Encoder Resolution for the ATA Antenna

12/13/01
updated: 1/22/3
G. R. Harp

Resolution
The pointing accuracy of the ATA antennas is to be at least one fifth of the primary beam width at 10 GHz. Following Dave DeBoer’s estimate of beam size (Δθ = 3.5/f (GHz), see ATA Memo 23), the beam width is about 21’. Thus the pointing accuracy should be at least 4’.

Dividing 360° by this value, we get 5400, which is the minimum number of encoder counts per revolution, if we are to encode at the resolution limit. We probably want 3-4 times this number of counts, so we don’t blow our entire pointing error budget on the encoder (we need to have some leftover budget for wind, mechanical error, etc.).

BEI Encoder
We have an incremental encoder from BEI which has nominally 7200 pulses per revolution (square wave form). Because we can measure both rising and falling pulse edges we automatically have 14400 counts per revolution. In addition this encoder uses quadrature encoding where ordinary pulses come in on the “A” line, and a second set of phase shifted pulses come in on the “B” line. Defining one pulse wavelength as 360°, the phase shift between “A” and “B” pulses is 90° ± 18° (manufacturer’s spec.). Using edges on both the “A” and “B” lines gets us to 28800 counts per revolution.

The Error Budget

For a given number of counts per revolution, we know the encoder position to plus or minus one half of the distance between counts. Thus, a perfect encoder with 28800 counts per revolution provides a pointing accuracy of ±0.38’.

The dominant error in the BEI encoder is the phase shift between “A” and “B” pulses. This is a constant over the entire revolution and can be accounted for in software, even “on the fly” without direct calibration. However, if not accounted for this error amounts to 0.05 of one pulse wavelength or a pointing error of ±0.15’. This is a systematic error that is additive with the error described above, so the total error is ±0.53’.

To this error we must add the 1) the jitter in the edge position of the “A” pulses and 2) the error in our knowledge of the encoder zero position. The “A” jitter is supposed to be significantly smaller than the “B” phase shift. We don’t know much about the statistics of this error, so let’s suppose it is systematic and 1/5 as large as the “B” phase shift (0.03’).
Incremental encoders have a special line called “z”, which delivers a pulse only once per revolution. The pulse width is as wide as one of the “A” pulses. We can use the rising edge of “z” as encoder zero, so our knowledge of the encoder zero is as good as the jitter error mentioned above (0.03’).

Adding in these errors, the total pointing error arising from this encoder is about 0.6’, or 1/7 of our error budget. Because errors from wind or mechanics should add in quadrature with encoder error, the encoder consumes only 1/25 of our total error budget, which is probably acceptable.

**Addendum: 1/22/3**

During the prototyping phase it was determined that a higher resolution encoder would be preferable, so 4x interpolation BEI encoders are installed as of this date. The next revision will use Gurley encoders having 10x interpolation.

**Error Breakdown (Gurley Encoders)**

From the Gurley rep, here is a breakdown of the accuracy for the 9220 encoder with 3,600 lines and 10x interpolation:

- 4.5” quantization error
- 10.0” instrument error
- 8.0” quadrature error
- 0.9” interpolation error
- 10.0” coupling error - SCA coupling
- 3.6” drift

---

37” Total Pointing Error (+/-) from encoder plus coupling, including drift

The random errors (repeatability) is directly related to the drift value, which is typically ten times better than the accuracy. However, temperature cycling and electrical noise can alter this figure to say five times lower than the total accuracy. Hence, as it stands the random error expected for this encoder is 3.6” to 7.4” (+/-).

BTW, the Gurley rep. claims that the random errors on their encoders are smaller than on equivalent BEI encoders.

**Distance Coded Reference Marks**

The Gurley encoders are electronically identical to the BEI encoders, except that they use distance coded reference marks (DCRM) to simulate an “almost” absolute behavior. This means that there are multiple zero pulses (48) per revolution. The spacing between each adjacent pair of pulses comprises a unique number of steps, so that after passing any two DCRM’s you will know the absolute position. Here is what the vendor says:
The special index pattern would be provided at no charge. For a 3,600 cycle encoder I suggest the following sequence of 48 "indexing intervals" (the Amer/English term), namely: [76, 74, 77, 73, 78, 72, 79, 71, 80, 70, 81, 69, 82, 68, 83, 67, 84, 66, 85, 65, 86, 64, 87, 63, 88, 62, 89, 61, 90, 60, 91, 59, 92, 58, 93, 57, 94, 56, 95, 55, 96, 54, 97, 53, 98, 52, 99, 51, wrap]. Starting from directly adjacent to an index and proceeding in the "wrong" direction, up to 2 consecutive intervals may need traversing to assure detection of 2 indices and consequent determination of initial absolute position by measuring the interval between them. Thus the worst-case initialization traverse is determined by the largest sum of 2 adjacent intervals, which in this case is 151 optical cycles, and best-case by simply the shortest interval, 51 cycles. These yield 15.1 and 5.1 degrees respectively, with an average somewhere between. Once absolute position is initialized, subsequent position readings can, and probably should, be validated "on the fly" whenever an index occurs (roughly every 5 to 10 degrees) during normal antenna motion. Note that the intervals are here stated in optical cycles, for which there will be 40 measuring steps each to be recorded by an up/down counter or its software equivalent. Thus the shortest interval of 51 optical cycles, for example, would correspond to 2,040 measuring steps of 0.0025 degrees each.
Nulling Constraints on Encoder Resolution

In discussions with Jack Welch and Mike Davis, it was noted that pointing constraints related to RFI nulling are much more stringent than constraints related to simple radio pointing. Here we quantify some of those concerns:

Synthetic Beam Constraints

Mike Davis wrote:
Interesting comment from Jack Welch a week ago; He thinks that if we are serious about putting accurate nulls on satellites, then we will need this pointing accuracy, far better than the nominal 2' rms.

Jack raises an important issue. For a symmetric aperture, a pointing offset introduces a purely real amplitude error into the measured signal. From the memo, “Customized Beam Forming at the ATA”, we find that the maximum tolerable amplitude error for synthetic beam nulling is ~10%. Since the phase of the actual pattern also varies and we want to be conservative, let’s suppose the maximum tolerable error is 5% in amplitude.

Starting from a random point in the beam pattern and moving in the direction of fastest variation, the beam pattern can be approximated (over a small patch) as

\[ p \propto \sin(\alpha \theta) \]

for a suitably chosen \( \theta \). Here \( \alpha = \frac{2\pi}{\text{Beam Width}} = \frac{2\pi}{0.35^\circ} \) at 10 GHz. If we are displaced by a distance \( \Delta \theta \) from the ideal point in the beam pattern, the amplitude error is

\[ \Delta A \sim \left( \frac{dp}{d\theta} \right) \Delta \theta = \alpha \cos(\alpha \theta) \Delta \theta. \]

We wish that \( \Delta A \leq 0.05 \), or

\[ \Delta \theta \leq \frac{0.05}{\alpha} \sec(\alpha \theta). \]

Below is a plot of \( \Delta \theta \) versus \( \theta \). Also plotted are the current values of plus or minus one encoder step. You want \( \Delta \theta \) to be smaller than one encoder step. As you can see, most of the time our present encoders are not good enough. Ideally we would like to have encoders with a resolution of about 0.002°, or 3x better than our current resolution.

On the other hand, notice that in L-band, the present encoders are probably fine.
Using Antenna Null for RFI Mitigation

Jack Welch wrote:

One point to keep in mind is that we may want to put a null on a high frequency satellite even though we are observing at a low frequency if the satellite is quite strong - strong enough to overdrive the fiber channel.

Restated, the idea is to use the antenna pattern null to get rid of the interference (instead of a null in the synthetic beam). The accuracy with which you can place a null on the interferer is exactly the same as the pointing accuracy.

Following the approach from above, the minimum separation $\theta_{\text{min}}$ between two nulls of the beam pattern is

$$\theta_{\text{min}} = \frac{\pi}{\alpha} = \frac{\text{(Beam Width)}}{2}.$$ 

Near the bottom of the null, the slope of the beam amplitude $\frac{dA}{d\theta} = \alpha$, so the null suppression factor is simply $\frac{2\pi}{(\text{Beam Width})} \Delta \theta$. Setting $\Delta \theta = (1 \text{ encoder step}) = 22''$ for
the current encoder, this gives a null suppression factor 10 dB over the 35 dB that you already get from the antenna pattern. This isn’t great, but the situation improves at lower frequencies (16 dB at 2 GHz). Turning it around, to get 20 dB suppression at 10 GHz requires 2” pointing.