Solar System SETI Using Radio Telescope Arrays

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Abstract

The search for extraterrestrial intelligence must include complementary observing programs that investigate our solar system and near Earth. Solar system observing strategies involve a search for energy (e.g., artificial microwaves) or physical manifestations (e.g., exploratory robotic probes) that may be present. Artificial electromagnetic emissions from robotic probes may be detectable using existing ground-based radio-telescope observatories like Arecibo, or those undergoing construction such as the Allen Telescope Array (ATA). Future systems like the SETI League's Array2k and the SETI Institute's ATA are well suited to the task of searching the solar system for anomalous microwave phenomena. Steerable phased arrays have the unique ability to produce multiple beams, and shaped antenna patterns to target and track specific planet-moon systems or regions of deep space. At distances less than 50 AU, large SETI arrays can detect electromagnetic emissions much fainter than those from light years away. Lower free space attenuation (i.e., higher signal-to-noise ratios), a reduced amount of scintillation from the interstellar medium, and other factors improve system performance. Solar System SETI is a search for active exploratory robotic probes within the solar system. These probes can possibly be discovered if they emit secondary or leakage microwave energy. The radial velocity, range and location of these emissions can be estimated from analysis of measured one-way doppler drifts and data from a synthesized quad-beam monopulse antenna array configuration.

1. Introduction

The working hypothesis and assumptions of the microwave SETI strategy have not changed significantly since its introduction in 1959 with Cocconi and Morrison's seminal paper[1] and Frank Drake's Project Ozma in 1960[2]. The SETI Electromagnetic Hypothesis can be stated as follows:

> *Technologically mature extraterrestrial intelligences will recognize and use electromagnetic energy, at certain universally known frequencies or bands, as a means to remotely explore the universe, or to detect, signal or communicate with other intelligences.*

This hypothesis is based on the premise that ETI exists, are technologically mature, sufficiently intelligent to utilize electromagnetic energy, and recognize that certain frequency bands in the electromagnetic (EM) spectrum can be used to signal or communicate with other intelligences. The underlying assumption is that ETI are motivated for some reason to expend energy to signal other intelligences across vast interstellar space. In the quest to find these distant transmissions, our own solar system has been excluded from the SETI search because of arguments that reject the practicality of interstellar travel for us and ETI civilizations[3,4]. The impracticality of interstellar travel has been frequently used to argue that ETI will be motivated to employ EM signaling because it's more affordable than spaceflight. In that sense, any possibility that ETI could be nearby threatens to overturn these arguments. Accepting the possibility that ETI could be nearby doesn't automatically negate decades of microwave SETI interest which has served to keep the SETI researchers focused on sharpening their instrumentation, methods and infrastructure.

Some philosophically[5] and biologically[6] based arguments conclude humanity is unique and quite possibly the first intelligent civilization to arise in the galaxy. These arguments, if accurate, seriously undermine the possibility of detecting any ETI near or far. If we could be certain that we are unique in the galaxy, then there would be little point in conducting SETI observing projects.

Since we don't know if our place in the universe is unique or not, we continue to wonder: "Are we alone?" Because we are motivated by curiosity to find an answer to this question, it still makes sense to undertake certain kinds of SETI observing program. Since 1959 several possible strategies to search for evidence of extraterrestrial intelligence (ETI) have been proposed. The dominant strategy has been to search the microwave frequency band for artificial signals originating far outside the solar system. It is also productive, given the available and emerging technological resources, to search within the solar system for evidence of extraterrestrial intelligence. This paper introduces an observing strategy called Solar System SETI (S^3ETI). This strategy is designed to employ ground-based radio-telescope resources, like the Allen Telescope Array, to search the solar system for anomalous microwave emissions. Such emissions could prove to be artificial, thereby offering unequivocal evidence of the existence of extraterrestrial intelligence.

2. Searching our Solar System

The solar system is essentially our civilizations back yard, and cis-lunar space is like our back porch. The solar system is generally viewed as the sun and 9 planets, but includes the Kuiper belt and Oort cloud. Search strategies for ETI nearby hypothesize that it is located somewhere in the solar system and possess a physical form. The physical form is expected to be an artifact. These artifacts are thought to be either relics, functioning robotic spacecraft or exploratory probes. There is a rich history behind the ideas and proposals to search for ETI nearby. Ronald Bracewell was instrumental in introducing to the scientific community the concept of "Messenger Probes"[7,8,9] sent here by a "Galactic Club" to contact us and exchange knowledge. Following Bracewell's pioneering work Freeman Dyson wrote on searching for Extraterrestrial Technology[10]. In the mid 1970s Lawton[11,12,13] made a detailed study of the controversial long-delayed radio echoes claimed to be evidence of an ETI presence in the solar system. In the late 1970s Chris Boyce wrote about robotic probes in the context of von Neumann self-replicating automata (SRA)[14]. The idea of SRA was developed by von Neumann and detailed in a seminal paper co-authored by Burks and published in 1966[15]. Arbib also added to the ideas of SRA[16]. By far the most significant contributions came from Robert Freitas and Francisco Valdes. In 1979 and 1982 these astronomers carried out an optical search of the Earth-Moon-Sun Lagrange orbits L4 and L5 for parked artifacts[17,18]. They developed the SETA (Search for Extraterrestrial Artifacts) strategy[19]. Freitas wrote further about new SETI strategies[20], self-replicating spacecraft[21] and later nano-machines and nano-medicine. Concerning L4 and L5, in 1980-81, Suchkin, Tokarev, et al., searched these locations with pulsed radar for evidence of artifacts in parking orbits[22]. Infrared observations for evidence of astroengineering in the asteroid belt were proposed by Pappagainnis[23]. Alexy Arkhipov made contributions toward a lunar search for evidence of ETI artifacts[24]. Other notable authors include: A.C. Clarke[25], Robert L. Forward[26], Robert ML Baker[27], J. Allen Hynek[28], Tom Kuiper[29], Greg Matloff[30], Richard Burke-Ward[31], Allen Tough[32,33], Massimo Teodorani[34] and Claudio Maccone[35].

2.1 Refocusing the SETI More Inward

These writings, although rational and extensive, were accompanied by only very limited observational efforts. These occurred during a period when the search for ETI was overshadowed by the microwave strategy which is focused outside the solar system. Microwave searches have not yet resulted in detecting ETI. The negative results of searching for distant ETI should not overshadow the progress made by the microwave SETI researchers. Their noteworthy contribution has been a significant knowledgebase and infrastructure specifically tailored to search for microwave emissions. The negative microwave search results lend support to the argument that while advanced ETI may exist in great numbers in the galaxy, they don't seem to be intentionally transmitting microwave signals to civilizations like ours. This helps strengthen the argument that finding evidence for ETI may also require searching our own backyard.

There is a consensus among SETI scientists that the first civilization we encounter will be much older and technologically mature than ours. This intelligence, if nearby and motivated to explore the cosmos, could have discovered life's signature in our solar system long ago with powerful astro-sensing instruments complemented by exploratory probes. If ETI had recognized the emergence of an intelligent civilization on Earth, and wanted to signal us with microwaves during our present radio-telescope epoch, then we should have detected them by now. Even though microwave SETI advocates have identified a preferred frequency band and carried out a reasonable search effort, the fact remains nothing unequivocal has been detected. What perplexes some researchers is why there hasn't been a detection given the efforts made. This conundrum is what fuels continuing debates about our being unique in the galaxy (e.g., the Fermi Paradox). The lack of detection may have everything to do with the motivations and actions of the ETI along with the search space chosen. By considering ETI's motives and capabilities it is possible to rationalize re-focusing part of the search effort inward to our own solar system.

3. Current Perspectives on ETI Motives and Observable Manifestations

We can only deduce, based on our limited human experiences, what might motivate an ETI. We recognize, based on our technological achievements, a lower limit for ETI's technical capabilities. We enjoy contemplating the upper limits of ETI's capabilities, but really know nothing about what's ultimately possible. Confession of our ignorance about ETI civilizations does not give us permission to ignore or minimize the importance of ETI's motives or actions. Using our limited experiences and technological history as a template, it is useful to first construct a basic set of working assumptions for ETI's motives. This set spawns a range of potentially observable manifestations. The assumptions and manifestations collectively can in turn be used to argue for searching the solar system for evidence of ETI.

3.1 Working Assumptions

Can we assume ETI would be like us, motivated to explore and understand the cosmos? Do we share with ETI any objective knowledge? Can we assume ETI thinks and acts in ways we would find rational? Can we assume ETI's core technology is similar to ours, or based on an artificial intelligence (AI) and nano-technologies? Do we assume ancient ETI are "masters of the universe" physically, morally and spiritually, and capable of anything we can imagine? Can we assume ETI is in the galactic neighborhood or in our backyard? Questions like these proliferate the SETI, giving rise to an array of assumptions that are numerous, varied and oftentimes frustrating. This variety has lead to several proposed scenarios of first contact with an ETI.

Much has been written about ETI in the context of contact and its possible consequences. Obviously, the consequences of contact become more accelerated and immediate the closer we are to an ETI presence. It is the ancient, wise and advanced civilizations we expect to encounter first; not the young, irrational and self-injurious ones. The widely accepted microwave SETI viewpoint is that ETI is very distant and first contact will be limited to slow information exchanges across vast interstellar space. That contact scenario is only one of many that are possible.

Another conceivable class of scenarios involves contact with an ETI presence in our solar system. In such scenarios, either we find ETI or they find us. Since humanity has not accepted any such contact event as having taken place up to the present, for discovery to occur it seems we have to take the initiative in establishing contact. The Internet based "Welcome ETI"[36] effort is one such example. Before initiating a search for ETI in our solar system, it's prudent to identify and justify a set of working assumptions under which it would be possible or even reasonably likely that ETI would be present here.

First, to reach our solar system from even the nearest star, ETI must be far more technically advanced than us. To ascend to such an advanced state they are much "older" than us. The civilization age reached by these ETI is of academic interest, but not necessarily important to the search. What is important is that any ETI capable of traveling here are very experienced and knowledgeable in science, math and engineering. In the pursuit of knowledge ETI is expected to undertake projects that have high investment value. We know exploration of our solar system has proved to be remarkably valuable to our own pursuit of objective knowledge. Future astro-sensing of nearby star systems is expected to be similarly profitable. Mature ETI will invest proportionately in astro-sensing and interstellar exploration efforts because they both have a high return-on-investment value.

Second, we must assume advanced ETI possess the competence to explore interstellar space. Interstellar travel is not forbidden by the laws of physics *even as we know them*. Given what we know is possible with our present level of technology, interstellar travel is very difficult, costly and time consuming, but not impossible. Although it's possible, we are not ready to start building interstellar missions based on anything resembling the Orion or Daedalus designs[37]. For us, practical interstellar travel remains a drawing-board dream. Nonetheless, it is sensible to continue research into technologies like propellantless propulsion systems[38] because it helps us to appreciate the hurdles advanced ETI may have faced in developing propulsion technologies to make practical interstellar travel possible.

Third, we must assume that if ETI is here, it is for the purpose of exploration or surveillance. Harrison[39] makes a very strong case against ETI coming here for colonization purposes or overt conquest of Earth. Furthermore, since humanity is apparently struggling with itself and not an alien presence, we can surmise ETI may be indifferent toward our civilization. An ETI presence may have taken notice of the "life signatures" of Earth, but have shown no intention to contact us.

Fourth, science is filled with examples of discoveries that overturned established theories, explanations or caused paradigm shifts. The SETI should not ignore certain issues, like the true origin of the ETI we might discover, just because they seem extreme or don't fit neatly within the present SETI paradigm. Somewhat extreme issues like Panspermia and the origin of intelligent life on Earth are of academic interest, but should have only minimal influence on the design of new SETI strategies. Hence, we assume that any extraterrestrial intelligence we discover is not native to the solar system and ventured here from far away.

Fifth, any physical presence in the solar system must produce some kind of manifestation, either an energy emission or a physical artifact. Even if the ETI consisted of an immense swarm of nano-probes possessing a collective intelligence and sentience, they should still produce some kind of observable manifestation. We must assume that if ETI is in the solar system they are observable in some way. It's pointless to search for a presence that is not observable. The range of observable manifestations will be explored in a subsequent section.

Sixth, we must assume if ETI is present in the solar system they are not completely and effectively avoiding detection. Successful identification of ETI is difficult if they intentionally employ stealth ("low observable") tactics, actively confound our efforts to identify them by mimicking our spacecraft or their emissions, have placed our solar system off limits to exobiological study (e.g., Zoo Hypothesis[40]), or avoid contact due to a "prime directive". Given our level of social and technological advancement, any ETI present in the solar system is probably indifferent to needing to use stealth tactics.

Lastly, we must assume there are consequences involved in searching for and finding ETI nearby. To search for ETI in our backyard without exploring the consequences is irresponsible scientific inquiry. Searching for ETI far away is relatively safe. The impact of detecting a microwave beacon from say 200 light years away can be safely managed and integrated into our collective consciousness with minimal long-term political, social and religious side-effects[41]. Finding an active ETI presence nearby requires a careful response in order to avoid both a negative first contact outcome and societal alarm. Hence, it is wise to adopt and follow a set of working post-detection protocols and contingency plans. A draft of SETI post-detection protocols has been written in anticipation of contact with ETI[42,43]. Table 1. summarizes these working assumptions.

1.	ETI will invest in large scale exploratory efforts that produce value to them.
2.	ETI have the capability to physically explore the galaxy.
3.	ETI is here to explore or study the solar system.
4.	ETI we seek to discover originated from outside the solar system.
5.	ETI in the solar system will produce observable manifestations.
6.	ETI is detectable and not effectively invisible.
7.	Finding ETI nearby will produce consequences requiring post-detection protocols.

Table 1. Working Assumptions

3.2 Observable Manifestations of ETI

If ETI is present in the solar system, what are its possible manifestations? Discussing possible manifestations is important because it identifies the search articles, bounds the search locations and characteristics of the possible energy emissions or artifacts. Large and small scale manifestations are possible. A set of large-scale manifestations are listed in table 2. Table 3 lists a set of possible small-scale manifestations.

1.	High energy leakage from fusion power sources.
2.	Optical emission/absorption lines associated with artificial effusion clouds.
3.	Anomalous radio emissions from recombinations in gas clouds.
4.	Artificial hyperfine transition lines (Helium isotopes and tritium).
5.	Anomalous deviations in blackbody radiation.
6.	Artificially appearing x-ray and gamma ray bursts.
7.	Cosmic ray emissions from unexpected places.
8.	Large scale planetary, moon or asteroid belt mining.
9.	Emissions from antimatter, fusion or mag-sail propulsion systems[44].

Table 2. Large-Scale Manifestations

Searches within the solar system mainly focus on the detection of small-scale manifestations. These manifestations can be divided into sub-sets of electromagnetic energy markers and matter markers. Table 4 lists a sub-set of the possible energy marker manifestations from manifestations 5 and 6 in table 3. Microwave and optical energy markers are electromagnetic emissions of artificial origin. Of these two types the main interest has been microwave markers 1 and 2. The focus of the search has been in the 1 to 10 GHz microwave window, with particular attention given to the 1 to 3 GHz frequency band. The search for markers 3 and 4 is now being investigated more intensely. Some work has been done to search for artificial hyperfine emissions[45,46]. A search for markers of type 6 is an open area of research best suited to large ground-based optical observatories.

1.	Artificial Infrared, visible or UV emissions.
2.	Concentrated ionized gases–hot or cold plasmas.
3.	Periodic soft x-ray or gamma burst emissions.
4.	Anomalous electrophonic, ultrasonic or infrasonic emissions.
5.	Anomalous, non-terrestrial telecommunications activity (radio or optical).
6.	Anomalous microwave or optical phenomena.
7.	Varying albedos (radar or optical) from peculiar orbiting structures.
8.	Physical artifacts or waste products of unusual design or origin.
9.	Clearly visible signs of intelligent macro, micro or nano structural design.
10.	Clearly visible artificial structures on the moon or other solar system bodies.
11.	Observed artificially intelligent and/or autonomous behavior.
12.	Statistical anomalies in observed meteor activity or cometary patterns.
13.	Unusual or concentrated neutrino emissions.

Table 3. Small-Scale Manifestations

1.	Pulsed or CW Microwave Beacons (1 to 60 GHz)
2.	Microwave Pulsed Radar or Telecommunications leakage.
3.	Pulsed Laser Beacons (λ = 1 μm to 10 μm).
4.	Optical Laser Telecommunications Leakage.
5.	Artificial Hyperfine Line Emissions.
6.	Artificial emission lines (Fraunhofer, Balmer and Lyman series).

Table 4. Electromagnetic Energy Markers

Table 5 lists a sub-set of possible matter markers in the solar system derived from manifestations 1,2,3,4,7,8,9,10 and 11 in table 3. Matter markers are artificial structures engineered, constructed and operated for some extraterrestrial purpose. While an extraterrestrial bacterium can be considered a matter marker, it may not be possible to determine if it was engineered for a specific purpose or is a natural outcome of extraterrestrial evolutionary processes.

1.	Relativistic or High Velocity Artifact flybys.
2.	Artifact "Drift-Throughs" swept up by the Solar System's motion about the Galactic Center.
3.	Asteroid Belt Artifacts[23].
4.	Heliocentric, Sun-Synchronous, Elliptical, or Earth-Crossing Artifact Orbits.
5.	Self-Reproducing Automata (SRA).
6.	Earth-Moon-Sun Lagrange Parking Orbits[17].
7.	Geocentric Orbits.
8.	Lunar Orbiters or Lunar Artifacts.
9.	Planetary Orbiters or Artifacts.
10.	Bracewell Messenger Probes.

Table 5. Matter Markers

Marker 1: Relativistic or high-velocity flybys are artifacts that have trajectories taking them close to or through the solar system. High-velocity flybys could take from a year to a decade.

Marker 2: Drift-throughs are artifacts that pass through the solar system on a random trajectory. When the Voyager probes pass through neighboring star systems they would be classified as drift-through artifacts.

Marker 3: These are large artificial structures located in the asteroid belt. It has been proposed to search the asteroid belt for anomalous infrared radiation indicative of artificial energy sources used in mining activities.

Marker 4: These orbits propel the artifacts around the sun or planets in elliptical orbits. Heliocentric artifact orbits may periodically cause the artifacts to cross Earth's path such as that proposed by Steel[47].

Marker 5: SRA are artifacts that travel from star system to star system making copies of themselves at each stop. The replication process is expected to require hundreds or thousands of years depending on the size of the SRA[21]. The use of advanced nano technology to replicate swarms of nano-probes may take less time and energy.

Marker 6: The SOHO (Solar and Heliospheric Observatory) is presently orbiting about L1 as is the ACE (Advanced Composition Explorer). The NGST (Next Generation Space Telescope) is being designed to orbit about L2 as is the MAP (Microwave Anisotropy Probe) mission. Lagrange points also exist for other planet-sun and planet-sun-moon systems.

Marker 7: Earth-crossing orbits would periodically bring an artifact relatively close to the Earth-Moon system. These orbits are elliptical and may or may not be inclined with respect to the ecliptic plane.

Marker 8: Probe artifacts may be orbiting the moon. Lunar artifacts may have landed or impacted on the surface.

Marker 9: Probes may be orbiting a planet or its moons. Planetary artifacts are artificial structures that have landed or impacted the body's surface.

Marker 10: These are probes designed and constructed by ETI for purposes of contact and intelligent dialog with other intelligent species capable of detecting them and responding to their communication protocols.

Whether the interest is to search for energy emissions or artifacts, different markers require different kinds of sensors, instruments and strategic responses.

3.3 Searching for Manifestations of ETI in the Solar System

Solar system SETI (S^3ETI) is a search for ETI in the solar system. S^3ETI scans beyond the cis-lunar volume of space which is the realm of near-earth strategies (e.g., SETV). S^3ETI presumes there are observable energy-marker or matter-marker manifestations from an ETI presence. We observe these manifestations through the medium of electromagnetic radiation or physical effects. The S^3ETI search volume is defined as a heliocentric sphere having a 50 AU radius -- roughly the 1.4×10^{34} cubic meter volume contained within the orbit of Pluto[48]. This volume also encompasses part of the Kuiper belt. Detectable energy or matter markers may be present within this search volume. Given the distances involved, it is unlikely that most of the matter markers listed in table 5 could be directly imaged. Near-earth objects (NEOs) are an exception, and could be detected if they were fairly large (>10 meters), with limiting magnitudes of > +20 and albedos of >20%. Matter-markers, such as robotic probe artifacts, within the search volume might be found indirectly through the detection of certain energy-markers listed in table 4. Hence, S^3ETI is the search for artificial electromagnetic energy markers at microwave or optical wavelengths in the solar system.

The S^3ETI Hypothesis is presented as follows:

> *Technologically advanced extraterrestrial civilizations exist in the galaxy and are actively exploring interstellar space. There is a non-zero probability that ETI have reached our solar system and are detectable through the use of ground-based sensing instruments.*

The assumptions of the S^3ETI hypothesis closely follow the working assumptions listed in table 1. If probe artifacts are present, they could be emitting microwave energies. These emissions could simply be leakage, or for purposes of telecommunications, navigation, collision detection, or other purposes unknown to us. They could be a byproduct of high velocity space particle − SP (i.e., microscopic dust particle) impacts with an artifact.

EM telecommunications signals could be anything from simple amplitude or phase-modulated signals to complex spread spectrum, polarization-hopping or more exotic signals. Telecommunications could be taking place between a probe and a destination outside the solar system, or another probe within the solar system. In that case, we might detect leakage or indirect communication if the receiving probe happens to be in alignment with Earth or nearby. It's possible the telecommunications signals could be intended for us. This would be the case if the artifact were a Bracewell probe, which would probably position itself at a fixed location near Earth.

Navigation emissions could be ranging beacons employing sequential clock signals. They could be used as accurate timing signals, not unlike those produced by some galactic pulsars. Beacons could be CW or have pulse periods. Beacons could be deployed on planets, moons, asteroids, comets, orbiting about a solar system body, or be fixed in space. There could also exist warning beacons, repetitious data signals, or reflected signals.

Collision detection, avoidance or identification emissions could be from a pulsed radar used to detect sizeable objects such as comets, comet fragments, meteoroids or asteroids in the probe's path.

Secondary microwave emissions or EM bursts are another possibility. As a probe's velocity increases beyond thousands of kilometers per second, it must have the capability to deal with SPs. Large dust clouds or sizeable objects can be detected far enough ahead of the probe to permit timely reaction and avoidance. For high-velocity (e.g., relativistic) interstellar travel, microscopic particles (both charged or uncharged) that could damage a probe must be counteracted. Hence, a SP deflection system is a mandatory component for relativistic interstellar travel. It most likely involves some type of shielding mechanism in front of the craft. An energy absorbing defense shield, a la Star Trek, that weakens with every *direct* impact is not an ideal solution. Rather a system that could deflect high velocity SPs, while sustaining negligible energy loss, is preferred.

For such a deflector to be effective, some of the kinetic energy of the SPs must be dispersed by altering their $\vec{v}$ enough so their trajectory is tangent to the curvature of the field. This might be accomplished by high voltage electrostatic fields surrounding booms that shape the deflector. The deflection fields around these booms may be polarized and shaped like ellipsoidal shells enveloping and extending in front of the probe. SPs could gain a slight charge when passing through a larger outer shell and upon encountering inner smaller polarized shells slide along them as if were an aerodynamic surface. This concept is similar to the Bussard Ramjet[49], but in reverse.

The energy released during an impact with such a shield might produce secondary EM noise emissions. If such technology is present on an interstellar probe, faint noise bursts produced as the probe encounters SPs in its path could be detectable. If a probe travels through our solar system at a high velocity in a region where SP density is higher, such as concentrated areas of the Kuiper or asteroid belts, collision rates and secondary EM noise would increase. Presuming manmade noise bursts have been eliminated, detecting a short EM burst could indicate a limited duration SP deflection. A long burst or a series of short bursts may indicate that a probe deflected varying densities of SPs. If these bursts can be electronically tracked as they traverse antenna beams this could indicate an artificial quality. Such a detection may not necessarily indicate an artifact under intelligent control, unless it could be shown that the trajectory of EM bursts are not consistent with random motion. Another secondary emission could be from microwave pump generators used to drive laser transmitters operating at optical, IR or terra-hertz wavelengths.

A fair question is why would an ET presence in the solar system produce microwave energy emissions of any kind? It may not. Only a rigorous search, over a limited time period, of the most likely places such anomalous emissions would originate can help to get an answer.

3.4 A Search for Anomalous Microwave Phenomena

Anomalous Microwave Phenomena (AMP) are defined as unusual detected emissions in the 1 to 60 GHz microwave frequency band originating within the solar system. AMP are the result of either natural or artificial sources. For an example of natural AMP, Lash and Fremont[50] reported the detection of a pair of anomalous "radio bursts" using the BAMBI radiotelescope while observing Jupiter during the Shoemaker-Levy comet impacts. Natural AMP could result from comet or meteor impacts with Jupiter, Saturn, Uranus or Neptune.

If an artifact has an interplanetary microwave communications capability, it should employ carrier frequencies with daily stabilities better than 1 part in 10^{12}. Hence we should assume artificial communications signals from probes will be coherent and stable. However, other AMP emissions unrelated to communications may not be coherent or stable. Secondary emissions from probes are expected to be transient and non-coherent.

The search for any AMP in the solar system should account for the fact that emission sources will have an arbitrary motion relative to a receiving station on Earth. For natural or artificial AMP sources located in the solar system there are ten types of motions that can be considered (see table 6).

1.	Geocentric orbits: elliptical or synchronous.
2.	Lunar orbits: elliptical or synchronous.
3.	Heliocentric Orbits.
4.	Earth-Moon-Sun Lagrange Orbits.
5.	Elliptical Planetary Orbits.
6.	Synchronous Planetary Orbits.
7.	Solar-Planetary Lagrange Orbits.
8.	Relativistic Trajectories advancing or receding.
9.	Arbitrary Trajectories within the solar system.
10.	Gravity Assist Trajectories.

Table 6. Motions of AMP

AMP emissions from sources having arbitrary motions exhibit doppler frequency components. Doppler frequency shift and drift effects are well known to SETI researchers. Typically, the Cosmic Microwave Background (CMB) reference frame, the Galactic Barycenter (GBC) inertial frame, the Heliocentric Local Standard of Rest (LSR) and Earth's rotational period are used to compensate the frequency shift and drift of any interstellar signals received. Interstellar beacons are assumed to be doppler pre-compensated in some way. Artificial AMP emissions may or may not be doppler pre-compensated relative to any inertial frame. Natural sources of AMP will definitely not be doppler pre-compensated, nonetheless they will contain doppler components. Sources of AMP originating within the solar system are not assumed to be doppler compensated. We have no evidence ETI must pre-compensate their signals, and we don't need to dynamically doppler compensate the signals we transmit from our own spacecraft. Hence pre-compensating AMP signals for CMB, GBC and LSR is not necessary for S^3ETI research. Earth's rotational doppler acceleration is fairly large and must be "de-chirped" to remove its drift, which also aids in locating strong local sources of terrestrial Radio Frequency Interference (RFI). S^3ETI differs from traditional microwave SETI searches that expect an artificial microwave signal to be partially doppler drift compensated at the source.

While stellar doppler frequency drifts are unimportant to S^3ETI, there are other doppler drifts besides those produced by Earth's rotation that are important. AMP emissions from the types of motions listed in table 6 contain doppler components. Table 7 lists the absolute value of the doppler drifts of three different carrier frequencies (f_c) for transmissions located on or very near the major solar system bodies and those resulting from planetary heliocentric orbits. Most of the doppler drifts are small, and some are relatively large, but most of them can be examined while tracking the planets.

Table 8 lists the various doppler drifts for AMP located in the Sun-Earth-Moon system, including the Lagrange orbits. The values listed are not doppler compensated for the Earth's geo-rotational doppler drift, and the receiving ground station is assumed to be located at the Earth's equator (i.e., zero degrees latitude).

Table 9 lists examples of doppler drifts for sources of AMP orbiting the planetary bodies in prograde motion (i.e., the AMP's orbital motion is in the same direction as the planets rotation). The drift rates listed include the cyclic variation of the particular planet's heliocentric orbit, and Earth's heliocentric orbit, but not Earth's geo-rotational velocity. Again, the receiving ground station is located on the Earth's equator.

Table 10 lists examples of doppler drifts for sources of AMP on a rotating Trojan asteroid, AMP having the same orbit as an asteroid belt object, AMP within the Kuiper belt and following a comets orbit. These drifts are relatively small, but measurable nonetheless.

Table 11 gives three examples of doppler shifts for sources of AMP on solar system flyby or drift-through trajectories. The artifacts are assumed to be on cruise (non-accelerating) trajectories and producing very small doppler drifts. By themselves these tables have limited significance. However, in terms of an S^3ETI observing strategy, it is necessary to know the bounding doppler shifts and drifts for the various targets of interest. The importance of one-way doppler in an observational strategy will be clarified in a following section.

When analyzing the one-way doppler signature of radiating targets in motion, the total doppler producing velocity needs to include additional doppler components for ground based observations. The following basic formulas form the basis for the doppler analysis.

Classical Doppler Shift (Moving Source):

$$f_d = f_c / (1 \pm V_T \cos\theta / c) \qquad (4\text{-}1)$$

where:

f_d = Doppler shifted frequency (Hz).
V_T = Radial Velocity of target (+ for approaching, − for receding) (km/s).
θ = Angle between radial and orthogonal velocity vectors ($\theta = 0$ to π).
f_c = Carrier frequency (Hz).
c = Speed of light (2.997925×10^5 km/s).

Generalized Doppler Rotational Shift:

$$f_d = \pm\Omega\, a\, f_c / c \quad (4\text{-}2)$$

where:

Ω = Angular velocity (+ for retrograde rotation, − for prograde rotation) (radians/s).
a = Radial distance (km).
c = Speed of light (2.997925×10^5 km/s).

Generalized Doppler Rotational/Orbital Drift:

$$f_d/dt = \Omega^2\, a\, f_c / c \quad (4\text{-}3)$$

where:

f_d/dt = Doppler frequency drift rate (Hz-s^{-1}).
Ω = Angular velocity (radians/s).
a = Radial distance of orbit or radius of body (km).
c = Speed of light (2.997925×10^5 km/s).

Doppler Shift for Ground Station Receiving Antennas:

$$f_d = (V_T \cos\theta \pm V_E \cos\xi \cos\alpha)\, f_c / c \quad (4\text{-}4)$$

where:

V_T = Radial velocity of the target (km/s).
θ = Angle between radial and orthogonal velocity vectors ($\theta = 0$ to $\pm\pi/2$).
V_E = Geo-Rotational velocity (radians/s)
ξ = Latitude of the receiving antenna (0 to $\pm\pi/2$).
α = Receiving antennas elevation angle, (i.e., declination angle δ of target). ($\alpha = \pi/2 - \beta - |f_0 - f_e|$).
β = Angle made between the target, the ground station and Earth's center.
f_0 = True anomaly angle of the target.
f_e = Angle made between the ground station and the targets perigee (i.e., planet; $f_e = 0$).
c = Speed of light (2.997925×10^5 km/s).

Planetary Body	**Equatorial Rotational Velocity (m/s)**	**Equatorial Rotational Doppler Drift ($\lvert\text{Hz-s}^{-1}\rvert$) for f_c** 1 GHz	10 GHz	60 GHz	**Heliocentric Orbital Acceleration (m/s^2)**	**Heliocentric Orbital Doppler Drift ($\lvert\text{Hz-s}^{-1}\rvert$) for f_c** 1 GHz	10 GHz	60 GHz
Mercury	3.03	0.000013	0.000125	0.000751	0.03958	0.13	1.32	7.92
Venus	1.81	0.000002	0.000018	0.000108	0.01133	0.0378	0.378	2.268
Earth	465.1	0.113131	1.131307	6.787845	0.00595	0.02	0.20	1.18
Mars	240.8	0.056935	0.569347	3.416081	0.00255	0.0085	0.085	0.511
Jupiter	1.257E+4	7.375390	73.75390	442.5234	0.00022	0.00073	0.00731	0.04386
Saturn	1.029E+4	5.861397	58.61397	351.6838	0.000065	0.00021	0.00212	0.01275
Uranus	2,492.12	0.810538	8.105384	48.63230	0.0000163	~ 0	0.00054	0.00323
Neptune	2,680.94	0.968835	9.688350	58.13010	0.0000067	~ 0	0.00022	0.00132
Pluto	12.95	0.000492	0.004916	0.029499	0.0000038	~ 0	~ 0	~ 0

Table 7. Solar System Body Doppler Drift Rates

Conditional Motions	**Mean Doppler Producing Velocity (km/s)**	**Doppler Drift ($\lvert\text{Hz-s}^{-1}\rvert$) for f_c** 1 GHz	10 GHz	60 GHz
Low Earth Orbit (320 km, $e = 0$)	7.714	497.58	4975.77	29,854.63
High Earth Orbit (100,000 km, $e = 0$)	1.936	25.07	250.68	1,504.06
Synchronous Earth Orbit (35,798 km)	3.074	72.57	725.71	4,354.23
Low Lunar Orbit (20 km, $e = 0$)	0.795	1.86	18.64	111.87
High Lunar Orbit (100 km, $e = 0$)	0.777	1.67	16.66	99.93
Synchronous Lunar Orbit (86,720 km)	0.112	0.00048	0.00477	0.0286
Heliocentric Lagrange 1 Orbit	30.1	0.02	0.199	1.199
Heliocentric Lagrange 2 Orbit	29.5	0.02	0.196	1.175
Heliocentric Lagrange 3 Orbit†	29.8	0.02	0.198	1.187
Heliocentric Lagrange 4 Orbit	29.79	0.02	0.20	1.18
Heliocentric Lagrange 5 Orbit	29.79	0.02	0.20	1.18

† Approximately stable for 150 years, opposite the sun.

Table 8. Earth-Moon-Sun System Doppler Drift Rates

Conditional Motions: Planet	Conditional Motions: Orbit†	Mean Doppler Producing Velocity (km/s)	Doppler Drift (|Hz-s^{-1}|) for f_c: 1 GHz	10 GHz	60 GHz
Mercury	20 km, *e* = 0 (circular)	2.98	12.14	121.44	728.64
	100 km, *e* = 0	2.93	11.39	113.91	683.47
	Synchronous (239,340 km)	0.305	0.00126	0.01257	0.07543
Venus	20 km, *e* = 0	7.314	29.39	293.92	1,763.50
	100 km, *e* = 0	7.267	28.63	286.32	1,717.94
	Synchronous (1,532,229 km)	0.458	0.000455	0.004546	0.027278
Mars	20 km, *e* = 0	3.544	12.29	122.86	737.19
	200 km, *e* = 0	3.5032	11.73	117.30	703.78
	Synchronous (17,071 km)	1.340	0.25	2.512	15.07
	Elliptical *e* = 0.66, T = 16 hrs	2.18	2.92	29.22	175.33
Jupiter	100 km, *e* = 0	42.085	82.52	825.22	4,951.32
	1000 km, *e* = 0	41.968	80.48	804.85	4,829.14
	Synchronous (88,511.6 km)	28.15	16.52	165.21	991.26
	Europa (670,900 km)	13.74	0.848	8.482	50.89
Saturn	100 km, *e* = 0	25.073	34.736	347.36	2,084.15
	1000 km, *e* = 0	24.888	33.723	337.228	2,023.37
	Synchronous (48,896 km)	18.645	10.623	106.226	637.358
	Titan (1,221,850 km)	5.44	0.077	0.770	4.620
Uranus	100 km, *e* = 0	15.06	29.486	294.865	1,769.19
	500 km, *e* = 0	14.94	28.588	285.882	1,715.29
	Synchronous (59,222 km)	8.28	2.701	27.009	162.053
Neptune	100 km, *e* = 0	17.028	37.262	372.618	2,235.71
	500 km, *e* = 0	14.802	36.090	360.904	2,165.42
	Synchronous (58,942 km)	2.4435	3.284	32.844	197.06
Pluto	20 km, *e* = 0	17.607	893.807	8,938.07	53,628.44
	100 km, *e* = 0	17.0287	781.936	7,819.36	46,916.16
	Synchronous (17,561 km)	4.379	3.422	34.223	205.34

† Prograde Orbits

Table 9. Planetary Orbital Doppler Drift Rates

Solar System Object	Rotational Velocity (km/s)	Mean Orbital Velocity (km/s)	Doppler Drift (|Hz-s^{-1}|) for f_c: 1 GHz	10 GHz	60 GHz
Trojan Asteroid - Hektor	---	13.10	0.00063	0.00631	0.03785
Asteroid Belt Object - Ceres	0.091	18.143	0.061	0.610	3.659
Kuiper Belt Object – VC95	---	4.36	0.000009	0.000091	0.000544

Table 10. Asteroid and Kuiper Belt Object Doppler Drift Rates

Conditional Trajectory	Radial Velocity (km/s)	Doppler Shift (MHz) for f_c: 1 GHz	10 GHz	60 GHz
Solar System Fast Flyby (100 AU / year) 15.8% C †	4.7437E+4	172.982	1,729.824	10,378.947
Solar System Flyby at 10% C †	2.9979E+4	105.541	1,055.415	6,332.496
Solar System Slow Flyby (6.3 AU / year) 1% C †	2.9979E+3	10.050	100.505	603.030
Solar System Drift Through	38.75	0.013	0.129	0.776

† Relativistic doppler for moving source

Table 11. Artificial Trajectory Doppler Shifts

4. The Application of Radio Telescope Arrays to Solar System SETI

Certain energy-markers have been identified that could originate from an ETI presence in the solar system. That presence is expected to take the form of exploratory robotic probes. On the matter of searching for exploratory probes, the SETI 2020 report co-authored by Jill Tarter of the SETI Institute[51] recommended:

> "In the case of probes, the most promising strategy is to take advantage of every opportunity to investigate interplanetary space…while conducting traditional ground-based astronomical observations."

The ATA, Square Kilometer Array (SKA)[52] and Array2K[53] can be classified as "traditional ground-based" radio-astronomy observatories. These arrays are under design and/or construction and not yet operational. They represent preferred SETI resources for carrying out S^3ETI compared to government operated antennas such as the Deep Space Network (DSN), the Very Large Array (VLA) or the large number of military operated antenna terminals. These facilities are presumed to be unavailable for SETI research, but could possibly be harnessed if the need was crucial. Ground based radio-telescopes destined for microwave SETI research can be used to search for AMP within the solar system. Of the SETI phased-array antennas presently being designed and constructed, the ATA stands out as the preferred ground-based asset to conduct S^3ETI research.

4.1 Characteristics and Capabilities of the Allen Telescope Array

The Allen Telescope Array is presently under construction at the site of the Hat Creek observatory in Northern California, USA. Table 12 lists the published ATA system level specifications that constitute the basic operating parameters[54]. Whilst developing the S^3ETI observing strategy in this monograph we are constrained to these operating specifications. The ATA is still undergoing design and is slated to see first light with a sub-array in 2003. It is planned to go into full operation in 2005 with its tested technologies feeding into the SKA system. The specifications in table 12 are subject to change, hence any implementation plan of S^3ETI research in the future will need to adapt to fit within those constraints.

Based upon a review of the available ATA system level specifications, the instrument has the capability to carry out an effective search of the solar system for AMP. The specific targets and regions it can observe, search and track are listed in table 13.

Parameter	Value	Comments
Observatory Latitude	40.8173 N	Region Spans 40º 00? to 42º 00?
Observatory Longitude	121.469 W	Region Spans 120º 15? to 122º 15?
Number of Elements	354	Scalable from the initial 350
Antenna Element Size	6.1 meter	6m x 7m Offset Gregorian
Aperture Feed	Log-Periodic	Integral Cryogenic MMIC LNA
Frequency BW	0.5 to 11.2 GHz	1 to 10 GHz Optimized
IF Channel BW	1 GHz	
Instantaneous BW	4 GHz	4 IF channels
Aperture Collecting Area	10345.53 m^2	Based on 354 antenna elements
Effective Collecting Area	6517.6 m^2	Based on 354 antenna elements
System Noise Temperature	43 K	
Aperture Efficiency	63%	Actual value will be derived from known calibration sources
Effective Gain	2.332 K/Jy	≈60 dBi @ 1 GHz ≈80 dBi @ 10 GHz
System Equivalent Flux Density (SEFD)	18 Jy	System Sensitivity 1 Jy = 10^{-26} (W/m^2Hz)
Number of Beams	= 16	E and H polarizations
Primary Field of View (FOV)	3.5º @ 1 GHz; 0.4º @ 10 GHz	3 dB Beamwidths
FOV Synthesized	0.03º @ 1 GHz; 0.003º @ 10 GHz	3 dB Beamwidths
Number of Channels per IF	$>10^8$	Scalable with added hardware
Channel Isolation	> 60 dB	
Timing Standard	> 1 Part in 10^{14}	Hydrogen Maser Clock
Tracking Slew Rate†	Az = ? deg/sec El = ? deg/sec	Belt-Drive X-Y Mount
Project Duration	> 20 years	Extendable if warranted

† Not published at the time of publication

Table 12. ATA Operating Specifications

1.	All the individual planets and their moon systems.
2.	The moon.
3.	The four Lagrange points (L1, L2, L4, L5).
4.	Known Near Earth Objects.
5.	Known Asteroids including the Trojans.
6.	Known Comets.
7.	Kuiper Belt Objects.
8.	Regions of interest near the ecliptic plane.

Table 13. ATA S^3ETI Targets

4.2 An S^3ETI Observing Strategy Utilizing the Allen Telescope Array

The architects of the ATA recognize the fact that it can support a wide range of SETI research. However, unless specific attention is paid to the S^3ETI search space, detection of AMP in the solar system would be serendipitous and most likely rejected as the result of adaptive filtering and RFI mitigation algorithms[55,56]. Regardless of the ATAs intended search space, S^3ETI observations can make excellent use of the observatory to test the S^3ETI hypothesis, and study the characteristics of AMP detections. The power of the ATA lies with its ability to scan planets, moons or other solar system targets with single or multiple antenna beams and examine the doppler drifts, coordinates, trajectory and radial velocity of any AMP emissions that are detected.

4.2.1 Doppler Correlations

Experiments that use the ATA should concentrate on finding correlations between the one-way doppler drift or shift of the AMP emissions and a priori values from a set of modeled orbits and motions for solar system targets of interest[57,58]. For example, if the planet Jupiter is being scanned by the ATA and an AMP emission at 6500.58 MHz with a drift rate of 4.97 Hz/s is measured, this correlates well with a 6500 MHz signal emanating from the surface of Jupiter's moon Europa. Analysis of one-way doppler signals can help in estimating the relative radial velocity of the AMP as long as the signal can be integrated and is not a short burst. The stability of the ATA hydrogen maser clock provides sufficient doppler accuracy to measure fractional doppler shifts and drifts.

The ATA system divides each receive antenna's 0.5 to 11 GHz frequency bandwidth into 4 dual polarization channels each with an IF bandwidth of 1 GHz. Presumably a drifting signal passing from one IF channel to the next can be measured. If this is correct then the system has approximately 4 GHz of instantaneous bandwidth. With this much bandwidth doppler shifts of several MHz/sec can be detected. The receive bandwidth of the system allows a wide range of radial velocity AMP emissions to be detected. Figure 1 is a graph plotting the relative radial velocity of a signal versus the relativistic Doppler Δf of the signal. The solid black line is the ATA receive bandwidth boundary. Only doppler shifted frequencies to the left of the solid line are detectable. For example, a Bracewell probe entering the solar system at 50% C transmitting a beacon frequency >6.5 GHz would be undetectable with the ATA.

4.2.2 Single Beam Observations

The ATA can use different numbers and combinations of phased array elements to synthesize different size FOVs. Using all the antenna elements, Gaussian beamwidths of 0.03º at 1 GHz and 0.003º at 10 GHz can be synthesized. The FOV of 0.03º subtends an angle smaller than all of the planet-moon systems in the solar system. The entire Neptune planet-moon system can be observed with an FOV of 0.137º, while the Jupiter planet-moon system can be observed with an FOV of 2.91º. For solar system targets larger beams, or those producing elliptically shaped Gaussian patterns (i.e., asymmetrical HPBW in the E-H planes) are necessary, and can be accomplished by trading some array gain and efficiency. Increased beam sizes allow entire planet-moon systems or groups of planets in close conjunction to be tracked. This is a way to optimize the amount of planetary observing time by increasing the number of targets. During a single beam observation, a solar system body is tracked as it traverses the sky and any detected emissions are examined for doppler correlations. The disadvantage of a single beam observation is that it does not contain enough information to determine where in the target region the AMP originated.

4.2.3 Multiple Beam Observations

The ATA can synthesize up to 16 simultaneous dual-polarization beams. Multiple beams allow multiple targets to be observed. For example, from early February to mid April 2020, all eight planets can be simultaneously observed an average of three hours per day with separate beams. Furthermore, from 2005 to 2025 there is an abundance of between two and seven planetary combinations that can be observed. As with single beam observations, some gain and efficiency are traded so that multiple targets can be observed with reduced sensitivity. Again, these observations are designed to search for AMP whose doppler characteristics can be measured and correlated with a database of calculated values.

Multiple beam observations of a single planet-moon system are also possible. If several overlapping beams are employed in a drift scan mode then the transit time of an AMP emission can be measured as it passes from one beam to the next, presuming it persists long enough.

Of special interest is the ATA's capability to produce a monopulse scanning mode. One beam is centered on the target to primarily measure doppler drifts. The other beams simultaneously scan four overlapping quadrants around the target. This method can produce an accurate 2-D position map of emissions allowing the ΔAz and ΔEl coordinates to be determined. By configuring sum (Σ) and difference (Δ) channels from the quad beams and sending the signals to a phase-sensitive amplitude detector the sign and angle-of-arrival of the signal can be found. An amplitude or phase comparison monopulse mode allows AMP having short bursts or pulse-like characteristics to be measured (see figure 2). Lastly, dual beams can be used to look for two-way transmissions between planets that are nearly opposite each other.

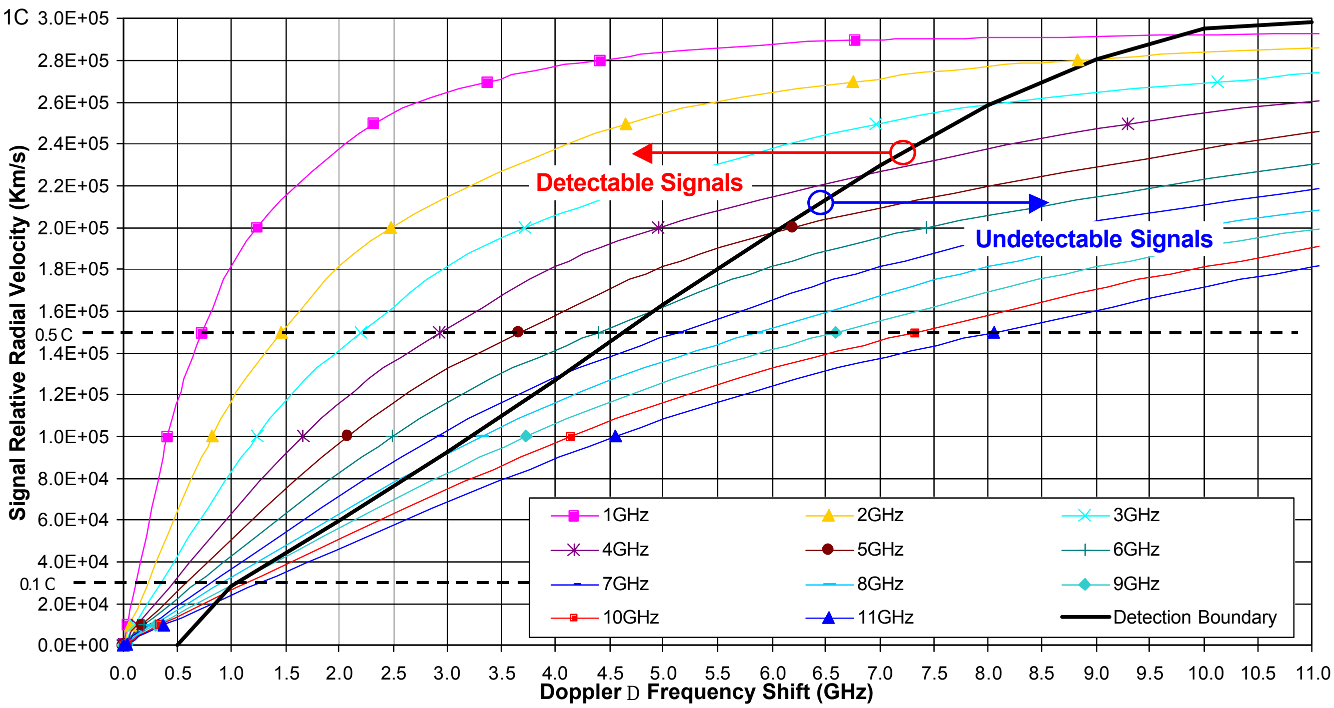

Figure 1. Doppler Shift vs. Signal Radial Velocity

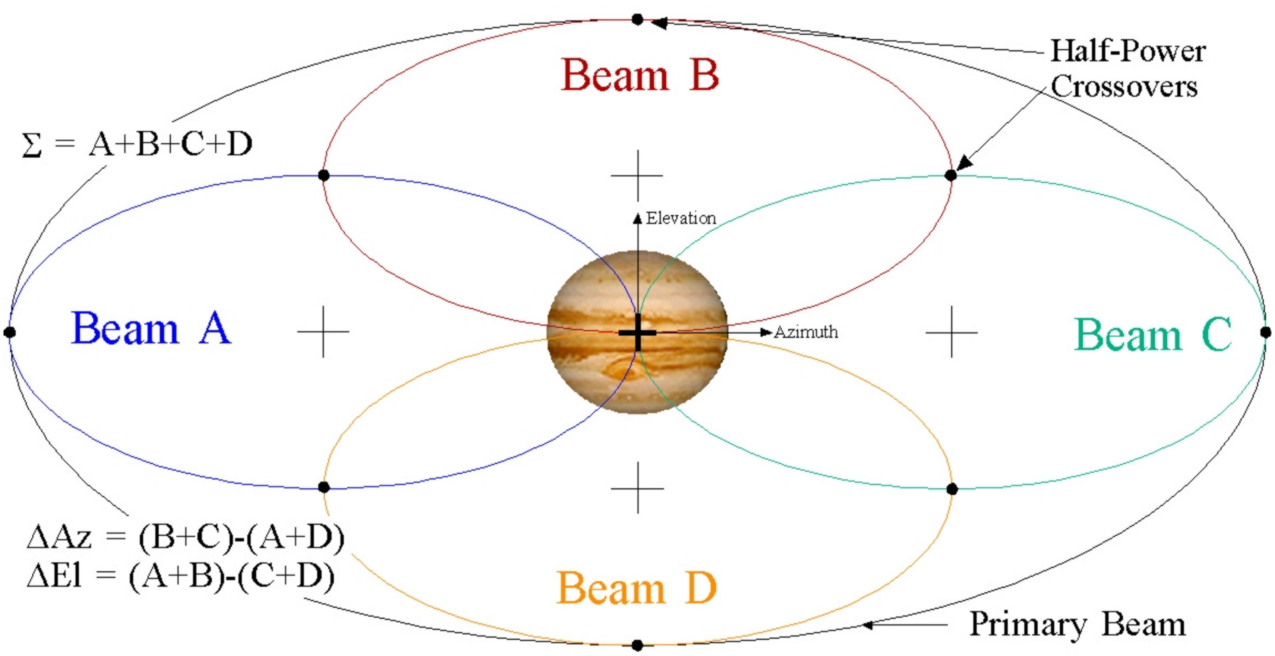

Figure 2. Synthesized Monopulse Configuration for Jupiter Observations

4.2.4 Signal-to-Noise Ratio Advantages

Solar System SETI targets are vastly closer than even the nearest star system Alpha Centauri, which is 4.4 light years away. For an arbitrary frequency the free space path loss difference between 4.4 LY and 50 AU is approximately 75 dB. If reduced space loss is equated to an increase in collecting area, then at 11 GHz, 75 dB gain is comparable to a 590m diameter reflector. Interplanetary scintillations (IPS) are mainly caused by scattering from the solar wind, and fields emanating from the gas giant planets. IPS can affect a microwave signal's amplitude and phase. These IPS are considered "noise-like" and occur with gain modulation time-scales of 10^2 to 10^4 seconds. Searches for interstellar signals must contend with both IPS and interstellar scintillations (ISS). ISS can occur with gain modulation time-scales as short as 0.1 to 1 second or as long as hours, and depends on the distance and declination angle of the target. Strong ISS can cause a 100% amplitude modulation of the signal intensity driving it below its mean value into the receiver systems noise floor for long times. Thus ISS effects require long observation times and repeated SETI observations of interstellar sources already extensively weakened by free space path losses[59]. S^3ETI targets are only affected by IPS which are offset greatly by lower path losses. This equates to a remarkably good Signal-to-Noise ratio (SNR). For example, given the ATA system specifications, using a 1 second integration time, an 11 GHz, 72W isotropic signal radiated near Pluto could be detected with a 2 dB SNR. To detect the same 11 GHz isotropic signal from 4.4 LY with a 2 dB SNR, it would need to be at least 2.2 GW; from 150 LY it would need to be at least 2.55×10^{12} W!

4.2.5 AMP Signal Verification

False positives are always a headache for SETI efforts. The ATA architects are well aware of the myriad of manmade satellites whose emissions fall within the passband of the ATA. Steps are being taken to mitigate the EMI and RFI caused by these sources. RFI mitigation algorithms will allow the system to quickly filter and eliminate false positives. However, in the case of AMP, there is a fine line between false positives and true positives. Artificial telecommunications signals from Earth's known deep space probes, when detected, can easily be recognized and rejected so they won't be falsely interpreted as AMP.

For signal verification purposes, an ATA drift-scan sub-array can be used. The sub-array can be pointed one beam diameter ahead of the target being tracked. If the primary beam detects a signal the sub-array is halted allowing the target to drift into the sub-array beam. If the signal is real then it should be detected in both beams.

It's also possible to coordinate some of the ATA detections with other facilities. By 2005, the Arecibo antenna receiver should upgraded to cover the frequency band between 1 and 10 GHz. Arecibo is capable of independently verifying ATA detections provided the target is within Arecibo's declination window ($\delta = 1° 24'$ S to 38° N) and the emission persists long enough for Arecibo to find it.

In any case, signal verification procedures for the ATA are needed whether the ATA is being used for conventional SETI or S^3ETI. Signal confirmation depends on proving that the AMP signals were not terrestrial RFI and the AMP source really is within the solar system

4.3 Targets of Opportunity

The solar system is filled with objects and regions to observe for AMP. Individual planets, comets and asteroids are worthy targets. Multiple planets, the asteroid belt, Trojan asteroid regions, the Kuiper belt, and along the ecliptic plane offer more opportunities. These solar system targets are now briefly examined.

4.3.1 Observations of Individual Planet-Moon Systems

Each planet-moon system can be systematically scanned for AMP. Table 14 summarizes the number of days and hours for single target observations in the year 2005. Subsequent years offer similar opportunities. For example, the Jupiter system can be systematically observed for 343 days, for an average of 11.21 hours per day. Shadowing of some ATA antenna elements by others can reduce planetary tracking time. If, for example, the elevation angles are limited to >15° above the horizon to improve signal correlations, then in that case Jupiter tracking time is reduced by approximately 25%. If ¼ of the days are excluded for bad weather and station down time that still offers 255 days of observations. At least one planet is visible every day during some time of the day.

Planet	No. of Days†	Total Hours	Average Daily Hours
Mercury	304	3,651.13	12.20
Venus	312	3,550.25	11.43
Mars	351	4,198.83	12.40
Jupiter	340	3,808.37	11.21
Saturn	343	4,932.97	14.40
Uranus	343	3,721.12	10.85
Neptune	345	3,447.70	9.98
Pluto	365	3,607.40	10.08

† Hat Creek Longitude and Latitude; $\theta_{SEP} > 5°$

Table 14. Planetary Observations for 2005

Another constraint on observations is the sun. Targets that are < 2° of the sun must be avoided due to increased thermal noise and scintillations induced by the solar wind. The SEP (Sun-Earth-Planet) offset (θ_{SEP}) is the angular separation between the sun and the planet under observation. While observing a single planet, or multiple planets, a minimum SEP offset of θ_{SEP} >3° (~ 11.3 solar radii) can be chosen so that noise contributions to the system noise temperature will be small. For θ_{SEP} of >5° the solar noise is near or beyond the first null of the ATA antenna elements so its noise contribution is negligible. If a θ_{SEP} of >5° is not enough, the null forming capabilities of the ATA can be used to suppress interfering or noisy signals off boresite or within a bandwidth of frequencies.

4.3.2 Observations of Multiple Planet-Moon Systems

Multiple planet-moon systems can be observed and tracked with the ATA. To increase observing efficacy, planets which are in close conjunction should be considered prime targets. Table 15 lists the two-body planetary conjunctions between 2005 and 2025. A conjunction separation angle (θ_c) of ≤ 2.5° was chosen. A total of 181 conjunction events are observable. Also, two planetary bodies in opposition with the Earth between them can be observed. This makes it possible to search for evidence of telecommunications leakage or beacon signals sent between probes located at two planets. Table 16 lists the two-body planetary oppositions between 2005 and 2025. An opposition angle of 170°< θ_{Opp}<179° was chosen with a θ_{SEP} of > 5°. A total of 73 opposition events are observable. For all oppositions, the one-way light time for signals between the two planets exceeds 2 hours. Consequently one planet would be observed for at least 4 hours before it sets and the other 4 hours after it rises to attempt detection of AMP from both bodies indicative of some kind of two-way communication. Figure 3 illustrates the planetary conjunction, opposition and SEP concepts.

Planetary Bodies in Conjunction	Conjunction Statistics† No. of Events	No. of Days	No. of Hours
Mercury + Venus	11	54	636
Mercury + Mars	14	47	428
Mercury + Jupiter	5	13	266
Mercury + Saturn	5	15	177
Mercury + Uranus	11	32	395
Mercury + Neptune	13	42	617
Mercury + Pluto	2	15	138
Venus + Mars	7	50	625
Venus + Jupiter	15	71	835
Venus + Saturn	7	27	321
Venus + Uranus	14	49	443
Venus + Neptune	17	52	518
Venus + Pluto	7	32	277
Mars + Jupiter	9	69	907
Mars + Saturn	6	43	476
Mars + Uranus	11	56	522
Mars + Neptune	10	53	582
Mars + Pluto	3	17	152
Jupiter + Saturn	1	35	324
Jupiter + Uranus	4	131	1,694
Jupiter + Neptune	3	133	1,376
Jupiter + Pluto	3	98	897
Saturn + Uranus	0	0	0
Saturn + Neptune	1	104	1,212
Saturn + Pluto	2	33	301
Uranus + Neptune	0	0	0
Uranus + Pluto	0	0	0
Neptune + Pluto	0	0	0
TOTALS	181	1,271	14,119

† Hat Creek Longitude and Latitude; θ_{SEP} >3°; θ_c ≤ 2.5°

Table 15. Two-body Planetary Conjunctions

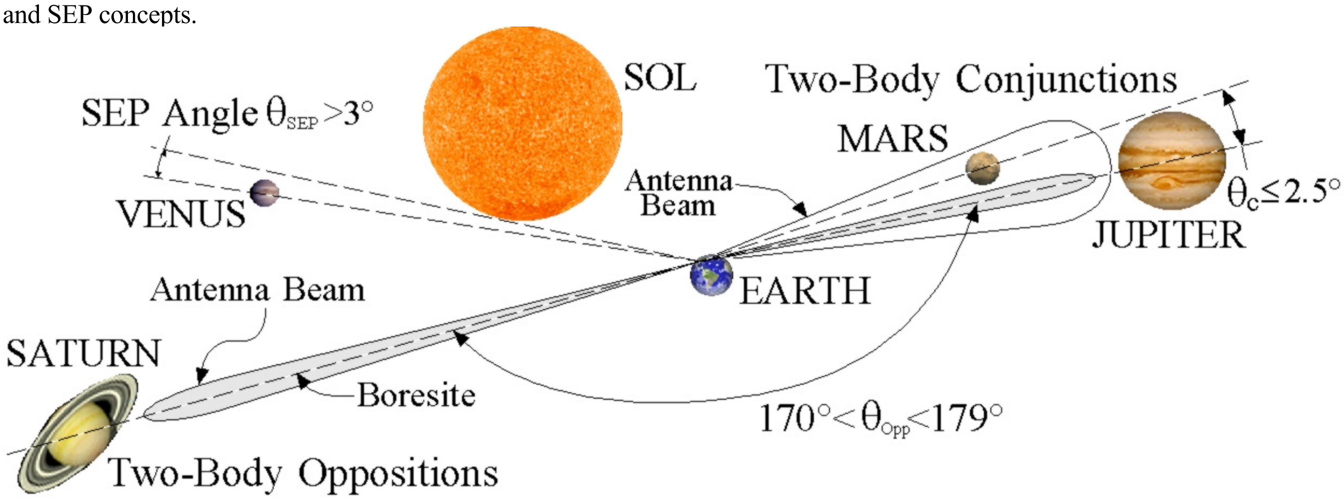

Figure 3 Conjunctions, Oppositions and SEP Angle

Planetary Bodies in Opposition	Opposition Statistics† No. of Events	No. of Days
Mars + Jupiter	12	424
Mars + Saturn	10	252
Mars + Uranus	12	430
Mars + Neptune	13	451
Jupiter + Saturn	4	329
Jupiter + Uranus	3	230
Jupiter + Neptune	3	216
Jupiter + Pluto	3	270
Saturn + Uranus	8	766
Saturn + Neptune	5	642
Saturn + Pluto	0	0
Uranus + Neptune	0	0
Uranus + Pluto	0	0
Neptune + Pluto	0	0
TOTALS	73	4,010

† Hat Creek Longitude and Latitude, $\theta_{SEP} > 5°$; $\theta_{Opp} > 170°$

Table 16. Planetary Oppositions

4.4 ATA S^{3}ETI Research Proposals

Written proposals to use the ATA instrument must follow the proposal guidelines established by the ATA administrators. At this time, it is not clear that such guidelines exist and they are probably in the draft stages. In any case, the demands on the ATA once it goes into operation are expected to be high. Like most specialized and costly observatories, daily, monthly and yearly schedules are drawn up in order to optimize the observing time of the instrument, and to serve as many customers as possible. There will probably be a "SETI target scheduler", standardized user interfaces and data products which the customers will need to become familiar with and take into consideration when they write their proposals. To assist in optimizing the use of the ATA, certain observations will be fully or semi-automated. Non-standard measurements that require added computer data processing, pointing accuracies, signal processing or other resources would likely require additional funds that may or may not be in the ATA operating budget. In that case customers that require specialized ATA configurations may be required to fund them. S^{3}ETI research proposals must take into account all the factors involved in carrying out observational experiments with the ATA.

It is expected that "piggyback" modes of operation will be commonplace with the ATA, like those with Arecibo. Piggybacking allows two or more users to simultaneously carry out independent experiments. For example, one user might use the ATA to map certain regions of the galaxy concurrently with someone who is searching for new pulsars. The S^{3}ETI strategy is focused on observing a rich volume of bounded and finite outer space. There are so many targets of opportunity within that space that the ATA could be used full time to support S^{3}ETI. The S^{3}ETI strategy has considerable merit but the ATA is not being built to support only one dominant strategy – it needs to be a shared resource. As with other research proposals, S^{3}ETI researchers can use the ATA in a piggyback mode.

Even restricting S^{3}ETI to a piggybacking role there are still plenty of opportunities. For example, any AMP signal that is detected can have its one-way doppler analyzed. Special attention can be given to times when planets traverse the ATA beams, especially when two planets are in conjunction. In the case of non-SETI proposals planning to use the ATA to study solar system targets, S^{3}ETI can piggyback on those experiments.

A simple S^{3}ETI proposal, which shouldn't consume too much ATA resources, is to carry out a limited experiment that exercises all the different observational modes described in sections 4.2 and 4.3. A single planet or two could be tracked for one day while exercising the doppler correlation database. Two planets in close conjunction could be tracked and scanned for a few days. Two planets in opposition could be observed. The monopulse scanning mode could be tested. All of these cases can be exercised at least once to see how well they work and the lessons learned.

5. Summary

It is possible, within the laws of physics and biology as we now understand them, for ETI to exist and be capable of actively exploring interstellar space. It's plausible that advanced and ancient ETI could have discovered our solar system long ago and sent exploratory robotic probes to study our solar system. These probes could be here now and it's possible for them to be actively engaged in some kind of scientific exploration or surveillance activity. Several SETI observational capabilities and opportunities are emerging as our sensor, antenna and computer technology improves. The Allen Telescope Array, which is expected be a very powerful microwave sensing instrument, is well suited to carry out a search of the solar system for anomalous microwave phenomena.

The ATA can be used to scan individual planets, entire, planet-moon systems, planets in conjunction with other planets, multiple planets simultaneously, planets in opposition with other planets, known comets, asteroids and other targets of interest.

A methodical examination of these targets may uncover microwave emissions that, through doppler analysis and monopulse techniques, prove they are originating from within the solar system. If it is concluded these emissions statistically correlate with originating from the target being scanned, exhibit unambiguous artificial qualities, and are verified to be a true positive then a strong case can be made of the scientific discovery of extraterrestrial intelligence.

We encourage the ATA administrators to recognize the potential benefits an S^3ETI strategy presents to the SETI. By focusing some of our attention and resources inward to the solar system the SETI effort will be more comprehensive and less exclusionary. A tacit recognition of these possible benefits could be given by accepting scientifically grounded proposals to carry out S^3ETI experiments using the ATA. Whether for SETI or not, we encourage researchers, and those in academia who are interested in using the ATA to come forward with research proposals to study our solar system.

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7. Glossary of Terms

AI – Artificial Intelligence
AMP – Anomalous Microwave Phenomena
ATA – Allen Telescope Array
AU – Astronomical Unit (1.4959787×10^{11} meters)
Az – Azimuth
DEC – Declination (δ)
DSN – Deep Space Network
e – Eccentricity
E-Plane – Electric-field plane
El – Elevation
ETI – Extraterrestrial Intelligence
EM – Electromagnetic
EMI – Electromagnetic Interference
FOV – Field of View
GHz – Giga-Hertz
H-Plane – Magnetic-field plane
HPBW – Half Power Beam Width
IF – Intermediate Frequency
IPS – Interplanetary Scintillation
ISS – Interstellar Scintillation
L1, L2, L3, L4, L5 – Lagrange Orbit 1….5
LNA – Low Noise Amplifier
MHz – Mega-Hertz
MMIC – Monolithic Microwave Integrated Circuit
RA – Right Ascension
RFI – Radio Frequency Interference
SEP – Sun-Earth-Planet or Sun-Earth-Probe
SETA – Search for Extraterrestrial Artifacts
SETI – Search for Extraterrestrial Intelligence
S^3ETI – Solar System SETI
SETV – Search for Extraterrestrial Visitation
SKA – Square Kilometer Array
SNR – Signal-to-Noise Ratio
SRA – Self-Replicating Automata
VLA – Very Large Array

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