Introduction to Gemini’s Instrument Development Process

The process used to take instruments from basic concepts to completed systems can be broadly decomposed into 4 components, as shown in Figure 1. This multi-year process begins with Community based strategic planning to define future science directions for the Observatory and roughly the resources needed to reach these goals. From there Gemini’s worldwide set of instrument builders are invited to participate in competitive design studies for new instruments. After a down-select phase, instruments are awarded to qualified teams who build them under contract to Gemini. Each of these steps is discussed in more detail below and together they describe a science driven process for defining and developing future instruments. It is admittedly difficult to forecast scientific trends, given the rate of discovery within astronomy today, but this process ensures an instrument set that is well-reasoned with requirements tempered by a vision of where the Observatory should be headed in the context of other ground and space based facilities. Currently Gemini is in the first phase (Science Definition and Long Term Budget Planning) of the development program for its next round of instruments. It is also in the last phase (Completion Phase) for a number of instruments which are being delivered now at Gemini-North and Gemini-South. Maintaining continuity between these beginning and ending steps in the program is crucial to provide a steady stream of state-of-the-art instruments for Gemini’s community to use in the future.

It is important to remember that even though many instruments are being delivered now, it takes years to complete the “lifecycle” illustrated in Figure 1. Furthermore, astronomy has always been a technology limited scientific enterprise, and the instruments being delivered now were designed, on average, about 5 years ago. Given that it will take at least 5-7 years from now to build the next generation of instruments for Gemini, the current round of instruments will be over a decade old from a technology perspective, making them obsolete in many ways by the time the next generation of instruments arrive. The time to start building the next generation of instruments for Gemini is clearly at hand, if Gemini is to retain its preeminent role as a leader among ground based observatories.

Step 1 - Science Definition and Budget Planning

Determining which instruments are developed through the design study level requires input from a variety of sources. Broad community involvement is needed to determine an optimal set of scientific drivers, from which an initial instrumentation suite can be derived. This initial science definition phase is led by Gemini, working in close cooperation with Gemini’s National Offices, which act as conduits for astronomers within each Partner country. In essence the National Offices are Gemini’s portal to its “customer”, the astronomers who will use new instruments at Gemini in the future.
The science definition phase is centered around a series of scientific workshops which are topic based to organize participation along lines of expertise in astronomy. Topics include everything from planetary science and star formation to nearby galaxies and cosmology. The product of these scientific workshops is a series of legacy-caliber science missions that could be pursued with Gemini. A broadly defined set of new instrumentation requirements that will be needed to fulfill these missions is derived from these potential science missions. Beyond providing overall organization, one of the Gemini’s primary roles in this process is to provide technical support for astronomers who need guidance on telescope and possible instrument capabilities (e.g., sensitivities, image quality, spectral coverage, etc.). This type of interaction is crucial to ensure that the science objectives defined by the community are technically feasible.

This whole process of mapping science goals into instrument requirements is inherently non-linear and circuitous, with design trades being weighted by various reality factors, including technical feasibility, risk, cost, etc. Though complex, within a year of the culminating international science workshop, Gemini will develop a science mission and corresponding next-generation instrument program, with clear traceability to the science goals identified by its community.

Beyond leading the definition of new instrumentation, Gemini will also modify existing instrumentation if cost-effective approaches to augment capabilities exist. A phased approach to deployment may also be used to maximize the scientific return of instruments. For example, it may not be possible to design instruments in the initial phase with sufficient detector coverage to meet all of the science goals, but sub-populating the focal plane with detectors initially while designing the optical train, array read-out controller, data handling system, etc. to handle an upgraded and fully populated focal plane in the future is a cost effective approach to providing instruments with staged capabilities.

Finally, during this stage preliminary cost estimates need to be generated to support broad trades both between competing instruments and within instruments as different modes are considered for inclusion or deferral. Performance models also need to be developed in order to guide and constrain the process of refining the science possibilities identified in this early stage of the project. Such early cost and performance containment is intended to guide the process of defining scientific capabilities, not overwhelm it, in an early stage where scientific creativity and originality is valuable. This step in the lifecycle of an instrument is explained in more detail in the next section, where the Aspen Workshop is described in detail.

**Step 2 - Announcements of Opportunity**

The output of the previously described science definition phase will be a set of design guidelines and rough cost estimates for a set of instruments that can be used to launch frontier science with Gemini. In some cases it may be necessary to fund technology development, at modest levels, to establish the viability of particularly challenging new instruments, reduce the risk of actually developing them, and define cost estimates with much better accuracy for budget planning purposes.
A balanced approach that takes advantage of varying site conditions, spectral/spatial resolution, and wavelength range, with at least some instruments having relatively simple designs leaves the community with varied capabilities that can be used to address both predicted and unforeseen research pathways. Other factors which feed into developing the next suite of instruments includes the long term north/south instrument balance, phasing new capabilities with older ones that are likely to be decommissioned, and in some cases recognizing that finite resources preclude developing some instruments now but they can potentially be built in the next round of development. A good example of many of these issues is GIRMOS. Several years ago, when the Phase 2 instrument set was devised, it was determined by Gemini and the National Offices that the technology needed to make a deployable cryogenic integral field infrared spectrograph was highly uncertain, not to mention any cost estimates for such an instrument. As a result Gemini funded several technology studies to look into both cryogenic fiber based and image slicer concepts for this instrument. One of the concepts which emerged was the novel GIRMOS concept, from the UK/ATC. Even though the design approach to build such an IRMOS was much better defined at the end of that process, the cost (now known with fairly high confidence, thanks to the study) was found to be prohibitively expensive and its applicability with MCAO marginal given typical target sky densities and apparent magnitudes. Now, ~3 years later, an instrument with roots back to GIRMOS has once again emerged, this time on the proposed instrument list from the Aspen Workshop and working behind a Ground Layer Adaptive Optics System, to boost the sky coverage of the instrument. While these steps have necessarily added delays in the development of the world’s first cryogenic deployable integral field spectrograph, they have also led to careful assessments of cost, risk, and science capability that will, in the end, lead to an instrument with enormous research potential.

With design guidelines and ROM cost estimates developed for instruments and key areas of technology development, Announcements of Opportunity (AO’s) will be released to solicit proposals to conduct design studies and/or development programs. These AO’s will be distributed through a variety of mechanisms (e.g., Web pages, advertisements, Commerce Business Daily, etc.) to stimulate interest in a broad range of potential bidders, ranging from the private sector to universities and national laboratories and facilities. The product of the AO’s will be a series of proposals, submitted to Gemini, for review by Source Selection Boards (SSBs), which will be chaired by Gemini but will also have membership derived from specialists, consultants, and experts from around the world. They will be relatively small groups with ~5-6 members and use common selection guidelines and criteria with other SSBs used for years successfully by Gemini in its “project days”. Selection criteria will range from the quality of the proposal submitted, cost, facilities available, past experience, various merits of the technical approach proposed, etc. Where possible more than one team will be selected to conduct design studies for an instrument since this stimulates competition and ultimately cost reduction.

**Step 3 - Conceptual Design Phase**

From here the design study phase for a new instrument is launched, having been selected from a variety of proposals submitted to Gemini. The core product of this step in the instrument’s development is sufficient information to make a decision about proceeding with actually building it. During this phase detailed and complex trades will be made between scientific capability, cost, schedule, and risk in a variety of forms. Assessments of exact plate
scales, optical throughput, spectral resolution, stability, etc. will be made between the instrument team scientists and engineers, with regular input from the Gemini Observatory, to ensure that high level scientific goals and technical/programmatic constraints are adhered to as trades are made. The design study teams will be given cost envelopes to work within, which were derived earlier by Gemini in consultation with experts in various fields, so that teams do not produce designs which are well beyond the fixed budgets available to design and build instruments. Specific design study deliverables typically include:

- **Overall Instrument Design Description** – Illustrates all aspects of the design at a level needed to develop a reliable cost estimate for completing the instrument, including mechanical 3D renderings, electronics schematics, optical designs, sensitivity estimates based upon performance models, etc.

- **Functional Performance Requirements Document (FPRD)** – A document which describes all of the technical requirements the instrument must achieve and substantially acts as the guide for the engineering team to continue with detailed design and fabrication of the instrument.

- **Observational Concepts Definition Document (OCDD)** – A document which is substantially derived by the instrument science team which describes how the instrument will be used at the telescope. The OCDD and FPRD are cross-linked since scientific performance derived requirements map directly into engineering technical requirements. They will be further refined before being frozen at the CDR level of the design phase of the instrument.

- **Unique Interface Control Documents (ICDs)** – While Gemini will issue ICDs to define key electrical, mechanical, optical, and software interfaces to the telescope, some interfaces will be unique to an instrument and must be sourced by the instrument team.

- **Management Plan** – Describes for the remainder of the project the management approach intended to complete the instrument, including how it will be designed, fabricated, integrated, tested, and commissioned at Gemini. This also contains a detailed Work Breakdown Structure (WBS) for the entire project, with costs, manpower requirements, and durations associated within each WBS component. A detailed schedule to complete the design, then fabricate, test, and commission the instrument should also be submitted. A procurement list describing the components and materials that will need to be purchased to complete the instrument and a total cost to complete the instrument is also submitted to Gemini.

- **Science and Technical Trade Studies** – These describe the derived science applications for the specific design proposed, as well as the results of individual and important technical trade studies conducted during the design of the instrument, e.g., trades between mechanical layout and cooling efficiency, total mass and rigidity of the optical train in a varying gravity load environment, etc.
• **Error Budgets** – Detailed error budgets applied to the opto-mechanical design of the instrument, indicating allowed positional errors of optical components, wavefront errors, throughput allocations, and demonstrating how errors stack up to meet required image and/or slit-throughput requirements, factoring in telescope and atmosphere errors provided by Gemini.

As mentioned before, if the budget permits, design studies will be issued on a competitive basis between at least two teams. This naturally promotes competition in what will undoubtedly be an expensive arena, leads to greater technical diversity, and since all aspects of the designs are owned by Gemini (except for those agreed to be proprietary) the Observatory can explore taking the strongest aspects of different designs or design teams to merge them into more optimized designs, as well as merging teams into collaborative efforts. Furthermore, design study teams will be given cost envelopes to work within through the Requests for Proposals and, without competition, teams will lack motivation to develop designs that come in under the indicated budget available. Despite the higher initial costs of competing design studies, the use of competitive design studies at this early stage in the process has repeatedly been demonstrated to be a net cost reducer in the overall Gemini development program.

**Step 4 – Completion Phase**

At this point detailed cost estimates have been derived for instruments and various forms of key or enabling technology identified and, if possible, developed in parallel. Historically, the most risk prone period in this phase tends to be when the first instrument tests are completed, early in the integration phase of an instrument, when unforeseen problems emerge and rework is required. The instrument developer is also at risk as slips accumulate, since running costs are dominated by the on-going unforeseen manpower needed to keep a project going well beyond its planned duration. Management structures and development strategies must be used during Phase 2 to minimize such risks. In general terms this can be done by freezing out decisions early in the process, recognizing that while such decisions may impact performance at some level, they ultimately bring forward the key initial tests of the project and expose issues before they necessarily become time critical to resolve. The use of existing or previously proven designs or technology also reduces risk and is reflected in the types of technology development that would be funded early in the project, through the Conceptual Design Phase. Identifying through a detailed project plan any long lead items that need to be purchased, combined with aggressive procurement methods soon after authorization to build is issued from Gemini, are other methods repeatedly proven by past Gemini instrument teams, to “buy” schedule contingency early in the Completion Phase and reduce the impact of technical problems that do not emerge until the instrument goes into its test phase.

The Completion Phase includes a number of key project milestones on the path toward delivering the instrument. This part of the design work substantially culminates in the Critical Design Review (CDR), which includes deliverables such as:

• **Final FPRD and OCDD** – Final changes are made to these fundamental design and operational documents up to the CDR, upon consultation with Gemini. Note that the FPRD serves as the basis for the Acceptance Test Plan, while the OCDD serves as the
basis for the User’s Manual, i.e., though frozen at CDR they are drawn from heavily in subsequent delivered documentation.

- **Compliance Matrix** – A detailed summary table indicating where the design proposed meets and fails all design requirements listed in the FPRD.

- **Final derived error budgets** – Again, any changes in error budgets compared to those submitted during the conceptual design phase are made in consultation with Gemini.

- **Final system design** – This typically includes a complete 3D opto-mechanical model which is sufficiently well developed that fabrication drawings can be immediately extracted. Also included are predicted cooling performance of cryogenic instruments, mass budgets, finite element analyses indicating predicted flexure or thermal performance under varying environmental conditions, etc.

- **Software** – Detailed software designs, including all ICDs, flow charts, etc. needed to begin coding the actual software, immediately.

- **Electronics** – Final design documentation for all electronic systems, including cabling descriptions, layouts for wiring throughout the instrument, grounding schemes, all of sufficient depth that the electronics can be manufactured immediately.

- **Acceptance Test Plan** – In draft form, a plan which describes the procedures needed to verify that the instrument meets all requirements listed in the FPRD, using a variety of tests before the instrument is shipped and after it is connected to the telescope.

- **Verification and Commissioning Plan** – In draft form, a plan which describes how to systematically characterize the performance of the instrument on the telescope, in all of its modes. Such tests will allow astronomers to formulate observing proposals using the measured performance of the instrument.

- **A revised budget and schedule to complete the instrument** – Including a WBS showing all the tasks needed to fabricate, integrate, test and commission the instrument.

- **Draft manuals** – Such manuals should include a user manual, software manual, and service and calibration manual.

- **Safety Review** – As part of CDR a safety review is conducted to determine if the design meets safety requirements, particularly in the area of installation, maintenance, repair, and operation of cryogenic systems, high voltage drivers, large and potentially dangerous mechanisms, etc.

Some aspects of the design are actually frozen well before CDR. For example, the optical design is often frozen at the Preliminary Design Phase (PDR) because optics are often long lead items and the instrument design substantially flows from the optical design, meaning it is of limited use to delay procuring optics until a later stage.
Actual fabrication of instrument components proceeds from here, with the noted exceptions of key long lead items. The build phase of the project no longer involves detailed or complex design trades with the science team, as all key decisions impacting performance should have been made long ago. Instead this is a period of intense parts procurement, issuance of various subcontracts to machine shops or specialty vendors, careful tracking of components as they arrive, etc. This tends to be a relatively low risk phase of the effort and leads to an integrated instrument that requires extensive testing in a lab environment to verify functionality and performance. As mentioned before, this critical period of initial laboratory testing substantially defines the likelihood of the instrument being delivered on schedule, so steps taken to advance this milestone invariably reduce the risk of schedule and cost growths. Though subsystem testing certainly helps reduce complications downstream with full-up system tests, it is only with the instrument fully integrated that complex system-level interactions, whether optical (focus or light leaks), mechanical (flexure), electronic (unexpected noise), or software (unforeseen control system interactions), are finally recognized and therefore can be addressed. This is particularly the case for large cryogenic instruments, which have long thermal cycle times. For Gemini class instruments, every time rework is required it could take weeks just to thermally cycle the instrument, which adds up to enormous costs over a protracted troubleshooting period.

With the integration and test effort completed, the Completion Phase leads into on-site acceptance testing by Gemini. Typically this involves a team sent by Gemini with expertise in a broad range of engineering disciplines, as well as science and management representatives. They will use an acceptance test plan, which was agreed well in advance and derived from the FPRD, to formally work through all aspects of instrument performance and functionality to verify that contractual obligations have been met. In cases where the instrument fails to meet performance specifications, assessing the impact from a science perspective before making a final pragmatic assessment of the real impact of such problems is needed. All interfaces that can be checked should be verified on-site before the instrument is shipped to either Gemini-North or Gemini-South. In general up to 95% of the acceptance test plan can be executed before the instrument is shipped, with final verification occurring after the instrument is mated to the telescope and final checks on key interfaces are verified and on-sky performance is measured. Finally, at the end of this multi-year process, commissioning can begin, the purpose of that being detailed characterization of the instrument’s actual performance, working in conjunction with the Gemini science staff, so that in the future astronomers understand the instrument/Gemini telescope system’s performance well enough to design research programs around its capabilities.