Estimating the costs of extremely large telescopes

Larry Stepp[a], Larry Daggert[b] Paul Gillett[a]

AURA New Initiatives Office, Tucson, Arizona 68519

National Optical Astronomy Observatory, Tucson, Arizona 68519

ABSTRACT

For future giant telescopes, control of construction and operation costs will be the key factor in their success. The best way to accomplish this cost control, while maximizing the performance of the telescope, will be through design-to-cost methods that use value engineering techniques to develop the most cost-effective design in terms of performance per dollar. This will require quantifiable measures of performance and cost, including: (1) a way of quantifying science value with *scientific merit functions*; (2) a way of predicting telescope performance in the presence of real-world disturbances by means of *integrated modeling*; and (3) a way of predicting the cost of multiple design configurations.

Design-to-cost methods should be applied as early as possible in the project, since the majority of the life-cycle costs for the observatory will be locked in by choices made during the conceptual design phase. However, there is a dilemma: how can costs be accurately estimated for systems that have not yet been designed? This paper discusses cost estimating methods and describes their application to estimating the cost of ELTs, showing that the best method to use during the conceptual design phase is parametric cost estimating. Examples of parametric estimating techniques are described, based on experience gained from instrument development programs at NOAO.

We then describe efforts underway to collect historical cost information and develop cost estimating relationships in preparation for the conceptual design phase of the Giant Segmented Mirror Telescope.
Key words: Cost estimating; Design to cost; Giant Segmented Mirror Telescope

1. INTRODUCTION

As telescope builders contemplate an order of magnitude increase in the size of giant optical/infrared (OIR) telescopes, cost control has become the most important factor in the success of these projects.

The current generation of large OIR telescopes, constructed over the past 15 years, has required an investment equivalent to approximately 2×10^9 US dollars, or approximately $130 million per year. This rate of investment is completely unprecedented in the history of astronomy, but even assuming it continues over the next decade, it is clear that if telescope costs were to increase with size according to traditional scaling laws, the extremely large telescopes on the drawing boards would not be affordable. At that rate, the entire world could not afford a single 30-meter telescope in the next 15 years.

This paper discusses the approaches that will be necessary to make next-generation telescopes affordable, describes how these approaches depend on accurate cost estimates, and summarizes the cost estimating methods that will be required.

2. HISTORICAL PERSPECTIVE

Since the Whitford report[1] was published in 1964, it has been traditional to relate the cost of ground-based optical telescopes to the diameters of their primary mirrors, using a power scaling law. Several authors[2,3,4,5] have analyzed this relationship between telescope size and cost, and different exponents have been proposed. The consensus seems to be that the traditional cost scaling law is:

$$\text{Cost} \propto D^{2.7}$$

where D is the diameter of the primary mirror.

At one time, it was assumed that this empirical "law" would make telescopes larger than about 5-m aperture unaffordable.[6] However, telescope builders began to realize that it was possible to take advantage of modern design approaches to effect significant cost reductions largely by engineering telescopes to be smaller and lighter. In the 1970s and early 1980s, several pioneering telescopes were built that departed from traditional designs, including: the Multiple Mirror Telescope (MMT), United Kingdom Infrared Telescope (UKIRT), and the 2.3-m Advanced Technology Telescope (ATT) at Siding Spring Observatory. In each case, design innovations led to costs below the canonical cost curve.

The Keck telescopes provide a recent example of how radical design innovations can "break the cost curve." A comparison with the Mayall 4-m telescope at Kitt Peak National Observatory (KPNO) illustrates the point dramatically. The Mayall telescope was completed in 1973 at a cost of $10.65 million. By comparison, Keck I, completed in 1992, cost approximately $100M. The ratio in diameter between the two telescopes is 2.5; raised to the 2.7 power, this predicts that a 10-m telescope would cost 12 times as much. Factoring in inflation, the cost of the Mayall would be about $33.7 million in 1992 dollars. Multiplied times 12, this becomes $400 million. Therefore, compared to the Mayall, Keck I beat the cost curve by about a factor of four, a remarkable feat considering that the Keck telescopes are sited on Mauna Kea, a higher and more remote site than Kitt Peak.

Why is the Keck design so much more cost effective? A primary reason is that it is relatively smaller and lighter than the Mayall. The moving mass of the Mayall is about 350 metric tonnes, while the moving mass of Keck I is only 270 tonnes. The Mayall dome is 30 meters in diameter. The Keck domes are 37 meters diameter.

What if the Keck design were scaled to a 30-m diameter? Using the $D^{2.7}$ scaling relationship, the 30-m telescope would cost $1.94 billion in 1992 dollars. If inflation over the next ten years is the same as in the past ten, a 30-m telescope completed in 2012 would be expected to cost $3.2 billion. If a 30-m telescope is to be affordable, it will be necessary to beat the scaling law by at least an additional factor of 4.

Of equal or greater importance is the need to control operating costs. For most telescopes in the 4- to 10-meter class, current operating costs fall within a relatively narrow range of between 3% and 6% of the (constant dollar) construction cost of the facility, depending on how the cost of scientific staff are included in the accounting. (In 1964, the Whitford report stated that large observatory operating costs ranged between 2.5% and 3.5% of facility construction cost not including “salaries of academic or scientific staff, support of graduate students, or other program-cost items such as scientific libraries.”) Most large observatories spend another 3% to 5% per year on development of new instruments and/or adaptive optics systems. Therefore, over a ~ 30 year lifetime, the cost of running an observatory is two to three times higher than the construction cost.

Clearly, to make extremely large telescopes affordable, we need to find ways to minimize the full life-cycle cost, including development, construction, operation and instrument replacement. The best way to achieve this is to follow a design-to-cost (DTC) management approach.

3. DESIGN TO COST

Design to cost – also known in Department of Defense programs as “Cost As an Independent Variable” (CAIV) – is a management approach in which cost is considered a design variable in the trade space that includes performance and schedule.[7] A key part of the DTC philosophy is that trades of cost with performance and schedule should not be at the expense of basic functionality or quality.

The DTC philosophy normally considers all life-cycle costs, not just construction costs, in key system trades. An example of a trade between construction and operations cost is the use of high-durability optical coatings. It now appears possible to coat mirror segments with protected silver coatings that will be able to maintain high reflectivity over life times of many years.[8] The sputtering equipment required to deposit these coatings may add several million dollars to the initial cost of the facility, but over the life time of the observatory, the payback in terms of reduced maintenance cost and increased telescope availability will likely amount to several times the cost of the enhancements to the coating equipment.

3.1 Value engineering

One of the central concepts of design-to-cost is that of value engineering. Value engineering is the formal discipline of reducing life cycle costs while preserving the essential performance of the system. It requires finding ways to simplify designs and reduce construction and maintenance costs, as well as a clear understanding of what truly constitutes value to the customer (i.e., the astronomical community). Value engineering is a planned methodology to reduce unnecessary costs without sacrificing functional worth.

The functions to be performed by the system (i.e., the observatory) can be classified into primary and secondary functions. The value engineering approach concentrates on meeting the primary, or basic, functions and avoids letting secondary functions drive up the life-cycle costs of the system.

An example from astronomy is a solar telescope, whose primary function is to observe the sun; this only requires the telescope to cover a limited range of declination angles, approximately +/- 22 degrees. A secondary function of a solar telescope can be to serve as a night-time telescope that observes a wide range of objects over the entire sky. However, to control costs, the project team must resist the temptation to add design requirements to achieve secondary goals. Unless night-time observing is truly a primary goal of a solar telescope, it should not be allowed to drive up the cost.

It is important to identify the functions required rather than specifying systems. For example, instead of stating that a tip-tilt mirror is required, the specification should state a requirement for image stabilization.

Value engineering can be used to maximize performance within a given budget, or it can be used to maximize cost effectiveness, in terms of science value per dollar. In this latter approach, both budget level and performance goals are allowed to vary, for example, by considering a range of different telescope sizes or performance levels. Sometimes the maximum cost effectiveness can be obtained by a more modest, or more ambitious, program than the one originally envisioned.

3.2 Importance of early application of design to cost

The design-to-cost approach should be applied as early as possible in the project. Experience with large, technically complex projects in a number of fields has shown that approximately 2/3 of the *life cycle* cost of such programs is determined by decisions made before the end of the conceptual design phase. After that time, it becomes increasingly difficult to accomplish significant savings. Cost reductions imposed later in the program will result in a disproportionate sacrifice in performance and/or quality. This is illustrated in Figure 1.

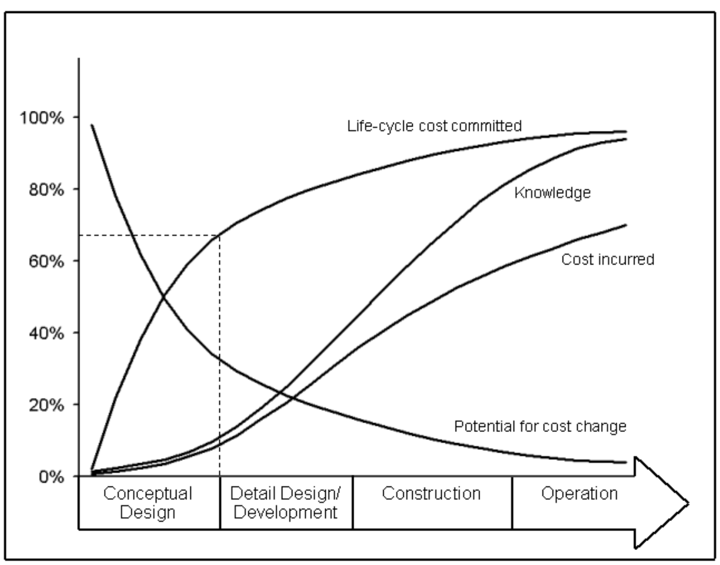

Figure 1. The decisions that determine the life-cycle costs of technical programs occur primarily in the conceptual design phase, while the available knowledge on which to base decisions increases more slowly (figure adapted from a presentation by Joseph Hamaker of Marshall Space Flight Center).

For typical high-tech projects, the cost of the design phase is only 5% to 10% of the cost of construction. A design-to-cost effort can add about 20 percent to the cost of the design phase, but this amounts to only about 1% to 2% of the total. It is an investment that can bring a significantly greater reward later in the project, but it does take a commitment on the part of program management and the funding agency.

To implement design to cost in the conceptual phase, it will be necessary to have quantifiable measures of performance and cost. This will require three things:

1. A way of quantifying science value with *scientific merit functions*;
2. A way of predicting telescope performance in the presence of real-world disturbances by means of *integrated modeling;* and
3. A way of predicting the cost of multiple design configurations.

3.3 Scientific merit function

In order to do performance/cost trade studies, there must be a quantitative way to express the scientific value that can be attained by a particular telescope design, in terms of its performance parameters. This type of quantitative measure is analogous to the merit function that is calculated when optimizing an optical design, so we call this a *Scientific Merit Function,* or SMF. Each observing program / instrument capability has its own SMF, usually related to the signal-to-noise ratio achievable in a given length of time for a given brightness of object, and the level of multiplexing (number of objects that can be observed simultaneously). The total scientific value can be expressed as:

$$\text{Scientific value} = \Sigma W_i * T_i * SMF_i$$

where:

W_i = the weighting factor for the ith science program
T_i = the time fraction for the ith science program
SMF_i = the scientific merit function for the ith science program

This concept of a scientific merit function is a departure from the more traditional method of flowing down science requirements. In the traditional approach, the system requirements for each proposed science mode are specified in "wish list" fashion. The collection of science modes is then scrutinized to find the tightest requirement on each design parameter, and the science requirements document is then the collection of the tightest requirements. If design studies show that some of the requirements can't be met, formal approval is required for descoping.

With the SMF approach, an expression is developed for the effectiveness of each observing mode, based on such parameters as collecting aperture, throughput, wavelength range, image size, spectral resolution, field of view, background radiation level, sky coverage, degree of multiplexing, etc. As different system concepts are considered, the values of the merit functions are calculated based on predicted system performance. In many cases, improving the value of one merit function will degrade another. For example, enlarging the secondary mirror to illuminate a wider field of view for one instrument will degrade on-axis coronagraphic performance in another. The scientists then work with the engineers to maximize the merit functions through a series of trade studies, taking into account the planned time fraction for each observing mode and setting the weighting factors based on scientific priorities.

3.3 Integrated Modeling

Extremely large telescopes will incorporate sophisticated active systems to control the pointing of the telescope, the cophasing of mirror segments, and the alignment of the optics in the presence of disturbances such as wind. They will also incorporate adaptive systems to correct atmospheric seeing. Therefore, to simulate the performance of an ELT will require integrated modeling that not only includes structural, optical and thermal analysis, but also simulates the performance of the controls systems in the presence of disturbances.

In recent years, the development of better software tools and faster computers has increased the application of integrated modeling in ground-based telescope programs. For example, a conference on integrated modeling was held in Lund in February.[9]

Using the results of integrated modeling, the SMFs can be designed to consider statistical measures of performance rather than absolute requirements. Instead of specifying a single criterion that must be met under worst-case operational conditions, the merit function can consider the distribution of predicted performance under varying conditions, for example evaluating telescope performance over the range of the wind velocity at the chosen site. The merit function can then be based on average performance, or can apply a higher weight to the performance under the best conditions.

The other requirement in doing performance/cost trade studies is the ability to establish the relative costs of available options. In general, the success of design to cost depends on how accurately and efficiently costs can be estimated, so correct design decisions can be made and realistic cost goals can be established.

The next three sections of this paper describe cost estimating methodology and describe the most effective cost estimating methods for the conceptual design phase of a telescope project.

4. Cost Estimating Methods

Like error budgets, cost estimates can be classified as top-down or bottom-up. Top-down methods start with the complete project and break the total cost into a relatively small number of parts. Costs are estimated by analogy or by statistical methods. For example, estimators often look at the fractional breakdown of costs for historical projects into different categories such as site development, optics, enclosure, etc., and draw conclusions about the cost distribution of future projects.

Top-down methods are best applied in the early phases of the project, when little detailed information is available.

Bottom-up methods start with estimates for each task or piece part, and build up the complete price as the summation of the individual parts. Bottom-up methods require much more detail about the system design and operational modes, and so are best suited to the detail design and construction phases of the project.

Four widely-recognized cost estimating methods are listed below. The first three are primarily top-down methods, and the fourth is bottom-up.

4.1 Expert opinion

An estimate falls in this category if it has no basis except that it is the best guess of an expert in the field. This type of estimate is also called a WAG. If there is little historical data on which to base an estimate, this approach can be used to provide a number to serve as a placeholder. The credibility of this method depends on the independence of the expert; if the estimator is an advocate for the program in question, the estimate has little credibility because of the potential for bias.

An added concern is that technical experts are not always experts on cost estimating. Some telescope and instrument projects have cost 2 to 5 times what the "experts" initially predicted.

4.2 Analogy

This type of estimate is based on the actual cost of similar programs. Analogous estimates are relatively quick and simple to prepare. They can provide a good starting point when there is little detailed information, or they can serve as a sanity check on a more detailed estimate.

Usually, some adjustment is needed to account for a difference in project size or complexity, and to account for inflation. The adjustments are often made using some form of parametric information, as described in the next section. The accuracy of the estimate depends on the similarity of the programs and the expertise of the person doing the adjusting. If large adjustments are needed because the historical and future programs are of significantly different scale or complexity, the validity of the estimate declines.

4.3 Parametric

Parametric cost estimating (PCE) techniques were first developed in the 1950s for the Department of Defense by the Rand Corporation. In this method, cost estimating relationships (CERs) are derived from historical cost data and then used to estimate the cost of similar future programs. These CERs relate the cost of the system to its technical parameters such as size, power, or weight. PCE focuses on the few, important cost drivers that have the predominant effect on program cost.

In this approach, historical cost, schedule and technical data are collected for a large number of similar projects. The independent variables that have the strongest effect on cost are determined by expert judgment and statistical methods. Then the dependence of cost on each of these variables is determined by multiple regression analysis, resulting in a CER for each. It is important that the independent variables are parameters that can be measured or accurately estimated, since the accuracy of the estimate depends on knowing their magnitudes.

CERs can also be developed in relation to other costs, for example, predicting overhead costs based on direct labor costs. These are called "cost-to-cost" CERs.

Parametric cost estimating methods have been used in the aerospace industry for decades, but their use in ground-based astronomy projects has been relatively limited. The curves relating telescope cost to primary mirror diameter cited in section 2 are simple CERs, and a few authors, notably Schmidt-Kaler and Ruchs (reference 3) have derived additional scaling laws. Other parametric studies done for NASA and other agencies have included the costs of ground-based telescopes as part of their data, but often they are not published in open literature because they include proprietary cost information.

PCE is the best method to develop a detailed estimate from the limited data available during the conceptual design phase of a project. It provides a relatively efficient and inexpensive means of estimating the cost impact of a variety of changes in system design or performance requirements. Therefore, it is the preferred estimating technique for design-to-cost trade studies during the conceptual phase of a project.

Considerable effort must be invested to collect the historical data on which the CERs can be based. Other data can also be included, for example rough order of magnitude (ROM) estimates from knowledgeable vendors. However, estimates are less credible than actual costs as a basis for CERs. For example, more than one paper has been published showing current generation projects as examples falling below the canonical cost curve based on their project budgets; later it was found that their actual costs, including debugging and rework, significantly exceeded those budgets.

Because PCE is based on statistical analysis, it provides a statistical measure of the confidence level for the estimate. PCE models can also be calibrated by using them to estimate the cost of a completed project whose actual costs are known.

There are many good sources of information on PCE techniques, including references 10-11.

4.4 Industrial Engineering

In contrast to the three primarily top-down methods described above, *Industrial Engineering* is a bottom-up approach that estimates the cost of each item using catalog prices, vendor quotes or ROMs, standard costs derived from time-motion studies, and so on. This approach can provide accurate cost projections when a detailed design has been developed. However, it requires a lot of investigation and must be repeated in detail for each alternative design considered, so it is better suited to later program phases.

The advantages and disadvantages of each estimating method are described further in Section 5.3, below.

5. Cost Estimating Methodology

The following sections describe some of the principal steps in cost estimating. For complete descriptions of cost-estimating methodology, see references 11-13.

5.1 Work Breakdown Structure

The backbone for any cost estimate is a well-thought-out work breakdown structure (WBS). The WBS breaks all the tasks in the project down to the lowest level at which costs will be estimated. A similar WBS should be created for the operations phase, to list the regular and periodic activities that will occur during the lifetime of the observatory.

The WBS contains entries for all cost categories except the allowances needed for cost escalation and contingency. *Cost escalation* is the term often used for cost increases that are foreseeable, but of unknown magnitude. For example, an allowance can be made for the cost increases that will inevitably result if the requirements are not well understood at the start of the project, or are allowed to change during the project. Cost escalations are sometimes called "known unknowns". *Contingency* refers to an allowance for cost increases caused by unforeseen events, such as an earthquake, or the bankruptcy of a major vendor during construction. Contingencies are also called "unknown unknowns".

The WBS will be needed throughout the phases of the project, so it should be organized in a way that can be easily adapted as the project moves from development through design into construction. As such, it must be suitable for both top-down and bottom-up estimating approaches.

5.2 Ground rules and assumptions
Ground rules define the factors that can influence the cost of the project. They are specified by the customer or funding agency – when important ground rules have not been explicitly specified, the cost estimator has to make assumptions. It is important to carefully document the ground rules and assumptions used to develop the cost estimates, and they should be clearly stated in any cost estimate documents.

The following are some of the factors that should be specified, or assumed, when estimating the cost of a telescope project:

- Type of project organization
- Project schedule
- Science requirements
- Description and quantities of deliverables, including:
  - Telescope and its enclosure
  - Instruments
  - Auxiliary facilities, including offices, laboratories, dormitories, computer networks, etc.
  - Handling and maintenance equipment
  - Spare parts
- Where the work will be done:
  - Choice of observatory site
  - Will project team be centrally located or scattered around the world?
- Procurement rules
- Types of contractual relationships: fixed price or best effort
- Use of existing facilities or customer-furnished equipment
- Required components that are currently unavailable, or have long lead times
- What costs are to be included in the accounting?
- Inflation rates assumed

Although these ground rules and assumptions may seem like minor details, they have a strong impact on the cost of a program. The current generation of large telescopes provides an example – all the 8-meter telescopes are very similar in size but their per-telescope costs vary by more than a factor of three. The factors that make these costs so different are such things as: number of secondary mirrors; number of initial instruments; extent of sea-level facilities; level of automation of handling equipment; and to some extent, the project management plan; contracting procedures; and vendor selection processes.

5.3 Selection of estimating methods
Table 1 lists some of the advantages and disadvantages of each method. Often, cost models include more than one method. For example, some items in an industrial engineering type estimate may be provided by vendor ROMs, which the vendors may have developed by parametric methods.

During the conceptual design phase, certain parts of the WBS will be best estimated by a particular method. For example, the largest part of the cost of systems relying on new technology (e.g., large adaptive secondary mirrors) may be in the development effort, which can best be estimated by expert opinion. Site development is an area that can be estimated well by analogy, since the work required for a future telescope will be very similar to the work required for existing telescopes, with some adjustments required for relative sizes.

Table 1. Advantages and disadvantages of each of the four cost estimating methods.

Estimating Method	Advantages	Disadvantages
Expert Opinion	Quick, simple & inexpensive	Subject to bias
		Hard to substantiate
Analogy	Quick, simple & inexpensive	Hard to factor in changing technology
	Based on actual historical data	Adjustments depend on expert judgment
	Easily understood	Accurate only for close analogs
Parametric	Based on actual historical data	Sufficient data may not be available
	Statistical techniques provide a measurement of confidence level	Predictions less valid outside range of historical data
	Defensible methodology	Often difficult to understand
	Can quickly evaluate cost impact of design trades -- provides insight into cost drivers	Sensitive to inconsistencies in the historical data
	Provides detailed estimate from limited data	Assumes forces affecting future costs will be same as in past
Industrial Engineering	Most accurate	Most expensive
	Easily understood	Time consuming
	Defensible & credible	Requires knowledge of detailed design
	Provides insight into cost contributors	Less insight into cost drivers – hard to evaluate cost impact of design trades
	Easily translated into project budgets	

5.4 Construct cost model

A cost estimating model is a group of cost estimates organized according the WBS that represents the cost of the entire project. Very often, cost models are organized as multi-sheet spreadsheets, but commercial cost models are also available. NASA works with two commercial off-the-shelf cost modeling programs: PRICE Estimating Suite[14] and SEER™.[15]

5.5 Gather & normalize data

Analogous and parametric estimating require historical data on similar projects. Often, there has not been a previous project that is equal in scope and complexity to the future project envisioned – this is certainly the case for ELTs. To some extent, this can be remedied by collecting data from dissimilar projects that have common features. If no optical telescope equally large has been built, data can be collected on the cost of radio telescope structures. If no observatory has been built at so high an altitude, the relative cost of construction of high-altitude mines can be studied.

Usually the cost data must be adjusted to compensate for differences in project scope, project schedule, and technology level. Adjustments are also required for any anomalies in the original program.

The data must also be normalized for inflation and for learning-curve issues resulting in lower costs as the quantity of an item increases. For example, Gemini benefited in several areas by following other 8-meter telescope projects that had already paid for studies, or for the development of fabrication facilities.

Industrial engineering estimates also require a lot of data collection. In some cases, accurate vendor estimates may only be available if study contracts are offered to proposed contractors to cover their costs.

5.6 Documentation

The cost estimate should be carefully documented to allow reviewers to understand how the cost elements were derived, and to ensure traceability. The documentation should include all pertinent information about the estimate, including the ground rules and assumptions, the cost structure embodied in the WBS, the historical data used and how it has been adjusted and normalized, descriptions of the estimating methods, and summaries of risk assessments and any trade studies.

It is important that cost estimates be credible, because difficult trade decisions must be made on the basis of the estimates, and that credibility depends on proper documentation.

6. Estimating the cost of instruments

Examples of the cost estimating methods described in Sections 4 and 5 can be found in the techniques developed at NOAO to estimate the cost of new instruments. The instruments are among the most complicated parts of an astronomical telescope and each instrument is a significant project in itself.

NOAO Engineering and Technical Services (ETS) department has developed a methodology for estimating the cost of astronomical instruments. Instrument project estimates are completed at three different levels. All estimates begin with a list of Scientific Requirements for the instrument. Once an understanding of the science requirements has been developed, an optomechanical schematic of the instrument is prepared. An example is shown in Figure 2. A notional optical design is required but it need not be the final optical design.

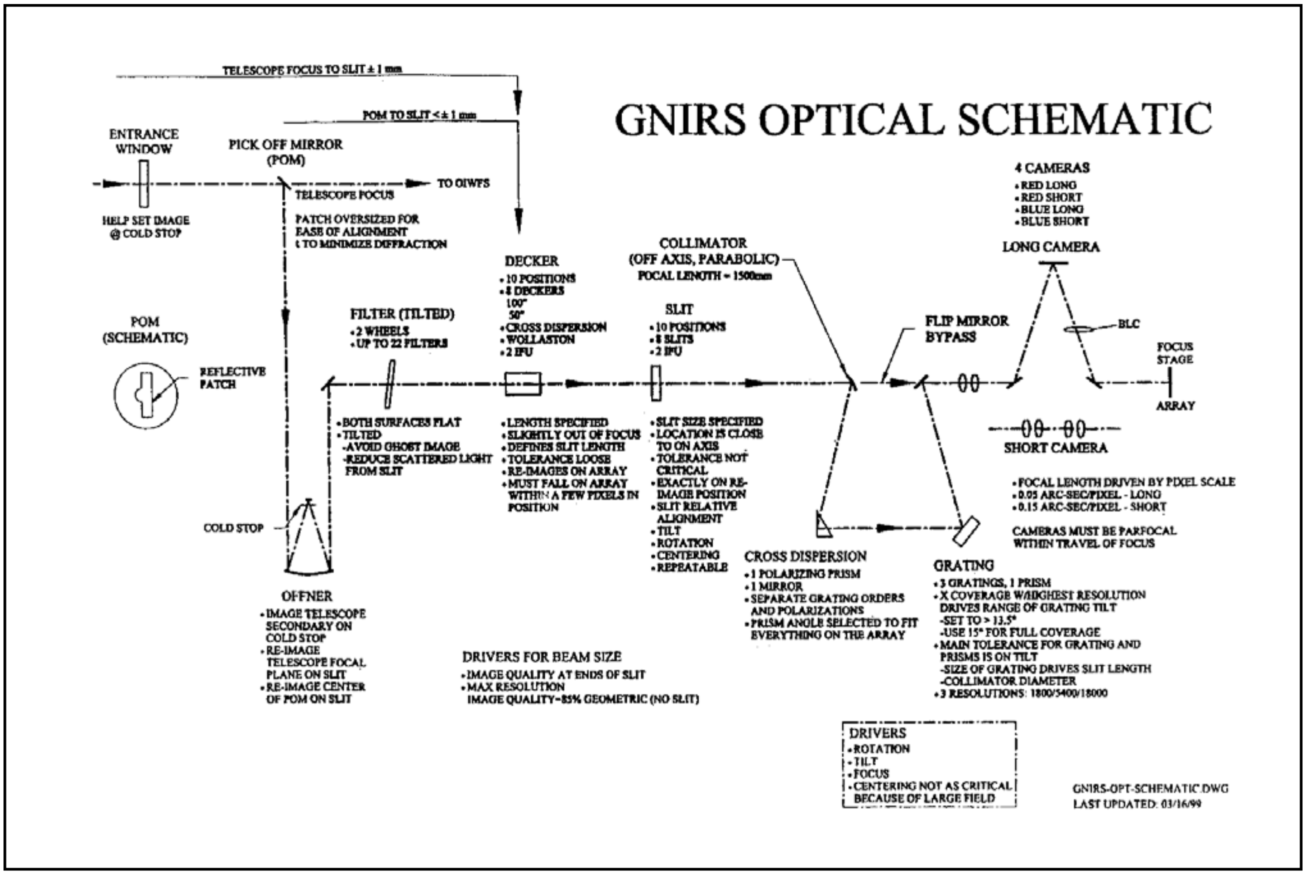

Figure 2. A schematic diagram of the Gemini Near Infrared Spectrograph that allows an assessment of the optomechanical systems that will be required.

6.1 Order-of-magnitude estimate

With the block diagram an *order-of-magnitude* analysis can be made without any detailed engineering data. This is an analogous estimate based on past experience, scale factors, and expert opinion. The estimate is prepared by the Project Scientist and Manager of Engineering and will take several days to prepare. The order-of magnitude analysis may have an accuracy of +/- 35%. One problem that can occur – after the estimate is complete, people tend to forget that the estimate is only order of magnitude and has a large error bar. Also, it is important to remember that *changing requirements change cost.*

6.2 Top-down detailed estimate

If the order-of-magnitude estimate does not scare everyone, the ETS Manager will prepare a more detailed *top-down* estimate. This estimate is also made without detailed engineering data. The estimate is based on previous projects that are similar in scope and complexity. Parametric curves, rules of thumb, and indexed costs of similar projects adjusted for size and technical innovations are used as the basis for the estimate. A WBS is prepared, to the third and fourth level, to assist in the identification of work elements and their costs. This type of estimate will take a few weeks to prepare.

Table 2 provides some comparison data for projects completed at NOAO between 1990 and 2002. Capital dollars have been inflated to calendar year 2001.

Table 2. Comparison data for instrument projects completed at NOAO between 1990 and 2002.

Instrument	Capital Cost [4]	Labor Hrs	Detector Array Size	Project Years	Weight (lbs)	Wavelength	Mechanisms	Modes of Operation
CCD MOSAIC	$957K	32K	2Kx4Kx8	5		.3-.8 microns	2	1
CCD MOSAIC # II	$435K	10K	2Kx4Kx8	2		.3-.8 microns	2	1
HYDRA	$381K	28K	n/a	4			1	1
HYDRA # II [5]	$401K	18K	n/a	3			1	1
Bench Spectrograph	$141K	28K		5		.3-.8 microns		
SQIID	$224K	33K	512x512x4	3	600	1 - 5 microns	1	1
COB	$390K	37K	1024x1024	5	900	1 - 5 microns		
Phoenix	$659K	63K	1024x1024	6	1500	1 - 5 microns	7	4
GNIRS[1]	$1,455K [2]	77K [3]	1024X1024	5	3900	1 - 5 microns	9	8

Notes:
1. Project estimates to completion
2. Includes the cost of contract labor
3. Does not include the contract labor hours
4. Array costs not included; all costs inflated to 2001.
5. Improved drives and reconfiguration speed

An additional metric used for comparison and estimation is the number of drawings required for a project. Based on the optomechanical schematic and experience from previous projects, it is possible to produce a reasonably accurate estimate of the total number of drawings required for the detailed design. Table 3 provides historical drawing numbers for some completed projects.

Table 3. Numbers of drawings required for several NOAO instrument development projects.

Instrument	Number of Mechanical Drawings
CCD MOSAIC	296
HYDRA	486
Bench Spectrograph	486
SQIID	~300[1]
Phoenix	873
GNIRS	1750

Notes:
1. Approximate number, many hand drawn pre-CAD

For 15 years, the average number of engineering and design hours per drawing held steady at about 28 hrs per completed drawing. This average did not change significantly when the organization changed from drawings boards to computer aided design (CAD) in the mid 1980s. However, we recently made the transition to a popular solid modeling program, SolidWorks, and have seen a decrease in the average engineering and drafting time per drawing to approximately 20 hours/drawing. That decrease *included* the time for training and coming up to speed on the new software. Some of this improvement may be attributable to strong project management and a tight deadline, but we believe the effect is mostly due to the improved software tools.

In 1998 Jay Elias wrote a white paper[16] comparing costs and capabilities of IR spectrometers for large telescopes with two purposes in mind. The first was to confirm that the cost of the Gemini Near Infrared Spectrometer (GNIRS) is reasonable in relation to its capabilities. The second and more relevant purpose was to establish benchmarks for instrumentation of this type to help predict costs during the early design stage at, if not before, conceptual design reviews. Table 3 is taken from Dr. Elias's paper and is included as an example of the level of detail that can be included in parametric studies.

Costs from Table 4 should not be used without reading Dr. Elias's paper to see what is included or excluded in normalizing the various project costs.

Table 4. Comparison of IR spectrometers for large telescopes.

Telescope	Gemini	Gemini	Gemini	Keck	Subaru	VLT
Instrument	GNIRS	GNIRS Baseline	Phoenix	NIRSPEC	IRCS	ISAAC
Motion	2-axis	2-axis	2-axis	None	2-axis	1-axis
n-inst derotator	N	N	N	Y	N	N
Flexure pix/hr	0.1	0.1	<0.5 [a]	N/A	0.6	~0.25 [a]
Max weight(kg)	2100	2000	<1500 [a]	<1000	2000	1200[a,b]
Pixel scales	2	1	1	1	2/1[c]	3/2[d]
Spectral Resolutions	3	2	1	2	4/2[e]	2
Max Spect Resolution	18K	8K	100K	25K	20K	11K-23K[f]
IFU?		N	Y	N	N	N
Cross-disp?	Y[g]	N	N	Y[h]	Y[h]	N
Polarizer?	Y	Y[i]	N	N	N	Y[j]
True camera mode?	N[k]	N[k]	N[k]	N[k]	Y	Y
Fore-optics?	Y	Y	Y	Y	Y	N
Max slit(")	100	50	15	46	61	120
OIWFS type/speed	IR Fast	CCD Fast[l]	CCD Slow	CCD/IR[m] Slow/Slow	CCD/IR[m] Fast/Fast?	CCD[m] Slow
IR Arrays (1kx1k)	1	1.5[n]	1	1+[o]	2	2
Cryostat Size (m)	1.2Dx2.1	1.5Dx0.6	0.7Dx1.3	1x0.7x1.7	0.7x0.8 x0.9	1.6Dx1
Cold axes	8+4[p]	6	6	6	10	11
Adj. Axes[q]	8.5+5[p]	5	6	6.5	9	11
Obs mode variables[r]	8	5	4	5	6	7
Nom. $M[s]	6.1	2.2	2.8	3.6	3.35	5.8
Adj $M[s]	7.5	3.25	3.35	4.2	4.0	6.05
Adj$/ adj. axes	$0.56M	0.65	0.56	0.65	0.44	0.55
Adj$/ mode var.	$0.94	0.65	0.84	0.84	0.67	0.86

Notes:
a: Actual value
b: Weight excluding electronics
c: 2 pixel scales for low spectral resolution and imaging, 1 scale for high spectral resolution
d: 2 pixel scales for short wavelengths, 3 pixel scales for long wavelengths
e: 4 spectral resolutions for short wavelengths, 2 resolutions for long wavelengths
f: Maximum spectral resolution is a function of wavelength
g: Cross-dispersion optimized for R=1800
h: Cross-dispersion at high spectral resolution only
i: Limited functionality
j: Imaging mode only
k: Imaging acquisition mode
l: Concept not defined
m: Used slit-view camera
n: Second array is 2-quadrant ALADDIN array
o: Second array is 256^2 array
p: Science channel + OIWFS
q: Axes adjusted for complexity, as follows:
  1-axis mechanisms: 1
  Flip-in mirrors or equivalent: 0.5
  2-axis mechanisms: 2.5
  Continuous motion: add +0.5
r: Number of significant variables defining instrument configuration; see below for details.
s: Nominal cost, US$M, and cost adjusted to total direct cost, US$M. See below for details.

6.3. Bottom-up estimate

The final cost estimating method used at NOAO for instruments is the *bottom-up engineering estimate*. This method requires the development of a conceptual model with a flow down of engineering requirements from the scientific requirement document. Once a conceptual model is complete, the project team prepares a project plan. A WBS is then prepared to the 4^{th} and 5^{th} level as required. Each work element is assigned for estimating to the team member that is expected to complete the work. NOAO has developed a standard set of forms to use in estimating WBS work elements. Vendor quotes are developed for all equipment that will be procured. After the project costing is complete a series of sanity checks take place. Rolled up costs, as a percentage of the project, for the level 2 WBS elements are compared to completed projects. Costs are compared to the Top Down estimates and discrepancies are rationalized. Development of this level of a bottom-up estimate can take three to six months and several man years of effort to complete.

6.4. GSMT Point Design Instruments

Conceptual designs have been developed for several instruments for the GSMT Point Design 30-meter telescope.[17,18] Cost estimates have been prepared for four of these instruments using the estimating techniques described above. The average cost of these instruments is about $25 million, which highlights the size and complexity of instruments that will be needed for 30-meter telescopes. Each instrument project will require a similar level of cost estimating and project management expertise as current telescope projects.

7. AURA NIO Plans

We believe the design of the GSMT must be driven by the science goals, within limits set by the available budget. Once the GSMT Science Working Group has developed a community-wide consensus on the science goals for GSMT, design concepts will be refined to meet those science goals. To maximize performance and minimize the life-cycle cost of GSMT, key decisions must be made during the conceptual design phase, based on trade studies that consider the scientific merit and associated cost of alternative designs and associated operational models.

To be effective, the trade studies must be conducted as early in the project as possible and they should be undertaken in the most efficient manner possible. The key to this will be to make advance investments in tools that allow the design team to "hit the ground running" once the project is formally started. The AURA New Initiatives Office is developing the analysis tools mentioned in this paper: science merit functions, integrated modeling and parametric cost estimating.

Developing PCE capabilities requires: (1) training or hiring trained staff; (2) collecting and normalizing construction and operations cost data from a large number of existing observatories; (3) supporting vendor studies to develop cost estimates for new technical solutions; and (4) developing CERs for the major subsystems of the observatory.

Aerospace firms, the Department of Defense and NASA maintain staffs of full-time cost estimators who continuously collect information about the cost of related programs. Ground-based astronomy does not have similar institutional capabilities, but they will be needed for the GSMT. It is our intention to develop this capability in collaboration with other astronomy organizations that are interested in estimating the cost of future projects, thereby providing a uniform and objective cost estimating method that can be used to compare alternative designs.

Once the GSMT project begins, design to cost has to be part of the systems engineering structure for the duration of the entire project. The initial cost estimate will serve as the basis for allocation of cost goals to specific individuals or subcontractors, and the performance of each part of the project in meeting its cost goals has to be tracked in the same way that progress in meeting performance goals is, and remedial action taken when problems occur. Even the best cost estimate can't remedy bad project management, so cost-control vigilance will be required throughout the project.

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