Tech Brief:
Status of Electronically Steered Antennas

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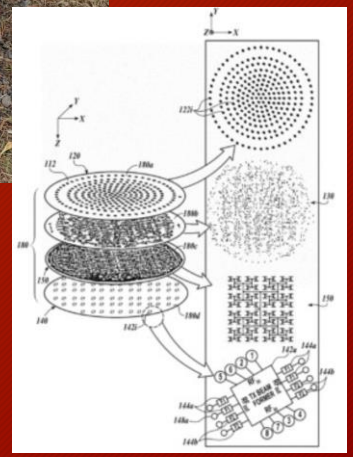
Adaptive Array Antennas Introduction

- The use of Adaptive Array Antennas Has been driven by several factors:
  - Mobility:
    - MEO/LEO satellites constellations require beam steering for maintaining a link
  - Physical Design:
    - Rugged : limited or no mechanical parts
    - Ideal form factor: Flat and thin for mounting aircraft, navy vessels, trains, trucks/Cars, or Man Pack
  - Cost:
    - Integrated RF and Digital circuit costs have put price points for array antennas in reach for consumer applications
  - Interference Reduction:
    - Fully adaptive antenna arrays can steer Nulls to avoid interference or reduce interference to other systems

MSS Array Terminal

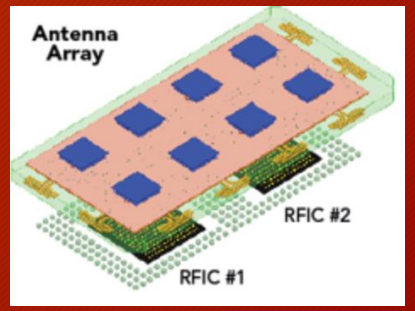
SpaceX Starlink Gen 1

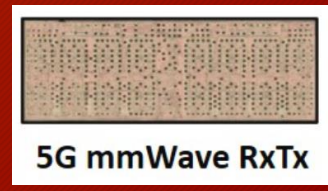


Adaptive Array Antennas: a brief history

- Adaptive Array technology started with Military RADAR
  - 1958 – 1960s research and technology development
  - 1973 Aegis Combat System AN/SPY1
    - Started with 931 antenna elements now at over 4000
- 1980s Intelsat IV & V- spot beams – satellite switched TDMA
- 2010s Satellite Terminal Applications flourish
  - Starting with Aircraft, moving to terminals as costs reduced
  - Driven by mobility, LEO/MEO systems, consumer adoption
- Massive Array deployment in cellular
  - Early 2010s 4G LTE, expanded with 5G NR – base stations
    - MIMO and Massive-MIMO – Space Division Multiple Access
  - Higher Frequencies of operation:
    - 60Ghz arrays in subscriber Wi-Fi & 26Ghz 5G handsets
- SpaceX – Starlink – Mass deployment of Satellite Adaptive Antenna

Agis Combat Systems Array



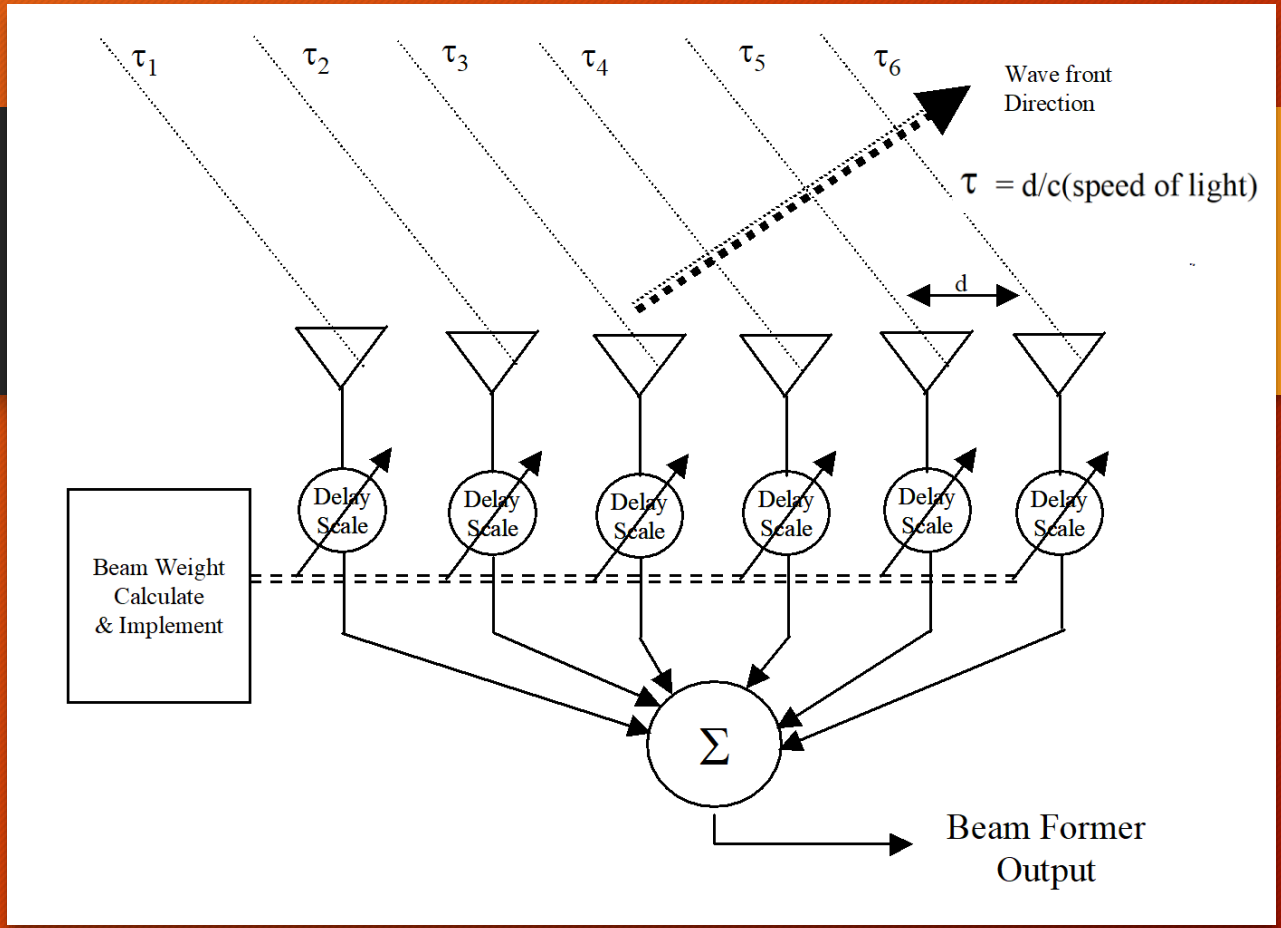


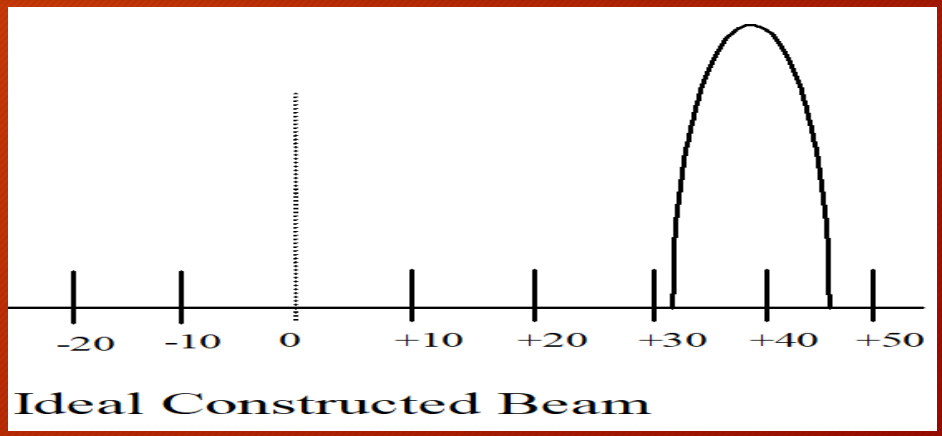
iPhone 12

Adaptive Antenna Array: Basic Operations

- Adaptive Array Antennas are wavefront processors, coherently (beam) or destructively (null) summing RF across the array
  - Array elements spacing d = λ/N (λ/ = RF wavelength)
  - N is typically 2 or 4
  - Sparse Array Antenna is an array in which many antenna elements have a value of zero
- The array coherently sums the wavefront components from a given direction by forming a time/phased delay at each element
- The delay, τ is given by:

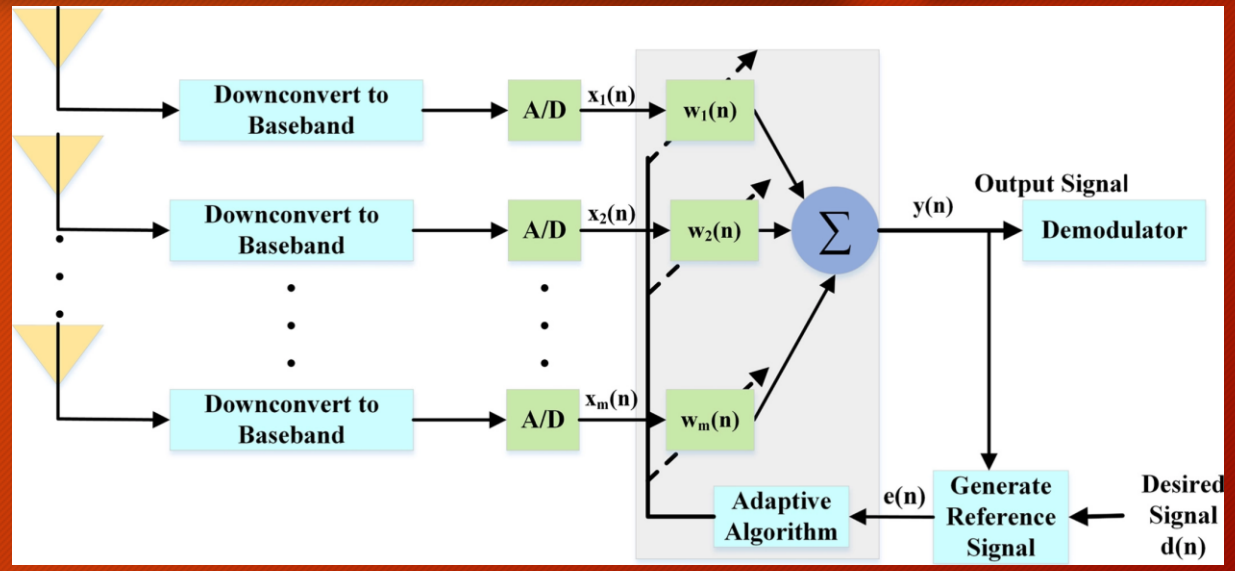
$$\tau = d/c(\text{speed of light})$$

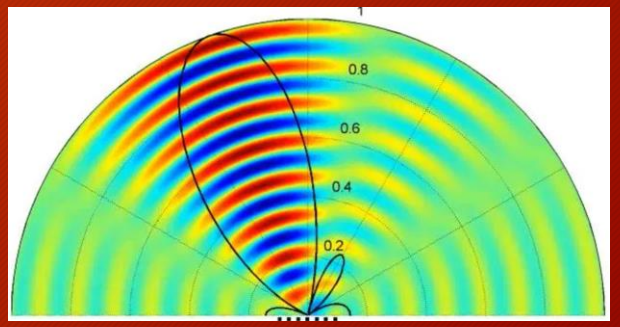




Adaptive Antenna Array: System Diagram

- Initially Arrays were made of analog RF components and formed a single beam
- Array processing is now performed digitally with ability to form many Beams and Nulls
  - Modulation and Demodulation path for each antenna element
  - RF up/down converter with LNA and PA
  - A/D (RX) and D/A(TX) processing at baseband
  - Weights are applied in digital signal processing (DSP)
  - Extensive DSP processing to adaptively create optimal beam and null patterns
- TDD systems are especially cost effective





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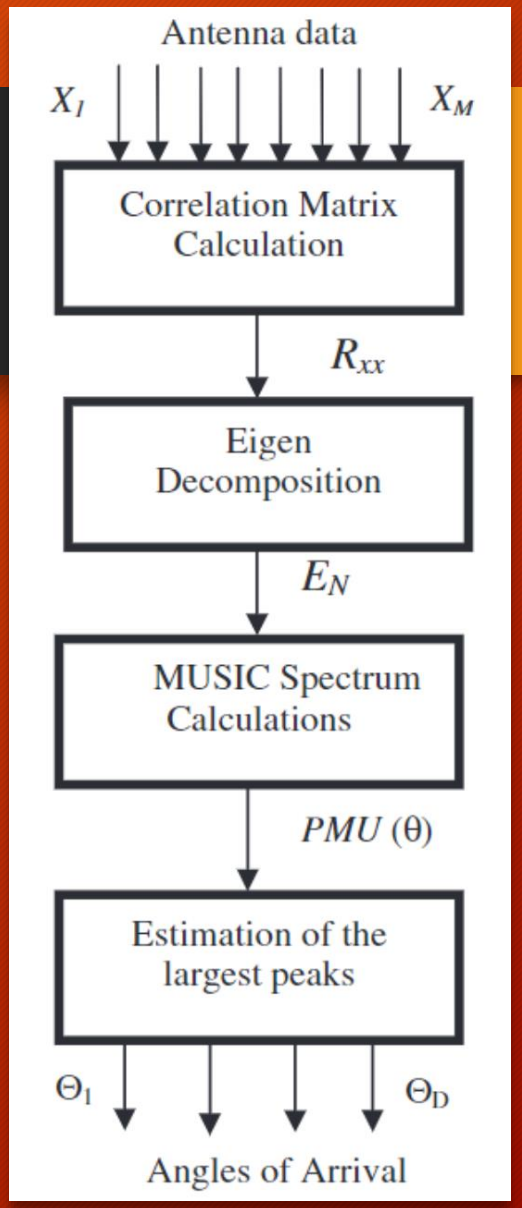
Beam Forming Algorithms

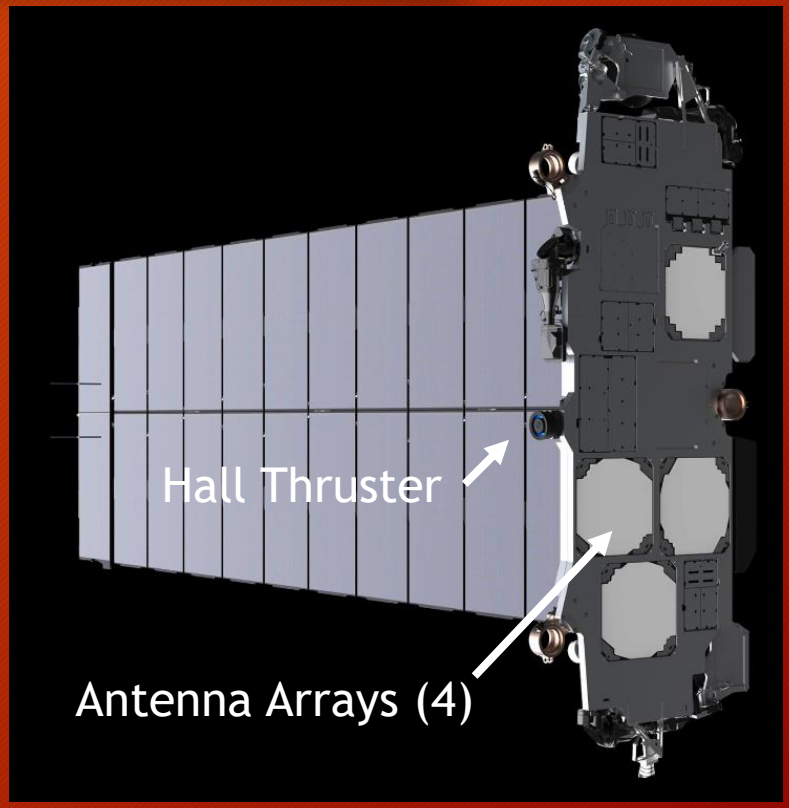
- Pre-Calculated/Stored Beams
  - Greatly reduced processing burden for terminal or satellite – the user must still be tracked
  - Ideal solution for fixed ground terminal
    - Use GPS location/time, calculate satellite angle from Satellite ephemeris and signal strength measurement
- Adaptive Algorithms for Blind Beamforming
  - 1960s/70s Early Algorithms derived from RADAR applications
    - AR (Autoregressive), MA (Moving Average), ARMA (Auto-Regressive & Moving Average)
  - 1977 - MUSIC (MUltiple SIgnal Classification) algorithm
  - 1985 - ESPRIT - Estimation Signal Parameters via Rotational Invariance Technique.



Basic MUSIC Algorithm

Starlink Gen2 Satellite: The State of Art in cost and technology

- **Specification :**
  - **Weight 1250 Kg (4x lager than the original V1 satellites)**
  - **Terminal Comms: 14-14.5GHz Earth to Space, 10.7-12.7 GHz Space to Earth**
    - **4 Phased Arrays - 48 beams Space to Earth, 16 beams Earth to Space**
  - **Gateway Comms:**
    - **New E Band: 71 -76 GHz Space to Earth, 81-86 GHz Earth to Space**
    - **Standard Ka-Ku band links**
- **Optical collision scan and automatic orbit adjustment via argon-fueled Hall thrusters**
  - **Over 25,000 anti-collision maneuvers and counting**
- **NRO – SpaceX StarShield**
  - NRO awarded SpaceX $1.8B multi-year program to develop and deploy several hundred intelligence/communications satellites



StarLink Gen 2 Satellite

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State of Art:
Low cost Commercial Satellite Array Antennas

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Starlink and Kuiper Terminals

- Amazon Kuiper terminals announced
  - Ultra-compact terminal 7” square ~100Mbps ($400)
  - Standard terminal 11” square ~400Mbps
  - High-bandwidth terminal 19”x30” ~1Gbps
  - Space to Earth: 4 Bands between 17.7 and 20.2 Ghz
  - Earth to Space: 3 Bands between 28.35 and 30 Ghz
- Starlink G3 terminals - available now
  - Mini terminal 6.92” x 13.14” 50Mbps down / 10Mbps up
  - Standard terminal 15” x 23” 200Mbps down / 20 Mbps
    - Down link 25 and 220 Mbps typically >100 Mbps.
    - Uplink 5 and 20 Mbps
- Based on link frequencies, Kuiper terminals will be smaller than Starlink terminals for a given performance level
  - Kuiper frequencies are more susceptible to rain outage

Kuiper Ultra-Compact Terminal

StarLink Gen 3 Standard Terminal

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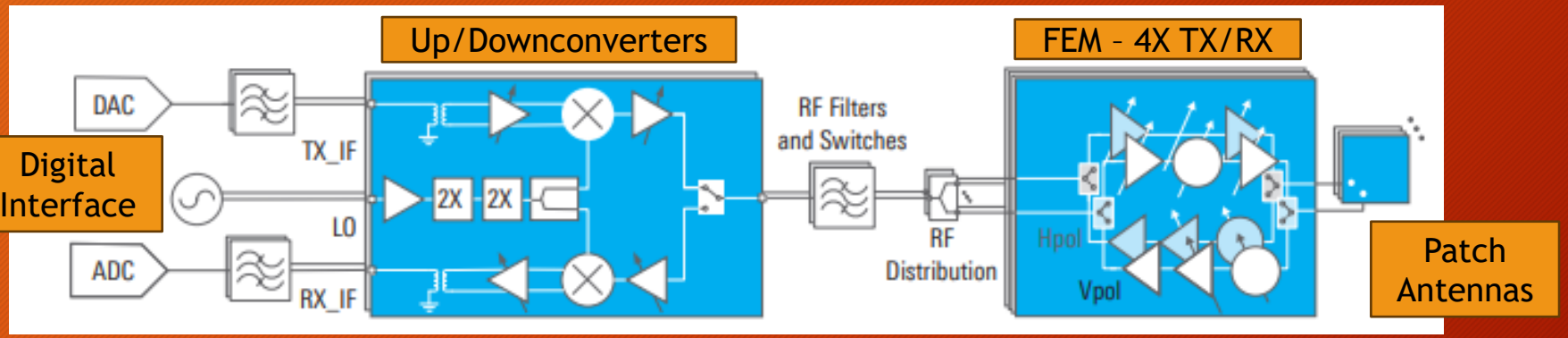
PCB based Terminal Array Antennas
The state of art for cost/quality

- Array antenna elements are embedded in FR4 or Rogers PCB material
  - Typically slot or patch antenna arrays (see diagram)
  - Dual frequency & simultaneous Tx/Rx designs used today
- RF FEM (RF Front end) digital control of gain an phase
  - RF FEM available 2, 4, or 8 channels



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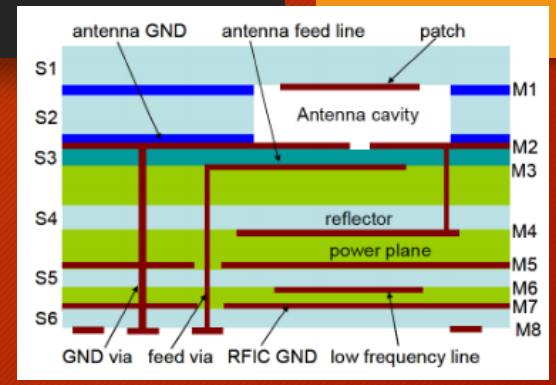
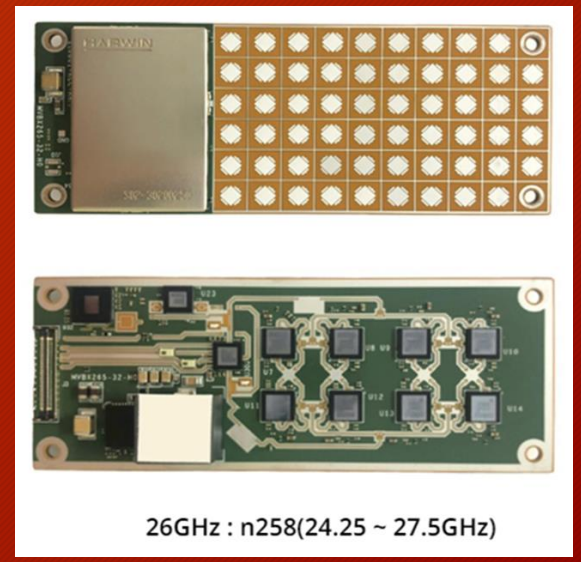


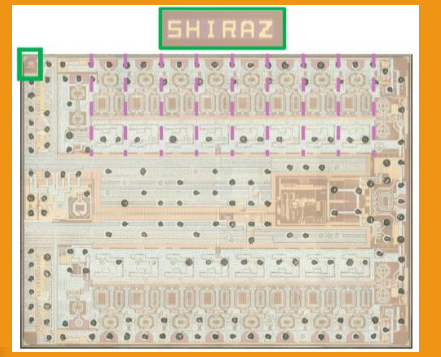
PCB Array element



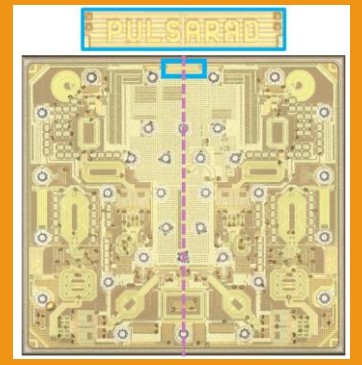
Doosan 5G base station array

Teardown of Starlink Gen3

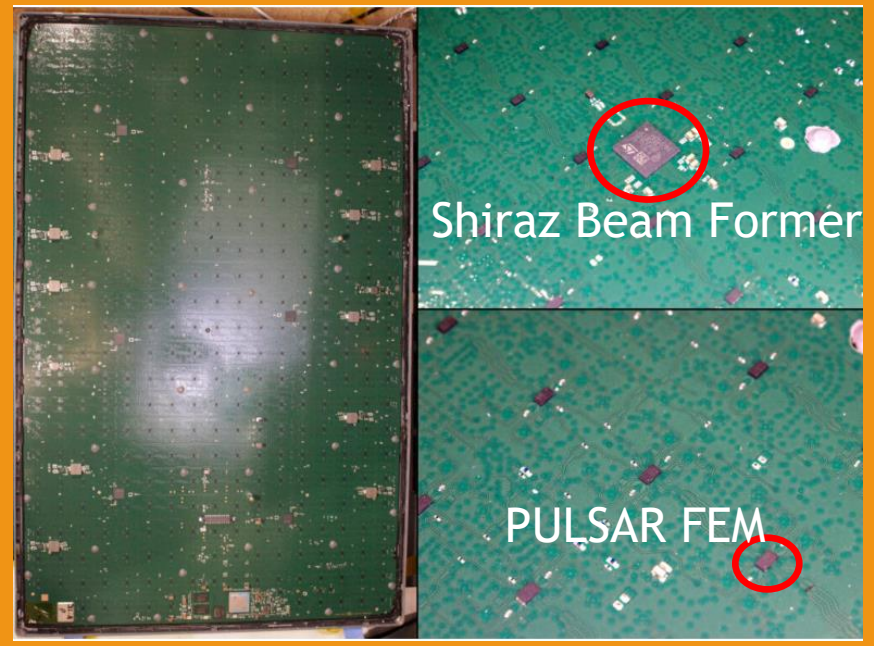
- Starlink Gen3 is a single PCB Array design
  - Shiraz 16 channel beam former (phase shifter)
  - Pulsar Front end module (FEM) – 4 Channel
- Antenna Array feed by 17 x 23 = 391 Pulsar FEM
  - 1,564 Antenna elements in the array
  - Which matches Lambda/2 ideal antenna spacing fat the midpoint between Starlink TX and RX frequencies
- SpaceX states that they now beak even at $599 cost for the Standard model
  - **Incredibly optimized and commoditized price**



ST Micro Shiraz
16x RF Front End



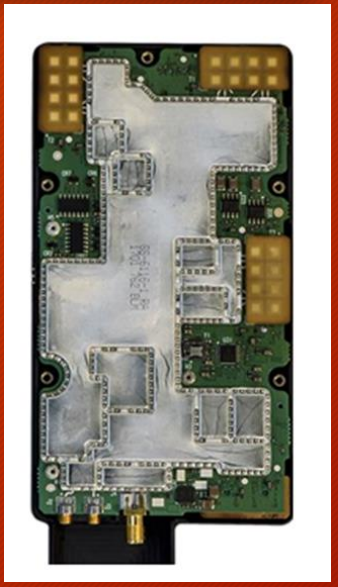
Pulsar
FEM



Starlink Gen3 Array PCB and close up

Direct to Satellite Cellular

- Starlink Direct to Satellite cellular
  - 4G LTE protocol support using PCS G Block 1910–1915 MHz and 1990–1995 MHz
    - LTE in G Block allows highest possible power to close satellite
  - Initial service offered through T-Mobile
  - Starlink V2 satellites include a large 2.7 m x 2.3 m advanced phased arrays coupled with high sensitivity radio receivers and high-powered transmitters
- Kuiper
  - NO Direct to cellular announced
  - Kuiper Terminal frequencies are close to the new 5G 26Ghz band
  - 5G cell phones include multiple 26Ghz antenna arrays
  - Cellular supply chain has state of art integrated antenna array MEMs



Early 5G Array Antenna Prototype with 3 x 8 element arrays (Qualcomm)

Integrated 16 element array (Samsung Galaxy 22)

Thank You

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