The Madawaska Highland Observatory Survey Capabilities

Frank Roy, mho@madawaskahighlandsobservatory.com
http://madawaskahighlandsobservatory.com

Abstract

The survey capabilities of The Madawaska Highlands Observatory Wide-Field-Telescope, a new Canadian high performance imaging Widefield instrument are discussed. The Madawaska Highlands Observatory Wide-Field-Telescope will be the only large Étendue (Area-Omega = 6.0) instrument in the world with a monolithic and gapless image sensor covering an area of some five degrees^2.

The seamless 5 degrees^2 field-of-view (FOV) coupled with small download times, high overall system efficiency yielding low cycle times and its autonomous operation will result in an unrivaled level of performance for its class size.

The ability to download the entire 5 deg^2 seamless FOV in less than 2 seconds opens up the possibility of searching for rapid variability in a wide FOV.

1. Introduction

An innovative approach to the total package of a high performance observatory has resulted in a one-metre class instrument that has no rivals in the world, and indeed has been shown to outperform instruments several times its size in terms of surveying large areas of the sky to faint limiting magnitudes.

The design of the Madawaska Highlands Observatory Wide-Field-Telescope is focused on achieving a high scientific yield under the climatic conditions of southern Canada while maintaining a low operational overhead. This has resulted in an autonomous instrument with an extremely large FOV that is exclusively committed to imaging. This focused approach will not only increase the total scientific yield but all also improve the consistency and quality of the science. The observatory has no manual intervention and thus will have a consistent, stable and an unchanging set of hardware. This makes for better quality science and vastly increases the efficiency and dramatically lowers the operating cost.

Unlike other large Étendue instruments, the Madawaska Highlands Observatory Wide-Field-Telescope is able to offer a seamless and gapless coverage. The Madawaska Highlands Observatory Wide-Field-Telescope is able to cover 5000 degrees^2 in an 8 hour period with a s/n=5, to magnitude 22 (r') with 1.25" seeing mean FWHM. The Madawaska Highlands Observatory Wide-Field-Telescope with its short download times is well suited to detecting transient phenomena and rapid periodic variations over large FOV's, such has GRB, red-dwarf flares, SNe, rapidly rotating solar system bodies or any unusual phenomena.

The MHO lends itself very well to several types of surveys including multiband, single band, selected area, entire visible sky or rapid temporal etc. The rapid download times open up the possibility for wide field temporal research on the order of a few seconds to sub-second. The wide field design and the overall system efficiency will result in the highest scientific yield. The Camera has the ability to bin and/or download selected areas thus facilitating research that does not required the full use of the 5 degrees^2 FOV.

2. System Parameters

The following parameters are used in all the calculations unless otherwise stated. All the performance calculations are based on equations by Bradley E. Schaefer (1998). The tool is available online at http://onemetreinitiative.com/ccd-limit-tool.html.

Clear aperture	1.0m, 0.65 m^2 effective area
Number of lenses	4, 8 surfaces
Optical system	Prime focus, f/2.4, 2.4 meters focal length
Spatial sampling	0.76 arcsec/pixel
Field of View	5 degrees^2, 2.23 x 2.23 degrees
Vignetting	6% (0.05 mag) at the corners
Site latitude/longitude	N45º 01’ 37.4”, W77º 05’ 57.4”
Étendue	6.0
Camera download time	~2 seconds
Spectral Bandwidth	ugriz + L(400-700nm) + wL(420-820nm)
Quantum Efficiency	80%, 95%, 94%, 88%, 54% (ugriz)
Filter change times	<10 seconds
CCD full well/illumination	80,000 e-, back illuminated double coated
CCD array size	10580 x 10560 (STA1600A)
Total system transmission	44%, 70%, 77%, 65%, 41% (ugriz)
Read noise	4e-/12e- (16s/2s download)
CCD operating temperature	-100ºC Cry-Cooled
Seeing	1.25 arcsec (expected)
Dark noise	1e-/hr/pixel
Sky Brightness	21.80 mag/arcsec^2 (v) measured
Telescope slew/settle/lock	<4s frame to frame (2.23 degrees)
Total cycle time	Exposure + 4 seconds, frame to frame
Angle relative to zenith	0 degrees, for reference
Altitude	400m

Table 1 - The Madawaska Highlands Observatory Wide-Field-Telescope System Parameters

3. Performance

The overall performance is related to several factors, the Delivered Image Quality (DIQ), system efficiency and scientific yield are prime drivers. The Madawaska Highlands Observatory Wide-Field-Telescope is designed to yield high system throughput and cover a large a FOV to deep limiting magnitudes. The entire design is optimized for the best possible local seeing and maximizing the science output. A gapless and monolithic image sensor eliminates any need for dithering and provides a ‘complete image’ when compared to other large Étendue telescopes. This is very advantageous when trying to produce contiguous images for surveys and other types of research.

The following graphs give some idea as to the performance of the Madawaska Highlands Observatory Wide-Field-Telescope. The performance is seeing limited and every effort has been employed to optimize the local seeing. For example: reducing the expected local seeing from 1.25” to 0.85” will half the total exposure to reach the same limiting magnitude.

The fast 2.4 optical system with a depth of field of 14µm (compared to the f/2.44 Oschin Schmidt) is extremely sensitive to any kind dimensional distortions either gravitationally or thermally induced. The Madawaska Highlands Observatory Wide-Field-Telescope incorporates an active optics system that has six degrees of freedom (3 lateral and 3 rotational) and allows for micron level adjustments and ultra precise focus (lateral z). The active optics is capable of keeping the entire 95mm x 95mm image frame in perfect focus across the sky. This will greatly improve the scientific yield and at the same time deliver a consistent image quality hour after hour, night-in and night-out. The dimensional distortions are mapped through the entire sky and this map is applied to the active optics in the course of the exposure. At the beginning of each exposure the image is analyzed (center + corners), the focus is adjusted and the active optics is adjusted with the offset (if any) applied to the calibrated map. The monolithic carbon fibre construction will minimize thermal dimensional issues thus giving a high assurance that the focus will remain sharp even during long exposures or large temperature variations.

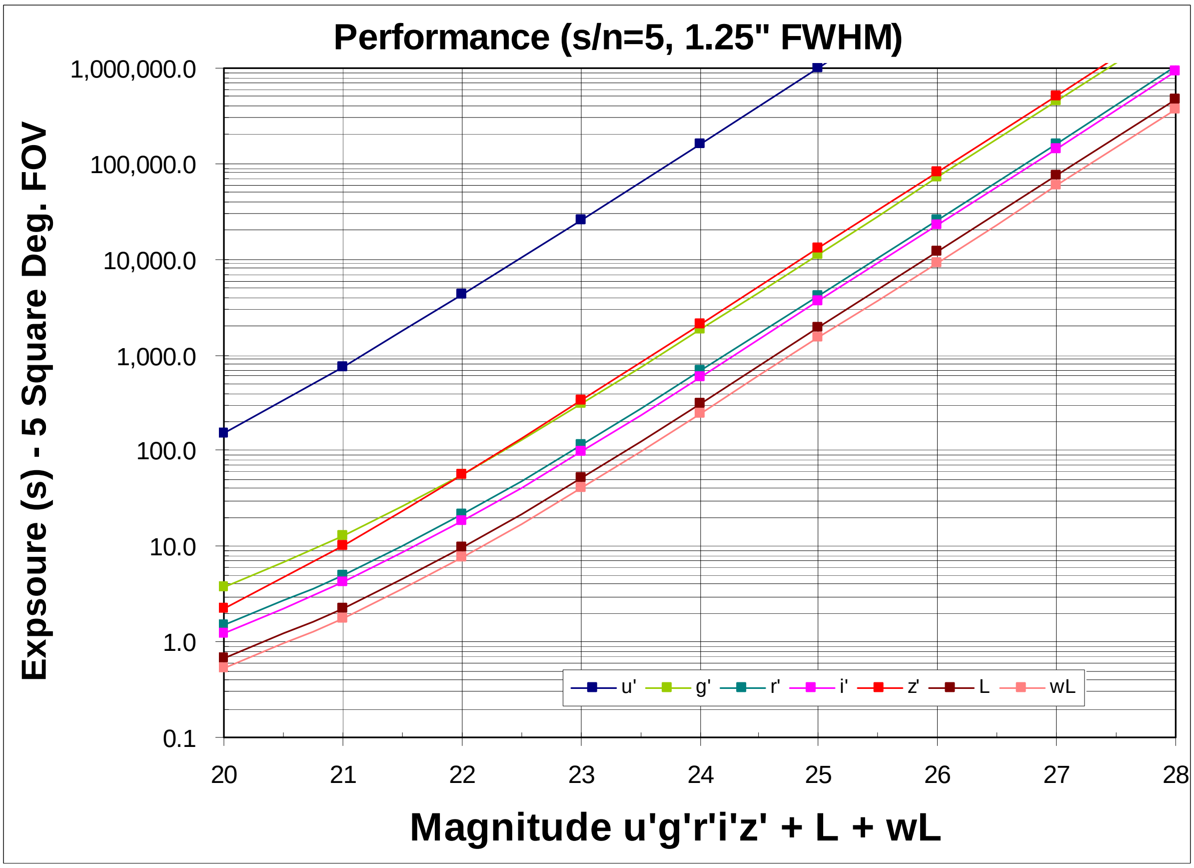

Figure 1 - MHO exposure to reach a given limiting magnitude with s/n =5

Figure 1 indicates the exposure for ugriz + L (400-700nm) and wL (420-820nm) for a s/n=5 and magnitudes 20-28. It will take about an hour to reach magnitude 25 (r') for a s/n=5.

4. Survey Coverage

The coverage will be limited by the depth of the exposure and the filter set. At the latitude of 45 degrees north the maximum southerly declination will be limited to -20 degrees, i.e. 25 degrees above the southern horizon. Going further south will introduce significant reddening. The northerly latitude will give excellent exposure to the far northern sections of the Milky Way as indicated in Figure 2, Gemini to Cygnus, (60º to 180º Galactic) which will be within 20 degrees of overhead. The 5 square degrees seamless FOV, rapid frame-to-frame cycle times, fast acquisitions times (~2s) and low filter change times (~10s) will allow for an extremely efficient wide-field imaging platform. For example the entire visible sky down to δ=-20º could be imaged in one 7 hour night in the r' or i' down to magnitude +20 with s/n=5.

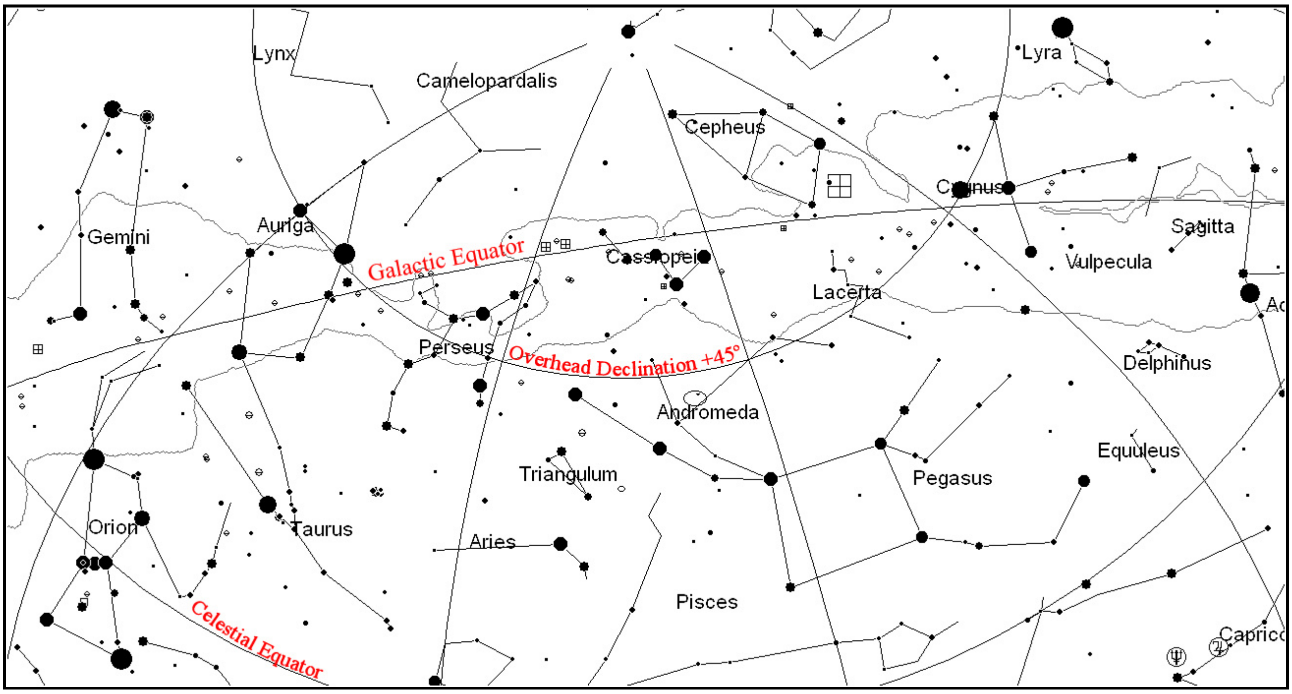

Figure 2 -Northern Milky Way Overhead from the Madawaska Highlands Observatory

Figure 3 shows 4 frames with 10% overlap (5% per side); the effective frame size is 4.5 degrees^2 and resulting in 2.12º centre-to-centre. The MHO has 6% (0.05 mag.) of vignetting at the extreme corners.

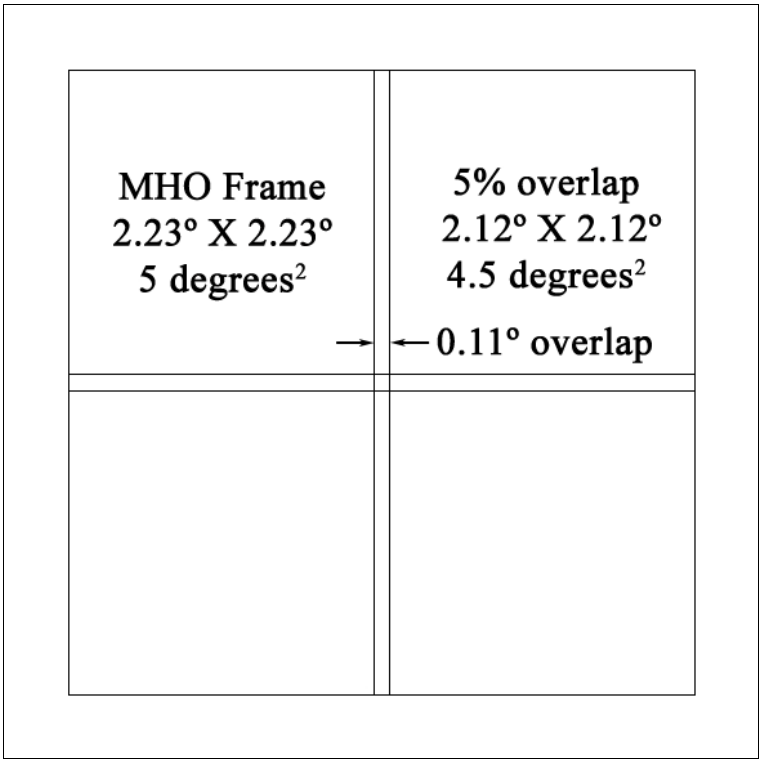

Figure 3 – Madawaska Highlands Observatory 10% Survey Frame Overlap (5%/side)

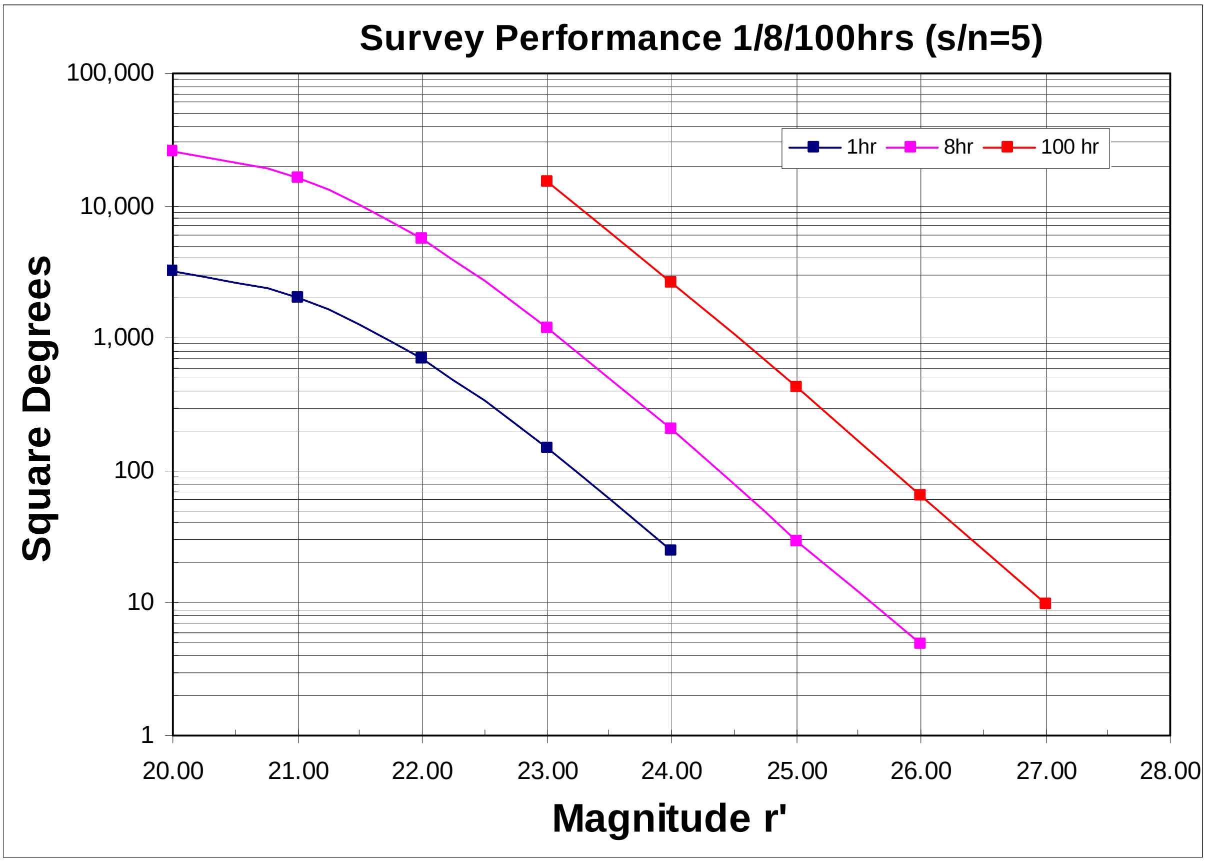

Figure 4 - MHO Survey coverage Performance to varying depth (mag r') and time frames

Figure 4 plots the coverage vs. magnitude (r') based on 1 hour, 8 hours and 100 hours. For example in 100 hours 2,000 degrees^2 could be imaged in the r' to magnitude 24 with a s/n=5.

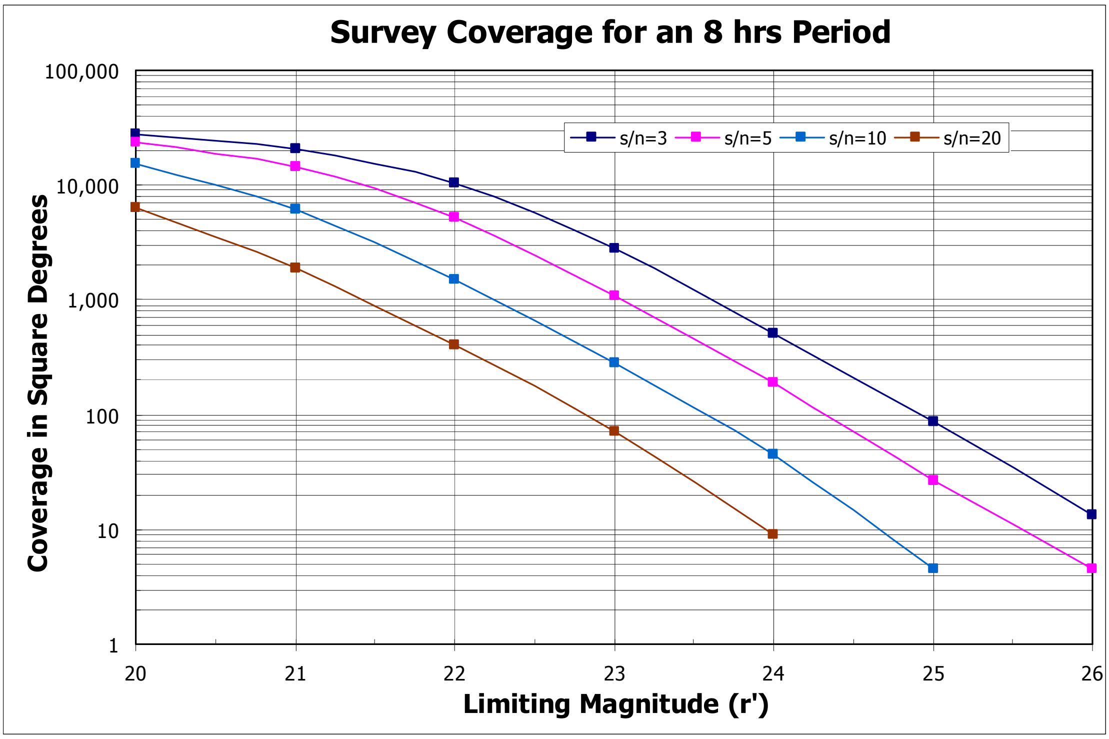

Figure 5 - Sky coverage based on an 8 hours average night for varying s/n

Figure 5 plots the sky coverage for an 8 hour period against limiting magnitude in the r' for varying s/n and a 10% overlap (4.5 degrees^2). The exposures allow for a 4 seconds slew and acquire between frames.

5. Types of Surveys

Various types of surveys are feasible from all sky down to declination δ=-20° to ultra deep 5 square degrees reaching magnitude 28, and large FOV temporal survey's of a few seconds to sub-second.

Ecliptic Survey:

This type of survey is excellent for detecting Solar System objects including NEO's, Asteroids, KBO's etc. For main-belt research the most productive ecliptic survey would be using the wideband (wL) of 420-820 nm, and 90s exposure for motions of 1"/min. This exposure will reach magnitude 23.5 with a s/n=5. Such a survey could cover 57 degrees of the ecliptic in a single 8 hour night with 3 passes and +/- 4.5 degrees width, a 57° X 9° strip (513 deg^2).

Filter	wL 400nm Bandwidth (420-820nm)
Exposure	90s
Limiting Magnitude	~23.5
Signal to Noise ratio	5
Passes	3
Coverage Rate	64 degrees^2/hour

Table 2 - MHO Ecliptic Survey Specifications

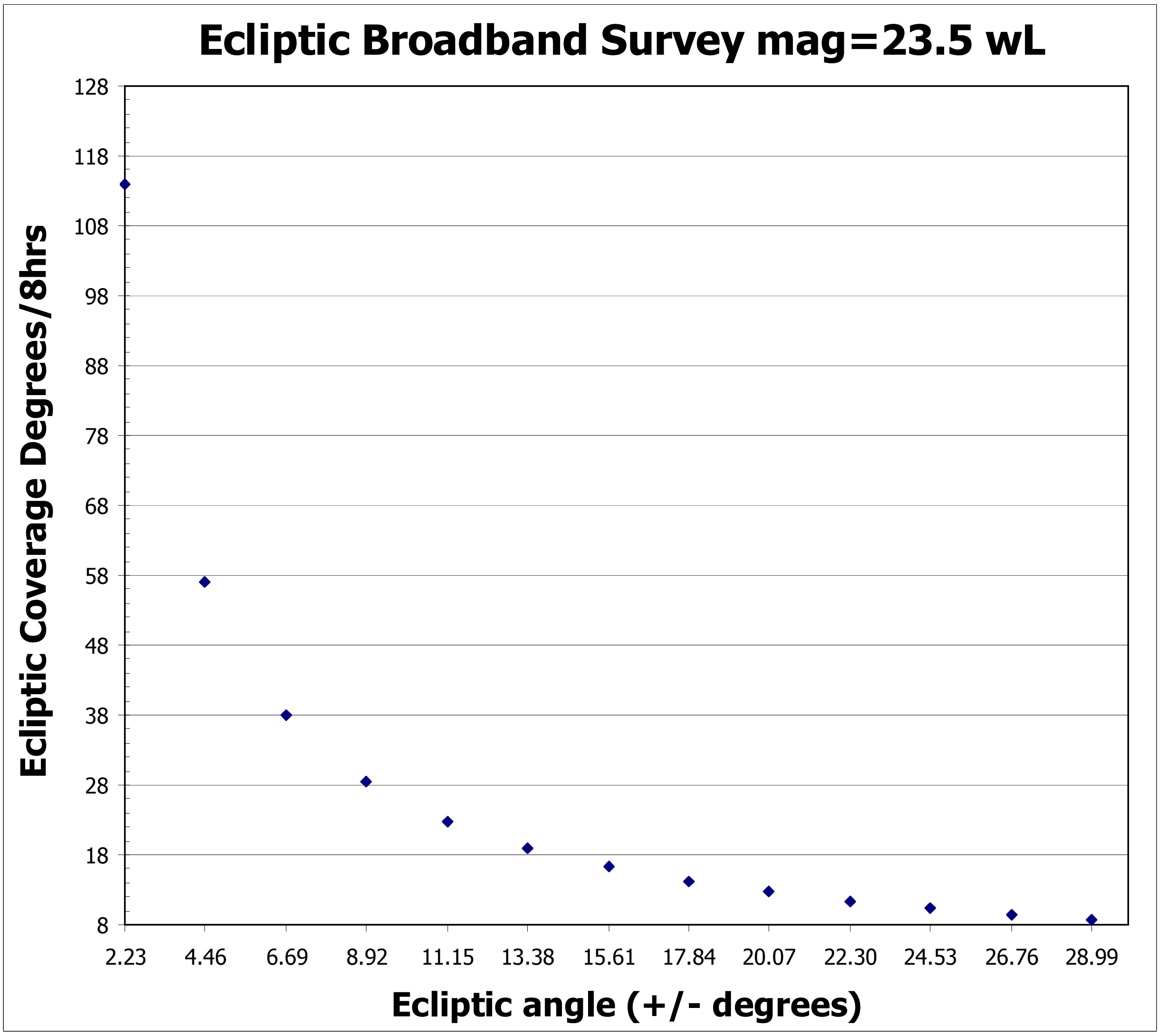

Figure 6 - MHO Ecliptic Survey Broadband Coverage for a s/n=5, 8 hour period with 3 passes

Figure 6 plots the ecliptic angle vs. the ecliptic coverage for 90s (94s cycle time) exposures and 3 passes yielding a limiting magnitude of 23.5 (s/n=5) with the broadband wL filter (420-820nm). Coverage further away from the ecliptic plane will potentially discover objects with higher orbital inclinations.

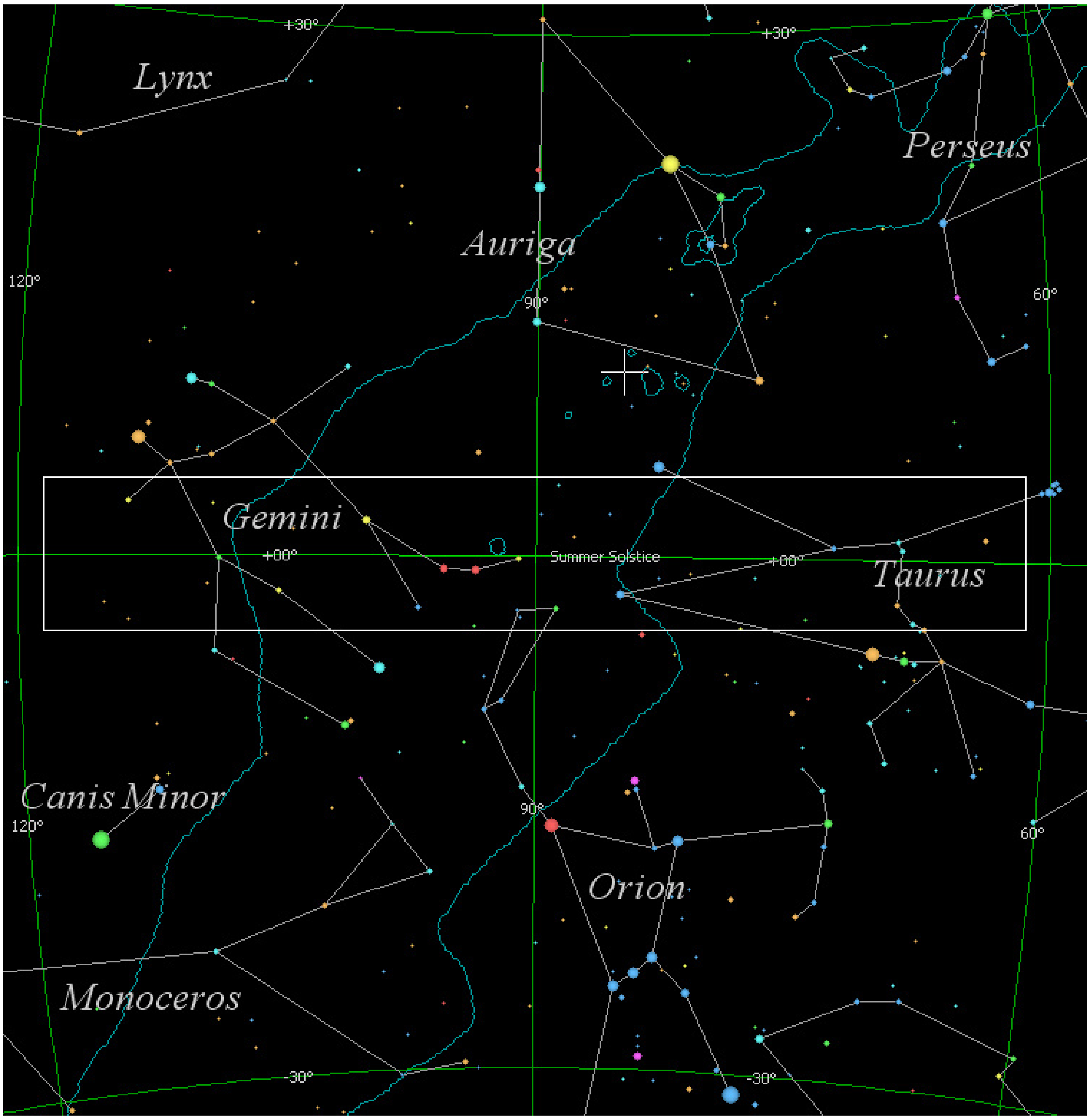

Figure 7 - MHO Ecliptic Broadband Survey for an 8 hr coverage (57º x 9º) reaching mag=23.5 (wL)

Figure 7 highlights a 57º X 9º (513 deg^2) strip centered on the ecliptic reaching mag (wL)=23.5 for an 8 hour coverage with 3 passes and s/n=5.

All Sky Surveys:

The latitude of N45 degrees limits the southern declination to δ=-20º, 25º above the southern horizon. Going further south would add a significant amount of reddening, the sky down to δ=-20º has 27,681 $degrees^2$ resulting in 6152 overlapping 4.5 deg^2 frames.

With a 10% overlap (5% per side) the effective FOV is 4.5 $degrees^2$, Table 3 and Figure 8 list the volume of hours required to survey the entire sky (δ=+90º to -20º) with varying limiting magnitudes to a s/n=5 for ugriz + L + wL with 4 seconds between frames.

Filter	Hours	Hours	Hours	Hours	Hours	Hours
Lim. Mag. ->	20	21	22	23	24	25
u’	268	1285	7308	44266	279153	1726028
g’	13	29	104	531	3122	19272
r’	9	15	43	202	1164	7165
i’	9	14	38	176	1013	6238
z’	11	24	103	586	3587	22581
L	8	11	24	95	531	3248
wL	8	10	20	77	420	2563
Total ugriz	310					
Total griz	42	82	288	1495	8886	
Total gri	31	58	185	909	5299	

Table 3 - MHO All Sky Surveys δ=+90 to -20º with a s/n=5

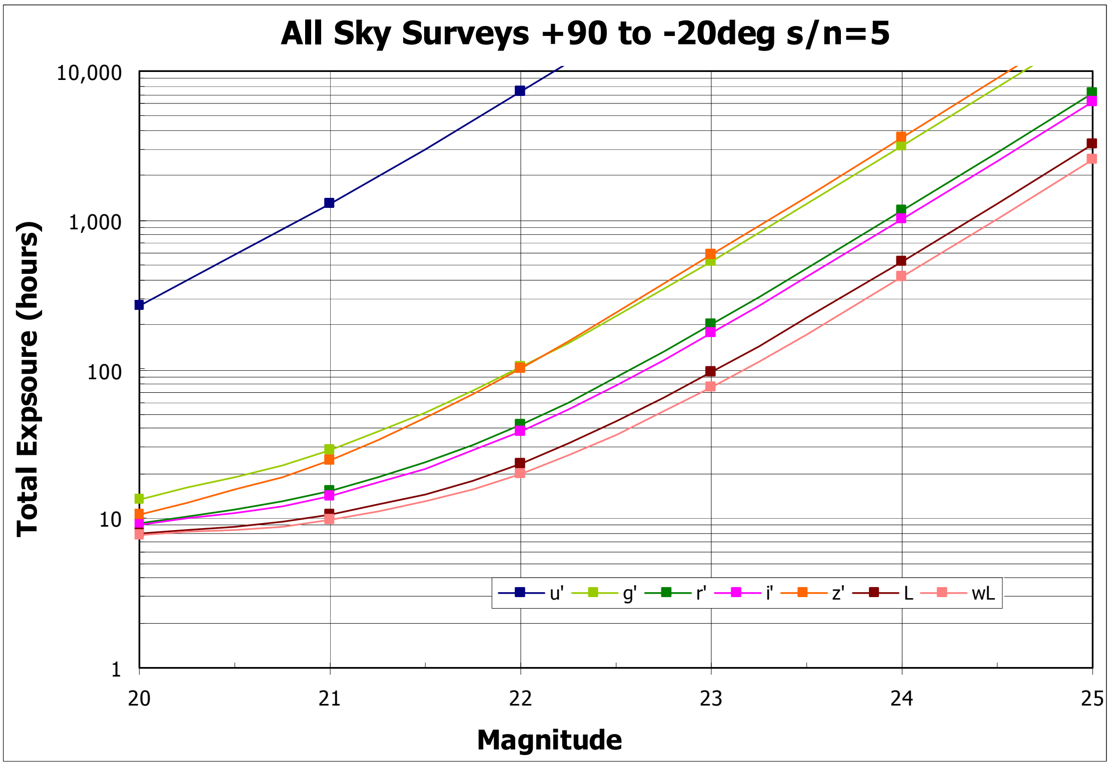

Figure 8 - MHO All Sky Surveys to varying depth with s/n=5

Figure 8 shows the exposure required for an all sky survey (δ=+90º to -20º) for ugriz and L and wL for a s/n=5. In the winter months (Nov. to Feb.) it would be possible to survey the entire visible sky to mag. 22 in the w or wL bands! In ~1500 hours it would be possible to survey the entire sky to δ=-20º in the griz to magnitude 23. The brighter magnitudes are limited by the cycle time (4s + exposure) thus the convergence at ~10hrs.

5 Degrees^2 Survey:

The 5 degrees^2 FOV lends itself nicely to very deep selected areas surveys. Table 3 list deep exposure data for 5 deg^2 FOV, reaching mag. 26 in griz in 57 hours and mag. 28 in the wL in ~100 hours.

Band →	**u'**	**g'**	**r'**	**i'**	**z'**	**L**	**wL**
Magnitude/Exp->	**Hours**	**Hours**	**Hours**	**Hours**	**Hours**	**Hours**	**Hours**
24	45	0.51	0.19	0.16	0.58	0.09	0.07
25	281	3.13	1.16	1.01	3.67	0.53	0.42
26	1770	20	7.20	6.39	23	3.32	2.57
27		125	45	40	143	21	16
28		770	286	254	903	132	102
29		4858	1805	1603	5693	851	657
						Total	
griz m=24		0.51	0.19	0.16	0.58	1.44	
griz m=25		3.13	1.16	1.01	3.67	8.97	
griz m=26		20	7.20	6.39	23	56.59	
griz m=27		125	45	40	143	353	
griz m=28		770	286	254	903	2213	

Table 4 - Exposures for deep limiting magnitudes for a s/n=5 and 5 degrees^2 FOV

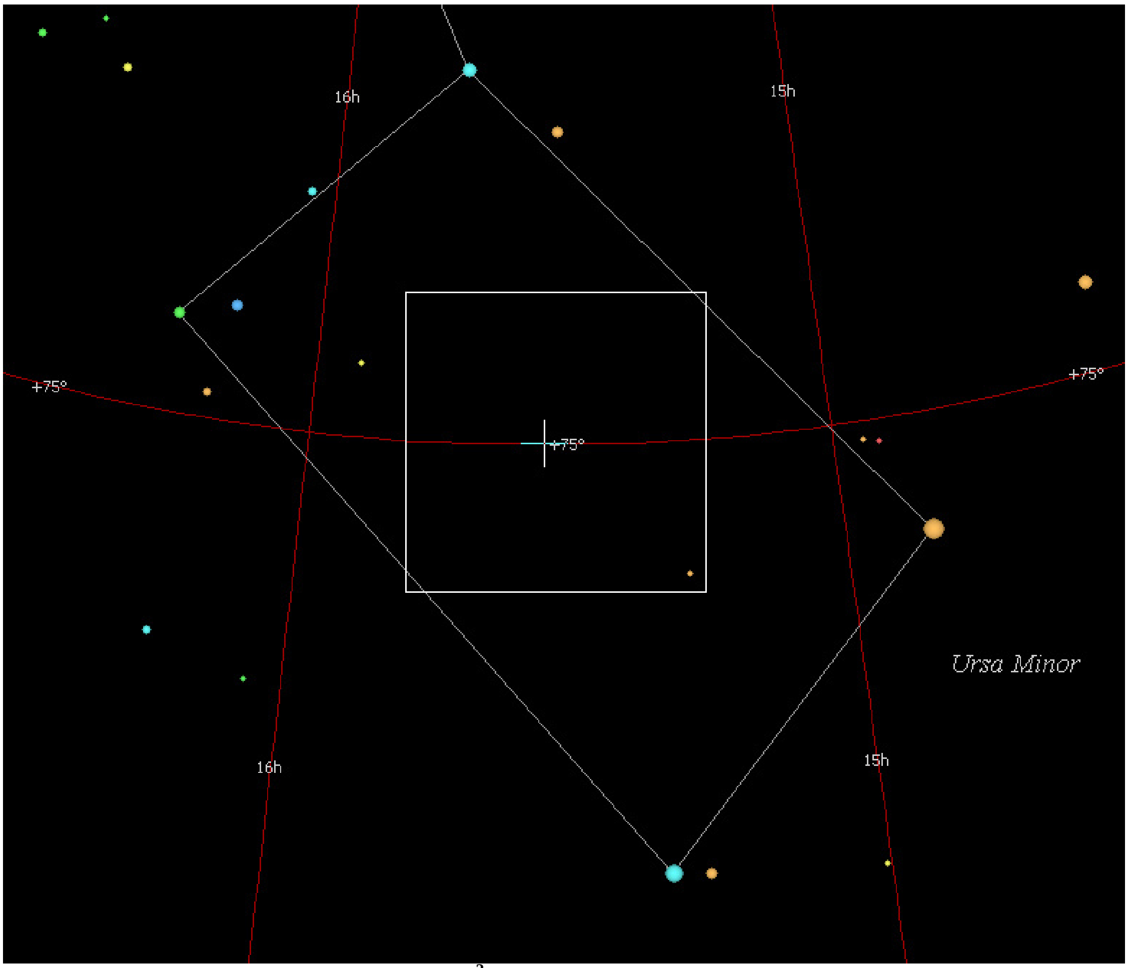

Figure 9 – The MHO 5 degrees^2 FOV with Ursa Minor used to gauge the scale

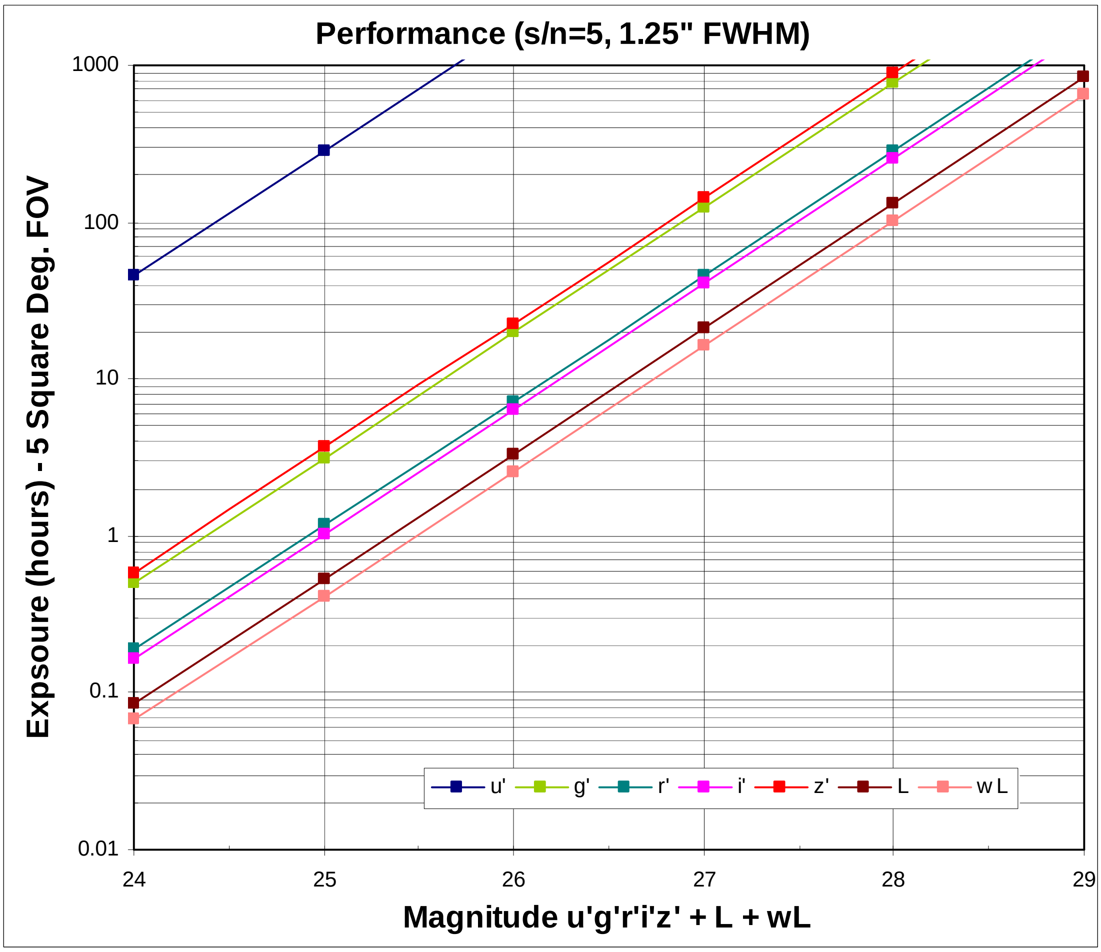

Figure 10 - Exposures for deep limiting magnitudes for s/n=5 and 5 degrees^2 FOV

112 Degrees^2 Survey:

Table 5 demonstrates a 112 degrees^2 survey using 25 frames in a 5 x 5 matrix with 10.6º X 10.6º FOV, to a s/n=5 with a 10% overlap with each sub-frame taking in 4.5 deg^2.

Band →	u'	g'	r'	i'	z'	L	wL
Magnitude/Exp->	Hours	Hours	Hours	Hours	Hours	Hours	Hours
20	1.09	0.05	0.04	0.04	0.04	0.03	0.03
21	5.22	0.12	0.06	0.06	0.10	0.04	0.04
22	30	0.42	0.18	0.16	0.42	0.10	0.08
23	180	2.16	0.82	0.72	2.38	0.39	0.31
24	1135	12.69	4.73	4.12	14.58	2.16	1.71
25	7015	78.33	29.12	25.35	91.77	13.20	10.42
						Total	
griz m=20		0.05	0.04	0.04	0.04	0.17	
griz m=21		0.12	0.06	0.06	0.10	0.34	
griz m=22		0.42	0.18	0.16	0.42	1.18	
griz m=23		2.16	0.82	0.72	2.38	6.08	
griz m=24		12.69	4.73	4.12	14.58	36.12	
griz m=25		78.33	29.12	25.35	91.77	224.57	

Table 5 - MHO 112 Degrees^2 Survey with 25 frames (5 X 5) with 10% overlap, s/n=5

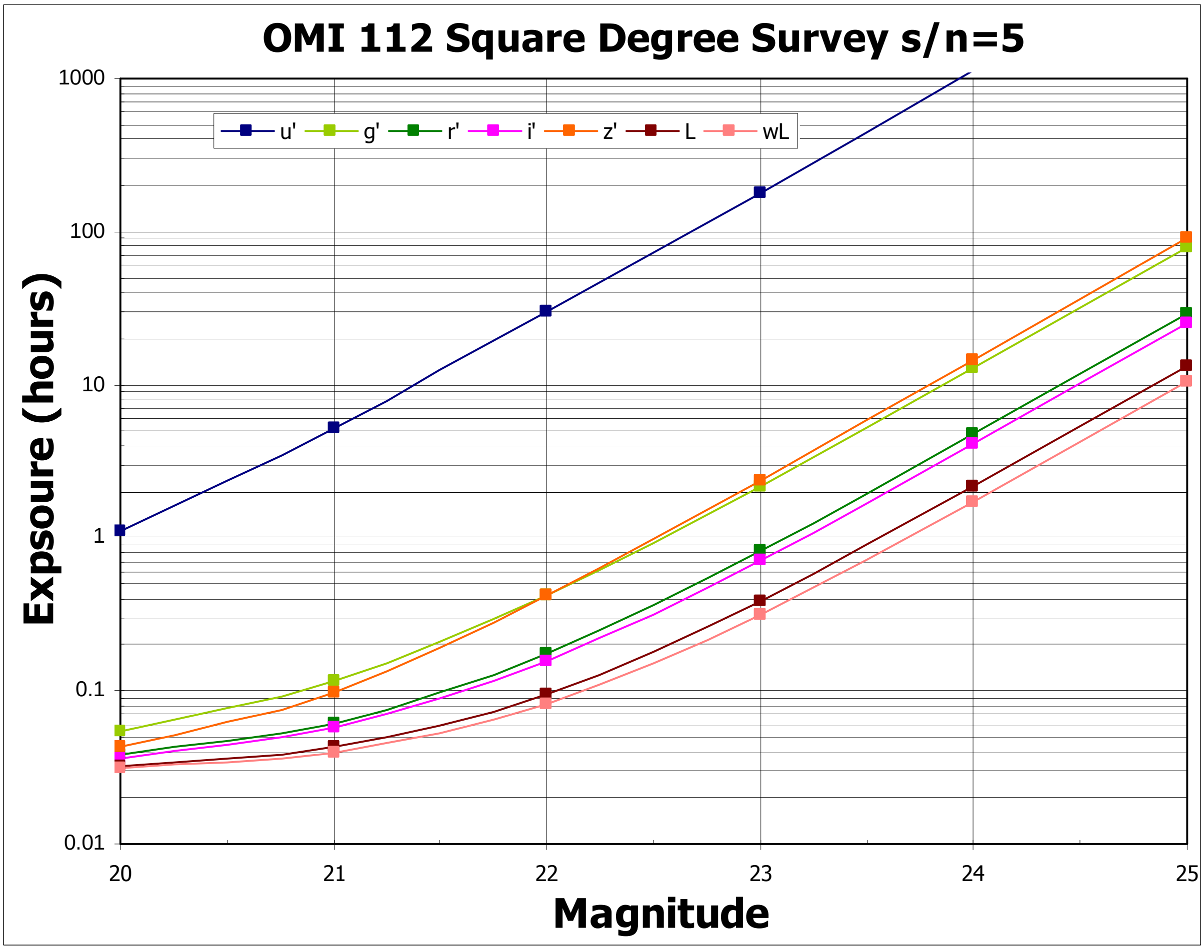

Figure 11 - MHO 112 Degrees^2 Survey

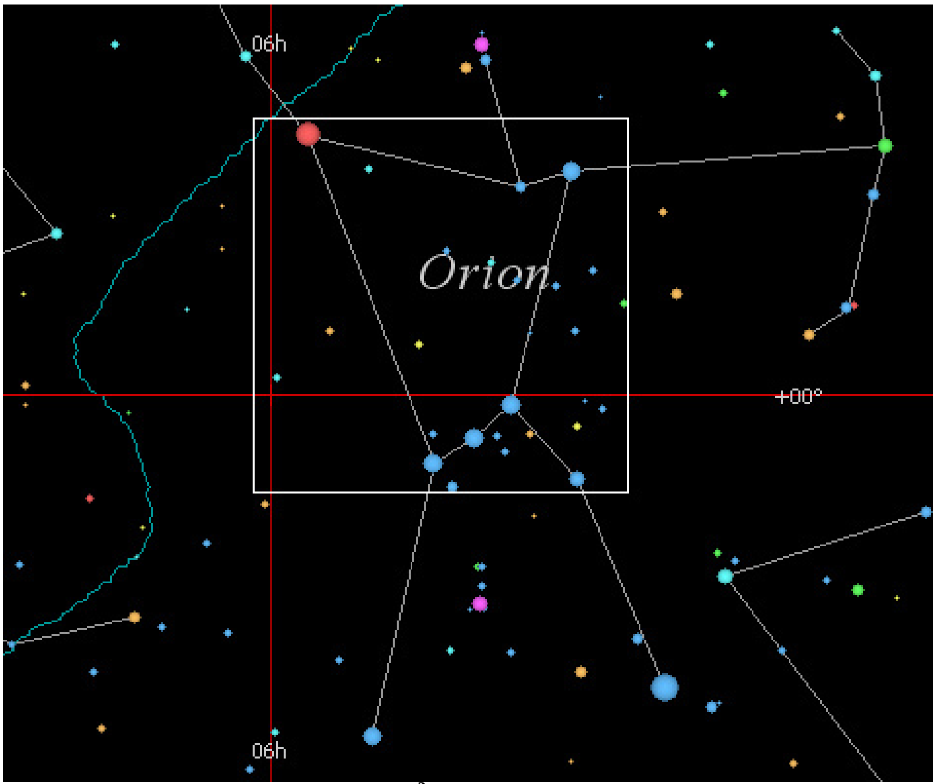

Figure 12 – The MHO 112 Degrees^2 Survey, 5 X 5 frames yielding 10.6º X 10.6º

Figure 12 shows the area in the sky covered by 112 degrees^2 which includes about half of the sky within the boundary of the constellation of Orion. The area could be imaged in the griz to magnitude 23 (s/n=5) in 6 hours. In a winter's night the 112 deg^2 could be imaged to a depth of magnitude 25 in the wL (420-820nm).

The Madawaska Highlands Observatory Wide-Field-Telescope lends itself to a broad range of selected areas survey, of which a few samples are demonstrated here.

<u>Rapid Temporal Survey</u>:

The Madawaska Highlands Observatory Wide-Field-Telescopes' large Étendue (6) together with its ability to download the entire 5 deg^2 with good spatial sampling (0.76"/pixel) in less than two seconds give it a unique ability in the world. By using the wL broadband filter it can reach magnitude 19.5 to 0.1 mag. resolution (s/n=10) in a 1 second exposure. By examining the same FOV in rapid succession it would be possible to detect rapid changes in brightness. This capability could potentially open up a whole new area that has never been explored at this scale and depth. The BONN shutter is capable of shutter times as short as 0.1s with +/- 0.3% accuracy. Thus it would be possible to sample the FOV at this time scale and get meaningful results. The maximum repetitive rate would be limited to 1.4 seconds download times for the full frame and less with binning. The camera has the capability to sample a smaller portion of the frame by downloading only the section (s) of interest.

Figure 13 plots the exposure in seconds against limiting magnitude with the wL filter at different sigma's. The volume of data is very large at 225MB per image. Several TFLOPS of computational power will be available for image analysis on site; this is expected to reach 20-30 TFLOPS in 3 or 4 with high end General Purpose Graphic Processing Unit (GPGPU) cards within the middle of the next decade. With this kind of horsepower, analyzing the volume of data won't be an issue.

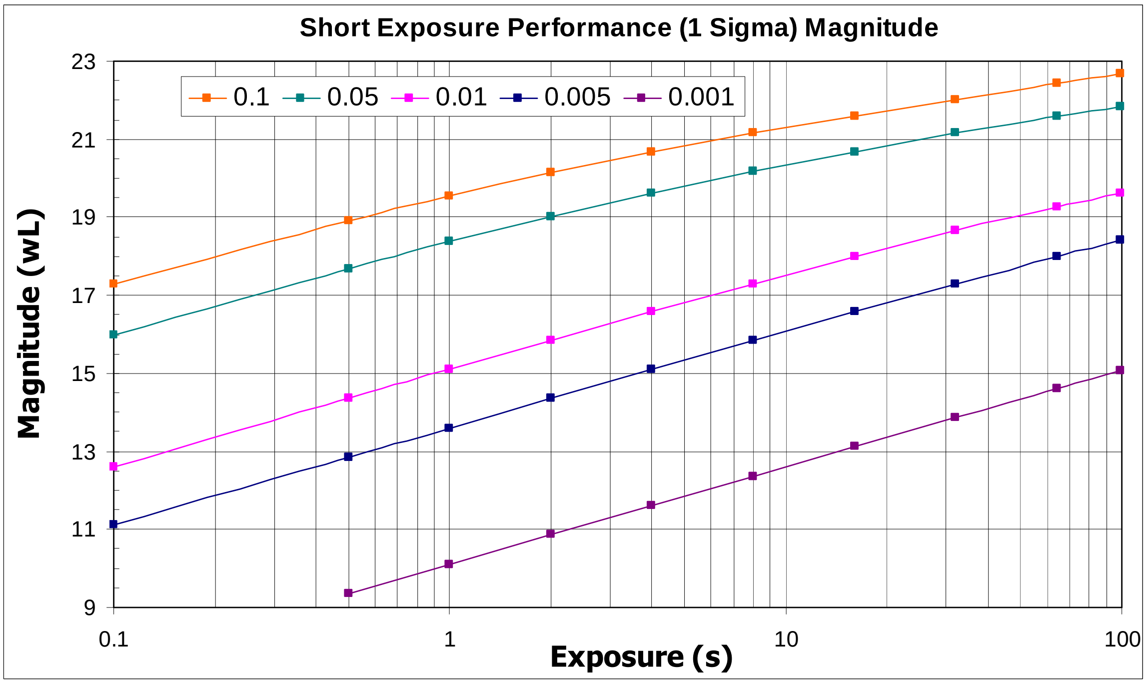

Figure 13 - MHO Rapid Temporal Survey Performance

6. A Canadian Perspective

It would seem that some in the Canadian Professional Astronomical community are ideologically opposed to having a powerful telescope on Canadian soil. I have received a rather aggressive letter by an [Canadian] anonymous astronomer who is strongly trying to dissuade me of building the Madawaska Highlands Observatory Wide-Field-Telescope on Canadian soil based on various arguments and even went so far as to suggest that the Mont-Mégantic Observatory should never have been built!!!

The primary target audiences are the Canadian Professional community. So far 3 Canadian institutions have showed a serious interest in using the instrument. A CASCA survey conducted in December of 2002 and published in the March 2003 Cassiopeia clearly indicates that many Canadian astronomers could use a modest 1-2 metre class instrument with the widest possible FOV. Although I don't think back 7 years ago they could have imagined a 1-metre class having the level of performance that the Madawaska Highlands Observatory Wide-Field-Telescope is offering. 1000 hours of observing time is expected per year. Some of the 1000 hours may be offered to the international community depending on the requirement of Canadian Astronomers and the international demand.

There are several reasons why a site in southern Canada was chosen; costing, logistics, revenue generation, funding, educational, economic impact and a desire to promote astronomy in Canada by having a high performance world class state-of-the-art telescope on Canadian soil. This last item has political benefits for Canadian Astronomers. Overall it is an investment in Canada and to its scientific culture.

Costing: Building the MHO in Southern Canada is extremely cost efficient in terms capital outlay and cost of operations. The same observatory in the Atacama, Hawaii or the south-west USA would be several times the capital and operational cost, making it much harder to raise the capital and fund the operations.

Funding: Access to funding is critical to realizing the Madawaska Highlands Observatory Wide-Field-Telescope. The Madawaska Highlands Observatory Wide-Field-Telescope is a Canadian effort to build a world class state-of-the-art observatory on Canadian soil, and that’s how it is promoted. Potential funding sources are broad and varied, ranging from corporate sponsorship, private donations, regional, provincial and federal grants of various kinds, the capital markets and commercial funding among others. A detailed 60+ page business plan has been prepared to examine the various facets including funding models. Building the Madawaska Highlands Observatory Wide-Field-Telescope outside Canada would remove all of these potential funding sources. Easy access for Canadians is important for the funding model and other reasons.

Logistics: Having the Observatory within 2-hours of Ottawa and accessible by good paved roads makes the construction and maintenance of the facility tenable. Although autonomous in its operation, maintenance will be required from time to time and having the observatory within range is certainly much more practical.

Revenue Generation: The operations are expected to be around the $200K per annum. The bulk of the revenue is expected to be generated mainly via tourism. A well equipped visitor centre is planned to be integrated into to facility. Upwards of 50,000 people per year could visit the Observatory in due course.

Economic:
A study of the economic impact was conducted as part of the business plan. Empirical data derived from the Mont-Mégantic and its associated Astrolab indicate that some $10.1M in economic activity (Sépaq August 2008) was generated through tourism. Mont-Mégantic gets 15,000 annual visitors of which 85% arrive from the metropolitan Montréal (~3.6 million populations) area some 3+ hours away.

The Madawaska Highlands Observatory Wide-Field-Telescope is within a 4-hours journey of some 12 million people from Ontario, Québec and the US. In addition within 30 minutes is Bon Echo Provincial Park with some 200,000 annual campers and within 2-hours of several hundred thousand cottagers who migrate to the numerous lakes of the area in the summertime. These numbers suggest a minimum of 50,000 and upwards of 100,000 annual visitors based on standard tourism statistics and compared to similar science venues. The economic impact to the area could be well above $10M per annum.

Educational: The Madawaska Highlands Observatory Wide-Field-Telescope can contribute in many ways to educating Canadians about astronomy. Discoveries made by the Madawaska Highlands Observatory Wide-Field-Telescope will be picked up the media and be headlined by major newspapers. This will get Canadians excited about astronomy. The Observatory is accessible within a modest journey to millions of Canadians who could visit where such discoveries are made. The facility will feature a visitor centre with display areas for research conducted at the Madawaska Highlands Observatory Wide-Field-Telescope, its advanced technology, a 'live' large high definition display of the latest images. Display areas for astronomy, cosmology and a high definition lecture room where invited astronomers would give talks. The facility would have its own 24" telescope with seats for real time outdoor lectures under the stars. Tours of the Madawaska Highlands Observatory Wide-Field-Telescope, the 0.7m telescope and the control room would be offered. Limited time on the Madawaska Highlands Observatory Wide-Field-Telescope would be offered to the general public, and a significant fraction of time on the 0.7m would be for outreach and education. The observatories being autonomous would be available to schools all across Canada and could be integrated into curriculums with assistance from the visitor centre with material and ideas for projects.

Political: Sufficient performance is built into the Madawaska Highlands Observatory Wide-Field-Telescope that discoveries are expected such has SNe, NEO's, and Extra-Solar Planets etc. These discoveries will be picked up by the national media and featured on the front page of major newspapers across Canada. These at home discoveries will get Canadians, the media and politicians excited about astronomy and are an extremely effective way of promoting the science and within a short journey to millions to visit the Observatory where these discoveries are made.

These at home discoveries will be a valuable political asset to Canadian Astronomers.

In comparison how many politicians have visited the CFHT or the Gemini's? And how many Canadians and media visit the CFHT and the Gemini's?

The value of the Madawaska Highlands Observatory Wide-Field-Telescope cannot be seen just in its scientific context, the political, cultural, economic, promotional and educational components must be weighted.

The Observatory is designed to achieve significant scientific results which are important for the scientific validity of the instrument. This scientific credibility is crucial in achieving a strong political, cultural, economic, educational and promotional impact.

The Madawaska Highlands Observatory Wide-Field-Telescope making discoveries on Canadian soil will give a boast to astronomy in Canada and add more visibility with the politicians and Canadians as a whole. As a political asset it will certainly be valuable when Astronomers approach [Ottawa] politicians for capital.

Investing in Canada: A key motivation for the initiative is to have this observatory situated in Canada. Fundamentally I believe that situating the telescope in southern Canada has the greatest overall benefit to Canadians.

6. Conclusion

To give a reference performance one can look at the POSSII which took some 15 years to cover δ= +90º to 0º and reached a depth of 22.5, 20.8 and 19.5 in the J, R, and N bands. Similarly the MHO could reach magnitude 23 in the three gri bands in about 500 hours with better spatial sampling and overall better image quality for the same coverage area. Thus it could accomplish two POSSII's per year! The MHO will be only large Étendue instrument in the world offering a monolithic and seamless FOV which has obvious advantages.

The ability to bin and/or download selected areas of the frame lends itself to research that doesn't require the full image size. The 0.75"/sampling and large the 5 degrees^2 FOV are designed for maximizing the volume of science from the expected 1.25" seeing. Coupled with its exceptionally low capital investment and its fully autonomous design resulting in a low operational cost, the MHO has been optimized to take full advantage of the 1000 observing hours expected from the site in Southern Canada.

The Madawaska Highlands Observatory Wide-Field-Telescopes' large Étendue, large 5 degrees^2 FOV, good spatial sampling (0.76"/pixel) coupled with its ability to the download the entire frame in a short time span (~2s), allows it to do rapid temporal research over a large FOV is unique in the world and could open up a whole new area of astronomy.

Beyond the science; dollars, logistics and political capital more than justify such an instrument on Canadian soil, but the benefits go way beyond this in terms of promoting science in Canada and an economic boost for the local economies amongst other reasons. The autonomous design allows access across the nation with the possibility of schools adding to their science curriculums via queuing time on the telescopes.

A powerful telescope is more than just pure science but can motivate and inspire young minds towards careers in science and technology. Important discoveries on Canadian soil will benefit the science in terms of exposure and promotion, and add some well needed political capital for Canadian astronomers.