Short Baseline Interferometry for Precision Landing

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Introduction

- This paper presents a concept for a precision landing guidance system using ground-derived measurements based on combined interferometry and ranging, called augmented interferometry.

RF Interferometry

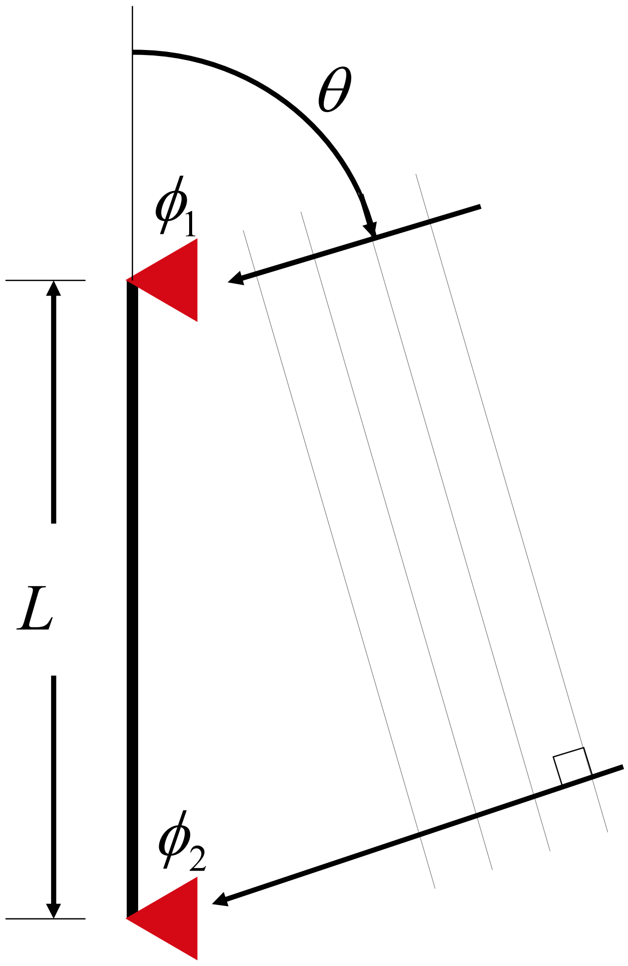
- ***RF Interferometry*** **is the science of measuring the arrival angle of a radio signal by receiving it at two or more points and processing the receptions for information-bearing data, such as:**
  - **RF phase difference (phase comparison interferometry)**

- ***Augmented interferometry*** **is the result of coupling angle measurement interferometry with a range measurement capability**
  - **Enables full three-dimendional position estimation**
  - **Assumed ranging method—two-way pseudonoise code (PN) ranging (there are others)**

1-D Phase-Comparison Interferometry

- **Two antennas separated by distance *L***
- **Relative phase of signals measured by a multiply-and-integrate receiver (cross-correlation)**
- **Measurement locates the source direction on a cone of half-angle θ around the antenna baseline**
- **There are angle ambiguities for *L* > λ/2, but standard means to resolve these exist**

$$\phi = \phi_2 - \phi_1 = \frac{2\pi L \cos\theta}{\lambda}$$

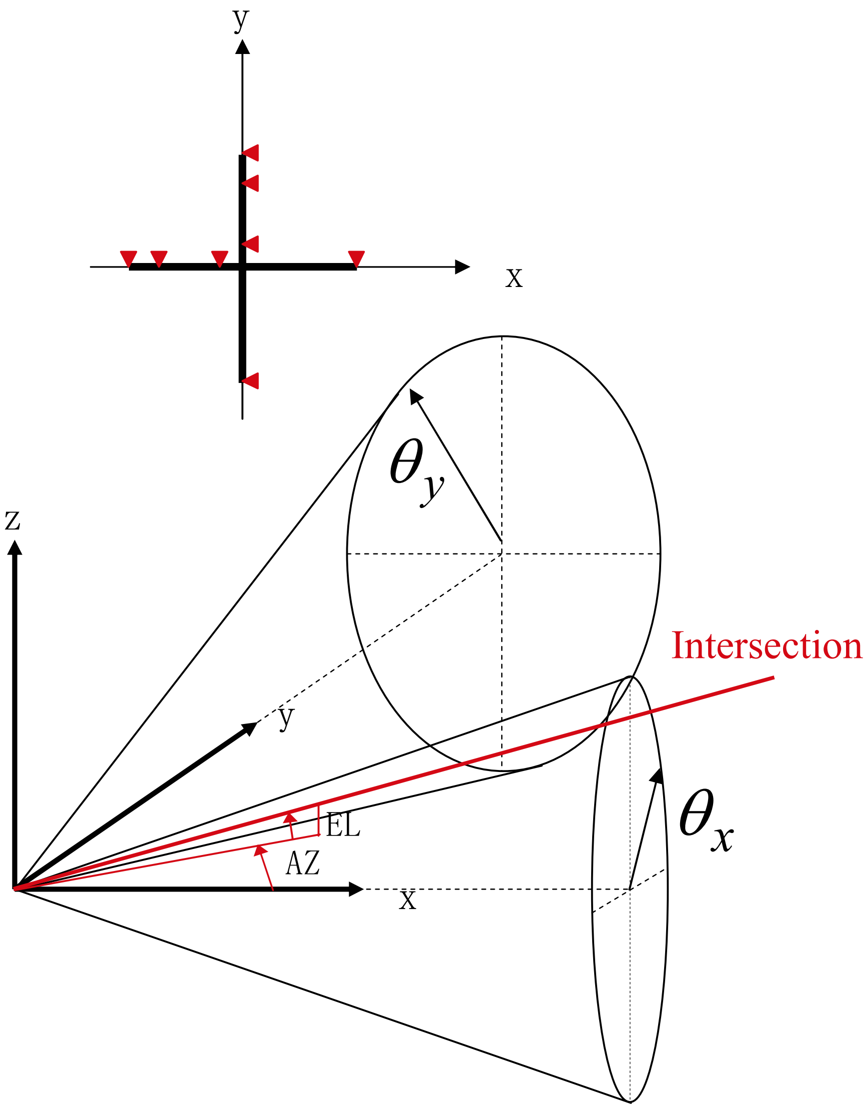


2-D Phase-Comparison Interferometry

- **Two perpendicular line arrays can measure two conical angles θ_x and θ_y …**
- **…and from them derive a line of bearing (LOB) to a target.**
- **<u>Application</u>: If the array is horizontal, it can measure azimuth (AZ) and elevation (EL) of an aircraft**

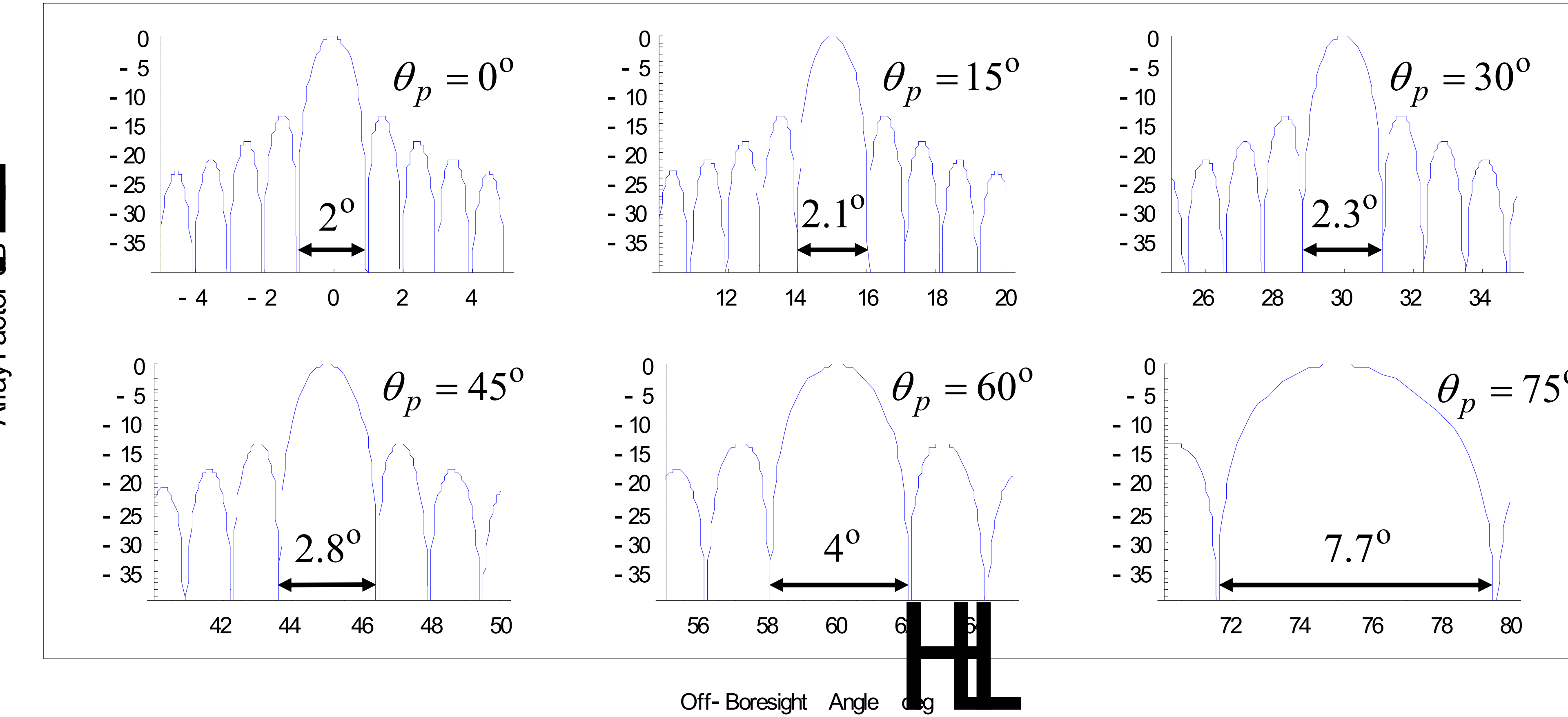
$$AZ = \tan^{-1}\left(\frac{\cos\theta_y}{\cos\theta_x}\right)$$

$$EL = \cos^{-1}\left(\sqrt{\cos^2\theta_x + \cos^2\theta_y}\right)$$



Example of Beamwidth vs. Steering Angle

Null-to-null beamwidth increases as the array is steered off boresite.



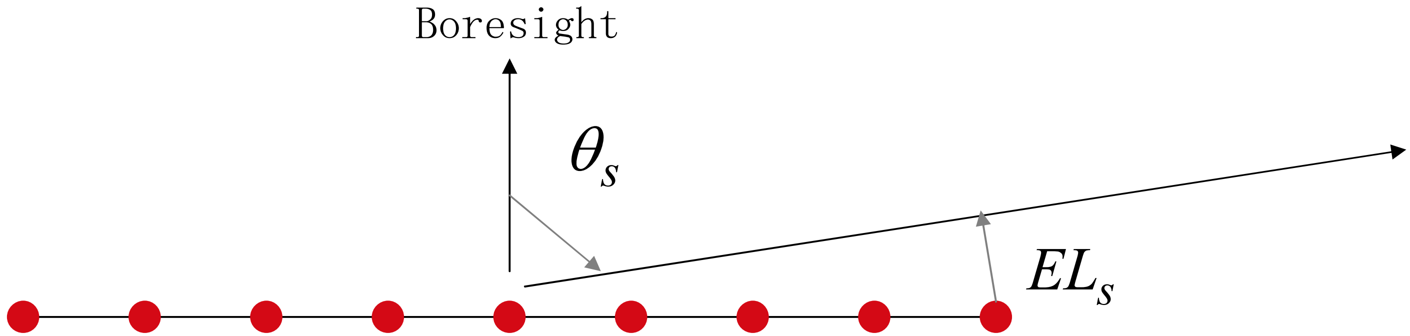
Accuracy of Elevation Measurements

- For a horizontal array, steering angle off boresight and elevation are complementary angles:

$$EL_s = 90^{\circ} - \theta_s$$

- Because the beamwidth increases as 1/(sin EL) as EL decreases, the errors any EL measurements made from that aperture (e.g. monopulse) will increase similarly.

$$\mathrm{BeamWidth}(EL_s) = \frac{\mathrm{BeamWidth}(0)}{\sin EL_s}$$



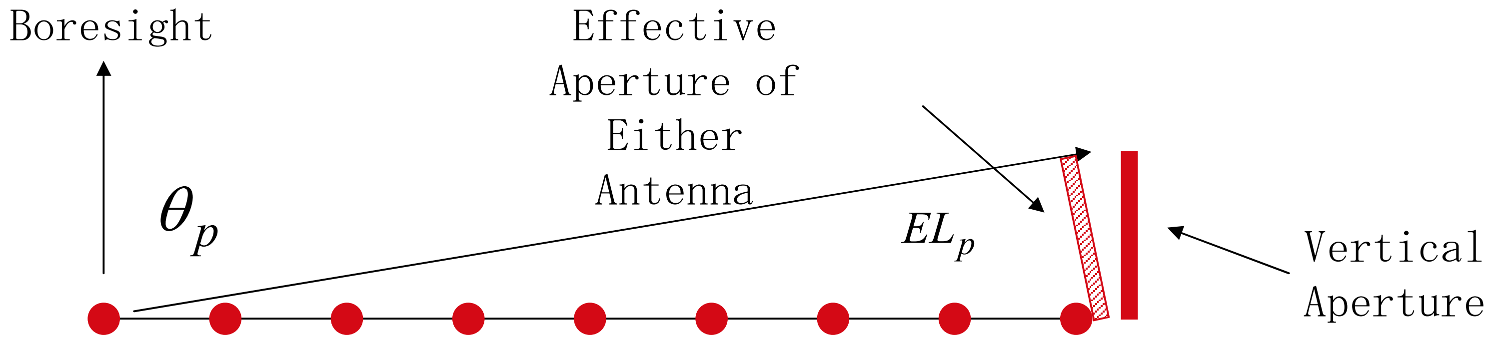
GDOP

- **GDOP—Geometric Dilution of Precision**
  - **Defined as the ratio of the error in the calculated coordinate to the error in the measured coordinate**
  - **Used to characterize systems in which measured and output coordinates are dimensionally equal**
  - **Example—GPS**
    - **Measurements are pseudoranges**
    - **Outputs are Cartesian coordinates**

- **We use GDOP to calibrate conversion from conical angles to (AZ, EL)**

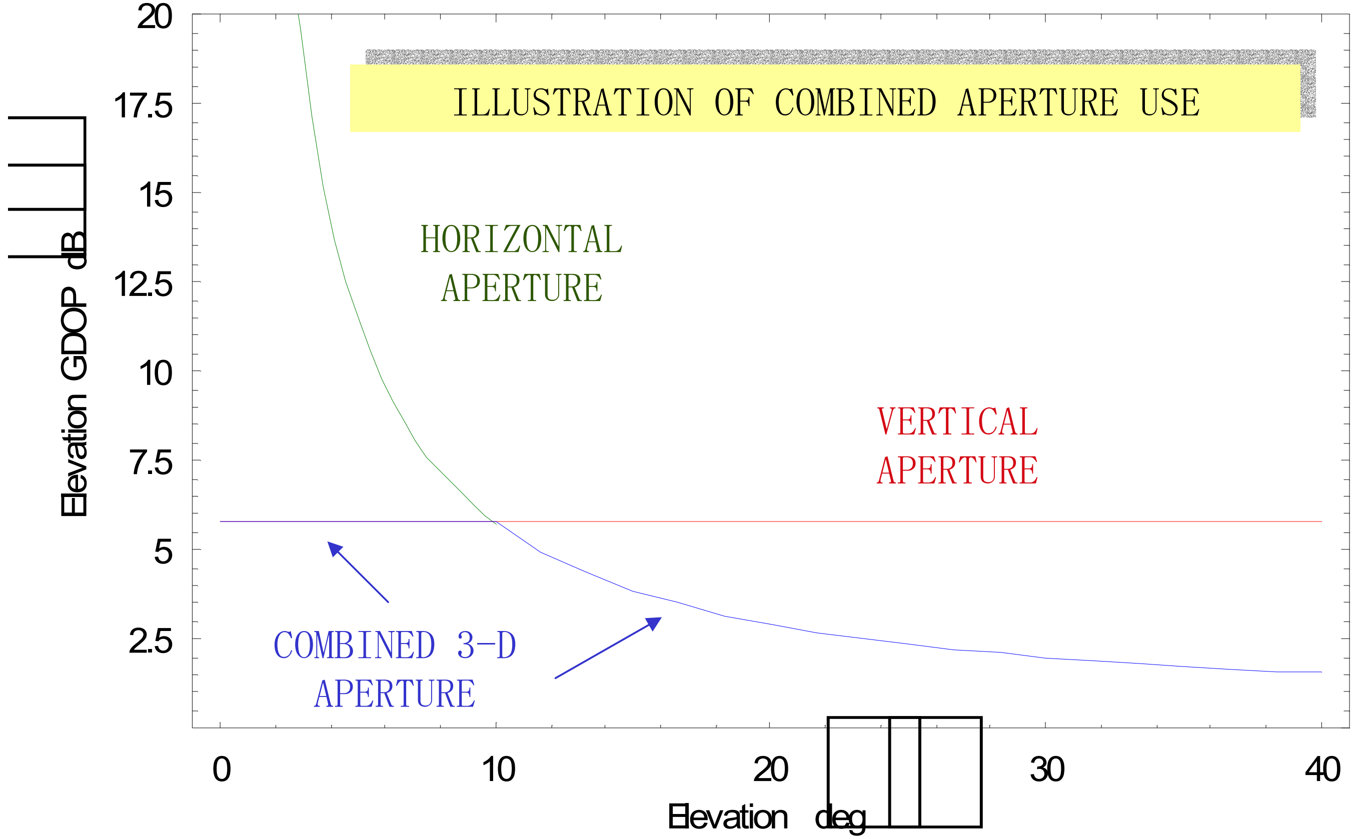
Horizontal vs. Vertical Aperture for EL Measurement

- **Horizontal aperture is used inefficiently for EL measurement because of the "endfire" effect**
  - **The effective aperture is the true aperture x (sin *EL*)**
- **Vertical aperture, on the other hand, is used very effectively because low elevation angles are in the broadside direction**
  - **There is no beam broadening—the minimum possible beamwidth of the aperture is achieved**
- **Restatement—Horizontal aperture has high GDOP at low EL, but vertical aperture does not**



3-D Interferometry

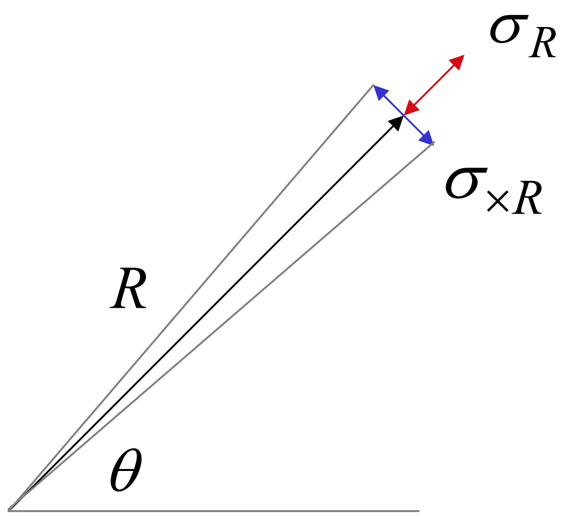
- **Simultaneous use of horizontal and vertical aperture is 3-D interferometry**
  - **A small amount of vertical aperture overcomes the low EL problem, while horizontal aperture provides coverge elsewhere**



Augmented Interferometer Error Behavior (cont.)

$$\sigma_R \propto \frac{f}{W\sqrt{E_p/N_0}} \propto \frac{fR}{W\sqrt{P_{Tx}T_p}}$$

$$\sigma_{\times R} \equiv R\sigma_\theta \propto \frac{R^2}{D\sqrt{P_{Tx}T_p}\,G(EL,EL_0)}$$



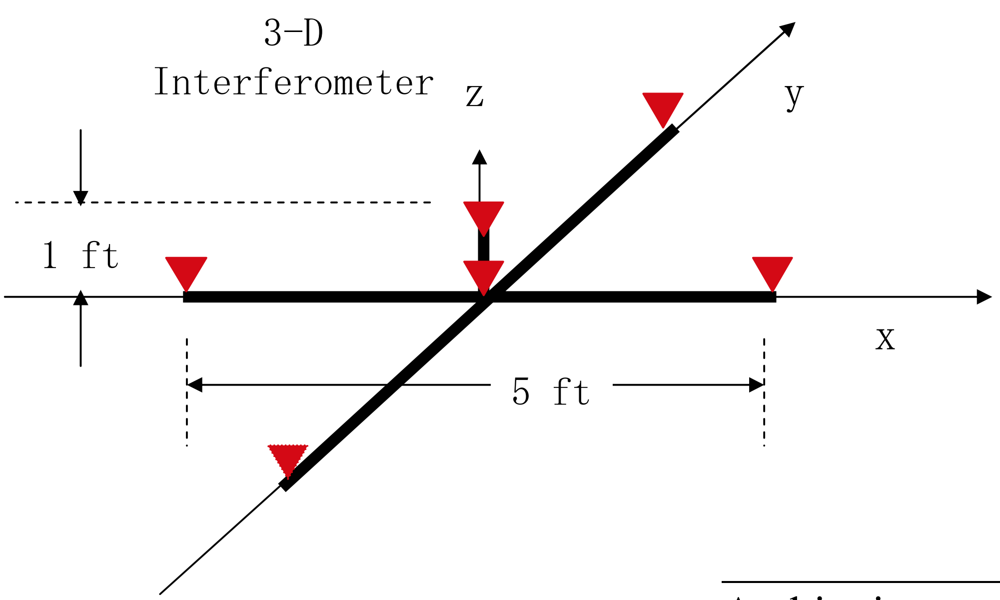
- **For constant transmit power and R^2 propagation:**
  - **Range Behavior**
    - **Along-range errors vary as R**
    - **Cross-range errors (xR) vary as R^2**
  - **Frequency Behavior**
    - **Along-range errors vary as frequency (f)**
    - **Cross-range errors are frequency independent**

Multipath Errors

- Multipath can be a significant error source in interferometry.
  - Particularly significant in the low elevation case
- Multipath suppression techniques:
  - Siting
  - Decorrelation via high bandwidth waveform
  - Low elevation antenna pattern rolloff
  - Time- and space-domain signal processing
- Appropriate combinations of these techniques can be used to bring multipath under control.

Approach and Landing Guidance Example

- **Example: Position estimate within approach and landing zone**
  - **0-20 mi from threshold**
  - **Assumes uncorrected 20-dB multipath fade**
  - **Results for two frequencies:**
    - **C-band (~5 GHz) and ~3.1 GHz**



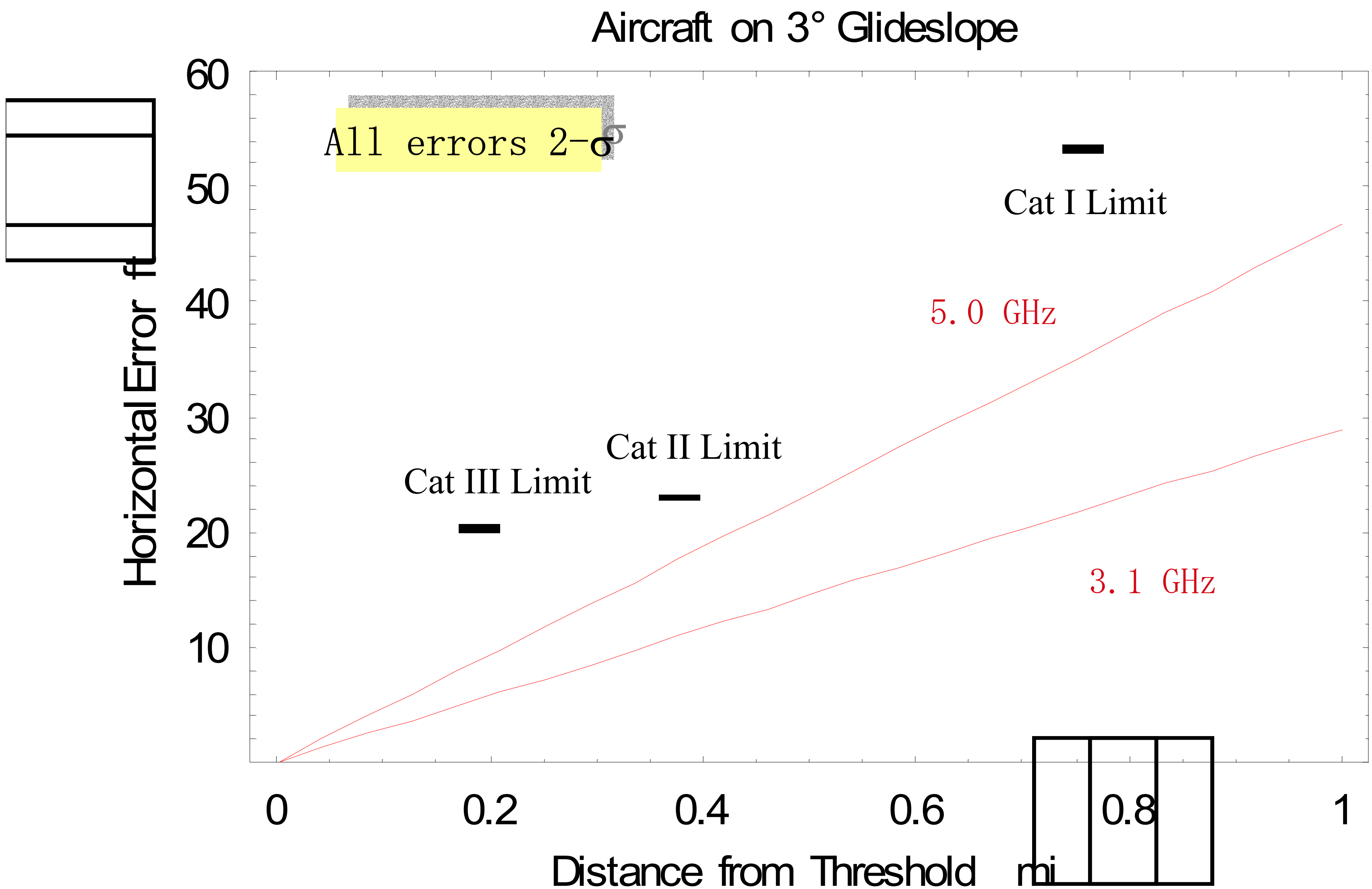
Ambiguity resolution elements not shown

Parameters of Design Example

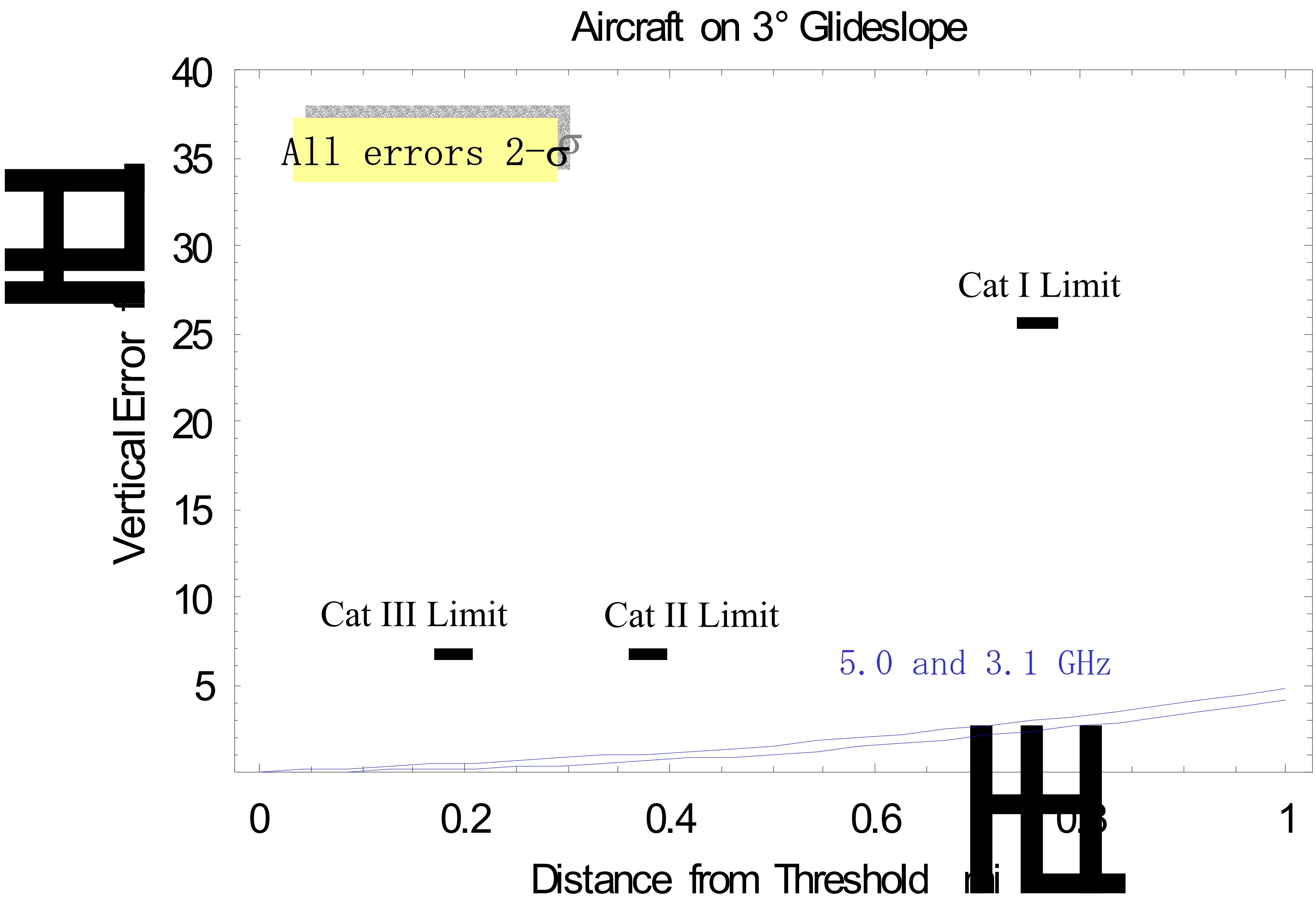
Interferometer		
Horizontal Baseline	5	ft
Vertical Baseline	1	ft
Frequency	5 or 3.1	GHz
Waveform and Link		
Transmitter Peak Power	2 (1 mi) or 600 (20 mi)	W
Transmit Gain	-3	dB
Receive Gain	0	dB
Pulse Length	2	ms
PN Code Bandwidth*	> 100	kHz
[illegible]	6	dB
Evaluation Scenario		
A/C on Glide Slope	3	deg
Range	0-20	mi
Fading (max)	20	dB

*Minimum required to support the ranging function.

Horizontal Error—5.0 and 3.1 GHz



Vertical Error—5.0 and 3.1 GHz



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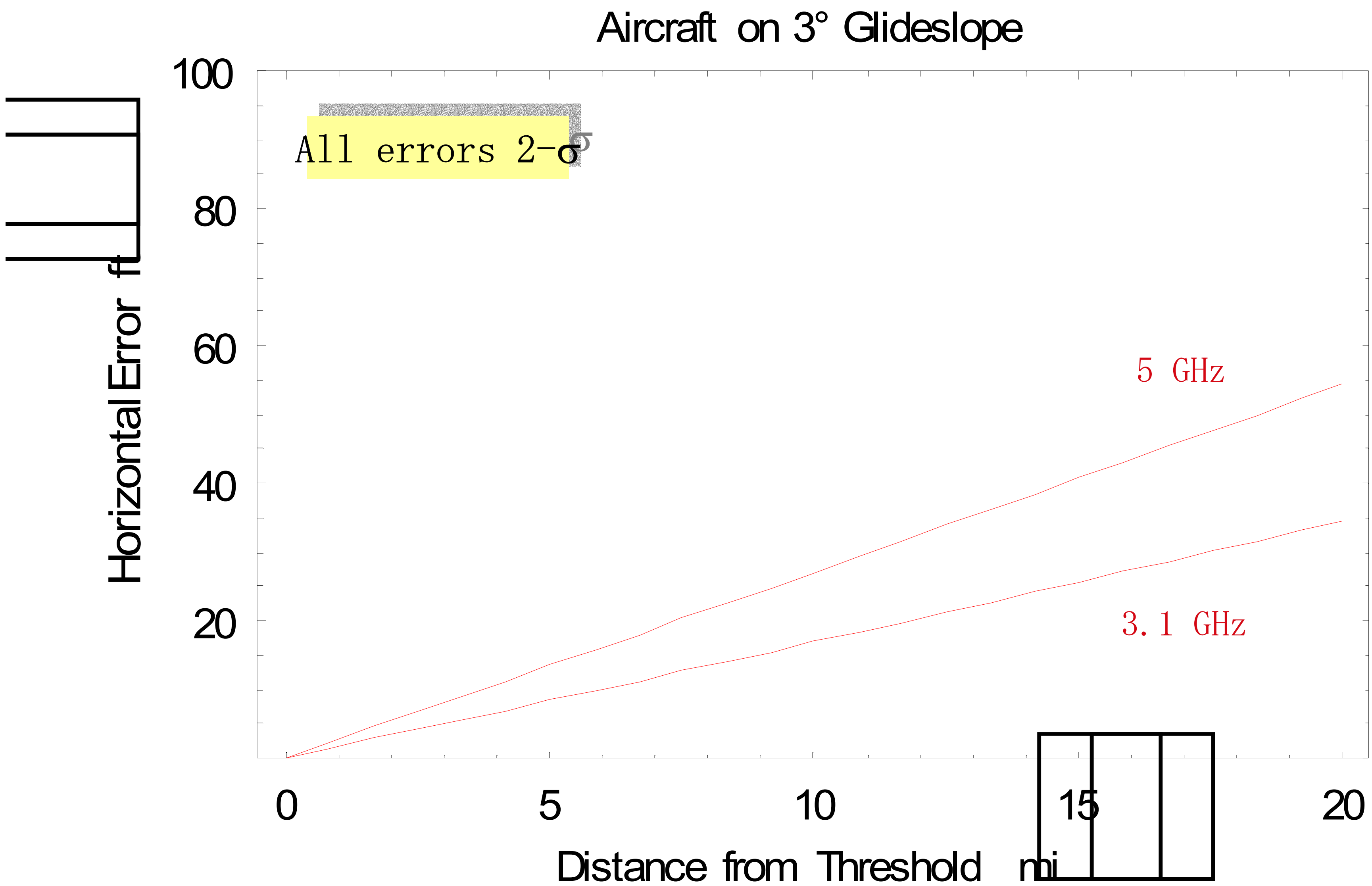
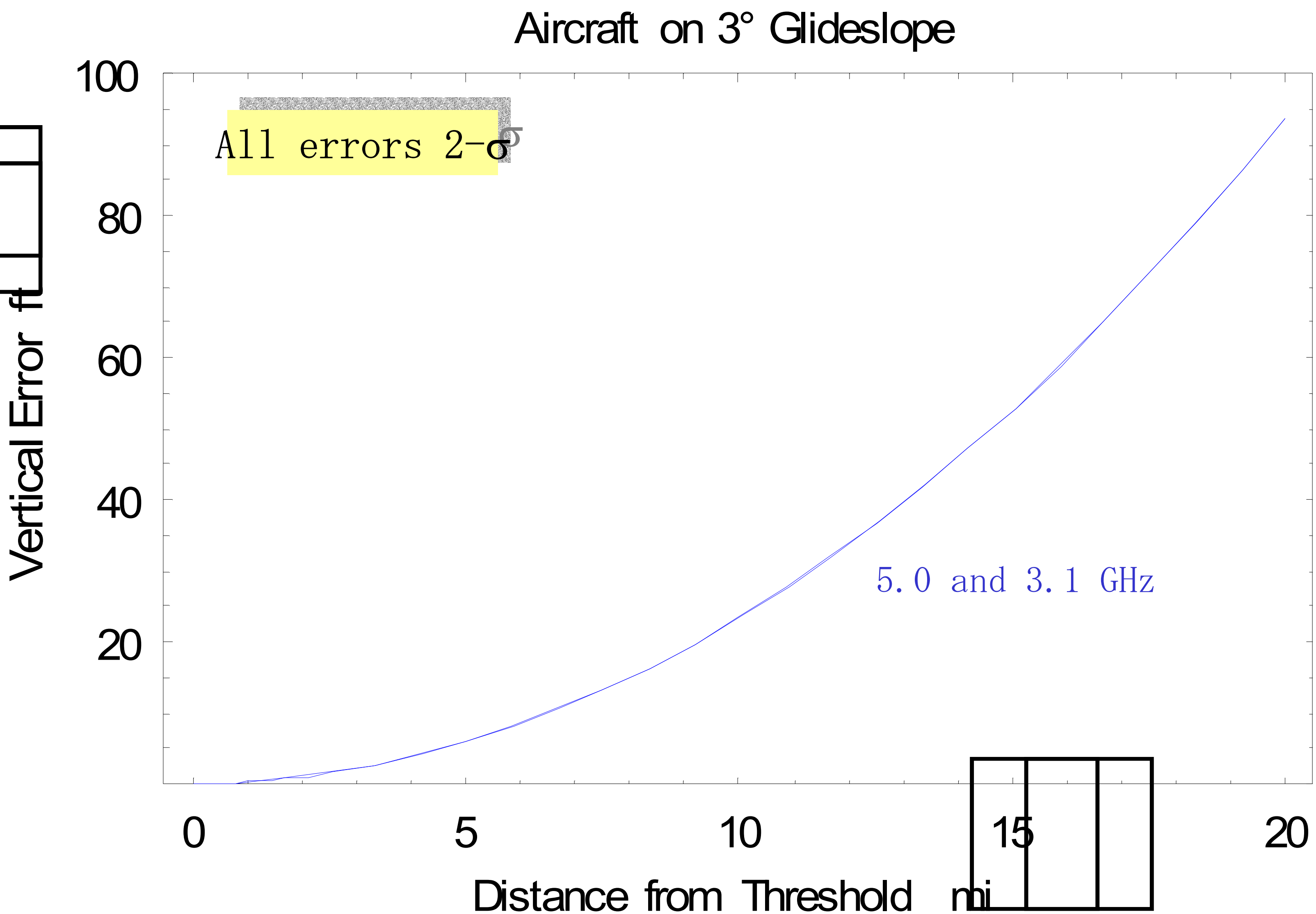


Vertical Error—5.0 and 3.1 GHz



Data Link

- The C-band link is strong enough to support up to 1000 bits per A/C reply
  - Assumes error-correction coding and E_b/N_0 = 5 dB
  - For a 2-ms pulse this is a peak data rate of 500 kb/s
    - This rate is higher than the minimum PN chip rate for acceptable ranging (and no data), meaning that the signal is strong enough to support a higher PN chip rate, up to the limit of available bandwidth

Summary Comments

- Augmented interferometry can provide a ground-derived approach and landing system having performance comparable to or better than GPS.
- Equipment is compact enough for near-runway siting, but may be placed at other locations as well.
- User avionics burden is minimal—low power, off-the-shelf digital processing.
- Good performance can be obtained at a variety of frequencies.

Back-up Charts

Use of 2-D Interferometry for Elevation Measurement

- It is sometimes overlooked that a 2-D interferometer having horizontal aperture only can make elevation measurements
  - Quality of the elevation estimates is not uniform in angle
- The analogy with filled-aperture antennas is useful to explain this behavior and motivates some of our development

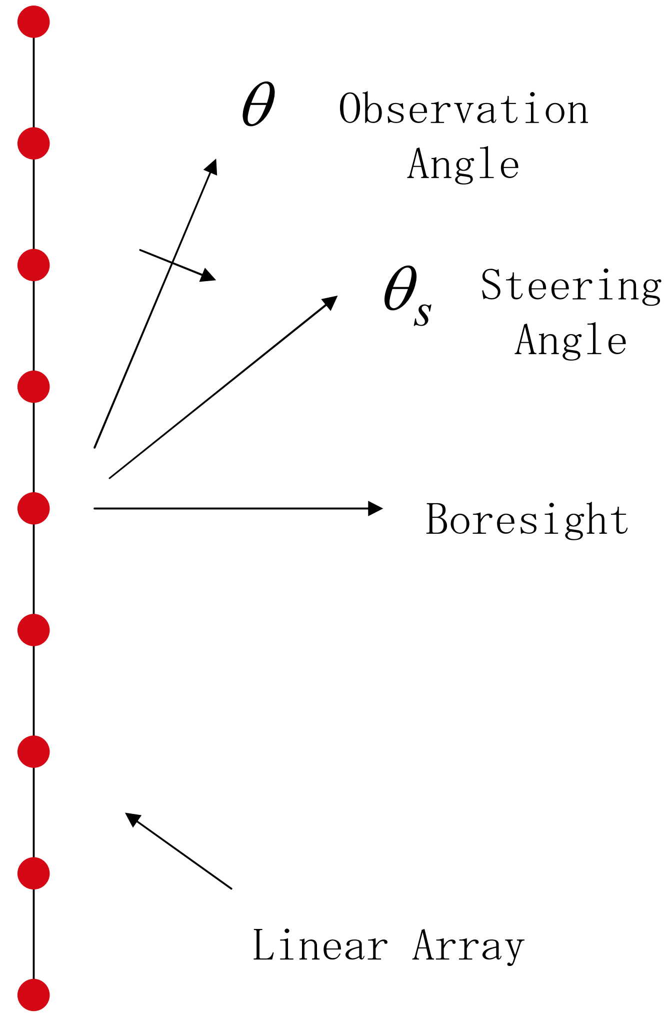
Linear Array Antenna

- **A linear array of *N* elements has the antenna patern shown below**
- **Beamwidth increases as steering angle deviates from boresight**

$$A(\theta,\theta_s)=\frac{\sin\left[\frac{\pi ND}{\lambda}(\sin\theta-\sin\theta_s)\right]}{\sin\left[\frac{\pi D}{\lambda}(\sin\theta-\sin\theta_s)\right]}$$

θ_s = steering angle

θ_p = pointing angle



H-V Equivalence for Elevation Measurement

- **The effective horizontal and vetical apertures are the projections of their true apertures normal to the LOB to the target**

$$L^{\mathrm{H}}_{\mathrm{true}} = (N-1)D;$$

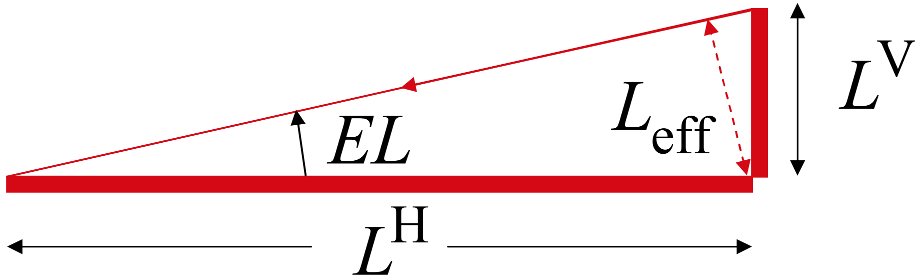
$$L^{\mathrm{H}}_{\mathrm{eff}} = L^{\mathrm{H}}_{\mathrm{true}} \sin EL; \quad L^{\mathrm{V}}_{\mathrm{eff}} = L^{\mathrm{V}}_{\mathrm{true}} \cos EL;$$

- **Therefore, V aperture is as effective as H aperture for EL measurement when**

$$L^{\mathrm{V}}_{\mathrm{eff}} = L^{\mathrm{H}}_{\mathrm{eff}}$$

- **i.e.**

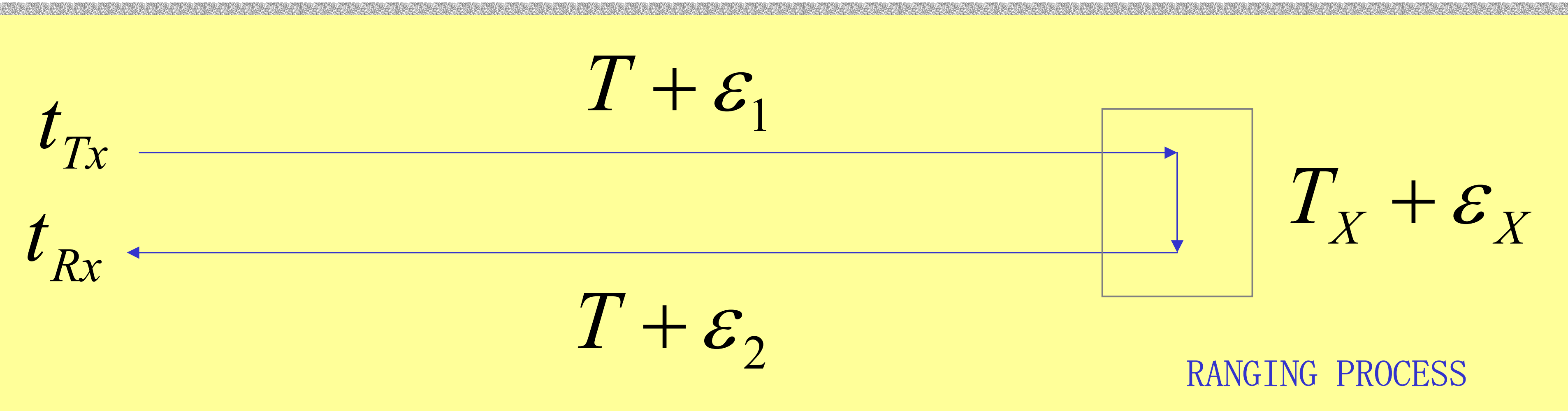
$$L^{\mathrm{V}}_{\mathrm{true}} = L^{\mathrm{H}}_{\mathrm{true}} \tan EL$$



Range Measurement Methods

- **One-Way Ranging—Receive a transmission time-stamped signal and estimate its arrival time**
  - Interferometer-to-user or user-to-interferometer
  - Requires transmission time stamp and arrival time measurement
  - User clock must accurate
    - For time stamp or arrival time reference
- **Two-Way Ranging—Two-way signal exchange between interferometer and target from which round-trip range is measured**
  - Either terminal may initiate
  - Eliminates time-stamping and accurate clock requirements
  - Requires known and stable turn-around time
- **Tolerance of low-accuracy user clock makes two-way ranging preferable for avionics applications**

Two-way Ranging Process and Errors



$$t_{Rx} = t_{Tx} + T + \varepsilon_1 + T_X + \varepsilon_X + T + \varepsilon_2$$

$$\hat{R} = \frac{c(\hat{\tau}_{2\text{-way}})}{2} = \frac{c(\hat{t}_{Rx} - t_{Tx} - T_X)}{2} = R + \varepsilon_R$$

$$\varepsilon_R = \frac{c(\varepsilon_1 + \varepsilon_X + \varepsilon_2)}{2}$$

RANGE ERROR

Frequency Errors

- **Frequency uncertainty can cause error in the angle estimate made by an interferometer**
  - **For a 1-D interferometer, the error is**

$$\delta\theta = \left(\frac{\Delta f}{f}\right)\operatorname{ctn}\theta = -\left(\frac{\Delta\lambda}{\lambda}\right)\operatorname{ctn}\theta$$

  - **Angle dependence—at broadside incidence there is no effect, impact increases as incidence moves toward endfire**
  - **When the uncertainty is due to Doppler shift, the error can be written**

$$\delta\theta = \left(\frac{v}{c}\right)\operatorname{ctn}\theta$$

  - **At Mach 1, $v/c = 10^{-6}$: Doppler error tends to be dominated by noise error**

Further Detail on Multipath Errors

- **Evaluation of Multipath Suppression Techniques**
  - **<u>Bandwidth</u>—delays of 10s of ns require 100s of MHz bandwidth to decorrelate**
  - **<u>Elevation rolloff</u>—achievable, as a function of amount of vertical aperture on the array elements**
  - **<u>Time-domain signal processing</u>—works best with a continuous signal, e.g. GPS narrow correlator or leading edge detection, but possible under pulsed operation**
  - **<u>Space-domain signal processing</u>—full vertical aperture of the array can be used to discriminate against multipath**
    - **Example: Lincoln Lab, Precision Altitude and Landing Monitor (PALM)—L-band vertical array for low elevation measurement (circa mid-70s)**

Further Detail on Multipath Errors (cont.)

- **Multipath Effects Specific to Interferometry:**
  - **Fading—destructive interference between direct path signal and (e.g.) runway reflection**
    - Reflected signal is ~ out-of-phase with direct
  - **Change in multipath presentation from one array element to another**
    - If two elements see same multipath, they cross-correlate perfectly (except for fading)—no relative phase differential
    - Difference in multipath results in decreased signal-x-signal correlation and differential phase error
    - This is more severe for a vertical array than a horizontal

- **Conclusion:**
  - **Multipath problem must be quantified and worked for the landing scenario, but adequate solution is not out of reach**

Assumed Landing Guidance/Approach Requirements*

	Decision Height	Distance from Runway Threshold(1)	Required Accuracy:(2) 95% or 2-σ
Cat. I Precision Approach	200 ft (60 m)	4000 ft (1200 m)	H: 16 m V: 7.7 m G: N/A
Cat. II Precision Approach	100 ft (30 m)	2000 ft (600 m)	H: 6.9 m V: 2.0 m G: N/A
Cat. III Precision Approach	50 ft (15 m)	1000 ft (300 m)	H: 6.1 m V: 2.0 m G: N/A

(1) 3^{o} glide slope

(2) Sensor only, excludes flight technical error

*Source: Table 2-1, NAS Performance Requirements, GPS Risk Assessment Study, VS-99-007, The Johns Hopkins University, January 1999. (Hopkins sources include FAA, RTCA and private communications.)