Ultra-Precision Angle Measurement Sensors with Optimized Size, Weight and Power

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Summary

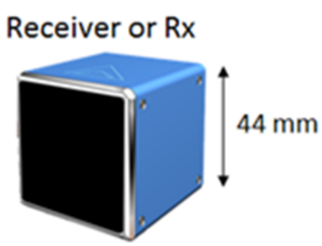
Ultra-precision angle measurement sensors have been developed for a large number of high-performance commercial, industrial and military applications. The sensors are designed to answer the general questions “where am I?” or “where is that?” in indoor and outdoor environments. These angle measurement sensors are composed of ultra-precision optical modules, specialized coding masks, analog optical detectors and digital processing. We call the general technology “Angle Coding” and the particular products Accu-Arc sensors.

In comparison to all previous systems, Accu-Arc sensors are composed of small, lightweight, monolithic optical components that have a wide field of view and an intrinsically rugged package, have no moving parts, use low complexity electronics enabling low power and high speed, and use modern ultra-precision optical fabrication and assembly techniques for the lowest possible production costs combined with the highest possible performance.

Ultra-precise angular sensors can be used in a wide range of applications including:

- Navigation/localization of autonomous vehicles or handheld tools in controlled environments
- Localization of distant targets/tools relative to a fixed reference system
- Ultra-precise measurement/localization of distant objects via laser scanning
- Enabling high-speed ultra-precise closed-loop control of a wide variety of specialized systems, such as fast steering mirrors. These systems can be configured to reach angular precision of micro radians or tenths of arc seconds with kHz bandwidths.

Some characteristics of our Accu-Arc systems are shown in Figure 1. The nominal receiver (or Rx) contains an optical module, analog and digital processing electronics and fits within a roughly 4.5 cm cube. The volume of the optics module is only about 1 cm^3 and so significantly more compact packaging is possible. The nominal angular precision can be about 1 arc second, depending on system SNR and processing update rate. The FOV is +/- 20 degrees and the current system update rate is 100 Hz or less. Targets (or Tx) consist of 950nm modulated LEDs, laser diodes or reflected modulated light from laser scanning systems. Sixteen independent targets can be simultaneously measured.



Angular Precision	≥ 1 arc second (nominal)
Field of View	± 20 degrees
Update Rate	≤ 100 Hz
Number of Targets	≤ 16
Illumination Wavelength	950 nm

Figure 1: Typical housing and table of system characteristics.

An example of measured angular precision is shown in Figure 2. The measurement was via a back-and-forth motion of +/- 180 arc seconds (or +/- 0.05 degrees) with a 25 Hz estimation update rate. With a nominal configuration, a particular Accu-Arc system can achieve an angular precision of about 4 arc seconds. With other configurations for applications requiring much higher precision, 0.1 or better arc second precision can be routinely measured.

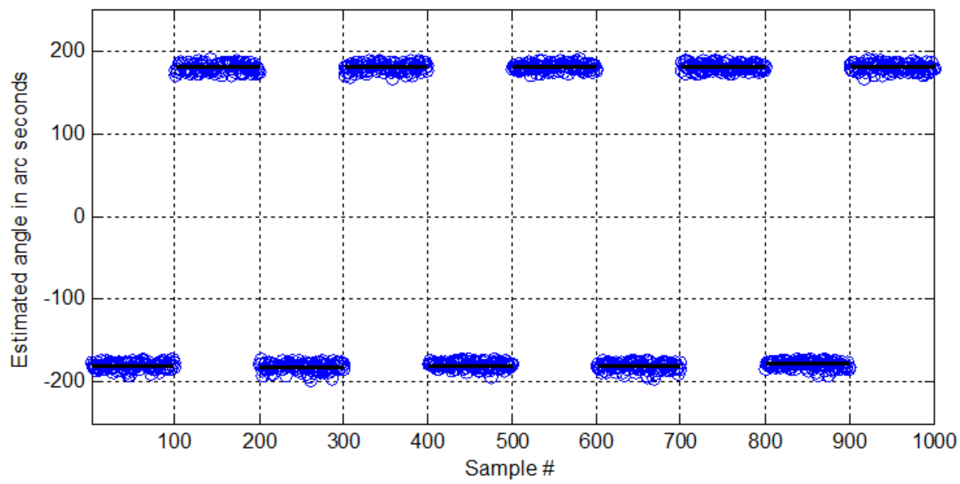


Figure 2: Example measured precision is about 4 arc seconds for a nominal configuration with an update rate of 25 Hz. The black lines in Figure 2 represent the mean value of each section of estimates.

Angle Coding and Accu-Arc sensors are possible today because of a relatively recent convergence of ultra-precision optical array design, fabrication and assembly and advanced remote sensing theory and optimization. The Ascentia Imaging team pioneered many aspects of ultra-precision optical design, fabrication and assembly, including the development of wafer scale optics and cameras for the cell phone industry. The application of advanced radar techniques to what can be loosely called “cameras” was also pioneered by the Ascentia Imaging team, beginning in 1995.

Theory of Operation

A camera can be considered as a general electromagnetic sensing device, not unrelated to that of a radar system. In both cameras and radar, information travels on waves described by a wavelength. Radar wavelengths are often measured in meters and optical wavelengths in microns, but the fundamental concepts of electromagnetics remain the same for both.

Consider Figure 3. The left describes a block diagram of a classical coherent phased array radar system. The right describes an equivalent block diagram from a system that uses Angle Coding, or an Accu-Arc system. In the Accu-Arc or Angle Coding system multiple optical channels (corresponding to array elements in the radar shown at left) are configured so that the overall system can be “steered” and angles estimated. Both systems in Figure 3 are designed through fundamental estimation concepts such as the Cramer-Rao estimation variance lower bound and related Fisher Information. Both systems are designed to maximize the Fisher Information, within their constraints, and minimize the resulting system estimation variance through the Cramer-Rao lower bound. While these concepts are nothing new in radar, Ascentia Imaging’s approach does lead to new types of optical sensor technology and systems that have features and performance that was previously impossible. When designed in this way, no angular estimation system can be more precise given the assumed constraints.

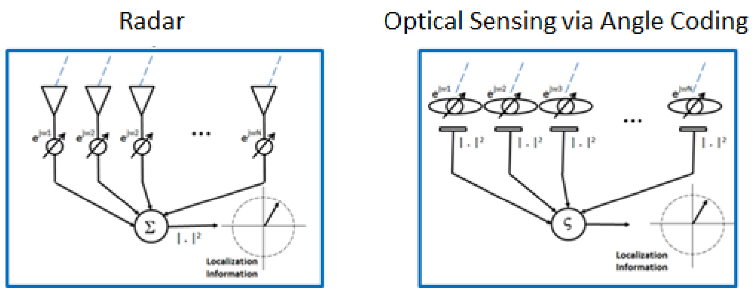


Figure 3: Modern optical angle measurement has many similarities with long-understood radar systems.

Optics and DSP

Figure 4A and 4B describes the interior components of an Accu-Arc receiver. The major optical components from 4A are the custom visible-block color filter, the 16 channel two-lens optical module, the light-absorbing lithographic intensity and optical NIR absorbing wedge masks and a 16 channel detector and trans-impedance amplifier board. Figure 4B shows the entire system assembled with the addition of an ADC board, processor board and I/O hardware.

Summary characteristics of the optical components include:

- Visible-block color filter: Custom dye formulation that acts as a high-pass optical color filter with cutoff at about 900nm. As the silicon detector has a steep cutoff at about 1000 nm, the combined color filter/detector has about a 100nm band pass filter form.
- 16 channel optical module: 4x4 optical modules includes a first and second lens arrays and two spacers. Each optical channel is identical in the module and is designed so that the image of a point (or PSF) is a specialized form that acts with a lithographic intensity grating (as part of the mask assembly) positioned near the classical image plane to form sinusoidal intensity responses vs angle to a Tx. The aperture arrays, lens arrays, and spacers are all injection molded, and have molded self-aligning features that allow each component in each channel to be centered and spaced to better than 5µm relative to its desired position. Both lens arrays and the color filter are AR coated. Because all the optical components are made from materials with very similar coefficients of thermal expansion, thermal effects on the PSF and ultimately on the angular accuracy can be minimized even with polymer optical components.
- Mask assembly: Consists of a series of molded optical NIR optical absorbing “wedges” that act to form essentially linear intensity responses in NIR illumination vs angle to a Tx, and a series of NIR opaque lithographic gratings (seen as grey objects in the mask assembly in Figure 4A). Since the alignment requirements for the lithographic gratings are even tighter than those for the other optical components, the gratings are actively aligned during the assembly process.
- 16 channel detector/TIA board: Single-pixel photon detectors, one for each of 16 optical channels, act to count the total photons that are received through the optics after the intensity masks. Trans-impedance amplifiers, with gains of about 1M, act to maximize received SNR for weak Tx signals in the presence of strong interferers, such as the sun, or at a maximum range. Negative DC feedback circuitry acts to prevent strong signals, like the sun when in the FOV of the Rx, from saturating the ADC.

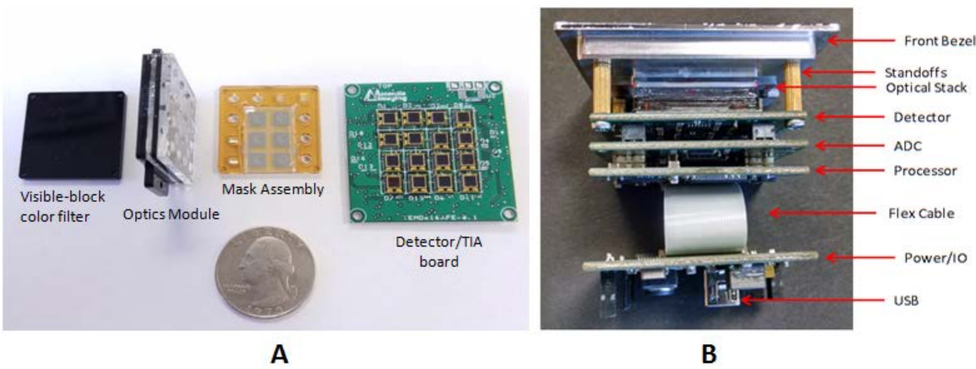


Figure 4: Optical assembly (A) and optical/digital system (B).

A more detailed view of the Accu-Arc sensor of Figure 4 is described in Figure 5. This view represents a slice through the 4x4 optical/digital structures. The completely-custom analog optics front end consists of the visible-block color filter (CF), the lens arrays (L1 and L2), the spacer arrays (S1 and S2) and the mask assembly (Ma). The digital detector board (D/TIA) has a trans-impedance amplifier with a gain of about 1M and a DC negative feedback circuit to reduce any DC offset from interfering sources. The digital section consists of off-the-shelf electrical components configured to convert the analog output from the D/TIA into digital form (A/D) and then process the resulting 16 channel digital stream into angle estimates.

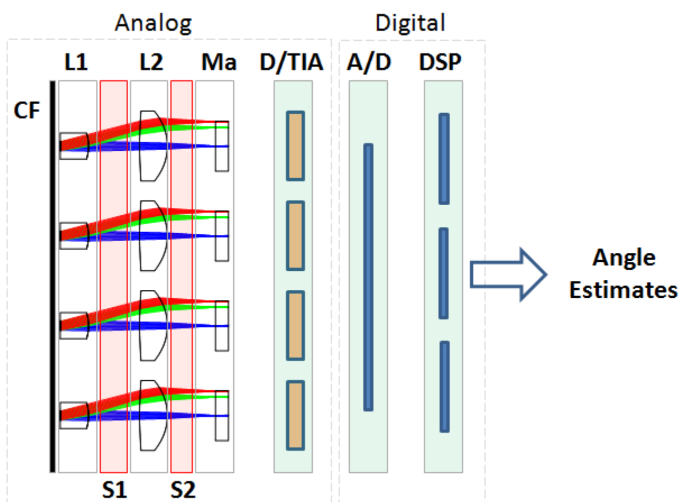


Figure 5: Layout of optical module and electronics.

The three sets of rays (colored blue, green and red) traced through the optics of Figure 5 represent the ray paths for three Tx's positioned boresight to the sensor, 14 degrees to the sensor and 20 degrees to the sensor. The two lens system is designed so that the rays intersect the mask assembly close to perpendicular and with a specially designed form (or PSF) so that the response measured at the output of the detector/ TIA is sinusoidal with angle.

Figure 6 shows example normalized response vs angle of three channels of the Accu-Arc system. The mask assembly acts to make the output of each optical channel unique and orthogonal to each other as a function of angle to a Tx. The signals from what we call low frequency (LF) channels vary essentially linearly with angle. The signals from what we call high frequency (HF) channels vary sinusoidally with angle. The HF signals are purposely designed so that pairs of resulting signals are shifted 90 degrees relative to each other. Because of the specialized optics, signals from the two high frequency channels closely follow a cosine and sine form. Or, pairs of high frequency channels are orthogonal to each other in Tx angle space. This is a fundamental characteristic of Accu-Arc systems that directly leads to ultra-precise angular estimation.

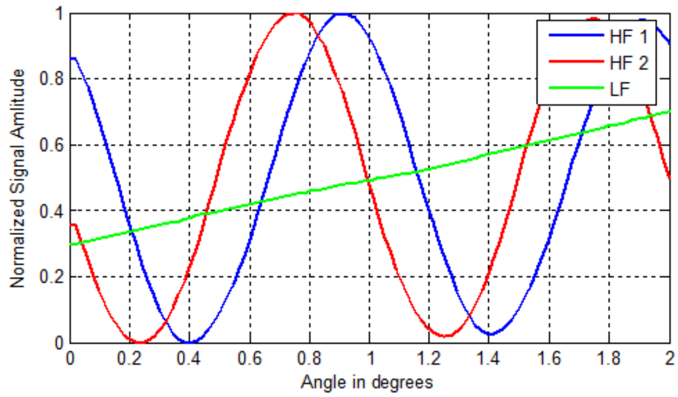


Figure 6: Example normalized signals vs angular position of a Tx.

The HF channels can be seen to have a much larger sensitivity vs angle than the LF channel. The HF channels in effect are responsible for high angular estimation precision, but with angular ambiguity. The LF channels are designed to un-wrap this angular ambiguity. The combination of LF and HF channels then enables high angular estimation precision over a wide FOV.

Another type of representation of the three curves of Figure 6 is shown in Figure 7. Instead of three 2D plots, Figure 7 shows the data plotted in 3 dimensions. Angle is now represented as position along a curve. Notice that the overall shape of this curve can generally be described as a "spiral" through 3 dimensions. Any valid data from the 3 channels of Figure 6, over the same angular degree range, has to lie somewhere along this curve. The red circle of Figure 7 for example represents the data of Figure 6 from the 1 degree point on the horizontal axis. Any invalid data, possibly due to reflections, covered apertures, rain, etc. must lie significantly off this curve. This type of multi-channel configuration enables very fast and very precise digital detection and estimation.

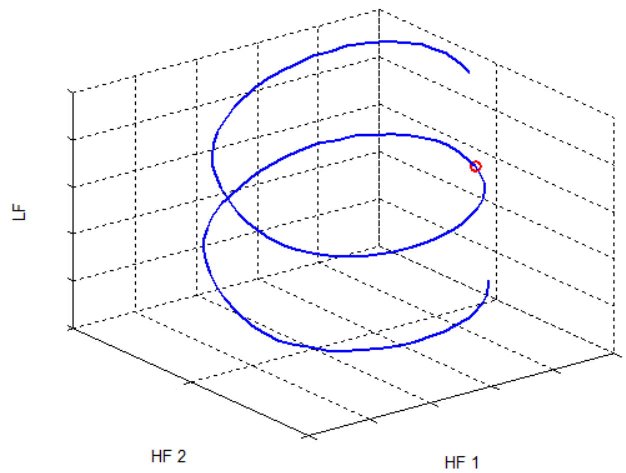


Figure 7: The curves of Figure 6 represented as a 3D plot.

The general algorithm used to estimate angle is then to compare measured data to curves similar to Figure 7 (i.e. calibration curves), for both X and Y angles, and calculate the closest point on a calibration curve in a least squares sense. With real systems there will always be noise so that measured data will never exactly match the calibration data. The expected distance between the measured data and the calibration curve can be described by the noise or equivalently the received signal-to-noise ratio (SNR). Any measured data “too far” from the calibration curves, relative to the measured clear-channel SNR, can be declared “bad data”.

System Scaling

Given the large number of potential Rx/Tx system configurations, having simple first-order scaling rules between systems can be helpful in understanding the broad Accu-Arc system trade space. Table 1 describes some of the main scaling rules relative to the standard-configuration system that formed the data of Figure 2. Each parameter of Table 1 affects the overall system precision through the system SNR.

For example, decreasing the system update rate, or increasing the sampling integration period, acts to linearly increase the received SNR. A linear increase in SNR acts to linearly increase the system angular precision. An increase in the number of temporally averaged angle estimates to N acts to statistically increase the SNR/system precision by only the square root of N. A standard LED used in the Tx from Figure 2 has a field of view of about 120 degrees and was used at a range of about 2 meters. This type of LED enables a very loose positioning between the Rx and Tx, such as found in hand-held tools. In order to achieve a significantly larger Tx range, with constant or increasing angular estimation precision, either the total radiant power of the LED (or laser diode, in general) has to increase or the FOV of the LED should decrease. Decreases in the FOV of an LED can be enabled through secondary optics. Linear decreases in the FOV of the LED, for a constant total radiated optical power, leads to a second order increase in the system SNR and precision. And, increasing the range of the Tx acts to a second order decease of the SNR and hence system precision.

Table 1: General first-order system tradeoffs in precision angle estimation

System Parameter	Change in SNR/Precision
Decrease update rate from 100 Hz	increase by (100/rate)
Temporally average N angle estimates	increase by sqrt(N)
Reduction of Tx beamwidth to θ	increase by $(120 / \theta)^2$
Increase Tx range to R meters	decrease by $(2 / R)^2$

The system parameters that were used to generate the data shown in Figure 2 are:

- Update rate : 100 Hz
- Temporal Averaging: N = 4
- Tx Beam width: 120^o (conservative)
- Tx Range: 2 meters

Given the nature of Accu-Arc systems the above parameters enable a system with an estimated angular precision of about 4 arc seconds, as shown in Figure 2. Consider a new long-range system with the following parameters:

- Update rate: 4 Hz

- Temporal Averaging: N = 4
- Tx Beam width: 10^o
- Tx Range: 60 meters

The new parameters above describe a Tx at 30X the range of the system related to Figure 2, but with a much slower update rate and 12X reduction in the LED beam width. Using the first order scaling parameters from Table 1 we see that the expected system SNR with the long-range system parameters increases by a factor of 4, or the expected system angular precision with this particular long-range system should be about 1 arc second. So, a long range but relatively slow update rate system configuration can also directly have an estimated angular precision of about 1 arc second. Numerous other potential system configurations can be broadly understood through the same first-order scaling method

Conclusions

Angle Coding and Accu-Arc angle measurement sensors are a modern combination of ultra-precision array optics design, fabrication and assembly and advanced radar signal estimation theory. These sensors can achieve angular estimation precision on the order of low arc seconds in standard configurations. When used in specialized systems these sensors enable ultra-precision measurements with fast update, low power, low weight, no moving parts and very low cost in volume production.