MRO Delay Line

Timing Requirements for Control Loops

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Objective

To present our current best assessment of the requirements on delay and jitter for each operation within the cats-eye control loop. To outline the sampling rate, correction rate and servo bandwidth for the other delay line control loops.

This memo aims to provide as full an answer as possible to two of the questions raised by New Mexico Tech after the presentation on Delay Line Controls by JSY (INT-406-VEN-0006). As such, this memo does not supersede that document but should be read in conjunction with it.

Summary

The top-level requirements for the cats-eye loop are:

- The OPD error shall be measured at a sample rate of 5 kHz.
- The latency between measurement of the OPD error and actuation of the cats-eye to correct that error shall be less than 50 μs.
- There is *no requirement* for synchronisation between different trolleys or between the trolleys and other interferometer subsystems.
- In tracking mode, the demanded position is a function of Universal Time: the delay between calculating the sidereal OPD and commanding the cats-eye must be known and accounted for.
  If the cats-eye position is calculated for (not *at*) time t, but realised at time $t+\Delta t$, the *rms jitter on* Δt shall not exceed $0.59\,\mu$s over any 10 ms interval, $1.6\,\mu$s over any 35 ms interval, or $2.2\,\mu$s over any 50 ms interval. Futhermore, the absolute value of Δt shall not exceed ± 0.39 ms.

For the implementation we plan to deliver (i.e. using a single CPU to calculate the error signals for 10 trolleys, interfaced to three Zygo 4001/2001 boards used to read the laser metrology), the derived requirements are:

- The time allowed to transmit and apply the correction to the cats-eye, for the group of up to 4 trolleys interfaced to each Zygo board, is $27.6\,\mu$s.

1 Introduction

Control of OPD with the delay lines in tracking mode is accomplished through two nested control loops as outlined on slide 6 of the presentation. This document expands on the treatment in that presentation, giving detailed information on the timing of the inner "cats-eye" loop.

There are timing requirements for the other control loops within the delay line, but the sample rates and bandwidths of the loops are much lower, hence they should not give rise to any implementational difficulties. The basic parameters of these other control loops are listed in Section 4.

2 Cats-eye Loop Top-level Requirements

2.1 Loop Timing

The top-level requirements for the cats-eye loop are:

- The OPD error shall be measured at a sample rate of 5 kHz.
- The latency between measurement of the OPD error and actuation of the cats-eye to correct that error shall be less than 50 μs.

2.1.1 Justification

These values come from on our latest modelling, based on that described in Chapter 8 of "Results of the Risk Reduction Experiments" (INT-406-VEN-0005). Simulations were used to predict the closed-loop OPD jitter of an MROI trolley given the disturbance spectrum measured on the "embryo trolley" running in the pipe test rig. As part of the Risk Reduction Experiments, this modelling was validated by comparing results from an equivalent simulation of the COAST trolley with measurements of the rejection achieved in practice.

We have allowed a factor 2 safety margin in the required latency, to allow for possible inaccuracy in our preliminary understanding of the cats-eye structural resonances. A low frequency structural resonance which is excited by piston of the cats-eye will introduce phase lag in the servo loop and cause instability and eventually oscillation. To prevent this the servo gain (and hence bandwidth) would need to be reduced leading to poorer rejection of disturbances. The effect of latency is to introduce a linear phase lag with frequency characteristic. This has the effect of increasing the likelihood that a structural resonance could limit the allowable bandwidth of the servo.

Interval	Max. rms jitter on Δt
10 ms	$0.59\,\mu$s
35 ms	$1.6\,\mu$s
50 ms	$2.2\,\mu$s

Table 1: Maximum allowed values for the rms jitter on the delay Δt between the time the demanded cats-eye position is calculated *for*, and the time the position is realised at.

The servo model does include the first and second structural resonances of the cats-eye, but they are derived from a first cut Finite Element Analysis (FEA). The FEA is being refined as the design of the secondary assembly proceeds. Hence we will be able to refine the servo model, and thus the latency requirement, over the next month or so.

2.2 Synchronisation and Jitter

The requirements for synchronisation between the different trolleys and to external signals are as follows:

- There is *no requirement* for synchronisation between different trolleys or between the trolleys and other interferometer subsystems.
- In tracking mode, the demanded position is a function of Universal Time (UTC): the delay between calculating the sidereal OPD (the geometric delay that must be corrected by the delay lines) and commanding the cats-eye must be known and accounted for.
  If the cats-eye position is calculated for (not *at*) time t, but realised at time $t + \Delta t$, the *rms jitter on* Δt for various time intervals shall not exceed the values in Table 1. Futhermore, the absolute value of Δt shall not exceed ± 0.39 ms.

2.2.1 Justification

The trolleys will not be modulating the OPD in order to generate temporal fringes, hence there are no OPD scans to synchronise with the detector readout (and hence with scans on other trolleys).

The second requirement derives from the need to deliver the correct sidereal OPD. In practice the measured cats-eye position must be differenced with the sidereal OPD calculated *for the time of that measurement*, in order to derive the correct error signal. If the time of measurement is uncertain (i.e. non-zero Δt), this will give rise to an

OPD error. If the uncertainty Δt varies on short timescales, this will give rise to OPD jitter.

The rate of change of sidereal OPD z is given by

$$\frac{dz}{dt} = B \cos\theta \frac{d\theta}{dt}, \tag{1}$$

where B is the baseline length and θ is the zenith angle. Hence the OPD error Δz due to Δt is given by

$$\Delta z = B \cos\theta \frac{d\theta}{dt} \Delta t, \tag{2}$$

and this is maximised at $\theta = 0$. Hence the maximum OPD error is $B\frac{d\theta}{dt}\Delta t$; to keep this below the specified maximum intra-night OPD error of 10μm on a 350m baseline (see INT-406-VEN-0000), Δt must be less than 0.39 ms.

If Δt varies with time, the resulting rms OPD jitter $< \Delta z >$ is given by

$$< \Delta z >= B \cos\theta \frac{d\theta}{dt} < \Delta t >, \tag{3}$$

where $< \Delta t >$ is the rms jitter on Δt. The values in Table 1 were obtained by substituting the OPD jitter requirements for the delay lines (see INT-406-VEN-0000) into equation 3 and setting $\theta = 0$ and $B = 350$m.

In practice the jitter requirements can be met by reading a clock immediately before measuring the cats-eye position. The demanded position is then calculated for the clock time plus a small fixed interval.

2.3 Approximation of Demanded Position

The demanded trajectory can be very accurately approximated as a constant-velocity trajectory over time intervals up to 0.1 s.

2.3.1 Justification

With an ideal trajectory, the acceleration of the cats-eye is obtained by differentiating equation 1 to obtain

$$a = \frac{d^2 z}{dt^2} = -B \sin\theta \left(\frac{d\theta}{dt}\right)^2. \tag{4}$$

The zenith angle varies with time as $\theta = 2\pi t/T$ with T equal to 24 hours, so the maximum acceleration is given by

$$a_{\max} = B\left(\frac{2\pi}{T}\right)^2. \tag{5}$$

The maximum error from assuming a constant velocity over an interval t is therefore

$$\Delta z_{\max} = \frac{1}{2} a_{\max} t^2 = \frac{1}{2} B \left(\frac{2\pi t}{T} \right)^2, \tag{6}$$

which gives 9 nm for $t = 0.1$ s.

3 Cats-eye Loop Derived Requirements

We now flow down the top-level requirements listed in Section 2 to derive other timings for the cats-eye loop. We do this for one particular implementation of the delay line control system (DLCS) hardware and software. This implementation, described in the next subsection, should be very similar to that which is finally delivered by Cambridge (subject to discussions with MRO about interfacing to the overall interferometer control system).

Whatever implementation is chosen, the sequence of operations that must be performed within each 200μs loop period is as follows.

1. Read laser metrology to measure actual cats-eye position
2. Calculate demanded position and hence correction
3. Transmit correction to receiver circuit on trolley
4. Apply new voltage to voice coil driving cats-eye

In performing the flow-down, we must consider two top-level requirements (see Section 2.1). First, all of above the steps, for all trolleys, must be completed in one loop period of 200μs. Second, the time between measurement (step 1) and completing the correction (end of step 4) must be less than 50μs for any given trolley. We must also realise the demanded position at the appropriate UTC, with timing jitter that does not exceed the limits in Table 1.

3.1 Control System Implementation

A diagram of the implementation is shown on slide 12 of the presentation. The key features are:

- A single workstation that performs the following functions:
  - Interfaces the DLCS to the Interferometer Control System (ICS)

- In tracking mode, pre-calculates the demanded cats-eye positions with 0.1 s time resolution

- Three Zygo 4001/2001 measurement boards to read the metrology signals for 10 trolleys (each 4-axis 4001 board can handle up to 4 trolleys; 2001 is the 2-axis version)

- A single VME CPU that, in tracking mode, closes the cats-eye position loop for all 10 trolleys. This involves:
  - Reading the laser metrology signals at 5 kHz sample rate
  - Interpolating the pre-calculated demanded positions for the times at which the metrology signals were measured
  - Calculating and transmitting correction signals to the receiver circuits on the trolleys at 5 kHz, via the low-latency RF link

We expect that the workstation will pre-calculate 10 demanded positions every second, driven by a 1 Hz interrupt derived from a GPS signal. The positions will be tagged with the UTC times they should be realised at, and transmitted to the VME CPU via wired ethernet.

3.2 Loop Timing Requirements

In tracking mode, we assume the following sequence of operations on the VME CPU, triggered by a 5 kHz interrupt derived from a GPS signal:

1. Measure actual positions – trolleys 1–4
2. Calculate demanded positions and hence corrections – trolleys 1–4
3. Transmit corrections – trolleys 1–4
4. Apply corrections – trolleys 1–4

5. Measure actual positions – trolleys 5–8
6. Calculate demanded positions and hence corrections – trolleys 5–8
7. Transmit corrections – trolleys 5–8
8. Apply corrections – trolleys 5–8

9. Measure actual positions – trolleys 9–10

10. Calculate demanded positions and hence corrections – trolleys 9–10

11. Transmit corrections – trolleys 9–10

12. Apply corrections – trolleys 9–10

According to the datasheet for the Zygo 4001 measurement board, the cats-eye positions for the group of trolleys associated with each board are all sampled within 30 ns of a sample pulse being output, and a further 305 ns elapses before the measurements are available to the CPU.

With a 850 MHz VME bus CPU at COAST, step 2 takes 22μs for 4 trolleys, using interpolation as described above.

Hence to meet the 50μs latency requirement the time allowed to transmit and apply the correction for 4 trolleys is $50 - 22 - 0.305 = 27.6\,\mu$s (rounding down). Depending upon the RF link chosen, we expect that most of this will take place in parallel for the 4 trolleys, hence it is *not* a requirement to transmit and apply the correction in $27.6/4 = 6.9\,\mu$s.

To meet the 200μs loop period requirement, the time allowed to transmit and apply the correction for 4 trolleys is $(200/3) - 22 - 0.335 = 44.3\,\mu$s. This requirement is clearly less stringent.

3.3 RF Link Technologies

We now briefly address the issue of whether wireless Ethernet will meet this requirement on the worst-case transmission time.

A typical 802.11g link is optimised for total data throughput rather than latency, and as the reviews below show, it's unlikely to have a transmission latency shorter than about 1 ms, which is over 30 times longer than the requirement derived above.

- `http://www.g4techtv.ca/callforhelp/shownotes/0236.shtml?extremetips`
- `http://www.mobilepipeline.com/showArticle.jhtml?articleId=15800160`

We have now identified low-noise COTS devices that should meet the transmission time requirement for the low-latency RF link. To get the necessary bandwidth, we had to look at products that use the 900 MHz American ISM band, as it is much wider than the UK equivalent (this will also simplify eventual US deployment). We have identified two suitable products. There was a delay while we checked that it was legal to import and possess these devices in the UK (it is). We are now in the process of ordering the devices for trials.

4 Other Loops

Working values for the parameters of the other control loops are listed in Table 2. The cats-eye loop (see Sections 2 and 3) is also included for completeness. Some further details of the loops are given in Table 3.

The definitions of the parameters given in Table 2 are as follows:

Sample Rate The frequency with which the specified error signal is measured

Correction Rate The frequency with which a correction signal is applied to the specified actuator ("=SR" in Table 2 specifies that the correction rate is identical to the sampling rate).

Servo Bandwidth The 3dB closed loop bandwidth (what we have in the past loosely referred to as "the bandwidth" of the loop)

Maximum and minimum values (separated by a slash) are given for some parameters — in these cases the definitive value will be selected later (there is no requirement to support a range of values in the final implementation).

4.1 Notes

As explained in Section 2.3 of the Strategy Document (INT-406-VEN-0004), the OPD, shear, and steering (roll) control loops operate independently of each other.

The "trolley management" loop mentioned in the tables is in effect an internal compensation loop and plays no part in the OPD loop. It improves the effectiveness of the cats eye mechanical arrangement. Although not mentioned in the presentation it is mentioned in the risk reduction experiment results (INT-406-VEN-0005) as a feature on COAST and on the MROI trolley as a means of reducing the apparent flexure stiffness. This loop will be implemented entirely in hardware on the trolley.

The differential position sensor (possibly an LVDT, depending upon the desired sampling rate) which measures the relative position of the cats-eye with respect to the cart serves two purposes:

1. It provides a position error signal to the "carriage position (outer OPD)" servo which operates to adjust the position of the cart to be directly under the cats-eye thereby maintaining the minimum deviation of the cats eye flexures. This minimises power dissipation in the voice coil and maximises isolation of the cats eye in the OPD direction.

2. The same position signal from this sensor can be used to reduce the apparent stiffness of the flexures by adding a percentage of it to the voice coil demand

signal from the off-board VME CPU. Incorporating this “trolley management” loop lowers the resonant frequency of the cats-eye mass/spring system which improves mechanical isolation and power dissipation. If the position signal is differentiated to provide a velocity term then a similar compensation effect is achieved by apparent reduction of the induced losses or “drag”. This further reduces the unwanted coupling between the carriage and cats-eye and hence increases isolation in the OPD direction. We have not yet decided whether to include a velocity term.

Loop name	Source of error signal	Sample Rate	Actuator	Corr'n Rate	Servo BW
Tracking Mode Only					
Cats-eye (inner OPD)	Laser metrology	5 kHz	Voice coil	=SR	180 Hz
Carriage pos'n (outer OPD)	Pos'n carriage w.r.t. cats-eye	5 Hz/20 Hz	Motor	=SR	1 Hz
Trolley management	Pos'n (& vel.?) carriage w.r.t. cats-eye	100 Hz/5 kHz	Voice coil	=SR	10 Hz/180 Hz
Tracking or Slewing					
Shear	Metrology beam shear	10 Hz/40 Hz	Secondary tip-tilt	=SR	2 Hz
Steering	Clocking angle (tilt sensor)	0.5 Hz/100 Hz	Steering angle	0.5 Hz/2 Hz	0.1 Hz
Focus	TBD	TBD	Squiggle Motor (TBC)	Few/night	N/A

Table 2: Basic parameters of delay line control loops.

Loop name	Closed in	Using link
Tracking Mode Only		
Cats-eye (inner OPD)	SW	Low-latency RF
Carriage pos'n (outer OPD)	HW	On cart
Trolley management	HW	On cart
Tracking or Slewing		
Shear	SW	Wireless Ethernet
Steering	SW?	On cart
Focus	SW	Wireless Ethernet

Table 3: Further details of delay line control loops: whether the loop is closed in hardware or software, whether transmission to/from the cart is involved, and if so which wireless data link is used.