Yagi-Uda Antennas

Balanis Fig. 10.17

- A "Yagi-Uda" antenna consists of a *feeder* or driven element, a *reflector* (longer than the feed), and several or many *directors*, shorter than the feeder.
- Commonly used in the HF (3-30 MHz), VHF (30-300 MHz) and UHF (300-3000 MHz) bands, for:
  - High-gain (12 dBi) but narrow bandwidth (2%)
  - Modest gain (4-6 dBi) but much wider bandwidth (TV receiving antennas)
- The design parameters are:
  - the length and diameter of the feeder or driven element
  - the length, diameter and spacing of the reflector
  - the length, diameter and spacing, and number of the directors.

Yagi Design

- The "performance specification" consists of values for:
  - the forward gain
  - the "backward" gain or "front-to-back ratio"
    - Front-to-back ratio: The ratio of the field strength in the main lobe to the field strength "behind" the antenna in the backfire direction.
    - Front-to-back ratios of 15 dB can be achieved with wider-than-optimum director spacing, at the cost of lower gain.
  - the sidelobe level
    - Sidelobes about 5 dB below the main lobe can be achieved.
  - the input impedance
  - the *bandwidth* over which these figures must be maintained.

Driven Element or Feeder

- There is one excited element or "driven" element, usually a dipole or a folded dipole
- With a dipole as the driven element, the length of the dipole is typically 0.45 λ to 0.49 λ.
- The feeder length and radius have a small effect on the forward gain.
- The feeder length and radius have a strong influence on the input impedance, and the backward gain.

Reflector

- One "reflector" element is typically used.
- Very little performance increase is found by having two or more reflectors; consequently almost all Yagi antennas have only one reflector.
- The reflector longer than the feeder element and usually longer than half a wavelength.
- The reflector is more closely spaced to the feeder element than the directors, typically about 0.25 λ.
- The reflector spacing has very little effect on the forward gain.
- The reflector spacing and length strongly affects the backward gain (i.e., the gain in the direction opposite to the main lobe) and the input impedance.

Directors

- The "director" elements are typically slightly shorter than the half-wavelength, 0.40λ to 0.45λ.
- The directors are typically spaced 0.3 to 0.4λ from the feeder.
- In some designs the directors are not all the same length, but have individual lengths and individual diameters, and the spacing of the directors is not necessarily uniform.
- For a long Yagi antenna ($\approx 6\lambda$) the gain is approximately independent of the director spacing up to about 0.3λ
- Note that for a fixed Yagi length, a wider director spacing means less director elements, so a less expensive antenna.
- The directors act as a linear array with approximately equal currents on the elements, and an approximately progressive phase shift from element to element.
- Six to twelve directors is typical.
- Few Yagis have more than 12 directors as the antenna becomes too long to be practical from a mechanical point of view.
- The maximum gain is limited to about 12 dBi for "practical" antennas.
- If more gain is needed it is better to use a stack of two Yagis instead of adding more directors to make a very long Yagi.
- An "array" of two Yagis gives better control of sidelobe levels than a single very long Yagi.
- The director length and spacing have a strong effect on:
  - the forward gain
  - the backward gain
  - the input impedance

Typical Design Procedure

- In a typical design the director length and spacing, and the number of directors, are first chosen to achieve the needed gain.
- Then the feed length, the reflector length and the reflector spacing are adjusted to control the backward gain and input impedance.
- Two types of Yagis:
  - high-gain, narrow bandwidth
  - modest gain but wider bandwidth
- There is a trade-off between maximizing the gain and extending the bandwidth.
- For maximum gain the length of the directors is critical and as the frequency changes the directors become the "wrong" length in wavelengths and the gain decreases rapidly.
- Typical figures might be: (gains relative to a a half-wave dipole)
  - 12 dB over a 2% bandwidth for "maximum" gain
  - 8 dB over a 9% bandwidth
  - 4 dB over a 60% bandwidth
- loading the elements with ICE in inclement weather increases their radius and length and degrades the antenna's performance!
- Designs are often done by numerical simulation (with NEC, for example) using optimization techniques to adjust the various lengths and spacings to achieve the desired performance specification.

Yagi Analysis using the Numerical Electromagnetics Code

Balanis gives us an example of a Yagi-Uda antenna (page 522) as follows:

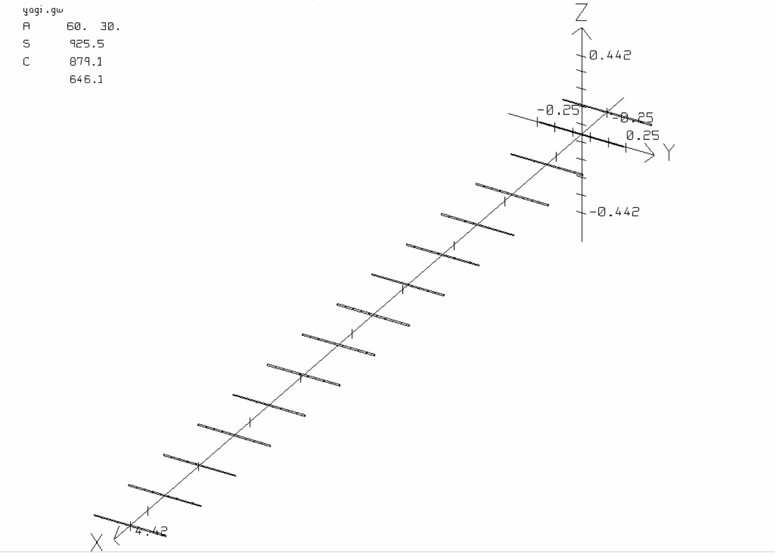
- Length of reflector= 0.5 λ
- Spacing of reflector= 0.25 λ
- Length of feed= 0.47 λ
- Length of director= 0.406 λ
- Spacing of director= 0.34 λ
- Number of directors = 13
- Radius of wires= 0.003 λ
- Frequency = 300 MHz.

Program GWYagi

- Get GWYagi.exe from the course web site (runs on MS Windows computers)
- Run GWYagi to create an input file for NEC for a Yagi-Uda antenna.
- GWYagi asks you for the value of each parameter.
- GWYagi creates a file “yagi.gw” for input to the NEC program, as follows:

```
CM Yagi-Uda Antenna
CM Frequency:            300.0000 MHz.
CM Reflector length:       0.5000 m.
CM Feed length:            0.4700 m.
CM Director length:        0.4060 m.
CM Reflector spacing:      0.2500 m.
CM Director spacing:       0.3400 m.
CM Number of directors:   13
CM Wire radius:            0.0030 m.
CM Segment length:         0.0500 wavelengths.
CM
CE
GW  1   11 -0.250000 -0.250000  0.000000 -0.250000  0.250000  0.000000  0.003000
GW  2    9  0.000000 -0.235000  0.000000  0.000000  0.235000  0.000000  0.003000
GW  3    9  0.340000 -0.203000  0.000000  0.340000  0.203000  0.000000  0.003000
GW  4    9  0.680000 -0.203000  0.000000  0.680000  0.203000  0.000000  0.003000
GW  5    9  1.020000 -0.203000  0.000000  1.020000  0.203000  0.000000  0.003000
GW  6    9  1.360000 -0.203000  0.000000  1.360000  0.203000  0.000000  0.003000
GW  7    9  1.700000 -0.203000  0.000000  1.700000  0.203000  0.000000  0.003000
GW  8    9  2.040000 -0.203000  0.000000  2.040000  0.203000  0.000000  0.003000
GW  9    9  2.380000 -0.203000  0.000000  2.380000  0.203000  0.000000  0.003000
GW 10    9  2.720000 -0.203000  0.000000  2.720000  0.203000  0.000000  0.003000
GW 11    9  3.060000 -0.203000  0.000000  3.060000  0.203000  0.000000  0.003000
GW 12    9  3.400000 -0.203000  0.000000  3.400000  0.203000  0.000000  0.003000
GW 13    9  3.740000 -0.203000  0.000000  3.740000  0.203000  0.000000  0.003000
GW 14    9  4.080000 -0.203000  0.000000  4.080000  0.203000  0.000000  0.003000
GW 15    9  4.420000 -0.203000  0.000000  4.420000  0.203000  0.000000  0.003000
GE
FR  0    0    0    0    300.0000
EX  0    2    5    0       1.0         0
RP  0    1  361            90.        0.        0.        1.
RP  0  361    1             0.        0.        1.        0.
RP  0  361    1             0.       90.        1.        0.
EN
```

You can draw this input file with program “MODEL” from the web site:



- Run the NEC program to obtain NEC’s output file: [Display the NEC output file.]()
- currents on the segments/wires

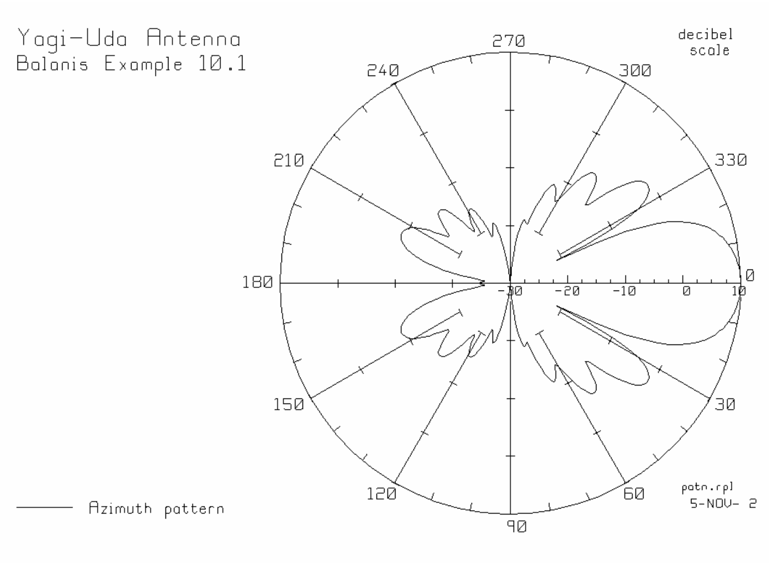
```
                         - - - CURRENTS AND LOCATION - - -

                 LENGTHS NORMALIZED BY WAVELENGTH (OR 2.*PI/CABS(K))

 SEG.  TAG    COORD. OF SEG. CENTER     SEG.          - - - CURRENT (AMPS) - - -
 NO.   NO.     X        Y        Z     LENGTH     REAL        IMAG.       MAG.        PHASE
    1    1  -0.2502  -0.2274   0.0000  0.04548   3.4037E-05  1.3124E-03  1.3129E-03   88.514
    2    1  -0.2502  -0.1819   0.0000  0.04548   6.6322E-05  3.1744E-03  3.1751E-03   88.803
    3    1  -0.2502  -0.1365   0.0000  0.04548   7.7489E-05  4.6642E-03  4.6648E-03   89.048
    4    1  -0.2502  -0.0910   0.0000  0.04548   7.7880E-05  5.7965E-03  5.7970E-03   89.230
    5    1  -0.2502  -0.0455   0.0000  0.04548   7.4717E-05  6.5064E-03  6.5069E-03   89.342
    6    1  -0.2502   0.0000   0.0000  0.04548   7.3058E-05  6.7485E-03  6.7489E-03   89.380
```

- radiation patterns

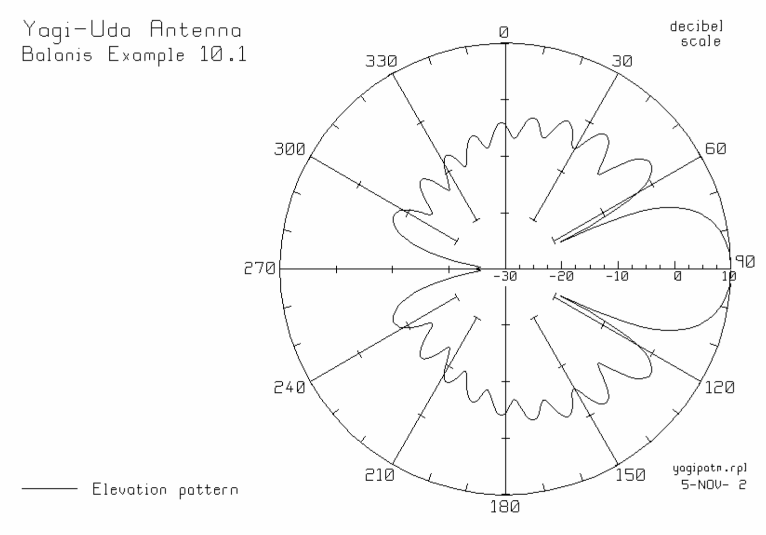
```
                                  - - - RADIATION PATTERNS - - -

 - - ANGLES - -          - POWER GAINS -          - - - POLARIZATION - - -     - - - E(THETA) - - -     - - - E(PHI) - - -
  THETA      PHI        MAJOR   MINOR    TOTAL     AXIAL      TILT   SENSE     MAGNITUDE     PHASE     MAGNITUDE     PHASE
 DEGREES   DEGREES        DB      DB       DB      RATIO      DEG.               VOLTS      DEGREES      VOLTS      DEGREES
   90.00      0.00      14.51 -999.99    14.51    0.00000   -90.00  LINEAR   0.00000E+00     0.00   3.17737E+00   175.62
   90.00      1.00      14.50 -999.99    14.50    0.00000    90.00  LINEAR   6.73789E-10   175.53   3.17237E+00   175.53
   90.00      2.00      14.46 -999.99    14.46    0.00000    90.00  LINEAR   1.34161E-09   175.24   3.15737E+00   175.24
```

Graphing Radiation Patterns in Polar Format

- It is very tedious to manually extract radiation patterns from the NEC output file!
- Program GETPATN reads a NEC output file and finds:
    - the azimuth pattern (must be the first RP card, with 361 points)
    - the elevation pattern (must be the second RP card, with 361 points)
    - only one frequency in the NEC output file
- GETPATN creates two output files:
    - PATN.RPL can be graphed with RPLOT (rectangular format) or PPLOT (polar format)
    - PATN.DAT has the radiation patterns in three columns (angle, azimuth field, elevation field) and can be graphed with your favourite plotting software, such as MATLAB.

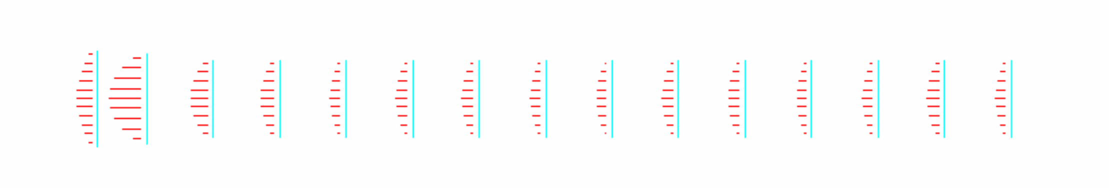


The Azimuth Pattern
(Compare with Balanis Fig. 10.19)



Elevation pattern

- Compare with Balanis Fig. 10.19
- Note that the first sidelobe is rather higher in the elevation pattern than in the azimuth pattern.



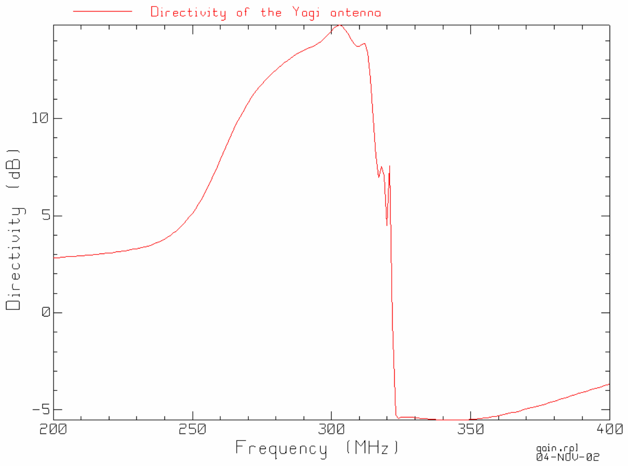
Current distribution on the reflector (left), feeder(2nd from left) and the directors of the Yagi antenna

Pattern Variation with Frequency

- NEC can solve the antenna at a sequence of frequencies by asking for looping on the “FR” card:

```
FR  0   10    0    0    300.0000      10.
```

  - By specifying the 2nd number as “10” we ask for 10 frequencies.
  - Asking for a frequency step of 10 MHz then obtains the solution at 300, 310, 320, …, 390 MHz
  - However, ONLY the radiation pattern on the FIRST RP card after FR is calculated.
  - Also, it is a nuisance to pick out the desired field value from the very-wordy NEC output file!
  - Program GETFREQ is available on the web site for ELEC456.
  - GETFREQ reads the NEC output file and extracts the directivity of the (lossless) Yagi antenna as a function of frequency.
  - The output file is “drctvty.dat”
  - Run program RPLOT to graph “drctvty.dat”



- The directivity of this Yagi peaks at 14.79 dB at 303 MHz and then declines very rapidly above 312 MHz.
- The 3 dB bandwidth (gain > 14.79-3=11.79 dB) is from about 282.5 to about 313.5 MHz, or about 31 MHz, but is not at all centered on 300 MHz!
- Balanis has an interesting discussion of optimization for this Yagi, see pages 525 to 527.

Example

- **Design a Yagi having:**
  - **minimum directivity of 6.5 dB from 85 to 115 MHz.**
  - **VSWR less than 3.4 over the 85 to 115 MHz frequency range.**
- **Plot the azimuth pattern at 85, 100, and 115 MHz as “electric field strength in mV/m at one kilometre” due to a 1 volt, 120 ohm generator.**

- Aluminium tube of diameter 2 cm is available to build this antenna.

Remark:

- What is really wanted is that the field strength in the main beam be larger than a critical minimum value from 85 to 115 MHz.

- This requires:
    - that the directivity be large enough over the whole frequency band
    - that the antenna's input impedance match to the generator reasonably well over the whole band.
    - If the impedance of the antenna matches the generator reasonably well then the VSWR will be small.
    - Together, these conditions should lead to sufficiently high field strength at the receiver over the whole frequency band.

Solution

Choose approximate dimensions as follows:

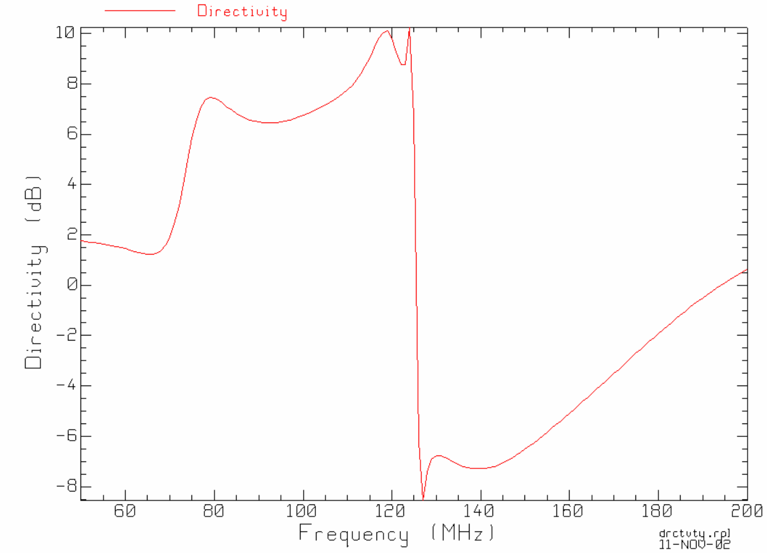
- Tube Diameter: aluminium tube of diameter 2 cm is available to build this antenna.
- Directors:
    - choose the length of the directors to be 0.40 λ at the HIGHEST frequency, 115 MHz, hence director length = 1.044 m
    - choose the spacing to be 0.3 λ at the highest frequency = 0.783 m
    - how many directors? We will find this by trial and error. Start with say 5 directors.
- Feeder:
    - choose the feed length to be 0.47 λ at the center frequency of 100 MHz, so feed length = 1.41 m
- Reflector:
    - choose the reflector length to be "longer than a half wavelength" so say 0.5 λ at the lowest frequency of 85 MHz, so reflector length = 1.767 m
    - choose the reflector spacing to be 0.25 λ at the lowest frequency, so 0.884 m.
- Segment length for NEC:
    - choose the "conservative" value of 20 segments per wavelength.
- Call this design "**trial #1**".
- Use program GWYAGI to make the input file for NEC with these dimensions

Drawing of the 5-director Yagi for Trial #1, using program MODEL.

- Edit the FR card for a “sweep” of frequencies:

```
FR   0  151    0     0       50.0000    1.
```

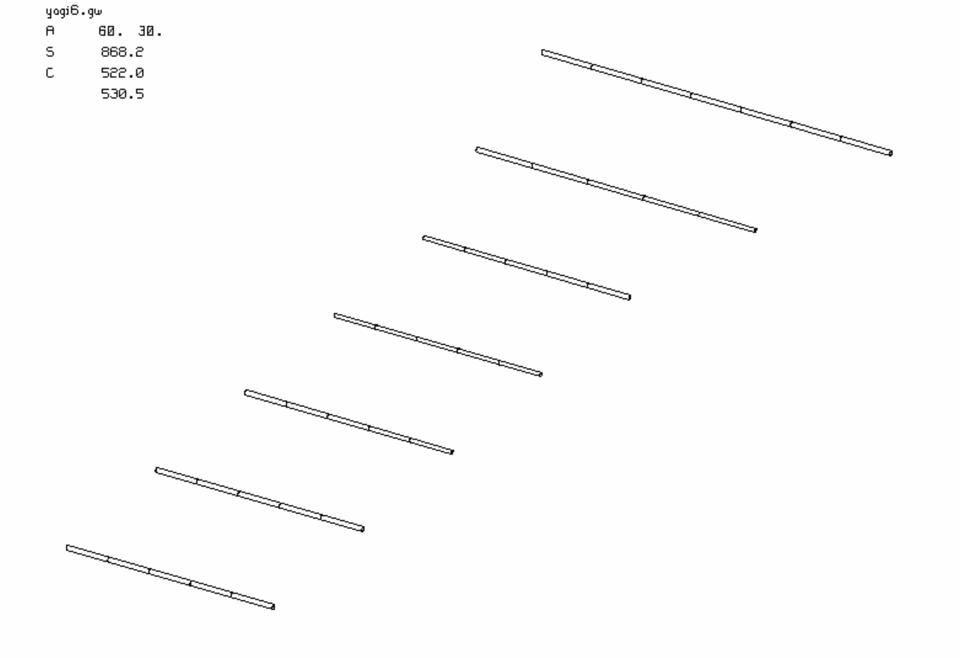
- This card asks NEC to calculate the first radiation (which is the azimuth pattern) at 151 frequencies from 50 to 150 MHz in 1 MHz steps.
- Run NEC with this input file to obtain a NEC output file
- Run GETFREQ to extract the gain vs. frequency from the NEC output file:



Gain as a function of frequency for trail #1, with 5 directors.

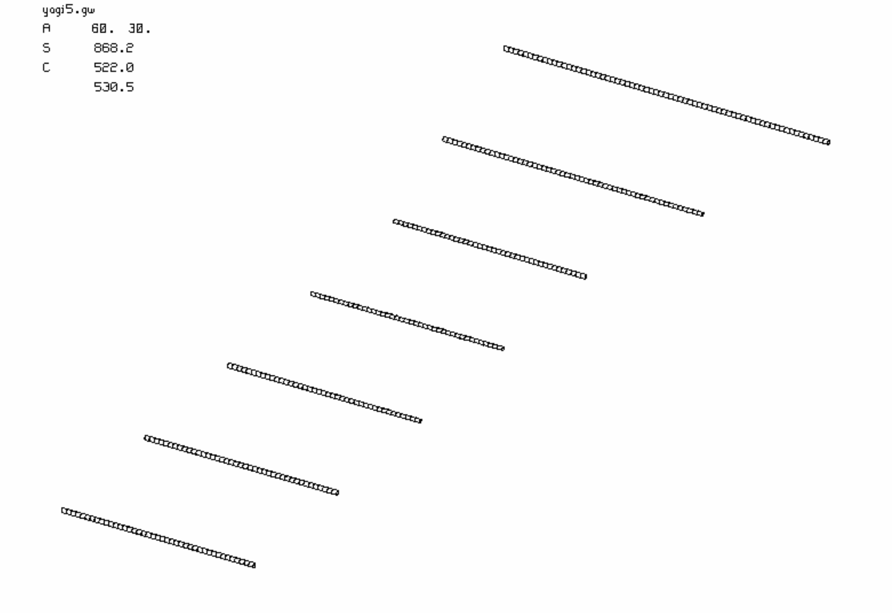
- We see that the gain is low up to about 75 MHz, then is in the 6 to 8 range to about 110 MHz, then rises to a peak at about 118 MHz, then drops off very rapidly as the directors become too long in terms of the wavelength.
- Our “spec” of 6.5 dB is almost met; the gain is 6.45 at 94 MHz.

Convergence Study



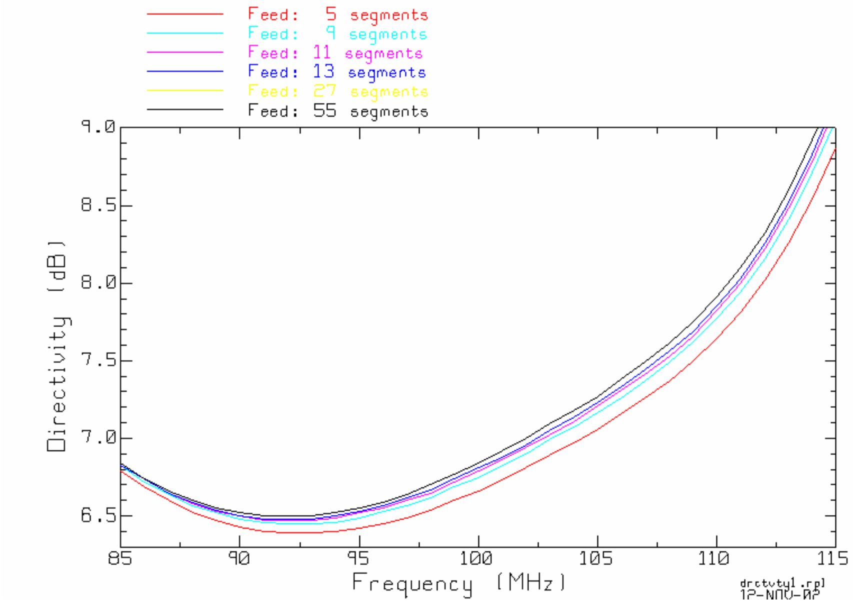
Yagi with 5 segments on the feeder

$$\Delta = \frac{\lambda}{10}$$



Yagi with 55 segments on the feeder

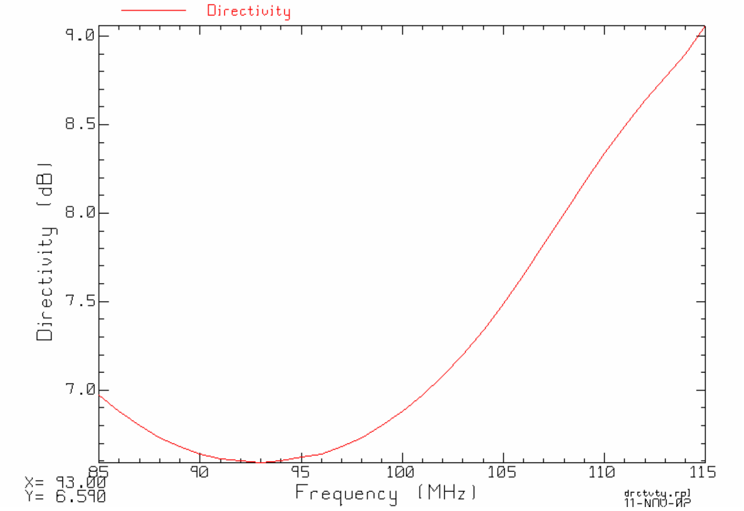
$$\Delta = \frac{\lambda}{100}$$



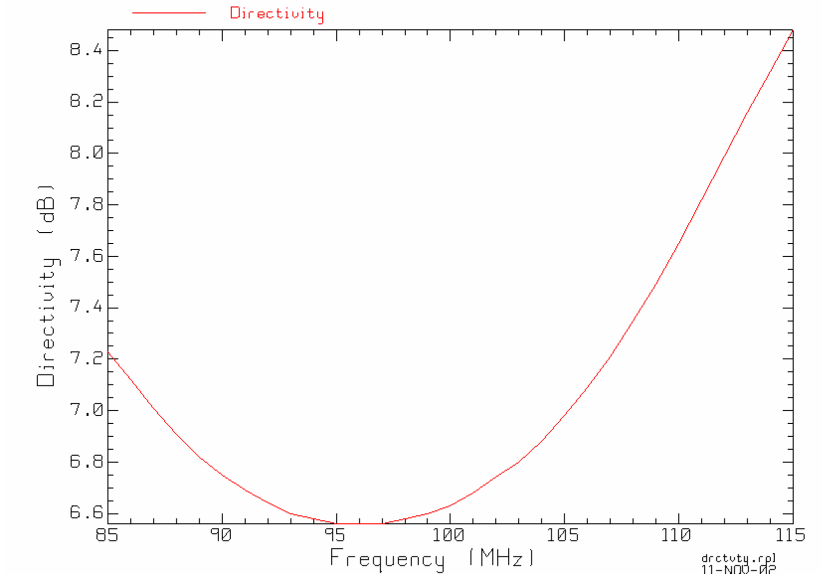
- The directivity increases as we increase the number of segments from 5 to 55 segments.
- This is typical behaviour for a “moment method” solution of a wire antenna problem
- Since the Etan=0 boundary condition is enforced at a “match point” a half-segment away from the end of each wire, effectively the wire gets a little longer as we increase the number of segments and so put the match point closer to the end.
- Evidently longer directors will give a slightly higher directivity.

Trial #2

- The directivity is low at 94 MHz with five directors.
- So for Trial #2, use 6 directors:

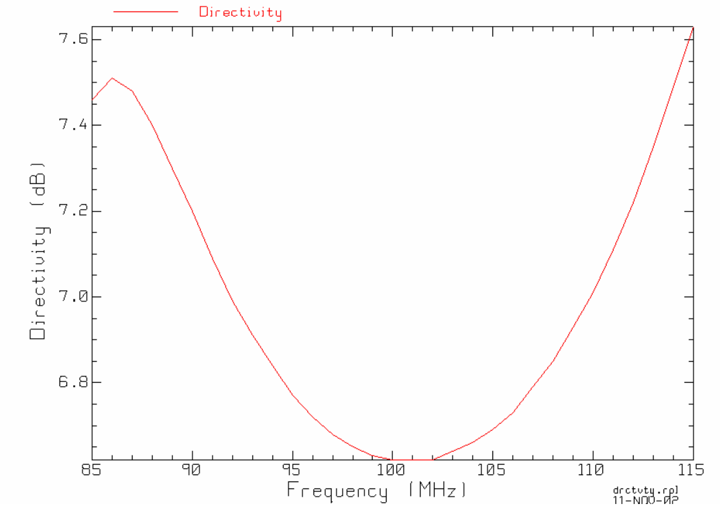


- Trial #2 has a minimum gain of 6.59 dB so is "in spec" across the whole frequency band.
- For trial #3, change the dimensions so that the minimum directivity is more centered on the frequency band.
- Scale the whole antenna by decreasing the size by 92/95 = 0.97:
    - Director length 1.044x0.97=1.0127
    - Director spacing 0.783x0.97=0.7595
    - Number of directors? 6
    - Feeder length 1.41x0.97=1.3677
    - Reflector length 1.767x0.97=1.714
    - Reflector spacing 0.884x0.97 = 0.8575

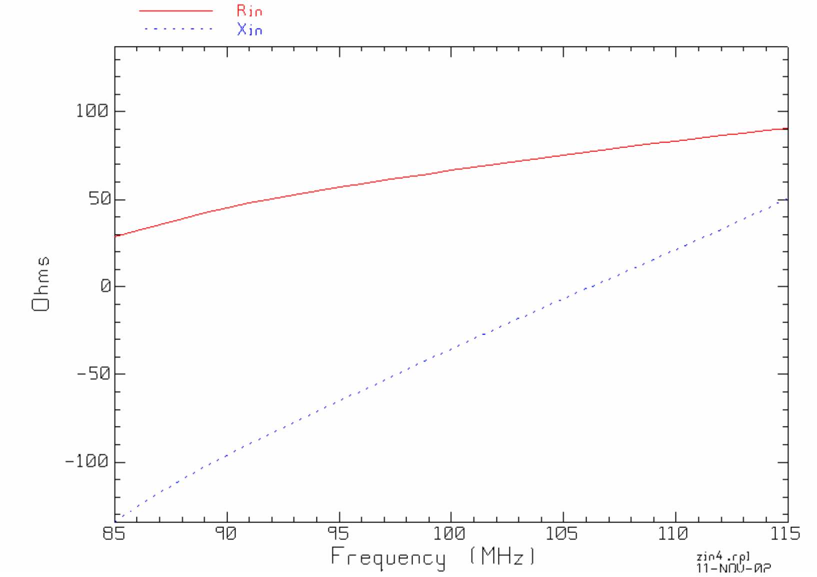


- Trial #3: flatter directivity.
- For trial #4, make the antenna even smaller. Multiply by 0.95
    - Director length 1.0127x0.95=0.9621
    - Director spacing 0.7595x0.95=0.7215
    - Number of directors? 6
    - Feeder length 1.3677x0.95=1.2993
    - Reflector length 1.714x0.95=1.628

- Reflector spacing 0.8575x0.95=0.8146



- The directivity for trial number 4 is "in spec" across the frequency band. It is larger at the extreme frequencies and smaller at mid-band.
- What is the input impedance?
- Look at the input impedance file, ZIN.DAT created by GETFREQ:



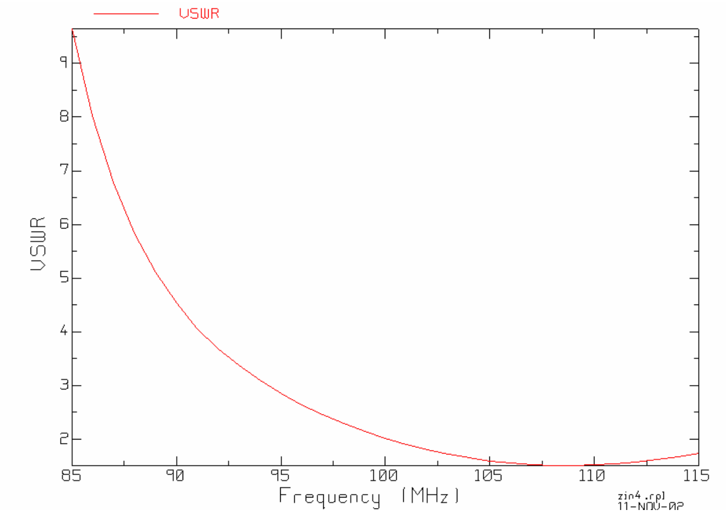
- The input resistance rises across the frequency band
- The input reactance rises linearly and has a zero around 106 MHz.
- What is the VSWR?
- Calculate the VSWR seen by the generator as a function of the frequency:

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$$

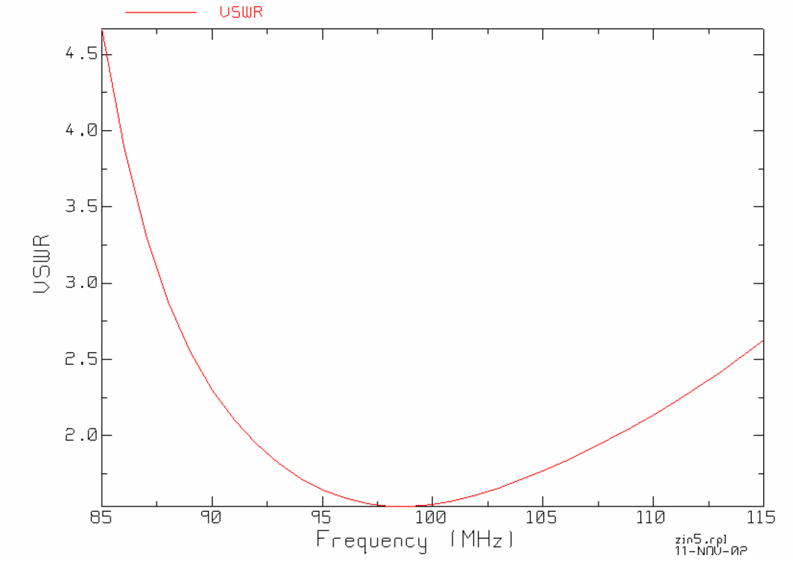
and Z_0 is the generator impedance of 120 ohms, and Z_{in} is the antenna input impedance. Then the VSWR is:

$$\text{VSWR}=\frac{1+|\Gamma|}{1-|\Gamma|}$$

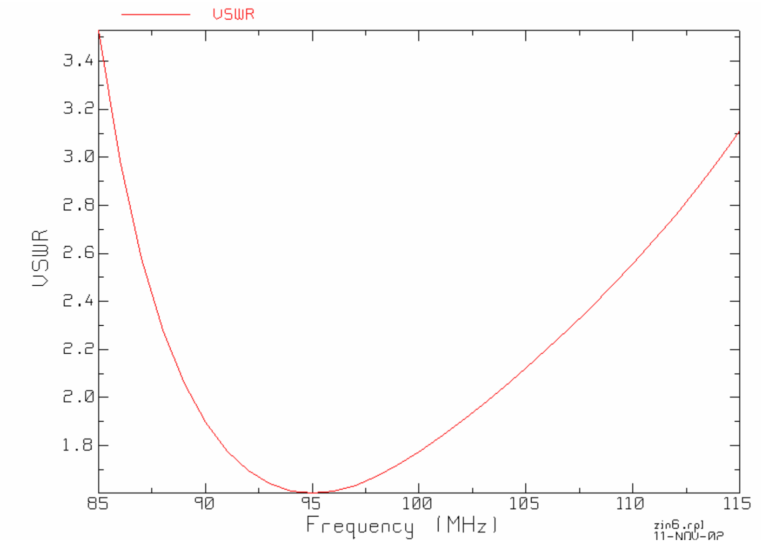
- Program GETFREQ does this for us, which is why GETFREQ asks for the generator impedance.
- The VSWR will be found in one of the columns of the ZIN.DAT file, and can be graphed with RPLOT:



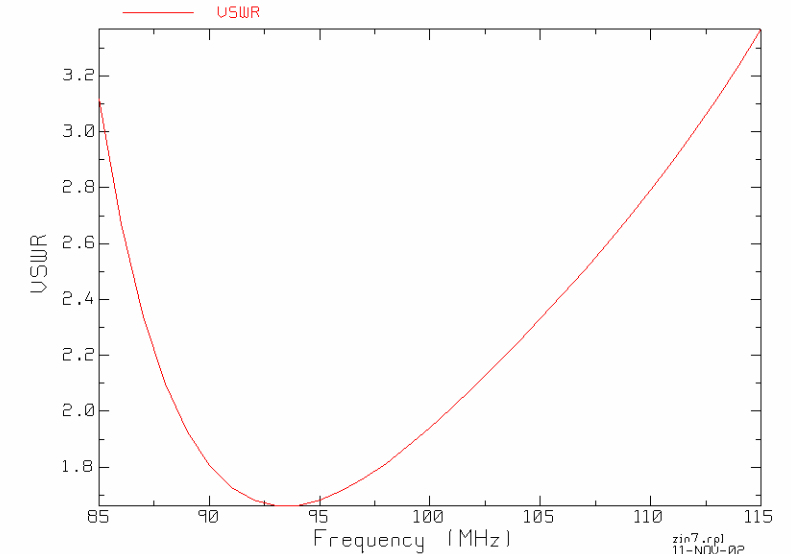
- We are very considerably “out of spec” here.
- We need to shift the minimum in the curve down to a lower frequency.
- We can do this by increasing the length of the feeder.
- Shift by 109/100 or about 1.1, so:
    - Feeder length 1.2993x1.1=1.4293



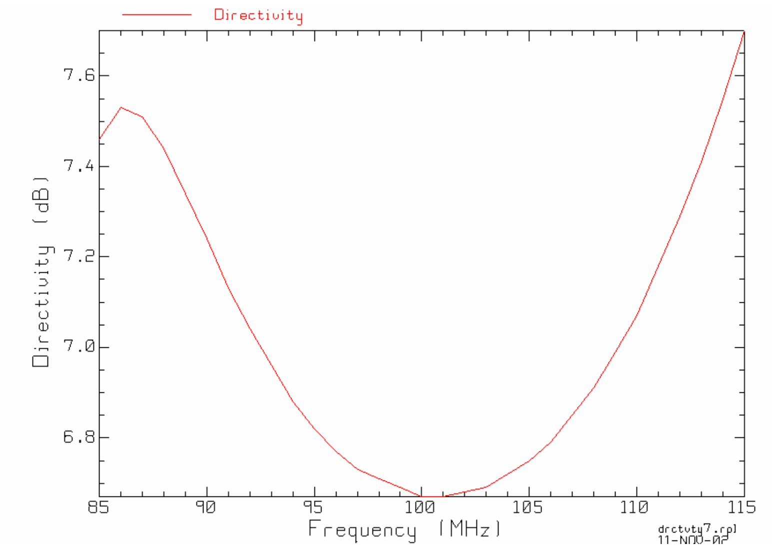
- Trial #5: longer feeder.
- The VSWR is still quite asymmetrical.
- We can shift the curve down more so that the VSWR at the low end and at the high end is about the same.
- Increase the feeder length by 99/95=1.04:
    - Feeder length 1.4293x1.04=1.4865



- Trial #6: even longer feeder
- The curve is still somewhat asymmetrical:
    - at 85 MHz, VSWR=3.5
    - at 115 MHz, VSWR=3.1
- So shift the curve down a little more by changing the feeder length by another 1.02:
    - Feeder length 1.4865x1.02= 1.5162

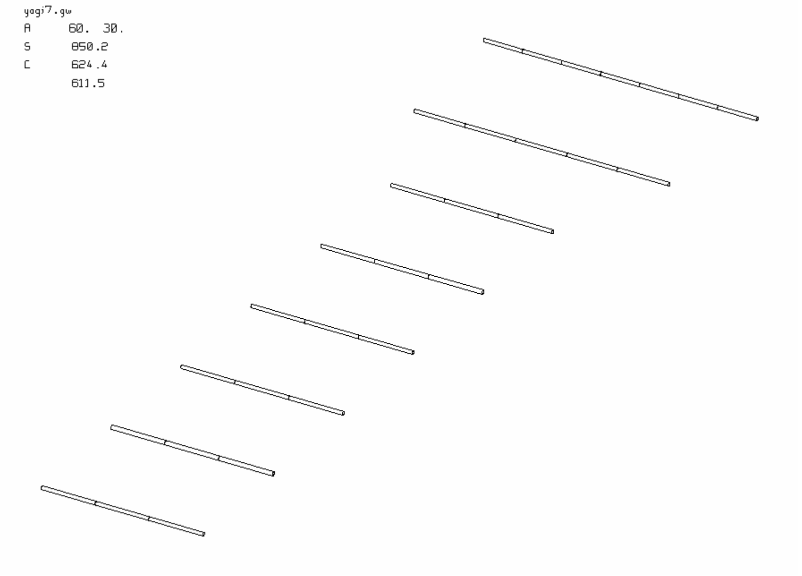


- Trial #7: yet longer feeder.
- This is reasonably symmetric.
- Also it meets the “spec” of VSWR<3.4 over the whole band.
- Verify that the directivity meets the spec:



- The directivity is > 6.5 over the whole band from 85 to 115 MHz.
- Note that changing the feeder length does not much affect the directivity, so the feeder can be used to “tune” the impedance.
- We will accept the final design as:

```
Frequency range:       0.8500000E+02 MHz, to   0.1150000E+03 MHz.
Reflector length:      0.1628000E+01 m.
Feeder length:         0.1516200E+01 m.
Director length:       0.9621000E+00 m.
Reflector spacing:     0.8146000E+00 m.

Director spacing:      0.7215000E+00 m.
Number of directors:     6
Wire radius:           0.1000000E-01 m.
Segment length:        0.1000000E+00 wavelengths.
```

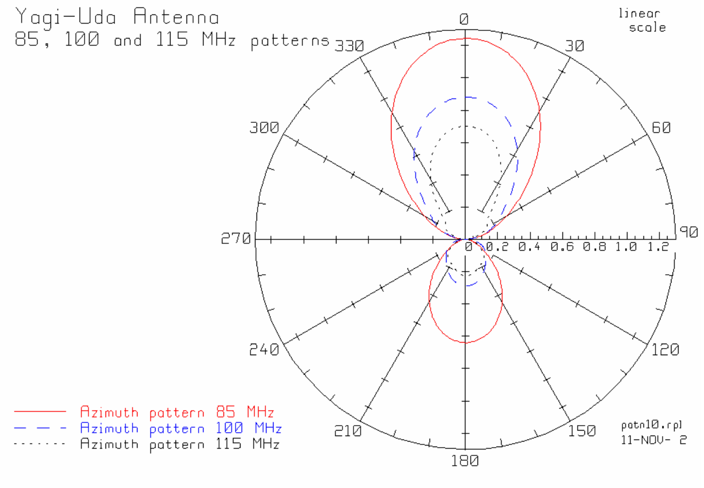


- We could also adjust the reflector. It may be possible to “meet the spec” with one less director, with careful adjustment.
- We are asked to graph the radiation patterns at 85, 100 and 115 MHz.

Radiation Patterns

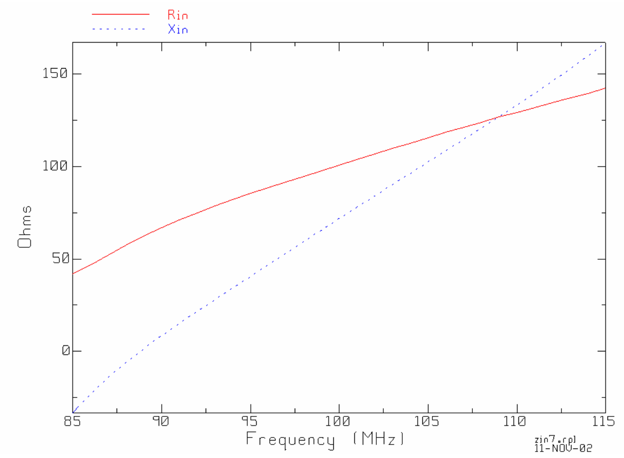
- We are asked to drive the antenna with a 1-volt, 120 ohm generator.

- We can simulate this with NEC by “loading” the generator segment with 120 ohms:
    - excite wire #2, segment #5 with 1 volt:
      ```
      EX   0     2     5     0         1.0          0
      ```
    - load wire #2, segment #5 with 120 ohms in series:
      ```
      LD   0     2     5     5       120.          0.          0.
      ```
- To get the radiation patterns, run NEC at 100 MHz with two “RP” cards:
```
FR   0     1     0     0    100.0000   0.
RP   0     1   361     0        90.         0.         0.         1.
RP   0   361     1     0         0.         0.         1.         0.
```
- Then run GETPATN to read the NEC output file and make a data file PATN.RPL for plotting with the polar plot program, PPLOT.EXE.
- The electric field strength output by NEC omit the $\frac{e^{-j\beta r}}{r}$ factor, so can be interpreted as:
    - either “field strength in V/m at 1 m distance”
    - or more usefully as “field strength in mV/m at 1 km distance”
- You can explicitly include 1000 m as the distance to the “far field” point in NEC, in which case the field strength output is V/m at 1 km.



Azimuth Pattern, linear scale, 100 MHz

- In this pattern the antenna is driven with a 1 volt, 120 ohm generator.
- Hence the field strength includes the effect of the impedance mismatch between the 120 ohm generator and the antenna’s input impedance.
- Recall the directivity is larger at 85 and 115 MHz than at 100 MHz.
- The azimuth pattern has the largest field strength at 85 MHz.
- Conversely the field on axis is smallest at 115 MHz, even though the directivity is largest at 115 MHz.



- The input impedance at 85 MHz has a small resistive part and a large reactive part.
- Conversely the input impedance at 115 MHz has a much larger reactive part.
- The performance of this antenna is not very satisfactory!
- We would prefer to adjust the antenna so that the on-axis field strength is roughly uniform across the frequency bandwidth.

Homework 7

Design a Yagi-Uda antenna to meet the following specification. The directivity must be greater than 9 dB from 800 to 900 MHz. The VSWR must be less than 2.1 across the whole frequency band, for a generator with internal impedance 50 ohms. The antenna is to be built of aluminium tubing 2 mm in diameter. Try to use as few elements as possible so that the antenna will be simple and inexpensive.

(i) Give all the dimensions of your design for the antenna.
(ii) Plot the directivity as a function of frequency from 800 to 900 MHz.
(iii) Plot the input impedance and the VSWR as a function of frequency.
(iv) Plot the azimuth pattern at 800, 850 and 900 MHz, for a 1-volt generator of 50 ohm internal resistance. Use millivolts per meter at 1 kilometer to plot the radiation patterns.

Continue with Lecture 15…