META AND BEYOND

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ABSTRACT: The Planetary Society's Megachannel ExtraTerrestrial Assay (META) at Harvard's 84-foot radiotelescope is the most recent in an evolving series of high-resolution searches for ultra-narrowband (< 0.1Hz) beacons at magic frequencies. High resolution SETI matches the properties of the interstellar medium, and the necessary Doppler corrections provide a high degree of interference rejection. We will briefly review the parameters of the 8-million-channel META spectrometer and show some data from its 5 years of continuous operation. It will soon be possible to extend the bandwidth of high-resolution SETI to cover the "waterhole" of 1.4 - 1.7 GHz, at a cost and complexity comparable to META. We will describe two such systems, which we call "BETA" (Billion channel ExtraTerrestrial Assay).

I would like to tell you about an evolving series of high resolution searches that we've been doing mostly at Harvard, and mostly, in fact now entirely, with support from The Planetary Society (although we started with funding from NASA). I think this is a particularly appropriate occasion to be talking about this, because, as you'll see in our experiments, we've been obediently following the teachings and instructions of Frank and Phil, whose names will come up again and again. Many of you have heard my story before, at least the old parts of it, so I'm going to zip along (as many of you know, I always zip along anyway!). So, the talk will be: (I.) *Why* high-resolution SETI, (II.) *How* high-resolution SETI (that is... how high-resolution should it be), (III.) What have we been doing, and (IV.) What are we thinking about doing next to follow this line of flaky experiments (if they're worth following at all).

Part I. *Why* high resolution SETI? A civilization transmitting a beacon that's meant to be heard over interstellar distances has, as its objective, (a) to make a distinctive signal (b) of adequate signal to noise ratio and (c) detectable in the presence not only of natural noise, but also the contaminating interfering signals of the target civilization itself. As Frank and Phil realized early on, a narrowband carrier does this well, although it's not, by any means, the only way you could do it. Natural signals rarely have features less than a kHz, or perhaps a few hundred Hz in the case of the masers, typically somewhat broader than that. Whereas carriers, even after traversing the galactic plasma, have bandwidths less than a Hz, usually a *lot* less than a Hz. I'll show you how that works later. This screenful (Fig. 1) was delivered to our META project last June 17, at six fifty nine GMT, by Lord knows who or what, but anyway, it's kind of nice. It's not fake; it actually came in just like this. It's a very complicated looking screenful, I'm afraid; anyway, the top graph shows our whole bandwidth of 400kHz, and this lumpy looking stuff is galactic hydrogen, and here's this little spike. The system blows it up and shows you on a scale of about 100,000 times higher resolution what that spike looks like, and it's still unresolved. That thing really sticks up, and just does not look like anything natural. We'll talk later about what that might have been.

So that's desirable feature #1: *distinctive*. Now for #2: *adequate signal/noise ratio*. Well, a carrier's a good thing if you want good signal/noise ratio, because you can sit there and just integrate on it. You can do Fourier transforms until the cows come home. You've all heard the numbers before, so I'll just summarize by saying if you took an Arecibo and radiated a megawatt at 10cm (that's something that Arecibo can do, and does do) it will be detected at 20 times noise by a similar aperture at 2,000 light years, if the information bandwidth is a tenth of a Hz. In other words, narrowband carriers can do the job.

The third desirable feature is that it's detectable in the presence of noise, in particular your own radio signals. Here comes this crazy thing of the chirp, and you've probably seen my chirp slide (Fig. 2) already, but the basic idea is that there's a Doppler shift owing to the earth's rotation, revolution whatever (is it revolution or rotation? -- you know, the earth goes around once in a day...). Whatever you call it, there's a Doppler shift from that; it's the component along the line of sight of your tangential velocity at the surface, and it has a rate of change because you're not in an inertial frame, but rather in an accelerating frame. It's maximum when you're looking overhead at the equator, but it isn't a whole lot smaller anywhere else because of cosines and stuff, you know? If you calculate how big this effect is at our favorite frequency here, 1420MHz, it's of order a few tenths of a Hz per second. It's always decreasing (which is amusing, think about that). But, here's how it goes: If you want to do high resolution SETI, and by high resolution I mean looking for a fraction of a Hz, let's say a hundredth of a Hz, you've got to have a hundred second time series, because of the Fourier duality thingy. In that time the signal, the apparent frequency of the signal will have changed by 16 Hz, given that the signal was at an unchanging frequency in an inertial frame, and therefore it has drifted through 1600 bins. Thus our receiver looking for this galactic "signature" must be designed to drift in the same way. That's easy enough to do, since we know our motion and pointing direction accurately. Better yet, the use of a drifting receiver renders fixed-frequency terrestrial interference both obsolete and impotent; in fact, it dilutes it by 30-something dB. It also renders it distinctive even if it's so strong that the Doppler smearing does not put it below your threshold, and I'll show you some examples later. That's the basic program and why we like narrowband signals. Also, it's terribly easy to do and you can do it much cheaper than if you try to look pulses and chirps, and maybe that's our real secret reason.

Part II: *How* narrow? Well, the first thing to note is that the narrowness is not limited by technology. We already on humble old earth can make carriers in L band (1-2GHz) whose stability is of order 10^{-12}, that have low close-in phase noise, and are entirely terrific for doing this type of communication. Rather as Frank and his student Helou showed back in ... when did you do this? ... '76, there is an effect that limits the narrowness of carriers that are traversing the interstellar plasma --- it's the multipath electromagnetic scattering off of globs of stuff (Fig. 3). Either the globs themselves are moving, introducing Doppler sidebands, or the motions of source and detector relative to this plasma do the job, or some combination of both. These calculations have sat dormant for 15 years, but Jim Cordes this last summer has been working on improved models. Let me show you, in fact, what kinds of numbers you get. Frank and George calculated (can I use first names? The invitation said we were invited to give a little informal chat with our favorite SETI folks, and then here comes a room full of 200 people and cameras running and everything.) Anyway..., they gave a little graph of their calculated effect, based upon data from pulsar scintillation; but here's an improved model, and as a function of distance away, my student Ken Clubok plots here bandwidth looking in certain directions (Fig. 4). This is an effect of the interstellar plasma, and if you look in the direction of the galactic center, you're looking through more of the stuff. So, here I show it toward the center, that's the worst direction, and this little mark here is the distance to the galactic center, and we see spreadings of order of a Hz at 1.4GHz, but that's the worst direction. If you look 30 degrees away from the center, but in the galactic plane, it drops to a fractional Hz, half a Hz or so. If you get out of the plane; if you look here, at 60 degrees away, or here, if you go 5 degrees out of the plane, looking toward the center, it's only of order 0.01 or 0.02 Hz. Once you're significantly out of the plane, it's only of order *milli*Hz, so carriers are not much corrupted. They *love* going through the galaxy, and that's why one might well expect narrowband beacons, and therefore employ high-resolution searches matched to the bandwidth of the signal you might find. So we might expect carriers of order 10mHz from nearby sources, where nearby in this context means, oh, a thousand light years, couple of thousand light years -- you know, sort of in our backyard. We might expect a maximum bandwidth of order of a Hz looking in the mucky directions through the center of the galaxy.

Part III -- maybe I'm going too fast here -- our search is mostly at Harvard. Well, I found this historic picture (Fig. 5) in the archives, of an early "search" at Harvard that's enjoyable to look back on. That's Doc Ewen, Ed Purcell's graduate student, in this picture taken around 1951. And this here thing is a horn sticking out of the fourth floor window of Lyman Lab, which was used to detect the 21-cm line for the first time from space. People knew the frequency because they had done laboratory measurements, but they had never seen it coming from the sky. There is an amusing little historical footnote here: This thing's cobbled together out of hunks of wood and bolts, and here's a little patch soldered in --- it really looks like a mess, some caulking compound running down the corner here, I don't know, wires hanging out the side. This object became of historical interest, of course, and so it now sits out on the lawn at NRAO. However, some of the plywood's been stripped off, the thing's been gold plated, and if you go inspect it, there's no patch left! The historians of science couldn't stand that ugly patch, just couldn't accept the idea that such a messy apparatus could discover anything.

The trouble with these high resolution searches in the microwave window is that too darn many channels are required. Here's how it goes (Fig. 6): If we're looking for a resolution bandwidth of order of a hundredth of a Hz to perhaps a tenth of a Hz (and that's Frank speaking here), to optimize the signal/noise ratio and reject RFI, you get an awful lot of channels --- 10GHz at 10mHz is 10^{12} channels! 10^{12} channels is probably something we could do in the not-too-distant future, but we sure as heck can't do it now. So, then the next step is to say "well look, they're not going to transmit any old frequency, they're supposed to be smart, not dumb. Why not pick a guessable, or a 'magic' frequency." And the usual arguments for beacons at magic frequencies become even stronger if you really believe in ultranarrowband matched-filtered detection of carriers propagated through the Drake/Helou plasma. So then you have frequencies like good ole 1420.405751768, the 21-cm line (thanks to Phil and Giuseppe), and some other distinctive frequencies or combinations of frequencies. Here's the formaldehyde line at 4.8GHz suggested by the Nobeyama gang of three; and then you can make various combinations. You can show off your knowledge of the natural numbers, or perhaps pi this way, or, here's one that Carl likes, it's the mass-weighted H and OH frequencies -- it's the "center of gravity" of water. You still need, it turns out, 10^8 channels because of Doppler effects. I have a picture of Doppler effects somewhere..., well, you know what they are.

So, the next step is to say "10^8 channels, that sounds like a lot!", especially five years ago. So, perhaps what we should do is choose a *guessable reference frame* in which we know the Doppler shift, and then we don't need to have so many channels to bracket our ignorance. Here are some choices: (1) The heliocenter, i.e., the Sun; or the not-too-different local standard of rest, where we started observing with Suitcase SETI (which I'll tell you about in a moment). (2) The galactic barycenter (center of mass of the galaxy) --- I think Bob Dixon may have been the person who started doing that. (3) The cosmic black body rest frame, suggested by Phil again* {* -- note added in proof -- I was wrong; it's Bob Dixon again!}. These reference frames, at least these two here, are known to approximately 30km/sec (probably better now for the cosmic black body, thanks to the excellent observations of COBE, which Sam Gulkis could tell us about), requiring something like 150kHz of bandwidth either side of center, something like 10 million channels.

Let me show you the first of these magic-frequency + magic-reference-frame searches that I got mixed up with. This is back in 1978 at Arecibo (Fig. 7) [lots of laughter], and this is our apparatus. I'd like to point out something about the apparatus, mainly that there *isn't* any really, this is just plain old radioastronomical instrumentation that was sitting down there for doing *real* physics and astronomy, not this kind of fruitcake stuff. I think it's worth noting that we OZMA follow-ons actually took a giant step backward from Frank's original search. Frank at least built his own hardware! And here we are just using what's sitting on the shelf.

But anyway, here's a block diagram of it (Fig. 8). This is a nice block diagram because it reduces Arecibo to a proper size here. [lots more laughter]. Compared with something like a mixer, you know, or a clock. Anyway, it looks pretty, but it's just stuff plugged together with those wires, and ultimately it goes into a big computer that sits there and goes jugga-jugga-jugga-jugga-jugga and takes little samples. Then you have to go off somewhere else and do Fourier transforms in an off-line search of a total bandwidth of a *kHz*, which after all isn't much when we're talking, what, 10MHz..., a hundred MHz, a GHz, or even 10 GHz now. So a kilohertz, my gosh $10^{-8\ (7?\ 9?)}$, I don't know...GHz, kHz, that's six, 10 to the sixth, seventh, I don't know. [yet more laughter] You know astrophysicists, they work in the *exponent*, the mantissa is really quite irrelevant.

Anyway, here's what we did (Fig. 9), we looked at a bunch of the right kinds of stars, at a terrestrial frequency corresponding to 1420MHz received at the heliocenter. In other words, the guys out there are going to aim the thing at the Sun, and of course they really know the Sun's velocity because they look at the spectral lines. Thus they can correct for stellar Doppler shifts to very good precision. So our search was a kilohertz total bandwidth at 15millihertz resolution, and it was done off line, and it didn't cover much frequency range. It didn't cover much in the way of possible kinds of signals. In particular, it was sensitive only to carriers directed at us with every precompensation made, but it sure was sensitive, and I think nobody's claimed things like 4×10^{-27} watts per square meter since. The most sensitive and least comprehensive search ever made.

We didn't find anything, of course, or you would have heard about it long ago, but it really did sell me on this idea that an ultra-narrowband chirped spectrometer is a good way to go, because of the stunning rejection of interference. Let me show you some test spectra made at Arecibo in 1978. I haven't shown these in a long time because they really are hard to look at, but I'd like to show them once again for nostalgic reasons. This (Fig. 10) is a crazy way to plot a spectrum, but when you have 64,000 channels you can't do much, so they're little salt and pepper specks on this rasterized spectrum. If you know what that means great, and if you don't... "if you have to ask, you can't afford it." This properly-chirped signal, injected 30dB below noise, pops up as a big 11-sigma hit here. On the next spectrum (Fig. 11) we've injected an *unchirped* signal, which might represent local interference. We've cranked it up 30 dB stronger and it doesn't show anywhere on the slide; the strongest signal is 5.4 sigma, down in the noise, and it's a completely unrelated frequency. This unchirped test signal is a thousand times stronger than the easily detected chirped signal, and yet it does not rise above noise. So, a chirped receiver really does get rid of local signals, that are not showing the correct chirp, the signature of an external...extra...y'know...ET thing. It also gives you a darn good signal noise ratio. Look at this graph (Fig. 12), which is just a little few Hz out of our full kilohertz, and here's the spectral peak of a signal that is 20dB below noise; but the peak isn't 20dB below noise, it's about 20dB *above* noise. That's because it's multichannel spectroscopy with very narrow bins. At the time it all sounded good --- it just didn't find anything!

The next search was in 1981, when I joined the friendly folks --- the real pros --- at Ames and Stanford. I'm still not sure exactly how it all got started. Jill somehow engineered this in her subtle way, and I found myself suddenly at Ames. I realize now, after I went back and looked at some of my mail from that time, that it was really very cleverly done. I got a letter from a character by the name of Charles Seeger coming from some address in Palo Alto, not associated with any organization whatsoever, asking me a bunch of very intelligent and pointed questions about an article that I'd published in *Science* about the search; and so I thought "Gee, there must be smart people in Silicon Valley. Maybe that's a good place to go."

At Ames and Stanford, on a NRC fellowship, some of the people here this afternoon finally helped me catch up to Frank by building something --- here it is (Fig. 13) --- and this was built with the help of Ivan Linscott and Cal Teague and Peter Backus and others, whom you all know. This is Suitcase SETI ... it's more like Steamertrunk SETI, but anyway there it is. It was funded about equally by NASA and The Planetary Society, and if you open this valise here, then you find this on the inside (Fig. 14)...just chips, you know! This thing does pretty much the same thing that we did earlier at Arecibo with software, but it does it with hardware. Here's its block diagram (Fig. 15) in lots of pretty colors. Now we have Fourier transforms computed on line, and the computer just sits there and shows you pretty pictures of what you haven't found.

So we did another search at Arecibo, this time of 250 stars at the hydrogen frequency, at twice hydrogen, and at some OH lines as well. Well, Suitcase SETI was like a fine French meal, where you spend two days cooking it and you eat it in one hour...we had spent a year building it and we ate it in about a week, and it didn't find anything. What to do with it? Well, it found its way to Harvard, thanks to The Planetary Society's support and a certain flexibility on the part of NASA and Ames that let us take the thing away. So here it is (Fig. 16) sitting at our radiotelescope site...it's sprung a few extra little goodies here and there that have to do with amplifiers and mixers and other things that we didn't have in our original system. I won't bother showing you results...well...I'll just show you this one slide.

Here's two and a half years of data plotted on one piece of film (Fig. 17). We started at the 1420MHz line of neutral hydrogen, working our way up in declination to cover the whole sky. Here's the galactic plane...this little crablike object here. And we had little mishaps --- here an FET amplifier went out. But we fixed things, and just kept going, chunka-chunka-chunka-chunk, and here we had a stroke of, not luck, but lightning, it knocked out our electricity so we lost a few days, but it came back. And then we discovered (here's our discoveries plotted up on top here) a 40-50 sigma peak here...really quite remarkable. It's a little curious, it has an interesting declination; it turned out to be the Sun --- we discovered the Sun after several months of running [lots of laughter] --- it really is up there. We continued up through the sky and then we came back down again. Here came ... what is that?...oh that's Christmas, oh yeah, we lost a few days because of Christmas, nobody to run the telescope. Then a chip died...here is a dead chip, with its legs up in the air...killed one of the two channels. Then winter came along, a big snowstorm knocked out our electricity, the power company reconnected it, but they connected it wrong...big puffs of smoke...and here we go again, now we're at one of the OH lines. A few funny little peaks popped up there, I don't know what they are. Anyway, by then we were used to ignoring data [more laughs]. And here look, this is something: Next summer lightning came along, but no interruptions at all --- we sailed right through, because we had festooned it with anti-lightning stuff.

Anyway, that was Sentinel. The trouble with Sentinel, from a philosophical point of view, if I'm allowed to get philosophical now, is that it also (like the work at Arecibo) required a directed and precompensated beacon, and how hard are these guys up there really going to work? Well, if they're next door they might as well do it, complete with all the Doppler precompensation: catch us while we're really dumb. Maybe that's asking too much. Maybe what we'd really like is enough instantaneous bandwidth to cover these Dopplers...there's my Doppler slide (Fig. 18)...and, again, there's still the issue that if you don't pick special inertial frames, you have to cover all frequencies, for which you would need something like 10^8 channels. However, life is much simpler if you choose guessable frames, such as the LSR, or the galactic center, or the cosmic black body rest frame --- that's probably a poor choice of word --- the "inertial frame in which the primordial three-degree Kelvin radiation looks the same in all directions." If we choose one of those frames, then we only need 300kHz total bandwidth, which at 0.03Hz resolution is 10 million channels. 10 million channels is something you can do, in fact that's META. META was 8.4 million channels, 0.05Hz resolution, i.e., 400kHz of total bandwidth, and...let's see, I've left out Phil's great letter here.

I was searching around for magic frames: the LSR was kind of obvious, and the galactic barycenter I had heard about through Dixon's work. But the cosmic blackbody frame came in the form of a letter, and I've reproduced the letter here. This is a letter from Phil (Fig. 19) in case you don't get letters like this. They're great, they come in fantastic envelopes and typically there are comets on the thing and maybe there's a salamander crawling up the side, and their car goes by and its got the Pleiades on the side, it's just...it's like Phil. This letter started --- but I had to cut it off because it wouldn't fit in the slide --- it started with HHHHHHHHH --- what does that mean Phil? Were you just warming up your ribbon? [laughter] --- and it's just like Phil, it's overflowing with ideas and it sputters and it spouts and he changes the ideas in real time and he crosses it out and he sticks little things on the side and it says this is the frame to use. No time to read it here, but it says this is the magic magic magic frequency, that blackbody thing, it really is great great great, and this letter reminded me. I looked around, and haven't I seen that kind of wild impulsive writing before? Sure, did you ever use Fermi's notes on quantum mechanics? It's just the same as Phil, he writes something, he crosses it out and he sticks a little thing in the margin and that's his notes, just ideas overflowing (Fig. 20).

Ok, here's META (Fig. 21)...META was built with lots of money from the Planetary Society, by way of Steven Spielberg, and it uses our 84 foot dish and dual polarization and lots of hardware (including the front end from the MCSA I that Jill told you about), and lots of little processors we built. There are 144 of them, each having a hundred and something chips --- about 20 thousand chips all together --- a half million solder joints, all done by hand, really absolute wild stuff. Let me show you what this looks like...here's the dish we used (Fig. 22), and way down there, that's Jake, whom a lot of you probably remember, he was six then, he's now 14. He was very small, he was about 25th percentile in height, and so he makes the thing look really big. He's still about 25th percentile, only it wouldn't look so big anymore. I guess the thing I forgot to say before, is that...[comment from audience member] yeah, the dish is also in the 25th percentile, that's right! I forgot to tell you that the original idea at Harvard was to put in the database the million nearest stars and just go chunka-chunka-chunk and look at each one, i.e., do a targeted search. But Mike Davis pointed out early on, he said, "You jerk, there's not a million resolvable points in the sky with a half a degree beam. Why don't you just point the thing on the meridian and let the earth do the scanning for you." So this is a "targetted all-sky search," thanks to Mike Davis.

Here's what the analyzer looks like (Fig. 23). These are the boards, each a little computer, and so on. Each of these does 64 thousand channels, so you're looking at a million channels. And now (Fig. 24) you're looking at 10 million channels (8.4 million actually), and now you're looking at the whole control room with all that stuff (Fig. 25). This thing modestly proclaims itself to be a supercomputer, all of 75 million instructions per second, which now, by the way, is like one chip -- right? The Intel i860 is maybe half that power, so life gets easier. Those of you who like to copy down the parameters in your notes, here they are (Fig. 26); but the rough idea is 8 million channels times 0.05 Hz = 400kHz bandwidth. Look at magic frequencies, correct to magic frames, see what you can find. Again, I guess you all know this, but it gives me an excuse to show a slide, when you talk 8 million channels we're not talking one after the other, we're talking *simultaneous* channels...*this* (Fig. 27) is a multi-channel analyzer [lots of laughter]...does anyone know what that is? Does anyone have *any idea*? I'm just at the end of what we've done, and a few minutes for what we plan to do --- is that okay Tom, or am I straining people's patience here?

Just to show a few results from META (Fig. 28). The top portion is one screenful of META's display, when we inject an artificial signal. This is the same kind of display as the very first slide I showed; the bottom graph of the 3 shown on the screen (Fig. 28A) is the high resolution one to look at. About 4 parts in 10^9 total bandwidth there, and here you see a flattop kind of spectrum. What is that? That's a fixed carrier injected into a system that's looking for a moving carrier because of the earth's rotation, so you get this flattop object. The power is diluted into many channels and it also looks pretty weird, so it gives you two screens against interference. Here (Fig. 28B), just to show you it really does work, is a chirp signal injected into this chirp thing, and it coheres up into one channel (Figures 28B-G show only the high resolution --- i.e., bottom graph --- of their respective screens).

Now, here's something (Fig. 28C) we saw on a certain day (this is real data), and it looks suspiciously like Fig. 28A. It's not as wide, but that's because we're out of the equatorial plane and the cosine factor is a little smaller, or something. Here (Fig. 28D) is a messy broadband signal --- somebody's crummy oscillator, you know we're talking 4 parts per billion. We expect the extraterrestrials to do better than that. Here's a very handsome rather symmetrical modulated carrier (Fig. 28E), again it could be extraterrestrials sending us the message, but we just look at that and say "oh well, that just looks like a modulated carrier, they'd never do that, that must be our own transmitters or..." (I'm being just a bit cavalier). We do indeed go back and look at these things, but the most likely explanation here is a modulated carrier with sidebands a few Hz out; I don't know what does that, but there it is.

Here's what happens (Fig. 28F) when a processor goes berserk --- it goes bonga-bonga-bonga full scale, something like this. This aberrant behavior was caught quite quickly because the system has fault tolerance through redundancy, and it checks its own processors in a way that I didn't describe to you. This processor's antisocial behavior was detected a few minutes later: It had its brain reprogrammed, was pulled out of the system automatically, and a replacement processor was allocated dynamically and then the system continued on. And here (Fig. 28G), just to get your blood pumping, here's a signal received on October 10, 1986, in the galactic barycentric frame, left circular polarization, at 17:57 Zulu, at a right ascension of 14 hours 27 minutes 28 seconds, at declination +61 degrees, and it looks for all the world like what we're looking for. And all I can say about it is it didn't happen again. We've looked at that position and about half a dozen other really convincing candidates many times. If any of you want a list of great candidates, I'll be happy to give them to you; but, like Jill, we insist on reproducibility.

Part IV. Well, what next? Where would one go from here? We've now looked at some 70 thousand gigabytes of data out of this thing! It's really a grand data machine, and it's also the world's biggest garbage can! We mostly just toss it straight into the can, but we preserve a little bit on the disk to look at later. It's "good news, bad news": The good news is that radio frequency interference is well handled, it's attenuated and also rendered identifiable. The bad news is that no signal has been found with it. So, what should we do next?

The first thing we decided, particularly with Planetary Society interest, is that we should at least finish the job at this resolution, and handle the Southern sky. So META II, a copy of META I with the same sensitivities and parameters, was built by a couple of Argentine folks and it was turned on October 12 of this year (1990). Again with Planetary Society's support. We will coordinate observations of the overlapping stripe that we can see from Buenos Aires and Harvard, Massachusetts. In addition, they will do a really nice job of covering the galactic center and the whole galaxy that we can't do from the North very well. The second comment is, it is probably time to search differently, or more, or something, and, perhaps I'm treading on someone else's jurisdiction here, but it seems to me maybe it is time to broaden out the frequency coverage. You can do it now because, as Jill has pointed out, silicon really does neat things if you just let it gestate a little bit. And here's the kind of thing you could get nowadays --- this (Fig. 29) is the Austek FFT chip (first pointed out to me by Dan Werthimer in Stu

Bowyer's group), a really nifty chip. Look --- it's got little motors going around in here, and little criss-crossy do-dads. It's a chip just for doing FFT's and that's all it knows how to do, it can't do anything else --- it can't tell you the time of day, although it can Fourier analyze the time of day, and boy, can it do that! It can do a thousand point transform in the blink of an eye, half a millisecond, it can do a megapoint transform in a half second. It can even do video --- four chips can do 256 by 256 in 13 milliseconds, so you can do a digital video: Instead of watching TV, you can watch the Fourier transform of TV, or something like that.

And so, we've been thinking, how do you use this thing to get more bandwidth, to get more channels, and so on? Mike Davis, as usual, came in with a wonderful suggestion --- If you're not going to stick with the ultranarrow bandwidths, you'd better do something about interference. Why not have a two beam antenna system like this (Fig. 30), which you could implement by having two feed horns at the focal plane of our parabolic dish. It turns out that parabolic dishes have very large unaberrated fields, and you could put not two, but a few hundred feed horns in the focal plane if you wanted, and thus tile a few tens of square degrees of the sky with simultaneous beams with the full antenna gain in each one. Two is enough, though, for our purpose: We orient them East/West, and as the sky rotates around the fixed Earth, a signal will appear first in the East beam and then disappear, and then appear in the West beam and then disappear. We demand a signature like this: First preceding, then go away, then following, then go away; not the other way around, not both at once, not one without the other (which is what the "WOW" signal did, I guess; its fatal flaw). That's a pretty stringent filter. When I get stuck against a problem, in this case it was interference, I call up Mike Davis and he's got absolutely the breakthrough. You know, this really should be the 30th...I don't know what you were doing, Mike, 30 years ago (maybe you were being born), but we ought to be celebrating your great ideas here too! Anyway, Mike came through with this one, and when I called him to ask him what do you do about interference, his response was, approximately, "Well, I was waiting for your call".

Here's how you'd build such a system (Fig. 31). Again just a thinking piece: A couple of horns in a two-channel system, looking with parallel spectrometers at both of these horns simultaneously, switching polarizations from time to time, and going into a pair of 50 megachannel, 30MHz spectrometers, doing their transforms in 1.6 seconds. Step along successively in frequency by 30MHz, and thus do the whole waterhole in 16 seconds.

There's a little bit of a problem here, in that you have some 120 megabytes *per second* coming out of this thing going into an ethernet, and ethernets don't work real great at 120 megabytes per second; in fact they don't work well at 1 megabyte per second! So, what you really do (Fig. 32) is to put a little more stuff inside those FFTs --- after the FFT you put smarts into each channel, in the form of little DSP processors that just love to eat lots of data and filter it out; and then by communicating through some other downstream controller CPU thingies to shared DSP memory you can basically do the job. We've thought out most of the details of this thing, and we believe we can do it. This gadget would have 30MHz dual channel instantaneous bandwidth, and could do the waterhole every 16 seconds.

We've calculated here (Fig. 33) the tradeoffs of going from the narrowband META system, to the "son of META" (the hundred megachannel system). If you assume that the probability of detection is proportional to bandwidth, in other words give up magic frequencies, if you assume the density of civilizations is associated with disk component stars, and use the Gilmore and Wyse thick disk model (whatever that is), if you assume a power-law luminosity function for civilizations, and if you use Jim Cordes' new model for multipath signal broadening, and then you calculate expected number of detections for that luminosity function, you get these numbers, displayed on a very log scale here. Something like 2 to 3 orders of magnitude better chance of finding something with this new system versus the old.

Well, but we've taken a step backwards, in going from mHz resolution almost up to Hz --- we'd really like to go back to the mHz. We have decreased sensitivity (from the broader band), and we also have a decreased duty cycle (because we don't cover the whole waterhole simultaneously, but rather have to step through it). *Is it possible to build a spectrometer with 300MHz instantaneous bandwidth and mHz resolution?* I think it is, or at least I think it will be in a few years. So let me just show you one last thinking piece (Fig. 34). We have to do a range of chirps in the 300MHz bandwidth, because there's a dispersion in chirp; so we have to divide it into about 10 bands. Then you just do your standard falling-off-the-log thing of building big analyzers these days, which is getting easier and easier. So I show here, as tiny little off-the-shelf black boxes, almost a chip, a 500 megachannel FFT here, which, by the way, consists of a 10 giga-instruction-per-second processing capability plus 3 gigabytes of RAM each! (By the way, Mike Davis has pointed out a clever scheme whereby you don't really need 3 gigabytes of RAM...he just can't keep his mouth shut.)

Thus a straightforward --- and not-too-inspired --- FFT design would look like the figure, followed by this standard array of DSPs and so on, and there you go. The reason you can't build this thing now is that memory prices are too high. We're paying about 50 bucks a megabyte, so you'd have $2 million worth of memory. However, they soon will be affordable, and for my authority here, I used a graph (Fig. 35) from a popular and authoritative electronics book that some of you may have seen [laughter]. Here is the so-called "Law of Silicon Valley," in which memory prices in cents per bit (very logarithmic) versus time (linear) are plotted, and this trend curve is extracted. If you continue the trend curve, you find that already in 1990 it's cheap enough to make 6 gigachannels affordable. Well, it turns out that things didn't go that way (so sue me!) --- they really went up to here --- this is what a megabit costs now. But that's okay, just take a more conservative trend line and you come out to here --- in 1994, about February the 14th, we'll be able to afford a 6 gigachannel analyzer. By the way, here's the median home prices in the Boston area [laughter] going up exponentially, but, you know that didn't do that either (so sue me again!).

Okay, one last foil (I've got to get off of the stage here!). (It does feel a little bit like a stage.) I'm not enthusiastic about these kinds of comparisons, but I was asked to do it, so I made a chart (Fig. 36) in which many many many parameters are compared, and then invidiously compared, and then really invidiously compared. This goes from OZMA through the narrowband searches up to the NASA searches. I've compared parameters such as instantaneous bandwidth and channel bandwidth and sensitivity, with lots of footnotes about what they all mean. Then some figures of merit. Well, here, it's rather interesting to see what's happening here, the instantaneous bandwidth has been going from 10^{-4}MHz up to tens of MHz or even hundreds. We're talking about going up but then back down in bin width, I think these narrow bins are good. Numbers of channels increasing rather nicely with time, factors of 10^{10} in that, factors of 10^6 here. A figure of merit (#1 on the chart) might be sensitivity, such as antenna area divided by system temperature multiplied by processor cycles in the project. It's heavy handed, because it doesn't say what you're *doing* with the processor cycle --- are you computing pi? or prime numbers? or are you actually doing something useful? --- but at least it's a figure of merit: If you get too philosophical about what a good one is, you never end up with anything.

This figure of merit, as you see, has been growing, by a factor of 10^{10} from OZMA to BETA-II. You can do Frank's figure of merit (#3 on the chart), that he proposed back some time ago, that had to do with the volume of the galaxy that you're actually sensitive to, and on that figure of merit we're talking an improvement by a factor of 10^{12}. Finally, if you want to get admiring of the cheapness of silicon, or admiring of how cheap it is to hire graduate students and then not pay them anything, you can calculate the cost in cents per channel of the whole project, and that's been going from $2x10^5$ for Frank's single solitary channel, to 0.01 for something that has 6 gigachannels. I think you should take these things with a truckload of salt, but they are, at least, amusing.

Let me end with just a little bit of philosophy, if I may be permitted. The first comment is that these narrowband searches are lots of fun, but they're really far from ideal, because they ignore completely the very real likelihood of pulsed or chirped signals. Barney Oliver has shown, rather convincingly, that pulsed signals are really a better bet than carriers, if the extraterrestrials are as smart as Barney. And it's possible that that is so! I think these searches and their hardware implementation should be viewed as attempts to conduct a meaningful university SETI exploration at low cost, and also to train enthusiastic and bright-eyed students in what I consider to be the ultimate bold adventure. We also serve to introduce the public to SETI --- we have about 2,000 visitors through the META project per year --- really an amazing figure. A lot of them are kids --- we catch them early and corrupt their minds! (I only wish that Conte had been one of them). My final comment is that Frank and Phil got us all going in this stuff; it's probably not so, but I'd like to think that our experiments have, at least in some small way, helped to bring about the public awareness, acceptance, and perhaps even *enthusiasm*, that's needed to sustain in the long run continued public support for major SETI efforts like the bold NASA plans that have now been approved, and are in high gear at last. Thank you.