COTS Options for Low-Cost SSA

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Abstract

Globally, the primary tool for observational space situational awareness of the geosynchronous orbital region is the ground-based optical telescope. Historically, such satellite observations have been made both by governments and private parties, with government observation systems typically being larger and more capable. In recent years, with the commercial availability of sensitive cameras, small aperture systems with wide fields of view have allowed amateurs to make observations that only a few years ago were only possible from government systems. Today, a myriad of modest-aperture telescopes are readily available as catalog items. When combined with commercial cameras, these systems provide significant satellite surveillance capability to anyone. In this paper, we examine the likely performance of commercial optical systems and cameras.

Introduction

Since the early days of military space programs, nations have used ground-based optical systems to detect and track earth-orbiting satellites. This practice has traditionally been a mixture of government and amateur observations. Amateurs mostly used smaller and less capable systems but were much more numerous. The result was that the best data came from the larger government systems, but amateurs frequently found objects of interest that the government observers missed.

In 1970, one seed of the modern commercial market for modest aperture telescopes was planted. The Celestron Corporation applied modern fabrication and assembly techniques to the production of an 8-inch aperture Schmidt-Cassegrain telescope (SCT) [1]. Other seeds included the development and commercial marketing of affordable personal computers; charge coupled device (CCD) electronic image sensors; commercial optical design software; and advanced, numerically-controlled optical component production techniques. Together, these innovations have resulted in an unimaginable variety of modest-aperture optical and imaging systems being available to the amateur at previously unheard of prices. Today, the commercial marketplace is flooded with high-quality optical systems of almost every imaginable configuration. Indeed, the market has become extremely competitive and it is difficult to introduce a new product, while at the same time, manufacturers are under ever increasing pressure to keep their product line up to date.

The result of technical developments and market forces is that a significant variety of commercial, off-the-shelf (COTS) equipment exists that could rapidly be pressed into service to produce observations for space situational awareness (SSA). With all the marketing strategies and competing claims, it is difficult to know what the real choices are and which combinations of CCD camera and optical system provide the highest performance, or the highest performance for a given investment.

In this paper, we have compiled a database representing most of the widely-available commercial optical systems and paired them with four COTS CCD cameras of various sizes. We have specifically avoided the small format cameras and not included optical systems with focal ratios longer than f/5. We are looking for wide-field imaging capabilities and neither small detectors nor large focal ratios are ideal for wide fields of view. We used standard methods for calculating optical throughput and estimation of system performance based on real-world noise and sky characteristics and calculate performance estimates for all systems using the same approach. The goal of this approach was to provide an "apples to apples" comparison.

The performance assessment results are both plotted and presented in tabular format. While some systems are called out by name as being better performers, the decision as to which system performs the best is left to the reader.

Targets and Simulated Observations

For each combination of telescope and CCD camera, we calculated expected performance against a target satellite in a geosynchronous earth orbit (GEO). Such targets move at a rate of 15 arc seconds per second relative to the fixed stellar background. The calculated measures of performance were the system sensitivity, as expressed by the limiting detectable magnitude target, and search rate, expressed in square degrees per hour.

Sensitivity Calculations

For sensitivity calculations, we calculate the telescope radiometric throughput, accounting for losses at reflecting surfaces, air-glass interfaces and geometrical obscuration. We use actual CCD camera performance parameters including wavelength dependent quantum efficiency, read noise and dark current. The calculations assume the telescope is tracking at the sidereal rate resulting in the GEO targets leaving short streaks on the CCD. The ideal exposure duration is determined to be the time required for the image spot from a satellite to cross a single pixel. Two frames are recorded a few seconds apart and then subtracted one from another both to eliminate the fixed stars and to identify the moving targets. The sensitivity threshold is determined to be the visual magnitude for a target that results in a detection with a signal to noise ratio of 6:1.

In addition to system mechanical, optical and electrical parameters, we calculated all performance values assuming an observing site similar to Ascension Island, being 8 degrees south of the equator, 100 m above sea level. Sky brightness was modeled based on being 7 days to or from a full moon. Seeing conditions were assumed to be 1 arc second. All observations were assumed to be near the local meridian. The wavelength dependent transmission for the atmosphere was included in all calculations.

A detailed discussion of how to calculate sensitivity can be found in reference [2].

Search Rate Calculations

The search rate for each system was calculated based on the maximum diameter of the image field, and the size of the CCD in use. Even when using large CCDs, only the portion of the illuminated portion of the CCD was used to calculate search rate. As a result, each telescope had a specific camera that gave the greatest search rate and larger cameras simply wasted pixels.

The search rate was calculated assuming a total of four frames were recorded at each location on the sky. Each frame required 3 seconds to record and download (this value was used even for the interline transfer CCD). After four frames were recorded at a given field location, it was assumed that the mount required 5 seconds to move to the next field before a new set of images could be recorded. We did not attempt to account for effects related to the quality of the mount or size of the telescope in determining how quickly one could move from one field to another.

The Cameras

We identified four readily available COTS cameras for use in our performance assessments. The CCDs range in size from a 43mm diagonal (full frame 35mm format) to a medium format 70mm diagonal. Three cameras are marketed by Finger Lakes Instruments (FLI) [3] while the fourth is from Apogee, now a part of Andor [4]. We are not attempting to express a preference for one camera manufacturer over another, but did select mostly cameras from FLI as their MicroLine series of cameras are physically smaller and thus block less light when used at prime focus. The Apogee camera was initially selected as it was available with the ON Semi KAF-4320 CCD, but we later learned that FLI will soon introduce their Cobalt series of cameras, one of which will use the KAF-4320 CCD. As the Cobalt camera will be smaller than the Apogee Alta, we would recommend it for prime focus applications. At the Cassegrain focus, either camera would work with almost identical results.

43mm Diagonal

The smallest format camera is the FLI MicroLine ML11002 featuring the ON Semi KAI-11002 CCD. This is a front-illuminated, interline transfer sensor with 4008 x 2672 pixels on a 9μm pitch. The camera has a typical retail price of $9,995. The interline transfer sensor is particularly useful in applications where rapid framing is required. Exposures at a rate of 1 frame per second are possible with no dead time as one image can be read off the CCD while the next is integrating. This basic camera is available with different sensors having the same approximate diagonal measurement, but different pixel counts and pitches.

Fig. 1. FLI ML11002 camera.

52mm Diagonal

The second to smallest format camera is the FLI MicroLine ML16803 featuring the ON Semi KAF-16803 CCD. This is a front-illuminated sensor with 4096 x 4096 pixels on a 9μm pitch. The camera has a typical retail price of $10,495.

Fig. 2. FLI ML16803 camera.

61.3mm Diagonal

The second to largest format camera is the FLI MicroLine ML50100 featuring the ON Semi KAF-50100 CCD. This is a front-illuminated sensor with 8176 x 6132 pixels on a 6μm pitch. The camera has a typical retail price of $15,995. The pixels on this sensor seem a bit on the small side, but when matched with high-quality optics, sensitivity is excellent. The user always has the option of 2x2 binning to achieve more rapid image download and faster image processing. For larger telescopes, where the point spread function is necessarily larger, 2x2 binning has some advantages.

Fig. 3. FLI ML50100 camera.

70mm Diagonal

The largest format camera is the Apogee Alta ASP-F4320 featuring the ON Semi KAF-4320 CCD. This is a front-illuminated sensor with 2048 x 2048 pixels on a 24µm pitch. The camera has a typical retail price of $44,200. The pixels on this sensor seem a bit on the large side, being best used with a telescope of longer focal length, and necessarily a larger point spread function. There are however advantages to using cameras with large pixels when looking for moving targets.

Fig. 4. Apogee ASP-F4320 camera.

A new arrival on the market with a 70mm diagonal CCD is the FLI Cobalt DC4320. This camera will use the same sensor as the Apogee ASP-F4320 but the camera housing has a much smaller form factor. No price data for the FLI DC4320 is available at present.

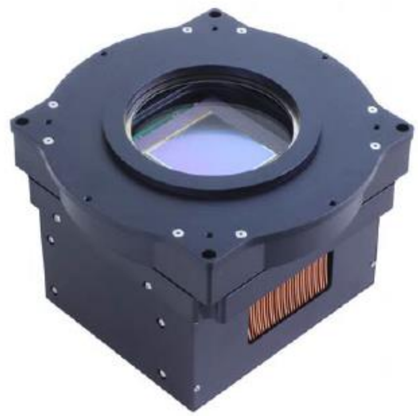

Fig. 5. New arrival, FLI Cobalt DC4320 camera.

The Telescopes

The list of telescopes considered is presented in table 1. The telescopes were selected based on an internet search of items that were readily available and considered to be standard catalog items. There are not custom optical systems included within the table. All systems were either identified by the manufacturer or a retail sales outlet as being an astrograph. We arbitrarily limited the focal ratio to f/5 and faster. The specifications are as provided by the manufacturers with price information available from commercial vendors. In some cases, prices needed to be converted to US dollars. This was done for exchange values recorded on August 18th, 2015. We do not claim the listed prices are exact, but only close to actual fair-trade retail values available to members of the public. In some cases, we included readily available aftermarket optics such as Wynne correctors and focal reducers (such as for the ASA astrographs) or prime focus correctors (HyperStar units for the Celestron C-11 and C-14 SCTs).

In some ways, it does not appear to be fair to compare an 800 mm aperture telescope costing over $100,000 with a small astrograph costing less than $3,000, but all such data are presented for the reader. While the 800 mm telescope will have impressive limiting magnitude values, the telescope costing less than $3,000 had an enormous search rate, so it is not always clear which way to apply the argument about fairness of comparisons.

Table 1. COTS Astrographs

Manufacturer	Model	Aperture (mm)	f/#	FOV (deg)	Wavelength Bandpass	Typical Price
APM	Large Prime Focus Astrograph	560.0	2.0	4.6	400-800	$101,250
APM	Wynne-Riccardi-Astrograph	305.0	2.8	6.0	400-800	$20,250
APM	Wynne-Riccardi-Astrograph	406.0	2.8	4.5	400-800	$50,625
APM	Wynne-Riccardi-Astrograph	560.0	2.5	3.5	400-800	$101,250
APM	Wynne-Riccardi-Astrograph	600.0	2.5	3.3	400-800	$118,100
Astro Systeme Austria	Astrograph 10N Reduced	250.0	2.8	2.3	400-700	$8,125
Astro Systeme Austria	Astrograph 10N Wynne	250.0	3.6	3.2	400-700	$7,900
Astro Systeme Austria	Astrograph 12N Reduced	300.0	2.8	1.9	400-700	$10,725
Astro Systeme Austria	Astrograph 12N Wynne	300.0	3.6	2.6	400-700	$10,500
Astro Systeme Austria	Astrograph 16N Reduced	400.0	2.8	1.5	400-700	$19,570
Astro Systeme Austria	Astrograph 16N Wynne	400.0	3.6	2.0	400-700	$19,345
Astro Systeme Austria	Astrograph 20N Reduced	500.0	2.8	1.2	400-700	$26,925
Astro Systeme Austria	Astrograph 20N Wynne	500.0	3.6	1.6	400-700	$26,700
Astro Systeme Austria	Astrograph 8H	200.0	2.8	5.3	400-700	$12,200
Astro Systeme Austria	Astrograph 8N Reduced	200.0	2.8	2.9	400-700	$6,825
Astro Systeme Austria	Astrograph 8N Wynne	200.0	3.6	4.0	400-700	$6,600
Astro Systeme Austria	Robotic Astrograph	600.0	2.3	3.4	400-700	$65,000
Astro Systeme Austria	Robotic Astrograph	800.0	2.3	3.3	400-700	$130,000
Celestron	C-11 HyperStar	279.4	2.0	2.9	486-656	$2,794
Celestron	C-14 HyperStar	355.6	1.9	2.8	486-656	$5,598
Celestron	RASA C-11	279.4	2.2	4.0	400-700	$3,499
Celestron	RASA C-14	355.6	2.2	4.4	400-900	$9,995
Officina Stellare	RiFAst 300	300.0	3.8	3.0	410-750	$26,995
Officina Stellare	RiFAst 400	400.0	3.8	3.0	410-750	$26,995
Officina Stellare	RiFAst 500	500.0	3.8	2.7	410-750	$49,695
Officina Stellare	RiFAst 600	600.0	3.8	2.5	410-750	$68,495
Officina Stellare	RiFAst 700	700.0	3.8	2.2	410-750	$90,795
Officina Stellare	RiFAst 800	800.0	3.8	1.9	410-750	$159,795
Officina Stellare	RiLA 300 F5	300.0	5.0	4.0	410-750	$23,095
Officina Stellare	RiLA 400 F5	400.0	5.2	2.9	410-750	$23,095
Officina Stellare	RiLA 500 F5	500.0	5.0	2.4	410-750	$40,095
Officina Stellare	RiLA 600 F5	600.0	5.0	2.0	410-750	$60,595
Officina Stellare	RiLA 700 F5	700.0	5.0	1.7	410-750	$79,995
Officina Stellare	RiLA 800 F5	800.0	5.0	1.5	410-750	$139,795
Officina Stellare	Ultra CRC 300	300.0	5.4	2.1	410-750	$16,475
Officina Stellare	Veloce RH 200AT	200.0	3.0	4.0	430-700	$7,795
Officina Stellare	Veloce RH 250AT	250.0	5.6	2.5	430-700	$15,795
Officina Stellare	Veloce RH 300	300.0	3.0	3.8	430-700	$24,395
Officina Stellare	Veloce RH 350	350.0	2.8	6.1	430-700	$40,695
Takahashi	CCA-250	250.0	5.0	4.0	436-656	$16,795
Takahashi	CCA-250 Reduced	250.0	3.6	3.9	436-656	$18,890
Takahashi	Epsilon 130D	130.0	3.3	5.9	436-656	$2,995
Takahashi	Epsilon 180	180.0	2.8	5.0	436-656	$5,400
TEC	TEC 300 ADL	300.0	5.6	1.8	400-700	$17,500
TS Boren-Simon	PowerNewton Astrograph	200.0	2.8	2.6	486-656	$2,160
TS Boren-Simon	PowerNewton Astrograph	200.0	3.7	2.0	486-656	$2,160
TS Boren-Simon	PowerNewton Astrograph	254.0	2.8	2.0	486-656	$2,575

Performance

Calculated performance values are presented in table 2 with results plotted in figures 6 and 7. In each figure, the best performing systems are identified. Ideal performance would be in the upper right corner of either plot with high sensitivity and high search rate. It is clear that the Takahashi Epsilon 130D has the greatest search rate, while the 600 mm APM Wynne-Riccardi Astrograph has one of the greatest sensitivities calculated. The Celestron RASA-14 appears to have some characteristics of each of these systems, with relatively high sensitivity and search rate combined in the same system.

The best performing individual systems are identified in table 3, with both physical parameters and performance values. The data in table 3 were sorted by price, from lowest to highest.

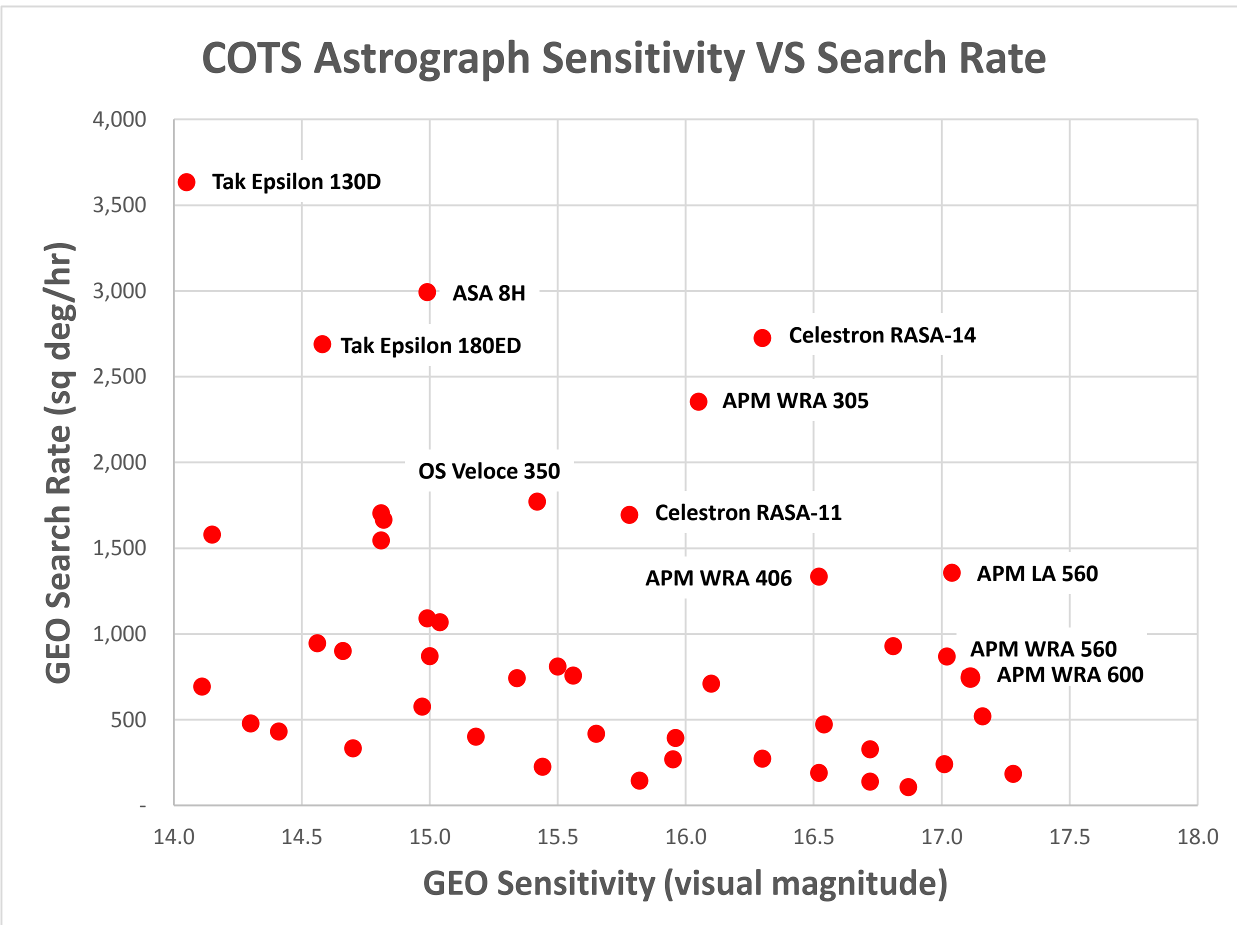

Fig 6. Plot of COTS Astrograph performance – calculated sensitivity VS search rate.

Table 2. Sensitivity and Search Rate Performance for COTS Astrographs

Manufacturer	Model	Typical Price	Performance: Limiting Mag	Performance: Search Rate (sq deg/hr)	Performance: CCD Diagonal (mm)	Advanced Processing Lim Mag
APM	Large Prime Focus Astrograph	$101,250	17.0	1,356	70	18.3
APM	Wynne-Riccardi-Astrograph	$20,250	16.1	2,353	70	17.4
APM	Wynne-Riccardi-Astrograph	$50,625	16.5	1,332	70	17.9
APM	Wynne-Riccardi-Astrograph	$101,250	17.0	868	70	18.4
APM	Wynne-Riccardi-Astrograph	$118,100	17.1	757	70	18.5
Astro Systeme Austria	Astrograph 10N Reduced	$8,125	15.0	576	43	17.0
Astro Systeme Austria	Astrograph 10N Wynne	$7,900	15.0	1,068	52	17.1
Astro Systeme Austria	Astrograph 12N Reduced	$10,725	15.2	400	43	17.3
Astro Systeme Austria	Astrograph 12N Wynne	$10,500	15.3	741	52	17.4
Astro Systeme Austria	Astrograph 16N Reduced	$19,570	15.4	225	43	17.8
Astro Systeme Austria	Astrograph 16N Wynne	$19,345	15.7	417	52	17.8
Astro Systeme Austria	Astrograph 20N Reduced	$26,925	15.8	144	43	18.2
Astro Systeme Austria	Astrograph 20N Wynne	$26,700	16.0	268	52	18.2
Astro Systeme Austria	Astrograph 8H	$12,200	15.0	2,993	52	16.6
Astro Systeme Austria	Astrograph 8N Reduced	$6,825	14.7	900	43	16.6
Astro Systeme Austria	Astrograph 8N Wynne	$6,600	14.8	1,666	52	16.7
Astro Systeme Austria	Robotic Astrograph	$65,000	16.8	927	70	18.4
Astro Systeme Austria	Robotic Astrograph	$130,000	17.2	518	70	18.8
Celestron	C-11 HyperStar	$2,794	15.0	869	43	16.8
Celestron	C-14 HyperStar	$5,598	15.5	809	43	17.3
Celestron	RASA C-11	$3,499	15.8	1,694	52	17.1
Celestron	RASA C-14	$9,995	16.3	2,725	70	17.6
Officina Stellare	RiFAst 300	$26,995	14.6	946	61	17.3
Officina Stellare	RiFAst 400	$26,995	16.1	709	70	17.8
Officina Stellare	RiFAst 500	$49,695	16.5	472	70	18.1
Officina Stellare	RiFAst 600	$68,495	16.7	328	70	18.4
Officina Stellare	RiFAst 700	$90,795	17.0	241	70	18.7
Officina Stellare	RiFAst 800	$159,795	17.3	184	70	18.9
Officina Stellare	RiLA 300 F5	$23,095	15.6	756	70	17.4
Officina Stellare	RiLA 400 F5	$23,095	16.0	394	70	17.8
Officina Stellare	RiLA 500 F5	$40,095	16.3	272	70	18.2
Officina Stellare	RiLA 600 F5	$60,595	16.5	189	70	18.5
Officina Stellare	RiLA 700 F5	$79,995	16.7	139	70	18.7
Officina Stellare	RiLA 800 F5	$139,795	16.9	106	70	19.0
Officina Stellare	Ultra CRC 300	$16,475	14.3	477	61	17.5
Officina Stellare	Veloce RH 200AT	$7,795	14.8	1,702	43	16.5
Officina Stellare	Veloce RH 250AT	$15,795	13.9	638	61	17.1
Officina Stellare	Veloce RH 300	$24,395	14.8	1,544	61	17.2
Officina Stellare	Veloce RH 350	$40,695	15.4	1,770	70	17.0
Takahashi	CCA-250	$16,795	15.0	1,089	70	16.9
Takahashi	CCA-250 Reduced	$18,890	14.2	1,579	61	16.8
Takahashi	Epsilon 130D	$2,995	14.1	3,633	52	15.8
Takahashi	Epsilon 180	$5,400	14.6	2,688	52	16.3
TEC	TEC 300 ADL	$17,500	14.7	333	52	17.3
TS Boren-Simon	PowerNewton Astrograph	$2,160	14.1	693	43	16.3
TS Boren-Simon	PowerNewton Astrograph	$2,160	13.9	408	43	16.4
TS Boren-Simon	PowerNewton Astrograph	$2,575	14.4	430	43	16.7

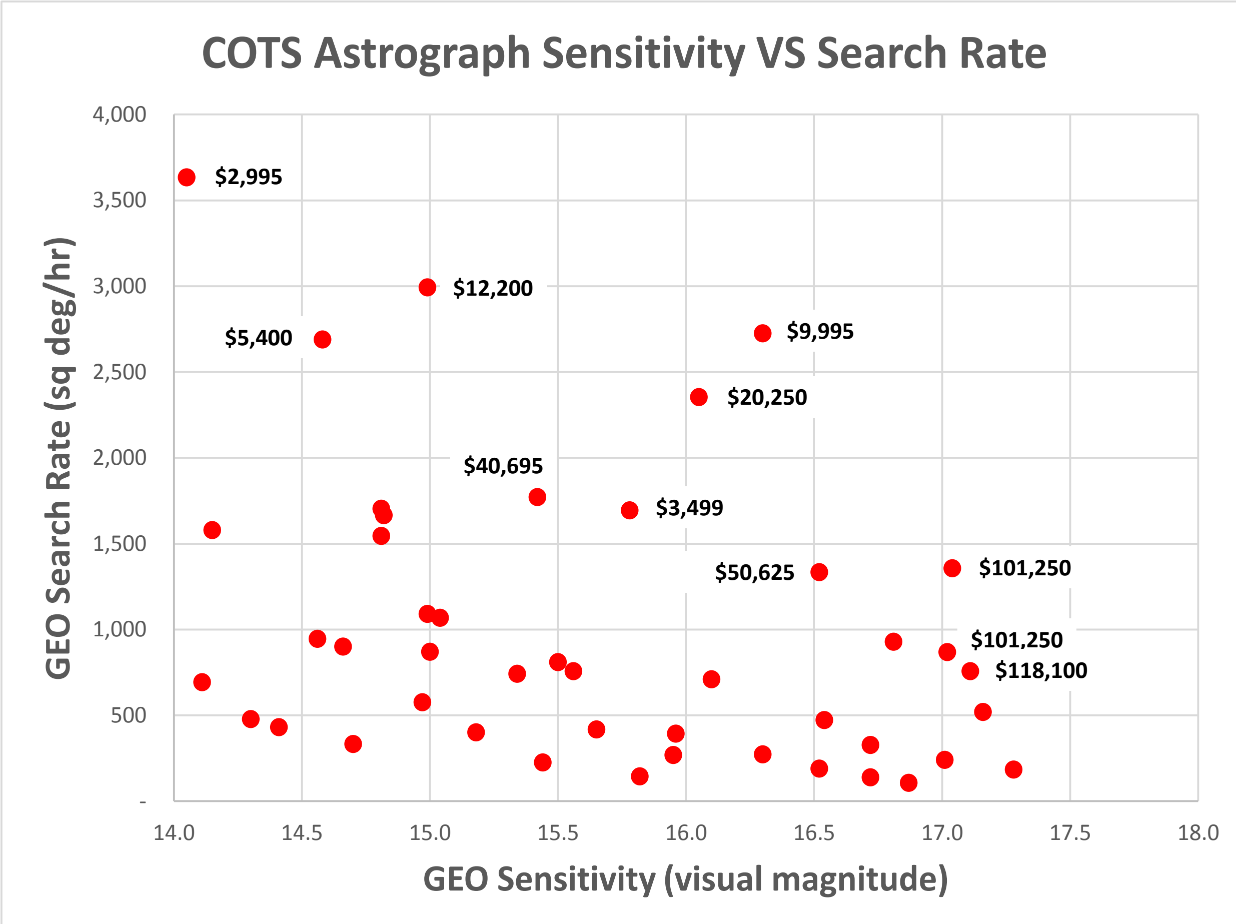

Fig 7. Plot of COTS Astrograph performance – calculated sensitivity VS search rate.

Table 3. Best Performing COTS Astrograph/Camera Combinations

		Specifications					Performance		
Manufacturer	Model	Aperture (mm)	Limiting Mag	Search Rate (sq deg/hr)	CCD Diagonal (mm)	Typical Price	Limiting Mag	Search Rate (sq deg/hr)	Advanced Processing Lim Mag
Takahashi	Epsilon 130D	130.0	14.1	3,633	52	$2,995	14.1	3,633	15.8
Celestron	RASA C-11	279.4	15.8	1,694	52	$3,499	15.8	1,694	17.1
Takahashi	Epsilon 180	180.0	14.6	2,688	52	$5,400	14.6	2,688	16.3
Celestron	RASA C-14	355.6	16.3	2,725	70	$9,995	16.3	2,725	17.6
Astro Systeme Austria	Astrograph 8H	200.0	15.0	2,993	52	$12,200	15.0	2,993	16.6
APM	Wynne-Riccardi-Astrograph	305.0	16.1	2,353	70	$20,250	16.1	2,353	17.4
Officina Stellare	Veloce RH 350	350.0	15.4	1,770	70	$40,695	15.4	1,770	17.0
APM	Wynne-Riccardi-Astrograph	406.0	16.5	1,332	70	$50,625	16.5	1,332	17.9
APM	Large Prime Focus Astrograph	560.0	17.0	1,356	70	$101,250	17.0	1,356	18.3
APM	Wynne-Riccardi-Astrograph	560.0	17.0	868	70	$101,250	17.0	868	18.4
APM	Wynne-Riccardi-Astrograph	600.0	17.1	757	70	$118,100	17.1	757	18.5

Sensitivity with Advanced Processing

The final column in both tables 2 and 3 presents the limiting magnitude that might be achieved with the use of advanced processing algorithms. A variety of such algorithms are detailed in the technical literature. Most of these can be described as multiple hypothesis testing (MHT) approaches, even though they will go by different names such as track before detect. The advanced processing algorithm predictions seen in these tables result from approaches developed by Peter Zimmer of J.T. McGraw and Associates (JTMA) of Placitas NM. These algorithms are somewhat unique as they do not neatly fall into any previous taxonomy for naming detection algorithms. The results of such calculations are shown here to demonstrate that significant sensitivity can be achieved even with relatively small aperture COTS optical systems. Algorithms are much easier and much less expensive to develop than custom optics or custom detectors.

Custom VS COTS

While the above data, particularly the cost data, make a strong case for the use of COTS astrographs, custom optical systems still have their place in the SSA world. Not all targets reside at GEO altitudes. Lower orbiting satellites present a significantly more challenging problem requiring wide-field optical systems with cameras capable of supporting high frame rates (nominally 1 frame per second).

Consider, for example, the Celestron RASA-14. This optical system provides excellent performance for GEO search and detection when paired with a camera of 60-70 mm diagonal. If the same telescope were used for low earth orbit (LEO) observation, it would either miss targets due to the time in between observations required to read out the camera, or it would need to use an interline transfer CCD with only a 43 mm diagonal measurement. This would reduce the effective image field from 9.35 square degrees to only 4.73 square degrees.

A custom astrograph being developed by JTMA will use a Celestron C-14 primary mirror, with no Schmidt plate and a 6-lens prime focus focal reducing optical system. It will image 2.4 x 3.6 degrees onto a 24 x 36 mm interline transfer CCD with a 43 mm diagonal, which will allow this custom astrograph to capture 8.64 square degree fields of LEO (or GEO) at a rate of 1 frame per second with 1 second integration time and no dead time on the sky. For GEO observations, the Celestron RASA-14 has a slight edge in sensitivity and search rate, but for LEO observations, the custom astrograph clearly wins. The difference in cost however is substantial. The target price for the Celestron RASA-14 will be $9,995 while the custom astrograph prototype will cost in excess of $50,000 to develop.

Summary

In this paper, we have presented a brief examination of the potential for COTS systems to contribute to global SSA. While governments and bureaucratic procurement systems move slowly, private corporations and universities can move much more rapidly to field global networks of telescopes for effective and highly sensitive SSA. The commercial hardware for such endeavors largely exists, only requiring acquisition and deployment.

While COTS systems perform well, it is important to note that custom optical systems still have their place within the industry and the world of SSA.

References

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