Cost estimate for the Kilometric Optical Interferometer (KOI)

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ABSTRACT

We present a parametric cost estimate for the Kilometric Optical Interferometer (KOI) in a classical array configuration: 24 telescopes, 4-meter primary mirror, up to 1 km baseline. The parametric cost estimate is based on available cost information from the Magdalena Ridge Observatory (MRO) Interferometer at New Mexico Tech. A Kilometric Optical Interferometer based on a classical array concept has an estimated construction cost between $1B and $3B if it would be built today (2008 dollars and technology).

The implication of the estimated construction cost is that cost reductions are critical in the planning phase to bring the cost within a reasonable envelope. Hence we propose to set a budget ceiling that seems feasible given the support to be expected from the scientific community and funding agencies. Given a budget ceiling, a design-to-cost process should be followed. We propose to set a construction phase budget cap of $800M (2008 dollars) for KOI as an initial goal.

Narrowing down of the science goals in combination with technology development to reduce cost and technological complexity are the main areas of activities for the next decade. We propose to establish a virtual project office to coordinate these activities.

Keywords: parametric cost estimate, optical interferometry, astronomical instrumentation, technology development, Kilometric Optical Interferometer, KOI

1. INTRODUCTION

Optical interferometry is maturing rapidly and seems to be in a transition stage from an experimental observational tool to a technique which can be used by main stream astronomy. Although the current generation of optical interferometers has still one to two decades to go in which they can provide cutting edge observations, discussions have started on the science case of the next generation optical interferometer [1].

A number of concepts are presented in literature for the next generation optical interferometer [2, 3, 4, and 5]. In this paper, we limit the cost estimate to a Kilometric Optical Interferometer in a classical configuration as presented in [3].

In Section 2 we review the science case for a next generation optical interferometer. Section 3 introduces first our baseline design adopted, the work breakdown structure used for cost estimating, and the parametric cost estimate. The final section of this paper present a conclusion and a suggested path forward.

2. SCIENCE CASE

The next generation optical interferometer array should be capable of addressing the outstanding science questions of its age. Such an array maybe implemented over a timescale of up to two decades from now. Over such a large period it is difficult and probably inadvisable to anticipate the science and target the design in any great detail. The concepts that we present here are only an attempt at designs that will be capable of probing the current issues as relevant perhaps for the next decade and with some flexibility to adapt over time to future needs. During the Tucson Workshop [2], several fundamental science topics that interferometers are ideally suited to examine were highlighted. We place each of the three concepts here in the context of one such fundamental science issue.

2.1 The classical array

The current generation of optical and infrared interferometers are largely limited by their sensitivity and u,v-coverage to fairly bright nearby objects. The vital need of any next-generation instrument will be to expand this reach to extra-galactic and indeed to cosmological distances. This would be a necessary requirement to bring in the vast majority of the astronomy community to the interferometry user base and of course to address a pre-eminent scientific issue of our age; the origins and eventual fate of our universe. A "classical" array with 20 to 30 telescopes of 4-6 m class, spread over a kilometer-baseline array, would be an ideal instrument to pursue cosmological studies over the coming decades. It would provide the resolution and sensitivity to look at the cores of AGNs and quasars to study their central engines and immediate environs and the requisite u,v-coverage to address structure-formation and galaxy evolution.

2.2 The 100-m ELT alternative

Detecting Earth-like planets and studying the formation and evolution of planets in other star systems, with the ultimate goal of searching for and understanding the origins of life, will be a fundamental priority for astronomy. An Extremely Large Telescope or ELT with an aperture of the order of a 100 m could possibly address this and other questions. An interferometer alternative to the ELT could achieve the required sensitivity, resolution and dynamic range while adding flexibility through reconfiguration. Such a design could involve 16 or so 8 m-class telescopes with a maximum baseline of the order of a 100 m.

2.3 The 20-20 concept

In addition to sensitivity, another limitation that has plagued optical and infrared interferometry is the fairly small fields they can examine. The 20-20 concept, as the name implies, would pair two large (~ 20 m) apertures over a baseline comparable to the aperture (~ 100m). This, an essentially scaled up LBT-like instrument, would be able to synthesize large fields of view with high sensitivity in very short timescales (essentially snapshots) and would, for example, be able to resolve entire stellar populations in nearby galaxies. Most fields of interest are crowded, and confusion places major limitations on the efficacy of a filled-aperture in such cases. An interferometer would have a clear advantage in this face-off.

3. COST ESTIMATE FOR KOI

3.1 Classical array design

In order to make a parametric cost estimate, a baseline design has to be adopted. Without going into the merits of one proposed concept above the other, we adopt the classical array concept. This classical array concept is based on work presented at [2] by various authors [3, 4]. For our cost estimate we use the basic parameters as listed below:

- 24 telescopes, each with a primary mirror diameter of 4 m, and adaptive optics;
- Continuous delay lines of each 600 meter;
- Y-shaped geometry, with each arm of 600 m length, 8 telescopes per arm;
- In the central part, stations are close to each other such that they can simulate a telescope with a diameter of 100 meter (separation about 3 times the telescope size up to a distance of 50 meter from the center, after which the separation is 50 meter till the end of the array);
- Station separation equals 50 meters (expected size of a large telescope in the year 2020). Hence there are 20 stations per arm, 60 stations for the full array;
- Beam transport with a 200 cm beam diameter, and vacuum pipes reach the last 6 stations in each arm. Each station has its own pipe which yields a total length of about 16 km;

- Beam combining in J, H, and K-band;
- Basis for cost estimate: MROI – Phase I: 6 - 1.4 m telescopes, 100 cm beam diameter, 28 stations Y configuration, 200 m arms (1.5 km beam relay pipes), 10 – 200 m delay line [6].

Fig. 1. Artist impression of the Kilometric Optical Interferometer (KOI).

3.2 Work Breakdown Structure (WBS)

A Work Breakdown Structure (WBS) is a standard approach in project management to break up the final product in small deliverables. Each work package, an element of the lowest level of the WBS, can be managed independently. In this paper we use the modified WBS as developed and in use for the Magdalena Ridge Observatory [6]. In the following sections, a parametric cost estimate is made based on this WBS, but only limited to the construction phase.

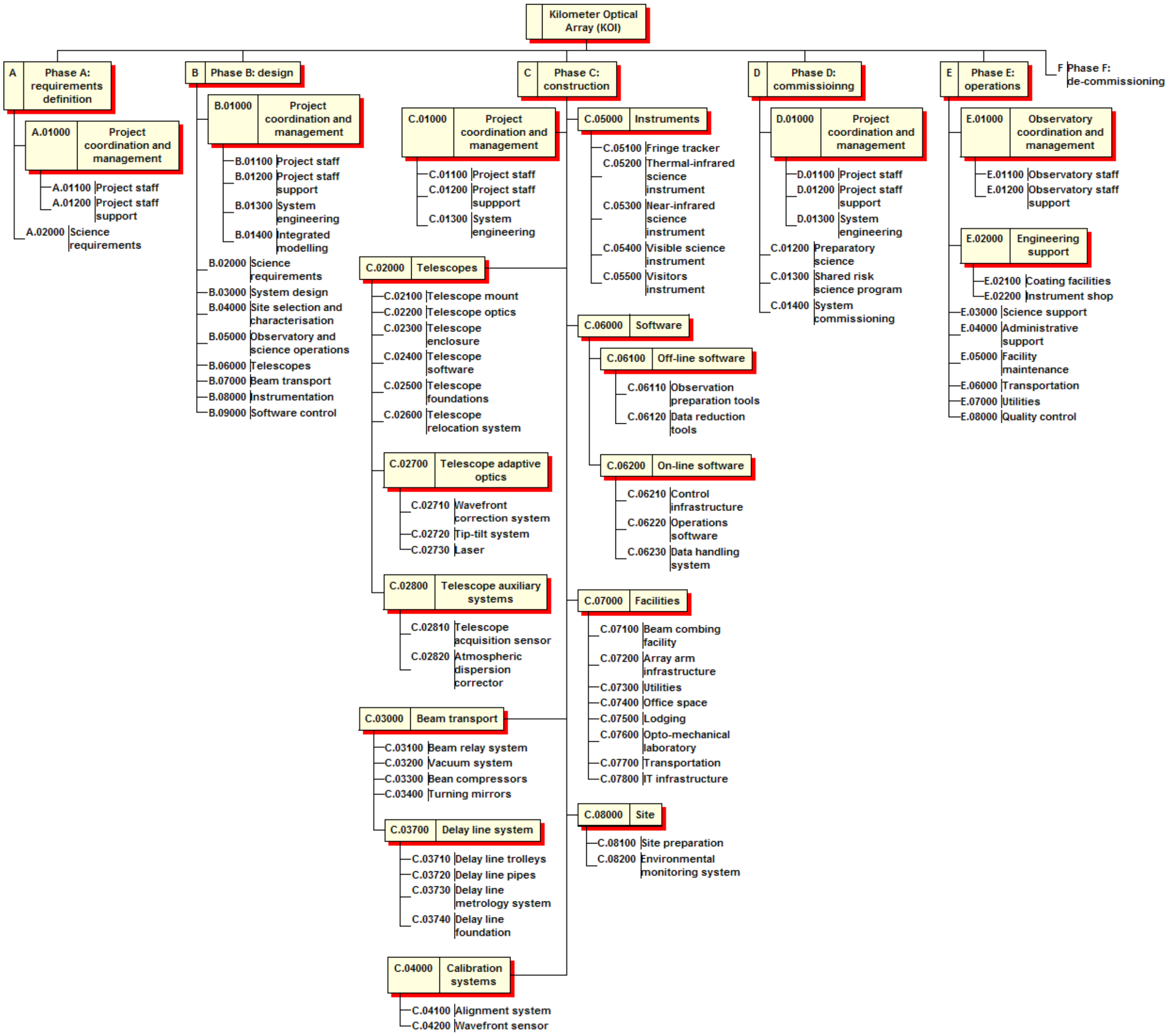

Fig. 2. Higher level WBS for the design, construction and commissioning of the Kilometric Optical Interferometer.

3.3 Parametric cost estimate

A parametric cost estimate is a standard approach in the early design phase of large projects to estimate the construction cost based on existing or current data from other projects. Scaling laws are applied from the existing or current projects to the new activity.

A parametric cost estimate is one that uses Cost Estimating Relationships (CERs) and associated mathematical algorithms (or logic) to establish cost estimates. A commonly used CER for the design and construction of a telescope is the 2.7 power law that scales the cost of the telescope with the diameter of the primary mirror [7]. This scales almost as the 3rd power, which is close to a volume that scales with the radius of the primary mirror. For a delay line, beam relay system, and other subsystems, a similar rough order of magnitude estimate can be made that scales with increase of area/volume expected for that subsystem. These scaling laws do not take into account technology development in the next 10 to 20 years. For the CER, existing or current project costs are scaled to get per-unit costs after applying the scaling law and then a concept factor (CF) based on the number of telescopes or the arm length is introduced. In addition, we inserted a technology factor (TF) that attempts to include cost saving due to future technology developments. The CER applied for each WBS element is:

$$Cost\_WBS\_element\_KOI = [Cost\_WBS\_element\_MRO / nr\_units] * [D^{SF}] * CF * TF$$

With D=4.0/1.4 ratio of diameters of the telescope primary mirrors or D=2.0/1.0 ratio of the beam diameters for the beam relay and delay line systems;

- SF is a scaling factor based on volume, area or length considerations;
- CF is a concept factor based on the number of telescopes, baseline etc.;
- TF is a technology factor which is based on expert opinion of the authors, and in some cases on market analysis.

If we do not apply technology factors, the construction cost of the KOI is around $2.5B FY2008 dollars. Given the uncertainties of the estimate, we estimate the construction cost between $1B and $3B dollars if built today with today's technology. This assumes the size and technology scaling laws as discussed in the next section.

Table 1. Cost estimate for the construction phase of the Kilometric Optical Interferometer.

WBS element	Scale Factor (SF)	Unit cost	Concept Factor (CF)	KOI classical array (2008 cost)	Technology Factor (TF)	KOI classical array (2008 cost with TF)
Project management	0.0	$7,876,539	4	$31,506,157	1.00	$31,506,157
System design and engineering	0.0	$100,000	4	$400,000	1.00	$400,000
Telescopes	2.7	$80,456,559	24	$1,930,957,420	0.25	$482,739,355
Telescope foundations	2.7	$3,404,445	60	$204,266,678	0.25	$51,066,670
Beam relay system	2.0	$4,187	15600	$65,315,297	0.25	$16,328,824
Delay line system	2.0	$13,960	14400	$201,024,000	0.25	$50,256,000
Interferometric instruments	0.0	$3,141,595	4	$12,566,380	1.00	$12,566,380
Interferometer control system	0.0	$162,134	24	$3,891,216	1.00	$3,891,216
Calibration systems	0.0	$50,532	24	$1,212,776	1.00	$1,212,776
Offline software	0.0	$39,933	24	$958,400	1.00	$958,400
Beam combining facility	0.0	$8,500,000	7.2	$61,200,000	1.00	$61,200,000
Telescope relocation system	2.7	$10,213,334	1	$10,213,334	0.25	$2,553,333
Commissioning and operations planning	0.0	$550,000	4	$2,200,000	1.00	$2,200,000
Site environmental monitoring	0.0	$17,187	4	$68,748	1.00	$68,748
Support facilities	0.0	$727,788	4	$2,911,152	1.00	$2,911,152
Site and infrastructure	0.0	$3,000,000	3	$9,000,000	1.00	$9,000,000
Project office and administration	0.0	$200,000	4	$800,000	1.00	$800,000
Adaptive optics	0.0	$1,000,000	24	$24,000,000	1.00	$24,000,000
Total Cost (2008 dollars)				**$2,562,491,558**		**$753,659,011**

First order parametric cost estimate using CER based on volume considerations and expert opinion on technology factors provide $753M. This assumes size and technology scaling laws as discussed in the next paragraph.

3.4 Cost scaling laws

The rationale for the scaling laws is very basic and open for discussion. For further iterations, cost estimates should be made by those who have a more intimate knowledge of the technology involved. Our hope is that in the next few years, independent groups will make cost estimates for subsystems they have developed in the past, or are planning to build in the future.

Table 2. Rationale for cost scaling laws.

WBS element	**Scaling Laws Rationale**	
Project management	This WBS includes staff salaries and project support. For the cost estimates, only cost from construction phase is considered.	
	D=1	The project management cost does not scale with the diameter.
	SF=0	
	CF=4	Project management cost scales by increase in the size of the project; here, 4 times increase to go from 6 telescopes to 24 telescopes.
	TF=1	No technology factor scaling has been assumed.
System design and engineering	Very important at the pre-construction phase, this WBS has very little work during construction phase except for critical oversight, monitoring of the implementation and addressing changes. Material costs are limited and labor costs are included as part of project management.	
	D=1	Design and engineering cost do not scale with the diameter.
	SF=0	
	CF=4	System engineering and design cost scales by increase in the size of the project; here, 4 times increase to go from 6 telescopes to 24 telescopes.
	TF=1	No technology factor scaling has been assumed.
Telescopes (including enclosures, optics)	A scaling law of cost $\propto D^{2.7}$ commonly used [7] to estimate telescope costs has been used where D=4.0/1.4 is the ratio of the primary diameters. The telescopes and its enclosure scales with the diameter of the telescopes. Note that interferometric telescopes have more stringent requirements than traditional telescopes.	
	D=4/1.4	
	SF = 2.7	The scaling factor 2.7 is based on existing and current data available from the literature.
	CF=24	For 24 telescopes in the classical array concept.
	TF=0.25	A technology factor of 0.25, for technology improvements and radical designs, is used. (based on past data and current technology developments).
Telescope foundations	A scaling law of Cost $\propto D^{2.7}$ has been used where D=4.0/1.4 is the ratio of the primary diameters. The foundation scales with the mass of the telescope. The technology factor can be attributed to the improvements in design of the telescope or to the foundation itself.	

	D=4/1.4	
	SF = 2.7	The scaling factor 2.7 is based on existing and current data available from the literature.
	CF=60	For 60 stations in the classical array concept.
	TF=0.25	A technology factor of 0.25, for technology improvements and radical designs, is used (based on past data and current technology developments).
Beam relay system	A beam diameter increase of 2 has been assumed.	
	D= 2.0/1.0	
	SF=2	A scaling factor of 2 for the increase in area due to increase in the beam diameter has been considered to calculate the per meter cost.
	CF = 24 * 650m	The cost has been scaled to a cost per unit meter; to get the cost for the concept proposed, a CF of 24 telescopes times the length of the array arms i.e., 650 m is used.
	TF=0.25	A technology factor of 0.25 is assumed.
Delay lines system	A beam diameter increase of 2 has been assumed.	
	D= 2.0/1.0	
	SF=2	A linear scaling factor of 2 for the increase in area has been considered.
	CF = 24 * 600 m	The cost has been scaled to a cost per unit meter; to get the cost for the concept proposed, a CF of 24 telescopes times the length of the delay lines i.e., 650 m is used.
	TF=0.25:	A technology factor of 0.25 is assumed.
Interferometric instruments	The interferometric instruments consisting of fringe tracker and science instrument are assumed not to scale with the diameter of the primary mirrors of the telescope and beam size diameter. For cost estimates, it is assumed the beam compressors in the classical array compress the larger beam size from the delay lines to the beam size as used by MRO, i.e. about 13 mm. Instead we assume a fourfold increase in number of instruments, scaled proportionately with increase in number of telescopes.	
	D=1	No scaling with diameter has been assumed.
	SF=0	
	CF=4	The cost scales by increase in the size of the project; here, 4 times increase to go from 6 telescopes to 24 telescopes.
	TF=1	No technology factor scaling has been assumed.
Interferometer control system	The interferometer control system consisting of software systems, supervisory systems etc., is assumed not to scale with the diameter of the primary mirrors of the telescope and beam size diameter. For cost estimates, the MRO cost was scaled as a cost per telescope. Instead we assume a 24 fold increase in the interferometer control system, scaled proportionately with increase in number of telescopes.	
	D=1	No scaling with diameter has been assumed.
	SF=0	

	CF=24	The cost scales by increase in the number of telescopes; here, 24 times increase to go up to 24 telescopes.
	TF=1	No technology factor scaling has been assumed.
Calibration systems	The calibration system consisting of alignment systems, wavefront sensors etc., is assumed not to scale with the diameter of the primary mirrors of the telescope and beam size diameter. For cost estimates, the MRO cost was scaled as a cost per telescope. Instead we assume a 24 fold increase in number of instruments, scaled proportionately with increase in number of telescopes.	
	D=1	No scaling with diameter has been assumed.
	SF=0	
	CF=24	The cost scales by increase in the number of telescopes; here, 24 times increase to go up to 24 telescopes.
	TF=1	No technology factor scaling has been assumed.
Offline software	The offline software consisting of offline software, data handling systems etc., is assumed not to scale with the diameter of the primary mirrors of the telescope and beam size diameter. Instead we assume a fourfold increase in number of instruments, scaled proportionately with increase in number of telescopes.	
	D=1	No scaling with diameter has been assumed.
	SF=0	However, the cost scales by increase in the size of the project; here, 4 times increase to go from 6 telescopes to 24 telescopes.
	CF=4	
	TF=1	No Technology factor scaling has been assumed.
Beam combining facility	Building scaled by a concept factor which shows the increase in length and width of the delay line area (7.2 in this case – 200 m to 600 m delay line length, 10 to 24 delay line number). The increase in office space and interferometer control area has been assumed to be minimal.	
	D=1	No scaling with diameter has been assumed.
	SF=0	
	CF=7.2	Scaled by increase in length and width of the delay line area.
	TF=1	No technology factor scaling has been assumed.
Telescope relocation system	The relocation system also scaled by the cost $\propto D^{2.7}$ scaling law since the size of the telescope scales by the same amount. A technology factor of 0.25 has been assumed which could be attributed to either telescope or relocation system.	
	D=4/1.4	
	SF = 2.7	The number 2.7 is based on existing and current data available from the literature.
	CF=1	For 24 telescopes only one relocation system has been assumed in the classical array concept.
	TF=0.25	A technology factor of 0.25, for technology improvements and radical designs, is used.

Commissioning and operations planning	The commissioning and operations planning, is assumed not to scale with the diameter of the primary mirrors of the telescope and beam size diameter. Instead we assume a fourfold increase in the effort, scaled proportionately with increase in number of telescopes.	
	D=1	No scaling with diameter has been assumed.
	SF=0	
	CF=4	The cost scales by increase in the size of the project; here, 4 times increase to go from 6 telescopes to 24 telescopes.
	TF=1	No technology factor scaling has been assumed.
Site environmental monitoring	The environmental monitoring systems, is assumed not to scale with the diameter of the primary mirrors of the telescope and beam size diameter. Instead we assume a fourfold increase, scaled proportionately with increase in number of telescopes.	
	D=1	No scaling with diameter has been assumed.
	SF=0	
	CF=4	The cost scales by increase in the size of the project; here, 4 times increase to go from 6 telescopes to 24 telescopes.
	TF=1	No technology factor scaling has been assumed.
Support facilities	Support facilities are assumed not to scale with the diameter of the primary mirrors of the telescope and beam size diameter. There may be some increase in storage and maintenance facility due to increase in size of the telescopes and has been assumed to be manageable in the cost estimate provided. Instead we assume a fourfold increase in the support facilities, scaled proportionately with increase in number of telescopes.	
	D=1	No scaling with diameter has been assumed.
	SF=0	
	CF=4	The cost scales by increase in the size of the project; here, 4 times increase to go from 6 telescopes to 24 telescopes.
	TF=1	No Technology factor scaling has been assumed.
Site and infrastructure	Site and infrastructure is assumed to scale with the size of the facility.	
	D=1	No scaling with diameter has been assumed.
	SF=0	
	CF=3	The cost scales by increase in the size of the project. We assume a 3 times increase to go from 200 m to 600 m arms.
	TF=1	No technology factor scaling has been assumed.
Project office and administration	Project office and administration is assumed not to scale with the diameter of the primary mirrors of the telescope and beam size diameter. We assume a fourfold increase in project office and administration, scaled proportionately with increase in number of telescopes.	
	D=1	No scaling with diameter has been assumed.

	SF=0	No scaling with diameter has been assumed.
	CF=4	The cost scales by increase in the size of the project; here, 4 times increase to go from 6 telescopes to 24 telescopes.
	TF=1	No technology factor scaling has been assumed.
Adaptive optics	Based on expert opinion cost estimates, a value of $1 million per adaptive optics system has been used. The adaptive optics system envisioned is a higher order adaptive optics system than the first order tip/tilt system used at MROI. This number is a higher limit, based on a Rayleigh beacon laser guide star system.	
	D = 1	
	SF = 0	Since, this is not a parametric estimate, the scaling factor used is 0 and no scaling with telescope diameter is assumed.
	CF = 24	For 24 telescopes.

3.5 Life cycle costing

Based on experience from MRO, for the requirements, design and partly for the construction activities (data available till 2008), the total life cycle cost for an optical interferometer has the distribution as listed below. All cost together (excluding a possible de-commissioning phase) add up to 100%. We assumed an operational life time of 25 years, and a yearly inflation of 3%. All cost is scaled to 2008 dollars. This overview demonstrates that the cost for operations exceeds the cost for construction by a factor 3.

Table 3. Life cycle costing on KOI.

Phase	Description phase	Cost contribution [%]
A	Requirements	1
B	Design	6
C	Construction	20
D	Commissioning	3
E	Operations	70
	Total [%]	100

3.6 Design-to-Cost

Given the huge dollar amount involved in the design, construction, and operations of KOI, containing the cost should be one of the main drivers between now and the realization of these plans.

In large government projects within the US, the cost as an independent variable (CAIV) is used to contain cost. The CAIV philosophy means that cost should be treated as an independent variable among the three variables traditionally associated with an acquisition program: cost, schedule, and performance. An independent variable is one that is “fixed,” and other variables react to (or are dependent upon) the stability imposed by that independent (fixed) variable. Continuous consideration is given to trading off performance requirements to stay within previously established total program fiscal constraints (i.e., complete life cycle costs, including development, production, operations, and disposal costs).

4. CONCLUSIONS

Using historical budgetary data from the Magdalena Ridge Observatory we have made an attempt to estimate the cost for a Kilometric Optical Interferometer.

Major uncertainties are the scaling laws to be applied. We have applied a scaling law as listed in literature, or based on dimensions of the subsystems. In addition, we have added a scaling factor for concept and a third scaling law for technology development in the next 10 to 20 years. All scaling laws are only initial guesses for further refinement, and very likely a source of many discussions for the years ahead.

The “classical array concept” for the Kilometric Optical Interferometer (KOI) would have a Budget-At-Completion (BAC) closed to $2.5B if built today.

Cost reductions as a result of technology development in the next 10 to 20 years, could bring this BAC down to less than $1B. We suggest adopting a BAC ceiling with a construction cost of $800M (2008 dollars).

The large cost to design and build such a complex research infrastructure, and the need to control cost during the design and construction process, would require a “Design-To-Cost (DTC)” or “Cost-As-an-independent-Variable (CAIV)” approach.

The realization of KOI is something that will span a few decades, and it will take a while before a legal entity takes ownership of this plan. In the mean time we suggest to establish a (virtual) project office by the major stakeholders, with the primary objectives:

- to coordinate the requirements and the design phase of a Kilometric Optical Interferometer;
- to coordinate stakeholders involvements in the design, construction, and operations of a Kilometric Optical Interferometer;

As cost will be a major component in any funding proposal to design and build a KOI. We hope that experts in the field will develop advanced scaling laws for each of the work package listed in the WBS presented in this paper. Summing up all the expert cost estimates will provide better cost estimate and gives more credibility to a formal funding proposal. After a Conceptual Design Phase, a bottom-up cost estimate can be attempted.

REFERENCES

[1] Surdej, J., Caro, D., and Detal, A., "Science cases for the next generation optical/infrared interferometric facilities (the post VLTI era)", Bulletin de la Société Royale des Sciences de Liège Année 2005 Numéros 1-2-3: I, (2005)

[2] Ridgway, S., "Workshop on the Future Directions for Ground-based Optical Interferometry", NOAO workshop on Future Directions for Interferometry Workshop http://www.noao.edu/meetings/interferometry/, (2006)

[3] Eklund, D., and Rajagopal, J., "Cost Modeling for Arrays", NOAO workshop on Future Directions for Interferometry Workshop http://www.noao.edu/meetings/interferometry/, (2006)

[4] Quirrenbach, A., "Classical Interferometric Arrays", NOAO workshop on Future Directions for Interferometry Workshop http://www.noao.edu/meetings/interferometry/, (2006)

[5] Quirrenbach, A., "Design considerations for an Extremely Large Synthesis Array", Proc. SPIE 5491, p. 1563-1573 (2004)

[6] Creech-Eakman, M. J., Bakker, E. J., Buscher, D. F., Coleman, T. A., Haniff, C. A., Jurgenson, C. A., Klinglesmith, D. A., III, Parameswariah, C. B., Romero, V. D., Shtromberg, A. V., and Young, J. S., "Magdalena Ridge Observatory Interferometer: status update", Proc. SPIE 6268, 62681 (2006)

[7] Stepp, L.M., Daggert, L.G., and Gillett, P.E., "Estimating the costs of extremely large telescopes", Proc. SPIE 4840, p. 309-321 (2002)

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