Gemini
Mount
Control
System
Report

Encoder Tests

Gemini

10 July 1996

MCSJDW11 (Issue 1) - This report explains the tests carried out upon the Heidenhain and Inductosyn encoding systems to assess suitability for main axis encoding on the Gemini telescopes.

1. INTRODUCTION

The servo system that controls the drives of the main axes (Azimuth and Elevation) on the Gemini telescopes requires position feedback of a certain accuracy in order to perform as desired. This feedback is to be provided by the encoder system. This report describes tests that were done to help decide between two tape encoder systems:

1. Heidenhain Optical Tape Encoder
2. Inductosyn Inductive Tape Encoder

1.1 History Of Gemini Encoder Selection

It was originally intended to provide feedback from the main axes of the Gemini Telescopes using an Inductosyn tape encoding system. The WHT tape encoder project, see Ref. [3] & [4], was intended to assess the suitability of such an encoder for large telescope applications. The performance required from the encoding system was specified as 30 milli-arcseconds per axis. The WHT project suggested that this was attainable.

Some time after, the encoder performance figure was re-specified to be 5 milli-arcseconds - well outside what was considered possible with a raw Inductosyn system. At about the same time, Heidenhain released an improved version of their LIDA tape encoder system. It was based upon a 40 µm pitch optical scale and its price was comparable with the Inductosyn system. Together with its associated compensation electronics (IK320), this new tape, it was claimed, would meet the new Gemini specification. Unfortunately, it proved very difficult to provide an interface between the IK320 and PMAC, the VME card already chosen to implement the main axis servos. Ref. [6] outlined the advantages and disadvantages of the two proposed encoding methods.

Heidenhain then suggested a much simpler way of interfacing their tape to PMAC, but this involved implementing the required compensation on the PMAC card using the Heydemann technique. Heidenhain supplied the relevant information to do this, Ref. [1] & [2]. It was also thought that a similar compensation method could be applied to the Inductosyn system in order to reduce error. It was also at about this time that Inductosyn reduced the price of their tape by almost a half.

Some tests then had to be carried out on both encoding systems. The interfacing and compensation techniques suggested by Heidenhain had to be tested, and a compensation technique had to be developed for the Inductosyn tape. This report describes those tests. The encoder error specification has now been re-negotiated to be 20 milli-arcseconds per axis.

1.2 References

[1] "Determination and correction of quadrature fringe measurement errors in interferometers" Peter L. M. Heydemann, APPLIED OPTICS Vol. 20 No. 19, 1 October 1981.

[2] "Optical fringe subdivision with nanometric accuracy" K. P. Birch, PRECISION ENGINEERING Vol. 12 No. 4, October 1990.
[3] "William Herschel Telescope Inductosyn Tape Encoder Project" C. S. Amos, J. E. Churchill, M. Fisher, R. A. Laing. September 1992. RGO Report - RGO-N-008.
[4] "A High Resolution Incremental Tape Encoder On The William Herschel Telescope" Martin Fisher, ADVANCED TECHNOLOGY OPTICAL TELESCOPES V, SPIE Vol. 2199, March 1994.
[5] "Comments on Report RGO-N-008 - William Herschel Telescope Project" Frank Ruhle, Inductosyn International. EN7032. January 1996.
[6] "Encoder Considerations" Martin Fisher and John Wilkes, GEMINI MOUNT CONTROL SYSTEM REPORT, November 1995.

2. TEST SET UP

2.1 Mechanical Set-up

The tests were carried out using a linear stage supplied by Physik Instrumente (Model number M-535.22). The stage is made up of a DC motor, encoder, gear box and lead screw arrangement. The encoder and gearing give a resolution of 0.034 µm and a repeatability of 1 µm.

A saddle, which held both the Inductosyn and the Heidenhain read heads was mounted upon the stage, as shown in Figure 1.

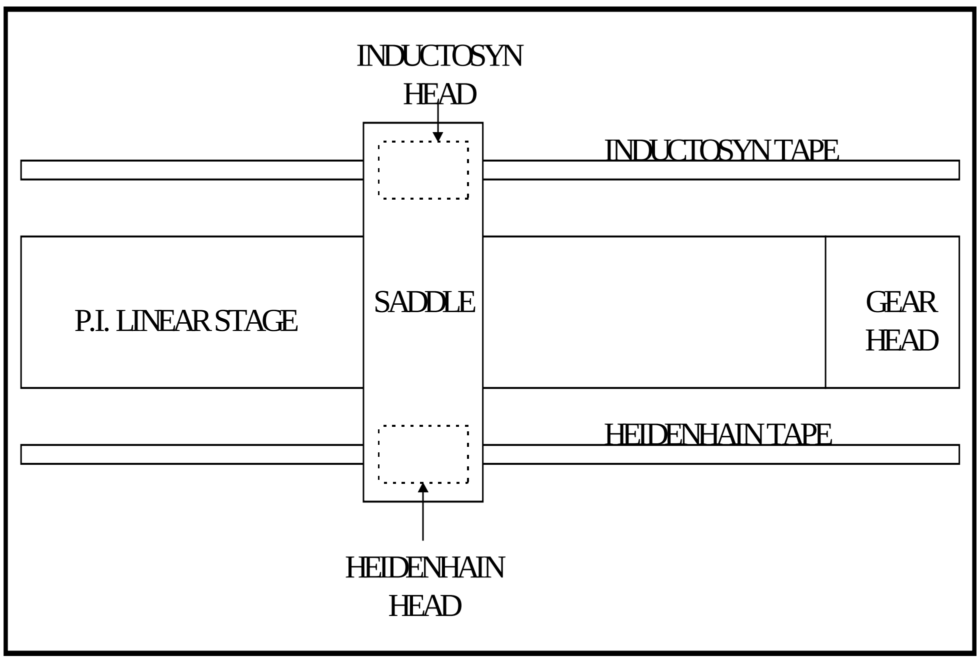

Figure 1 - Mechanical Test Set-up

2.2 PMAC Set-up

The stage was controlled using a Delta Tau PMAC-VME card. This card was used to close a position loop by reading the stage encoder and supplying torque demands to the motor via a small power amplifier based upon an LM759 power op-amp (gain = 20 mA/V). The PMAC card also read, and acted upon, the limit switches on the stage.

The servo parameters used to control the stage were:

```
Scale Factor (Ix08) = 96
P .......... (Ix30) = 1000000
I .......... (Ix33) = 20000
D .......... (Ix31) = 6800
Velo. FF ... (Ix32) = 6958
Accel. FF .. (Ix35) = 40000
```

These values were derived using the tuning tools available with the PMAC Executive software.

The actual tests involved the stage being moved over a given distance in steps of a set size. At each step, the stage was stopped and all three encoders were logged (see data gathering as described below). This action was implemented using a PMAC motion program as shown in Appendix A. The overall distance and step size used depended upon the nature of the test, these values were passed as parameters to the motion program using PMAC 'P' variables.

The position value read from the stage encoder (the reference encoder) was converted into units of microns and stored in a 'P' variable using a PMAC PLC program. This PLC program (shown in Appendix B) was also used to implement the correction algorithms for each encoder. Note that since, in this application, no servo loop is to be closed from the compensated tape encoder values, the processing delay caused by using a low priority PLC program is not important. When used in a closed servo loop, however, this delay will cause problems and the correction algorithm should be implemented as a high priority user written servo algorithm. It is assumed that the PMAC card will have enough processing power to allow this.

The data gathering feature of PMAC was set up to gather some or all of the following data on a one shot (I19 = 0) basis:

- Reference Encoder Position Value
- Heidenhain Encoder Position Value
- Inductosyn Encoder Position Value
- Heidenhain Sine Head Amplitude
- Heidenhain Cosine Head Amplitude
- Inductosyn Sine Head Amplitude
- Inductosyn Cosine Head Amplitude

Exactly what is gathered, is set by 'I' variable I20. In the normal mode, only the three encoder position values are stored, therefore I20 = 7.

The gathered data was read into MATLAB using a C program that reads and writes to the PC's serial port. The program issues a 'LIST GATHER' command to PMAC then converts the response into an array which is then stored as a MATLAB '.MAT' file.

2.3 Calculation Of Encoder Error

The object of the encoder tests is to measure the position error due to each encoding system. The best way to do this would be to use a reference encoder which has no errors, and compare the output of the encoding system under test with this. In practice, this is not possible since there is no such thing as an error free reference encoder, if there were, it would be used to encode the telescope axes.

Therefore, the encoder errors have to be determined using the following method, implemented using MATLAB:

1. From each test run obtain the position vector for each of the three encoders:
    - H = Heidenhain
    - I = Inductosyn
    - R = Reference encoder on stage
2. The difference between two encoder position vectors (the residual) will be due to errors from both encoders.
3. Each residual vector can be divided up into its spatial frequency components by using Fourier analysis (i.e. an FFT). Each frequency component will be due to either or both, of the encoding systems involved.

4. There are three sets of residuals H-R, I-R, H-I, hence three spatial frequency spectra. By inspection of these spectra each spatial frequency component can be attributed to the relevant encoding system. Table 1 shows an example of this. Knowledge of the physical make up of each system, as shown in Table 2, will assist in this process.
5. Inspection of the results from a number of test runs will allow the errors of the stage reference encoder to be completely determined in terms of a set of spatial frequency components. The root sum square (RSS) of the amplitudes of these components will give an overall RMS error for the reference encoder. The RMS value of each residual is easily determined, and so the RMS error of the two tape encoders can be calculated.

   Table 1 shows the spatial frequency components due to the reference encoder are 0.25, 0.5, 1, 1.17 and 32.67 cycles/mm. The RSS of the amplitudes of these components is 0.37 μm. The RMS of either tape encoder, then, is given by:

$$R_t = \sqrt{R_r^2 - 0.37^2}$$

   R_t is the RMS error of H or I when R_r is the RMS of the residual H-R or I-R respectively.

   Note the relationship between microns and milli-arcseconds for each axis of the Gemini telescopes:

   Azimuth - milli-arcseconds ≈ 43 × microns
   Elevation - milli-arcseconds ≈ 52 × microns

H-R	**Freq. (cyc/mm)**	0.15	0.25		0.50	1.00	1.17	24.99	32.67
	RMS Amp. (μm)	0.06	0.31		0.10	0.05	0.17	0.96	0.05
H-I	**Freq. (cyc/mm)**	0.15	0.20	0.40	0.50	1.00		24.99	
	RMS Amp. (μm)	0.10	0.13	0.1	2.02	0.89		0.96	
I-R	**Freq. (cyc/mm)**		0.27	0.37	0.50	1.00	1.17		32.67
	RMS Amp. (μm)		0.33	0.05	2.03	0.93	0.17		0.05

KEY:	H	I	R	I+R

Table 1 - Spatial Frequency Components of Encoder Residuals

Encoding System	**Heidenhain**	**Inductosyn**	**Reference Encoder**
Spatial Frequency (cycles/mm)	25	0.5	0.5
Physical Cause	Tape Pitch	Tape Pitch	Lead Screw Pitch

Table 2 - Main Periodic Errors Expected From Encoding Systems

3. HEIDENHAIN TESTS

3.1 Interfacing To PMAC

In order to derive a position value from the Heidenhain encoder, we need to count pitches (every 40 μm) and interpolate between these pitches using the two, quadrature, sinusoids. Figure 2 shows the required interface between the tape head and PMAC.

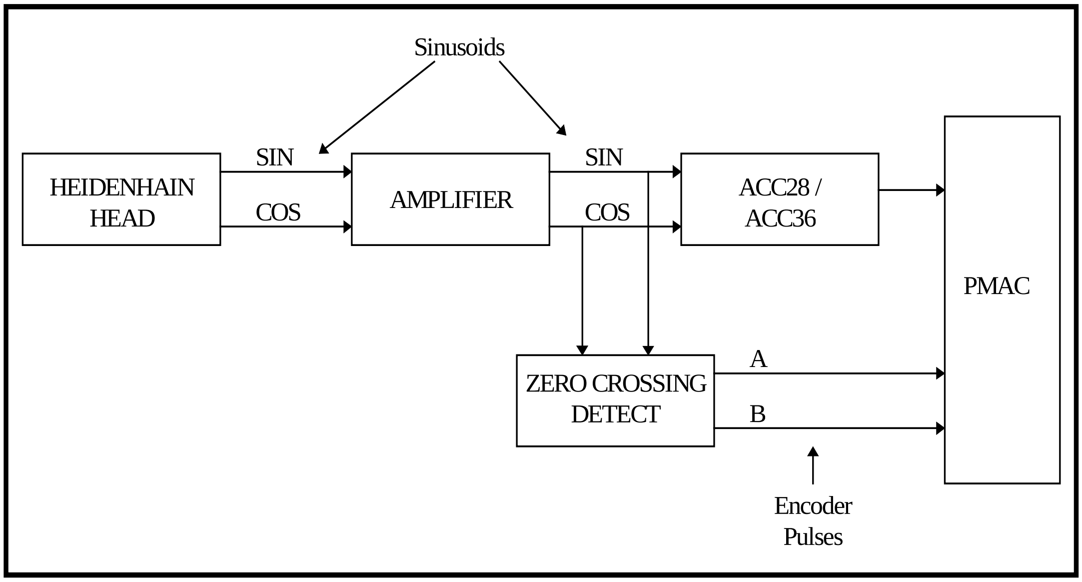

Figure 2 - Heidenhain / PMAC Interface

To provide a position value out, we need to interpolate between pitches using the analogue sine and cosine signals. The following algorithm will do this:

- Normalise the sinusoidal signals so that they lie between -1 and 1.
- Take the arc-tangent of the sinusoidal amplitude, using both the sine and cosine values to obtain an unambiguous angle, *A*, in the range 0°-360°.
- Calculate *Position* using:

$$Position = \left[PitchCounts + \frac{A}{360} \right] \times 40\mu m$$

PitchCounts is taken from the output of the counter associated with the A/B encoder pulses (set-up as 1x interpolation in PMAC). This interpolation algorithm is implemented using a PMAC PLC, see Appendix B.

The resolution, R, of this system is not constant since the value represented by one bit will vary across the pitch; however, it is given approximately by:

$$R = \frac{40\mu m}{2^{N+1}}$$

Where N is the number of bits used in the ADC process. When using PMAC's ACC28 in its default state, then $N = 13$ and $R \approx 2.4$ nm ($\approx$ 0.125 milli-arcseconds on the elevation axis). When using PMAC's ACC36, $N = 12$ and $R \approx 5$ nm ($\approx$ 0.25 milli-arcseconds on the elevation axis). Note that resolution is not related to accuracy since there is no error improvement in being able to resolve noise better! Once the noise threshold is reached, there will be no improvement in accuracy from increasing the resolution of the ADC process.

Apart from resolution, there are other differences between PMAC's ACC28 and ACC36 ADC accessories. The ACC36 is much cheaper than the ACC28 and can be expanded up to 384 channels. However, the conversion process takes longer and it may not be possible perform conversions at the servo rate from within a user written servo routine. If this is the case, then an ACC28 must be used. the ACC28 allows up to 16 channels of ADC.

The parameters for the PMAC motion program described in Section 2.2, as used for the Heidenhain tests, are shown in Table 3.

VARIABLE	MEANING	UNITS	VALUE
P4	Increment	μm	10
P5	Feed Rate	μm/s	4000
P6	Dwell Time	ms	200
P7	Start Position	μm	20000

Table 3 - Motion Program Parameters For Heidenhain Tests

3.2 Applying The Heydemann Compensation Technique

The majority of the periodic errors present in the Heidenhain measurement will be due to:

- Lack of quadrature (phase shift between sin and cos signals is not exactly $\lambda/4$ or 90°).
- The sinusoidal signals having unequal amplitudes.
- A finite DC offset in either or both of the sinusoidal signals.

These errors can be reduced by using a well known compensation technique, developed by Peter L. M. Heydemann (see Ref. [1] & [2]). This technique was developed for use in interferometers with quadrature detector systems. The Heidenhain tape encoder is, effectively, such a system.

3.2.1 Acquiring Data To Calculate Heydemann Compensation Parameters

Before the relevant parameters can be calculated, a set of quadrature values, i.e. the sine and cosine values that are used by the arc-tangent function, need to be acquired. The question arises, how many samples are needed, and where on the tape should they be taken from? There are a number of things to bear in mind when answering this question:

- The total length of the tape should be divided into a number of equal regions, and each region should use its own local compensation parameters. This allows compensation for local patches of dirt and scratches. For each region, a lower limit on the number of samples per compensation run is arbitrarily set at 20.
- The number of regions depends upon how much data we are prepared to store on the host and the amount of time allowed to do a compensation run. Each region will require the storage of five floating point values. A space of 200 Kbytes will allow about 8000 regions. A reasonable limit for compensation time is one hour per axis.
- The samples must be equally spaced across the 0-360° sub-pitch range.

So, the minimum region size on azimuth is 30 metres divided by 8000, or 3.75 mm. If each region has 20 samples then we must sample once every 187.5 μm. In order to complete a compensation run in one hour the axis must be moved at a minimum of 8.3 mm/s. This requires a sample rate of 45 Hz.

In order to equally space the samples across the pitch the remainder on dividing the sample period by 40 μm must be 1 divided by the number of samples. The easiest way to ensure this is to round the sample distance up to the nearest whole number of 40 μm pitches then add the required remainder. In our case we would round 187.5 μm to 200 μm and add 40 μm divided by 20, or 2 μm. So the sample interval would be 202μm, giving the following:

- Sample frequency approx. 41.5 Hz.
- Region of 4.04 mm
- 7425 Regions

More generally, the sample interval in microns, I, is given by:

$$I = 40\mu m \times \left[\mathrm{int}\left(\frac{L}{40\mu \times R \times N} \right) + \frac{1}{N} \right]$$

Where N = No. of samples per region, R = No. of regions and L = Total length of tape.

Axis Velocity, V, in mm/sec, and sample frequency, F_s, in samples/sec are given by the following equations:

$$V = \frac{L}{t} \quad \text{and} \quad F_S = \frac{V}{I}$$

Where t = time allowed for a compensation run.

Note, it may be necessary to allow overlapping regions if there are problems with the change over of compensation parameters at the region boundaries.

3.2.2 Calculation Of Compensation Parameters

When the quadrature signals from the read head are plotted against one another, they will form an ellipse. Differences between this ellipse and a perfect circle are caused by the factors mentioned in Section 3.2. The ellipse can be described using four parameters:

- DC offset in the sine channel, p.
- DC offset in the cosine channel, q.
- Quadrature Error, a (i.e. phase between sine and cosine channels minus 90°).
- Ratio of the sine and cosine amplitudes, G.

Using this description, a system of simultaneous equations in five unknowns can be obtained, see Ref. [1] & [2]. If there are more than five pairs of data samples (there should be at least 20), this system of equations is over defined and can be solved using a least squares fitting routine. Appendix C lists a MATLAB m-file that solves these equations and obtains the four compensation parameters.

Figure 3 shows the effect of Heydemann compensation on the raw quadrature signals. Note that the amplitude of the compensated signals is less than one. This is because the technique compensates only for relative differences in amplitude between the two signals, not for the absolute amplitude of each signal. However, this does not matter since the arc-tangent function works on the ratio of the two signals.

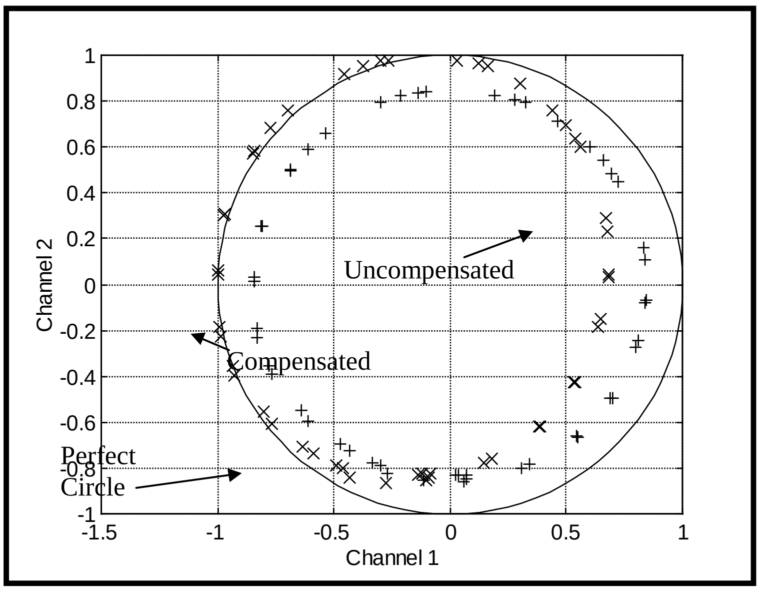

Figure 3 - Quadrature Signals, Before And After Compensation

Note that this method compensates for errors in the tape/head arrangement and errors in the subsequent processing electronics. Compensated errors will re-appear if the errors due to the processing electronics drift over time. Therefore, it is important to use high quality, low drift components in the head interfacing circuitry.

3.2.3 Applying Compensation To Heidenhain Output

If *ch1* and *ch2* denote the uncompensated quadrature signals, then the compensated signals, *ch1c* and *ch2c*, are given by the following equations (see Ref. [1] & [2]):

$$ch1c = ch1 - p$$

$$ch2c = \frac{ch1c\sin(a) + G(ch2 - q)}{\cos(a)}$$

The results of this, i.e. *ch1c* and *ch2c*, are applied to an arc-tangent function to obtain a compensated angle. The compensated angle is then compared with the uncompensated angle, and the difference in microns is added to the Heidenhain position output. All this is done within the PMAC PLC as listed in Appendix B. The compensation parameters are stored as five PMAC 'P' variables, P10-P14 denoting p, q, $\sin(a)$, $\cos(a)$ and G respectively.

3.3 Obstruction Tests

The main problem expected from the Heidenhain system is a degradation of performance in the presence of optical obstructions on the tape. The two main causes of these obstructions are scratches and dirt. Each were simulated by the tests described below. For each obstruction, the following was performed:

- A test run with no compensation.
- A test run with compensation parameters derived from a clean tape.
- A re-compensation run.
- A test run with the new compensation parameters.

3.3.1 Scratch Obstructions

Scratches on the tape scale will cause loss of signal. Rather than cause permanent damage to our segment of tape, we simulated scratches by placing small pieces of paper onto the tape.

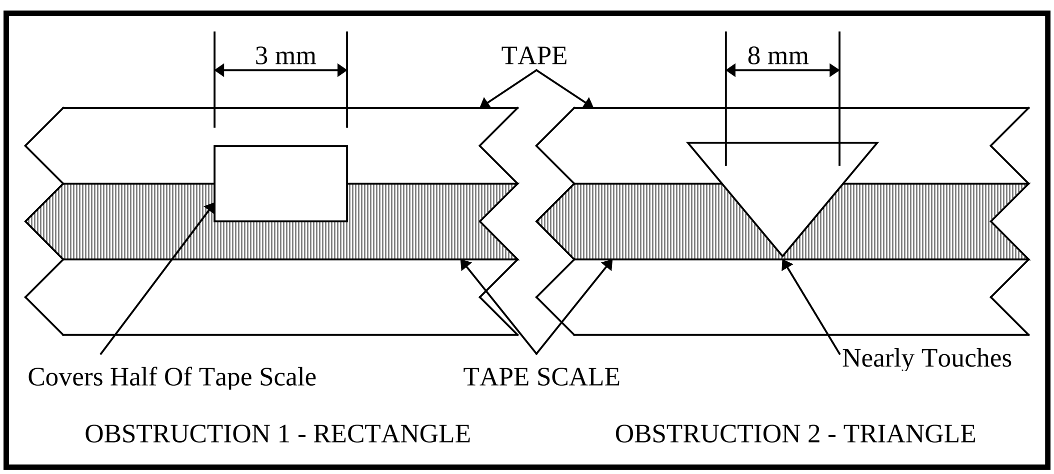

Figure 4 - Heidenhain Paper Obstruction Tests

3.3.2 Dirt Obstructions

In the telescope environment, the tape is likely to come into contact with oil. Dirt particles will then stick to the tape. To simulate this a paste was made by mixing used photocopier toner powder with general purpose lubricating oil. A segment of the tape was painted liberally with this paste and a set of tests were carried out. The tape was then cleaned using a clean pad impregnated with isopropyl alcohol and another set of tests were carried out.

3.4 Results

Table 4 shows the results of the various tests upon the Heidenhain tape encoding system. The numbers in the table denote RMS error calculated by removing the error of the reference encoder from the RMS of the residual H-R, as described in Section 2.3. The results are shown in microns and in milli-arcseconds on the elevation axis. The errors will be smaller on azimuth since the effective diameter is larger.

RMS ERROR	Microns			Milli-Arcseconds On Elevation		
Case	**No Comp**	**Comp**	**Re-Comp**	**No Comp**	**Comp**	**Re-Comp**
Clean Tape	0.93	0.09	-	48.31	4.50	4.50
Rectangle Obstruction	1.03	0.37	0.32	53.31	19.00	16.70
Triangle Obstruction	1.09	0.42	0.47	56.62	21.86	24.56
Dirt Obstruction	3.84	2.26	0.73	199.80	117.52	38.05
After Cleaning	-	0.34	-	-	17.49	-
I/F using ACC36	0.98	-	0.12	51.10	-	6.41
After 3 Weeks	-	0.39	-	-	20.45	-
After 6 Weeks	-	0.29	-	-	15.07	-

Table 4 - Summary Of Results From Heidenhain Encoder Tests

3.5 Heidenhain Conclusions

3.5.1 Encoder Performance

It can be seen, from the results shown in Section 3.4 (Table 4), that:

- With a clean tape and fresh compensation, errors of less than 0.2 microns (10 milli-arcseconds on elevation) can be achieved.
- These errors vary with time (probably due to temperature) but do not get any worse than 0.4 microns (20 milli-arcseconds on elevation).
- Fixed obstructions (e.g. bits of paper partially covering the tape and scratches) can increase errors slightly. Re-compensation will NOT improve this unless very small compensation regions are used.
- Severe dirt obstructions can increase errors by a factor of 5-10. Re-compensation can reduce errors to a factor of 2-3 times those on a clean tape. The best defence, however, is to regularly clean the tape with isopropyl alcohol. Note that the amount of dirt used in the tests was far in excess of that expected in the telescope environment, even after a prolonged period (> 1 year) without cleaning.

3.5.2 Encoder Interface

The analogue signals from the Heidenhain head can be interfaced to PMAC using an Accessory 28 or an Accessory 36. However, the Accessory 36, though more desirable in terms of cost, may cause timing problems when the encoder is read at the servo rate in the virtual encoder.

4. INDUCTOSYN TESTS

4.1 Interfacing To PMAC

Interpolation between the 2 mm pitches of the Inductosyn tape is carried out with a resolution of 16384 (0.122 μm) on a board supplied by Inductosyn. This is based around a Resolver to Digital Converter (RDC) chip. This board outputs 5 V quadrature pulses similar to a rotary incremental encoder so these can be interfaced to PMAC in the conventional way. Figure 5 shows how the elements of the Inductosyn system should be connected together.

All that needs to be done inside PMAC is to convert encoder counts to microns. This is done in a PMAC PLC program, as shown in Appendix B.

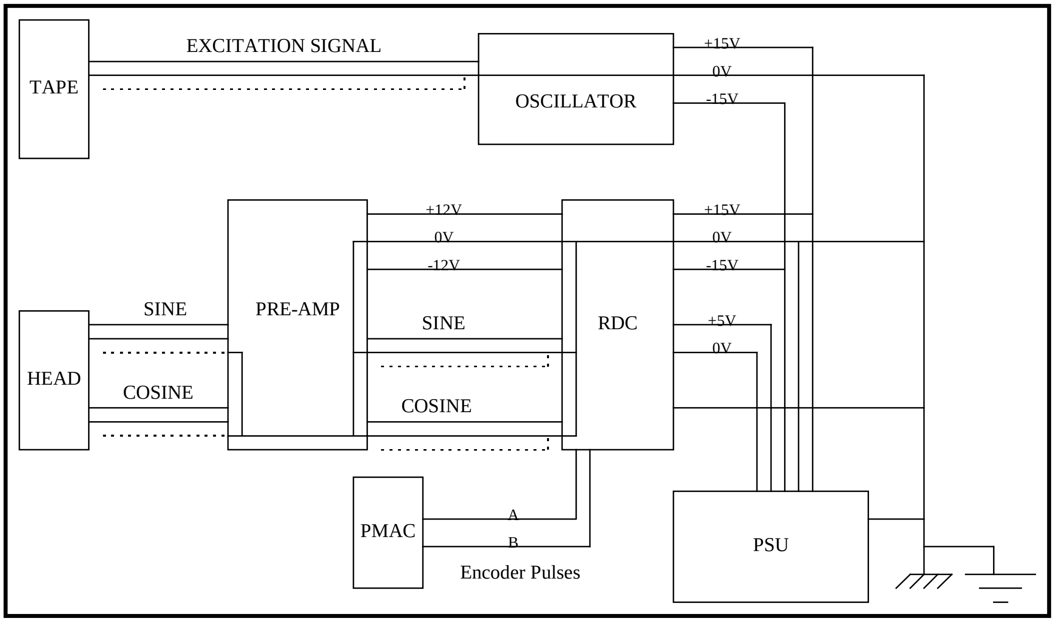

Figure 5 - Inductosyn Interface To PMAC Via RDC

It is very important to ensure that the shielding and grounding of the Inductosyn signals, particularly the high frequency signals, is done correctly. It is also important to keep the modulated head signals well away from the excitation signal and the pre-amp circuit must NOT be housed in the same enclosure as the RDC board which contains the 10 kHz oscillator.

In order to apply the Heydemann compensation technique the sine and cosine signals are needed. The Inductosyn head signals consist of these signals modulated by a 10 kHz carrier (the tape excitation signal). Figure 6 shows how the quadrature signals can be extracted from the head signals using an AM demodulator circuit and some summing circuits. This can be easily implemented using op-amps.

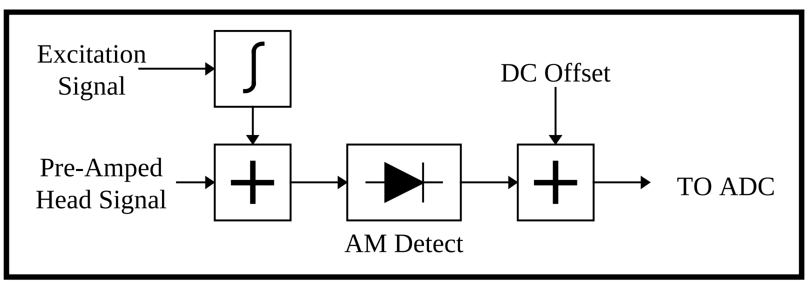

Figure 6 - Obtaining Quadrature Signals From Inductosyn Heads.

The parameters for the PMAC motion program described in Section 2.2, as used for the Inductosyn tests, are shown in Table 5.

VARIABLE	MEANING	UNITS	VALUE
P4	Increment	µm	100
P5	Feed Rate	µm/s	4000
P6	Dwell Time	ms	200
P7	Start Position	µm	130000/ 30000

Table 5 - Motion Program Parameters For Inductosyn Tests

4.2 Compensation

As pointed out in Ref. [5], the majority of errors that appear in the Inductosyn output have one of three spatial frequencies, with the following causes:

1. First harmonic error (0.5 cycles per mm). This is caused by cross-coupling between the head signals and the tape excitation signal. They are removed by paying attention to correct grounding and shielding of the head and excitation signals.
2. Second harmonic error (1 cycle per mm). This can be caused by any of the following:
    - Gain difference between the two head channels.
    - Lack of quadrature.
    - Cross coupling between sine and cosine channels.

   Ref. [5] claims that this error can be reduced using a new pre-amp design which incorporates gain balance and sine/cosine cross coupling features. These claims have not been verified since the new pre-amp was not available for the encoder tests.
3. Very low frequency periodic and non-periodic error. It is not totally clear what causes these errors, probably non-linearity of the tape scale itself.

Because of the high repeatability of these errors, it should be possible to use compensation to reduce them.

4.2.1 Heydemann Compensation

Applying Heydemann compensation to the Inductosyn encoding system was not successful. In fact it actually made the error bigger by introducing first harmonic errors which were not present in the uncompensated system. This is because the technique will compensate for errors in the circuitry used to derive the quadrature signals (see Figure 6), these errors do not appear in the signals that are processed by the RDC and so are introduced by the compensation.

4.2.2 Curve Fitting Compensation (CFC)

This is an alternative method of compensation that requires a reference encoder that is independent from and does not have spatial errors that are similar to the main encoder. This technique attempts to characterise the encoding error, simulate it and remove it from the encoder output. The highly periodic errors are modelled with sinusoids and the very low frequency errors are modelled with a polynomial. Both these methods are described below.

4.2.2.1 Acquiring Data To Calculate CFC Parameters

Data need to be acquired at a fast enough rate to see all the spatial frequency features likely to be present in the error signal. For Inductosyn a spatial sample period of 100 μm (10 samples/mm) should be sufficient; this will allow characterisation of errors with a spatial frequency of up to 5 cycles/mm.

The speed and storage restrictions as described in the Heidenhain case (Section 3.2.1) also apply to the Inductosyn system. This leads to a maximum of 1600 regions, each covering approx. 18.75 mm. Tests have been successful, however, with regions as large as 250 mm. The sampling frequency should be about 83 Hz with an axis velocity of 8.3 mm/s.

Again, it may be necessary to allow overlapping regions if there are problems with the changeover of compensation parameters at the region boundaries.

4.2.2.2 Sinusoidal Curve Fitting

This technique relies upon a reference encoder that does not contain periodic errors at the same spatial frequency as those present in the Inductosyn system (i.e. 0.5 and 1 cycles per mm). On the telescope there will be a friction driven encoder (FDE) that can be used for this purpose - as long as its periodic errors are not the same as those of the Inductosyn. The reference encoder on the test rig cannot be used since the lead screw pitch is the same as the Inductosyn tape pitch and it has already been seen, Section 2.3, that the reference encoder contains periodic errors at 0.5 cycles/mm. Therefore, the Heidenhain tape encoder must be used to implement sinusoidal CFC upon the Inductosyn tape for the purposes of our tests.

To implement this compensation, an FFT is performed on the residual of I-H. The amplitude and phase of the errors at 0.5 and 1 cycles/mm are determined from the FFT and these form the compensation parameters. This can be done quite easily using MATLAB.

To perform the correction, a sinusoid of the correct amplitude and phase is added in real time to the Inductosyn position value. This is implemented in the PMAC PLC as shown in Appendix B. The compensation parameters are stored as PMAC ‘P’ variables.

4.2.2.3 Polynomial Curve Fitting

After the higher frequency periodic errors have been removed, those that remain are primarily very low frequency periodic or non-periodic errors. From inspection these errors are present in all three encoders, but mostly in both of the tape encoders. Therefore, any attempt to characterise these errors for the purpose of compensation must use the stage encoder (R) as a reference encoder, or the compensation will have little effect and may even make things worse. After the polynomial errors have been removed by this process, the remaining errors will be due to very low frequency periodic or non-periodic errors that exist in the reference encoder.

These errors are characterised by a 20th order polynomial and this is evaluated at 20 uniformly spaced intervals across the region giving 21 data points. These are stored in PMAC as ‘P’ variables and, in real time, a correction based upon a linear interpolation of the data points is calculated and added to the Inductosyn output.

In theory, the application of the compensation can be done automatically using PMAC’s ‘Leadscrew Compensation’ feature. However, for a currently unknown reason this feature did not work during the encoder tests so the compensation was applied in the PMAC PLC program, as shown in Appendix B.

4.3 Results

Table 6 shows the results of the various tests upon the Inductosyn tape encoding system. As in the Heidenhain case, the numbers in the table denote RMS error calculated by removing the error due to the reference encoder from the RMS of the residual I-R, as described in Section 2.3. The results are shown in microns and in milli-arcseconds on the elevation axis. The errors will be smaller on azimuth since the effective diameter is larger. The main spatial frequency of each residual is also shown; this gives a clue as to the main cause of the error. Note that V.L.F. indicates very low frequency periodic or non-periodic errors.

RMS ERROR	**Microns**		**Milli-Arcseconds On Elevation**		**Main Spatial Freq. Component (cyc/mm)**	
Case	**Small Run (60 mm)**	**Large Run (260 mm)**	**Small Run (60 mm)**	**Large Run (260 mm)**	**Small Run (60 mm)**	**Large Run (260 mm)**
Initial Set-up	2.03	2.50	105.38	130.15	0.5	0.5
After Re-Wiring Crate	0.93	1.55	48.31	80.41	1	V.L.F.
Heydemann Comp.	0.95	-	49.43	-	0.5	-
CFC Sin	0.62	1.36	32.12	70.75	1	V.L.F.
CFC Sin + Poly(I-H)	0.41	1.07	21.16	55.52	1	V.L.F.
CFC Sin + Poly(I-R)	0.43	0.41	22.55	21.16	1	1

Table 6 - Summary Of Results From Inductosyn Encoder Tests

For comparison, the errors found from the WHT tape encoder project were approximately 1.3 μm RMS. See Ref. [3] and Ref. [4].

4.4 Inductosyn Conclusions

4.4.1 Encoder Performance

The tests described in this section show that:

- It is not possible to use Heydemann compensation for error correction on the Inductosyn encoder.
- Curve fitting compensation can be applied. However, this requires a suitable reference encoder that is independent from and does not have errors that are similar to the Inductosyn system. That is, periodic errors at 0.5 and 1 cycles/mm and very low frequency periodic or non-periodic errors.
- By using CFC, the Inductosyn encoding system should just about meet the 20 milli-arcsecond specification on elevation.
- The system is not affected by dirt and scratches and so is likely to continue to perform at the same level without re-compensation or a program of tape cleaning. Note that obstructions from conductive and/or magnetic objects will cause problems, however, such objects would have to be of a relatively large size and it should be very easy to free the tape of them.
- The tape is manufactured using a step and repeat process. Previous investigations (Ref. [3] & [4]) suggest discontinuities in the order of ±19 μm. Errors due to these discontinuities will occur gradually, over the length of a head (100 mm). Though not tested, it can be expected that polynomial CFC will remove the effect of these errors.

4.4.2 Interfacing To PMAC

The following points are noted:

- It is very important to observe proper shielding and grounding practices. It is especially important to keep the modulated head signals well away from the excitation signal and the pre-amp circuit must NOT be housed in the same enclosure as the RDC board which contains the 10 kHz oscillator.
- Inductosyn claim that a new pre-amp design is available. This includes features that may significantly reduce the uncompensated 2nd harmonic error.

5. CONCLUSIONS

Both tape encoders have been shown to perform to about 1 μm (52 milli-arcseconds on elevation) without any compensation. With compensation, the required performance of about 0.4 μm (20 milli-arcseconds on elevation) can be achieved from both systems. The residual errors on both systems should not be correlated, so an improvement can be expected by taking the average of a number of read heads. Each extra read head should reduce the error by a factor of √2.

Therefore, factors other than error performance must be taken into account when making the final decision. Table 7 shows a comparison of these other factors.

ITEM	INDUCTOSYN	HEIDENHAIN
Uncompensated Errors	Approx. 1 µm. May be better with new pre-amp.	Approx. 1 µm
Compensation	Reference encoder needed.	No reference encoder needed.
Stability	Likely to be very stable	Errors can vary over time.
Dirt and Obstructions	Not affected	Performance can be sustained a clean tape.
Scratches	Not affected	Has a minimal effect which CANNOT be removed by re-compensation.
Registration Errors	± 19 µm every 1 m due to step and repeat process. Should be able to compensate for this.	Not affected (continuous process).
Interfacing to PMAC	More complex pre-amp and RDC circuits. Vulnerable to incorrect wiring practices.	Simple op-amp circuit to PMAC counters and ADC's
Absolute Encoding	Not Available	Built in distance coded reference marks.
Head Curvature	Needs to be reasonably matched to tape surface.	None required. Will operate on any curvature down to 1.2 m diameter.
Price	Lowest.	Highest.

Table 7 - Comparison Of Tape Encoder Systems

Both tape systems will suffer from errors at the tape join. There has been no effort to try and characterise this. Since it is a problem that affects both tapes, it should not figure largely in the tape choice.

APPENDIX A - PMAC MOTION PROGRAM

The following listing shows the PMAC motion program that carries out the step and gather action needed for the encoder tests.

```
;
; Motion program to perform encoder tests. Each run is programmed
; using the following P variables :
;  P4  - Increment in microns
;  P5  - Feed Rate in microns per second
;  P6  - Dwell time in milliseconds
;  P7  - Start and Finish position in microns
;  p8  - counter variable used to track gather buffer pointer
;  p24 - number of words gathered in a data gather cycle
;
; In order for this program to run correctly, the following M
; variable needs to be defined :
;  M303->Y:$F20,24 - Gather Buffer Pointer
;

A
CLOSE
DELETE GATHER
DELETE TRACE
OPEN PROG 1
CLEAR
   F(P5)
   ABS
   X(-P7)
   WHILE (INT(P2+1)!=-P7) WAIT
   P8 = M303
   INC
   WHILE (P2<P7)
      X(P4)
      DWELL (P6)
      P8 = P8+P24
 N10  COMMAND "GATHER"
      COMMAND "ENDGATHER"
      IF (M303<P8) DWELL (P6)
      IF (M303<P8) GOTO10
   ENDWHILE
CLOSE
```

APPENDIX B - PMAC PLC PROGRAM

The following listing shows the PMAC PLC program used to apply compensation to the tape encoders and convert all encoder values to microns.

```
;
; A PLC program to handle the Heidenhain interpolation between
; pitches and apply Heydemann compensation. The program also
; applies the sinusoidal and polynomial curve fitting compensation
; to the Inductosyn. The position of all three encoders is stored
; in microns.
;
; The following must be defined for this PLC to work :
; M100->y$ffe0,24 ----- OR relevant ACC36 base address
; M101->y$ffe0,0,12,s ---- OR relevant ACC36 base address
; M207->y$c00e,8,16,S
; M208->y$c00f,8,16,S
; M209->y$c006,8,16,S
; M210->y$c007,8,16,S
; M211->d$a3
; M212->d$67
; M213->d$2b
; I15 = 0
;
; THIS PROGRAM USES THE FOLLOWING P & Q VARIABLES
; P0 - Intermediate Variable
; P1 - Heidenhain (microns)
; P2 - Reference (microns)
; P3 - Inductosyn (microns)
; P9 - Compensation Flag (1=Comp. On)
; P10 - Compensation Parameter (p)
; P11 - Compensation Parameter (q)
; P12 - Compensation Parameter (Sin (a))
; P13 - Compensation Parameter (Cos (a))
; P14 - Compensation Parameter (G)
; P15 - Intermediate - Compensation Angle
; P16 - Inductosyn Comp. Flag
; P26 - CFC Sin Parameter - Amplitude 1 Hz
; P27 - CFC Sin Parameter - Phase 1 Hz
; P28 - CFC Sin Parameter - Amplitude 0.5 Hz
; P29 - CFC Sin Parameter - Phase 0.5 Hz
; P30 - CFC Intermediate Variable
; P31 - CFC Poly Intermediate Variable
; P32 - CFC Poly Range Of Compensation (in Microns)
; P33 - CFC Poly Number of correction points minus one
; P34 - CFC Poly Intermediate Variable
; Q0 - Compensated sine wave amplitude (Channel 1) (Mostly !)
; Q1 - Sine wave amplitude (Channel 1)
; Q2 - Sine wave amplitude (Channel 2)
; Q3 - Compensated sine wave amplitude (Channel 2)
; Q4 - Inductosyn Sine
; Q5 - Inductosyn Cosine
; Q6 - Inductosyn Compensated Sine
;
CLOSE
DELETE GATHER
DELETE TRACE
OPEN PLC 1
CLEAR
   ; SETUP
   ADDRESS &2

   ; READ HEID. ACC36
   M100 = 8;
   Q2 = -M101/2047;
   M100 = 9;
   Q1 = M101/2047;

   ; READ HEID. ACC28
   ; Q1 = 5*M210/32767
   ; Q2 = -5*M209/32767

   ; READ IND. ACC28
   ; Q4 = 5*M207/32767
```

```
   ; Q5 = 5*M208/32767

   ; HEIDENHAIN COMPENSATION
      ; CALCULATE UNCOMPENSATED ANGLE
      Q0 = Q1
      P0 = 180 + ATAN2(Q2)

      ; COMPENSATION
      IF (P9 = 1)
         Q0 = Q1-P10
         Q3 = (Q0*P12 + P14*(Q2-P11)) / P13
         P15 = P0 - 180 - ATAN2(Q3)
         IF (P15 < -180)
            P15 = P15 + 360
         ENDIF
         IF (P15 > 180)
            P15 = P15 - 360
         ENDIF
      ELSE
         P15 = 0
      ENDIF

      ; IF SIGNAL NEAR CROSS OVER THEN IGNORE
      IF (M209>-150 AND M209<150 AND M210<0)
      ELSE
         ; ADD PITCH COUNT AND CONVERT TO MICRONS
         P1 = ((M211/32) + ((P0-P15)/360))*40
      ENDIF

      ; STORE SIGNAL IN ENCODER TABLE
      M220 = P1 * 960

   ; INDUCTOSYN COMPENSATION
   P30 = (M213/(32*8.192))
      IF (P16 = 1)
         ; SINUSOIDAL COMPENSATION
         P30 = P30 + P26*SIN(360*P30/1000+P27) + P28*SIN(180*P30/1000+P29)

         ; POLYNOMIAL COMPENSATION
         P31 = P30*P33/P32
         P34 = 100+INT(P31)
         P3 = P30 - ( (P(P34+1)-P(P34))*(P31-INT(P31)) + P(P34) )
      ELSE
         P3 = P30
      ENDIF

   ; CALCULATE REFERENCE ENCODER
   P2 = M212/(32*96*29.64063)
CLOSE
ENABLE PLC 1
```

APPENDIX C - MATLAB SCRIPT FOR CALCULATING HEYDEMANN PARAMETERS

The following listing shows a MATLAB m-file that applies the Heydemann compensation technique to the quadrature signals defined by the MATLAB variables `ch1` and `ch2`. The corrected quadrature signals are stored in the variables `ch1c` and `ch2c`. The compensation parameters are stored in the variables `pLS`, `qLS`, `aLS` and `GLS`.

```
% Works out lissajous figures and correction for them after Heydemann.

% Perfect Signals
u1 = cos(2*pi*(0:0.01:1));
u2 = sin(2*pi*(0:0.01:1));

% Perform Least Squares Approx.
A = [ch1.^2 ch2.^2 ch1.*ch2 ch1 ch2];
b = ones(size(ch1));
x = A\b;

% Calculate correction parameters
i1 = 4*x(1)*x(2);
aLS = asin (x(3)/sqrt(i1));
GLS = sqrt (x(2)/x(1));
i2 = x(3)*x(3)-i1;
pLS = (2*x(2)*x(4)-x(5)*x(3))/ i2;
qLS = (2*x(1)*x(5)-x(4)*x(3))/ i2;

% Compensated signals
ch1c = ch1-pLS;
ch2c = (ch1c*sin(aLS) + GLS*(ch2-qLS)) / cos(aLS);

% Plot
plot(u1,u2, ch1,ch2,'x', ch1c,ch2c,'+'); grid;
title ('Perfect = yellow; Actual = purple; Comp. = cyan');
```