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INTRODUCTION TO SETI SCIENCE AND TECHNOLOGY

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ABSTRACT

This brief overview of SETI science and technology has become an annual fixture to lead off the IAA SETI I sessions. It is offered for the benefit of those many students attending the 2012 International Astronautical Congress. These students tend to be long on enthusiasm and short on experience. They can best appreciate the more advanced technical material being presented by the various speakers if they first have a basic understanding of SETI concepts. This introduction is intended not to be exhaustive, but rather representative. Summarizing a half-century of observational SETI science, it explores the nature of radio telescopes, experimental design strategies, SETI instrumentation, signal analysis, and the hallmarks of artificiality which allow us to differentiate between natural astrophysical emissions and intelligent interstellar transmissions.

KEYWORDS

SETI, radio astronomy, radio telescope, signal analysis, existence proof

BIRTH OF RADIO ASTRONOMY

Are we alone, the sole sentient species in the vast cosmos, or might there be others out there, with which we may some day hope to communicate? This is a fundamental question, which has haunted humankind since first we realized that the points of light in the night sky are other suns. Now, for perhaps the first time in human history, we have the technology to seek a definitive answer.

That technology derives largely from radio astronomy, a relatively young science which was born quite accidentally in the 1930s, with the chance discovery that stars emit electromagnetic radiation in the radio spectrum. At Bell Laboratories in New Jersey, USA, a young radio engineer, Karl Jansky, was tasked with tracking down a source of interference that was plaguing transatlantic radiotelephone communications. Building a large, steerable directional antenna, he tracked the noise source across the sky, to determine its periodicity. The interference did indeed repeat, on a 23 hour, 56 minute cycle. From this observation, Jansky concluded that the emissions were not originating on Earth, or from the Sun, but rather from interstellar space. Today, we know that Jansky was detecting radio emissions from the center of the Milky Way galaxy. Thus, was radio astronomy born.

Jansky's report, published in a radio journal, was read with considerable interest by another radio engineer, Grote Reber, in Wheaton, IL, USA. It was Reber, an accomplished amateur radio experimenter, who built the first modern radio telescope, a 10 meter diameter parabolic reflector, and used it in 1937 to produce the first known radio maps of the Milky Way.

Although in hiatus during the Second World War (during which most of the world's physicists were otherwise occupied with matters of weaponry), radio astronomy emerged as an observational science in 1951, with the first detection (by Harold Ewen, a graduate student at Harvard University, and his research advisor, Edward Purcell) of the 21 cm hyperfine emissions from interstellar Hydrogen, the most abundant element in space.

RADIO TELESCOPE MODALITIES

The three primary operating modes for modern radio telescopes include radiometry, spectroscopy, and interferometry. Each mode requires unique hardware and a specific experimental design.

The early observations of Jansky and Reber are examples of total-power radiometry, a time-domain measurement in which the thermal blackbody emissions from astrophysical sources are plotted against antenna aiming coordinates. Aiming can be either dynamic (i.e., actively varying the antenna in azimuth or elevation) or drift-scan (in which the Earth's rotation causes the antenna to sweep varying right ascensions over time). Radiometers are the simplest of radio telescopes, requiring only that the incoming signal be sufficiently amplified, and then applied to a square-law detector.

Spectroscopy is a frequency-domain mode, used to observe the molecular absorption or emission lines of the source being monitored. Ewen's pioneering hydrogen emission detection was an early example of astrophysical radio spectroscopy. In its most common implementation, spectroscopes involve downconversion of a portion of the electromagnetic spectrum, using a fixed intermediate frequency and a swept local oscillator.

Interferometry uses the interference fringes from multiple antennas to generate a spatial-domain image of an area of space. Interferometers require complex digital correlators along with well-matched antennas and receivers. Examples of advanced interfometers include the 27-dish Very Large Array (VLA) in Socorro, New Mexico, USA, and the 30-dish Giant Meterwave Radio Telescope (GMRT) in Khodad, India.

EARLY SETI SCIENCE

The notion that existing radio telescopes were capable of receiving purported artificial transmissions from distant, technologically advanced civilizations was first articulated by Cocconi and Morrison exactly a half-century ago. Their short paper "Searching for Interstellar Communications" in the journal <u>Nature</u> (1959) is generally regarded as the blueprint for the modern Search for Extra-Terrestrial Intelligence (SETI).

Even as that paper was in press, Frank Drake, then a young radio astronomer at the newly formed National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia, USA, was quietly preparing to perform the very experiment which the two Cornell professors were proposing. Drake and Coconni/Morrison had independently arrived at similar search strategies, and independently derived nearly identical experimental designs. Clearly, SETI science was ready to be born.

Project Ozma, Drake's Green Bank effort, observed two nearby sun-like stars (Tau Ceti and Epsilon Eridani) for a few weeks in the Spring of 1960, scanning a narrow band of frequencies surrounding the Hydrogen emission line, using an 85 foot diameter parabolic reflector. Drake's receiver effectively combined radiometry and spectroscopy, in that it employed a square-law detector, but scanned a range of frequencies related to a known astrophysical emission line.

Although he detected no promising candidate signals, Drake's *Project Ozma* served as a model of hundreds of SETI searches to follow.

The year after conducting *Project Ozma*, Drake convened at Green Bank the world's first scientific conference devoted to SETI. The agenda for that week-long meeting consisted of seven topics, touching upon various astrophysical, biological, technological, and societal aspects of the emergence of potential communications partners in the cosmos. Stringing those seven topics together into a multiplicative model, Drake created the now-famous Drake Equation, a tool widely used for estimating the number of communicative civilizations which might exist in our Milky Way galaxy.

THE NASA YEARS

In the summer 1971, a landmark study was conducted at the NASA Ames research center in Mountain View, California, USA. Chaired by Dr. Bernard M. Oliver, then vice-president of engineering for the Hewlett-Packard company, *Project Cyclops* sought to design (on paper) the ultimate SETI receiving system which could be conceived, if money were no object.

A proposed interferometer array, consisting ultimately of 900 large parabolic reflector antennas coupled to an advanced optical computer for multi-channel spectral analysis, would have cost in the tens of Billions of US dollars. It was never seriously considered for funding, and hence never built. However, the resulting publication (which was reprinted in 1996, and is still available) serves to this day as a blueprint for how large-scale SETI hardware and software might be developed.

A modestly funded NASA SETI program followed in the US. In other countries, parallel studies ensued, each receiving limited government or institutional financial support. Most borrowed limited observing time on existing radio telescopes.

The NASA SETI office, headquartered at the Ames Research Center, where the Project Cyclops studies had been conducted, expended significant effort on the development of advanced Multi-Channel Spectrum Analyzers (MCSAs) capable of scanning hundreds to thousands of MHz of the electromagnetic spectrum in real time. This was in marked contrast to earlier SETI efforts, whose receivers had been restricted to merely a few tens to hundreds of kHz of bandwidth.

NASA SETI launched a ten-year, two-pronged search in October of 1992, significantly the five hundredth anniversary of Columbus' first voyage of discovery. Its two complementary strategies involved a targeted search of nearby sun-like stars, and a methodical sweep of the entire sky for signals emanating from the vicinity of stars not specifically known to us. Each search strategy required a different instrumentation approach. Targeted searches are conducted by tracking known stars with the largest, highest gain antennas available, for hours on end. Sky surveys, on the other hand, tend to be operated in meridian transit (drift scan) mode, employing smaller antennas (to provide increased spatial coverage) and limiting observing time in any one direction, in favor of maximizing sky coverage. As an analogy to the differing equipment capabilities required for each of these two modalities, you can mentally contrast optically viewing the night sky through a toilet paper roll, vs. a soda straw.

Although budgeted at a mere five cents per US citizen per year, NASA SETI's \$12.6 million annual budget proved an easy target for legislators. The US Congress cancelled the NASA SETI program in 1993, after just one year of observations (and, in the process, reduced the federal deficit by 0.0006 percent). Some in the SETI community have taken this as definitive proof that there exists no intelligent life in Washington.

PRIVATIZATION OF SETI

With the demise of NASA SETI, two nonprofit organizations in the US stepped up to privatize and continue SETI research. The California-based SETI Institute revived the targeted-search prong of the late NASA SETI program in 1995, under the guise of *Project Phoenix* (symbolically named for having risen from the ashes of its predecessor search). The SETI Institute secured for its *Project Phoenix* observations the spectral analysis equipment which it had previously developed on contract in support of NASA SETI.

In ten years of observations involving renting time on large radio telescopes at Parkes and Mopra in Australia, Green Bank in West Virginia, Woodbury in Georgia (US), Arecibo in Puerto Rico, and at Jodrell Bank, UK, *Project Phoenix* monitored 1,000 nearby sun-like stars across a substantial portion of the microwave spectrum. The project employed sophisticated follow-up detection procedures to validate candidate signals and eliminate terrestrial interference. *Project Phoenix* achieved a null result, in that none of its candidate signals passed the follow-up detection test.

Beginning in 1996 from donated office space in New Jersey, the nonprofit SETI League's *Project Argus* is an ongoing attempt to resurrect the all-sky survey component of the NASA SETI effort. *Project Argus* is named for the mythical Greek guard-beast who had 100 eyes and could see in all directions at once. It seeks to see in all directions at once, in real time, by bringing online thousands of small radio telescopes around the world, built and operated by dedicated amateur radio astronomers, whose efforts are coordinated through the internet. To date, *Project Argus* has 144 stations in operation, in 27 different countries on all seven continents. It too has yet to detect conclusive evidence of ETI.

DEDICATED SETI INSTRUMENTS

While in recent years dozens of SETI experiments have begged, borrowed, or bought observing time on various radio telescopes in England, Germany, Russia, Argentina, Italy, Japan, Australia, Puerto Rico, and elsewhere, ever since the *Project Cyclops* study the dream of a full-time SETI observatory, optimized for the detection of intelligently generated extraterrestrial signals, has remained foremost in the minds of SETI scientists.

In 1999 the nonprofit, membership-supported SETI League began planning its *Array2k* observatory. Receiver prototypes were constructed and tested, key technologies developed and patented, land acquired in New Jersey, and a prototype *Very Small Array* (VSA) constructed in Pennsylvania, before global economic conditions brought an end to the project's private funding. It is hoped that work on this instrument can resume, should new funding materialize.

In California, the nonprofit SETI Institute was initially a little more fortunate in securing funding for its Allen Telescope Array (ATA). Planned as a phased array of 350 Gregorian antennas with cryogenically cooled broadband front-ends and fiber-optic links to its advanced MCSA, the ATA went online two years ago with 42 dishes, and began a galactic-centre search over the L-band to X-band spectra for candidate SETI signals. Unfortunately, operation of the ATA was curtailed early in 2011 due to a funding shortfall. The SETI Institute has, thankfully, recently secured funds both to reactivate the 42 dish array, and eventually to expand it to its full planned strength.

When fully implemented, it is expected that the ATA will permit fulltime SETI observations of the entire sky which can be seen from its location in Hat Creek in Northern California, and will be used to survey upwards of one million stars across the entire microwave spectrum.

SIGNAL ANALYSIS TECHNIQUES

A challenge facing all SETI observatories, extant and planned, is differentiation between candidate signals and the ever-present natural background noise of the cosmos. Whereas natural thermal emissions are broadband, extending across the entire electromagnetic spectrum, it is expected that signals used for deliberate electronic communication over interstellar distances will likely have narrow-band components. Thus, minimizing receiver bandwidth is an accepted technique for pulling such weak signals out of the noise.

However, the actual frequency of transmission is not known to us *a priori*. The quietest portion of the electromagnetic spectrum that could efficiently support interstellar contact is extremely wide, spanning from a few hundred MHz to tens of GHz. Assuming a sufficiently narrowband receiver, there are billions of possible frequencies to which it might be tuned. Here is where digital signal processing (DSP) techniques become an important part of SETI research.

It is common SETI practice to receive, amplify, filter, and digitize extremely wide portions of the electromagnetic spectrum. DSP is then employed to subdivide the broad received spectrum into a multitude of contiguous, vanishingly narrow frequency bins, each of which excludes much of the broad spectrum of noise so as to maximize signal to noise ratio. Most frequently, the fast Fourier transform (FFT) is employed to produce these narrow bins. At 1 Hz of bin width, for example, a 1 billion point FFT can simultaneously monitor all 1 billion such 1 Hz channels within 1 GHz of bandwidth.

A limitation of the FFT is that it is optimized for the detection of sinusoidal signal components. If the nature of the incoming signal is unknown, one would desire an adaptive transform to detect it. One such tool, which makes no *a priori* assumptions as to the characteristics of the signals hidden in the noise, is the Karhunen-Leove transform (KLT). SETI scientists have for years sought, with mixed success, to implement the KLT on radio telescopes in Ohio, Italy, and elsewhere.

Unfortunately, the KLT is extremely demanding of computer power. As the state of the art in computer technology continues to experience Moore’s Law exponential growth, it is felt that the KLT will eventually displace the FFT as the SETI signal analysis algorithm of choice.

HALLMARKS OF ARTIFICIALITY

Most SETI scientists hold that detection of artificially generated electromagnetic waves remains the most likely mechanism of contact between humans and ETI, at least at our present state of technological development, and excluding from consideration any laws of nature not presently in evidence. The photon is, after all, the fastest spaceship known to man. It travels relatively unimpeded through the interstellar medium, at the fastest speed which our understanding of physics would allow.

Based upon the primitive state of Earth's communications technology, such contact is most likely to occur in the microwave spectrum, although optical SETI is becoming more viable. We would have a high confidence level that such contact had taken place upon simultaneous detection (at widely separated terrestrial coordinates) of signals of sufficient duration or periodicity to allow multiple independent observations. In addition, such signals must exhibit some reasonable combination of the following hallmarks of artificiality:

- spatial / temporal characteristics consistent with sidereal motion,
- coherence not achievable by known natural emission mechanisms,
- Doppler signatures indicative of planetary motion,
- frequency selection which exhibits a knowledge of one or more universal constants, and
- information content suggestive of a mathematically based culture.

STANDARDS OF PROOF

We now address the issue of what constitutes incontrovertible proof of ETI contact. The question is complicated by the fact that the general public may make only a vague distinction between fact and faith. The spectrum of human skepticism vs. gullibility encompasses a wide range of extremes, characterized by diverse viewpoints ranging from "of course they exist -- we couldn't possibly be alone!" to "I'll believe in the existence of intelligent extra-terrestrials only when one walks up and shakes my hand." We must take pains to prevent such declarations of faith from clouding the judgment of our SETIzens.

We start by acknowledging that one can never conclusively prove the negative, but that it takes only one counter-example to disprove it. Conservative experimental design demands that we frame our research hypothesis in the null form: "resolved that there are no civilizations in the cosmos which could be recognized by their radio emissions." Now a single, unambiguous signal is all it takes to disprove the null hypothesis, and negate the notion of humankind's uniqueness.

What exactly constitutes an unambiguous signal? A popular definition holds it to be one which could not have been produced by any naturally occurring mechanism which we know and understand. But this is an insufficient condition. The first pulsars, after all, fitted that definition. They were first labeled "LGM" for Little Green Man, and their intelligent extra-terrestrial origin seriously considered for several months, until our knowledge of the mechanics of rapidly rotating, dense neutron stars became more complete. There is the risk that any signal which cannot be produced by any known natural mechanism could well have been generated by an astrophysical phenomenon which we have yet to discover. So, we need an additional metric.

We listed above several of the hallmarks of artificiality, which we can expect to be exhibited an electromagnetic emission of intelligent origin. The common denominator of all these characteristics, in fact of all human (and we anticipate, alien) existence, is that they are anti-entropic. Any emission which appears (at least in the short term) to defy entropy is a likely candidate for an intelligently generated artifact. In that regard, periodicity is a necessary, though not a sufficient, condition for artificiality (remembering once again the pulsar).

Ideally, we would hope to receive communication rich in information content, signals which convey otherwise unknown information about the culture which generated them. Unless we are blessed with such a message, we are unlikely to ever achieve absolute certainty that what we have received is indeed the existence proof we seek. Multiple independent observations, however, can do much to dispel the obvious alternative hypotheses of equipment malfunction, statistical anomaly, human-made interference, and deliberate hoax. In that respect the development of well coordinated signal verification protocols can do much to narrow our search space.

Once again, in signal verification activities, it is the null hypothesis we should be attempting to verify. We thus expect that we will continue to rule out most candidate signals. There may eventually come a signal, however, which simply cannot be explained away. At that point, we may dare to conclude that *we are not alone*.

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