SETICon03

SOLAR SYSTEM SETI USING RADIO TELESCOPE ARRAYS

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S³ETI

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Overview of the SETI in the Solar System

- **The Solar System is Essentially our Civilizations Back Yard**
  - Cis-lunar space is like our back porch. ***It's closer and a rational place to search!***
- **Searching the Solar System has been Proposed by Many**
  - Bracewell, Dyson, Boyce, Pappagainnis, Tough, Matloff, Arkhipov, et al.
- **A Major Strategy Emerged – SETA**
  - The Search for Extraterrestrial Artifacts.
  - Developed by Robert Freitas and Francisco Valdes (1980-85).
  - Defined a bounded search space, artifact size and visual magnitude.
  - Performed an optical search for robotic probe artifacts in Lagrange orbits.
  - Carried out a radio-telescope search for hyperfine tritium line emissions.
- **New Ideas and Strategies to Search the Solar System, Near Earth and Elsewhere are Emerging**
  - Open SETI (Zeitlin), Welcome ETI (Tough), SETV, S^3ETI (Cornet,Stride).

Current Perspectives and Working Assumptions

First Order Working Assumptions for a Backyard Search

1. To reach the solar system from even the nearest star, ETI must be moderately more technologically mature than we are.
2. ETI possesses the competency to explore interstellar space.
3. If ETI is now here, the purpose is for exploration and/or surveillance, not conquest or exploitation.
4. Science is filled with examples of discoveries that overturned established theories and paradigms. ***SETI should expect the unexpected!***
5. A physical presence should produce some kind of manifestation, either an energy emission, a physical artifact or both.
6. If ETI is present in the solar system they are not effectively avoiding detection. ***If here, we should be able to find them!***
7. We need to understand the consequences of searching for and finding ETI nearby. ***Finding a lone robotic probe nearby is relatively safe.***

Observable Manifestations of ETI

▸ Focusing the SETI Inward

- ∗ The effort to find ETI has been ***dominated*** by microwave SETI.
- ∗ The negative microwave outcome to date ***suggests*** advanced ETI may not be intentionally transmitting microwave signals to civilizations like ours.
- ∗ Additionally, we may have to look for evidence of ETI nearby. Our backyard.

▸ ETI Motives and Observable Manifestations

- ∗ Understanding ETI's motives for exploration and contact is tempered by our human experiences and history.
- ∗ Our ignorance does not give us blissful permission to minimize the importance of ETI's motives, actions or inactions.
- ∗ Our technological achievements provide a lower bound for ETI's.
- ∗ From our technological advancements and history we can construct a basic set of working assumptions for ETI's motives.
- ∗ Working assumptions spawn a range of potentially observable manifestations, leading to arguments favoring a search our own solar system.

Observable Manifestations of ETI

▶ Observable Manifestations of ETI

- It's important to place bounds on the search locations and characteristics of possible ETI energy emissions or artifacts.
- Categorized as having ***Large Scale and/or Small Scale*** features.

▶ Examples of Large Scale Manifestations

- High energy leakage from fusion power sources.
- Optical emissions/absorption lines associated with large artificial effusion clouds. ***A byproduct of circumstellar fusion power systems.***
- Artificial hyperfine transition lines (He isotopes or Tritium).
- Anomalous deviations in blackbody radiation.
  - Excess IR radiation caused by partial circumstellar blockage.
- Cosmic ray emissions from unexpected places. ***e.g., near stable stars.***
- Large scale planetary, moon or asteroid belt mining.
- Emissions from antimatter, fusion or mag-sail propulsion systems.

Observable Manifestations of ETI

Examples of Small-Scale Manifestations

* Artificial Infrared, visible or UV emissions.
* Concentrated ionized gases – hot or cold plasmas.
* Periodic soft x-ray pulses or gamma burst emissions.
* Anomalous, non-terrestrial telecommunications activity (radio or optical).
* Varying albedos (radar or optical) from peculiar orbiting structures.
* Physical artifacts or waste products of unusual design or origin.
* Clearly visible signs of intelligent macro, micro or nano structural design.
* Clearly visible artificial structures on the moon or other solar system bodies.
* Observable artificially intelligent and/or autonomous behavior.
* Statistical anomalies in observed meteor activity or cometary patterns.
* Unusual or concentrated neutrino emissions.
* Artifacts found on Earth or in cis-lunar space.

Manifestation Markers

- **Electromagnetic Energy Markers**
  - Pulsed or CW Microwave Beacons (1 to 60 GHz).
  - Pulsed radar emissions or Telecommunications leakage.
- **Matter Markers**
  - Bracewell Messenger Probes.
  - Relativistic or High Velocity probe flyby's.
  - Artifact "Drift-Throughs" swept up by the Solar System's motion through the Milky Way galaxy.
  - Asteroid Belt Artifacts.
  - Heliocentric, Sun-Synchronous, Elliptical, or Earth-Crossing Orbits.
  - Self-Reproducing Automata (SRA).
  - Artifacts parked near the Earth-Moon-Sun Lagrange orbits.
  - Geocentric orbits.
  - Lunar Orbits or Lunar Artifacts.
  - Planetary Orbits or Artifacts.

Anomalous Microwave Phenomena

Anomalous Microwave Phenomena – AMP

- Defined as unusual detected emissions in the 1 to 60 GHz microwave frequency band. *An EM Energy Marker.*
- AMP sources originate within the solar system.
- The result of either natural or artificial sources.
- AMP motions are arbitrary and have doppler characteristics.
- Not assumed or expected to be doppler compensated.
- AMP emissions could be pulses, bursts, CW, coherent or non-coherent.
- AMP polarizations could be elliptical, linear or circular.
- Natural AMP could be associated with planets, moons or other solar system bodies.
- Artificial AMP could exhibit orbital motions or intentional trajectories.
- AMP has been detected before by ***amateur SETIzens.***
  - Lash and Fremont (Project BAMBI, 1994), Jupiter Drift-Scan Observations.

The Solar System SETI Observing Strategy

Searching for Manifestations of ETI in the Solar System

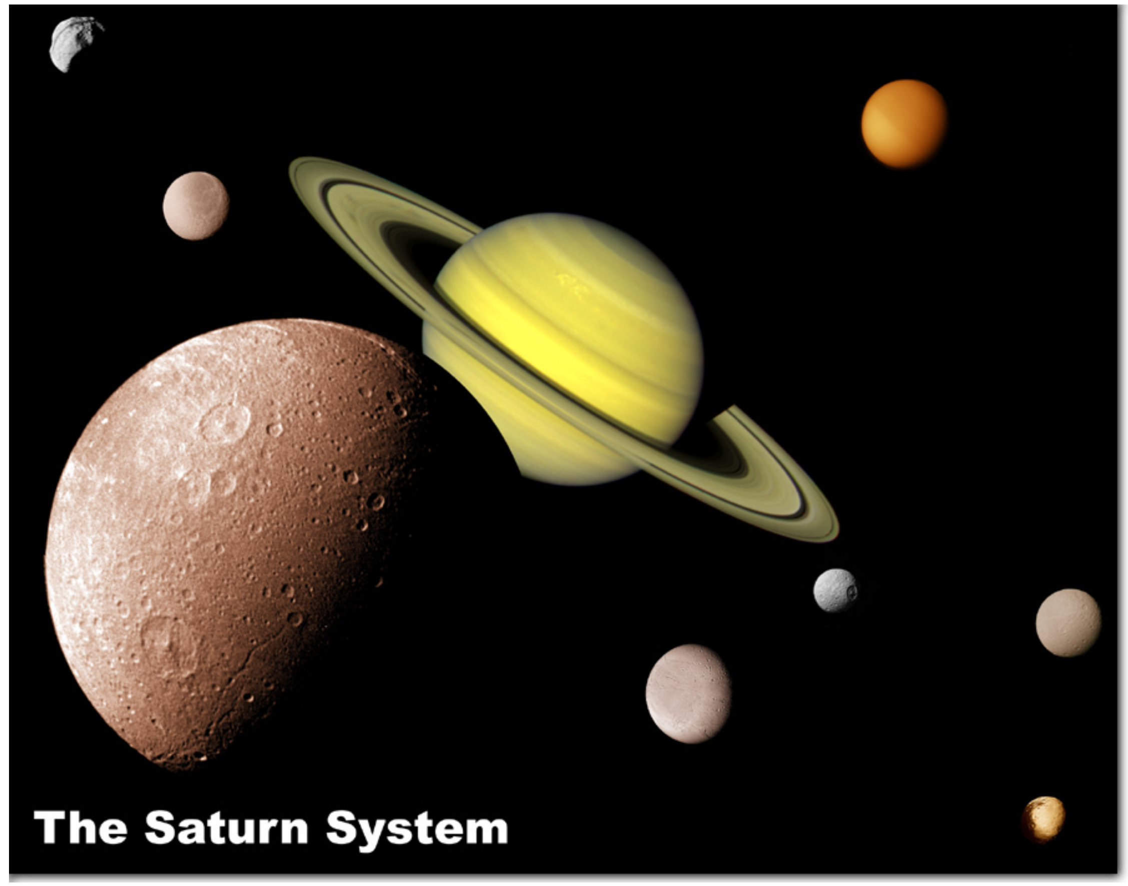
- Solar System SETI is a search for ETI artifacts in the solar system.
- S^3ETI scans ***beyond*** the cis-lunar volume of space which is the realm of near-earth strategies (e.g., SETV and SETA).
- The S^3ETI search volume is defined as a heliocentric sphere having a 50 AU radius – roughly the space contained within the orbit of Pluto.
- S^3ETI asserts there are possibly observable ***energy-marker*** manifestations in the solar system from an ETI artifact.
- These energy-markers may take the form of AMP.

Use Existing or Future Resources to Search the Solar System

- S^3ETI proposes carrying out ***targeted*** observational experiments to search for AMP using existing radio-telescopes, groups of radio-telescopes or antenna arrays now being designed and constructed.

Where to Search for AMP in the Solar System

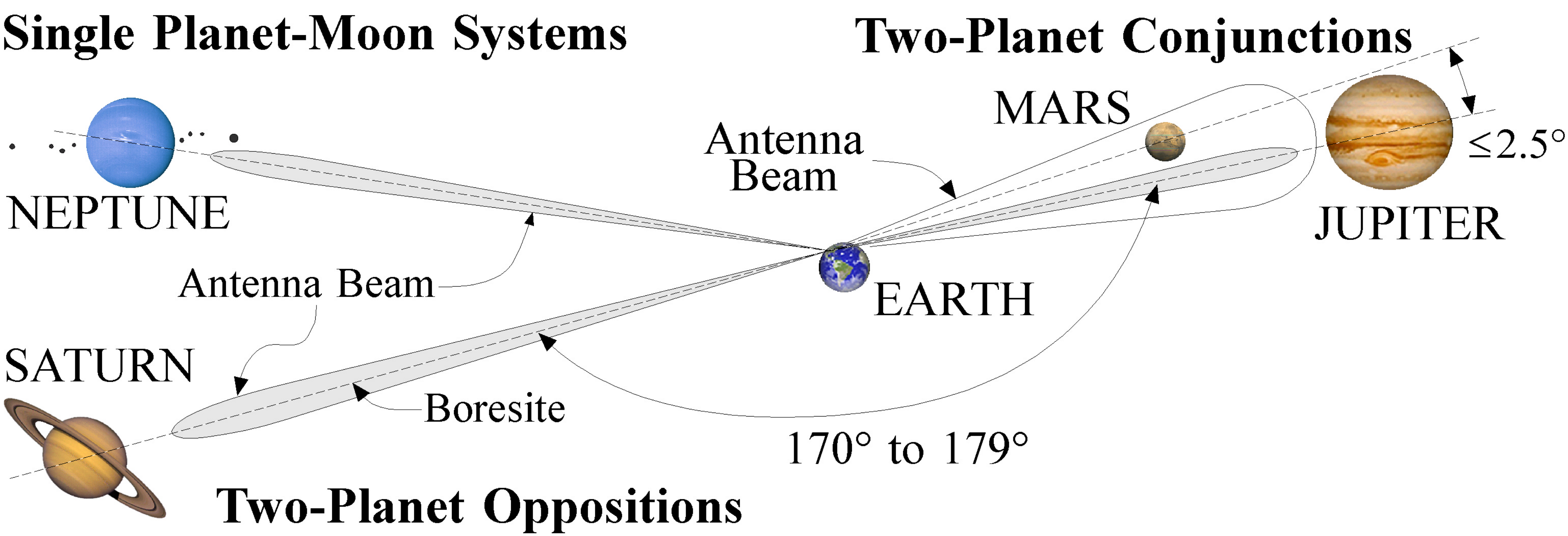
- All of the Planet-Moon Systems
- The Asteroid Belt
- Planetary Conjunctions
- Planetary Oppositions
- The Trojan Asteroids
- Kuiper Belt Objects



- Known or Newly Discovered Comets
- Earth-Crossing Objects or Near Earth Objects (NEOs)

Where to Search for AMP in the Solar System

OBERVATION EXAMPLES



Detecting AMP during a targeted observation, and verifying that it's artificial and not manmade (or RFI) constitutes valid objective evidence for an ET artifact in the solar system.

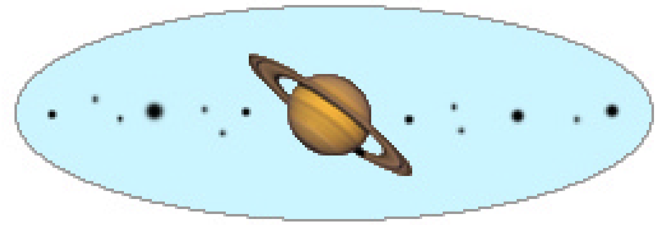
Using Radio Telescope Arrays for SETI

Examples of some Steerable Antenna Arrays

- Steerable Arrays are an excellent tool for Microwave SETI, Radio Astronomy (RA), and S^3ETI efforts.
- Project Cyclops Design Study (1973)
  - Detailed how to build and use an array of 100m Cassegrain Antennas for Microwave SETI and RA.
  - Considered the "Bible" for Large Aperture SETI.
  - ***Far too grandiose for its time – 5km diameter at a cost up to $25B.***
- The Very Large Array (1980 to Present)
  - Steerable array of twenty-seven 25m dishes (≅ 128m diameter dish).
  - Featured in ***Contact*** the movie but ***never used for SETI***.
- SETI League's Array2k (1995 to Present)
  - Thirty-two 1.8m dishes; 2000 ft^2 Collecting Area; Sub-Array's; Beam-Shaping.
- Rapid Prototype Array - RPA
  - UC Berkeley; Testbed for the Allen Telescope Array, and SKA.

Advantages of Using Arrays for S^3ETI

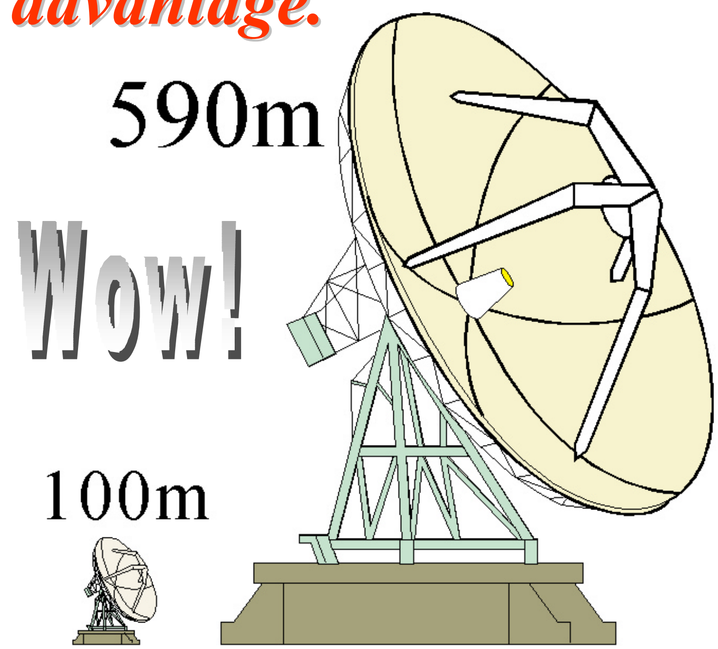
- **Arrays have RF *beam-forming* capabilities**
  - Most S^3ETI target regions are elliptical so the antenna beams need to be shaped accordingly.



- **Sub-arrays can produce *multiple-beams***
  - With multiple beams more than one S^3ETI target can be observed in parallel which reduces observing time.
- **Targets are closer therefore sensitivity can be traded for *wider-beams* allowing more spatial coverage**
- **An array's *null-forming* ability makes it possible to actively suppress interference and synthesize S and D patterns**
- **Multiple antenna elements improve the systems *"reliability through redundancy"* thereby extending target observation time and improving detection probabilities**

Advantages of Using Arrays for S³ETI

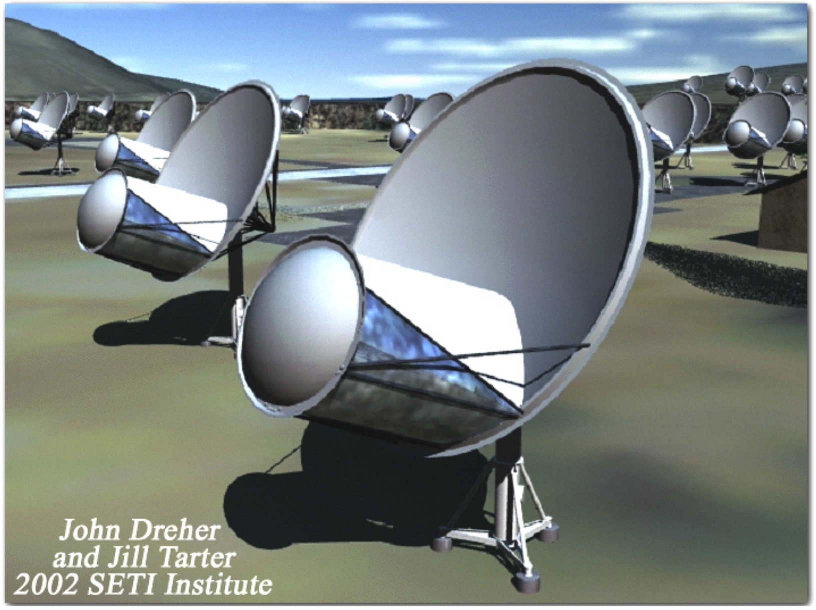
- **Being far closer than even the nearest star system (Proxima Centauri) means S³ETI has a big *SNR advantage.***
  - Trading range for SNR is like upgrading to a 590 meter dish.
- **The amplitude-modulating effects of Interstellar Scintillation are very small for S³ETI.**
- **S³ETI signals are affected mainly by Interplanetary Scintillations**
  - **Solar winds, magnetospheric activity near gas giants and Earth's atmosphere**
- **Targets are closer therefore integration times can be reduced and still detect certain emissions.**



The Allen Telescope Array - ATA

First Facility Dedicated to Microwave SETI

- "First Light" in 2005.
- Capable of 24-7 operation.
- Extends microwave search effort by ***20 years.***
- > 350 steerable phased array elements.



Outstanding Sensitivity, Gain and Instantaneous Bandwidth

- 18 Jy SEFD; 2.332 K/Jy (~80 dBi @ 11GHz); 4 GHz Instantaneous IF Bandwidth.

Piggyback Modes Support both SETI and RA (e.g., Pulsar Surveys)

Main attraction is beam-shaping and null-forming

- Digital control over beam shape or amplitude taper.
- Null-Forming assists in rejecting RF interference (i.e., noisy jammers).
- Multiple Beams allow simultaneous observations of deep space targets.

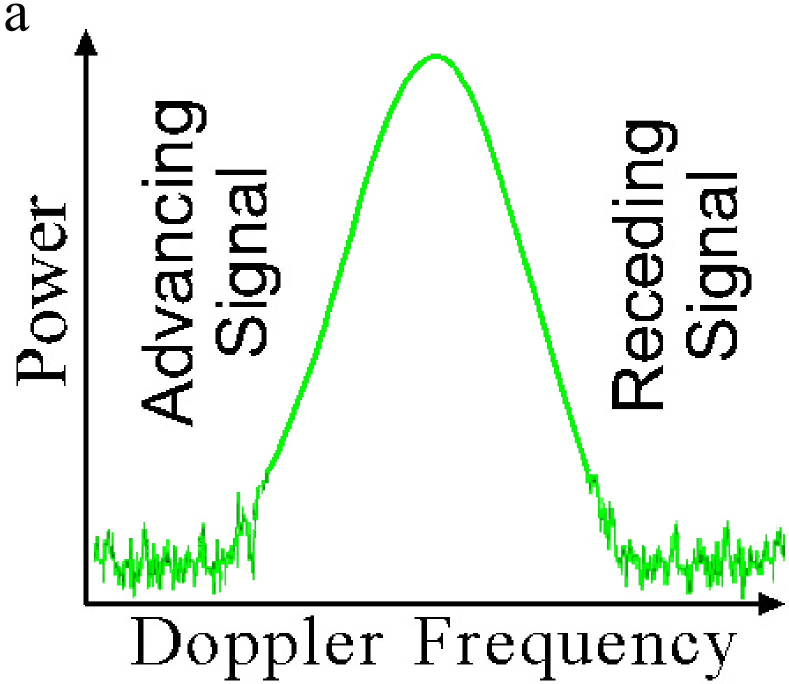
ATA's topology gives it *interferometric* capabilities

Doppler and Monopulse Parameters

Relative Velocity is an Important ATA Detection Parameter

Doppler Parameter

- One-Way Doppler Shift and Drift Rates provide information on the relative velocity of the AMP.
- Doppler data can help determine if the signal is approaching or receding
  - Slope of doppler curve gives valuable information.
- Measured Doppler can be compared with a database of doppler shifts and drifts.
- A Doppler Processor can be developed to automatically analyze AMP signals.
- Doppler Correlations and signal timing can help to indirectly infer AMP range.
- System Bandwidth limits the detectability of some high velocity targets.



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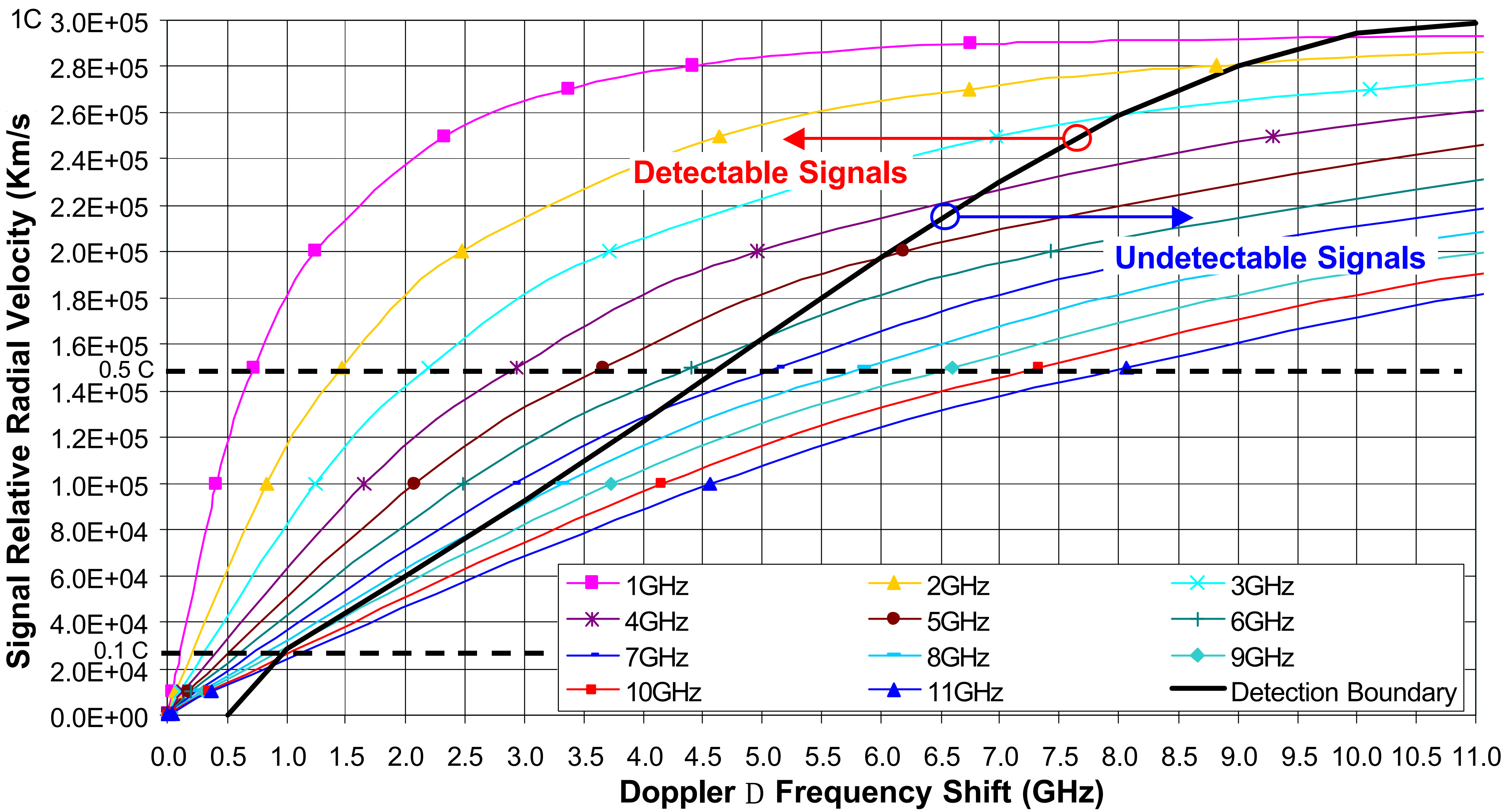
Doppler and Monopulse Parameters

Some Doppler shifted signals can exceed ATA bandwidth



Doppler and Monopulse Parameters

Location is an Important ATA Detection Parameter

Monopulse (MP) Parameter

- Monopulse-like mode of operation can provide angle-sensing of AMP
  - A Direction-Of-Arrival (DOA) or Angle-Of-Arrival (AOA) measurement.
- Two Classes of Monopulse Systems
  - Amplitude-Comparison and Phase-Comparison. ***Class based on antenna patterns***
- Amplitude Class – Squinted Beams; adjustable Gaussian beam shapes; common phase center.
- Phase Class – Parallel Beams; same beam shapes; different phase centers.
- Sum (Σ) and Difference (Δ_{el}, Δ_{az}) outputs are formed
  - Complex ratios are calculated and normalized to the Σ pattern signal.
  - Ratios converted to sine-space or cosine-space angles (*uv-plane*) off boresite.
  - Transformed to az-el degrees or fractions of degrees relative to boresite.
- Monopulse Digital Signal Processing
  - Comparator functions are performed digitally after IF downconversion – using DSPs or FPGAs.

Doppler and Monopulse Parameters

Monopulse Equations

1. Signals from beams (A, B, C, D) are complex valued quantities

   $A(t) = a\ e^{j(\omega t + \phi a)}$; $B(t) = b\ e^{j(\omega t + \phi b)}$; $C(t) = c\ e^{j(\omega t + \phi c)}$; $D(t) = d\ e^{j(\omega t + \phi d)}$

2. Σ signal = $A(t) + B(t) + C(t) + D(t)$
3. Δ_{el} signal = $(A(t) + B(t)) - (C(t) + D(t))$ ← Amplitude-Comparison MP Example
4. Δ_{az} signal = $(B(t) + C(t)) - (A(t) + D(t))$ ← Amplitude-Comparison MP Example
5. Normalized Δ_{el} and Δ_{az} signals: $|\Delta_{el}|e^{jf} / |\Sigma|e^{jq}$ and $|\Delta_{az}|e^{jf} / |\Sigma|e^{jq}$

   $\Delta_{el}/\Sigma = |\Delta_{el}| / |\Sigma|e^{j(f - q)}$ and $\Delta_{az}/\Sigma = |\Delta_{az}| / |\Sigma|e^{j(f - q)}$

6. The In-phase (I) and Quadrature-phase (Q) components:

   $I_{el} = RE\ (\Delta_{el}/\Sigma) = |\Delta|/|\Sigma|\cos\ (f - q)$; $Q_{el} = IM\ (\Delta_{el}/\Sigma) = |\Delta|/|\Sigma|\sin\ (f - q)$

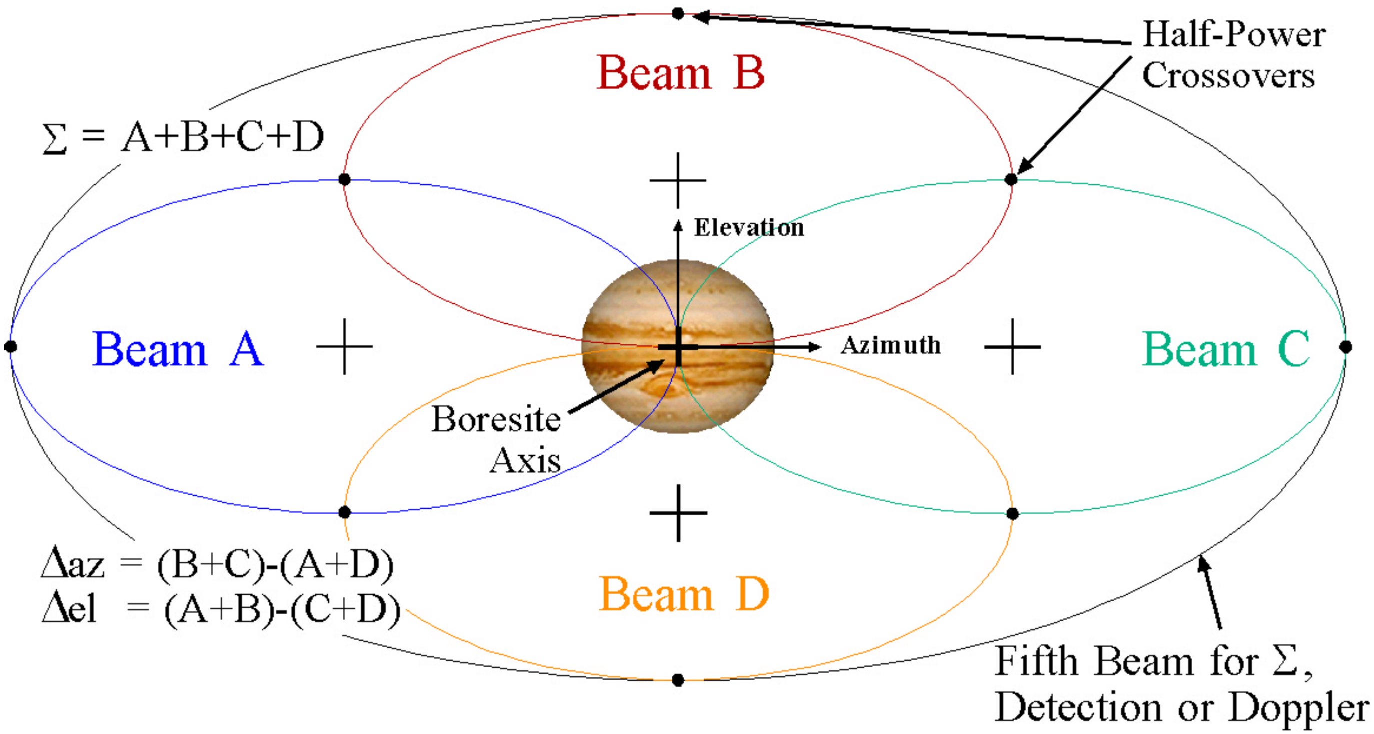
   $I_{az} = RE\ (\Delta_{az}/\Sigma) = |\Delta|/|\Sigma|\cos\ (f - q)$; $Q_{az} = IM\ (\Delta_{az}/\Sigma) = |\Delta|/|\Sigma|\sin\ (f - q)$

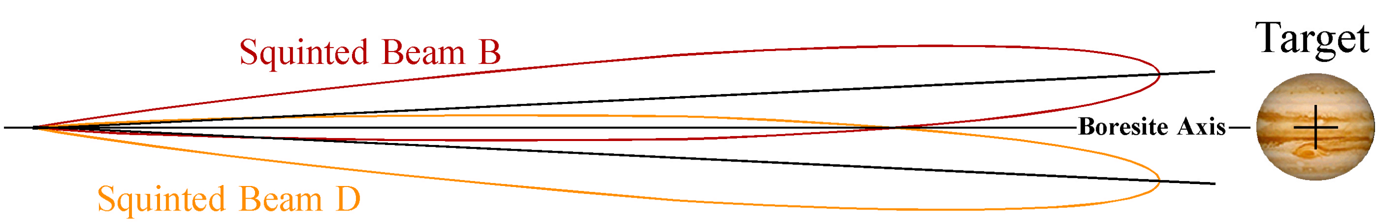
7. In most MP processors the I component of the complex ratio is extracted:

   $I_{el} = RE\ (\Delta_{el}/\Sigma) = (\Delta_{Iel}\Sigma_I + \Delta_{Qel}\Sigma_Q) / (\Sigma_I^2 + \Sigma_Q^2)$

Doppler and Monopulse Parameters

3-Channel Amplitude-Comparison MP Example

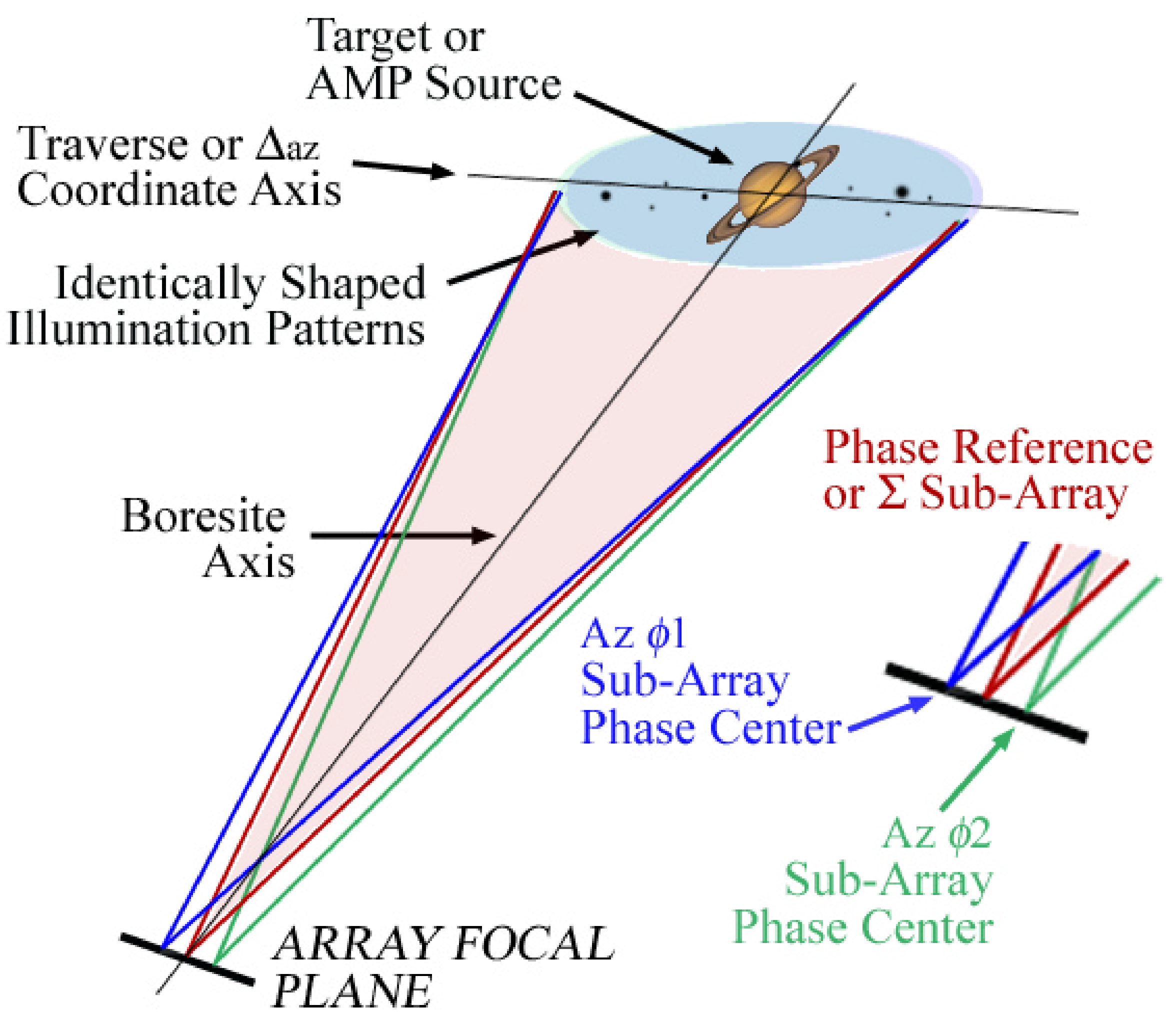




- 4 or 5 Beams (2 pairs of shaped patterns and a reference) required
- Beam pairs are squinted or offset from boresite axis
- Amplitude of arriving signals are compared
- Beam shapes are frequency and bandwidth constrained
- MP requires added processing if dual polarization is needed

Doppler and Monopulse Parameters

2-Channel Phase-Comparison MP Example



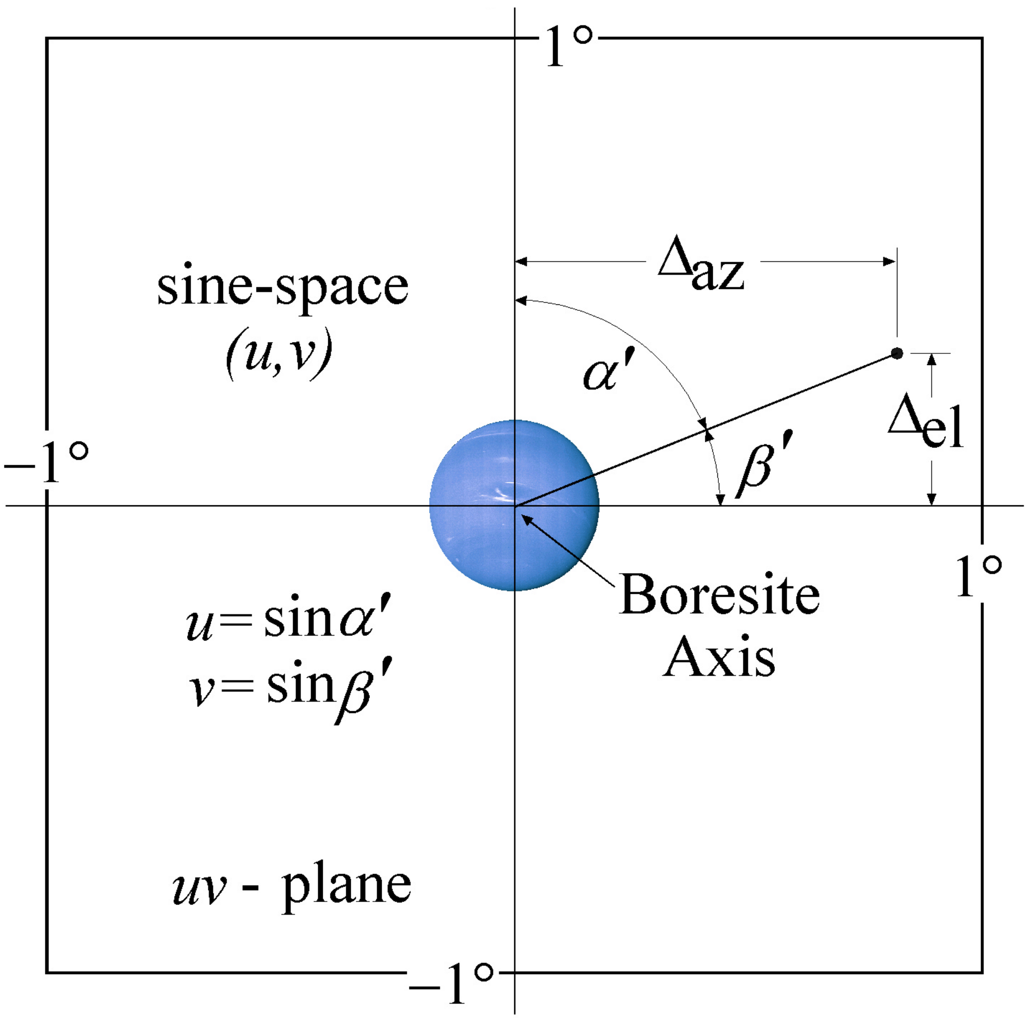
- 4 Sub-Arrays with different phase centers, used for phase-comparison.
- Phase of arriving signals are compared: $f1 - f2$
- System needs to be able to track a stable boresite.
- MP axis boresite needs to be calibrated with an RF source.

SETI Moonbounce? The Sun?

- ATA is not a radar system, so a closed-loop angle tracking function is not needed.

Doppler and Monopulse Parameters

Monopulse Coordinate System

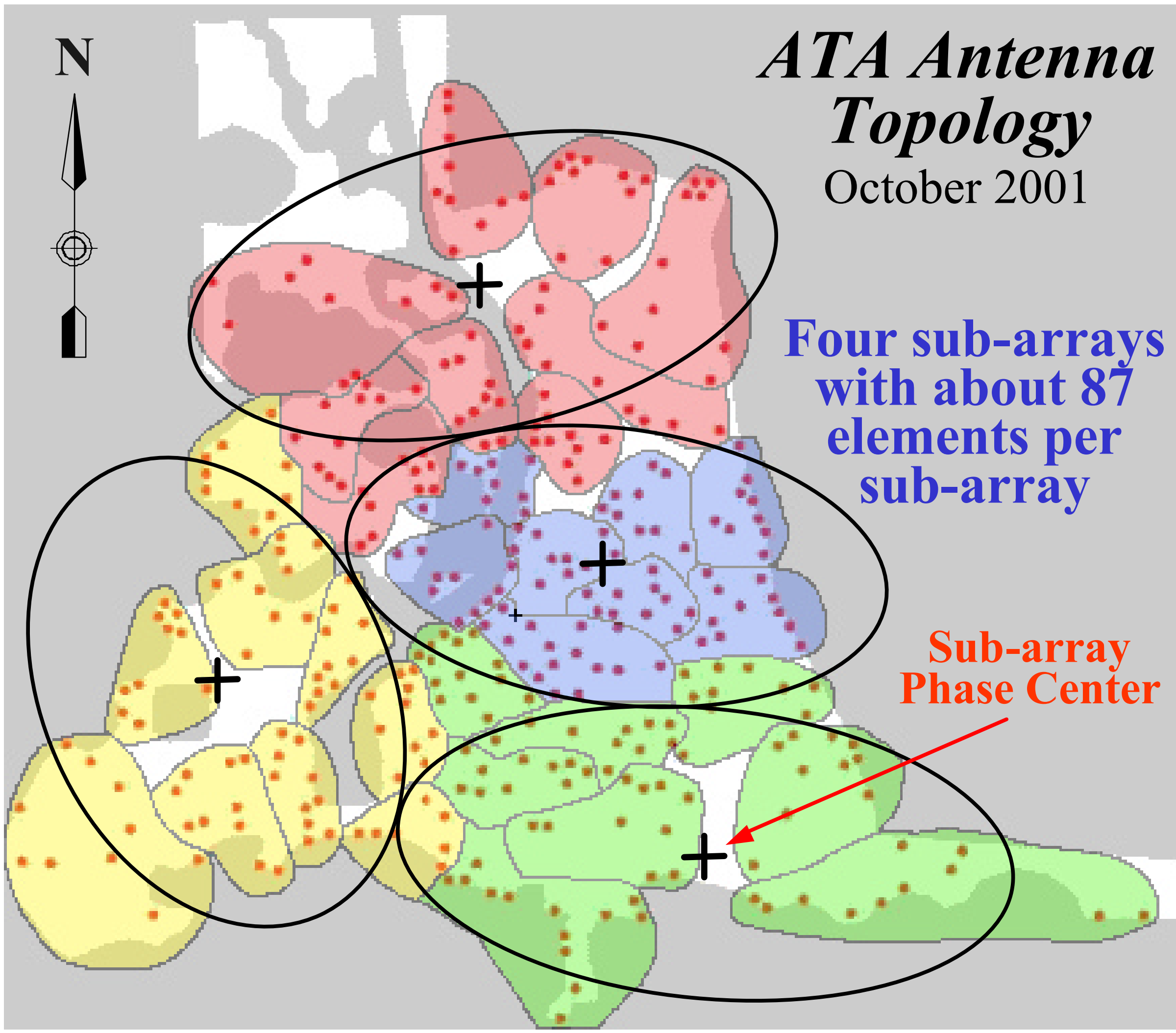


- MP Ratio Δ/Σ is a non-linear function for large angles.
- For small angles, Δ values can be made proportional to the displacement from the boresite axis and *uv* → az-el coordinates
- Beams can be shaped to generate linear functions within the main beams HPBW.
- Estimating AMP AOA can be done with high accuracy.
- RMS angular accuracy due to noise for both classes is $\Delta\theta = k_m \theta_\Sigma / \sqrt{SNR}$

k_m = Monopulse Slope
θ_Σ = Sum Pattern HPBW

Doppler and Monopulse Parameters

Phase-Comparison Monopulse with the ATA



- 4 Sub-Arrays with different phase centers are used for phase-comparison MP.
- Alternately, the Σ and Δ beams could be synthesized without using sub-arrays.
- Precise phase-tracking of the sub-array signals is critical.
- 3 MP Channels are needed: one Σ and two Δ for each of the four IF channels. 12 total.
- MP processing needs to be done in near real-time with dedicated DSPs or FPGAs.

Research Proposals to Use the ATA for S³ETI

- **So many "Targets of Opportunity" the ATA could be used *Full Time* for S³ETI but…**
  - The ATA is not being designed for only one strategy, no matter how traditional or promising it may be.
- **The ATA is a *Shared SETI Resource* therefore alternate observing proposals should be considered**
  - The proposal acceptance phase may begin a year after the ATA has been in operation and the hardware and software bugs have been fixed.
- **S³ETI targeted searches could be done in a *Piggyback Mode* like Phoenix at Arecibo**
- **Initial Proposals could be to test the various S³ETI observing modes and parameters using the entire ATA for short periods of time**

Summary

- Solar System SETI is a fresh and innovative strategy that *compliments* existing SETI efforts
- S^3ETI looks for evidence of ETI by searching the solar system for anomalous microwave phenomena that is clearly artificial and not manmade
- S^3ETI is possible because of new and emerging technologies, especially in signal processing and computer hardware
- If the Allen Telescope Array is built and lives up to our expectations it can be used to carry out S^3ETI experiments
- Professional and Amateur SETI researchers are encouraged to propose S^3ETI experiments to the ATA Administrators
- It is acceptable for the critics of S^3ETI and Near-Earth Strategies to demand hard scientific evidence of ETV…

…it takes courage to seek such evidence!