The Madawaska Highlands Observatory Wide-Field Telescope and the Array Telescope

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Abstract

This paper examines the technical and economic merits, and highlights the extreme flexibility and opportunities presented by employing an array of 1m to 2m class optical state-of-the-art telescopes to form the elements in a large array telescope. The array telescope has unique and powerful capabilities not found in current large telescopes.

An array telescope can be configured for the greatest depth or the largest field-of-view; it can build a medium resolution spectrum of every object in a large FOV and instantly determine distances for solar system objects. The array telescope can generate a large FOV (≥ 2 deg^2) even for 30m+ class instruments, it is the most cost efficient means of achieving large telescopes with large FOV and can be scaled ad infinitum by adding more elements.

The array telescope has a natural built-in resiliency with 100% availably. The nature of the instrument allows the largest possible community of users, as each element in the array can be used separately or in groups of any size up to unity. Its dynamic range is scaled as the number of elements is increased and can reach 125dB or more.

A quick return on investment is achieved as the array will start to come on-line within ~3 years and as elements are added. The revenue generation is excellent as individual elements could be rented out. The array only needs a modest initial capital investment because of its ability to grow organically to any size as required.

The Madawaska Highlands Observatory Wide-Field-Telescope and a comparable 2m class telescope are used as the models, representing a state-of-the-art wide FOV instrument for its class size. Such an instrument can build an equivalent large aperture from ¼ to ½ the cost of a comparable single large telescope in terms of aperture and overall performance but with capabilities far beyond a traditional single large telescope.

1. Introduction

A large telescope comprised of many smaller telescopes in an array has an extraordinary amount of flexibility currently not found in a single large telescope. In addition to other significant advantages simply not possible with a single large instrument. The capability of serving individual users with less demanding requirements to users requiring large telescopes cannot be satisfied today with any single instrument.

The Madawaska Highlands Observatory Wide-Field-Telescope and a 2-m telescope of similar design and technology are proposed as the elements in an array that could be scaled to any size. The key is to mass produce a small high performance telescope and leverage the economies of scale. Individual elements in the array are connected with Gbit fiber to a central computer for summing or using the elements on their own. The fiber would have sufficient bandwidth to supply all the communications, control, data etc. The power requirement for each unit would be no more than a few hundred watts and could be supplied from solar panels.

The unit elements designed for optimum performance will employ carbon fiber construction throughout with a single chip large CCD monolithic imaging solution. The goal is to produce a simple but extremely high performance instrument, each unit telescope being autonomous with the smallest possible footprint, thus saving cost and minimizing thermal inertia and maximizing airflow. The design of the Madawaska Highlands Observatory Wide-Field-Telescope satisfies these requirements. With current technological and cost limitations an array telescope is best suited for the 400-1000nm range. However with technological progress in sensors this could be extended further into the infra-red at reasonable cost. The UV performance is somewhat limited by the glasses used in the corrector lenses.

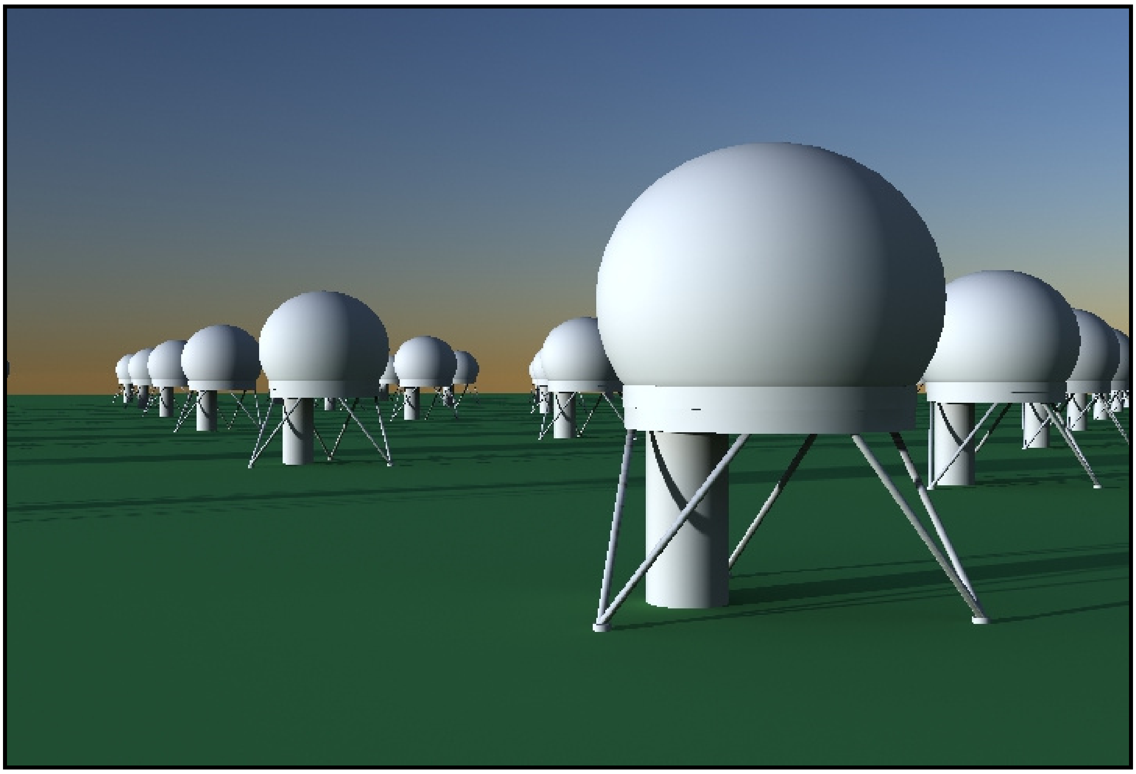

Figure 1 - Conceptualized Telescope Array

2. The Madawaska Highlands Observatory Wide-Field-Telescope

The Madawaska Highlands Observatory Wide-Field-Telescope is used as the model, a 2-m element would be very similar in its design, construction, technology etc, but with a narrower FOV.

The Madawaska Highlands Observatory Wide-Field-Telescope is designed as 1-m prime focus instrument with a 5 degrees^2 FOV. The entire observatory employs carbon fiber throughout for its light weight, superb thermal properties, high stiffness and its mechanical toughness. It allows the construction of monolithic components and permits much flexibility in shaping etc.

The CCD camera employs the largest imager in the world, the DALSA manufactured STA1600 with some 112 million pixels in a 95mm square arrangement. A monolithic array has many advantages over mosaics with much higher reliability due to fewer interconnections and lower cost. Such an imager is easier to calibrate, has a more even QE and has no gaps! The STA1600 has 16 read ports witch allows a readout in the 1 second range. The camera is cryo-cooled to -100ºC thus minimizing thermal noise.

The Madawaska Highlands Observatory Wide-Field-Telescope employs active optics to assure a sharp focus by compensating for gravity induced dimensional distortions. The use of carbon fiber in the mount allows for a lower mass and increased stiffness.

The dome will also be made of carbon fiber and employs a ¾ sphere Calotte topology for optimum local seeing. The dome will be elevated by some 3.5m from ground level to minimize ground thermals and accelerate dome cooling while improving air flow. The Observatory is designed to minimize its total mass thus its thermal footprint and track ambient temperature in quasi real time.

The Madawaska Highlands Observatory Wide-Field-Telescope is believed to represent the state-of-the-art for a modest size instrument and thus well suited to form the model element in such an array.

3. Optimum Aperture Telescope Unit

A 2-m class version of the Madawaska Highlands Observatory Wide-Field-Telescope using a 140mm square monolithic CCD sensor, the biggest chip to fit on a 200mm wafer, with a field of two degrees^2 would yield a PSF of 0.33”/pixel; a good fit to a 0.65” FWHM mean site. The telescope would have a focal ratio of 2.84 with a focal length 5.7m. An f/2.84 optical system is easier to manufacture than the f/2.4 of the MHO. The 2-m class is believed to be the maximum economic size in terms cost, manufacturability and logistics.

4. Performance

For a ground based instrument the performance is seeing limited no matter how big the telescope; a 1-m instrument has a natural disk of 0.26” (see Figure 2) even the best site in the world could not deliver its full potential. Due to the cost of adaptive optics and their extremely limited FOV, they are not considered; a similar rationale applies to mosaic CCD imagers. The objective is to produce a very high performance telescope and paying close attention to the cost and manufacturability of the unit.

As plotted in Figure 2, a 1-m class telescope would be the smallest unit size suitable for the array telescope, as its performance would match the best sites in the world (~0.65" FWHM mean). A 2-m class telescope is believed to be the upper limit to maintain cost efficiency.

It is much easier and cost efficient to optimize a small telescope in terms of overall performance as compared to a single giant telescope. The bulk of local seeing issues are associated with thermals and achieving perfect temperature equilibrium with the ambient. This is much easier when dealing with a few hundred Kg vs. hundreds of thousands of Kg total mass. For example the LSST mirror weights 16,300 Kg compared to the MHO mirror at ~60 Kg. Thus an equivalent aperture array has a huge advantage over a comparative single large telescope because the thermal load is smaller to begin with and spread over a vast surface area and can track the ambient temperature almost instantly and thus will perform much better with ambient temperature fluctuations amongst other considerations.

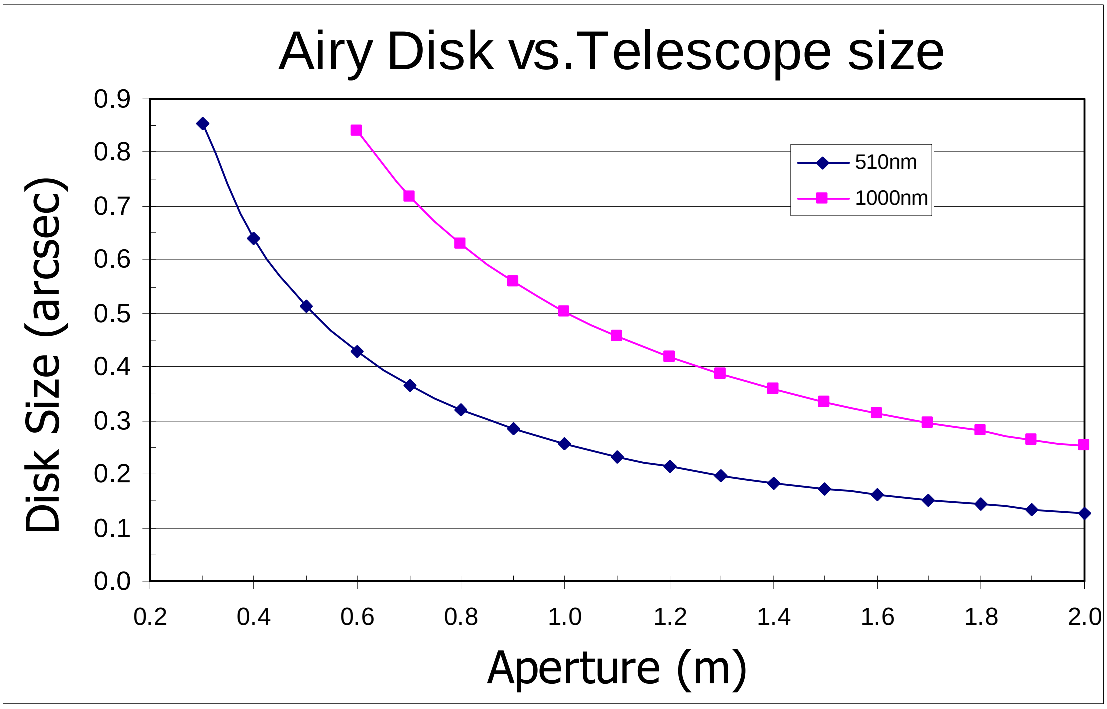

Figure 2 – Disk Size vs. Aperture at 510nm and 1000nm

5. Revenue Generating Capability

In terms of generating revenue, such an array is extremely efficient. Many users employing one or a small number of units would in effect generate more dollars per unit time than one user using the entire array. For example with 1-m units, a 100 unit array could generate ~$3000/hr for 10m equivalent aperture. The same array with 100 users at say $125/hr would generate $12,500/hr. Similarly a 2-m unit, a 100 unit array would generate ~$5000/hr for the 20m equivalent or $25,000/hr for 100 users ~ at $250/hr.

6. Funding Model

Large telescope projects are typically funded by many institutions across many countries. The array telescope presents a very unique ability to attract the largest possible audience in terms of the funding model. The ability to use the array in its unit elements permits smaller institutions to participate; somewhat analogous to a share based model (the telescopes represent the shares). Where institutions would own units and share in the unison use by the proportion of their investment. For example if the array was dedicated to 50% unison and 50% unit use, institutions would be guaranteed 50% of the time on a small but very powerful telescope at a superb site. The economies of scale would in effect allow each institution to obtain maximum return on investment. Indeed several institutions may want to combine their 50% unit time to achieve a greater aperture for specific projects. The model allows for institutions to have a greater participation by acquiring more shares (telescopes). The ability to permit modest capital investments and yet have access to a very large telescope with unique and powerful capabilities is bound to be very attractive. The array telescope allows institutions to add to their portfolio at any time and new institutions to join the array. Since adding each new unit in the array could probably be executed in a short time frame. Indeed units could be bought, sold or rented as required by institutions adding an extra degree of flexibility.

Institutions could use the array as an investment opportunity, renting out the majority of the time with the occasional use. Indeed the institution may not have any interest in the unit time and rent that fraction out and use only the unison time with its maximum aperture. Such an approach would in effect pay for the initial investment within 10 years.

The array telescope, beyond its technical and economic merits, offers an extremely flexible funding model with a very modest initial investment by the broadest possible community. The model offers an opportunity to start small, and grow to meet demand without any real limits and permitting anyone to join at any time. As the array grows, the unison power (effective aperture) grows with it and the ability of the array increases. Thus the traditional boundaries of classical large telescopes are removed by allowing the telescope to grow as required with modest investments.

7. Operational Model

The nearest operational analogy is a condo corporation, where users own the individual units and pay a ‘condo fee’ in effect an operational fee. Thus the unit holder would own unit telescopes. The difference here being the corporation would be responsible for the maintenance and repair of the unit in addition to the array as a whole. The condo model allows the unit holder to rent, buy and sell units. A pool could be setup were holders put their unit into the pool to dispense with administrative logistic and collect their rent so to speak, albeit with some overhead. This type of model allows much flexibility and revenue potential for the unit holder. The array telescope would be located at a superb site, making it very attractive as an investment. There would be logistics to setup at the site etc which could be rolled into the operational fee, thereby easing the capital investment. Such a model changes the structure to finance the endeavor making it look more like an investment that will open up new financing possibilities not presently feasible under current models.

The operational model with a wide participation spreads the operational cost over all the unit owners and thereby minimizing each unit owner's annual cost. For example in a 100 unit array with 50 owners (2 units each) and an annual operating cost of ~$15M, each owner would only pay $300K , very reasonable for 50% of the time on a state-of-the-art 3m telescope (2 x 2-m) with access to 30hrs annually of time on a 20m equivalent telescope!

8. Array Flexibility

The array can be in any size or configuration. In volume each unit is expected to be in the low million dollar range (~$1.2M for the 1-m and ~$3M for the 2-m) adding more elements is very cost efficient. The flexibility of such a telescope is unmatched today.

Flexibility is the greatest strength of such an array. It be can configured to cover the maximum area or to reach to the greatest depth. The array would also be very reliable as any unit failure would not bring down the array, in effect the array would be accessible 100% of the time. Even scheduled maintenance, mirror recoating etc. would have no noticeable effect on the array.

A 100 unit array with 1-m units configured into 4 groups of 25 units, each covering 5 degrees^2 FOV with a combined FOV of 20 degrees^2 has an equivalent aperture of a 5 metre instrument with an Étendue of 340. Two 50 unit groups configured to have an effective FOV of 10 degrees^2 with an equivalent aperture of a 7 metre instrument; this 100 unit array has an effective collecting area of 65 m^2.

9. Economies of Scale

The key to the success of an array telescope lies in the economies of scale, able to produce identical telescopes at low cost. Each observatory (unit) would be fully assembled, tested and integrated at the factory and shipped whole to the site. The dome would be disassembled into a few components. The complete optical tube assembly made entirely of carbon fiber and weighting ~200 Kg (1-m unit) would ship as a complete unit to the site. The mount, partly made of carbon fiber, would also be shipped as an assembly coming in at the 200 Kg range. The site would be ready with pier, dome skirt, pedestals and logistics. The observatory could be made operational within a week. Factory testing and integration would give a high degree of confidence that the reassembled telescope would become quickly operational. Sufficient spare parts will be on hand to minimize telescope downtime to perhaps a day, baring a catastrophic failure. Telescope components are very light thus 1 or 2 persons could easily handle the task, even the mirror weights only ~60 Kg (1-m unit).

10. Array Topology

A likely scenario is a tight circular arrangement (52 units), Figure 3, with a second group separated by 100 Km or more. With the array separated into two groups, as in Figure 4, an immediate distance to an object is obtainable (see Figure 10) for solar system bodies. The further the two groups are apart the greater the range of the parallax. The groups would be connected with a multi-Gbit wireless or potentially with fiber. This technique is extremely useful in NEO search and general solar system studies.

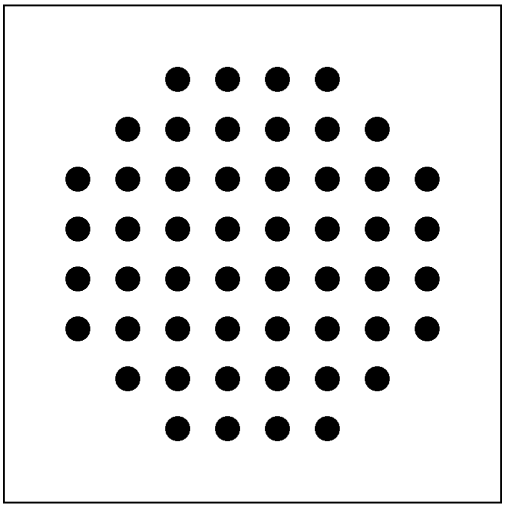

Figure 3 – 52-Unit Tight Circular Arrangement Array Topology

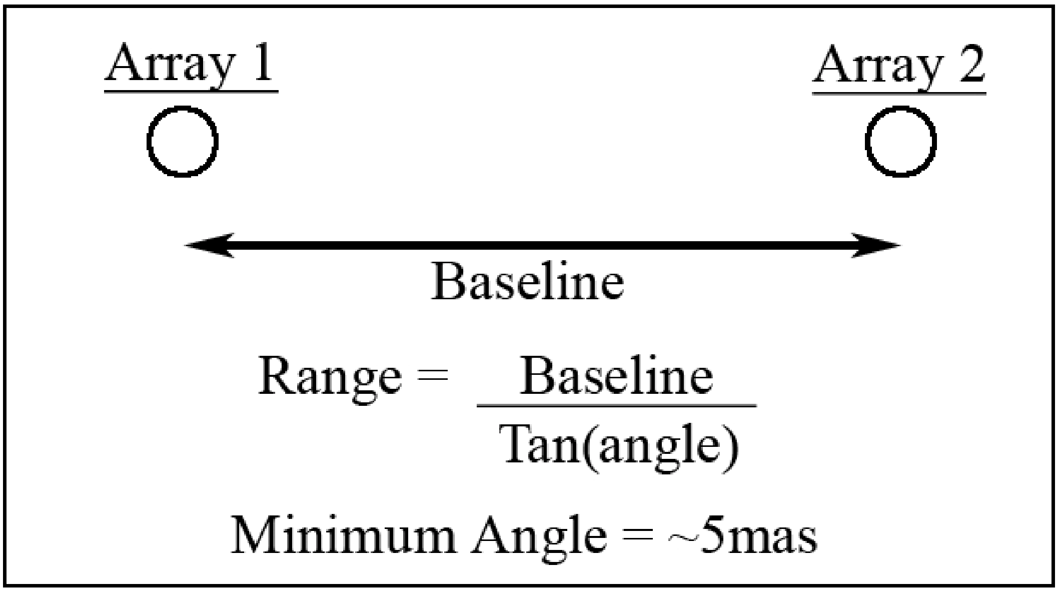

Figure 4 - Array Topology for Instant Distance Measurement

11. Equivalent Collecting Area, Étendue and FOV

When the units in the array are used in unison they will have the largest equivalent aperture, Figure 5 and Figure 6 plot the equivalent aperture and the equivalent collecting area in m^2. Three Hundred 2-m units would produce the equivalent of a 40m instrument with a 2 deg^2 FOV and an Étendue of 2000 and cost somewhere in the ~$1B to build.

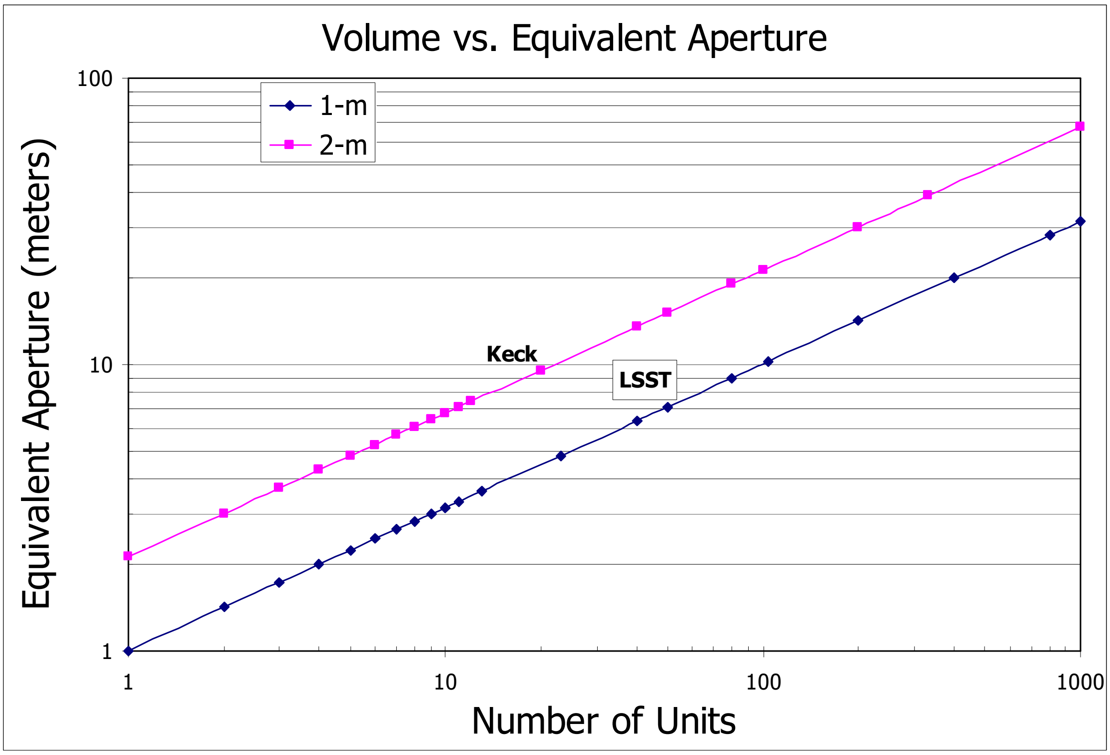

Figure 5 - Volume vs. Equivalent Aperture

Figure 6 plots the volume of units vs. the equivalent aperture in square meters (m^2), the Étendue $\Omega \cdot A$ ($deg^2 \cdot m^2$) and the FOV in square degrees (deg^2). The 1m units are calculated with a FOV of 5 deg^2 and the 2m units with a 2 deg^2. As units are added to the array the performance of the array rises linearly. The nature of the array permits the Étendue to be deployed in terms of sky coverage or aperture, in either case the Étendue remains constant. If the sky coverage is emphasized then the effective aperture on the part of the sky will diminished on the other hand of effective aperture is emphasized then the sky coverage will be reduced per unit time. This is a feature not found or even possible on current or planned large telescopes.

Additionally the spectroscopic performance also increases as units are added. For example with a 3.5nm BW filters covering to 400nm to 1100nm band, it will require 200 filters to cover the entire band, accomplished in one exposure with 200 units or 4 exposures with 50 units and so on.

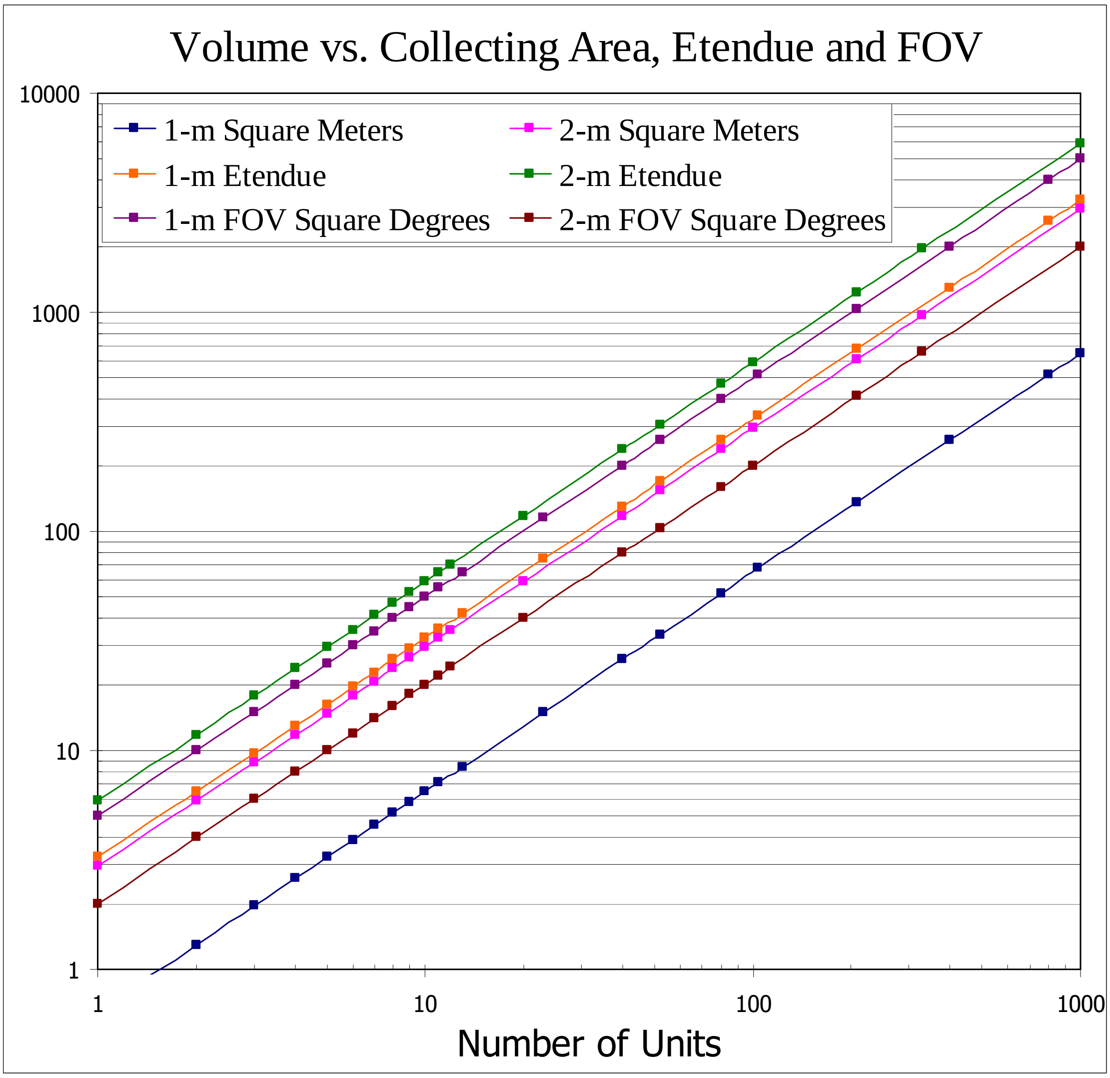

Figure 6 – Unit Volume vs. Equivalent Collecting Area, Étendue and FOV (1m-5 deg^2, 2m-2 deg^2)

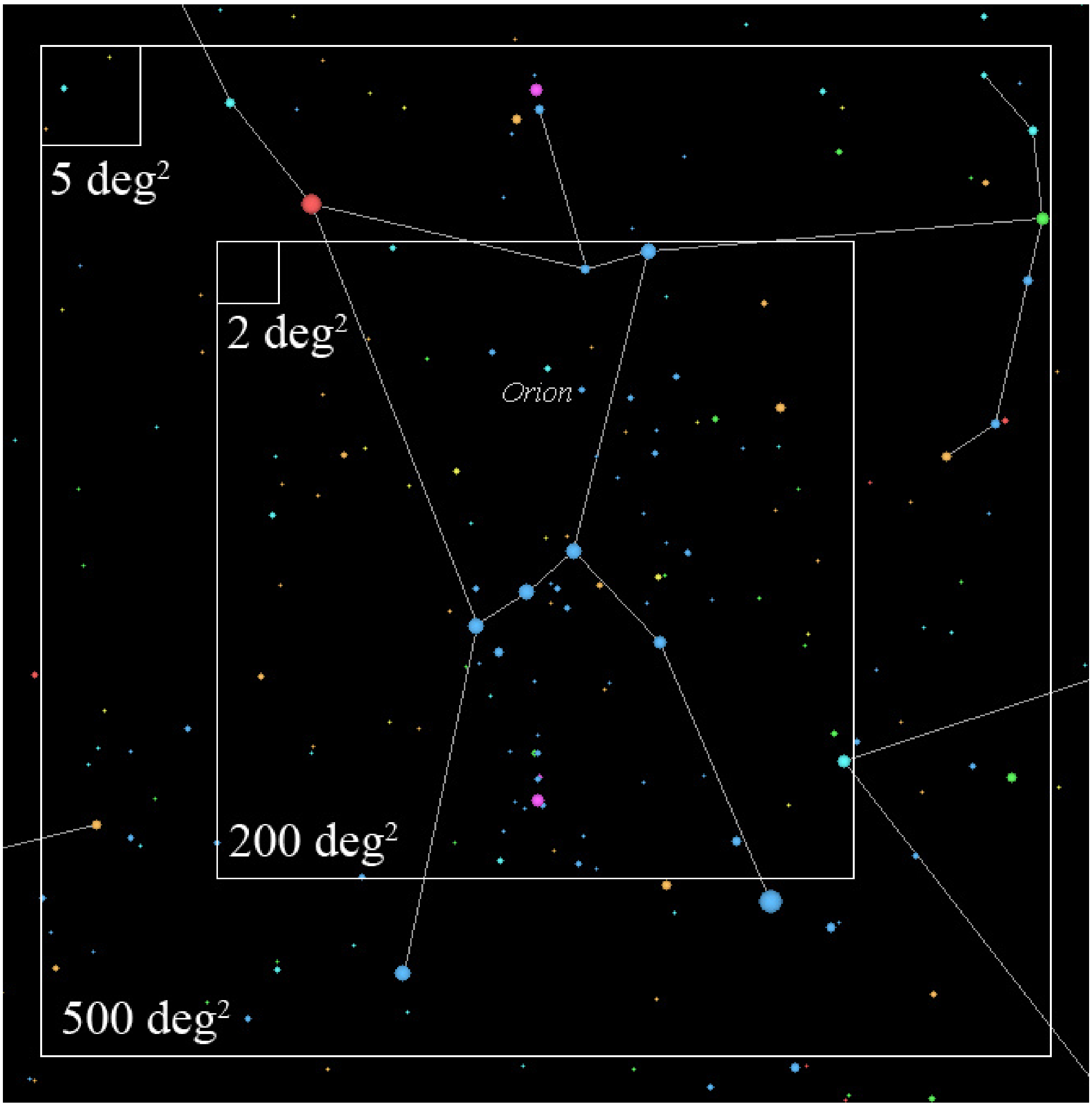

Figure 7 - Array Field of View with 100 units

Figure 7 is the array used in its maximum sky coverage mode with the 1-m 5 deg^2 and 2-m 2 deg^2 units' elements. With such a massive FOV could the entire visible sky could be covered every night and without any seams! The smaller squares shows the FOV of the units, when used in unison the FOV would be probed with 10-m (5 deg^2) and 21-m (2 deg^2) telescopes.

12. Unit Elements (Telescopes)

FOV:

The design of the Madawaska Highlands Observatory Wide-Field-Telescope can be adjusted to yield different size FOV. For example a 100-unit 9 deg^2 version (although more expensive than the 5 deg^2 version due to the higher cost in producing faster optics) would allow the same coverage as the LSST but with a 10 m aperture, twice the effective mirror area of the LSST reaching that much deeper. On the other hand a version with a FOV of 2 deg^2 would yield 0.46"/pixel for better PSF. A 2m telescope with a 2 deg^2 FOV is a good compromise for aperture and PSF, yielding 0.33"/pixel with the 140mm sensor.

Figure 8 plots the field size in deg^2 vs. pixel pitch in arcsec/pixel for the existing STA1600; a 9,000 mm^2 112Mpixel monolithic image sensor. Using a 200mm wafer, a monolithic sensor of 20,000 mm^2 with 250Mpixel could be made, the biggest sensor that could fit on such a wafer, this would result in 2-m telescope with the 2 degrees^2 FOV with 0.33"/pixel

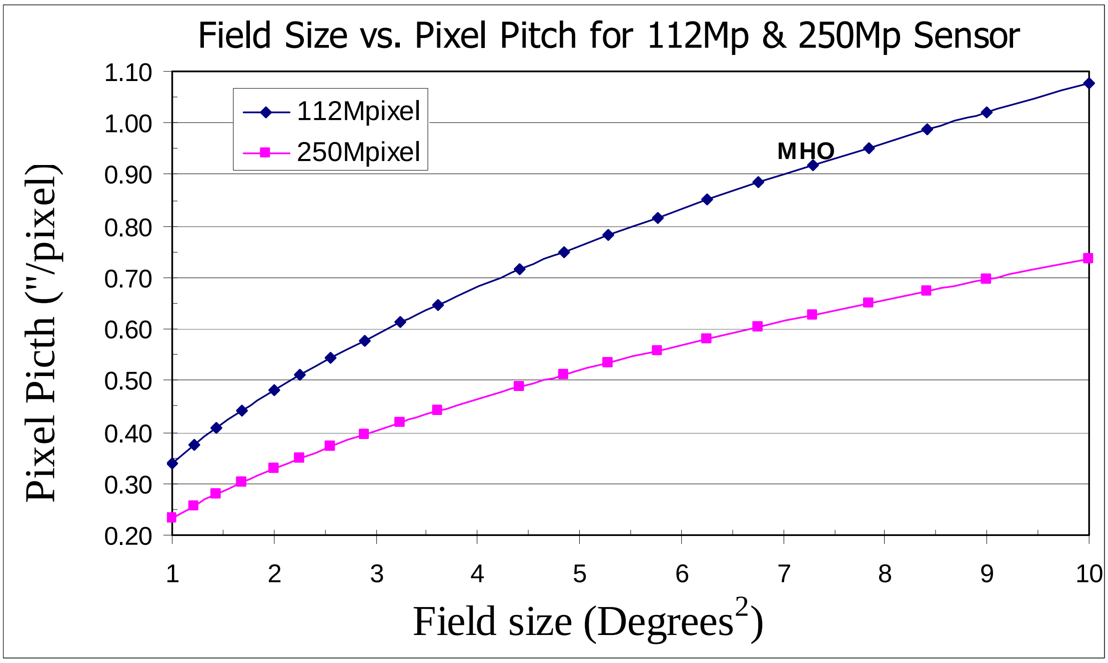

Figure 8 – Field size vs. Pixel Pitch with the Monolithic 112M and 250M pixel imager

APERTURE:

Increasing the aperture increases the cost, typically much faster than aperture. Larger apertures make it much more difficult to produce a wide FOV without dramatically escalating the cost. A 2-m class could be produced for perhaps ~2.5x the cost, say in the ~$3M range in volume. With 4X the area, 100 such units would be equivalent to a 20m instrument. A two-metre aperture is the largest size that is believed to be feasible in terms of unit costing and volume manufacturing.

13. Real-Time Multi-Spectral Wide-Field Imaging

The array will permit to obtain real-time (in one exposure) ugriz images, with sufficient units in each color to achieve the same limiting magnitude. Indeed the units could be outfitted with a multi-slot filter-set with up to ~20 filters.

Beyond ugriz and broadband filters, outfitting units with different groups of narrow band filters yields a Widefield medium resolution spectrum for every object in the FOV. This is a big advantage over current methods, without plates, fibers, gratings etc and no preparation required, thus much more efficient. Indeed it would be possible to reach magnitude 25.5 in the r’, BW=3.5nm in 10,000s (s/n=5) with 2m units; each telescope unit would contain part of the filter set with some units using identical bands for greater depth.

A 3.5nm BW seems a reasonable compromise, with high transmission, less sensitivity to temperature variations and angle of incidence. A 200 unit array would require one exposure to cover the entire 400-1100nm band in 3.5nm bands. For spectral areas of particular interest several units could be equipped with identical filters thereby reaching the maximum possible depth. Filter(s) [trays] could be made removable for added flexibility.

Obtaining spectrums without spreading the light is tremendously advantageous, as much greater depths can be obtained with a smaller aperture. Although the unit telescopes in the array are small by comparison to a 10m telescope single telescope, the large single telescope must spread the starlight in order to obtain a spectrum. To reach an even greater depth several units can be combined.

Although limited to medium resolution spectrograms the parallel nature of the array telescope is unrivaled when trying to simultaneously measure hundreds of thousands if not millions of objects in a large FOV.

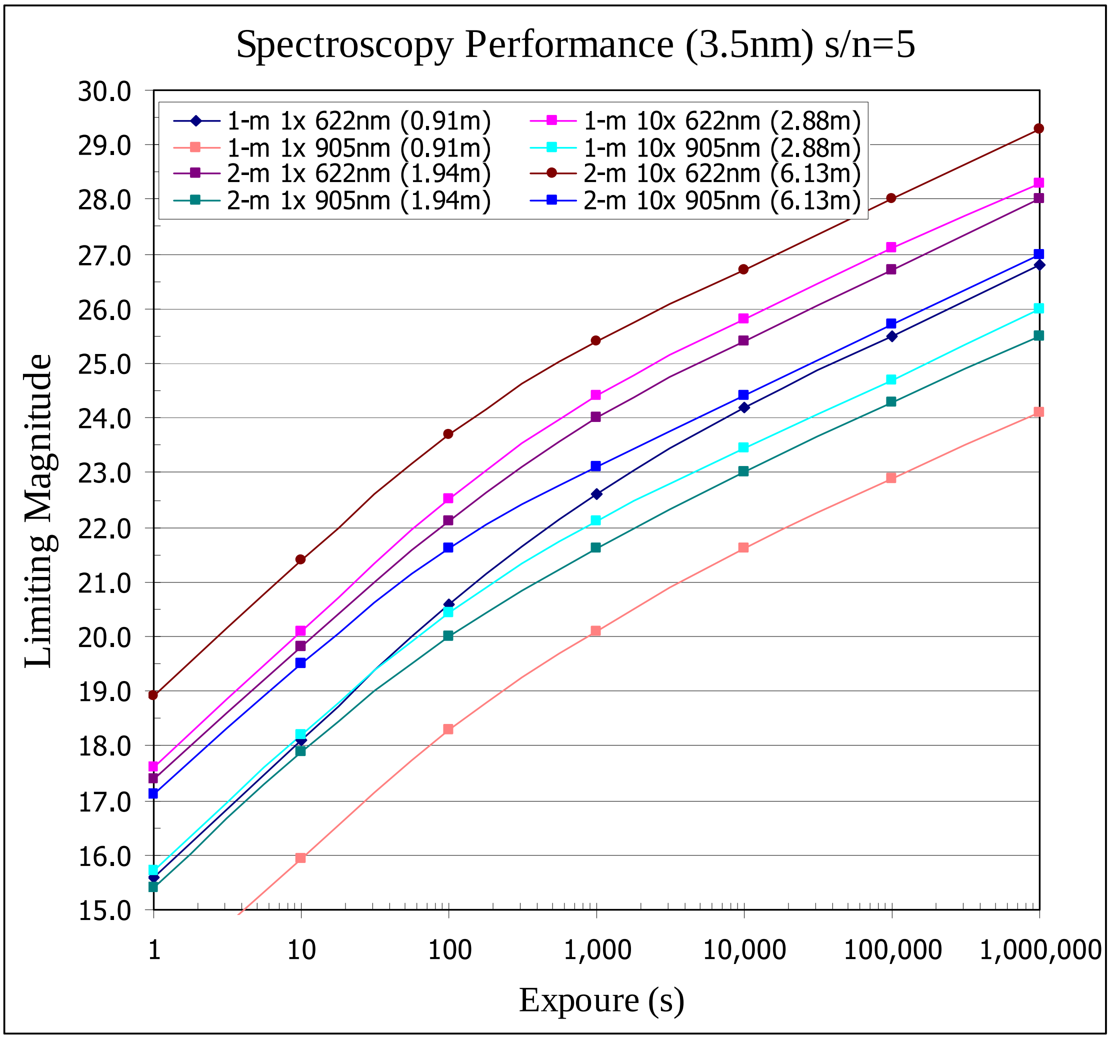

Figure 9 – Spectrographic performance with a 3.5nm BW

Figure 9 plots the exposure vs. limiting magnitude for 1m and 2m units at 622nm and 905nm. Also plotted are exposure with 10 units (filters) used in unison to reach much deeper. The calculations are based on a filter BW=3.5nm with 60% transmission and a site at 5000m with a mean seeing of 0.4" FHWM and RN=4e- per unit and 0.51"/pixel for 1m units and 0.33"/pixel for the 2m units.

14. Measuring Solar System Distance in Real Time

An array telescope arranged in two groups would instantly determine distance to nearby solar system objects and be a very powerful tool for NEO search and general solar system studies. The parallax range is determined by the baseline and the s/n (exposure). Depending on the baseline, the range could extend beyond 1000 a.u. A tight circle would have range of ~0.04 a.u. for a 150m diameter array. The groups could be connected with fiber or Gbit wireless. Figure 10 plots the range vs. baseline with a 5 milli-arcsec resolution.

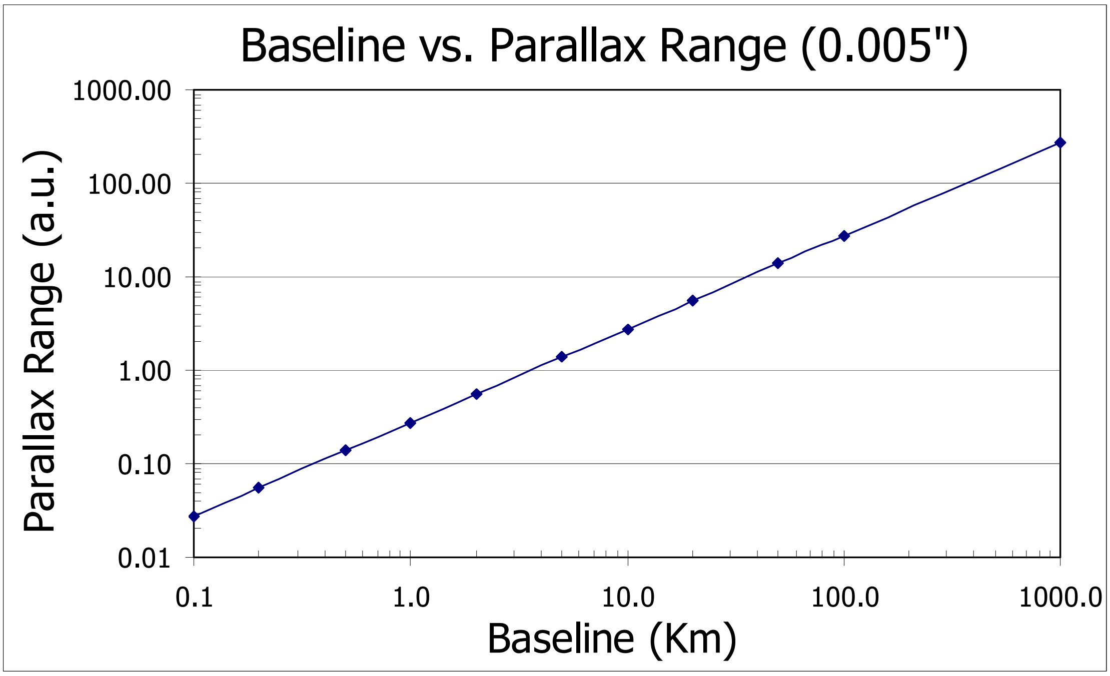

Figure 10 - Solar System Parallax Range with 5mas

15. Specifications and Limiting Magnitudes

Figure 11 plots the array limiting magnitude for 1m and 2m units at 622nm and 905nm. Calculations are based on a site with a 5000m altitude, 21.8 mag/arcsec^2, 0.4" FWHM seeing and 5e- RN per unit. 112Mp is the STA1600, the 250Mp as yet to be fabricated, it is the biggest monolithic chip that would fit on a 200mm wafer and is believed to be the ideal sensor for an array telescope working in the 300-1000nm band. The calculations are based on the current STA1600 QE.

Specification	**100 unit 1-m 112Mp**	**100 unit 1-m 250Mp**	**100 unit 2-m 250Mp**
Unit FOV (degrees^2) (seamless)	5	5	2
Unit image size (pixels)	10,580 x 10,560	15,500x 15,500	15,500 x 15,500
Maximum array FOV (degrees^2)	500	500	200
Array image size in max FOV	105,800 x 105, 800	155,000 x 155,00	155,000 x 155,00
Equivalent collecting area (m^2)	67	67	300
Equivalent aperture (m)	8.5	8.5	20
Array Étendue (m^2·deg^2)	340	340	600
PSF ("/pixel)	0.76	0.51	0.33

Table 1 – 104 unit Array Specifications

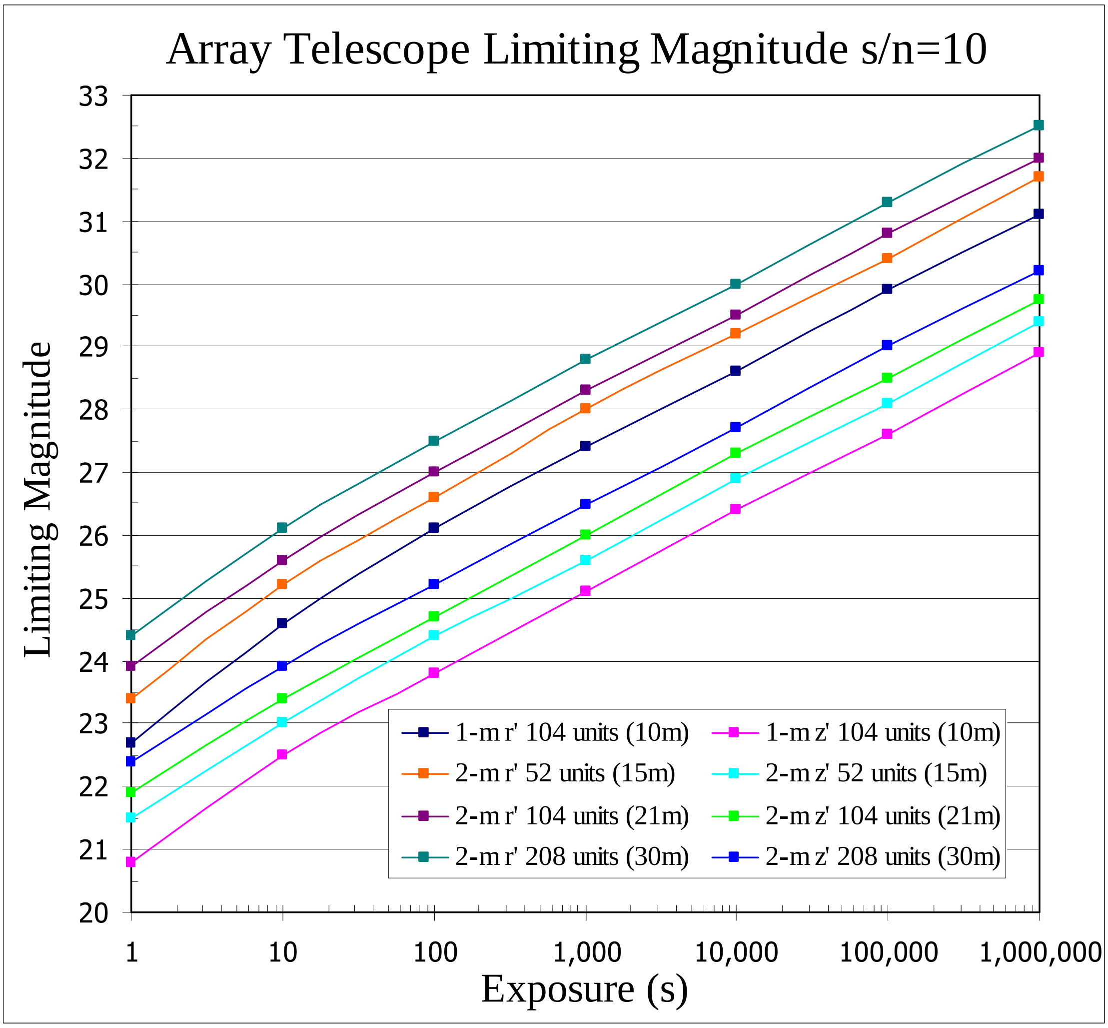

Figure 11 - Array Telescope Limiting Magnitude When Used in Unison

16. Cosmic Rays and Correlation Analysis

Having more than one image of the FOV in real time has several inherent advantages. For example cosmic rays can be easily removed. Multiple images of the same FOV in real time have many interesting correlation applications. It would also be possible to study cosmic ray distribution, as the cosmic rays are easy to identity on the images and using the large spatial area (22,500 m^2 for a 150m array) covered by the array to advantage.

17. Comparative Analysis

Table 2 highlights the key advantages when comparing an array telescope to a single large instrument. The array telescope has many significant advantages over a large single instrument; the most significant is its flexibility in reconfiguration and the ability to generate extremely wide FOV. The array elements can be configured as a single narrow field, where all elements are imaging the same part of the sky or distributed to yield the maximum field of view, potentially several hundred square degrees. Any combination thereof is possible.

Parameter	Array	Large Single
Configuration Flexibility	Infinite (Large FOV or large Aperture)	Very limited
Instrumentation	Imaging only	Very flexible
Resiliency	Very large	NONE
Multi-Spectral (ugriz)	Real Time	Time delayed
Instant Parallax	Yes up the 1000 a.u.	NO
Dynamic Range	Very Large, multiplies by #units	Wells fill up quickly, limited
Number of users (projects)	Single or Limited by # units in array	Single
Downtime	100% always available	YES
Cosmic ray removal	Very easy	Tedious
Revenue generation	Significant (~5X than single)	Limited and fixed
Real time correlation analysis	Yes	NO
Expandability	Yes (cost efficient)	Very difficult (very expensive)
Large FOV	Yes – extremely efficient (very large)	Very difficult and expensive
Time to bring on line	~3 years first element, successive elements added every few weeks	Up to a decade or more
Operational cost	Higher than single telescope due the large number of elements to maintain	Industry average
Spectral Range	ugriz	Broadband
Spectroscopy	Every object in the field through distributed narrowband filters	Selected objects through optical fibers, gratings etc

Table 2 - Array Telescope Compared a Large Single Telescope

18. Dynamic Range and Pixel Saturation

The dynamic range of the CCD image sensor is directly related to the size of the well and the read noise. For example the LSST with its 9µm pixel (~85,000 e^- well size) will saturate in 15s on a 19.5mag star in the r'. An MHO array would need 800s (53x longer) to reach saturation with a 19.5 mag star, and would require a mag 15 star (r') to reach saturation in 15s. In effect each additional unit increases the well size, thus a 100 unit array would have 100 times the effective well size of a single unit, 8100μ^2m equivalent (for 9µm well size) or about 8,000,000 e^-. The readout noise of the STA1600 at ~14s is about √100 x 5e^- and well capacity of 8,000,000 e^- gives an effective dynamic range of 20 log (8,000,000/50) of 104 dB, see Figure 12.

The read noise for an array telescope is a limiting factor has each unit telescope adds to the read noise, albeit the noise increases by the square root. Thus reducing the read noise will have a direct improvement on system performance. Currently 4e- is achievable at low read speeds; pushing read noise to the ~1e- level would see a huge improvement in dynamic range. Perhaps a version of the photon counting CCD with sub-electron RN that also promises a wider band QE. Although photon counting CCD's tend to reduce the well size.

Figure 12 plots the volume vs. effective dynamic range for several download times/read noise. The faster download time have lower dynamic range; likewise the slower download times have higher dynamic times. The chart is projected to 3e-, 1e- and 0.5e- RN.

Figure 13 plots the dynamic range vs. download times for a 100-unit MHO array. Six second downloads yields 100dB of dynamic range.

Figure 14 Plots the saturation vs. magnitude (r') based on reaching 70,000 e- with an 80,000 e- full well capacity. A magnitude 15 star would reach 70,000e- in 15 seconds.

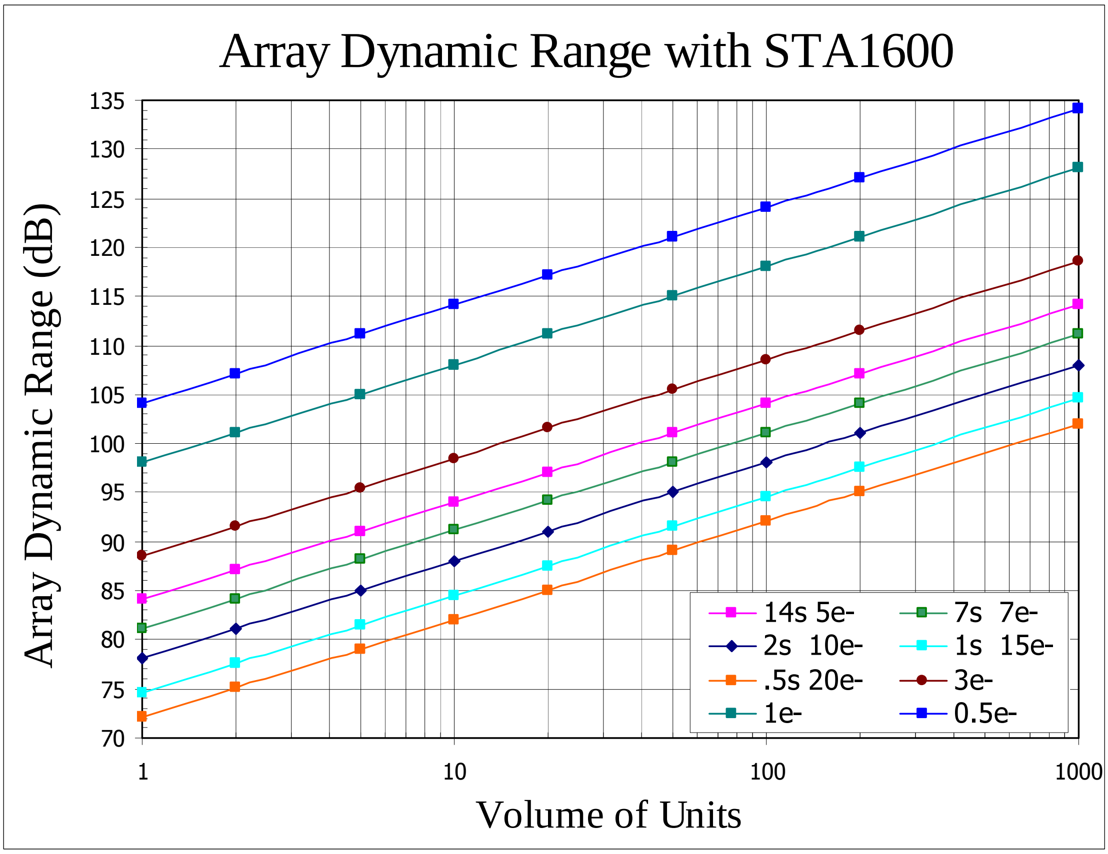

Figure 12 - Array Dynamic Range (dB) with various read noise values and related download times

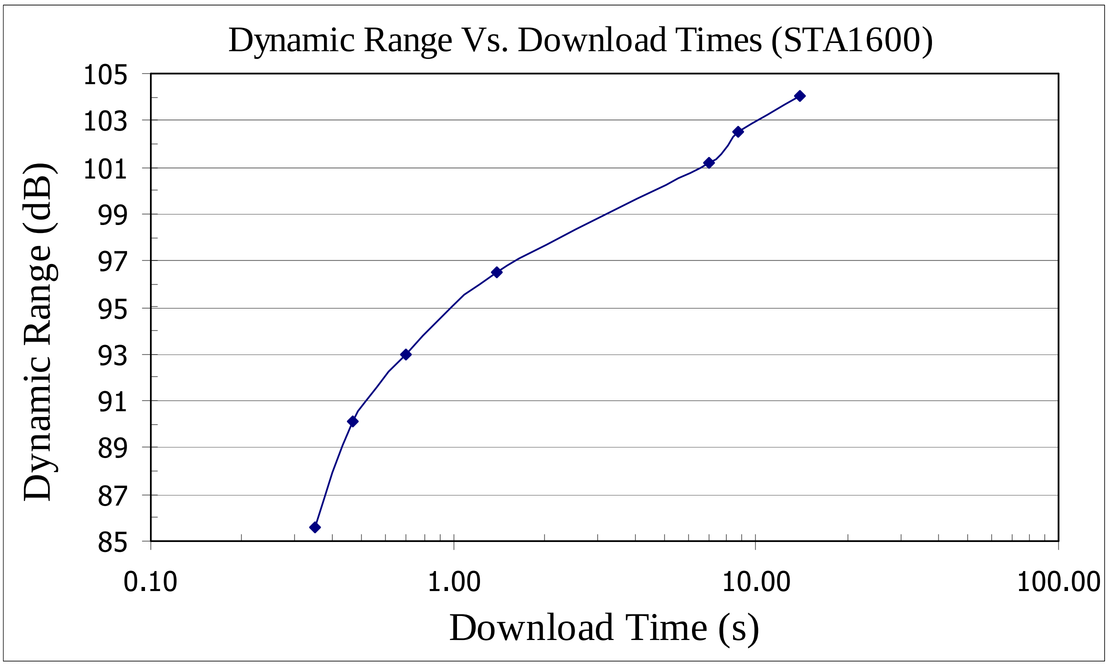

Figure 13 - 100 MHO Array Dynamic Range vs. Download Times with 112M pixel imager

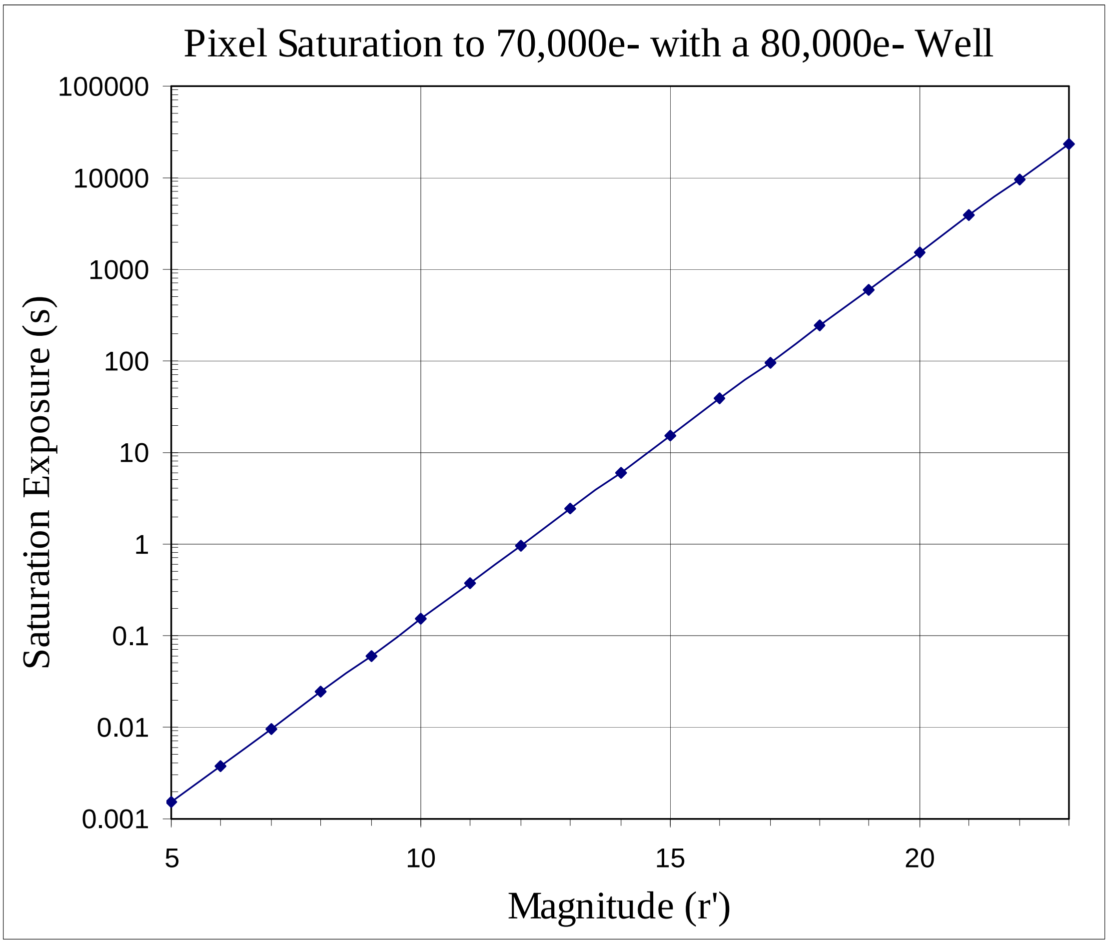

Figure 14 - MHO saturation to 70,000e- based on 80,000e- well with the STA1600

Having a larger effective well size has another advantage in terms of requiring fewer downloads to prevent saturation. A single large telescope fills the well size very rapidly and requires frequent reads to prevent saturation. An array with its larger effective well size requires fewer downloads.

19. Natural Dithering

The availability of real time images of the same FOV has important significance in terms of image reconstruction and minimizing sensitivity difference among the different units. It is particularly useful when the image is undersampled to adequately represent the PSF falling on the pixels. Small shifts in position from unit to unit (natural dithering) can be used to advantage to reconstruct an image with more spatial information.

20. Cost vs. Equivalent Aperture

Producing an extremely wide FOV with a small telescope has very significant advantages over larger instruments. For example a 5m class instrument with an array using twentyfive 5 deg^2 MHO units would cost in the ~$30M range. An 8.4m LSST class instrument would cost in the ~$75M range with fifty-three MHO 5 deg^2 units. This capital estimate cost does not include the support infrastructure

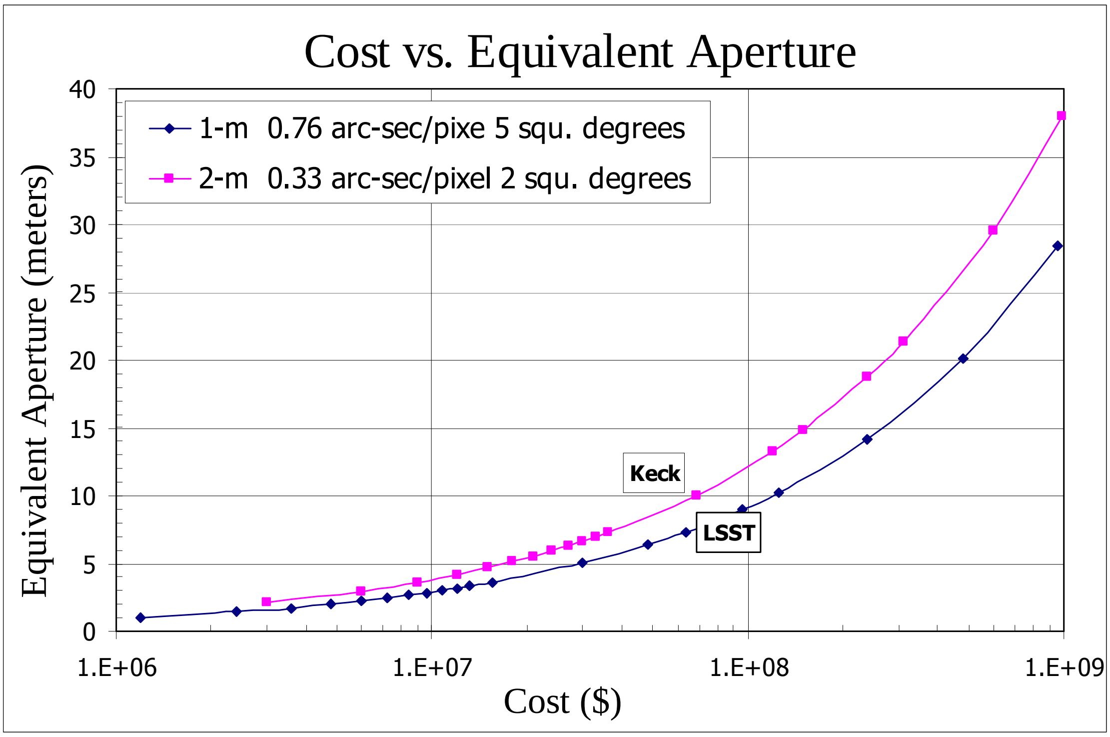

Figure 15 -Cost vs. Equivalent Aperture at $1.2M/$3M per unit

Figure 15 plots the cost of an MHO type telescope array vs. an equivalent aperture. The unit telescope could have anywhere from a 1 to 10 deg^2 FOV. The mass produced cost of the MHO is expected to be in the $1.2M range. With the ultra wide FOV (>5 deg^2) having a premium due to the difficulty in producing the faster optical system. To remain cost efficient a 2-m class would necessitate a narrower maximum FOV, in the 2 deg^2 range. Thus a Keck sized instrument with a 2 deg^2 FOV would cost in the neighborhood of $75M to build and require about twenty-four 2-m units.

21. Beyond the LSST

The 8.4m LSST has a FOV 9.6 deg^2 and is expected to come on stream in 7 years at a total cost of $800M over 12 years (capital + operating). A 100 element array with an MHO unit instrument configured with a ~10 deg^2 FOV would yield a 10m equivalent aperture instrument, twice the aperture of the LSST and cost some ~$150M, the Étendue would be in the 640 range, albeit with lower PSF. 200 MHO units would produce a 14m class instrument with over 4 times the aperture of the LSST yet still cost less than the capital cost of the LSST ~$400M.

22. Instrument Upgradability

Upgrading the array is synonymous with improving the camera. For example looking towards the future where an image sensor is made using high yield 200mm wafers the biggest sensor that could fit on such a wafer is about 140mm x 140mm (5.5” x 5.5”). With 9µm pixels this would yield about 242 million pixels with a 15,500 x 15,500 pixel array. With 5 deg^2 it would result in 0.5”/pixel. Coatings on the CCD are also expected to improve over the years and the application of other processes such has pink silicon could potentially give an extremely high QE from the near UV to >1200nm range. Other properties of the CCD would also be expected to improve in the coming years such has read noise, low level signal extraction (photocounting CCD) etc. Electronically tuned filters may also be developed which would greatly simplify and enhance the telescope.

23. Technical Challenges

The greatest technical challenge lies not in the unit elements but in their interconnection and control. To limit power consumption in each unit, data and control is routed via optical fiber to a central processing cluster who can rapidly analyze the data. Sufficient computing power will be required to calibrate, analyze and stack the images as required. A sophisticated queuing system will be required to manage and control the array. Most technical challenges can be solved by scaling up and adapting existing technologies. Computing power is doubling every 18 months thus this will not be an issue. Hundreds of TFLOPS in the size of small refrigerator will be available by the end of this decade. Thus there are no real fundamental technical challenges.

Unit matching in terms of image scale and so on will be optimized in the production process and quality control. Any residual differences can be compensated for by image manipulation and adjustments.

24. The MEarth Comparison

The only example of an array telescope known is that of the MEarth operated by David Charbonneau at the Harvard-Smithsonian Center for Astrophysics. The array consists of eight off-the-shelf 0.4m RCOS telescopes and is located on Mt. Hopkins, Arizona. The 8 telescopes normally work as individual units (covering the maximum area) when searching for planets around M-stars and used in unison to get better quality photometric data when a planet is suspected. Indeed this technique has already yielded one new planet, a super-Earth.

25. More Telescope time

The nature of the array telescope helps to alleviate a constant significant issue to astronomers; the availability of telescope time. In the 50%/50% share model with 100 telescope units, when not used in the unison mode, hundred 2-m telescopes would become available!

26. Array Limitations

To control the unit cost and remove any kind of manual intervention in the unit operation some limitations are inevitable. It would be possible to have a dual (multi) focus system with a second camera (IR) and different PSF (FL) but such added complexity would add to the cost and have a higher probability of failure.

Fixed Instrumentation: The array unit element has a fixed instrument (optical camera 350-1100nm). A medium resolution spectrum can be synthesized with discrete filters, the use of high resolution spectrometers and other such instrumentation is not possible.

Fixed Focal Length: To keep the unit telescope cost efficient a fixed prime focus design is adopted. Having multiple focal lengths will add a significant amount to the cost and add complexity to the unit, with its higher probability of failure.

27. Conclusions

In terms of flexibility, adaptability, tolerance to failure, configurability, the ability to serve a broad base of users simultaneously, frame correlation, real-time multi-spectral imaging, instant distance determination, large dynamic range, etc. the list is very large, an array telescope has enormous advantages over a traditional single large telescope. One-metre class unit is better suited for the larger FOV while the 2-m class unit is best suited for maximum aperture. There is a higher operational cost due to the higher number of telescopes to maintain. This is offset by the array’s much higher (up to 5X) revenue generating capability. The array telescope can be easily and efficiently scaled to any size. Such a telescope takes advantage of the economies of scale using efficient assembly line production techniques and pre-assembly to deliver the most cost efficient means to achieving a high performance and powerful large telescope with capabilities that go far beyond a classical monster telescope.

A small high performance state-of-the-art one to two metre class telescope would have a modest development cost thus limiting the investment capital required to get the project going. A private firm could be setup to handle the manufacturing, integration and testing thus removing a financial burden form the array project. Or perhaps an existing firm with some investment could manufacture the units. The 140mm CCD sensor would need to be developed, perhaps Semiconductor Technology Associates, the company behind the STA1600, with their expertise in very large sensors, could develop the chip. A computing, software, archiving and data analysis centre would be required. Other resources exist that would help in this regard such as the LSST etc. This cost could also be rolled in the long term operational cost for each unit.

The funding model allows for the broadest participation with a modest investment and permits scaling the array to any size. Participants can join at any time and grow their participation by purchasing units. Units (telescopes) holders could buy, sell and rent their units at will. With a 50% share model, unit holders would have 50% of the time on their telescope and proportional time on the unison. Cooperation with other unit holders will permit larger effective apertures for greater depth and filter performance for specific projects.

Viewed has an investment the array telescope opens up new and innovative means to finance such a project through the proposed funding and operational models.

Key Highlights of an Array Telescope

a) **Flexibility –** Can be optimized for the largest equivalent aperture or FOV

b) **Volume of users –** Can serve as many users as there are array elements up to unity, thus serving the largest possible community

c) **Wide-Field Multi-Object Spectroscopy –** Able to generate medium resolution spectrums of every object in the FOV over the 400-1100nm range with ~3.5nm BW resolution and reaching magnitude 25.5 with a s/n=5 in 10,000s at 622nm (2m)

d) **Real Time Distance–** Generates instant distances with the array split into two groups with the range dependant on the separation, potentially up to 1000 a.u.

e) **Resiliency –** Can tolerate failures and unit downtime with 100% availability

f) **Cost Efficiency-** Most efficient means if achieving large apertures using economies of scale especially with a large FOV, ½ to ¼ the cost a comparable large telescopes

g) **Low Startup Cost –** The capital cost the get the project rolling are very modest. The baseline unit telescope is small and would require minimal investment. The array can start off with a small number of units and grow as required, somewhat organically

h) **Wide FOV –** Extremely easy to obtain large FOV (>2 deg^2) even with 20+m equivalent aperture. Could cover hundreds of square degrees

i) **Expandability –** Very easy, just add more elements. The FOV, Étendue and effective aperture increase has elements are added. Additionally the spectroscopic performance increases has more elements are added

j) **Cosmic Rays –** Easy to remove through image correlation

k) **Time to First Light –** Within 3 years and as instruments are added

l) **Dynamic Range-** Greatly expanded dynamic range, up to 130dB, each additional element expands the dynamic range

m) **Revenue Generation** – Capable of generating 5X the revenue per unit time as compared to single large telescope

n) **Well Saturation** – With a larger effective well size an array takes much longer to reach saturation and requires fewer downloads before saturation. This saves download time and reduces the effective read noise (i.e. fewer reads required)

o) **Monolithic FOV** – An array telescope using the Madawaska Highlands Observatory Wide-Field-Telescope as the unit element would have a contiguous and gapless image which can be used to potentially cover hundreds of square degrees without gaps

p) **Correlation** – The image data is extremely well suited to correlation analysis as many instantaneous images are available of the same FOV

q) **Funding Model** – Extremely flexible and allows the greatest number of participants with minimal capital investment. In a 50%/50% share participants have 50% of the time on their unit telescope and participate in the unison proportional to their unit investment. New participants can join at any time and portfolio's can added at any time to buy, sell and rent units

r) **Natural Dithering** – Small shifts in position from image to image can be use to advantage to reconstruct an image with more spatial information (better PSF)

s) **More available Telescopes** – The operational model of 50%/50% share makes a large number of high-performance modest size telescopes available to astronomers

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