Systems Engineering

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Z.1. INTRODUCTION

This appendix of the report has a number of goals. One purpose is to show how a systems engineering methodology was adapted to meet the development needs of the CHARA Array. Another issue discussed here pertains to how the science goals drive the top-level hardware system requirements and how the system-level requirements drive the subsystem design requirements. The final goal of this appendix is to set the stage for the more detailed technical descriptions of the various subsystems that makeup the system, and to show some of the relationships between various system and susbsystem requirements.

Z.2. SYSTEMS ENGINEERING METHODOLOGY

For a project of this magnitude and complexity to be sucessfully completed in a 3-5 year period, a systems engineering methodology must be developed and put in place to help manage the technical aspects of the project as well as the logistics, schedule, and cost aspects. The methodology to be adopted must be tailored to meet the needs of the project and the organizations involved with the project. Typical system engineering approaches used by aerospace companies and military agencies offer many good examples of practices and procedures that are applicable to the development of the CHARA Array. Some commercial engineering management practices are also useful in this context; however, most commercial product engineering development is aimed toward production design practices which are overly expensive for prototype development.

For the CHARA Array project, the goal is to develop a systems engineering methodology, and therefore a developmental and operational philosophy, that fits the requirements of the project. The key idea that guides the development of the array is to let the science define the requirements for the hardware/software and let the hardware/software requirements drive the design. During this phase of the project, the CHARA team has spent an appreciable amount of time blending the appropriate mix and degree of systems engineering procedures and techniques to establish the methodology required to successfully take the project from scientific concept to a scientifically productive operational facility. The team has begun building the programatic infrastructure necessary to support the tasks ahead.

The CHARA Array is intended as a research tool to produce new scientific data; however, since it is not yet known what new scientific discoveries will be made, it is difficult in some instances to define all of the hardware requirements necessary to satisfy the yet unknown scientific measurements that may be needed over the next 10-20 years. However, the proper systems engineering methodology will allow all decisions regarding performance, operational, environmental, physical, and budgetery issues to be decided on a quantifiable, justifiable, and documentable basis and will allow the optimum system to be developed based the knowledge available at this time.

A simplified diagram representing the systems engineering process is shown in Figure Z.1. This diagram shows the initial phases of the process expanded in detail to highlight some of the important tasks completed, in progress, or to be started in the near future. One of the most important aspects of a developmental science project, compared to a developmental engineering project, is the lack of quantifiable top-level requirements and the difficulty of developing accurate mathematical models that represent the correct experimental procedures and techniques necessary to collect and interpret useful scientific data. For whatever reason, many science projects tend to be open-ended — providing some answers, but generating more questions — while engineering projects provide closed solutions to specific problems. At the present time, the CHARA Array project is more of a science project than an engineering project. The goal of the CHARA team is to methodically transform the development part of the project from a science project into a engineering project. This will allow the team to produce an experimental tool for scientific investigations. It is the early phases of this transformation process that are shown in Figure Z.1, and it is necessary to iterate the tasks between top-level requirements and final design concept a number of times before all the subtle interactions are understood and the concept design is optimized for the appropriate input requirements. During the most recent project funding period, the CHARA team has made great progress in optimizing a final design concept.

Z.3. SYSTEM REQUIREMENTS

The science objectives have discussed in the main body of this proposal and in Appendix A. The purpose of this section is show how those science objectives have been translated into project requirements and system level hardware specifications. The subsystem requirements and specifications are presented in greater detail in the various appendices which comprise this report.

In general, the science objectives are responsible for establishment of the experimental approach and techniques, and the experimental measurement parameters and measurement accuracies primarily drive the performance requirements of the array. However, the experimental approach also has impact on the other functional requirements of the system.

The science, operational, and cost objectives associated with this project have led to the following list of top-level project objectives to be satisfied by the system requirements:

1. The CHARA Array should be capable of making visibility measurements of binary systems and stellar diameters with sufficient accuracies to significantly extend the scientific measurement capability over existing techniques.
2. The CHARA Array should be capable of producing two-dimensional imagery of extended objects with resolution capabilities beyond what is presently available with existing instruments and techniques.
3. The CHARA Array must have the capability to operate at scientifically significant visible and infrared wavelengths.
4. The CHARA Array must have observational capabilities that allow adequate signal-to-noise measurements over a significant range of stellar magnitudes.
5. The project must produce an operational instrument that is capable of making scientifically productive measurements, as outlined in requirements 1-4 above, at the end of the project. This project is not open-ended. It must provide a complete instrument ready to make scientific measurements. This does not mean that improvements and modifications are precluded after completion of the project.

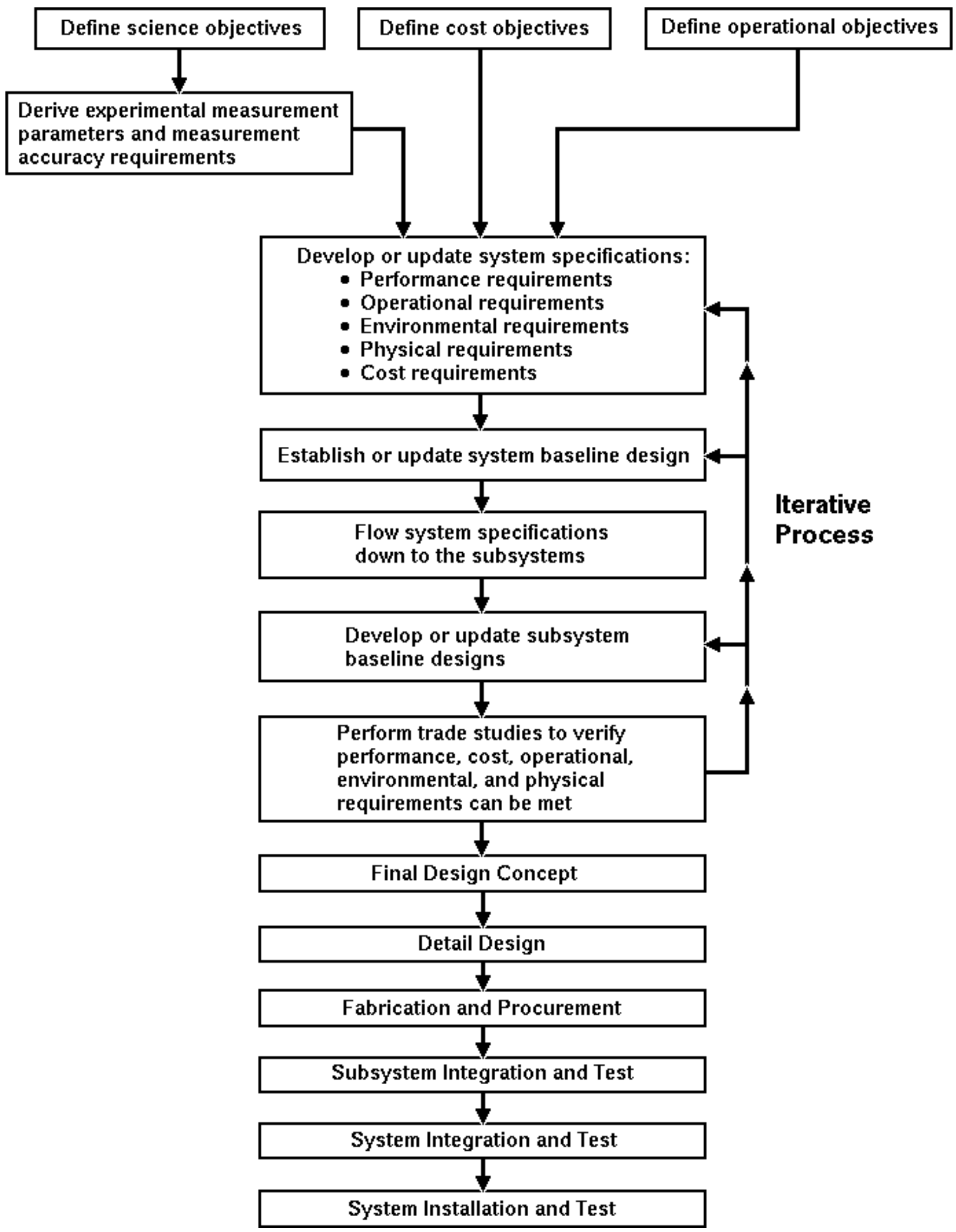

FIGURE Z.1. Hardware/software development project events.

6. The lifetime of the project, culminating with an operational Array, should be in the range of 3-5 years. The exact period of performance will depend on funding profiles, availability of resources, and other parameters that impact schedules.
7. Funding for the project will be limited in quantity and time availability. Again, it is assumed that the project will not have open-ended funding either in the amount of funding available or the time span over which funding is available to complete the project.
8. Long term (20 years) operational costs should be minimized and traded against acquisition costs to provide a balanced life-cycle cost.
9. Where practical, technical growth paths should not be limited by design; however, future growth should be carefully weighed against increased complexity and cost.

A review of the above project objectives indicates that objectives 1-4 primarily affect the performance requirements of the system, but may also shape the operational requirements to some extent. Objectives 5-8 contribute to the operational requirements of the system and the programmatic issues involved with the project. The last objective affects short and long-term performance and various operational requirements.

With the above top-level project objectives in mind, a system level specification was generated. This specification was written, not to produce the usual procurement document, but as a systems engineering exercise in defining and documenting the flow of project objective into system requirements. These quantifiable and measurable system requirements can then be flowed down to the various subsystems to aid in the development of design requirements. The system specification will undergo a number of modifications and updates, as indicated in Figure Z.1, before being released and placed under formal configuration management by the Systems Engineer. Once the system specification is complete and placed under configuration management control, the project can primarily be thought of as an engineering project and completed in a manner based on common engineering management techniques. However, the critical phase of the project is the initial iterations that are necessary to understand the trade-offs necessary to define a realistic system specification and design concept. It is the completeness of this initial phase that will determine the productivity of the operational system. As mentioned earlier, the CHARA Array team has made great progress in completing this phase. The system requirements definition function is damping rapidly and we are approaching the time where we can call the system specification finished for release. Concurrently with this release, the system concept design will be complete and ready for preliminary design review (PDR). Other critical milestones in the life of the project are discussed in the program plan.

The system specification was written following the same format used for military and aerospace projects in an effort to follow industry practices and because the format is already designed to address all of the aspects of a specification for projects like the CHARA Array project. The specification is divided into a number of sections, but the sections that are most important for this report are the performance, physical, operational, and environmental characteristics.

The remaining parts of the specification outline requirements in other important areas related to design and construction practices, documentation practices, quality assurance procedures, and other miscellaneous issues. The performance requirements of the system are summarized in Table Z.1.

Note that some of the values may not have been updated to reflect final values. In some

TABLE Z.1. CHARA Array performance requirements.

TOP LEVEL REQUIREMENT	SPECIFICATION
Total accumulated wavefront error	Less than 20% of average atmospheric turbulence
Visibility measurement error	Max. of 0.05 on a scale of 0–1
Closure phase measurement error	$\leq$0.01 rad
$u-v$ plane sampling frequency	Suitable for imaging of extended two dimensional objects
Collecting aperture size	Sufficient diameter to maximize signal-to-noise measurements for r_o at 2.2 μm for 1$''$ seeing.
Pupil management configurations	Upgradeable to accomodate: (1) subchannel aperturing and control, and (2) full aperture adaptive optics
Wavelength coverage	0.5 – 0.9 μm (visible) and 2.1 – 2.5 μm (infrared)
Sky coverage	$Z = +0\overset{\circ}{.}5$ to $Z = +50°$
Telescope pointing error	Less than 25×10^{-6} rad (5 arcsec) diameter circle
Tracking error	$\leq 8.8\times10^{-8}$ rad ($0\overset{''}{.}018$)
Beam registration	Greater than 95% of the beam cross sectional areas must overlap
System throughput	Optical throughput of a collecting channel shall be greater than 35%.

cases, the value in the spec. document may not be the latest value determined as part of the iterative process described earlier.

Z.4. RELIABILITY AND MAINTAINABILITY

Without control of hardware and software reliability and maintainability, system operational costs increase and system availablility decreases. However, improved hardware and software reliability and maintainability can often increase the acquisition costs of the system. Trade studies must be performed to determine the optimum compromise for minimum life cycle costs. One way to help insure the proper balance between reliability, maintainability, and life cycle cost is to consider these parameter in early design studies. By iteratively developing top-down mean-time-between-failure (MTBF) allocations to the various subsystems and bottom-up MTBF estimates, a realistic determination of problem areas can be established and these problem areas can be eliminated or at least minimized. Issues such as mean-time-to-repair (MTTR), spare parts inventory requirements, long term availability of replacement parts, maintenance documentation requirements, and special maintenance tools or equipment can be best identified and addressed during the design phase of the project and integrated into the design process.

The results of a top-down allocation of MTBF to the individual subsystems are shown in Table Z.2. Notice how a change in the MTBF of the Telescope Subsystem and OPLE

TABLE Z.2. MTBF Calculations. Subsystem requirements for 1,000 hr system MTBF (seven channels operating, reduced MTBF for some subsystems (*))

Subsystem	Subsystem Failures per Hour	MTBF (hrs) for each subsystem	Number of subsystems	System Failures per Hour	MTBF (hours)
Telescope	0.00048	2,083 *	7	0.001270	787
Beam transfer	0.00010	10,000	7	0.000265	3,780
OPLE	0.00048	2,083 *	7	0.001270	787
Beam sampler	0.00010	10,000	1	0.000100	10,000
Visible fringe tracker	0.00017	6,000	1	0.000167	6,000
Visible imager	0.00017	6,000	1	0.000167	6,000
IR beam combiner	0.00017	6,000	1	0.000167	6,000
System alignment	0.00017	6,000	1	0.000167	6,000
System control computer	0.00010	10,000	1	0.000100	10,000
Data aquisition computer	0.00010	10,000	1	0.000100	10,000
Site, buildings, and facilities	0.00010	10,000	1	0.000100	10,000
				0.001857	539
Total system MTBF (months)					2.5
Operational assumptions:					
Number of hours/day	10				
Number of hours/week	50				
Number of hours/month	217				

Subsystem, two of the most complex mechanical subsystems, can have a large effect on the overall system MTBF due to the large number of these subsystem in the system.

Z.5. RISK MANAGEMENT

During the development of the system and subsystem, risks must be identified and quantified. The effects of these risks on performance, cost, and schedule must be understood and work-around options developed or new approaches taken to mitigate the risks to an acceptable level. These risks will initially be reviewed at PDR and then again at CDR, at which time decisions will be made to continue development based on the information presented or to initiate a different approach.

Z.6. SYSTEM CONCEPT SUMMARY

During this phase of the project, several iterative passes have been made down through and back up the chart of Figure Z.1. The design concept, cost estimates, and schedules developed during this phase are nearing the state at which the system concept can be finalized and a PDR can be held. At that time, all design features, costs, and schedules will be traceable to the top-level objectives and backed by analysis documenting the design paths, cost estimates, and schedule assumptions that led to the PDR.