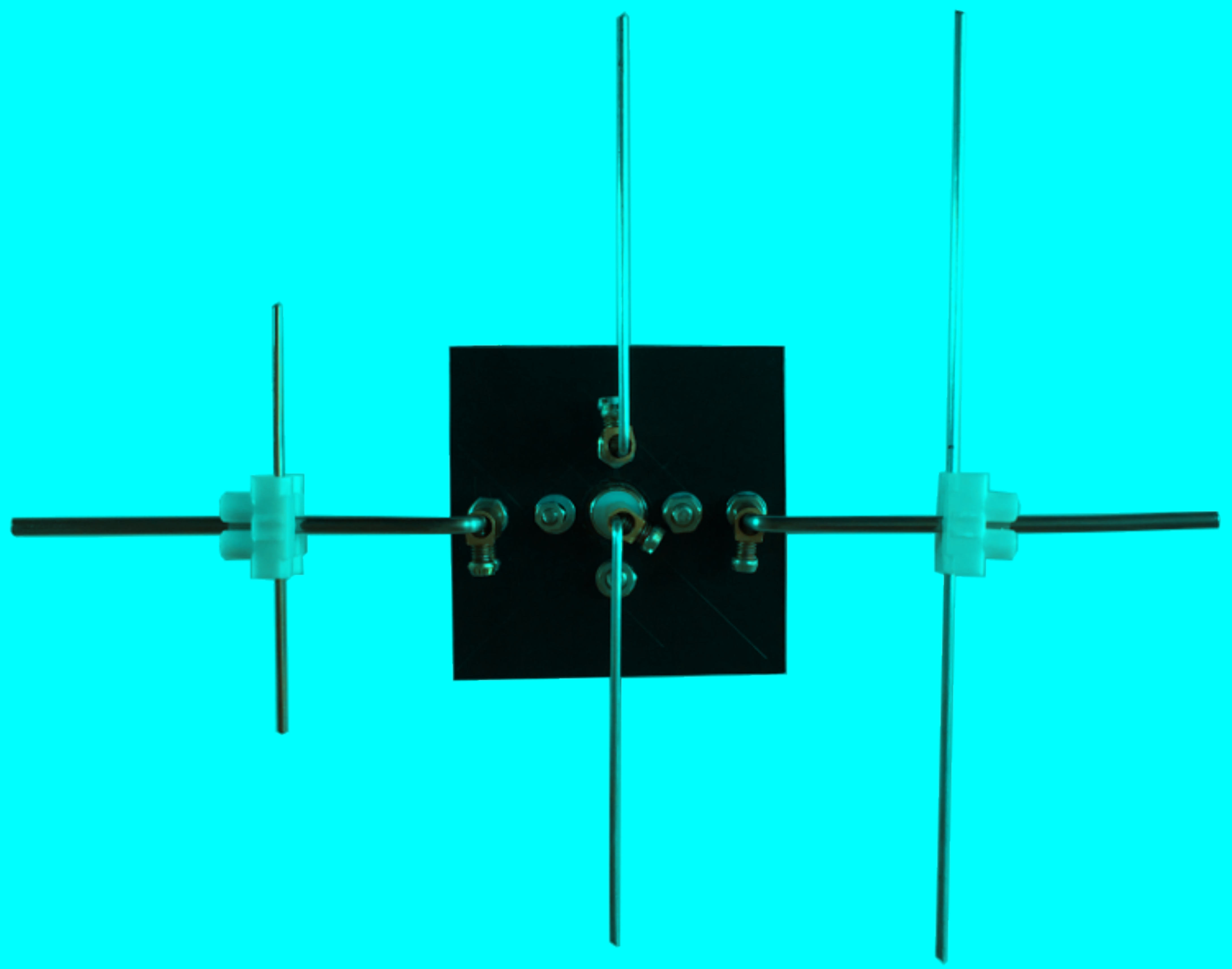
LORA / LORAWAN TUTORIAL 48

Yagi-Uda Antenna



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INTRO

- In this tutorial I will explain what a Yagi-Uda antenna is and how to build one.

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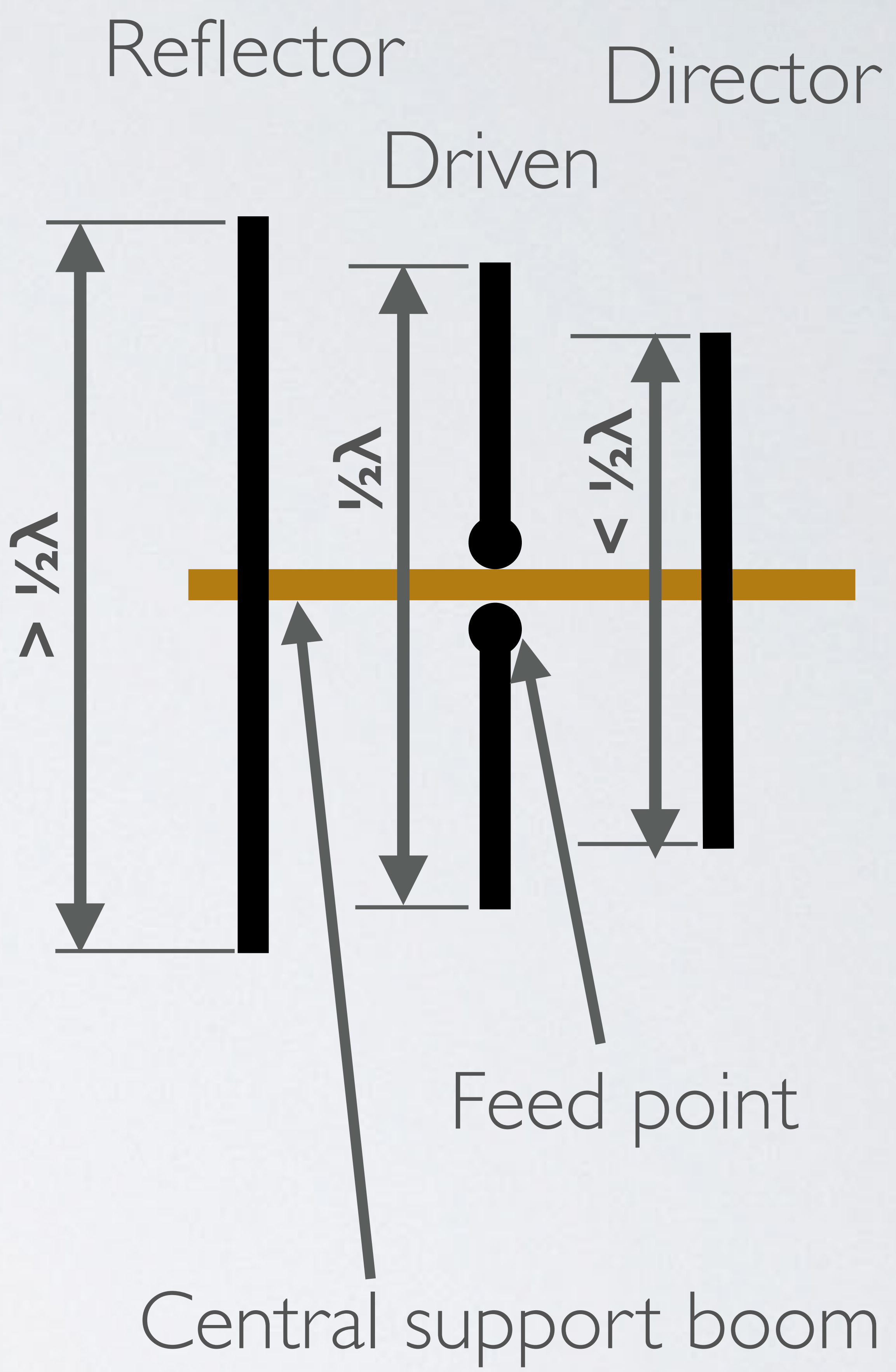
ATTENTION

- **The antennas built in this tutorial are intended for test and educational purpose and should be used indoors.**
- **The antennas are constructed in such a way so it can be easily disassembled and its parts can be re-used in other antenna projects.**
- **The antennas are not properly constructed and the antenna performance can be improved by using better materials, parts or another way of construction.**

YAGI-UDA ANTENNA

- The Yagi-Uda antenna, also known as Yagi antenna, is a directional high gain antenna.
- A basic Yagi-Uda antenna consists of three elements. A reflector, a driven element and a director.
- The driven element is a half wave dipole and parallel to the driven element on either side of it, are straight wires, the reflector and the director.
- The reflector is slightly longer than 1/2 wavelength, the driven element is 1/2 wavelength long and the director is slightly shorter than 1/2 wavelength.



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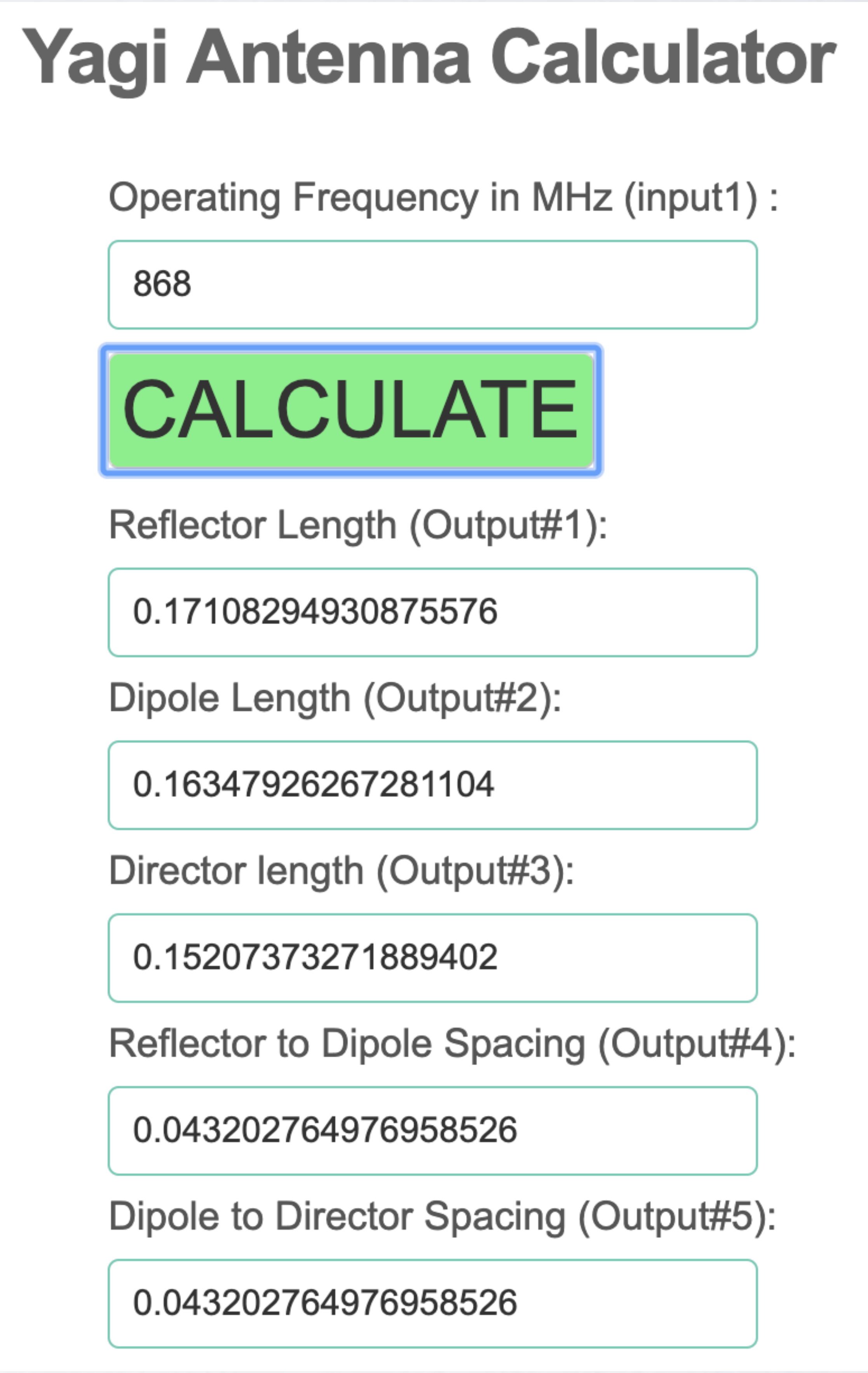
YAGI-UDA ANTENNA

- I used an online Yagi-Uda antenna calculator to calculate the antenna dimensions: https://www.rfwireless-world.com/calculators/3-element-Yagi-Antenna-Calculator.html

- This online calculator uses the equations found on the next slide to calculate the 3 element Yagi-Uda antenna dimensions.



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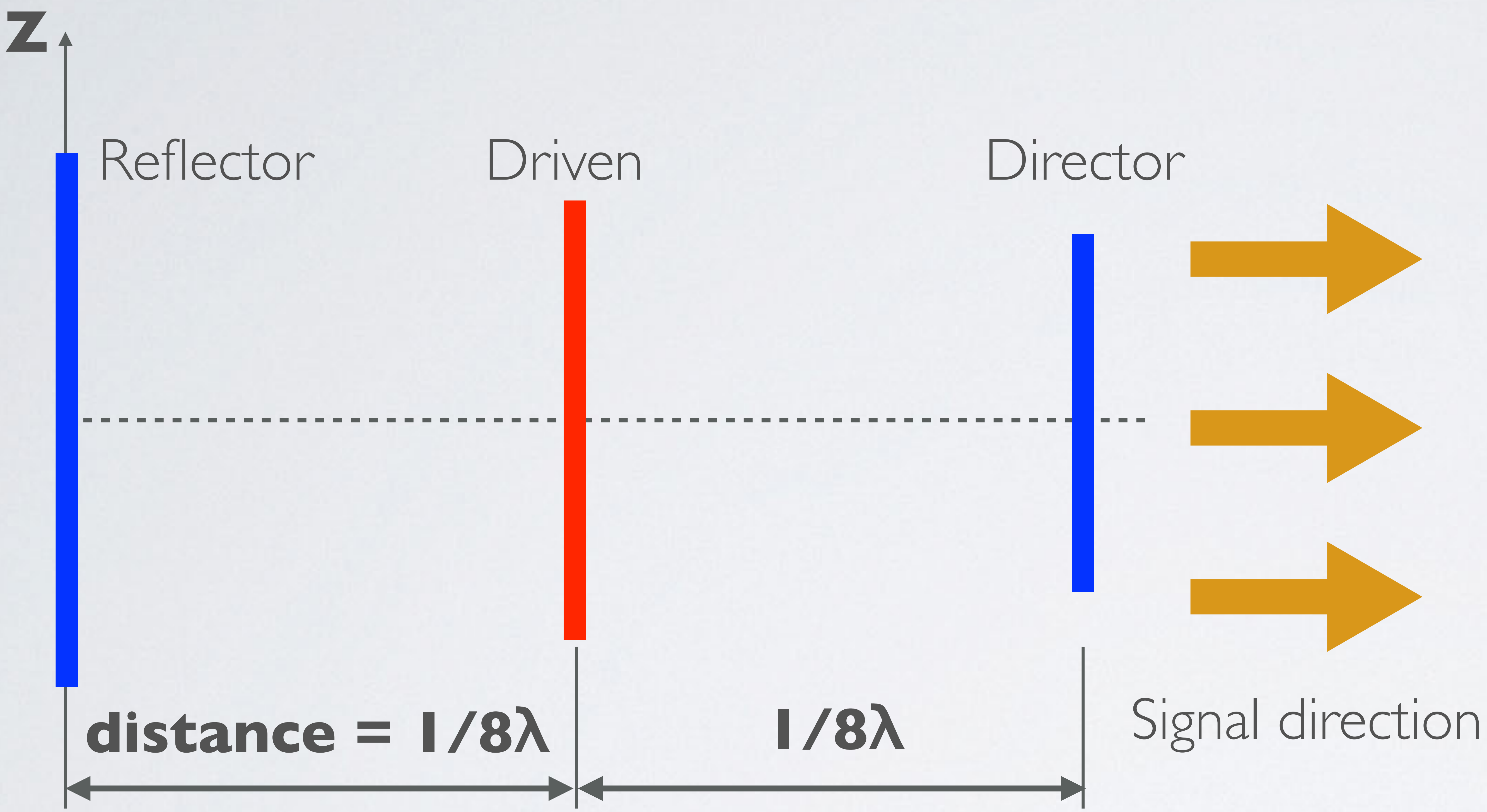
YAGI-UDA ANTENNA DESIGN



$f = 868$ MHz

$\lambda = c / f$

$\lambda = 299792458 / (868 \times 10^6)$

$\lambda = 345.38$ mm

$L_{Reflector} = 171$ mm

$L_{Driven} = 163$ mm

$L_{Director} = 152$ mm

distance = 43 mm

Drawing not to scale

$\mathbf{L_{Reflector} = 0.495\ \lambda}$

$\mathbf{L_{Driven} = 0.473\ \lambda}$

$\mathbf{L_{Director} = 0.440\ \lambda}$

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YAGI-UDA ANTENNA

- I have used the 4NEC2 antenna modelling software to verify the design.
- 4NEC2 card deck:
  https://www.mobilefish.com/download/lora/yagi_868mhz_4nec2_before_optimisation.nec.txt

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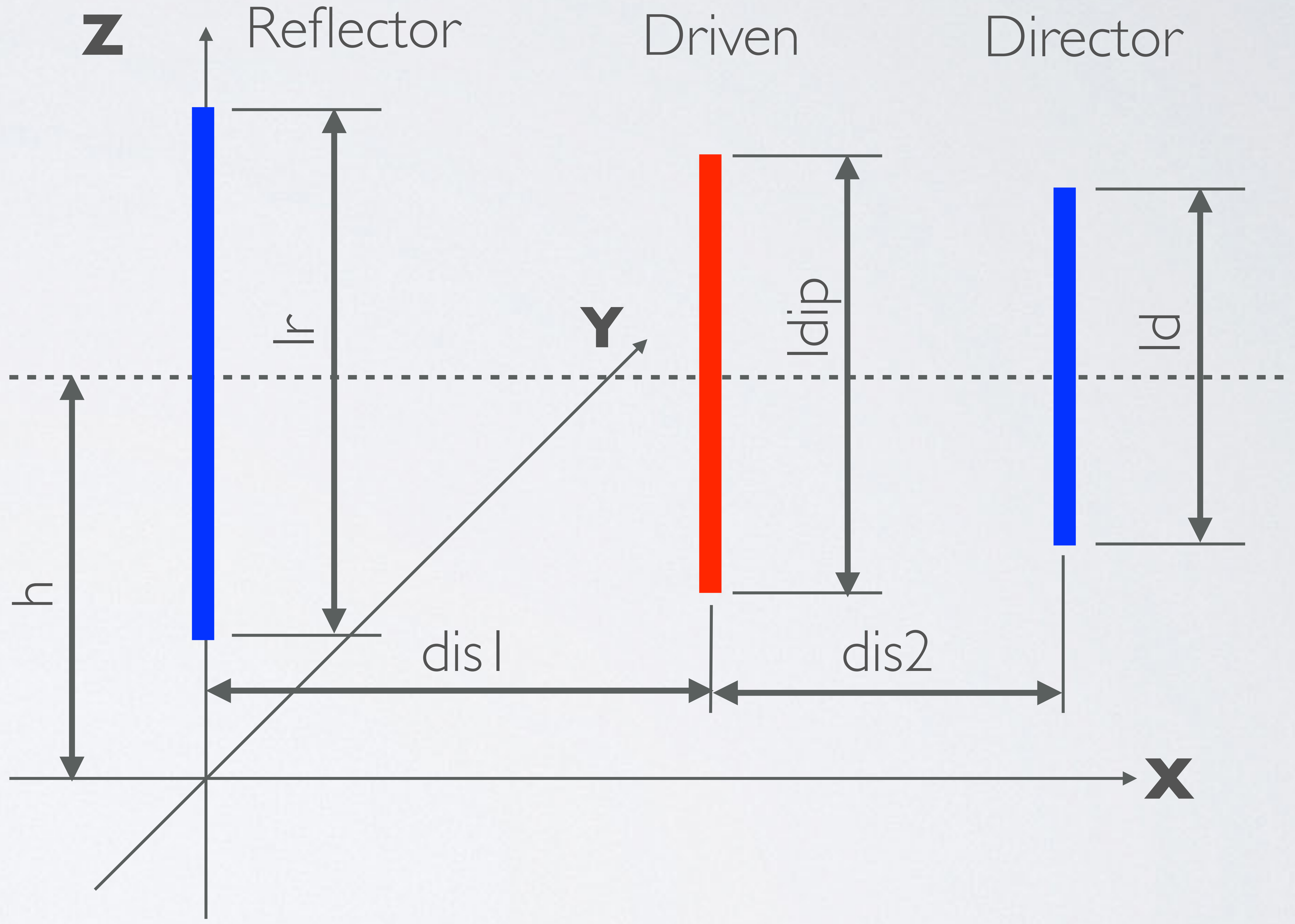
ANTENNA MODELLING NEC-2 BEFORE OPTIMISATION

- Yagi-Uda antenna
  f = 868 MHz
  wire diameter = 1.8 mm
  wire material: stainless steel

  h = 1 m
  lr = 171 mm
  ldip = 163 mm
  ld = 152 mm
  dis1 = 43 mm
  dis2 = 43 mm

  Drawing not to scale



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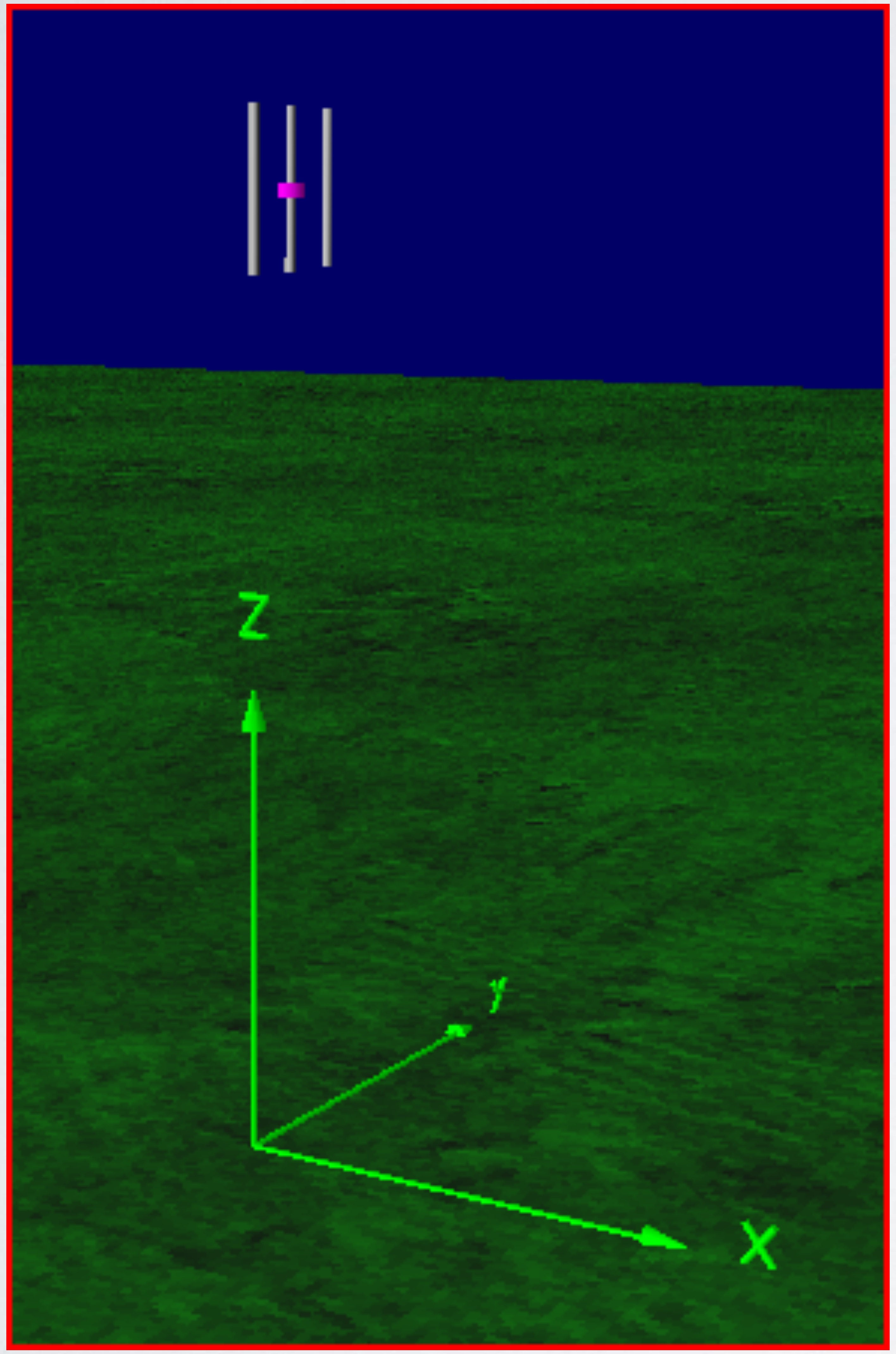
ANTENNA MODELLING NEC-2 BEFORE OPTIMISATION



Created in 4NEC2

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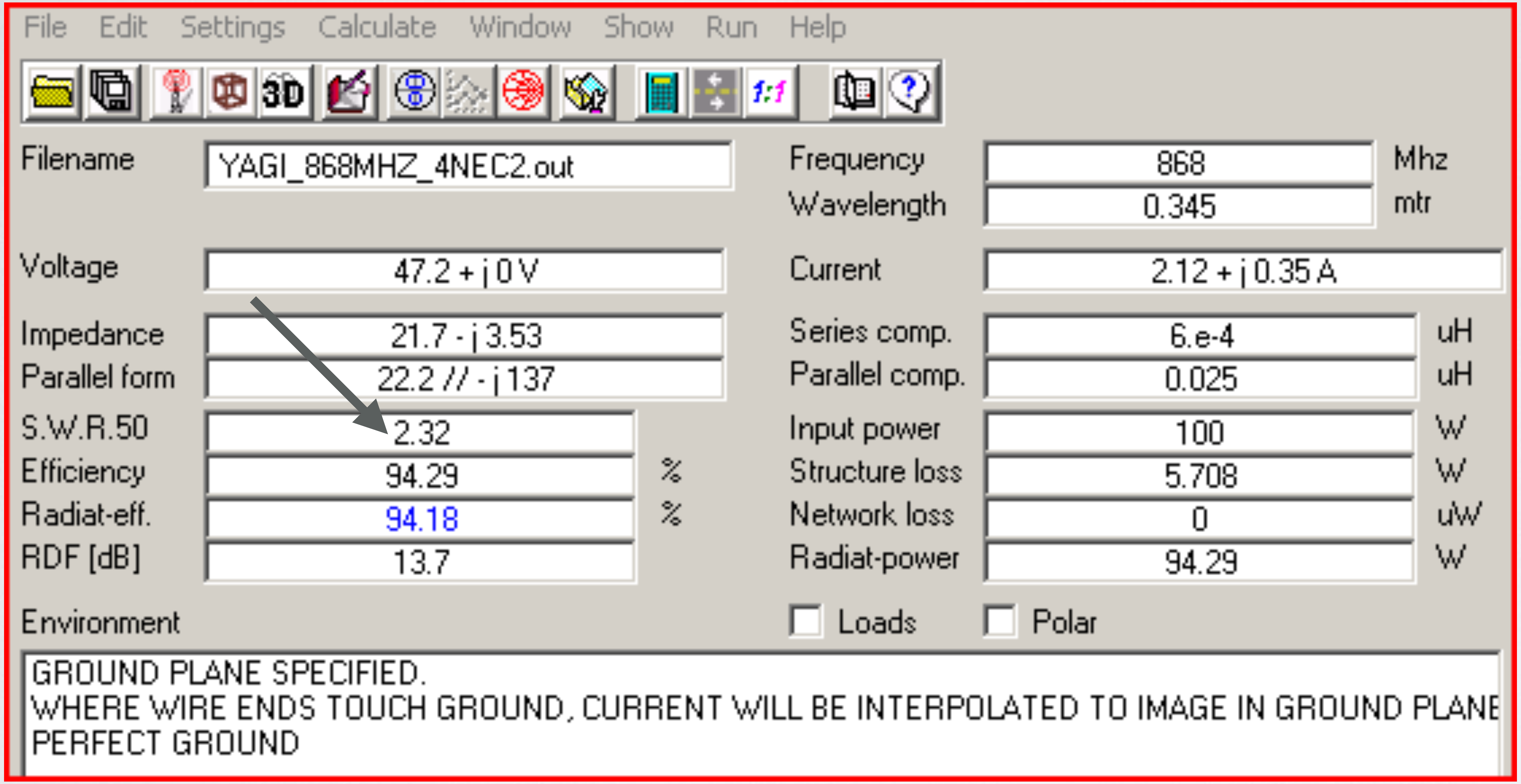
ANTENNA MODELLING NEC-2 BEFORE OPTIMISATION



VSWR=2.32

Ground: **Perfect ground** (= perfectly conducting ground). Height: 1m above ground.

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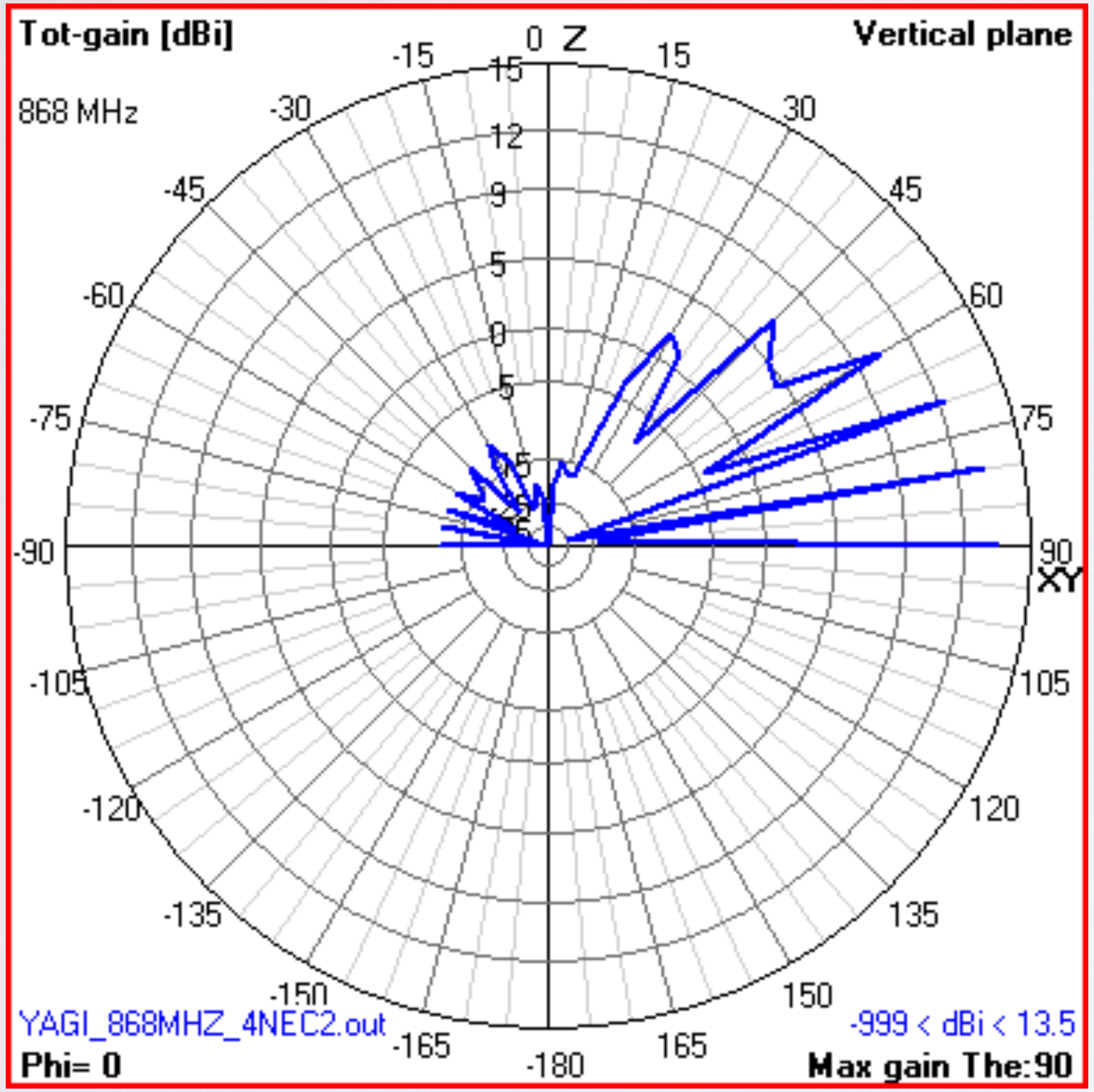
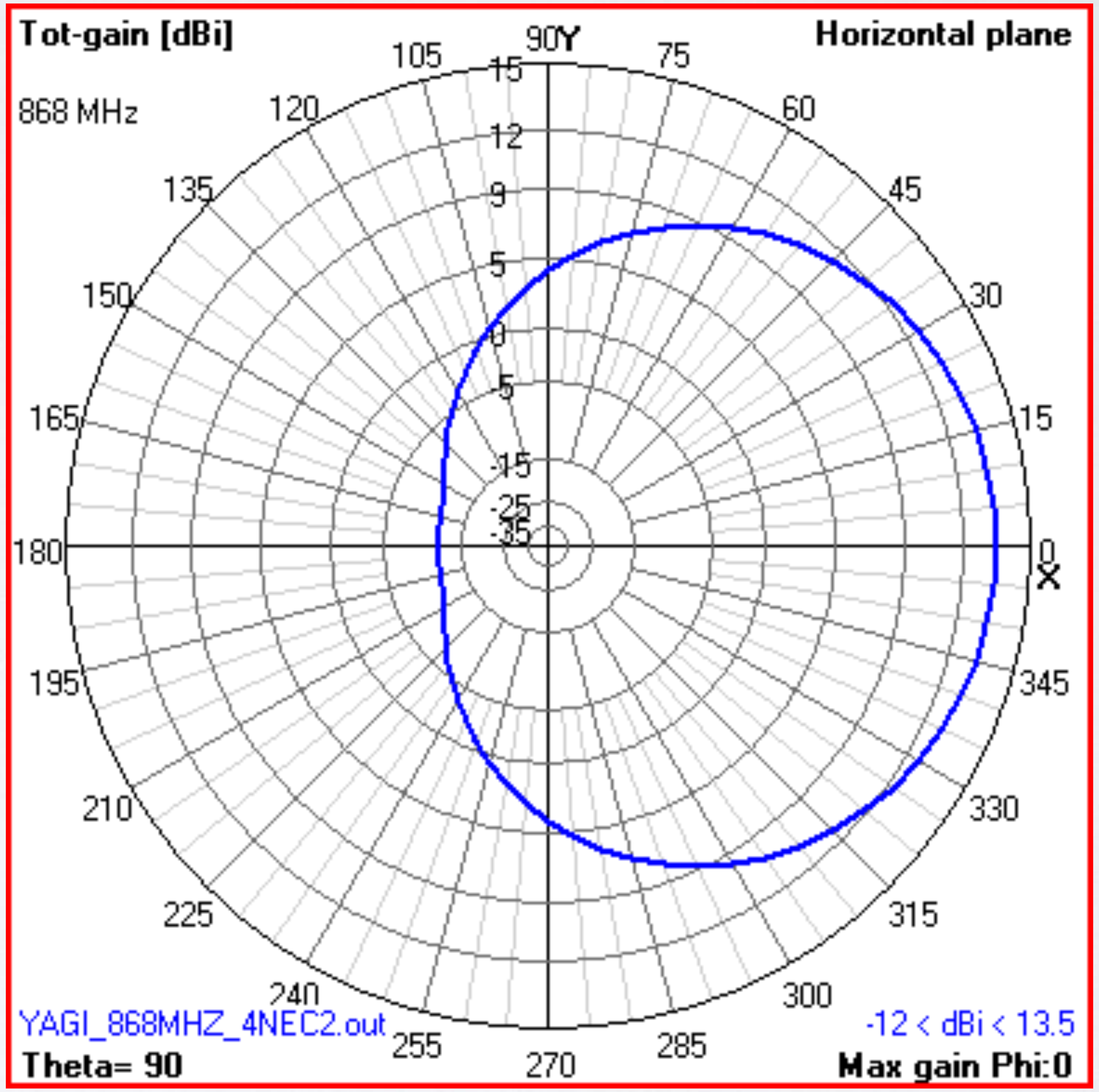
ANTENNA MODELLING NEC-2 BEFORE OPTIMISATION

- Ground: **Perfect ground** (= perfectly conducting ground).





Height: 1m above ground

Max gain: 13.5 dBi @ Θ=90°

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ANTENNA MODELLING NEC-2 BEFORE OPTIMISATION

- Next I used the 4NEC2 optimising functionality to improve the design.
- 4NEC2 card deck:
  https://www.mobilefish.com/download/lora/yagi_868mhz_4nec2_after_optimisation.nec.txt

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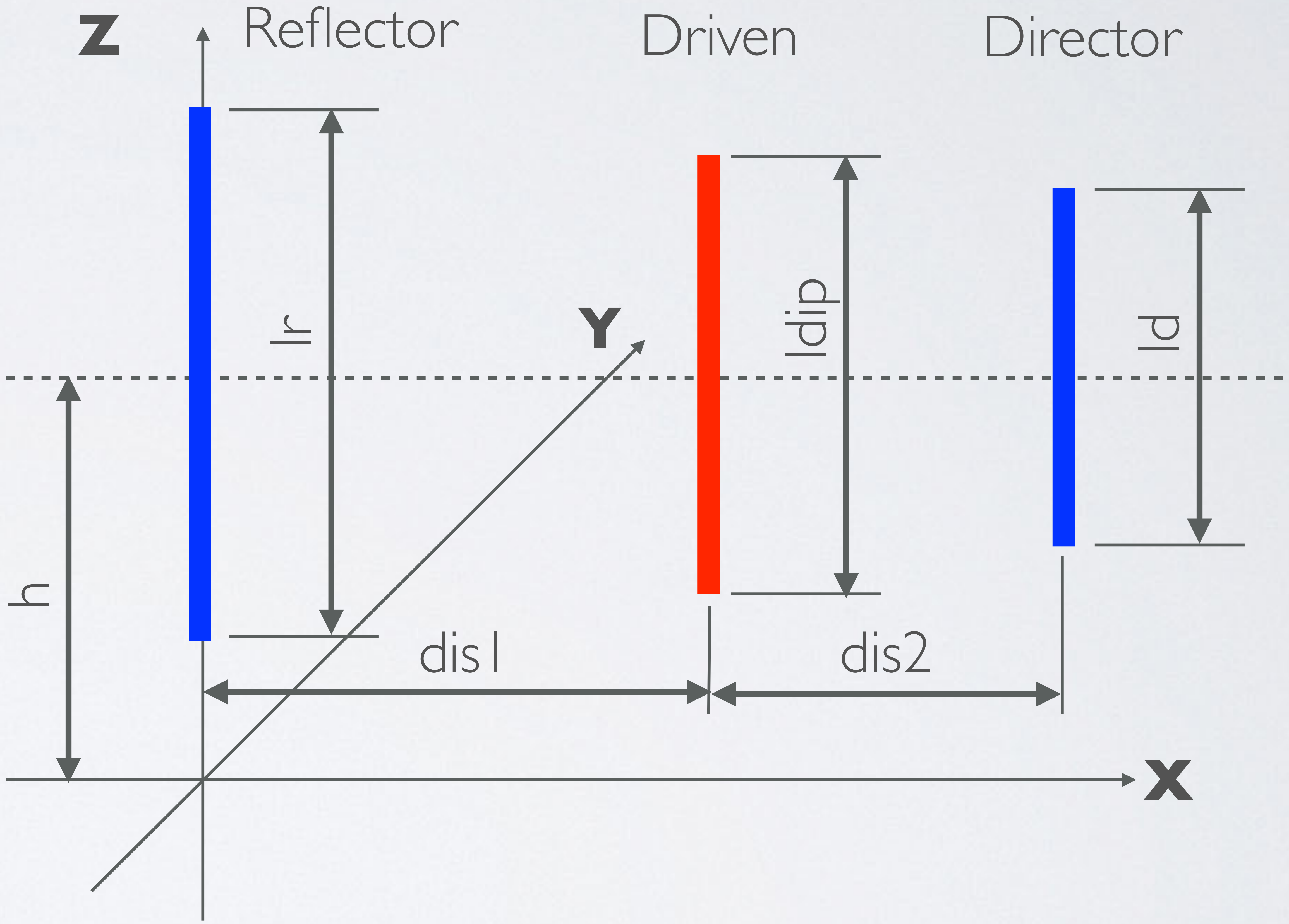
ANTENNA MODELLING NEC-2 AFTER OPTIMISATION

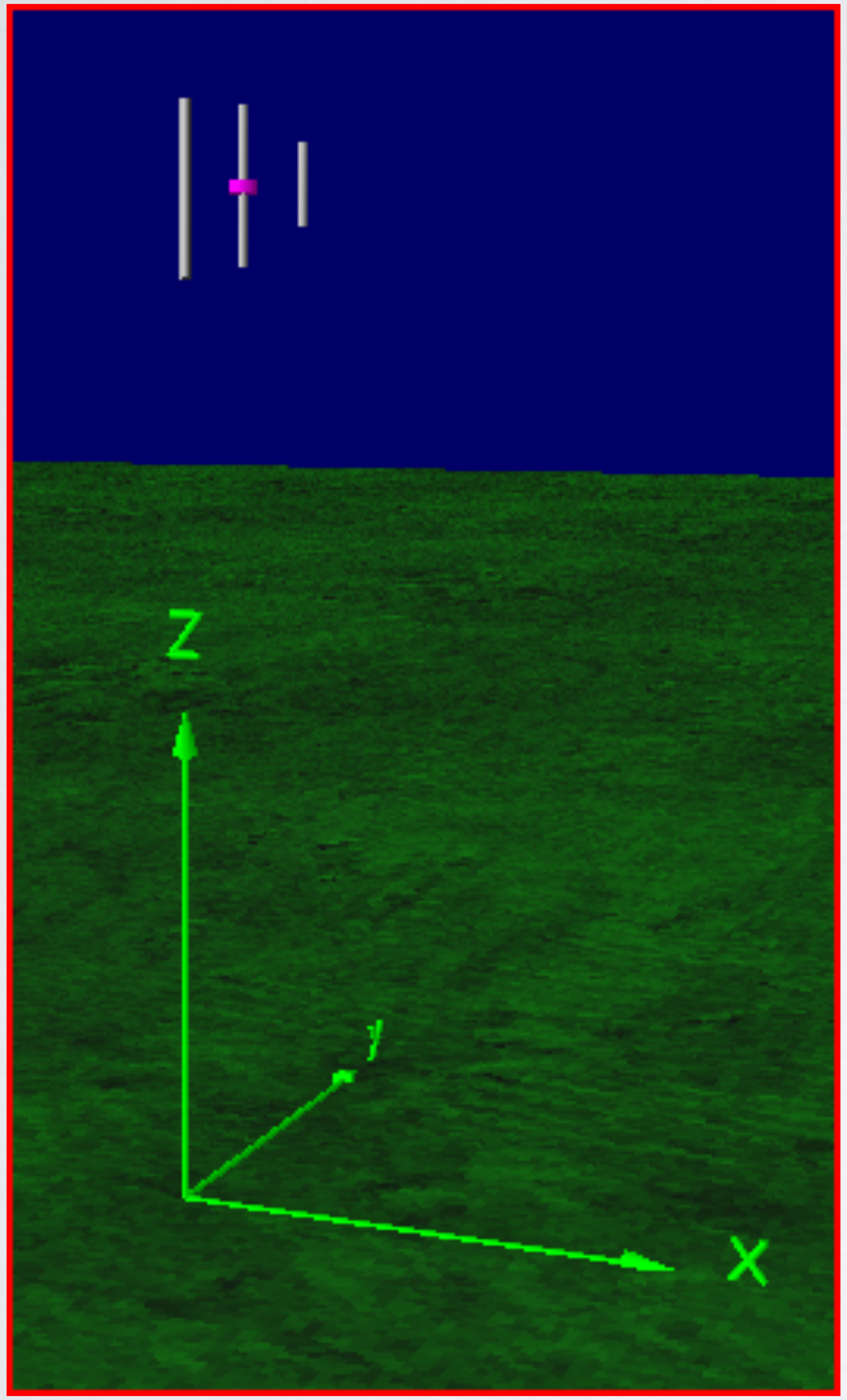
- Yagi-Uda antenna
  f = 868 MHz
  wire diameter = 1.8 mm
  wire materia: stainless steel

  h = 1 m
  lr = 171 mm
  ldip = 154 mm (was 163 mm)
  ld = 76 mm (was 152 mm)
  dis1 = 60 mm (was 43 mm)
  dis2 = 61 mm (was 43 mm)

  Drawing not to scale



ANTENNA MODELLING NEC-2 AFTER OPTIMISATION



Created in 4NEC2

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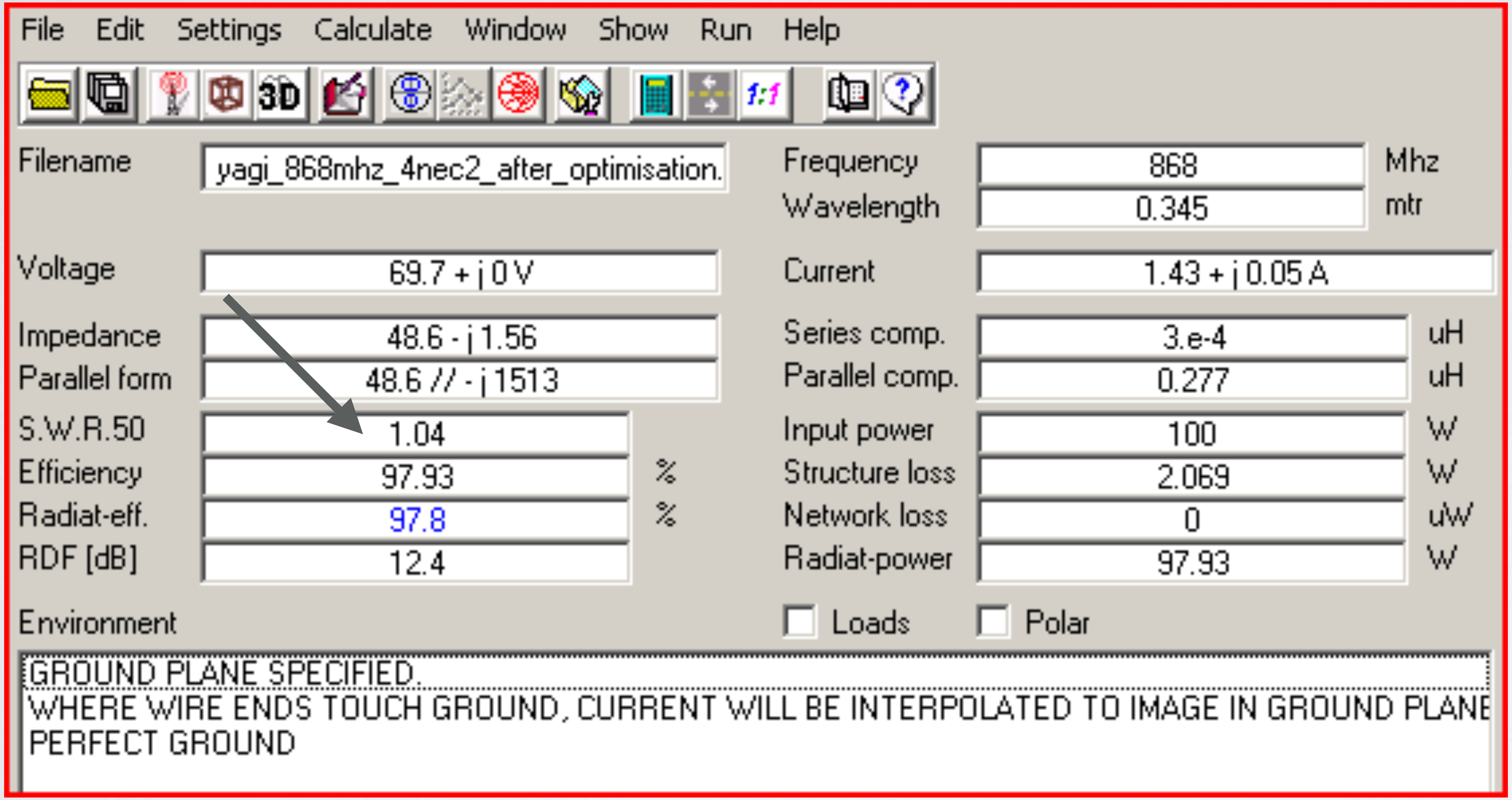
ANTENNA MODELLING NEC-2 AFTER OPTIMISATION



VSWR=1.04

Ground: **Perfect ground** (= perfectly conducting ground). Height: 1m above ground.

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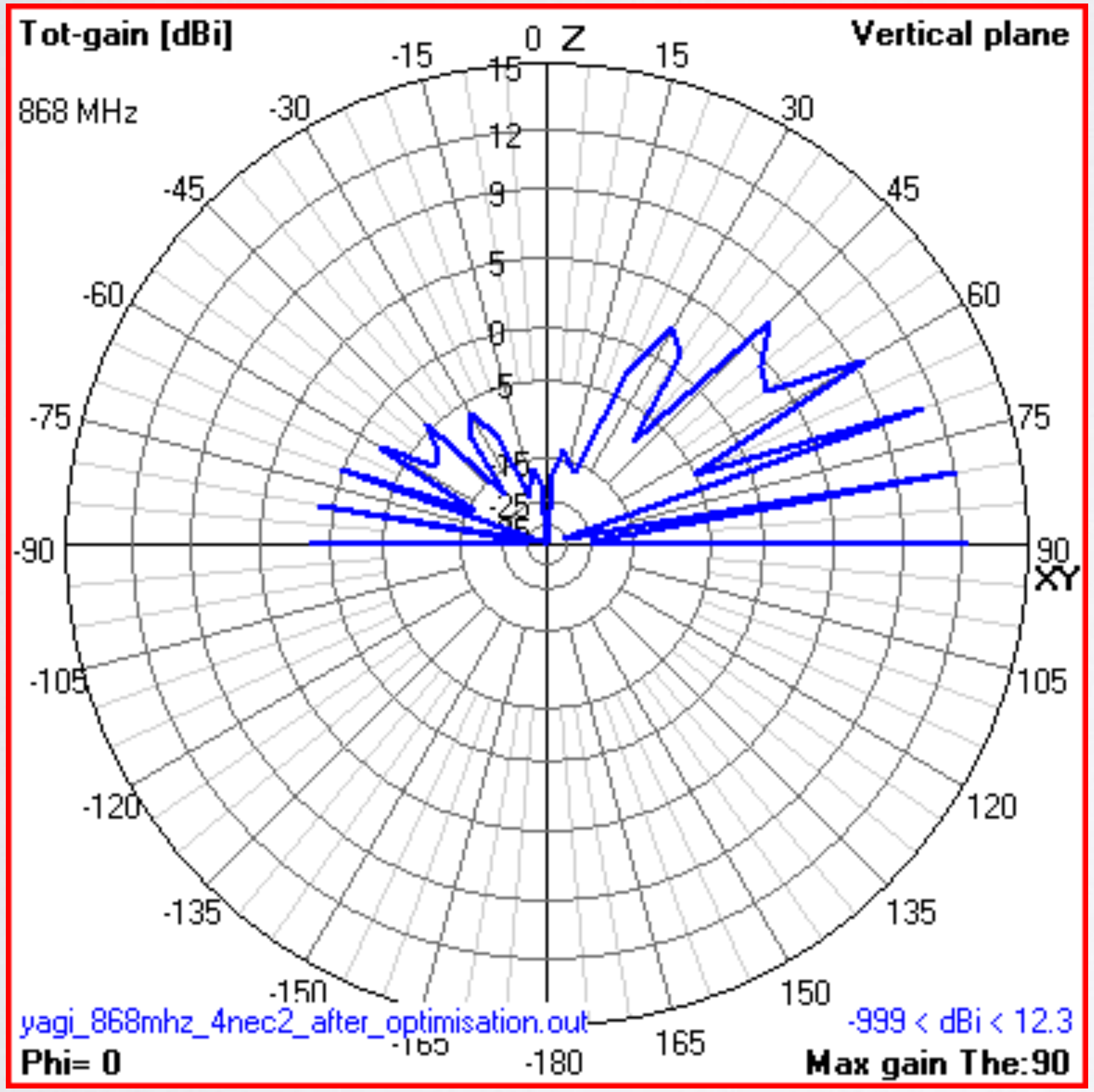
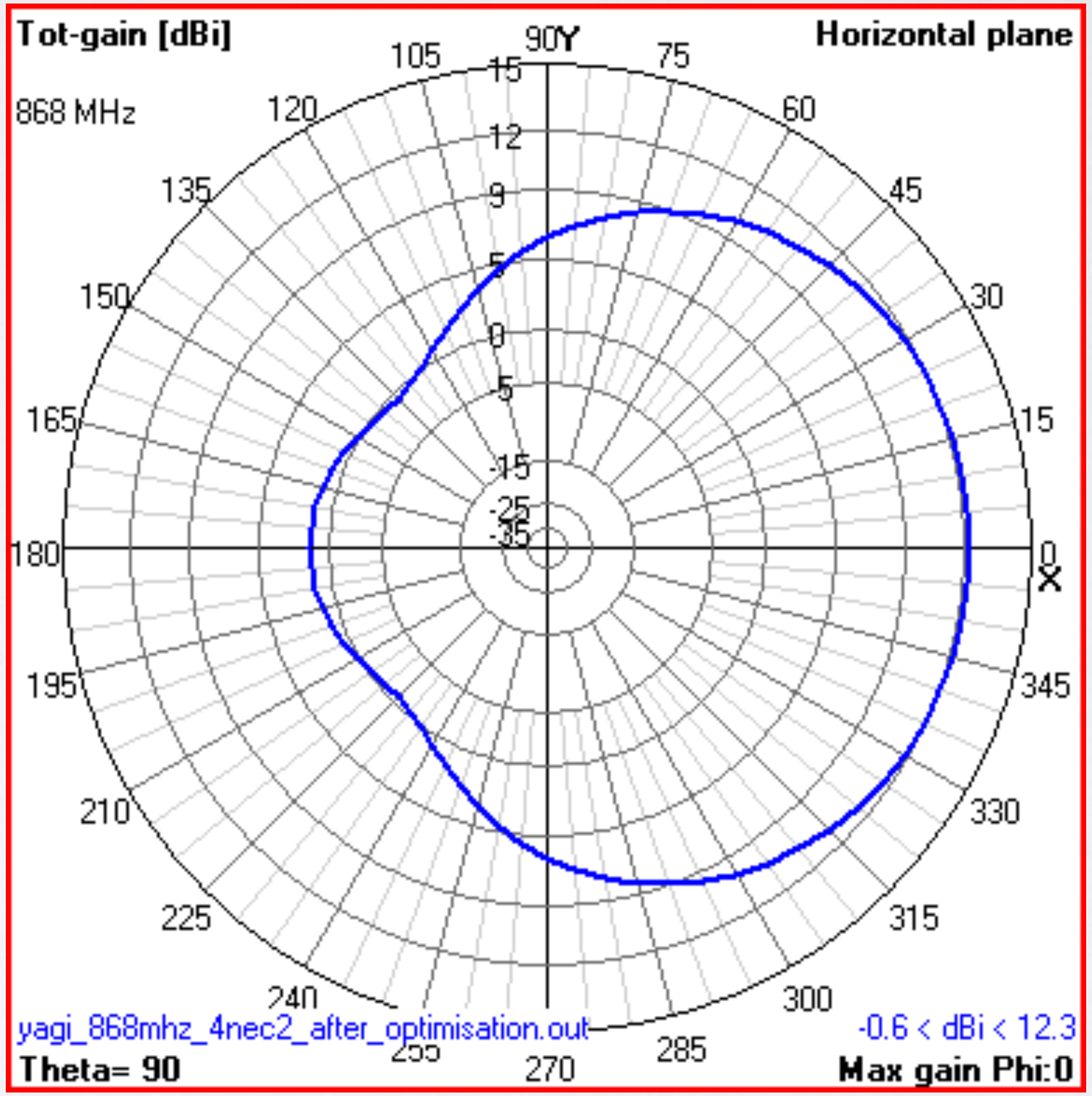
ANTENNA MODELLING NEC-2 AFTER OPTIMISATION

- Ground: **Perfect ground** (= perfectly conducting ground)



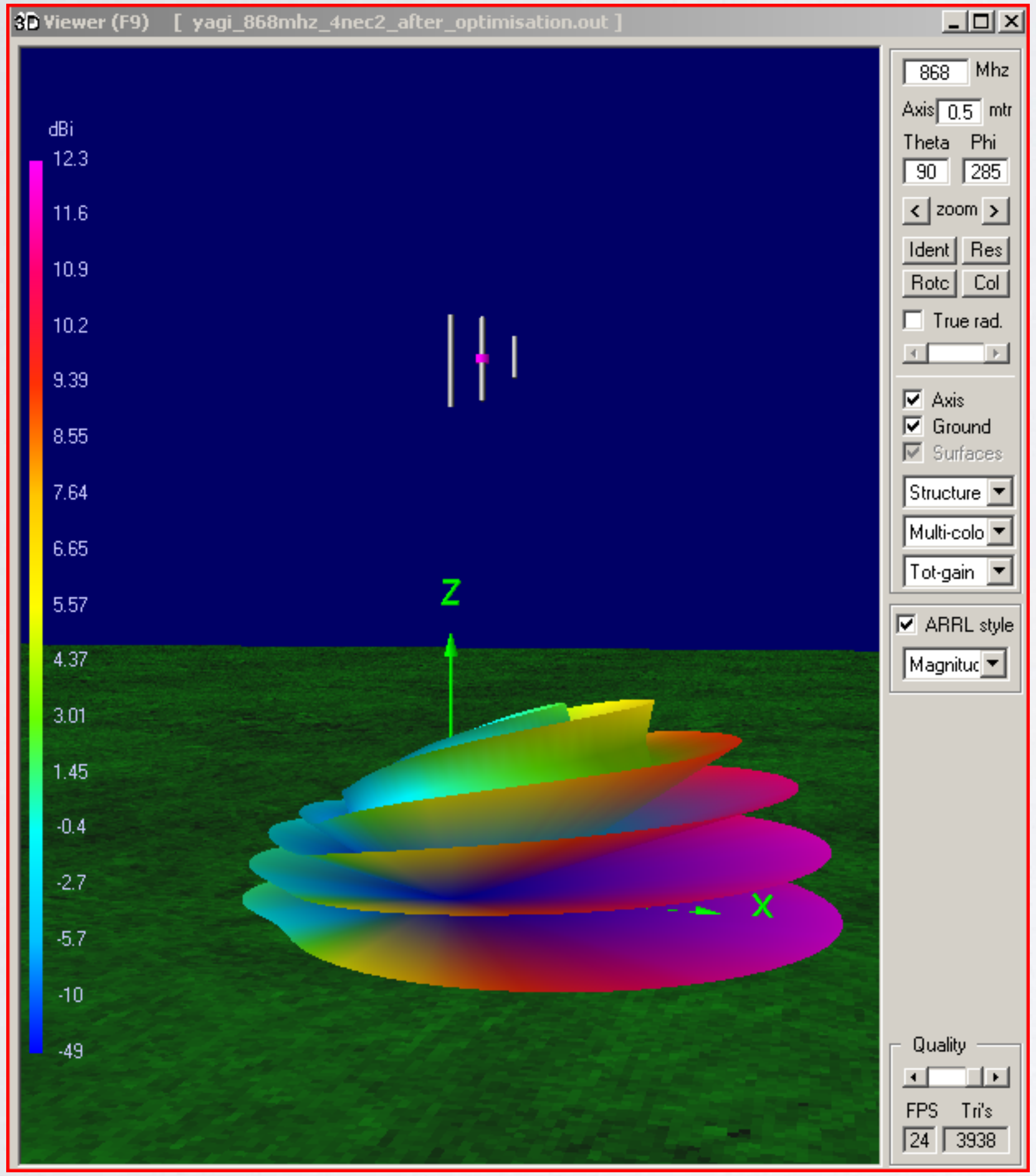


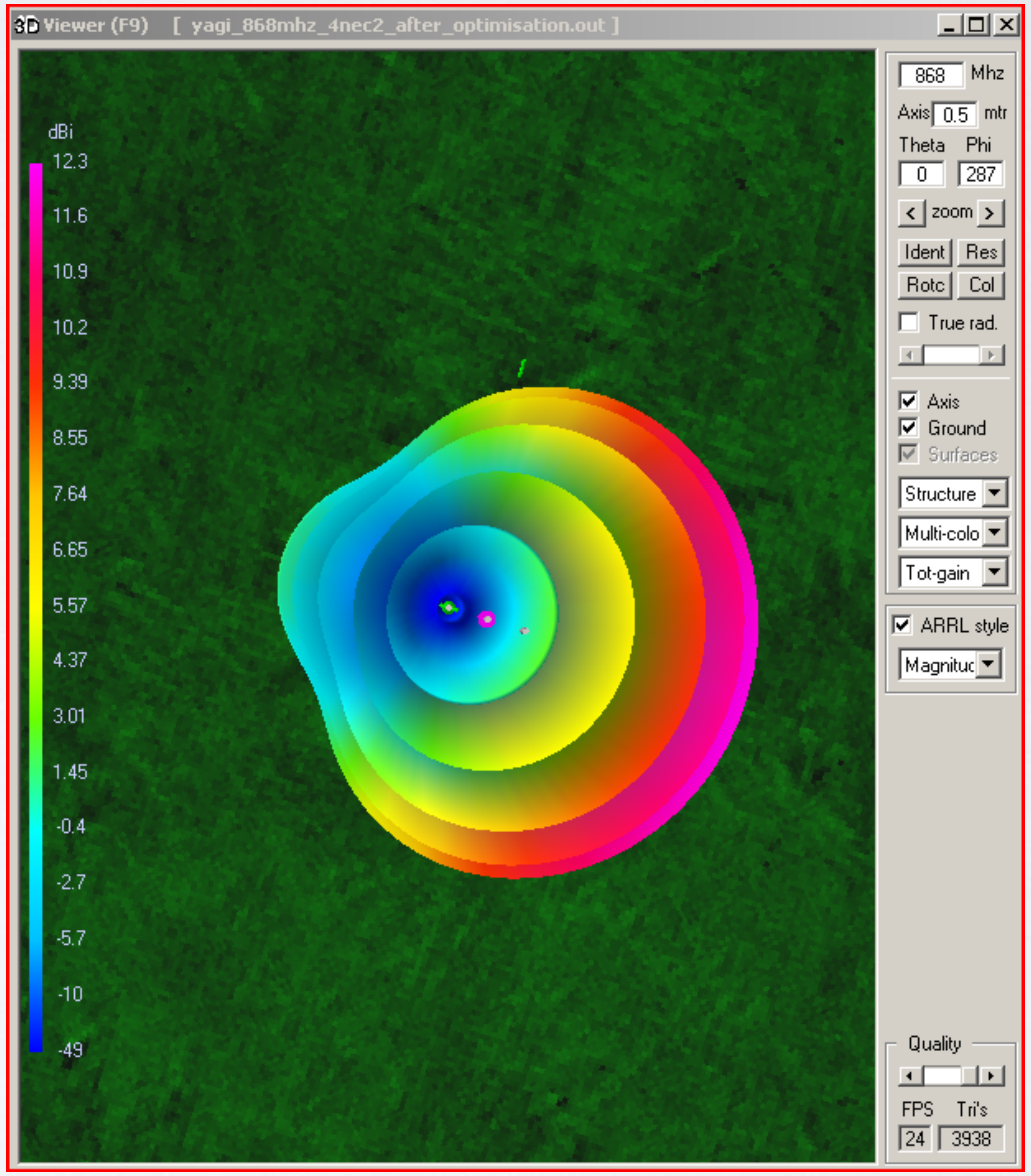
Height: 1m above ground

Max gain: 12.3 dBi @ Θ=90°

ANTENNA MODELLING NEC-2 AFTER OPTIMISATION

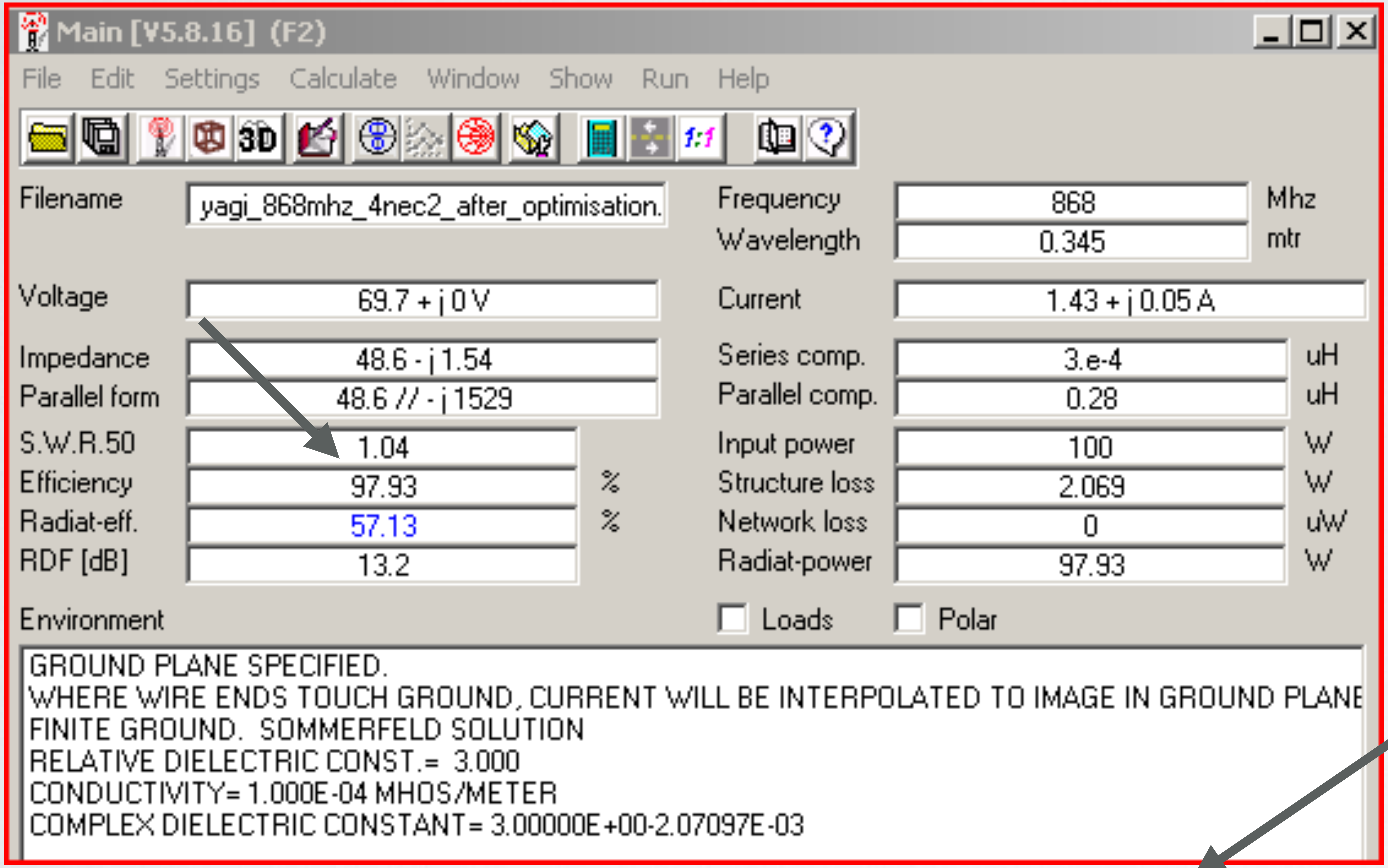
- Ground: **Perfect ground** (= perfectly conducting ground)





Height: 1m above ground

ANTENNA MODELLING NEC-2 AFTER OPTIMISATION



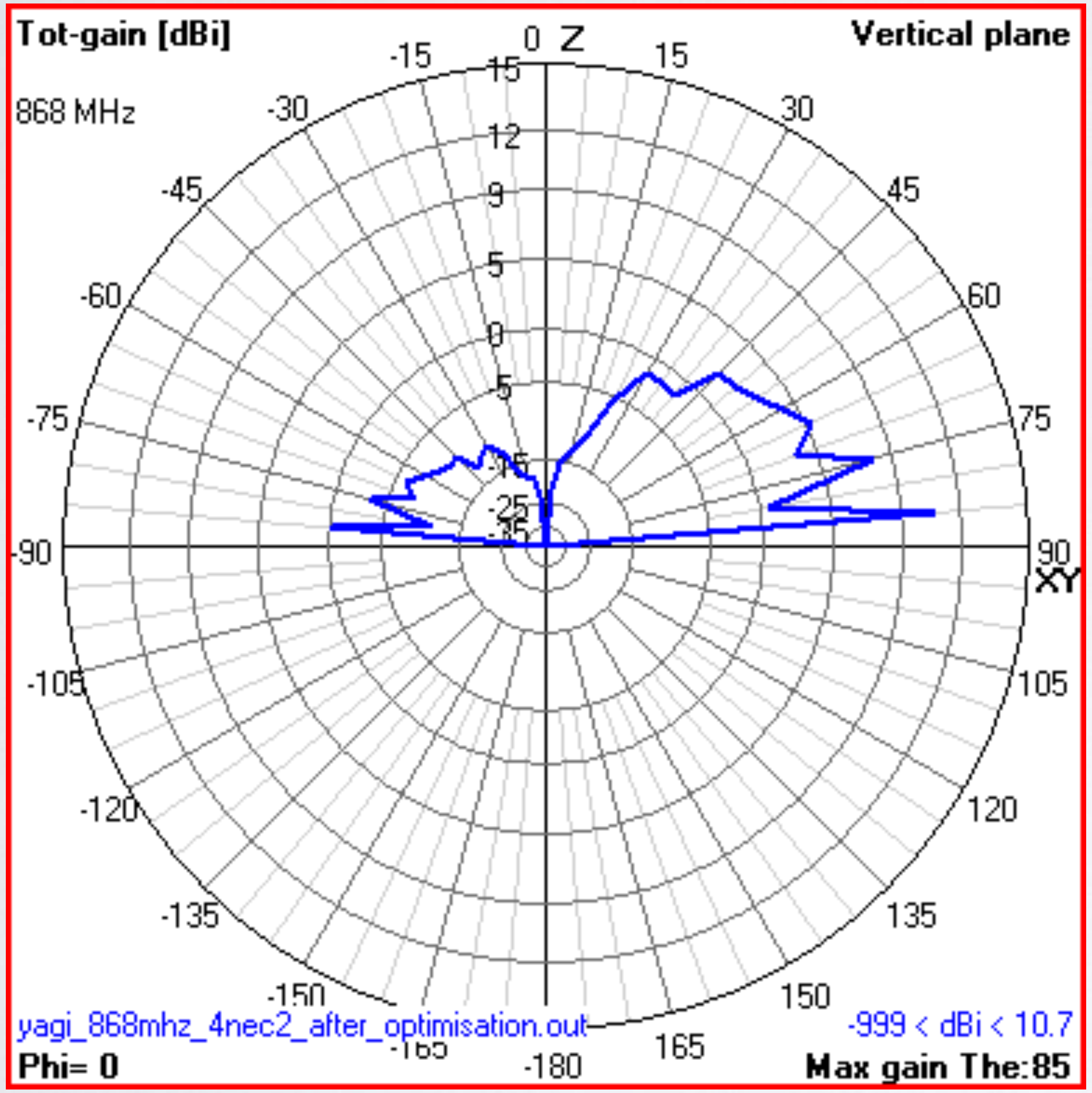
VSWR=1.04

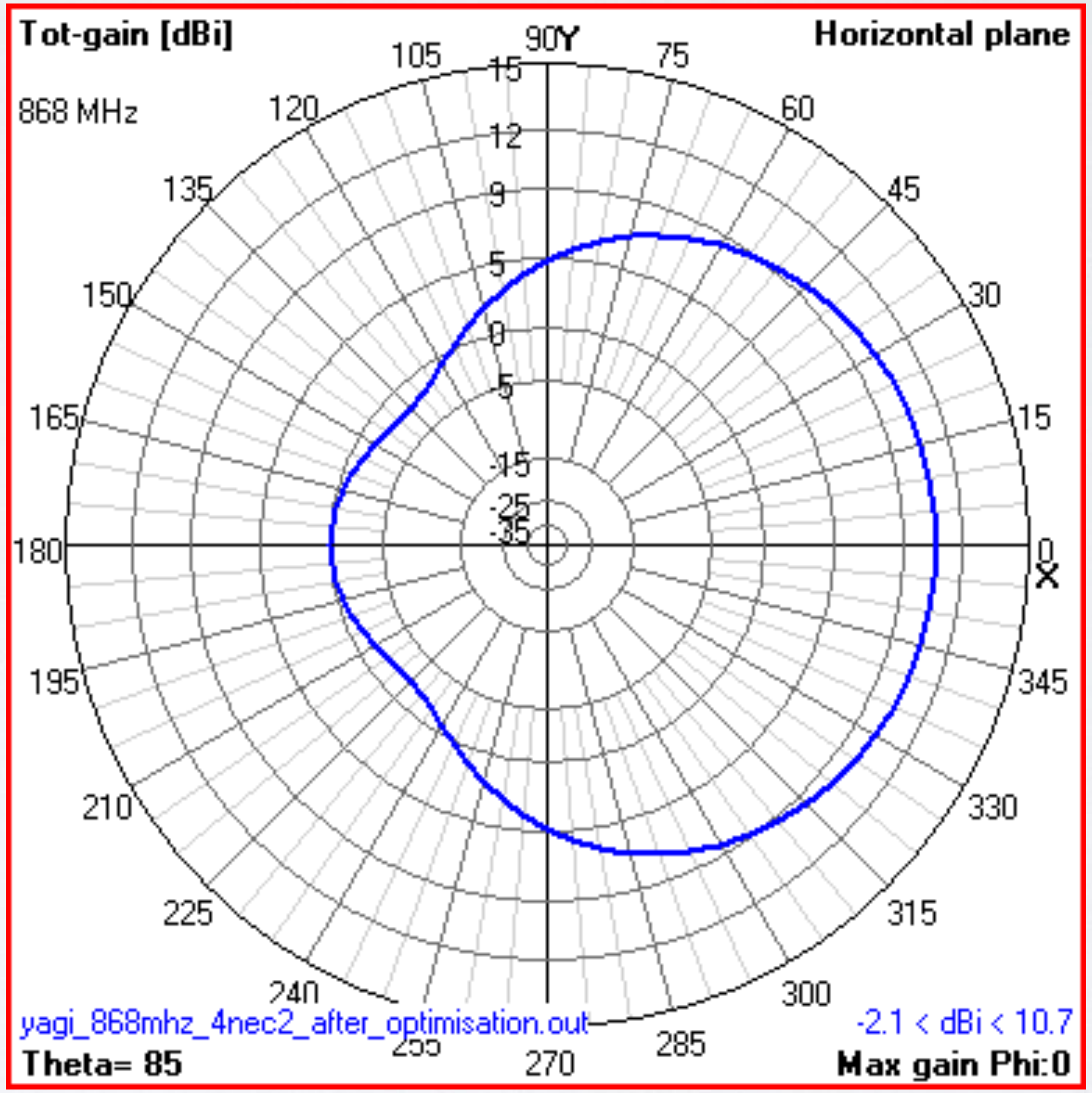
Change ground

Ground: **Real ground** Ground type: **City industrial area** Height: **1m above ground**

ANTENNA MODELLING NEC-2 AFTER OPTIMISATION

- Ground: **Real ground** Ground type: **City industrial area**





Height: 1m above ground

Max gain: 10.7 dBi @ Θ=85°

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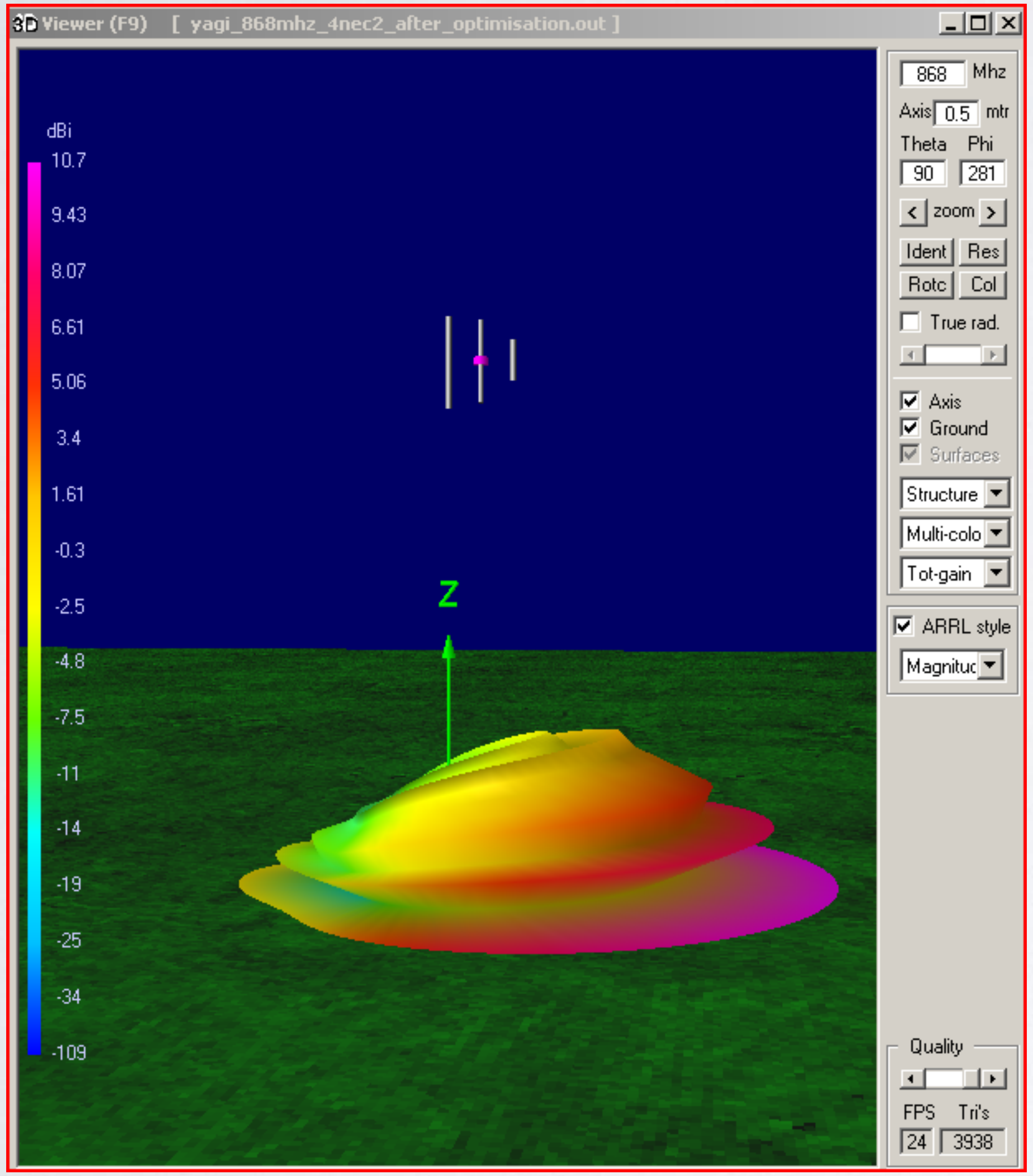
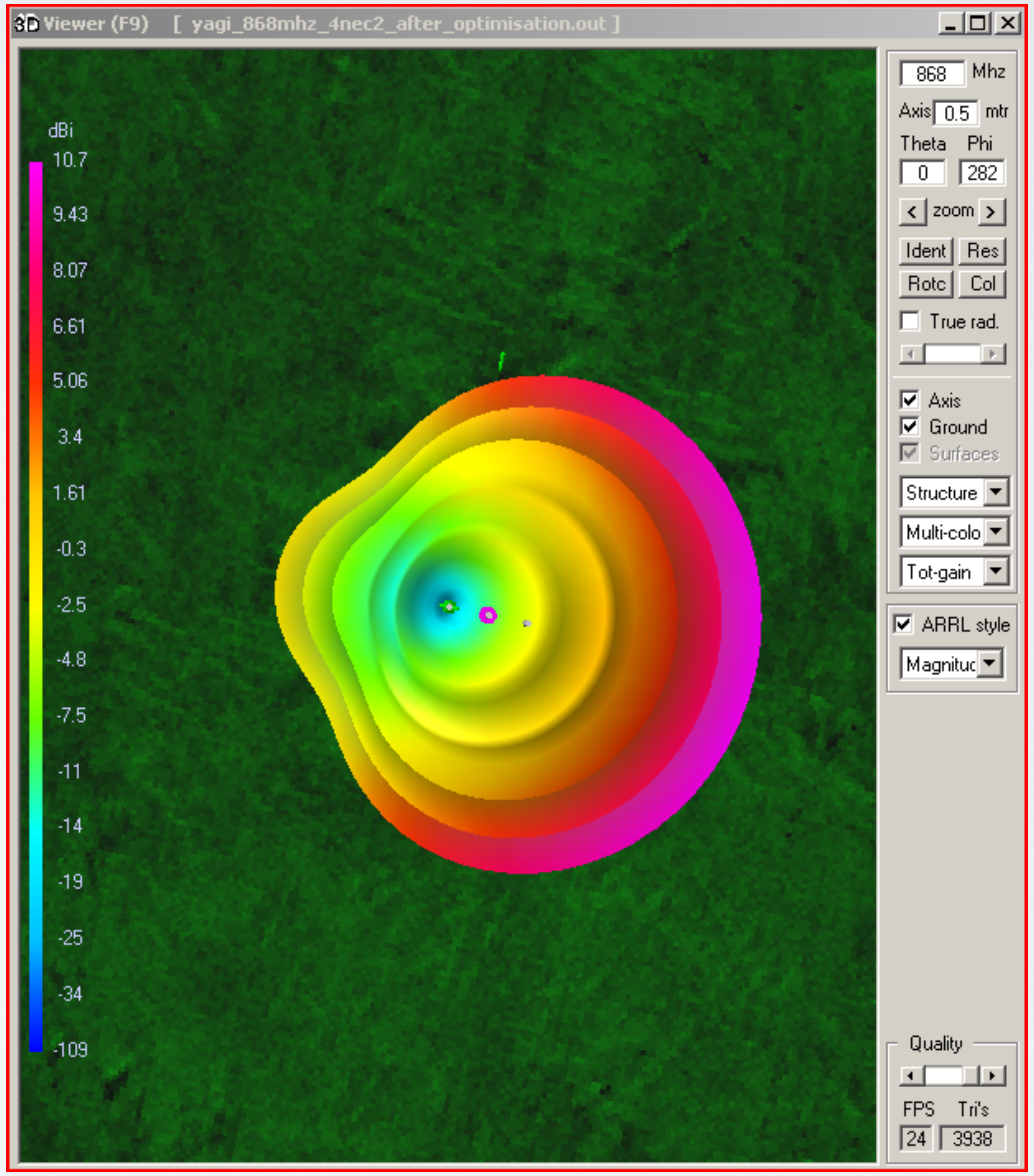
ANTENNA MODELLING NEC-2 AFTER OPTIMISATION

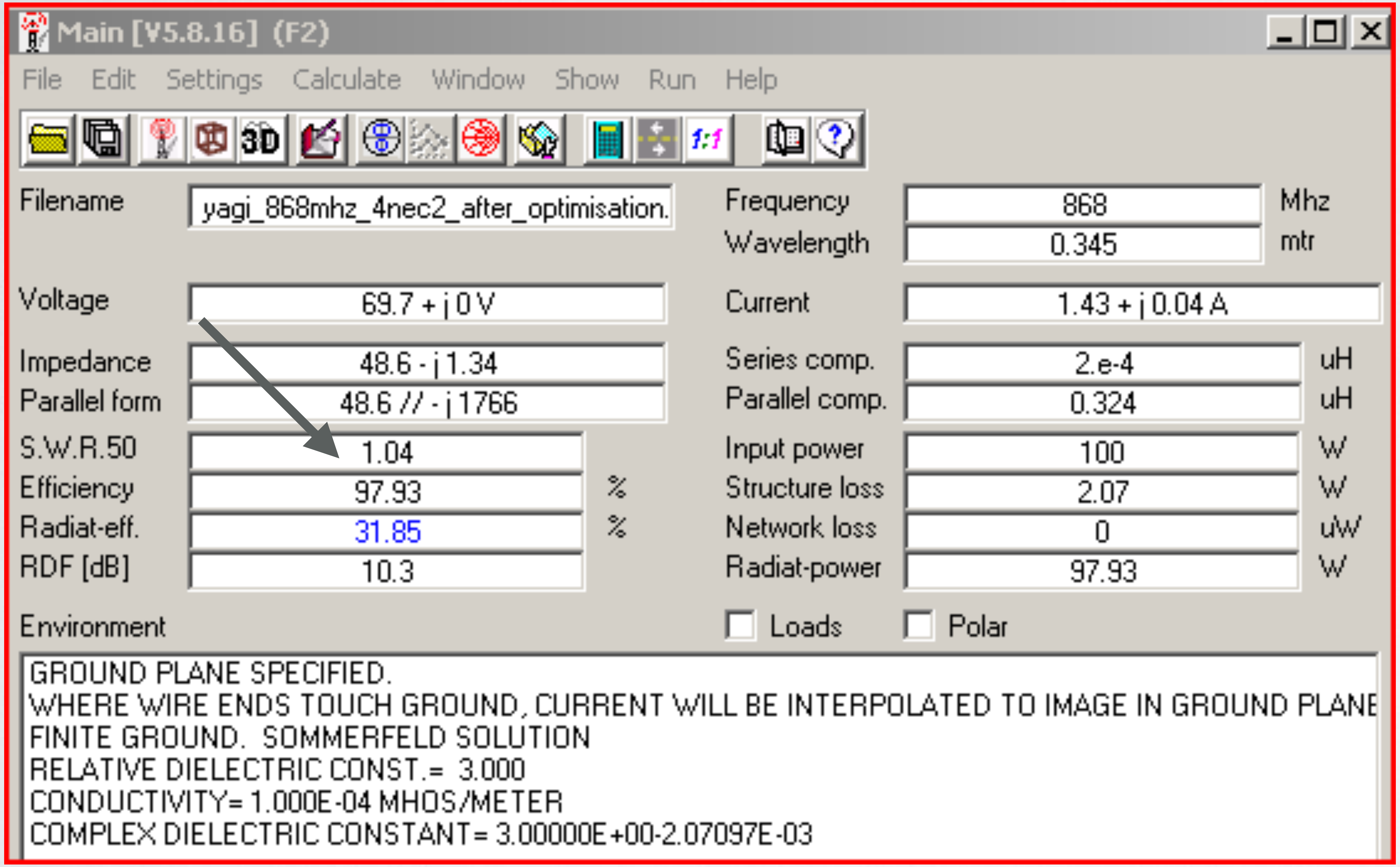
- Ground: **Real ground** Ground type: **City industrial area**





Height: 1m above ground

ANTENNA MODELLING NEC-2 AFTER OPTIMISATION



VSWR=1.04

Change height

Ground: **Real ground** Ground type: **City industrial area** Height: **10 m above ground**

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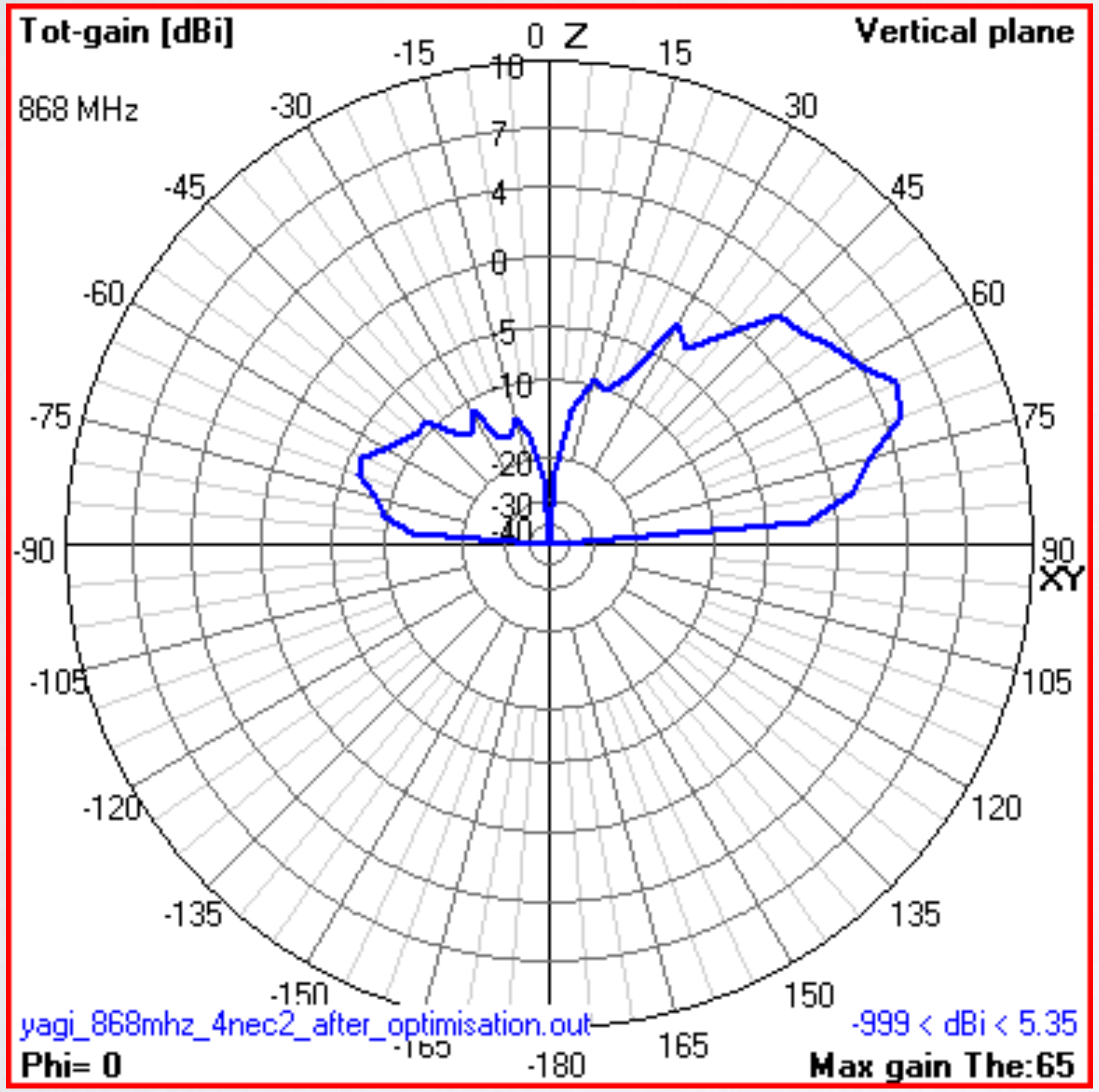
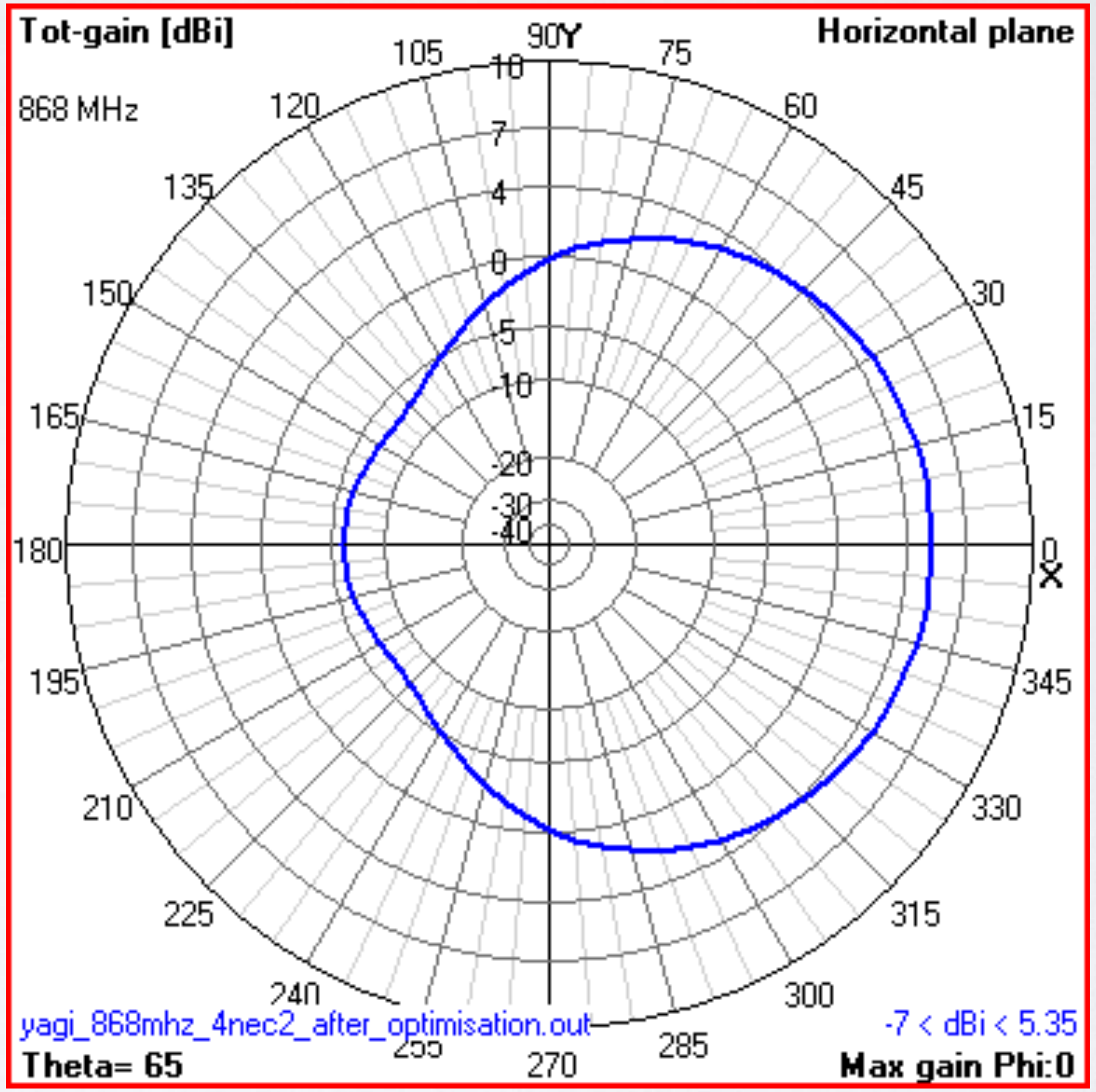
ANTENNA MODELLING NEC-2 AFTER OPTIMISATION

- Ground: **Real ground** Ground type: **City industrial area**

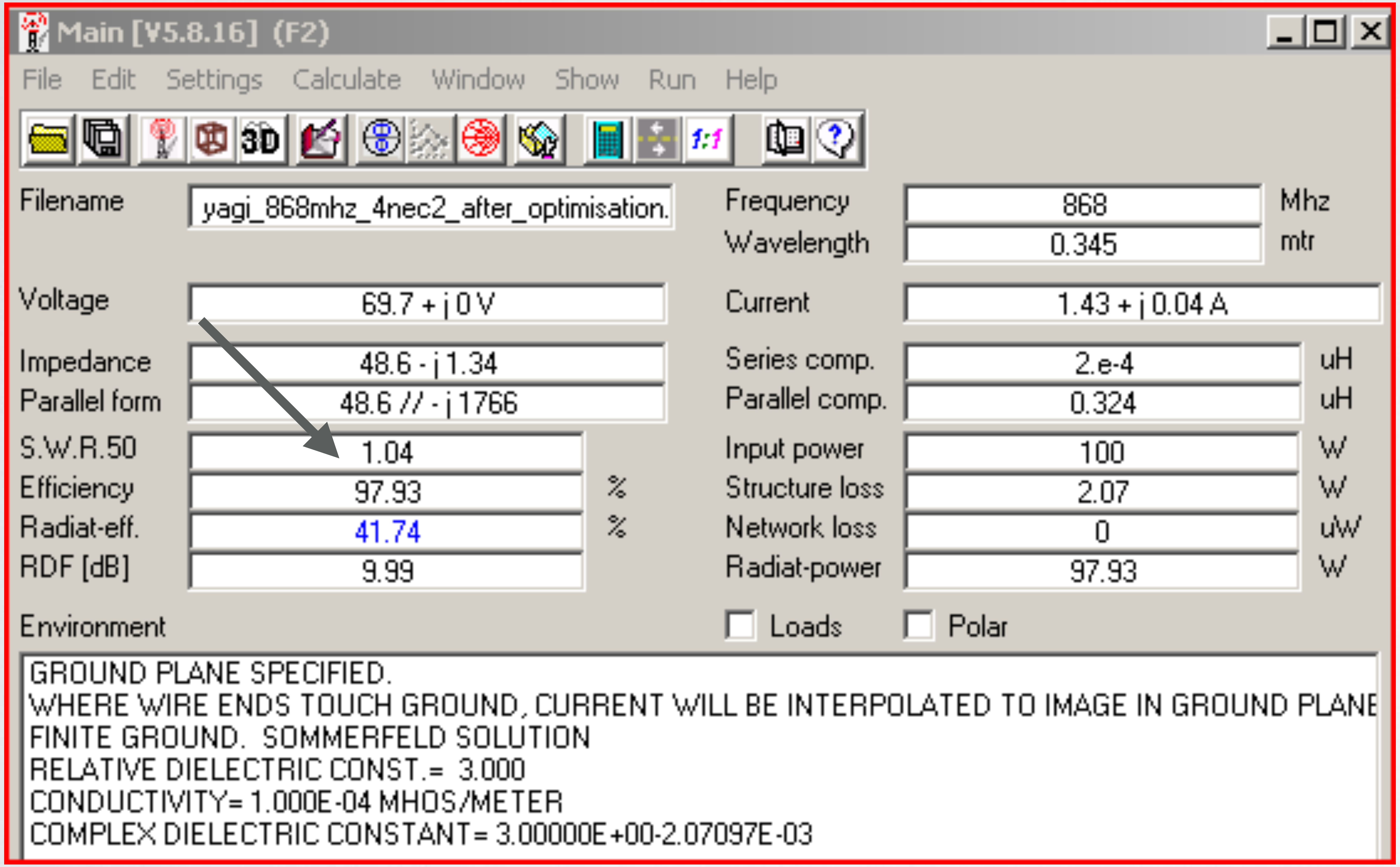




Height: 10 m above ground

Max gain: 5.35 dBi @ Θ=65°

ANTENNA MODELLING NEC-2 AFTER OPTIMISATION



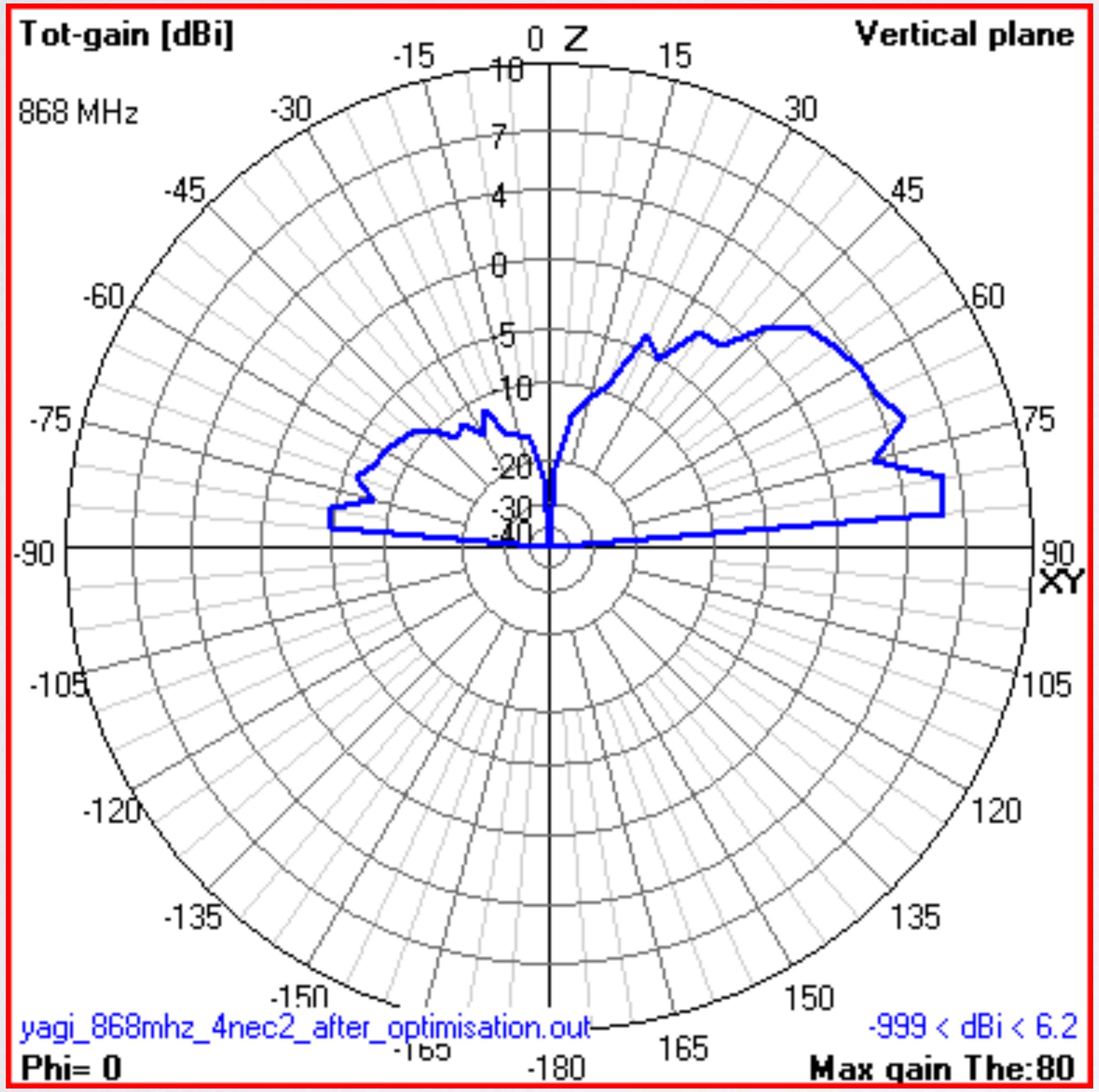
VSWR=1.04

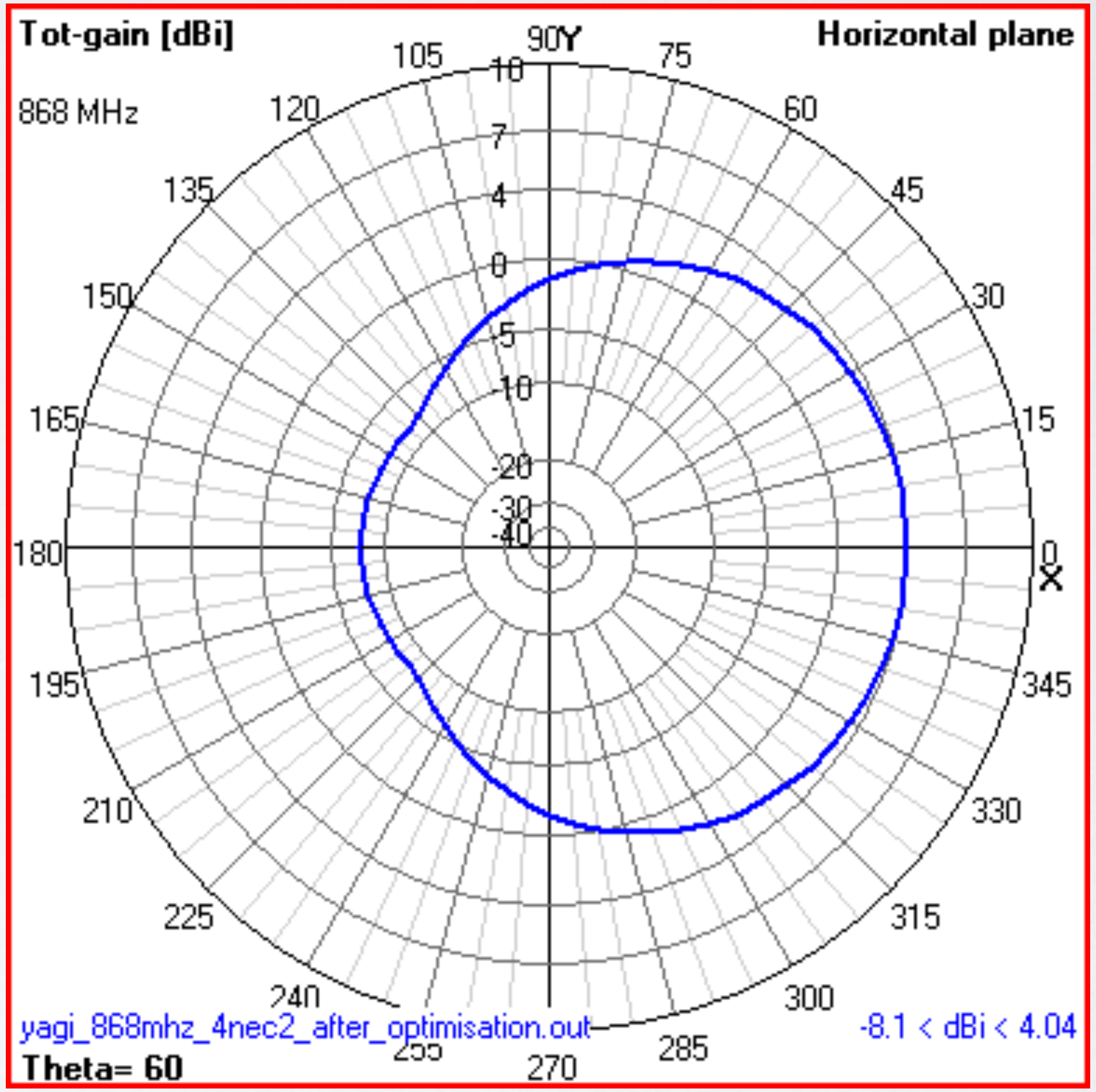
Change height

Ground: **Real ground** Ground type: **City industrial area** Height: **40 m above ground**

ANTENNA MODELLING NEC-2 AFTER OPTIMISATION

- Ground: **Real ground** Ground type: **City industrial area**





Height: 40 m above ground

Max gain: 6.2 dBi @ Θ=80°

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BUILD A YAGI-UDA ANTENNA

- Based on the 4NEC2 antenna design, after optimisation, I have build the Yagi-Uda antenna.

BUILD A YAGI-UDA ANTENNA

- Bill of materials
  - Type N female chassis mount 4-hole connector
    LxW: 2.5 x 2.5 cm / 1" x 1"
    Hole diameter: 3.5 mm / 0.137"
    Impedance: 50Ω
    Material: Metal alloy
    Cost: € 0.96

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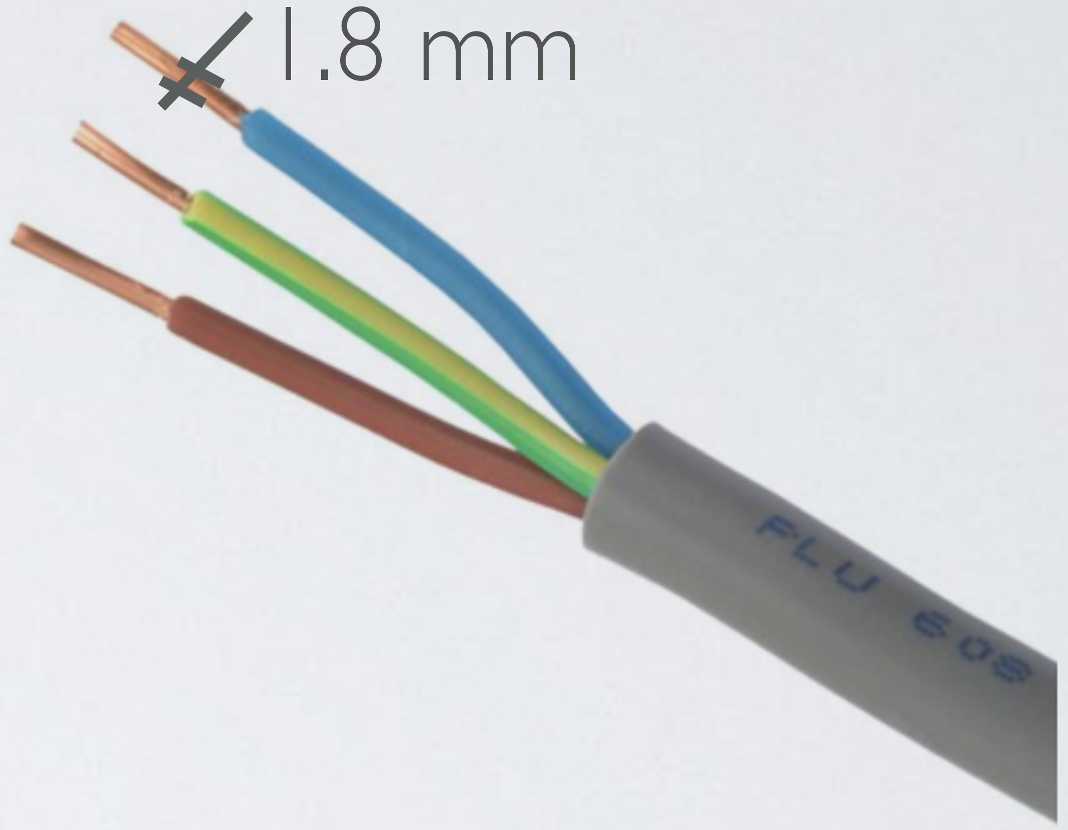
BUILD A YAGI-UDA ANTENNA

- Outdoor cable XMVK 3x2.5 mm^2 grey.
  The copper wire has a diameter of 1.8 mm.
  Only 1 meter is needed.
  Cost: € 1.75 per meter

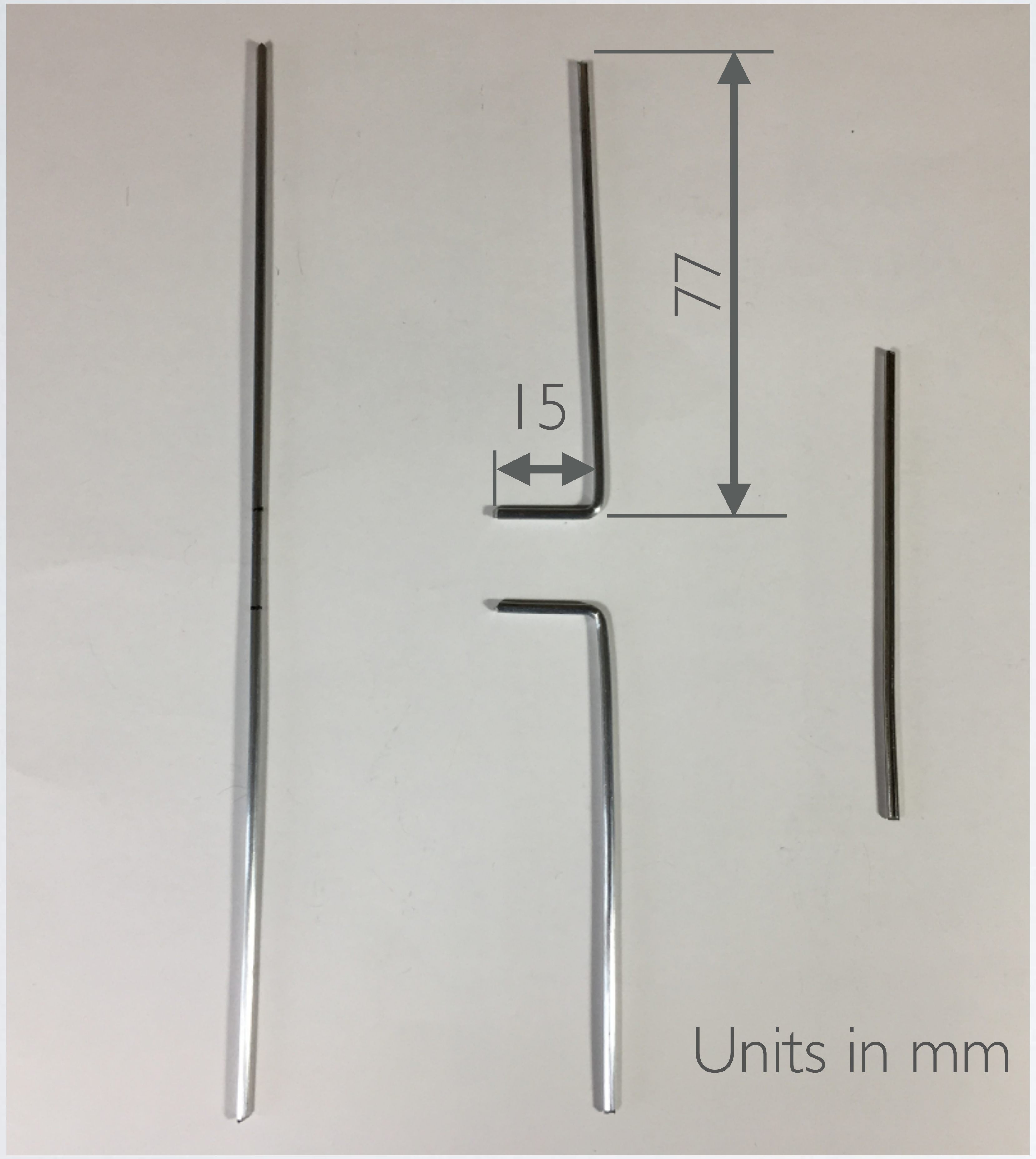
- The electrical insulator can be easily removed using a Stanley knife.

- Instead of copper wires I used bicycle spokes (stainless steel) which also have a diameter of 1.8 mm.

- With these bicycle spokes I made the reflector, driven element and director.



BUILD A YAGI-UDA ANTENNA



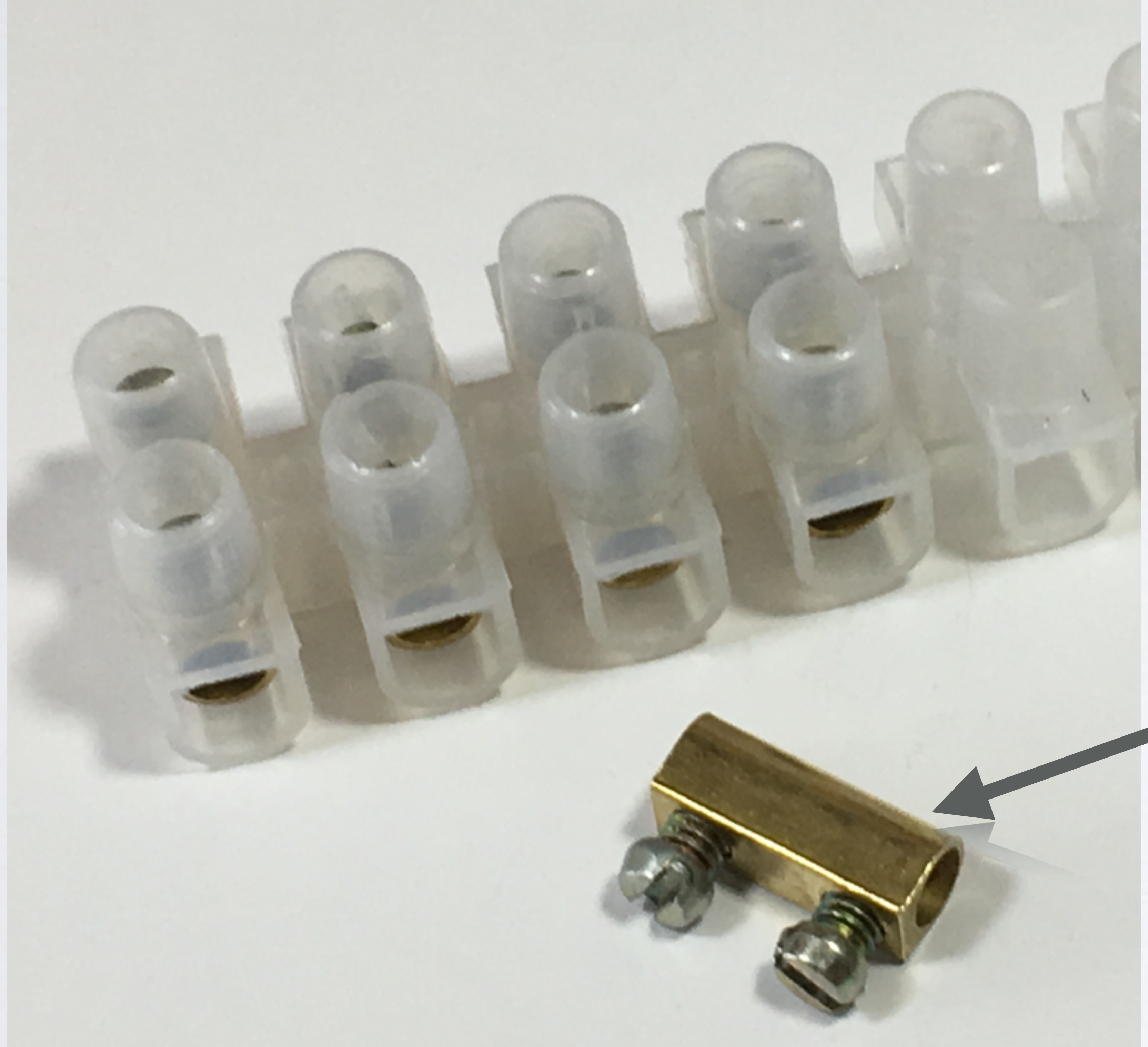
Reflector
Director
Driven element

- Reflector length = 171 mm, d =1.8 mm
- Driven element = 154 mm, d = 1.8 mm
- Director length = 76 mm, d = 1.8 mm

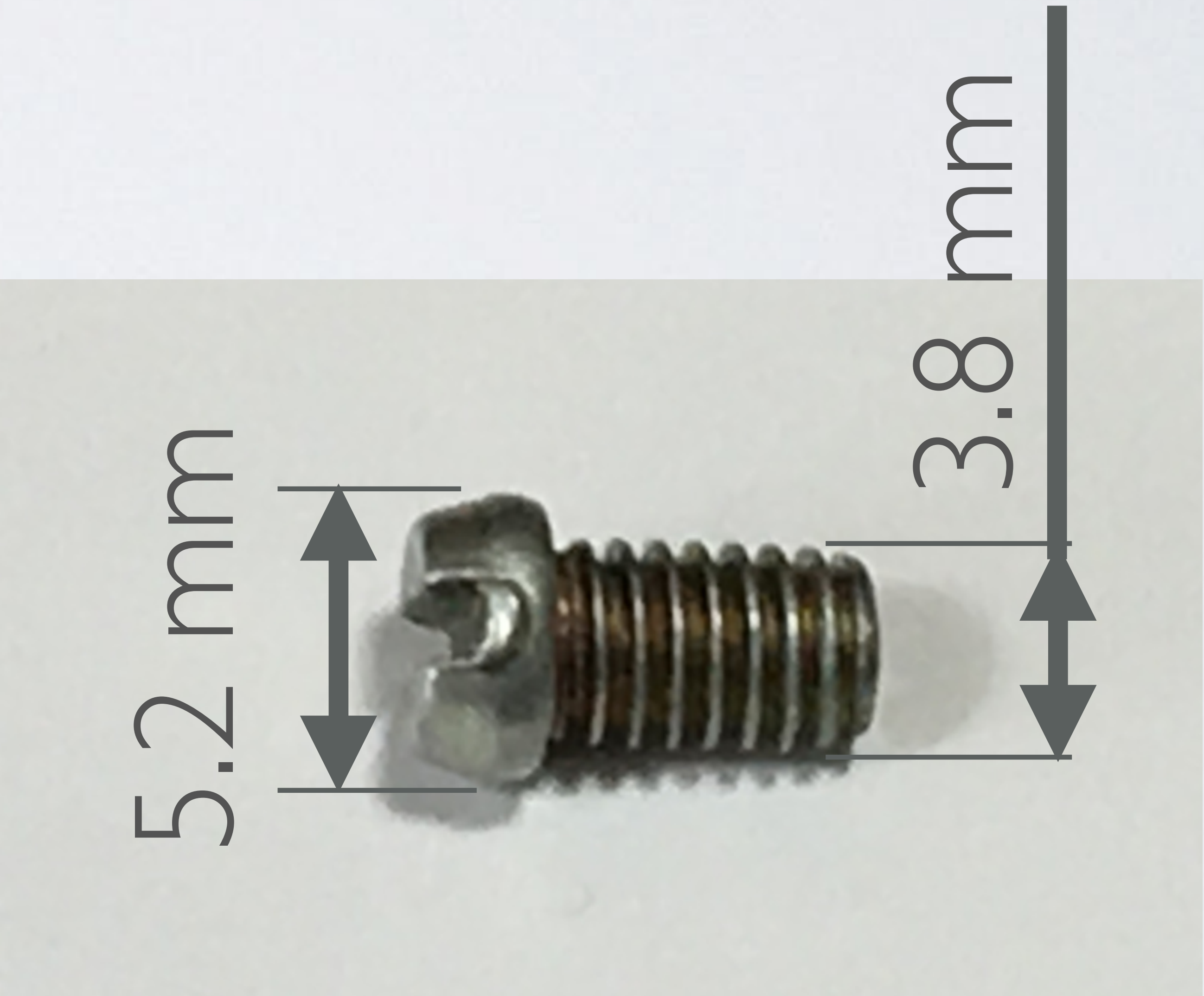
Driven element consists of two parts, each has a length of 77 mm (= 2x77=154)

BUILD A YAGI-UDA ANTENNA

- Terminal strip block (3 Ampere)
  Cost: € 1.80 (3 strips, each strip has 12 terminals)



terminal
length = 16 mm



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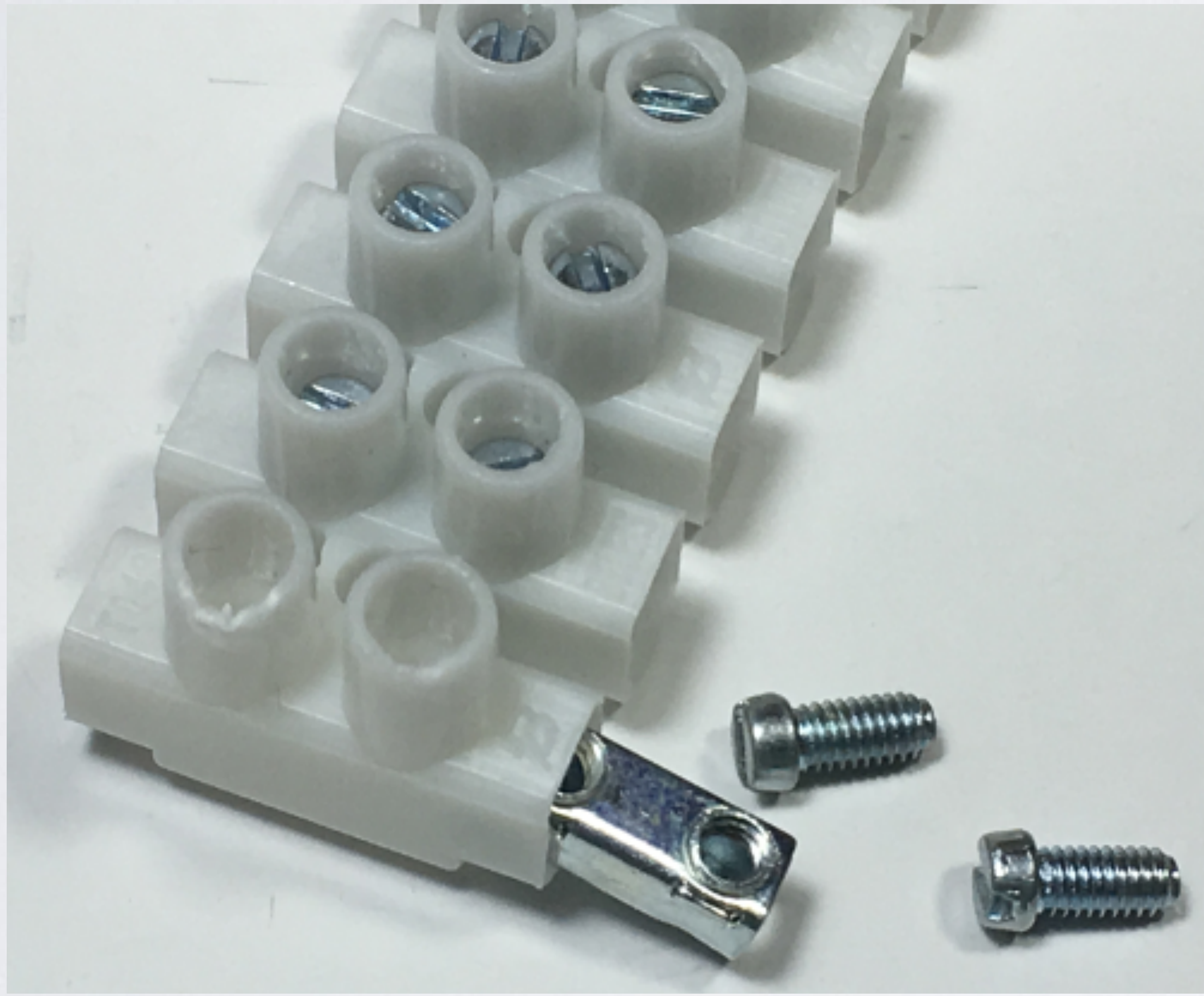
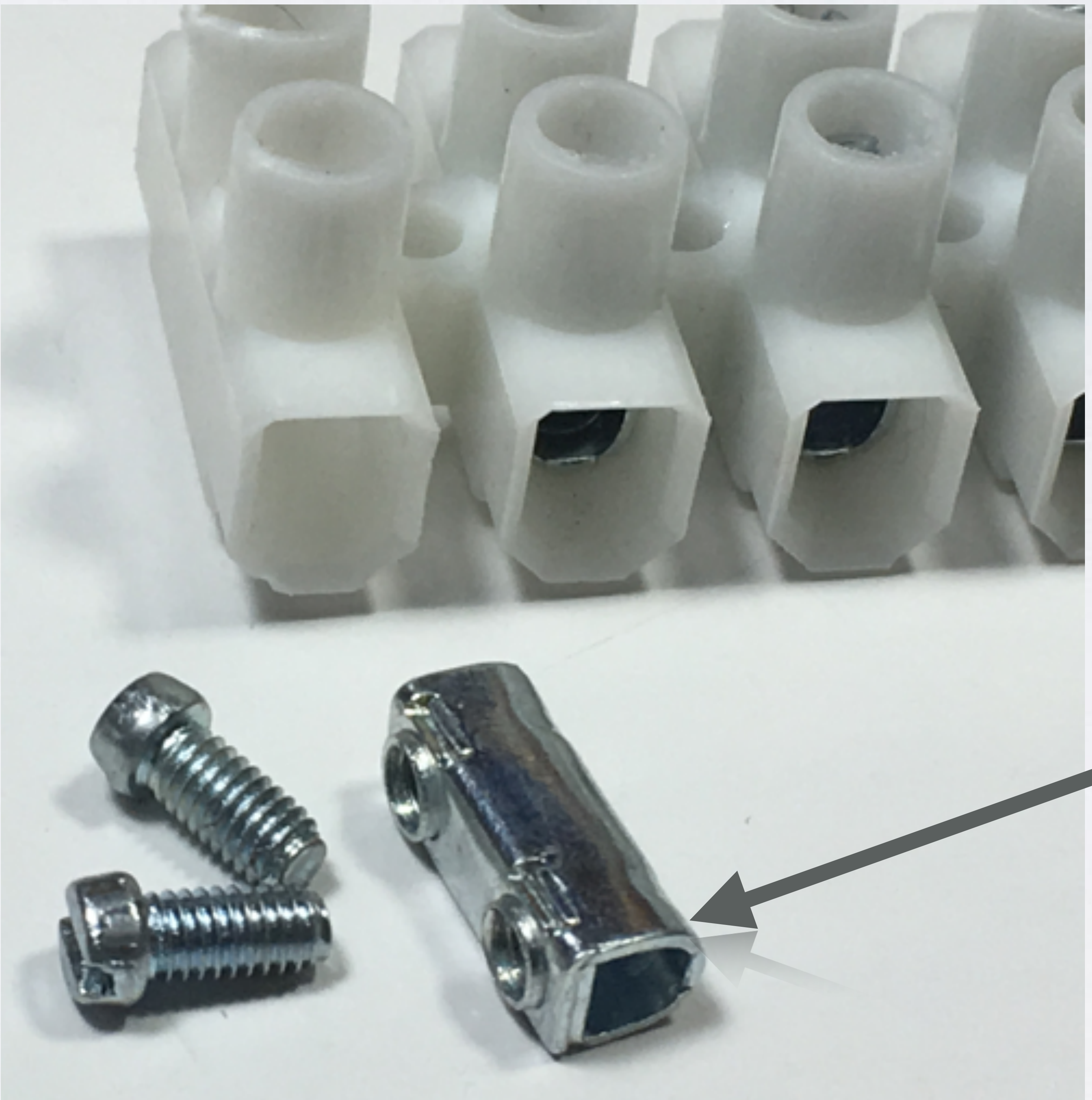
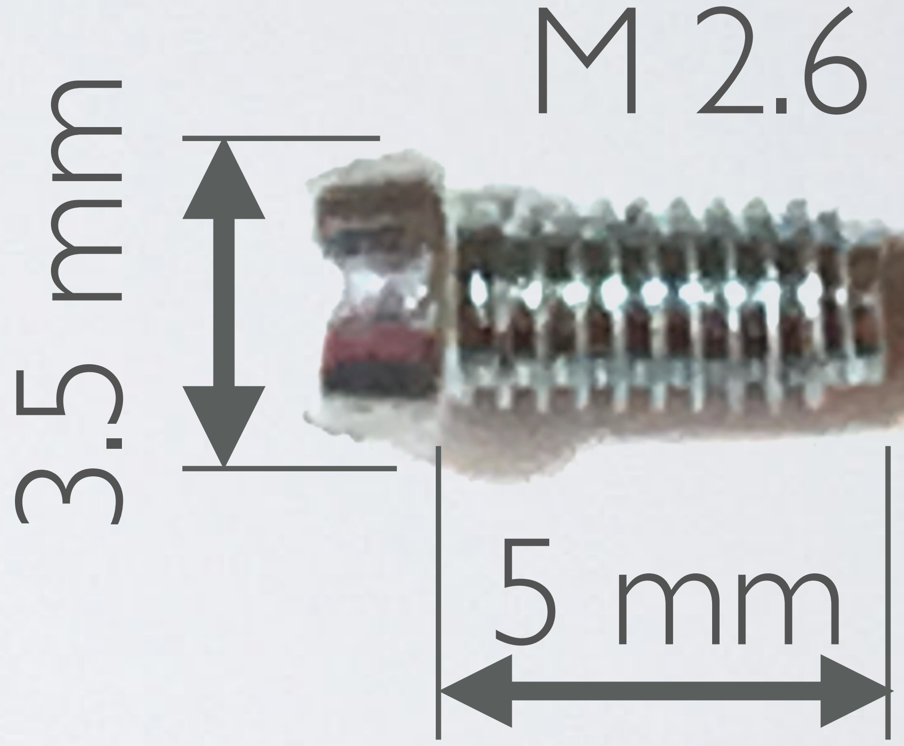
BUILD A YAGI-UDA ANTENNA

- Terminal strip block 1.5-4.0 mm^2
  To be used for wires with a diameter of 1.38 mm - 2.26 mm
  Cost: € 1.98 (2 strips, each strip has 12 terminals)







I need the plastic blocks and the terminals!

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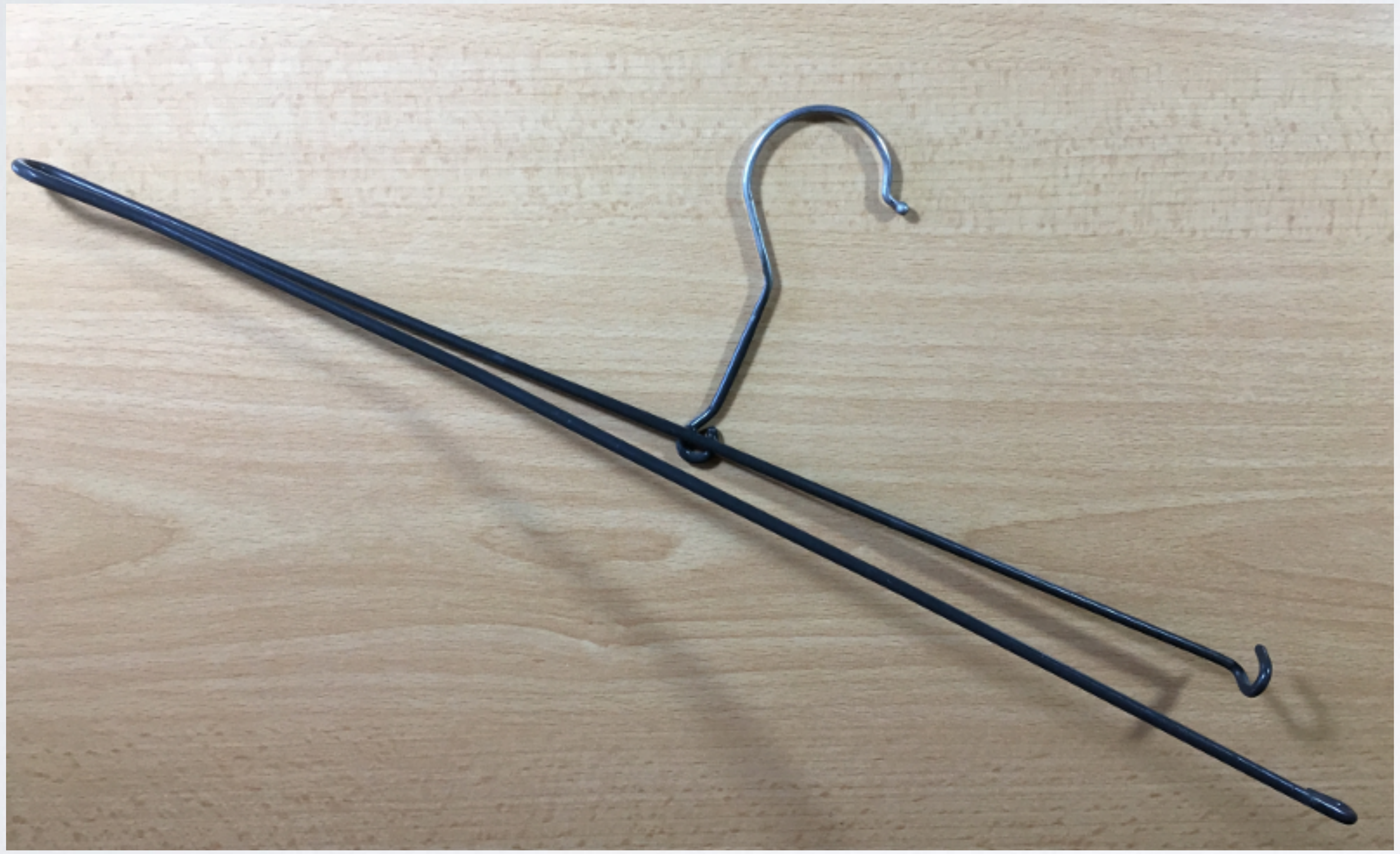
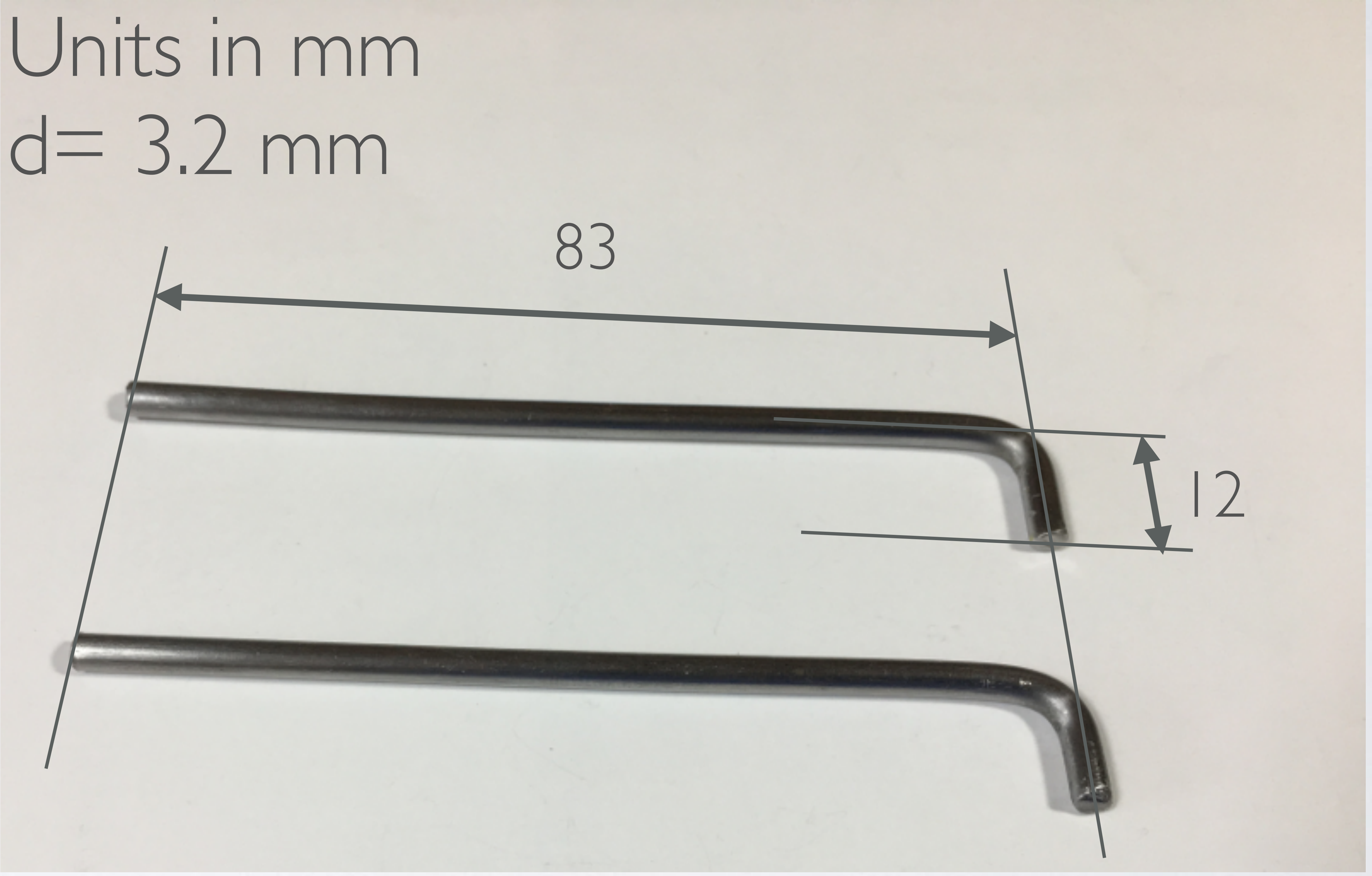
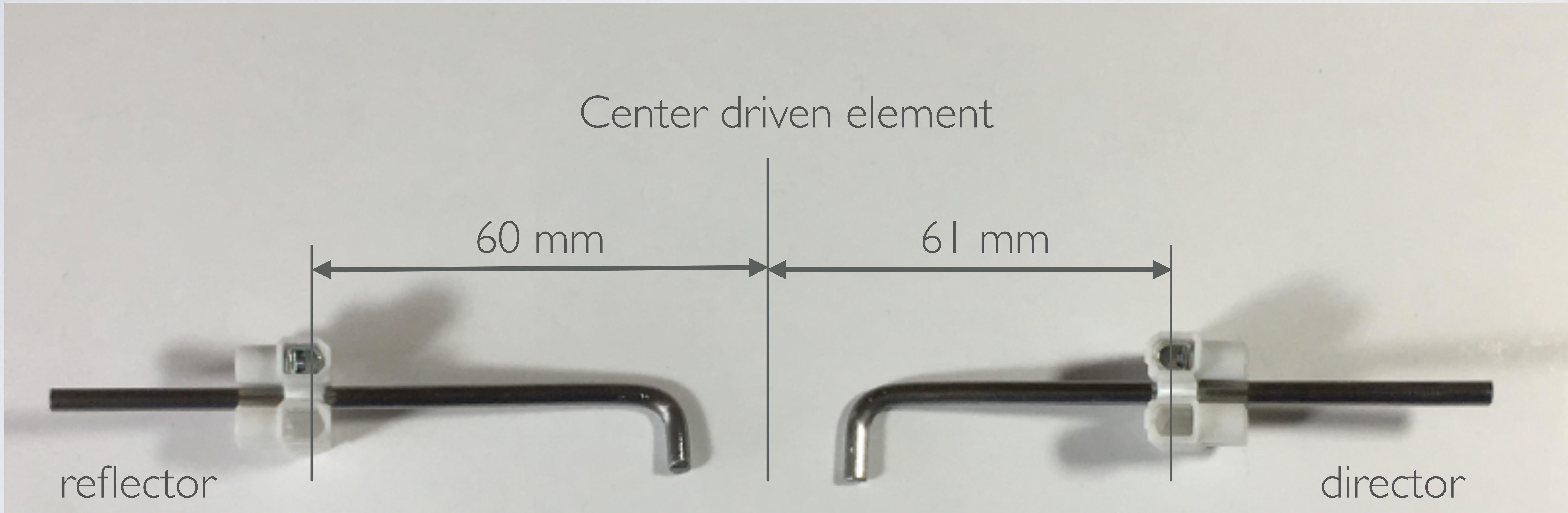
BUILD A YAGI-UDA ANTENNA

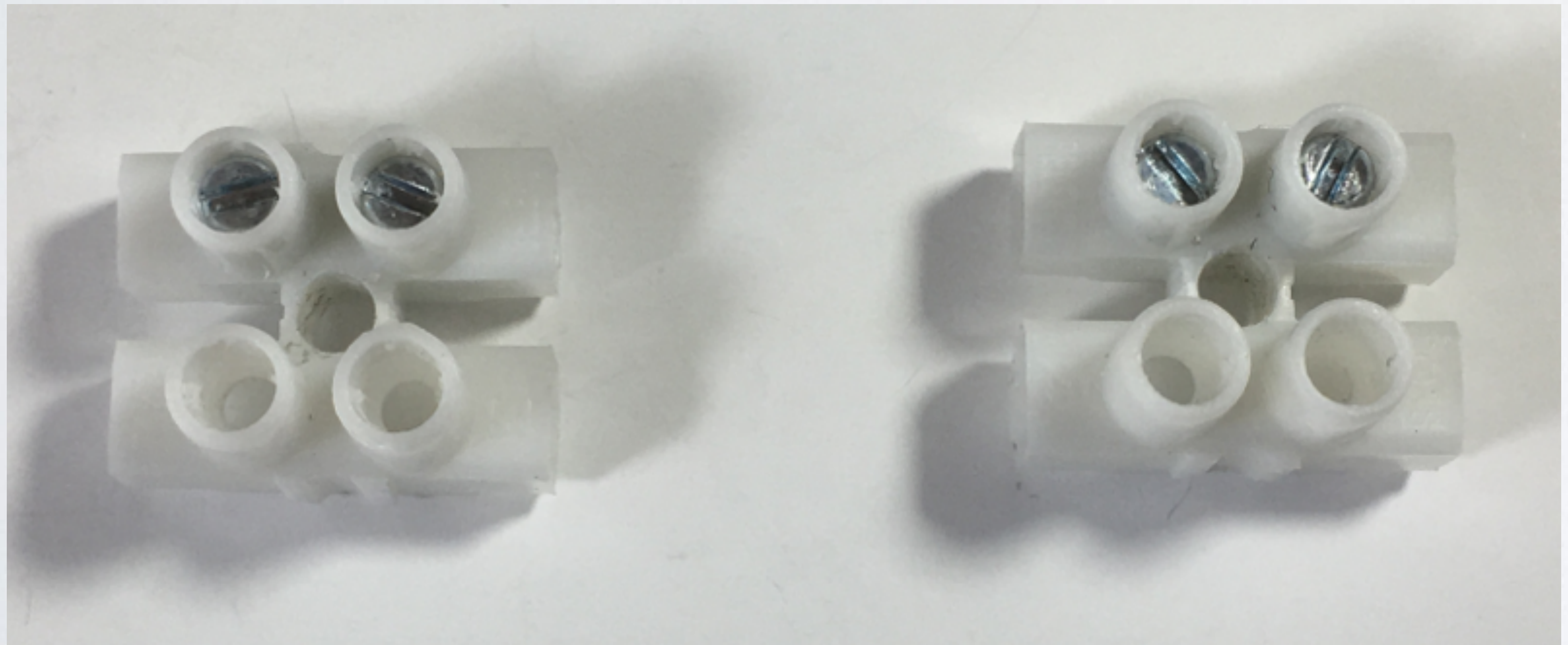
- The support boom is made from a metal cloth hanger.
  Cost: unknown





BUILD A YAGI-UDA ANTENNA

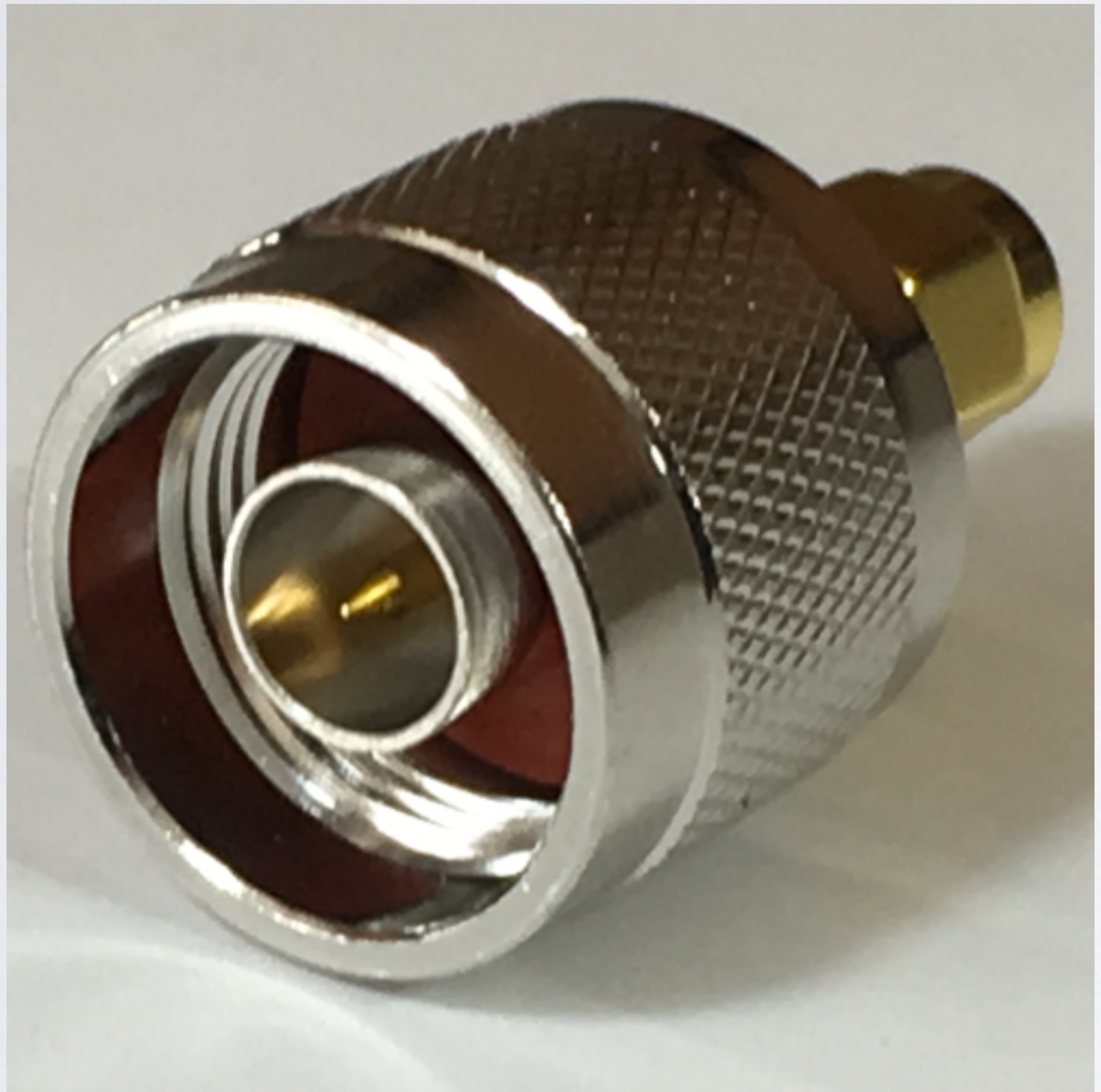


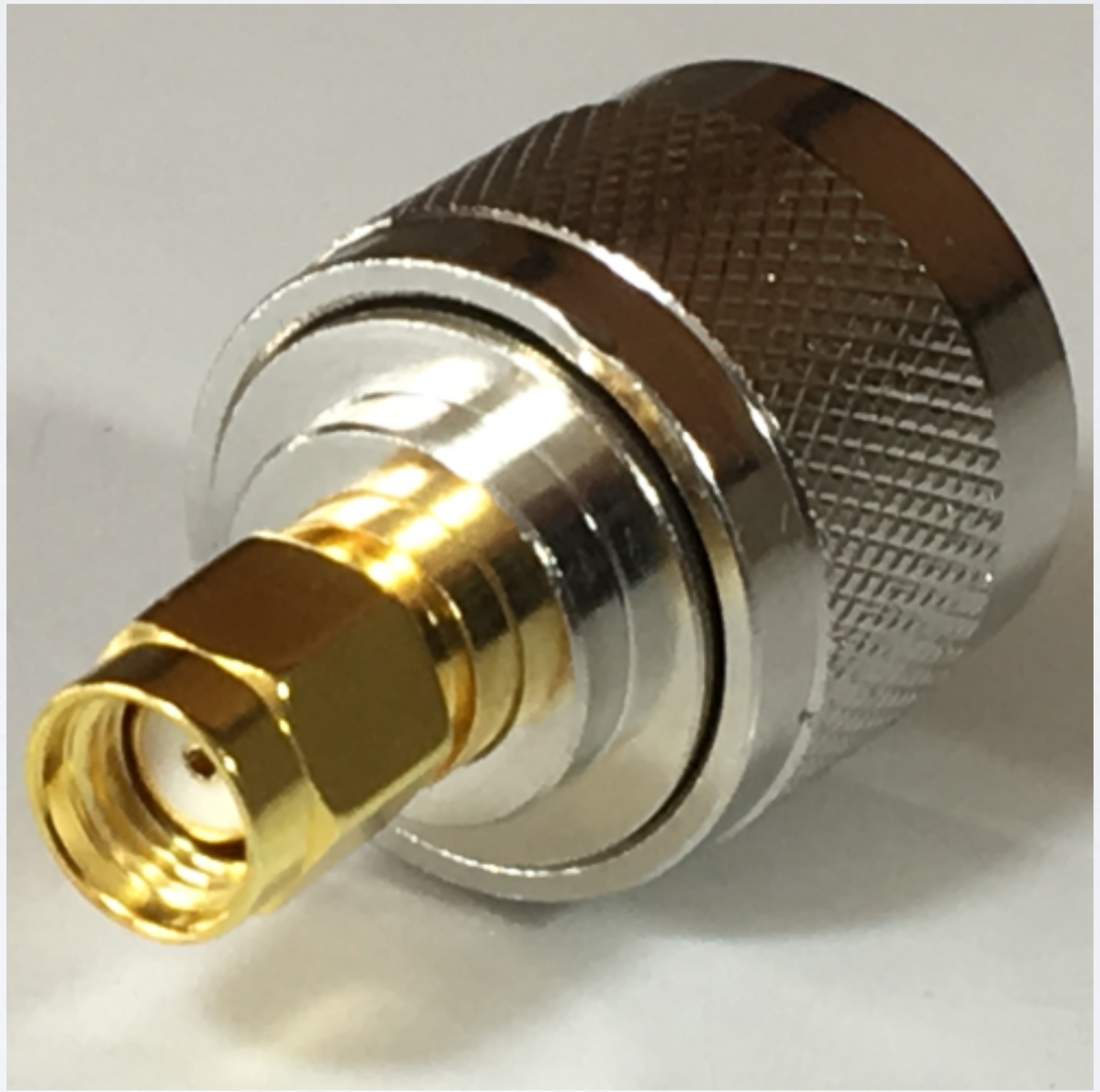


Plastic terminal blocks

BUILD A YAGI-UDA ANTENNA

- Type N male to RP-SMA male plug adapter coaxial cable connector.
  Cost: € 1.44





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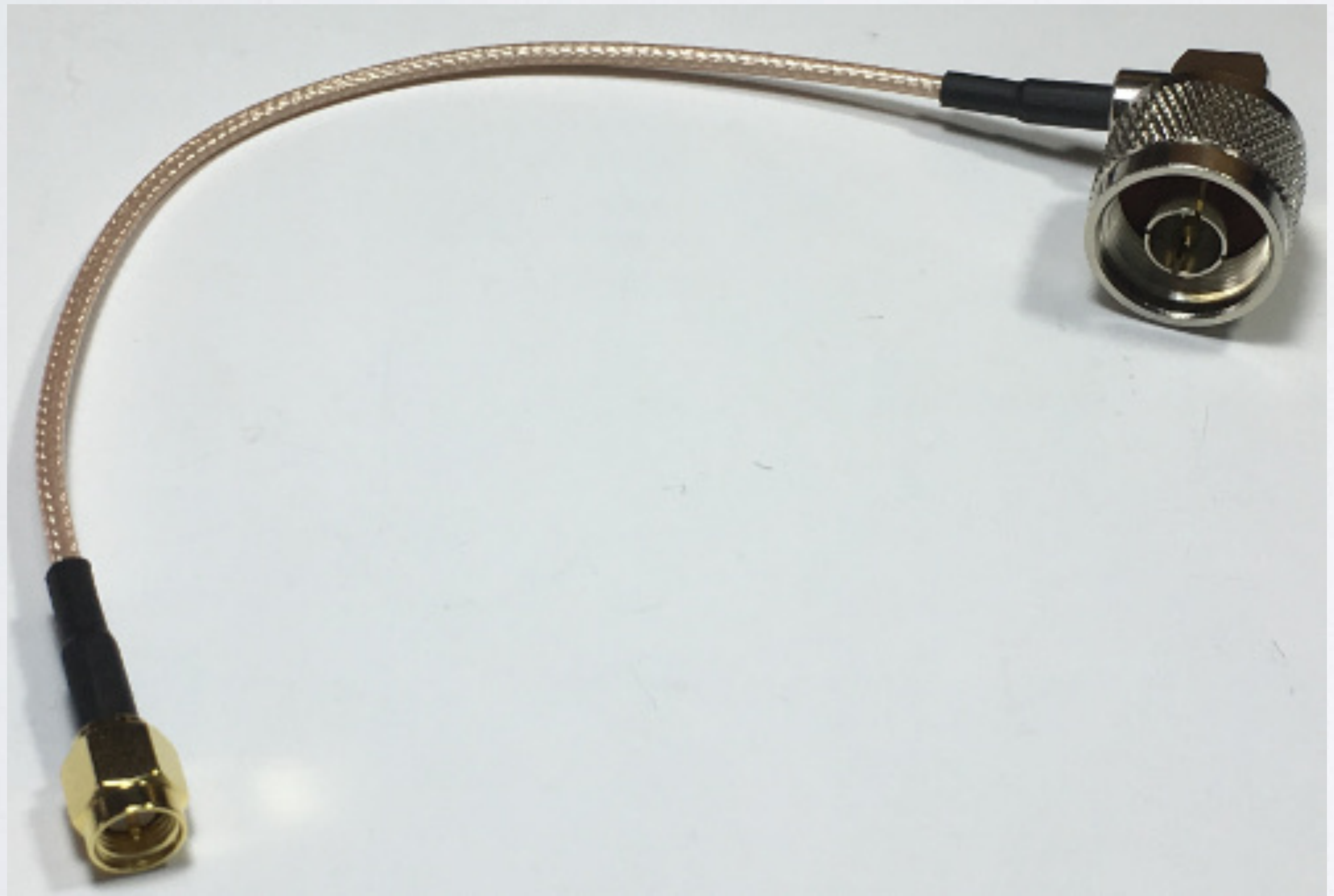
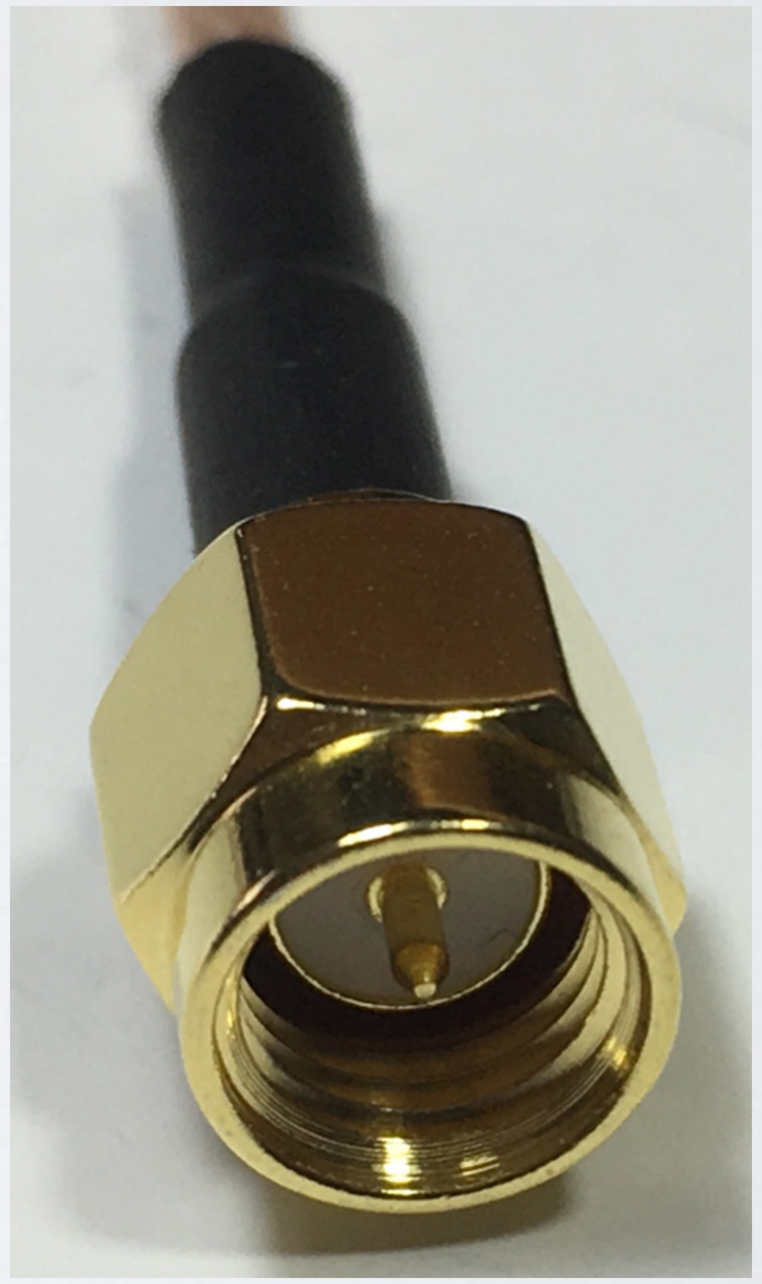
BUILD A YAGI-UDA ANTENNA

- RF coaxial cable RG316, length 20 cm with type N male plug right angle to SMA male connector.
  Impedance: 50Ω
  Coax: RG316
  Cost: € 3.39





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BUILD A YAGI-UDA ANTENNA

- Bolt: M4x10 (but preferable M4x12)
  Nut: M4
  Metal washer 7.8 x 4.4 x 0.5 mm (outer diameter, inner diameter, thickness)
  Cost: unknown

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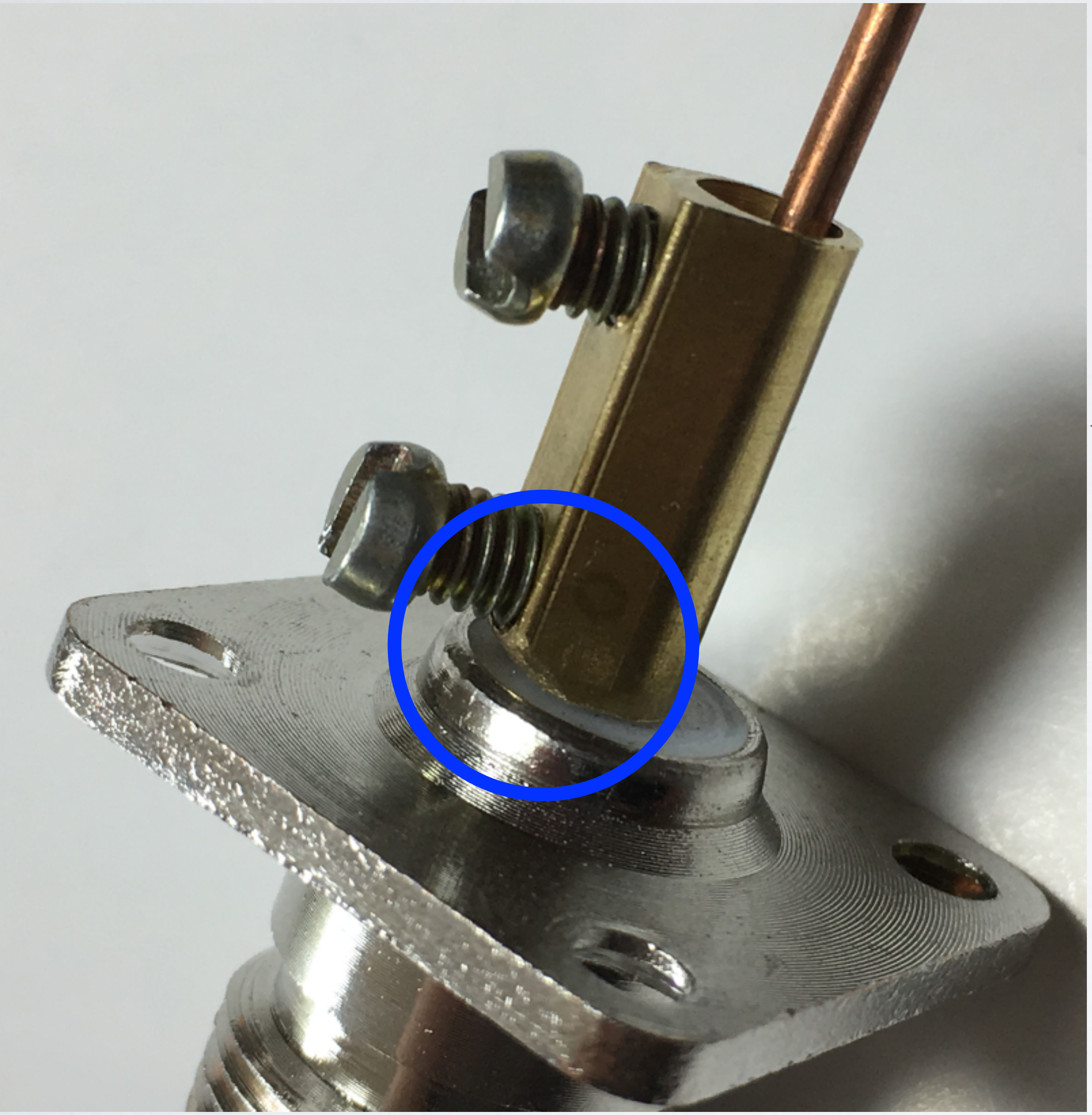
CONNECTING ANTENNA TO TYPE N FEMALE CHASSIS

- The driven elements will be attached to type N female chassis mount 4-hole connector using terminals.

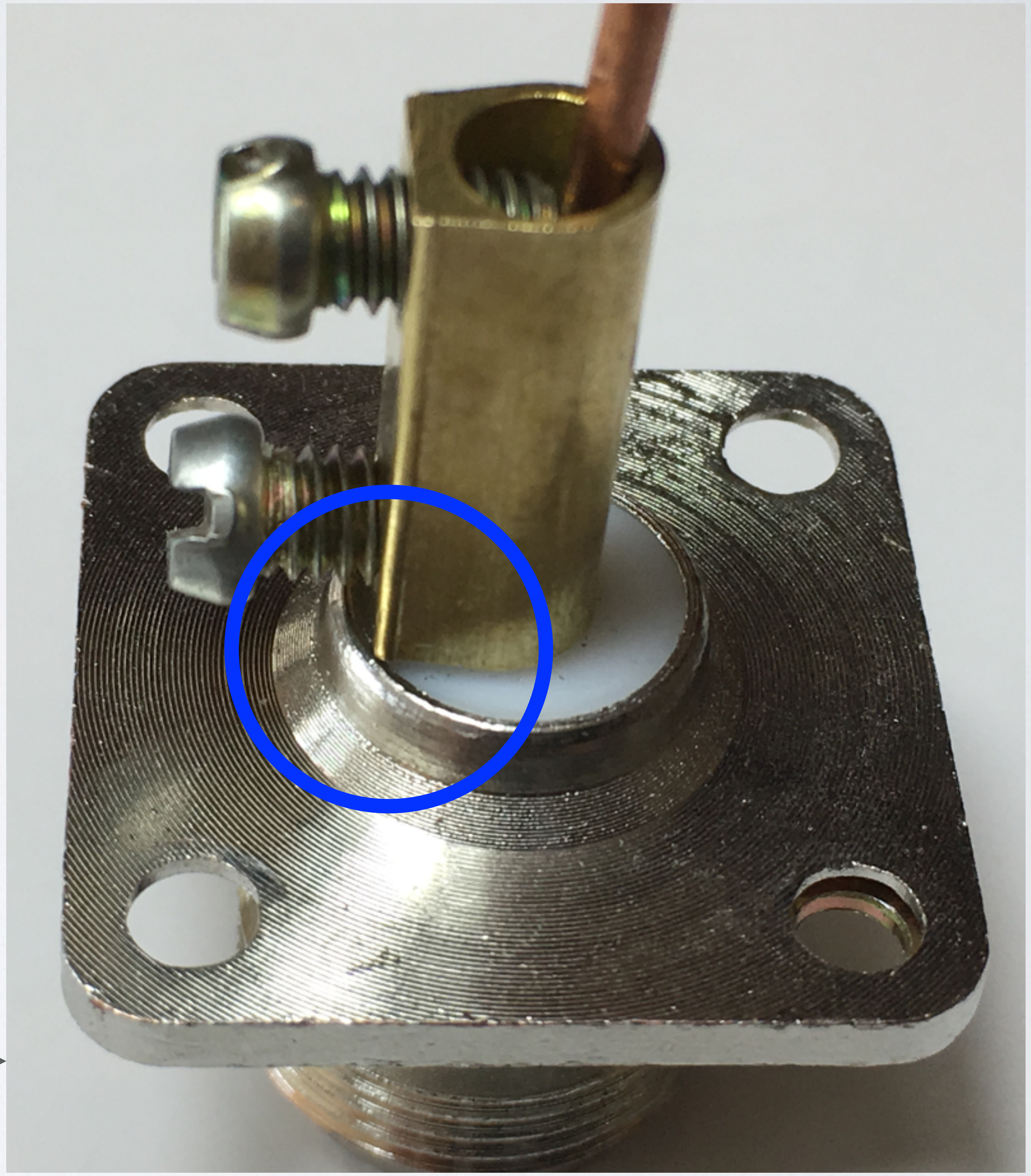
- But first I have to round the edges of one terminal using a Dremel tool.

CONNECTING ANTENNA TO TYPE N FEMALE CHASSIS



Rounded, terminal does not touch the type N chassis.

Not rounded, terminal does touch the type N chassis.

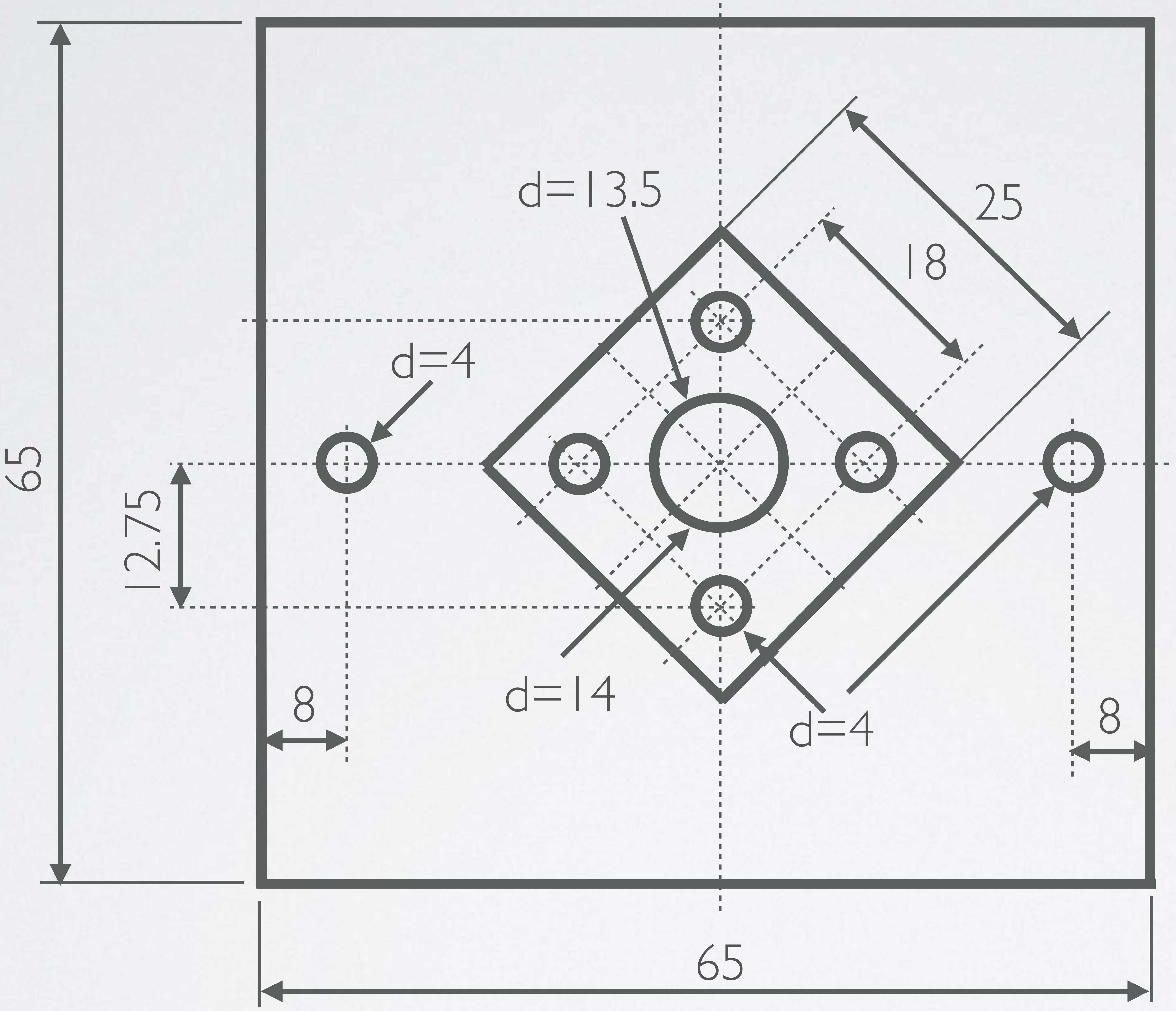


BUILD A YAGI-UDA ANTENNA

- Plastic plate made from a MacBook Pro packaging.
  Cost: unknown

Use a Stanley knife to cut out the plastic plate.

BUILD A YAGI-UDA ANTENNA

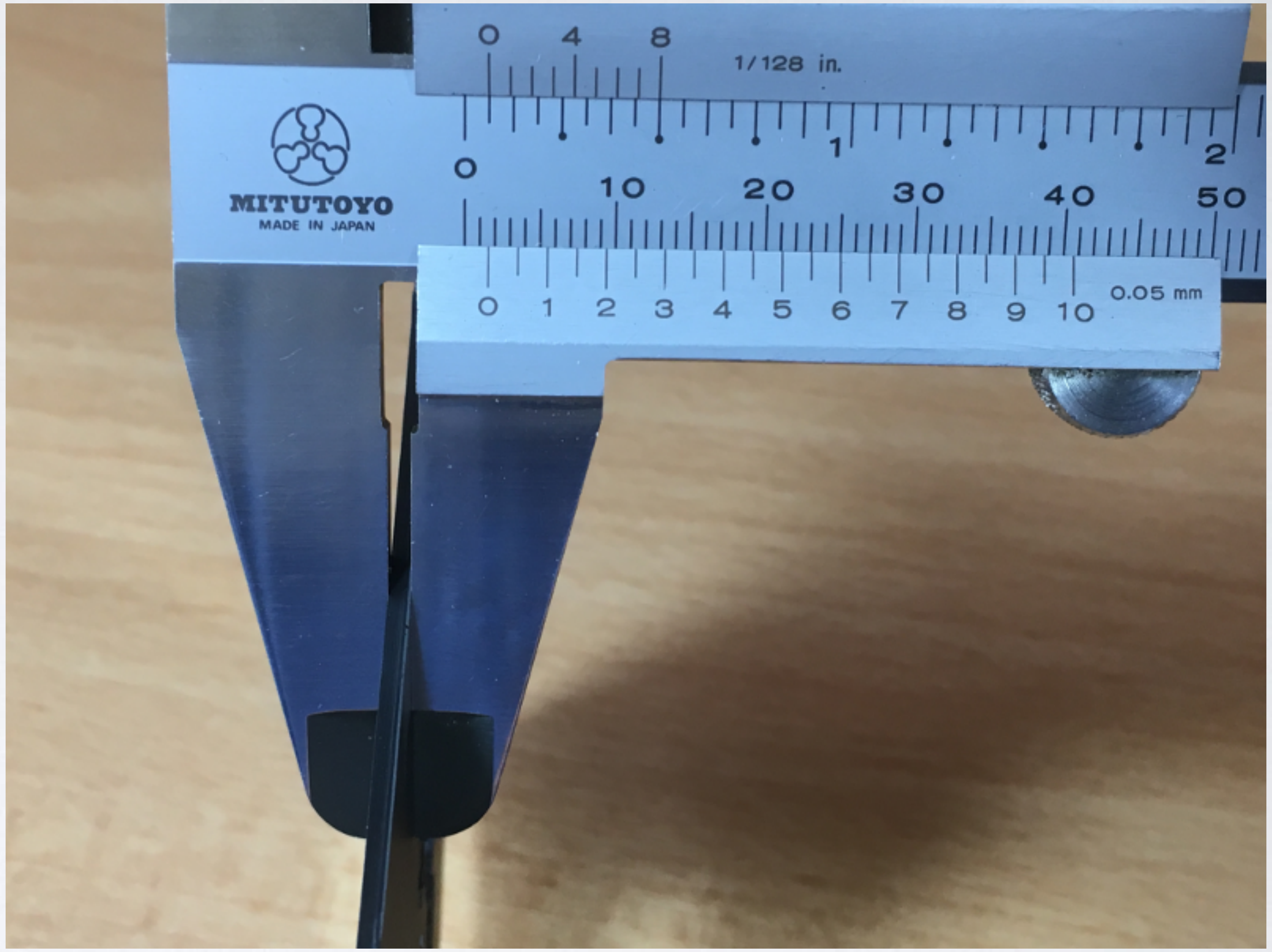


Plastic plate dimensions

Units in mm
Drawing not to scale

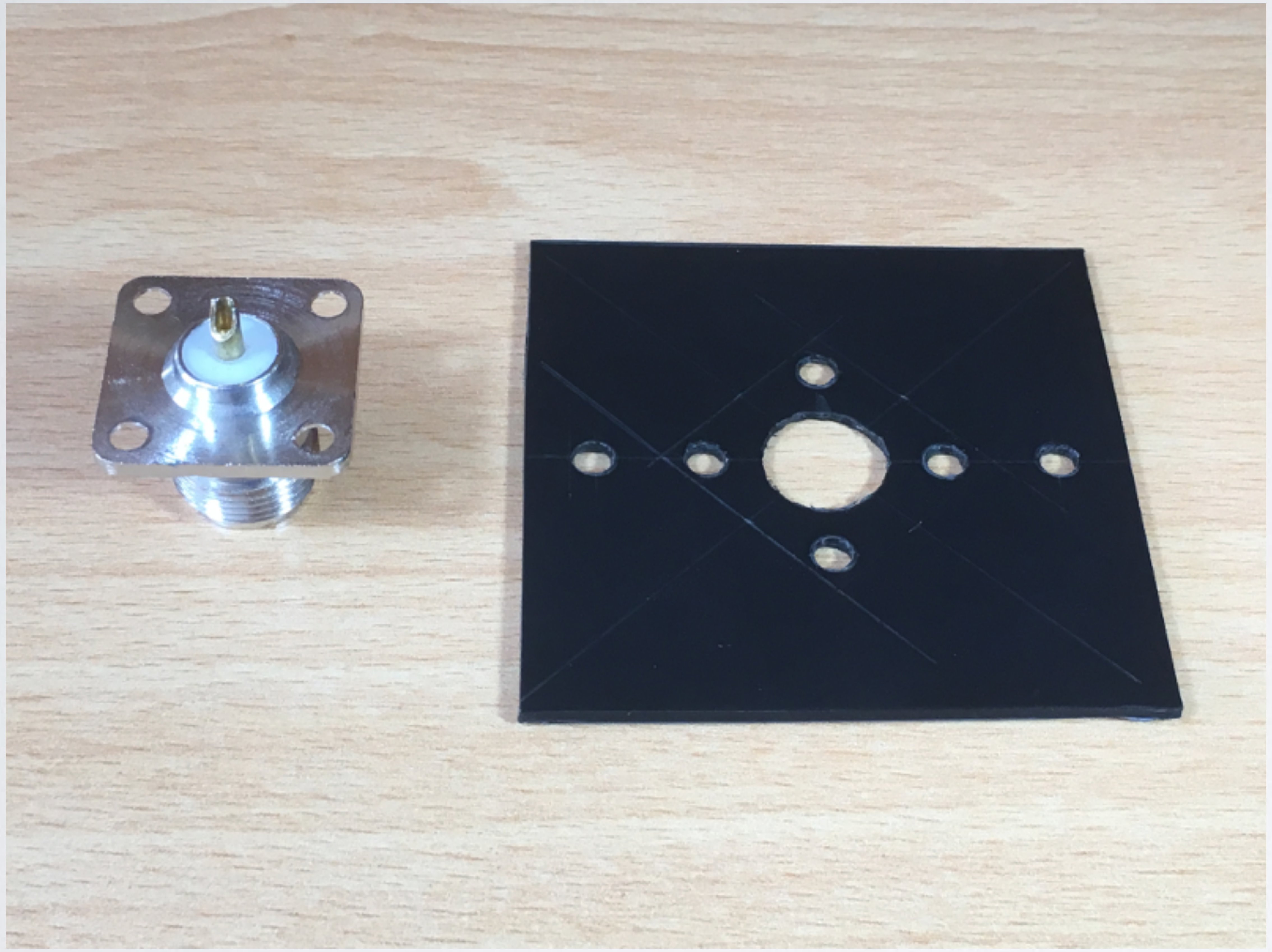
Thickness = 1.6 mm

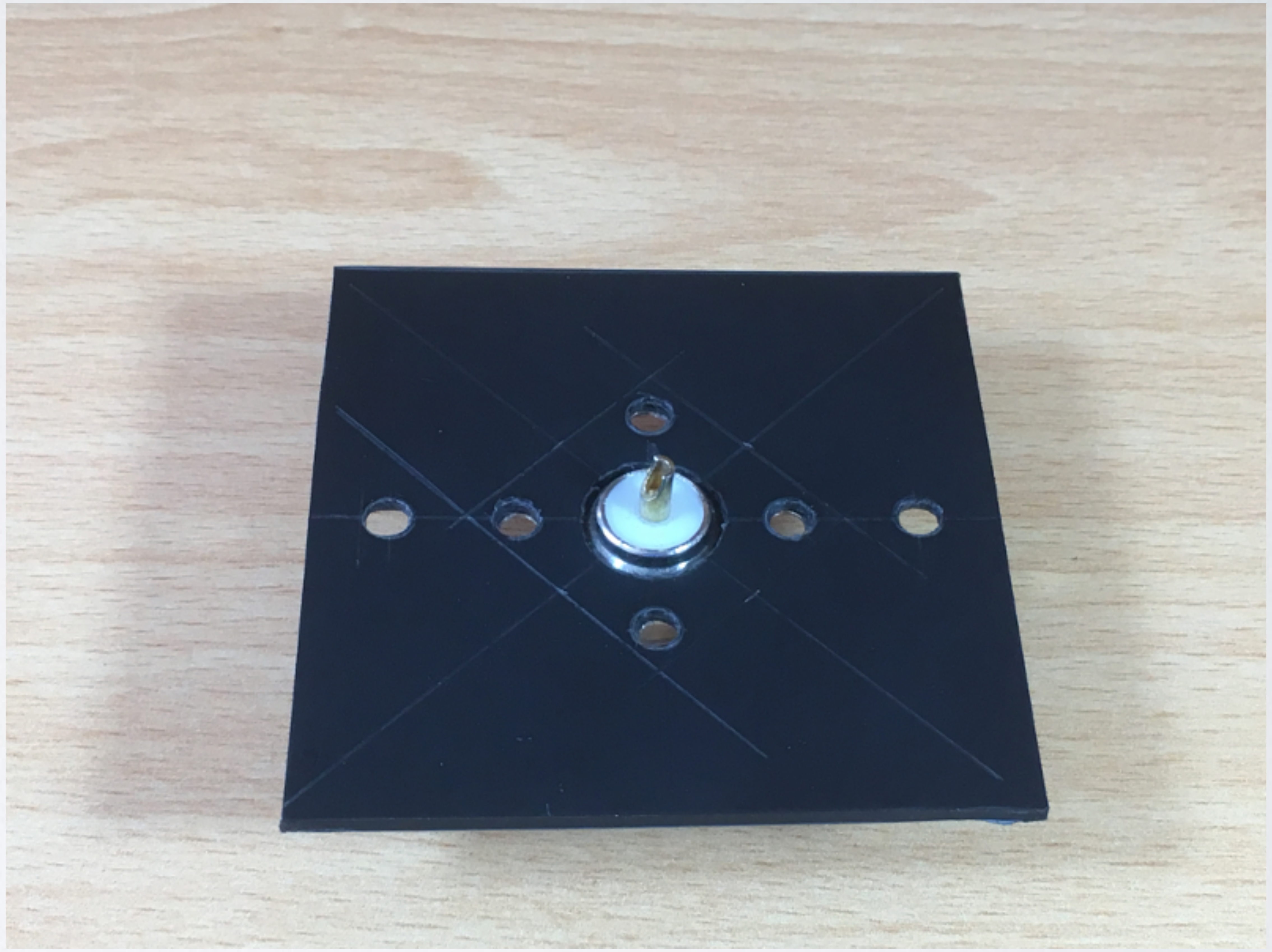
BUILD A YAGI-UDA ANTENNA



Mark out the locations where holes need to be drilled.

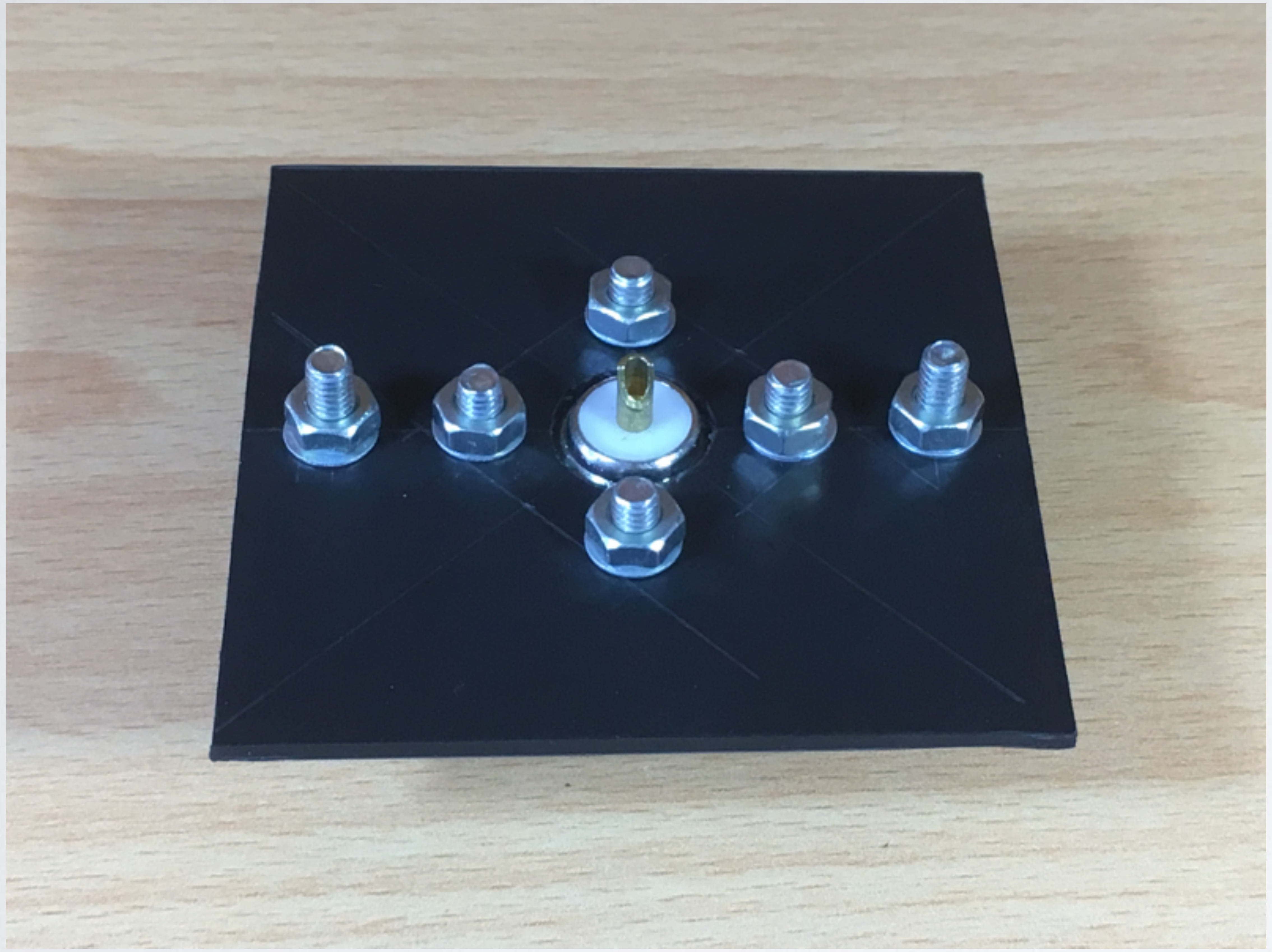
BUILD A YAGI-UDA ANTENNA

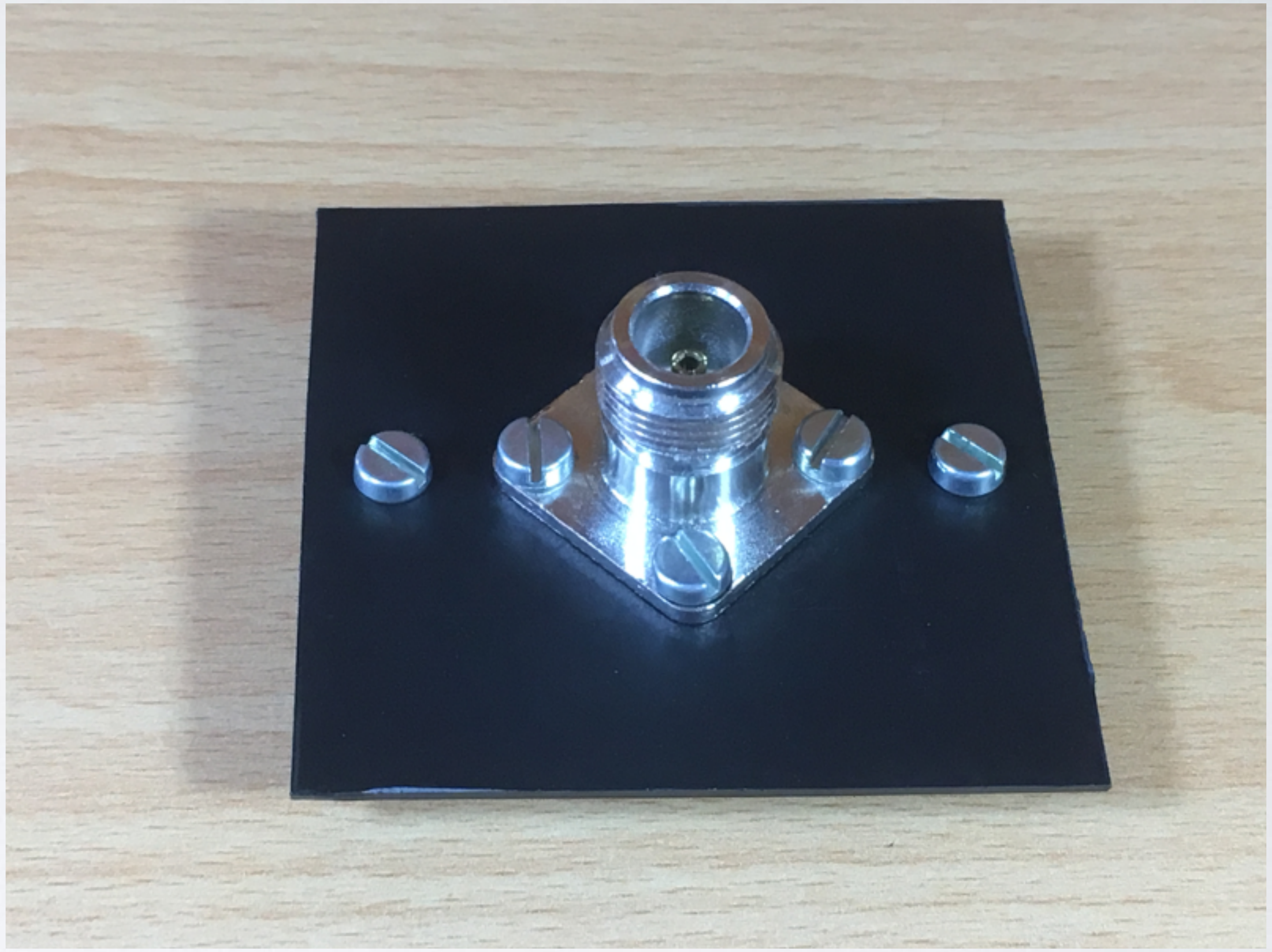




Holes drilled.

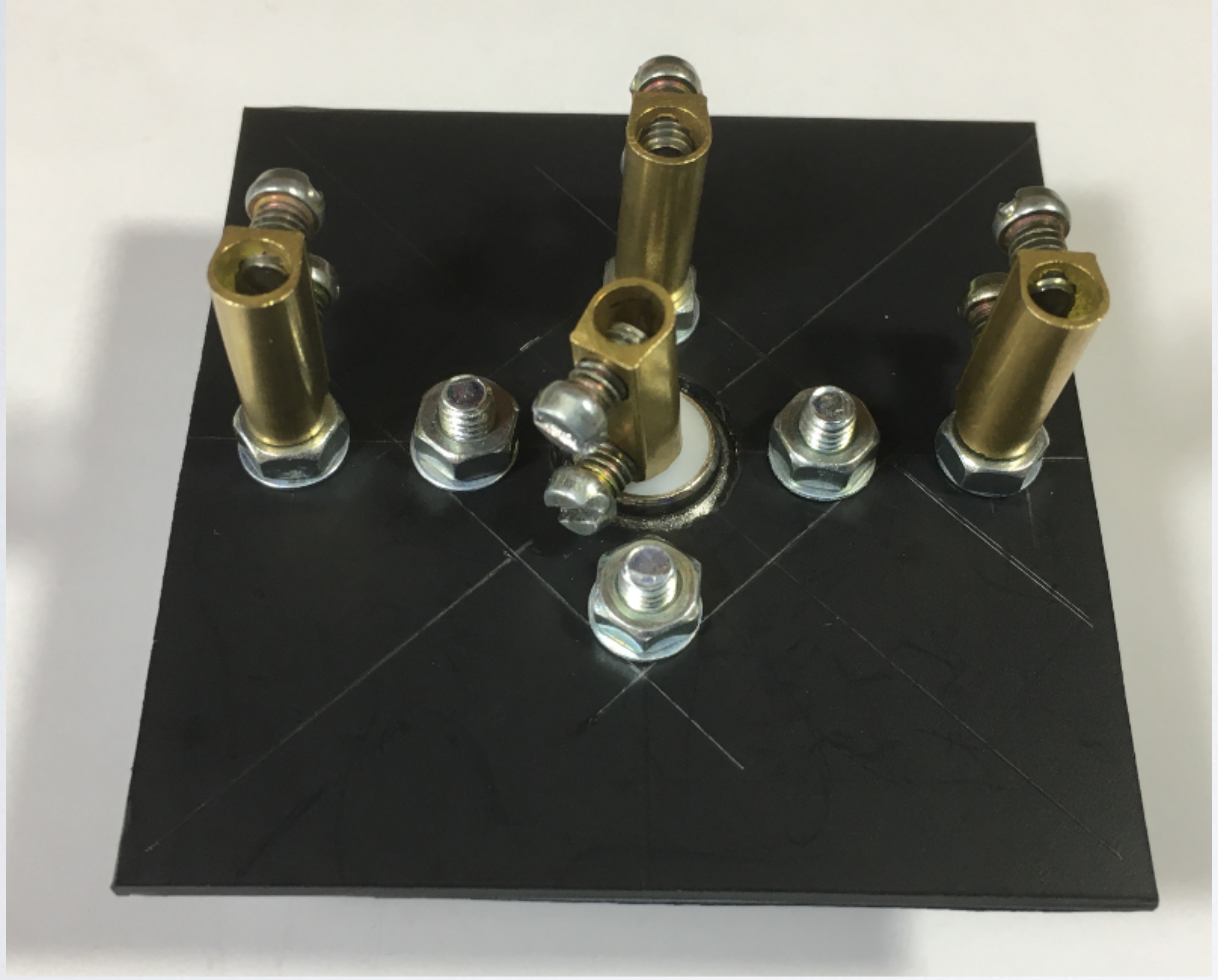
BUILD A YAGI-UDA ANTENNA





Attach plastic plate to type N connector.

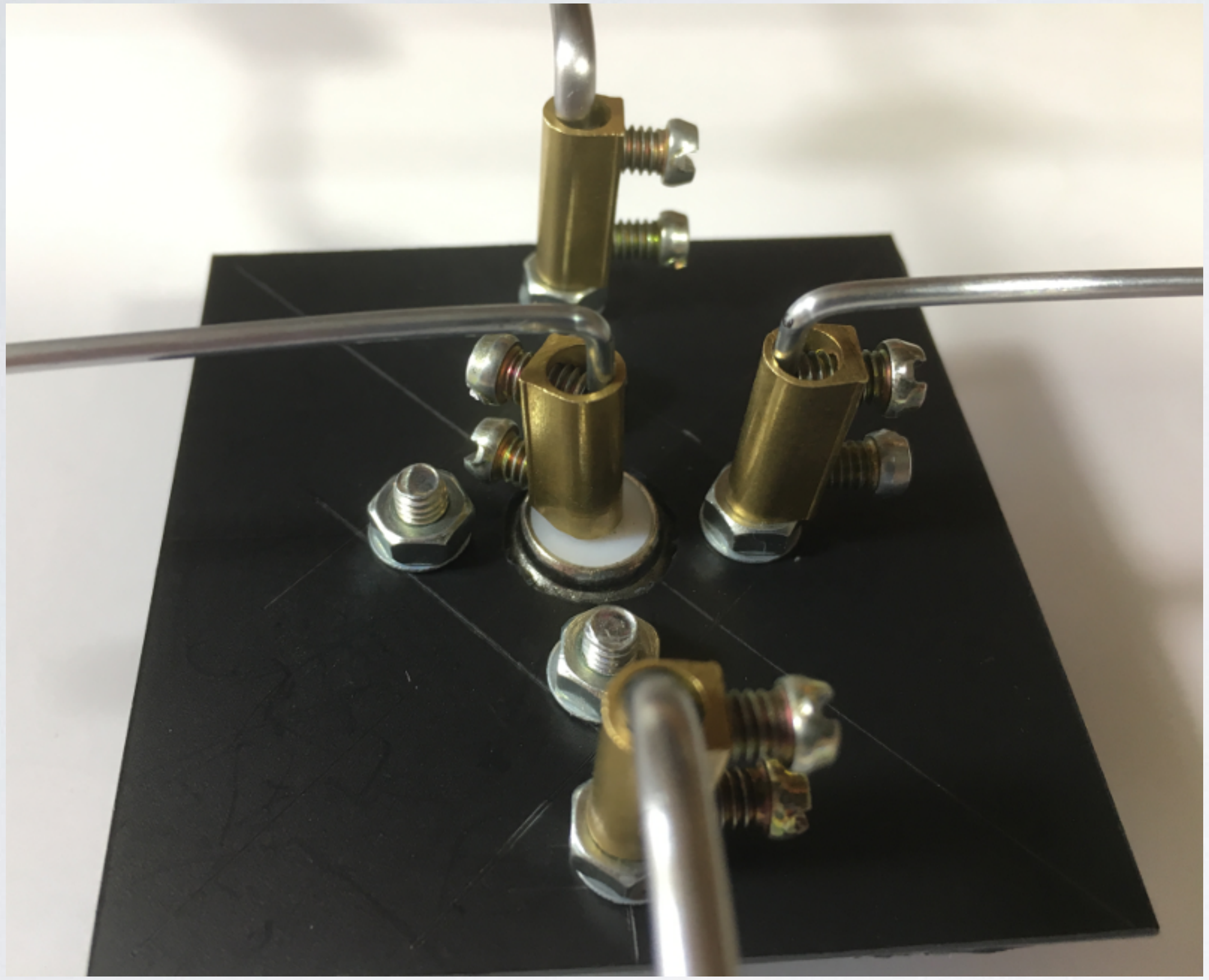
BUILD A YAGI-UDA ANTENNA



Attach the terminals.

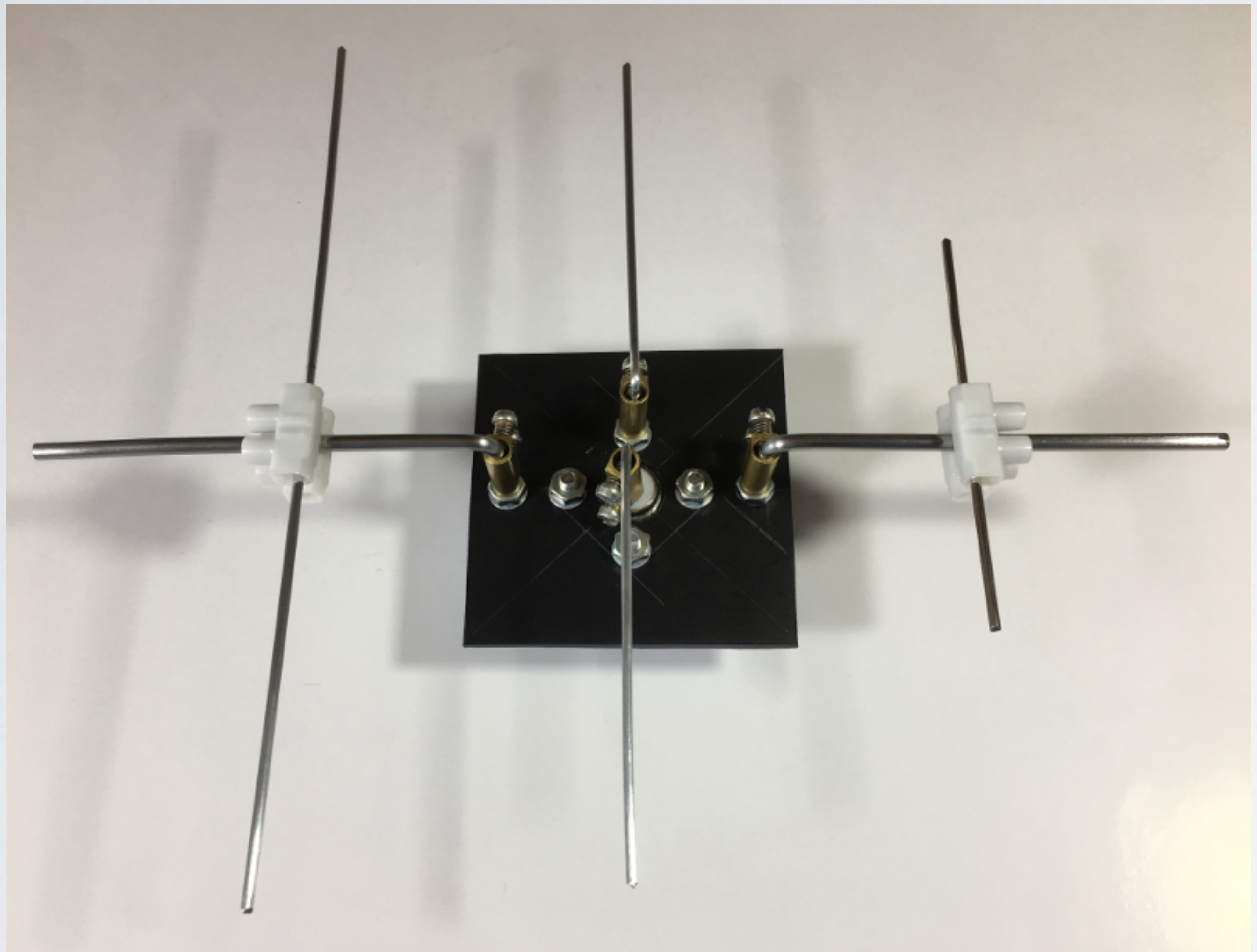
Attach driven element & support booms.

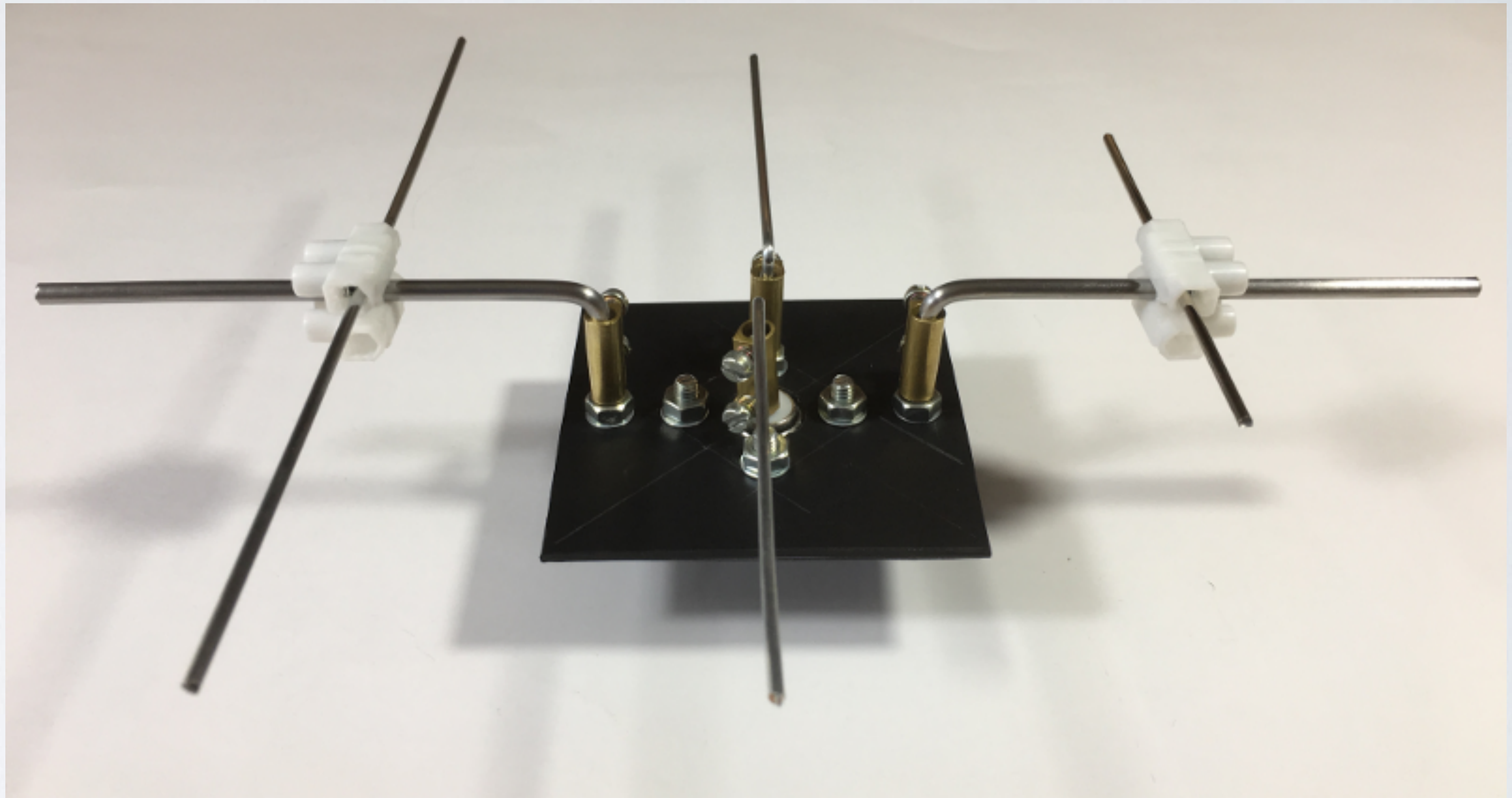
BUILD A YAGI-UDA ANTENNA



Attach driven element & support booms.

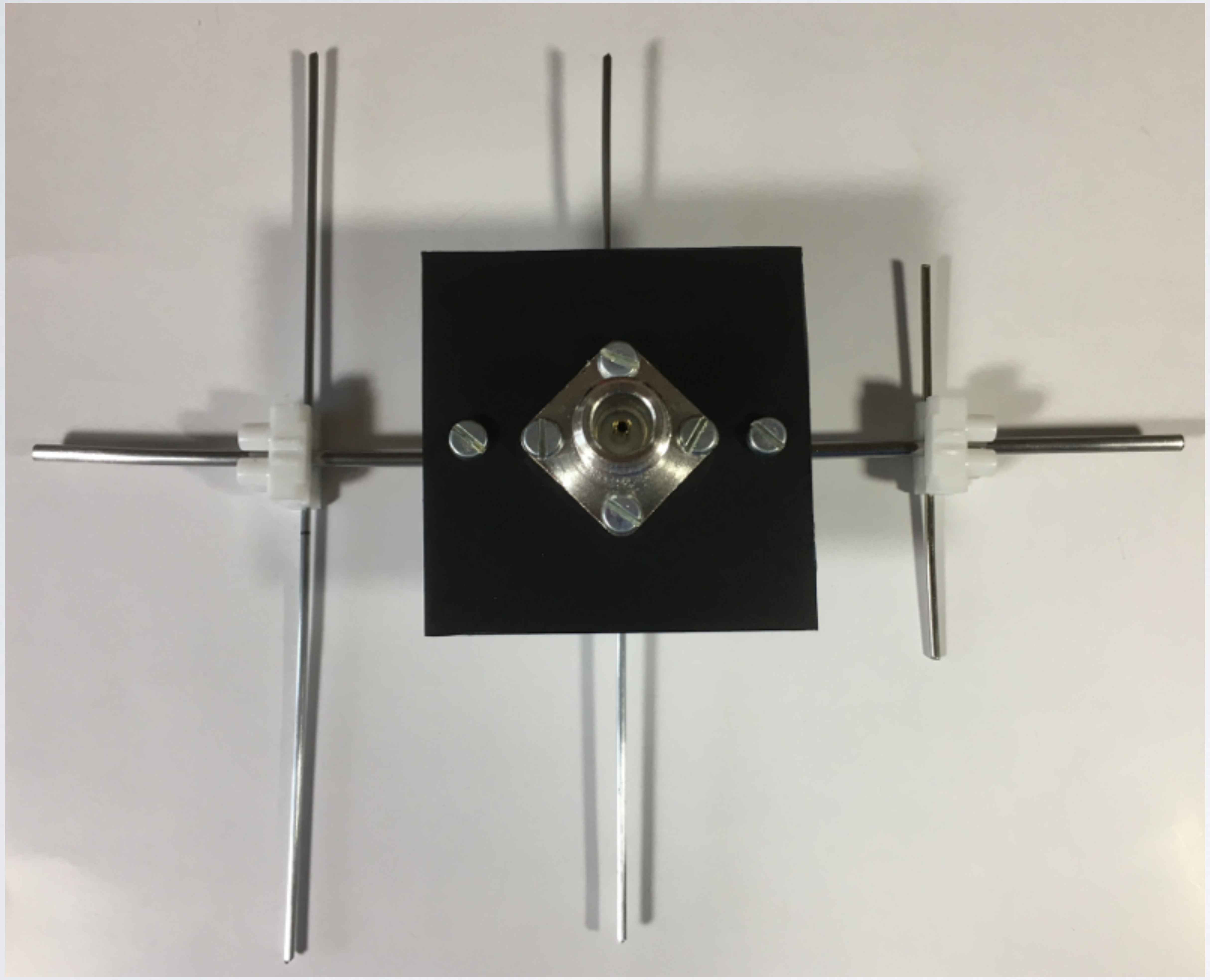
YAGI-UDA ANTENNA





Attach reflector and director

YAGI-UDA ANTENNA



Bottom view.

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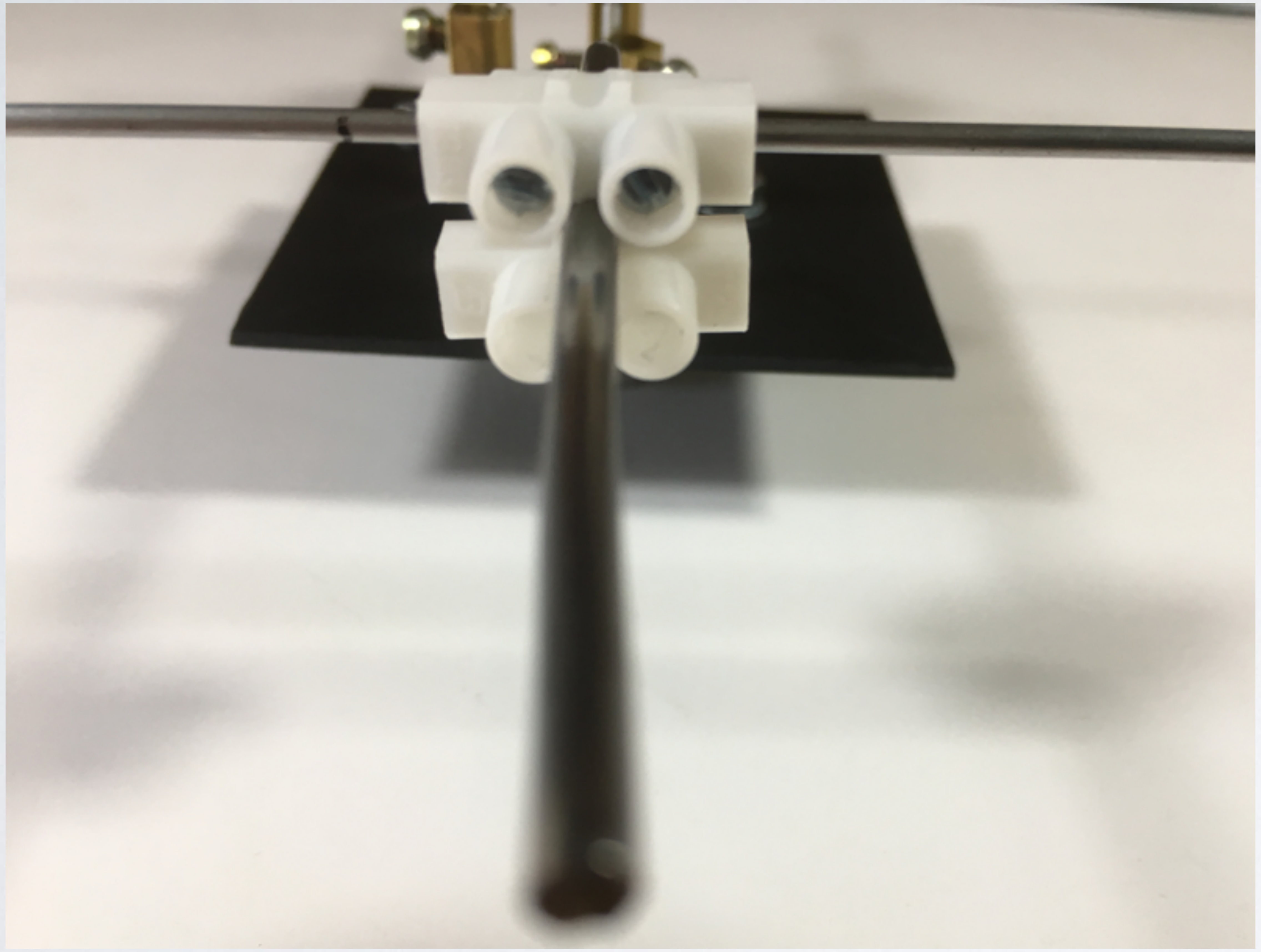
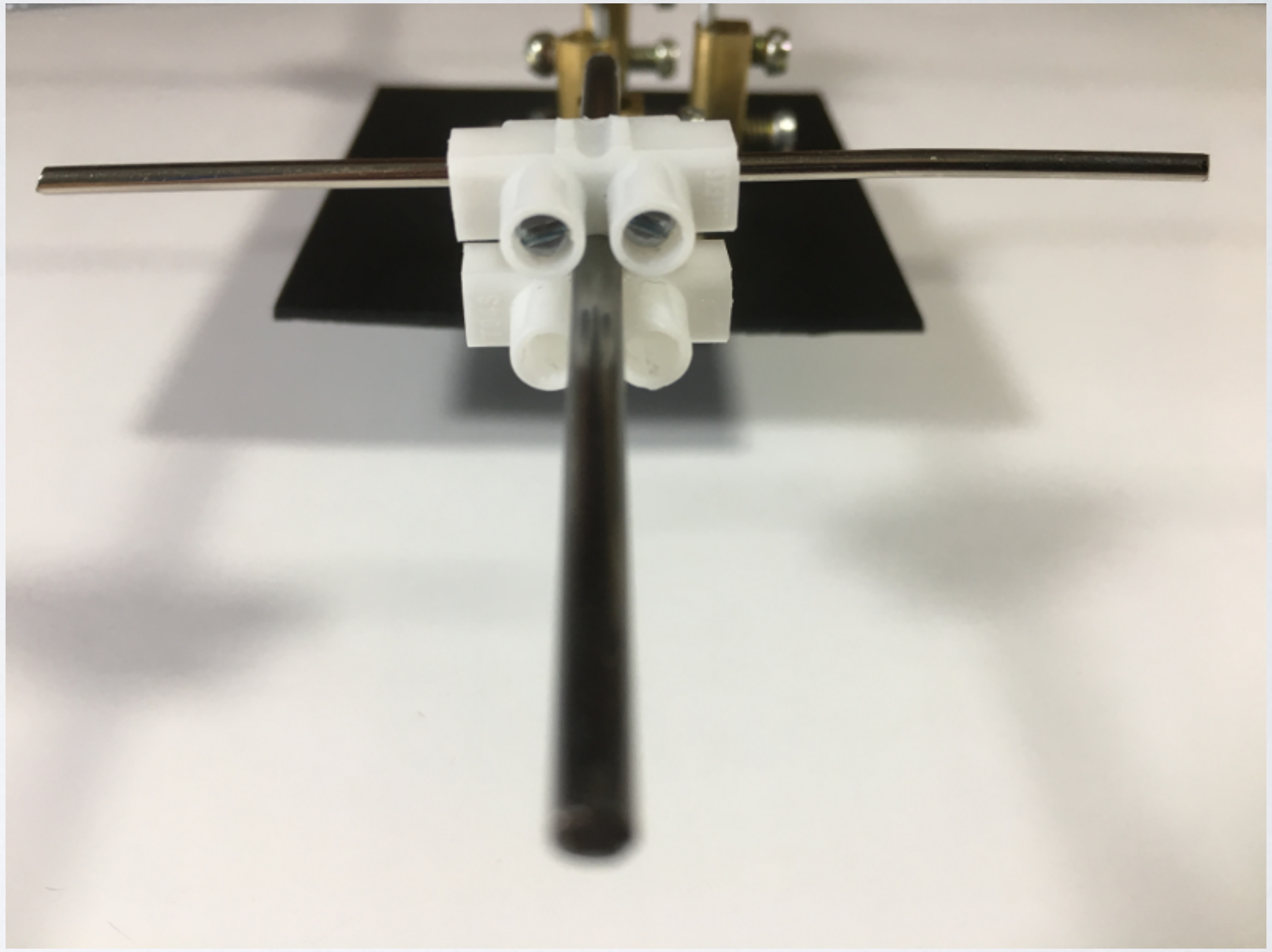
YAGI-UDA ANTENNA

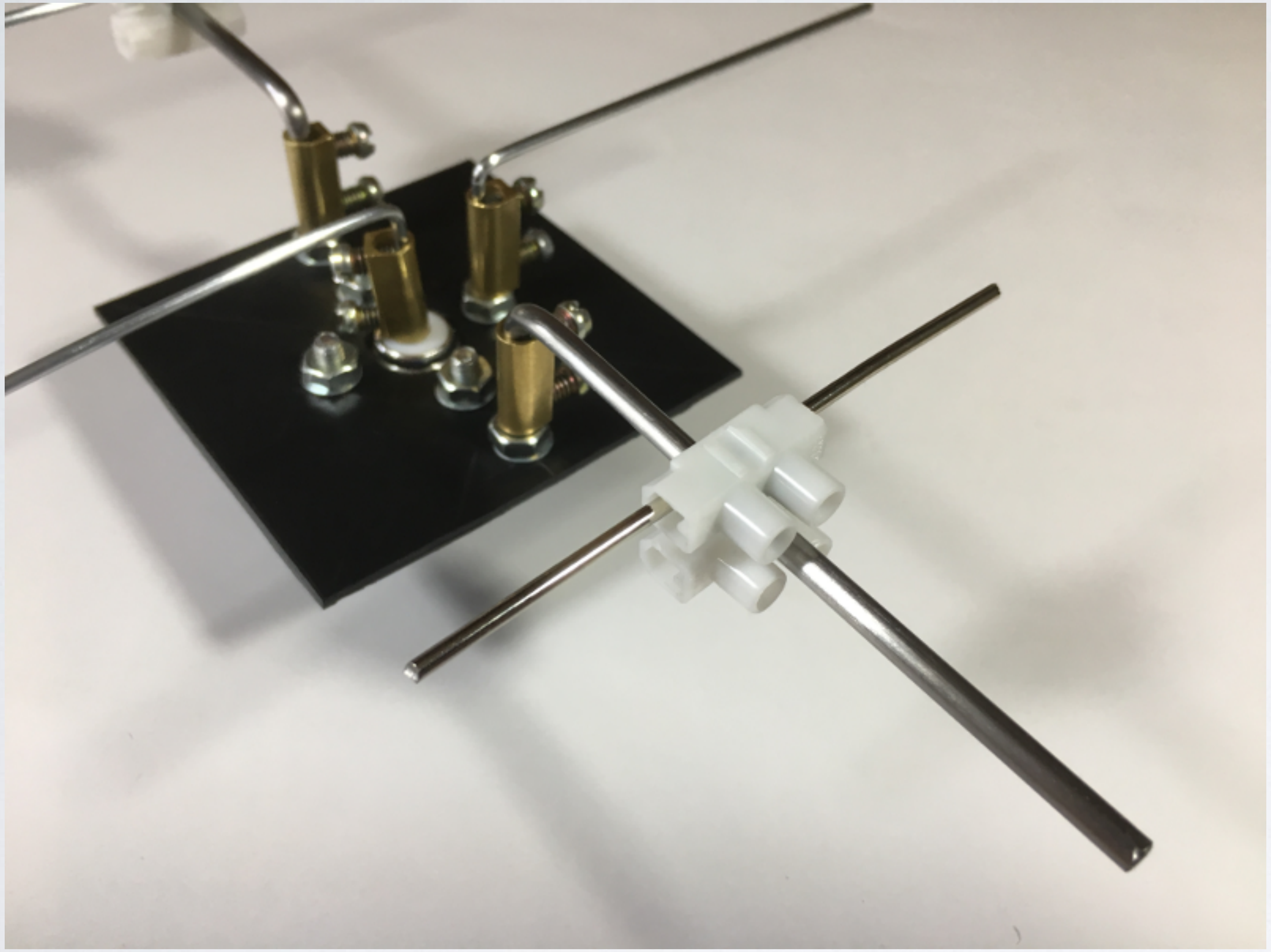


Terminal strip block and reflector



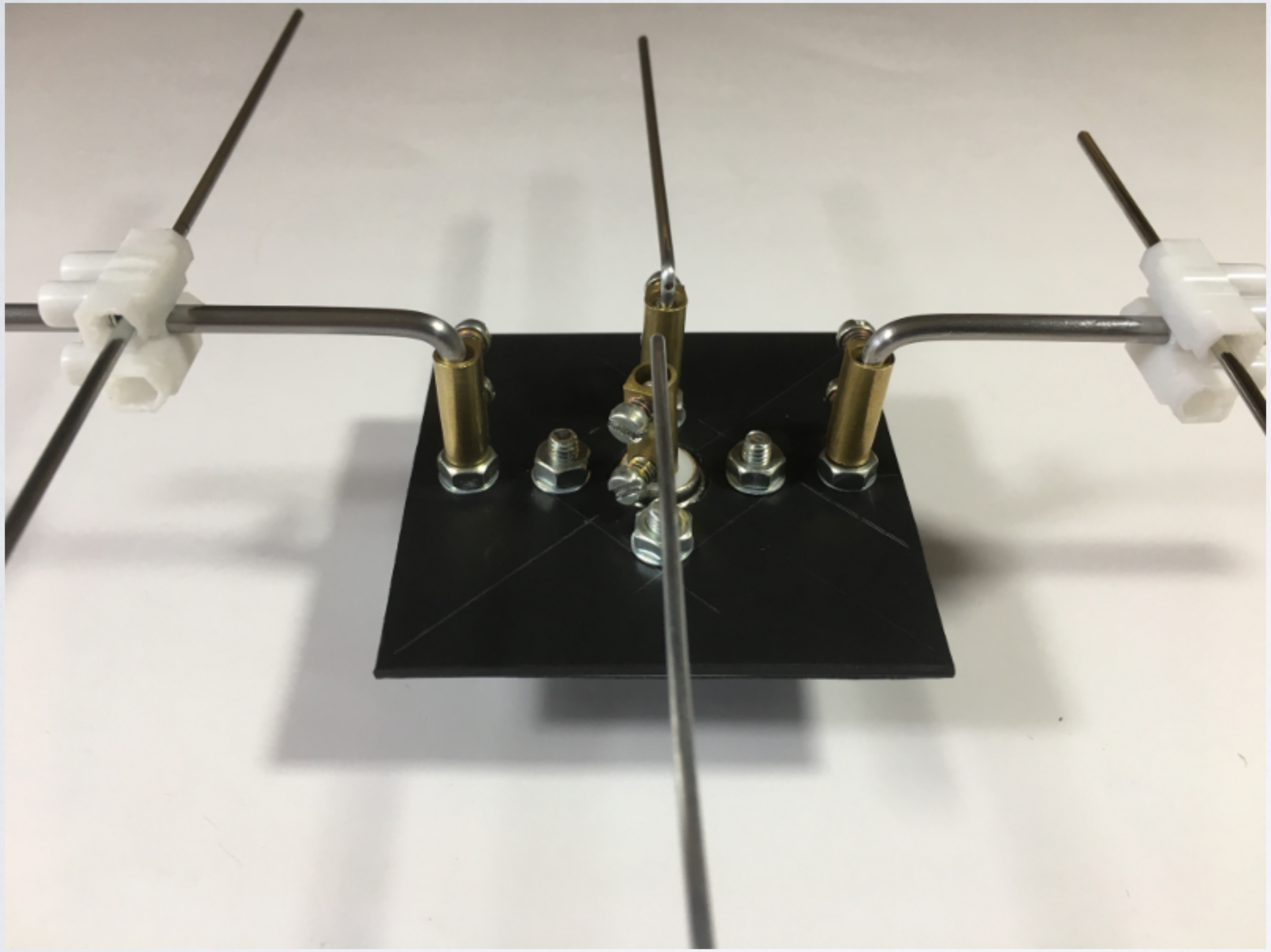
Terminal strip block and director

YAGI-UDA ANTENNA



Director and driven element.

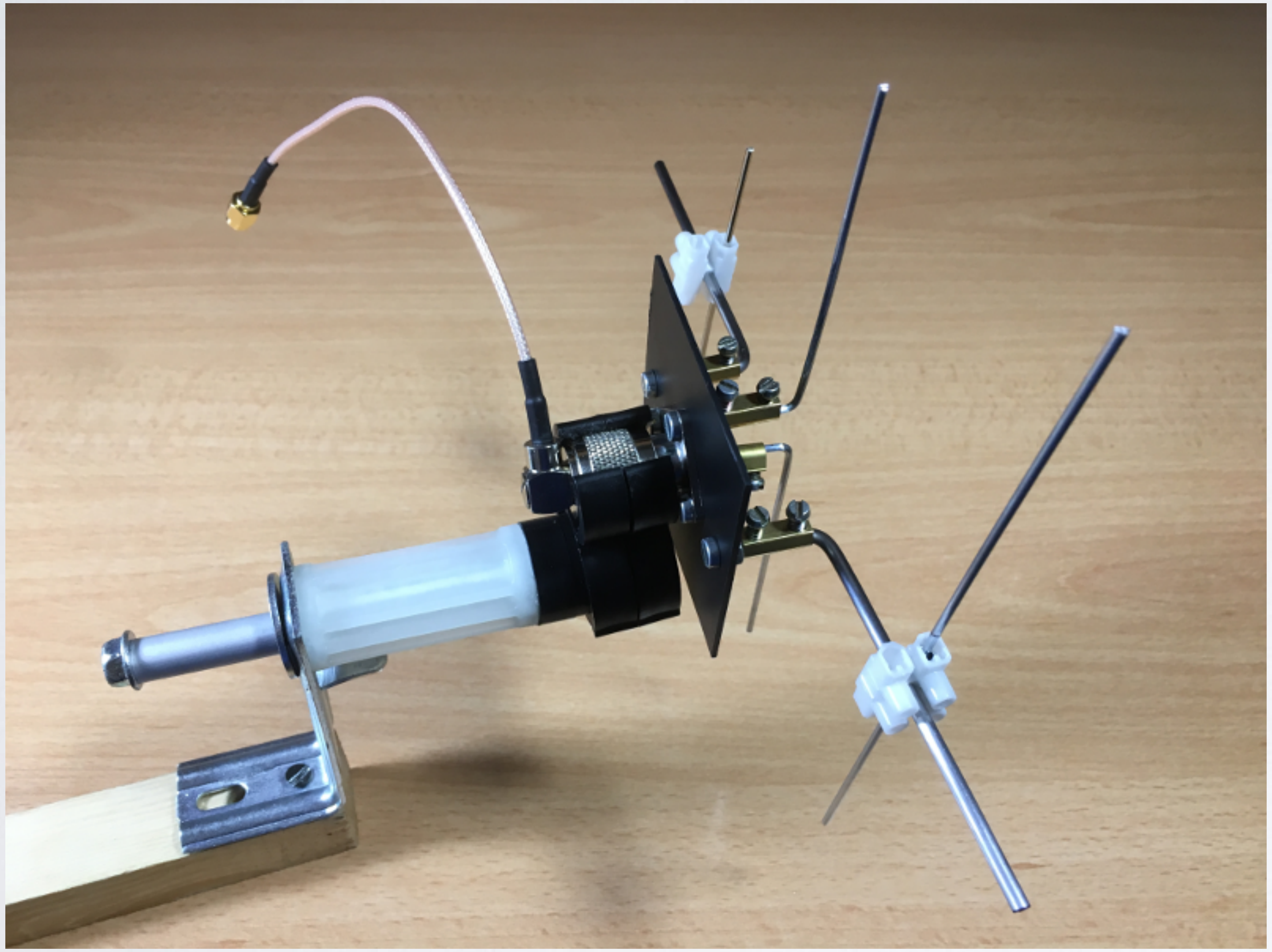
YAGI-UDA ANTENNA

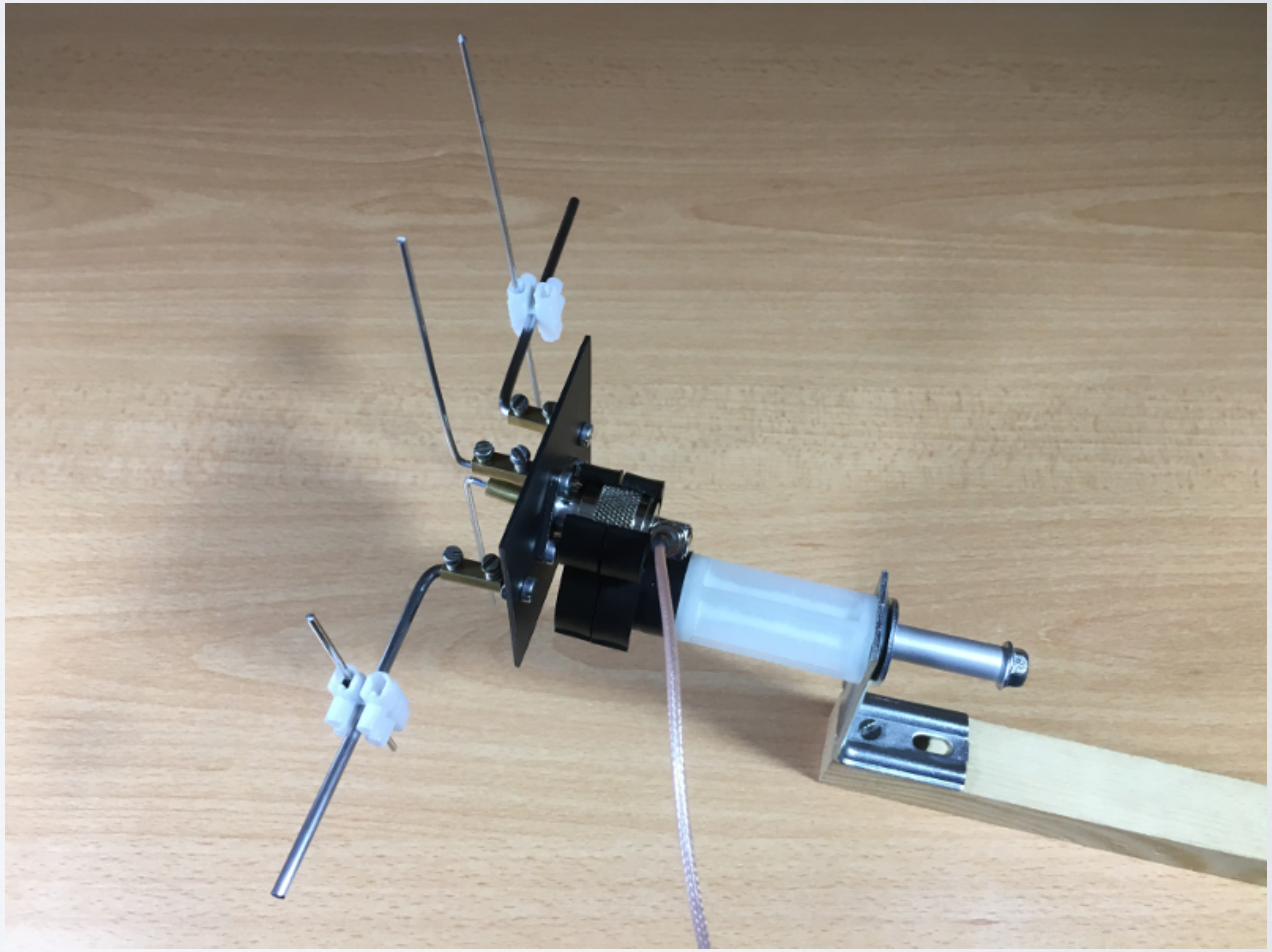


Close up reflector, driven element, director and support booms.

YAGI-UDA ANTENNA MOUNTED ON TEST RIG

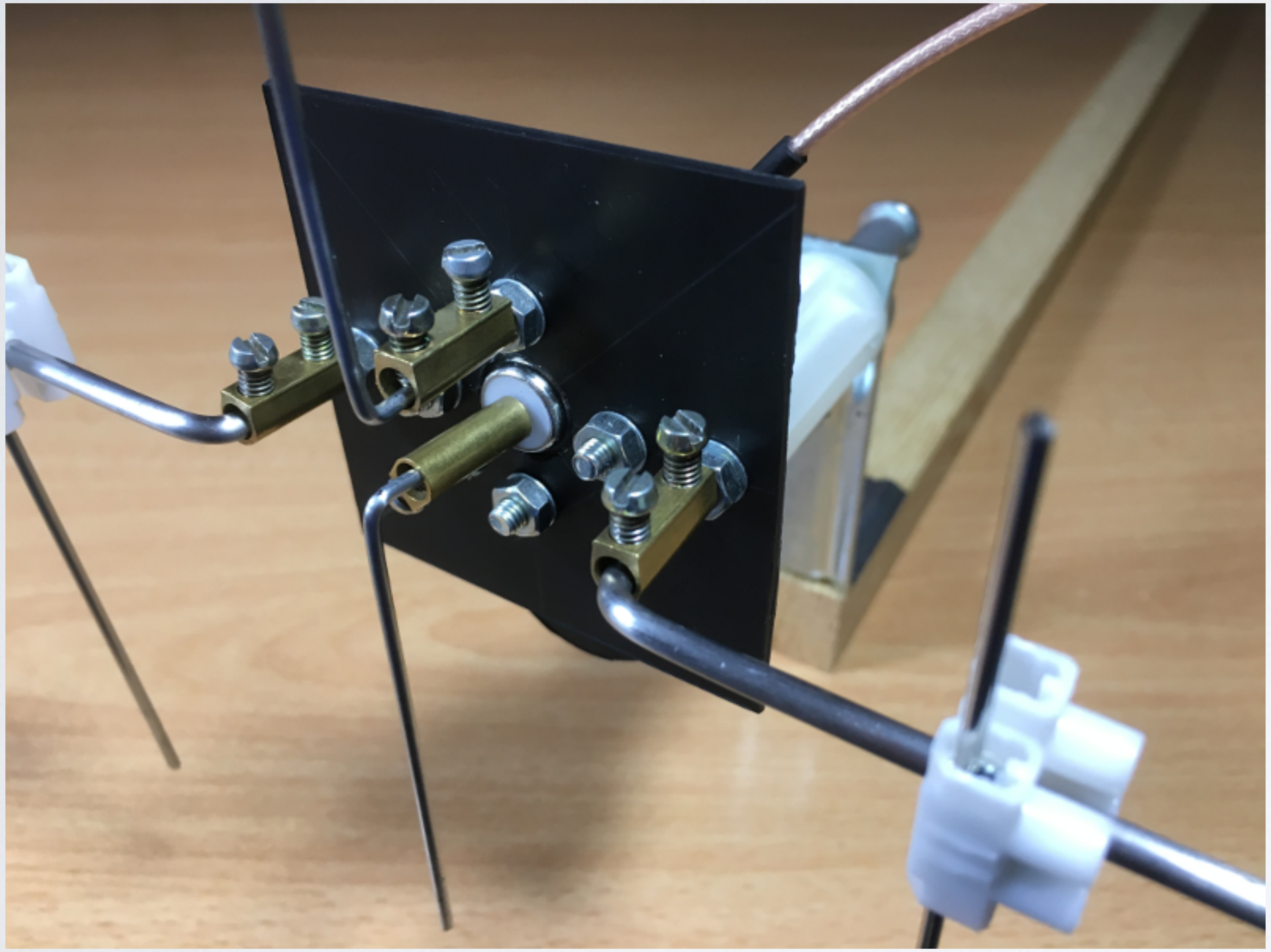
- Antenna clamped to test rig. Test rig explained in tutorial 40.

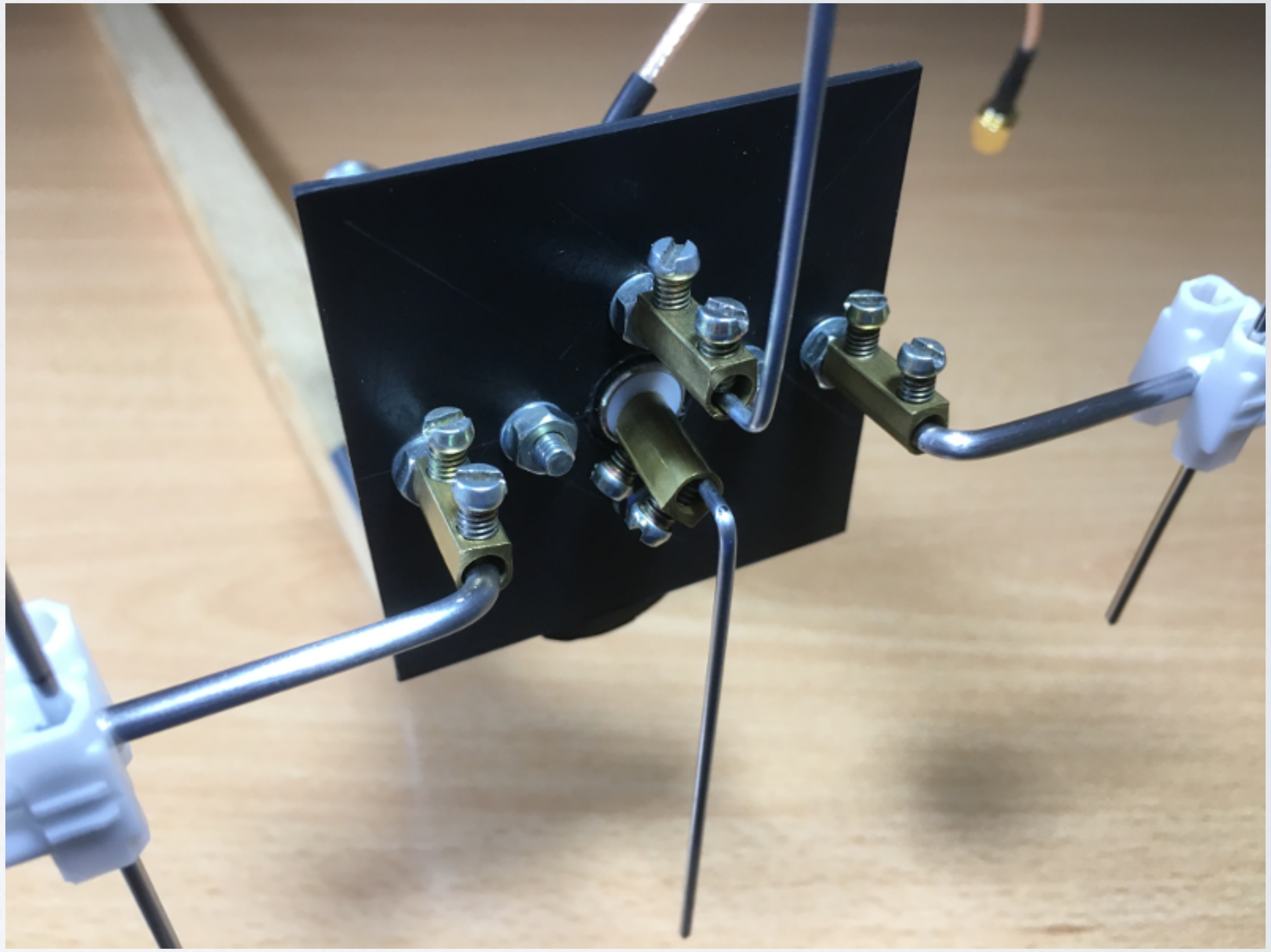




YAGI-UDA ANTENNA MOUNTED ON TEST RIG

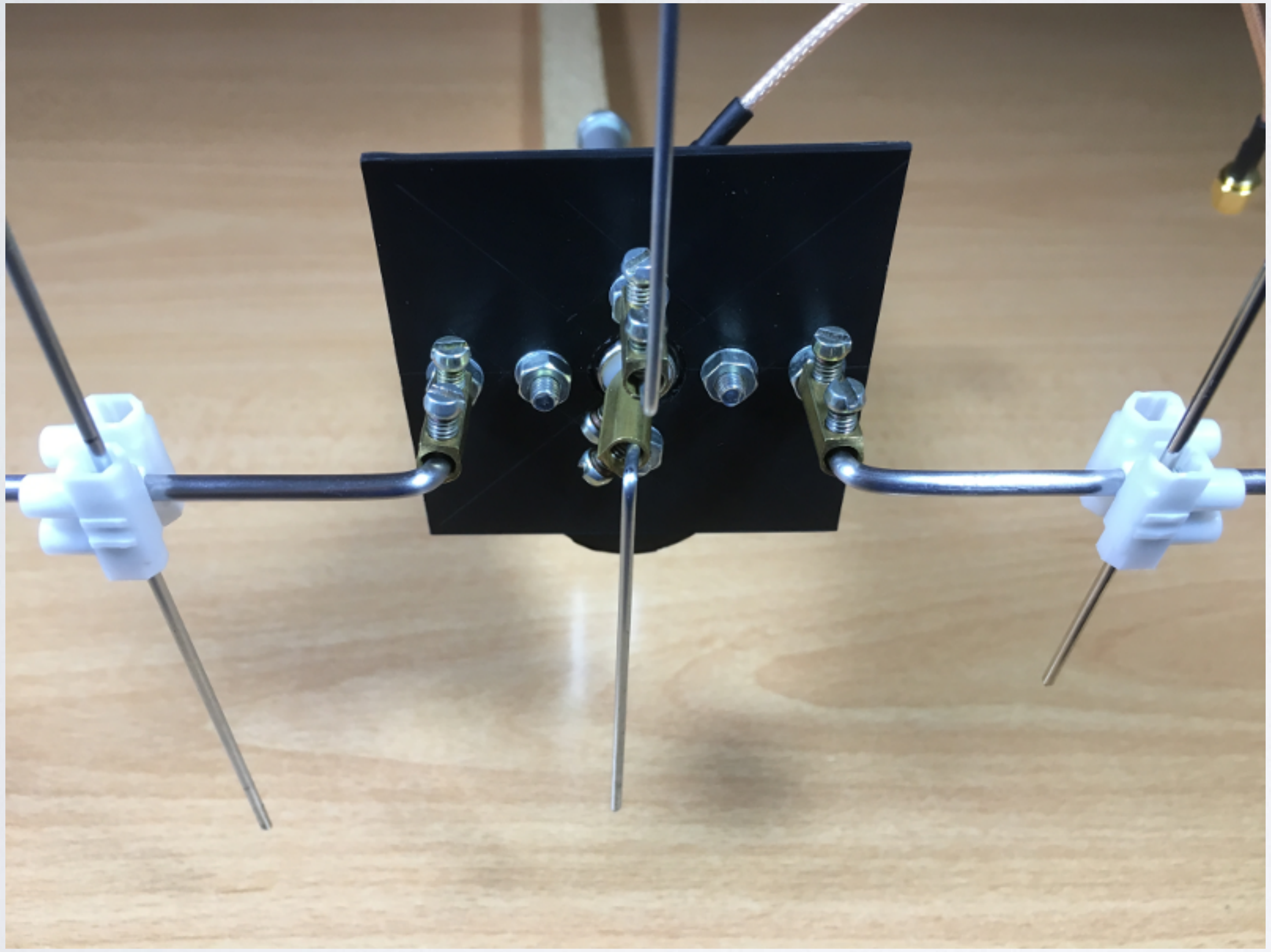
- Front view close up.

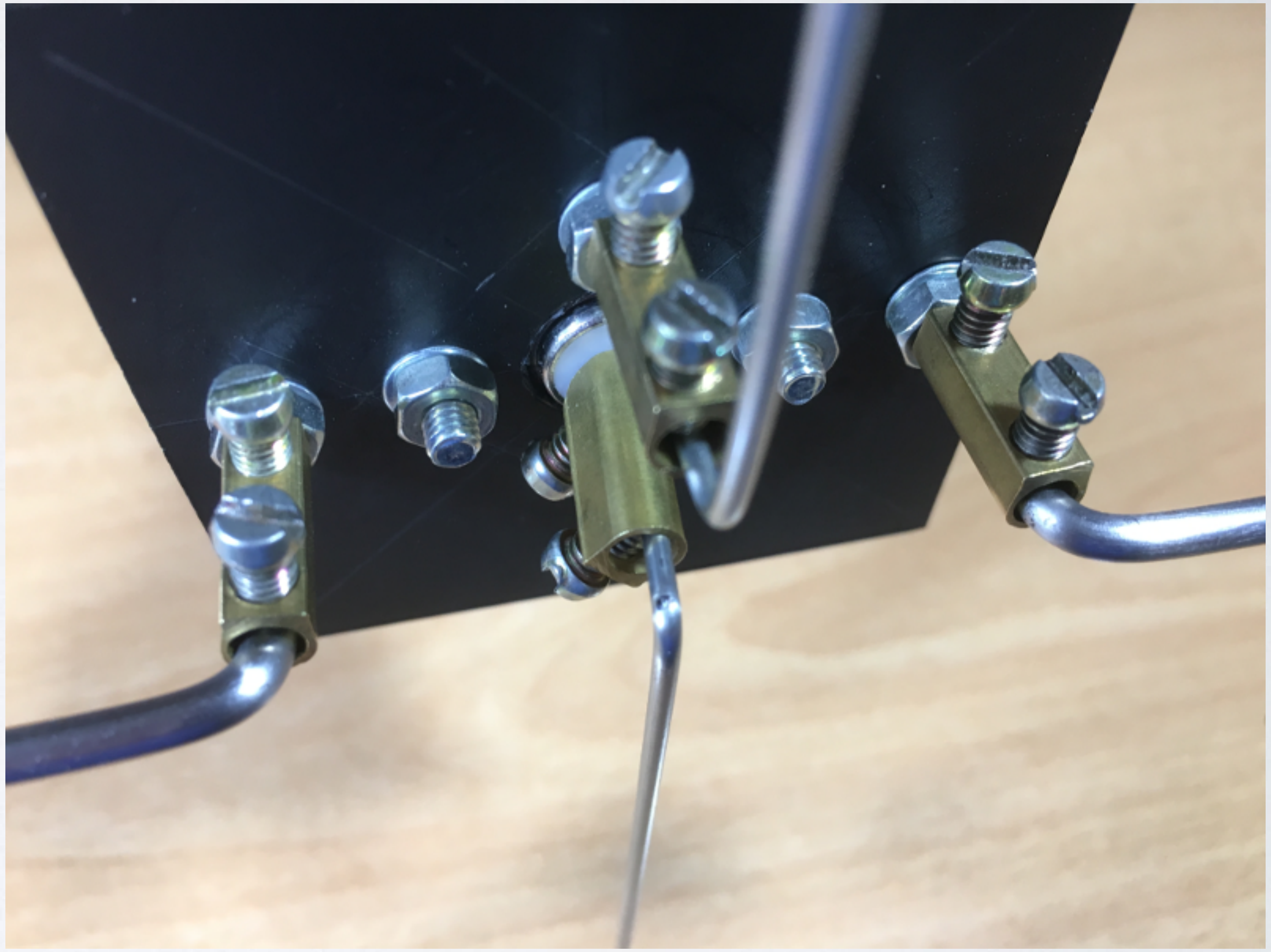




YAGI-UDA ANTENNA MOUNTED ON TEST RIG

- Front view close up.





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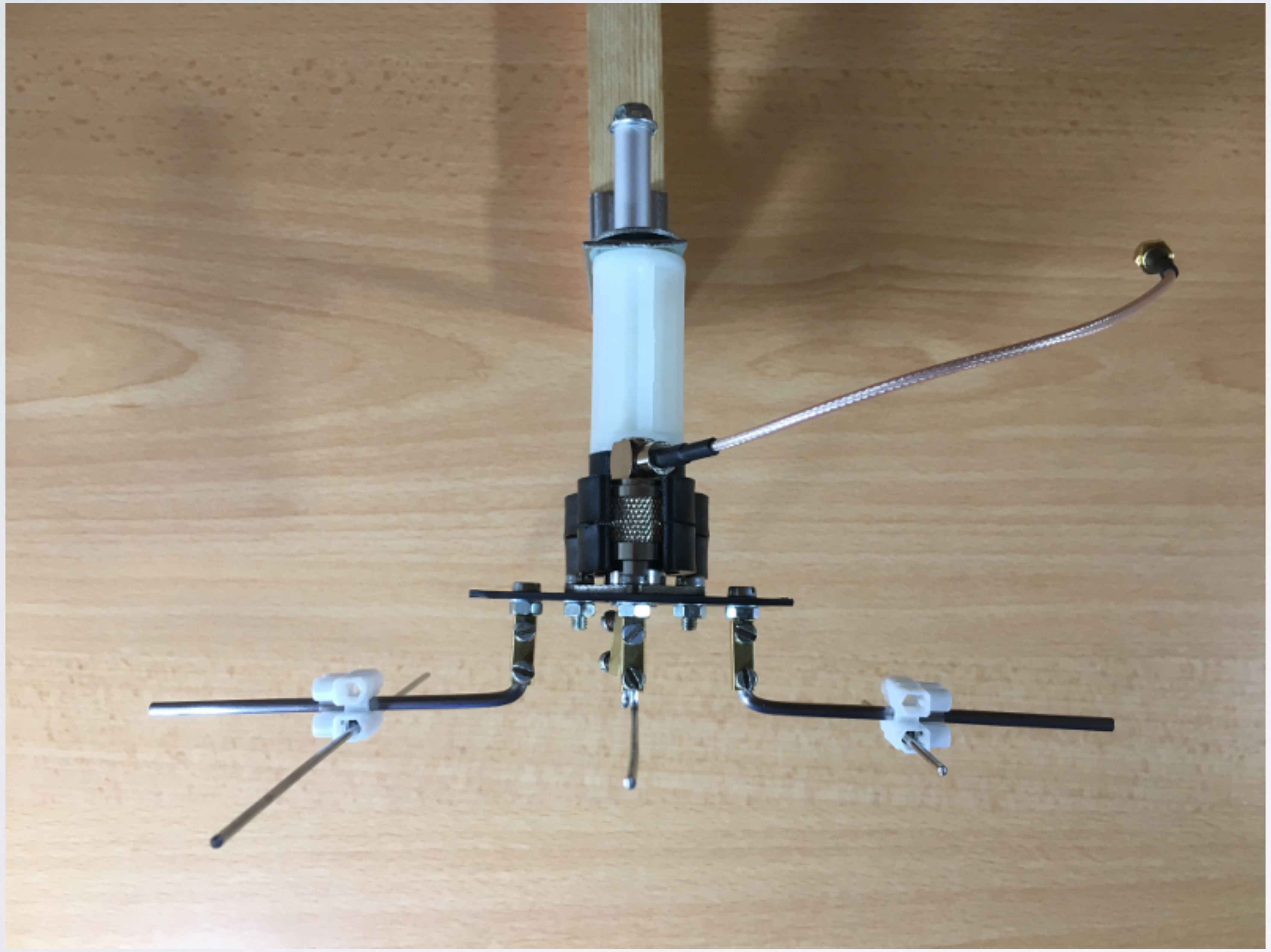
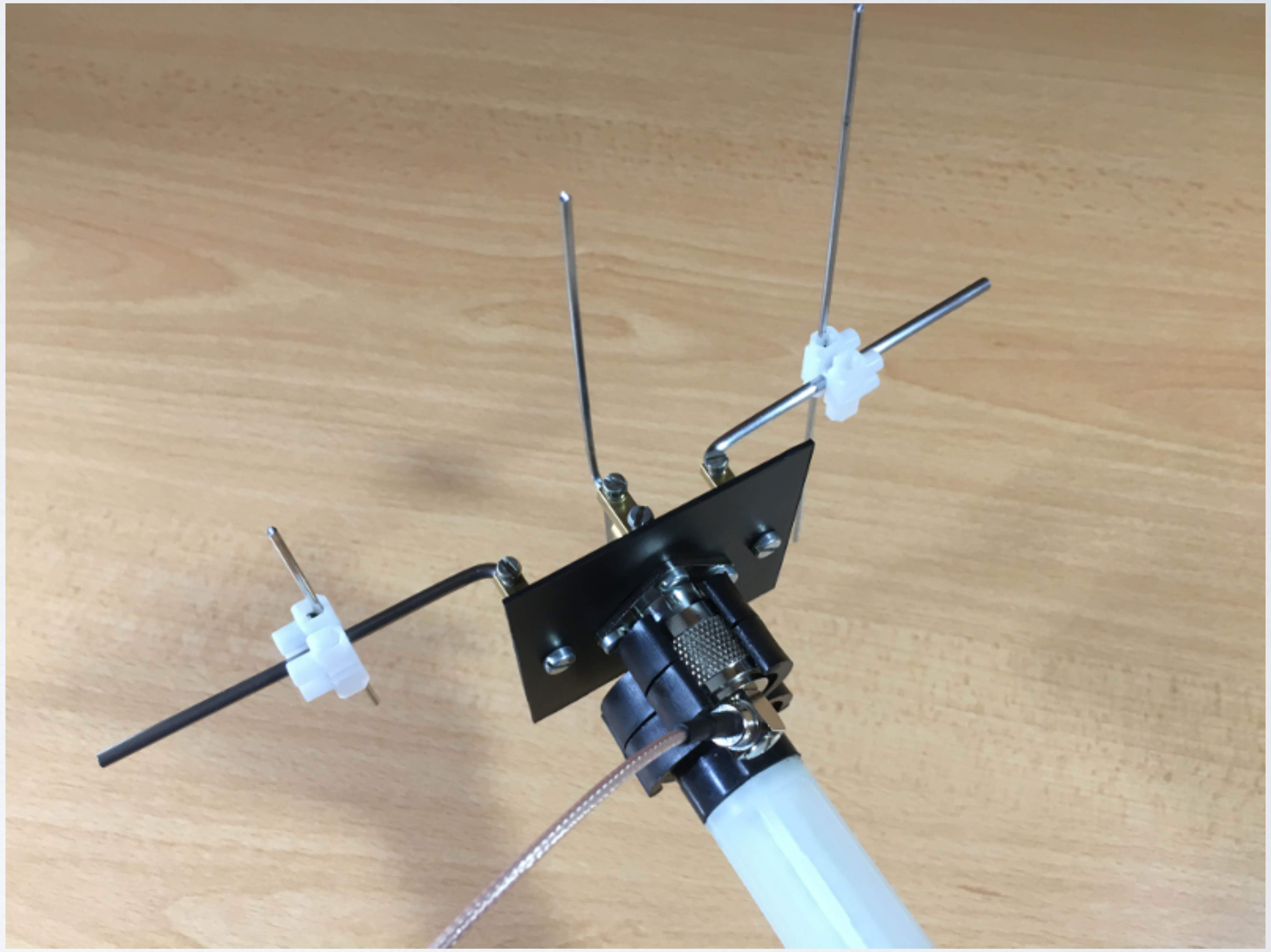
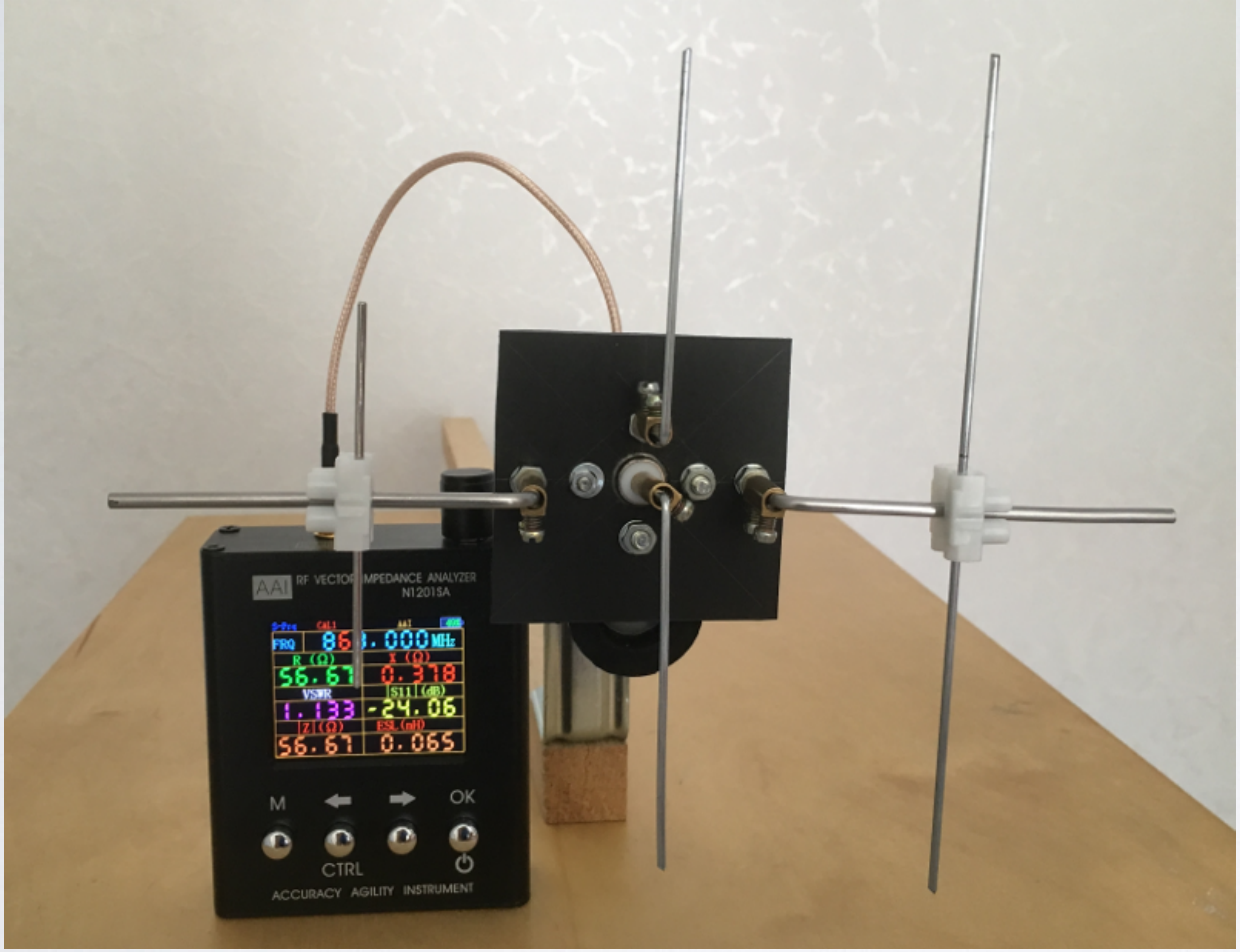
YAGI-UDA ANTENNA MOUNTED ON TEST RIG

- Coax cable does not touch antenna or test rig.





YAGI-UDA ANTENNA



Measuring antenna parameters

The antenna analyser with the Yagi-Uda antenna.

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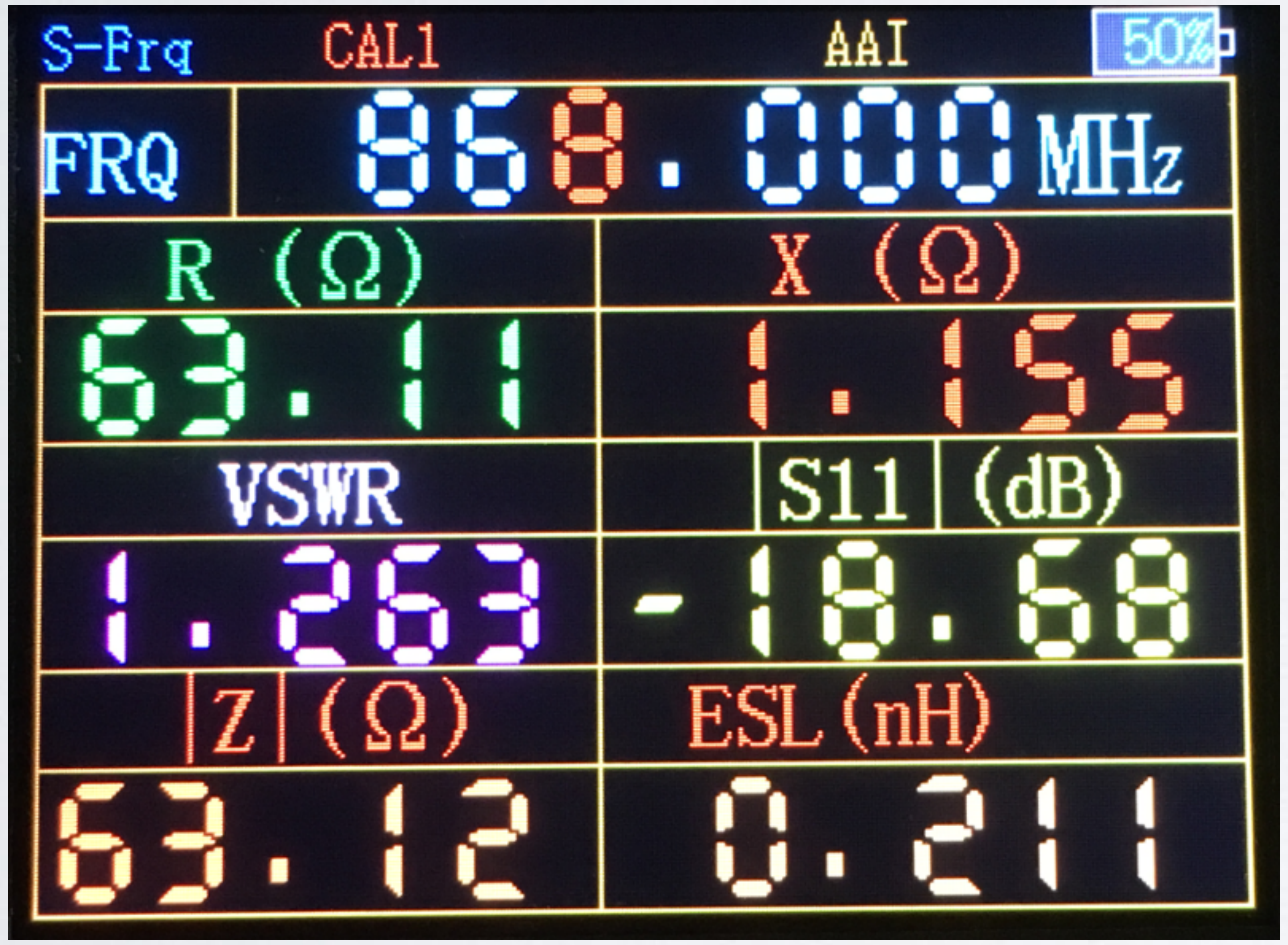
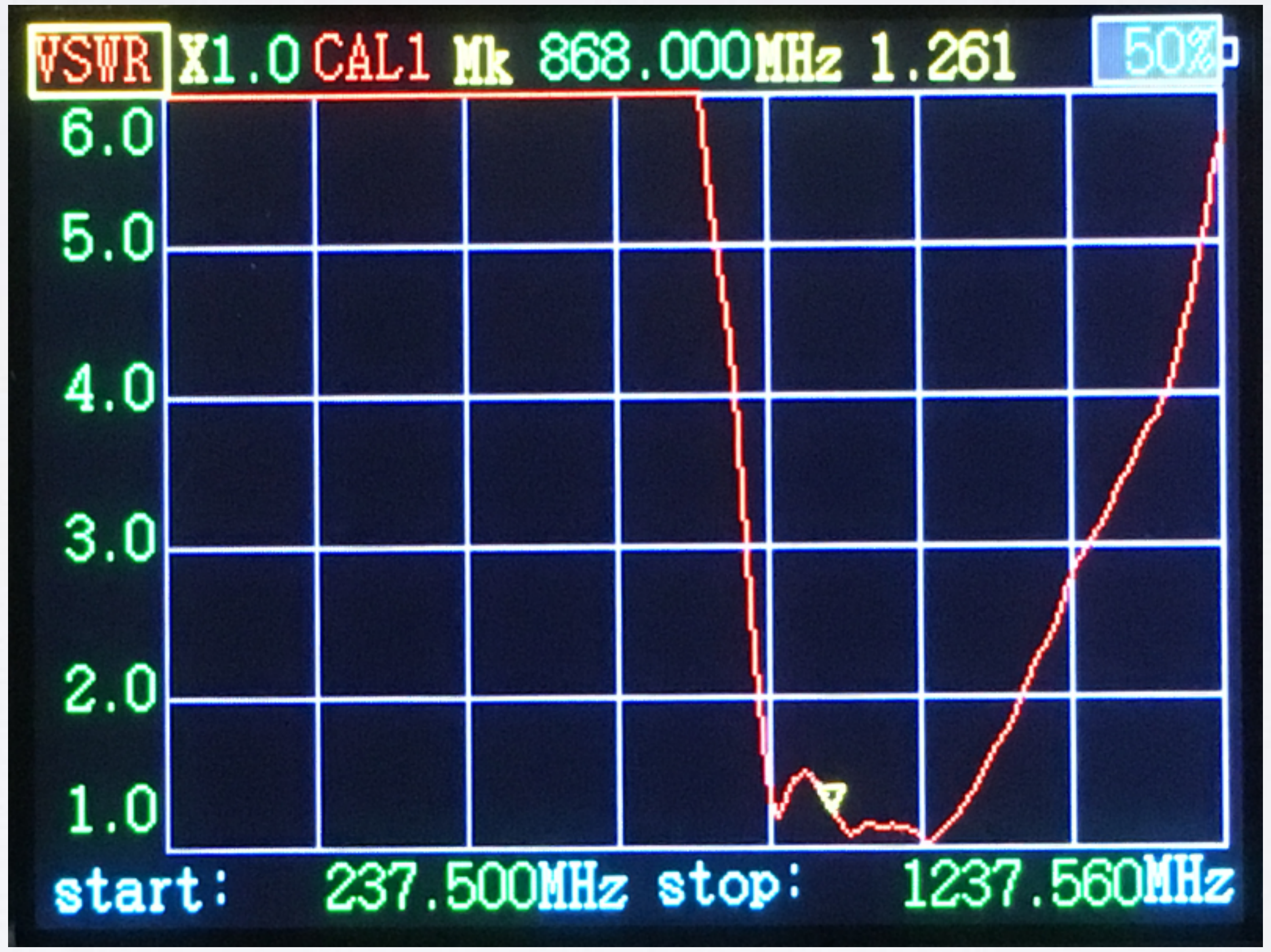
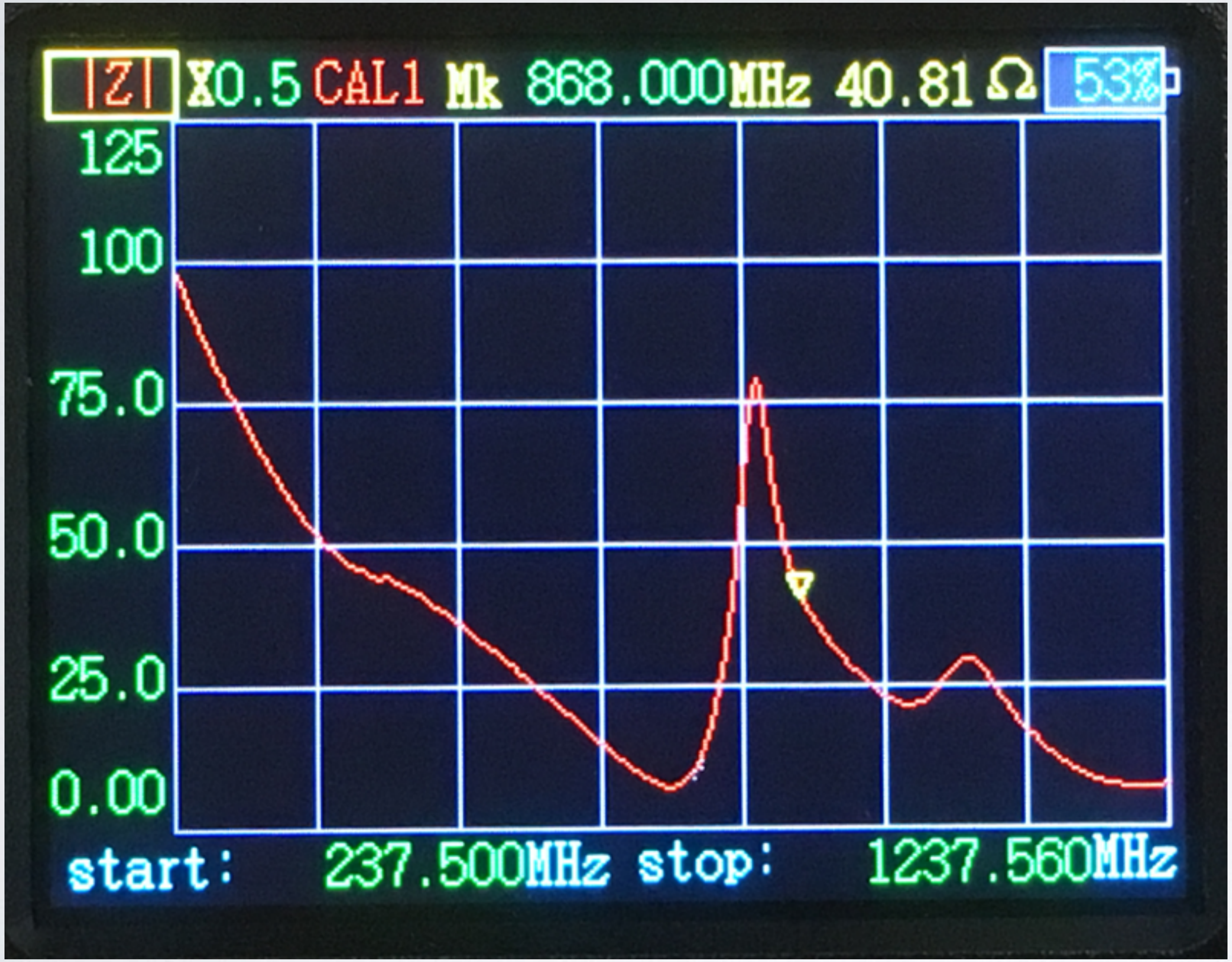
MEASURED ANTENNA PARAMETERS

- Based on the Yagi-Uda design:
  VSWR ≈ 1.3 ← Good. It is < 2
  Z ≈ 63Ω ← Not good. Should be approx. 50Ω
  S11 ≈ -19 dB





MEASURED ANTENNA PARAMETERS



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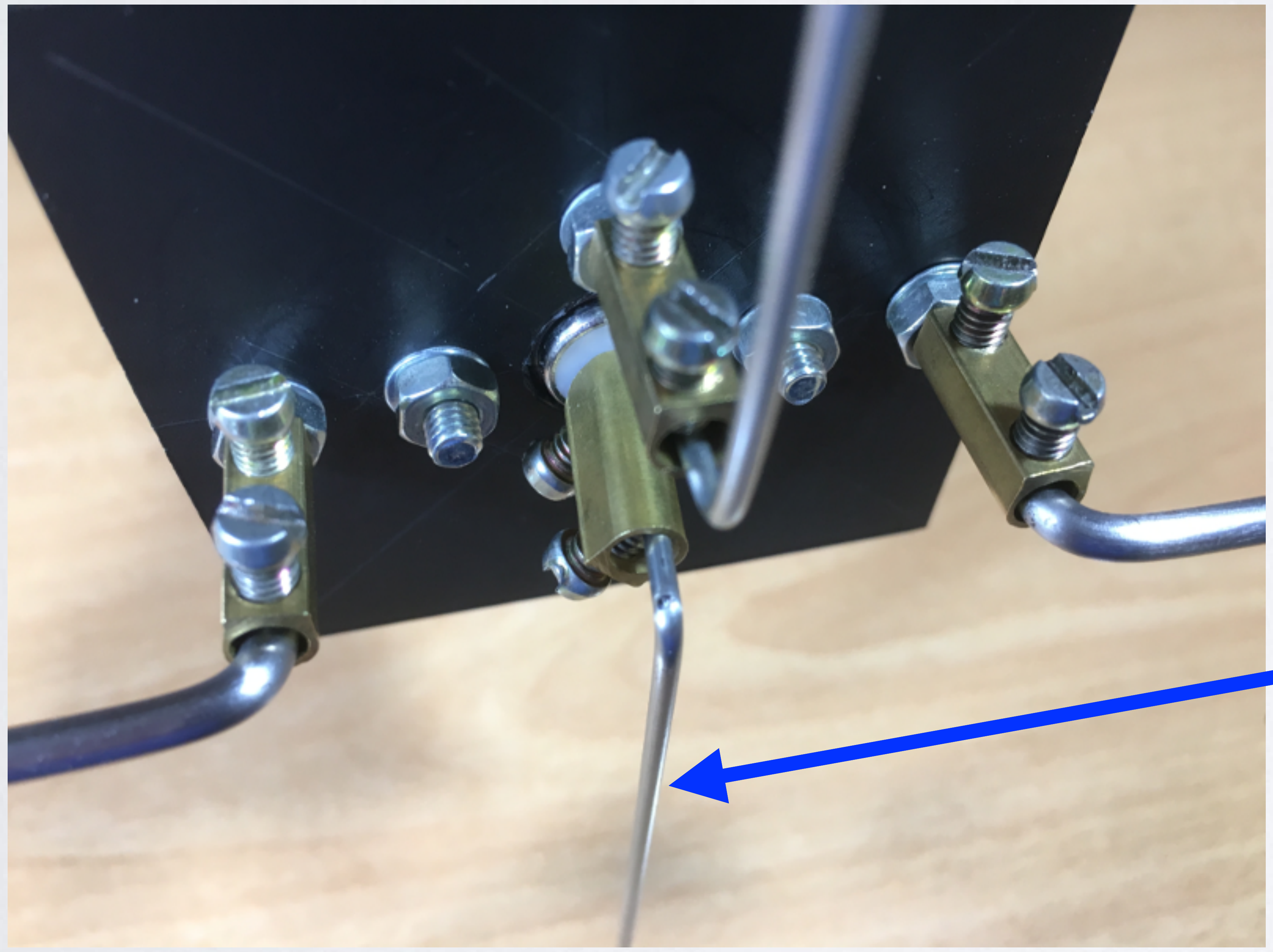
LESSONS LEARNED

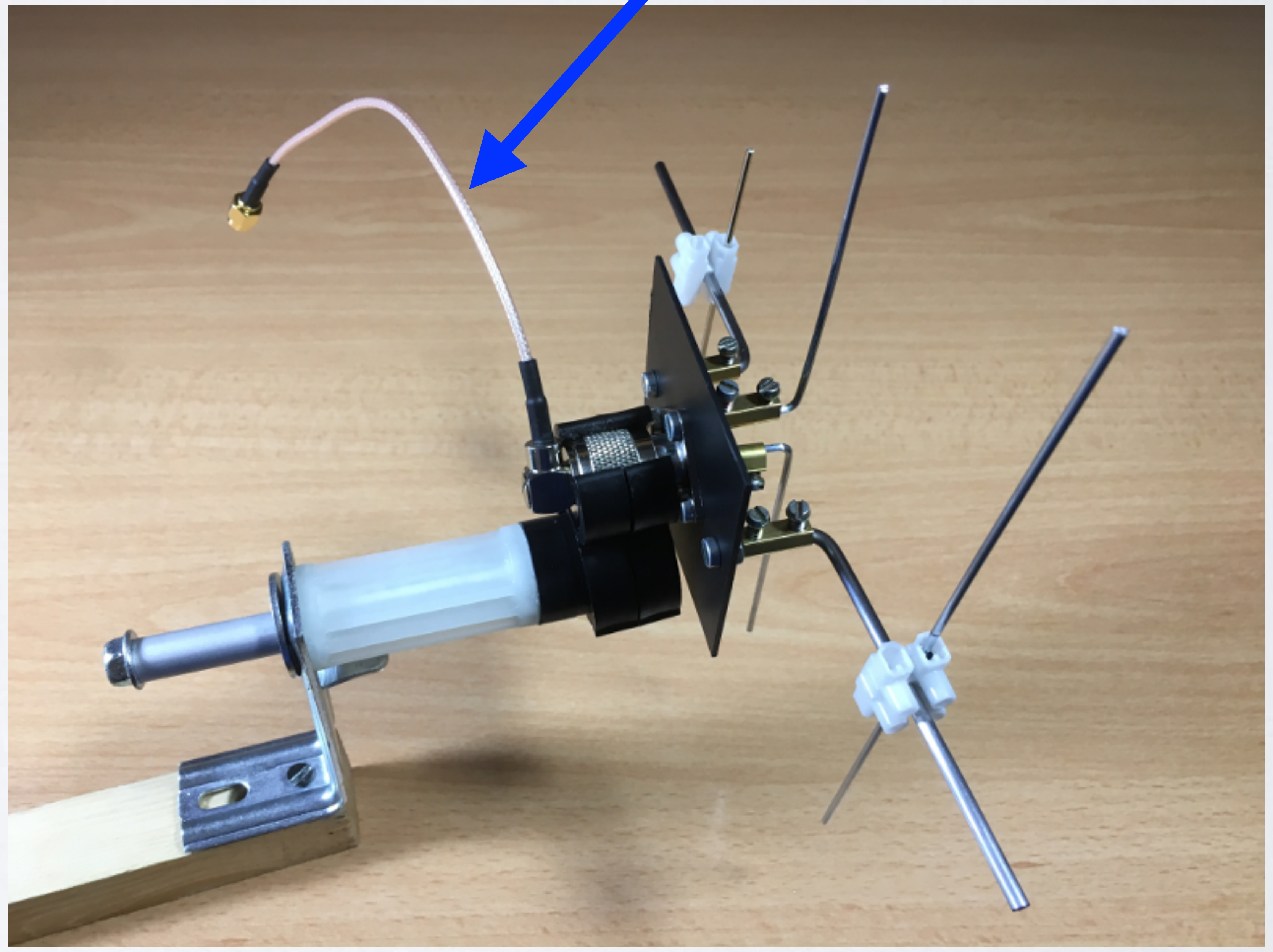
- It is not recommended to use the RF coaxial cable RG316, if you bend the coax cable the antenna analyser will show a different result. Use a better quality (thicker) coax cable e.g. RG58. The RG58 has lower signal loss but is less flexible compared to RG316.

- Point the active element downwards.



Active element

RF coaxial cable RG316



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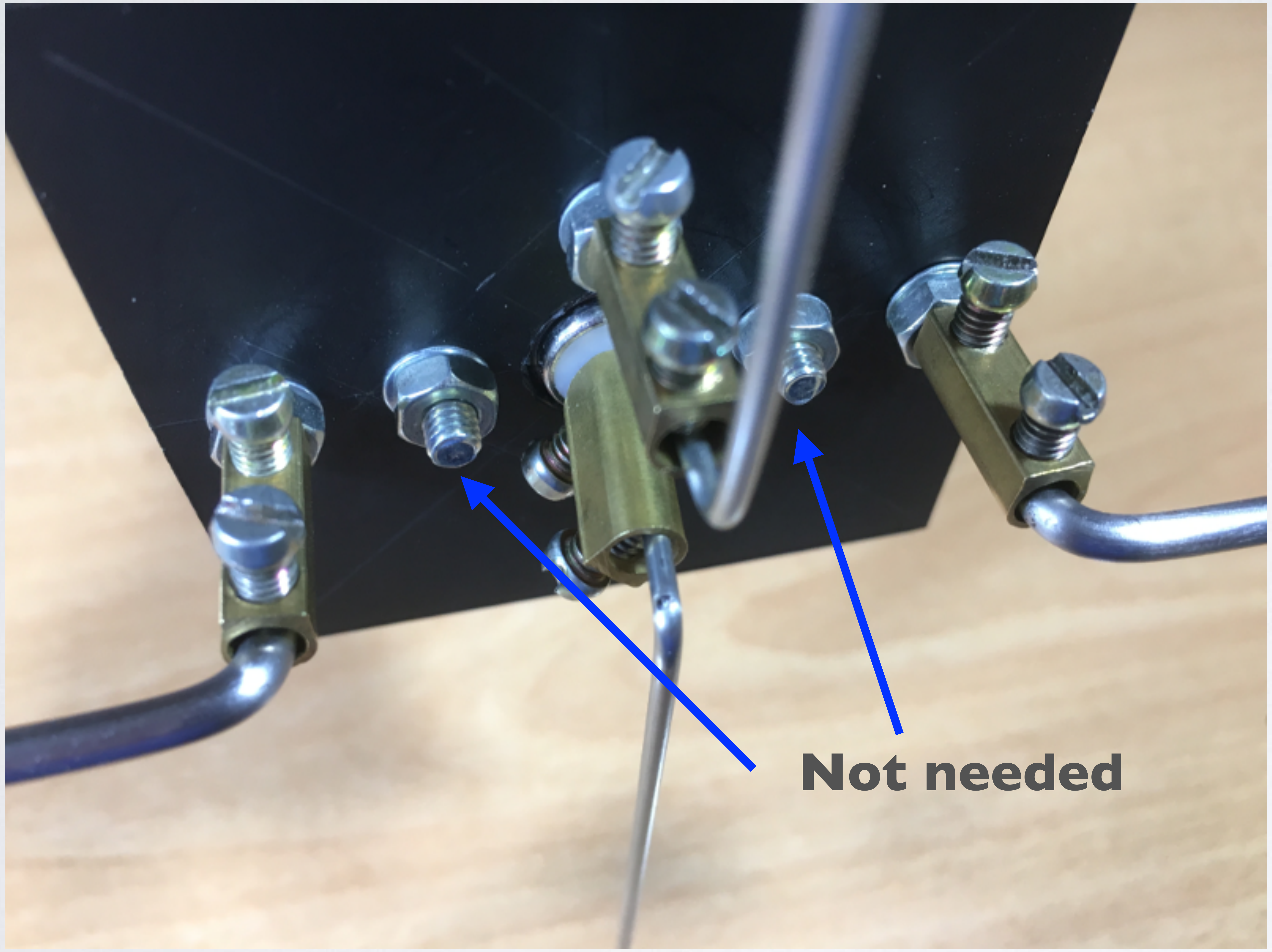
LESSONS LEARNED

- Minimise the use of bolts and nuts.



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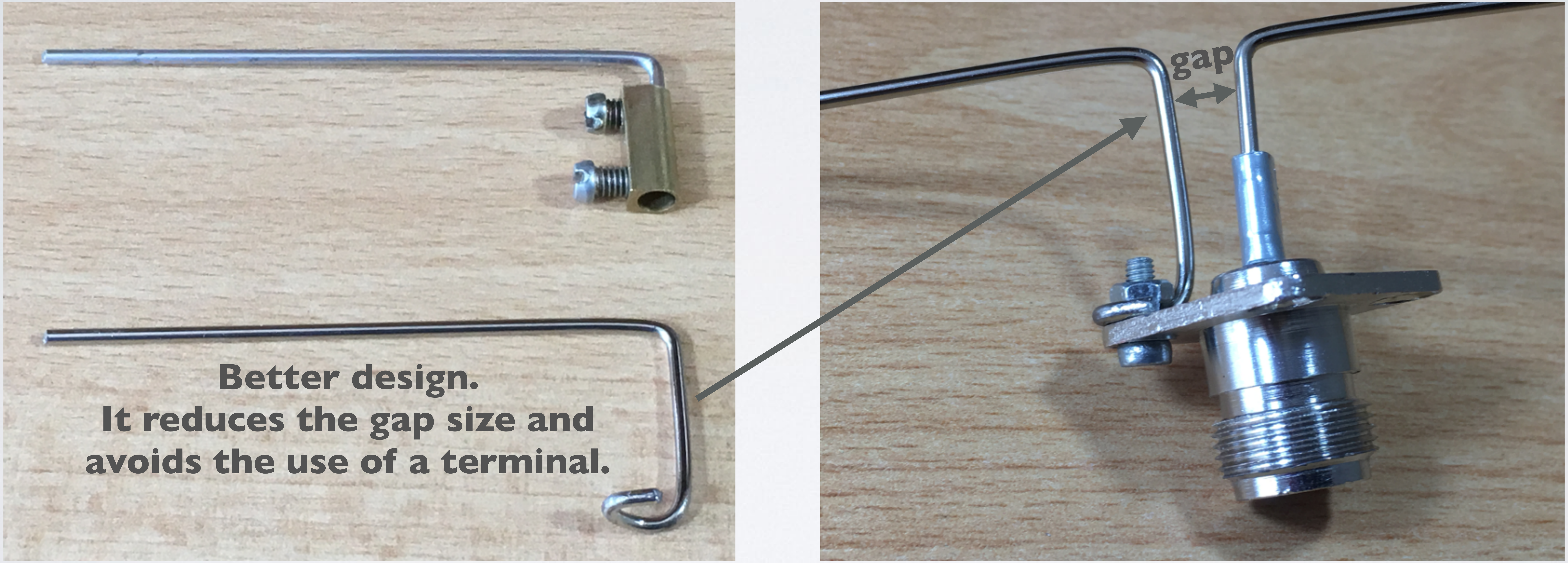
LESSONS LEARNED

- Minimise the use of terminals.



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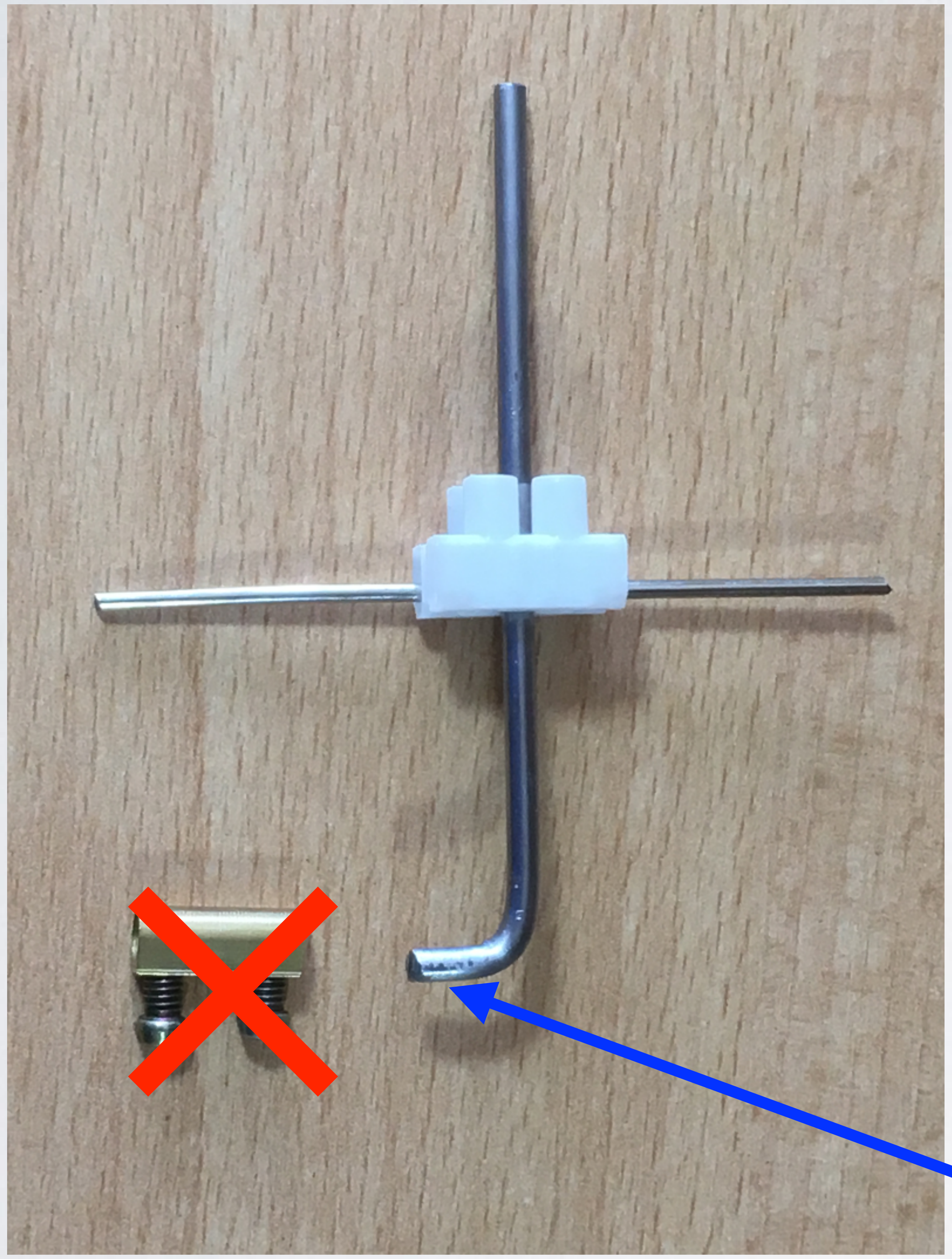
LESSONS LEARNED

- Use smaller terminals.

If possible use a smaller terminal.

LESSONS LEARNED

- Use a die set to cut threads on the support booms. I have not tried this myself!



Use a die to thread the metal rod.

Cut threads at the end and use two nuts to attach the boom to the plastic plate.

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ANTENNA PERFORMANCE TESTS

- How well does my self build Yagi-Uda antenna performs? To answer this question, two performance tests will be conducted.

- **Performance test A**:
The Yagi-Uda antenna is attached to an end node, which is located inside a building, and transmit messages which will be received by nearby gateways in my area.
In this test I am only interested which gateways were able to receive the transmitted sensor data. The test will be repeated using a sleeve dipole antenna.

- **Performance test B**:
The Yagi-Uda antenna is attached to an end node and transmit messages which will be received by a dedicated gateway 6 meters away. Both devices are indoors.
The average RSSI is calculated and also the total time it took to receive 15 messages.
The test will be repeated using a ½λ dipole antenna.

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ANTENNA PERFORMANCE TESTS

- Performance test A and B are simple tests and will give me a **ROUGH INDICATION** how well my antenna performs compared to the dipole antenna.
- Both tests are conducted indoors which means the walls reflects the transmitted signals thus influencing the measurements.
  Therefore take the results with a grain of salt!
- A much better method to tell how your antenna actually performs in the real world, see this procedure: https://github.com/LoRaTracker/AntennaTesting

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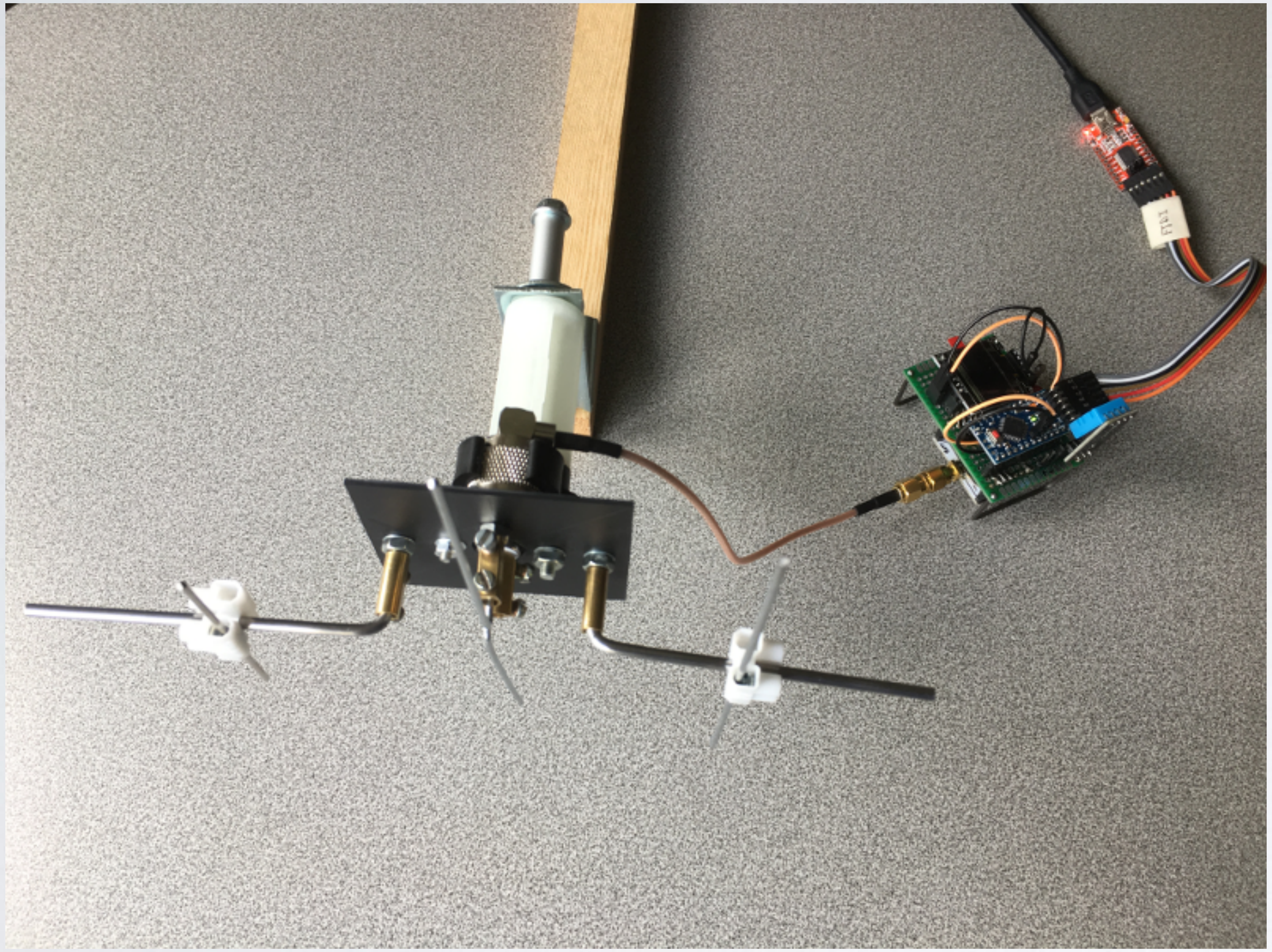
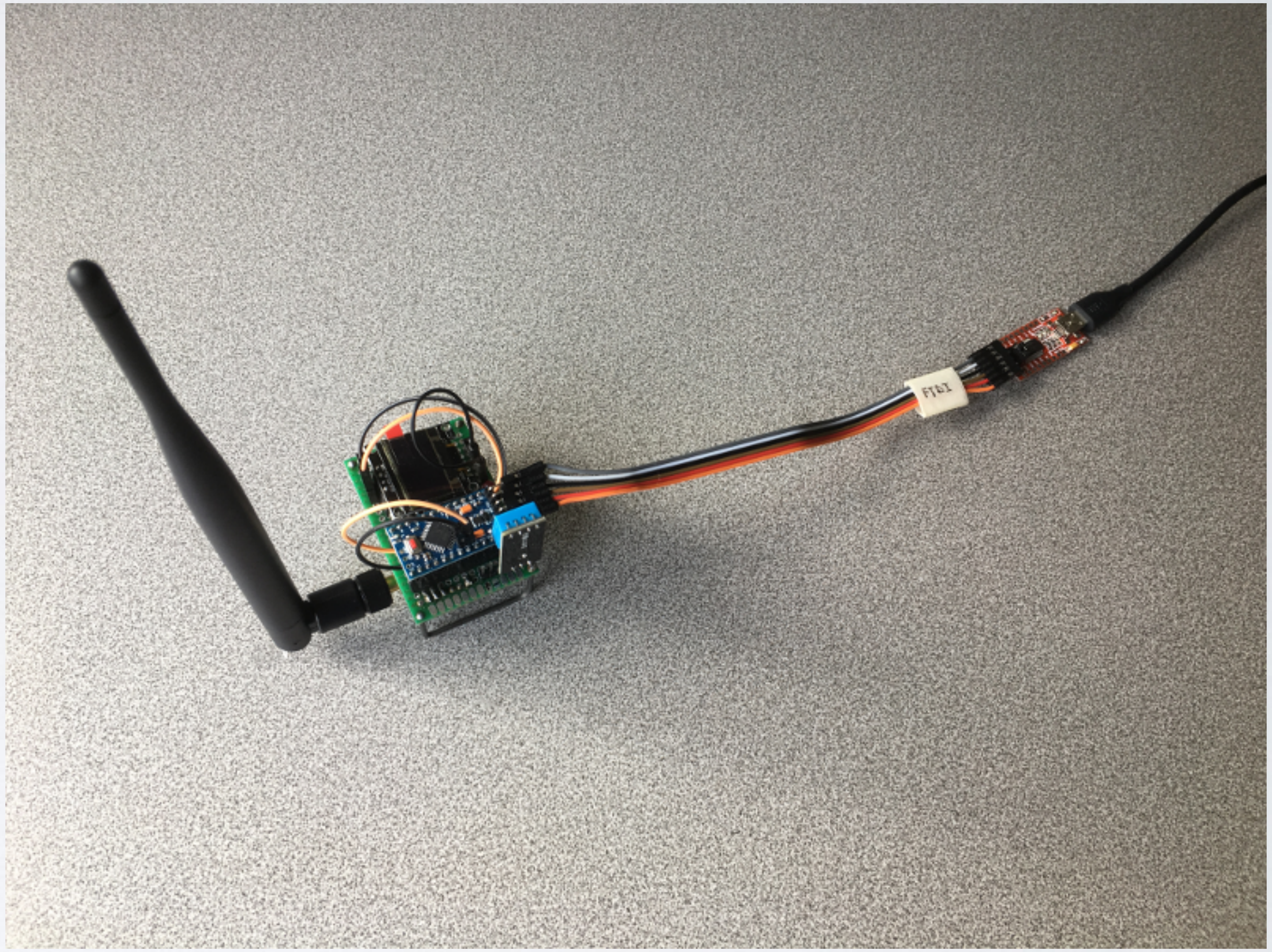
PERFORMANCE TEST A

- The Yagi-Uda antenna performance is compared with a sleeve dipole antenna. More information about sleeve dipole antennas, see tutorial 43.
- For this test I am using the end node and antenna C as demonstrated in tutorial 33.
- More information about this end node, see: https://www.mobilefish.com/developer/lorawan/lorawan_quickguide_build_lora_node_rfm95_arduino_pro_mini.html
- The end node uses the MCCI LoRaWAN LMIC Library: https://github.com/mcci-catena/arduino-lmic
- The end node uses the following sketch: https://www.mobilefish.com/download/lora/ttn-otaa-pro-mini-sensors.ino.txt

PERFORMANCE TEST A

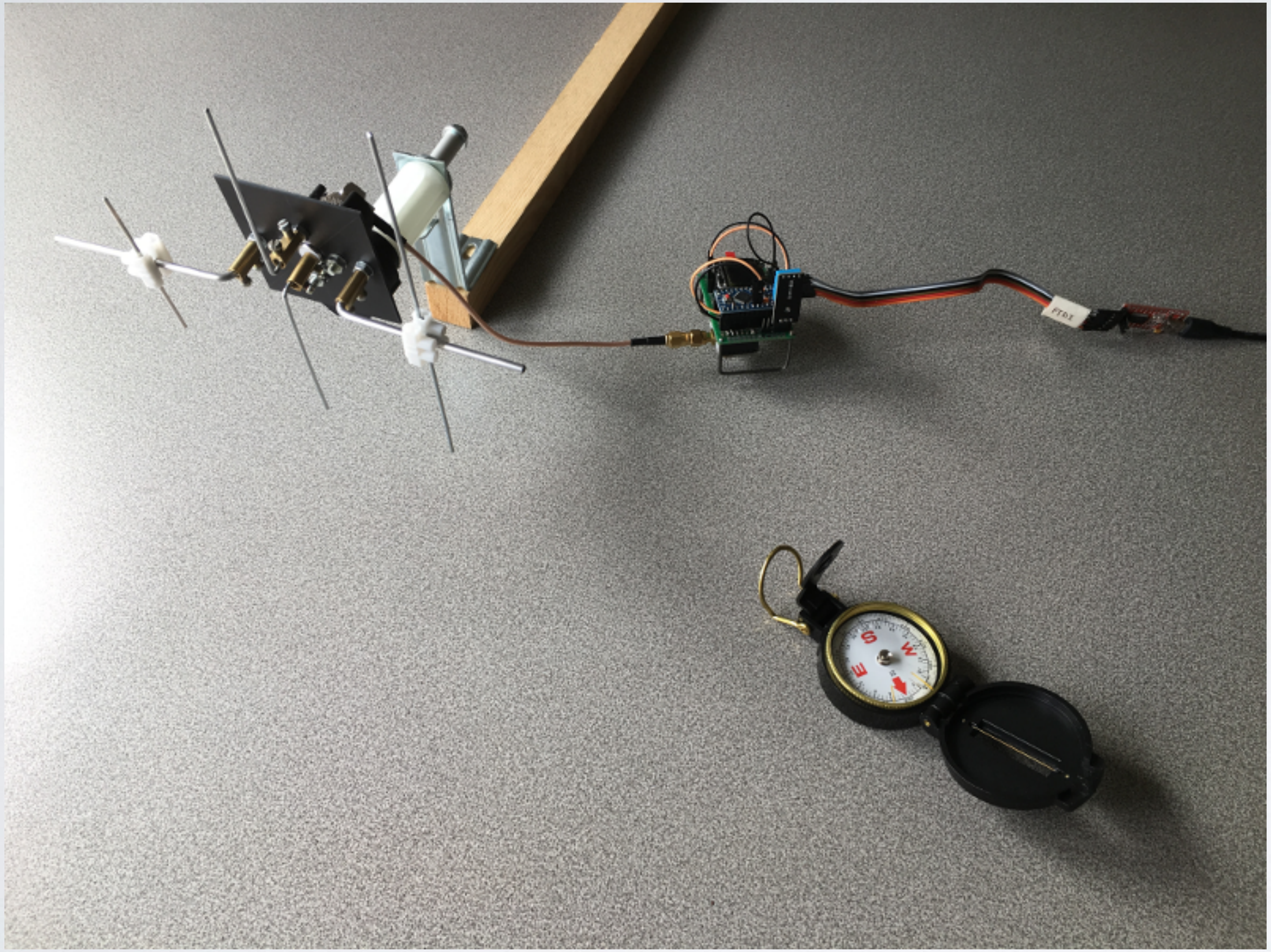


Yagi-Uda + end node



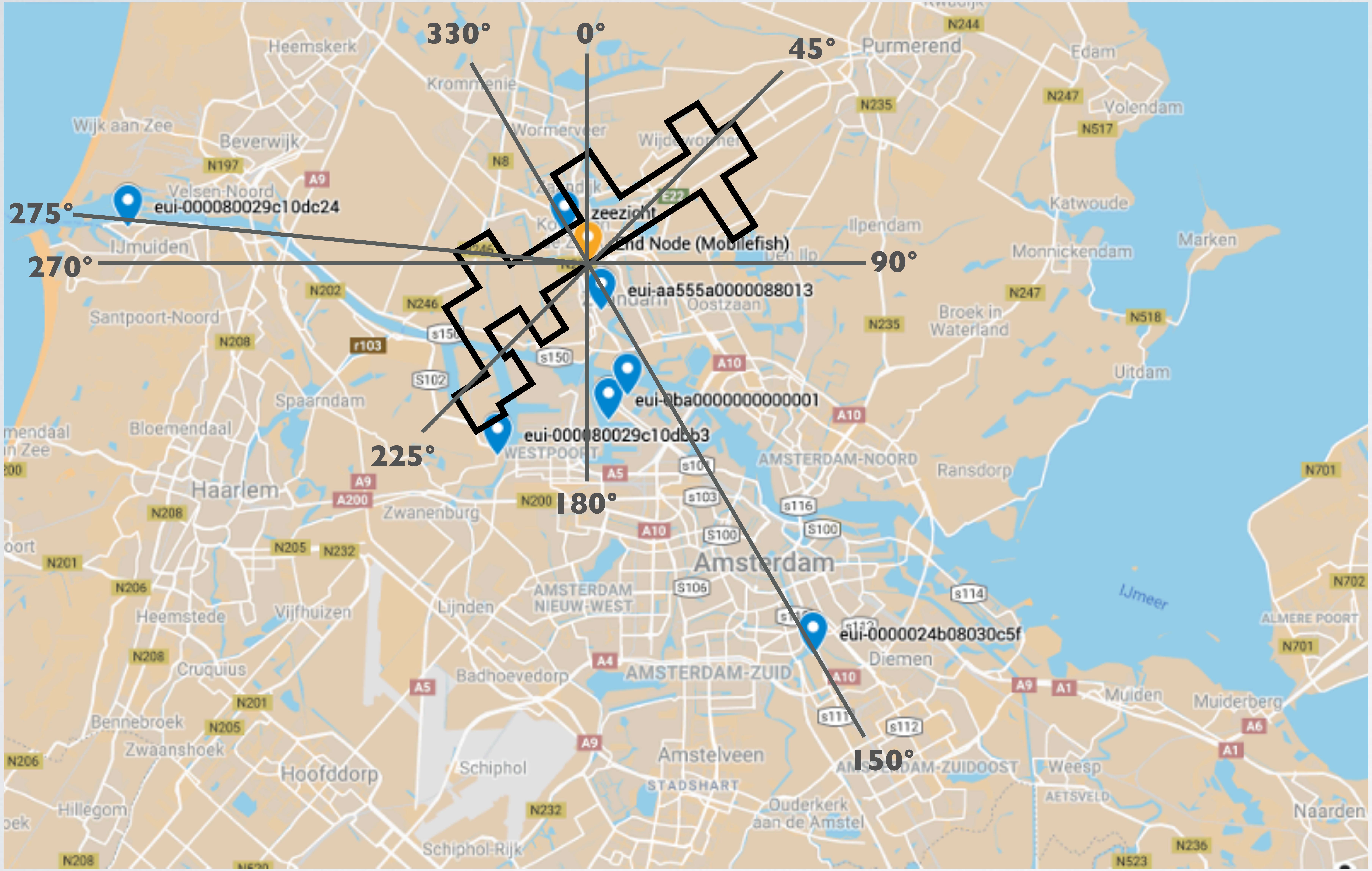
Sleeve dipole + end node

PERFORMANCE TEST A



Use a compass to point the Yagi-Uda antenna to different directions.

ANTENNA TEST SETUP



The building circumference.

The end node is placed inside the building in front of a window.

Two end node locations:

Location A, facing East and South. Altitude = ~11m

Location B, facing West and North. Altitude = ~11m

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PERFORMANCE TEST A

- I have NOT modified the end node transmission power when using the Yagi-Uda antenna.

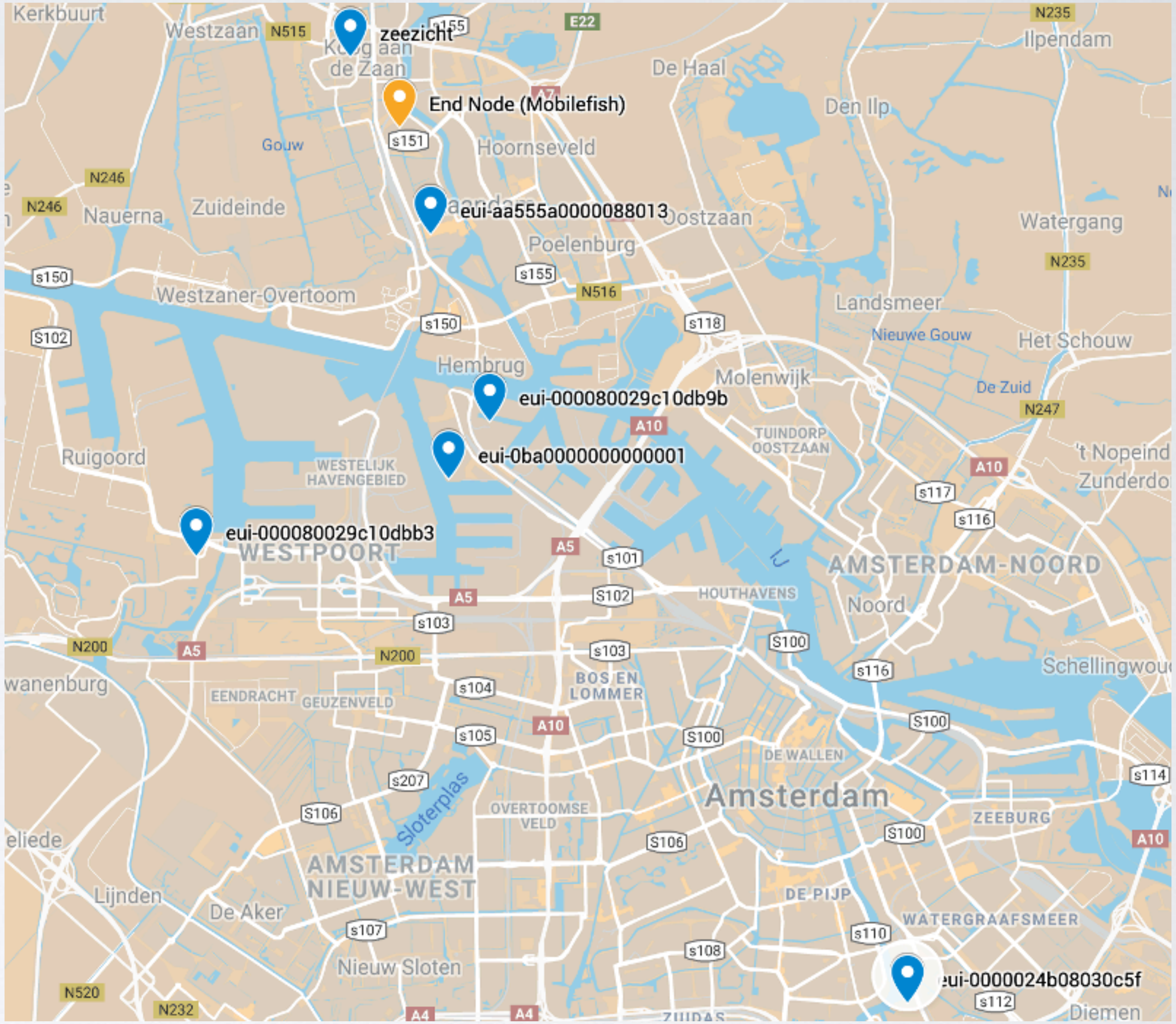
- In my area there are several gateways and I know that these gateways, which are connected to The Things Network, can receive my transmitted data.

- The Yagi-Uda antenna is attached to the end node at location A and transmits data.
  I have done the same with the sleeve dipole antenna.
  In both cases two messages per minute were transmitted.

- The logged data can be found at:
  https://www.mobilefish.com/download/lora/yagi_uda_test_results.txt

ANTENNA TEST RESULTS

- One or more gateways were able to receive my transmitted sensor data, see: https://drive.google.com/open?id=18SKbHVEIFHU6YjzYpgZL98vuHcmV4OPQ&usp=sharing



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PERFORMANCE TEST A

- End node tx power = 14 dBm
  Data from: yagi_uda_test_results.txt

Gateway	Distance from end device [km]	Altitude [m]	Sleeve dipole	Yagi-Uda
eui-aa555a0000088013	1.57	42		
eui-0ba0000000000001	5.03	20		
eui-0000024b08030c5f	14.4	40		
eui-000080029c10db9b	4.36	30		
eui-000080029c10dbb3	6.73	5		
zeezicht	1.23	10		

The Yagi-Uda antenna was pointed to different directions.
Green = Gateway has received the transmitted sensor data.

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PERFORMANCE TEST B

- Make sure you keep everything in your setup the same when switching from the Yagi-Uda antenna to the ½λ dipole antenna.

- A slight change can impact your measurements.

- - Do not change the height of the end node and the height of the gateway.
  - Do not change the distance between end node and the gateway.
  - Use the exact same end node and gateway.
  - Use the same coax cables and connectors.
  - During the measurements I did not stay in the same room.
  - The distance between transmitter and receiver should be > 4λ (Far field region)
  More information about near and far field, see tutorial 34.

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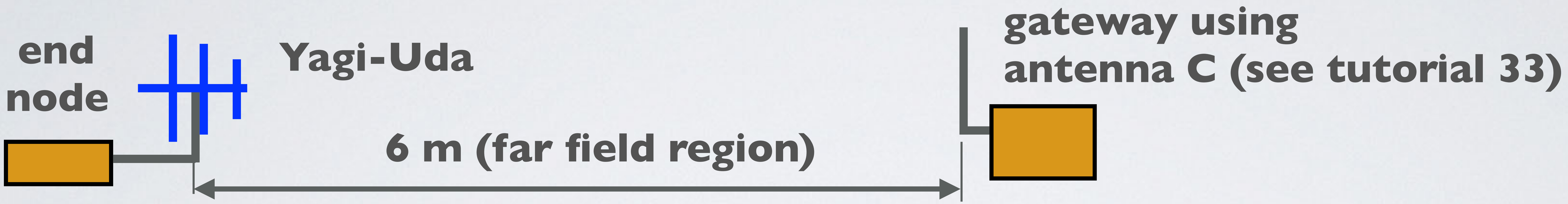
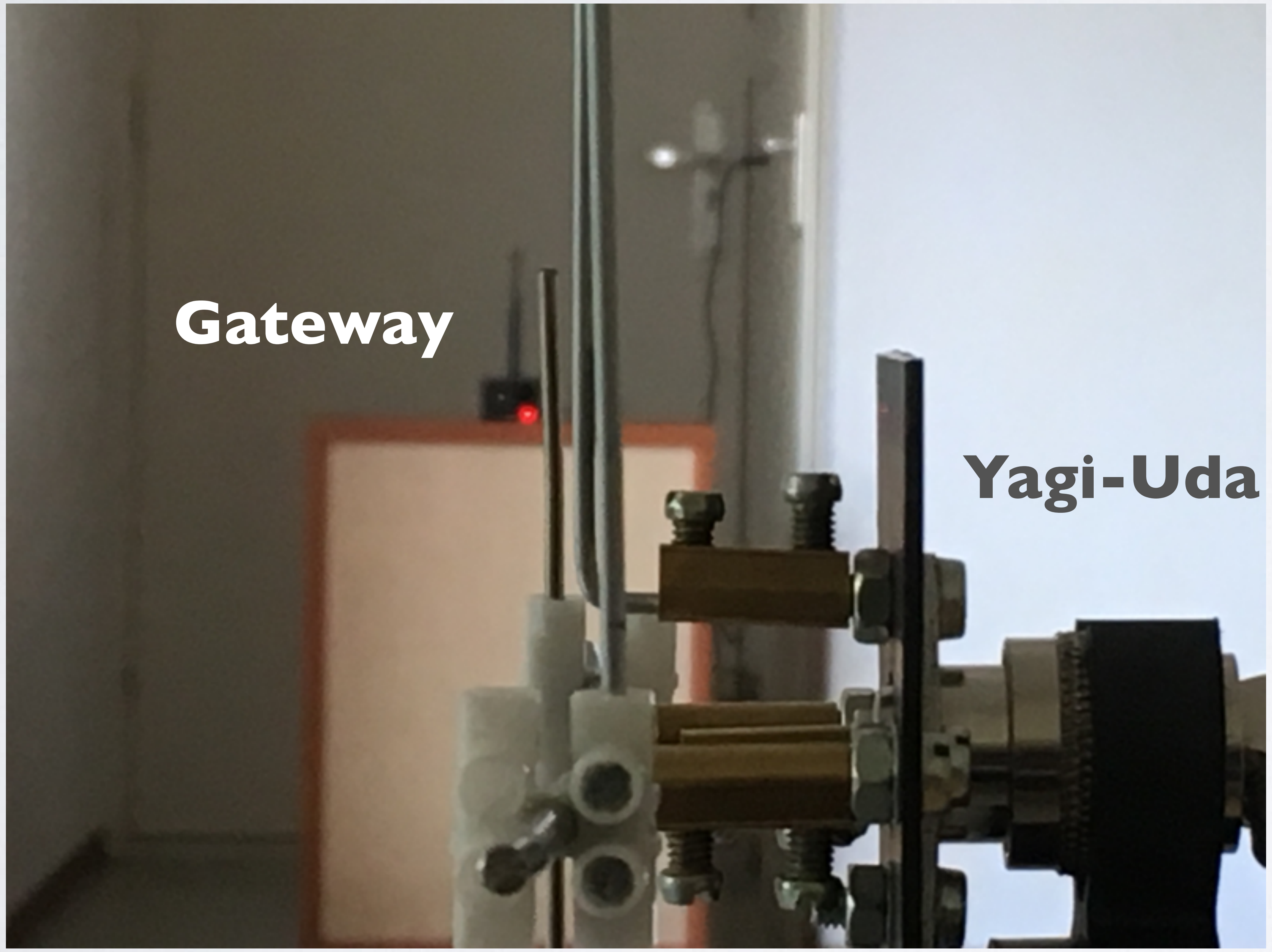
PERFORMANCE TEST B





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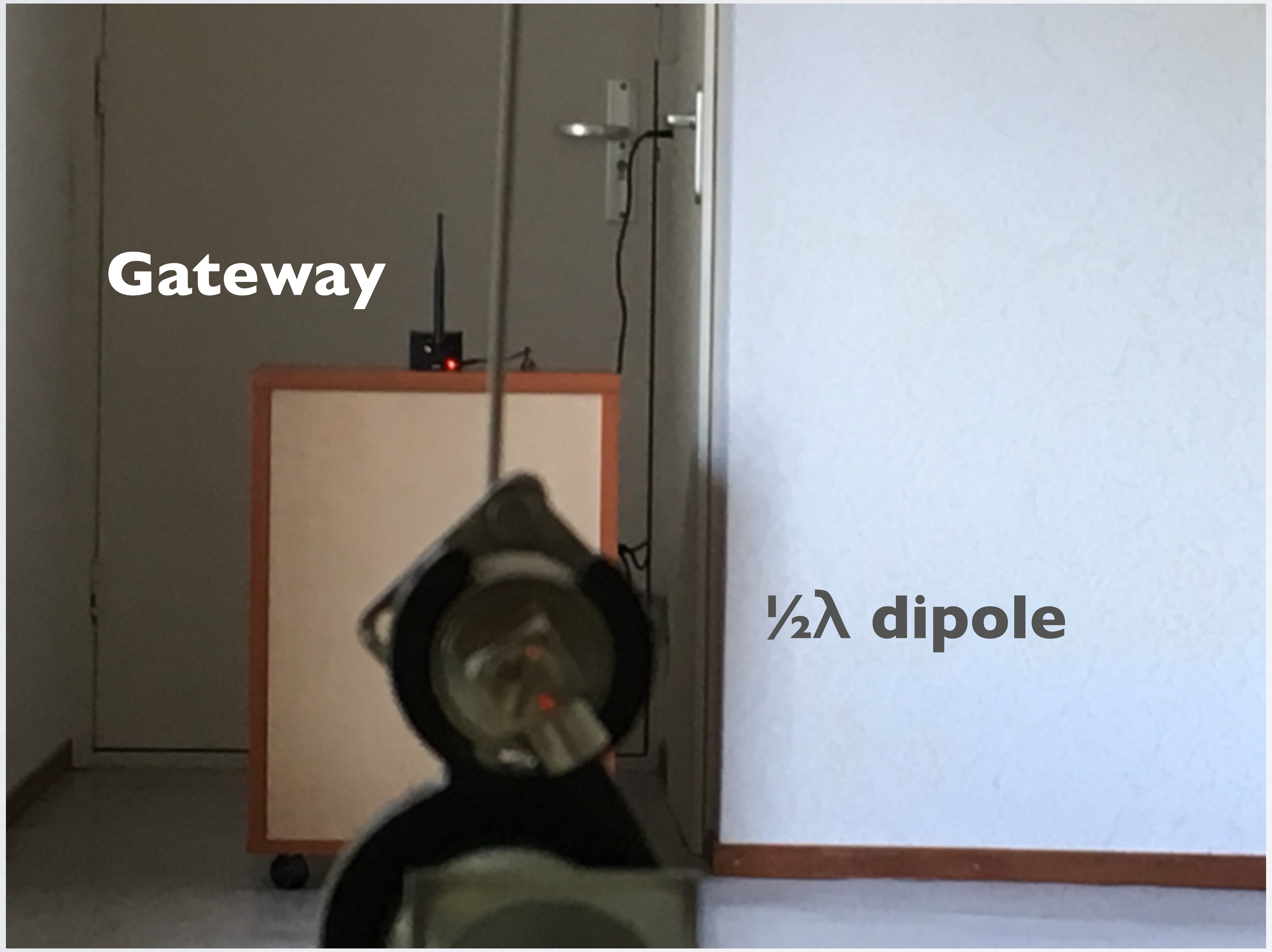
PERFORMANCE TEST B



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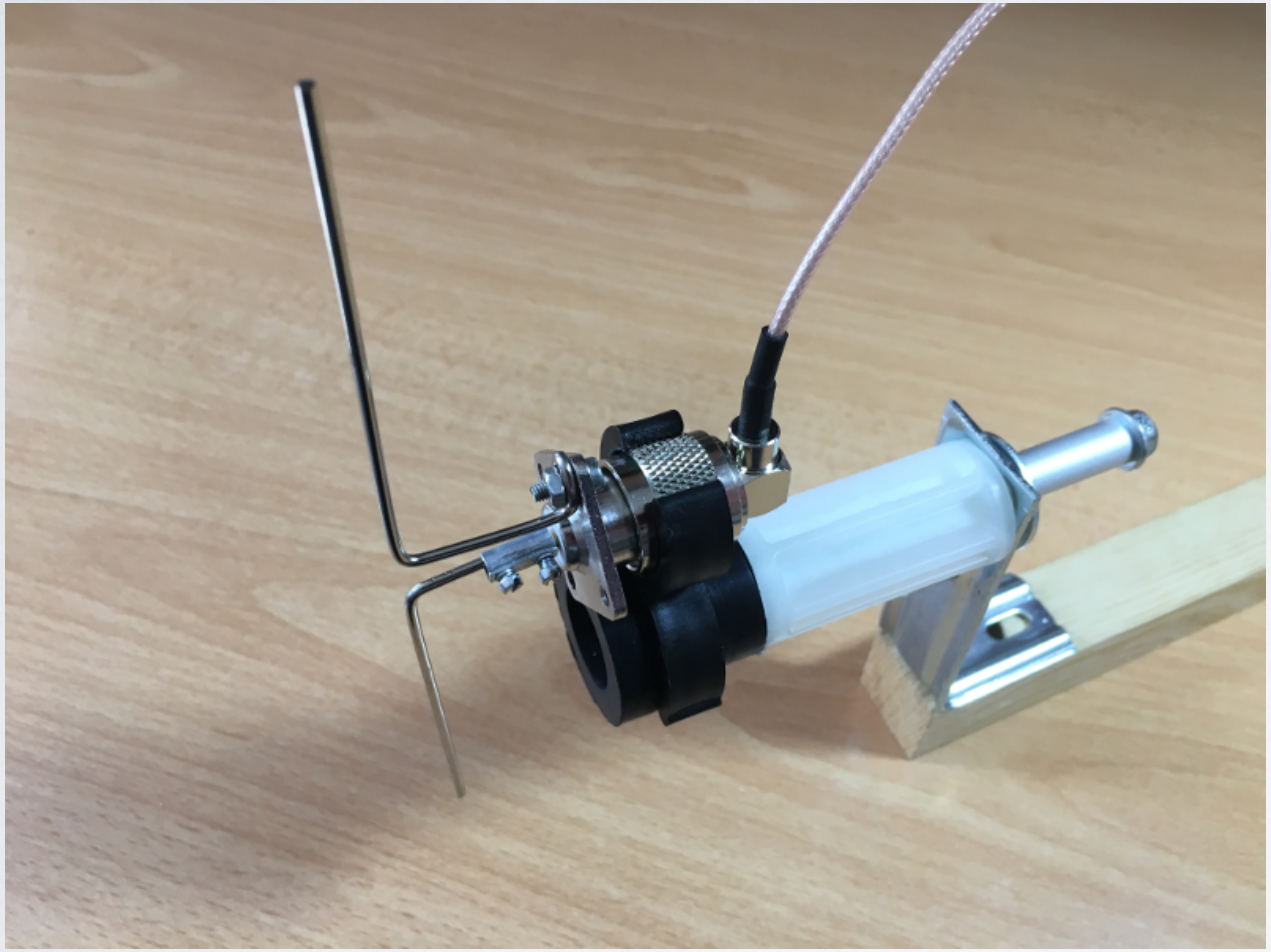
PERFORMANCE TEST B

- This ½λ dipole antenna is used in this setup, see tutorial 41.



VSWR ≈ 1.1
Z ≈ 54Ω
S11 ≈ -27 dB

PERFORMANCE TEST B

- The logged data can be found at:
  https://www.mobilefish.com/download/lora/yagi_uda_antenna_gain.txt

- The average RSSI when using the ½λ dipole antenna: -28.0 dBm
  The average RSSI when using the Yagi-Uda antenna: -22.1 dBm

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PERFORMANCE TEST B

- The time it took for the gateway to receive the 15 messages from the end node:
  Using the ½λ dipole antenna: 15 minutes
  Using the Yagi-Uda antenna: 15 minutes

- The Arduino sketch is configured to transmit 1 message per minute. In a perfect situation it should take 15 to 16 minutes to transmit these 15 messages.

- Conclusion:
  Based on the average RSSI test results and the results from performance test A, the Yagi-Uda antenna performs better compared to the sleeve dipole antenna.
  …but…
  the Yagi-Uda antenna is a directional antenna, you need to point it to the correct direction. The sleeve dipole antenna is an omnidirectional antenna.

REMARKS

- The 4NEC2 program simulates how the antenna behaves but MY Yagi-Uda antenna is not accurately modelled. Which means that the generated radiation patterns and other antenna parameters are just a rough indication of how the real Yagi-Uda antenna behaves.

- If you want accurate radiation patterns and other antenna parameters, these antenna measurements should be performed in an anechoic chamber.

- Let's assume you bought a Yagi-Uda antenna with a maximum gain of 10 dBi and attached it to the gateway. This is the same as 7.85 dBd
  Calculation: dBi = dBd + 2.15; 10 = dBd + 2.15; dBd = 10 - 2.15 = 7.85
  In the gateway global_conf.json file (see tutorial 30) you must specify the
  antenna_gain = 7.85

REMARKS

- When using the Yagi-Uda antenna at the end node make sure it points to the correct direction where a gateway is located otherwise the end node has a difficult time to join the network.
- When using a sleeve dipole antenna, which is omnidirectional, the end node can easier join the network without having to "point" it to the correct direction.
- The Yagi-Uda antenna, which is directional, can send data to gateways which are further away.

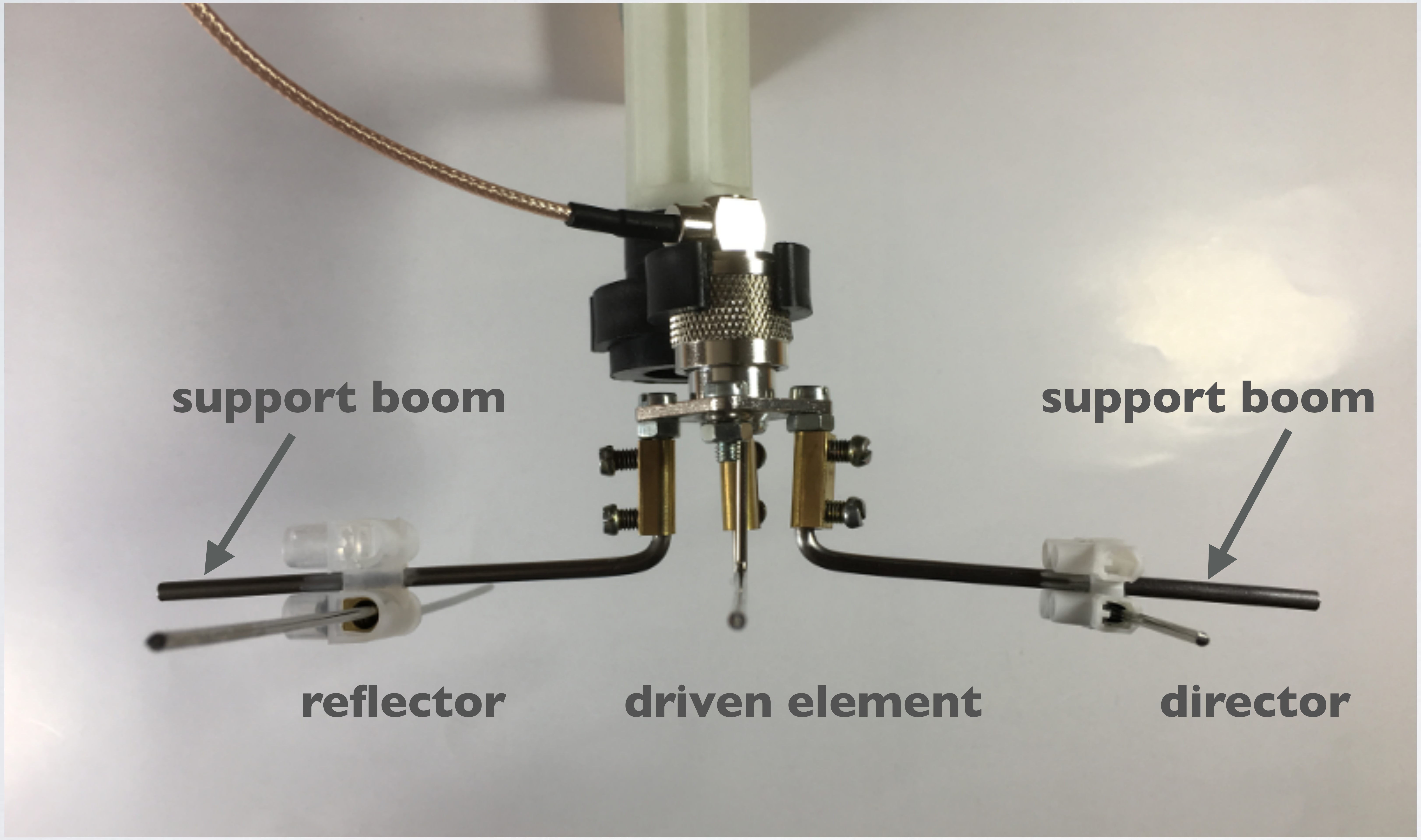
Experiment

Attach support booms to type N female chassis, not using plastic plate.

DO NOT DO THIS!

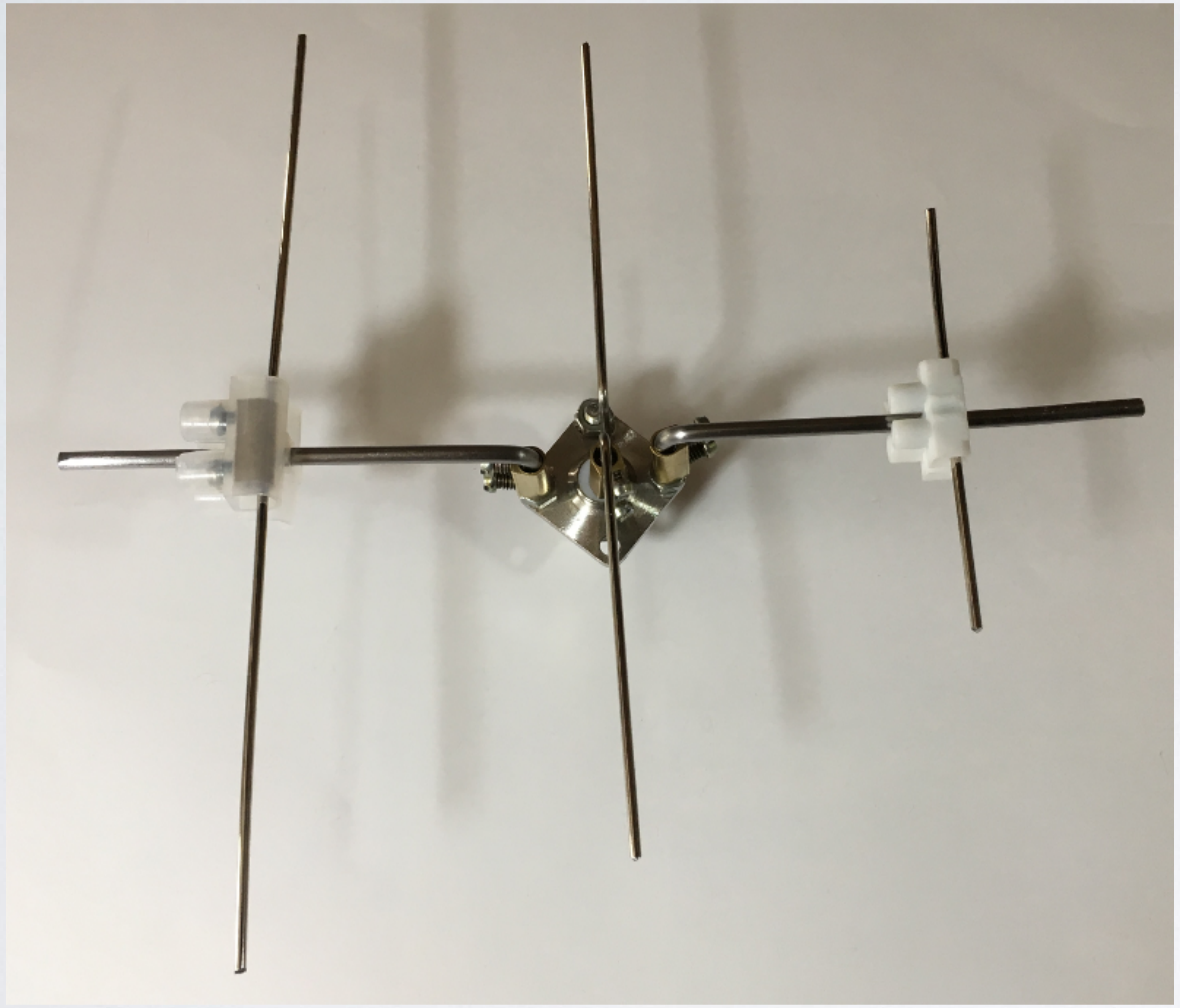
YAGI-UDA ANTENNA

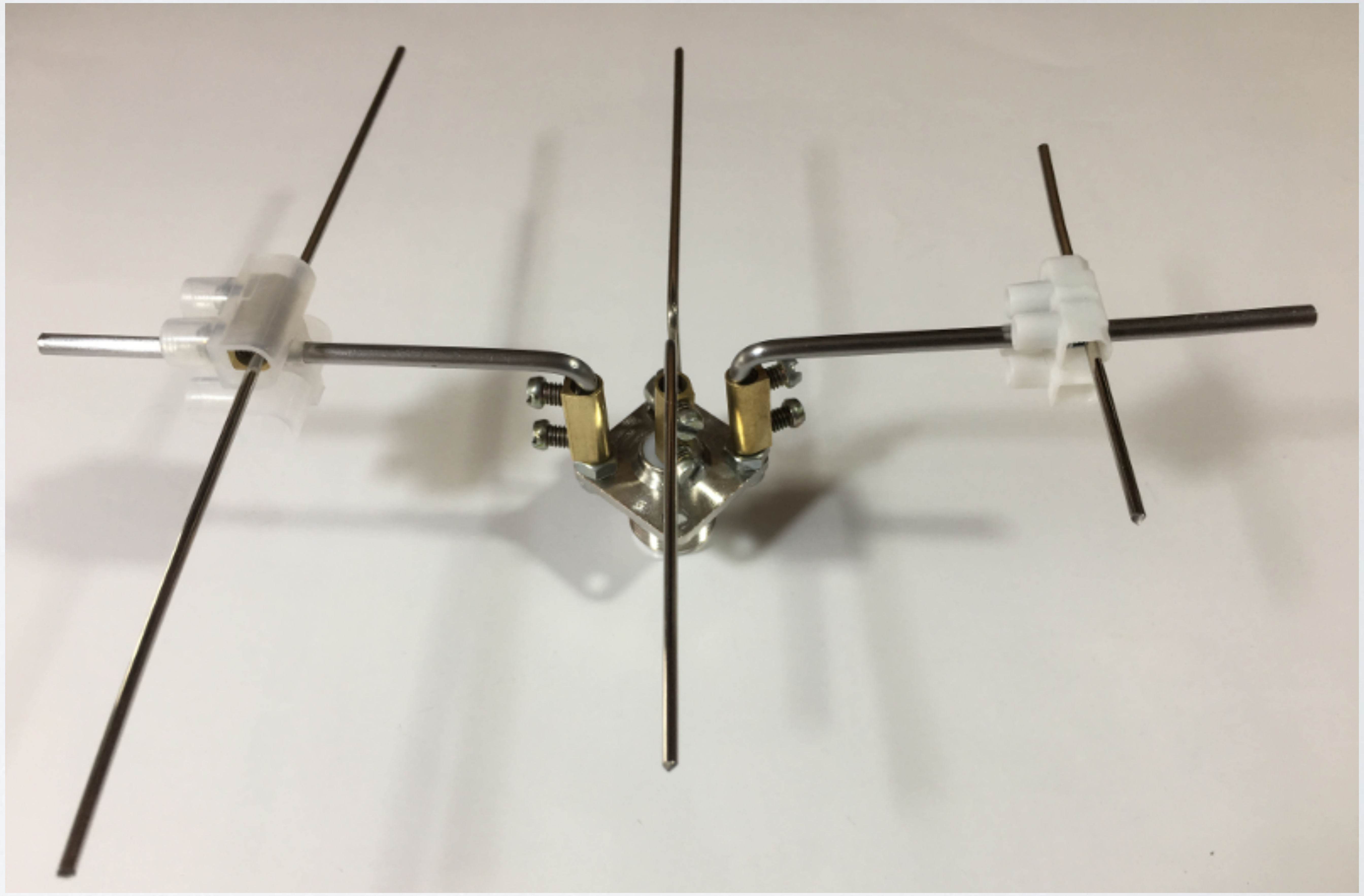
- Support booms attached to type N female chassis.



YAGI-UDA ANTENNA

- Support booms attached to type N female chassis.





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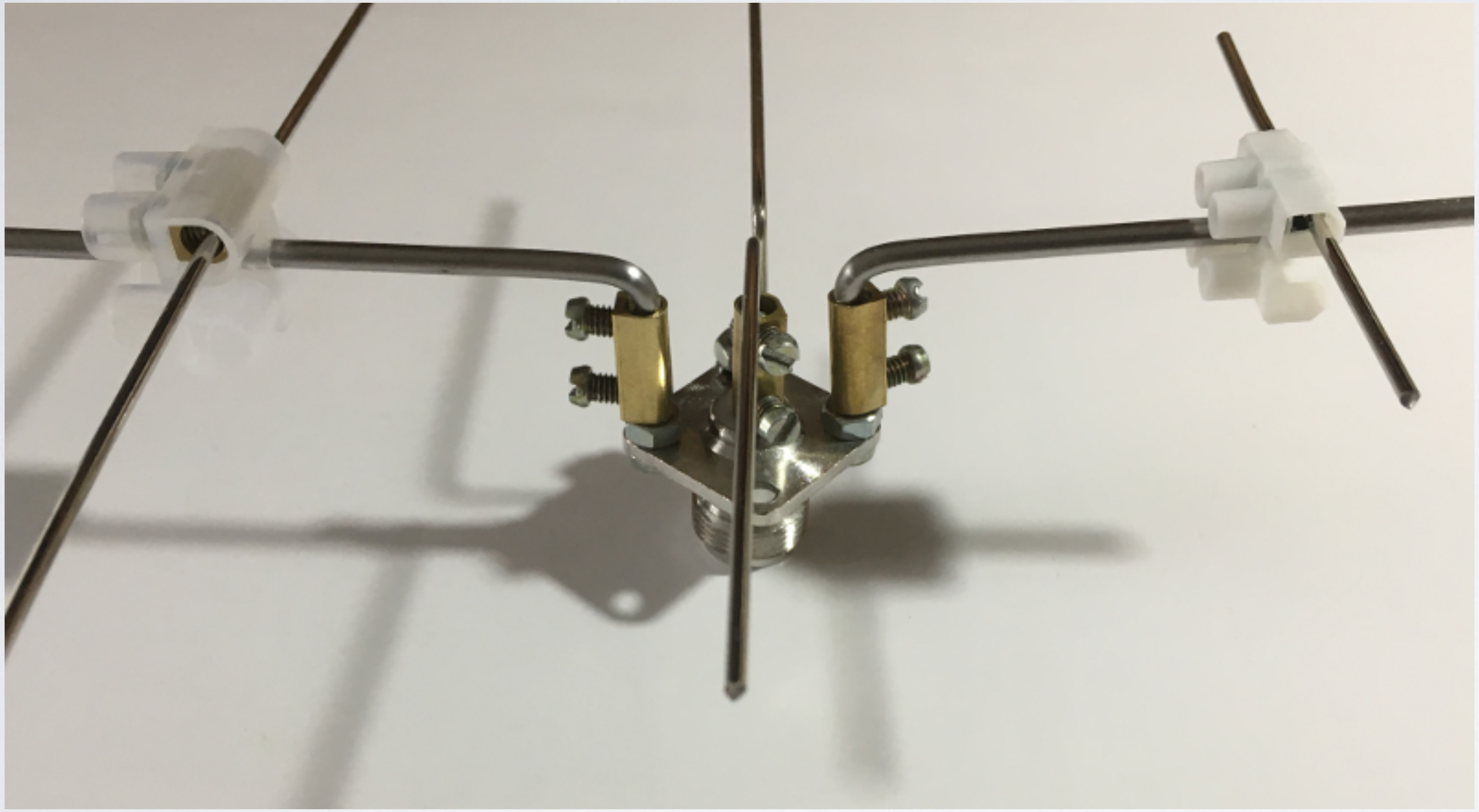
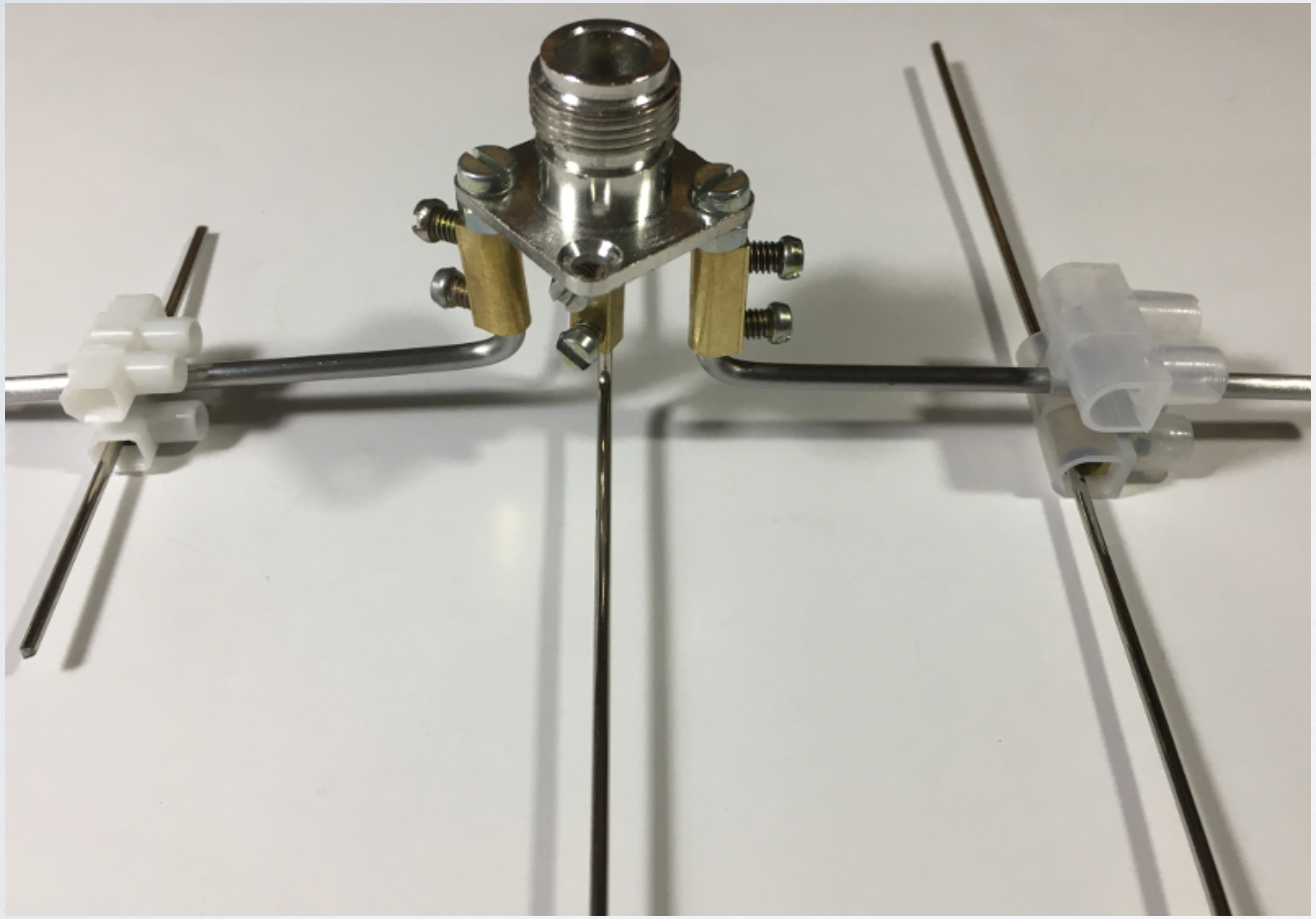
YAGI-UDA ANTENNA

- Close up reflector, driven element, director and support boom.



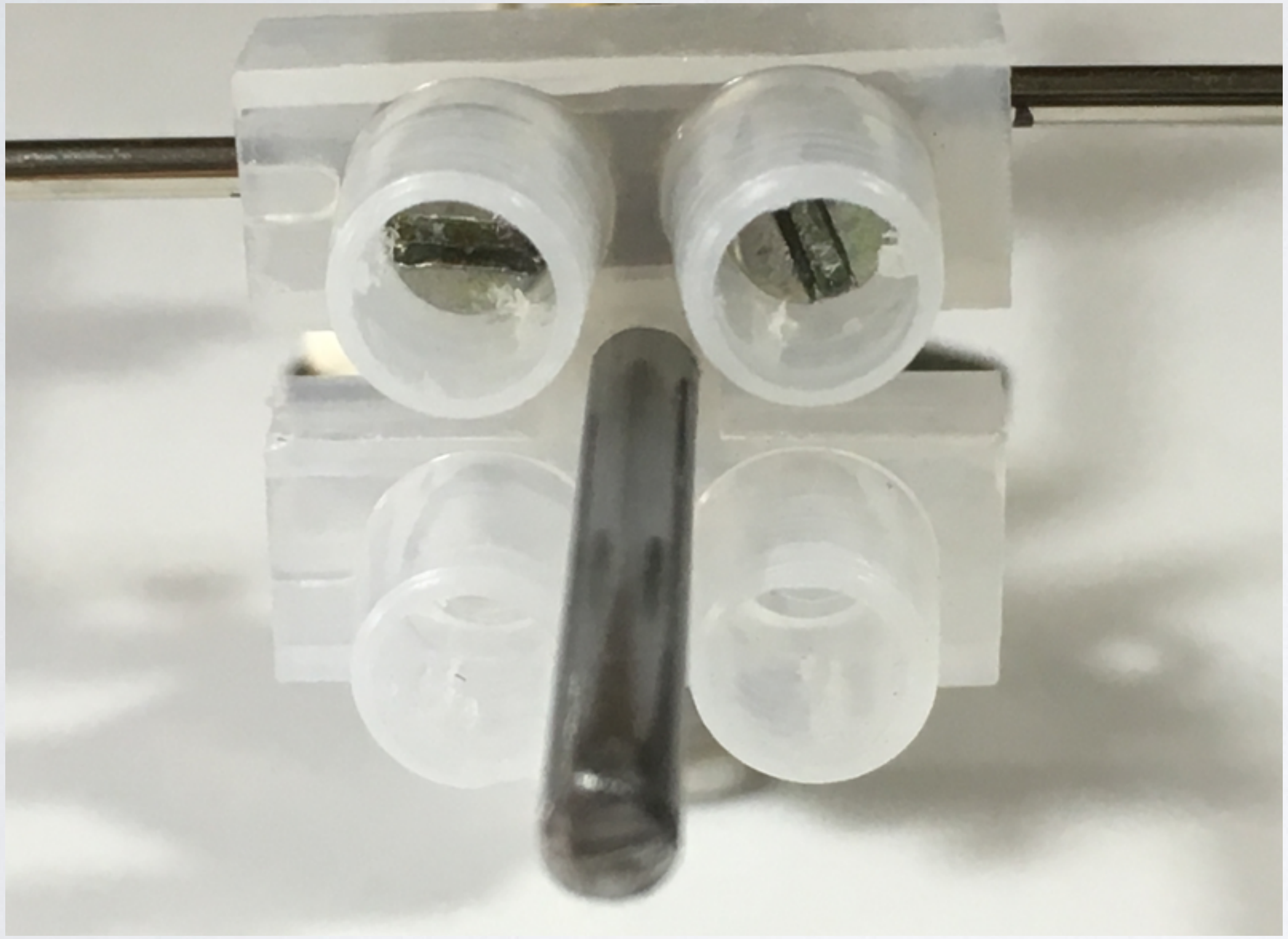
YAGI-UDA ANTENNA

- Bottom view.

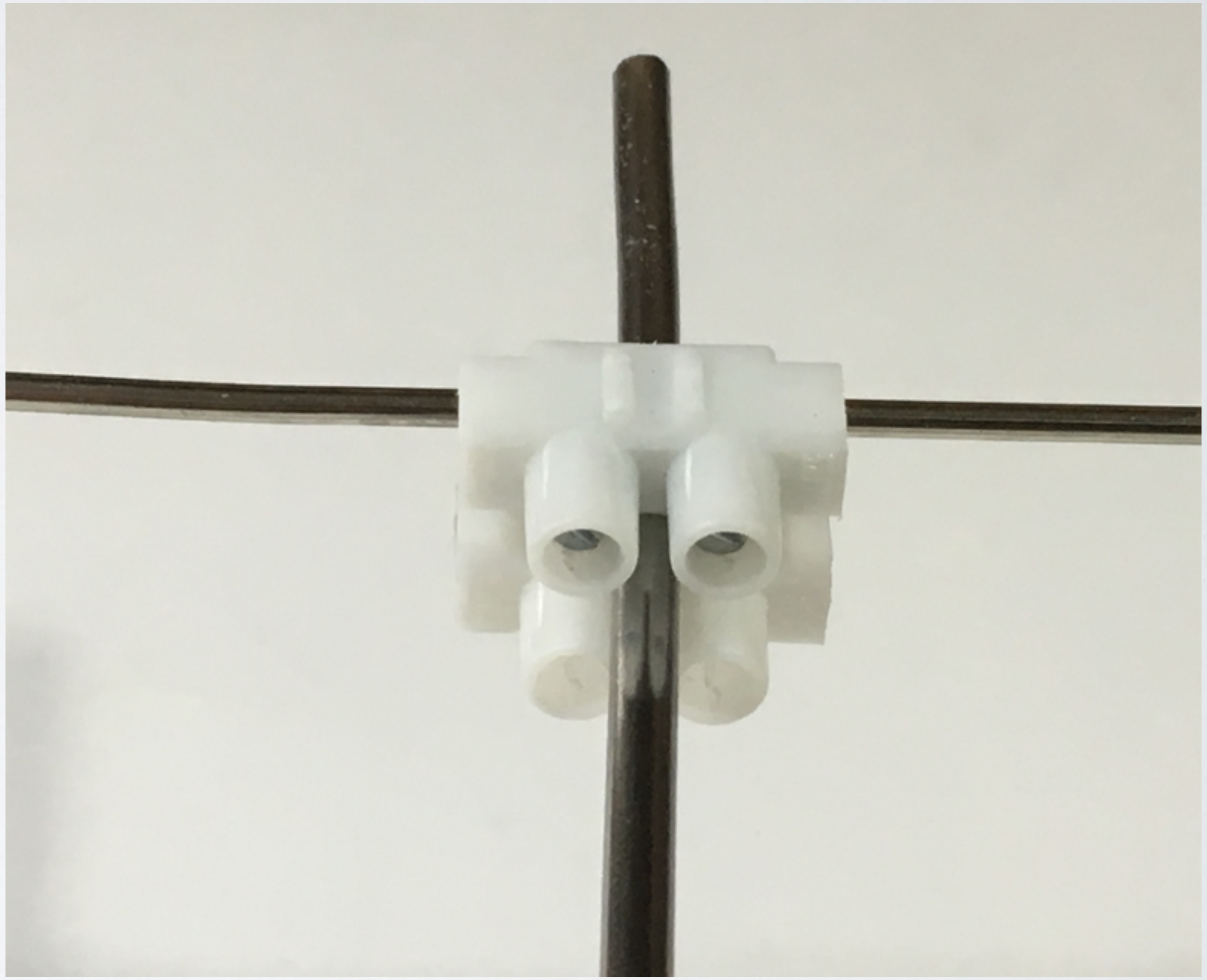


YAGI-UDA ANTENNA

- Close up terminal strip blocks



Large terminal strip block for reflector



Small terminal strip block for director

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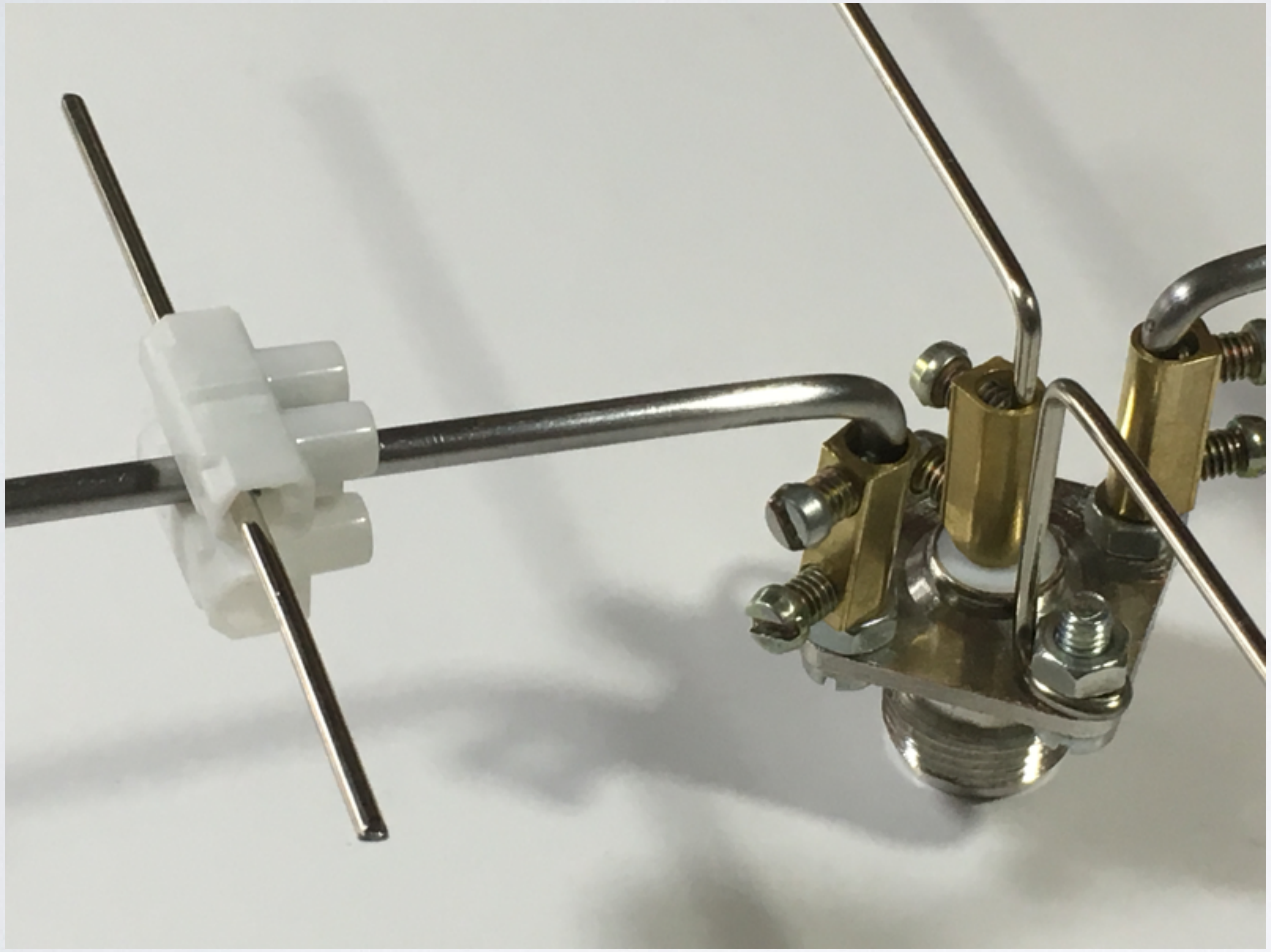
YAGI-UDA ANTENNA

- Director and driven element.



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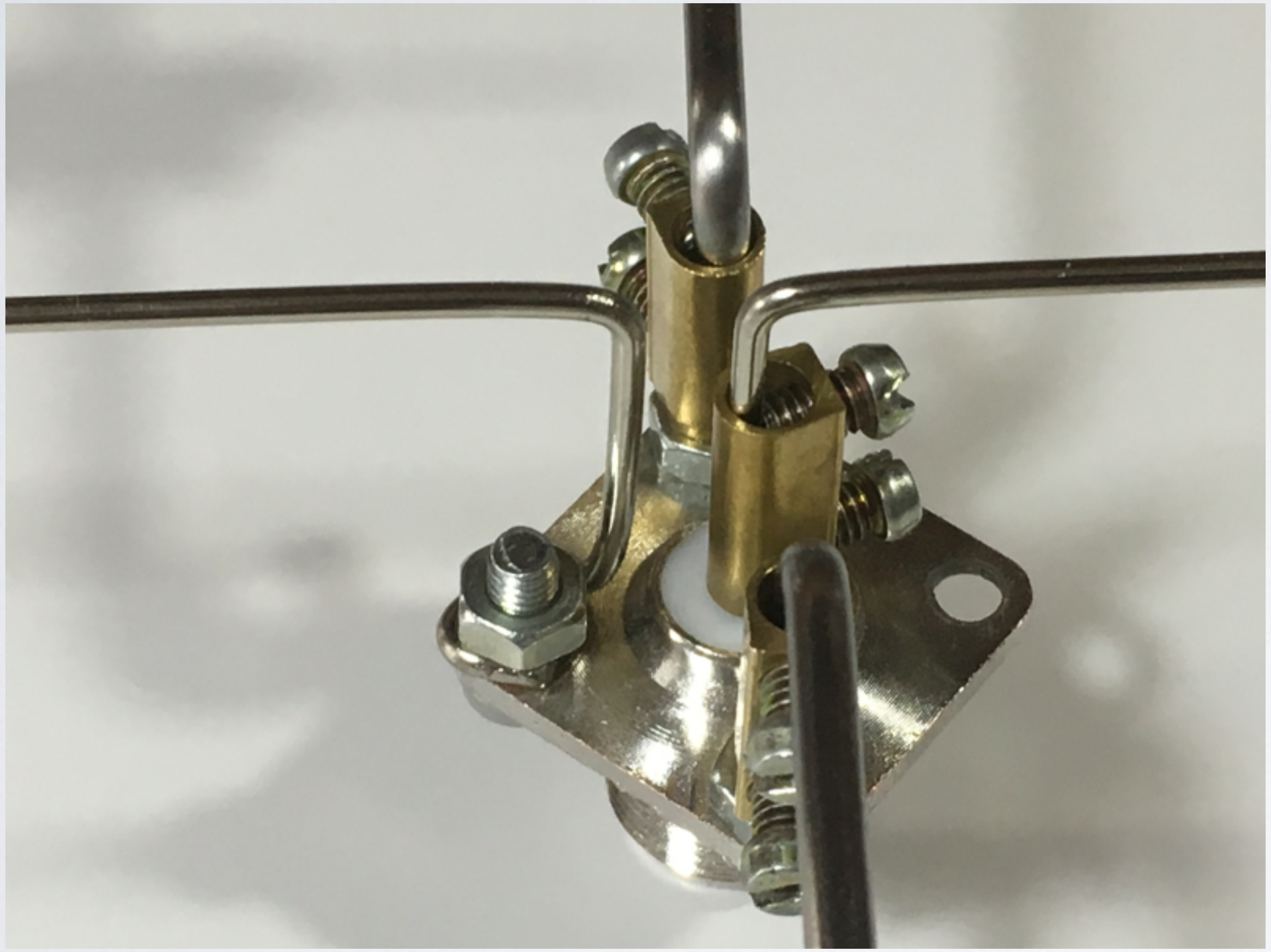
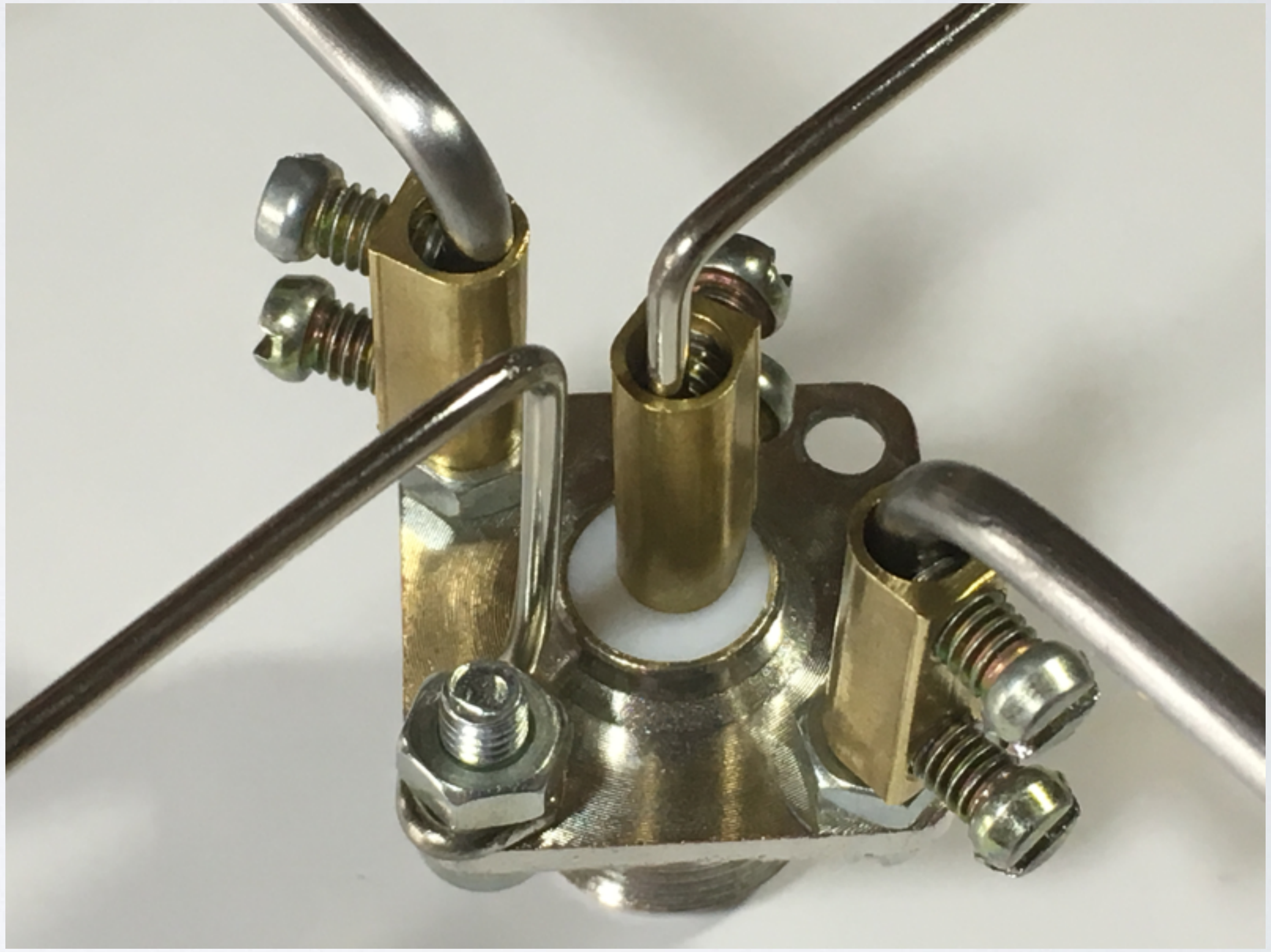
YAGI-UDA ANTENNA

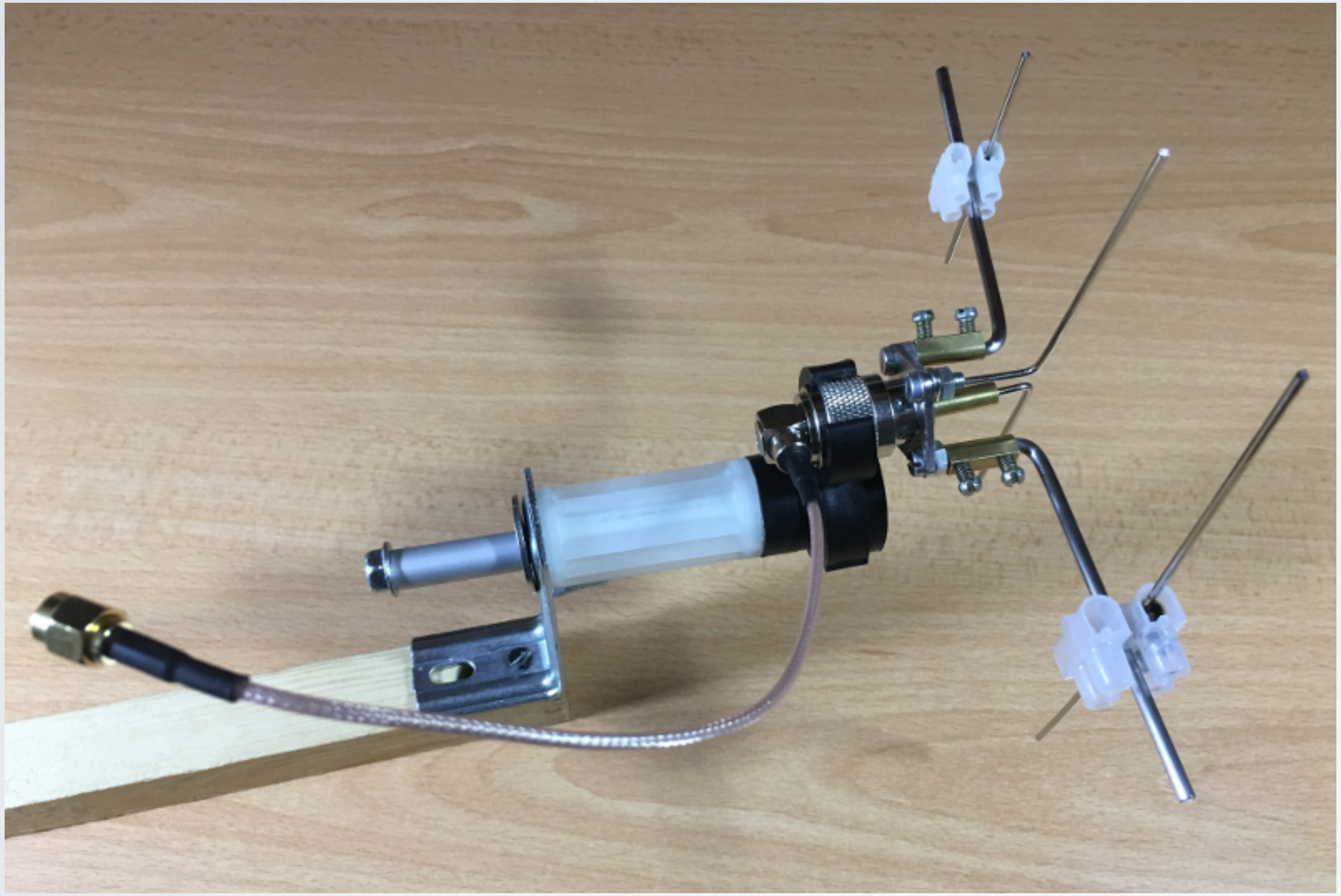
- Close up driven element.

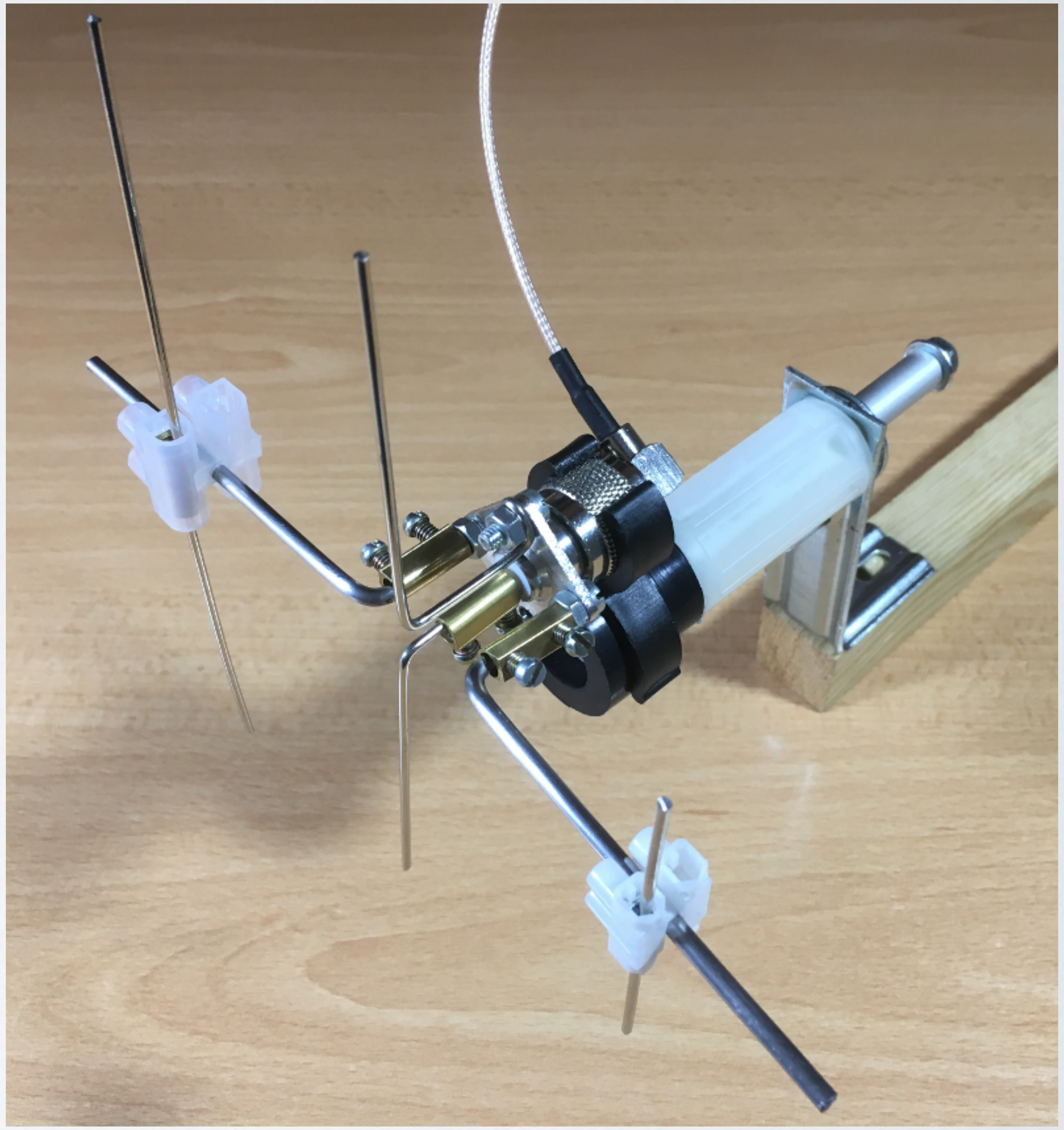




YAGI-UDA ANTENNA MOUNTED ON TEST RIG

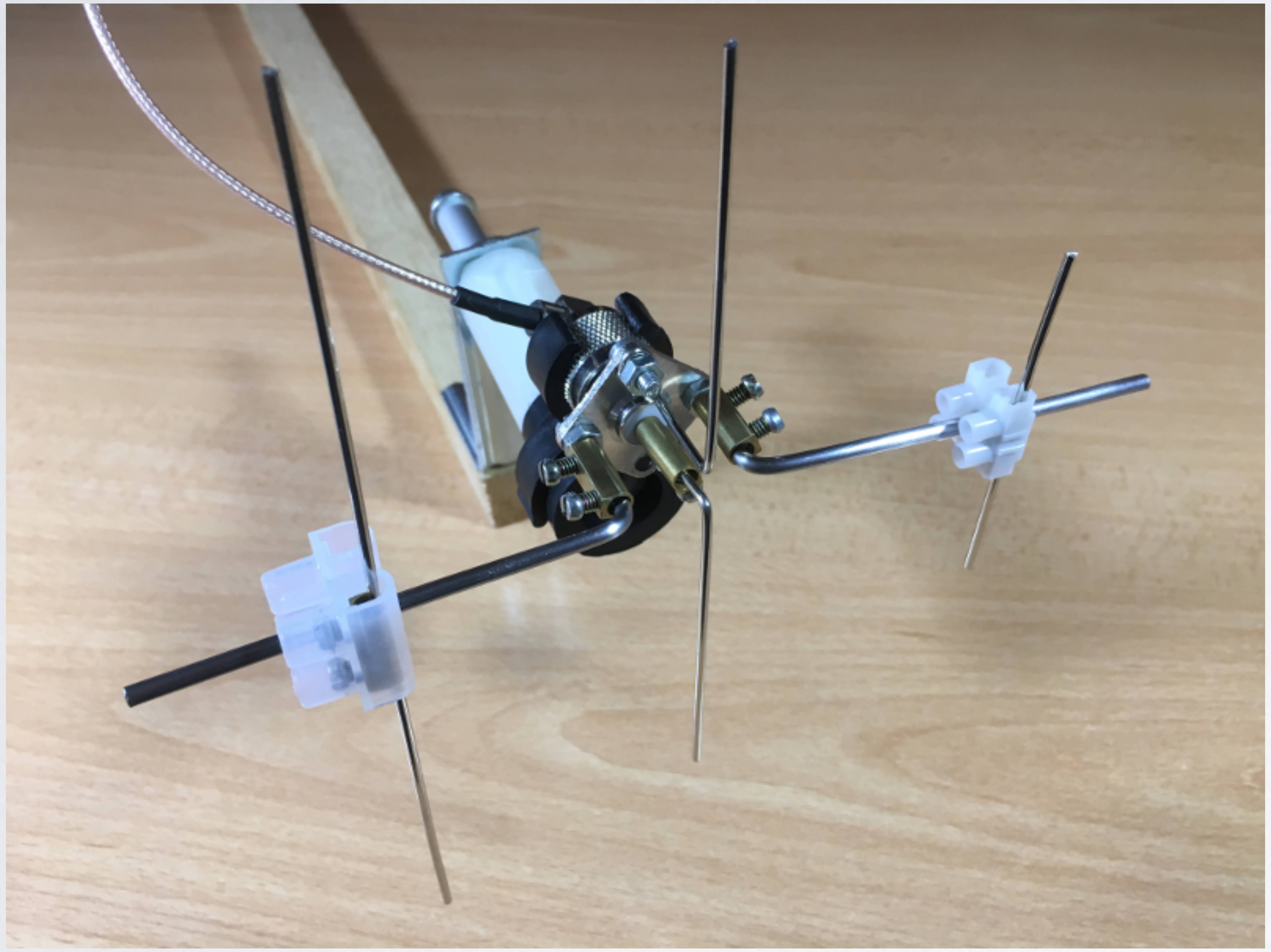
- Antenna clamped to test rig.

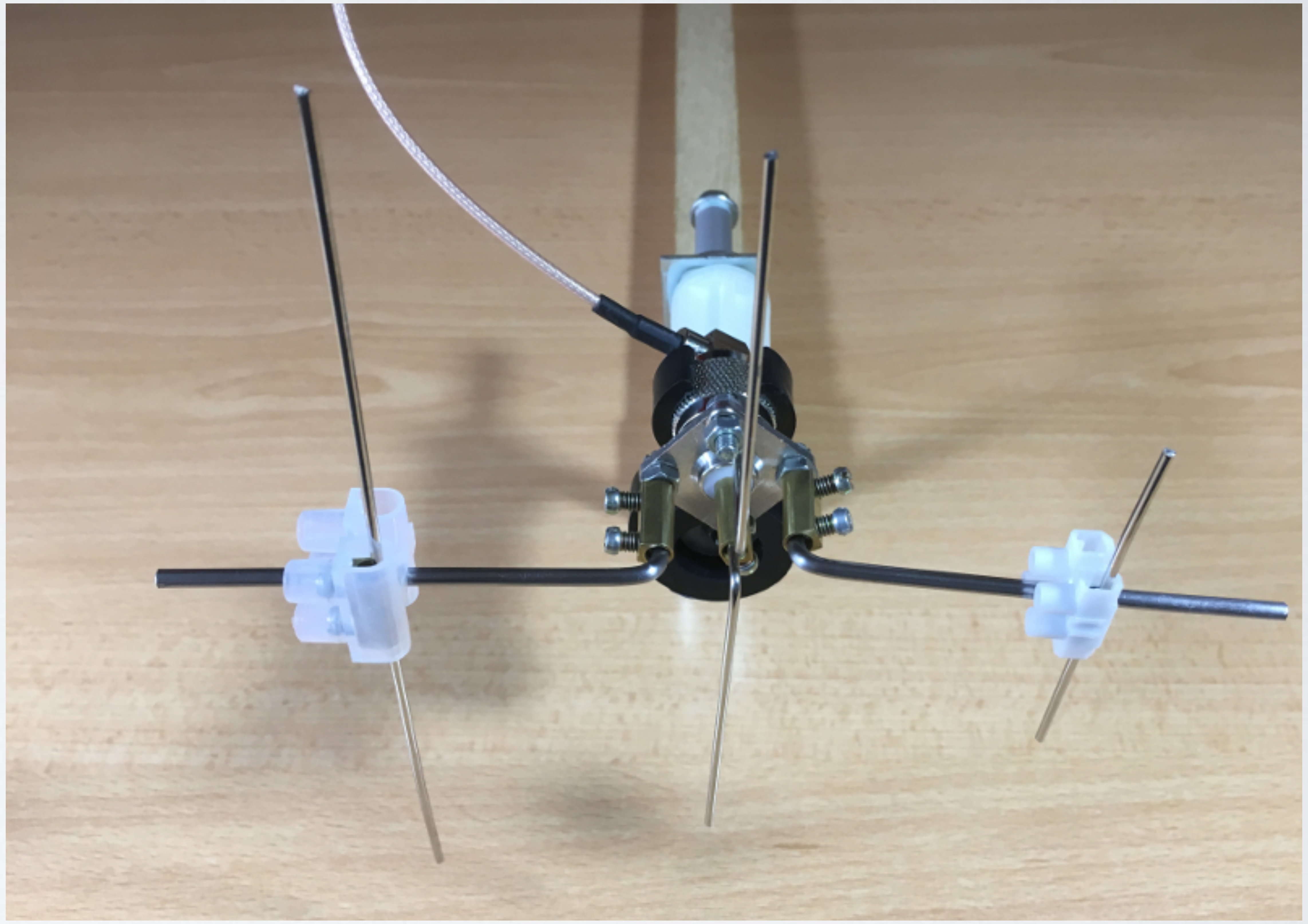




YAGI-UDA ANTENNA MOUNTED ON TEST RIG

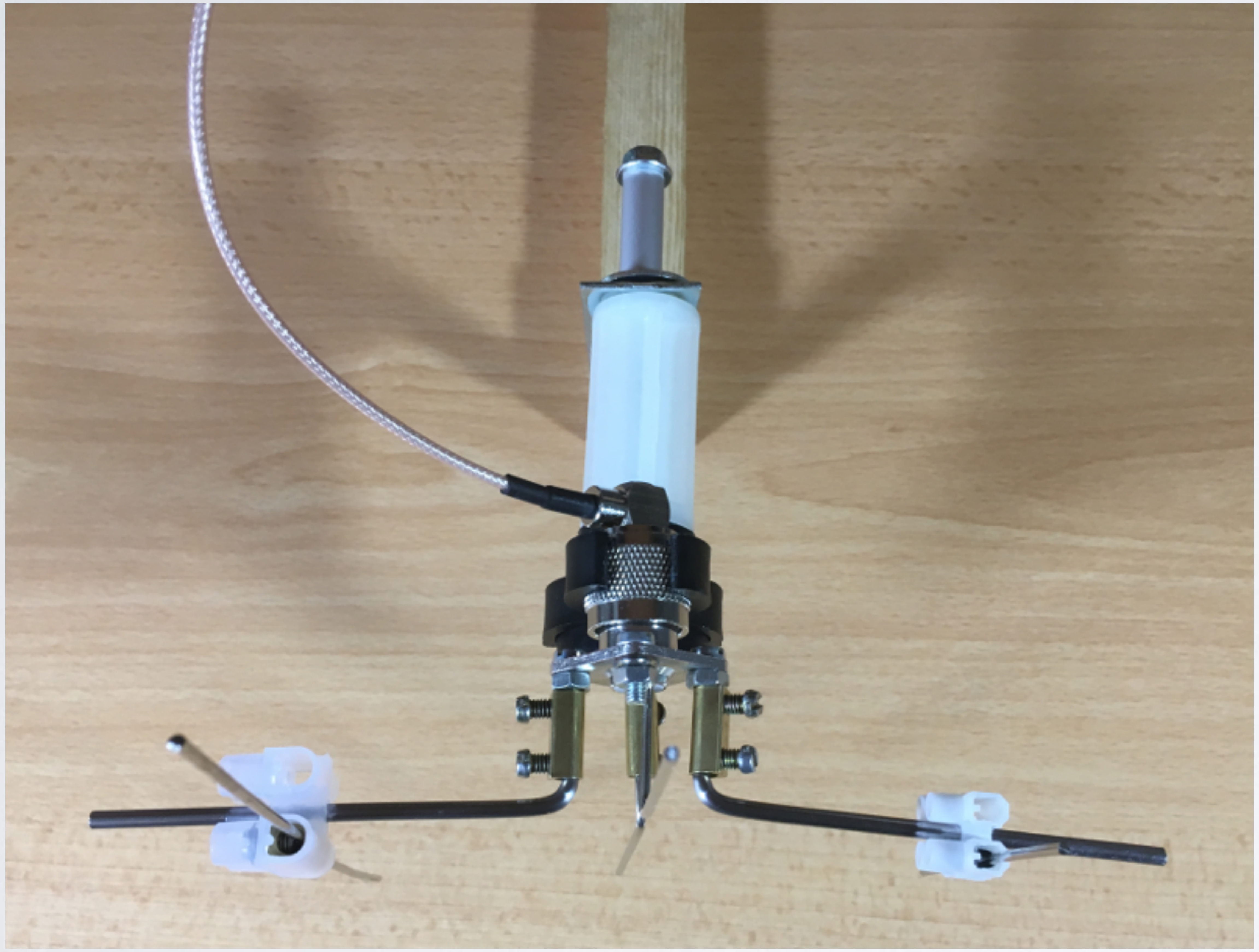
- Front view close up.

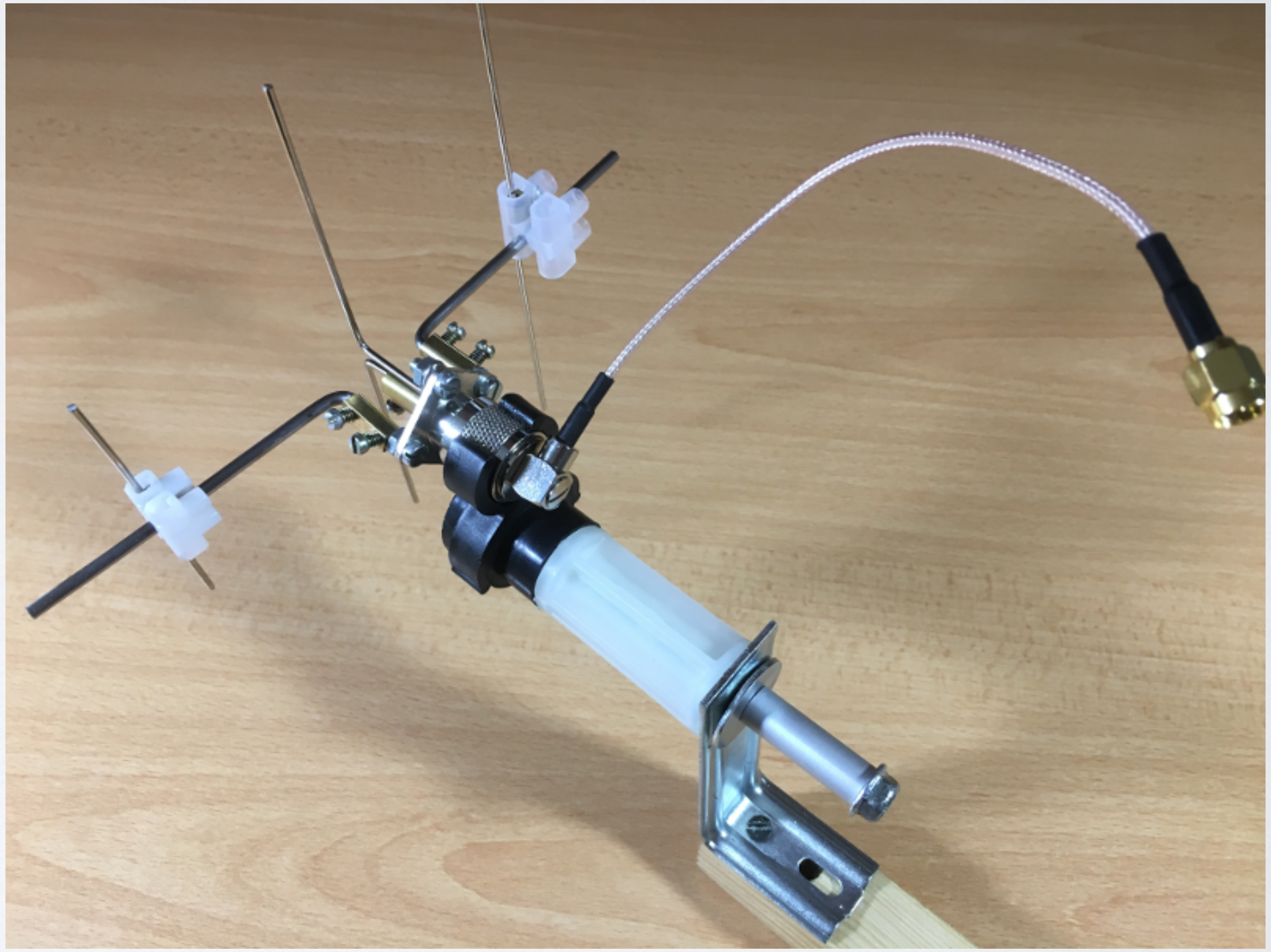




YAGI-UDA ANTENNA MOUNTED ON TEST RIG

- Coax cable does not touch antenna or test rig.





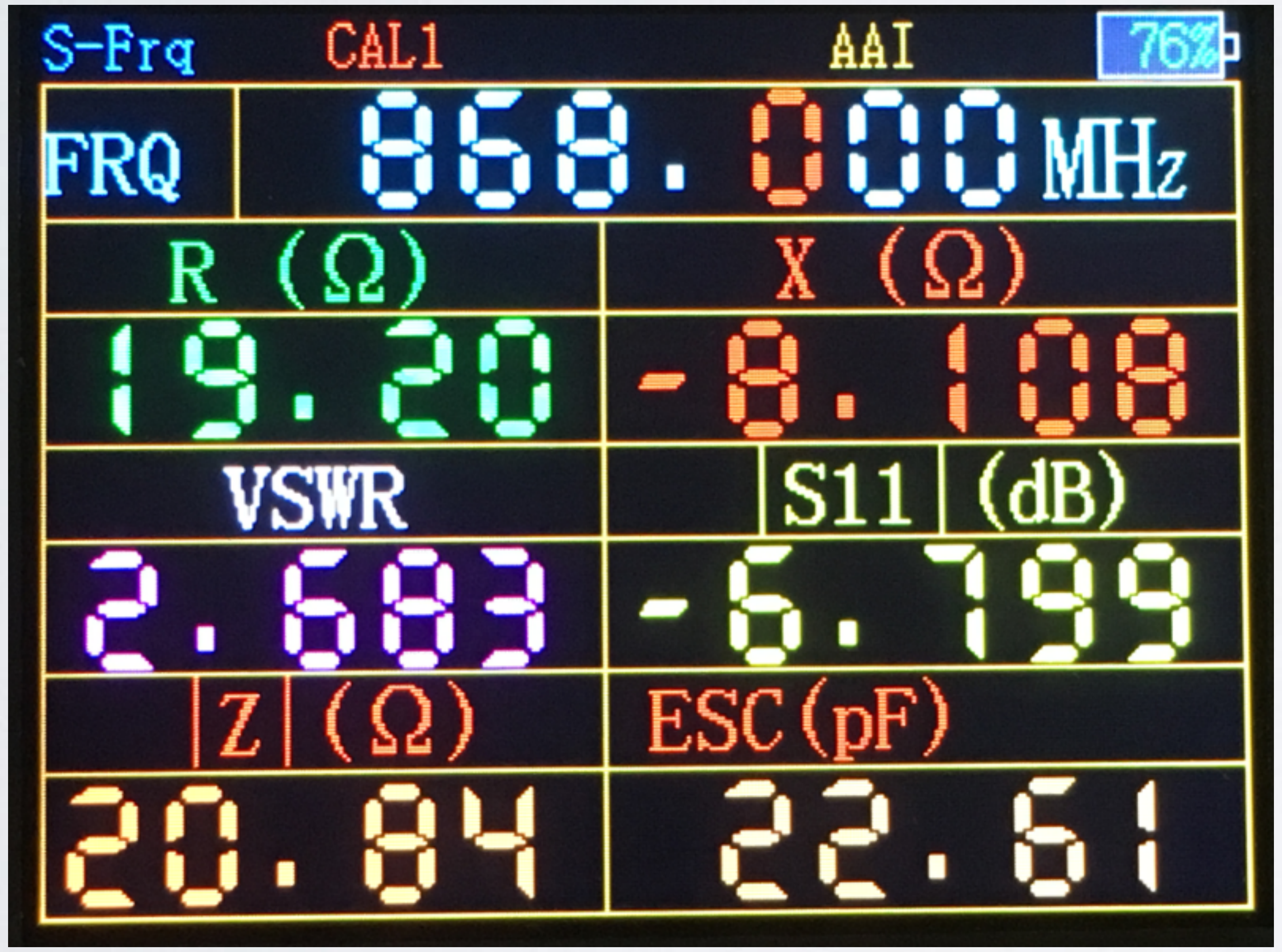
YAGI-UDA ANTENNA

Measuring antenna parameters

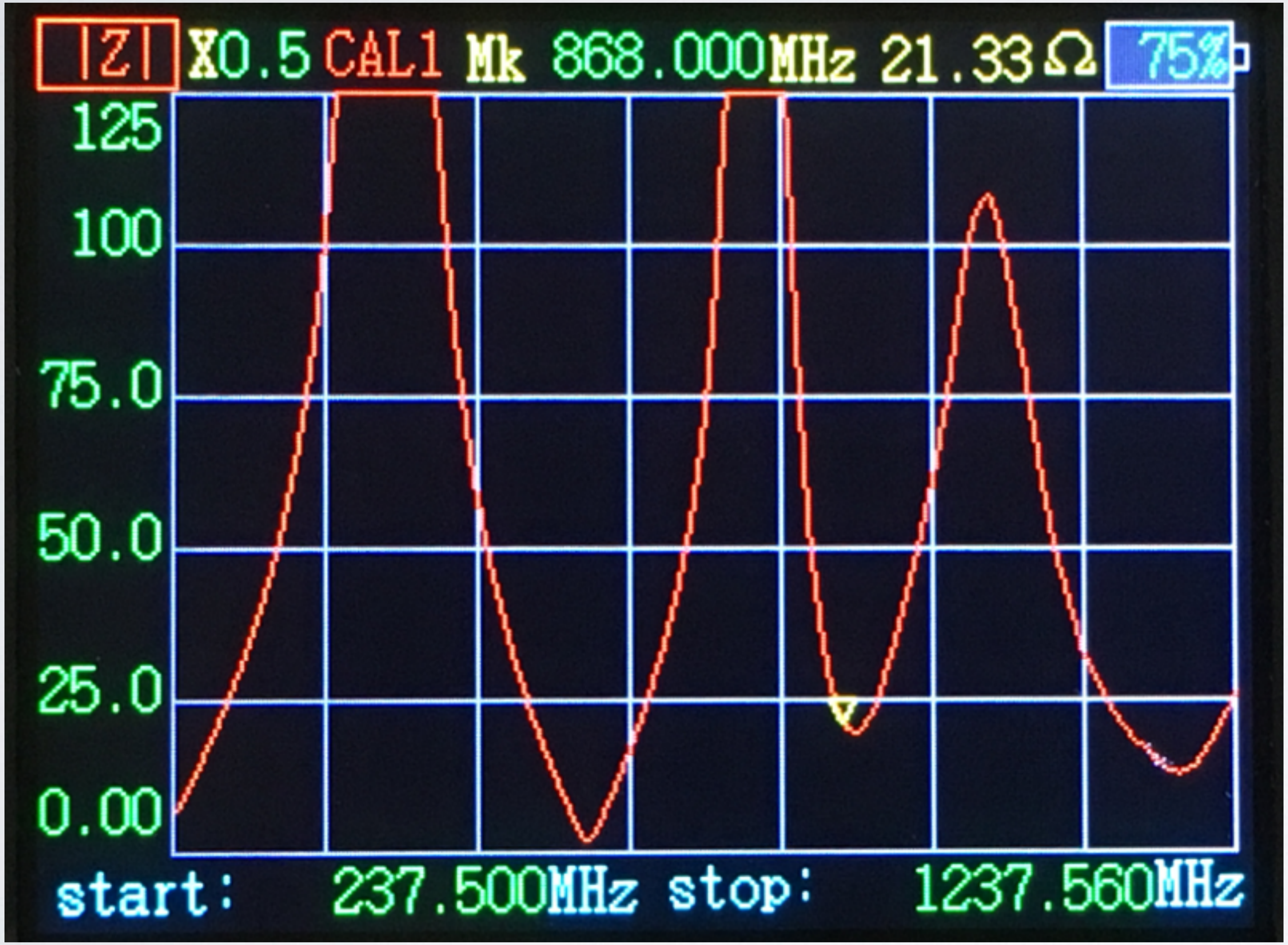
The antenna analyser with the Yagi-Uda antenna.

MEASURED ANTENNA PARAMETERS

- Based on the Yagi-Uda design:
  VSWR ≈ 2.7 ← Not good. It is > 2
  Z ≈ 21Ω ← Not good. Should be approx. 50Ω
  S11 ≈ -7 dB



MEASURED ANTENNA PARAMETERS



DISCREPANCY

- When using the 4NEC2 antenna modelling software, the VSWR=1.04
- After building the actual Yagi-Uda antenna and testing it with the N1201SA the VSWR=2.7
- What causes this discrepancy?
- The support booms are also connected to the N type connector (ground).
- Conclusion:
  Do not conductively attach the support booms to the N type connector, use the plastic plate.