Yagi Antenna Q factor

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Introduction

In one of my previous articles [1] I proposed use of the antenna SWR working bandwidth as contributor in evaluation of Yagi antenna figure of merit. Antenna VSWR bandwidth is important as relative measure of antenna Q factor and overall antenna reproducibility and sensitivity to presence of other objects in its near field. Because of that, VSWR bandwidth or Q factor contribute to overall characteristics of antenna.

The VSWR bandwidth is relative measure of antenna Q factor and it is very important factor for any evaluation of overall Yagi antenna quality. In this article I want to show how we can calculate antenna Q factor for use in antenna quality evaluation instead of previously proposed use of VSWR bandwidth.

Antenna Q factor importance

We can discuss how antenna Q factor influence is considerable, how it is sized for our goals and what we want to get from our antennas, but we mustn't forget that a truly good antenna must have low Q factor and high radiation resistance, not only the maximum possible gain!

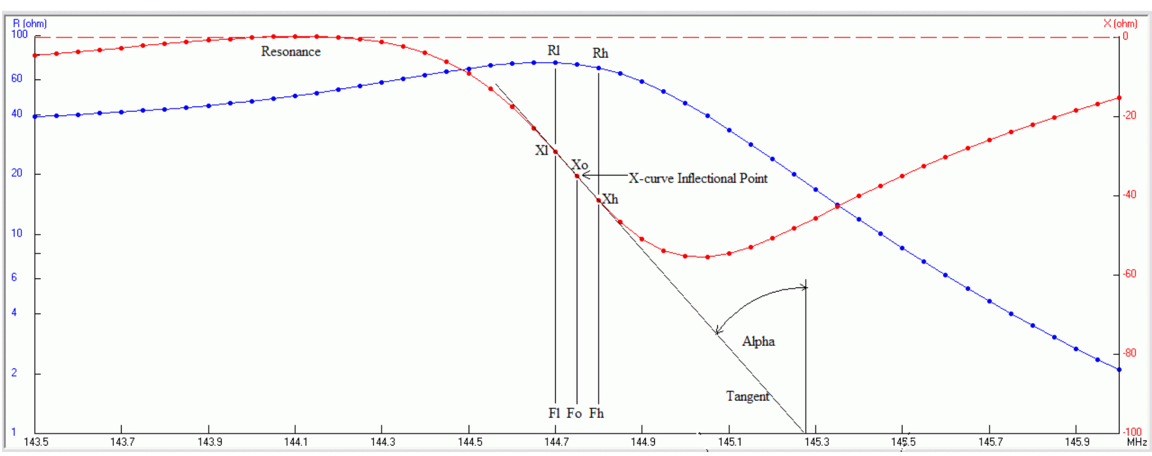
Possibility for realization of this projected maximum gain in practice depends on the antenna's Q factor. It is similar as how antenna low noise temperature realization in practice (increased receiving signal to noise ratio) strongly depends on environment equivalent noise temperature as described in referenced article [1]. In practice, an antenna will perform according to real environment noise conditions regardless of how low sky noise standard is used for its noise performance evaluation. If we want to know how an antenna performs in practice we have to use the most probable sky and ground noise temperatures standards for antenna evaluation. Surely it is not the absolute minimum sky noise temperature which is possible for a given frequency at one very small and limited part of the sky [1].

Antennas with high Q factor with narrow bandwidth or low radiation resistance have high sensitivity to invasive environmental factors (rain, snow, ice, other antennas and objects) and low practical reproducibility of performances. It is not good if the VHF/UHF Yagi antenna VSWR bandwidth is merely wide enough for the specific antenna use. For instance, 200 kHz bandwidth is more than enough for EME.

What is the benefit of the antenna with high projected gain if it is so critical that it's impossible to reproduce its performance in practice due to its very critical behavior? Highly optimized antenna gain can be fully realized in practice only if the conditions in practice are the same as conditions under which the antenna is optimized in the computer simulation program. Usually, during computer simulation and optimization of the antenna performances, antenna working condition is "free space". Contrary to that, practical antennas never actually work in free space condition! In practice there are plenty of various objects around very close to the antenna which may not be considered in the antenna simulation model whatsoever. Impact of all those objects to the antenna performances will be minimal but only if the antenna is not sensitive to environmental influence.

The only way to preserve antenna performance despite these negative, detuning and destructive factors is to build the antenna with very low Q factor. This is particularly important for Yagi antennas because they achieve high performances due to very precise balance of currents magnitude and phase which are flowing in its passive elements. Any detuning and environmental influence to that balance can severely ruin the antenna performance, especially if the antenna is critical due to its high Q factor. Big antenna systems with many individual antennas that are stacked and phased or with many close spaced different antennas on the same tower are also very susceptible to high mutual influences.

The low Q factor of an antenna significantly increases the possibility that the performances derived as a computer simulation and optimization results can be realized in practice. It means that realization of: antenna gain, system stacking gain, radiation diagram, SWR and gain working bandwidth, proper impedance of each antenna in the system and thus proper power distribution and phasing in multi antenna stacked systems, behavior of the antenna system in different weather conditions and the antenna responses to influence of surrounding objects, all that strongly depend on antenna Q factor value. That is the reason why Q factor, besides the antenna gain, is one of the most important factors of every antenna. Another important factor for the antennas at frequencies above around 1 GHz is its effective noise temperature.



Example of antenna Q-factor calculation
from antenna resistance and reactance diagram

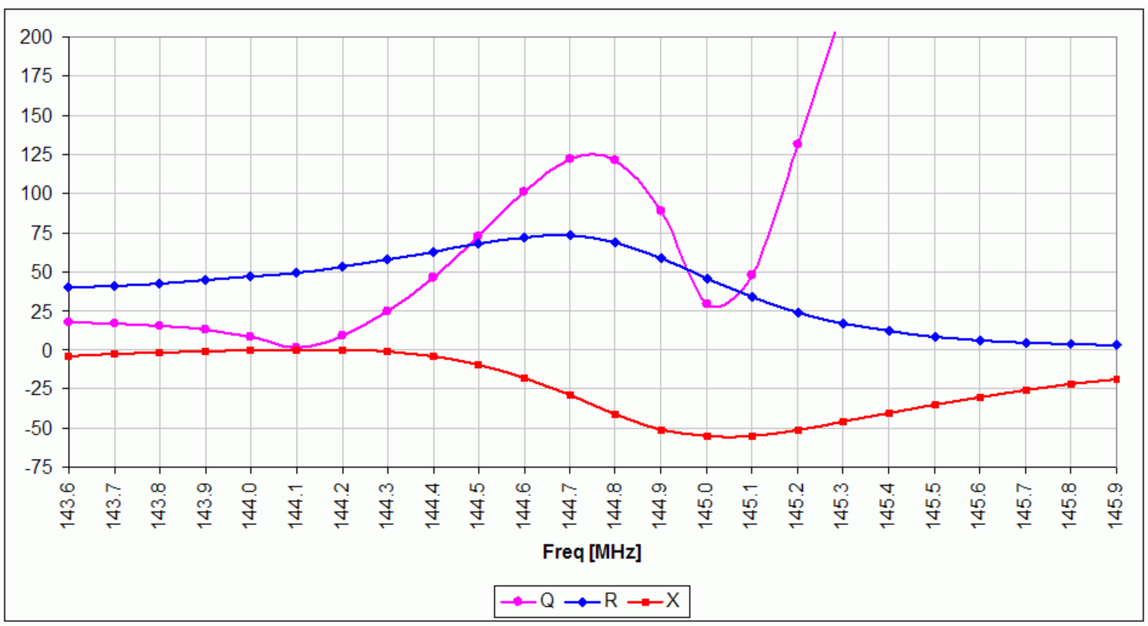
Antenna Q factor calculation

The standard Q factor calculation of antenna in resonance or at any other frequency is given in appendix of article [2] and in book [3].

The calculation uses given formulas and can be performed together with simulated antenna resistance and a reactance diagram. From this diagram it is possible to get R and X values for different frequencies close to the resonance or at any other frequency in the working bandwidth. Such antenna Q factor calculations give even more precise results than SWR bandwidth although both are causally related to antenna impedance behavior around the resonance.

This Q calculation is much more complicated and time consuming. So I decided to propose in my previous article [1] the direct use of the VSWR bandwidth as a relative measure of the Q factor which is much simpler for use and gives results which shouldn't be very different than direct Q factor use. This is because of close causal relations of Q factor and SWR bandwidth.

Direct use of the VSWR bandwidth as a measure of Q factor of antenna is much easier than exact calculation of Q factor but in some cases it can lead to inaccurate results. Although Q factor and SWR bandwidth are causally connected, for multi-element antennas such as Yagi these values are connected in a much complicated way and can be different from the simple one-element antennas. This can give inaccurate results.
It was obvious that it is much better to calculate the Q factor of the antenna and get accurate results although it needs much more effort to accomplish this.



Result of antenna Q-factor calculation from antenna resistance and reactance diagram

An antenna, as any series RLC circuit, has a Q factor which can be calculated according to following equation [2], [3]:

$$Q = F / 2R * (dX / dF + |X| / F)$$

where F is frequency, X is antenna reactance and R is antenna resistance consisted of radiation and loss resistances.

Because loss resistance is usually very small for Yagi antennas, radiation resistance play an important role in Q factor of antenna.

Antenna input resistance R can change within the limits of a frequency segment in which Q is calculated, so it is convenient to use the mean average value of resistance in that segment. Mean average value of R for the segment is $Rm = (Rl+Rh) / 2$ and formula for the Q factor calculation can be rewritten as

$$Q = Fo / (Rl+Rh) * | (Xh-Xl) / (Fh-Fl) + |Xo/Fo| |$$

where indexes **l**, **h** and **o** denotes values at lower, higher and central frequency. This standard equation is valid for (series) resonance frequency and also for frequencies much below or above the resonance. [2], [3]

The program for antenna simulations gives the antenna input impedance data which can be used for the Q factor calculations according to given formula for any frequency in the working bandwidth of antenna. This tedious task is accomplished with the aid of an Excel spreadsheet in which all necessary input data are imported from the antenna simulation program output file and results are very easily and quickly combined giving all necessary data comparisons.

The value of dX/dF is the slope of tangent at X-curve at desired frequency. The more vertical slope of tangent, the higher the antenna's Q factor is on that frequency. Minimum angle between tangent and vertical axis shows were the maximum Q factor usually happens. It is at the frequency where Alpha angle is minimal and tangent most vertical. It is possible to compare antennas either according to their maximum Q factor values or according to their average Q values in a specific working bandwidth.

The Excel spreadsheet program takes a small "straight" (linear) part of the X curve between two consecutive frequency steps and uses 3 points on that line on 3 frequencies: low (Fl), high (Fh) and middle or center (Fo). X and R values on all 3 frequencies are used in the program for the Q factor value calculation according to the formula above.

Because the Q factor depends on value and slope of both X and R curve, the Q factor value changes in the antenna's working band. Accuracy of results is improved if the program uses as linear as possible parts of X and R curve for this calculation (small frequency step), so that Fl, Fo and Fh are close enough to each other.

How small antenna Q-factor should be?

The answer to this question is very similar as for antenna effective noise temperature. It should be so small that effects in practical work can be neglected. Antenna Q factor should be low enough that influence of the antenna's surrounding objects are so small that they can be ignored because the antenna is projected and very precisely optimized by computer simulation programs for work in free space conditions as though free of any object in its proximity.

If the Q factor is not so small that influence of the antenna's closely spaced objects can't be ignored, then it is not the same antenna so precisely optimized and which we are talking about because in practice it doesn't match the performances that were calculated in the simulation program.

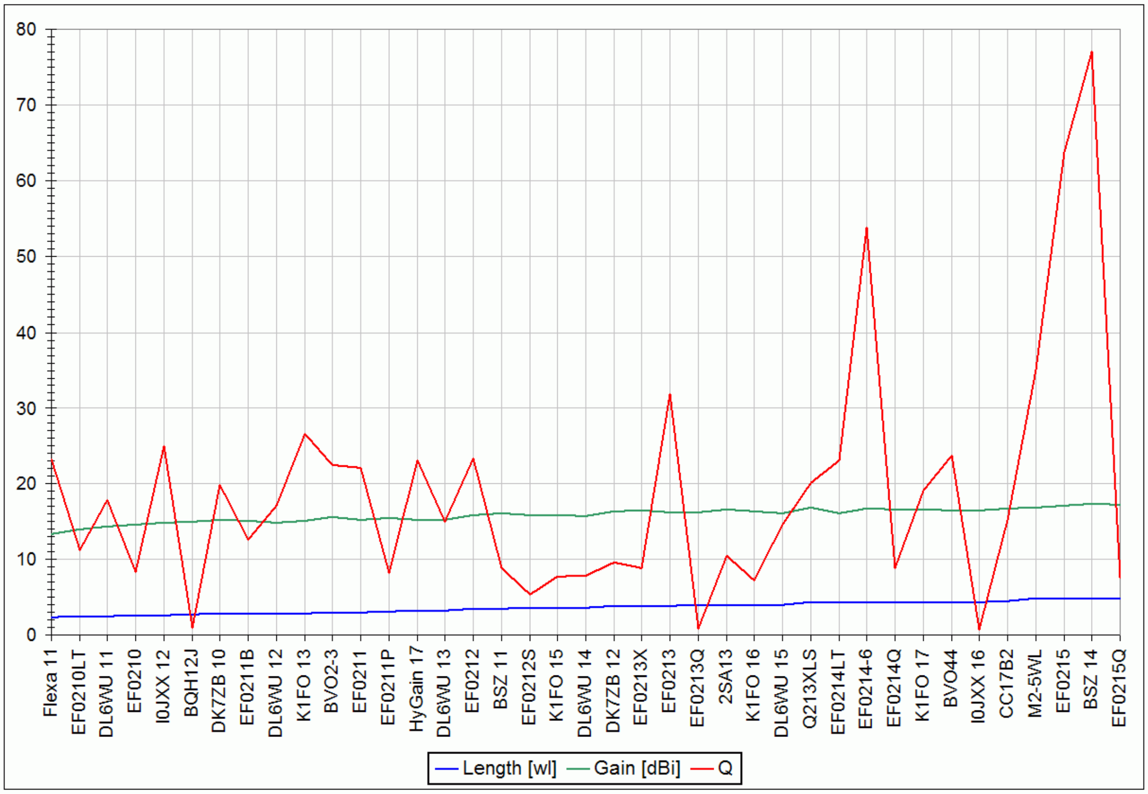
Whether these newly determined performances are still good for us is another question, but it is obvious that they probably will be closer to projected performances if the antenna suffers less degradation of its performances due to negative impact of environmental conditions. The antenna will suffer less degradation if it has lower Q factor.

It would be very nice if we had a "rule of thumb" where an antenna Q factor would be low enough to guarantee negligible antenna performance degradation. But unfortunately there is no such arbitrary rule because of so many different antennas and many environmental factors involved.

It is true that an antenna with extremely low Q is a good antenna, but it doesn't mean that all antennas have to have such a low Q factor. For instance, DL6WU antennas are very tolerant because you can add or subtract some of the antenna end director elements without any noticeable degradation of performances except some expected change in antenna gain due to its different boom length. But DL6WU antennas don't have extremely low Q.

It is obvious that it is very difficult to find demarcation between critical and not critical antennas because the margin is not so sharply defined but it is rather transitional from good to bad antenna when slowly increasing its Q factor. Besides that, the number and type of other antennas and other objects around the antenna also play an important role in what will happen with a particular antenna in a particular environment.

It is not the same if the antenna, which is optimized in simulation program to work as isolated in free space, when in practice works alone on the top of slim high pole or on a big fat lattice mast in companion with various other close-spaced antennas. Because of that the first circumstances are much more similar to virtual circumstances in which the antenna was optimized in simulation program. In the latter situation it could be expected that in a real environment, which is in practice drastically different from computer simulation environment, antenna performances will be considerably different, especially if the antenna has a high Q factor—the measure of antenna sensitivity to environment change. In principle, the rule of thumb is: the smaller the antenna Q factor, the better (less sensitive) the antenna.



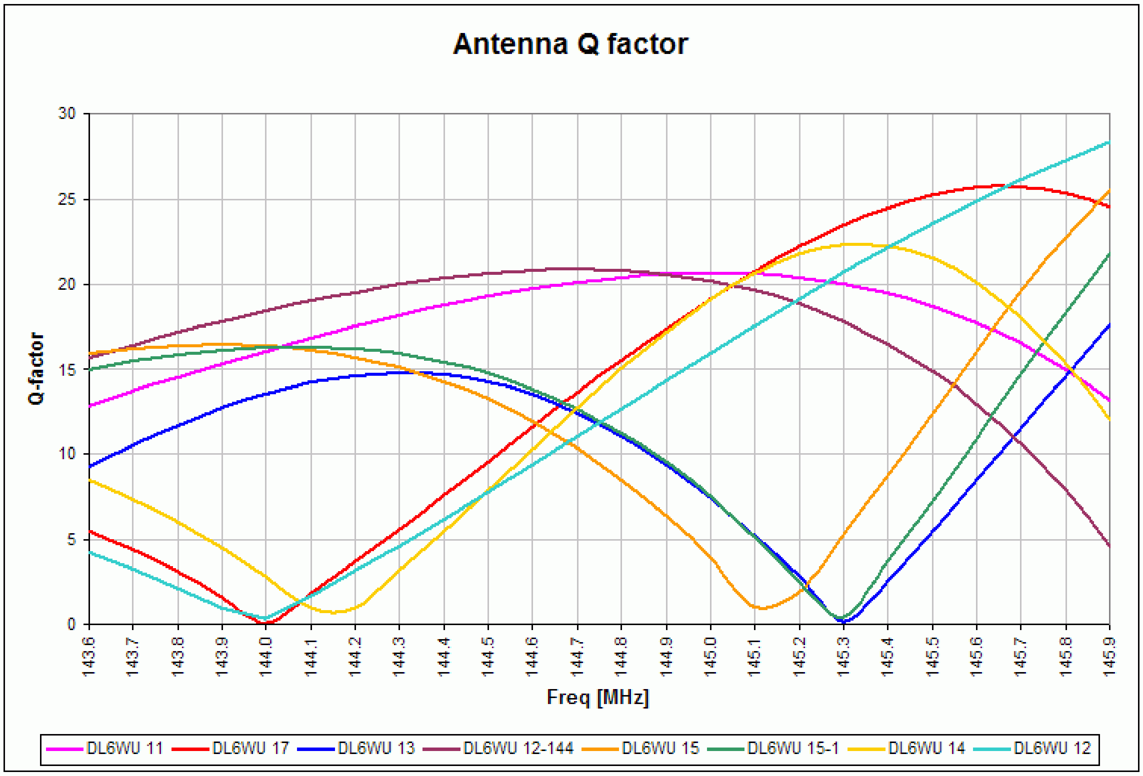
Q-factors around resonance, Boom Length and Gain of various Yagi antennas

Yagi antenna boom length, gain and Q factor

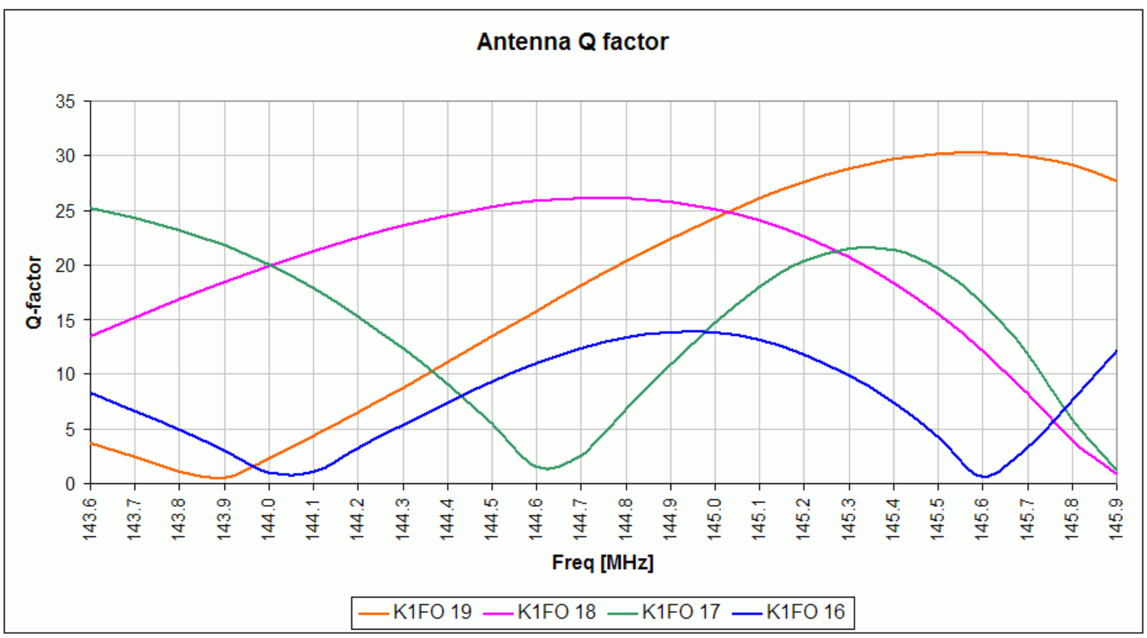
As can be seen from the diagram, uniformly increasing boom length of optimum designed antennas produces uniform increase of gain. This gain increase is, according to early works of Gunter Hoch, DL6WU, about 2.3 dB per every boom length doubling. But what happens to the antenna Q factor? It seems that Q factor is almost independent of boom length and of antenna gain. The only observed dependence is that with squeezing the last bits of dB in order to get maximum gain of the antenna with extreme suppression of side lobes to produce an extremely high F/B, its Q factor increased considerably. But this maximized gain is very rarely larger than 0.5 dB compared to other antennas of the same length with reasonable Q factor.

Also, extreme suppression of side and rear lobes in order to achieve the best possible antenna noise performance produces considerable increasing of the antenna Q factor. But on the other side, practical realization of these projected better F/B and noise performances strongly depends on noise and multipath reflection conditions on the site where antenna is located and very often can’t be realized in its full extent.

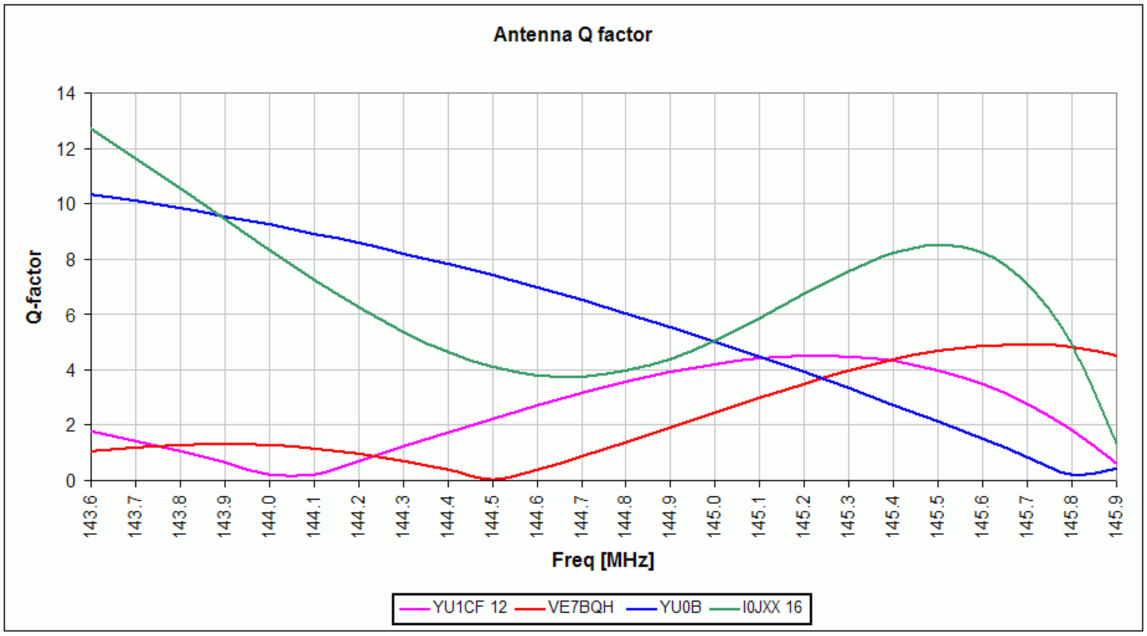
Computer optimization of antenna parameters for work in very narrow VSWR working bandwidth inevitable leads to high Q factor of antenna. On balance, it is clear one who carefully chooses good compromises between mutually confronted performance requirements can make good antennas. This is so even it is not instantly visible on the antenna simulator because the Q factor effects are not visible in free space antenna simulations!



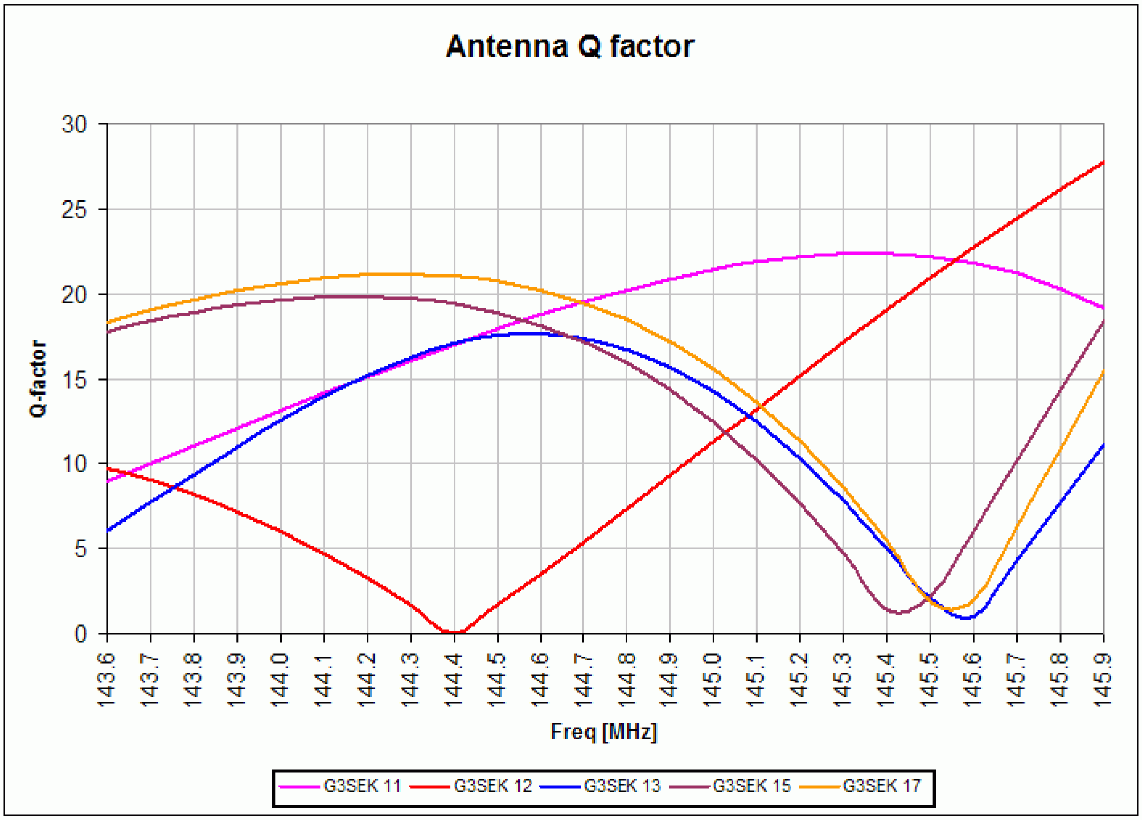
Q-factors of DL6WU Yagi antennas with various boom length



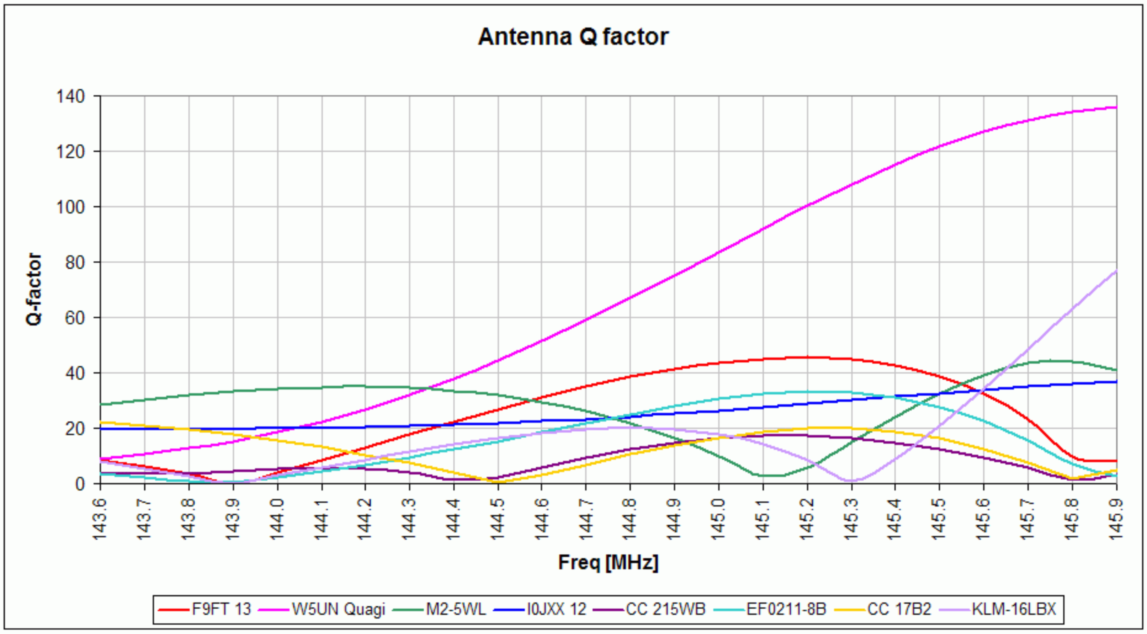
Q-factors of K1FO Yagi antennas with various boom length



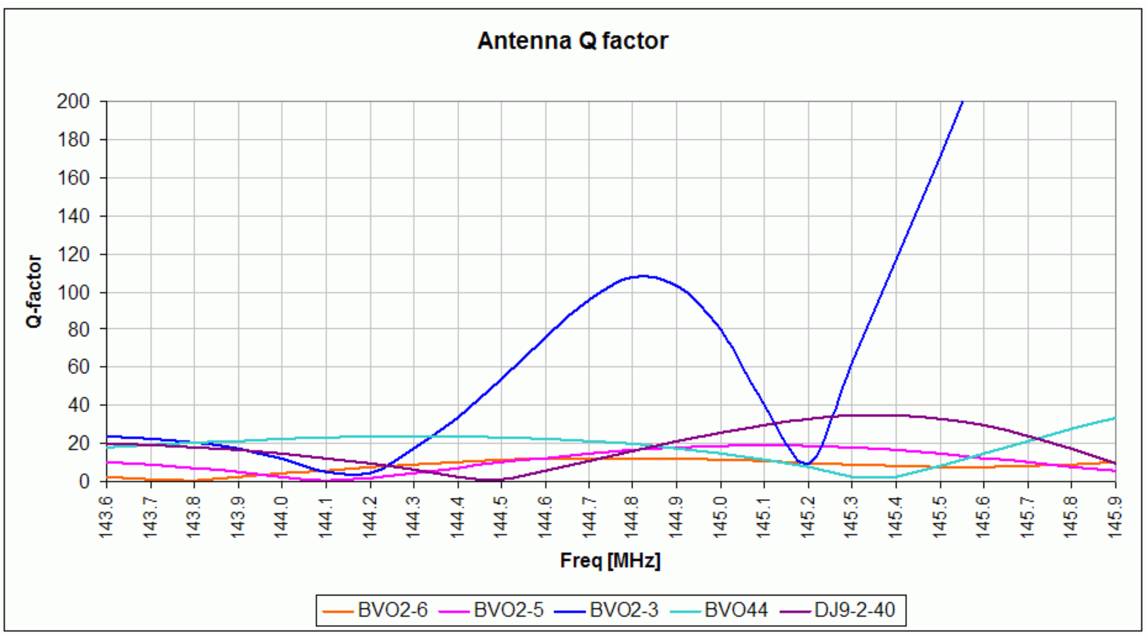
Extremely Low Q-factor Yagi antennas of various experimenters



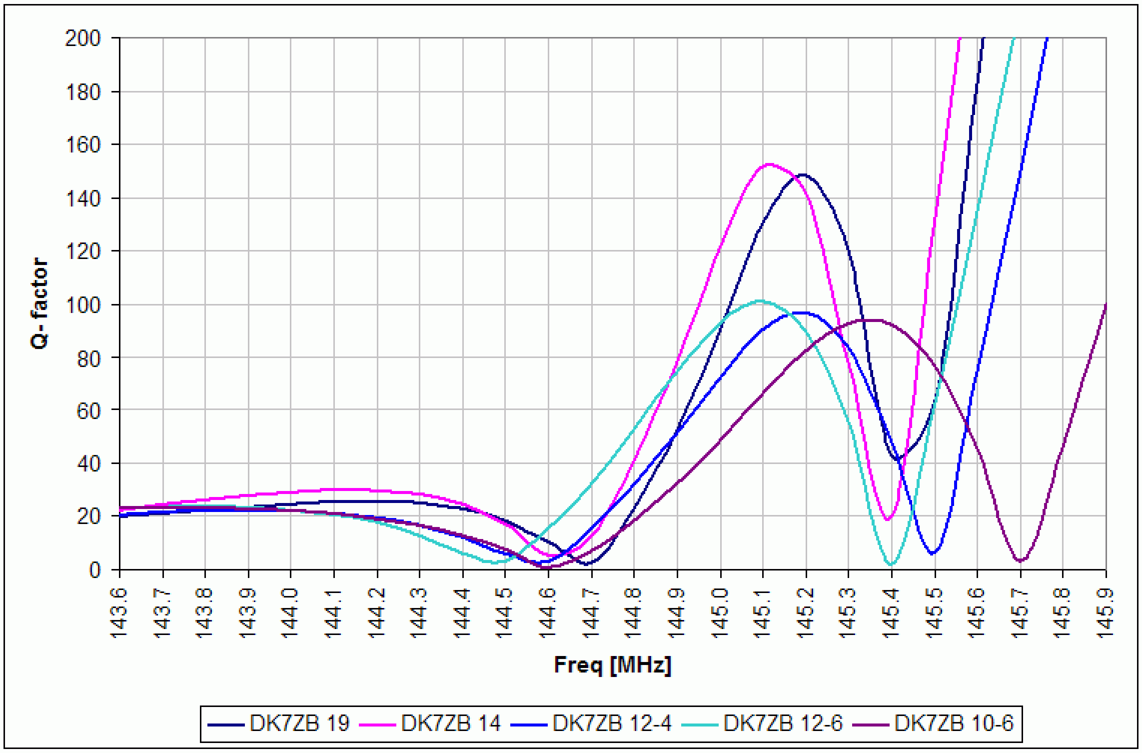
Q-factors of G3SEK Yagi antennas with various boom length



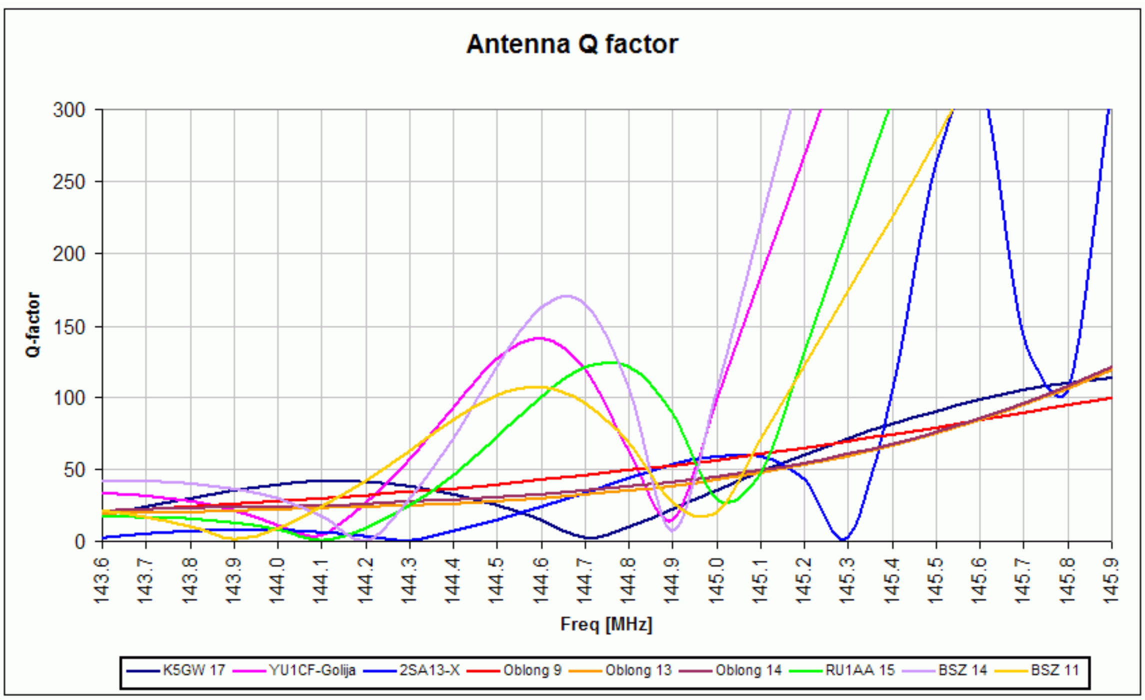
Medium Q-factor Yagi antennas of various experimenters



Q-factors of DJ9BV Yagi antennas with various boom length



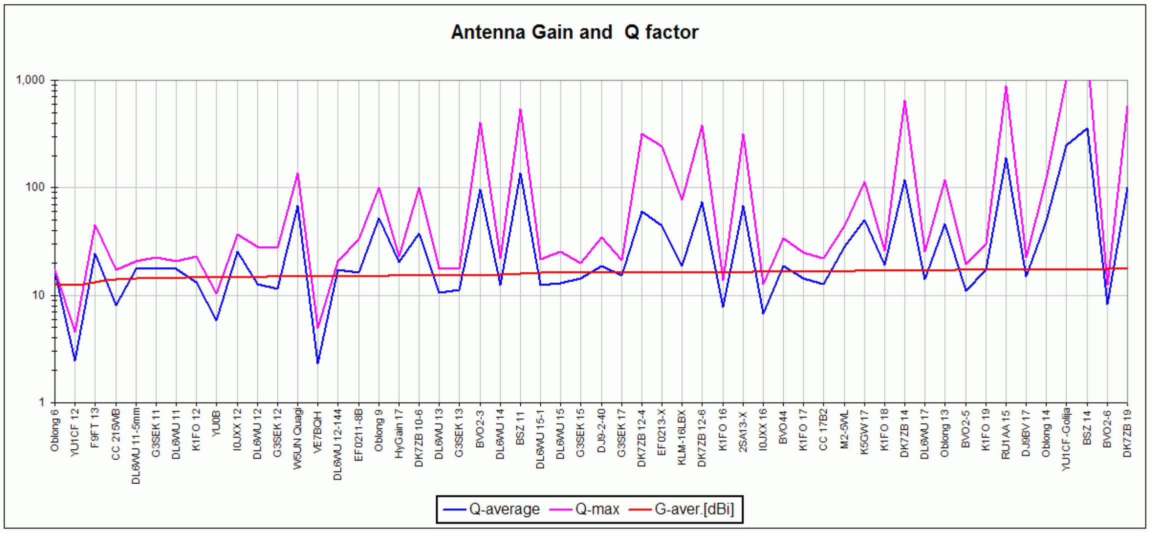
Q-factors of DK7ZB Yagi antennas with various boom length



High Q-factor Yagi antennas of various experimenters

All this antenna high Q factors clearly show that many experimenters projected their antennas choosing poor compromise between some of important antenna performances.

Their antennas look very nice on antenna simulators in a free space environment because, on the simulator, the environmental things that occur in practice are not considered and will differ from those nice predictions on the computer screen. Antenna SWR measurements usually cannot provide a complete insight to the problems and render true answers to this question of difference.



Gain and Q-factor of Yagi antennas from various authors

Conclusion
In this paper, according to presented material, I show that proper Yagi antenna design philosophy must take into account all important factors of antenna, not only gain or any single requirement alone (F/B, effective noise temperature, etc.). Among them, it is shown that Q factor plays an important role in overall antenna quality and especially in its behavior in a practical environment.

The antenna Q factor value presents a measure of probability those successful performances from the virtual world of computer simulations will be realized in the real world of a hostile environment in which antenna must work.

It is obvious from the diagram above that the antenna Q factor is relative to gain in such way that it is possible to achieve high gain antenna together with low Q factor.

There are many antennas with almost identical gain but with enormous difference in antenna Q factors!

So it seems that there is nothing to stop us to simulate, build and use high gain, low Q factor Yagi antennas! **-30-**

Reference

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BRIEF BIOGRAPHY OF THE AUTHOR

Dragoslav Dobričić, YU1AW, is a retired electronic engineer and worked for 40 years in Radio Television Belgrade on installing, maintaining and servicing radio and television transmitters, microwave links, TV and FM repeaters and antennas. At the end of his career, he mostly worked on various projects for power amplifiers, RF filters and multiplexers, communications systems and VHF and UHF antennas.

For over 40 years, Dragan has published articles with different original constructions of power amplifiers, low noise preamplifiers, antennas for HF, VHF, UHF and SHF bands. He has been a licensed Ham radio since 1964. Married and has two grown up children, a son and a daughter.

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