412th Test Wing

412 TW

Boresighting Issues for High Accuracy TSPI Sensors

Gary Glazner

412 RANS/ENRT

661-277-5369

Background

- In order to meet modern testing requirements, current and future TSPI sensors need to provide at least position, velocity, and attitude. Some tests also require acceleration and attitude rates.

- TSPI sensors are used as the "truth source" against which to compare the "system under test" (SUT).

- The test customers typically need TSPI at some point on the instrumented vehicle, not at the sensor itself. The TSPI solution must be rotated to the vehicle coordinate system and translated to the point of interest.

- In addition to the accuracy of the TSPI sensor itself, the accuracy of installation measurements, particularly boresight angles, can have significant impact on the accuracy of the final product.

GPS-only Sensors

- Because a GPS-only sensor does not provide attitude information, the resulting solution will be at the phase center of the GPS antenna.

- Without attitude information, the solution cannot be translated to any other point on the vehicle.

- Under some conditions, the SUT navigation system attitude information can be used for the translation, but that is generally not done because it uses SUT data mixed with truth data.

- The remainder of this presentation is concerned only with sensors having GPS combined with an Inertial Measurement Unit (IMU).

Geometry and Nomenclature
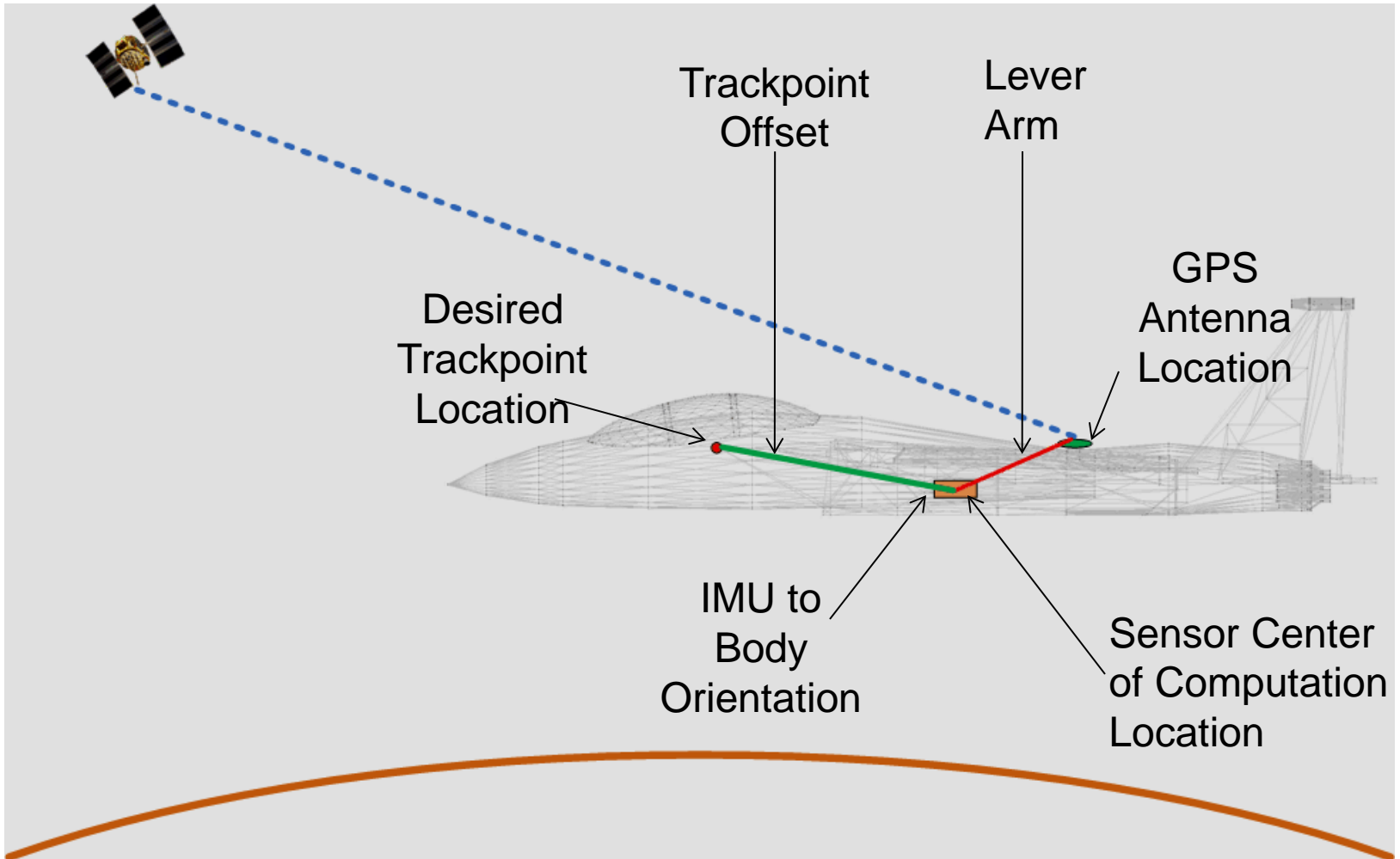
Installation Information

- When a sensor with an IMU is installed in a vehicle, measurements need to be taken in order to reference the TSPI data to the vehicle coordinate system.

- The trajectory solution for a GPS+IMU sensor is usually calculated at the center of rotation of the IMU.

- Sensors generally have reference points on the external box with known values in the coordinate system of the IMU.

- Sufficiently accurate measurement of these reference points in the vehicle coordinate system is necessary to calculate both position and attitude of the IMU in the vehicle coordinate system, which is the main goal.

Position Error Contributions

- Any errors in the positional measurement of the IMU will show up as a fixed bias (in the vehicle coordinate system) in the final solution after trackpoint offset calculations.

- If a TSPI sensor is advertised to have a positional accuracy of 20 cm, the position of the IMU should be measured to an accuracy of about 2 cm (using 10x rule of thumb).

- This is not tough using calibrated rods or a laser based measuring system.

Attitude Error Contributions

- Errors in the attitude boresight measurement have more significant contribution than the positional measurement.

- Boresight errors show up as…

  - a bias in the solution attitude angles (roll, pitch, heading), both before and after trackpoint offset calculations

  - additional position errors as a multiple of the boresight error times the trackpoint offset distance

  - additional velocity errors as a multiple of the boresight error times the attitude rate

- To meet a TSPI sensor attitude accuracy of 0.05 degrees, the boresight of the IMU should be measured to an accuracy of 0.005 degrees (best case using 10x rule of thumb) or 0.025 degrees (worst case using a 2x rule of thumb).

- This is tough.

Methods for Measuring Boresight Angle

- **Measured Points**
  - Measure positions of reference points on the sensor body and the aircraft body, then use geometry to calculate the sensor coordinate system relative to the aircraft coordinate system.

- **Wire Frame Matching**
  - Measure a cloud of points from the sensor body and the aircraft body, fit wireframe models of the aircraft body and sensor to the point cloud, then read out angles from the transforms.

- **Estimating Planes**
  - Use a laser scanner to measure a point cloud for a known planar surface on the sensor body and a known planar surface on the aircraft body. Fit each point cloud to a plane, then mathematically generate the transform from the sensor plane to the aircraft plane.

- **Measuring Planar Differences**
  - Build a high accuracy jig that fits the reference points on the sensor and brings a reflective planar surface into view. Use an optical autocollimator to directly measure the angular difference between this plane and a reference plane on the vehicle body. Do this from two points of view to get 3-D angles.

Measured Points

- Whether measuring discrete reference points or getting a point cloud, all the measurements must be taken in the same coordinate system and must include the airframe and the sensor.

- If calculating angles from discrete points, required measurement position accuracy (σ) can be derived from the required angular accuracy (θ) and the distance between points (ρ)
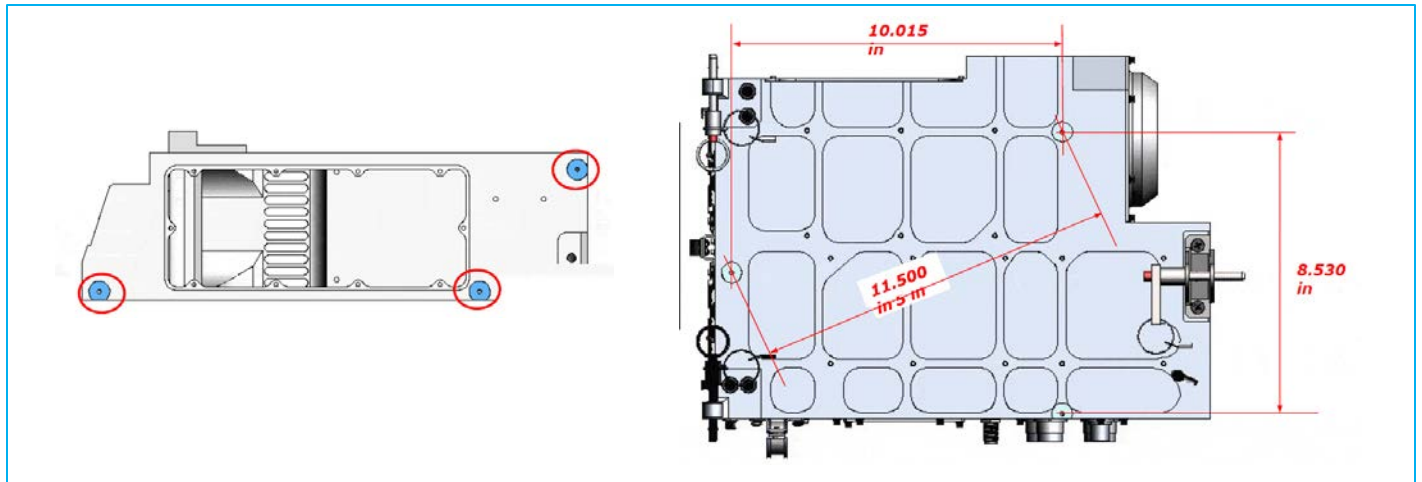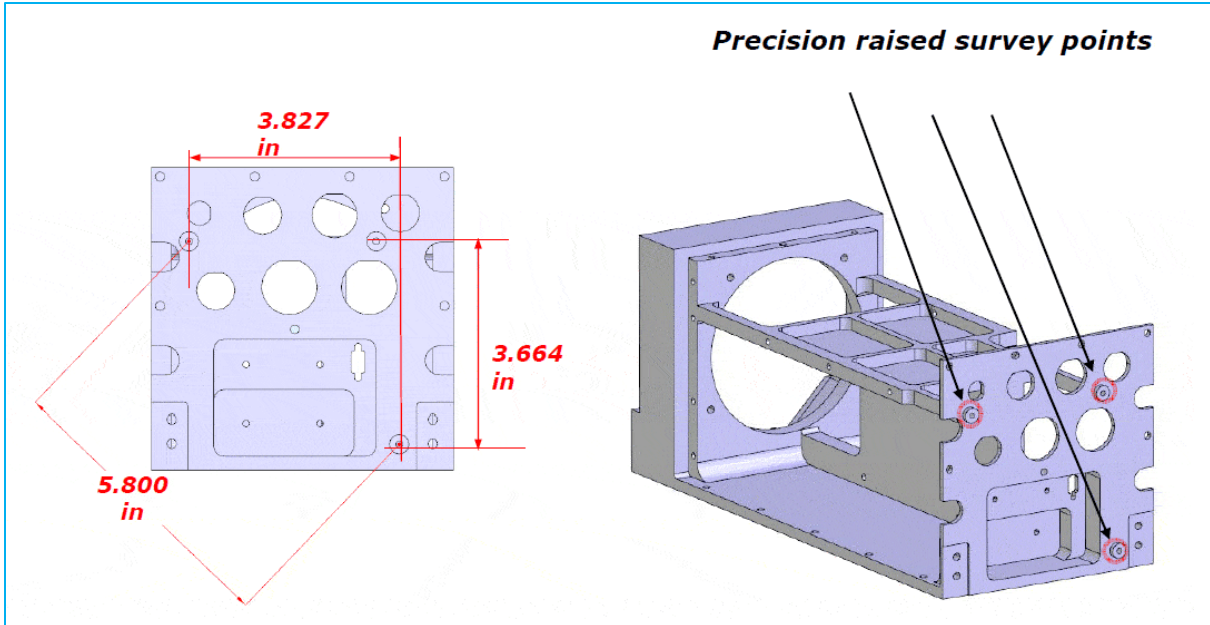
$$\tan(\theta) = \left[\frac{\sigma}{\rho}\right]$$

or $\quad \sigma = \rho \tan(\theta)$

Precision raised survey points

Required Measurement Accuracy

- Using a desired angular accuracy of 0.05 degrees and a 2x rule of thumb, we need to measure 0.025 degrees.

θ	ρ	σ
0.025 deg	3.664" = 93 mm	0.041 mm
0.025 deg	6" = 152 mm	0.066 mm
0.025 deg	8.53" = 217 mm	0.095 mm
0.025 deg	11.5" = 292 mm	0.127 mm
0.025 deg	2' = 609 mm	0.265 mm
0.025 deg	3' = 914 mm	0.400 mm
0.025 deg	4' = 1219 mm	0.530 mm
0.025 deg	5' = 1524 mm	0.665 mm
0.025 deg	6' = 1829 mm	0.800 mm
0.025 deg	7' = 2134 mm	0.930 mm
0.025 deg	8' = 2438 mm	1.065 mm

Boresight and Vehicle Frame

- The measurements must be to this accuracy in the vehicle coordinate system, which means that reference points on the vehicle must also be measured to sufficient accuracy.

- Problem: Aircraft reference points can move around
  - Panels removed and reinstalled
  - Racks shift in flight
  - Aircraft reskinning
  - Airframe warping
  - On-wheels versus in-flight warping

- Mitigation:
  - Where possible, use vehicle hard points least susceptible to warping
  - Use vehicle points as far apart as possible
  - Collect a large number of reference points and include warping in the fit functions

A Solids Model Measurement Idea

- Use a 3d scanning laser system to collect measurements on the sensor and the airframe in a consistent coordinate system with high fidelity.

- This results in a point cloud that includes known points and surfaces on the aircraft and known points and surfaces on the sensor.

- Use one of the previously mentioned techniques to map the point cloud to the airframe coordinate system.

- From the resulting cloud, find the location of sensor reference points OR resolve a sensor planar surface in the aircraft coordinate system.

- This should provide position and angular information which is the desired boresight result.

Measurement Requirements

- The scanner must be able to see or reach the sensor points and surfaces.

- The scanner must work over a distance of potentially tens of feet in order to get widely separated points on the airframe.

- The scanner must be accurate enough to support the desired final boresight accuracy.

- The measurement process must not modify the test articles while collecting measurements.

Sample Solids Modeling Camera
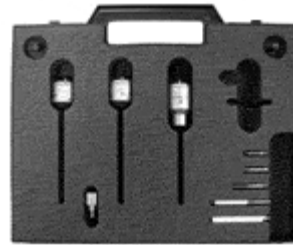
Advertised Resolution

0.0249 mm 2-sigma corner test

0.0045 mm 2-sigma feature resolution

0.0050 mm 2-sigma feature repeatability

What Now?

- As far as I can tell, no one is using solids modeling laser scanners for boresight of equipment.

- We are looking for an opportunity to conduct experiments using known sensors in a lab environment where truth can be measured using high accuracy bench-mounted laser systems or auto-collimators.