Methodology for TIS-B Integrity Monitoring

- **Purpose: Provide TIS-B data quality measures, i.e. NIC, NAC, SIL**
- **Needed for MASPS:**
  - Guidance Material for Horizontal Position quality measures in State Vector Reports for Radar Derived TIS-B Tracks
  - Guidelines to achieve SIL=1 and SIL=2 integrity levels, e.g.

    10^-3 and 10^-5 allowed probability of horizontal position integrity error.

    (Note: SIL=1 may only require field test data and fixed containment radius)
  - **Alerting Time Requirement**, i.e.max allowed time for estimated target to be outside a specified horizontal containment radius without alerting (for an appropriate probability level)
- **Main Elements for Radar Based Integrity Monitoring (?)**
  - Sensor Calibration and Report Compensation
  - Sensor Level Integrity Monitoring
  - Track Level Integrity Monitoring
  - Containment Radius Derivation for TIS-B Reporting

Potential TIS-B Integrity Monitoring Elements

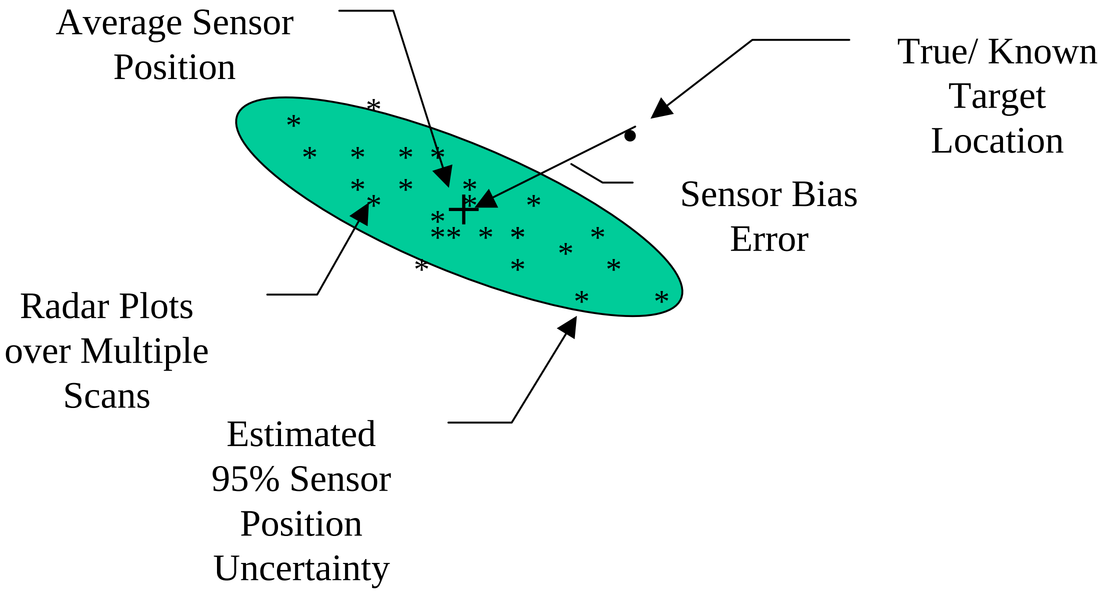
- Single Radar Integrity Monitoring (Horizontal Plane)
  - Sensor Calibration and Report Compensation
    - First Step Integrity: Reduce Radar Bias Errors
    - Typically, performed at least once a day using one or more Parrots or other reference points
    - Unbiased estimate of compensated plots desired, e.g. bias error residual less than noise_std / 4 with specified probability
    - Output (?): Report Compensation parameters, Estimated RMS and Bias Residuals, 95% Position Accuracy Metric (Single Plot)
  - Sensor Level Integrity Monitoring
    - Routine Cross-Checking of Outputs from Nearby Radar Sensors
    - Uses Targets of Opportunity, i.e. A/C in range of two overlapping sensors
    - Typically, may be performed during transit from one sensor to another
    - Output(?): Integrity Alert (i.e. Possible sensor failure or need for recalibration); If Integrity O.K., Horizontal Containment Radius associated with alerting algorithm

TIS-B Track Level Integrity Monitoring

- **Track Level Integrity Monitoring Alternatives:**
  - **Based on Radar Plot Residuals**, i.e. difference between sensed plot position and tracked position relative to track position uncertainty (?)
  - **Based on Direct Comparison with Remote Sensor Data,** i.e. cross checking of predicted track position versus remote sensor plot data
- **Complications to Overcome:**
    - Noisy measurements; Integrity Monitoring may require alerting based on multiple plots, i.e. two out of three plot threshold alerting criteria
    - Track Adaptation methods to compensate for unknown target dynamics, e.g.adaptive alpha-beta tracking, Multiple Maneuver Model track adaptation. (Track adaptation results in faster track convergence to true state vector based on larger state uncertainty modeling or larger tracker gains.)
  - Track Integrity is poor / unknown when Radar Plot Residuals are Large, or no measurements fall into the track correlation window,
  - Track containment radius is best estimated when Radar Plot Residuals are small relative to expected track position uncertainty.

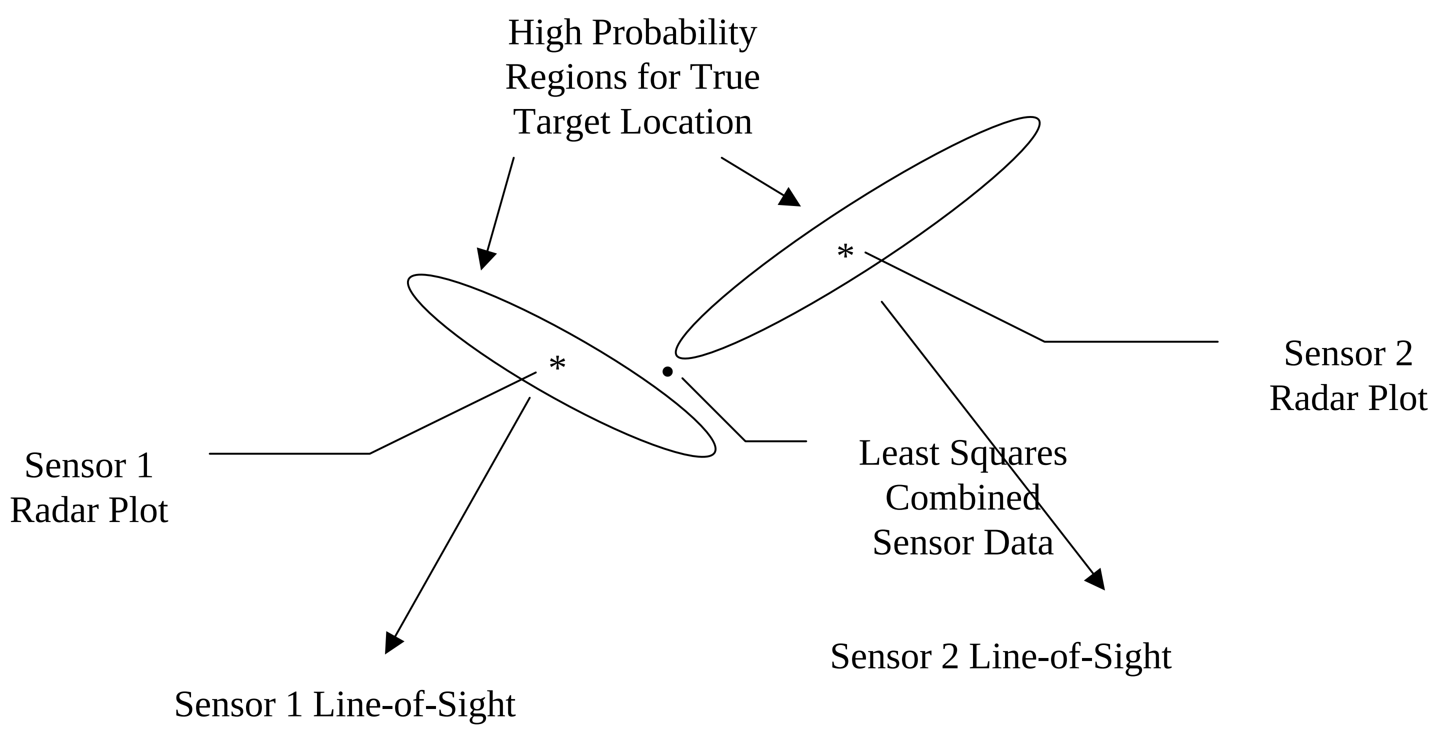
Sensor Calibration and Accuracy Metrics

- General concept is to measure sensor bias errors using radar returns from a target with known position. It is feasible to estimate sensor noise parameters as well, provided enough scans are available.



- Sensor Accuracy ~ 95% Radial containment bound for single plot return of calibrated sensor with bias error vector removed. (Includes bias error estimation residual and sensor noise uncertainty (sigma_r, r*sigma_az).)

Dual Sensor Integrity Monitoring Concept



• **Sensor Integrity Alerting:** No common region associated with high probability of True Target, i.e. either sensor 1 or sensor 2 may have a loss of integrity. (Note: Several scans may be needed to reduce false alarms due to sensor noise.) Three sensors or alternate means may need to be used to determine which sensor is probable cause of alert.

Sensor Integrity Monitoring: LS Problem Formulation

- Least Squares / Maximum Likelihood Integrity Monitoring :
  - Least Squares Minimization Criterion:
    - Find estimate $\underline{Z} = (x, y)^T$ that minimizes the criterion function

$$L(\underline{Z}) = (\underline{Z} - \underline{Z1})^T R1^{-1} (\underline{Z} - \underline{Z1}) + (\underline{Z} - \underline{Z2})^T R2^{-1} (\underline{Z} - \underline{Z2})$$

where $\underline{Z1} = (x1, y1)^T$ is the 2-D radar plot for sensor 1

R1 = Covariance uncertainty matrix for $\underline{Z1}$ (Sensor 1)

$\underline{Z2} = (x2, y2)^T$ is the (time adjusted) radar plot for sensor 2

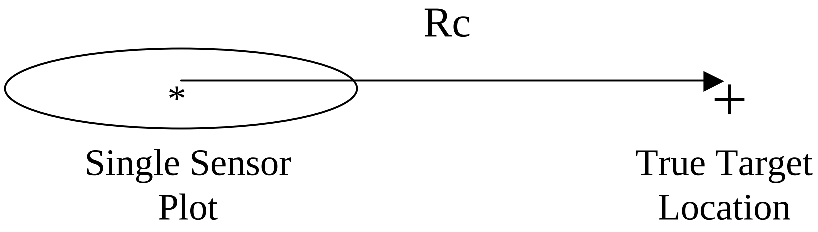
R2 = Covariance uncertainty matrix for $\underline{Z2}$ (Sensor 2)

  - Integrity Monitoring: Declare Integrity Alert if likelihood Value is Large

If $L(\underline{Z}) >=$ Threshold, Declare Integrity Alert

  - Note (1): Other forms of LS criterion are possible, e.g. only the cross-track uncertainty may be available for integrity monitoring with a remote sensor
  - Note (2): Threshold may be chosen at a specified probability level, assuming that $L(\underline{Z})$ is a Chi-squared random variable with 2 degrees of freedom

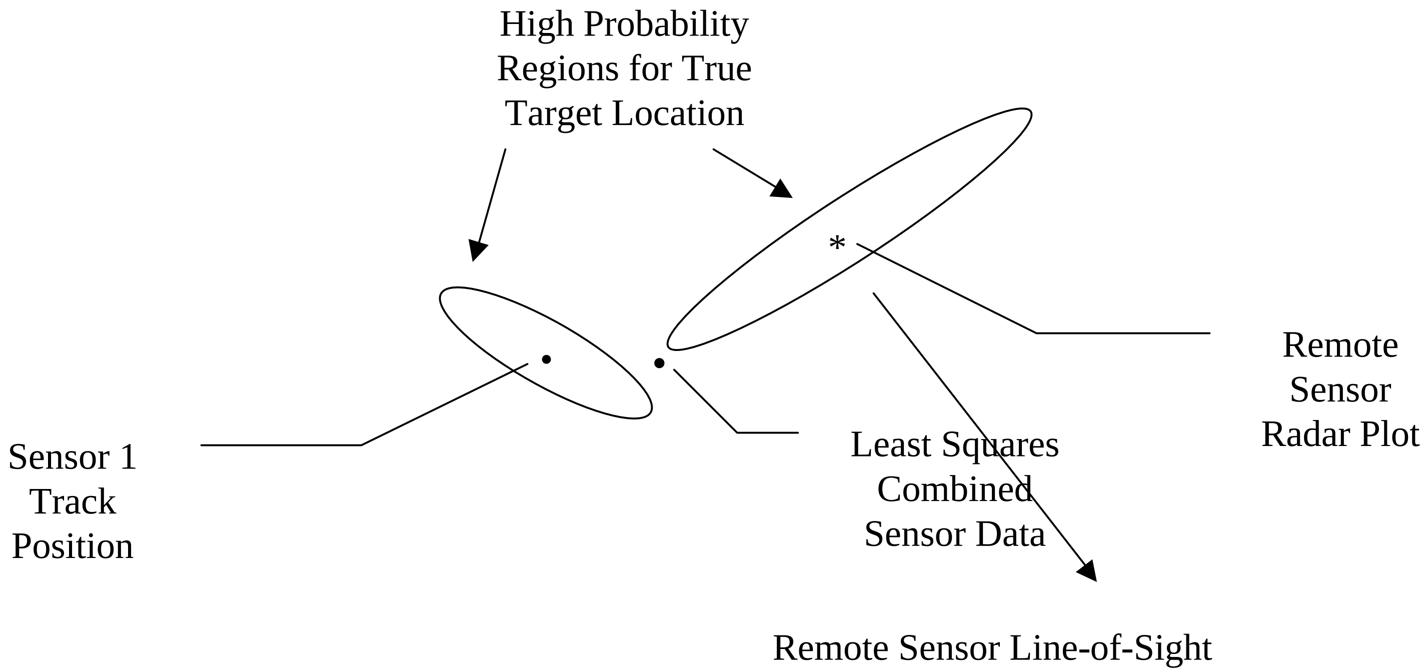
Horizontal Containment Radius (For Integrity Alerting)



• **Horizontal Containment Radius**: The largest possible distance that the true target location could be (in the largest axis uncertainty direction) such that the probability that no integrity alert is declared is <= 10^-5. (Note: this assumes desired SIL=2, and one or more very large noise returns in the opposite direction, that hides the large bias error Rc.)

<u>Issue</u>: Do we need to compute Horizontal Containment Radius for Sensor Level Integrity, or just for Track Level Integrity Monitoring?

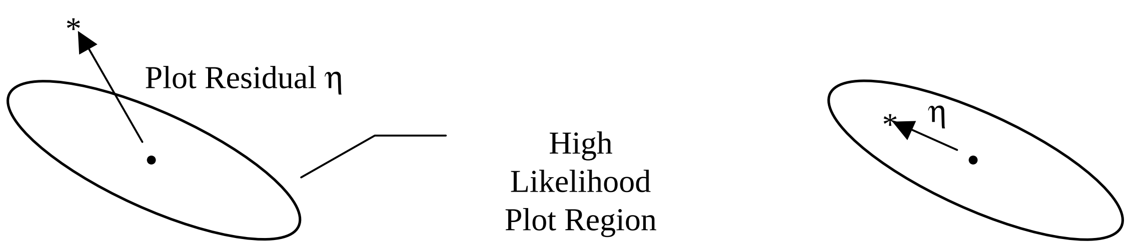
Track / Sensor Integrity Monitoring Concept



• **Track Integrity Alerting:** No common region associated with high probability of True Target, i.e. sensor 1 track may have a loss of integrity. (Note: Several scans may be needed to reduce false alarms due to sensor noise.) The above diagram assumes that (1) track measurement residuals are small, and (2) remote sensor integrity has been verified.

Track Level Integrity Monitoring with Plot Residuals

- Plot Residual(η) = Difference between sensed position and track predicted position
- Theoretical Properties (for a Kalman filter based tracker):
  - Plot Residuals are independent from scan to scan
  - Plot Residuals are zero mean and known Covariance = R + P, where
    - » R = Covariance uncertainty of sensed radar plot
    - » P = Covariance uncertainty of track predicted position



Example with Large Residual Error:

Track Integrity Difficult to Assess

Example with Small Residual Error

Relative to Predicted Track Uncertainty

TIS-B Position Source Uplink Options:

- **Option 1: Uplink TIS-B Track Data and Track Integrity**
  - Pro's: Consistency between position and velocity data; provides smoothed data for more accurate non-maneuvering position estimates
  - Con's: SIL=0 (unknown integrity) is probably required during maneuver periods, or whenever the measurement residuals are large

- **Option 2: Uplink TIS-B Sensor Plots, Velocity Track Data and Sensor Integrity**
  - Pro's: Consistency with controller displays; constant SIL (1 or 2) during both maneuver and non-maneuver periods
  - Con's: Relatively noisy position estimates; no indication of loss-of-velocity integrity during turn maneuvers

- **Option 3: Uplink TIS-B Track Data and Track Integrity or TIS-B Sensor Plots and Sensor Integrity Depending on Track Integrity, i.e. Use data source with highest integrity level**