<u>Keck Adaptive Optics Note 824</u>

Statement of Work For: Modifications to the Keck AO NGWFC to Support the Near-Infrared Tip-Tilt Sensor Project

Version 0.4
March 22, 2011

Authors:
Peter Wizinowich, Roger Smith, Thomas Stalcup, Ed Wetherell

Contributors:
Roberto Biasi, Sudha LaVen, Marcos van Dam

Revision History

Revision Number	Revision Date	Summary of Changes	Author
0.3	10/29/2010	New format. Incorporates input from Biasi plus responses from SL, RS & TS; plus input from van Dam Added correlation & focus algorithms	PW, RS, EW, TS
0.4	3/22/2011	Section 4.1 edited for maximum number of ROIs and pixels, and bandwidth range. Section 4.2.1 removed alternative to special characters. Section 4.2.2 removed flag option for error detection. Section 4.25 added to cover new ROI offset synchronization. Section 10 schedule changed. Section 11 management change.	PW based on discussion with Microgate and Caltech

1 Acronyms

ADC	Analog to Digital Converter
AO	Adaptive Optics
ARC	Astronomical Research Cameras
ATI	Advanced Technologies and Instrumentation
CARA	California Association for Research in Astronomy
DSP	Digital Signal Processor
IDL	Interactive Data Language
IR	Infra Red
I&T	Integration and Testing
KAON	Keck Adaptive Optics Notes
NGWFC	Next Generation Wave Front Controller
NIR	Near InfraRed
NSF	National Science Foundation
ROI	Region Of Interest
RTC	Real Time Controller
SC	Supervisory Controller
SOW	Statement Of Work
STRAP	System for Tilt Removal with Avalanche Photodiodes
TRICK	Tilt Removal with Ir Compensation at Keck
TTS	Tip Tilt Sensor
WCP	Wavefront controller Command Processor
WFS	Wave Front Sensor
WIF	Wavefront controller InterFace
WMKO	W.M. Keck Observatory

2 Introduction

This Statement of Work (SOW) is written in support of the NSF ATI-funded near-infrared (NIR) tip-tilt sensor (TTS) project. The purpose of this SOW is to document the required changes to the existing Microgate real-time controller hardware and software in support of adding this NIR TTS capability to an existing Keck AO system. These changes include: providing a fiber optic interface to accept a continuous stream of unprocessed data from the NIR TTS camera controller, process this data to provide a centroid estimate and use this centroid estimate to control the existing tip-tilt mirror.

The NIR TTS is intended to provide improved tip-tilt information to control the existing Keck AO tip-tilt mirror via the Microgate real-time control system. The data from this sensor is intended to be used instead of or in addition to the existing STRAP data.

3 Top Level Schematics

The existing Next Generation Wavefront Controller (NGWFC) Real Time Controller (RTC), provided by Microgate, and its interfaces are shown in Figure 1. The interface between the NGWFC RTC and the AO Supervisory Controller (SC) and User Tools is through the Wavefront Controller Command Processor (WCP) on the AO side and the Wavefront Controller Interface (WIF) on the NGWFC RTC side. This interface will not be changed, although some new command and status items will be required.

We will be adding a new NIR TTS camera to the existing system. Figure 2 provides a schematic of the major elements of the NIR TTS system. This camera is also referred to by the acronym TRICK for Tilt Removal with Ir Compensation at Keck. The TRICK camera controller (AKA Leach) will interface to the NGWFC RTC through a new interface to the WIF. The data interface will be a single fiber optic link providing a continuous data stream along with configuration information. No command or status information will be sent over this interface.

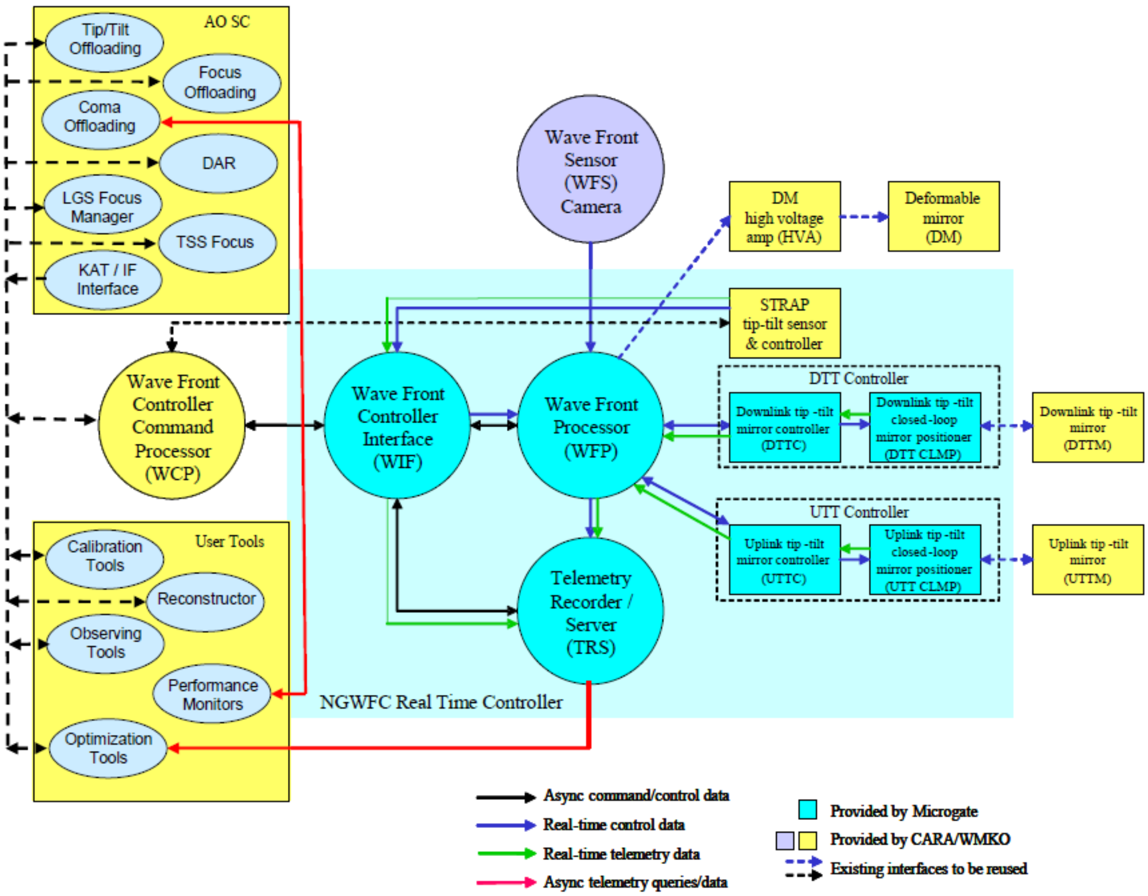

Figure 1: The main components of the existing real-time controller

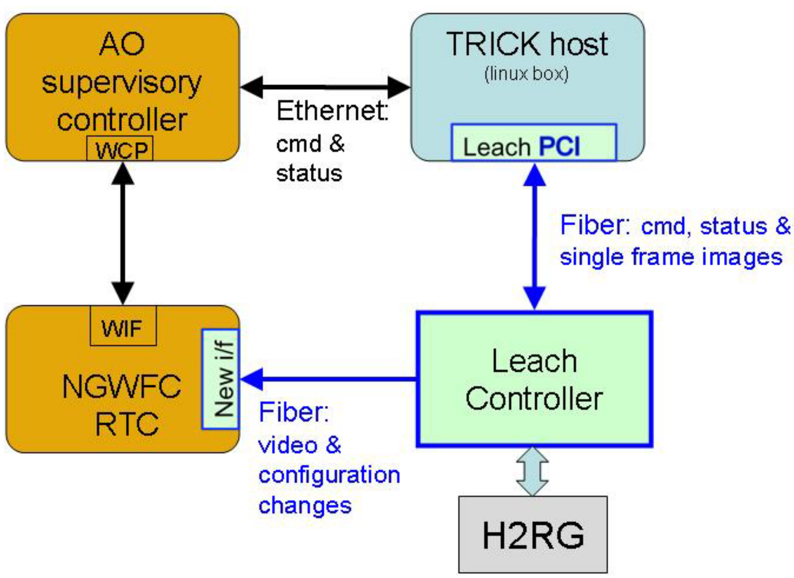

Figure 2: Top-level interface schematic.
Data and configuration changes are provided over a fiber optic link from the NIR TTS camera readout electronics to the Microgate RTC. Commands to the Microgate RTC are provided over the existing interface between the AO system and the Microgate RTC.

4 Camera Readout and Interface

4.1 Camera Readout to Microgate Controller

The NIR TTS camera will be read out using the Astronomical Research Cameras (ARC) (AKA Leach) controller. A window, or region of interest (ROI), on the detector is read out non-destructively in "differential multi-accumulate" readout mode, as shown in Figure 3, in order to reduce the read noise. The detector continues to integrate during readout mode and is reset only when necessary to avoid saturation, typically every 100 to 1000 frame scans. Since a window with a randomly selectable start address is used, the detector must be read out through a single channel.

No processing of the data occurs in the camera readout electronics. All of the data processing (including the coadding and differencing in Figure 3) will occur in the Microgate controller.

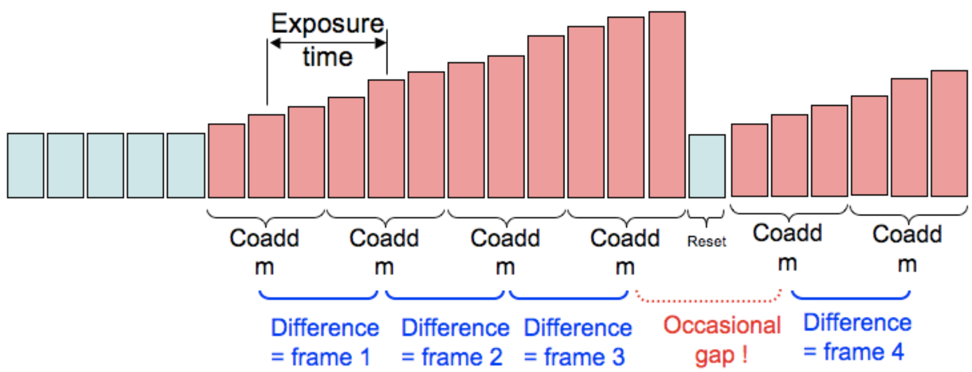

Figure 3: In "Differential Multi-Accumulate" readout mode the detector is reset only when necessary to avoid saturation to obtain ~100% duty cycle. *Reset occurs every 100 to 1000 frame scans. Non destructive reads are averaged and exposures are synthesized by differencing averaged frames.*

The maximum number of ROIs will be 8. The following modes will be supported for each ROI: 2x2, 4x4, 8x8 and 16x16 pixels up to a maximum number of pixels of 512. Different ROIs can be read at different rates.

The range of tip-tilt control bandwidths will be from 40 to 2000 Hz.

The data rate will be 6 micro-seconds per pixel. There will be one ROI per data packet (an option which may be considered is to have one packet for all ROIs acquired together (i.e. consecutively)).

4.2 Camera Interface to Microgate Controller

The raw camera pixel data will be provided to the Microgate controller via a fiber optic interface from the ARC timing board. The fiber optic circuits on the ARC timing board contain Agilent parts operating in the IR regime at a bit rate of 250 MHz, derived from Cypress Hot Link parallel-to-serial and serial-to-parallel converters (CY7B923 and CY7B922) that synthesize a 250 MHz clock from an input clock of 25 MHz. The parts require ten clocks to transmit or receive each byte, so the 250 MHz bit rate translates into a byte speed of 25 Mbytes/sec, or 12.5 Mpixels/sec. There must be no gaps in between the bytes of a word in the serial data stream. Data will always be 16 bit; either a 16 bit data conversion value per pixel or a 16 bit header word.

4.2.1 Packet format

Any change in the pixel readout cadence imprints a pattern on the data via the self heating pattern in the sensor and through electrical crosstalk from digital to analog circuits within the detector controller. Therefore it is essential for the data transmission to occur at the same cadence as the readout, and highly desirable for pixel data to be transmitted as soon as it is digitized, without buffering or manipulation by the digital signal processor (DSP) which manages the waveform generation and data conversions within the detector controller.

It follows that data packets should map to a single ROI. Since ROIs can be quite small the header which identifies the origin of the data needs to be very short, to minimize overheads. It is proposed that data be transmitted in packets whose format and purpose are identified by single 16 bit header word.

Special characters will be used to identify the packet header word. This will be based on the special characters (K28.x) made available by the 8-10 bit encoding technique used by the Hotlink transceivers. This requires further investigation to ensure that the ARC controller supports these special characters. The special characters will identify the header word, leaving the entire 16 bit (65536 codes) word value for packet type definition.

4.2.2 Error Detection and Recovery

A detection and recovery scheme is required to prevent loss of packet synchronization (the knowledge of the location of the start of data packets within the continuous data stream) in the event that a word is dropped or header word is corrupted during transmission over the fiber.

Loss of packet synchronization will be detected when an invalid or missing header value is detected. If an invalid header is found then a counter should be incremented to identify a synchronization error and the data should be ignored until a valid header is identified. If corruption of data within the packet does not lead to loss of packet synchronization, it will not be detected and should only produce a minor momentary glitch in the tip/tilt servo loop.

Since pixel data never contains values reserved for headers, packet synchronization can be recovered simply by searching for the next valid header value in the word stream coming from the fiber.

4.2.3 Packet Types

4.2.3.1 Configuration Packet

The header in every packet will contain a unique code that identifies it with a function and predefined format. The reasoning for this is that the length and format of a data packet will remain stable for many packets and thus does not need to be contained within each packet.

A packet whose data fields contain configuration information will be transmitted whenever the readout mode changes. This information is embedded within the data stream rather than being passed (exclusively) across command links, to avoid race conditions between multiple command paths which might occur due to different transmission delays. The configuration packets unambiguously mark the point in the data stream where the format or meaning of the data changes.

The configuration information (whose format is TBD by mutual agreement) will convey all information required to interpret and correctly utilize subsequent pixel data, for example, ROI locations and dimensions, length of the data packets, and number of data packets between array resets.

It remains to be decided whether configuration packets will have a fixed length or contain a length field.

4.2.3.2 Data Packet

A data packet will be identified by its single word header. The remainder of the packet contains only pixel values. Its length will have been predefined in the most recent configuration packet.

It remains to be determined whether each data packet will contain pixels for just one ROI or for all ROIs within a single frame scan. If the data packet format is defined to contain data from a single ROI scan, then different header values can be allocated to associate the data packet with its respective ROI.

4.2.3.3 Reset Packet

This empty packet is sent to indicate a gap in the data stream while detector reset is occurring. The first group of packets to be coadded after a reset (see Figure 3), serves only as the baseline for the next difference frame and does not generate output. It will be necessary to use the last good sample, unless the tip-tilt servo can tolerate a missing sample. The Reset Packet marks when this is necessary.

An alternative to the Reset Packet would be for the detector controller to identify the data packets immediately preceding and/or following reset by giving them a different "type" in the header. The "reset packet" is proposed since it is simpler to implement in the detector controller.

4.2.3.4 Detector status packets

If necessary additional packets can be sent to indicate a change of state within the detector controller, such as stop, abort, idle. These would probably have no data fields and thus be just one word long. Possible reasons to supply such status information to the RTC would be to either simplify the RTC algorithm so that it is (primarily) data driven, or to avoid timeout errors being flagged by the RTC when data flow is halted.

4.2.4 Packet Sequence

1) A configuration packet will be sent whenever the readout mode, ROI position or size changes. It will always be possible to decode the data packets using the information supplied in the configuration packet.

2) A reset packet will be sent.

3) N*M data packets will be sent at a regular cadence. M is the number of frames per coadd. By computing differences of the coadds, N-1 exposures will be synthesized by the RTC.

4) A reset packet will be sent. The Nth exposure must be extrapolated from prior exposures.

5) Loop over 3) and 4). Until a new configuration packet is received.

4.2.5 Changing ROIs and Centroid Offsets

The AO Supervisory Controller (SC) will provide centroid offsets to the Microgate Controller for each ROI. The centroid offset will change when the ROI location changes. The use of the new centroid offset associated with a new ROI location must be synchronized with the change in ROI location. It is proposed that the Microgate controller store the new centroid offset until the ROI location change is identified in the data from the camera. The Microgate controller should send back an ACK to the SC concerning the receipt of the new offset for a new ROI location before the SC changes the ROI configuration to ensure that the ROI and associated centroid offset changes are synchronized.

5 Microgate Controller Software

5.1 Data Processing Prior to Centroiding

The Microgate controller will need to perform the following processing steps in real-time:

- coadd multiple samples for each pixel for noise reduction.
- subtract the preceding co-added packet to obtain the difference (or "frame" value shown in Figure 3) for that pixel.
- subtract sky frames and
- scale by a flat field.

The equation describing this process is

$$i_c[k,t] = i_f[k](i[k,t]-i[k,t-1] - i_b[k])$$

where $i[k,t]$ is the coadd of m frames of incident flux at pixel k, $i[k,t-1]$ is the coadd of the previous m frames at pixel k, $i_b[k]$ is the background level at pixel k, $i_f[k]$ is the normalized flat-field gain response for pixel k, and $i_c[k]$ is the resulting compensated pixel. A pixel gain map file in a TBD format will be provided to the Microgate controller by the AO control system whenever the controller is restarted. This gain map should be used in the above calculation.

The processed pixel values should be thresholded: $i_c[k,t] = \max(i_c[k,t], i_{thresh})$, where i_{thresh} is the threshold value.

A check should be performed by the Microgate system of whether the ic[k,t] values are above some threshold value (i.e. saturated). If this threshold is exceeded then the frame should not be used.

The camera will be "reset" only occasionally (as shown in Figure 3). When a reset is performed the first co-add after the reset should not be used for a centroid calculation. It should only be used to provide a difference with respect to the next coadd.

If more than 4x4 pixels are used then the larger array must be binned into 4x4 at this point.

All of this has to happen before centroids are calculated. From this point on the centroiding process and tip-tilt mirror control is the same as that described in KAON 517.

5.2 Centroiding and Correlation Algorithms

The Microgate controller shall support two algorithms to determine the tip-tilt for each ROI. Only one algorithm will be used at a given time as selected by the user. In both cases, the residual tip-tilt error input into the tip-tilt mirror controller must be in units of arcsec.

The centroiding process is the same as that described in KAON 517. The NIR TTS centroids will be calculated in the same manner as used for the existing STRAP and WFS for the cases of 2x2 and 4x4 pixels. The NIR TTS system matrix values will be determined offline using an IDL calibration tool and are provided to the Microgate controller.

The correlation algorithm is that presented by Poyneer (Lisa A. Poyneer, "Scene-Based Shack-Hartmann Wave-Front Sensing: Analysis and Simulation," Appl. Opt. 42, 5807-5815 (2003)). The correlation, C, between the reference image, r[i,j], and the subimage from each ROI, s[i,j], is calculated either directly or using FFTs (whichever way is faster). The reference image will be determined offline and will be provided to the Microgate controller. The direct implementation is

$$C[m,n]=\sum_i \sum_j r[i-m,j-n]s[i,j]$$

And the Fourier transform implementation is

$$C[m,n]=F^{-1}\left[F^*\{r\}\cdot F\{s\}\right]$$

Given the discrete maximum, (Δ_x,Δ_y), the sub-pixel shift is found using parabolic interpolation in one direction at a time:

$$\hat{x}=\Delta_x+\frac{0.5(C_{-1}+C_1)}{C_{-1}+C_1-2C_0} \quad \text{and} \quad \hat{y}=\Delta_y+\frac{0.5(C_{-1}+C_1)}{C_{-1}+C_1-2C_0}$$

Note that the star images used for the tip-tilt measurement will not normally be located at the intersection of 4 pixels. In addition, the star image will move on the detector during the course of a science exposure due to such effects as differential atmospheric refraction. The position of the centroid offset position to which the tip-tilt mirror should drive the star image and the location of the ROI will therefore need to be periodically updated. These updated positions will be provided to the wavefront controller.

5.3 Focus Algorithm

The Microgate controller will need to calculate the focus for each ROI. This calculation is very similar to the centroid calculation described in KAON 517 except that the summation is along the diagonals instead of along the x and y directions. The conversion factor will be determined offline and will be provided to the Microgate controller. Our current intention is to only use this focus term for experimental purposes to determine the utility of this approach to focus sensing for future instruments.

5.4 Tip Tilt Sensor Selection

The Microgate controller can currently take data from either the Microgate provided STRAP unit or the wavefront sensor (WFS) to use to control the AO tip-tilt mirror.

The upgraded Microgate controller should support the option of providing tip-tilt information from any one of the STRAP sensor, the WFS or the NIR TTS. In addition, it should be possible to operate the STRAP and NIR TTS in parallel.

The AO control system will provide a command to determine which sensor(s) is to be used by the Microgate controller. Currently the code uses a keyword "DTSENSOR" to choose between the WFS and STRAP.

No synchronization of tip-tilt data from the NIR TTS and STRAP is currently envisioned.

5.5 Combining Centroid Data

Centroid data may be available from multiple ROI. Simultaneous STRAP and NIR TTS data may also be available. Since the STRAP and NIR TTS data are not synchronized the Microgate controller will need to take the most recent centroids from each sensor to perform the matrix multiply.

The Microgate controller shall perform a matrix multiply of the centroid data from multiple ROIs or sensors to obtain the centroid data to be used to drive the tip-tilt mirror. The matrix will be 2xN where N is the total number of input centroids ($2 \le N \le 8$). The matrix to be used will be provided by the AO control system according to the observing conditions (i.e., the coefficients will depend on the magnitudes of the tip-tilt stars, their off-axis distance and the relative performance of the NIR TTS versus STRAP).

5.6 Tip Tilt Mirror Control

There should be no change in the Microgate control of the tip-tilt mirror. The only change is in the source of the tip-tilt data.

5.7 Tip Tilt Latency

The compute latency between the end of each block of M coadds from the NIR TTS and a command to the tip-tilt mirror shall be less than or equal to 0.5 ms.

6 Implementation Plan

WMKO has a spare Microgate controller, WFS camera and STRAP unit. A tested ARC controller, providing pixel data, will also be available to support interface testing. To the extent required by Microgate we will ship this hardware to Microgate to support development and testing, and/or provide Microgate with remote access to the spare controller.

This system will also be setup in the WMKO headquarters lab for system I&T prior to I&T on the summit AO system. Microgate is expected to provide support for both lab and summit I&T at a TBD level.

As soon as the specifications are finalized, Microgate will proceed through the task of designing the modifications to the NGWFC real time code. The WMKO and Microgate teams would teleconference to review the design. This would be followed by implementation of the code and testing. When completed, WMKO will checkout, build, install, and test the changes based on the Microgate test plan. Once the testing is satisfactory, Microgate will update documentation of the MGAOS system. This will complete the development activity for Microgate. The migration of these modifications to the summit will be the responsibility of WMKO with support provided for TBD months from Microgate.

The NIR TTS will only be implemented on one of the two Keck AO systems, likely Keck I. We would prefer however, not to have the Keck I and II control systems diverge. The base software should remain common, with a switch between modes (the current WFS and STRAP mode and the new NIR TTS mode), to the extent practical. A configuration switch (NIR TTS yes/no) would be acceptable.

7 Work Breakdown Structure

The major phases of the parametric oscillator demonstration are as follows:

WBS #	Element Name
1	NIR TTS
1.1	Project Management
1.2	Systems Engineering
1.3	NIR TT Sensor Camera
1.4	Opto-mechanics
1.5	Controls
1.6	Operations Software
1.7	Integration, Test & Commissioning
1.8	Operations Handover

The sub elements of the Microgate subcontract are as follows:

WBS #	Element Name
1.2.3	Requirements Definition
1.2.4	Interface Definition
1.5.3	Real time control
1.5.3.1	RTC Software Design
1.5.3.2	RTC Software Coding
1.5.3.3	RTC Modifications Contract
1.5.3.4	As-built Documentation
1.7.1	Laboratory I&T
1.7.1.1	Lab System Setup
1.7.1.1.1	RTC Crate with WFS and STRAP
1.7.1.2	Lab System I&T
1.7.1.2.3	RTC with camera simulation
1.7.1.2.4	RTC with camera
1.7.1.2.5	RTC Full test

8 Deliverables

8.1 Intellectual Property Rights

Intellectual property rights to all deliverables to WMKO shall be governed by the following considerations: Foreground intellectual property (FIP) is defined as intellectual property developed as a result of work performed under the contract resulting from this SOW. Background intellectual property (BIP) is defined as intellectual property belonging to the RTC vendor and developed prior to the start of the contract resulting from this RFP.

The RTC vendor shall grant to CARA a royalty free non-exclusive license to all BIP required for, or used in, any deliverables, including software source code.

Ownership of all FIP, including all software source code shall belong to CARA. CARA shall grant to the RTC vendor a non exclusive license to all FIP developed as a result of work performed under the contract resulting from this RFP.

8.2 Software Deliverables

The software deliverable will include the following:

- Modifying the software to add the functionality described in sections 4 and 5.
- Modifying the BCU DSP data structures and software to accommodate the following data for real-time archiving of new telemetry. WMKO will deal with The TRS server and client side updates. The telemetry record will be modified to always contain this new information and the specific fields of the record will be populated upon availability.
    - Raw NIR TTS pixel data, including packet header
    - Coadded pixel data for each data packet and ROI
    - Computed centroid for each data packet and ROI
    - Computed focus for each data packet and ROI
    - Combined centroid for multiple ROI and sensors sent to the tip-tilt mirror
    - Configuration state changes, including pixel gain/sky/background, algorithm weights etc.,
- Updated source code files with procedures for compiling and generating executables. Copy of executable(s) generated by Microgate with procedures to download the program to the controllers/DSPs.
- Relevant test tools and routines required to support the test plan.
- Test plan document and test results.

8.3 Configuration Management

Configuration management will consist of Microgate delivering source code updates to WMKO. WMKO will be responsible for committing the updated files into our repository and rebuilding of the system executables.

8.4 Hardware Deliverables

Microgate will be responsible for incorporating necessary changes to the NGWFC hardware to support the fiber channel interface to the Leach controller.

8.5 Documentation

The existing Microgate controller documentation shall be updated to cover the hardware and software changes (as-built). All new or modified code shall be explicitly documented for ease of maintenance.

8.6 Support for Integration and Testing

It is anticipated that Microgate will provide support to WMKO total 10 hours (TBC) during summit integrations and testing.

9 Administrative Deliverables

9.1 Reporting

Microgate will be expected to provide status reports on a monthly basis during the design and implementation phases of this contract. The Microgate design reports will suffice in the months where there is a design review.

9.2 Project Coordination

Good communication between the WMKO staff and the Microgate is absolutely critical to the success of this project. E-mail will be used as the primary means of intra-project communications. Ad-hoc phone conversations will also be used and WMKO will accommodate Microgates time zone. Team teleconferences will be held to support the reviews associated with the major milestones listed in section 10.

9.3 Support of Development Reviews and Testing

WMKO requires that Microgate support the internal reviews of the RTC modifications specified in the proposed schedule, see section 10. These will be done by teleconference between the WMKO and Microgate teams.

9.4 Payments

Milestone payments will be made to Microgate based on the successful completion of Microgate's portion of the milestones in section 10.

10 Schedule

Microgate will be expected to provide the required support to meet the following milestones for the development of this NIR TTS.

Milestone	**Completion Date**
System Design Review	December 7, 2010
Preliminary Design Review	April 25, 2011
Detailed Design Review	September 30, 2011
Microgate implementation	December 15, 2011
Microgate support for lab I&T	October 15, 2012
Microgate support for telescope I&T	January 31, 2013

11 Technical and Management Contacts

Sudha LaVen will be the software engineer at WMKO responsible for coordinating technical issues with Microgate for the purposes of this contract.

Thomas Stalcup will be the AO scientist and system engineer at WMKO responsible for system level technical issues on this project. Chris Neyman will initially play this role until Thomas is freed up from another project.

Peter Wizinowich will be responsible for management issues.