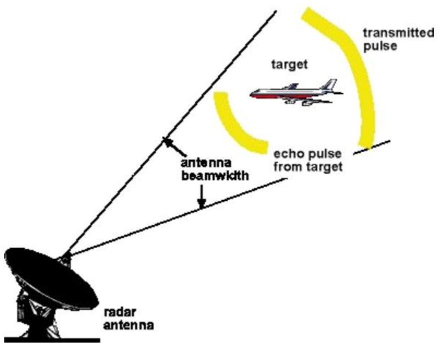
TRACKING RADAR
With Application to Satellite Networks

ECE 514E – RADAR & SATELLITE ENGINEERING

Monday, 1 December 2025

WHAT IS A TRACKING RADAR?

1. A **Tracking radar** continuously monitors the position of one or multiple targets in space.



2. Before the tracking process, the radar has to detect targets and find their range, angular location, and sometimes velocity.

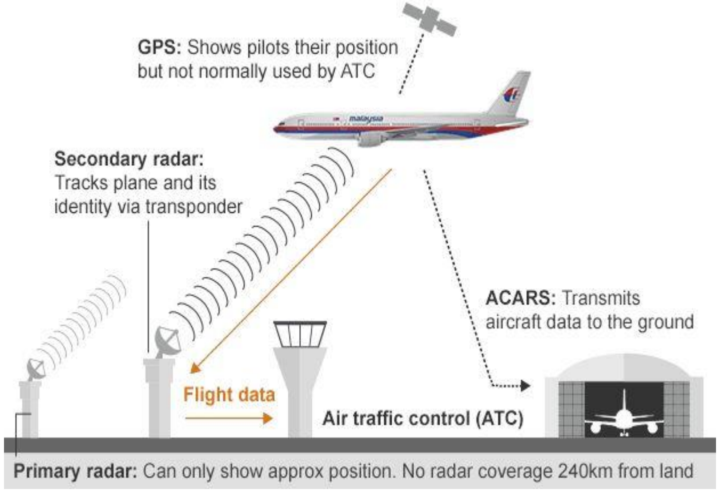
3. Tracking can be in 2-dimension or 3-dimensions.

RADAR TRACKING PRINCIPLES

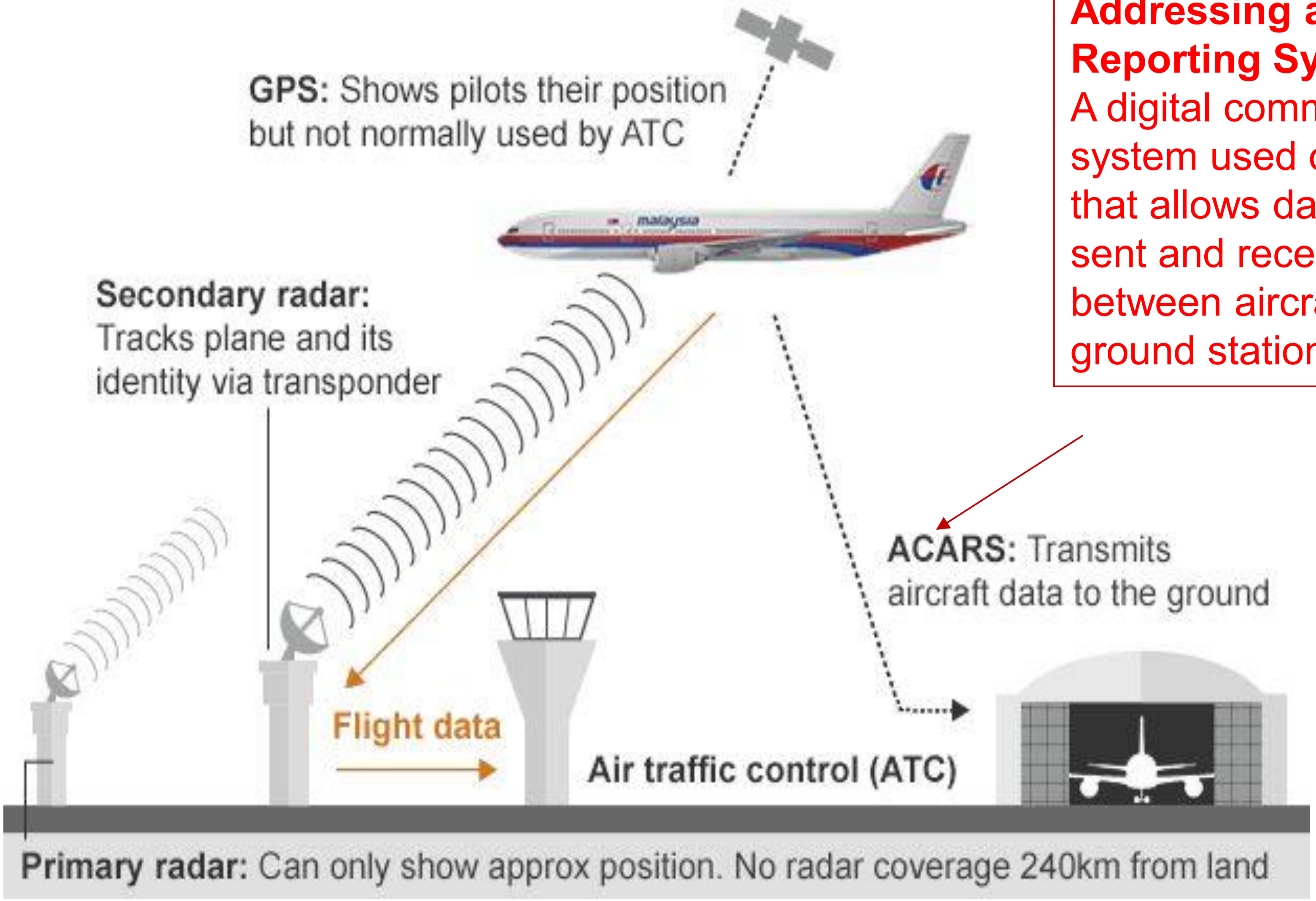
1. A tracking radar system measures the following parameters of a target to determine target path and to predict its future position:
   a) Range
   b) Elevation angle
   c) Azimuth angle
   d) velocity
2. A radar set is said to be tracking the target when it is continuously predicting the location of the target from the data received.
3. Tracking radars utilize antennas with pencil beam (very narrow) patterns.

APPLICATIONS OF TRACKING RADAR

1. Target tracking is important in military radars as well as most civilian radars.
   a) In military radars, tracking is responsible for fire control and missile guidance;
      - Missile guidance is almost impossible without proper target tracking.
   b) Civilian airport traffic control utilize tracking radar as a means of controlling incoming and departing airplanes.

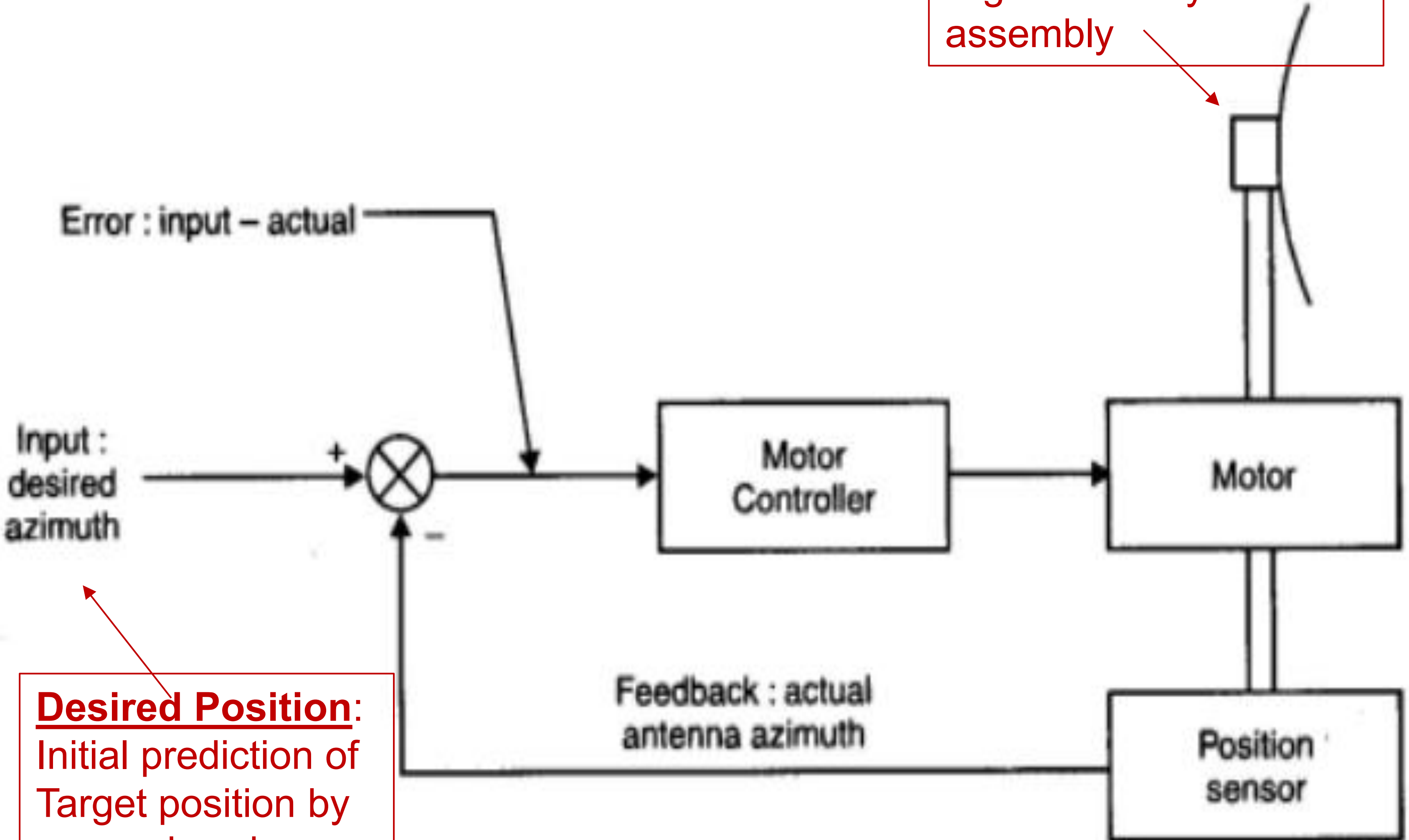


ACARS (Aircraft Communications, Addressing and Reporting System)
A digital communication system used on aircraft that allows data to be sent and received between aircraft and ground stations.



RADAR SERVO TRACKING SYSTEM

Antenna
High directivity antenna assembly



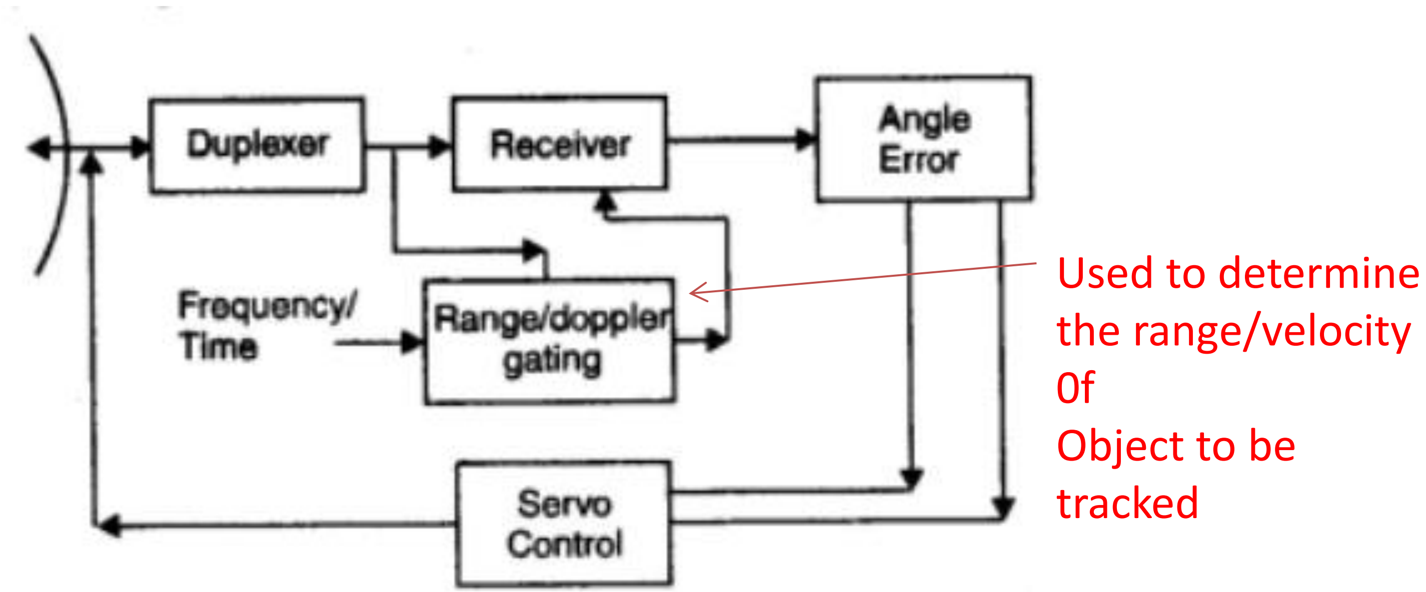
Desired Position:
Initial prediction of Target position by a search radar

PRINCIPLE OF OPERATION OF THE SERVO CONTROL SYSTEM

1. The antenna is rotated by a motor which provides negative feedback signal to the controller.
2. The error signal can be generated by any of the following methods:
   a) **Sequential lobbing-** A single beam is switched between two angular positions to obtain the angular position
   b) **Conical scan** – The sequential beam is scanned rapidly and continuously in a circular path.
   c) **Mono pulse** - Extract the angular position from only one pulse. The information on the target angular position is determined by comparison of signals received from two or more simultaneous beams.

3. Tracking information may be displayed on a screen or forwarded to a computer which after determining the target path can predict its future path.
4. Usually, the search and track radars are separate due to the long time required to scan and find a target.

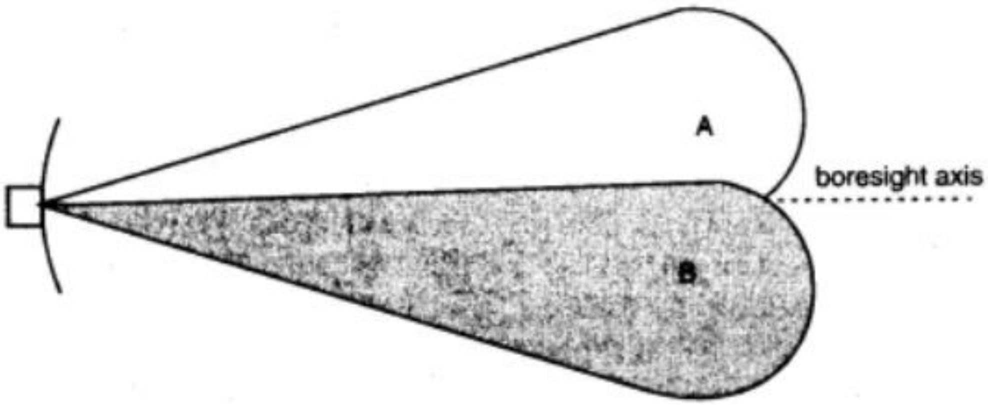
BLOCK DIAGRAM OF MECHANICAL TRACKING RADAR

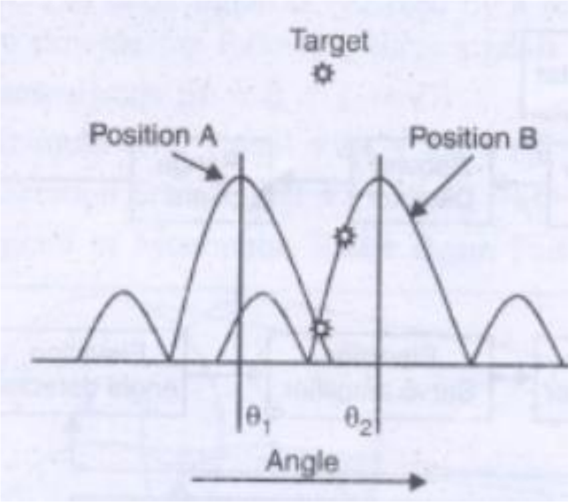


1. Most tracking radars use angular information as a basis for tracking
2. For better accuracy, the system concentrates on one target at a time
3. Angular error signal for the desired target is developed in the error demodulation block and feedback to steer the antenna through the servo control system.

SEQUENTIAL LOBBING /01

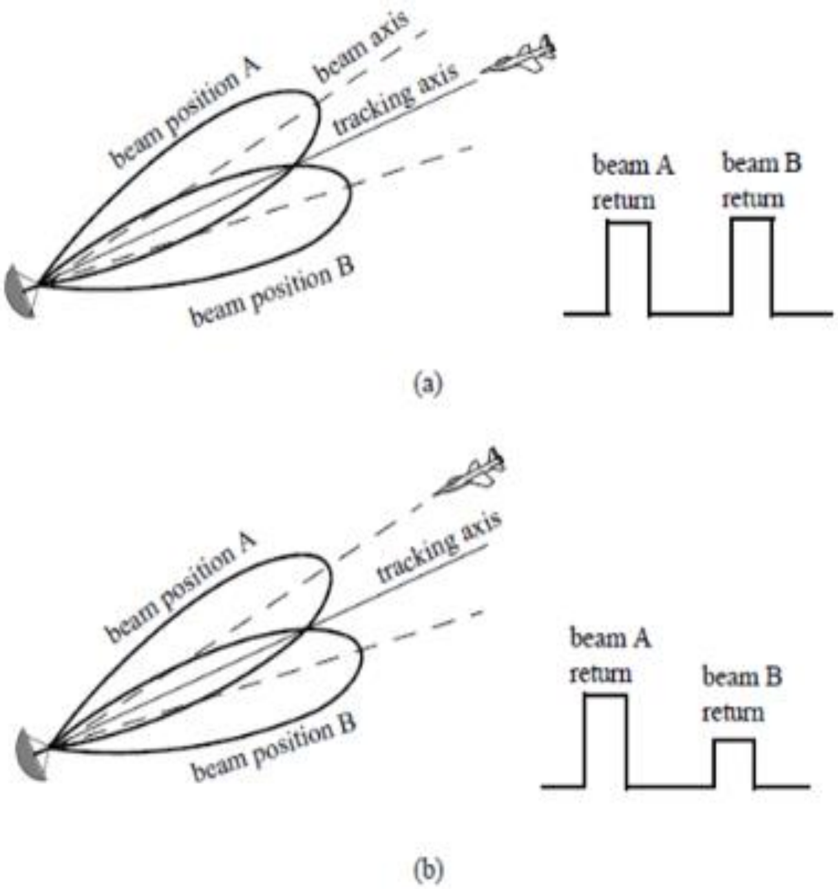
1. The direction of the beam is rapidly switched from positions A and B
2. The echo signal from the target fluctuates at the switching rate until the target is exactly between the two directions.

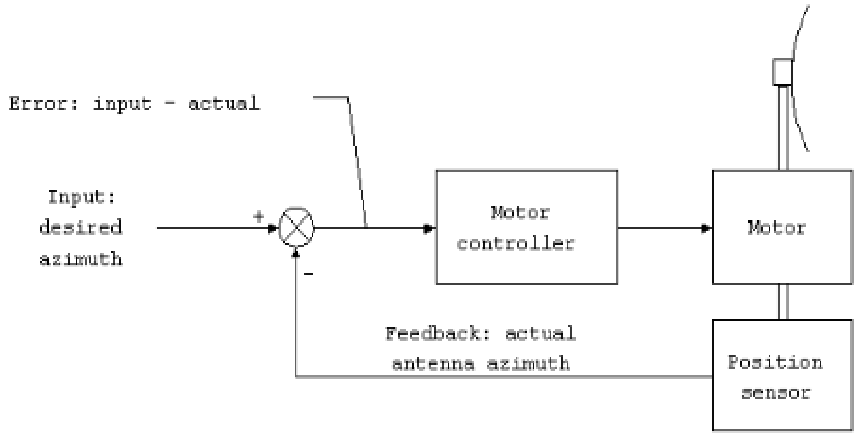




SEQUENTIAL LOBBING /02

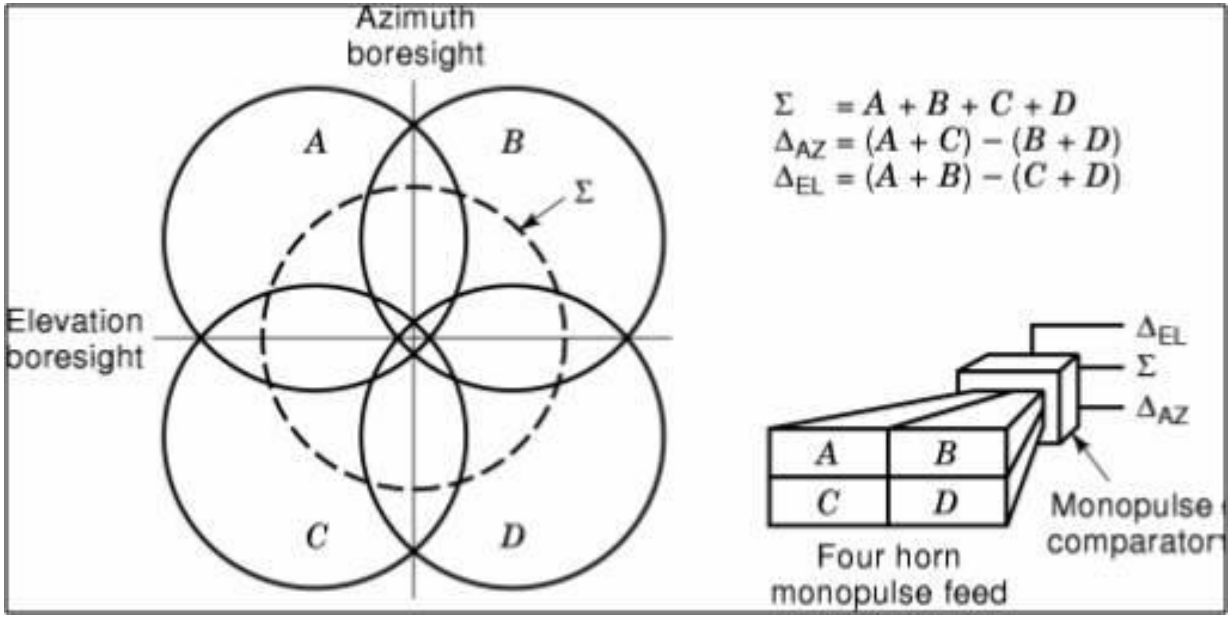
When the target is tracked on the tracking axis (a), the voltage difference is zero and error signal is zero. However, when the target is off the tracking axis (b), error signal is produced.



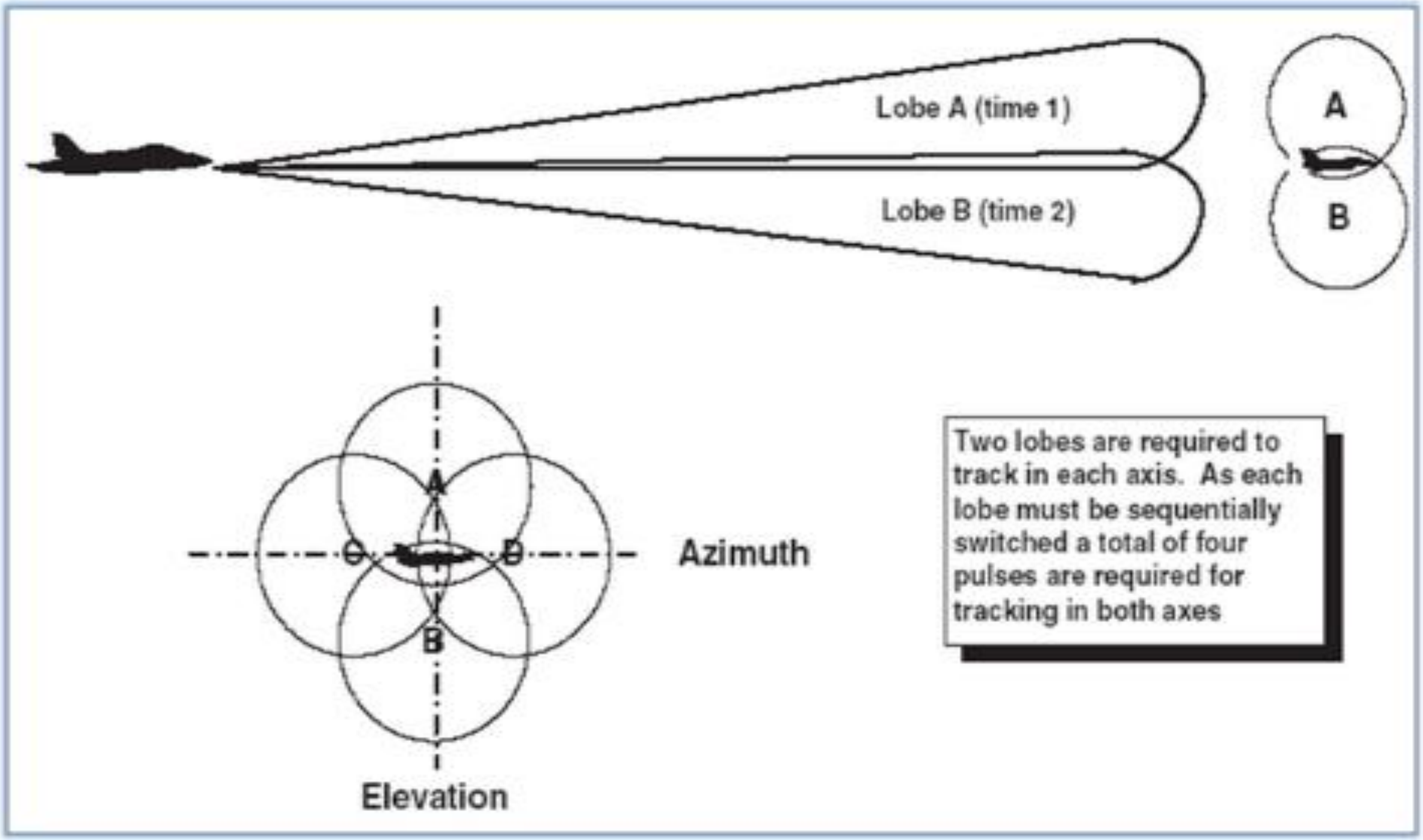


2D SEQUENTIAL LOBBING /01

1. Sequential lobbing with two position switched beam is used to track a target in one dimension.
2. The sign of the angular error determines the direction of the antenna to move in order to focus on the target.
3. Four beams (switching positions) are required in order to perform 2-dimensional tracking.

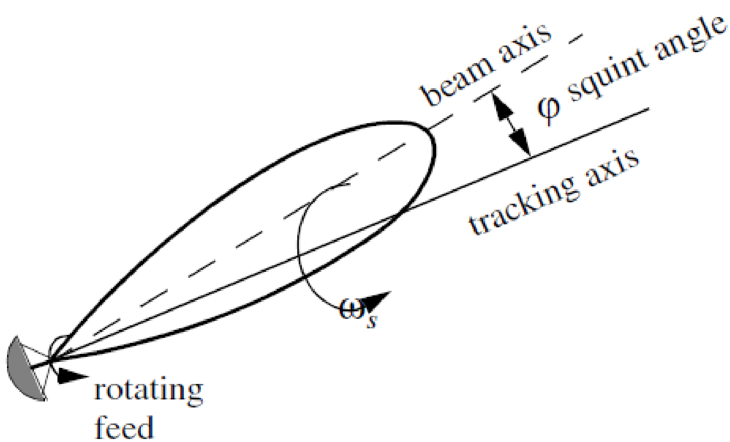


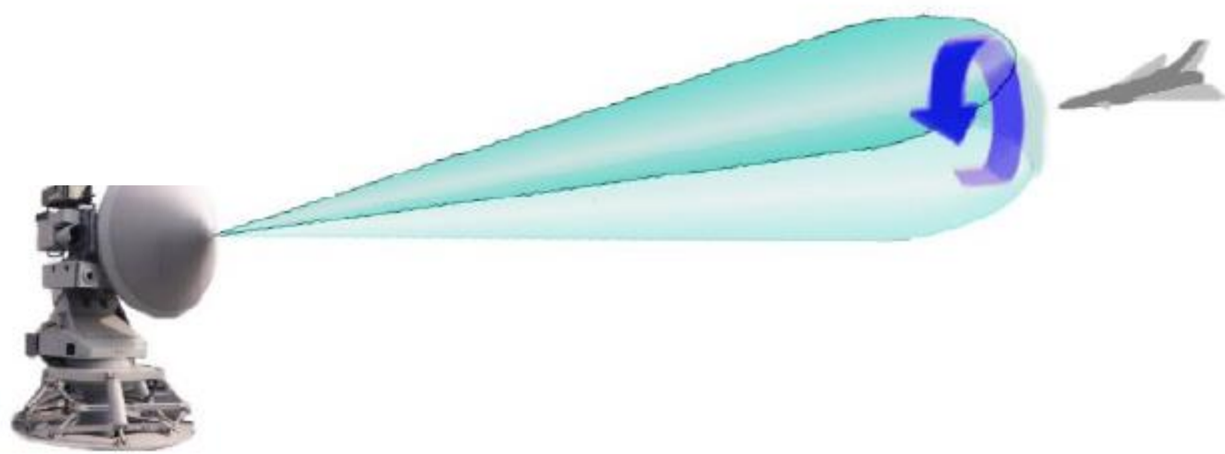
2D SEQUENTIAL LOBBING /02



CONICAL SCANNING

1. **Conical scanning** is a radar tracking system that uses a rotating beam to track targets and improve accuracy.
2. The **radar beam is rotated in a small circle** around the boresight axis, which is pointed at the target.
3. **The rotating beam modulates the energy** on target and the radar antenna's effective gain, which creates a modulation in the radar signal.

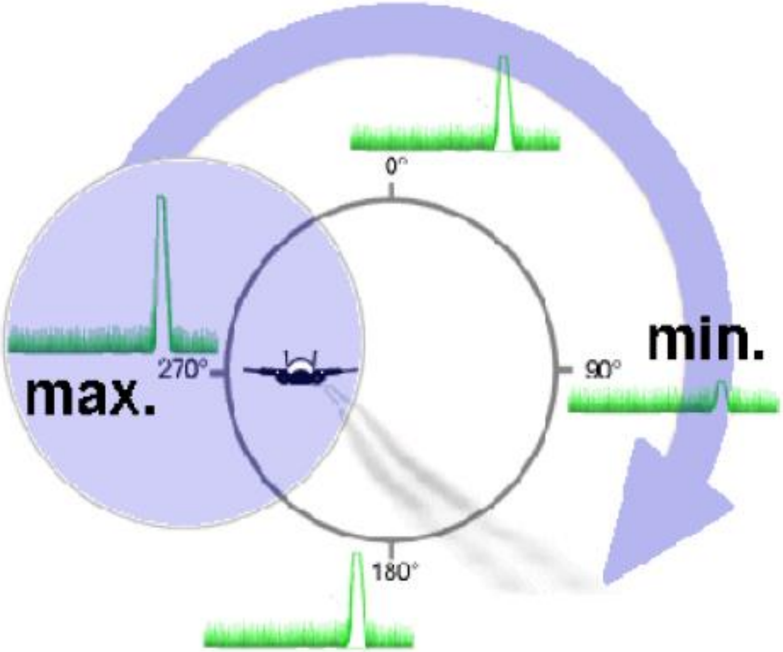


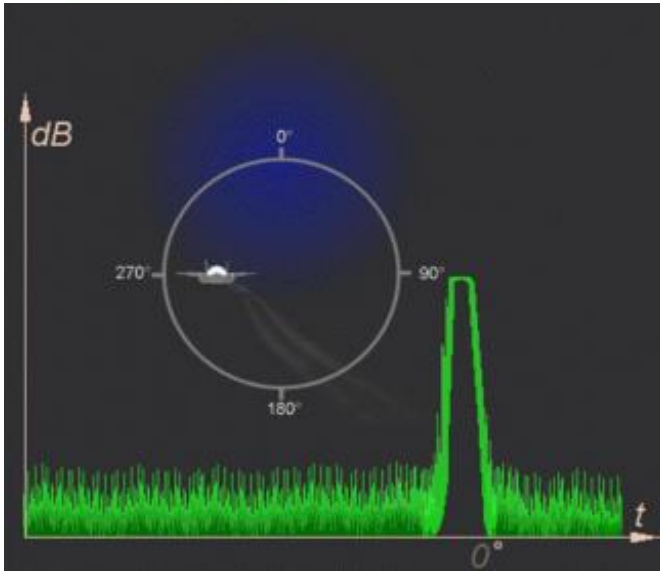


PRINCIPLE OF THE OPERATION OF CONICAL SCAN

1. If the target is in the boresight direction, then a maximum of backscattered power will be received in direction of the eccentric moving.

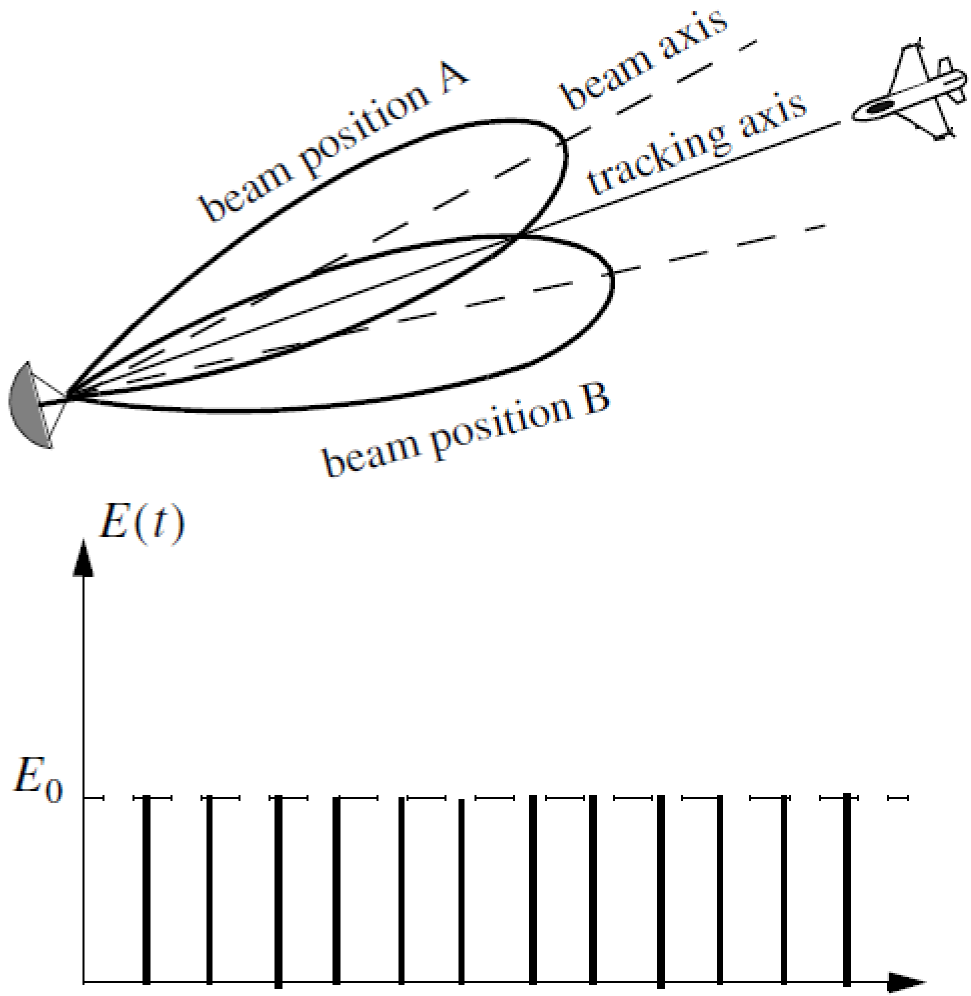
2. Tracking is achieved by steering the antenna in the direction with maximum return.





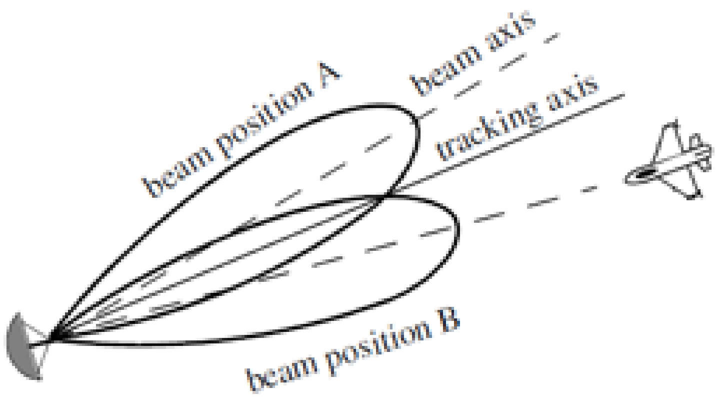
PRINCIPLE OF OPERATION: CONICAL SCANNING

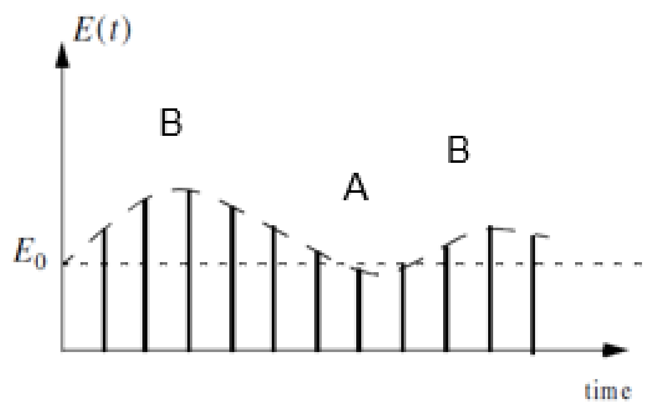
1. If the antenna rotates around the tracking axis and **all target returns have the same amplitude (zero error signal),** no further action is required.



PRINCIPLE OF OPERATION: CONICAL SCANNING

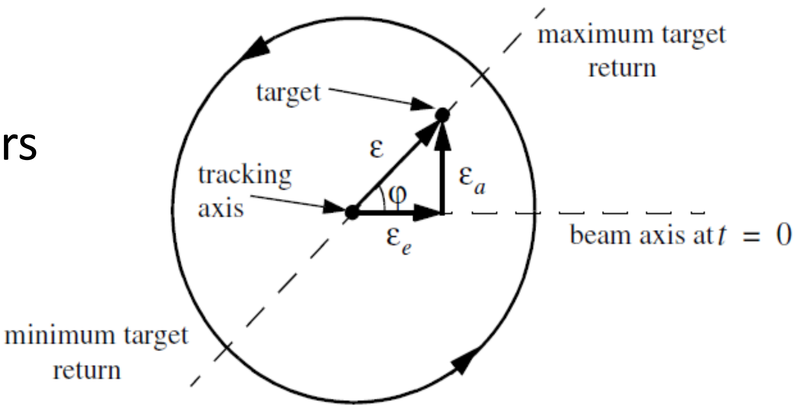
1. When the beam is at position B, returns from the target will have maximum amplitude
2. When the antenna is at position A, returns from the target have minimum amplitude.
3. Between those two positions, the amplitude of the target returns will vary between the maximum value at position B, and the minimum value at position A.
4. Therefore, Amplitude Modulation (AM) signal exists on top of the returned signal. This AM envelope corresponds to the relative position of the target within the beam.
5. The extracted AM envelope is used to derive a servo-control signal used to position the target on the tracking axis.





CALCULATION OF THE ERROR SIGNAL IN CONICAL SCANNING

1. Assume that t=0 is the starting beam position. The locations for maximum and minimum target returns are known. The quantity ε defines the distance between the target location and the antenna's tracking axis.
2. It follows that the azimuth and elevation errors are, respectively, given by



$$\varepsilon_a = \varepsilon \sin \varphi$$

$$\varepsilon_e = \varepsilon \cos \varphi$$

3. The AM signal can then be written as

$$E(t) = E_0 \cos(\omega_s t - \varphi) = E_0 \varepsilon_e \cos \omega_s t + E_0 \varepsilon_a \sin \omega_s t$$

Where E_0 is a constant called the error slope, ω_s is the scan frequency in radians per seconds.

CALCULATION OF THE ERROR SIGNAL IN CONICAL SCANNING

1. The scan reference is the signal that the radar generates to keep track of the antenna's position around a complete path (scan).
2. The elevation error signal is obtained by multiplying the signal E(t) with Cos(ω_st) (the reference signal) followed by low pass filtering , i.e

$$E_e(t) = E_0 \cos(\omega_s t - \varphi) \cos \omega_s t = -\frac{1}{2} E_0 \cos \varphi + \frac{1}{2} \cos(2\omega_s t - \varphi)$$

3. After lowpass filtering we get

$$E_e(t) = -\frac{1}{2} E_0 \cos \varphi$$

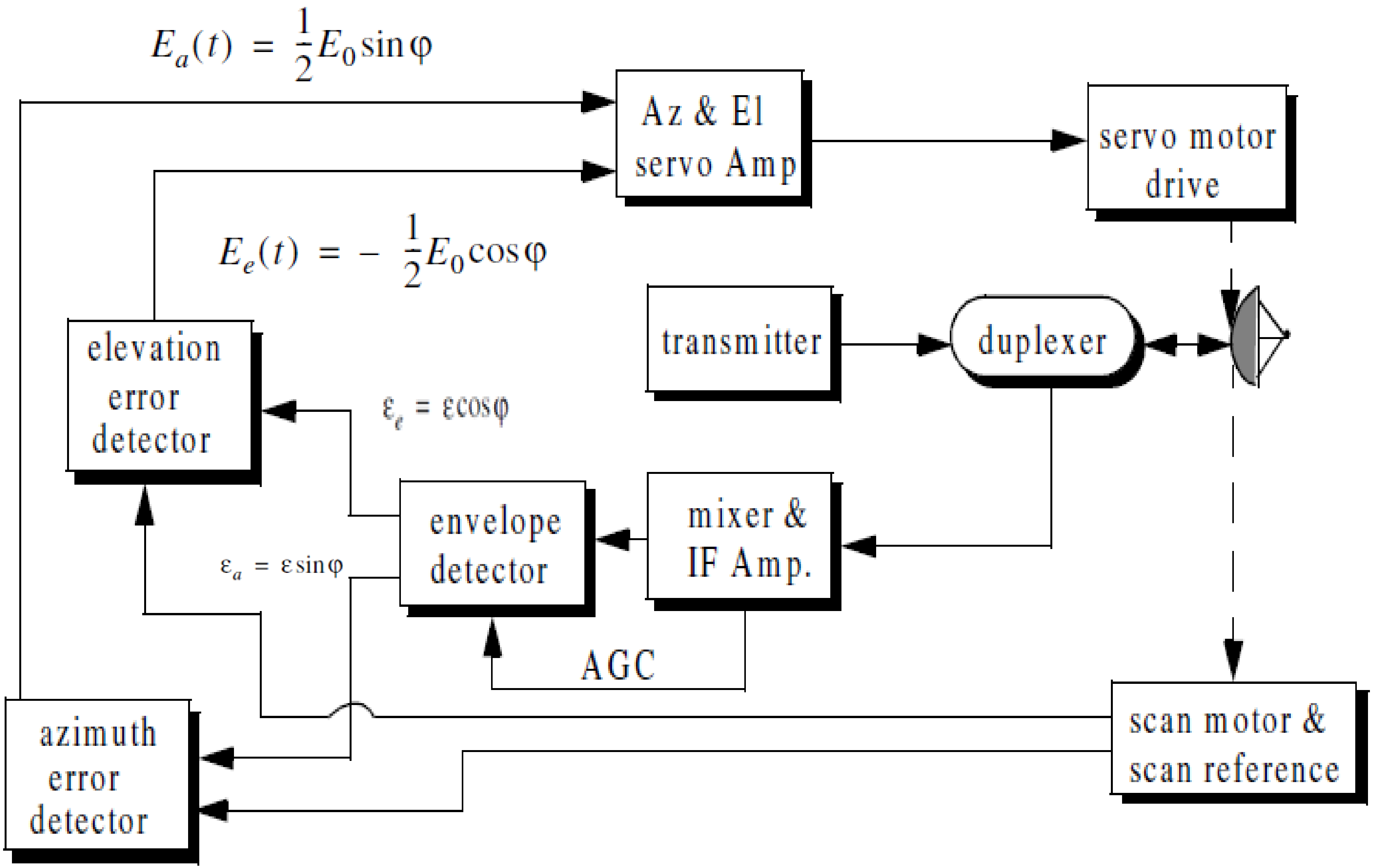
CALCULATION OF THE ERROR SIGNAL IN CONICAL SCANNING

1. Similarly, the azimuth error signal is obtained by multiplying E(t) by sin(ω_st) followed by low pass filtering, i.e

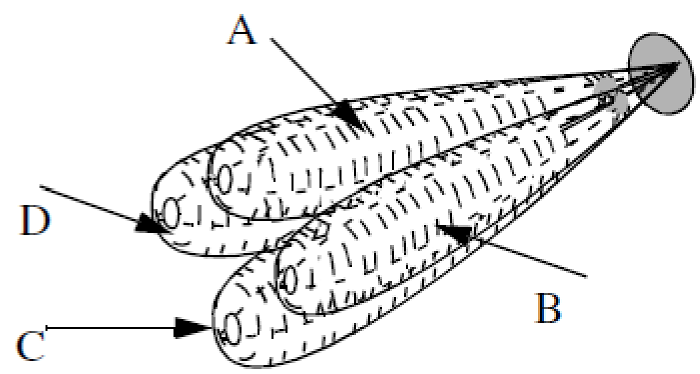
$$E_a(t) = \frac{1}{2}E_0 \sin\varphi$$

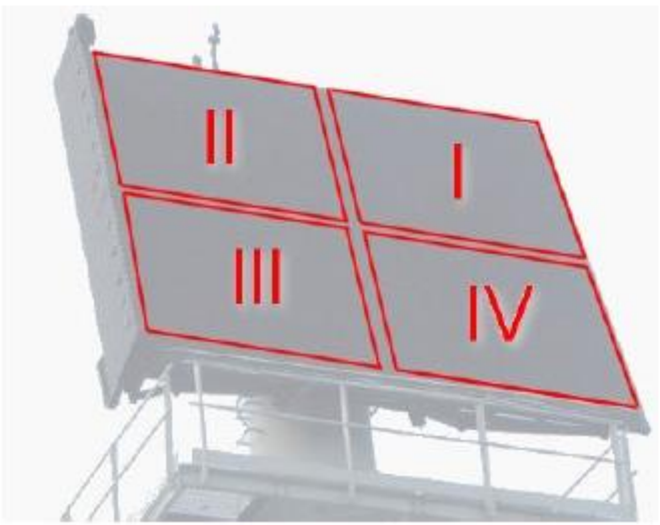
2. The antenna scan rate is limited by the scanning mechanism (mechanical or electronic)
3. Electronic scanning is much faster and more accurate than mechanical scan.
4. In either case, the radar needs at least four target returns to be able to determine the target azimuth and elevation coordinates (two returns per coordinate).
5. Therefore, the maximum conical scan rate is equal to one fourth of the Pulse Repetition Frequency(PRF).

BLOCK DIAGRAM OF A SIMPLIFIED CONICAL SCANNING SYSTEM



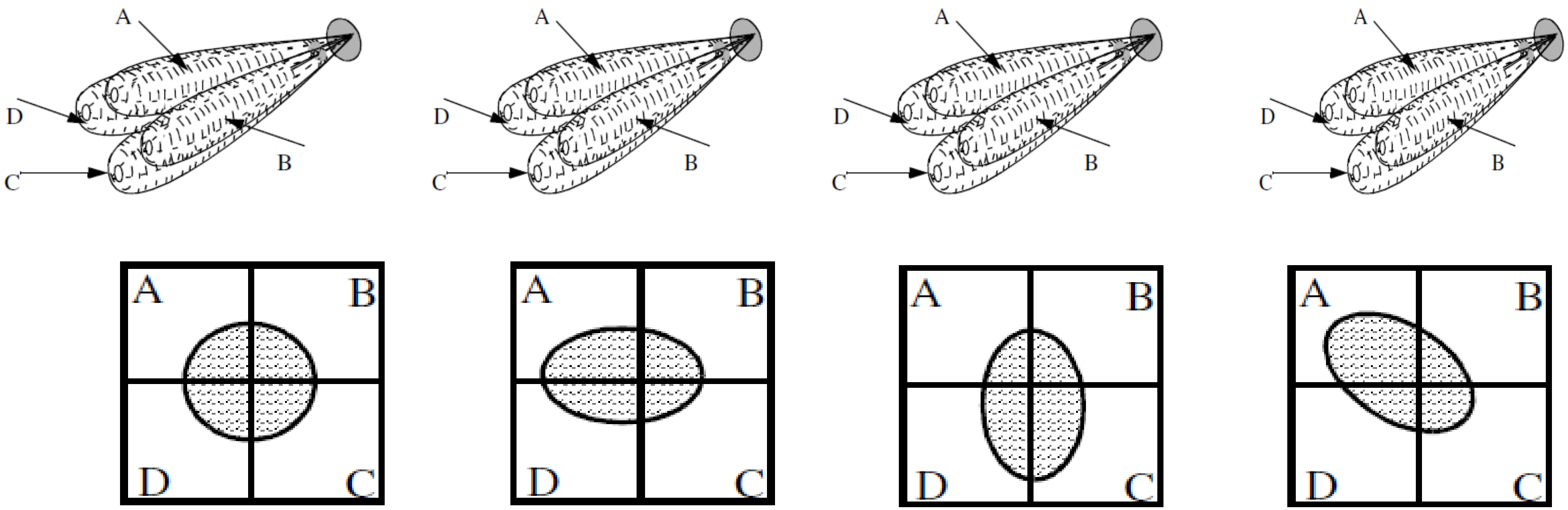
1. **Monopulse tracking** radar is a radar system that uses a single pulse to measure and track the angle of a target
2. It splits a beam into multiple parts and send them in slightly different directions.
3. The reflected signals are then amplified and compared to determine which direction has the strongest return.





PRINCIPLE OF OPERATION OF MONOPULSE TRACKING

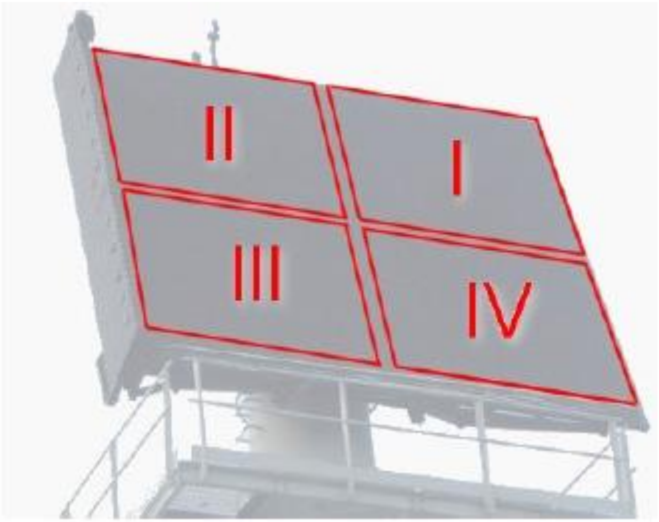
1. In (a) the four horns receive an equal amount of energy, which indicates that the target is located on the antenna's tracking axis.
2. In (b), (c) and (d) an unbalance of energy occurs in the different beams. This unbalance of energy is used to generate an error signal that drives the servo-control system.



(a) (b) (c) (d)

ANALYSIS OF RECEIVED SIGNAL

- The Monopulse antenna is divided up into four quadrants as shown.
- The following signals are formed from the received signals of these four quadrants:
- Sum: S = I + II + III + IV
- Difference: signal Δ_{az} = [(I + IV) - (II + III)]
- Difference: signal Δ_{El} = [(I + II) - (III + IV)]



COMPUTATION OF ERROR IN MONOPULSE SYSTEM

- If

  S = Sum of all channel signals

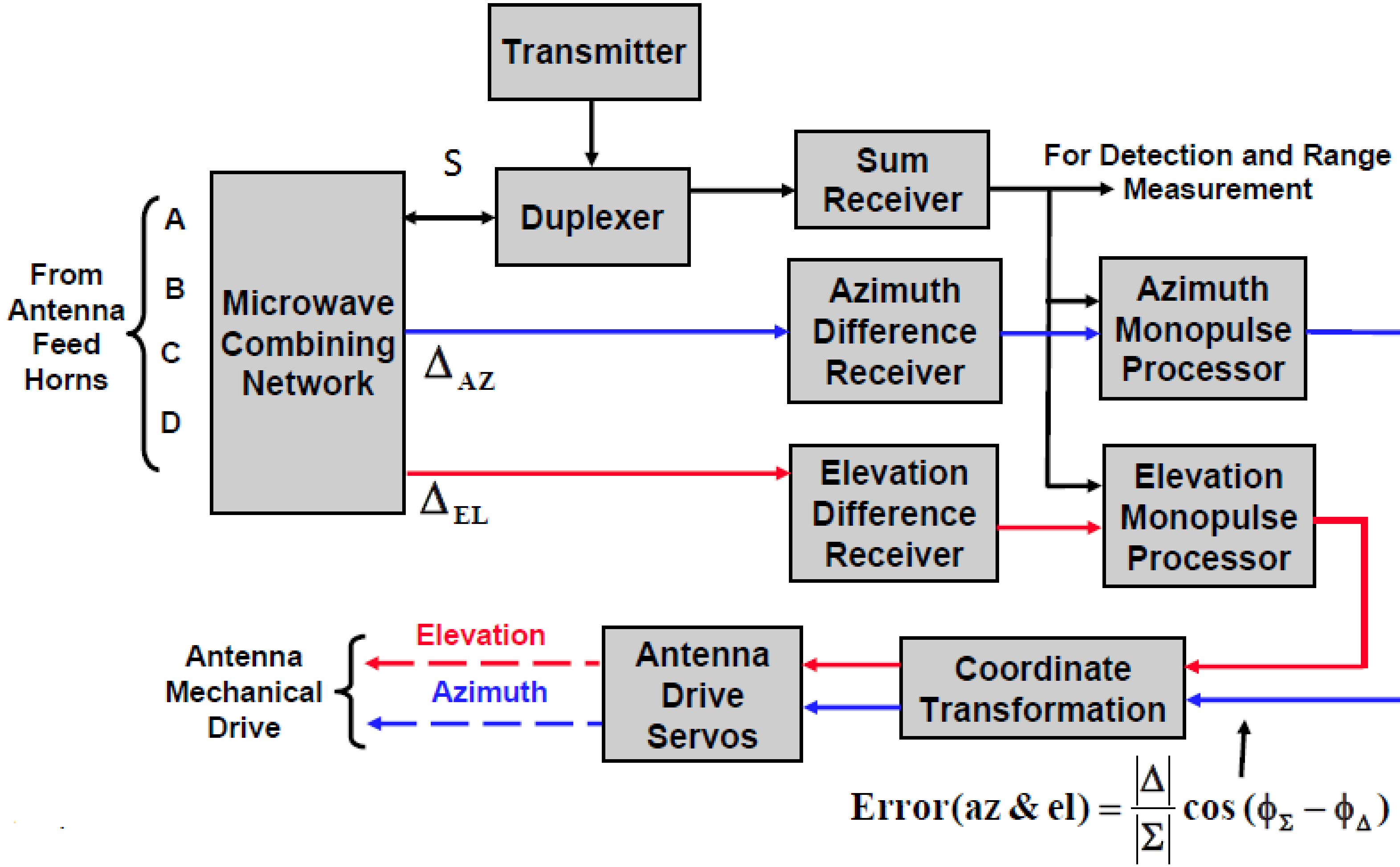
  Δ = Difference channel signals in plane

  ϕ = phase difference between S **and** Δ

- Then the Error signal, is given by

$$\boldsymbol{e = \frac{\Delta cos\emptyset}{S}}$$

SIMPLIFIED BLOCK DIAGRAM OF MONOPULSE TRACKING

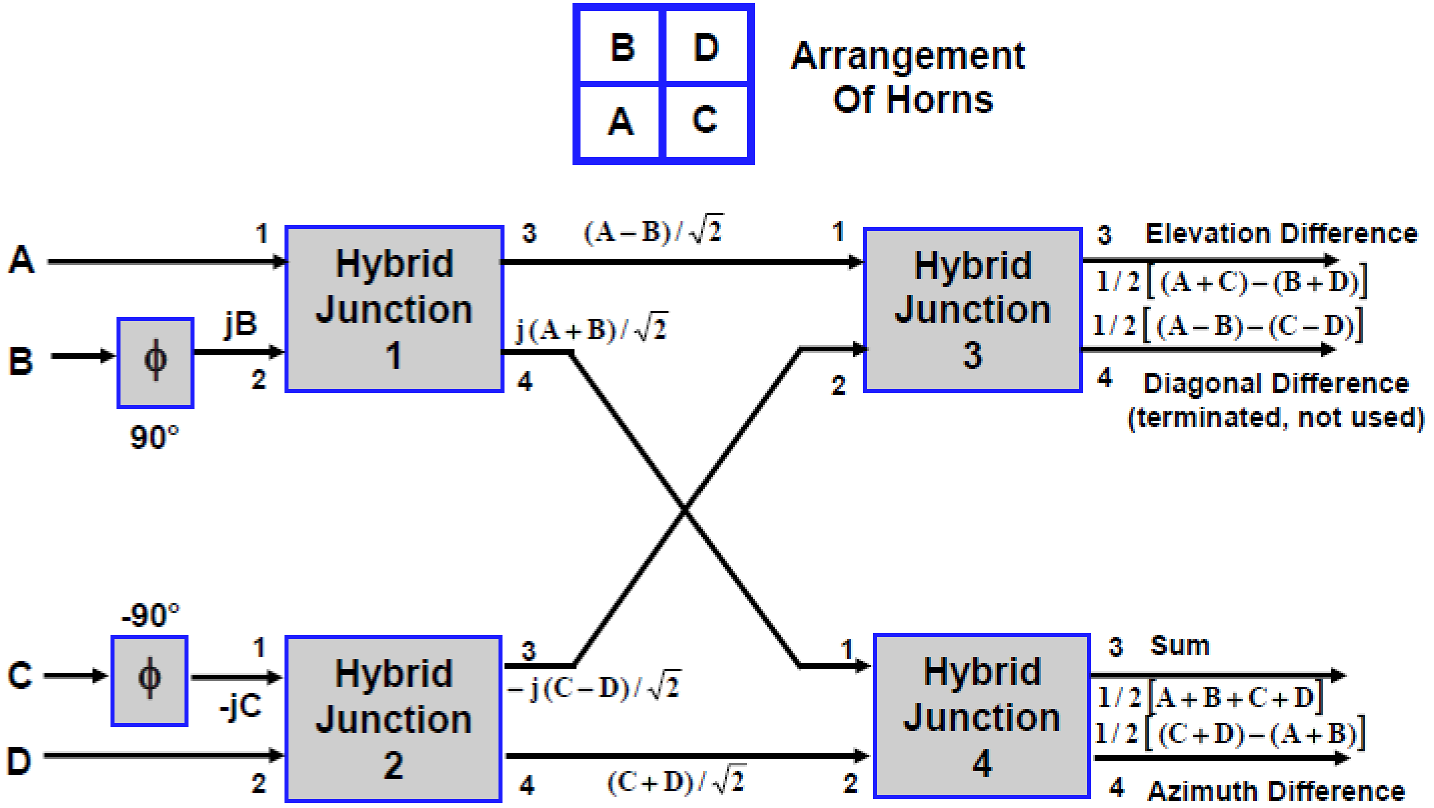


ADVANTAGES OF MONOPULSE TRACKING

1. **Improved accuracy:** Monopulse radars can improve pointing accuracy by a factor of 10 compared to conical scan systems.
2. **Resistant to jamming:** Monopulse radars are resistant to jamming since angle measurement is based on phase comparison, amplitude-based jamming has limited effect
3. **Unaffected by amplitude fluctuations:** Monopulse systems are not affected by amplitude fluctuations of the target echo.
4. **Fewer interrogations:** Monopulse tracking radar requires fewer interrogations to determine the azimuth.

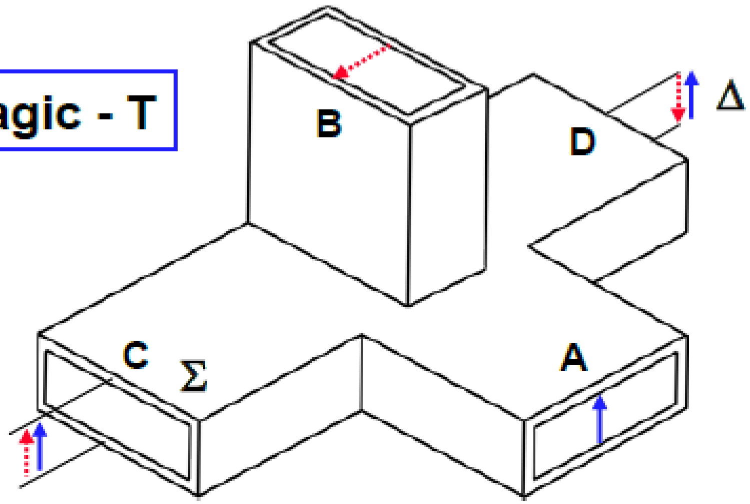
Further Reading:

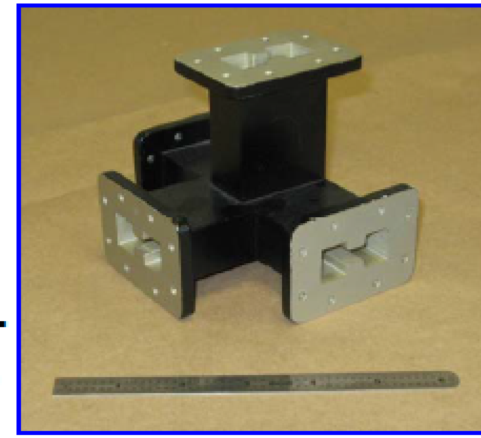
MICROWAVE COMBINING NETWORK



HYBRID JUNCTIONS FOR MONOPULSE RADARS

Magic - T





Photograph of
C - Band Magic - T
(Ridged waveguide)

Courtesy of Cobham Sensor Systems.
Used with permission.

- A signal input at port A divides equally in amplitude and phase between ports C and D, but does not appear at port B
  - Port B cannot support that propagation mode
- A signal input to port B divides equally but with opposite phases between ports C and D
  - Does not appear at port A
- If inputs are applied simultaneously to ports A and B, their sum will appear at port C and the difference at the D

CAMPARISON OF MONOPULSE & MECHANICAL STEERED /01

FEATURE	MONOPULSE TRACKING RADAR	MECHANICAL TRACKING RADAR (CONICAL SCAN)
1. Basic Principle	**Simultaneous Lobing:** Angular error (in azimuth and elevation) is derived from the same, single radar pulse by comparing signals from multiple, simultaneous antenna beams (Sum and Difference patterns).	**Sequential Lobing:** Angular error is derived by sequentially sampling the target echo from different antenna beam positions (e.g., a rotating offset beam) over multiple pulses.
2. Antenna System & Feeds	**Complex antenna feed system (e.g., four-horns or a multi-mode horn)** with a microwave hybrid network (e.g., magic-Ts) to generate simultaneous Σ (Sum), ΔAZ (Azimuth Difference), and ΔEL (Elevation Difference) channels.	**A single, moving feed** or a mechanically wobbling sub-reflector that causes the main beam to rotate or nutate around the boresight axis.

CAMPARISON OF MONOPULSE & MECHANICAL STEERED /02

FEATURE	MONOPULSE TRACKING RADAR	MECHANICAL TRACKING RADAR (CONICAL SCAN)
3. Data Rate for Angle Measurement	**Very High**. A complete, accurate angle measurement is obtained from every single pulse.	**Lower**. Requires a full scan cycle (multiple pulses) to determine the angle of the target. The effective data rate is the scan frequency.
4. Susceptibility to Target Scintillation	**Low.** Since error is measured from one pulse, rapid amplitude fluctuations of the target echo (scintillation) have minimal effect on accuracy.	**High.** The system compares signal amplitudes from different pulses. If the target's radar cross-section fluctuates between pulses, it is interpreted as a false angle error, leading to tracking jitter.

CAMPARISON OF MONOPULSE & MECHANICAL STEERED /03

FEATURE	MONOPULSE TRACKING RADAR	MECHANICAL TRACKING RADAR (CONICAL SCAN)
5. Susceptibility to Electronic Countermeasures (ECM / Jamming)	**More Robust.** Difficult to deceive because the angle measurement is instantaneous. Jamming would need to precisely replicate the complex monopulse signal structure.	**Vulnerable. Susceptible to Inverse Gain Jamming,** where a jammer synchronizes its signal with the scan frequency, sending strong pulses when the antenna is off-target and weak ones when it is on-target, confusing the tracker.
6. Accuracy & Precision	**Very High.** No inherent lag between error sensing and correction. Provides high precision and is the standard for high-accuracy systems like missile guidance and instrumentation tracking.	**Lower. Accuracy** is fundamentally limited by scan rate, signal fluctuation, and the servo bandwidth needed to smooth the sequential error data.

CAMPARISON OF MONOPULSE & MECHANICAL STEERED /04

FEATURE	MONOPULSE TRACKING RADAR	MECHANICAL TRACKING RADAR (CONICAL SCAN)
7. Complexity & Cost	**High.** Requires multiple, parallel receiver channels (for Σ, ΔAZ, ΔEL) that are precisely amplitude- and phase-matched. The feed and comparator network is complex and expensive.	Lower. Requires only a single receiver channel. The system is mechanically complex but electronically simpler and less costly than a monopulse system.
8. Target Acquisition	Can be slower initially, as it often requires a separate search mechanism to bring the target into the narrow monopulse beam for lock-on.	The scanning motion of the beam can naturally facilitate acquisition of a target within a small volume.

APPLICATIONS OF TRACKING RADARS

1. Satellite tracking
2. Missile Guidance Radars
3. Precision Instrumentation Radars (e.g., range tracking)
4. Modern military fire-control systems

TRACKING RADAR FOR SATELLITE SYSTEMS

ECE 514E – RADAR & SATELLITE ENGINEERING

Monday, December 1, 2025

TYPES OF TRACKING RADAR FOR SATELLITES

MECHANICAL DISH Traditional high-gain antennas that physically steer to track a target. Excellent for deep space and high precision on single targets.

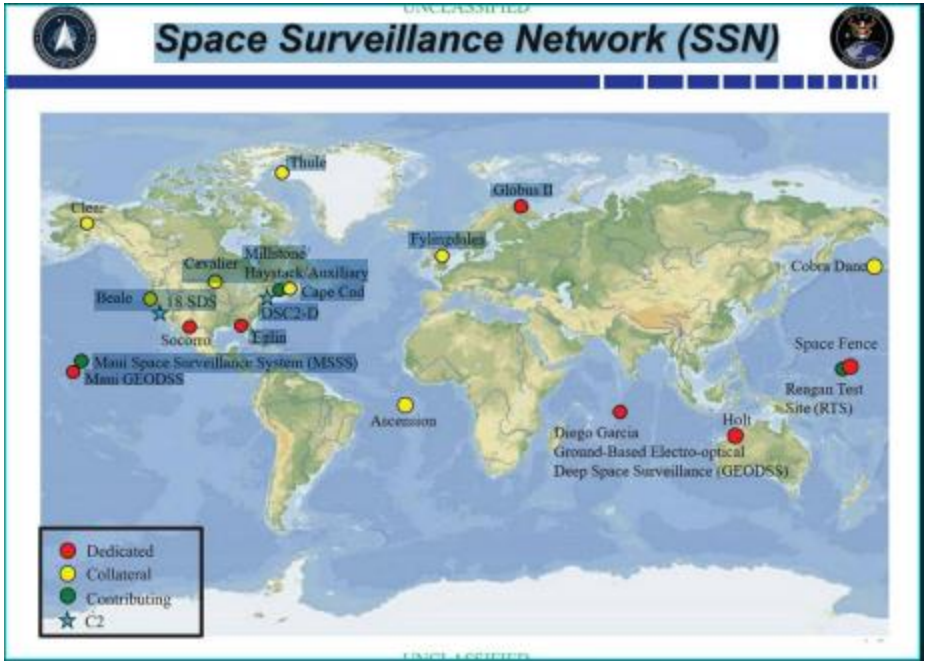
PHASED ARRAY (AESA) Steers the beam electronically without moving parts. Can track hundreds of objects simultaneously with extreme agility.

SALIENT FEATURES

1. **COLLISION AVOIDANCE** Satellite Operators receive "conjunction warnings" when debris passes too close. Accurate radar data reduces false alarms and saves fuel.
2. **ORBIT DETERMINATION** Precise orbital elements (TLEs) are generated from radar tracks, allowing the system to predict where a satellite will be days in the future.

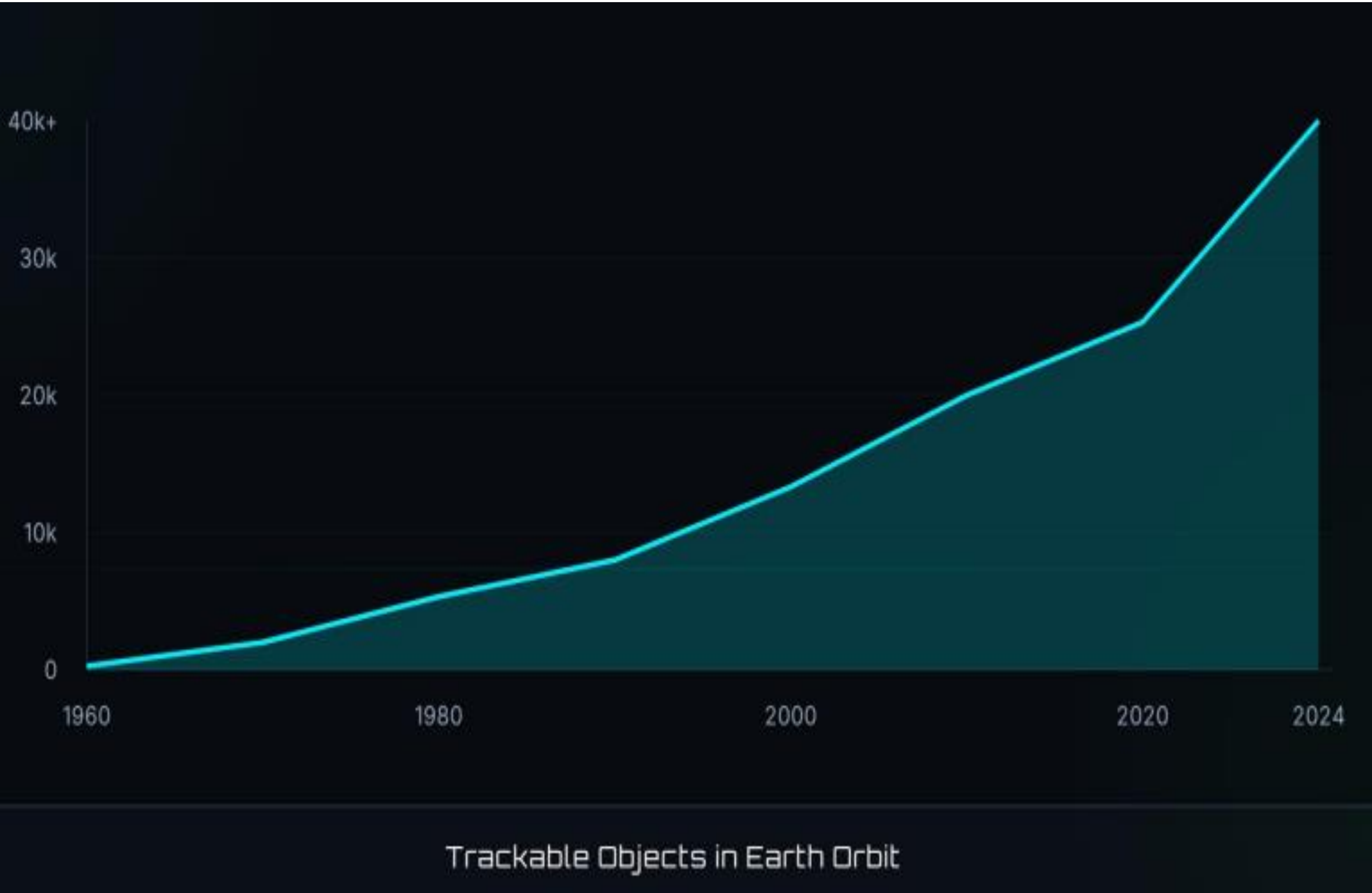
WHO PROVIDES GLOBAL SURVAILLANCE?

1. **US SPACE SURVEILLANCE NETWORK(SSN)** is a global gold standard utilizing a mix of phased array radars (e.g., Cavalier, Eglin), mechanical radars, and optical telescopes (GEODSS).
2. **A distributed network is required to maintain a constant** "chain of custody" on objects.



Space Surveillance Network (SSN)

GROWTH OF TACKABLE OBJECTS



TRACKING DIFFICULTIES

SMALL SIZE

Objects smaller than 10cm are extremely difficult to track consistently, yet carry enough kinetic energy to destroy a satellite.

HYPERVELOCITY

Targets move at ~7.8 km/s (17,500 mph). Radars must acquire and lock onto these fast-moving targets in seconds.

VOLUME

With 47,000+ trackable objects, the "correlation problem" of matching a radar blip to a known object is computationally intense.

NEXT GENERATION TRACKING

1. **Moving from UHF/VHF to S-band and X-band** allows for much higher resolution, enabling us to see smaller debris fragments.
2. **New US Space Fence** is a massive S-band radar capable of detecting marble-sized objects, significantly expanding the catalog.
3. **Companies like LeoLabs** are building their own global radar networks to provide commercial "Space Traffic Management" services.