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White Paper — MEMS on the Level

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Specifying Accuracy for a New Generation of Digital MEMS

The GEOKON 6150E MEMS In Place Inclinometer (IPI) is designed to make sensitive and repeatable angular measurements. This paper explains how we derived, validated and expressed our specifications in universal metrological terms.

Figure 1 — GEOKON's new 6150E MEMS IPI reports angles digitally via Modbus (RS-485).

Characterizing the Output

GEOKON 6150E IPI performance is published in accordance with international metrology standards, whose foundation is the Guide to the Expression of Uncertainty in Measurement (GUM)[1]. In the U.S., the GUM concepts are codified in ISO/IEC 17025[2], ANSI/NCSL Z540.2[3], and NIST Technical Note 1297[4]. The authors discard the nebulous term "accuracy," and instead advise engineers and scientists to quantify "trueness" and precision, accompanied by a statistically-valid statement of *uncertainty*.

We specify all 6150E parameters using a 99-percent *confidence interval*, which means that all but one in a hundred individual readings would fall within our published tolerance. (Most measuring devices are specified with only a 95-percent confidence interval, meaning one in twenty readings exceed the stated limit, on average.)

Truth and Uncertainty

Resolution quantifies sensitivity

Resolution is the smallest input change that produces a corresponding output change. It is the smallest angle in the 6150E specification because the MEMS IC is extremely responsive to acceleration and gravitational force.

We could not measure resolution directly — the MEMS IC responds to angle changes too small for any practical calibrator — but we could infer the value by analyzing experimental data.

The GEOKON design digitizes the MEMS output voltage into one of millions of discrete intervals. Much of that granularity is unusable. Just as one would ignore digits that change erratically on a multimeter display, we must disregard any analog-to-digital converter (ADC) bits that just jitter when angle is held constant.

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We suppress the random variation by *oversampling* the IC. A 6150E reading is an average of almost 800 separate ADC samples, all taken in just a tenth of a second. By isolating signal and noise mathematically, we determined that there are more than a half million *meaningful* intervals in the 30° span of the 6150E. The resolution is stated as the span divided by the number of significant intervals.

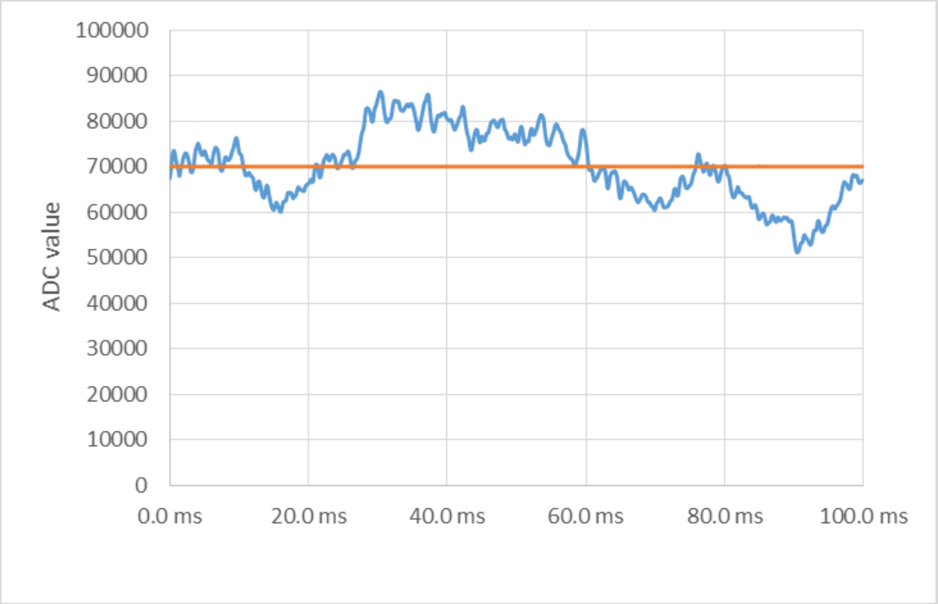


Figure 2 — Hundreds of samples are averaged to produce a single 6150E reading.

Precision quantifies repeatability and reproducibility

The most important specification for an IPI is precision. Often depicted as the grouping of arrows around a bulls-eye, precision represents the ability of a system to produce consistent results. Precision is an attribute of each *individual* sample.

When multiple samples are measured in different labs, keeping only the methods constant, the term *reproducibility* is applied. *Repeatability* is a purer concept, referring to one gauge's variation when measuring an unchanging quantity again and again. Repeatability is most relevant to IPI installations, where changes in angle are the primary concern.

As noted in the *resolution* discussion, noise is the enemy. The oversampling described above reduces overall noise by 29 dB, sharpening precision by a factor of 30.

6150E repeatability was measured by placing multiple specimens in a structurally stable laboratory, then measuring angle every few seconds. We ignored structural movement, subtle but measureable over the course of hours. Since any individual measurement should be almost the same as the one preceding it, we studied the *differences* between consecutive readings.

The 6150E proved remarkably consistent. We retested the MEMS in one of the boreholes in our Lebanon, New Hampshire labs. After four months in the borehole, four 6150Es exhibited only tiny variations reading-to-reading[5].

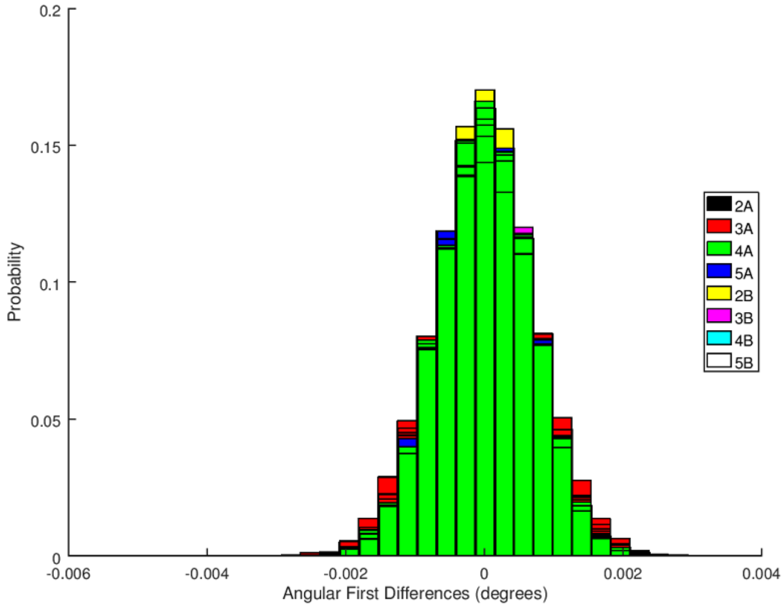


Figure 3 — Long-term data exhibited narrow bell curves for "angle random walk," the noise that delimits precision.

The actual precision is probably better than we can specify. Seismic noise[6] permeated our tests. We are confident that most of the observed variation was real. The equipment needed to isolate the 6150Es from the earth's constant tremor is prohibitively expensive. More importantly, seismic noise prevails at any site, so there is no benefit to specifying precision beyond the practical limit.

Accuracy quantifies consistent offset from a calibrated reference

As the "umbrella" term in the measurement lexicon, *accuracy* is the most misused and misunderstood. Applied strictly, accuracy just represents a gauge's "trueness," or agreement with a traceable standard.

Accuracy is a characteristic of *multiple* samples. Repeated trials must be run to eliminate random errors (defining precision, above). Averaging reveals the *systematic* measurement error, or "bias," the difference from the *true*[7] value.

GEOKON engineers do not specify 6150E accuracy. We can compute trueness, but the number loses meaning the moment we unbolt a 6150E sensor from our calibration fixture. Offset from true zero encompasses every mechanical link.

In practice, geotechnical engineers lump all the angular offsets together when commissioning IPIs. They subsequently track angular *change* from those initial readings.[8] Thus, resolution and precision, not trueness, are the primary determinants of an effective IPI.

Nonlinearity quantifies curvature of the input-output relationship.

The name is self-explanatory, but derivation proved tricky. We first used polynomial regression to find the weighted center of calibration data. The equations for sixteen 6150E MEMS (32 axes) are shown below.

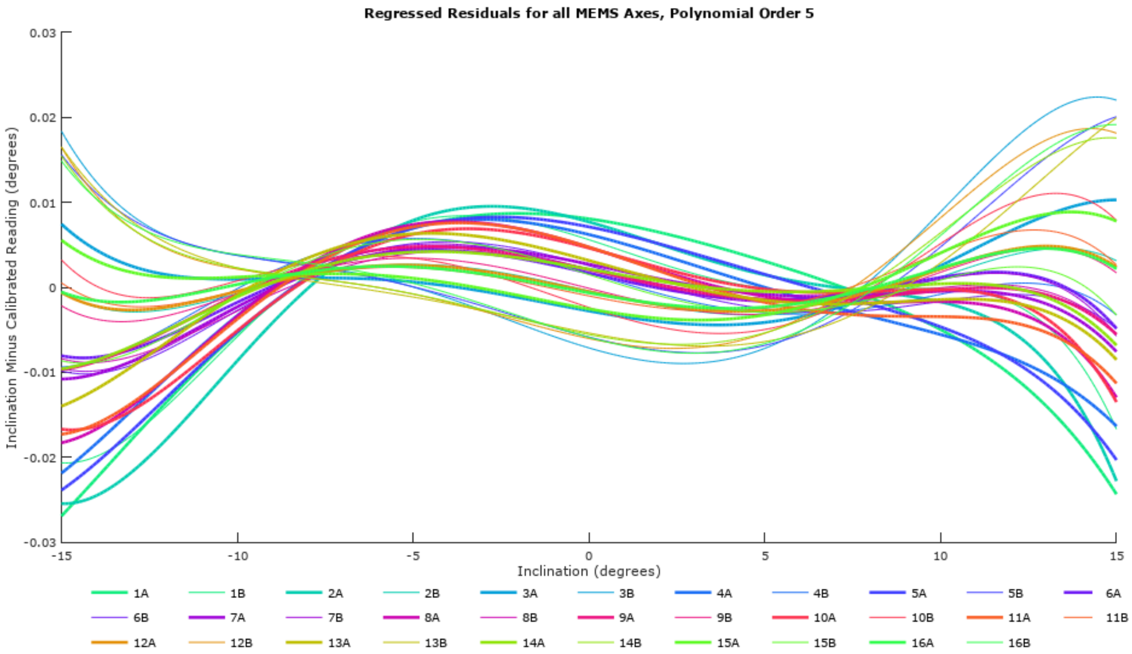
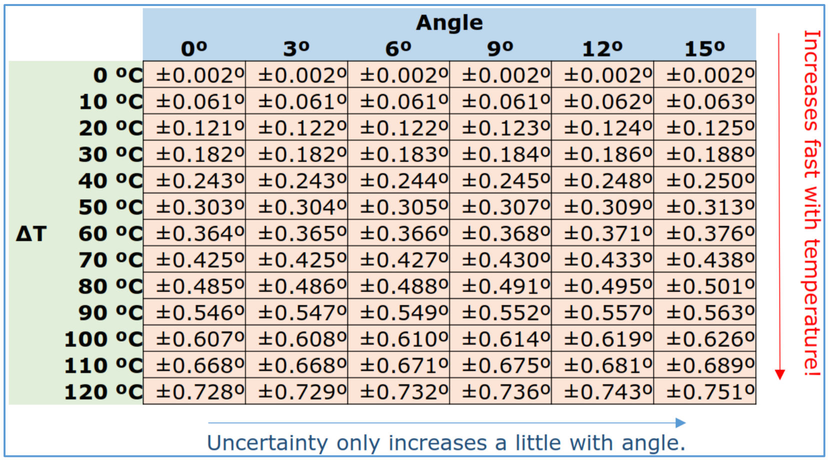


Figure 4 — Nonlinearity was computed by fitting complex nonlinear curves to calibration data.

The original computation became impractical as calibration data accumulated. Nonlinearity is now determined statistically. It is the *standard error of the forecast* for our (linear) calibration regressions. The uncertainty is "expanded," per GUM, to fit a 99 percent confidence interval.

Temperature dependent uncertainty quantifies thermal effects

The greatest degradation to any MEMS angle measurement is caused by temperature change. We compensate to minimize uncertainty, but it still increases proportional to temperature differential. Temperature affects both the voltage (zero) offset and the angle-to-voltage ratio of the IC at the core of the 6150E. Figure 5 shows the combined effects.



		Angle					
		0°	3°	6°	9°	12°	15°
ΔT	0 °C	±0.002°	±0.002°	±0.002°	±0.002°	±0.002°	±0.002°
	10 °C	±0.061°	±0.061°	±0.061°	±0.061°	±0.062°	±0.063°
	20 °C	±0.121°	±0.122°	±0.122°	±0.123°	±0.124°	±0.125°
	30 °C	±0.182°	±0.182°	±0.183°	±0.184°	±0.186°	±0.188°
	40 °C	±0.243°	±0.243°	±0.244°	±0.245°	±0.248°	±0.250°
	50 °C	±0.303°	±0.304°	±0.305°	±0.307°	±0.309°	±0.313°
	60 °C	±0.364°	±0.365°	±0.366°	±0.368°	±0.371°	±0.376°
	70 °C	±0.425°	±0.425°	±0.427°	±0.430°	±0.433°	±0.438°
	80 °C	±0.485°	±0.486°	±0.488°	±0.491°	±0.495°	±0.501°
	90 °C	±0.546°	±0.547°	±0.549°	±0.552°	±0.557°	±0.563°
	100 °C	±0.607°	±0.608°	±0.610°	±0.614°	±0.619°	±0.626°
	110 °C	±0.668°	±0.668°	±0.671°	±0.675°	±0.681°	±0.689°
	120 °C	±0.728°	±0.729°	±0.732°	±0.736°	±0.743°	±0.751°

Increases fast with temperature!

Uncertainty only increases a little with angle.

Figure 5 — Changes in temperature obscure angle changes.

The uncertainty gets a little worse at extreme angles, but is primarily a function of temperature change.

In practice, the temperature difference would be the comparison of any current reading with the historical reference. For example, suppose a 6150E sensor deployed near the surface of a hole measured a 3° inclination at 5 °C. Say the same sensor measured a 2° inclination at 15 °C when it was installed. The temperature change is 10 °C. In the table, the 10 °C uncertainty is the same for angles between 0 and 3°: ±0.061° (use the larger uncertainty if they're unequal). Consequentially, we would say the total angle change is 1 ± 0.061°.

Fortunately, most IPI sensors are installed at depths where daily and seasonal temperature variations are insignificant.

Putting the Numbers Together

The combined GEOKON 6150E uncertainties determine the total potential error of the application. Precision, nonlinearity and temperature-dependent uncertainty can be added *in quadrature* to determine margins for each 6150E reading. Refer to statistics texts or other authoritative references for *propagation of uncertainty.*

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[1] https://www.bipm.org/en/publications/guides/gum.html
[2] https://www.iso.org/standard/66912.html
[3] http://www.ncsli.org/i/c/p/NCSL_International_Z540.2_Standard.aspx
[4] https://www.nist.gov/pml/nist-technical-note-1297
[5] The jitter is called random walk in inertial systems literature.
[6] Peterson J. (1993), Observation and modeling of seismic background noise. U.S. Geological Survey Technical Report 93-322
[7] Exact true values are unknowable, so scientists use a chain of calibrated references as proxies.
[8] Our Model GK-604D inclinometer probe, designed to be inserted and retracted to survey multiple bore holes, is reinserted with a 180-degree twist to negate mechanical and electronic biases.