Long range tracking radar system

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CSIST Part

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Contents

Fundamentals of Angle Sensing (Radar & Navigation.)

- Manual Observation and Aide
- Amplitude Comparison, historically
- Sequential Lobing, Auto Tracking
- Conical Scanning --- historically so many
- Beam Rotation (omni), Beam Scanning
- Beam Switching ----- not so many

Slow, low sensitivity, weak to scintiration

Simultaneous Lobing (Mono-pulse)

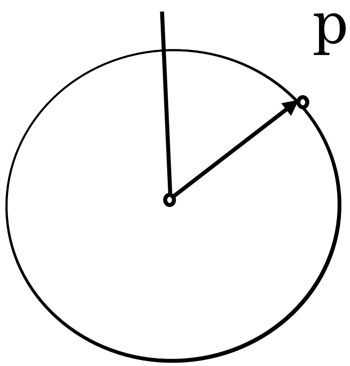
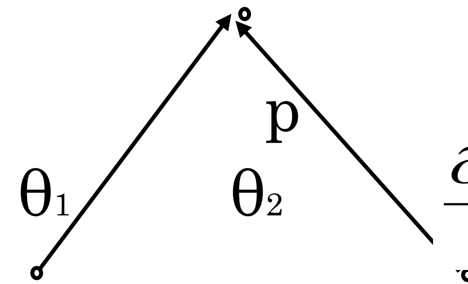
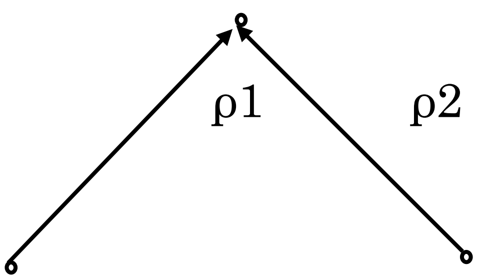
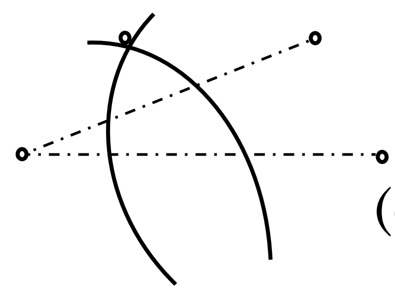
So many now,

Quick, High sensitivity (optimum design)

Present and Future System

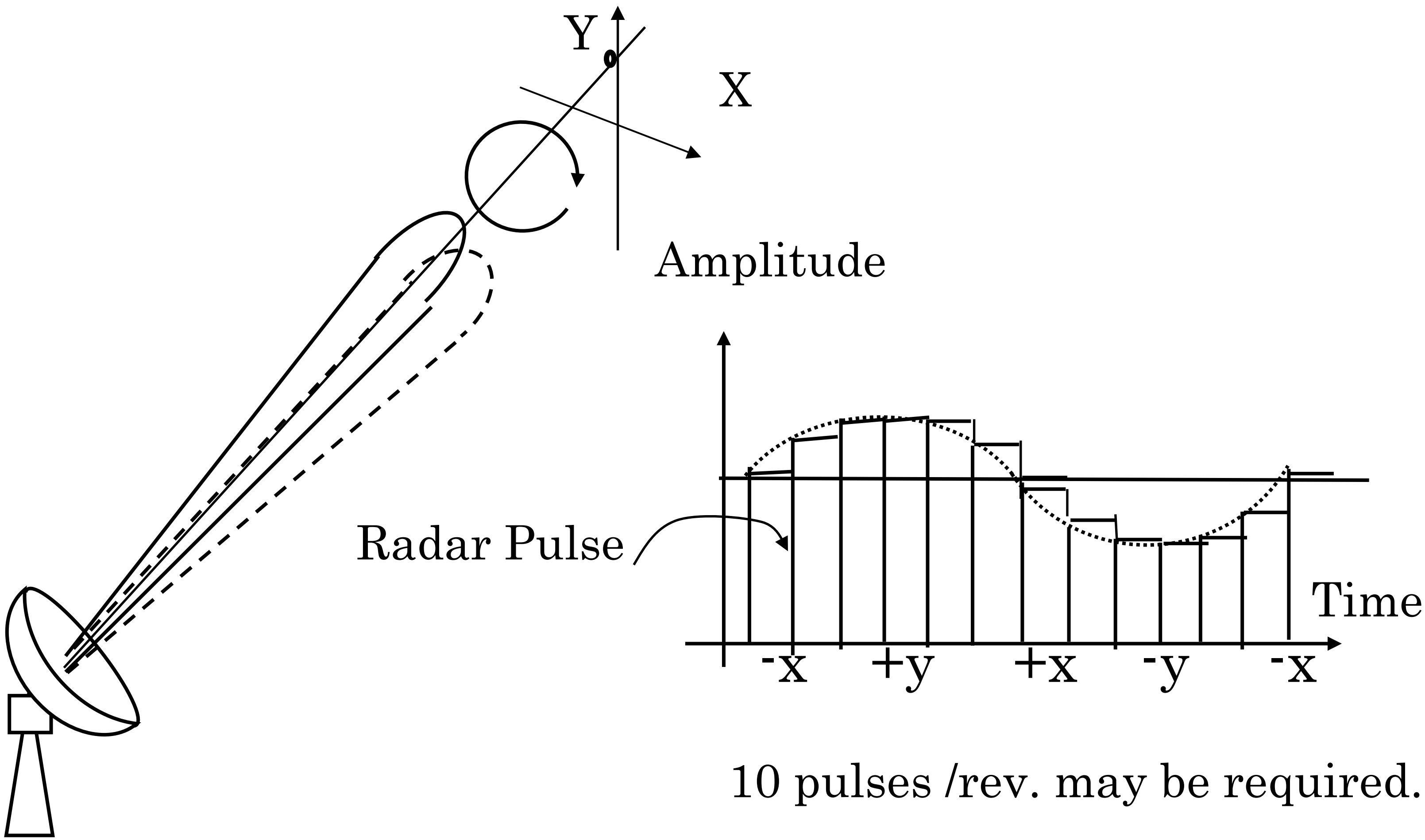
- Synthetic Antenna with multi monopulse beams
- Sophisticated Control & Signal Processing

Basic Position Sensing Concept

ρ, θ method	θ, θ method
 ρ, θ $\frac{\partial \rho}{\partial t}, \frac{\partial \theta}{\partial t}$	 $\frac{\partial \theta_1}{\partial t}, \frac{\partial \theta_2}{\partial t}$
TACAN, Tracking Radar,	Two Radars, VOR,
ρ, ρ method	Hyperbolic Method
 $\frac{\partial \rho_1}{\partial t}, \frac{\partial \rho_2}{\partial t}$	 Min.3 stations Hyperbolic Curves (Constant Diff.)
Two Radars, DME/DME,GPS	LORAN, OMEGA

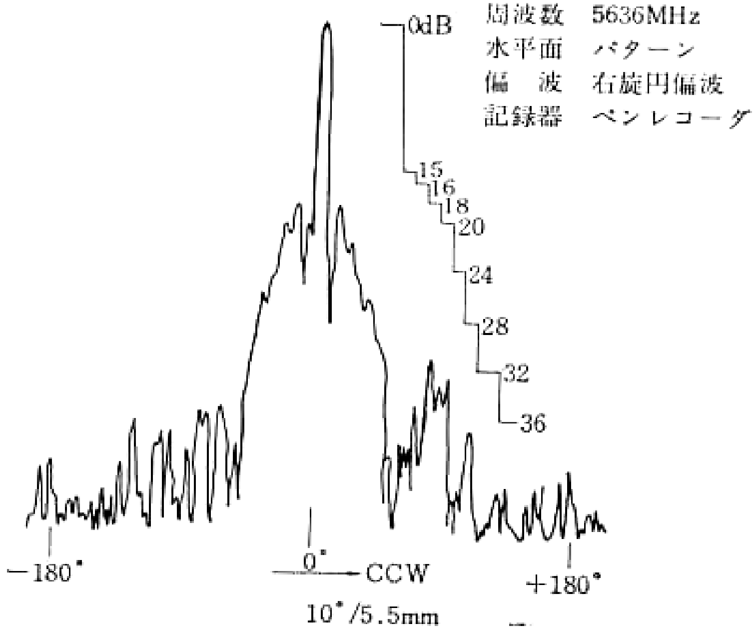
Conical Scanning (Sequential Lobing)

Many historical examples since War Ⅱ.

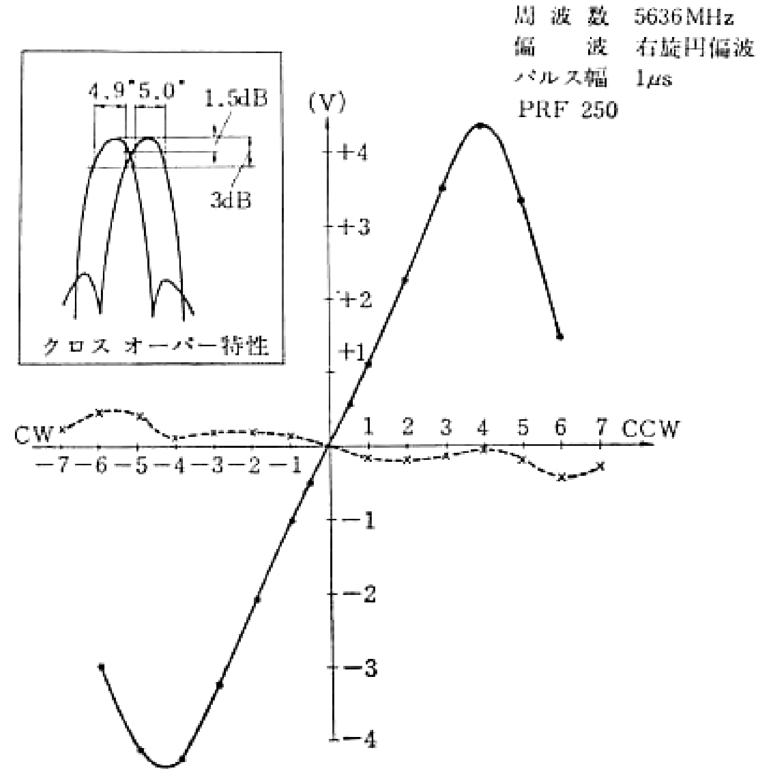


10 pulses /rev. may be required.

Slow, angle error is sequential. Far slow AGC is required.
Angle errors x, y are cross-coupled along range.



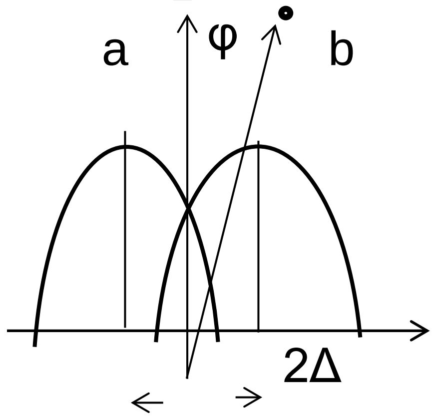
第２図　輻射パターン
Fig. 2 Antenna pattern.



第３図　クロスオーバ特性
Fig. 3 Crossover.

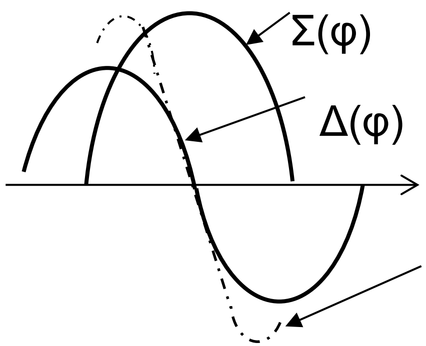
An Example of Conical Scanning Tracking System

Monopulse (Simultaneous Lobing)



$$(a+b)(\phi) = \cos(\Delta+\phi) + \cos(-\Delta+\phi) = 2\cos\Delta\cos\phi$$

$$(a-b)(\phi) = \cos(\Delta+\phi) - \cos(-\Delta+\phi) = -2\sin\Delta\sin\phi$$



Sigma Beam $\Sigma(\phi) = 2\cos\Delta\cos\phi$

Delta Beam $\Delta(\phi) = -2\sin\Delta\cdot\sin\phi$

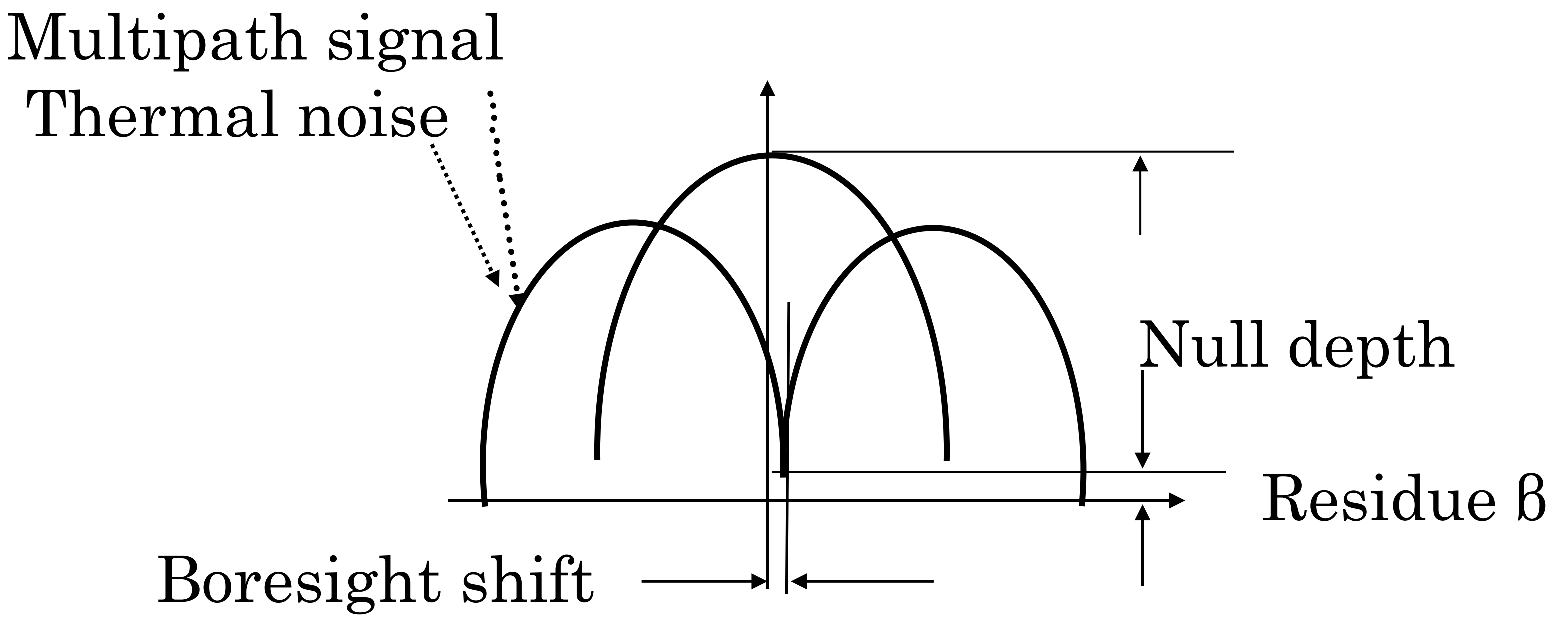
Angle Error $e(\phi) = {\Delta(\phi)}/{\Sigma\phi} = -\tan\Delta\tan\phi$

Single beam is assumed by $\cos\phi$ shape

Actual beam width will be $\approx 70\,\lambda/D$ deg

Monopulse Antenna Angle Sensing & Error Analysis

－Antenna & Receiver imperfection－



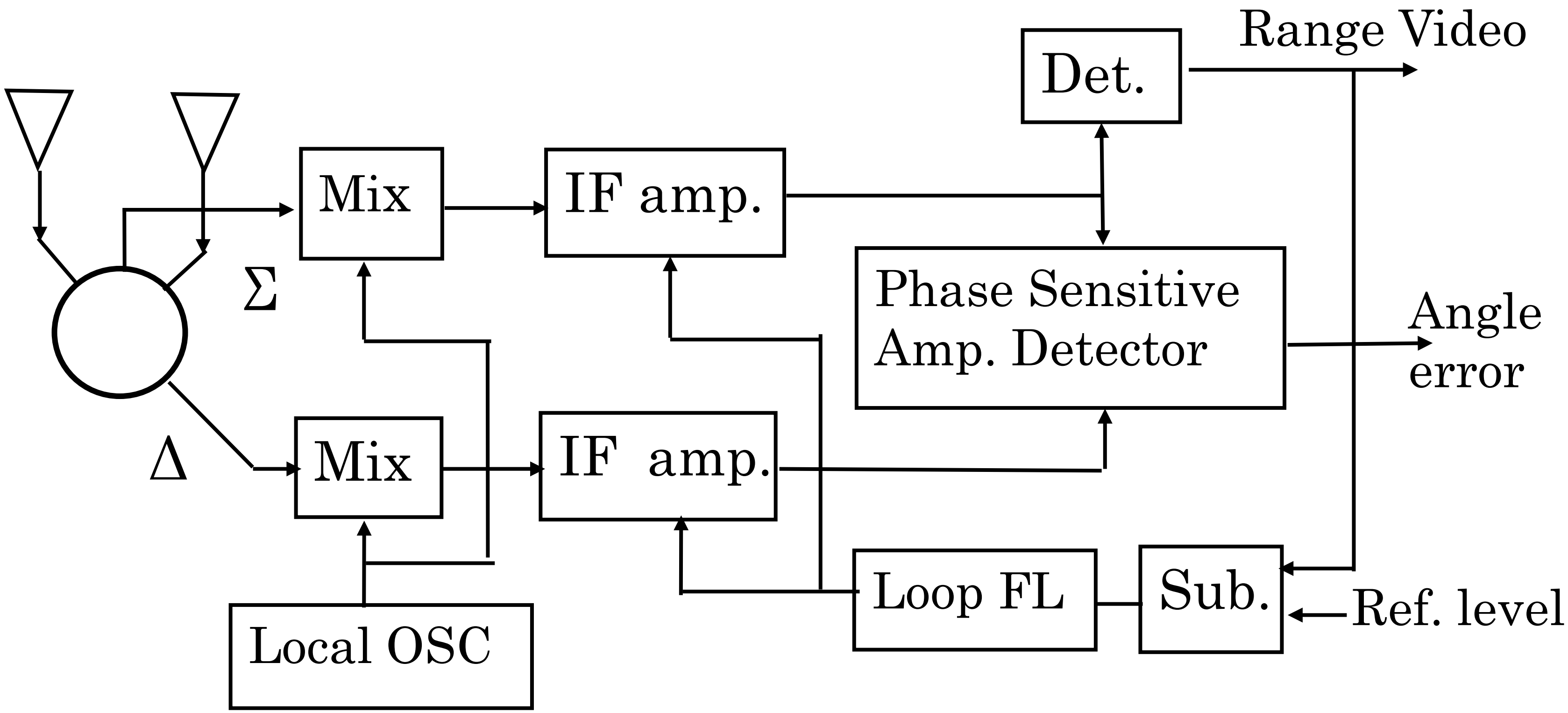
$$(a-b)(\phi)\ \text{with}\ \alpha=(1+\alpha)\cos(\Delta+\phi)-\cos(-\Delta+\phi)=-2\sin\Delta\sin\phi+\alpha\cos\Delta$$

$Boresight \cdot shift=\alpha\cos\Delta$ At φ=0, α: unbalance

Null residue by quadrature β& Receiver phase shift δ produce boresight error.

$$Boresight \cdot Error=\beta\sin\delta$$

Angle Sensing Receiver (one axis)



Conventional Monopulse Receiver

- Angle Detection at every radar pulse for quick angle tracking.
- Higher signal level and angle sensitivity than sequential lobing.
- Faster AGC loop than conical but may still limit for quick action.
- IF-amp amplitude & phase matching are required over some 80dB.

To supplement 3pages

Multipath error

It is so severe for elevation angle, due to earth surface reflection.

$$\sigma_{mE} = \frac{\rho \cdot BW}{2\sqrt{2G_{se(Peak)}}}$$

ρ: the earth surface reflection coefficient (some 0.2 up to 1)

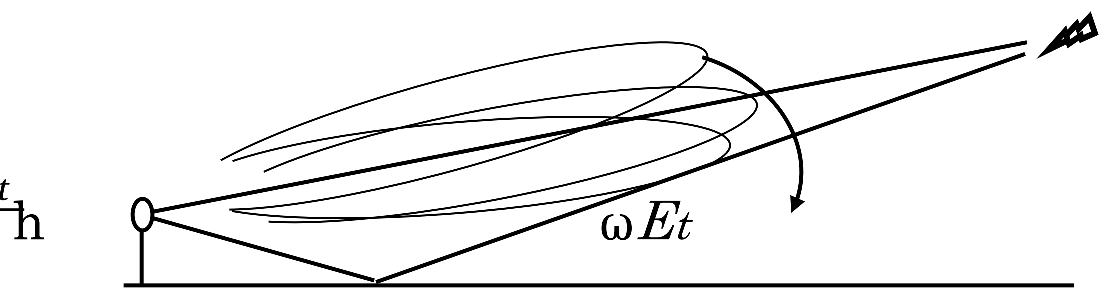
σ_{mE}: rms multipath elevation error degree

BW: one way –3dB beam width degree

Gse: power ratio of Σbeam peak and Δbeam level (main or sidelobes), where multipath reflection signal is coming.

Cyclic multipath error frequency f_m may be

$$f_{mE} = \frac{2h \cdot \omega_{Et}}{\lambda}$$



h: antenna height ωE_t: Elevation angle changing rate rad/s

Δ beam sidelobe is a key point to evaluate monopulse antenna.

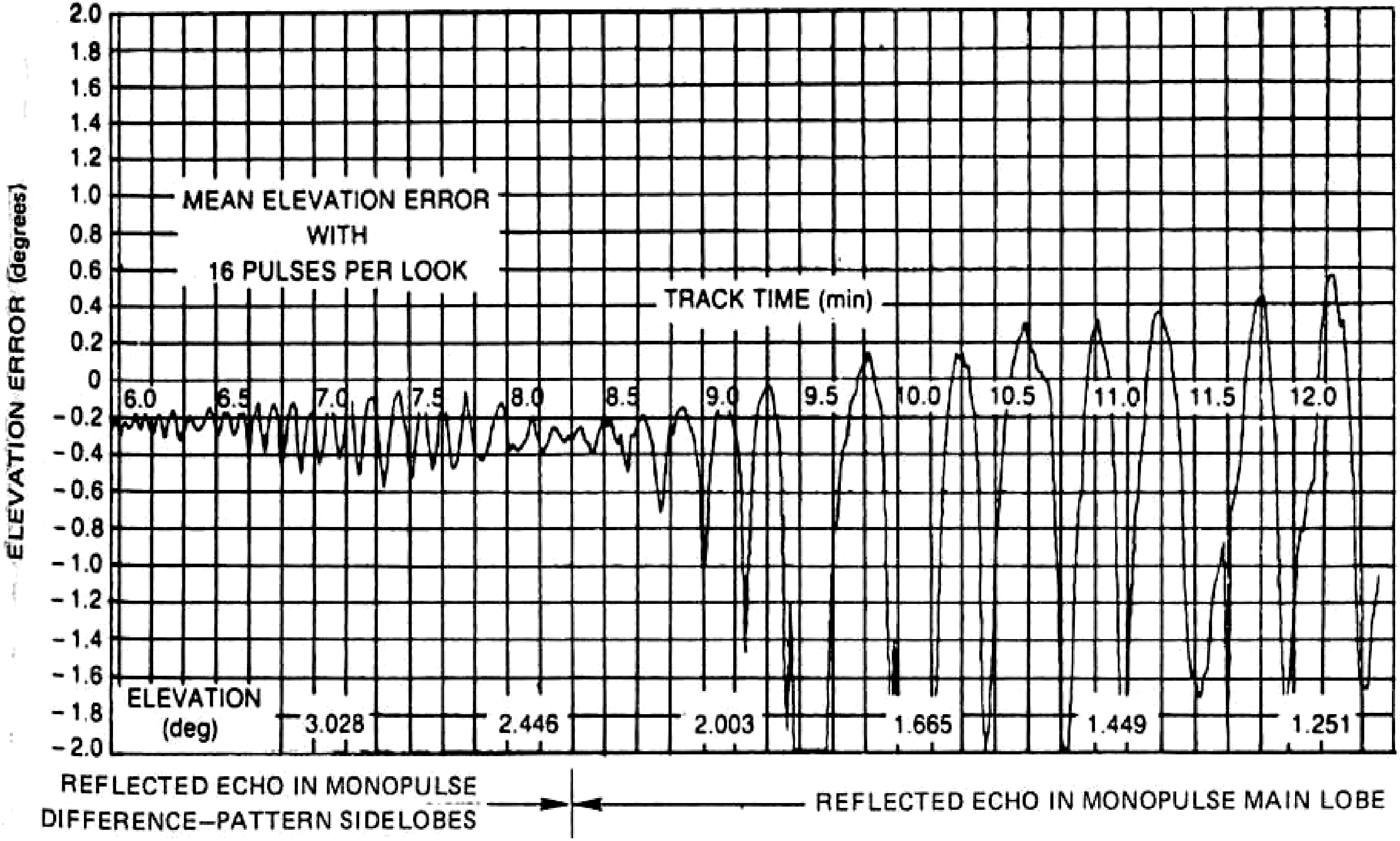


FIG. 18.37 Measured elevation-tracking error of an S-band radar using an AN/FPS-16 radar for a target elevation reference.

Tracking radar low elevation angle error example

(BW≒1deg, on Radar HDBK)

Thermal noise fluctuation

Thermal noise contribution becomes significant at far range.

$$\sigma_{th} = \frac{BW}{k_m \sqrt{B \cdot \tau \left(S/N \right) \left(f_r / \beta_n \right)}}$$

σ_{th}: rms thermal noise angle error [degree]

BW: one way –3dB beam width [degree]

k_m: angle sensitivity of antenna (typical 1.5).

B : IF bandwidth [MHz] τ: pulse width [μs] ($B\tau$ will be 1.2~)

S/N: signal to noise ratio at Σ beam (true number)

This formula may be not applicable at low S/N<8dB.

f_r : pulse repetition frequency [Hz]

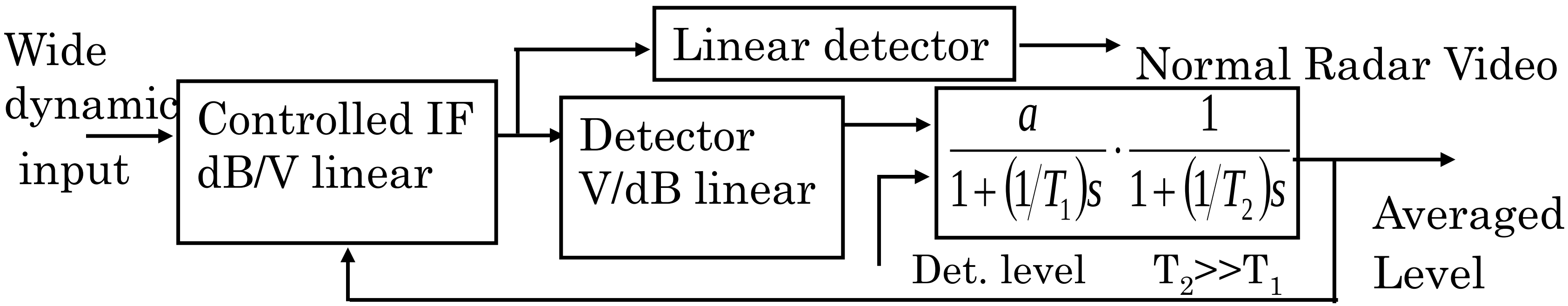
β_n: servo noise band width [Hz]

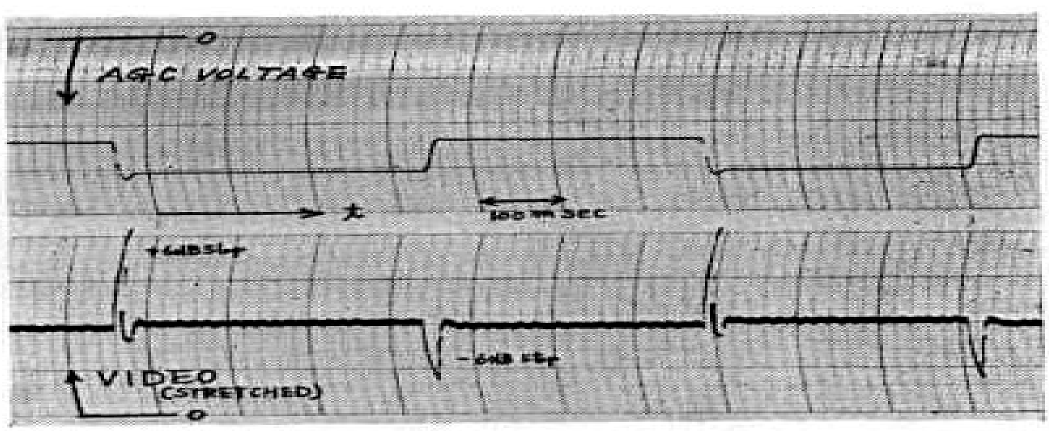
Sequential lobing noise error is large by $\sqrt{2}$ and $k_s \leqq k_m$

What is a good AGC? −fast and quick recover for steep level dip

AGC has been taken less notice by radar engineers, because, circuit is simple, but nonlinear circuits could not be suitable for analysis. IF amp and Detector are generally not dB linear device as big change as one decade sensitivity.

The other hand, Fast AGC is preferable for monopulse system.





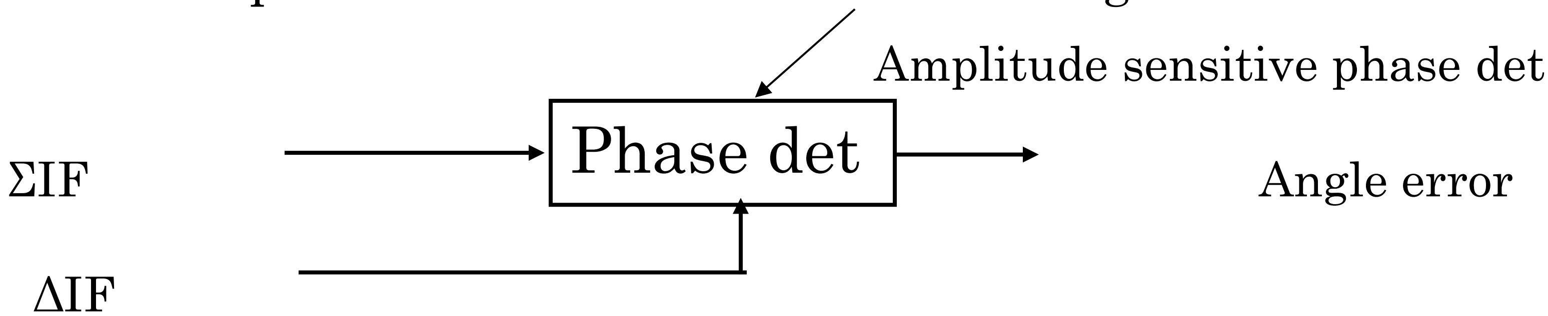
第3図 AGC 応答特性

Fig. 3 AGC response.

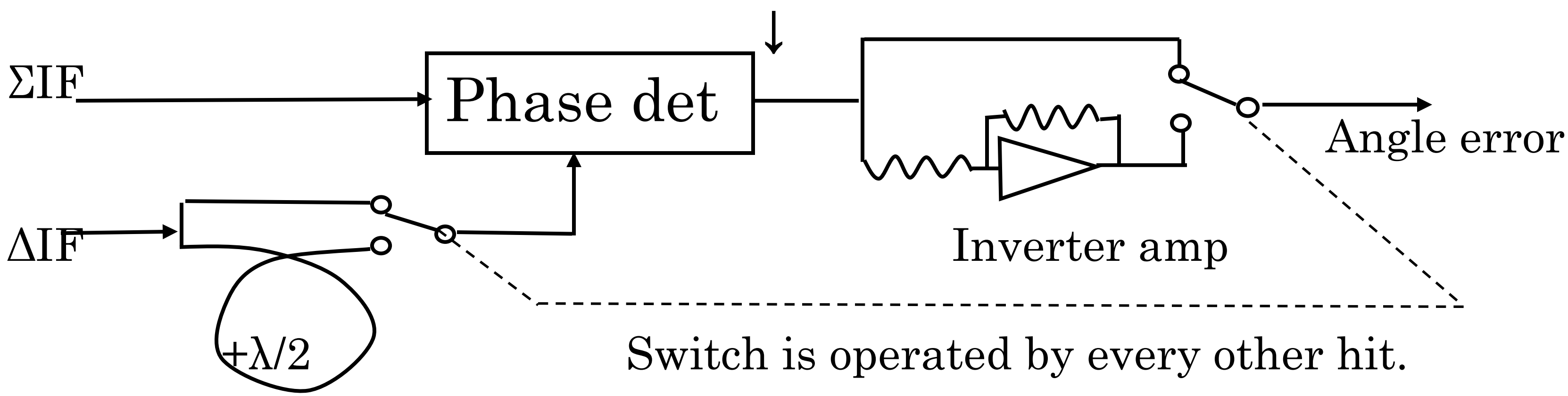
To supplement 2pages

Practical Difficulty of Receiver is Noise Unbalance

Noise & noise product at limited BW makes a large error at low S/N

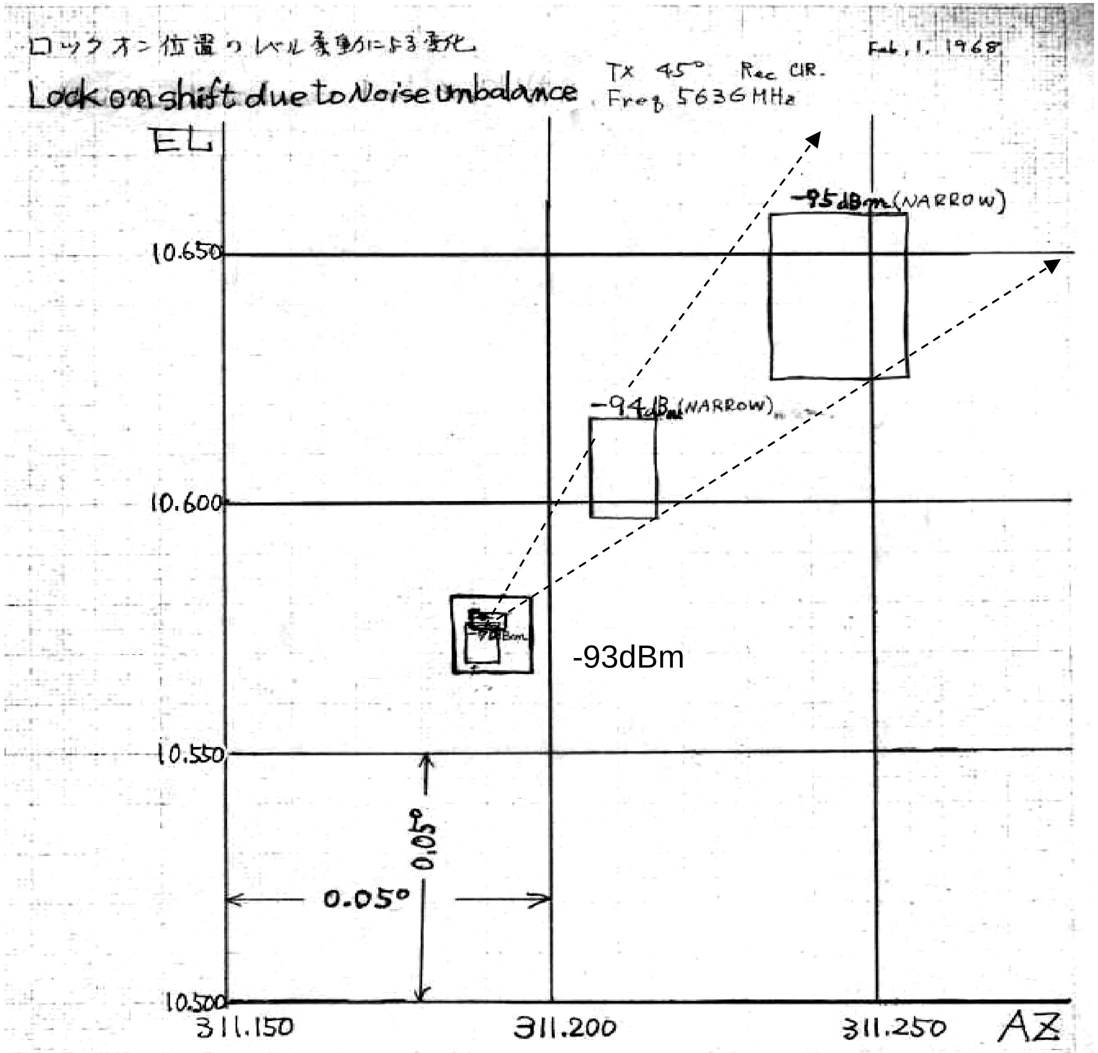


Conventional angle error detector



Noise unbalance cancelled angle error detector

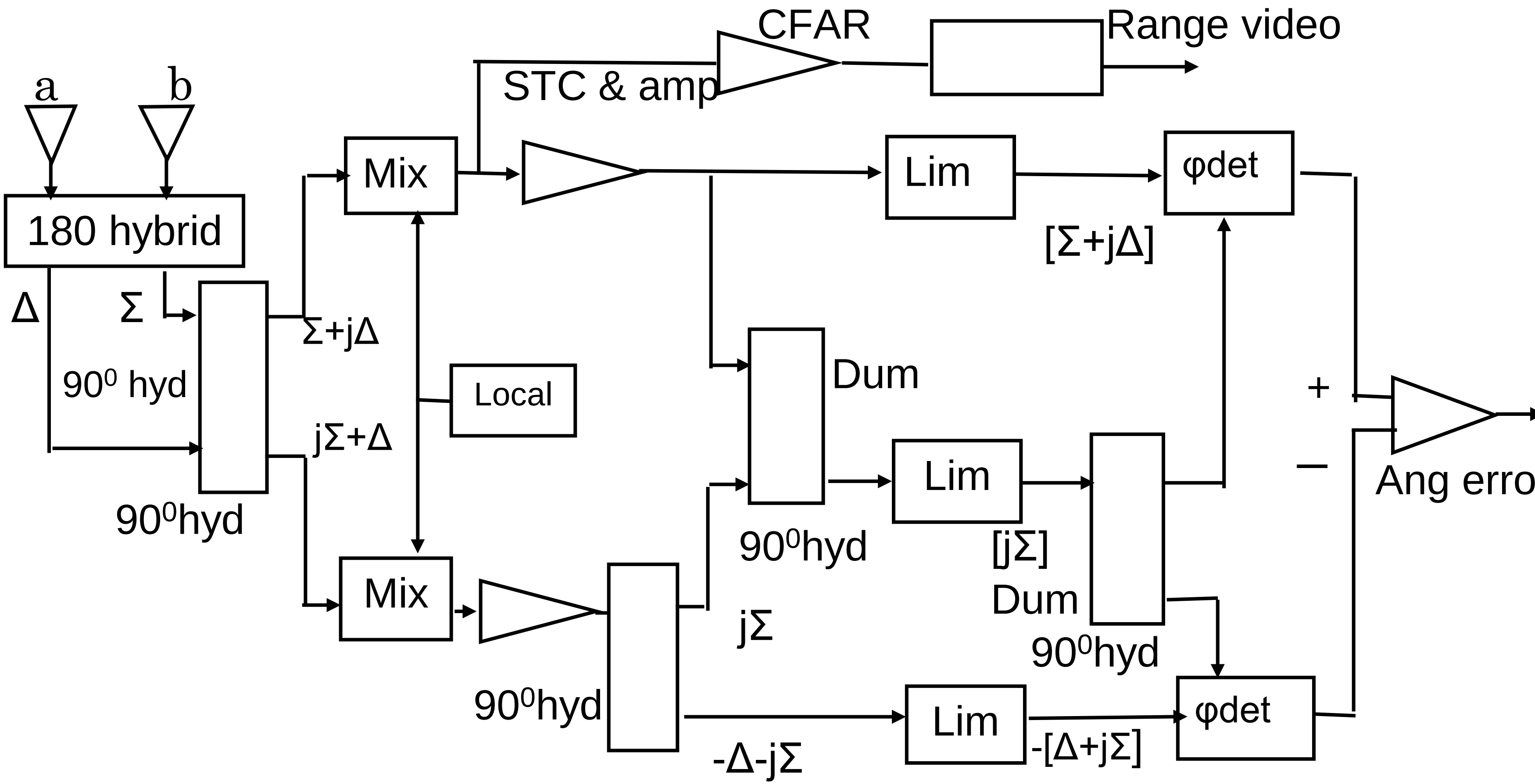
Error voltage due to noise product can be cancelled to zero.



Real example of lock-on position shift at low S/N
(Without noise cancellation).

True Monopulse Angle Sensing Receiver

Fast AGC is required, but difficult by loop design.



Vector addition, limiting and phase detection can derive normalized angle error along wide dynamic range by every pulse.

The system can be applicable tracking radar & many other systems.

To supplement 4pages

Advanced design of monopulse antenna

1. Focus on advance of monopulse feed.
2. Optimum design is done by sophisticated phased array
3. Concept of a fine monopulse feed
4. Dipole array feed (with some weakens)
5. 4 horn for Cassegrain reflector (with some weakens)
6. Some historical view of monopulse feeds
7. A fine example AZ only, equivalent to 5 horn
8. Multimode feed horn & X,Y monopulse beam scanning

Advanced design of monopulse antenna

1. Σ beam efficiency ~70% & low sidelobes
2. Δ beam high sensitivity & less sidelobes
3. Required horn aperture, $\Sigma < \Delta AZ$ or ΔEL

   How to overcome this contradictive themes

<u>Phased Array is one solution</u>

Σ & Δ distribution by independent optimum over aperture, but complicated circuits, and is so costly.

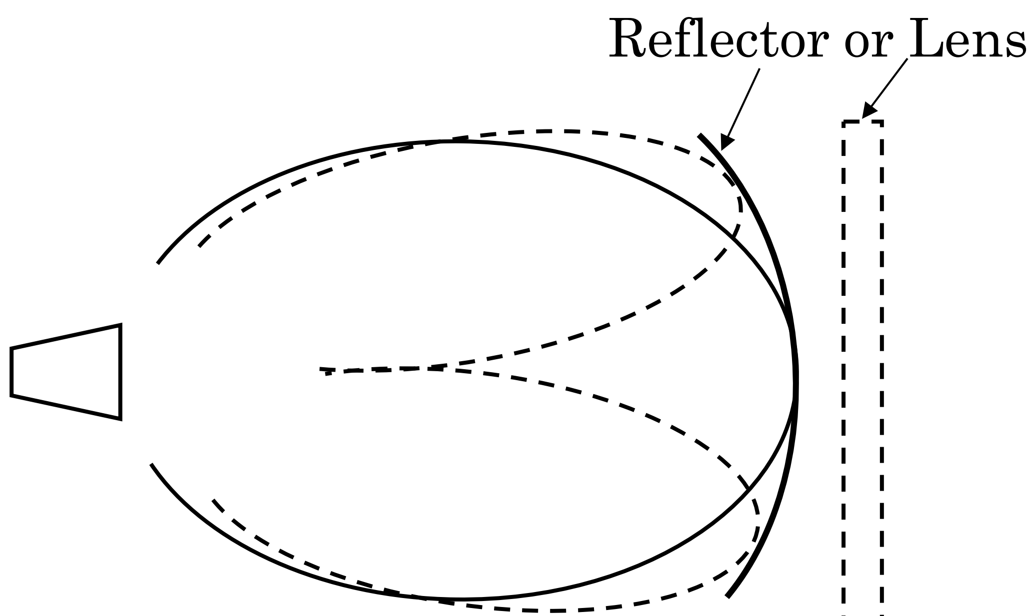
<u>Multimode horn is another solution.</u>

An advanced feed horn for reflector or lens.

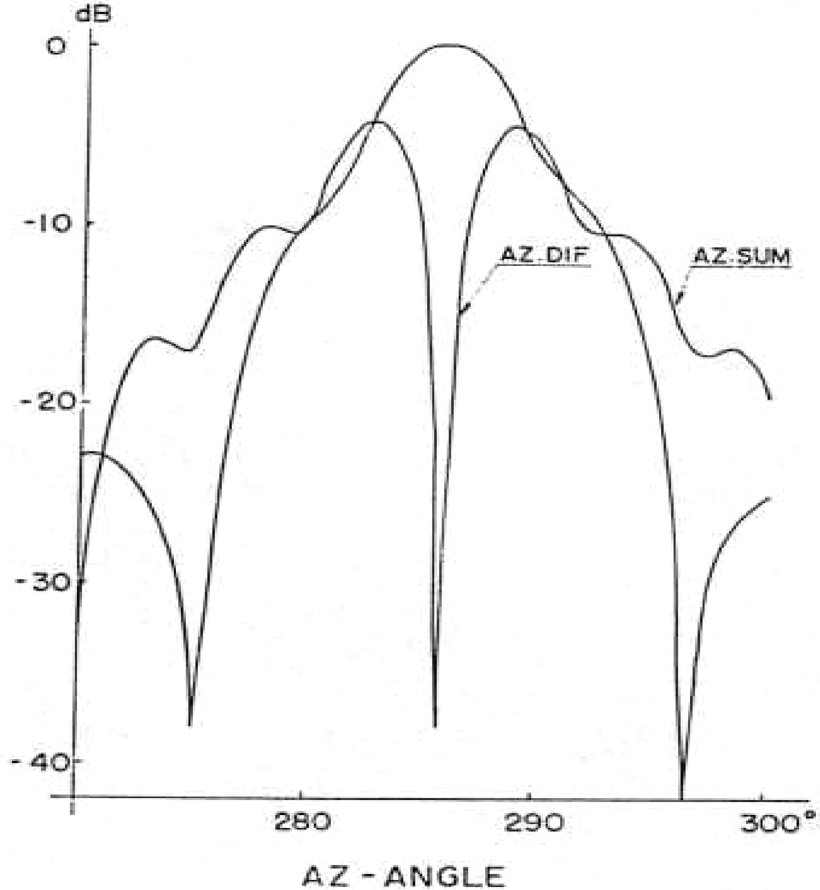
Artful dominant & higher modes combination

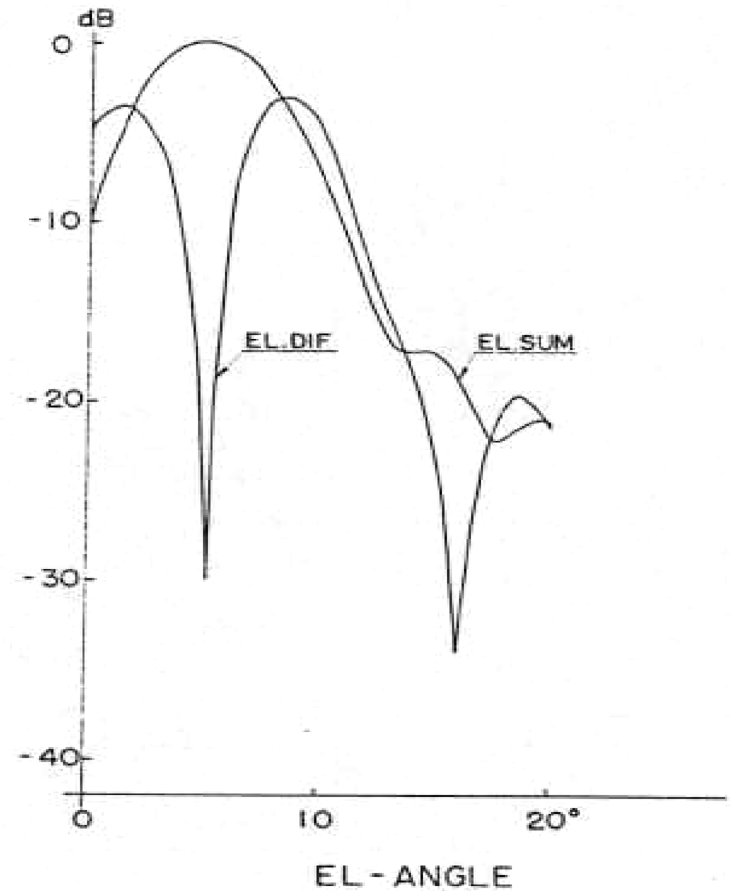
- Smaller horn aperture for Σ
- Larger horn aperture for Δ

by single horn



Concept of a fine illumination of Σ&Δ



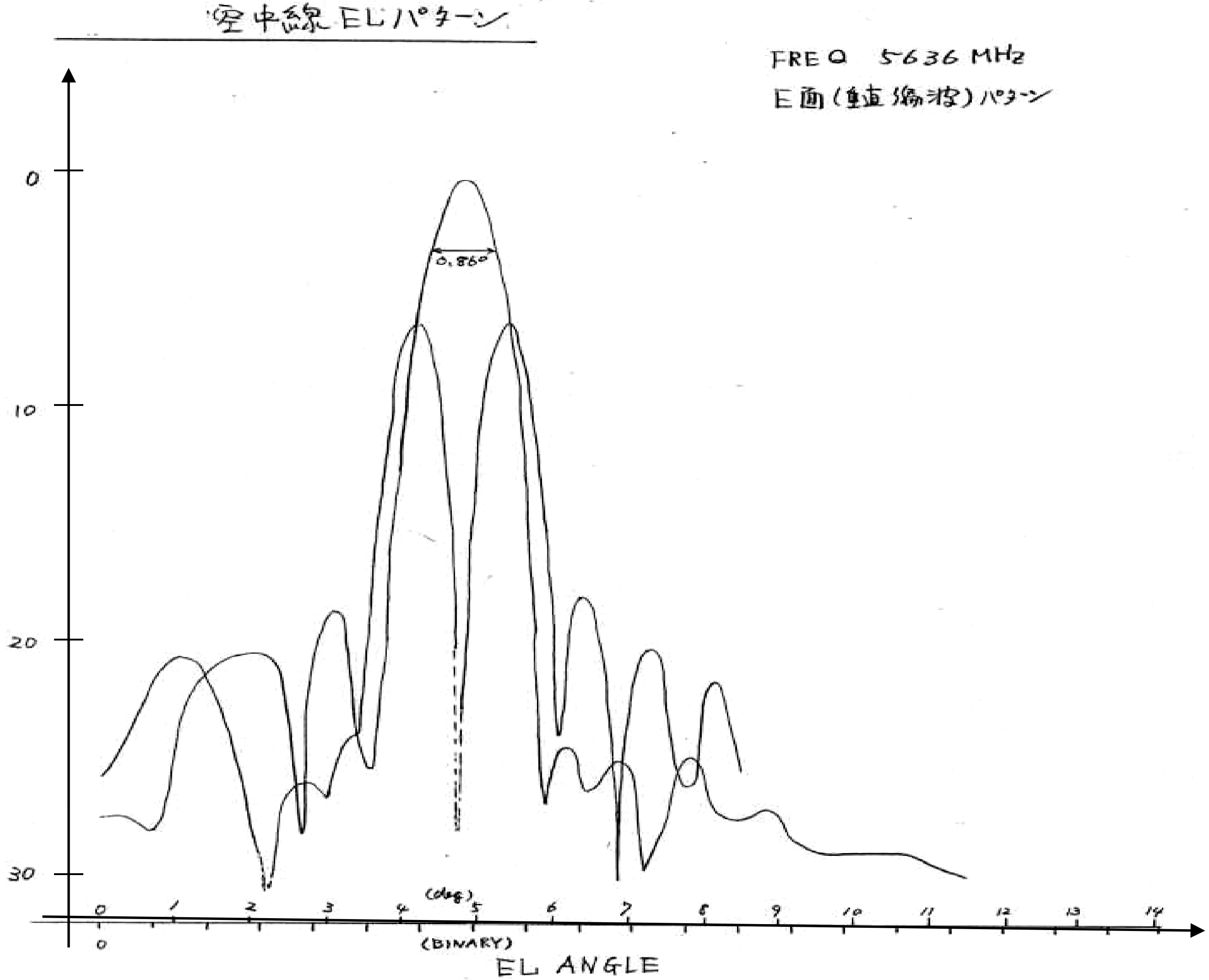


4 vertical dipoles feed for parabola reflector at 30mφdish

Difficulty of beam shaping of dipole makes high sidelobe on AZ.

(Over off focus dipoles position due to Cassegrain sub reflector 1963)

To supplement 10pages



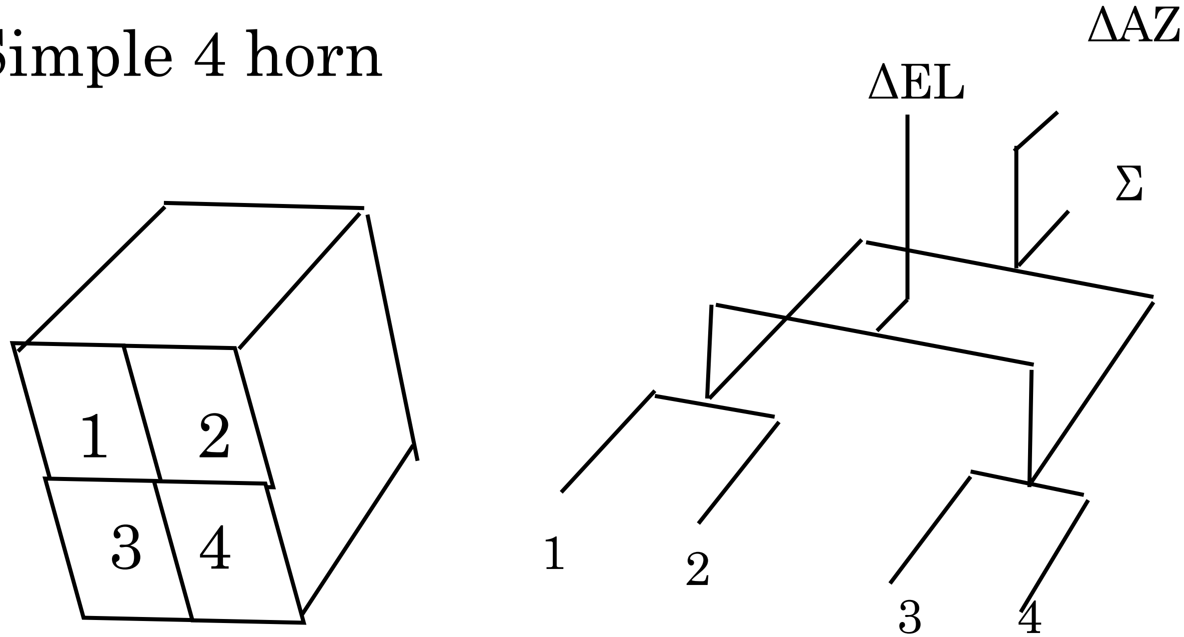
Example of 4 horns monopulse pattern

(Σ is fine, but Δ beam is not so high,)

(Difficulty of Cassegrain feed for 4mφdish)

Monopulse feed horns before multimode horn

1) Simple 4 horn

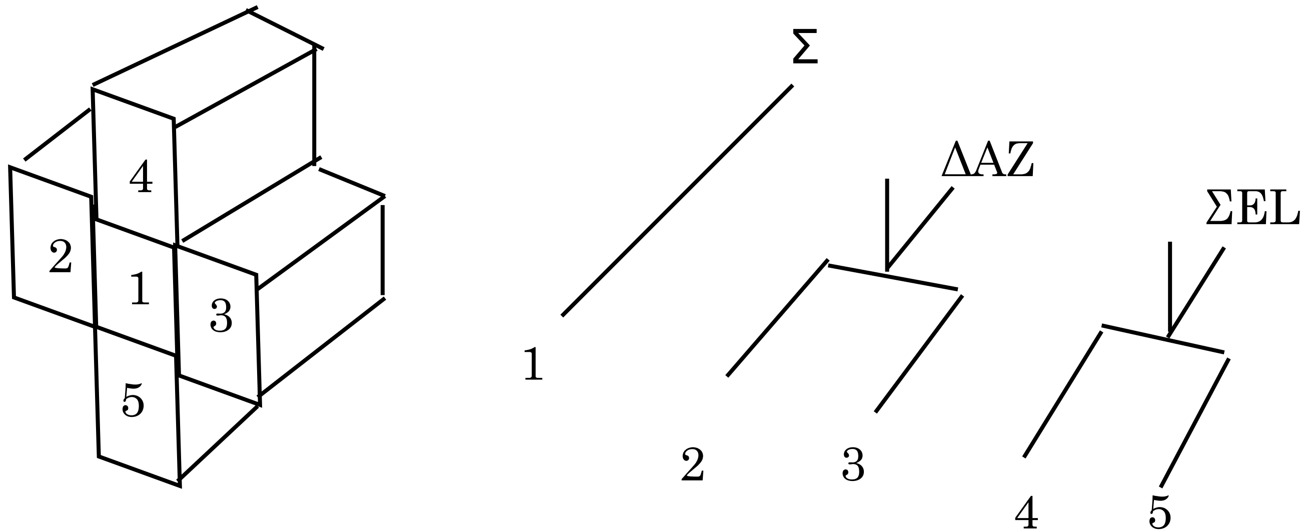


1) Σ, Δ optimum for both could not be obtained.

2) If Σ optimum, more wide aperture is needed for Δ.

3) E field and H field optimum could not be obtained

5 Horn technique,   4 up to 12 horns

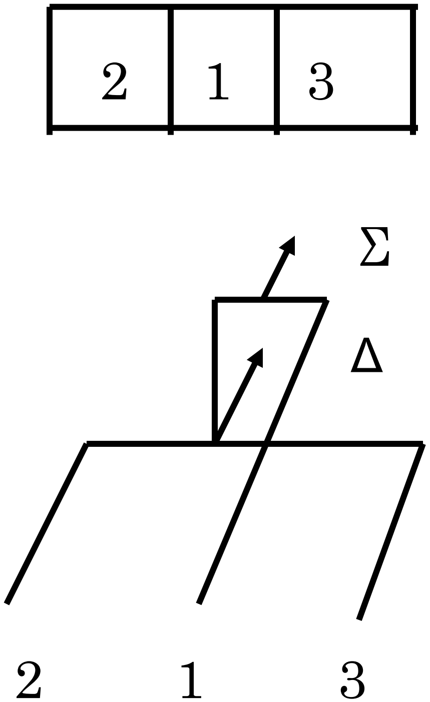


1) Simple configuration

2) Horn size can be adjusted by dielectric material.

3) Optimum of Σ and Δ can nearly be expected.

4) Relatively simple, V, H, & circular polarization may be relatively easily available.



3horn optimum AZ feed horn

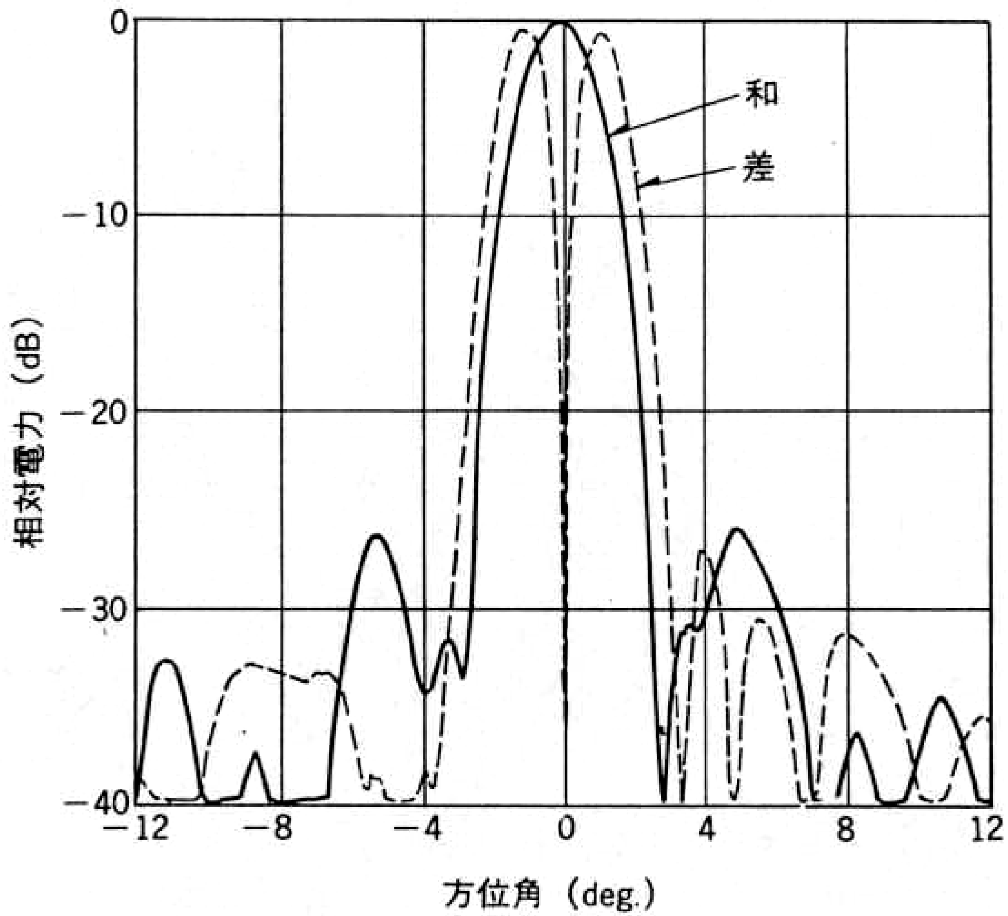
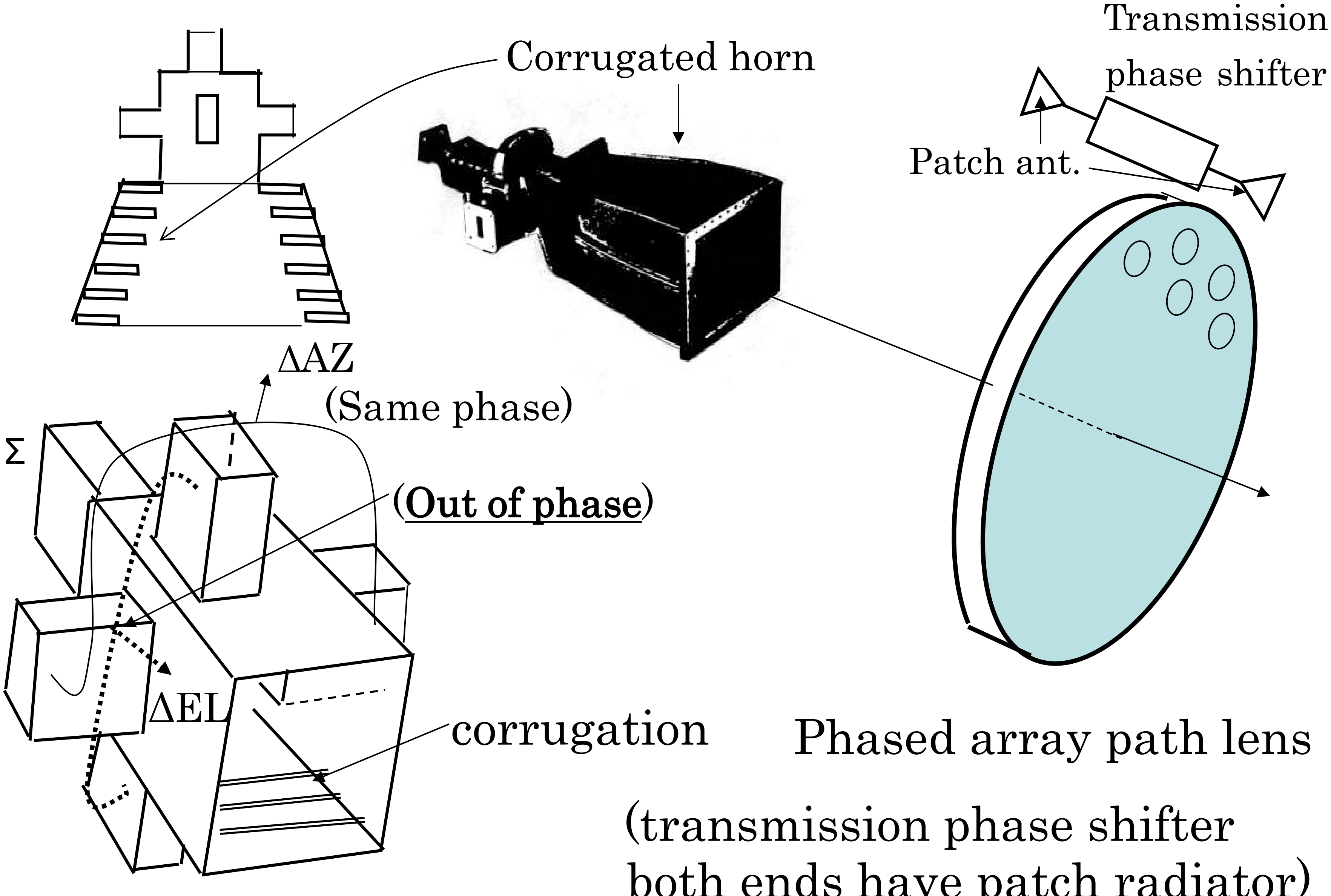


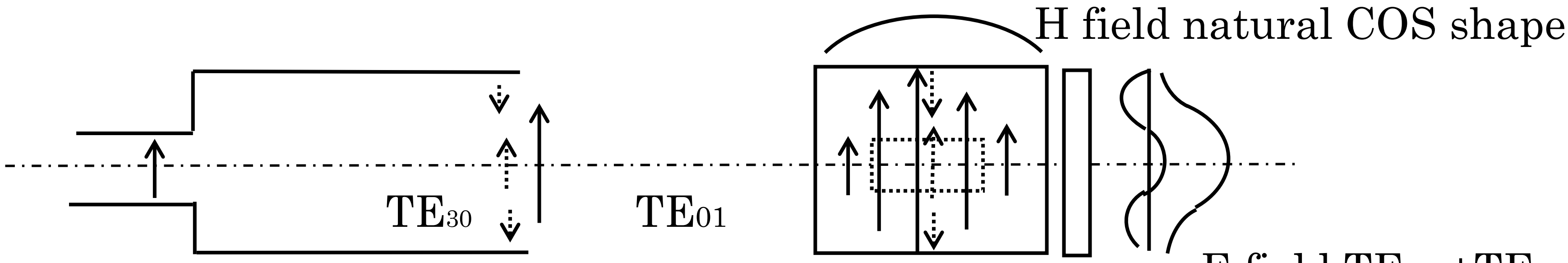
図４　実測 SSR 水平パターン
Fig. 4　Measured SSR azimuth pattern.

- Fine Σ beam, by optimum amplitude combination of 3horns.
  Horn size can be adjusted by permittivity material.
- Low sidelobe Δ beam by near optimum separation and high gain to Σ.

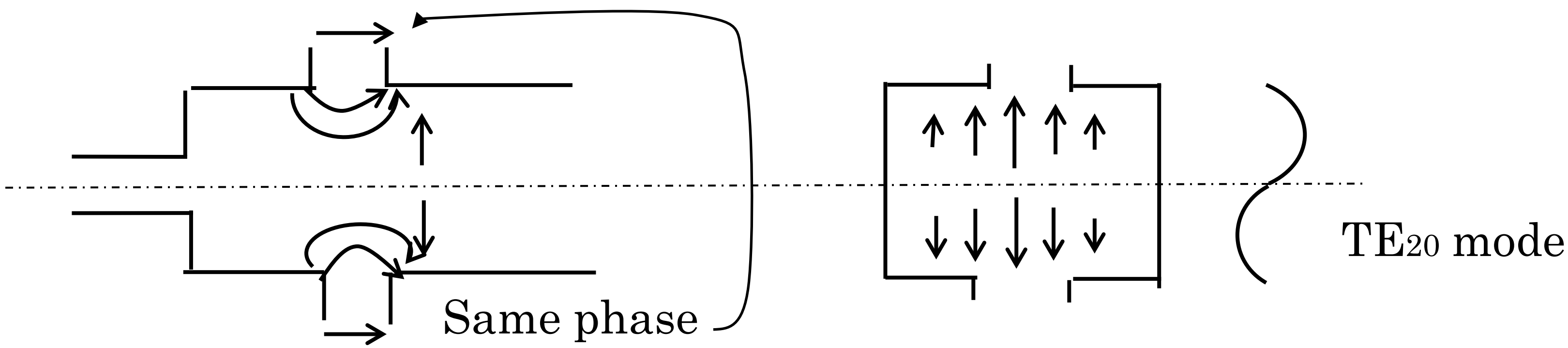
Supplement 2 pages



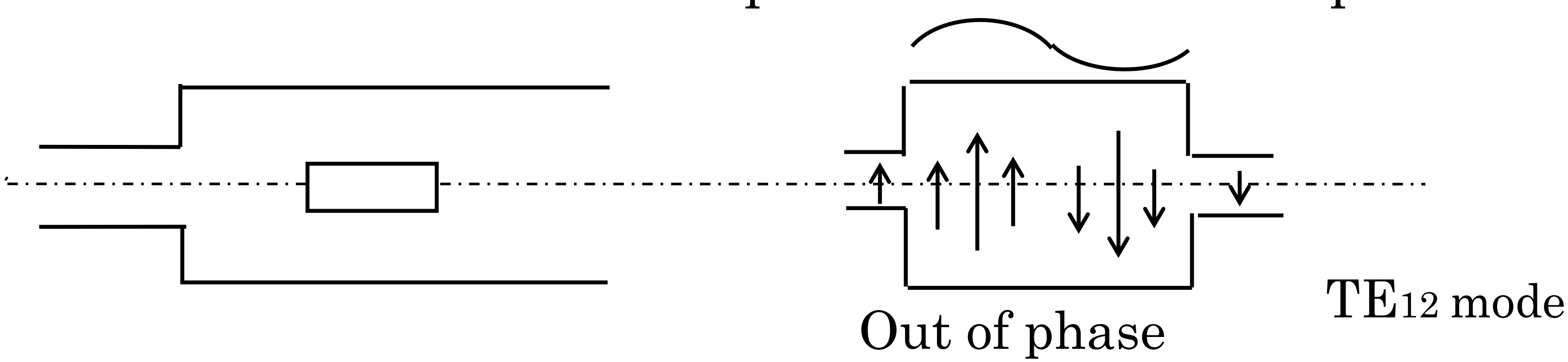
Advanced higher modes primary feed & phased lens



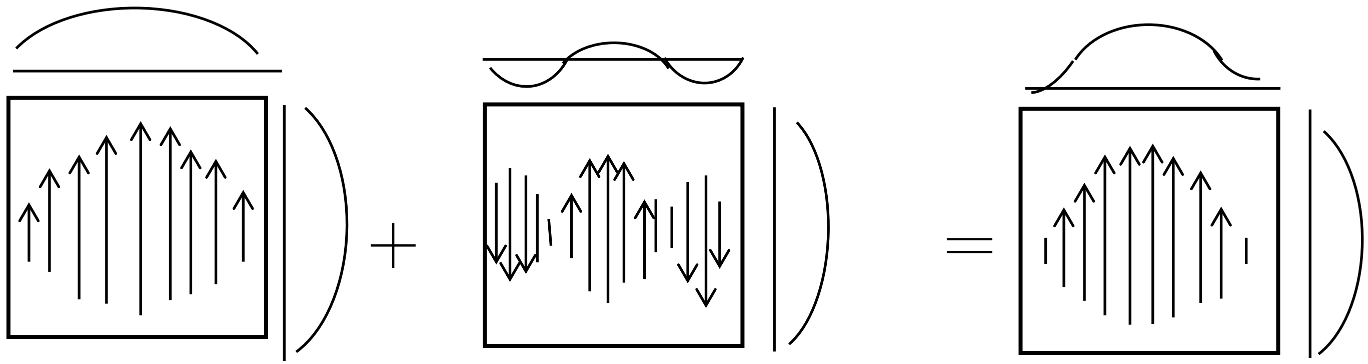
Basic concept of Σ pattern



Basic concept of multimode Δ EL pattern

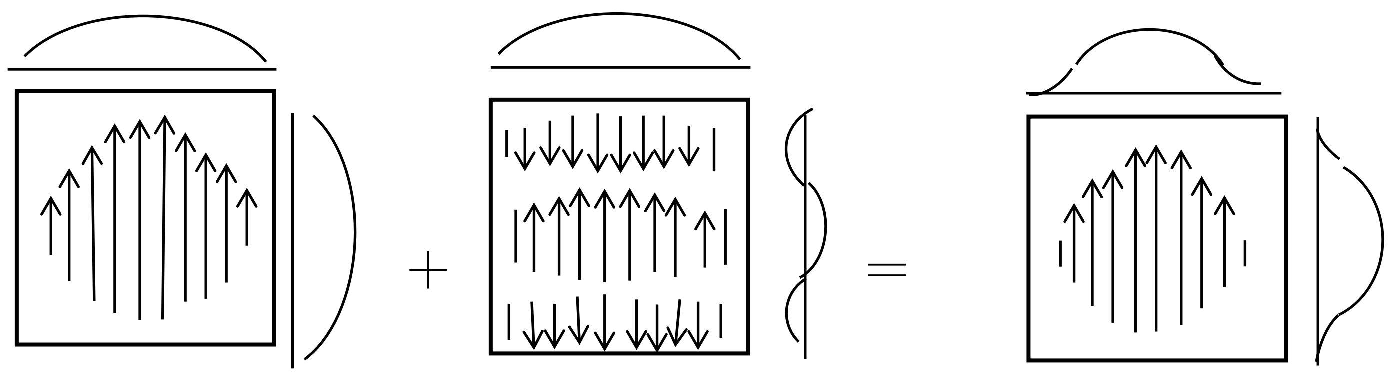


Basic concept of multimode ΔAZ pattern



TEY_{11} TEY_{13} $TEY_{11}+TEY_{13}$

Σ Azimuth, mode combination

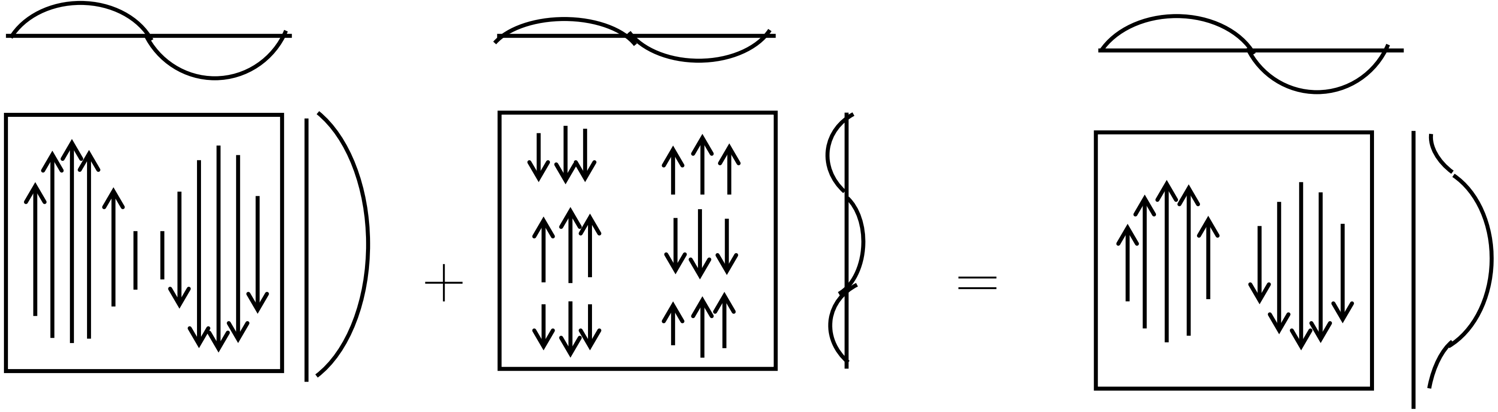


TEY_{11} TEY_{31} $TEY_{11}+TEY_{31}$

Σ Elevation, mode combination

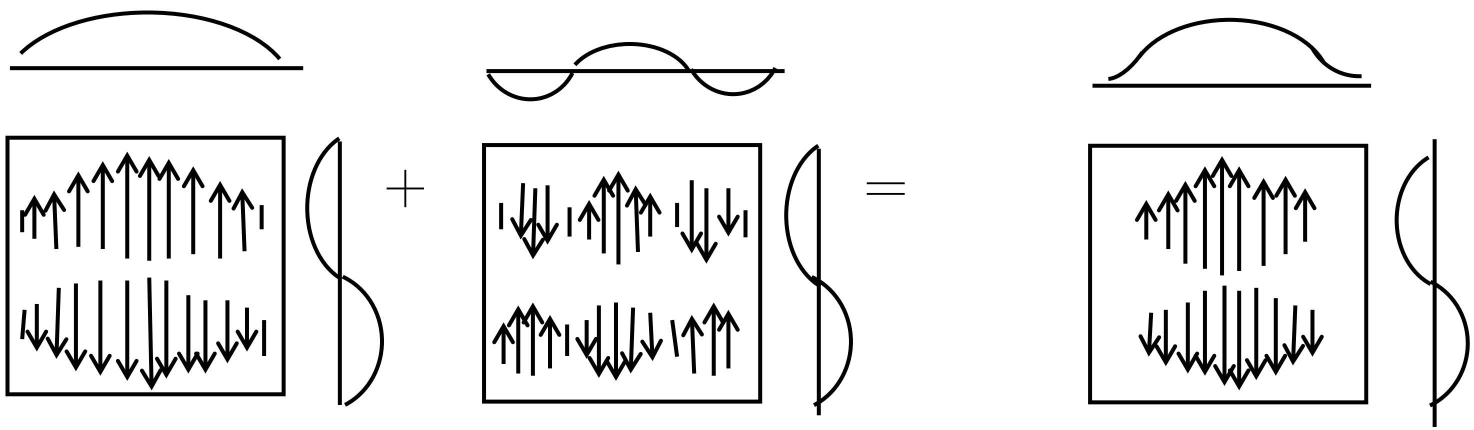
Higher modes monopulse feed, Σ field distribution

Mode designation is changed due to in the corrugated horn.



TEY_{12} TEY_{32} $TEY_{12} + TEY_{32}$

Δ AZ, mode combination



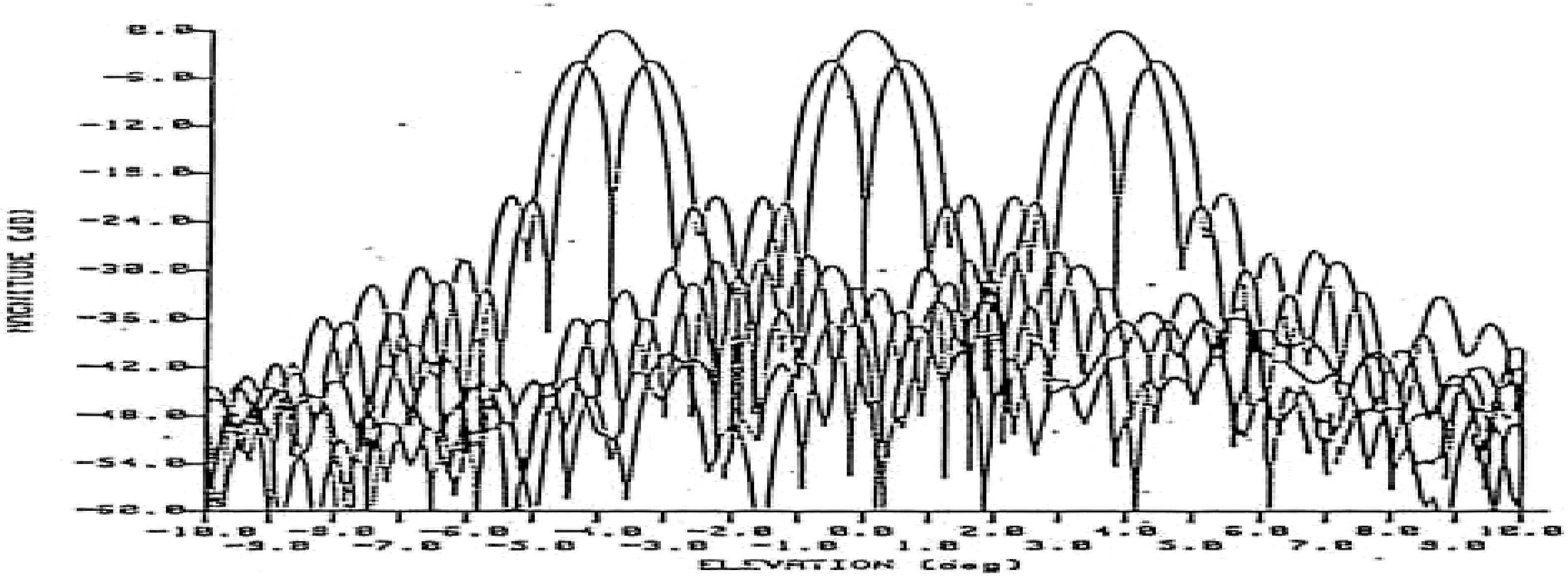
TEY_{21} TEY_{23} $TEY_{21} + TEY_{23}$

Δ EL, mode combination

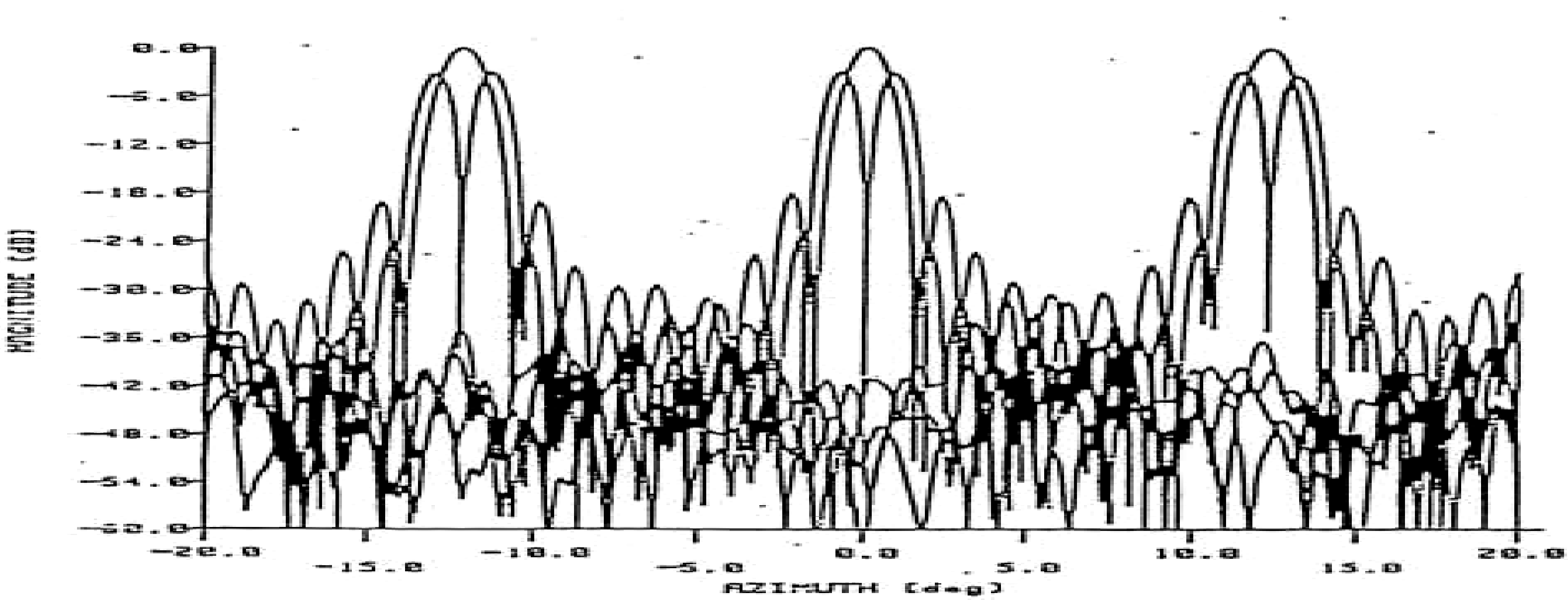
Higher modes monopulse feed, Δ field distribution

Mode designation is changed at corrugated horn

ANTENNA VERTICAL PATTERN



ANTENNA HORIZONTAL PATTERN



Angle tracking servo mechanism / angle tracking loop

- Ant. construction & mechanism is another large issue
- If X, Y mount is applied,

AZ speed will be so high at high EL angle, sensitivity goes down *cosθ*, compensation by **secθ** should be provided,

AZ mechanism has always a heavy, has mechanical resonance.

Frequency is key issue to expand servo band. $\beta_n / f_{r \cdot mech} \leq 1/10$

Limit cycle motion due to backrush & friction will be common difficulty.

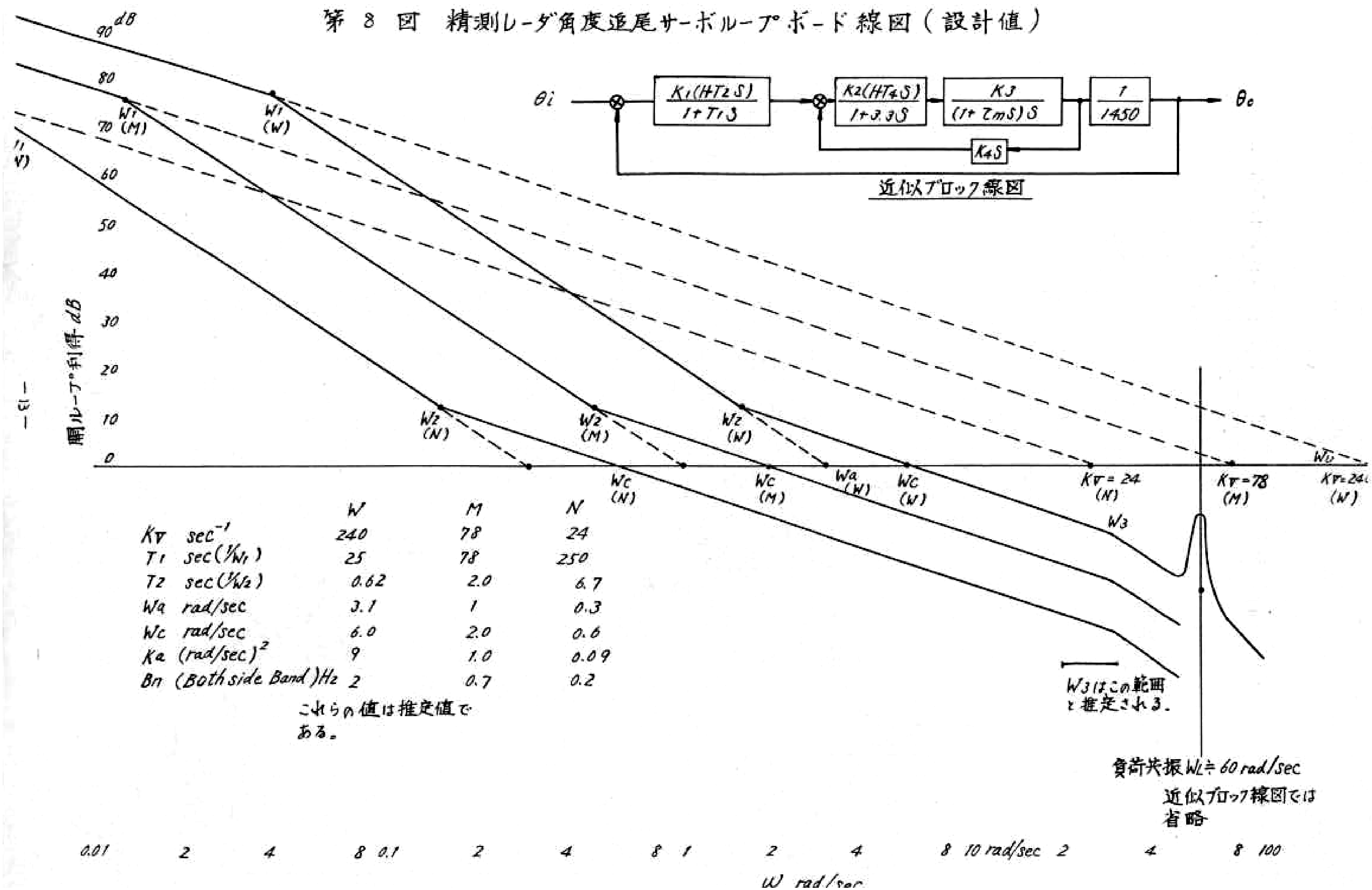
Many efforts have been done such as dual drive with offset torque, direct drive “torquer” motor and/or intensive nonlinear circuit.

- Selection, servo bandwidth according to target motion

Speed lag, Acceleration lag, Noisy fluctuation

$\beta_n = 2 \sim 6\text{Hz}$ will be typical noise bandwidth 4m class antenna.

Optimization, bandwidth, lag compensation by data processing.

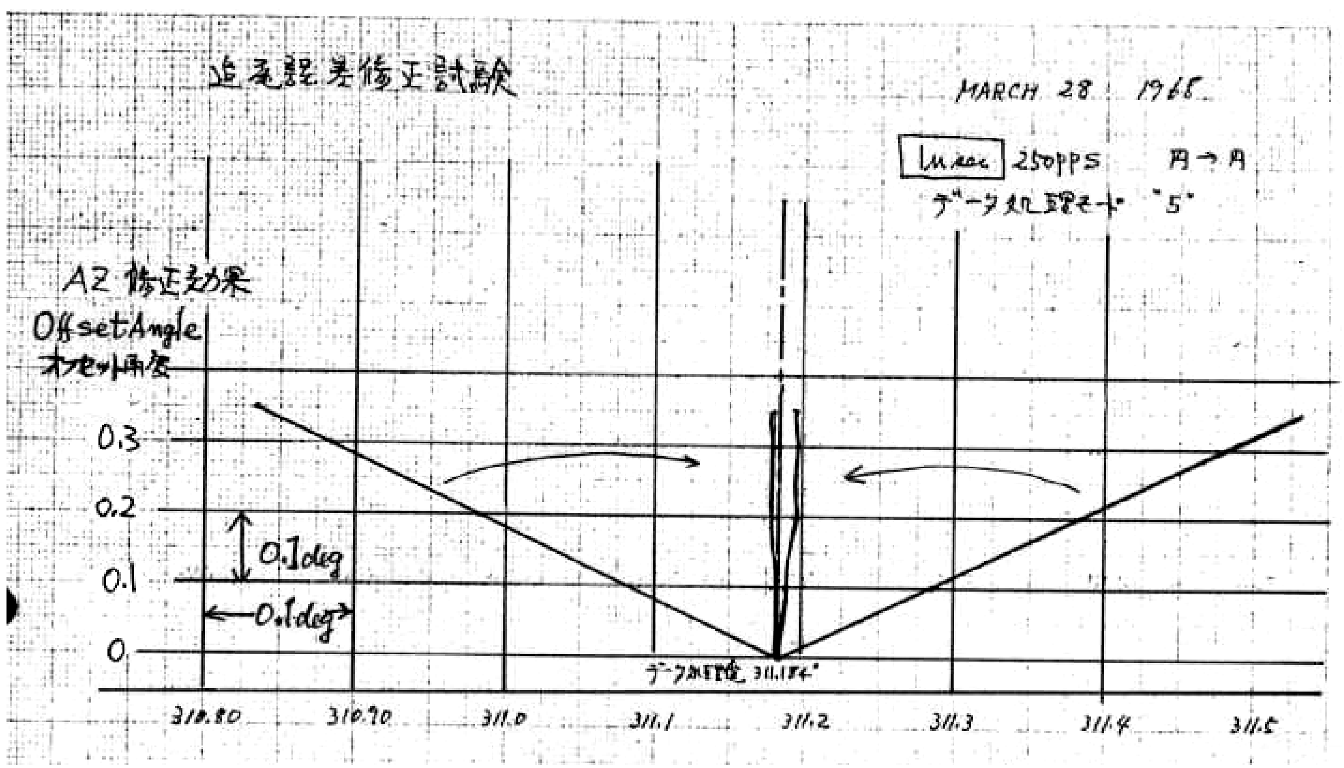


Real Bode diagram of an angle tracking servo loop AZ, EL

Servo droop error and it’s compensation

Servo droop error

- At constant speed, Angle droop = 1／Kv
  Example, 5deg/s, Kv = 250／s, angle droop = 5/250 = 0.02deg
- For acceleration, similar to 1／Ka/s^2, Ka= 9, 0.5deg/s^2/ 9 = 0.05deg
  Selection of servo bandwidth is important to get total error minimum including noise fluctuation.
- If error curve is smooth, angle droop error can be compensated by data processing. An example data is as follows.



Various error source

ー Primary radar mode

•Amplitude noise, monopulse is much better than conical scan

•Glint---most reflection point is always moving over target,
TRK radar tracks a kind of "reflection center of gravity".

ー Beacon mode (with transponder)

•Some periodic signal fading and also polarization change, caused according to platform motion, such as vehicle spinning.

•Quick and faithful AGC is preferable. However -----

Combination of rotating linear polarization & TRK linear polarization antenna with a large cross coupling causes unexpected large error.

(Under polarization mismatch, signal level goes down, but, AGC recovers detection level, The other hand unqualified angle sensing pattern causes large error. If precise circular polarization is applied, only –3dB down and qualified angle pattern does not cause large error.)

•Precise circular polarization with qualified small error is preferable.

•Stable, far range tracking is expected. At some case, exhaust gas----.

Propagation Error
Tropospheric refraction
- Refraction along elevation angle and slant range. (same to K-fading)
- Predictable component can be compensated by data processing.

Refractivity N of air at earth surface, (refraction index n)

$$N = (n-1)\times 10^{-6} = \frac{77.6\cdot p}{T} + \frac{3.73\cdot 10^{5} e}{T^{2}}$$

T: temperature of air ^{0}Kelvin , p : air pressure, [hecto Pascal]

e: partial pressure of water vapor, [hecto Pascal]

Typical number is N=0.000313=313ppm

Two decades change from Clear dry air to Heavy cumulus

Example, El =3deg, (0.006deg, up to 0.6deg)

N reduces significantly with height, so propagation path is bending as like as nominal 4/3 radius of the earth.

Proper correction program is usually provided to reduce elevation angle error and also range error. But a large change due to weather

So no satellite launching may be done under storm weather.

Ionospheric refraction

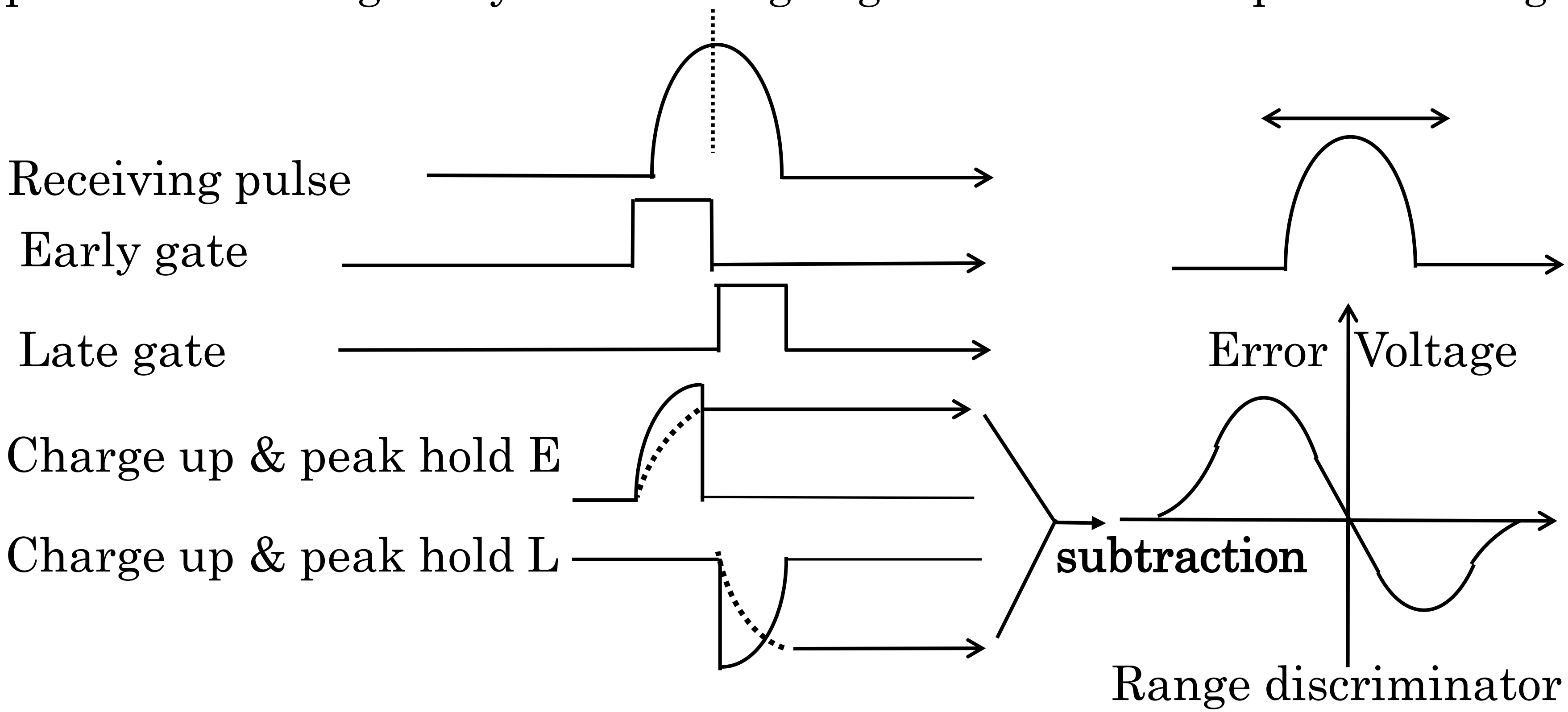
- L to C band, almost half.--- $\propto 1/\sqrt{f}$

Range Tracking

1. Traditionally, instrument mechanical servo using a key phase shift device of high frequency resolver / goniometer had been applied.
2. Assume 10m accuracy over 3000km, which is order of 3×10^{-6}!!
3. There are so many error factors, light velocity definition, hardware related factors to target related and propagation error. as same as angle part.
4. Digital, inertia less tracking loop
   - According to digital device progress, digital loop has been attempted.
   - As 1m means 0.0067ns, some interpolation technique such as tapped delay lines are used in the beginning of digital tracker.
   - Now enough speed digital devices are fully available with GHz clock.
5. In this section, following sub items are described.
   - An example of precise range tracker up to 8000km by 1m LSD.
   - A method of High PRF non ambiguous with finding true range.
   - A sample of digital tracking loop

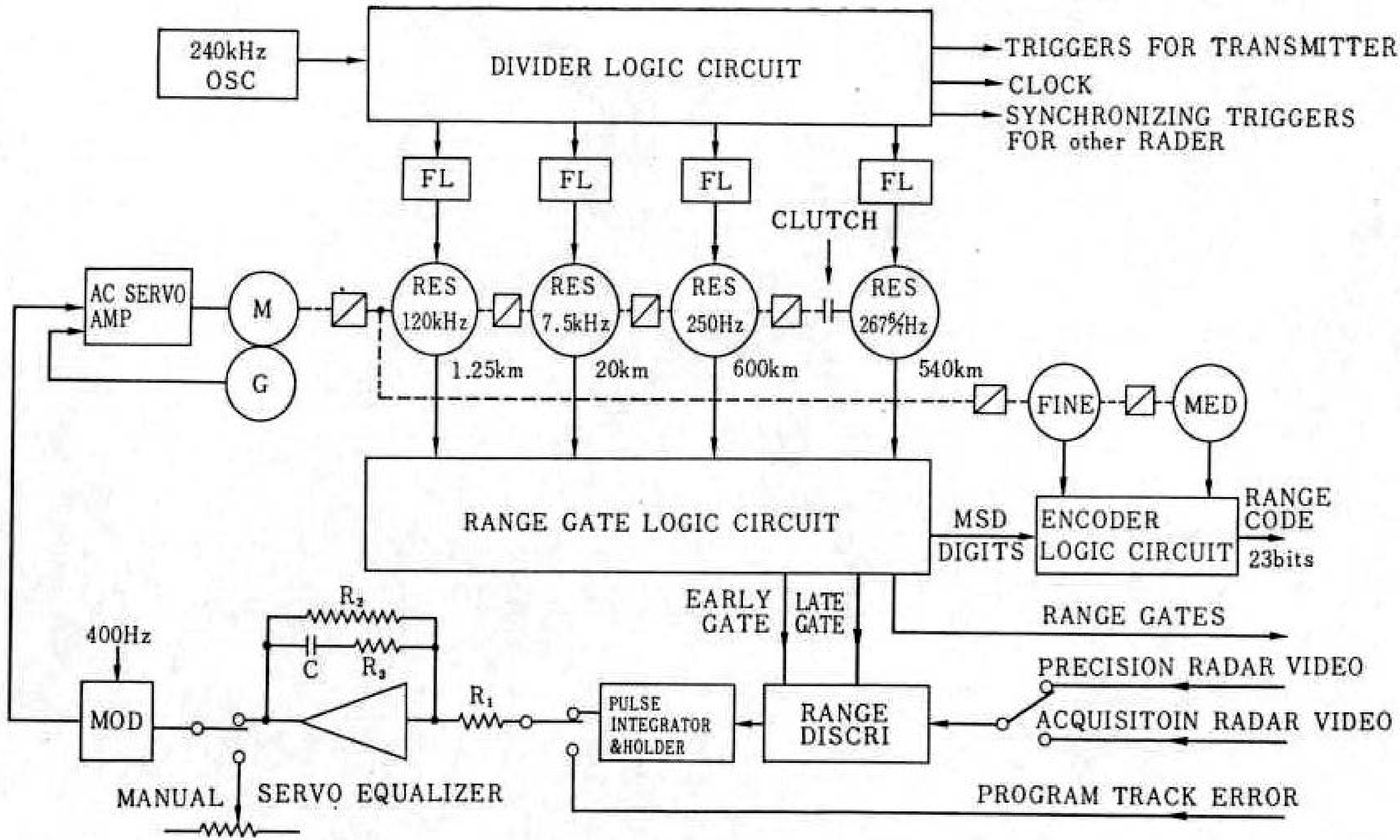
Range sensing

Basic circuit for range discrimination is early & late gate lock on receiving pulse, which is a kind of phase discriminator, to generally get pulse center of "gravity" not leading edge. This is a monopulse sensing.



Charge up is done by CR integration circuit over a half pulse width and subtracted, and voltage is kept to just before next pulse

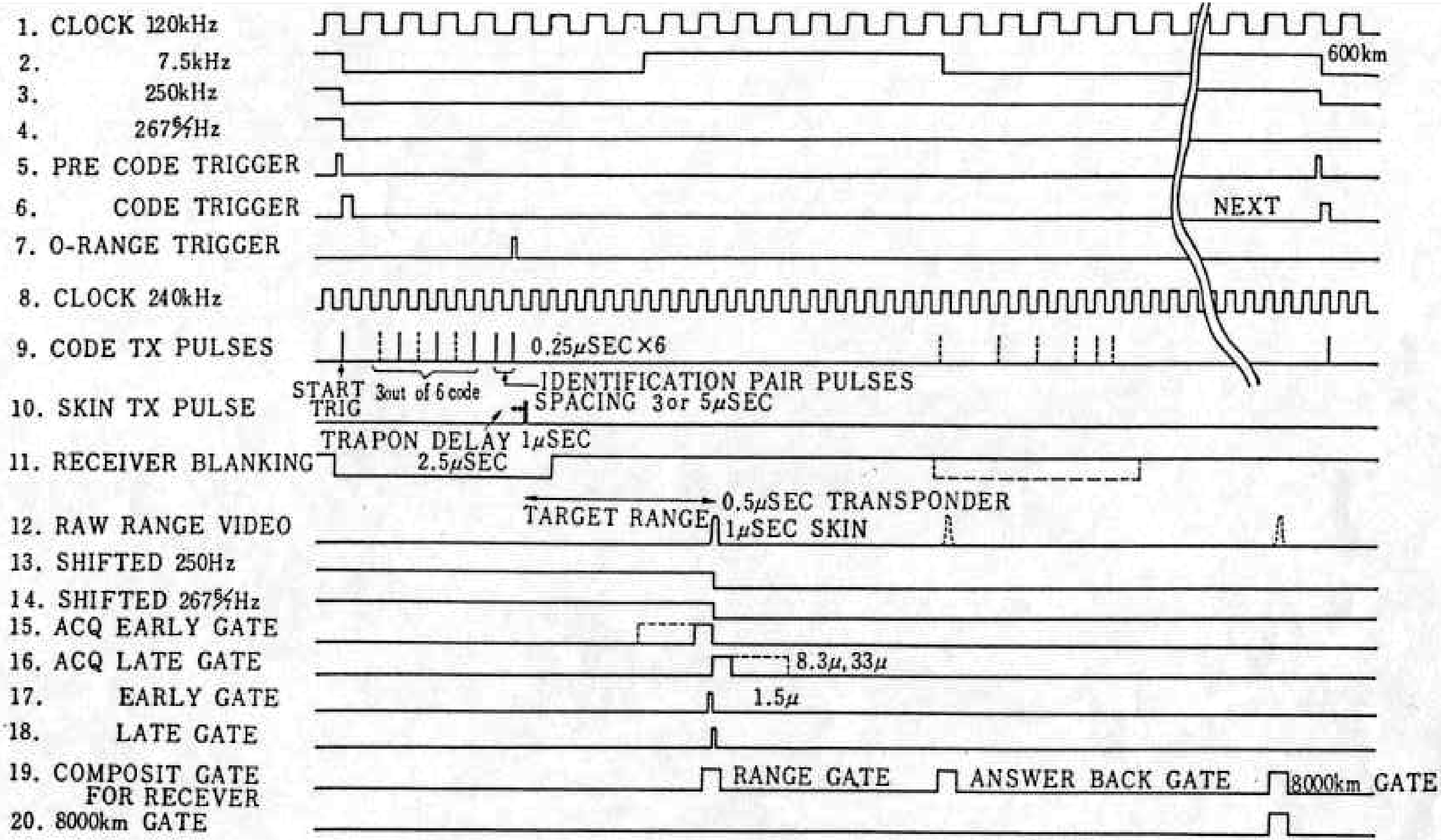
Schematic of Early & Late gates pulse range discrimination



第1図 測距装置系統図

Fig. 1 Blockdiagram of the range tracker.

Block diagram of 8000km analog servo range tracker



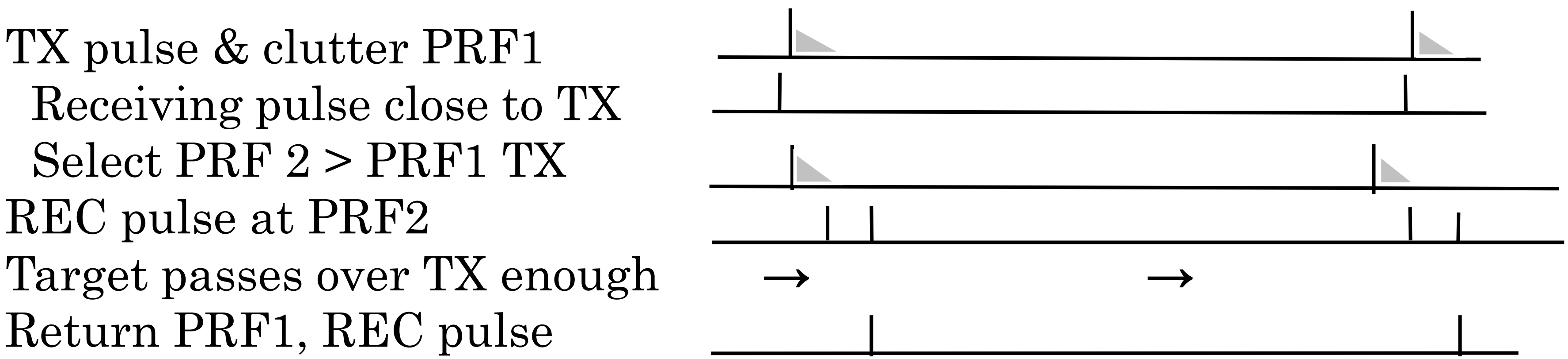
第２図　測距装置タイミングチャート

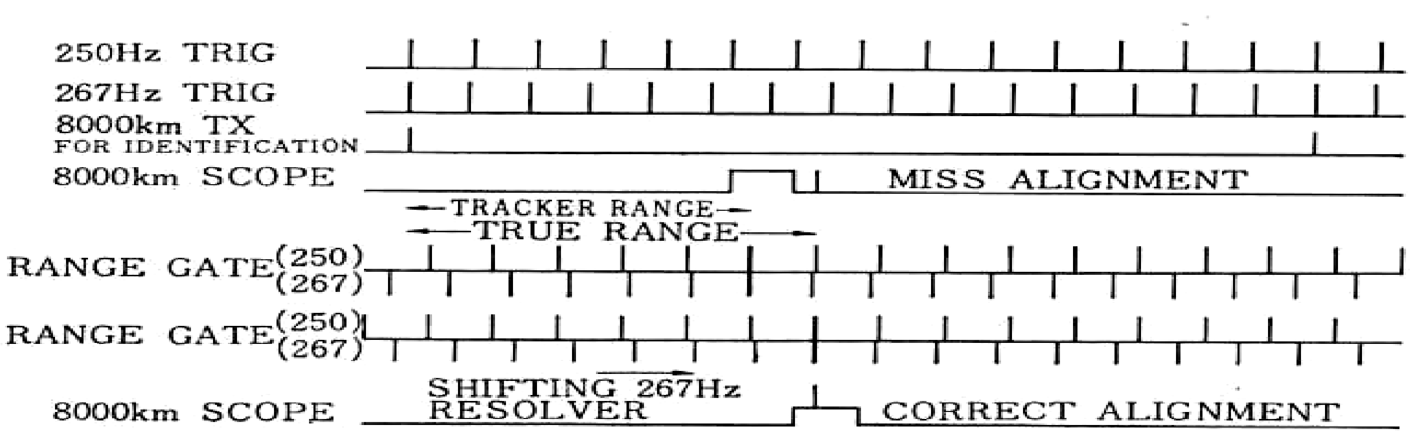
Fig. 2 Timing chart of the range tracker.

Timing chart of 8000km seamless tracker using two PRF

Unambiguous tracking method using two PRF

- High PRF is preferable for quick track &reduces noisy fluctuation.
- Low PRF is needed to get unambiguous range finding.





第３図　PRE 区間の判定法

Fig. 3　Discrimination of range ambiguity.

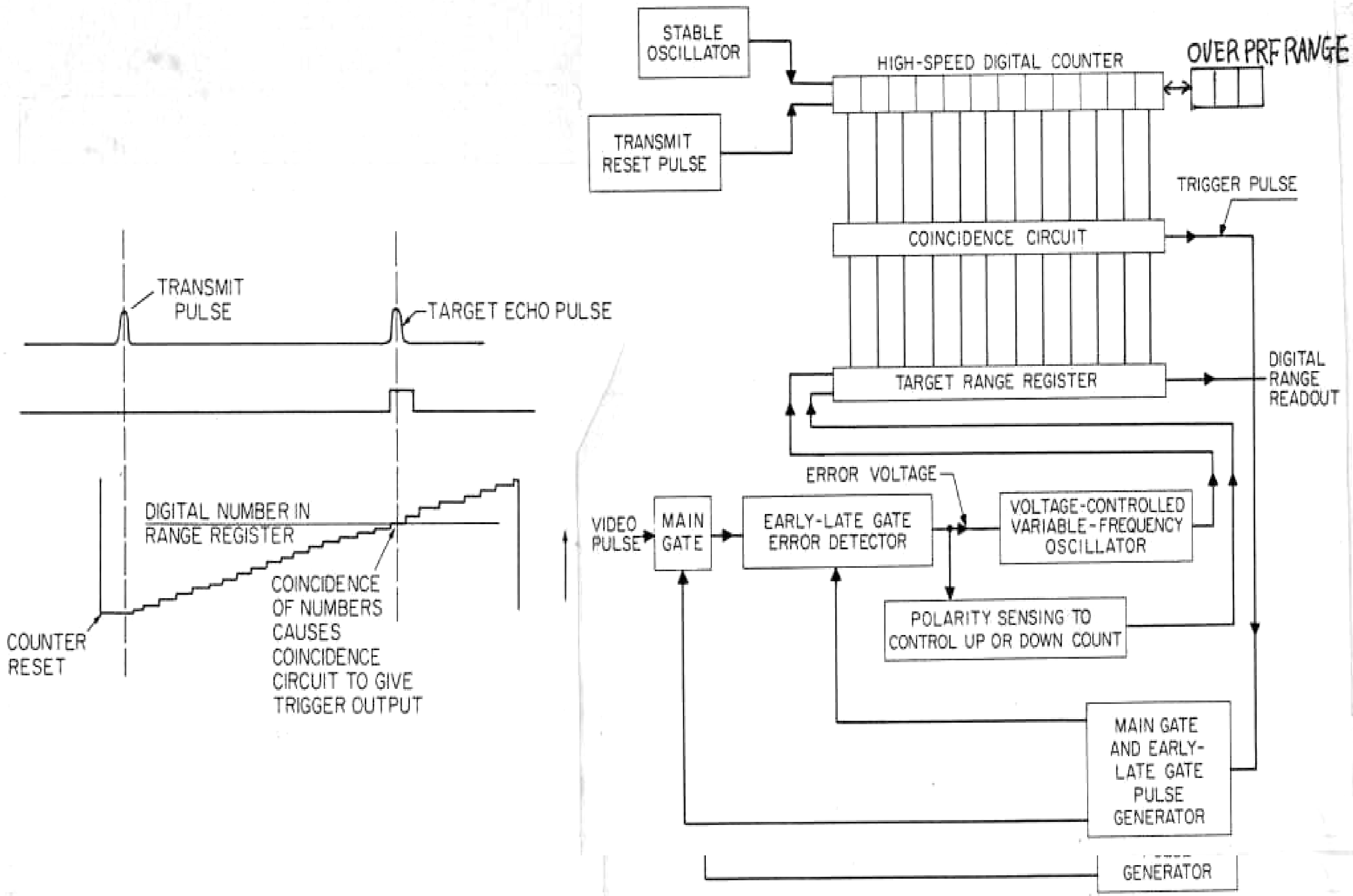
Discrimination of ambiguity over multi PRF range

Digital range tracker

1. Major advantages of digital loop
    - No inertia, expecting quick response.
    - Instant setting at any range.
    - Servo band width can be expanded up to theoretical limit

2. Applying digital counter
    - Digital counter is a perfect integrator without self discharge or drift.
    - True second order loop without velocity lag can be designed.

3. Various uncertainty such as various analog circuits especially resolver error can be eliminated.

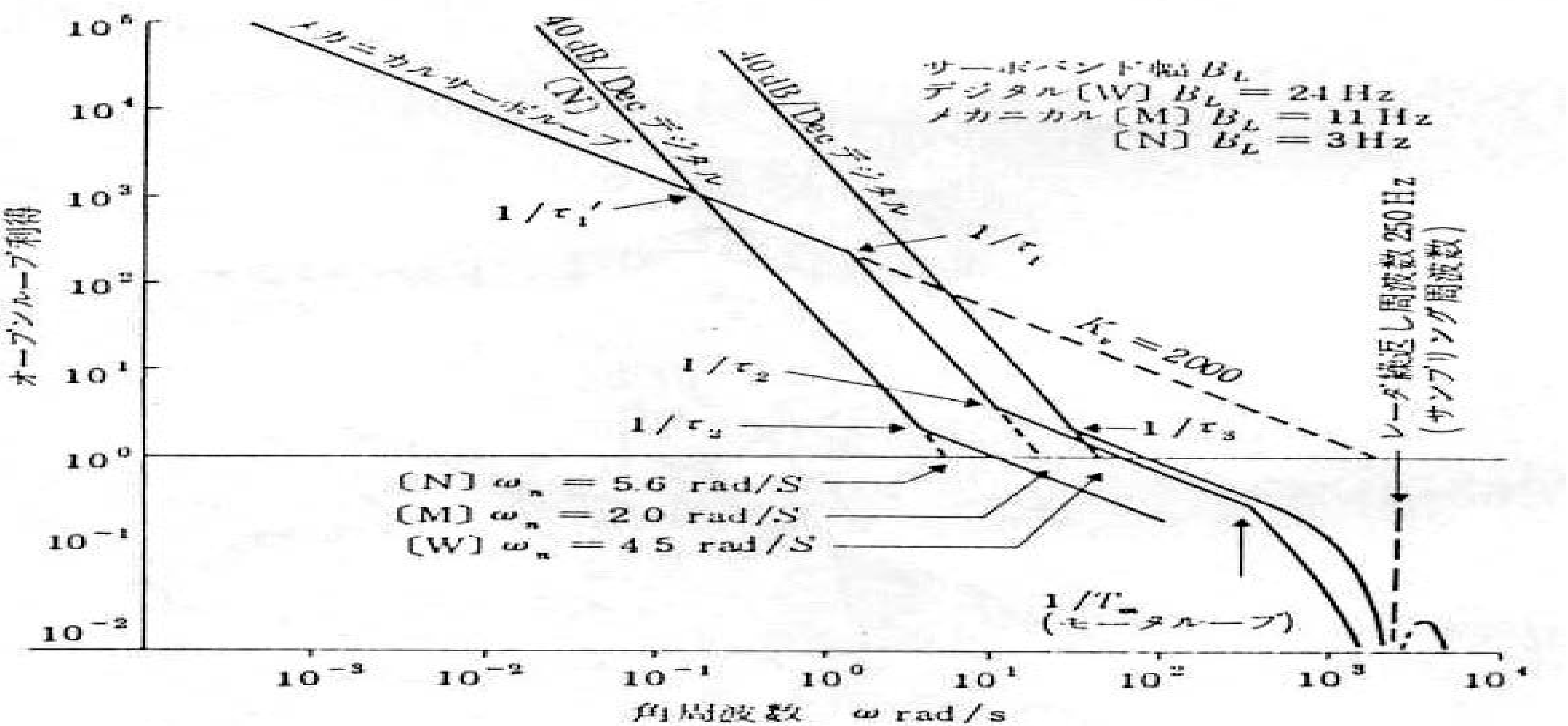


Digital range tracking concept & simplified schematic diagram

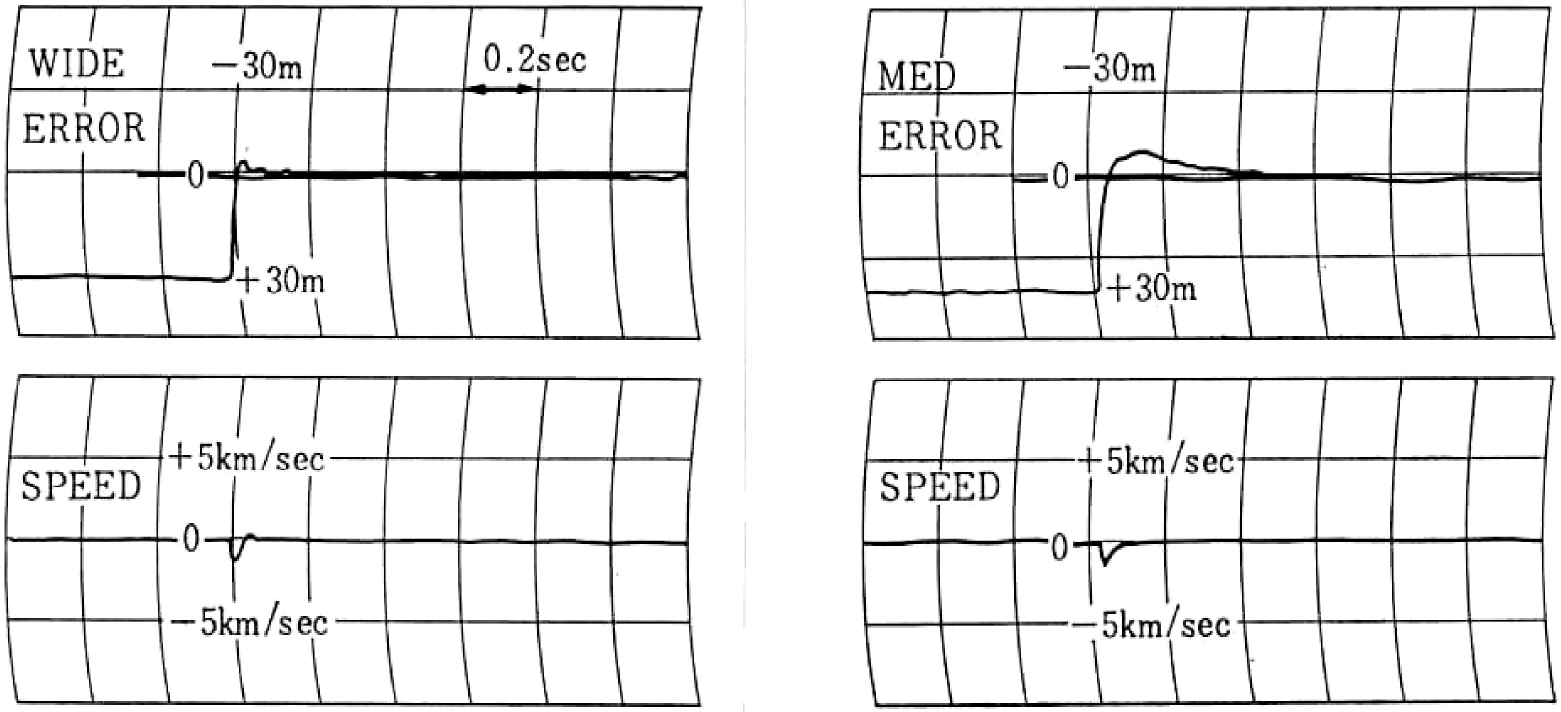
(I have experience, but materials is missing. This schematic is on HDBK.)

Achievable range servo loop band limit

- Instrument servo still has inertia, motor rate loop limitation.
- Digital servo has no inertia. Has no bandwidth limit?
- No, every loop shall be under sampling theory.
  1/10 *fr* will be limit.
- When set wide band, oscillatory and with much digital noise.



Range tracking Bode diagrams, analog & digital loop
(from my co-authored book)



第４図　測定装置ステップ応答

Fig. 4　Step responses of the range tracker.

Indecial response examples of range tracker

Equivalent or more quick and clear response at digital loop

Error Analysis and Inventory of Range Tracking

Similar to angle, there are so many error factors

Equation of noise fluctuation σ*rt*

$$\sigma_{rt} = \frac{150\tau}{\sqrt{k_r (S/N) f_r / \beta_n}} m$$

τ:Pulse width μs

kr：Range error coefficient, which will be up to 2.5 in the case of Bτ=1.4

S/N: Signal to Noise ratio

Example

τ=1μs, S/N=20dB=100, f_r=500Hz, β_n=10Hz

$$\sigma_{rt} = \frac{150 \cdot 1}{\sqrt{2.5 \cdot 100 \cdot 500 / 10}} = 1.34m$$

Periodical range error due to grand reflection multipath

$$\sigma_{rmt} = \frac{\rho \cdot h \sin \omega_E}{2\sqrt{2A_s}}$$

ρ: reflectivity of earth surface (some 0.1 to 1),
h : antenna height m
ω_E : angler velocity of elevation angle
A_S : D/U: power ratio of direct path & multipath signal level at skirt of Σ beam.

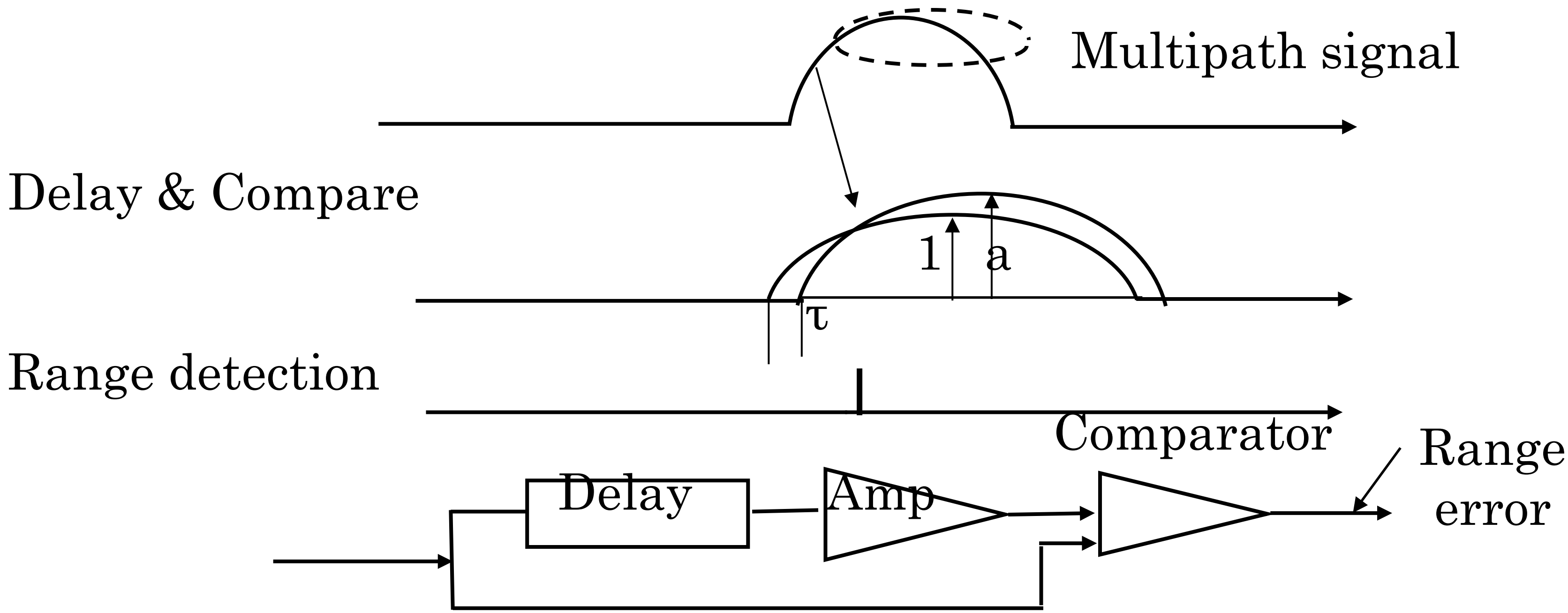
Frequency of periodical error due to grand reflection

$$f_{mrE} = \frac{2h \cdot \omega_{Et}}{\lambda}$$

h: Antenna height m
ω_{Et} : Target elevation angular velocity rad/s
λ: wave length m

Multipath error reduction by front edge detection

As multipath reflected wave is somewhat delayed, if range detection can be made before reflection wave comes, error will be reduced. Applicable condition is limited at short range however, because, a high signal level is needed.



Delay & Compare Circuit

It is a kind of self correlation and is independent to signal level change

System error budget / inventory

It is not so familiar term for engineers, but is important to every system designer. Typical process is as follows.

1) List up error sources and categorize (TRK radar angle part)
   - Radar dependent error
   - Radar dependent conversion error
   - Target dependent error
   - Propagation, environment dependent error
   - Instrumentation error for calibration

2) Estimate each error by bias and random component under set conditions.

3) Feed back to select key parameters such as antenna diameter or select another method or optimize to satisfy required performance.

4) Evaluation based on the list & conditions.

   Compare and investigate design and achieved value.

Example of a real error budget and achieved data.

C band 4m diameter tracking radar angle part (translated) new

	Category and Error sources Items	Design error		Achieved value				Condition
		Bias [mil]	Random [mil]	Bias error [mil]		Random error [mil]		
				AZ	EL	AZ	EL	
1.	Radar dependent tracking error							
	1)Boresight axis collimation	0.02		0.018	0.018			
	2)Angle detector unbalance	0.02		0.014	0.007			
	3) Axis shift due to monopuls coupler	0.03		0.029	0.014			
	4) Axis shift due to receiver phase shift	0.06		0.009	0.017			
	5) Antenna unbalance	neg						
	6) Antenna angle servo unbalance /drift	0.02		0.012	0.006			
	7) Thermal noise		0.02			0.017	0.022	3000km, 1kW transponder
	8) Angle servo dead zone	0.02		0.012	0.006			
	Sub total	0.08	0.02	0.042	0.031	0.017	0.022	
2.	Radar dependent conversion error							
	1) Azimuth axis leveling	EL 0.02			0.043			Unequally depression
	2) True north alignment	AZ 0.02		0.02				
	3) Orthogonality of axes	AZ 0.02		0.02				
	4) Static flexure of antenna	EL 0.02			0.019			
	5) Encoder	0.01	0.01	0.01	0.007	0.004	0.004	
	Sub total	0.03	0.04	0.03	0.048	0.004	0.004	

	Category and Error sources Items	Design error		Achieved value				Condition
		Bias [mil]	Random [mil]	Bias error [mil]		Random [mil]		
				AZ	EL	AZ	EL	
3	Environment dependent error							
	1) Wind pressure	neg	neg	neg	neg			
	2) Wind gust	0.01				0.01	0.01	5m/s, servo band N
	3) Solar heating deformation	AZ 0.04 EL 0.06		0.023	0.025			
	Sub total	AZ 0.04 EL 0.06		0.023	0.025	0.01	0.01	
4	Target dependent error							
	1) Velocity droop	$C_1\ d\varphi/dt$ $C_1\ d\theta/dt$	variation	$C_1\ d\varphi/dt$	$C_1\ d\theta/dt$			C_1=0.01 to 0.004/sec (able to compensate)
	2) Acceleration droop	$C_2\ d^2\varphi/dt^2$ $C_2\ d^2\theta/dt^2$	variation	$C_2\ {}^2\varphi/dt^2$	$C_2\ \theta/dt^2$			C_2=0.17 to 0.08/sec^2 (able to compensate)
	3) Polarization rotation by spin		0.04			0.008	0.04	servo BW W, at 1Hz
	4) Amplitude modulation by spin		neg			neg	neg	
	Sub total		0.04			0.008	0.04	
5	Radio propagation dependent							
	1) Atomospheric refraction	EL 0.05						compensation residue
	2) Tropospheric refraction	(EL 0.07)						at irregular weather
	3) Ionospheric refraction	EL 0.01						
	4) Multipath error	EL 0.03						θ=10deg,ρ=0.35
	Sub total	0.06						

Closing

・All of tracking radar system design is so difficult to explain during a few hours, which contains various engineering fields.

Only one engineer can hardly cover all, so a design group by several experts is needed to perform design.

・Today, I explained some of tracking radar system design based on my real experience and knowledge of antenna.

・I frankly recommend you, when you develop or purchase a tracking radar, you try error budget analysis cycles and evaluation based on it.

-Time change to the future-

Some of tracking radar may be replaced by non mechanical phased array system and GPS navigation & communication.