FAA Key Integrity Risks
Update

2nd GBAS/FAA Europe Coordination Meeting
Technical Session 4.1:
Integrity Issues/Risk Reduction

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Overview

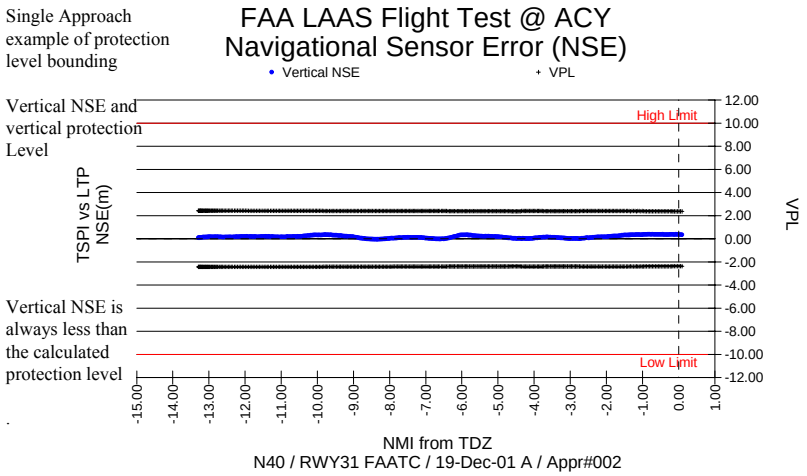
- LAAS Integrity Method
- Key Risk Areas
  - Integrity Parameters
  - Progress/Data
  - Work Items
- Summary

LAAS Integrity Method

- Responsibility for LAAS Integrity resides in the LAAS Ground Facility (LGF)
  - The user (aircraft) receives a set of integrity parameters from the LGF and applies those in a set of standardized equations to determine protection levels
  - The user must check the calculated result against the requirement
    - A protection level bound, or Alert Limit, is transmitted from the LGF with each procedure
- The Service Provider is responsible for ensuring that the uplink integrity parameters are accurate and that they provide the required function
  - When used in the specified equations, the protection level must always* bound the user error
    - *The probability of not bounding is the required integrity probability
      - CAT I is 2.0×10^{-7} per approach

Integrity Performance Protection Level Bounding

Single Approach example of protection level bounding



Key Risk Areas
LAAS Category I

- The FAA developed a list of the technical areas considered most challenging to both ground equipment manufacturers and certification authorities
- This list of CAT I Key Risks was used to establish priorities for FAA work
- Fifteen key areas have been identified
  - Risks are summarized on the next charts in numerical order with identified priority
  - Covered in detail in priority order

Key Risk Areas

KRA	Priority	Description
1	6	Position Domain to Range Domain Transformation
2	*14*	*Per Approach Integrity (Re-scoped and renamed)*
3 (1)	4	Correct PR Distribution (σ_{pr_gnd}) – Temporal Variation Effects
3 (2)	4	Corrected PR Distribution (σ_{pr_gnd}) – Site Variation Effects
3 (3)	4	Corrected PR Distribution (σ_{pr_gnd}) – Time Correlation Effects (e.g., measurement sampling rate effects)
3 (4)	4	Corrected PR Distribution (σ_{pr_gnd}) – AZ/EL Correlation
3(5)	4	RR Independence (σ_{pr_gnd})
3(6)	4	Iono Divergence (σ_{pr_gnd})

Key Risk Areas Continued

KRA	Priority	Description
4	2	Non-Zero Mean
5	8	RFI
6	5	Sigma Monitoring
7	1	Sigma Iono Characterization and Monitoring
8	14	Sigma Tropo Characterization and Monitoring
9	7	Ephemeris (Type B) Characterization and Monitoring
10	7	Ephemeris (Type A) Characterization and Monitoring
11	3	Signal Deformation Monitoring (SDM) (a.k.a., Evil Waveforms)

Key Risk Areas Continued

KRA	Priority	Description
12	12	Low Power Monitoring
13	10	Code/Carrier Divergence Monitoring
14	11	Excessive Acceleration Monitoring
15	13	Executive Monitor (e.g., resolving RR and SV errors)
16	9	Per Approach Integrity LAAS Fault Tree Analysis

Key Risk Area 7
Sigma Ionosphere

- Highest priority Risk area
  - Ionosphere activity is variable depending on location
  - Recent solar storms (10-11/2003) have produced some of the worst gradients in CONUS US
- Ionospheric work will be covered in detail in a later briefing
- Parameters and requirements for KRA 7 are covered in this briefing

KRA 7 Integrity Parameters

RTCA LAAS CAT I ICD $\sigma_{vert_iono_gradient}$

2.4.4.2 Message Type 2 Parameters

$\sigma_{vert_iono_gradient}$: is the standard deviation of a normal distribution associated with the residual ionospheric uncertainty due to spatial decorrelation such that the uncertainty in the differential ionosphere delay correction is:

$$\sigma_{iono} = F_{PP} \times \sigma_{vert_iono_gradient} \times (x_{air} + 2 \times \tau \times v_{air})$$

where:

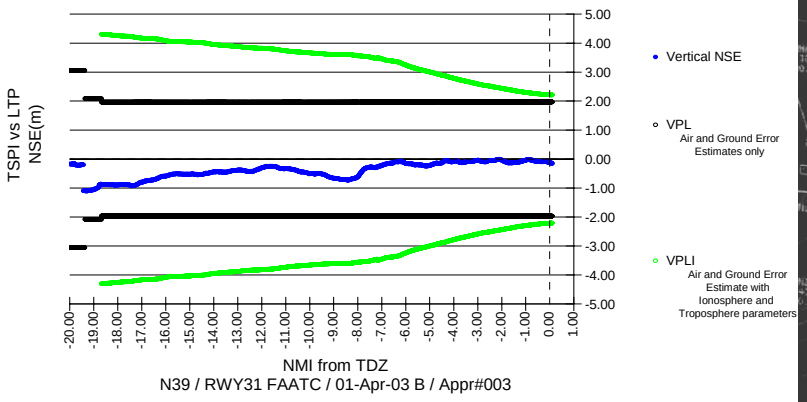
F_{pp} = the vertical-to-slant obliquity factor for the given satellite and

$$F_{pp} = \left[1 - \left(\frac{R_e \cos \theta}{R_e + h_I} \right)^2 \right]^{-\frac{1}{2}}$$

R_e = radius of the earth = 6378.1363 km
h_I = ionospheric shell height = 350 km
θ = the elevation angle of satellite
$\sigma_{vert_iono_gradient}$ = parameter provided by the ground subsystem in Message Type 2
x_{air} = slant range distance in meters between the current aircraft location and the reference point
τ = 100 seconds, the time constant of the smoothing filter
v_{air} = the horizontal speed of the aircraft in meters/sec

KRA 7
Integrity Performance

FAA LAAS Flight Test @ ACY
Navigational Sensor Error (NSE)



KRA 7 Integrity Parameters

$\sigma_{vert_iono_gradient}$

FAA Specification

3.2.1.3.5 Sigma Ionosphere

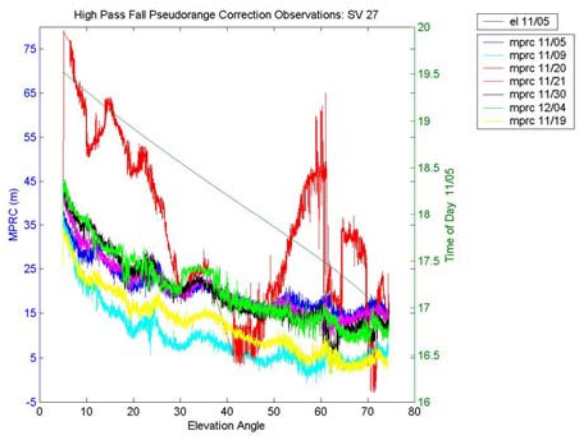
The Sigma Vertical Ionosphere Gradient Field shall denote the value stored in LGF NVM.

3.2.1.3.5.1 Condition for Valid Sigma Ionosphere

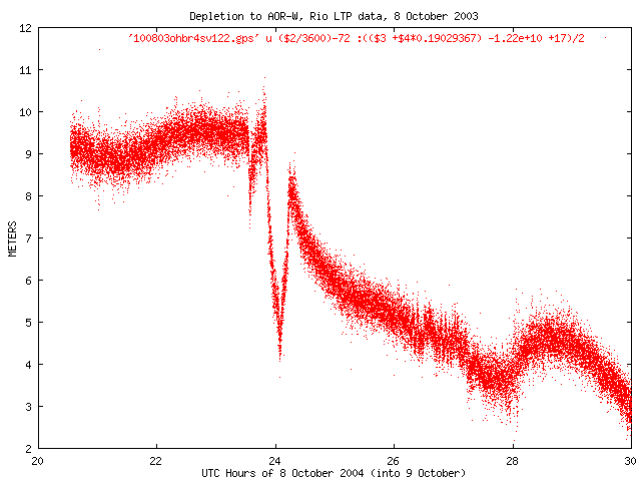
The LGF shall detect Ionospheric conditions that result in noncompliance with the requirements in Sections 3.1.2.1 and 3.1.2.2. When the increase in system risk associated with increased ionosphere gradients exceeds design tolerances, the LGF shall exclude the offending ranging source(s) and generate alerts as appropriate. When ionospheric disturbances cannot be isolated to specific ranging sources, and system risk is not minimal (increases by more than one order of magnitude) as a result, the LGF shall generate an alarm. Self-recovery shall be accomplished after ranging source exclusions or alarms are generated once the integrity requirements in Sections 3.1.2.1 and 3.1.2.2 are again met. The probability of a false alarm shall be less than 5×10^{-8} per 15-second interval.

Note: The sigma ionosphere vertical gradient term must be valid for all users within D_{max} from the LGF reference point, as identified in Section 3.1.2.

KRA 7 Integrity Parameters
Ionospheric Anomaly 11/20/2003
LTP Pseudorange Correction



KRA 7 Integrity Parameters
Ionosphere Bubble 10/08/2003
WAAS Geo (122) as Observed by the LTP



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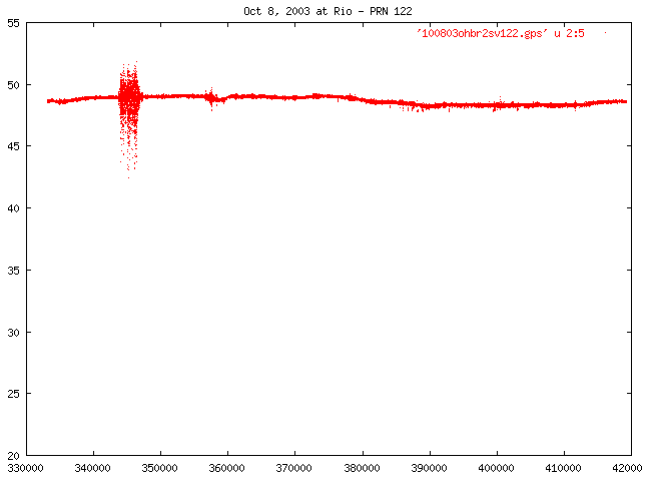
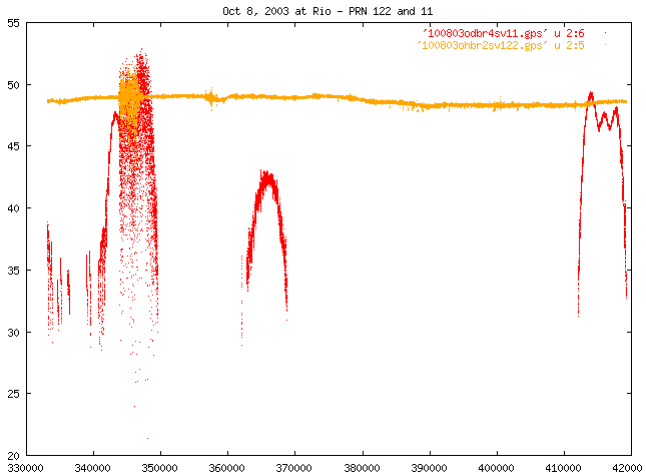


KRA 7 Integrity Parameters
Ionosphere Bubble 10/08/2003

C/N0 of the WAAS Geo (122) and SV11 as Observed by the LTP



Key Risk Area 7
Sigma Ionosphere

- **Work Items**
- Determine nominal values for $\sigma_{vert_iono_gradient}$
- Validate bounding performance
  - Simulation
  - Data replay of nominal data and storms
- Develop the treat model for Anomalous Ionospheric events
  - Determine what parts of the threat space can be detected or mitigated by existing ground monitors
  - Determine what additional ground monitors can achieve
    - Storm precursor event monitors
  - Develop mitigation methods to provide integrity during ionospheric events

Key Risk Area 3
Corrected Pseudorange Error Distribution "Overbounding"

- Priority 4 risk area
- Six-part KRA covering:
  - 3 - (1) Temporal variation, both seasonal and environmental changes
  - 3 - (2) Site Specific installation criteria
  - 3 - (3) Time correlation of measurements and sampling choices
  - 3 - (4) AZ/EL Characterization, binning and masking
  - 3 - (5) Independence of measurements between reference receivers
  - 3 - (6) Impact of Ionospheric divergence on smoothing filter transient error behavior

LAAS Integrity Protection Level Equations

Fault Free Integrity

- Primary LAAS integrity come from the measured statistical performance of the LGF
  - Error in the calculation of pseudorange corrections
  - The uplink parameter is σ_{pr_gnd}, a one sigma estimate of the correction error
  - This parameter is set at installation using a service provider approved procedure
    - Proving the procedure is correct is the responsibility of the manufacturer
    - The LGF must continuously monitor the correction performance to ensure the broadcast σ_{pr_gnd} is still accurate
- Method relies on range domain error analysis to represent position domain error

KRA 3 Integrity Parameters

LGF Specification σ_{pr_gnd}

3.2.1.2.8.7.1 GPS Sigma Pseudorange Accuracy

In the standard interference environment defined in appendix D of the LAAS MOPS (RTCA/DO-253A), the accuracy of the LGF shall be such that the broadcast σ_{pr_gnd} satisfies the following inequality:

$$\sigma_{pr_gnd}(\theta_n) \le \sqrt{\frac{\left(a_0 + a_1 e^{-\theta_n/\theta_0}\right)^2}{M(n)} + (a_2)^2} \qquad (6)$$

where θ_n is the nth ranging source elevation angle, a_0, a_1, a_2, and θ_0 are the coefficients for the applicable Accuracy Designator defined in Table 3-3.

Table 3-3. GPS Accuracy Designator C Coefficients

Accuracy Designator C	a_0 meters	a_1 meters	a_2 meters	θ_0 degrees
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LAAS Integrity
Protection Level Equations
Fault Free Integrity

- The H_0, or fault-free hypothesis equation, combines the ground error estimate and a similar airborne estimate and multiplies the sum by a geometry projection unit vector Sii for each SV
  - Sii provides the weight, or relative importance of each SV in the solution
- Given by the equation:

$$PL_{Apr_H0} = K_{ffmd}\sqrt{\sum_{i=1}^{N} s_{Apr,i}^2 \sigma_{i_H0}^2}$$

$$\sigma_{i_H0}^2 = \sigma_{pr_gnd}^2[i] + \sigma_{tropo}^2[i] + \sigma_{pr_air}^2[i] + \sigma_{iono}^2[i]$$

- This equation is essentially a geometry filter, that excludes certain constellations based on the capability of the ground and airborne system

Key Risk Area 3
Corrected Pseudorange Error

- Data and analysis must show that the value selected for σ_{pr_gnd} is appropriate for any user
  - Must include non-Gaussian characteristic present in the observed or expected distributions
  - Must include consideration of seasonal changes, environmental changes
    - May be characterized by long-term data collection with test systems
    - A methodology must be established to approve installations in a reasonable period of time
    - Sigma Monitor required (KRA 6) to protect against sudden changes
  - Must take into account changes in the orbital tracks of the ranging sources
    - A GPS signal model capable of producing predicted errors based on the installed environment is required to augment collected performance data where no SV measurements are available

Key Risk Area 3
Corrected Pseudorange Error
LAAS Test Prototype Error Samples

- Long-term observation of GPS ranging errors using Ground Accuracy Designator C equipment is ongoing
  - Near continuous LTP raw data collection since 9/98
    - dB Systems MLA antennas
    - Novatel OEM3, OEM4, LGF4 receivers
    - Simultaneous L1/L2 Ashtech data for Ionospheric delay estimation and removal
- Errors are estimated by using code-minus-carrier observables
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  - One day per two-weeks of data; 1 sample per 200 seconds
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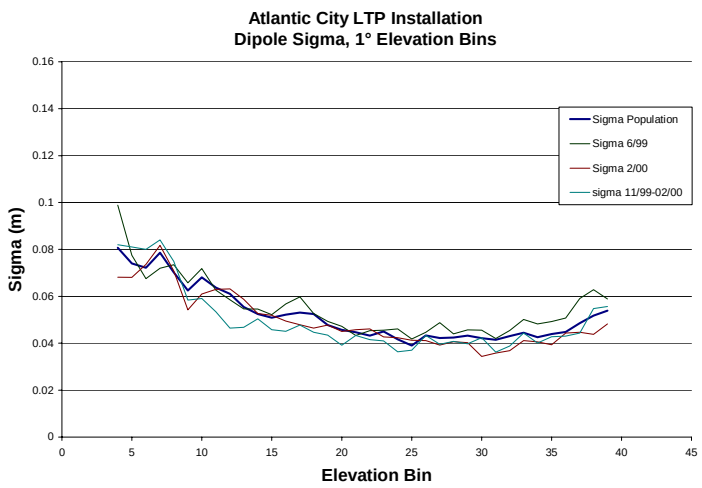
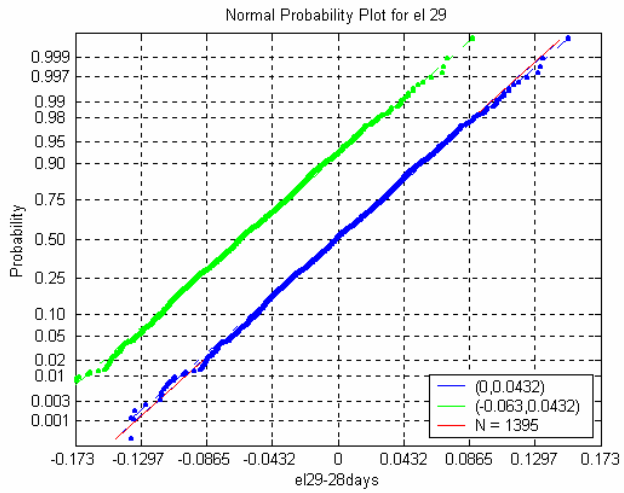
Key Risk Area 3
Corrected Pseudorange Error



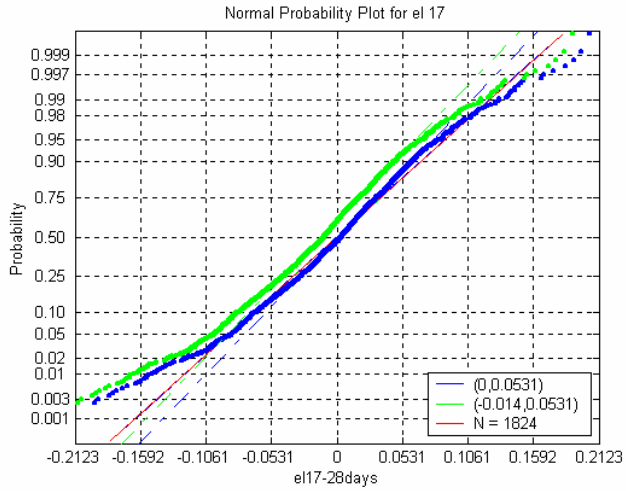
Comparison of short-term and long-term statistical correction error performance FAA LTP

Key Risk Area 3
Corrected Pseudorange Error



Distribution Analysis
Gaussian nature of data
Gaussian log-normal plot
One degree elevation Bin

Key Risk Area 3
Corrected Pseudorange Error



Distribution Analysis
Non-Gaussian data
Gaussian log-normal plot
One degree elevation Bin

Key Risk Area 3
Corrected Pseudorange Error
Normal Inverse Gaussian

– Normal Inverse Gaussian (NIG) defines a family of distribution shapes that range from Gaussian to very heavy tails

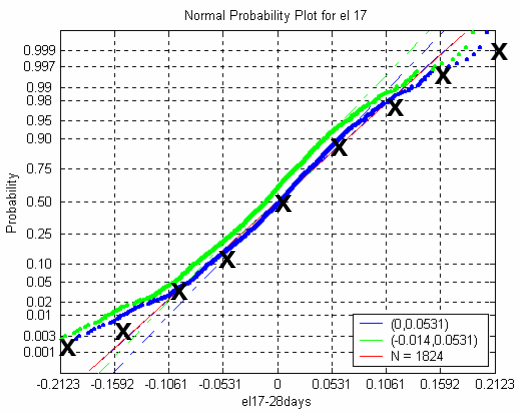
$$\mathrm{NIG}(r,\delta_0,M,\sigma_0)=\frac{M\delta_0^{\,2}}{\pi}\frac{\exp\left(M\delta_0^{\,2}\right)}{\sqrt{r^2+\sigma_0^{\,2}\delta_0^{\,2}}}K_1\left(\frac{M\delta_0}{\sigma_0}\sqrt{r^2+\sigma_0^{\,2}\delta_0^{\,2}}\right)$$

r: multipath error
δ_0: distribution shape parameter for single reference receiver
M: number of reference receivers
σ_0: multipath sigma for 1 RR
Note σ_0 can be set equal to 1 without any loss of generality
K_1: modified Bessel function of the second kind, degree 1

– The NIG PDF used here is a modification of that found in the literature

MITRE CAASD

Key Risk Area 3
Corrected Pseudorange Error
Normal Inverse Gaussian



– Shape parameter (δ_0) defines NIG

MITRE CAASD

LAAS Integrity
Protection Level Equations H_1

- An additional source for LAAS integrity come from the measured real-time performance of the measured range comparisons
  - Error in the calculation of pseudorange corrections
  - The uplink parameters are the B-values
  - These are estimate of the instantaneous code noise and multipath of each reference receiver
- Method relies independence of reference receiver measurement
  - Any error common to multiple references will be averaged into the correction and will not be evident in the B-value
- A protection level for each reference receiver is calculated

$$PL_{H1,j} = \left| \sum_{i=1}^{N} S_i B_{i,j} \right| + K_{md} \sigma_{H1}$$

Key Risk Area 3
Corrected Pseudorange Error

- Work Items
  - Continue collection and characterization of LAAS Ranging errors
    - Long-term FAA site, Atlantic City NJ
    - Additional test locations
    - LAAS vendor testing
      - Develop a database of locations with observed data over time and environmental changes
  - Describe observed distributions using NIG tool
    - Provides an basis for non-Gaussian sigma inflation
    - Provides mathematical language to describe field data
  - Quantify protection provided by H1
  - Continue math modeling efforts to predict performance

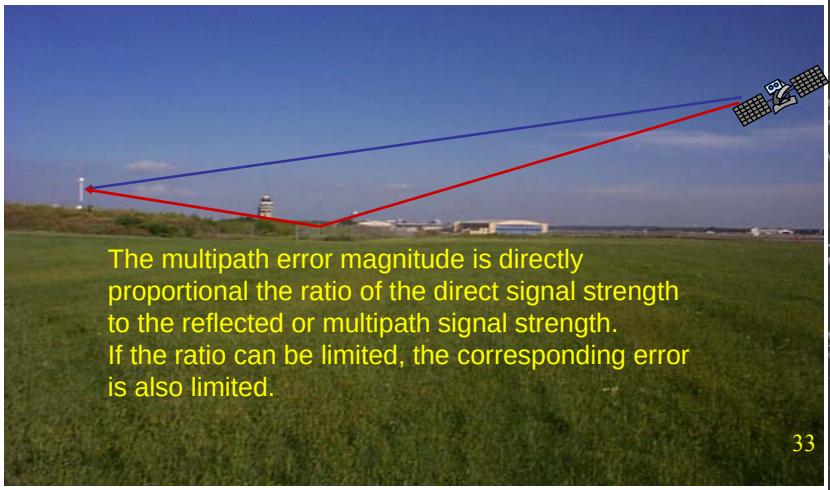
Summary

- LAAS uses a number of protection level equations that include statistical and instantaneous measures of system performance
  - The LAAS Ground Facility is required to monitor the validity of the statistical parameters is broadcasts
- The KRAs each examine the details of the integrity parameters used in these protection levels and the combined coverage of the multiple protection levels
- Discussion of the remaining KRAs are provided in additional slides

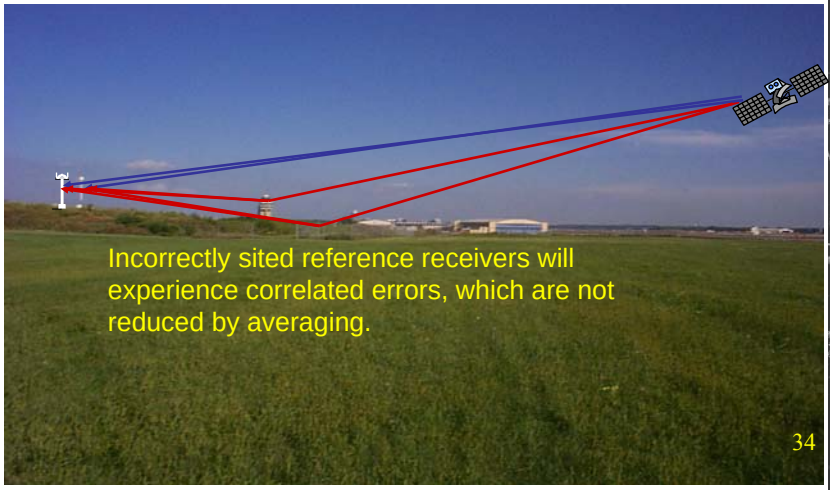
Key Risk Area 4
Non-Zero Mean Errors

- Second highest priority risk area
  - LAAS integrity parameters represent Pseudorange correction errors as zero-mean Gaussian distribution
  - Error sources that may cause non-zero mean errors must be calibrated or proven insignificant
    - Single reflection ground bounce multipath has the highest potential to produce significant long-term or bias-like errors
  - Multipath limiting antenna (MLA) technology utilize antenna patterns to mitigate ground multipath
    - MLA code and carrier phase center biases have proven difficult to calibrate
    - MLAs also increase the dynamic range of GPS input power

Key Risk Area 4
Non-Zero Mean Errors
Single Reflection Ground Multipath



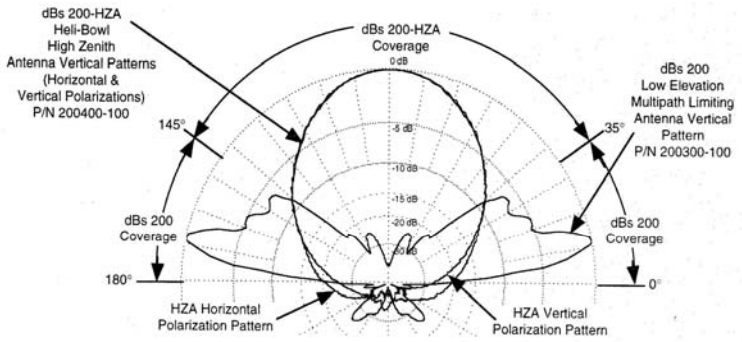
Key Risk Area 4
Non-Zero Mean Errors
Potential Correlation of Ground Multipath



Key Risk Area 4
Non-Zero Mean Errors
Multipath Limiting Antenna

- The MLA is a two-part antenna system
  - Dipole array for Satellites at elevation angles between 5 and 30 degrees
    - High Gain lobe in Coverage Volume
    - Sharp Gain Reduction Below 5 degrees
    - 35dB Direct to Indirect (Ground Reflection) Ratio
      - *Bounds errors from ground reflections to 0.2m
  - High Zenith Array (HZA) for Remaining Coverage
- Introduced by Dr. Mike Braasch of Ohio University "Optimum Antenna Design for DGPS Ground Reference Stations," ION GPS-94, 20-23 September 1994

Key Risk Area 4
Non-Zero Mean Errors
Multipath Limiting Antenna



IMLA Antenna Patterns Superimposed

dBsystems Inc.

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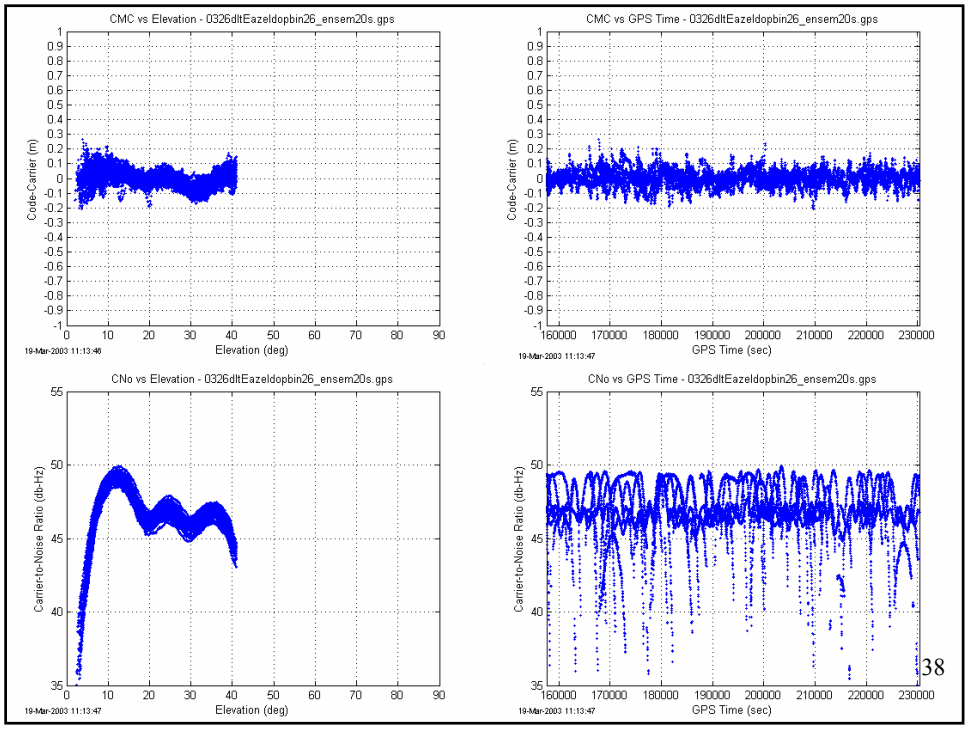
CMC vs Elevation - 0326dltEazeldopbin26_ensem20s.gps
Code-Carrier (m)
Elevation (deg)
19-Mar-2003 11:13:46
CMC vs GPS Time - 0326dltEazeldopbin26_ensem20s.gps
Code-Carrier (m)
GPS Time (sec)
19-Mar-2003 11:13:47
CNo vs Elevation - 0326dltEazeldopbin26_ensem20s.gps
Carrier-to-Noise Ratio (db-Hz)
Elevation (deg)
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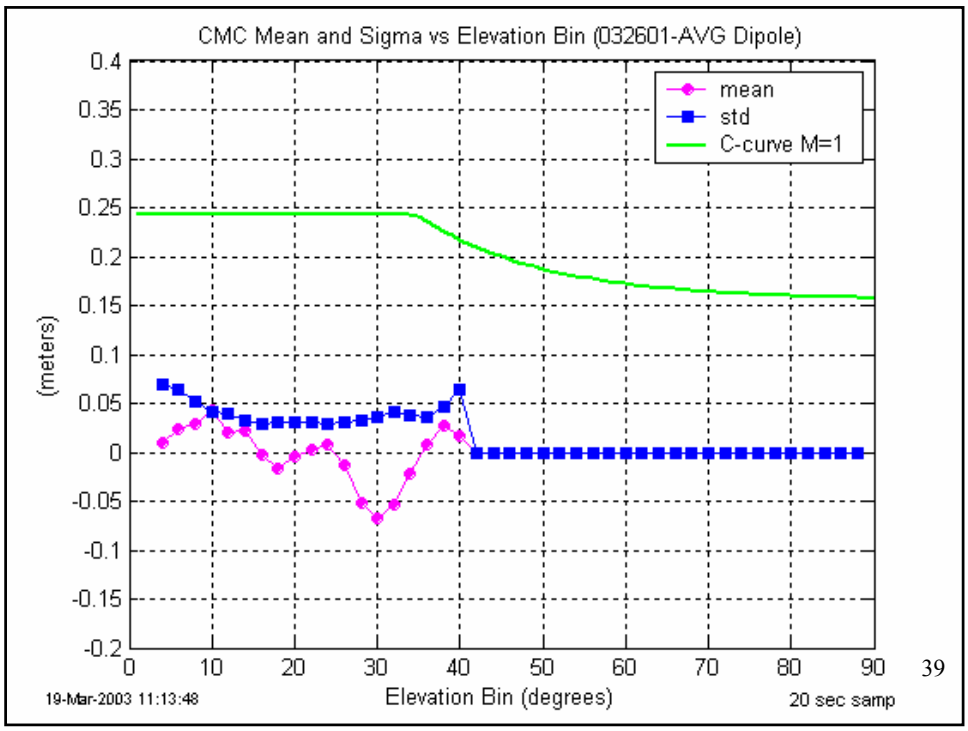

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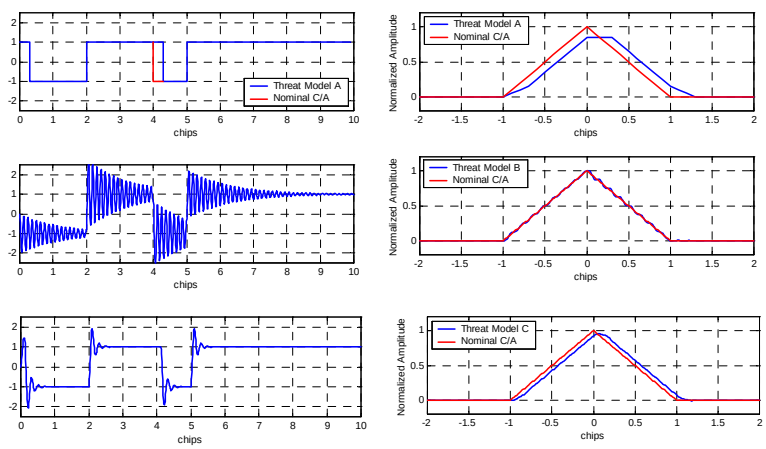
Key Risk Area 4
Non-Zero Mean Errors

- Work Items
  - Continue collect and characterize GPS pseudorange correction data
    - Identify all sources of long-term or bias-like errors. Show that they are:
      - Insignificant
        - » Calibrated
        - » Mitigated by antenna/receiver technology
        - » Mitigated by siting requirements
      - Bounded by the broadcast integrity parameter
  - Determine calibration for current MLA

Key Risk Area 11
Signal Deformation Monitor

- Priority 3 risk area
- Signal deformation was shown to cause non-differentially correctable errors when user and reference GPS reception techniques differed
- Although there is a well-developed, internationally coordinated threat model, several implementation issues remain:
  - Proof of acceptable false alarm and missed detection performance
    - Characterize the performance in the presence of multipath
    - Develop the IF filter model to incorporate variation over the range of expected nominal receiver production
  - Demonstration and analysis to prove that all transient modes are protected within the existing threat space
  - Demonstrate the implementation can be adequately tested

Key Risk Area 11
Signal Deformation Monitor



Key Risk Area 11
Signal Deformation Monitor

- Work Items
  - Continue to work SDM with LAAS vendor and Government team
    - Prove that the monitor protects all users and under all conditions
  - Monitor US Wide Area Augmentation System performance
    - Detects several forms of signal deformation
    - Collecting performance data with prototype equipment
  - Further develop simulation and test capability
    - Simulation capability for generation of integrated SQM failure modes
    - Develop statistical test methods to evaluate SQM failures

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Corrected Pseudorange Error Distribution "Overbounding"

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LAAS Integrity Protection Level Equations

Fault Free Integrity (2)

- In addition to the pseudorange error measurement statistics, H_0 also includes terms for ionosphere and troposphere.
  - $\sigma_{vert_iono_gradient}$, discussed in KRA 7
  - Scale Height -
  - Refractivity Index | Discussed in KRA 8
  - Refractive Uncertainty -
- These terms increase in significance as the range from the LGF reference point increases
  - 4mm/km is used in the presented plots
- Compliance must be monitored
  - Unpredicted conditions must be protected
    - Increase the transmitted values or shut down the LGF

LAAS Integrity Protection Level Equations

Fault Free Integrity (3)

- The H_0, or fault-free hypothesis equation, combines the ground error estimate and a similar airborne estimate and multiplies the sum by a geometry projection unit vector Sii for each SV
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Key Risk Area 3
Corrected Pseudorange Error
Temporal Variation 3 – (1)

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  - Must include non-Gaussian characteristic present in the observed or expected distributions
  - Must include consideration of seasonal changes, environmental changes
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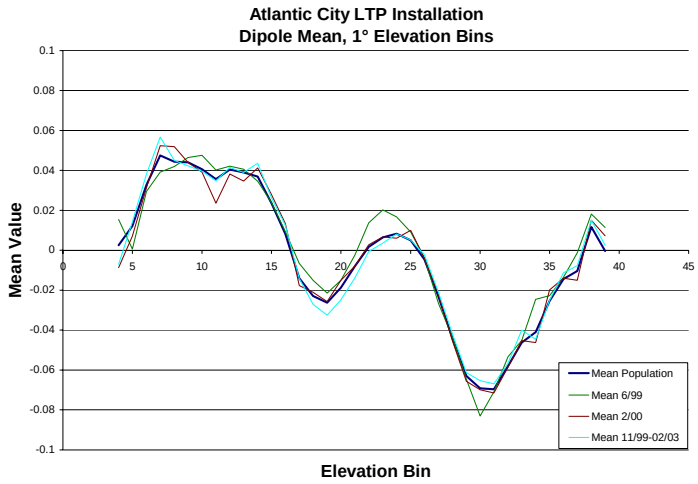
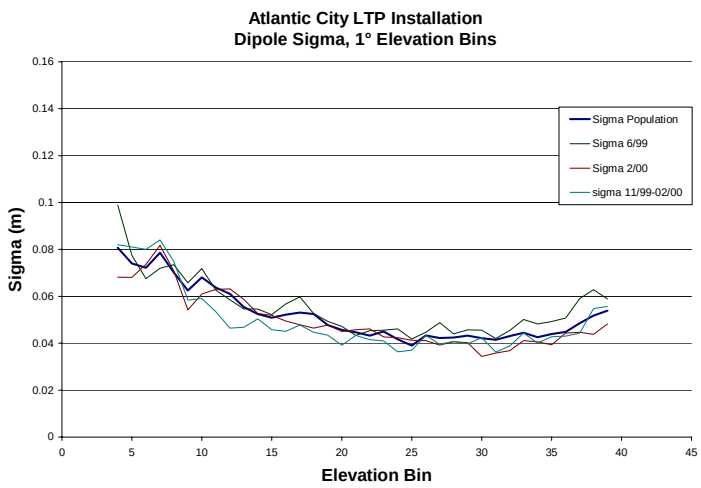
Key Risk Area 3
Corrected Pseudorange Error
Temporal Variation 3 – (1)



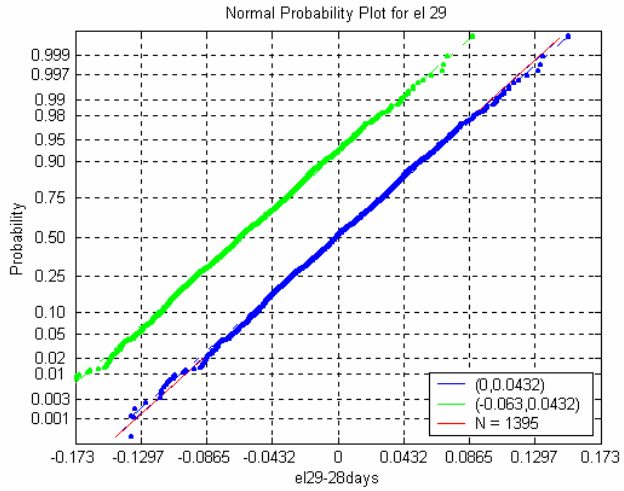
Comparison of short-term and long-term mean correction error performance

Key Risk Area 3
Corrected Pseudorange Error
Temporal Variation 3 – (1)



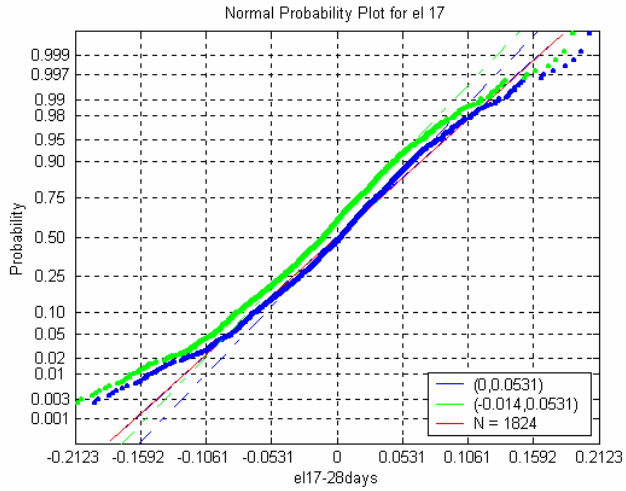
Comparison of short-term and long-term statistical correction error performance FAA LTP

Key Risk Area 3
Corrected Pseudorange Error
Temporal Variation 3 – (1)



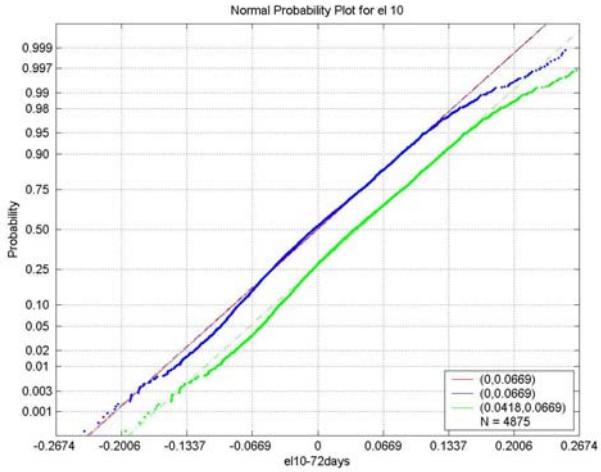
Distribution Analysis
Gaussian nature of data
Gaussian log-normal plot
One degree elevation Bin

Key Risk Area 3
Corrected Pseudorange Error
Temporal Variation 3 – (1)



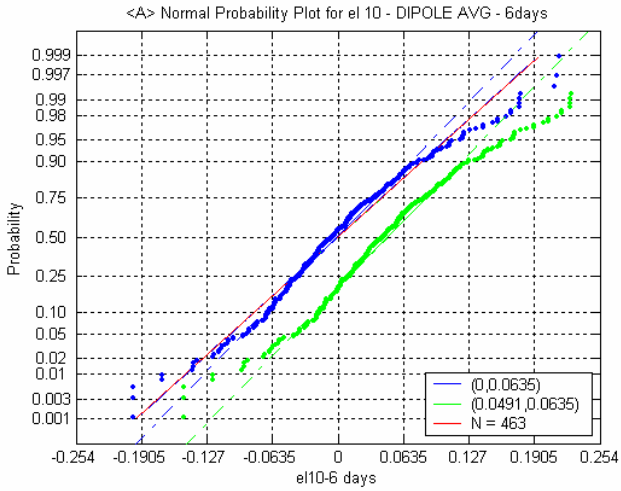
Distribution Analysis
Non-Gaussian data
Gaussian log-normal plot
One degree elevation Bin

Key Risk Area 3
Corrected Pseudorange Error
Temporal Variation 3 – (1)



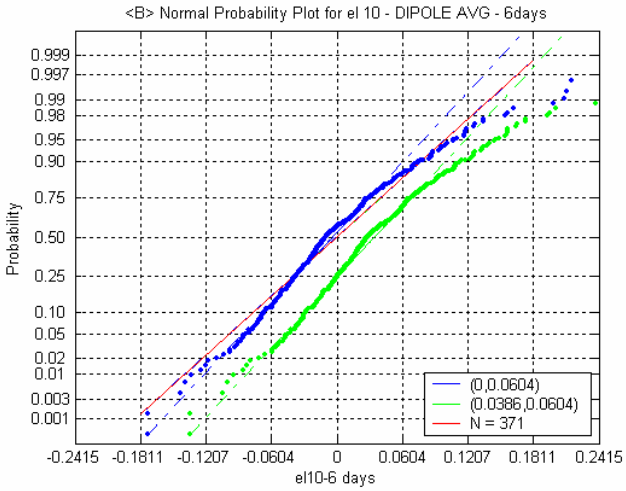
Distribution Analysis
Gaussian log-normal plot
One degree elevation Bin

Key Risk Area 3
Corrected Pseudorange Error
Temporal Variation 3 – (1)



Distribution Analysis
Gaussian log-normal plot
One degree elevation Bin

Key Risk Area 3
Corrected Pseudorange Error
Temporal Variation 3 – (1)



Distribution Analysis
Gaussian log-normal plot
One degree elevation Bin

Key Risk Area 3
Corrected Pseudorange Error
Temporal Variation 3 – (1)

- Observed data does not have significant temporal variation properties
- Distribution tails are consistently fatter that Gaussian
  - Mixture possibility suggested
    - Pooling data from distributions with dissimilar sigmas
  - Systematic errors proving limiting error analysis
    - KRA 4 high priority
- Distribution repeatability is a positive aspect

Key Risk Area 3
Corrected Pseudorange Error
Normal Inverse Gaussian

– Normal Inverse Gaussian (NIG) defines a family of distribution shapes that range from Gaussian to very heavy tails

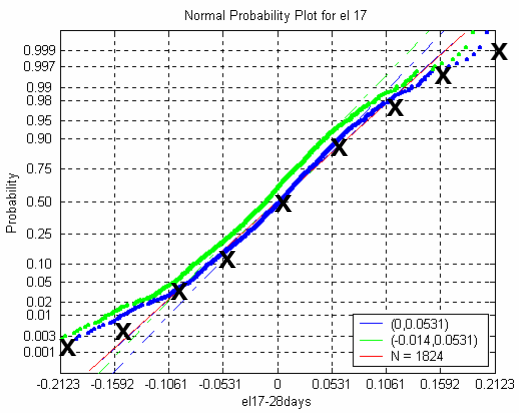
$$\mathrm{NIG}(r,\delta_0,M,\sigma_0)=\frac{M\delta_0^{\,2}}{\pi}\frac{\exp\left(M\delta_0^{\,2}\right)}{\sqrt{r^2+\sigma_0^{\,2}\delta_0^{\,2}}}K_1\left(\frac{M\delta_0}{\sigma_0}\sqrt{r^2+\sigma_0^{\,2}\delta_0^{\,2}}\right)$$

r: multipath error
δ_0: distribution shape parameter for single reference receiver
M: number of reference receivers
σ_0: multipath sigma for 1 RR
Note σ_0 can be set equal to 1 without any loss of generality
K_1: modified Bessel function of the second kind, degree 1

– The NIG PDF used here is a modification of that found in the literature

MITRE CAASD

Key Risk Area 3
Corrected Pseudorange Error
Normal Inverse Gaussian



– Shape parameter (δ_0) defines NIG

MITRE CAASD

Key Risk Area 3
Corrected Pseudorange Error

Temporal Variation 3 – (1)

- Work Items
  - Continue collection and characterization of LAAS Ranging errors
    - Long-term FAA site, Atlantic City NJ
    - Additional test locations
    - LAAS vendor testing
  - Describe observed distributions using NIG tool
    - Provides an basis for non-Gaussian sigma inflation
    - Provides mathematical language to describe field data
  - Develop a database of locations with observed data over time and environmental changes
  - Continue math modeling efforts to predict performance

Key Risk Area 3
Corrected Pseudorange Error

Site Specific Installation Criteria 3 – (2)

- The FAA is in the process of defining siting criteria and installation procedures to support the acquisition and fielding LAAS
  - Based on equipment used to validate LAAS requirements and FAA math modeling efforts
  - The LAAS manufacturer is responsible for development of a siting plan that will contain engineering siting criteria, siting procedures, operational considerations, and cost tradeoffs.
  - Specific to their design and equipment
    - Required clear areas, equipment separation
- Must consider the need to maintain any assumption made during the installation and approval process

Key Risk Area 3
Corrected Pseudorange Error

Site Specific Installation Criteria 3 – (2)

- Work Items
  - Continue to refine the FAA capability to model airport environment
    - Predict ranging errors based on obstacles
  - Develop criteria for locating LAAS equipment in airport environments
    - FAA LAAS siting order
  - Ensure vendor results agree with FAA expectations
  - More discussion in session 4.1.6 “LAAS Siting Analysis”

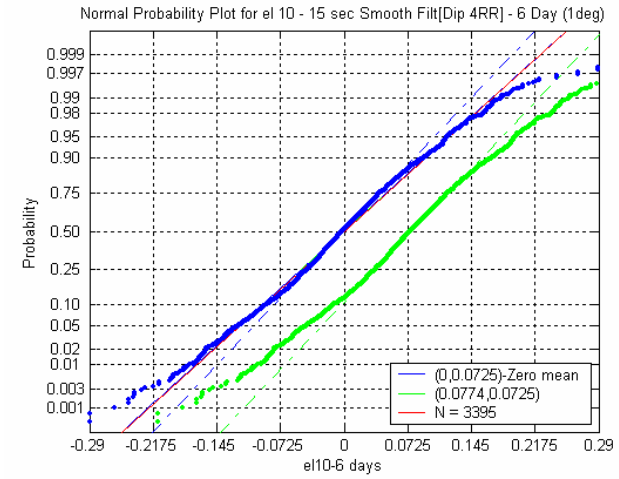
Key Risk Area 3
Corrected Pseudorange Error

Time correlation 3 – (3)

- In order to properly determine the appropriate statistical confidence in a given data set, the time correlation must be considered
- Carrier Smoothed Code filter correlates pseudorange correction errors over time
  - Current conservative correlation time considered to be twice the smoothing time constant, 200 seconds
  - Sampling for independence limits the number of samples available for LAAS monitor
    - Limits reaction time
    - Limits confidence based on the number of samples available

Key Risk Area 3
Corrected Pseudorange Error

Time correlation 3 – (3)



Distribution Analysis
Gaussian log-normal plot
One degree elevation Bin

Shorter time constant applied to evaluate similarity of resulting distribution

Key Risk Area 3
Corrected Pseudorange Error

Time correlation 3 – (3)

- Work Items
  - Analyze techniques to utilize alternate smoothing, binning, and sampling improve monitor confidence and reaction time
  - Analyze true time correlation of reference receiver data
    - Determine if 200 second sampling is appropriate

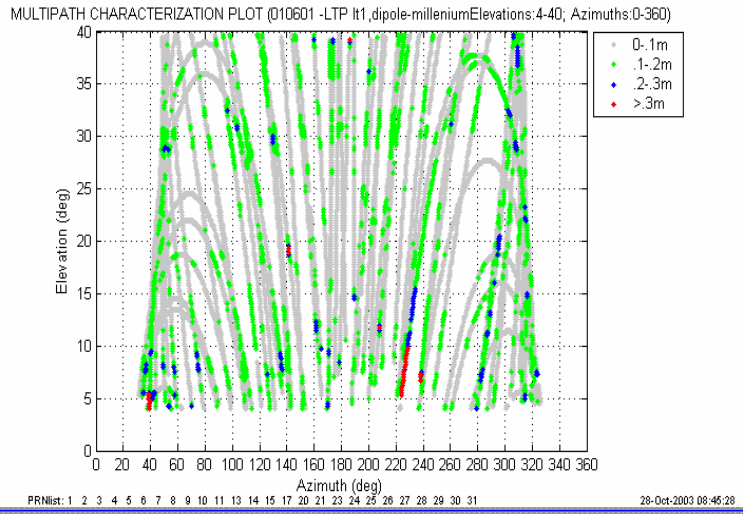
Key Risk Area 3
Corrected Pseudorange Error

Az/El Characterization 3 – (4)

- Each Pseudorange correction must be broadcast with an overbounding sigma
  - Sigma estimate must remain accurate with SV motion
- Gaining sufficient independent samples at discrete SV locations remains a challenge
  - Trade off between SV motion and Time correlation
  - Smaller bins may provide the best description of the ranging error performance
  - Small number of samples acquired yield low confidence statistics

Key Risk Area 3
Corrected Pseudorange Error

Az/El Characterization 3 – (4)

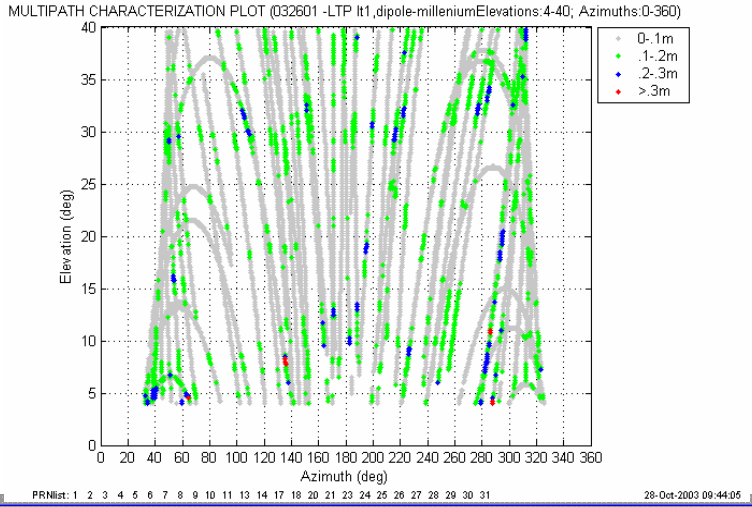


Sky Plot view of LTP observed Errors
Single Reference 01/06/01

Small Az/El bins are used to collect maximum observed errors

Key Risk Area 3
Corrected Pseudorange Error

Az/El Characterization 3 – (4)



Sky Plot view of LTP observed Errors
Single Reference
02/26/01

Typical Variation of observed errors

Key Risk Area 3
Corrected Pseudorange Error

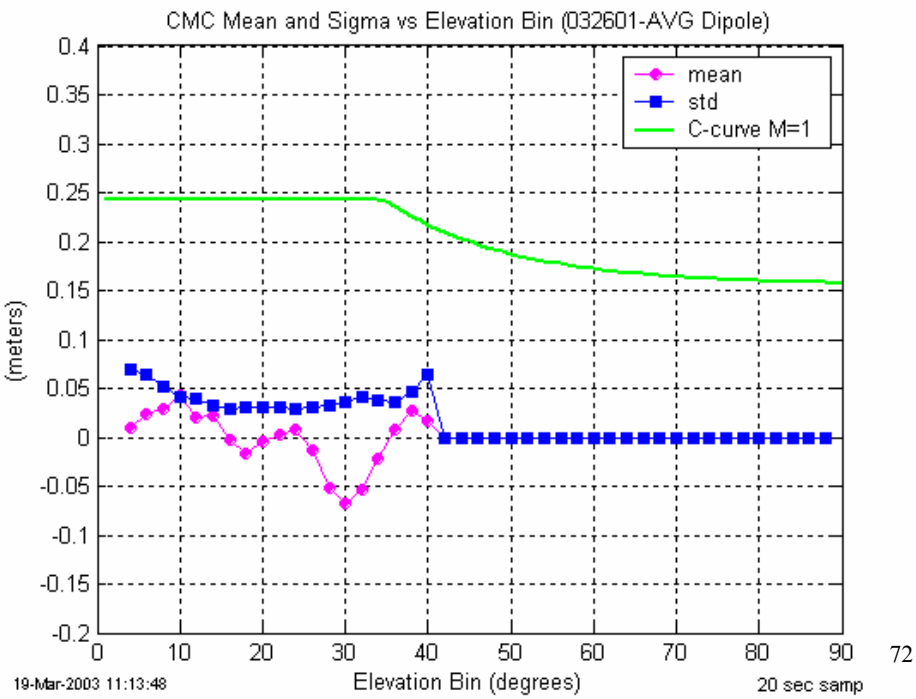
Az/El Characterization 3 – (4)

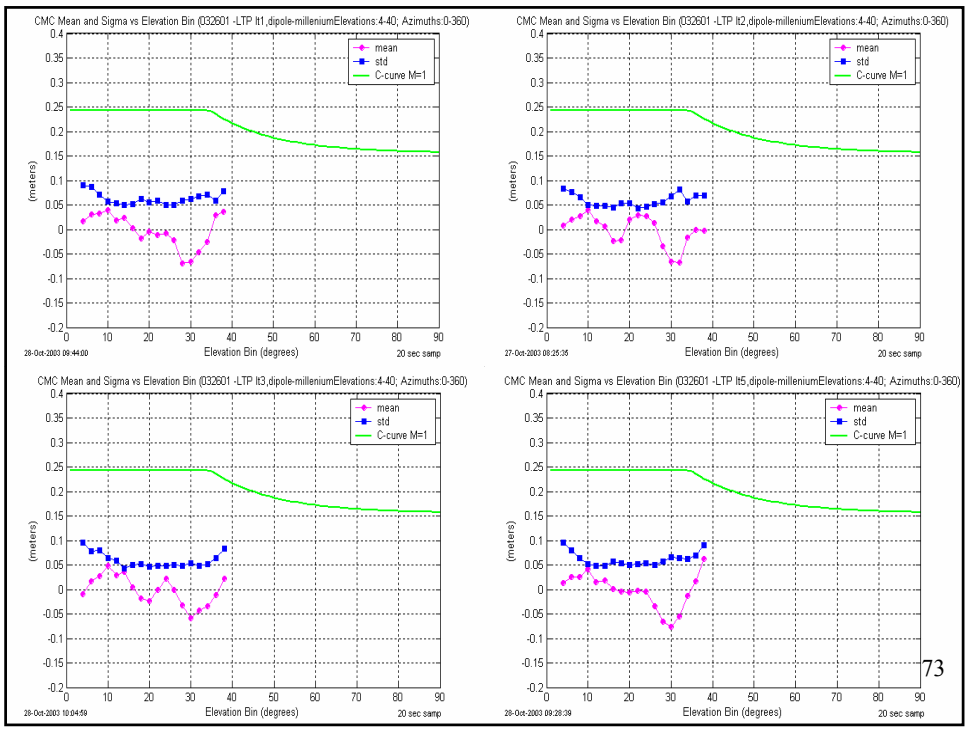
- Work Items
- Analyze tradeoff between Az/El bining, sampling, and required confidence
  - Number of samples available for monitor decision

Key Risk Area 3
Corrected Pseudorange Error

Reference Receiver Independence 3 – (5)

- LAAS relies on having multiple independent measures of each pseudorange
  - Reduce noise in LAAS corrections
    - $\sigma_{ave} = \sigma_{rr} / \text{sqrt}(M)$
  - Provide B-value measurements for per-epic protection level sensitivity to receiver failure
    - Including large, unpredicted multipath errors
- Correlated errors pass directly in pseudorange corrections
- Object-based correlation can be predicted by accurate GPS error models and mitigated by siting
  - Considered in siting analysis and site specific parameter KRA





Key Risk Area 3
Corrected Pseudorange Error

Reference Receiver Independence 3 – (5)

- Work Items
  - Determine why expected noise reduction is not achieved
    - Single reference data sigmas are not generally reduced by the expected sqrt(M)
  - Continue link with LAAS Siting efforts
    - Ensure LAAS siting guidelines consider independence requirement

Key Risk Area 3
Corrected Pseudorange Error

Ionospheric divergence 3 – (6)

- Determine the impact of ionospheric divergence on the carrier smoothed code filter transient behavior

- Work Plan
  - Ionosphere storm analysis under KRA 7 has limited the work being done on this topic
  - Storm threat model determination will help bound these errors
    - Storm conditions will not be counted in this KRA

Key Risk Area 6
Sigma Monitor

- Priority 5 risk area
- LAAS Protection level bounding requires that the broadcast sigma represent the current pseudorange correction noise
- Monitoring must be capable of maintaining and confirming the prior probability of 10^{-5} of latent Reference Receiver faults
- Trade off areas include sample independence, AZ/EL binning, and required confidence

Key Risk Area 6
Sigma Monitor

- Work Items
  - Monitor the performance of the test systems
    - Short-term and long-term analysis
    - Position monitor performance
  - Continue to examine the results of KRA 3 – (1) to determine which events may trigger temporal variation
  - Evaluate algorithms to improve response time

Key Risk Area 1
Position Domain Error Bound

- Priority 6 risk area
- Proof that the broadcast integrity parameters provide the required position bound for all users
  - Broadcast σ_{pr_gnd}
  - Ionospheric parameters and anomalous detection capability
  - Broadcast P-value covers users at any location within the coverage volume
  - Tropospheric parameters under all potential conditions
  - Combination fault free (H0) and faulted (H1) protection levels

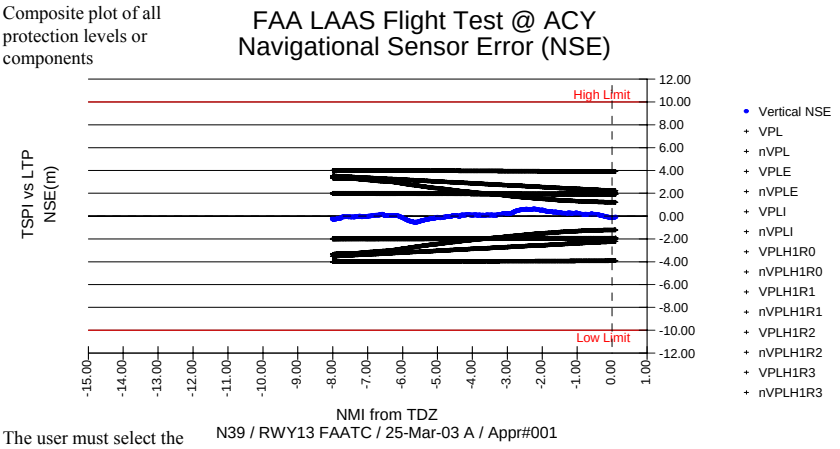
LAAS Integrity
Protection Level Equations H_1

- An additional source for LAAS integrity come from the measured real-time performance of the measured range comparisons
  - Error in the calculation of pseudorange corrections
  - The uplink parameters are the B-values
  - These are estimate of the instantaneous code noise and multipath of each reference receiver
- Method relies independence of reference receiver measurement
  - Any error common to multiple references will be averaged into the correction and will not be evident in the B-value
- A protection level for each reference receiver is calculated

$$PL_{H1,j} = \left| \sum_{i=1}^{N} S_i B_{i,j} \right| + K_{md} \sigma_{H1}$$

Protection Level Bounding

Composite plot of all protection levels or components



The user must select the Maximum calculated Protection level.

Key Risk Area 1
Position Domain Error Bound

- Work Items
- Determine constraints on range domain distribution such that the composite (position domain) is still overbounded
  - Explore limits of non-Gaussian nature of PRC distribution
  - Examine residual bias contribution
- Incorporate the any constraints in LAAS system level requirements

Key Risk Areas 9 & 10
Ephemeris Errors: Types B and A1

- Priority 7 risk area
- KRA 9: Type B ephemeris failure defined as an anomalous broadcast ephemeris not proceeded by a SV maneuver
- KRA 10: Type A1 ephemeris failure defined as an anomalous broadcast ephemeris proceeded by a scheduled SV maneuver
- Challenge is detecting SV position errors with relatively short LAAS baselines
  - On-airport installations

Integrity Parameters

Ephemeris Decorrelation Parameter

3.2.1.2.7 Ephemeris Decorrelation Parameter (P)

The Ephemeris Decorrelation Parameter field shall characterize the impact of residual ephemeris errors due to spatial decorrelation for the ranging source, associated with the first ranging source measurement block, in the Type 1 message. For every valid GPS ranging source, the LGF shall broadcast a *P*-value to represent the impact of undetected ephemeris errors on user range error. The maximum value for *P* shall be 1.5×10^{-4} m/m. The LGF shall exclude any ranging source for which the *P*-value cannot be validated. The broadcast ephemeris *P*-value for a given satellite shall account for the condition where the broadcast reference point (Section 3.2.1.3.9) does not match the reference receiver centroid location. When a healthy SBAS ranging source is within the reception mask, the impact of SBAS ephemeris monitoring shall be reflected in the *P*-values for all ranging sources included in the SBAS messages broadcast by this ranging source (except those indicated as "Do Not Use", which must be excluded per Section 3.2.1.2.8.3.1(h). When a healthy SBAS ranging source is not available within the reception mask, the *P*-values shall be based on GPS SPS signals.

LAAS Integrity

Protection Level Equations VPL_E

- LAAS integrity for SV position errors comes from the estimate of the ephemeris error and its projection into the position solution
  - Ephemeris error source is the GPS navigation data transmitted from the SV, or from a maneuver.
  - The uplink parameters are the p-values
  - These are measures of the uncertainty remaining after an ephemeris test has been performed
    - Almanac/Ephemeris tests provide little proof
    - Yesterday's and Today's (YE-TE) tests provide good confidence
    - WAAS broadcast ephemeris errors greatly reduce required p-value
- A protection level for each satellite is calculated

VPL_E Equation

LGF-User Distance

From weighted p-inverse of user geometry matrix

Missed-detection multiplier

$$VPLe_j = \left|S_{3,j}\right| \left|x\right| \frac{MDE_e}{R_j} + K_{md_e}\sqrt{\sum_{k=1}^{N} S_{3,k}^2 \sigma_k^2}$$

SV index

Differential ranging error variance

LGF broadcasts "*P*-value" for each approved GPS satellite.

•The lower the MDE, the larger the LGF-User distance can be without availability impact.

Key Risk Area 9 & 10

Ephemeris Errors: Types B and A1

- Work Items
  - Demonstrate system is protected from a
  - Demonstrate the broadcast P-value bounds the minimum detectable ephemeris error
  - Define the methodology for setting the P-value
    - Based on YE-TE LAAS detection
    - Based on LAAS station in view of a WAAS Geo

Key Risk Area 5
RFI

- Priority 8 risk area
- Demonstration that the broadcast integrity parameters provide the appropriate error bound at the edges of the required performance region
  - SV pseudorange correction bounding sigmas must performance is still valid:
    - At the minimum broadcast signal power
    - While in the presence of the most severe levels of RFI allowed by the standards
- Data collected in the nominal environment does not address the interference and minimum signal aspects of the requirement

Key Risk Area 5
RFI

- Work Items
  - Determine the ranging accuracy performance in the presence of interference
    - Simulation testing
      - LTP reference receivers
      - LAAS Verification Receiver
        - » Rockwell Collins GLNU-930
  - Effort has been delayed due to the challenge of developing an appropriate noise source
    - Several false starts caused by improper source calibration indicators
  - Vendor and FAA are using common test equipment

Key Risk Area 12
Low Power

- Priority 8 risk area
  - The LGF must detect if the broadcast power of any ranging source is transmitting less that the specified minimum power
    - While it may be able possible to adequately track this signal, it is an indication the SV has other failures
  - Low SV power is difficult to distinguish from other potential threats
    - RFI
    - Signal fading due to multipath
- Work Items
  - Determine an adequate set of test cases to verify the LGF can correctly identify this failure mode

Key Risk Area 14
Excessive Acceleration

- Priority 10 risk area
  - The LGF must detect if the acceleration calculated from the range measurements from each SV is less than the maximum expected
    - Selective Availability (SA) maximum specified rate
    - Appropriate non-SA rate if appropriate
  - Excessive acceleration is difficult to distinguish from other potential threats
    - Scintillation
    - Ionospheric activity
- Work Items
  - Determine an adequate set of test cases to verify the LGF can correctly identify this failure mode

Key Risk Area 13
Code/Carrier Divergence

- Priority 11 risk area
  - The LGF must detect if the code and carrier signals broadcast signal from the ranging source are coherent
  - Code/Carrier divergence is difficult to distinguish from other potential threats
    - Scintillation
    - Ionospheric activity
- Work Items
  - Determine an adequate set of test cases to verify the LGF can correctly identify this failure mode

Key Risk Area 15
Executive Monitor

- Priority 12 risk area
  - The executive monitor must be capable of distinguishing between reference receiver failures and ranging source failures
  - The execution and priority of the fault monitors must be determined such that erroneous data is not passed into additional monitor streams
- Work Items
  - Determine the system response to expected error modes

Key Risk Area 8
Sigma Troposphere

- Priority 13 risk area
- Development of criteria for setting troposphere-specific site parameters
- Verify that the tropospheric errors can be represented by a zero-mean Gaussian distribution

Integrity Parameters

σ_{tropo}

3.2.1.3.6 Refractivity Index

The Refractivity Index Field shall denote the refractivity index stored in LGF NVM.

3.2.1.3.7 Scale Height

The Scale Height Field shall denote the scale height stored in LGF NVM.

3.2.1.3.8 Refractivity Uncertainty

The Refractivity Uncertainty Field shall denote the refractivity uncertainty stored in LGF NVM.

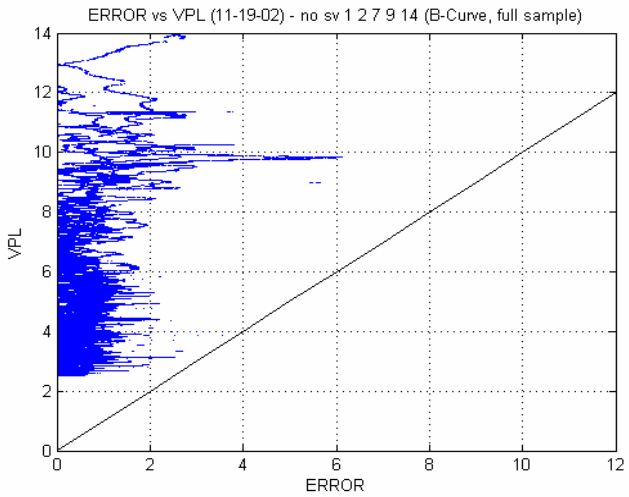
Key Risk Area 8
Sigma Troposphere

- Work Items
- Analyze the distance related effects of tropospheric errors
- Determine if localized tropospheric activity is an integrity threat
- Determine nominal values for tropospheric parameters
  - Verify validity with data collection and simulation
- Gather additional verification data from available public sources

Key Risk Area 16
Integrity "Per Approach"

- Reprioritization of vendor activities
- Priority 14 risk area
- Demonstrate by analysis that the LAAS integrity parameters, applicable over a wide variety of conditions, are valid for each approaching aircraft
  - Examine any averaging used to determine integrity parameters to ensure no corner condition is diluted

Protection Level Bounding

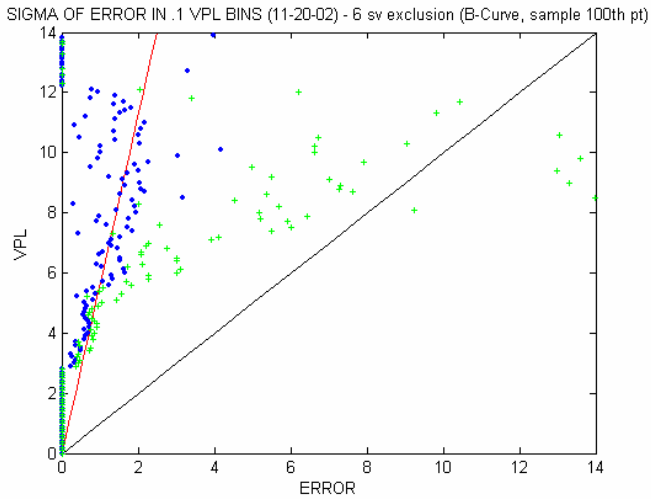


Demonstrates position errors Always less than the Protection level

The data presented was generated by post-processing 24 hours of ground monitor data and eliminating 5 SVs to artificially increase the protection level.

GAD B was used for the airborne sigma estimate because the ground monitor antenna is a choke ring.

Protection Level Bounding



Demonstrates position statistics are smaller than expected.

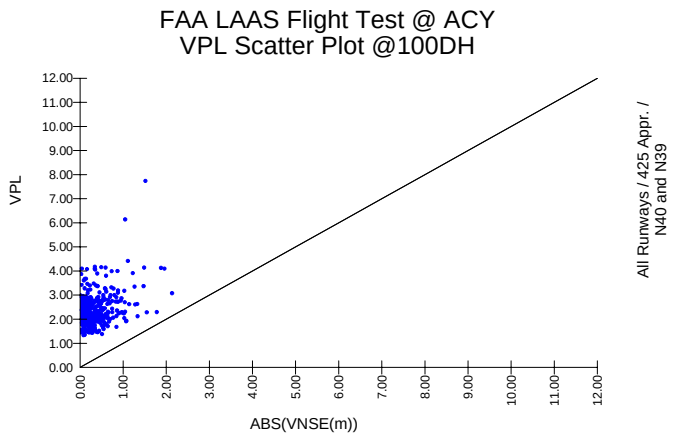
VPL=K*Sigma Position

Sigma Position = VPL/K (shown in Red)

The blue points are the standard deviation of the position error within 10cm VPL bins.

The green points are 95% confidence values of the standard deviations.

Protection Level Bounding



Even with several hundred approaches represented on this plot, little can be proven
with regard to the integrity requirement.

There would be low Statistical confidence in this Data sample.

Determined VPL is based on only on the ground and airborne sigmas and was calculated at 100' above touchdown

Key Risk Area 16
Integrity "Per Approach"

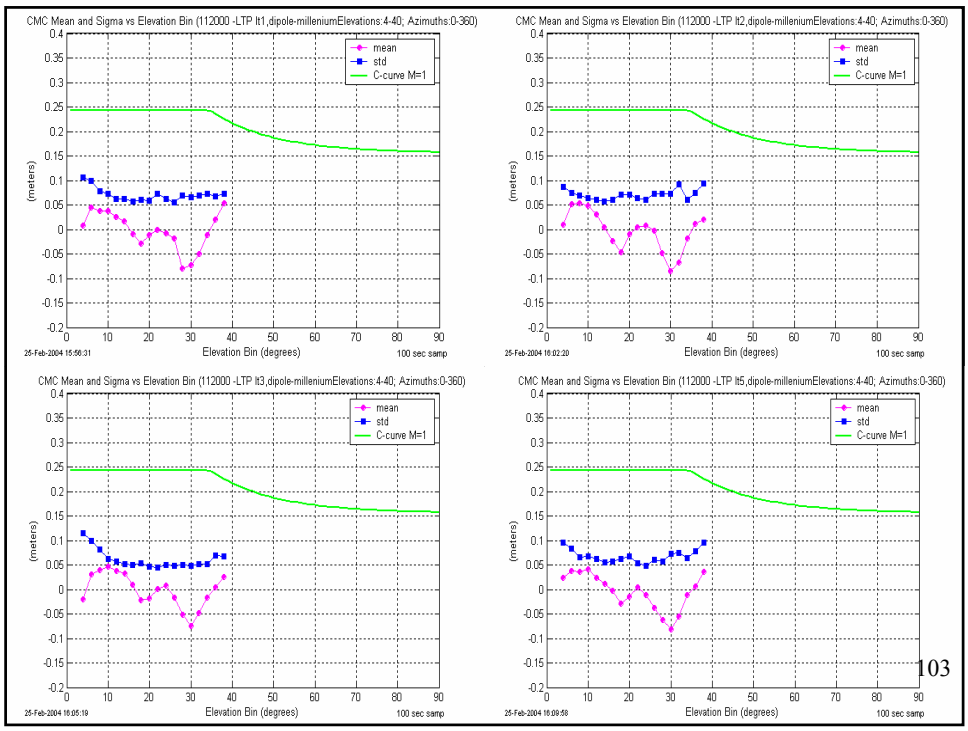
- Work Plan
  - Enumerate the assumptions over which integrity requirements
    - Trace to integrity analysis to where the assumption are applied
    - Incorporate elements of the system safety process that were re-scoped in the FAA contract replan effort
      - Integrity trees
      - Fault tree analysis
      - Traceability to KRA work

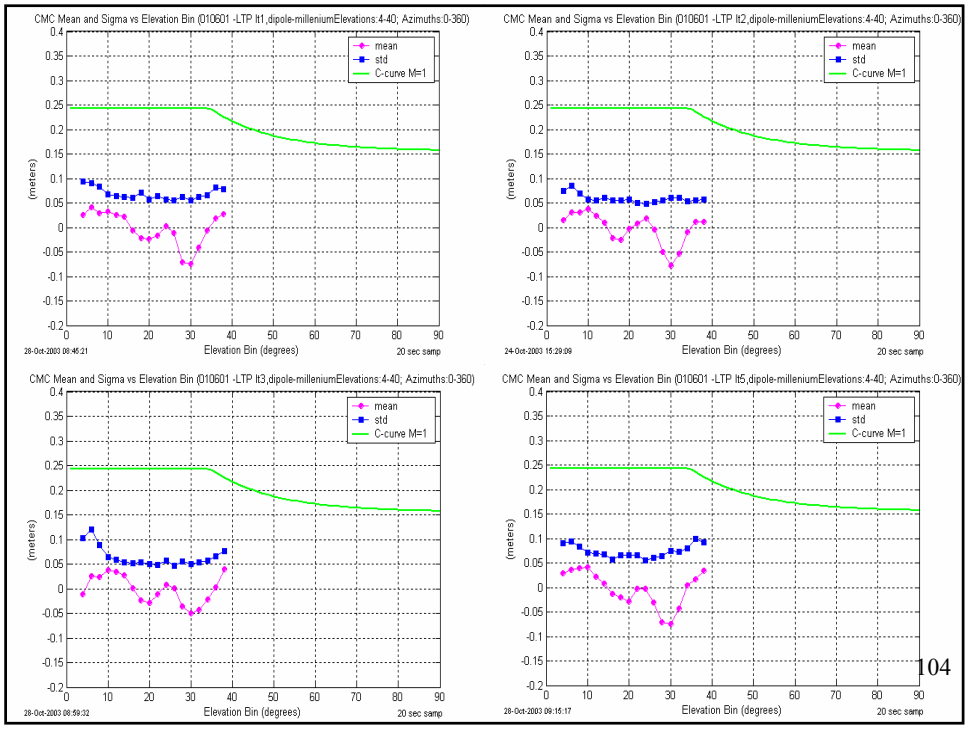
Additional Slides

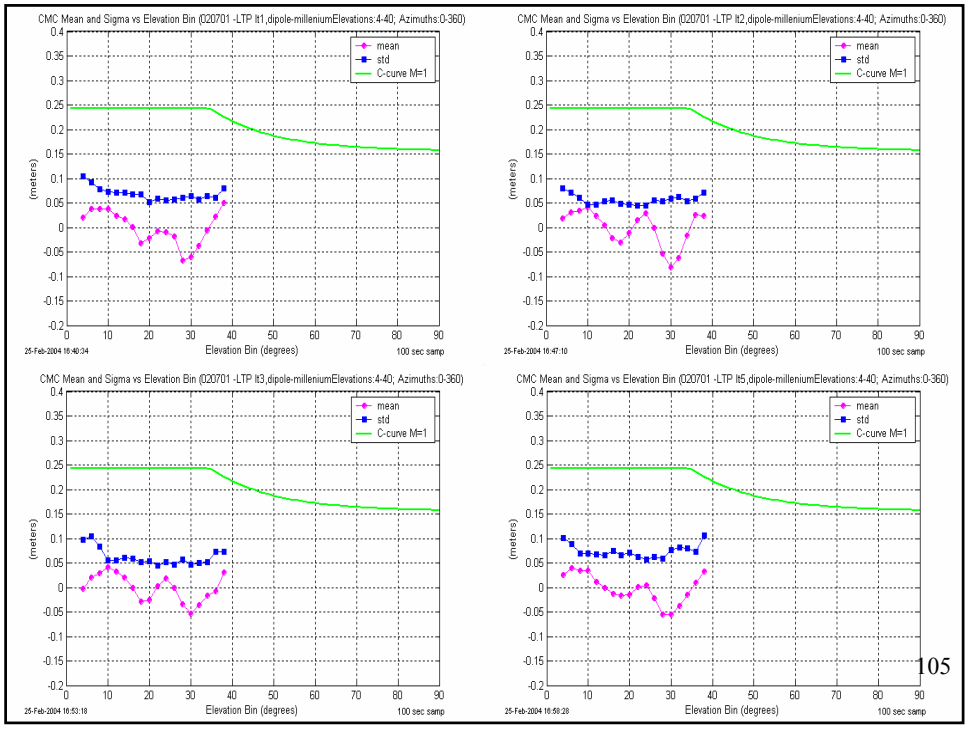
- LAAS Test Prototype MLA Data

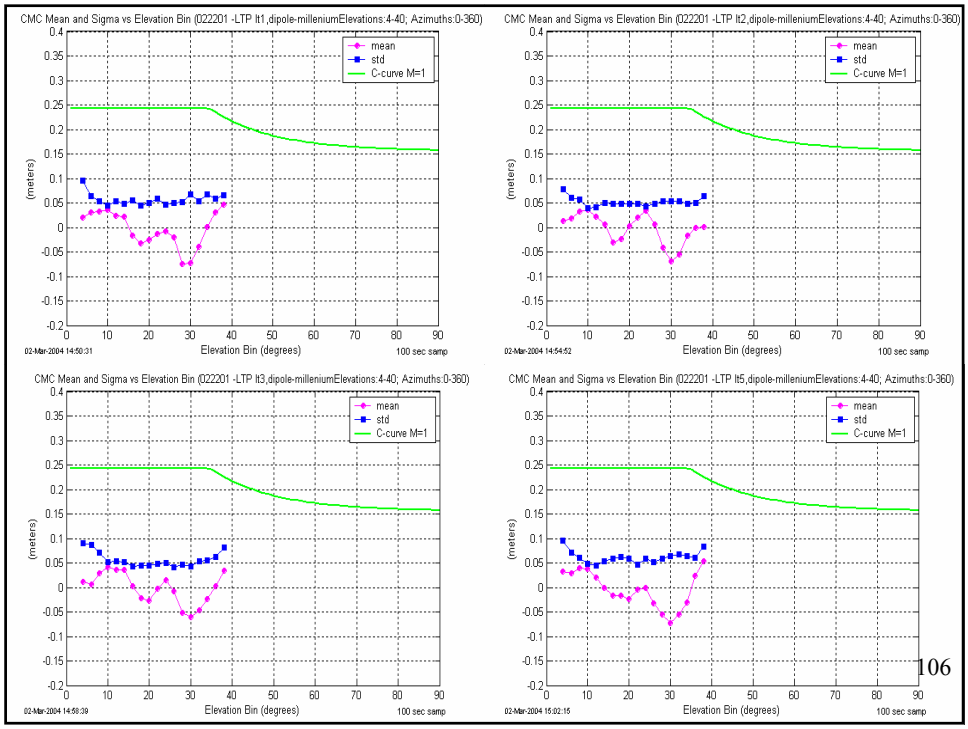
MLA Bias
100 second Smoothing

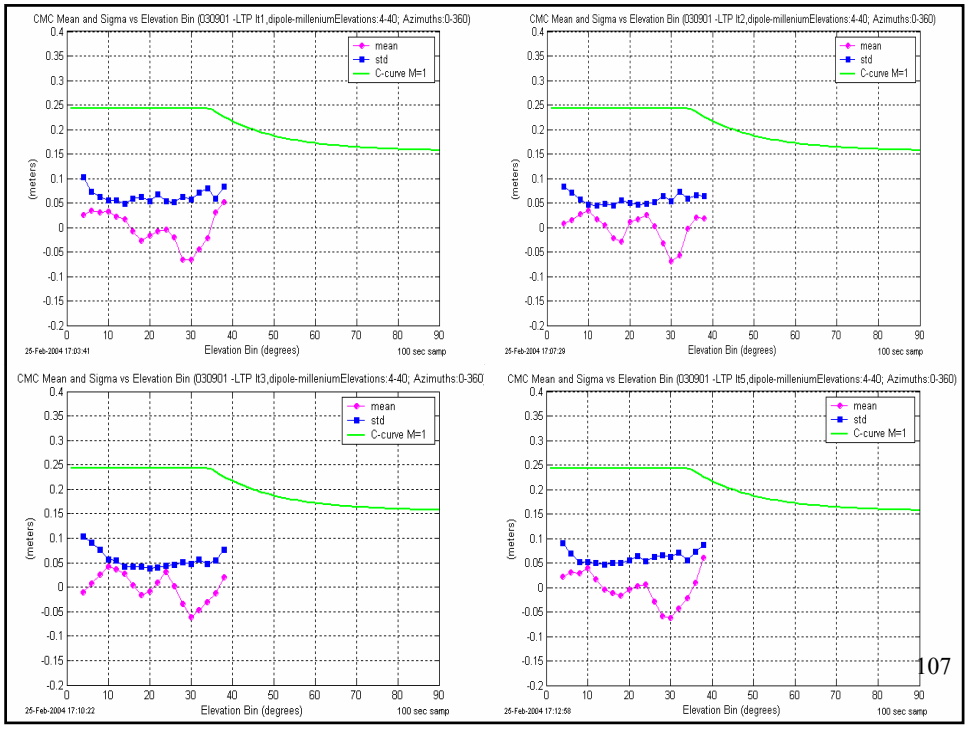
- LTP data 2000-2001
- Standard CMC Processing and Binning
- Long-term MLA error observations


CMC Mean and Sigma vs Elevation Bin (112000 -LTP lt1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (112000 -LTP lt2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (112000 -LTP lt3,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (112000 -LTP lt5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
25-Feb-2004 15:56:31
25-Feb-2004 16:02:20
25-Feb-2004 16:05:19
25-Feb-2004 16:09:58
100 sec samp

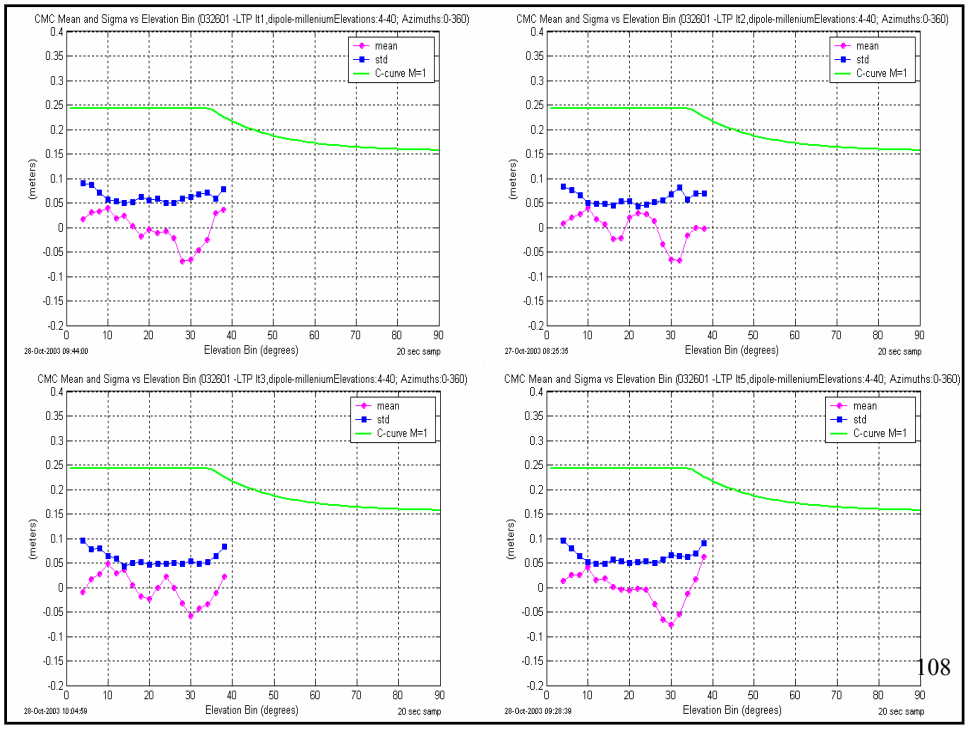

CMC Mean and Sigma vs Elevation Bin (010601 -LTP lt1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (010601 -LTP lt2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (010601 -LTP lt3,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (010601 -LTP lt5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
28-Oct-2003 08:46:21
24-Oct-2003 15:29:09
28-Oct-2003 08:59:32
28-Oct-2003 09:15:17
20 sec samp


CMC Mean and Sigma vs Elevation Bin (020701 -LTP lt1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (020701 -LTP lt2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (020701 -LTP lt3,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (020701 -LTP lt5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
25-Feb-2004 16:40:34
25-Feb-2004 16:47:10
25-Feb-2004 16:53:18
25-Feb-2004 16:59:28
100 sec samp

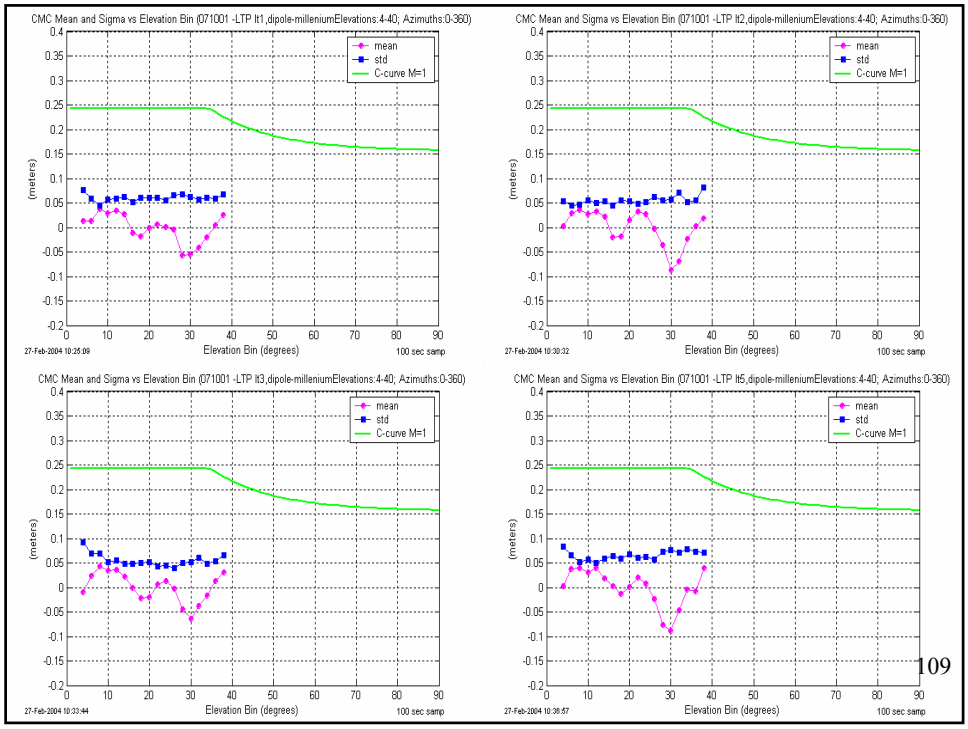

CMC Mean and Sigma vs Elevation Bin (022201 -LTP lt1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (022201 -LTP lt2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (022201 -LTP lt3,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (022201 -LTP lt5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
02-Mar-2004 14:50:31
02-Mar-2004 14:54:52
02-Mar-2004 14:58:39
02-Mar-2004 15:02:15
100 sec samp

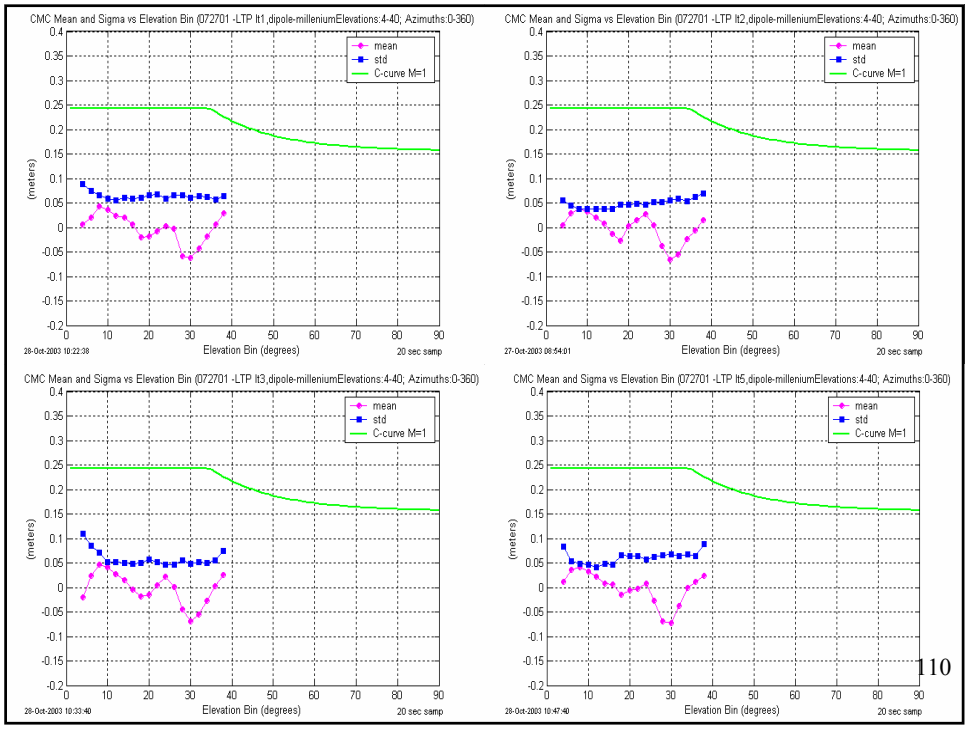

CMC Mean and Sigma vs Elevation Bin (030901 -LTP lt1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (030901 -LTP lt2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (030901 -LTP lt3,dipole-milleniumElevations:4-40; Azimuths:0-360
CMC Mean and Sigma vs Elevation Bin (030901 -LTP lt5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
25-Feb-2004 17:03:41
25-Feb-2004 17:07:29
25-Feb-2004 17:10:22
25-Feb-2004 17:12:58
100 sec samp

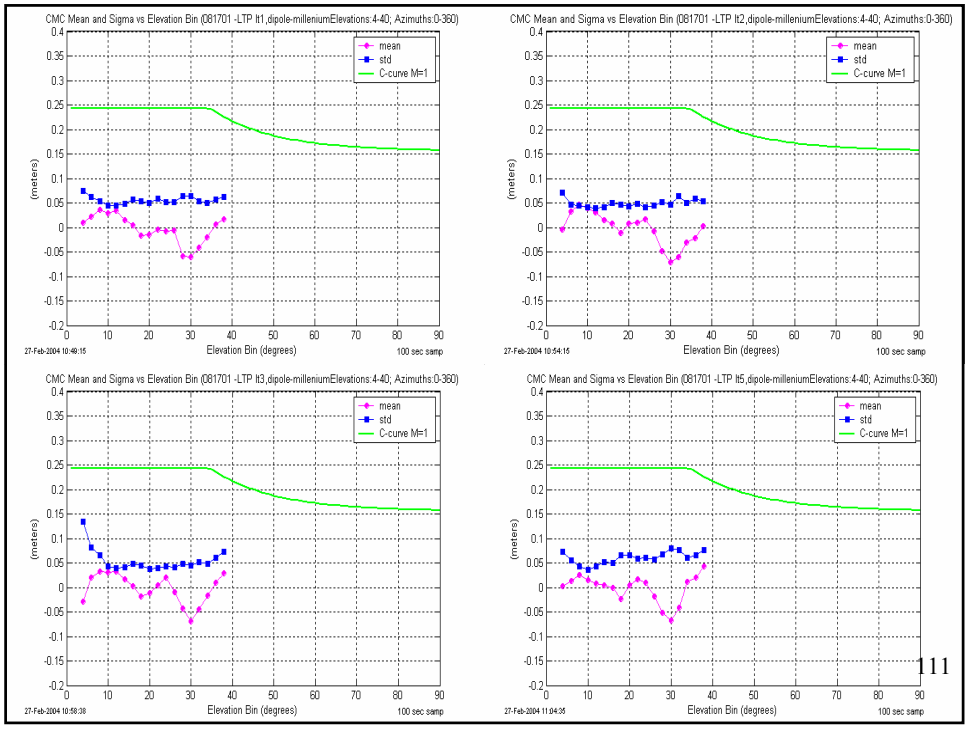
107


CMC Mean and Sigma vs Elevation Bin (032601 -LTP lt1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (032601 -LTP lt2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (032601 -LTP lt3,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (032601 -LTP lt5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
28-Oct-2003 09:44:00
27-Oct-2003 08:25:36
28-Oct-2003 10:04:59
28-Oct-2003 09:29:39
20 sec samp

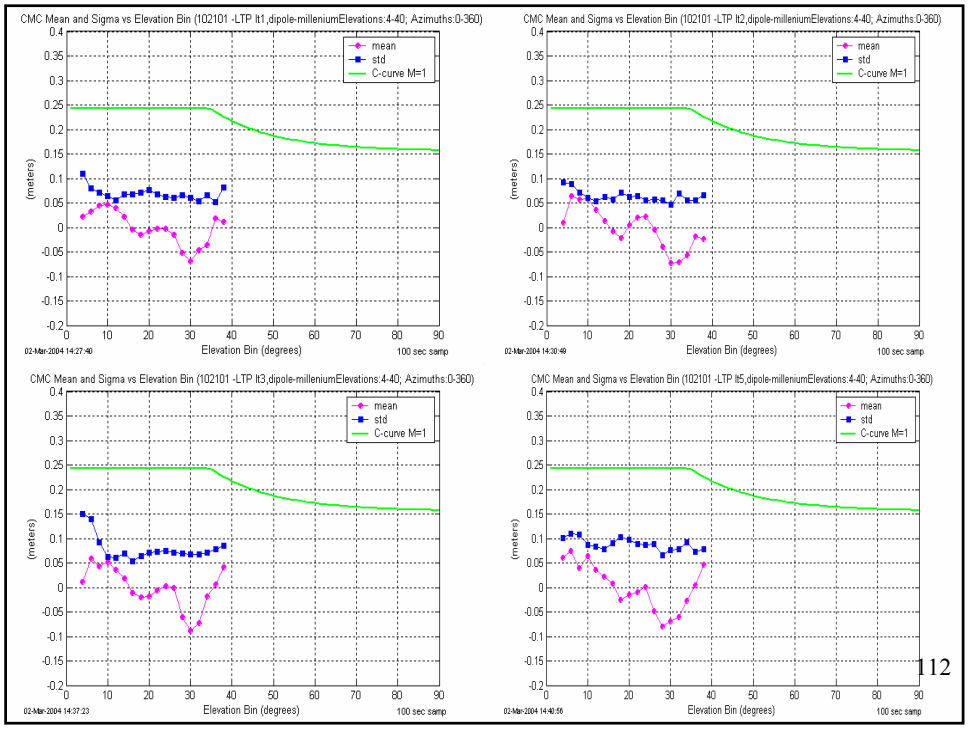
108


CMC Mean and Sigma vs Elevation Bin (071001 -LTP lt1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (071001 -LTP lt2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (071001 -LTP lt3,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (071001 -LTP lt5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
27-Feb-2004 10:25:09
27-Feb-2004 10:30:32
27-Feb-2004 10:33:44
27-Feb-2004 10:36:57
100 sec samp

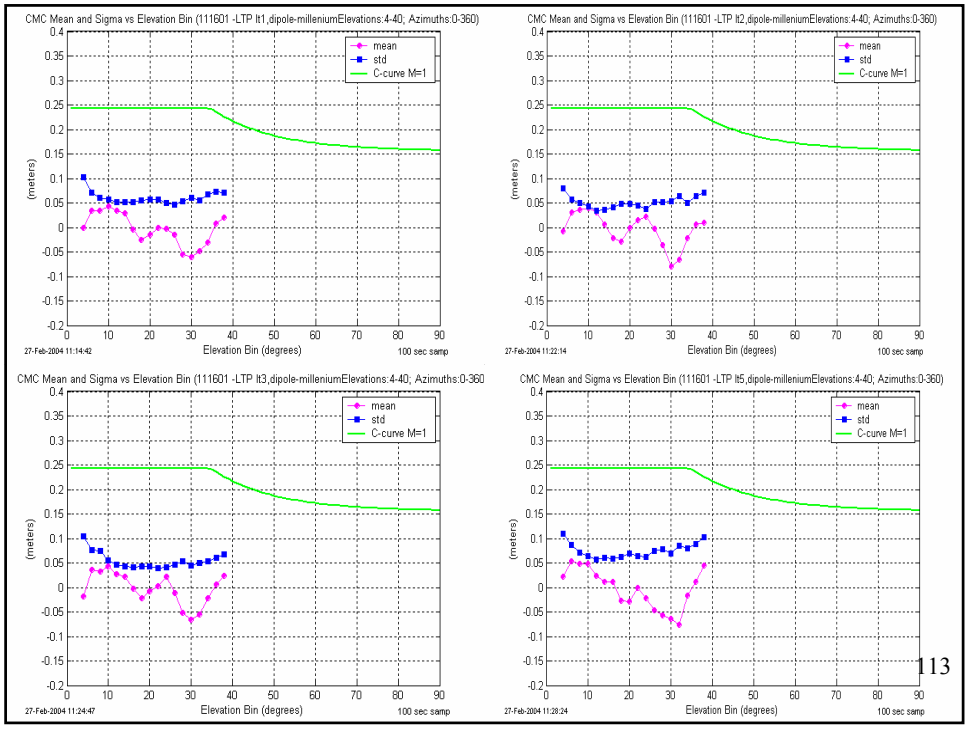

CMC Mean and Sigma vs Elevation Bin (072701 -LTP lt1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (072701 -LTP lt2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (072701 -LTP lt3,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (072701 -LTP lt5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
28-Oct-2003 10:22:38
27-Oct-2003 08:54:01
28-Oct-2003 10:33:40
28-Oct-2003 10:47:40
20 sec samp

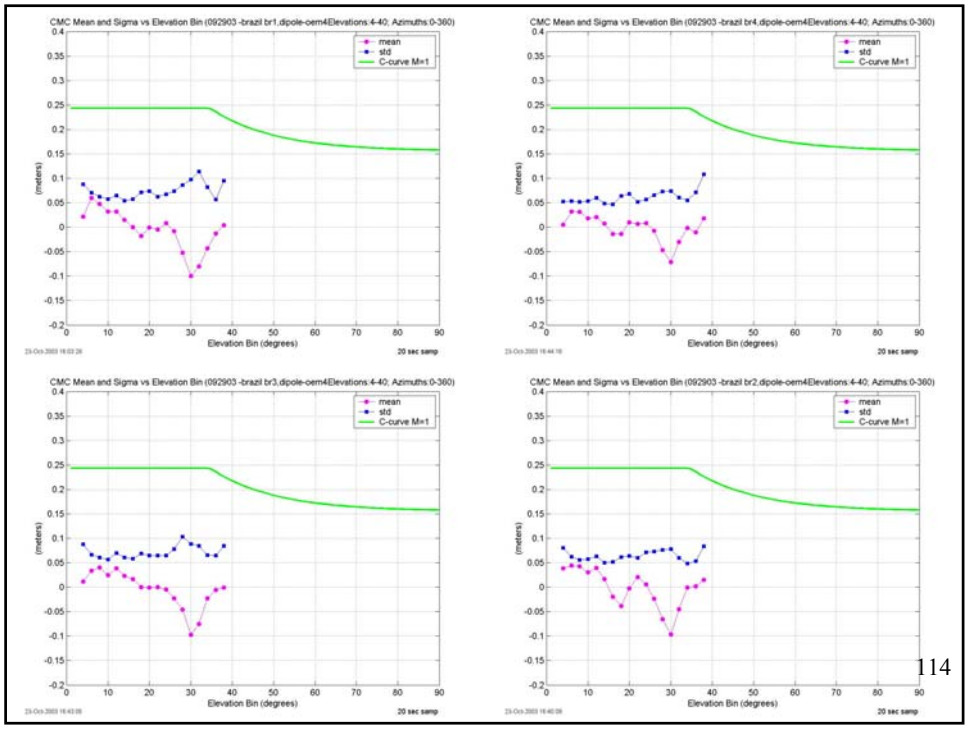

CMC Mean and Sigma vs Elevation Bin (081701 -LTP It1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (081701 -LTP It2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (081701 -LTP It3,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (081701 -LTP It5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
27-Feb-2004 10:49:15
27-Feb-2004 10:54:15
27-Feb-2004 10:58:38
27-Feb-2004 11:04:35
100 sec samp

111


CMC Mean and Sigma vs Elevation Bin (102101 -LTP It1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (102101 -LTP It2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (102101 -LTP It3,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (102101 -LTP It5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
02-Mar-2004 14:27:40
02-Mar-2004 14:30:49
02-Mar-2004 14:37:23
02-Mar-2004 14:40:56
100 sec samp

112


CMC Mean and Sigma vs Elevation Bin (111601 -LTP lt1,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (111601 -LTP lt2,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (111601 -LTP lt3,dipole-milleniumElevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (111601 -LTP lt5,dipole-milleniumElevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
27-Feb-2004 11:14:42
27-Feb-2004 11:22:14
27-Feb-2004 11:24:47
27-Feb-2004 11:28:24
100 sec samp


CMC Mean and Sigma vs Elevation Bin (092903 -brazil br1,dipole-oem4Elevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (092903 -brazil br4,dipole-oem4Elevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (092903 -brazil br3,dipole-oem4Elevations:4-40; Azimuths:0-360)
CMC Mean and Sigma vs Elevation Bin (092903 -brazil br2,dipole-oem4Elevations:4-40; Azimuths:0-360)
mean
std
C-curve M=1
(meters)
Elevation Bin (degrees)
20 sec samp