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ERROR SOURCES APPLICABLE TO PRECISION TRAJECTORY RADAR CALIBRATION

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ERROR SOURCES APPLICABLE TO PRECISION TRAJECTORY RADAR CALIBRATION

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FOREWORD

This document attempts to identify potential sources of error inherent in precision tracking, land-based monopulse, and phased array radar systems. Comments and recommendations for improving its contents should be brought to the attention of:

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INTRODUCTION

The purpose of this document is to identify possible sources of error in measurements by land-based monopulse and phased array radar systems. Recognition of these error sources will be useful in several ways. Operations personnel will be able to more easily recognize deficiencies in calibration procedures and utilize existing procedures more proficiently to minimize calibration errors. System design/procurement engineers will be reminded of potential error sources enabling more realistic design and acceptance specifications to be written for future equipments. Planning groups will be able to identify the limitations which affect the applications of the radar. Those engaged in operations engineering may utilize this document as an aid in identifying those modifications which would be more beneficial in improving the performance or accuracy of operational radar systems. In addition, data reduction personnel will be aided in the evaluation of the total effects of current and/or proposed data reduction and analysis techniques of radar data by recognizing the source and in some cases the magnitude of system bias errors.

The authors of this publication (Electronic Trajectory Measurements Group members and associate members) have concluded that mission requirements at the individual test ranges vary to such an extent any attempt to provide standard techniques for the elimination of the various error sources would be futile. Therefore, this document does not include suggestions or recommendations concerning the "best approach" for avoiding the errors listed herein.

1. SOLAR HEATING EFFECTS

1.1 Pedestal Mislevel

A change in the level of the azimuth platform due to solar heating.

1.2 Pedestal Base Distortion

Mechanical distortion of the pedestal base as a result of solar heating which causes changes in antenna orientation, orthogonality, etc.

1.3 Trunion Shaft Effect

Movement of the mechnical elevation axis due to solar heating of trunion shaft and bearings.

1.4 Aperture Distortion

Deviations in the standard aperture dimensions and surfaces caused by solar heating.

1.5 Comparator Shift

Changes caused by solar heating in the position and/or orientation of the feed horn assembly relative to the geometric axis of the antenna.

1.6 Boresight Tower Deflection

Changes in the absolute (surveyed) position of the target boards or feed horn of the boresight tower due to solar heating of the tower itself. Also, changes in the relative positions of the parallaxed target boards and feed horn due to solar heating of the support members, etc.

1.7 Axes Nonorthogonality

Deviations in the angle between the elevation axis and the azimuth axis (90°) caused by solar heating of the pedestal base, trunion shaft and bearings, etc.

1.8 Radiating Element Misorientation

Changes in element orientation due to temperature differentials across the array. (5)

1.9 Other Equipment Effects

Changes in the characteristics of heat sensitive electronics, telescopes and optical calibration devices due to solar heating.

2. PEDESTAL ERRORS

2.1 Pedestal and Antenna Flexure

Mechanical distortion of the pedestal-antenna assembly caused by inertial-acceleration forces, thermal gradients, wind loading, unbalanced moment-arm loading, etc.

2.2 Dynamic Mislevel

Changes in the level of the azimuth platform caused by an unbalanced moment arm as the antenna varies in elevation.

2.3 Pedestal Overturning

A condition caused by imperfect antenna/pedestal geometry and counter weighting wherein the center of gravity of the pedestal/antenna configuration shifts off the azimuth centerline, as a function of the antenna elevation angle, resulting in pedestal base distortion and mislevel.

2.4 Elevation Shaft Torque Windup and Bend.

Rotational and longitudinal flexure of the elevation mechanical axis due to inertial loading and torque-moment to trunion-bearing offsets.

2.5 Dynamic Deflection

A random deflection in pedestal mechanical and tracking geometry resulting from random wind loading forces.

2.6 Data Gear Nonlinearity and Gear Backlash

A cyclic and random offset error between the pedestal mechanical axis and the data encoders due to inexact gear tooth meshing, gear runout (wobble), backlash, and gear nonlinearity.

2.7 Encoder Zero Misalignment

A fixed offset error in antenna position data outputs due to misalignment of the data axes encoders with the true mechanical positions of the data axes.

2.8 Intermediate Frequency (IF) Phase Angle Variations

A changing IF phase shift with changing azimuth position due to imperfectly compensated slip rings.

2.9 Level Instability

Movement of the pedestal mount due to ground movement and shifting terrain.

2.10 Bearing Wobble

A random error introduced in the data axes outputs when the data axes are mechanically loose or wobble about their true centers of rotation.

2.11 Orthogonality Error

Deviation of the angle between the elevation axis and the azimuth axis from exactly 90°.

2.12 Data Shaft Eccentricity

A cyclic error introduced into the encoder outputs when the rotational center of the data encoder shafts do not align with the antenna mechanical axes.

3. ANTENNA ERRORS

3.1 Droop

A variable elevation axis shift caused by mechanical sag due to gravitational loading on the various components of the antenna. Droop produces a shift of the Radio Frequency (RF) axis which is proportional to the cosine of the elevation angle. The antenna components most affected by droop are the reflector, the subreflector and/or the feed assembly.

3.2 Antenna Unbalance

A condition affecting the antenna dynamic geometry wherein a varying elevation axis torque is required to support the antenna at different elevation angles, contributing to variable elevation-axis torque windup and longitudinal deflection.

3.3 Aperture Distortion.

Nonuniform distribution of weight causing aperture surface flexure and distortion of the RF beam.

3.4 Wind Gusts - Dynamic Deflection

Random antenna movement and aperture distortion resulting from random wind loading forces.

3.5 Constant Wind Torque

Bias errors in azimuth and/or elevation due to uniform wind loading forces.

3.6 Collimation Errors

3.6.1 Mechanical Misalignment. An error due to imperfections in the aperture surface, mechanical assembly, and/or orientation of the feed assembly which results in the noncolinearity of the geometric (mechanical) axis and the tracking (RF) axis of the antenna.

3.6.2 Optical Misalignment. An error which occurs when the optical and mechanical axes are not parallel. Such an error will result in a calibration bias since the optical axis is normally used to calibrate the electrical axis.

3.6.3 Electrical Misalignment

3.6.3.1 Phasing Effects. Encountered when an improper phase adjustment in the receiving system results in an apparent shift of the RF tracking axis.

3.6.3.2 Antenna Beam Distortion. Occurs in planar-array antennas when the beam width and pattern are distorted as scan angle is increased.

3.6.3.3 Beam Generation Errors. Occur in series-fed, planar-array antennas when cumulative phase shift errors between radiating elements cause a loss of precision in determining beam direction and shape.

3.6.3.4 Environment Induced RF Axis Errors. An RF axis shift in array antennas caused by watersheet and other related effects on the array face.

3.7 Phased-Array Blindness

Loss of radiated or received power in the phased array due to mutual coupling between radiating elements. (4)

4. TARGET DEPENDENT ERRORS

4.1 Target Noise

A tracking error introduced into the radar by the target. Target noise refers to a whole class of wave interference phenomena which occur whenever the physical dimensions of the moving multiple-point target encompass a number of wave lengths of the radiation in use. The echo signal from a multiple-point target is a vector summation of various reflections changing unpredictably in phase and amplitude as a function of such interdependent parameters as aspect angle, target motion, wave length, and polarization of the radiation.

4.2 Skin Track Error Factors

4.2.1 Scintillation (Amplitude Noise). Amplitude modulation of the return echo of a multiple-point target as the vector sum of the individual points changes with time due to aspect angle variations, propeller rotation, skin vibrations, etc.

4.2.2 Glint (Angle Noise). Variations in the apparent angle of arrival of the echo signal due to phase front tilt introduced by interaction of the returns from a multiple-point target. Angle glint is directly proportional to target span and inversely proportional to target range. In general, the apparent center of the reflection may not correspond to the center of the target and need not be confined to the physical extent of the target.

4.2.3 Multiple Target Errors. Multiple targets within the radar tracking cell (that volume of space defined by the antenna beamwidth and range gate) which appear as a single complex target with the apparent center determined by random amplitude and phase relationships of the combined returns.

4.3 Transponder-Track Error Factors

4.3.1 Transponder Misfiring (Countdown). Failure of the transponder to reply to all interrogation pulses, resulting in countdown of the received signal and degradation of tracking data.

4.3.2 Radar Receiver Saturation. Range errors due to video distortion which occur when the signal exceeds the dynamic range of the receiver system.

4.3.3 Transponder Delay Variation. Changes in the fixed transponder delay as a function of the interrogate power levels sensed at the transponder. This variation may introduce a random range bias error on transponder augmented targets during adverse atmospheric conditions, long range tracking, and/or low altitude nape of the earth tracking.

4.3.4 Transponder Lobing. Low frequency variations in apparent signal strength such as those caused by antenna shading due to changing aspect angles.

4.3.5 Multiple Antenna Anomalies. An interference phenomena caused by the simultaneous transmission and reception of transponder signals on targets equipped with multiple antennas. This condition destroys the point source characteristics of the transponder signal creating errors in the radar from signal glint and scintillation.

4.3.6 Transponder Modulation. A rapid variation of apparent signal strength which generally exceeds the bandwidth (frequency response) of the Automatic Gain Control (AGC) circuit resulting in erratic error signals and degraded radar tracking performance. Sources of modulation include effects caused by aircraft propellers, helicopter rotor blades, turbine blades, and the fluttering and vibration of other mechanical devices.

4.3.7 Transponder Jitter. A variation in time delay between the interrogate pulse and the transponder transmitted pulse.

4.3.8 Frequency Dependent Boresight Shift. A boresight shift caused by improper radar receiver frequency tracking of the transponder signal which in turn creates an off-axis RF boresight shift.

4.4 Flame Effects

4.4.1 Skin Track. A target aspect dependent error caused by flame effects an overall target reflectivity which results in attenuation of the skin echo return, erratic shifts in the perceived centroid of the target return (analogous to glint), and modulation of the return due to apparent large variations in the target radar cross section.

4.4.2 Transponder Track. A target induced error critically dependent on target aspect angle which results in erratic transponder operation due to attenuation of both the transponder interrogation and reply signals. In addition, flame interference may introduce a refractive effect on the transponder signal creating an apparent random variation in the target location.

4.5 Reentry Effects

Such effects include attentuation of the transponder signals and phase distortion of the reflected signal due to the ionization sheath and the shock wave generated upon reentry.

4.6 Polarization Effects

4.6.1 Phase Front Error. The difference between the nominal center of reflection and the RF null point which is caused by phase front distortions (tilt) of the energy reflected from a complex target. The error magnitude is primarily a function of phase-front size versus antenna-aperture size. (Changing phase front errors resulting from changing aspect angles of a complex target produce the apparent wandering of the target known as "glint.")

4.6.2 Polarization Ellipticity Error. The apparent shift of target position which occurs when a linearly-polarized signal is rotated with respect to an elliptically-polarized receiving system. (Polarization ellipticity of the radar receiving system is derived from the design goal of circular polarization and is a function of the design and manufacturing precision of the circular polarizer and the receiving system gain/phase linearity.)

4.6.3 Cross-Polarization Error. The apparent shift of target position resulting when a linearly-polarized signal is rotated with respect to a linearly polarized receiving system. Such an error increases rapidly and is accompanied by a signal null as the cross-polarization passes through 90°.

5. PROPAGATION/REFRACTION ERRORS

5.1 Propagation Noise Factors

5.1.1 Tropospheric Noise. Noise due to the space and time variability of atmospheric refractivity which results from turbulence and the uneven distribution of moisture, temperature and pressure.

5.1.2 Ionospheric Refraction. A change in the incident angle of an electromagnetic wave traversing the ionospheric atmospheric layer due to a refraction index variation caused by variations in atmospheric temperature, pressure, vapor content, and ionization. The total ionospheric refraction error at C-band is less than 0.01 mil under normal mid-day conditions. Short-term variations should never exceed 0.005 mil RMS.

5.2 Atmospheric Refraction Factors

5.2.1 Tropospheric Effects. The integrated effect of the change in atmospheric refractivity along the radar tracking path caused by the average change in the atmospheric parameters of temperature, water vapor and pressure with height above the earth's surface, and the incident angle of the traversing electromagnetic wave.

5.2.2 Ionospheric Effects. Refractive errors less than 0.01 mil in elevation which are affected by the ionosphere. (For frequencies greater than 1 GHz, ionospheric refraction is negligible.)

5.3 Range Refraction Induced Errors

Those caused by variations in the velocity of propagation which retard the signal, yielding an incorrect time interval measurement. Such errors may be corrected by determining the average refractive index of the atmosphere along the signal path and adjusting the free-space propagation figure (assuming the range oscillator is calibrated for vacuum propagation). For elevation angles above 10°, through a standard atmosphere with a surface refractivity of $N=(M-1)\times10^6=343$, the maximum error introduced is about 40 feet in range.

5.4 Elevation Refraction Induced Errors

Those in the target elevation angle measurement resulting from the characteristics of the atmosphere through which the radar signal passes. A radar elevation angle measurement taken with a surface refractivity of $N=(n-1)\times10^6=400$ and no ducting conditions on a target at a known elevation angle of 0° traveling in earth orbit will yield an apparent elevation angle measurement error of approximately 1.2° due to refraction. A signal measurement made vertically under otherwise similar conditions will experience no error. For elevation angles above 10° in a standard atmosphere with a surface refractivity of N=343, the maximum error introduced is about .08° in elevation angle.

5.5 Index of Refraction Variation Induced Errors

Those arising from a failure to make observations of the index of refraction during or near the time a target measurement is made. This usually results in increased residual refraction errors in refraction corrected data. The magnitude of the errors depends upon the atmospheric conditions at the time of measurement. If the refractivity gradient decreases smoothly with increasing height and the hourly surface observations of the index of refraction near mission time are essentially constant, it is probable that the errors will be small. If the hourly surface observations vary considerably, a relatively poor correction can be expected. Such corrections are poorest if the refractivity gradient is nonlinear and the refractive index used is flagrantly noncurrent.

5.6 Multipath Errors

Those experienced at low elevation angles when the apparent signal received at the radar is the resultant of the direct signal path through the atmosphere and the reflected signal path from the earth's surface. The net result is an apparent target position fluctuating about and between these two points as the phase and amplitudes of the signals vary to form rapidly changing vector sums. Multipath errors which can be very large at low elevation angles are primarily dependent on the elevation angle, the reflectivity characteristics of the earth's surface along the ray path, and the radar antenna design.

5.7 Transit Time Error

An error resulting from the distance a target moves while the reflected energy returns to the radar. The error is equal to the target velocity (angular or radial) multiplied by the target apparent range and divided by the propagation velocity of the reflected energy.

6. TRANSMITTER ERRORS

6.1 Pulse Shape Variation

A change in the distribution of power and/or frequency of the transmitter output, with respect to time, resulting in a range measurement error.

6.2 Jitter

A random variation in the time between the reference synchronizing signal and the modulated output of the transmitter resulting in random range measurement errors.

6.3 Countdown Errors

Variations in the transmitter pulse repetition frequency over a given interval of time resulting in periodic loss of transmitter output and degraded radar performance.

6.4 Misfire

Random loss of modulated transmitter outputs resulting in degraded radar tracking performance.

6.5 Frequency Instability

Frequency deviation around the correct transmitted frequency resulting in unstable receiver performance, RF axis variations, and erratic transponder interrogations.

6.6 Power Instability

Power deviation about a given power level for a given time.

7. RANGING SYSTEM ERRORS

7.1 Zero Range Setting Error

That resulting from the inability to adjust the range system to zero, or a predetermined position, and maintain that setting.

7.2 Range Discriminator Shift

Degradation of range track due to unbalanced discriminator operation resulting in a range bias error.

7.3 Servo Unbalance

A servo output which is not a true indication of the input resulting in instability and random bias errors.

7.4 Receiver Delay Error

A change in the calibrated propagation time of the video through the receiver resulting in a range bias error.

7.5 Range Oscillator Frequency Misalignment

Improper adjustment of the reference oscillator for the correct output frequency (the time standard for the ranging system) which results in a range scaling error.

7.6 Range Oscillator Instability

Deviation of range precision over a given period of time due to oscillator drift which results in random range errors.

7.7 Data Take-Off Zero Setting Error

The inability to calibrate and maintain locked tracking between the output data transducer and the range tracking mechanism.

7.8 Range Phase Shifter Error

A random and cyclic error attributable to the 82 kHz phase shifter in electro-mechanical range systems.

7.9 Quantization Error

That generated by rounding off input samples and computed values to a limited number of digits; a process inherent in digital ranging systems. (5)

7.10 Internal Jitter

Timing changes between the zero range-reference and the target range-reference track gate resulting in random range deviation errors.

7.11 Data Gear Nonlinearity

A nonlinear functional change of the input versus the output shaft which produces a cyclic and/or scaling error in the output data (electro-mechanical system).

7.12 Data Gear Backlash

Slack in the meshing of the data take-off gears which reduces the precision of the range output data in mechanical ranging systems.

7.13 Dynamic Lag

7.13.1 Velocity Constant (Kv). The constant ratio of range error versus velocity; a function of the gain of the servo system.

7.13.2 Acceleration Constant (Ka). The constant ratio of range error versus acceleration; a function of the gain and the bandwidth (frequency response) of the servo system.

7.14 Glint

An apparent displacement of the target position due to changes in the tracking centroid of the video return.

7.15 Scintillation

Amplitude modulation of the return due to changes in the apparent cross-sectional area of a complex target resulting in unstable range tracking performance.

7.16 Multipath

Range error and noise which are introduced into the system due to the different path lengths of the direct and reflected returns.

8. RECEIVING SYSTEM ERRORS

8.1 Frequency Detuning

Local oscillator (LO) detuning shifts the apparent center of the detected pulse envelope, creating a range error. RF boresight shifting errors can also be caused by local oscillator induced phase angle modulation effects.

8.2 Thermal Noise

8.2.1 Angle Component. The angle noise component generated by thermal noise in the radar angle receiver and tracking subsystems limits the precision of the angle error detection process resulting in a statistical random angular tracking error component.

8.2.2 Range Component. The range noise component generated by receiver thermal noise introduces a statistical random error into the precision of the range measurement.

8.3 Receiver Amplifier Mismatch

Improper receiver amplifier gain control and receive signal pulse width to amplifier bandwidth mismatch will result in video distortion and offset, causing a range bias error and larger systematic errors.

8.4 RF Axis Shift

8.4.1 RF Tuning. A change in the lock-on point as a function of the RF frequency. This is a systematic error which can be calibrated and corrected in real time by a computer. The effect is commonly encountered when changing operating frequencies or switching between skin and transponder track.

8.4.2 IF Tuning, Local Oscillator. Local oscillator detuning which may cause a shift of the lock-on point. Generally, this is minimized by the use of an Automatic Frequency Control (AFC) circuit.

8.4.3 RF Gain Selection Null Shift. A shift in the tracking null point caused by switching the parametric amplifiers on or off.

8.4.4 RF Null Shift with Frequency (Skin and Transponder). Shift of tracking null point caused by switching between skin and transponder track.

8.4.5 Difference between Linear/Circular Track Point. The shift of the tracking null point caused by a change of polarization selection.

8.5 Doppler Induced Errors

A receive signal doppler shift which results in an IF frequency offset with attendant range bias, RF axis shift, and signal degradation. The magnitude of these effects is dependent on the amount of the doppler shift and on the bandwidth of the receiver. The effects worsen as the system bandwidth narrows.

8.6 Nonoptimum Tracking Receiver Bandwidth Selection

Nonoptimum bandwidth selection results in degradation of signal-to-noise ratio (SNR) and may result in a range bias due to improper compensation for delay in the IF strip.

9. DATA HANDLING FACTORS

9.1 Nonlinearity Effects

Nonlinearity of such rotary translation devices as range and angle encoders, potentiometers, synchros, and resolvers will result in cyclic/angle-dependent errors of various magnitudes.

9.2 Encoder Quantum Error

A likely error resulting from minimum encoder resolution.

9.3 Sampling Rate Errors

a. Data resolution lost due to a data bandwidth limitation determined by the sampling rate.

b. Errors in synchro or resolver-to-digital converters at various shaft rotation rates.

9.4 Time Tag of Data Error (Data Recording)

One which occurs when the recorded time word does not coincide with the time of the data samples.

9.5 Data Transmission Errors

Errors in time correlation of transmitted data which arise when all data are not sampled simultaneously.

10. PRIME POWER VOLTAGE AND FREQUENCY INSTABILITY

Variations in prime power voltage or frequency that exceed the design capabilities of the system and result in random unpredictable errors of varying magnitudes.

11. SERVO ERRORS

11.1 Servo Noise

The hunting action of the tracking servo-mechanism which results from backlash, compliance and friction in the gears, shafts, bearings, and structures of the assembly.

11.2 Stiction (Starting Friction, Breakaway Torque)

The static friction which must be overcome to initiate movement of a mechanical servo system. The presence of stiction prevents the servo system from responding to small displacement errors and causes the servo to hunt across the target in a sawtooth or staircase function during low tracking rates. Stiction is the major contributor to angle noise during low tracking rates.

11.3 Lag Error

The difference between the position of the target and the position indicated by the physical position of the servo output shaft.

11.4 Servo Unbalance

The condition existing when the servo output is other than zero for a zero-input error signal. Servo unbalance results in a servo output which is not a true indication of the output.

11.5 Velocity Constant (Kv)

The constant ratio of servo error versus velocity. Kv is a measure of the gain of the servo system.

11.6 Acceleration Constant (Ka)

The constant ratio of servo error versus constant acceleration. Ka is a measure of the frequency response of the servo system.

11.7 Jerk Constant (Kj)

The ratio of servo error versus constantly changing acceleration. Kj is a measure of the third order derivative response of the servo system.

12. VELOCITY MEASUREMENT ERRORS

12.1 Radar Transmitter Errors

Those which result from phase contamination of the signal in the radar transmitter subsystem derived from the reference oscillator.

12.2 Radar Receiver Errors

12.2.1 Reference Oscillator Errors. Those which result from the frequency instability of the reference oscillator from which the transmitter and local oscillator frequencies are derived.

12.2.2 Frequency Discriminator Errors. Those comprised of zero set and drift bias errors in combination with tuning errors (shifts after calibration).

12.3 Doppler Servo Errors

12.3.1 Tracker Lag Error. A dynamic lag error which results from limitations imposed by servo design characteristics on the servo response to target velocity, acceleration, jerk, and higher derivatives of range.

12.3.2 Tracker Noise Error. A random error which is determined by the servo characteristics and the target SNR.

12.4 Signal-to-Data Conversion Errors

12.4.1 Doppler Frequency Granularity Error. A quantizing error which results from the conversion of the doppler frequency into a digital word to be used in the computation of radial velocity.

12.4.2 Transmitter Frequency Encoding Error. One which results from the conversion of the transmitter frequency to a digital word to be used in the computation of radial velocity.

12.4.3 Velocity of Propagation Encoding Error. One associated with conversion of velocity of propagation into a digital word to be used in the computation of radial velocity.

12.4.4 Velocity Readout Granularity Error. A quantizing error which results from choosing an erroneous value for the least significant bit of the velocity data word.

12.5 Target Dependent Errors

12.5.1 Flame Effect Errors. Those induced in velocity measurements which result from modulation of the RF signal by exhaust flame plasma in the region of the vehicle being tracked.

12.5.2 Velocity of Propagation Error. One which results from a difference between the true value of velocity of propagation and the assumed value used in computations.

12.5.3 Refraction Errors. Those caused by random fluctuations of the phase of RF signals due to atmospheric inhomogeneities along the signal path between the target and the radar.

12.5.4 Multipath Errors. Random errors which result from phase distortion of the RF signal due to the existence of more than one signal path between the radar and target.

12.5.5 Aspect Angle Change Errors

12.5.5.1 Skin (Echo) Track Errors. Those which result from deviations of the tracking phase center from the true phase center of the target as a function of aspect angle.

12.5.5.2 Coherent Transponder (Beacon) Track Errors. Those which result from changes in the transponder antenna pattern phase center with changes of aspect angle.

12.6 Coherent Transponder Errors

Those which result from contamination of the radar transmitted signal by the beacon circuits prior to retransmission of the signal.

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