GEMMA
Real Time Computer
Project Execution Plan

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A - RTC 003

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List of Acronyms

Acronym	Definition
ARC	Astronomical Research Cameras (A detector controller vendor)
AO	Adaptive Optics
AOB	Adaptive Optics Bench
ASM	Adaptive Secondary Mirror
AURA	Association of Universities for Research in Astronomy
BTO	Beam Transfer Optics
CDR	Critical Design Review
CP	Cerro Pachón (the site of the Gemini South telescope)
CPU	Central Processing Unit
CSA	Cooperative Support Agreement
DM	Deformable Mirror
DM0	Deformable Mirror of GeMS conjugated to 0m. Others are DM4.5 and DM9.
DSP	Digital Signal Processor
ELT	Extremely Large Telescope
EMCCD	Electron Multiplying Charge Coupled Device
FTE	Full-Time Equivalent
FWHM	Full-Width Half Maximum
GEMMA	Gemini Observatory in the Era of Multi-Messenger Astronomy
GeMS	Gemini Multi-Conjugate Adaptive Optics System
GIRMOS	Gemini InfraRed Multi-Object Spectrograph
GLAO	Ground Layer Adaptive Optics
GN	Gemini North
GNAO	Gemini North Adaptive Optics system (a generic name for the proposed new AO system)
GNAOI	Gemini North Adaptive Optics Imager
GNIRS	Gemini Near InfraRed Spectrograph
GPI	Gemini Planet Imager
GSAOI	Gemini South Adaptive Optics Imager
ICD	Interface Control Document
IDF	Instrument Development Fund
IQ	Image Quality
IR	Infrared
ISS	Instrument Support Structure
KPP	Key Performance Parameter
KSR	Key Science Requirement
LGS	Laser Guide Star
LGSF	Laser Guide Star Facility
LGSWFS	Laser Guide Star WaveFront Sensor
LLT	Laser Launch Telescope
LPC	Laser Pointing Camera
LQG	Linear Quadratic Gaussian

LTAO	Laser Tomographic Adaptive Optics
MCAO	Multi-conjugate Adaptive Optics
MOAO	Multi-Object Adaptive Optics
NCOA	National Center for Optical-Infrared Astronomy
NCPA	Non-Common Path Aberration
NFIRAOS	Narrow FIeld Infrared Adaptive Optics System TMT
NGS	Natural Guide Star
NGS2	Next Generation Sensor for Natural Guide Star
NGSWFS	Natural Guide Star WaveFront Sensor
NIR	Near InfraRed
NSF	National Science Foundation
NUMA	Non-Uniform Memory Access
O&M	Operations and Maintenance
OAP	Off-Axis Parabola
OCS	Observing Control System (Gemini operations software)
ODGW	On-Detector Guide Window
OIWFS	On-Instrument WaveFront Sensor
OIR	Optical and Infrared
PC	Personal Computer
PI	Principal Investigator
PM	Project Manager
PMB	Performance Measurement Baseline
PMKB	Project Management Knowledge Base (Gemini's Project Management Database)
PMO	Portfolio Management Office
POLC	Pseudo Open Loop Control
PSF	Point Spread Function
PWFS	Peripheral WaveFront Sensor (two located in the A&G system)
RTC	Real-Time Computer or Real-Time Controller
SFS	Slow Focus Sensor
SH	Shack-Hartmann
SHWFS	Shack-Hartmann WaveFront Sensor
SCAO	Single Conjugate Adaptive Optics
SIMD	Single Instruction Multiple Data
SR	Strehl Ratio
TDA	Time Domain Astronomy
TTM	Tip-Tilt Mirror
WBS	Work Breakdown Structure
WFS	WaveFront Sensor
XAO	eXtreme Adaptive Optics

1 Introduction

The Gemini observatory plans to build a common Adaptive Optics (AO) Real Time Computer (RTC) platform that can serve the needs of current and foreseeable future AO systems on Gemini. By aligning all AO systems to the same RTC platform, we leverage shared spares, shared expertise, and increased hardware and software commonality which in turn reduces training requirements on support staff. In order to serve this purpose, the new RTC platform must be capable of supporting current and future AO system hardware. New RTCs will be built for both GeMS, the multi-conjugate AO system at Gemini South, and GNAO, the new AO system under development for Gemini North.

Over the last 15 years, technological advances in computing hardware and software mean that the AO computation problem is now tractable using more conventional hardware and software techniques than were possible when the current GeMS RTC was built. Multi-core x86 architecture Central Processing Units (CPUs) are now available with up to 72 cores, with clock speeds of a few GHz and including floating-point Single Instruction, Multiple Data (SIMD) vector processing instructions that are very well suited to very rapid low latency calculations such as centroiding and matrix-vector multiplications that dominate AO computation.

In addition, these architectures include extremely high bandwidth CPU core interconnects, high bandwidth multi-channel memory and memory controllers in Non-Uniform Memory Access (NUMA) architectures, and large amounts of on-core and on-CPU memory cache. Such systems vastly reduce costs, and simplify design and implementation compared to more esoteric systems such as DSP or ASIC based solutions.

These technology features mean that even Extremely Large Telescopes (ELT) scale AO Real Time Control can now run on regular conventional server hardware with software written in conventional programming languages such as C, leaving more computation on a multi-conjugate AO (MCAO) system. Use of conventional hardware and software also allows an interface to a higher level code for performance analysis and other non-real time functionality written in Python, now the de-facto standard for scientific computing and data analysis. This allows Gemini to leverage a huge collaborative open-source library of code and algorithms maintained by the scientific community.

These new technology developments allow Gemini additional options to consider when designing the new RTC platform. Early in the design phase, we will compare the available code bases and associated hardware with what is currently available in alternate path custom hardware and non-CPU processors. We will weigh a variety of selection factors to determine the best platform for current and future use at Gemini.

1.1 Scientific Objectives

Adaptive Optics enhances science productivity across all scientific areas that the Gemini telescopes provide for, from increased precision on solar system object astrometry, to spatial structure in high redshift extragalactic objects. New technologies now used in AO control systems allow Gemini to deploy advanced AO modes such as Multi-Conjugate AO (MCAO), providing significantly increased (2-arcminute diameter) corrected fields of view, or Laser-Tomographic AO (LTAO), providing higher correction performance for LGS systems by accounting for the LGS cone effect.

All of these AO systems rely on real-time computers to analyse data from wavefront sensors and command the deformable mirrors that actually correct the science light. These are complex hardware and software systems that in the past have generally been provided as custom systems for each AO system built. New technologies allow Gemini to build a common RTC platform that can serve both our facility AO systems (including possible future upgrades for GPI, short term upgrades for Altair, and potentially the GIRMOS visiting AO instrument). This allows Gemini to more efficiently progress in the AO field, with new algorithms and techniques, and to analyse telemetry data from our AO systems to optimize their performance and understand better the characteristics of the atmosphere at our observing sites.

To this end, the project will create a common RTC platform under the GEMMA program will provide RTC systems for both GeMS, the existing MCAO system at Gemini South, and for the new MCAO GNAO system under development for Gemini North under the same GEMMA Program.

1.1.1 A new RTC for GeMS

1.1.1.1 Top Level Requirements

- GeMS performance using the new RTC must be at the same level of performance as the current RTC.
- The new GeMS RTC must be based on the Gemini AO RTC Platform.
- The new GeMS RTC must fit within the currently allocated space, mass, and power budget of the existing GeMS RTC.

1.1.1.2 Description and Background of current GeMS RTC

GeMS uses a five laser guide stars (LGSs) constellation on a 1 arcminute square with one LGS in the center. The 5 LGSs feed five 16x16 Shack-Hartmann (SH) wavefront sensors (WFSs), supplemented by 1 to 3 natural guide stars (NGSs) to compensate for the tip-tilt (TT) and plate scale modes. All the WFSs are currently used to drive 2 deformable mirrors (DMs), one conjugated at the Ground Layer (DM0) and one at 9 km above the telescope pupil (DM9), and a

TT mirror. A third mirror conjugated at a mid-altitude layer of 4.5 km above the telescope (DM4.5) has been purchased and is currently nearing completion by the vendor. With this arrangement, GeMS delivers a uniform, close to diffraction-limited correction over a 2 arcminute squared field of view (FoV) in the near infrared (NIR). GeMS is designed as a facility instrument in order to feed any instrument behind it and to be extensively used by the Gemini community. GeMS is currently used with a 4k x 4k IR imager GSAOI (Gemini South Adaptive Optics Imager). GeMS began its commissioning in 2011 and has been used in regular operation since 2013.

Several control loops are needed to provide all the laser guide stars, natural guide stars, and wavefront sensors to deliver the corrections needed for GeMS's excellent image quality. The RTC handles this task and is responsible for measuring and correcting the wavefront errors collected from 5 LGSs and 3 NGSs to control the 3 DMs and the TT mirror at a frame rate up to 800Hz. The frame rate has to be adjusted with respect to the LGS return flux, which depends on the actual properties of the mesospheric sodium layer during the observation.

The existing GeMS RTC embedded inside the Adaptive Optics bench was built by the The Optical Sciences Company (tOSC). It was designed in the mid-2000s when the latency requirements for the AO computation were difficult to meet and required specialized technology. As a result, the existing GeMS RTC uses 12 TigerSHARC Digital Signal Processors (DSPs) which are programmed in a very low-level DSP specific Assembly language. This is a highly esoteric programming language by today's standards and recruiting knowledgeable programmers is challenging, if not impossible. The system also has incomplete documentation.

Updating code is very difficult and the learning curve for working on the software is steep and long. The TigerSHARC DSP boards are housed on multiple PCI cards in a PCI extension bus chassis hosted by a Pentium class PC running Windows 2000, now obsolete. The software development tools used are based on Visual Studio C++ and Visual DSP programming that are also obsolete. Finally, the ARC CCD controller driver was custom built to be able to run under Windows 2000. This has prevented Gemini from upgrading the operating system to a more modern one. The fast I/O modules and board interfaces need to communicate with the DM electronics are interfaced directly from the DSP board using PCI mezzanine Digital I/O boards that are no longer commercially available. This hardware is now aging and the PCI extension system is a significant source of technical faults. In addition, performance analysis and improvements to the algorithms are difficult to implement given the difficulty of exporting data from the DSPs into external code.

This means that supporting any new algorithms or additional external instrumentation that needs visibility into the AO system (for example GIRMOS, the Gemini Infrared Multi-Object Spectrograph, a visitor instrument being built specifically to work with GeMS) requires a new RTC. Building a new RTC takes a similar amount of time as learning the skills needed to reverse engineer the current RTC and to make the needed changes. Building a new RTC allows more expansion and upgrades in the future the current RTC does not.

In addition to this, the memory of this system is under specifications, and full circular buffers of AO telemetry data cannot be stored, making AO loop analysis loop stability diagnosis and potential performance improvements difficult. To solve this issue during the commissioning, a workaround was developed in order to save very short temporal sequence of data, but it is unusable for science development. Another issue experienced is the instability of the RTC software, which relies on a clock synchronisation of the time. When the RTC requires restarting, it has happened that this synchronisation will not always occur, resulting in a failure of the software functionalities, making the AO instrument unusable. We have lost nights of observation because of this particular issue, much effort has been expended to tackle this with unsuccessful results. This is a critical required feature for the new RTC. Furthermore, GIRMOS could be a fortunate beneficiary of such an upgrade since it will have a Multi Object AO mode that requires access to the telemetry in order to reconstruct the pseudo open loop slopes and drive their own deformable mirror.

All of the above issues show the unavoidable need for the integration of a new, modern and reliable RTC. The new RTC must be built using modern hardware technology, and programmed using industry standard languages in order to facilitate in-house maintenance and possible future developments. The new RTC must also allow for interchangeable algorithms, including the wavefront reconstructor in order to facilitate development of new techniques and AO research, and to be able to leverage progress in the field to improve performance in the future.

1.1.2 The GNAO RTC

1.1.2.2 Description of GNAO RTC

GNAO is a new AO system under development for the Gemini North telescope (refer to the GNAO Project Execution Plan for details). Plans for a future upgrade to GNAO include an Adaptive Secondary Mirror (ASM) to supplement the baseline tradition post-focal deformable mirror in an off-axis AOB. The baseline mode is a 2’ FoV MCAO system that will provide high angular resolution to all instruments in the 0.6-2.5um range. There will be four or six (TBD) 16x16 Shack-Hartmann LGSWFSs and one NGS focal plane sensor with custom ROI to image 3 NGSs to measure TT.

The new AO RTC platform will be designed as a facility for the Gemini Observatory, and base the new GNAO RTC on this new platform. GNAO is well suited to take advantage of the capabilities offered by the new RTC facility as it will work in different AO configurations (MCAO initially, and potentially others in future).

1.2 Requirements

There are two sources of science requirements that will flow into the RTC:

1. The current GeMS science requirements
2. The GNAO Science Requirements

The Logical Decomposition process outlined in the Systems Engineering Management Plan will be followed to flow the relevant scientific requirements to the RTC. Pending the design phase work, the preliminary set of Key Requirements have been identified in the table below. This is an incomplete list that will be completed once the GNAO science requirements are developed. Additionally, we have defined several software level requirements related to maintainability, reliability, and flexibility based on lessons learned from the existing GeMS RTC, as described above. These software level requirements are also listed in a table below.

Relevant RTC Preliminary Key Requirements

Parent Science Requirement		RTC Child Requirement	
Scope	**Requirement**	**RTC Parameter**	**Threshold**
Strehl ratio in K-band (2.2um) with 3 NGSs under median seeing conditions	30% uniform over the entire FoV	Jitter	30nm rms
		Latency	TBD
		Frame rate	500 Hz
AO loop rate under median sodium column density	at least 500 Hz	Frame rate	500 Hz
System must run under seeing condition	up to 1.2” @ 0.5um	Computational Power (# of elements in matrix)	1.4 million elements
AO loop stability	AO loop shall be stable over the longest possible science exposure. ~30 min	TBD	TBD
Real time and logged information shall be recorded and stored for the following parameters: Fried parameter, temporal evolution of turbulence, outer scale, isoplanatic angle, Cn2 profile	10% Accuracy: Fried parameter, Temporal evolution of turbulence, outer scale, isoplanatic angle	The RTC shall receive real time telemetry feedback to generate a dynamic reconstructor	Update every 5 minutes

Preliminary Software and Hardware Requirements

Description of Scope	Threshold Key Requirement
Maintainability	RTC shall use hardware that can reasonably expected to be supported for at least the next 15 years, for example in that compatible components using the same architecture are expected to be commercially available.

Close AO loops	RTC must reliably close all AO loops required for the AO mode in use. Loops must be stable when closed and must remain closed despite varying atmospheric conditions.
Allows AO algorithm R&D	RTC shall allow for the testing and deployment of new AO algorithms and techniques.
RTC Architecture	RTC shall be based on an x86 architecture PC running Linux.
RTC programming	RTC shall be programmed using a modern high-level programming language and development tools consistent with standard Gemini ICDs.
Telemetry Storage	New RTC platform shall be able to continuously store AO telemetry data to disk while the loops are closed without impacting performance. Sufficient storage will be provided for 6 months of data at typical usage rates.
Switch Algorithms	New RTC platform shall allow to switch control algorithms without system reboots or software rebuilds.
Switch frame rate	New RTC platform shall allow to change frame rate at any time.
AO frame rate and latency	RTC shall support AO loop rate of at least 1kHz with a latency not more than 2 frames.
AO configuration	New RTC platform shall support GLAO, MCAO, MOAO.
Reconstruct open-loop slopes	New RTC platform shall be able to reconstruct Pseudo-Open Loop Slopes.
WFS and DM compatibility	New RTC platform shall be compatible with current and planned electronics (deformable mirrors and wavefront sensor cameras).
Power dissipation	RTC platform will comply with Gemini standards with regard to power dissipation into the dome environment and cooling systems.

1.3 Facility/Infrastructure

The RTC will use standard interfaces to the telescope and observatory infrastructure. The table below lists the existing Gemini ICDs that apply to the RTC, will be impacted by the new RTC interfaces, and developed for the new RTC interfaces.

General Gemini Facility ICDs
Gemini Observatory Facility Instrument Common Requirements and Standards Specification (version A)
ICD 1.9/5.0 Science and Facility Instruments to Transport, Observatory and Operations Environments ICD (version C)
ICD 1.5.3/1.9 ISS to Science Instruments ICD (version D)
ICD 1.9/3.6 Science and Facility Instruments to ISS System Services ICD (version F)
ICD 1.9/2.7 Science Instruments to Facility Handling Equipment ICD (version E)
ICD-G0014 Optomechanical Coordinate System (version B)
General Gemini Software Requirements, Standards, and ICDs
GIAPI Builder Req-01302009 GIAPI Software Requirements for Instrument Builders (version 04) ICD 50
GIAPI C++ Language Glue API ICD (version 11)
GIAPI Use-08292006 GIAPI Design and Use (version 08)
GPSG-STD-102 Coding Standards and Guidelines for the Gemini Data Processing Software (in development)
Gemini Recipe System documentation (in development)
Applicable Software ICDs
1.1.13/1.9 Interlock System to Science Instruments ICD (version A)
ICD 10 EPICS Synchro Bus Driver (version 13 - Nov 1997)
ICD 20 Synchro Bus - Node/Page Specifications (version D)
Applicable Telescope Subsystem ICDs
Telescope Control System (TCS) ICD
Secondary Control System (SCS) ICD
Acquisition and Guidance System (A&G) ICD
Observatory Control System (OCS) ICD
Data Handling System (DHS) ICD
Gemini Interlock System (GIS) ICD
Adaptive Optics Module (AOM) ICD (to be developed)
Adaptive Optics Bench
Laser Guide Star WFS
Natural Guide Star WFS
Deformable Mirrors
AOM Controller
MCAO Internal Subsystem ICD (to be developed)
BTO / LTT Controller
Laser System
Instrument Sequencer
Internal Data Network
Data Storage

Notable telescope infrastructure items needed to interface to are listed below:

Synchro-bus: This is the data transfer system used to send real-time commands to the telescope secondary mirror control system to move the M2 in tip-tilt and focus. This will be necessary in order for the RTC to use the telescope M2 to offload tip-tilt and focus from the AOB DMs and TTM. At present the Synchrobus is considered a longevity issue - the observatory has tentative plans to replace it with a more modern system. The RTC project will be aware of any proposals relating to the Synchrobus.

EPICS: The EPICS system will be used to send real-time commands to the telescope systems (TCS, PCS, SCS, CRCS, MCS) in order to offload higher-order optical aberrations to the secondary mirror positioner (Coma) and Primary mirror support (all other high order modes within the parameter space of the PCS).

Power and cooling: While the final mechanical arrangement is TBD, some components of the RTC system will need to be mounted in electronics racks adjacent to the AOB on the ISS of the telescope. These will require UPS backed mains power and house glycol cooling. It is likely that additional components of the RTC system will be mounted in the summit data center and they will also require UPS backed mains power and appropriate cooling.

Data Network: the RTC components will require high speed data networking between them. This will be a standard ethernet system, but it is yet to be determined exactly which form this will take (i.e. 1/10/40 Gbit Ethernet, and fiber vs copper physical connections).

Data Storage: the RTC will need to store significant amounts of telemetry data for both on-line and off-line use. It is yet to be determined whether the RTC will implement its own storage system or make use of existing data storage in the facility data center.

1.4 Scientific & Broader Societal impacts

1.4.1 Outreach, Education and Communications

Please refer to GEMMA Program Execution plan.

1.4.2 National and International astronomical meetings

With the development of the instrument, it will be critical to present to the community the progress of the work, fostering confidence that the project team is building a facility that provides desired capabilities to its future users. Regular presentations will be sent to national and international meetings such as:

- Adaptive Optics for Extremely Large Telescopes
- SPIE Astronomical and Instrumentations

2 Organization

2.1 Internal Governance & Organization and Communication

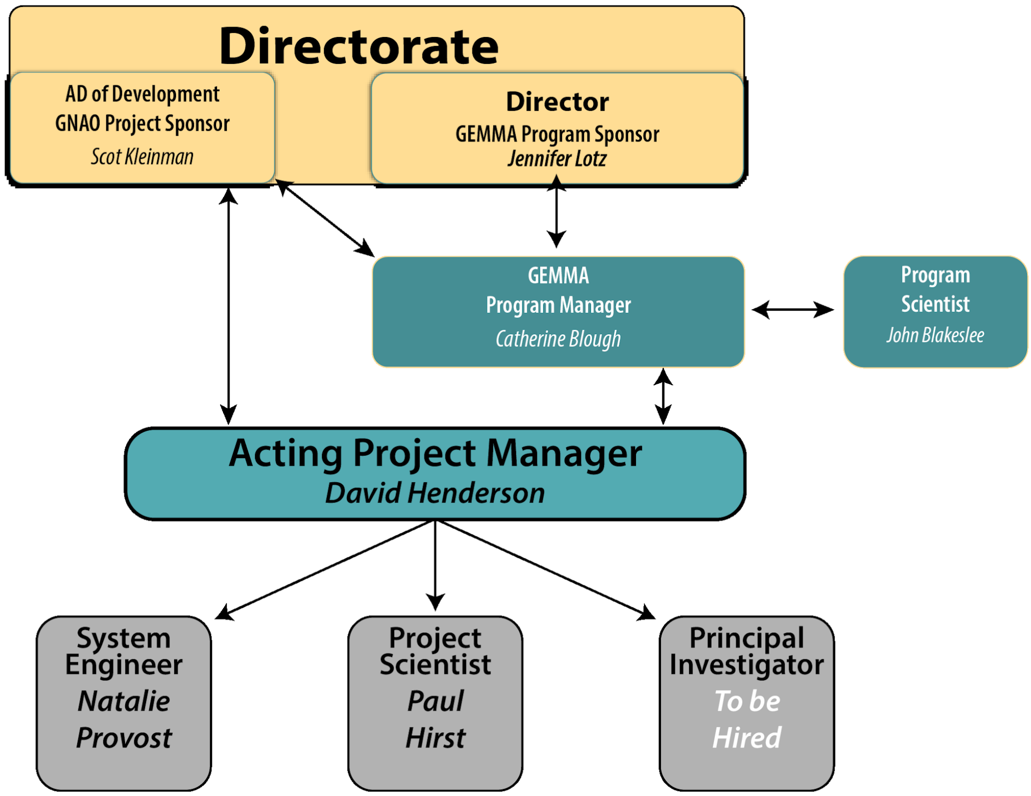

Figure 1 - Internal organization of current key project staff

Project Manager: Reports to the Project Sponsor and the Program Manager. The Project Manager is accountable to the Project Sponsor for the management of the projects and is accountable to the Program Manager for adherence to the program goals. Within the tolerances agreed upon with the Project Sponsor/Program Manager the Project Manager has the authority to make decisions on all aspects of the project. Decisions outside the tolerances must be approved by the Project Sponsor and Program Manager.

Project Sponsor: Reports to the Gemini Directorate. The Project Sponsor is responsible for supporting the Project Manager and ensuring that the Project Manager performs the assigned tasks. The Project Sponsor functions as a link between the directorate and the Project Manager and manages the escalation process outside of the purview of the Project Manager. The Project Sponsor works with the Program Manager to make decisions outside of the Project Manager's tolerances.

Program Manager: Reports to the Gemini Directorate. The Program Manager is accountable for setting program and project goals and ensuring that these goals are met. The Program Manager works with the Project Sponsor to make decisions outside of the Project Manager's tolerances. The Program Manager communicates directly with funding organizations, The Gemini Board and Science and Technology Advisory Committee (STAC).

Systems Engineer: Reports to the Project Manager. Responsible for the system engineering activities pertaining to the project as detailed in the GNAO Systems Engineering Plan (SEMP).

Principle Investigator: The PI has overall responsibility for the scientific success of the project and is the lead scientist for the project. In consultation with the Program Scientist provides the bridge between the science, technical, and management teams to ensure their vision for accomplishing RTC is realized.

Project Scientist: Reports to the Project Manager. Responsible for leading the science team in developing the science cases for use in the Concept of Operations (CONOPS) documents and in requirements development.

To lead this effort, we have put together a core team formed in advance of outside hires (see below):

- Dr Scot Kleinman, Associate Director of Development, as Project Sponsor for RTC.
- David Henderson, Project Manager, as Acting Project Manager for RTC.
- Natalie Provost, System Engineer, as Lead System Engineer for RTC.
- Dr. Paul Hirst, Lead Scientist, as Project Scientist for RTC.

In addition to the above team, recruitment has begun in order to hire qualified team members.

- Senior Adaptive Optics Scientist position who will be leading the RTC as the Principal Investigator (PI).
- Senior Project Manager with AO experience to manage the RTC project.
- Senior System Engineer, preferably with AO experience.

Please refer to the GEMMA Program Execution Plan for the Internal Communication Plan template as a reference document.

2.2 External Organization and Communication

Please refer to the GEMMA Program Execution Plan for 2.2 and the External Communication Plan template as a reference document.

2.3 Partnerships

When the RTC project requires feasibility and trade studies, we will solicit stakeholder feedback along with the results of these studies to better tailor our work to the needs of our users. In all cases, we will be guided by our top-level project requirements. While we can alter these requirements through our change-management process, when necessary, we try to work within our initial scope and address any new demands arising from additional stakeholder or technical concerns.

2.4 Roles and Responsibilities

Please refer to the GEMMA Program Execution Plan for external organization roles and responsibilities.

2.5 Community Relations and Outreach

Work from this project will be presented at appropriate Adaptive Optics and Astronomical Instrumentation conferences and workshops. Some of the work from this project will likely be suitable for publishing in the astronomical literature.

3 Design and Development

3.1 Project Development Plan

We are currently researching the AO RTC community to determine what technologies are available and how they might fulfil our needs. We expect to finalize the resultant internal trade study in FY2019Q2. Based on that study, we will decide which of the three main options (or combinations therein) to select to complete the RTC effort:

1) Select a publicly-available platform and perform the work in house, with additional contracted effort.
2) Select a publicly-available platform and issue an RfP for an external team to do the work based on that platform.
3) Issue an open RfP based on a set of requirements that do not specify a particular platform.

The RTC schedule will run “behind” the GNAO schedule during the Design Phase, in order to integrate the GNAO requirements, and once requirements are finalized, synchronize the build schedules. We plan to deliver various stages of the RTC build to GNAO to aid GNAO integration and testing. See section 3.3 for the derived baseline schedule.

Please refer to the RTC Systems Engineering Management Plan listed in Appendix A.

3.2 Development Budget and Funding Sources

The project is funded as part of the GEMMA program NSF funding.

Please refer to the RTC Project Plan listed in Appendix A.

3.3 Development Schedule

The baseline schedule below is based on option 1) from Section 3.1. The plan will be re-evaluated if an alternate option is selected. The schedule is interdependent with the GNAO effort to ensure GNAO provides the relevant RTC requirements for the required work - and the necessary hardware and software is then provided to aid GNAO’s development, integration, and testing.

Under option 1, the baseline schedule is below.

FY2019-Q2 - FY2019-Q4: Initial lab prototyping and familiarization with software.
- Demonstrate closed loop operation on a simple lab AO bench (Thorlabs AO kit at HBF)

FY2019-Q4 - FY2020-Q1: Develop and Document Conceptual Design
- CoDR after the GNAO CoDR to incorporate GNAO needs into the design

FY2021-Q2: Preliminary Design Stage Review

FY2022-Q2: Critical Design Stage Review
- All major software components developed at least at working prototype level
- All major hardware components in-house operating at least at working prototype level

FY2023-Q2: Build, document, and commission new GeMS RTC

FY2023-Q4: Build, document, and deliver GNAO RTC

Please refer to the RTC Project Plan listed in Appendix A.

4 Construction Project Definition

4.1 Summary of Total Project Definition

The RTC project will build a common Adaptive Optics Real Time Control system that can be used by current and future Gemini AO systems. Within the scope of the GEMMA program, it will be deployed on both the existing GeMS AO system at Gemini South, and the new GNAO system at Gemini North.

4.2 Work Breakdown Structure (WBS)

(for definitions of soft- and hard- real time terminology, see the WBS dictionary that follows.

WBS #	WBS Title	Deliverable
1.3.1	Project Management	
1.3.2	RTC hardware definition	Hardware definition
1.3.2.1	Hard-Real-Time computer	Hardware definition
1.3.2.2	Soft-Real-Time computer	Hardware definition
1.3.2.3	Telemetry server hardware	Hardware definition
1.3.3	Common RTC software	Software code

1.3.3.1	Hard-Real-Time software	Software code
1.3.3.2	Soft-Real-Time software	Software code
1.3.3.3	Telemetry server software	Software code
1.3.4	GeMS RTC implementation	Complete RTC for Gems
1.3.5	GNAO RTC implementation	Complete RTC for GNAO

4.3 WBS Dictionary

WBS #	WBS Title	WBS Description
1.3.2.1	Hard-Real-Time computer	Computer hardware that handles the hard-real-time processing, taking input data from the WFSs and generating commands for the DMs, TTM, and telescope. This includes the I/O interface hardware needed to read data from the WFSs and transmit data to the DMs, TTM and telescope.
1.3.2.2	Soft-Real-Time computer	Computer hardware that handles the soft-real-time processing, analyzing telemetry from the hard-real-time loop and updating parameters in the hard-real-time loop to optimize performance as atmospheric conditions change. Depending on the final design, this may or may not be a separate hardware system from the hard-real-time computer.
1.3.2.3	Telemetry Server Hardware	Computer and data storage hardware that captures telemetry from the hard and soft real-time loops, stores it for future analysis, and makes it available for analysis. The soft-real-time computer will access and analyze this data while the system is running, and staff scientists will access and analyze this data off-line. Data products may be derived from AO telemetry to be provided to users alongside the science instrument data. Data I/O to the telemetry server is anticipated to be by (multi-Gigabit) Ethernet. The telemetry server will require substantial (several TB) of data storage - this may be dedicated storage hardware or may be provided by facility network attached storage facilities.
1.3.3.1	Hard-Real-Time software	The software that runs the hard-real-time loop. This

		software has the most stringent requirements in processing speed, latency, and real-time performance. It is also the most computationally intensive, being responsible for analysing the wave front sensor data and generating the DM, TTM and telescope commands in real-time. This software runs on the Hard-Real-Time computer hardware
1.3.3.2	Soft-Real-Time software	The software that runs the soft-real-time loop. This software analyses telemetry and other inputs to update parameters in the hard-real-time loop, such as loop gains and wavefront reconstruction coefficients. The real-time performance of this software is not as critical as that of the hard-real-time loop, but it does need to respond promptly to changing conditions during observations.
1.3.3.3	Telemetry server software	The software that runs on the telemetry server hardware to capture, store, and publish telemetry data from the hard and soft real time loops. Telemetry data will be captured from the network and stored on suitable data storage. A database of stored telemetry will be maintained and used for both data access and data curation. Telemetry data will be published via a RESTFUL (stateless) http service. Both the soft-real-time systems and offline users will connect to this service to retrieve AO telemetry data.
1.3.4	GeMS RTC implementation	The complete RTC for GeMS. The common platform elements integrated and configured appropriately to run the GeMS AO system.
1.3.5	GNAO RTC implementation	The complete RTC for GNAO. The common platform elements integrated and configured appropriately to run the GNAO system.

4.4 Scope Management Plan and Scope Contingency

Please refer to the RTC Scope Management Plan listed in Appendix A.

4.5 Cost Estimating Plan, Cost Reports and Baseline Budget

This is covered in section 4.5 of the GEMMA Program Execution Plan.

4.6 Complexity Factor

A complexity factor of 22% was used for the NSF proposal to allow for increased costs due to project complexity. However, Gemini standard practice is to require facility class instrument vendors to withhold at least an additional 15% of the baseline budget for risk mitigation purposes. Gemini holds an additional 15% of the baseline budget, 30% in total.

4.7 Cost Book, Cost Model Data Set and Basis of Estimate

Not Applicable
Since this is not a large facility project and implementation is an addition to an existing observatory, this section is not applicable.

4.8 Funding Profile

This is covered in section 4.8 of the GEMMA Program Execution Plan.

4.9 Baseline Schedule Estimating Plan and Integrated Schedule

Baseline Schedule

WBS	Description	Schedule
1.3.2	RTC hardware	2019 - 2021
1.3.3	Common RTC software	2019 - 2021
1.3.4	GeMS RTC implementation	2021 - 2022
1.3.5	GNAO RTC implementation	2021 - 2022

Details depend strongly on technology selection decisions which are pending contracting advice from AURA/CAS - obviously, technical selections that do not have viable contracting options on the timescales necessary for this program will not be suitable for selection. The schedule below shows our plan to make decisions to achieve a conceptual design by October 2019:

- Perform RTC market research (complete)
- Develop RTC ConOps (January 2019)
- Perform RTC platform trade study to inform requirements development (January 2019)
- Develop RTC Functional and Interface Requirements (February - March 2019)
- Perform RTC cost, schedule, and labor projections (March 2019)
- Determine level of in-house versus external contract labor requirements (March 2019)
- If decision to develop RTC in house, develop conceptual design based on open source available software platform that was selected and well-defined set of requirements and ConOps (April - September)
- If decision to outsource RTC development:

- ○ Develop RFP for external contracted work based on a well-defined set of requirements and ConOps (April 2019)
- ○ Receive RFP Responses with proposed design concepts (June 2019)
- ○ Perform RTC design trades as part of RFP evaluation process (July - September 2019)
- ○ Select RTC conceptual design (by October 2019)

4.10 Schedule Contingency

Gemini requires contractors to maintain a baseline schedule and include schedule contingency beyond the baseline of a reasonable amount (at least 15% beyond the critical path). The schedule, including contingency, shall not exceed the required project completion date. For internal work, we will update our baseline schedule with appropriate contingency at each stage (Conceptual, Preliminary, Critical, Build) end.

5 Staffing

5.1 Staffing Plan

Senior positions:
Senior Project Manager: 0.3 FTE / year for duration of project
Senior Adaptive Optics Scientist (Principal Investigator): 0.4 FTE / year for duration of project
Senior Systems Engineer: 0.3 FTE / year for duration of project

Software engineer: Amount of effort depends heavily on the decision to implement the RTC in house using an open-source code, or to contract an external team to produce an RTC for Gemini.

AO fellow / junior scientist position:
AO RTC scientist: full time for duration of project. This position will be heavily involved in the implementation of the RTC, working either on in-house development, or working very closely with an external development team.

5.2 Hiring and Staff Transition Plan

Please refer to the RTC Resource Allocation Plan listed in Appendix A.

6 Risk and Opportunity Management

6.1 Risk Management Plan

Please refer to the RTC Risk Management Plan listed in Appendix A. This plan covers:

- Project Risk Process

- Other Roles and Responsibilities
- Budgeting
- Timing
- Risk Register Scoring and Interpretation, with Impact and Likelihood scoring
- Reporting Formats
- Tracking

6.2 Risk Register

Please refer to the RTC Risk Register listed in Appendix A. This register includes:

Part I - Risk Identification
1. Categorization & Description
2. Impact, Likelihood & Total risk scores

Part II - Existing controls, per risk:
1. Effectiveness
2. Residual risk score

Part III - Risk Response, per mitigation strategy:
1. Effectiveness
2. Residual risk score
3. Contingency Plan
    a. Cost
    b. Owner
    c. Review schedule
    d. Status

6.3 Contingency Management Plan

Please refer to the Part III columns in the Risk Register for Contingency Management information. The Risk Register is listed in Appendix A.

7 Systems Engineering

7.1 Systems Engineering Plan

An initial revision of the RTC Systems Engineering Management Plan (SEMP) has been developed to document the role of systems engineering throughout the TDA life cycle. We will refine this plan early in the Conceptual Design Stage to reflect systems engineering process and programmatic details as the system definition matures.

The primary systems engineering roles are to perform and/or lead the following activities:
- Technical management through all phases
- Concept of Operations Management
- Requirements Management
- System Design
- Interface Management
- System Integration
- Verification and Validation

- Quality Control Management

Please refer to the RTC Systems Engineering Management Plan listed in Appendix A. This plan has the following structure incorporated:

- Roles and Responsibilities

7.2 Systems Engineering Requirement

Please refer to the RTC Systems Engineering Management Plan listed in Appendix A. This plan has the following structure incorporated:

- System Design Process
- Logical Decomposition and Requirements Definition
- Requirements
- Decomposition Methodology
- System Design
- Conceptual Design
- Preliminary Design
- Critical Design
- System Development
- Documentation Plan
- Validation & Verification

7.3 Interface Management Plan

The objective of the interface management is to achieve functional and physical compatibility among all interrelated system elements. Early in the design phase, we will define external, internal, functional, and physical interfaces in an Interface Definition Document that will be maintained throughout development. This document will be the foundation for specifying interface requirements documented in an Interface Requirements Document (IRD). We will then manage external and internal interface via Interface Control Documents (ICDs).

Please refer to the RTC Systems Engineering Management Plan listed in Appendix A. This plan has the following structure incorporated:

- Interface Management Plan

7.4 Quality Assurance and Quality Control Plan

Quality Assurance (QA) provides an independent assessment to the project manager and systems engineer of the items produced and processes used during the project life cycle. The Project Manager and Systems Engineer will ensure that contractors implement a quality assurance program and ensure visibility into QA processes and risk mitigation. Internally, the project manager and systems engineer will manage quality risks and enforce adherence to procedures and specifications throughout the system development and system integration.

Please refer to the RTC Systems Engineering Management Plan listed in Appendix A.

7.5 Concept of Operations Plan

The Concept of Operations (ConOps) is an important component in capturing stakeholder expectations, driving system requirements, and driving the architecture of a project. It will serve as the basis for subsequent definition documents such as the operations plan and operations handbook and provides the foundation for the long-range operational planning activities such as operational facilities and staffing. We will generate a Concept of Operations as a first step in the Conceptual Design Stage, and will use it as a basis for requirements and interface definition.

Please refer to the RTC Systems Engineering Management Plan listed in Appendix A.

7.6 Facility Divestment Plan

Not Applicable

This is not a large facility project. The RTC project is an addition to existing observatory operations - this section is not applicable.

8 Configuration Control

8.1 Configuration Control Plan

This is covered in section 9.1 of the GEMMA Program Execution Plan.

8.2 Change Control Plan

This is covered in section 9.2 of the GEMMA Program Execution Plan.

8.3 Documentation Control Plan

This is covered in section 9.3 of the GEMMA Program Execution Plan.

9 Acquisitions

9.1 Purpose Of Acquisition Strategy

The overall objective of an Acquisition Strategy is to document and inform project stakeholders about how the acquisitions will be planned, executed, and managed throughout the life of the project. This Acquisition Strategy should outline the specific actions necessary to execute the approved acquisition strategy. The Acquisition Strategy documents the approach to be taken for items such as the actual acquisition, contracting, and fiscal, legal, personnel, considerations, etc. The Acquisition Strategy should also address any policy, process, regulatory, etc. necessary to comply with Federal Acquisition Regulation, and any other requirements related to the specific acquisition.

The intended audience of the RTC Acquisition Strategy is the project manager, project team, project sponsor, procurement officer/office, and any senior leaders whose support is needed to carry out acquisition plans.

9.2 Background and Objectives

9.2.1 Statement Of Need

The need for an RTC for both GEMS and GNAO is described in section 1.1.1.2. The new Facility AO RTC will be used to build the RTC for GNAO. The use of the facility as the base of the GNAO RTC will simplify the development and integration of the GNAO RTC by preventing the duplication of effort. Additionally, this allows for easier support during operations as the same set of personnel will be able to support both the GeMS RTC and the GNAO RTC. Building on the Gemini RTC facility to develop an RTC for GNAO is a prime example of why the Gemini AO RTC platform must be a facility. This adaptability to new and different systems will allow Gemini to offer the DSM of GNAO as a base for future facility and visitor instruments at a much-reduced cost versus building a new RTC for each new AO instrument.

9.2.2 Applicable Conditions

We propose to create an RTC platform that can be a facility. A facility is defined as all real-time AO systems will be able to benefit from the same RTC environment. The new RTC must be adaptable to our current and preferably to future AO systems, including the electronics currently used from the DMs and the WFS cameras, must be compatible and interfaced. Preliminary top-level requirements are listed in section 1.2.

9.2.3 Capability Or Performance

A standard personal computer (PC) server hardware will be used for the RTC systems significantly avoiding the problem of obsolete computer hardware on both facility AO systems. I/O boards and other interface hardware will require less invasive transitions than current systems. Common codebase will be employed across multiple facility AO systems. Each system will use separately appropriately configured code; however, the common elements are shared between the systems.

Open-source Real-time Controller codes are available and appear to be very versatile and suitable for use as a basis for such a codebase. The open-source controllers use codebases in standard C programming language and standard POSIX constructs such as shared memory and inter-process communication.

In addition, the use of conventional modern technology allows the AO RTC software to be modular, separating the hardware driver code from the AO calculations allowing a common RTC platform which can be connected to many different types of hardware. This allows code sharing between different AO systems. This will reduce the learning curve for software engineers and scientists to understand and modify the code.

9.2.4 Delivery Or Performance-Period Requirements

Several groups are working in the RTC market space, with varying degrees of ties to actual AO instrumentation. The approaching ELT era has driven a lot of work in this field because AO systems are an integral part of all the new ELT concepts (eg E-ELT, TMT, GMT) and essential for these telescopes to achieve their full potential. The large apertures of these telescopes, and the required AO performance mean that these systems will have unprecedented numbers of wavefront measurements to process into DM commands, therefore computational requirements for these systems will be orders of magnitude higher than for older systems.

There is a realization in the community that reinvention of the wheel for each new AO system is not an efficient route forward as AO systems become bigger and more complex. There are several different approaches to the problem favored by different groups. In some cases, one primary group has formed around each approach, and some of these groups are either actively seeking, or are open to, contractual work to build and/or support RTCs using their code. Some of the approaches are open source and freely available, some are proprietary, and some require the use of proprietary custom hardware.

9.2.5 Trade-Offs

A major trade-off to consider is the somewhat "black-box" nature of an externally provided solution vs the staff expertise on an in-house solution. Black box solutions have always been problematic in that Gemini may not have the expertise or internal knowledge of the system to update and modify it in the future, including addressing operational issues that arise, modifications that need to be made to maintain compatibility with other systems at the observatory that will get updated over time, or to simply improve performance as technology and techniques in the field progress.

9.2.6 Acquisition Streamlining

The Gemini AO team attended an AO conference in October 2018 [1] to conduct market research with teams attending the conference. Follow up questions were sent to teams to clarify information obtained at the conference.

9.3 Plan of Action

Following market research and AURA/CAS input on acceptable contracting strategies, a decision will be made whether to issue a broad RfP for an RTC system or whether to select to implement the RTC in house and contract expert support on the code base we use. It may be that other options intermediate to these exist.

9.3.1 Sources

The following is a review of the relevant projects of which we are aware. Some of these are introduced mainly for reference and are unlikely to be suitable for direct adoption by Gemini, but have been used or incorporated into other systems which are subsequently discussed.

[1] https://cias.obspm.fr/-Adaptive-Optics-wavefront-sensing-and-control-in-the-VLT-ELT-era-174-?lang=fr

GreenFlash

The GreenFlash project [2] is funded by the European Commission Horizon 2020 program to prototype an RTC for the 40m E-ELT. With an emphasis on academia - industry collaboration, power efficiency and high performance, the project settled on an approach using both FPGAs and GPUs to provide extremely high performance, in both low and predictable latency and large amounts of computer power.

This approach is in many ways an elegant and powerful solution to the challenges of an ELT scale RTC. A custom FPGA board made by Microgate implements high bandwidth communication channels (eg 10GigE or 40GigE) that are used to capture data from the WFSs. The FPGA also implements a PCI Express (PCIe) interface supporting NVIDIA GPUDirect, which allows the FPGA to write the WFS pixel data directly into the memory onboard an NVIDIA GPU card where the high-speed computation takes place. This provides a very low latency mechanism for getting the WFS data into GPU memory, compared to a more conventional approach which would involve at least 2 DMA transfers - a network interface card (NIC) writing the data to the main host memory using DMA, and then a memory copy via DMA from the host memory to the GPU memory.

In the GreenFlash model, the entire hard-real-time loop runs on (NVIDIA) GPUs. Again, this is an elegant solution - the GPUs have no operating system or BIOS responsibilities, and are therefore free from events such as NMIs or OS cache flushes or network transactions. The computational parts of the hard-real-time AO loop are extremely highly parallelizable, and are therefore well matched to a GPU architecture. The current NVIDIA Tesla V100 GPU card being used has over 5000 CUDA cores providing over 50 TFLOPS in single-precision, and 16GB of HBM2 RAM with a bandwidth of 900 GB/s.

The commands to the DM are likewise retrieved directly from GPU RAM by an FPGA interface card and transmitted to the DM hardware by an interface implemented on the FPGA, again providing a very low-latency path from the GPU to the DM hardware.

While the FPGA and GPU boards are hosted on a PCIe bus, most likely on a conventional x86-64 architecture server motherboard, the host system is not involved in the hard-real-time loop execution. The host CPU is used for housekeeping and start-up tasks such as uploading executable code to the GPU boards, and also provides a route to extract either bursts of real-time telemetry, or continuous streams of down-sampled telemetry, which can then be used both in the soft-real-time loop for loop parameter optimization, and also for after-the-fact diagnosis, troubleshooting, and performance analysis.

This is undoubtedly an elegant solution that avoids many of the issues associated with more conventional solutions, and some would argue that it is currently the only way to solve the RTC problem for a high-performance ELT scale system, especially if more advanced AO algorithms are required.

However, there certainly are down-sides to this approach, not least the dependence on specific hardware. Primarily, the FPGA communication boards are custom hardware provided by a single vendor (Microgate). While Microgate has been in the astronomy FPGA business a long time and shows no sign of leaving, a single vendor option has to be considered as a longevity and sustainability risk. Additionally, the GPU boards used have a relatively short product lifetime compared to CPU architectures. A presentation by NVIDIA indicated a product lifetime (ie how long a given component is manufactured) of 5 years for a GPU model, and that typically, support for GPU models may be dropped from recent updates of the software stack 5 years after that. This suggests that 10 years after a GPU goes into production, it may no longer be supported by the development toolchains.

This also presents a longevity / sustainability risk. In the GPU case, the mitigation of this risk would be to maintain the developer expertise to be able to migrate the system to newer GPU models as the older ones become unsupported. In general, major code revision should not be required to do this, and as a side benefit, the newer models would undoubtedly have increased compute power allowing yet more advanced algorithms to be implemented. The HPC GPU industry appears to be booming at the moment, driven by such industries as self-driving cars, deep learning and AI - support for the latter is driving the deployment of vast numbers of high-performance GPUs in the cloud computing industry. These are very dynamic industries - if a new technology arrives that surpasses GPUs in these applications, GPU interest will decline rapidly. However, it seems reasonable to assume that GPUs will be around in a suitable form at least for the lifetime of current AO instruments, so long as we accept that we may have to invest effort in porting our systems to new architectures as the industry progresses.

[2] http://greenflash-h2020.eu/

CACAO

Compute And Control for Adaptive Optics (CACAO) [3] is an open-source RTC code by Olivier Guyon at the Subaru Telescope. It was developed as the RTC for a high-performance extreme AO system (SCExAO) on Subaru. SCExAO has a history of very high AO performance, and rapid adoption of new techniques and technologies, but could be described more as a lab experiment than a common user instrument - a skilled and dedicated instrument team is needed to operate it. The code aspires to cutting edge performance, and uses GPUs and other hardware techniques to do that. The code is released open-source on GitHub, and could be described as complex, pulling in a lot of dependencies and including a lot of code modules that may not be currently in use, reflecting the rapid adoption of new technologies and techniques on SCExAO. Subaru plan to use CACAO on both their upgrade of the AO-188 system, and also in the new SUBARU-ULTIMATE GLAO system.

CACAO as deployed on SCExAO makes heavy use of GPUs, though the documentation suggests that GPU use is optional and that the code can run on regular and many-core CPUs.

The code doesn't appear to have gone through any release cycles, advertising itself on github as "Alpha Release", and we are not aware of any third parties using the code as the basis for their own RTCs. We understand that some of the CACAO code has been incorporated for use within the real-time loop of the GreenFlash system by the COSMIC project. Olivier describes CACAO as fundamentally an internal data stream format - the system is based around blocks of shared memory, which include internal semaphore sections. Code routines can then watch for state changes of the semaphores to decide when to execute, and set semaphores to trigger other code. This sounds like a reasonable architecture, but also suggests a box-of-parts approach where a large amount of assembly would be required to implement a system for Gemini. It is not clear that expert support would be available in any quantity to assist with this.

[3] https://github.com/cacao-org/cacao

COSMIC

The COSMIC project is consortium of Observatoire Paris, Microgate, ANU, and Swinburne University, that aims to produce working ready-to-go RTCs based in the outcome of the GreenFlash project (see above). The code is mostly open source, but they have concerns about releasing the difficult to understand parts. Because it uses the GreenFlash design, COSMIC relies on both NVIDIA GPUs, and also the GreenFlash uXComp FPGA boards produced by Microgate and based around an Intel ARRIA 10X115 FPGA.

Some code from CACAO (see above) is used in the real-time loop. It also uses OCTOPUS as the abstraction layer, together with the KRAKEN high-level user interface and management layer. COSMIC keeps a number of blocks of the current CACAO distribution, most notably the inter-process communication standard that was defined by Olivier and the process monitoring tools among others. This will allow, in the near future, to use "legacy" modules from the current CACAO distribution (mainly by Olivier for Subaru needs) together with the new modules we are adding, inherited from Green Flash and the COMPASS platform.

These additional layers we are adding will be open source and will allow more contributors to join the project for any instrument specific development.

An additional advantage of the COSMIC platform is that it includes a performance indicator that computes the end-to-end latency, performance stability (jitter), data transfer rate for real-time pipeline and telemetry, throughput supervisor, and data storage capacity. It also includes a simulator that can be used to test and validate the RTC commands sent to the DM.

It appears that the COSMIC collaboration aspires to provide RTCs and/or support on a "semi-commercial" basis to AO instruments needing an RTC. It also appears that platform has used a solid system engineering approach and software standards.

The COSMIC platform will be on sky at Keck in 18 months.

WM Keck Observatory RTC

In Dec 2017, the Keck Observatory put out an RFP for a new AO RTC. Several teams provided proposals, the one selected is essentially the COSMIC collaboration, and the RTC they will provide has been described as the first release of the COSMIC system, and the first real-world product of the GreenFlash project. PDR is scheduled for Dec 2018 and 1st light will be late 2020.

Microgate built the previous Keck RTC (http://www.microgate.it/Engineering/Adaptive-Optics-Electronics/Keck-NGWFC), and thus they are well placed to interface from their current FPGA hardware to the existing DM hardware on the Keck system.

The initial system is for a SCAO system, with the intent to add LTAO capability later. It is required to operate in 11 modes, combining WFSs, mirrors, NGS, and LGS. It requires 10 nights of telemetry storage at 100Hz and 1 minute per hour of full speed. Because it incorporates legacy and new interfaces and mirrors, the interface was designed for flexibility and expandability, using FPGAs.

The system is required to be capable of a 2 kHz loop rate, but is believed to be scalable to 4 kHz.It will use various legacy Keck interfaces (eg CCD39 with AIA interface, STRAP on RS422) and also implement new interfaces (eg OCAM2 camera and an E2V CCD4270 both via CameraLink interface, UH Saphira detector via USB 3.1, Boston micromachines DM via Aurora 2.5Gbit/s fiber interface. The compute engine is based on 2x NVIDIA V100 GPUs, one of which is dedicated to the hard-real-time loop. The full system includes a substantial telemetry server for both on-line and off-line use.

DARC

The Durham AO Real-Time Controller [4], is an open-source software code from the Center for Advanced Instrumentation at Durham University in the UK. It is primarily led by Alastair Basden. The code is on GitHub and is released under the GNU Affero GPL Open-Source license [5].

The code was originally developed for the CANARY MOAO demonstrator, but has since been deployed on various AO systems and many other CANARY modes. DARC is also the RTC platform selected by the GTCAO system at GTC.

The code runs on linux / x86, and can make use of x86 many-core CPUs such as the Intel Xeon Phi or AMD Epyc architectures for heavy parallelization (use of 72 core CPUs has been demonstrated). The code can also use GPUs if necessary. The code is modular with driver modules for WFS cameras and DMs, and can be flexibly configured to support a wide range of loop configurations and reconstructors.

The Durham group have expressed willingness to be involved in the Gemini AO program and to provide us with support for using the DARC code on our systems. There is some concern over support availability with the primary author of the code taking responsibilities outside the AO group at Durham, though Durham do have other commitments with the code (see HARMONI discussion later) that will require them to maintain expertise on it, and they do have other group members who are very familiar with the code.

Like many academically produced codes, the code lacks documentation and clarity. In addition, the code has become somewhat sprawling, with many modules added later that were not in the original plan - this is to a large degree as a result of DARCs use on CANARY, which as an on-sky-test-bench type instrument has by definition to support a large number of operational modes and a large variety of hardware.

An interesting recent development is that Durham will be providing the RTC for the ESO HARMONI E-ELT instrument, and will be working with a commercial software industry partner to bring the DARC code up to ESO software standards for delivery to ESO as part of the HARMONI instrument.

From a longevity and sustainability point of view, the ability to run on stock x86 hardware is a huge advantage. No custom hardware is required for DARC besides that which is necessary to interface to the WFS and DM hardware on the instrument. While certain chipsets and motherboards have been found to work better than others (e.g. in terms of not having housekeeping hardware generating interrupts etc.), there is very low risk that suitable hardware will not be widely available.

As compared to the GreenFlash architecture, DARC is elegant in a different way - by handling all the computation on the regular system CPUs, input data from the WFS can be DMA-ed into regular host memory by the NIC, Frame Grabber, or data acquisition system interfacing to them, and command output the DMs can be handled in the same manner, achieving suitably low latency due to the single DMA required. Computationally, many-core CPUs are now available - The Intel Xeon Phi is available with 72 Atom cores, and the AMD Epyc line has 32 (hyperthreading) cores to run 64 threads simultaneously. While this is far less than the thousands of cores available on GPUs, the CPU cores are more capable and this provides more than adequate compute power for a Gemini scale system.

Memory bandwidth is also a concern - however these many-core CPUs do have multiple memory controllers allowing a very high aggregate memory bandwidth - the challenge then becomes in leveraging the NUMA architecture efficiently to locate data in the correct area of physical memory such that it can be accessed as suitable bandwidth by the appropriate cores. DARC has been made NUMA aware and contains code to leverage the NUMA architecture in this way. This is related to the core connection fabric used to allow communication between all the cores, memory controllers, PCIe interfaces, etc. on the CPU. Intel and AMD have various offerings, all of which have their strengths and weaknesses.

By leveraging appropriate NUMA coding techniques, Durham have demonstrated DARC running an ELT scale RTC in real-time on a Xeon Phi CPU. It has to be acknowledged that with current CPUs, a significant amount of fine tuning is necessary to achieve this, and compute headroom is probably low. However, 8-meter systems are significantly lower demand than ELT scale systems in this regard, and many issues are much simpler on a Gemini size system. For example, the memory bandwidth issue is likely simply avoided as the control matrix for Gemini scale systems may fit entirely within L3 CPU cache. Even if it doesn't, then the control matrix size will of course be much smaller than for ELT size systems where memory bandwidth becomes an issue.

[4] https://www.dur.ac.uk/cfai/projects/darc/
[5] https://github.com/agb32/darc

HEART

The Herzberg Extensible Adaptive Real-Time controller (HEART) is the RTC derived from NRC's work on the TMT NFIRAOS system. It is the intellectual property of NRC and follows a closed-source model. NRC has expressed interest in a contract to provide an RTC for GNAO. NRC have provided some documents, including a description of how it could be applied to Gemini. Detailed information beyond the documents provided has proved difficult and slow to obtain.

Fundamentally, HEART is a similar approach to DARC - it uses regular x86-64 CPUs on PC servers running Linux. The design is based around quad CPU servers, likely in order to achieve the memory bandwidth needed on TMT/NFARAOS, with multiple servers being used in a cluster as necessary. For Gemini, likely only one High-Order processing server would be required.

Given the delays and slow progress made by NRC on other projects for Gemini, and the long delays we see from NRC responding to queries about their RTC system, we have serious concerns about NRC's ability to deliver on the aggressive time schedule of this program.

9.3.2 Source-Selection Procedures

The team is in the process of evaluating which of the potential sources meets the technical requirements. If determined that there are several external supplier options that meet requirements, a Request for Proposals (RfP) for Real Time Controller (RTC) will be based on a cost estimate, the available staff effort, and the perceived benefit and risks of the identified options will be issued. To further important goals of of the GNAO and RTC projects which are interdependent, Gemini has convened a community working group to encourage and involve more of the Gemini community to work with the observatory.

The RfP will be issued 2019 - Q2 with a required letter of intent (LOI). After receiving letters of intent Gemini will assemble a diverse, non-conflicted evaluation panel of experts to assess the proposals. The panel will include representation from the Gemini Science Technology Advisory Committee and technical expertise from Gemini engineering and science operations.

Each member of the panel will receive a copy of the proposals to be evaluated, instructions & guidelines, and the evaluation assessment workbook. The workbook includes the following information:

- Scoresheet that includes auto ranking
- Category scores
- Comments related to individual scores
- Individual comments on each proposal
- Proposal form checklist and proposal milestones.

Each member independently assesses the proposals and completes the workbook and returns to the contract officer for compilation and review and discussion by the entire panel. The panel recommendations will be forwarded to the RTC team and a decision will be made with input from the project sponsor and other observatory staff relevant to the project.

9.3.3 Acquisition Considerations

In collaboration with AURA CAS contract type selection will be determined depending on the organizations likely to propose and in the best interest and least risk to AURA Gemini. Off the shelf procurements will follow the AURA CAS policies and procedures.

Other procurement considerations:
COTS computer hardware
COTS I/O and interface boards
DMs Interface
WFS interface
RTC design contract / support

9.3.4 Budget And Funding

The budget identified for the RTC effort for the above list of procurements is $1.8 million. This amount may change as the cost estimate is completed.

10 Project Management Controls

10.1 Project Management Control Plan

Gemini has a Portfolio Management Office which provides guidance to the project management process by providing:

- Methodology for the Project Life Cycle
- Project Management and Systems Engineering Templates in the Toolkit.
- Reporting and resource allocation tools
- Training

Please refer to the Project Methodology documents listed under the GEMMA Program Execution Plan Reference Documents. This methodology and the applicable templates are used throughout this project.

10.2 Earned Value Management System (EVMS)

This is covered in section 10.2 of the GEMMA Program Execution Plan.

10.3 Financial and Business Controls

This is covered in section 10.3 of the GEMMA Program Execution Plan.

11 Site and Environment

11.1 Site Selection

Not Applicable
Since this is not a large facility project and implementation is an addition to an existing observatory, this section is not applicable.

11.2 Environmental Aspects

Not Applicable
This is not a large facility project and the RTC project is an addition to existing observatory operations; this section is not applicable.

12 Cyber Infrastructure

12.1 Cyber-Security Plan

This is covered in section 12.1 of the GEMMA Program Execution Plan.

12.2 Code Development Plan

This is covered in section 12.2 of the GEMMA Program Execution Plan.

12.3 Data Management Plan

Please refer to the GEMMA Program Execution Plan.

13 Environmental Safety and Health

13.1 Environmental Safety and Health Plans

This is covered in section 13.1 of the GEMMA Program Execution Plan.

14 Review and Reporting

14.1 Reporting Requirements

Gemini is required by the CSA to provide quarterly financial reports and an annual report in September. The reports are to coincide with other observatory reports required for the governance committees and Board.

14.2 Audits and Reviews

Expected reviews for this project: CoDR, PDR, CDR.

15 Integration and Commissioning

15.1 Integration and Commissioning Plan

When the project nears the final product delivery, an Integration and Commissioning plan will be developed. This will be based on the outcomes of the Systems Engineering Development efforts. The following items will be addressed as applicable:

- Pre-assembly and Testing
- Integration
- Verification and Validation
- Pre-shipment Review
- Reliability and Cost of Ownership
- Installation plan
- Manuals
- Spare parts lists
- Maintenance plan
- Shipping

15.2 Acceptance / Operational Readiness Plan

When the project nears the final product delivery an Acceptance / Operational Readiness plan will be developed. This will be based on the outcomes of the Systems Engineering Development efforts.

The following items will be addresses as applicable:

- Verification Methods Matrix
- Optical Requirements
- Mechanical Requirements
- Detector Requirements
- Control System Requirements
- External Interfaces
- Environmental Requirements
- Other Requirements
- Post-Delivery Test
- Inspection for Transport Damage
- Acceptance Test Repeated After Delivery
- Summary of Test Equipment and Test Software

16 Project Close-out

16.1 Project Close-out Plan

When the project nears the final product delivery a Project Close-out plan will be developed. Please refer to the Project Methodology documents listed under the GEMMA Program Execution Plan Reference Documents.

16.2 Transition to Operations Plan

When the project nears the final product delivery, a Transition to Operations plan will be developed.

17 Appendix A: Support Documents

1. Communication Plan Internal
2. Project Plan
3. Resource Allocation Plan
4. Risk Management Plan
5. Risk Register
6. Scope Management Plan
7. System Engineering Management Plan

18 Reference Documents

(PMO templates not included in the PEP submission)

1. Acceptance Test Plan
2. Acquisition Plan
3. Change Request
4. Closure Report (Programs)
5. Staffing Plan

GEMMA
Real Time Controller
Project Plan

December 20, 2018

A – RTC-003

Issued By:	Paul Hirst
Sponsored By:	Scot Kleinman
Approved By:	Catherine Blough

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1 Plan Description

This is the Project Plan for the Adaptive Optics common Real Time Controller (RTC) project, which will implement a new RTC for GeMS, an RTC for GNAO, and provide an RTC platform suitable for use with other current and future Gemini AO systems.

2 Plan Pre-requisites

- Suitable project staffing
- CAS contract support.

3 Planning Assumptions & External Dependencies

This project is part of the GEMMA program.

This project will deliver an RTC for use on the GNAO system, which is a separate GEMMA project / WBS item.

This project will deliver an RTC for GeMS which is an operational Gemini AO system.

4 Lessons Incorporated

This project will leverage the successful strategy used on the Gemini Observatory Archive project.

This project will incorporate lessons learned from the operations of the current Gemini RTCs, especially the current GeMS and Altair RTCs.

5 Monitoring & Control

The process of tracking, reviewing, and reporting the overall progress to meet the performance objectives is primarily completed by the project manager. The project manager is responsible for keeping the project on schedule, resourced, on budget, within scope, and maintaining quality using decision trackers, issues register and other PMO tools. The project manager is also responsible for communicating project progress to stakeholders, escalation, and decision making. The following RACI matrix may be used to monitor and control the project.

Role (→) / Deliverable (↓)	PS	PM	PA	SE	US	FL	PT
Issues list*	I	A	I	I	I	I	I
Decision tracker*	C	A	I	I	I	I	I
Action Items*	I	A	R	I	I	I	I
Risk Register*	C	A	I	I	C	C	C
Schedule*	I	A	R	C	I	C	C
Resource Plan (RAS)*	C	A	R	C	I	C	C
Change requests	C	A	R	C	C	C	C
Quality Assurance Plan	C	A	R	C	C	C	C

*Ongoing activities

Legend:

R - Responsible
A - Accountable (Author)
C - Consulted
I - Informed

PS - Project Sponsor
PM - Project Manager
PA - Project Assistant
SE - Systems Engineer
US - User
FL - Functional Leads
PT - Project Team

6 Budget & Schedule

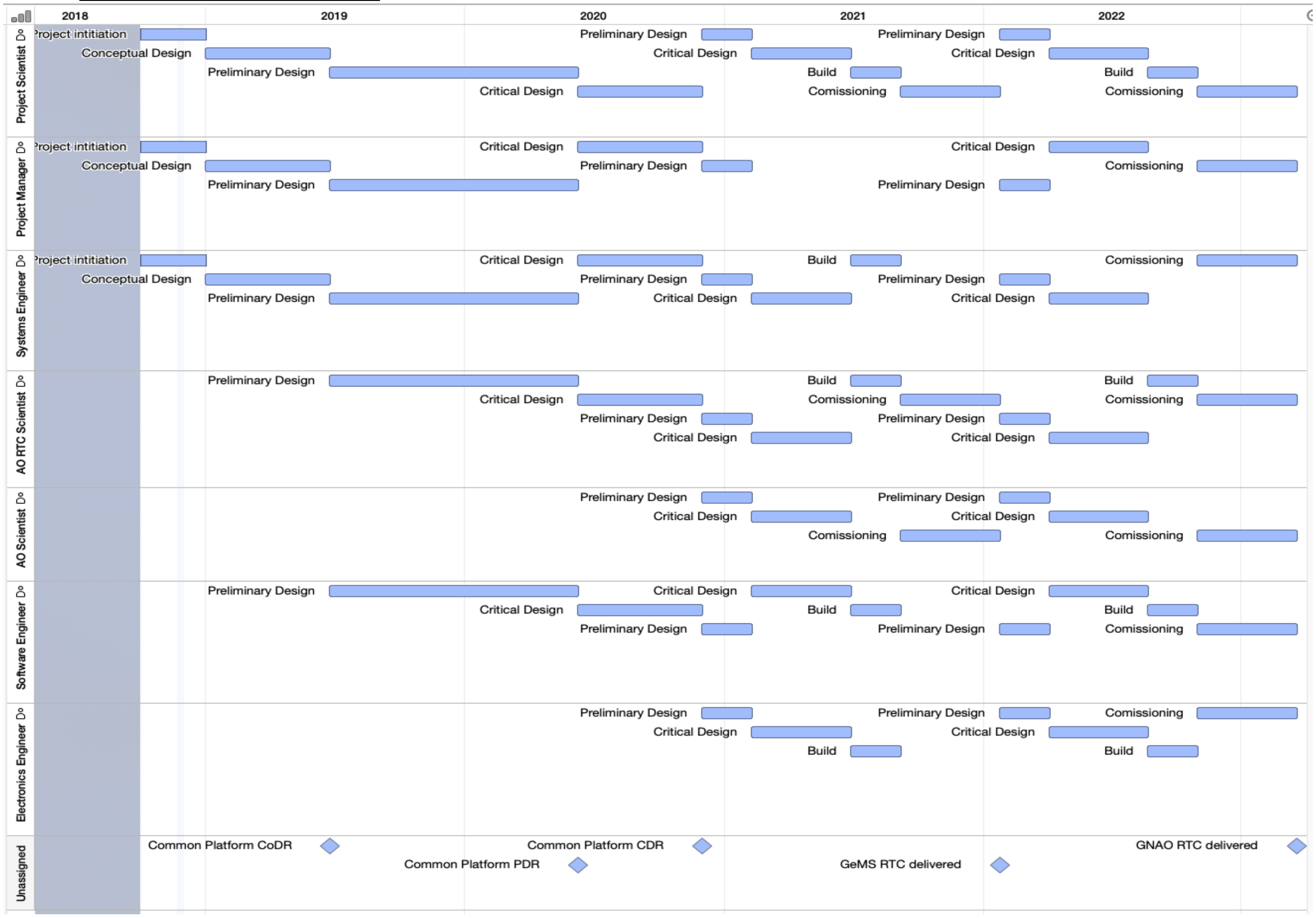
6.1 Summary

Investment in non-labor (K$):	1,800
Investment in Gemini labor (FTE[1]):	6.7
Investment in external labor FTE and K$):	TBD external labor vs contracted deliverables
Other Costs in Operations/ Maintenance (K$):	$10k / year power and cooling $10k / year spares replacement etc
Project Duration:	**1-Oct-2018 - 30 Sep 2024**
Benefits Realization:	**1-Oct-2020 - 30 Sep 2044**

[1] Full-Time Equivalent. 1 FTE = 1720 hours

GR2130000 AO RTC							
	FY 2019	**FY 2020**	**FY 2021**	**FY 2022**	**FY 2023**	**FY 2024**	**-Total Fiscal Years**
010 Salaries Wages - Regular	50,247	48,810	52,859	75,844	40,620	69,092	337,471
-TOTAL SALARY & WAGES	50,247	48,810	52,859	75,844	40,620	69,092	337,471
0FB Fringe Benefits	15,682	15,234	16,497	23,671	12,677	21,563	105,325
-TOTAL EE BENEFITS	15,682	15,234	16,497	23,671	12,677	21,563	105,325
-TOTAL WAGE & BENEFITS	65,929	64,044	69,356	99,515	53,297	90,655	442,795
750 Contracted Services	180,000	216,000	168,000	984,000	168,000	96,000	1,812,000
-TOTAL OTHER - SERVICES	180,000	216,000	168,000	984,000	168,000	96,000	1,812,000
-TOTAL OTHER DIRECT COSTS	180,000	216,000	168,000	984,000	168,000	96,000	1,812,000
-TOTAL EXPENSE	245,929	280,044	237,356	1,083,515	221,297	186,655	2,254,795
-GRAND TOTAL	**245,929**	**280,044**	**237,356**	**1,083,515**	**221,297**	**186,655**	**2,254,795**

6.2 Resource Plan



Resources (Hours)	2019	2020	2021	2023	2023	2024
Project Manager	30%	30%	30%	30%	30%	30%
Project Scientist	40%	40%	40%	40%	40%	40%
Systems Engineer	30%	30%	30%	30%	30%	30%
AO RTC Scientist	100%	100%	100%	100%	100%	100%
Software Engineer	TBD	TBD	TBD	TBD	TBD	TBD
Electronics Engineer	TBD	TBD	TBD	TBD	TBD	TBD

6.3 Acquisition Plan

Acquisitions planning is still under development as of this writing.

6.4 Milestone/Product Plan

Program and Projects	Schedule
RTC hardware	2019 - 2021
Common RTC software	2019 - 2021
GeMS RTC implementation	2021 - 2022
GNAO RTC implementation	2021 - 2022

7 Project Tolerances

Project Resource	Baseline value	Proposed Project Tolerance

Project tolerance continue to be discussed. Once identified, whenever the tolerance for one of the baseline values is exceeded (or expected to be exceeded), the Directorate will be alerted of the exception.

8 Applicable Reference Documents - Associated Products

None:

GEMMA
Real Time Controller
Scope Management Plan

December 20, 2018

A – RTC-003

Issued By:	Paul Hirst
Sponsored By:	Scot Kleinman
Approved By:	Catherine Blough

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1 Introduction

The purpose of this document is to provide an easy to understand summary of the project scope that can be used to help project team members understand why the project is being done, the scope and related boundary conditions of the project, and how they will be managed. The document should focus on the product or service being delivered by the project.

2 Scope Statement

2.1 Project Purpose

The RTC project will implement a common Adaptive Optics Real Time Controller that can be used on all current and future Gemini AO instrumentation. The baseline includes deployment on GeMS and GNAO. Deployment on other current and future Gemini AO instrumentation is desired, but outside the scope of this project

2.2 Product or Service Goals & Objectives

1. Gemini Common RTC platform.
2. Replacement GeMS RTC
3. GNAO RTC

2.3 Scope Summary

The RTC provides real-time control of the Adaptive Optics loops.

2.4 Scope Boundary Conditions

The RTC must interface with the Gemini Telescopes, and for the GeMS deployment, Canopus and the GeMS BTO.

2.5 Scope Details

In Scope	***Out of Scope***

Real Time AO control	Altair RTC
AO telemetry logging and storage	GPI RTC
GNAO RTC	GIRMOS RTC
GeMS RTC	

3 Change Management

All changes to the project are requested through a Change Request Form and submitted to the Project Manager. The Project Manager will assess the benefit of the change and the impact on cost, timeline and resources available and decides if the change can be implemented. If the scope of the change is outside of the tolerances for the Project Manager, the Project Sponsor will be asked to consult.

Resource Allocation Plan A - RTC-003									
Resource	**Role**	**Location**	**Duration**	**FY 2019**	**FY 2020**	**FY 2021**	**FY 2022**	**FY 2023**	**FY 2024**
Paul Hirst	Project Manager	Hilo	72 months	1	1	1	1	1	1
Natalie Provost	Systems Engineer	Chile	72 months	0.3	0.3	0.3	0.5	0.5	0.5
Paul Hirst	System Scientists	Hilo	72 months	1	1	1	1	1	1
Scot Kleinman	Project Sponsor	Hilo	72 months						

GEMMA
Real Time Computer
Risk Management Plan

December 20, 2018

A – RTC - 003

Issued By:	Paul Hirst
Sponsored By:	Scot Kleinman
Approved By:	Catherine Blough

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1 Project Risk Process

The RTC Risk Management process includes identifying, assessing, monitoring, mitigating, contingency planning, and closing risks. The first source of risk identification will be from our project kickoff pre-work and meeting. Attendees of the project kickoff will review this risk management plan prior to the project kickoff and email a list of potential risks to the project manager. The project manager will create a risk register for review and risk dispositioning at the project kick off. The risk register will follow the template provided on the Project Management Knowledge Base. The project manager owns the monitoring, mitigation, and contingency planning of these risks.

Another source for risk identification will be the interviews performed by the project manager at the beginning of the project and during the life of the project. The project manager will interview project team members from different functional areas and document the resulting risks. The project manager will review those risks with the project team. The project manager owns the assessment, mitigation, and contingency planning of these risks.

Finally, the project manager will review the risks on a weekly basis to ensure mitigation is occurring and is effective. The project manager will also review the risks with the project team members at the project status meetings, as needed. The project manager will make necessary changes to the risk register at the project status meetings, including changes to impact and likelihood, mitigation strategy, contingency plans, and close risks as required.

Once the project is completed, the project manager will close all risks and the risk register. The risk register and plan will then be archived with the project documents.

2 Other Roles and Responsibilities

The project manager will request input from functional area managers on project risks. The functional area managers or leads are responsible for defining, evaluating, and mitigating the risks in his or her area and reporting status to the project manager. All project team members are responsible for identifying and escalating all area specific risks to their team lead.

3 Budgeting

This project will require funding for risk management for:
Travel to collaborators / contractors to perform risk interviews and mitigation,
The expected cost is $10000

4 Timing

The project manager will write the risk management plan prior to the project kick-off.

The project manager and project team will complete the risk register at the project kick-off.

New risks will be added to the risk register within one business day of be identified and assessed during the next project team meeting.

The project manager will lead a discussion on project risks at each project team meetings where the project team will discuss mitigation and contingency plans and make adjustments to the risk register as needed.

5 Risk Register Scoring and Interpretation

Risks will be scored on a scale of 1-5 in two areas, impact and likelihood. The impact score reflects the impact to the project schedule, cost, scope, quality, or user acceptance if the risk realized. Likelihood reflects the probability that the risk will be realized. This project will use the following tolerances for rating impact and likelihood of risks.

5.1 Impact

4-5 (High)
Schedule slip > 20%
Budget overrun by > 10%
Resource shortage >10%
User acceptance unlikely
Quality guidelines will not be met > 90%

3 (Moderate)
Schedule slip > 10%
Budget overrun by > 5%
Resource shortage >5%
User acceptance questionable
Quality guidelines will not be met > 50%

1-2 (Low)
Schedule slip < 5%
Budget overrun by < 5%
Resource shortage < 5%
User acceptance is likely with some negotiating
Quality guidelines will be met > 90%

5.2 Likelihood

4-5 (High)
Risk mitigation is weak; there is minimal to no effective contingency plan. Realization of this risk is inevitable.
3-4 (Moderate)
Risk mitigation does not cover all areas of the risk; contingency plan is inadequate. Realization of the risk is likely.
1-2 (Low)
Mitigation plan is strong, contingency plan is effective. Realization of the risk is unlikely but still possible.

5.3 Reporting Formats

The project manager will create the risk register and ensure that the register is available on the project team site found in the Project Management Knowledge Base. The project manager will include the status of the medium and high risks on the project status report. During the initiation phase of the project, the project sponsor or project manager will include risk items of yellow or red status in the project mandate when the project sponsor or manager request execution phase approval.

5.4 Tracking

The risk register will be kept on the Project Management Knowledge Base in the project site and kept up to date by the project manager. All team members and sponsor(s) will have access to the register. All stakeholders with comments and concerns should forward them to the team leads and the project manager.

RTC Risk Register RTC-A-003

Part I. Risk Identification						Part II. Risk Analysis for Existing Controls			Part III. Risk Response							
Name	**Project Risk Category**	**Risk Description (ignoring controls)**	**Impact 1-5 (ignoring controls)**	**Likelihood 1-5 (ignoring controls)**	**Total Risk Score** Low = 1 - 8 Med = 9 - 16 High = 17 - 25	**What Controls (if any) are currently in place?**	**Control Effectiveness 1-5**	**Residual Risk Score** Low = 1 - 8 Med = 9 - 16 High = 17 - 25	**Control or Risk Mitigation Strategy**	**Control effectiveness based on mitigation strategy 1-5**	**Residual Mitigated Risk** Low = 1 - 8 Med = 9 - 16 High = 17 - 25	**Contingency Plan**	**Cost of contingency plan**	**Owner**	**Review Due Date**	**Status**
Hiring	Resources	If suitable staff cannot be hired, eg project manager, RTC scientist this may jeopardize the project.	5	3	**15**											
Procurements	Resources	If procurements and contracts may be delayed due to complex approval processes.	4	4	**16**											
Legacy hardware interfaces	Technical	Insufficient technical information on legacy hardware to implement interfaces to new RTC may influence the project performance.	5	2	**10**											

GEMMA
Real Time Computer
Systems Engineering Plan

December 20, 2018

A - RTC - 003

Issued By:	Natalie Provost
Sponsored By:	Scot Kleinman
Approved By:	Paul Hirst

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1.0 Plan Description

This is the Systems Engineering Management Plan for the Real Time Computer (RTC) part of the GEMMA Program. This project will allow Gemini to build a common Adaptive Optics (AO) Real Time Computer platform that can serve the needs of current and foreseeable future AO systems on Gemini

2.0 Roles & Responsibilities

The RTC project will use a team approach for Systems Engineering (SE) that will be closely tied to the larger GNAO system approach. This approach is a recognition that RTC is a critical subsystem to the larger GNAO system, and requires specialized knowledge in a number of areas. The team will include experts from areas including: Astrophysics and science, adaptive optics, electronics, and software engineering. Overall team organization is provided by a Lead Systems Engineer, who works closely with the RTC Software engineer and RTC Project Scientist, and reports to the RTC Project Manager.

The systems engineering team roles are defined and include the following:

- Systems Design and Analysis
  - Design and analysis of systems that cross over functional areas, subsystems or organizations (eg, end-to-end design user interface to science performance).
  - Formation and analysis of trade studies, to inform design choices management of up-scope and de-scope options
- Requirements Management
  - Identification, development, decomposition and linking of project requirements
  - Guide the translation of science cases into instrument technical requirements, incorporating the operational concepts and instrument architecture
  - Flow-down the system requirements to lower-levels (subsystems, then components) until requirements are independently testable
  - Communicate requirements to owners within the development team
- Interface Management
  - Define and document where interfaces exist within the instrument (internal interfaces).
  - Manage interface control documents (ICD's) with the observatory
- Configuration Management
  - Maintain consistency and visibility of current project documentation and data
  - Manage changes to project documents over the lifecycle of the project
- Quality Management

- Define a set of policies, procedures, tools and training to ensure that quality is maintained
- Verify that Quality Assurance procedures are followed during development
- Verify that the deliverables meet quality standards

- Verification Management
  - Identify verification method for each requirement (design, inspection, analysis, test, etc).
  - Identify at what project stage verification takes place
  - Write or manage the creation of verification test plans and procedures
  - Oversee requirements verification activities, and sign-off on results
  - Track open verification issues and develop a burn-down plan
  - Manage the Pre-Ship Review and Acceptance Test Review processes

3.0 Technical Processes and Systems Engineering Engine

The RTC project team will follow a tailored Systems Engineering “Engine” principle recommended by NASA. There are three sets of common technical processes in the principle: System Design, Product Realization and Technical Manage1. The processes of the Systems Engineering Engine will be used by the RTC team to develop and realize the end products of the Real-Time Computer and the Adaptive Optics (AO) system as a whole. There are 18 processes in this context. Processes 1 through 10 indicated in Figure 1 represent the activities in the execution of the project. Processes 11 through 18 are cross cutting tools for carrying out the project, they will be done as part of the Project Management and Project Engineering activities supported by the Systems Engineering.

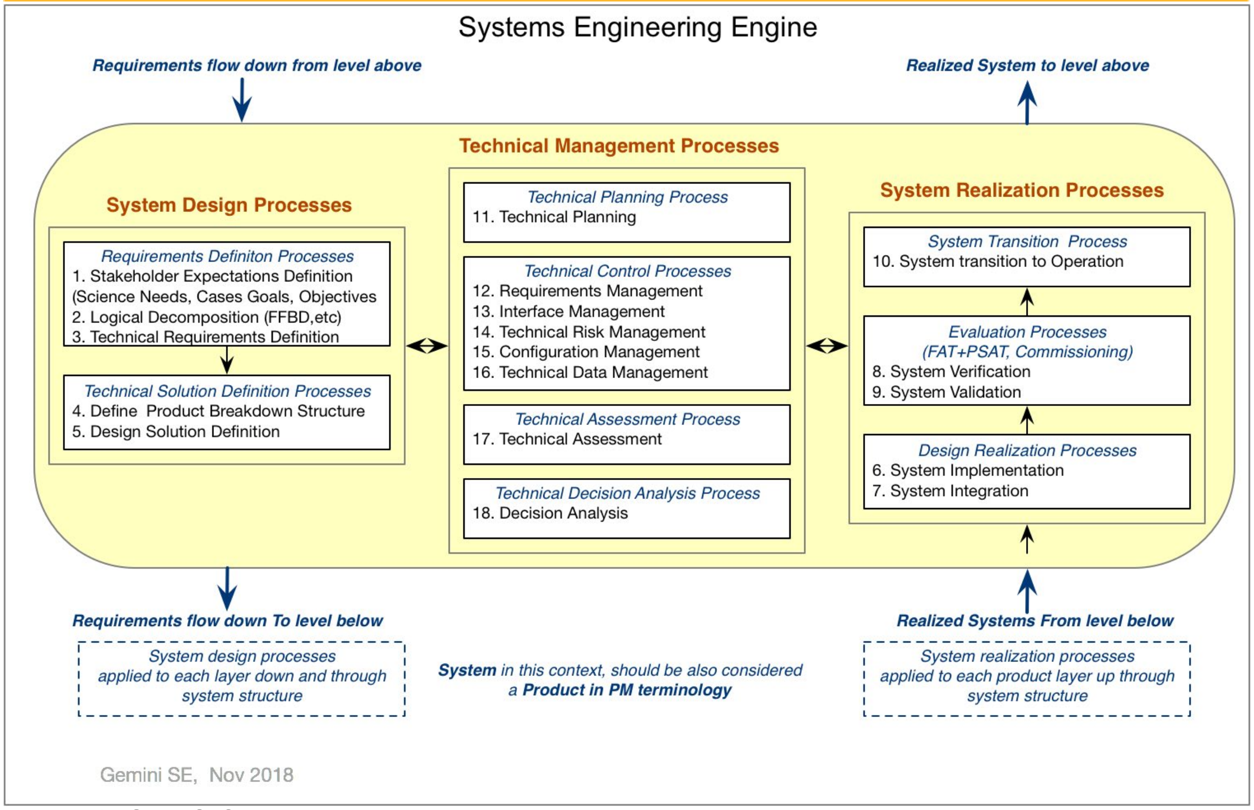

Figure 1. GNAO Systems Engineering Engine

3.1 System Design Processes

The five systems design processes shown at the left side of the Figure 1 will be used by the RTC systems engineering team to define and baseline stakeholder expectations. This will capture GNAO science drivers and objectives, perform initial Logical decomposition to the RTC , allocate and derive technical requirements, define the functional architecture of GNAO and generate the product breakdown structure (PBS), to then convert the technical requirements into the design solution that will satisfy the baselined stakeholder expectations.

These processes, when deemed necessary, will be also applied to each subsystem from the top of the GNAO structure to the bottom until the lowest elements in the system structure branch are defined to the point where they can be designed, built, bought and/or reused.

The system design processes are interdependent, highly iterative and recursive processes resulting in a validated set of requirements and design solution that satisfies the stakeholder expectations. The relationships among the system design processes is shown in Figure 3 below.

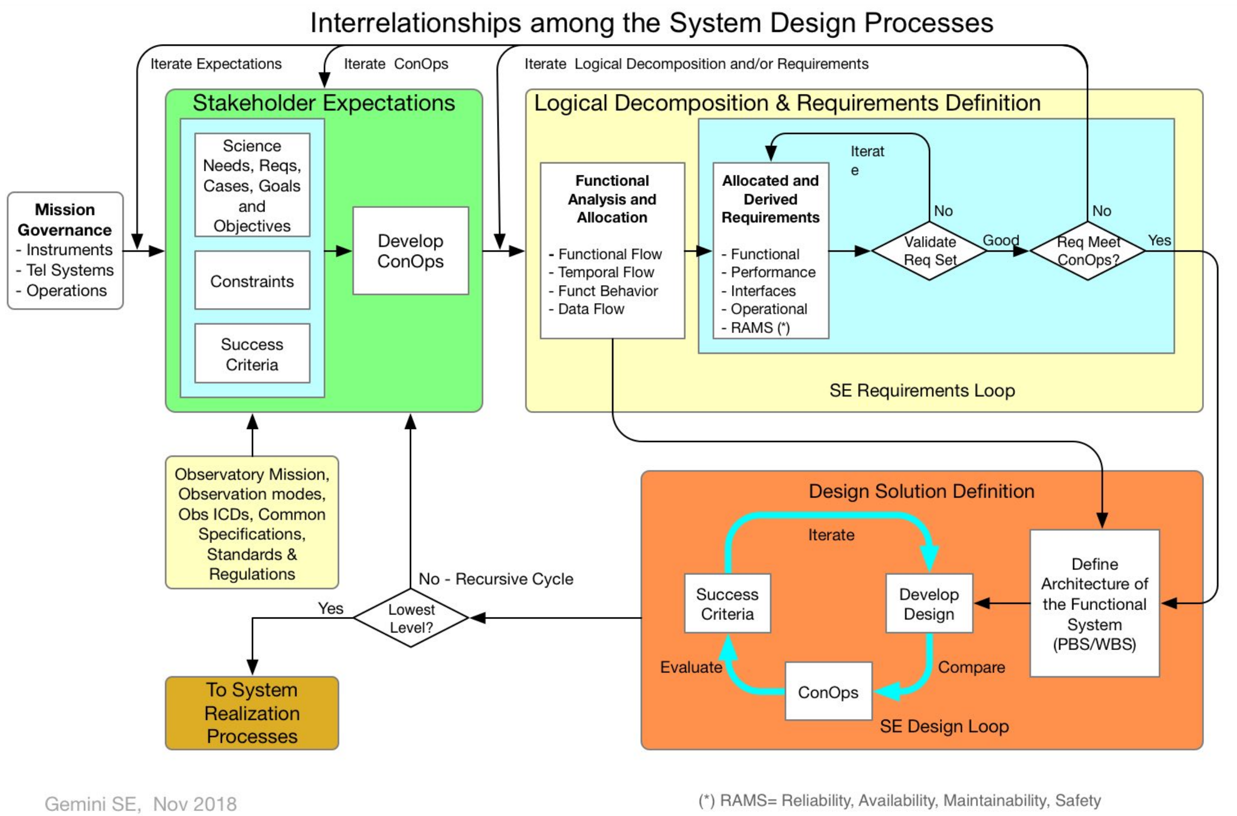

Figure 2. Interrelationship Among Design Processes

GNAO systems engineering processes start with the study by the science team defining and clarifying the science objectives and goals of the system. This includes the science cases, the operations modes, the design drivers, the constraints and science requirements to operate GNAO at Gemini Observatory, and provide the criteria for defining system success. A team of scientists and astronomers that include collaborators of Gemini Observatory will be formed to review and provide stakeholder feedback on the science cases, high-level science (needs) requirements, and Concept of Operations (ConOps).

This set of stakeholder expectations, plus the high-level science (needs) requirements and the Concept of Operations (ConOps), will be used to drive the iterative design loop. Then the functional architecture, the derived/allocated set of technical requirements, and the the product breakdown structure will be developed. These three products will be consistent with each other and will require iteration and design decisions to achieve consistency and agreement with the ConOps. The project team, led by the systems and project engineers, will perform consistency analysis with the project team to validate the proposed design against the stakeholder expectations. A simplified validation asks the following questions:

- Will the system work as expected?

- Is the system achievable within budget and schedule constraints?
- Does the system provide the functionality and fulfill the operational needs that drove the project's funding?

If the answer to any of these questions is no, then changes to the design and/or stakeholder expectations will be required, and the process starts again. This process continues until the system architecture, ConOps, and science requirements meets the stakeholder expectations to set the baseline of this process.

3.1.1 Concept of Operations (ConOps) Management

The ConOps is an important component in capturing stakeholder expectations, driving system requirements, and driving the architecture of a project. It also serves as the basis for subsequent definition documents such as the operations plan and operations handbook and provides the foundation for the long-range operational planning activities such as operational facilities and staffing.

The RTC is considered a critical subsystem to the larger Adaptive Optics system. We will develop the GNAO concept of operations based on science cases that are defined by stakeholders. This process will be led by the project scientist, who will form a team of Gemini and external scientists that will provide input and feedback. Once the GNAO ConOps is developed, an RTC specific ConOps will be developed to further define internal and external AO software interfaces and interactions.

The ConOps document will use the existing Gemini MCAO RTC system as a starting point for currently understood operations. The new capability requirements will be fleshed out such that there is a clear concept of how they can operationally be implemented. The ConOps document will reflect this agreed upon implementation, as well as describe operation timelines, operational scenarios, command and data architecture, and operator and software interfaces. The operational scenarios describe the dynamic view of the systems' operations and include how the system is perceived to function throughout the various modes and mode transitions, including interactions with external interfaces.

3.1.2 Logical Decomposition and Requirements Definition

We proposed top level science requirements that are largely based on the scientific performance improvements of the existing GeMS RTC. We will further develop these requirements based on the outcome of the Concept of Operations. Once the Concept of Operations is developed, technical requirements definition can be further decomposed based on system functions.

Logical decomposition systems engineering process will be utilized to generate the System Functional (parent) requirements. This process and associated activities are depicted in Figure 3. In RTC development, the logical decomposition process will be executed using Function Based Systems Engineering (FBSE). This will help to perform Functional Analysis to create the system functional architecture and decompose detailed functional requirements and interfaces that satisfy the stakeholder expectations and success criteria. This process identifies "what", (not "how well") should be achieved by GNAO at each level to enable success.

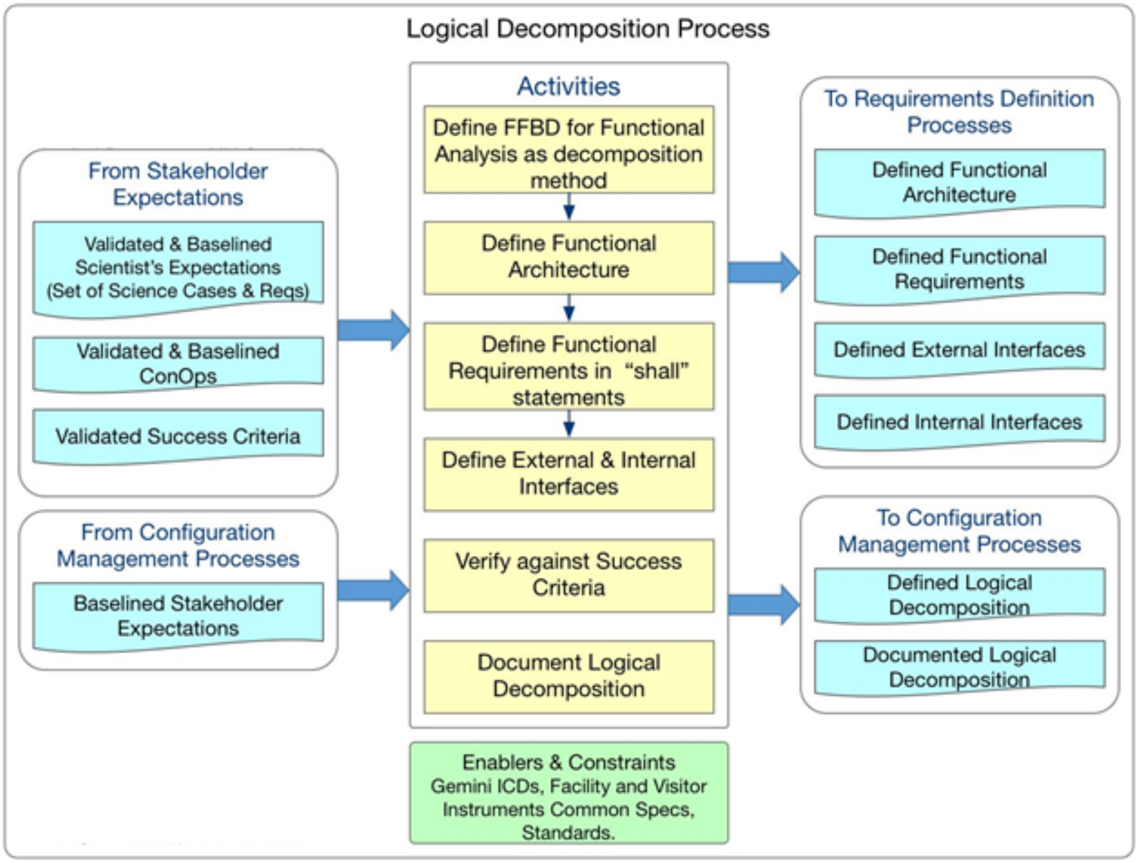

Figure 3. Logical Decomposition Process

The decomposed functional (or parent) requirements are then allocated down to the lowest required level that satisfies the objectives of the design of RTC. The Logical Decomposition, besides assisting to create RTC functional architecture, will also help the team to:

- Improve understanding of the scientists' expectations (RTC functions and performance, science requirements, ConOps, constraints, internal interfaces, Interfaces to the Observatory, etc.)
- Decompose the functional (parent) requirements into a set of logical decomposed functions and the set of derived technical non-functional requirements. Non-functional requirement in this context are: performance, interface, design, operations, and RAMS (reliability, availability, maintainability, safety)
- Develop the set of RTC Technical Requirements and the relationships (traceability) among the requirements (e.g., functional, performance, interface,

operational, behavioral, temporal, etc.) for input to the RTC Design Solution Definition process.

3.1 System Design

The RTC Systems Engineering role will be crucial during the conceptual design phase. The successful implementation of good system engineering practices early in the system design process will have implications throughout the system life cycle. Once the conceptual design is complete and successfully passes CoDR, the system enters the preliminary design phase. A successful PDR will demonstrate that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with detailed design. The next milestone, Critical Design Review (CDR), will demonstrate that the maturity of the design is appropriate to support proceeding with full scale fabrication, assembly, integration, and test, and that the technical effort is on track to meet system performance requirements within the identified cost and schedule constraints.

3.2.1 Conceptual Design (CoD) Phase

The GNAO project has begun the first steps towards achieving a feasible conceptual design by forming teams and working groups that will be tasked to generate science cases and develop the ConOps document. The science cases will drive the concept of operations, which will in turn drive the RTC concept of operations and functional requirements. At this point, the iterative design solution process will begin.
This section details our plan to achieve a technically feasible and robust conceptual design. The entrance and success criteria, which are largely derived from the NASA Systems Engineering Handbook, are listed for each design milestone in subsections below.

We will use the current GeMs RTC and associated lessons learned as a basis for developing the new RTC concept of operations, interface definition, and functional and performance requirements. In order to understand the state of today's technology, we have evaluated other RTCs that are commercially available and/or operational on other observatories. This market research will help inform the requirements development and design trade processes.

In order to achieve a robust Conceptual Design, we will perform the following activities:

- Perform RTC market research (complete)
- Develop RTC ConOps (January 2019)
- Perform RTC platform trade study to inform requirements development (January 2019)
- Develop RTC Functional and Interface Requirements (February - March 2019)
- Perform RTC cost, schedule, and labor projections (March 2019)
- Determine level of in-house versus external contract labor requirements (March 2019)

- Develop RFP for external contracted work based on a well-defined set of requirements and ConOps (April 2019)
- Receive RFP Responses with proposed design concepts (June 2019)
- Perform RTC design trades as part of RFP evaluation process (July 2019)
- Select RTC conceptual design (August 2019)

Once the conceptual design for system as a whole, subsystems described above, and the associated interfaces are defined, the project will be ready for the Conceptual Design Review (CoDR). The CoDR entrance and success criteria are listed below.

CoDR Entrance Criteria:

- A Project Execution Plan (PEP) has been approved by the NSF.
- Project requirements have been defined that support NSF and AURA requirements on the project.
- Top project risks with significant technical, safety, cost, and schedule impacts and corresponding mitigation strategies have been identified.
- The high-level project requirements have been documented to include performance, safety, and programmatic requirements.
- A project SEMP that includes project technical approaches and management plans to implement the allocated project requirements.
- An approach for verifying compliance with project requirements has been defined.
- Procedures for controlling changes to project requirements have been defined.
- Interfaces are understood and documented.
- Project acquisition strategy/strategies are defined.
- Development of technologies that cut across other projects have started.
- Initial cost estimates are derived and a project budget is approved.
- Draft Science Cases.
- Draft Concept of Operations (CONOPS).
- A document that describes the RTC conceptual design is available.
- End of Stage Report.
- Preliminary Design (PD) Stage Plan.

CoDR Success Criteria:

- With respect to CONOPS and science requirements, defined high-level project requirements are complete.
- The project requirements provide for a cost-effective project.
- Major risks are identified with suitable controlling or mitigation strategies.
- Project requirement verification approaches are defined appropriate .
- An appropriate project plan and management approach are complete.
- An appropriate SEMP and technical approach is complete.
- The schedule is adequate and consistent with cost, risk, and operational goals.
- Project cost and uncertainty are within the available budget and tolerance.

3.2.2 Preliminary Design Phase

Once the CoD is successfully complete, the system enters the preliminary design phase. A Preliminary Design Review (PDR) will occur near the completion of this phase to achieve the following objectives:

- Ensure a thorough review of the products supporting the review.
- Ensure the products meet the entrance criteria and success criteria.
- Ensure issues raised during the review are appropriately documented and a plan for resolution is prepared.
- Approve the design-to baseline
- Authorize the project to proceed into implementation and toward final design.

PDR Entrance and success criteria are listed below.

PDR Entrance criteria

- Successful completion of the CoDR and responses made to all RFAs and RIDs, or a timely closure plan exists for those remaining open.
- A preliminary PDR agenda, success criteria, and charge to the board have been agreed to by the technical team, project manager, and review chair prior to the PDR.
- PDR technical products listed below for both hardware and software system elements have been made available to the cognizant participants prior to the review:
    - Updated baselined documentation, as required.
    - Preliminary subsystem design specifications for each configuration item (hardware and software), with supporting tradeoff analyses and data, as required.
    - Updated technology development maturity assessment plan.
    - Updated risk assessment and mitigation.
    - Updated cost and schedule data.
    - Updated logistics documentation, as required.
    - Applicable technical plans (e.g., technical performance measurement plan, parts management plan, environments control plan,integration plan, producibility/manufacturability program plan,reliability program plan, quality assurance plan).
    - Applicable standards.
    - Safety analyses and plans.
    - Engineering drawing tree.
    - Interface control documents.
    - Verification and validation plan.
    - Plans to respond to regulatory requirements, as required.
    - Technical resource utilization estimates and margins.
    - System-level safety analysis.

PDR Success Criteria

- The top-level requirements—including success criteria, TPMs, and any sponsor-imposed constraints—are agreed upon, finalized, stated clearly, and consistent with the preliminary design.
- The flowdown of verifiable requirements is complete and proper or, if not, an adequate plan exists for timely resolution of open items. Requirements are traceable to science goals and objectives.
- The preliminary design is expected to meet the requirements at an acceptable level of risk.
- Definition of the technical interfaces is consistent with the overall technical maturity and provides an acceptable level of risk.
- Adequate technical interfaces are consistent with the overall technical maturity and provide an acceptable level of risk.
- Adequate technical margins exist with respect to TPMs.
- Any required new technology has been developed to an adequate state of readiness, or backup options exist and are supported to make them a viable alternative.
- The project risks are understood and have been credibly assessed, and plans, a process, and resources exist to effectively manage them.
- RAMS (e.g., reliability, availability, maintainability, safety) has been adequately addressed in preliminary designs and any applicable RAMS products (e.g., PRA, system safety analysis, and failure modes and effects analysis) have been approved.
- The operational concept is technically sound, includes (where appropriate) human factors, and includes the flowdown of requirements for its execution.

3.2.3 Critical Design Phase

Once the PDR is successfully complete, the system enters the critical design phase. A Critical Design Review (CDR) will occur near the completion of this phase to achieve the following objectives:

- Ensure a thorough review of the products supporting the review.
- Ensure the products meet the entrance criteria and success criteria.
- Ensure issues raised during the review are appropriately documented and a plan for resolution is prepared.
- Approve the build-to baseline, production, and verification plans.
- Authorize the coding of deliverable software (according to the build-to baseline and coding standards presented in the review),
- Authorize system qualification testing and integration.
- Ensure all open issues are resolved with closure actions and schedules.

The CDR entrance and success criteria are listed below:

CDR Entrance Criteria

- Successful completion of the PDR and responses made to all PDR RFAs and RIDs, or a timely closure plan exists for those remaining open.
- A preliminary CDR agenda, success criteria, and charge to the board have been agreed to by the technical team, project manager, and review chair prior to the CDR.
- Successful completion of the PDR and responses made to all PDR RFAs and RIDs, or a timely closure plan exists for those remaining open.
- A preliminary CDR agenda, success criteria, and charge to the board have been agreed to by the technical team, project manager, and review chair prior to the CDR.
- CDR technical work products listed below for both hardware and software system elements have been made available to the cognizant participants prior to the review:
    - updated baselined documents, as required;
    - product build-to specifications for each hardware and software configuration item, along with supporting tradeoff analyses and data;
    - fabrication, assembly, integration, and test plans and procedures;
    - technical data package (e.g., integrated schematics, spares provisioning list, interface control documents, engineering analyses, and specifications);
    - operational limits and constraints;
    - technical resource utilization estimates and margins;
    - acceptance criteria;
    - command and telemetry list;
    - verification plan (including requirements and specifications);
    - validation plan;
    - operations plan;
    - checkout and commissioning plan;
    - updated technology development maturity assessment plan;
    - updated risk assessment and mitigation;
    - update reliability analyses and assessments;
    - updated cost and schedule data;
    - updated logistics documentation;
    - software design document(s) (including interface design documents);
    - subsystem-level and preliminary operations safety analyses;
    - system safety analysis with associated verifications.

CDR Success Criteria

- The detailed design is expected to meet the requirements with adequate margins at an acceptable level of risk.
- Interface control documents are appropriately matured to proceed with fabrication, assembly, integration, and test, and plans are in place to manage any open items.
- High confidence exists in the product baseline, and adequate documentation exists or will exist in a timely manner to allow proceeding with fabrication, assembly, integration, and test.
- The product verification and product validation requirements and plans are complete.
- The testing approach is comprehensive, and the planning for system assembly, integration, test, and operations is sufficient to progress into the next phase.

- Adequate technical and programmatic margins and resources exist to complete the development within budget, schedule, and risk constraints.
- Risks to operational success are understood and credibly assessed, and plans and resources exist to effectively manage them.
- RAMS (e.g., reliability, availability, maintainability, safety) have been adequately addressed in system and operational designs, and any applicable RAMS plan products (e.g.,system safety analysis,and failure modes and effects analysis) have been approved.

3.3 System Development

Once the design is completed, the project enters the development phase. Much of the development work may be completed under contract. Design and purchase specifications will have been generated during requirements development and provided as inputs. The technical team will review these specifications and ensure they are adequate. The team will work with the acquisition team to ensure the accuracy of the contract Statement of Work (SOW) and ensure that adequate documentation, certificates of compliance, or other specific needs are requested of the vendor.

The Systems Engineer and technical team will provide oversight and review throughout the development phase. Major reviews include build and shipping reviews such as a pre-build review, pre-integration-review, and a pre-acceptance review. During validation and verification, the next phase, there are various testing and commissioning reviews including a pre-ship acceptance testing, post-ship acceptance testing, pre-install review, on-sky acceptance testing, and a final commissioning review. As the purchased products arrive, the technical team will assist in the inspection of the delivered product and its accompanying documentation. The team will ensure that the requested product was indeed the one delivered, and that all necessary documentation, such as source code, operator manuals, certificates of compliance, safety information, or drawings have been received.

Another major systems engineering function during system development is defining and managing interfaces, planning for system integration, and ensuring interface compatibility of the integrated system. Section 3.5 further details the System Interface Management Process.

3.3.1 Software development

The RTC system has several software interfaces that will need to be tightly coordinated with the other GNAO software subsystems. We will define these interfaces early in the Interface Definition Document, and then the interfaces will be maintained in Interface Control Documents. Existing operational and control software will need to be updated to interact with the new system. Therefore, it is critical that software development follow systems engineering processes outlined in the document throughout the project life cycle, which will be outlined in a Software Development Plan.

3.3.2 Documentation Plan

System engineering documentation will be configuration controlled, reviewed, and approved by the RTC technical team throughout the various phases of the project. System Engineering is responsible for initial development of the Concept of Operations, Top level specifications, System Verification and Validation Plans, and the Interface Definition Document. For work that is contracted, the Systems Engineering team will ensure accountability and completeness of documentation by working with the acquisition team in developing a deliverables list for the contract and SOW.

The following documentation will be required to be delivered at various milestones, at a minimum:

- Concept of Operations
- Requirements and Specifications
- Verification Plan
- Validation Plan
- Software Development Plan
- Interface Definition Document
- Interface Requirements Document
- Interface Control Documents
- Software Description Documents
- Software User Manual
- Integration and test plans and procedures
- Parts, Spares & Procurement Documentation
- Failure Modes and Effects Analysis
- Acceptance Test Report
- Operations User's Guide
- Quality Assurance Plan
- Commissioning Plan
- Operations Plan
- Quality Assurance Plan

3.4 Validation & Verification

Once the system development is complete, verification and validation processes on the realized products and system will be implemented to ensure they meet applicable life-cycle phase success criteria. Realization is the act of verifying, validating, and transitioning the realized product for use at the next level up of the system structure. This verification process will generate evidence necessary to confirm that end products, from the lowest level of the system structure to the highest, conform to the specified requirements (specifications and descriptive documents). For lower level products, this process may be conducted by the developer under contract.

Planning to conduct the product verification is a key first step that will occur in conjunction with the requirements definition process. From relevant specifications, the type of verification (e.g., analysis, demonstration, inspection, or test) will be established based on the life-cycle phase, cost, schedule, resources, and the position of the end product within the system structure. The verification plan will specify any specific procedures, constraints, and success criteria.

When verification of the end product is conducted, the responsible engineer will ensure that the procedures were followed and performed as planned, the verification-enabling products were calibrated correctly, and the data were collected and recorded for required verification measures. The Systems Engineer will analyze the verification results and ensure the following:

- End-product variations, anomalies, and out-of-compliance conditions have been identified
- Appropriate re-planning, redefinition of requirements, design and reverification have been accomplished for resolution for anomalies, variations, or out-of-compliance conditions (for problems not caused by poor verification conduct)
- Variances, discrepancies, or waiver conditions have been accepted or dispositioned
- Discrepancy and corrective action reports have been generated as needed
- The verification report is completed.

Once all of the lower level requirements and products are verified, system level verification and validation will be performed. System level verification could include a roll-up of children requirement verification reports or a system level analysis or test. System validation will also be performed to ensure compliance with the Concept of Operations. Validation testing is conducted under realistic conditions (or simulated conditions) on the system to determine the effectiveness and suitability for operations by typical users and to evaluate the results of such tests.

3.5 Interface Management Plan

The objective of the interface management is to achieve functional and physical compatibility among all interrelated system elements. Early in the design phase, external, internal, functional, and physical RTC interfaces will be defined in an Interface Definition Document that will be maintained throughout development. This document will be the basis for specifying interface requirements will be documented in an Interface Requirements Document (IRD).

For software that is subcontracted, interface requirements will be enforced. The RTC interfaces with nearly all GNAO subsystem. It will therefore be critical that these interfaces are define early, as they will be key drivers to the RTC system design. In addition, consideration of future instruments, the ASM, and capability upgrades (i.e. additional AO modes of operation), will be considered throughout. A well developed ConOps will be key to a well defined set of interface requirements.

Verification of implemented interfaces will be emphasized during system checkout, both prior to assembly and in the assembled configuration. Throughout the product integration process activities, interface baselines are controlled to ensure that changes in the design of system elements have minimal impact on other elements with which they interface. In verifying the interfaces, the systems and software engineers must ensure that the interfaces of each element of the system or subsystem are controlled and known to the developers.

Additionally, when changes to the interfaces are needed, the changes must at least be evaluated for possible impact on other interfacing elements and then communicated to the affected developers. Although all affected developers are part of the group that makes changes, such changes will be captured in a readily accessible place so that the current state of the interfaces can be known to all.

4.0 Quality Control and Quality Assurance

Quality Assurance (QA) provides an independent assessment to the project manager and systems engineer of the items produced and processes used during the project life cycle. The Project Manager and Systems Engineer will ensure that contractors implement a quality assurance program and ensure visibility into QA processes and risk mitigation. Internally, the project manager and systems engineer will manage quality risks and enforce adherence to procedures and specifications throughout the system development and system integration.

Resource Allocation Plan A - RTC-003									
Resource	**Role**	**Location**	**Duration**	**FY 2019**	**FY 2020**	**FY 2021**	**FY 2022**	**FY 2023**	**FY 2024**
Paul Hirst	Project Manager	Hilo	72 months	1	1	1	1	1	1
Natalie Provost	Systems Engineer	Chile	72 months	0.3	0.3	0.3	0.5	0.5	0.5
Paul Hirst	System Scientists	Hilo	72 months	1	1	1	1	1	1
Scot Kleinman	Project Sponsor	Hilo	72 months						