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Project Plans for the Development of the Large Adaptive Reflector Development-to-Demonstrator

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Development Strategy

A great deal of progress has been made in the development of the Large Adaptive Reflector (LAR). After some years of investigating the aerostat system, an understanding of many of the problems has developed, and solid solution-concepts are emerging. Also, progress on the design of an actuated reflector has reached beyond the concept stage, to a design from which a reasonable cost estimate can be obtained. New talent has been brought to bear recently on developing a design for the focal apparatus, and some research has been done on the focal-plane array feed.

Past planning has emphasized outside help in the LAR development work, through contracts, collaborations, and other relationships. In the work to date and in the plans presented herein, the following strategy has been used: 1. Develop concepts. 2. Select concepts for feasibility analysis and initial design work. 3. Carry out more design work as needed to evaluate costs and confirm feasibility. This iterative strategy ensures that no more work is done in a particular area than necessary, so that equivalent amounts of effort can be dedicated to areas of equivalent risk. Moreover, the adopted methodology emphasizes the need to complete investigations of the highest risk components as early as possible. Ideally this would mean that all the high-risk areas have been treated on an equal footing. Thus the plan for future work puts more emphasis on those areas lagging behind while avoiding a loss of momentum in other areas.

The development plan leads to, but does not include demonstrator construction, the first phase of which is considered to be the detailed design phase.

Resources: The LAR contains a wide mix of technologies, many of which are new to astronomy. Identifying useful and interesting collaborators/contributors who can provide assistance is a critical part of the LAR development. Considerable progress has been made here – a very strong university collaboration with McGill University is in place for the development of the aerostat system, and with industry partners for the reflector work and for key technology in the focal-plane array sub-system. Recently, important strides have been made in identifying a strong university collaborator, Laval University, for the focal apparatus sub-system.

Table 1 summarizes the resources already utilized for LAR development work, including available funds for FY 04/05. Not included are funds spent before April 2002 when the part time effort equivalent to 1-2 FTE's per year have been allocated for LAR development in HIA and universities since about 1998. The funds shown in Table 1 are available now.

Table 1: Canadian Funding for LAR Development ($C1000's)			
Fiscal Year (beginning April 1)	**"02/03"**	**"03/04"**	**"04/05"**
National Research Council	1010	1164	1164
Canada Foundation for Innovation	494	0	0
Natural Sciences and Engineering Research Council	75	75	**
Industry*	42	85	**
Total	1621	1324	1164

***AMEC Dynamic Structures Limited** ****Amounts not known yet.**

Development Plan: Appendix I is a detailed breakdown of the development plan, starting in FY04/05. Table 2 shows a summary of expenditures corresponding to Appendix I. For FY 04/05, the funds shown in Table 2 include those shown in Table 1 for FY 04/05. Not included in Table 2 are funds provided by the university granting agency, NSERC, to the McGill/Laval groups for development of the focal apparatus and the aerostat sub-systems. Their grant of $480k runs for three years, beginning in Oct. 2003.

Table 2: Estimated LAR Development Costs ($ 1000's)							
		Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	
		FY 04/05	**FY 05/06**	**FY 06/07**	**FY 07/08**	**FY 08/09**	**5-Year Total**
Aerostat		115	385	85	85	0	**670**
Focal Apparatus		50	200	400	400	50	**1100**
Reflector		850	170	150	320	50	**1540**
Feed		300	650	500	500	100	**2050**
Beam Former		50	50	100	100	0	**300**
Correlator		0	50	50	0	0	**100**
Project Management		100	110	110	110	110	**540**
Total Operations		1465	1615	1395	1515	310	**6300**
Continuing Salaries*		300	300	300	300	300	**1500**
New Salaries*		200	300	300	300	300	**1400**
Totals		1965	2215	1995	2115	910	**9200**
Including 30 % Contingency		2555	2880	2594	2750	1183	**11960**
Including 5% HIA Infrastructure Tax		2628	2960	2663	2825	1199	
						Grand Total	**12275**

* For the purposes of these estimates, salaries & benefits are included at a nominal annual value of $100k each.

The funds shown in Table 2 are part of a funding request and have not been secured. Although progress with the request is expected within a year, there is no fixed date as yet as to when these funds can be secured.

Schedule: The 5-year development schedule is implicitly outlined in Table 2, and more detail is available in Appendix I. The schedule is a compromise between resources, the size of the project, and the need to be ready for a potential SKA concept decision in the 2008 time frame. The construction of an LAR demonstrator could begin in FY 08/09 at the earliest. In principle, there could be overlap between the tail of the development work and detailed design work for construction in FY 08/09.

The LAR Demonstrator

The LAR concept is one that requires demonstration at a sufficiently large scale to confidently construct an SKA of 10^6-m^2 collecting area using LAR technology. Moreover, operational experience is also required so that the inevitable operational wrinkles can be "ironed out" before committing to a production of many LAR antennas for the SKA. There are strong arguments for combining demonstration of the technology with achieving major scientific goals, especially considering the significant cost of a demonstrator, even one capable of demonstrating only engineering sufficiency.

The plan described here aims to achieve both technology and science goals – a 300 to 350 meter diameter telescope with frequency coverage from 100 MHz to 1800 MHz, an instantaneous bandwidth ratio of 2:1, sky coverage down to 30° Elevation Angle, resolution of 2.4 arcmin at a wavelength of 21 cm, and a 0.62° diameter field-of-view.

The science goals are to use the LAR demonstrator for systematic discovery-mapping. It will not only demonstrate the LAR technology for the SKA, but at ~10% of the collecting area of the SKA will also be a pathfinder for SKA science. These design features will enable the demonstrator to jumpstart many of the science goals of the SKA, in particular deep spectral and broadband imaging over the sky. Such an increase in capability over present-day instrumentation in this field will provide pre-SKA scientific guidance to:

- Dark Energy and the Equation of State of the Universe
- Large-scale structure of the Universe, through the high-z detection of HI in galaxies
- Evolution of galaxies
- Mapping the Cosmic Web
- Pulsars – testing General Relativity in the strong field limit
- The epoch of re-ionization and the dawn of galaxies
- Evolution of Cosmic Magnetism

From a technology perspective, the telescope will demonstrate all of the required features of the LAR needed for the SKA, except for the ability to observe at high frequencies. High frequency operation requires a demonstration of two additional capabilities – a sufficiently accurate reflector system and several feed systems to cover the high-frequency bands. The substructure of the LAR reflector, including the main actuators, is designed to support sufficiently small panels for frequencies up to 22 GHz. The development plan includes a work package to equip and test a reflector section with high-frequency panels. A portion of the demonstrator reflector would be similarly equipped and operated as a smaller, high-frequency telescope. During the operational phase of the demonstrator, a high-frequency feed would be constructed and deployed as a test of high frequency operation.

At this stage only a rough guess of the construction cost for a science-capable demonstrator can be made. The best-known costs are for the reflector – reflector structure, \$130 / m^2, and main actuators, \$170 / m^2. It may be possible to build the reflector for \$350 / m^2, including \$50 / m^2 for other reflector components. Thus a 350-m diameter reflector, which has about 100,000 m^2 of area, would cost about \$35 M. The cost of the aerostat and feed system for that size of telescope is not well enough known to provide an estimate.

It is likely to take 2-3 years to construct a demonstrator, and at least 5 years of operation would be needed to achieve all the technical and scientific goals. If LAR technology is selected for the

SKA, SKA construction could start before the end of the operational phase of the LAR demonstrator. It is difficult to predict now when this could take place, but it does not seem possible before about 2014.

The LAR demonstrator plan described above can at present be best described as a goal, which has the support of a large segment of the Canadian radio astronomy community. But details are likely to change. Other scenarios have been discussed and this document can be considered only as a rough planning guide as far as an LAR demonstrator is concerned.

Appendix I

LAR Sub-System Development Plans

The LAR comprises five sub-systems: the reflector, the focal-plane array feed, the focal apparatus (feed actuation system), the aerostat system, and a beam-former. As a complete telescope system, these parts will be capable of generating digital data streams from a cluster of "beams" on the sky. In addition one or more "back-ends" are required for the telescope (e.g. correlator(s), pulsar processor). The sections below contain a structured "thumbnail" description of each development sub-project, including a brief statement of progress already achieved. In the following, most of the emphasis is on the telescope, itself, rather than back-end processing, with the exception of a nominal "correlator", which may be required to take full advantage of the multi-beam capabilities of the LAR.

The estimated costs associated with the work packages (bulleted lists) are provided in the form of a list of dollar amounts for each year of work. The totals appear in Table 1 of the body of this report.

Aerostat

Description: The aerostat sub-system consists of the aerostat, itself, and the tethering system, including winches. It encompasses its own control system for stabilizing the position (and possibly the orientation) of the focal apparatus. It also includes the means for supporting power and communications to all the airborne subsystems.

Past Progress: An aerostat was selected early in the program as the best concept for supporting the focal apparatus, because it is a passive lifting device, capable of unmanned operation for long periods. A large prototype (1/3 scale) was constructed to evaluate the concept, to develop a dynamical model of the system, and to understand in practice what is needed to operate an aerostat-based system. When verified by experiment, the model will become a powerful design tool for the LAR. Within measurement error, the model has been successful in predicting the dynamical behavior of the aerostat system in an "open loop" (no active control) situation. Considerable preparation for active control is complete, and a new set of field experiments is under way.

Plans:

- Year 1-2: Continue to develop control system software and test. (Cost: $20, 20k)
- Year 1-4: Continue flight operations as more aspects and design ideas for the tethered system and its control are tested. (Cost: $85, 95, 85, 85k)

- Year 1-2: Investigate concepts for an "all weather" (robust) aerostat system. The LAR project has unique needs in this respect, because all aerostat designs to date are predicated on portability, which lends itself to a design composed completely of fabric. Robustness can be improved by developing a design with a light skeleton, similar to designs used already for airships. (Cost: $10, 90k)
- Year 2: Expand the tether complex to a 6-tether system, and carry out further control tests. This will permit evaluation of telescope pointing control over the entire Alt-Az "workspace", and potentially permit the evaluation of new plans to use the tether system to assist in the orientation of the feed plate. (Cost: $130k)
- Year 2: Evaluate the potential of a spherical aerostat instead of a streamlined aerostat. Models indicate that there may be advantages to a spherical aerostat in the dynamical behavior of the system. A small series of tests are planned to evaluate a spherical aerostat. (Cost: $50k)

Collaboration: The aerostat program is being carried out in collaboration with the dynamics group headed by Prof. Meyer Nahon at McGill University, who has developed a dynamical model of the system. This model is a critical output of the development work. Prof. Nahon was awarded a CFI grant of $440k that provided partial support for the development of the 1/3-scale aerostat prototype. He is also the principal investigator of the NSERC Strategic grant ($480k) awarded in Sept 2003, in part to continue the aerostat program.

Personnel: HIA has an engineer and a technologist working full-time on this program. A McGill faculty member is supported by two Research Associates and 4 PhD/MSc students. The HIA engineer is vital to other aspects of the project. In the plan this responsibility will be transferred to a new hire (more junior engineer). (Total 5-yr FTE effort – technologist: 4, Engineer: 4, others part-time in Year 1-2: 0.3)

Focal Apparatus

Description: The focal apparatus sub-system can be viewed as a hierarchical structure. On the "inside" is the feed plate, a circular plate on which is mounted the focal-plane array that feeds the main reflector. The feed plate is attached to the focal mechanism, which orients the feed plate so that its axis of symmetry points at the center of the reflector. The focal mechanism is attached to the focal structure, the outside of the hierarchy and the boundary of the focal apparatus sub-system. The tethers to the ground and to the aerostat are attached to the focal structure.

Past Progress: A number of concepts for the focal apparatus have been put forward. Some of them were investigated as thesis projects at the University of B.C., but no concept was settled upon. The final requirements of the focal apparatus are closely linked with those for other parts of the telescope, but sufficient progress has been made on the requirements to enable a start on mechanism design. A survey of applicable concepts for the focal mechanism has been done recently at Laval University, and a candidate mechanism has been selected for more intensive investigation.

Plans:

- Year 1-3: Investigate potential mechanism concepts, and select at least one for more detailed analysis. Carry out the detailed analysis, using the best assumptions available for the characteristics of the feed plate. Construct a "table-top" sized model for tests of dynamical behavior and controllability. (Cost: $\$0_{nserc}$k)

- Year 1-2: Carry out a preliminary design of the structure, which must carry tether loads to the "leash", the cable that is attached to the aerostat. It is important to understand how much such a structure might weigh. A six-tether system can potentially be used to assist in orienting (tilting) the structure, thus reducing the size of the workspace needed for the mechanism. This is another reason for investigating structural concepts in the next two years. (Cost: $50, 50k)
- Year 2-3: Carry out a full-blown computer simulation of the focal apparatus, especially the mechanism. The purpose is to learn as much as possible before launching a large-scale prototype of the mechanism. (Cost: $50, 50k)
- Year 3-4: Build a 1/3 to 1/2-scale prototype of the focal mechanism, complete with an actuated perturbation system. In parallel, develop a control system to ensure that all aspects of the control system are well understood before committing to a full-scale design. Operate the prototype in years 4-5. (Cost: $350, 350k)

Collaboration: Prof. Clément Gosselin, who directs a large robotics and mechanisms group at Laval University, is leading the work on the focal mechanism concept, supported in part by an NSERC Strategic Grant. A small-scale prototype is one of the goals of this work.

Personnel: At Laval, one staff member and two students are carrying out the concept development for the focal mechanism. HIA requires a mechanical engineer to liaise with the group at Laval on the design of both the focal structure and the focal mechanism. A control engineer will be required to work with the Laval and/or the McGill control group on mechanism control. A technologist will be needed for prototype operations. (Total 5-yr FTE effort – Mech. Engineer: 1, Control Engineer: 0.3, Mech. Technologist: 2, others part-time: 1)

Reflector

Description: The reflector is a faceted approximation to the ideal parabolic shape. The facets are triangular panels supported by structure, which is actuated so as to be able to maintain a parabolic shape over the required range of Zenith Angles and Azimuths. A distinguishing feature of this design is that unlike conventional reflectors, the weight of the surface is not concentrated onto a single mount. Instead the reflector weight is distributed across the ground underneath. This results in a cost function that is closer to r^2 than is the case with conventional designs. The reflector is very shallow, almost flat – nevertheless the actual actuator strokes needed are up to 14 m for a 300-m diameter reflector.

Past Progress: Recently, a concept for an actuator design has been developed to provide the required actuator stroke at a relatively low cost. This is a break-through for the reflector design. A linking scheme for the panels has also been devised which permits the full range of actuation with minimal development of gaps between the panels as the shape is changed. The reflector design uses a "layered" structural technique – a "structure unit" is supported by large main actuators and supports a number of panels via secondary actuators. A "structure unit" has been built and evaluated, complete with two panels. The panels were designed for operation below ~2 GHz, but their rms fluctuation was actually sufficient for 5-GHz operation. The structure unit has been design so that it can be easily adapted to smaller panels, suitable in size to operate at frequencies in the 20 GHz range.

Plans:

- Year 1: Equip the prototype structure unit with actuators. Design and test a control system for the actuated structure unit. (Cost: $180k)
- Year 1: Carry out a study of available secondary actuators. (Cost: $50k)
- Year 1: Construct a group of linked, actuated structure units, complete with a partial complement of panels and secondary actuators. (Cost: $600k)
- Year 2-4: Continue with control system design and testing. (Cost: $\$0_{NSERC}$, 70, 50, 50, 50k)
- Year 3: Develop a measurement system suitable for measuring the positions of panels to an accuracy sufficient for 22-GHz operation. (Cost: $50k)
- Year 4: Design, construct and evaluate several high-frequency panels. (Cost: $50k)
- Year 4-5: Equip the structure units with high-frequency panels, a measurement system and refine the control system to deliver a sufficiently accurate prototype for 22-GHz operation. (Cost: $250, 50k)

Collaboration: Involved in the reflector work are engineering groups of Prof. Sigi Steimer at the University of BC and AMEC Dynamic Structures Limited (ADSL) of Port Coquitlam. HIA expects to award a contract to ADSL in the near future to provide an actuated structure unit. McGill University Prof. Benoit Boulet is collaborating on a number of control problems associated with the LAR, including the control of the actuated reflector system. The McGill work is partially supported by NSERC.

Personnel: HIA has one engineer working with ADSL. At McGill, one staff member and one student have started work on the control system design. A control/system engineer will be required to coordinate the development and operation of the prototype reflector system. (Total 5-yr FTE effort – Mech. Engineer: 1, Control Engineer: 1, Mech. Technologist: 4, others part-time: 1.5)

F*ocal Plane Array Feed*

Description: The LAR reflector subtends an elliptical solid angle, which changes with Zenith Angle. The illumination pattern must vary with Zenith Angle so as to fully illuminate the reflector. Simultaneously, of course, the pattern must be optimized to maximize the A_{eff}/T_{sys} (the ratio of effective area over system temperature). A widely used technique for producing a variable antenna beam is to use an array of elemental antennas, whose outputs are combined in a weighted sum. The weights can be used to shape the projected beam. For the LAR the focal plane array comprises a dense array of tapered slot antennas ("Vivaldi" antennas), which cover a feed plate several meters in diameter. These antennas afford very wide bandwidths while at the same time can be packed close enough together to completely sample the focal plane of the reflector. Horn antenna arrays, which are becoming more common at both microwave and millimetre wavelengths, do not have these two attributes. These two characteristics are crucial to meeting the LAR specifications. Because of the LAR's long focal length, it is possible to feed the reflector efficiently off-axis, thus enabling a field-of-view many beams across. The feed array enables many beams to be formed at once, providing a fully sampled field-of-view. The focal ratio and the size of the feed determine the size of the field-of-view. For the LAR parameters currently selected, the feed array for a 20-40 cm wavelength band must be 10-11 m in diameter to achieve a field-of-view of 0.6 degrees in diameter for a 350 m antenna. The feed plate consists of the array of antennas, each equipped with a low-noise amplifier, a following amplifier, a sampler, and an optical modulator. Thus the feed plate interfaces are free-space input and optical fiber output, as well as requisite power and timing signals.

Past Progress: The use of the phased array as a reflector feed has not been fully developed for radio astronomy antennas. However, the project is benefiting from phased array development going on around the world at observatories and in universities. Thus we are not developing the LAR feed from a zero base. Considerable progress has been made in defining the RF system concepts. Also, preliminary concepts have been developed for the stages subsequent to the antennas, the low-noise amplifier through to optical output at ground level. Much less progress has been made on an integrated RF/structural/mechanical design. The feed project has suffered most from lack of appropriate resources over the past few years, and this must be redressed in the next stage of planning.

Plans:

- Year 1-2: Construct a small (antenna-only) array prototype and measure its properties at the free-space and output ports (beam shape, polarization properties, isolation between elements, output impedance) over 2:1 bandwidth ratio (minimum). This may be followed by a few other array prototypes, as needed. Compare the results with specialized theoretical simulations done with collaborators. The goal is to optimize performance parameters for the LAR application (and possibly other applications). (Cost: $50k)
- Year 1: Develop a concept and preliminary design for the RF-to-optical signal chain. The inputs to this sub-system are the outputs of the Low Noise Amplifier (LNA)/antenna combination. The outputs are optical receivers on the ground, leading to the Beam Former. (Cost: $100k)
- Year 1-2: Construct a prototype of the on-board RF-to-optical module. (Cost: $100, 300k)
- Year 1: Develop an integrated RF/structural feed plate concept. (Cost: $50k)
- Year 2: Construct a prototype of the LNA. This amplifier is to be integrated with the array elements. (Cost: $100k)
- Year 2: Carry out a preliminary design of the feed plate. (Cost: $50k)
- Year 2-3: Carry out a detailed design of the feed plate. (Cost: $100, 100k)
- Year 3-4: Construct a fully operable prototype of a feed plate section, large enough to form at least one beam. (Cost: $300, 200k)
- Year 3: Carry out a detailed design for a high frequency feed. (Cost $100k)
- Year 4: Build a prototype of a high frequency feed. (Cost $200k)
- Year 4-5: Test and operate the high frequency feed. (Cost $50, 50k)

Collaboration: Current work on the array prototype is in collaboration with Prof. David Routledge at the University of Alberta, through a graduate student who is working at DRAO. The results of measurements made with the array will be compared with simulations developed by Prof. Christophe Craye at the University of Leuven, Belgium. BreconRidge Manufacturing Solutions of Ottawa have done significant concept work on the RF-to-optical signal chain. HIA expects to put out a Request for Proposals (RFP) to complete this concept work.

Personnel: A senior HIA engineer currently leads the RF work (shared with SKA support) and a senior mechanical engineer will be transferred to the complex work of combined mechanical/RF design of the feed plate structure. An RF engineer (new hire) is needed in addition to the existing RF engineer to liaise with BreconRidge, to work on the LNA (possibly with a collaborator), to work on the detailed design of the feed plate, and to work on the high-frequency feed. An electronics technologist will be needed for prototype development and operation. (Total 5-yr FTE effort – Mech. Engineer: 4, RF Engineer: 8, Elec. Technologist: 3, others part-time: 3)

Beam Former

Description: The Beam Former sums outputs from individual antenna elements to form signals that are effectively received from a cluster of beams that sample the field-of-view on the sky. It connects to optical fibers that bring the individual signals to the ground from the feed plate. The signals are split and used to form sums from adjacent, overlapping groups of feed elements. Each beam will require input from ten's to about a hundred elements. Depending upon the wavelength and the field-of-view, several hundred beams will be formed from the several thousand antenna elements.

Past Progress: Progress has been made on researching and developing a beam former signal-processing architecture. Also, work has been done on error and sensitivity analysis, although neither is complete.

Plans:

- Year 1-2: Complete the work on the architecture of the beam former. Carry out a digital design based on the required architecture. (Cost: $50, 50k)
- Year 3-4: Build a prototype capable of being integrated with the feed system prototype. (Cost: $100, 100k)

Personnel: A senior HIA staff engineer who is working on the architecture of the beam former. HIA has two other expert digital engineering staff who will be available in mid-FY04/05 to collaborate on this work. (Total 5-yr FTE effort – Digital Engineer: 4, others part-time: 1)

Correlator

Description: As a single-antenna telescope, the LAR will require an auto-correlator for each beam (or equivalently a direct Fourier transformer), including quasi-autocorrelation for cross-polarization measurements. In addition, a certain number of cross-correlations between beams may be required for calibration, stability and interference mitigation measures. In principle, it should be possible to confer the same level of stability to a multi-beam, single-antenna telescope as can be provided to an interferometer. The details of how this should be done and implemented are not yet worked out.

Past Progress: No progress has been made in this area yet.

Plans:

- Year 2: Develop a concept for post-beam-former signal processing. (Cost: $50k)

- Year 3: Carry out a preliminary design and cost analysis. (Cost: $50k)

Personnel: HIA has two expert digital engineering staff who will be available in mid-FY04/05 to collaborate on developing a correlation strategy and to carry out a preliminary design. (Total 5-yr FTE effort – Digital Engineer: 2, others part-time: 1)

Control Systems

Although control systems are not an isolated project, they play a vital role throughout the design of the LAR. The McGill University group led by Prof. Benoit Boulet has begun work on some of the control problems, and is interested in the overall control system. There will be contributions from all of the sub-system projects to control, but coordination of the various control projects will require continuous attention from HIA staff. (Total 5-yr FTE effort – Control Engineer: 2.5)

Data Communications

The LAR FPA will produce a large amount of data that must be transmitted to the ground, and each station will transmit high-rate data streams to the central correlation centre of the SKA. In the first instance, data communications will be part of the receiver contract with BreconRidge. Inter-station communication is not being addressed as it is a common problem for all SKA concepts.

Project Management

At present there are three people, each working part time on management, project planning, etc. (Total 5-yr FTE effort – Project Manager: 3)

Science Support

In addition to SKA science support, HIA has contributed the part-time work of three people towards science support for an LAR demonstrator. This contribution, estimated to be about 0.3 FTE per year, will have to continue as part of the collaboration with university colleagues. (Total 5-yr FTE effort – Scientist: 1.5)

SKA Support

Support for the international SKA initiative requires the part-time work of 3-4 people. The total effort now provided is estimated to be 1.2 FTE per year. There is a constant flow of work associated with reporting, planning, attending international meetings, and a large commitment to the International Engineering Management Team. (Total 5-yr FTE effort – Scientist/Manager: 0.2, Scientist: 0.3, Senior Engineer: 0.5, Others: 0.2)

Staffing Summary

Table A1 summarizes the allocations of personnel outlined in the sections above. Entries are integrated FTE's for the 5-year project. Two experienced electrical engineering staff will be available soon. One of them has experience with control systems, digital engineering, and radio frequency (RF) engineering. The other is a digital specialist, but is also capable of working in the analog signal processing area. The priority new hires are a mechanical engineer, an RF engineer, and a technologist who can cross over between mechanical and electrical technology (listed under MT in Table A1).

Table A1: Estimated Personnel Requirement at HIA (Totals for a 5-year Project)								
	ME	**RF**	**CE**	**MT**	**ET**	**DE**	**Misc.**	**FTE's**
Aerostat	4			4			0.3	**8.3**
Focal Apparatus	1		0.3	2			1	**4.3**
Reflector	1		1	4			1.5	**7.5**
Feed	4	8			3		3	**18**
Beam Former						4		**4**
Correlator						2		**2**
Control Engineering			2.5					**2.5**
Project Management							3	**3**
Science Support							1.5	**1.5**
SKA Support							6	**6**
Total FTE's	10	8	3.8	10	3	6	16.3	**57.1**
Average 5-yr Staffing Level	2	1.6	0.76	2	0.6	1.2	3.26	**11.42**
Existing Staffing Level	1	1	1	1	0	1	1.5	**6.5**
Average FTE Deficit	1	0.6	-0.24	1	0.6	0.2	1.76	**4.92**
Priority New Staffing	1	1		1				**3**

ME	Mechanical Engineering	**RF**	RF Electrical Engineering
CE	Control Engineering	**MT**	Mechanical Technology
ET	Electronics Technology	**DE**	Digital Electronics Engineering
Misc.	Science, Management, Project Management		
FTE	Full Time Equivalent or Person Year (PY)		