Upgrading your Argus station: where to put the money?

(SETICon02)

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ABSTRACT: Various ways of upgrading an Argus station, like bigger dish, better receiver, more computing power are compared. Emphasis is given to the price/performance ratio. For each possibility, the cost of doubling the detection probability is coarsely estimated. Because many of the upgrades require more signal processing, the cost of computer processing power is analyzed in a separate appendix.

1. INTRODUCTION

Subtitle aside, I do perfectly well know that the real question is where to GET the money. That is too tough a question to answer in a 6 page paper, so I'll stick too the easy one here. For the purpose of rough cost comparisons, I have used the following price list: 3m dish, receiver and (new) computer: $1000 each, new feedhorn and DIY upgrades: $100 each, and software $0 (GNU or homebrew or other freeware).

Of course, your mileage may vary, depending whether you prefer to shop Fifth Avenue or Flea Market or do some homebrewing. A typical Argus station, costing $3000 according to the above list, is taken as a reference in the calculations.

The detection probability is proportional to the amount of parameter space covered. This includes among others three spatial dimensions, the frequency (bandwidth) dimension and time dimension (how much time you spend listening). The spatial volume covered is

$$V = r^3 \frac{\Omega}{3} \qquad (1)$$

where r is range and Ω is solid angle:

$$r = \frac{C_1}{\sqrt{S_{min}}} \quad (2) \qquad S_{min} = \frac{C_2 T_{sys} B}{d^2} \quad (3) \qquad \Omega \approx C_3 \left(\frac{\lambda}{d}\right)^2 \quad (4)$$

where S_{min} is the minimum detectable signal power density, d is dish diameter, T_{sys} is system noise temperature and B is bandwidth. Various physical constants and other quantities like transmitter EIRP that aren't discussed in this paper are lumped together in the constants C_1,C_2,C_3. Constant C_2 also hides the required S/N ratio for the required false alarm rate, which depends on the sophistication of the processing. Explanation of these equations can be found in any reference book on radio communications, for example [1]. Taking this together, we get:

$$V = \frac{C_4 \lambda^2 d}{(T_{sys} B)^{\frac{3}{2}}} \qquad (5)$$

2. BIGGER DISH

This is probably the most obvious way to go, but also the most expensive. The cost of a new dish is approximately proportional to the third power of it's diameter. [2] To double the detection probability (DP) of a single station by dish size alone, you need to double it's diameter, doubling your instantaneous search volume. According to the above price list, this will cost you $8000. This may seem very pessimistic, but even if you get the dish for free, consider the costs of transport, stronger support structure, bigger concrete foundation, rental cost for the crane to put it up etc etc...

Things get even worse if we look at this from the viewpoint of the whole Argus system (whole sky coverage). Bigger dishes have narrower directional patterns - the number of dishes needed to achieve whole sky coverage goes up as the square of the dish diameter. So the cost of the complete system is proportional to the fifth power of the dish diameter! However because of the increased number of stations, the DP from the system viewpoint increases faster, namely with the third power of the diameter. Therefore, the whole system cost goes up as 5/3 power of the DP increase achieved by dish enlargement - if we neglect the cost of the receivers and computers for the additional stations.

There is a way around the need for additional dishes: by putting several feedhorns (see section 4 below) in a single bigger dish, the same amount of sky can be covered as with the small dish. Of course, each feedhorn still needs it's own receiver and signal processing. For such a multibeam station, the DP also increases with the third power of the dish diameter. For example, a dish twice the diameter needs four beams to cover the same solid angle and each beam has twice the DP because of the higher gain, together giving 8 times the DP.

For a dish twice the size with four beams, the extra cost is cca $12000..$16000, depending on the number of additional computers needed. But that buys you eight times the DP - equal to doubling it three times. Depending on how we divide the money between the three doublings (1:1:1 or 1:2:4) the first doubling costs between $1700 and $5300. (The price estimates I'm making here are VERY coarse)

3. MORE DISHES

Obviously, putting up two dishes with independent receivers and signal processors looking in two different directions will double your DP at twice the cost ($3000 extra).

What about connecting the dishes into a coherent array? By phasing two dishes together into a single-output antenna, you get 3dB more gain, the same as increasing your diameter by 41%, so your DP is 41% higher - less than two independent dishes!

The right way to do it is to synthesize two beams. This is relatively simple, requiring only some passive components. Now your DP has increased 2.83 times, better than two independent dishes. The two beams need separate receivers and processors, of course. This means $2000 for doubling the DP. The number of synthesized beams is limited by the beamwidth of the individual antennas. In a passive system it's probably best to make the number of beams equal to the number of antennas.

To get nicely shaped beams, the dishes should be mounted close together. For widely spaced dishes, the beams will split into multiple interferometric maxima, so one would have to synthesize 'interlaced' beams. For very wide spacings in longitude, this will cause amplitude modulation - 1Hz at 21 cm for cca 3km spacing. To avoid this, you need to do “fringe stopping” by constantly adjusting the phase of the LO at on end [3], effectively keeping your beams sidereal.

4. MORE FEEDHORNS

Array feeds are common on satellites that must service an odd-shaped geographical area. Closer to home, some people put several LNBs on their TVRO dishes to receive more than one satellite with the same dish.

In SETI, a second feedhorn, offset in right ascension, is sometimes used for a kind of 'self confirmation' system: if a signal first pops up in horn 1 only and a certain time later in horn 2 only, you can be pretty sure it hasn't arrived via the sidelobes or some other illegal path. Multiple feedhorns could be also used to increase the solid angle coverage of the dish.

Using two feeds in the same dish with independent receivers/processors will double your DP for $2000 - or even $1000 if your existing computer can handle two channels. It's almost the same as having two independent dishes (section 3 above), only your 'direction freedom' is more limited. Within reasonable limits on the number of the horns (say, a bunch of seven closely packed 17cm dia tubes on a 3m dish), the gain on each of them is virtually the same as that of a single central feed. It is only diminished a little because of the increased aperture blockade (unless you have an offset dish) and some phase errors (coma and astigmatism in optotalk) for the side feeds.

5. THE OTHER POLARISATION

We know nothing about the polarization of the signal we want to receive. On average when receiving a randomly polarized signal with a single polarization antenna, you get only half the power. Adding a second receiver for the other polarization will double your DP, for $2000 or $1000, depending on your existing computer. A high polarization discrimination is not needed, so you can simply put another probe at right angle into your existing feed. To get a real polarization analyzing system (which is not necessary just for increasing the DP), the two receivers should have common LO's, to preserve the phase relationships. This is probably more easily done with DIY kits like R2 than with commercial 'black-box' receivers.

6. BETTER PREAMP (LOWER NOISE)

There is not much room for improvement here. To double your DP, you have to reduce your system noise temperature 1.59 times. (The search volume is proportional to the third power of range, and range goes up with inverse square of the system noise temperature). And that is system temperature. If your preamplifier noise contributes 50% of the system noise, then you'll have to cut it to less than half of its original value to reduce the system temperature 1.59 times. HEMTs are a mature technology, so their noise figures won't fall very much in the future. Unless some new miracle devices appear on the market, cooling is the only way to go - but it brings so many additional problems with it that I don't think it's a viable option on a typical Argus station. Given this situation, it's impossible to say what a double DP (if possible at all) would cost.

7. BETTER RECEIVER

What makes one receiver better than the other for SETI? One obvious thing is a bigger bandwidth, but I'll discuss that in section 8 below. Other desirable traits might be frequency stability, if you are going for very narrow channels, or good selectivity and dynamic range, if you have to grapple with close-in interference. In my opinion, the best receiver is the one that gives you the same performance for a lower price - many of the multi-channel schemes mentioned above are 'receiver hungry', so a dollar saved here multiplies itself. An 'open architecture' that makes upgrades and modifications easy is also very desirable.
Again, it's hard to imagine how to double the DP with a change in the receiver (except for bandwidth increase), so I skip once more.

8. MORE BANDWIDTH

All of the upgrades above (except dual polarization) increase the DP by expanding the 'space space' of search - by increasing either the range or the solid angle coverage. Another possibility is to include more 'frequency space', in other words to listen on more channels simultaneously. It's easy to see that listening on twice the number of channels will double your DP. The simplest 'brute force' approach would be to split the signal from your dish and feed two receivers, tuned to two different non-overlapping frequencies. This will cost between $1000 and $2000, depending on your existing computer.

But there is a more economical way, namely modification of the hardware. There are basically three 'bandwith bottlenecks' in the system: the receiver, the A/D conversion and the amount of samples the computer can chew in real time. With commercial receivers, one is limited by the available IF crystal filters - and these don't come much wider than the 25kHz NBFM.

Homebrew direct conversion receivers are much more flexible - the R2 has already been modified from 2.5kHz to 20kHz, and it wouldn't be much harder to reach 200kHz bandwidth, for example. Also by feeding the I and Q channels to the right and left channel inputs, the bandwidth can be doubled without modifying the filters.

There are new PC sound cards coming to market just now that can sample at 90 and even 190 kHz. This way one can double the DP for between $200 and $1200.

Another possibility is to abandon sound cards altogether, and go for single bit sampling. Using just a comparator, a shift register with some timing circuits and a FIFO register connected to the EPP port on the PC, sampling rates in the hundreds of kHz would be possible. If there is no positive S/N interfering signal, no sensitivity is lost this way.

Note that I didn't mention tuning (scanning) your receiver here. That will only work if you count on the ET signal to stay there long enough. For short signals (like the famous 'WOW' signal) scanning won't significantly increase your DP, because scanning just means trading time coverage for frequency coverage (you spend less time at each frequency).

9. MORE CHANNELS WITHIN THE SAME BANDWIDTH

Another way to increase sensitivity and thereby range and search volume is to make your noise bandwidth smaller. This can be done by dividing your total bandwidth into more narrower channels by running a bigger FFT. However this has some drawbacks. All the upgrades discussed so far will increase your DP regardless of the signal modulation characteristics. In contrast, reducing your channel width requires your target signal to be narrowband enough to fit. Besides the signal's intrinsic modulation bandwidth, there are several other effects that tend to smear its spectrum, like the Doppler from Earth movement [4], instability of your receiver, interstellar scintillation etc. The Doppler is worst if you live at the equator and point your dish to the eastern or western horizon. In that case the narrowest usable channels for 21cm are about 0.5 Hz.
Doubling the size of your FFT will require a little more than twice the CPU power and will increase the DP 2.8 times for CW signals of appropriate duration. If you are currently using channels wider than a Hertz, chances are that you can double you DP at no cost, just by a software upgrade.

10. MORE SOPHISTICATED SIGNAL PROCESSING

If you have CPU power to spare, you can try improving your station by more sophisticated signal processing like multi bandwidth processing or coherent dechirping which enables you to use extreme narrow channels etc. (both of these are done in SETI@home [5]). Many possibilities are open here, and again one might gain a lot of DP without major cost or hardware modification. Skolnik [6] also has a good chapter on matched filters and detection probability.

11. CONCLUSION

In terms of cost effectiveness and work required (if you're not the man writing the software), the software alternatives are the best. They can be as simple as just increasing the size of your FFT. Next comes an increase of the search bandwidth, which 'requires some assembly'. For somebody prepared to invest in some new hardware (or who has some extra receivers and computers lying around in the cellar), adding the second polarization or an additional feedhorn (or both) makes sense. The most expensive variants on the other side, are increasing the size or number of the dishes.

APPENDIX I. THE COST OF COMPUTING POWER

In most of the examples, I have given two different prices of the upgrade, depending on whether you need to buy new computer(s). I think that today's typical cheap PC is capable of processing much more than the now standard one channel 20kHz wide, so in most cases you can take the lower price.

Regardless of that, sooner or later the power of the existing computer won't be sufficient any more. So how to buy more CPU power? The price of a typical low-cost department store new PC remains almost constant and the Moore law says their power doubles every two years or so. On the other side, the price of old PC's also decreases exponentially with an half life in the same range [7]. So theoretically, if you buy one new machine or several used ones, you get approximately the same power for the same price.

But there are some anomalies at both ends of the scale. On the high end, Intel will sell you a 10% faster CPU for three times the money - definitely not interesting here. On the low end, old machines are often available for free - or they will even pay you to take them away. Since they do have some CPU power, the performance/price ratio is infinity? Only if you have free electricity and real estate.

A typical PC, sans monitor, burns between 30 and 60W. In a SETI application, it runs 24h a day. With the current electricity prices here in Slovenia, that's approx $40 per year per machine. Ten old clunkers will burn $400 a year, probably enough to buy a newer PC with the same performance! So despite the fact that SETI signal processing is well suited for parallelization and distributed processing, too many too old computers are not economical. I reckon that it's best to buy computers that are one to two generations behind state of art - for example, if Pentium IV is the brand new chip in the spotlight, a Pentium II will be the best performer for the price.

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