LIMITING MAGNITUDE OF ASTROPHOTOGRAPHY SYSTEMS

A Comprehensive Analysis

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PRESENTATION GOAL

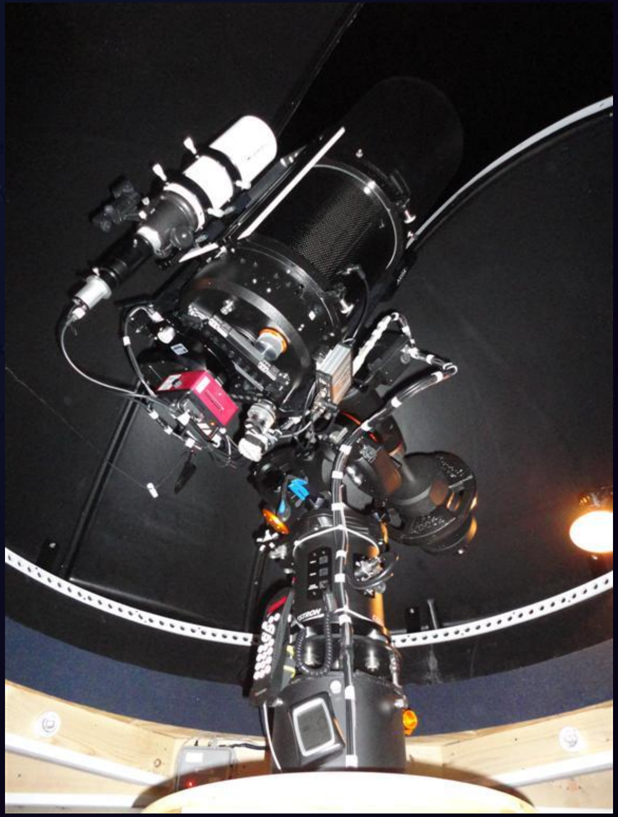
In this presentation we will look at various factors which affect the sensitivity of Astrophotography Systems.

Sensitivity, or “the Limiting Magnitude” is the magnitude of dimmest stellar object detectable by your system. This happens when the Target SNR = 3. Thus, this is all about optimizing the system SNR.

There are multitude of factors that effect AP system sensitivity, and complete treatment requires complex numerical simulation. It is important to understand how, and how much each of the different elements affect your system.

By means of quantitative data we will examine:

- The journey of Photons to your image file
- Effects of Telescope Aperture on Limiting Magnitude
- Impact of Telescope Type on Sensitivity
- Impact of Telescope Optics on Sensitivity (Coatings)
- Impact of Imaging Camera and its QE on Sensitivity
- Impact of the Seeing on Sensitivity
- Impact of Sky Pollution on Sensitivity
- Atmospheric Extinction
- Putting it all together



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JOYRNEY: from PHOTONS to ELECTRONS

When it comes to telescopes, we all know that bigger is better.

What else impacts the quantity of photons reaching the imager, and their conversion to signal?

Noise: what basic types of noise dominate imaging?

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HOW IS DATA GENERATED

All data was generated by Astrophotography CAD (v1.0.7.1) computation engine using numerical simulation and analysis. The simulation was performed over full 350nm – 1000nm spectral range.

Simulation Conditions:

- Ideal OTA for Limit Analysis
- Perfect Camera for limit Analysis
  - ✓ No Read Noise
  - ✓ Flat 100% QE across the band
- No Filters used in simulations
- Low Haze (AOD-0.06) for Extinction computation
- Suburban Photo Chromatic Sky (20 MPAS)
  - ✓ LED and HPS mixture
- K0 Stellar Type (for real life OTA comparisons)
- Exposure: 1Hr total, with 60 second subs
- Sea level observing Site altitude

Haze: (0.06)

Suburb

Sky Glow: 20.0 MPSAS (NELM: 5.5)

Seeing: 2.0 arcSec

Target Elevation: 90° Altitude: 0m

Target: 21.5 mag

● Stellar Type ○ B-V ○ Temp.(K)

Class F0 (7,350K) B-V 0.32

Camera Filter

NO FILTER

Total Exposure:

Seconds	0
Minutes	0
Hours	1

Focal Reducer

Show SNR ☐

Focal Reducer Effect on Sensitivity

Focal Reducer Optics NOT in Use

BIN: 1x

Fix Sub (s):	60
Desired SNR:	3

Current: 1 x
LM=22.351mag
Max SUB=10245sec

Nyquist: 0.32 x
LM=22.098mag

Exposure Parameters: 60 x 60s Subs
Current System FOV: 16.3' x 16.3' (0.54deg²)
Binned Resolution: 2048 x 2048
Best Achievable Lim. Mag: 22.351 @ 1.00x FR

Optical Tube Assy.

Celestron C11 XLT & EDGE

OTA/Telescope (Save As):

Celestron C11 XLT & EDGE

Used Optical Elements:

Corrector Lens × Primary

☑ Enhanced Coatings

Aperture (mm)	280
Obstruction (mm)	95
Focal Length (mm)	2800
Focal Reducer (X)	1
Extra Element1 (%)	100
Extra Element2 (%)	100
Extra Element2 (%)	100
Type: Celestron XLT	0

Imager / Camera:

SBIG AC2020BSI

☑ Use Off-Chip Binning

☐ Auto Set Binning

CMOS - COOLED

Pixel X (μm)	6.5
Pixel Y (μm)	6.5
X Pixels	2048
Y Pixels	2048
Binning	1
Well e⁻	54000
Read Noise (e⁻)	2
Dark (e/sec)	0.16
ADC Bits	16
Gain (e/ADU)	1
Dark Frames	100
Bias Frames	100
Flat Frames	100
Flats Well (%)	80

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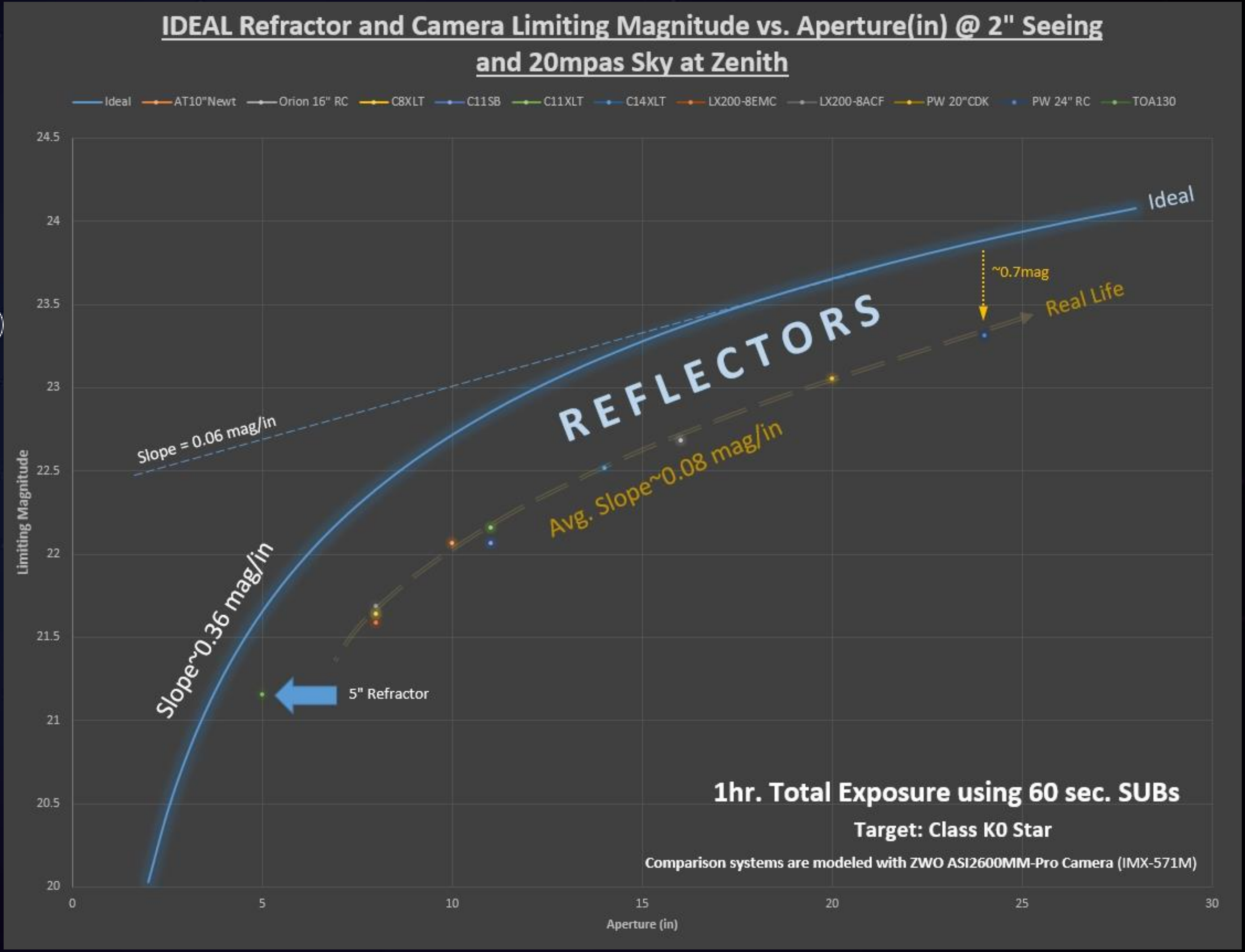
OTA EFFECTIVE APERTURE

Larger OTA aperture has larger area to collect incoming photons. The sensitivity gains do not scale linearly with the aperture or the OTA collection area due to noise considerations.

Using numerical simulation it is possible to predict the and compare the limiting magnitude of idealized system to that of well known telescope OTAs.



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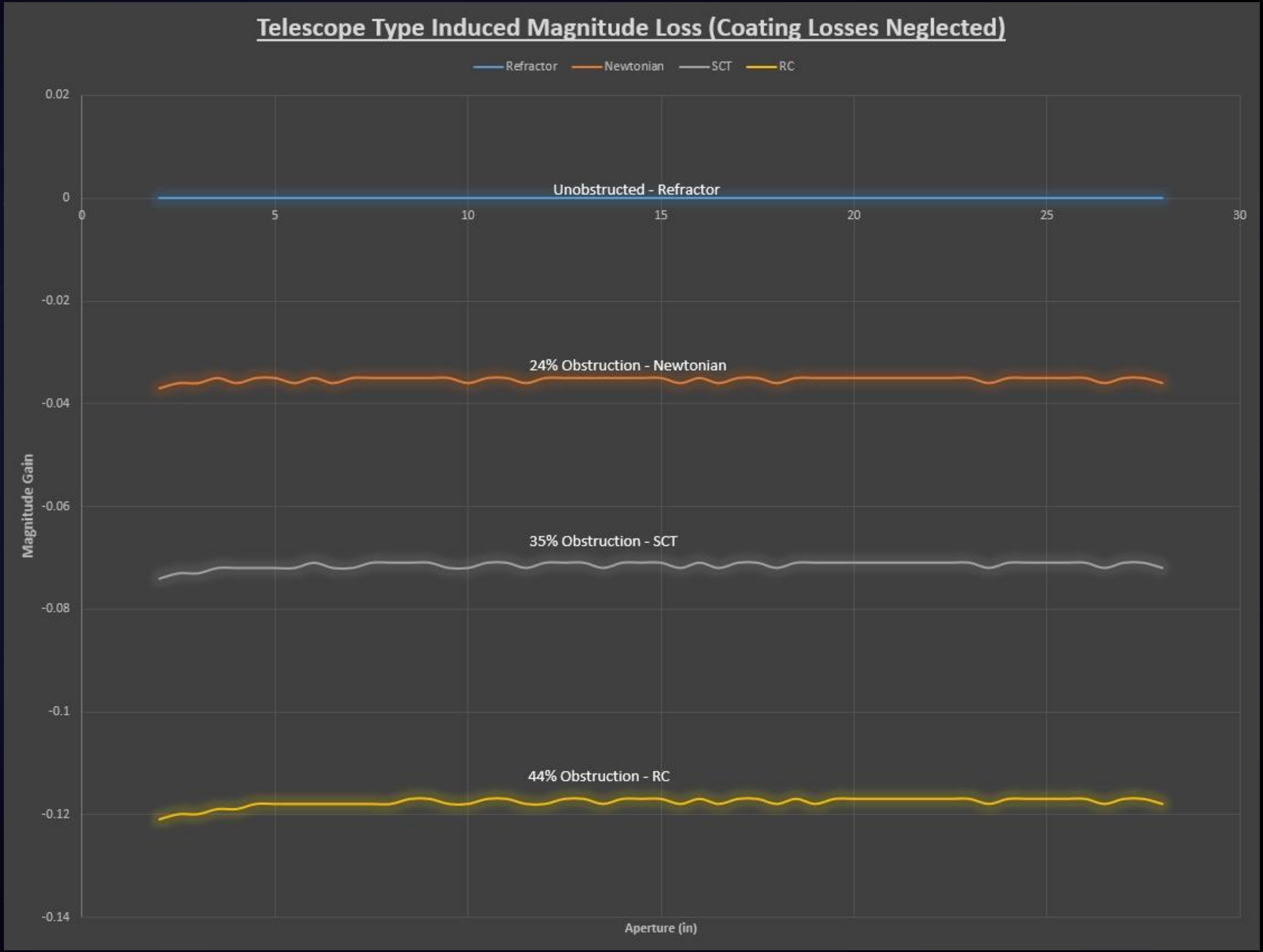
OTA TYPES

The amount of light reaching the imaging sensor is modulated by the telescope construction. Some OTA types are constricted by secondary elements which reduce the effective OTA's collecting area.

Refracting telescopes are the most efficient, however it is difficult to manufacture very large lenses. Reflecting telescopes are generally used above 6″ in the amateur world, but are subject to secondary photon flux obstructions.



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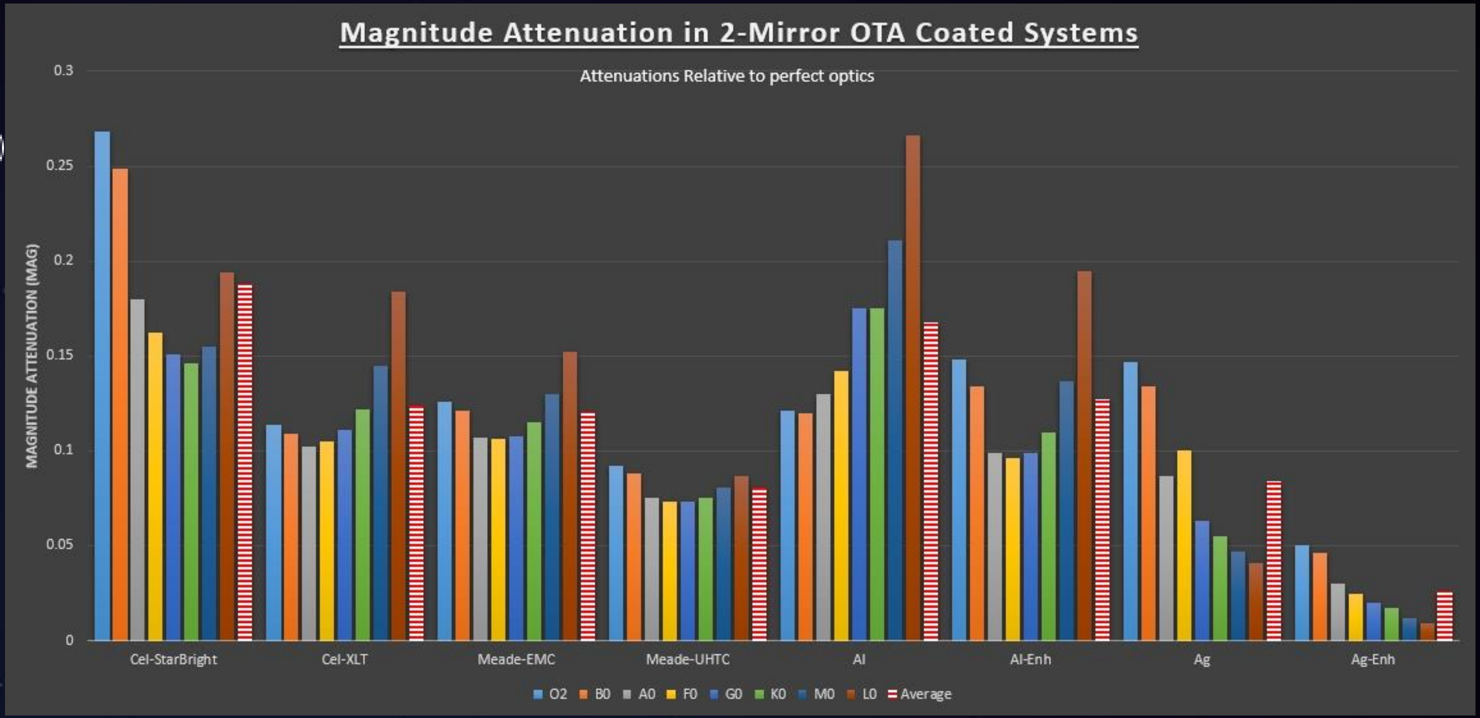
COATED MIRROR OPTICS

With very few exceptions, reflecting OTA systems are two mirror systems. Two surface reflection multiplies the OTA transmission loss, so it is important to use mirrors with high reflectance coatings.

This chart examines mirror induced losses for various manufacturers and coating technologies.

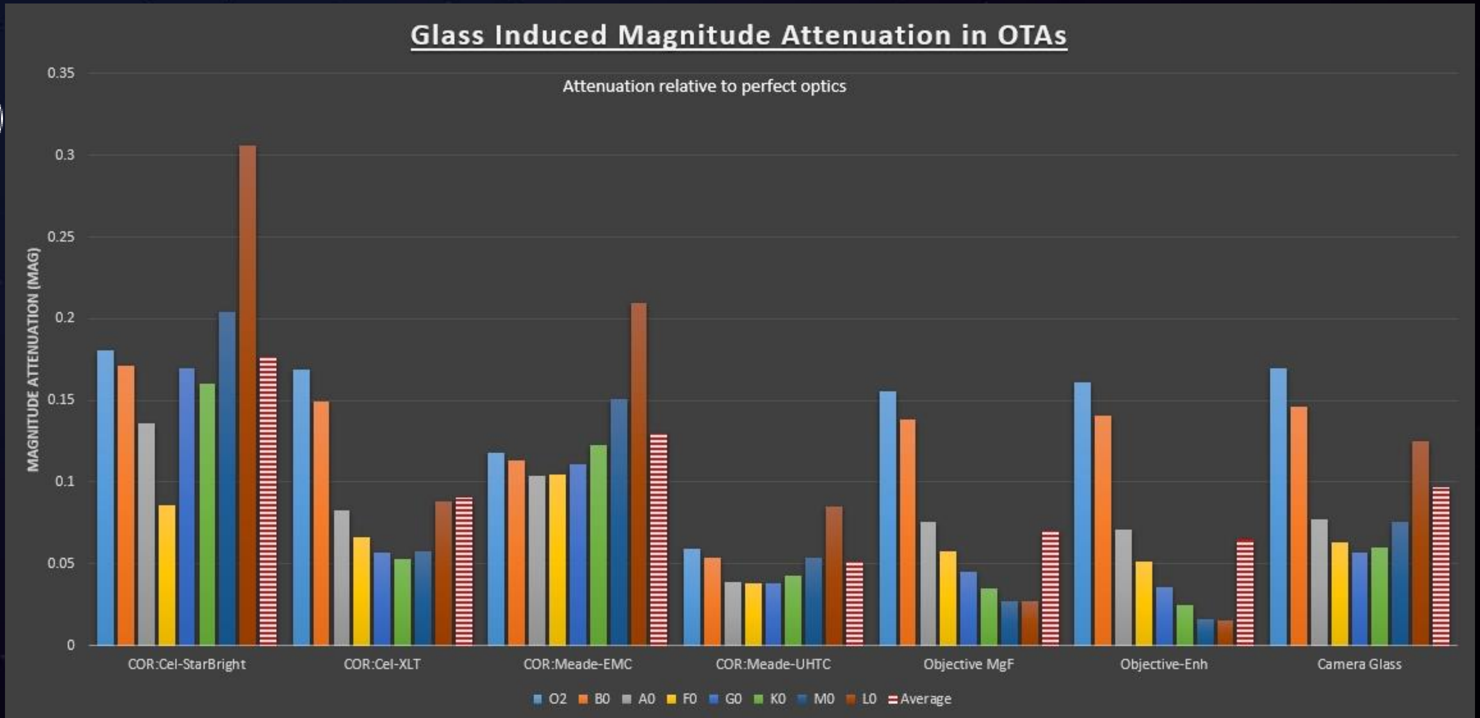

Magnitude Attenuation in 2-Mirror OTA Coated Systems

Attenuations Relative to perfect optics

COATED TRANSMISSIVE OPTICS

Many OTAs also contain transmissive glass optical elements such as corrector plates, objectives, Focal Reducers etc. They induce additional system loss, and their coatings and glass used are selected to optimize performance.

This chart examines mirror induced losses for various manufacturers and coating technologies.


Glass Induced Magnitude Attenuation in OTAs

Attenuation relative to perfect optics

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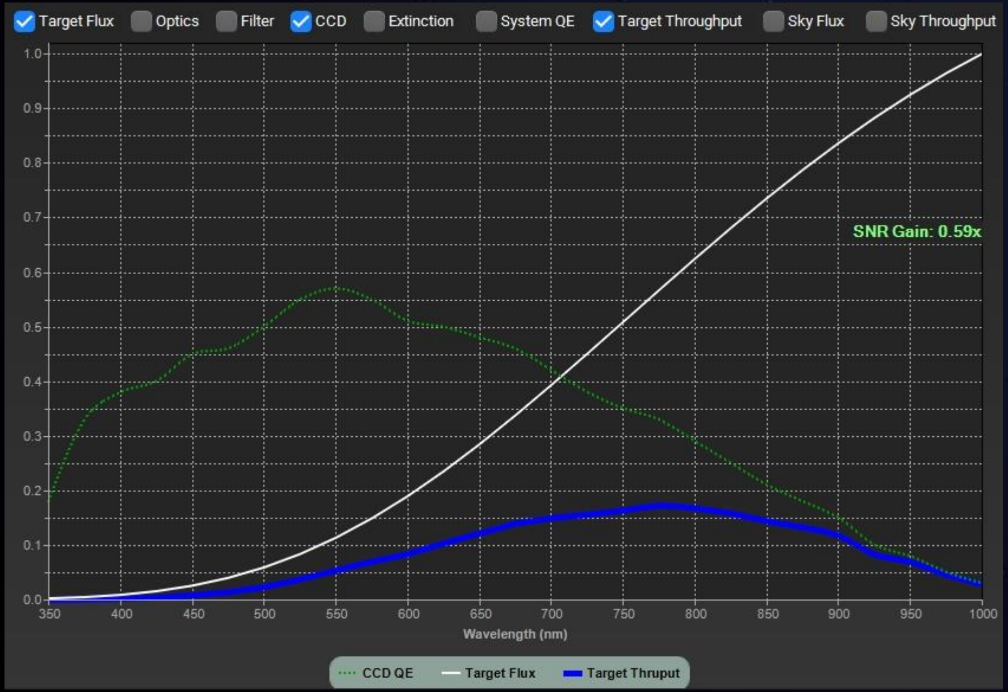
CAMERA SENSORS

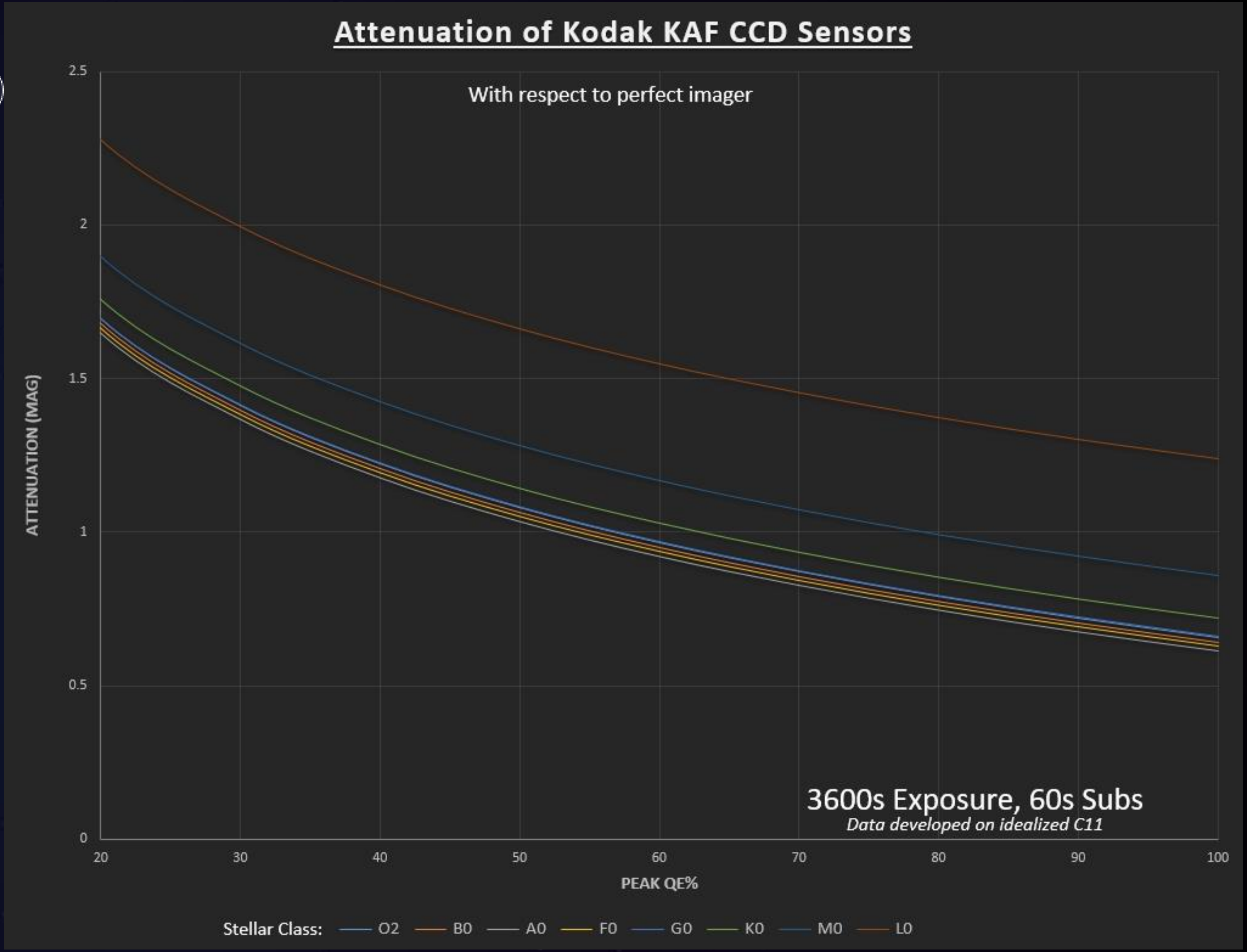
Since the camera sensors do not have flat response across the entire spectral region, objects of different color temperature will be detected with different efficiency. A deep red object will not do very well on a sensor in the example below.

Since imager manufacturers employ standardized production methods, the general shape of the QE curves is very similar, differing only in peak QE%. This allows us to approximate expected response for entire families for purpose of this presentation.

Since the sensors do not have flat 100% QE response, they will exhibit attenuation with respect to perfect camera, even at 100% peak QE, thus the concept of "Average QE".



☑ Target Flux ☐ Optics ☐ Filter ☑ CCD ☐ Extinction ☐ System QE ☑ Target Throughput ☐ Sky Flux ☐ Sky Throughput



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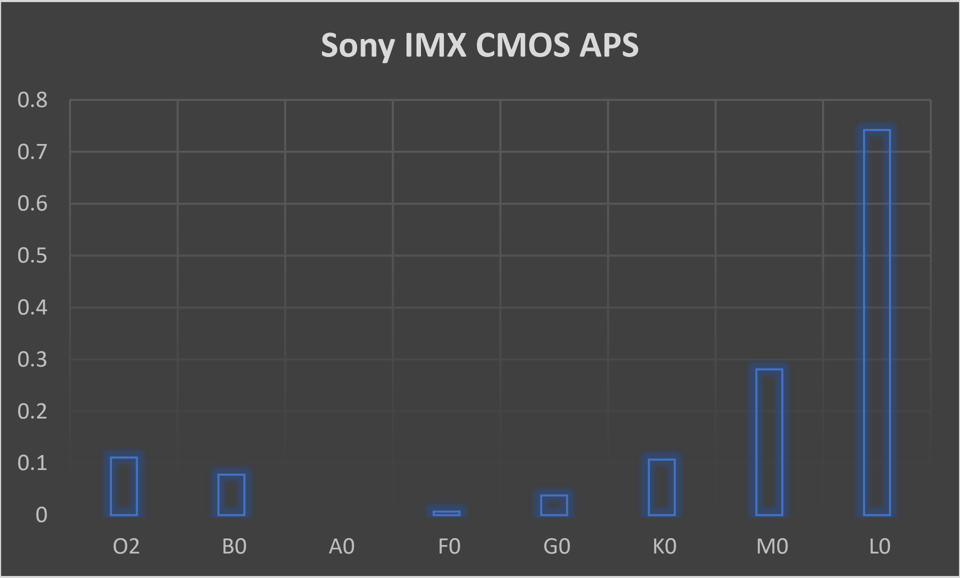
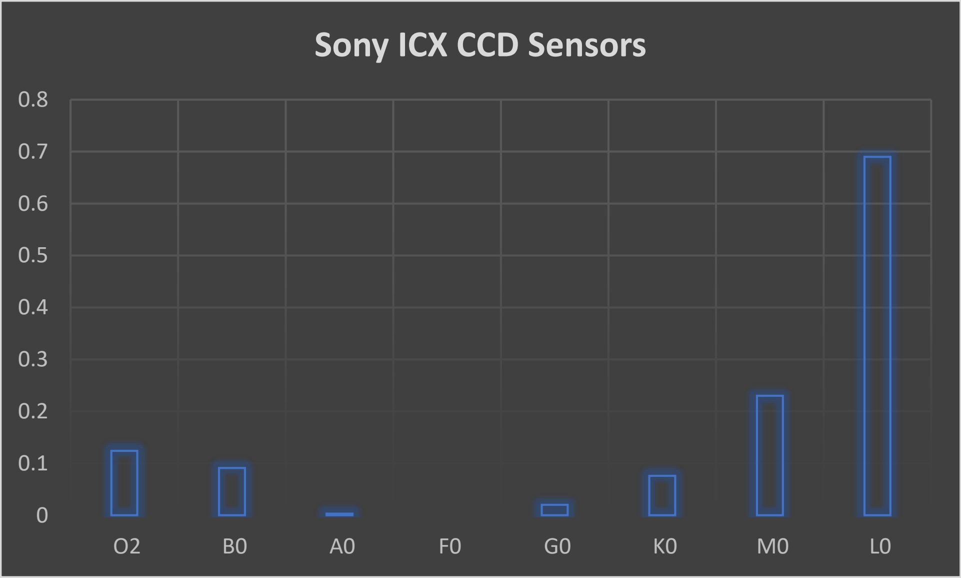
IMPACT of SENSOR RESPONSE CURVE and TARGET STELLAR CLASS

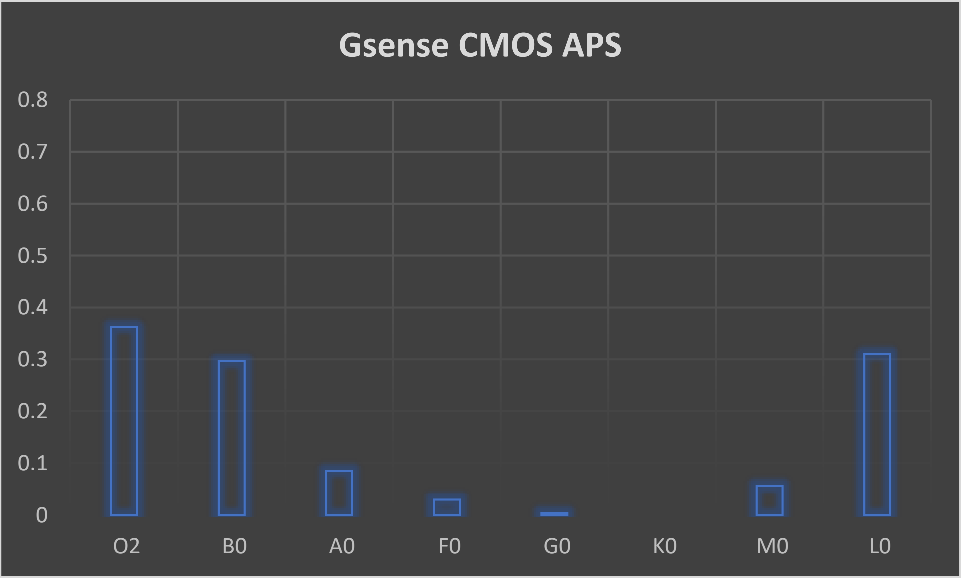
Magnitude Degradation

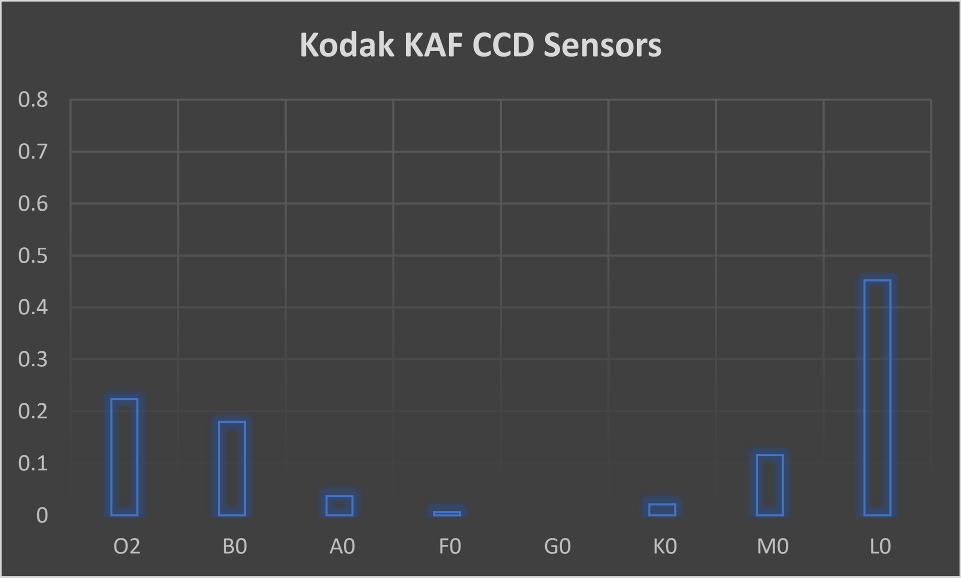
Previous analysis allows us to comparatively study sensors built on different technologies, and how they perform for different stellar class types.

Sony sensors (although providing high peak QE) are more sensitive to blue targets, but perform 0.6 mag worse for deep red objects, so not the best choice for studying red dwarfs.


Sony IMX CMOS APS


Sony ICX CCD Sensors


Gsense CMOS APS


Kodak KAF CCD Sensors

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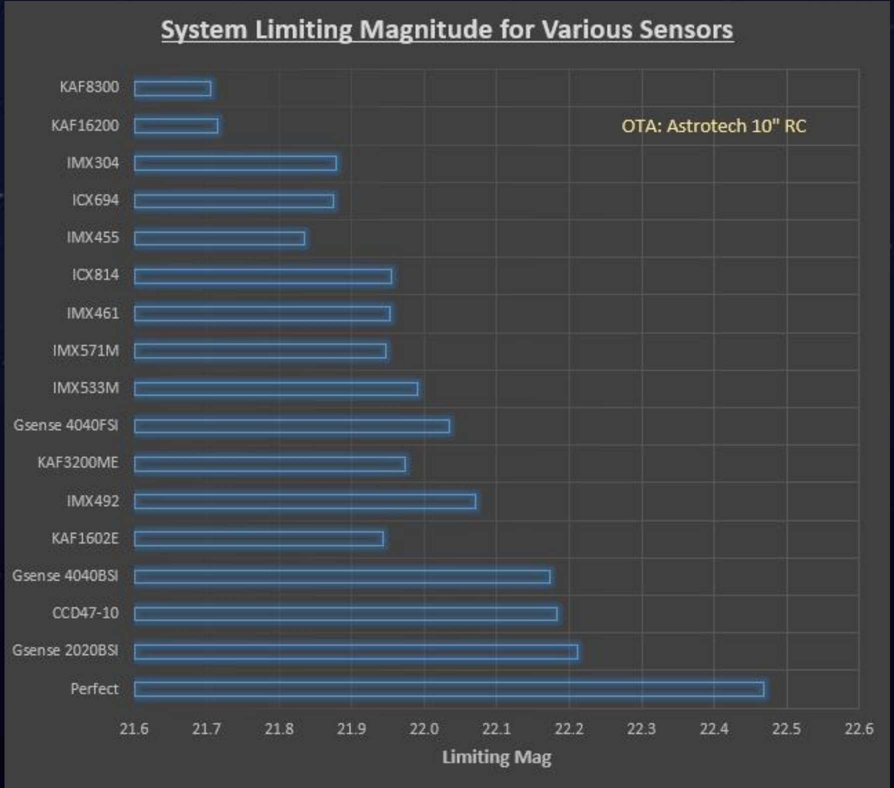
CAMERA COMPARISONS

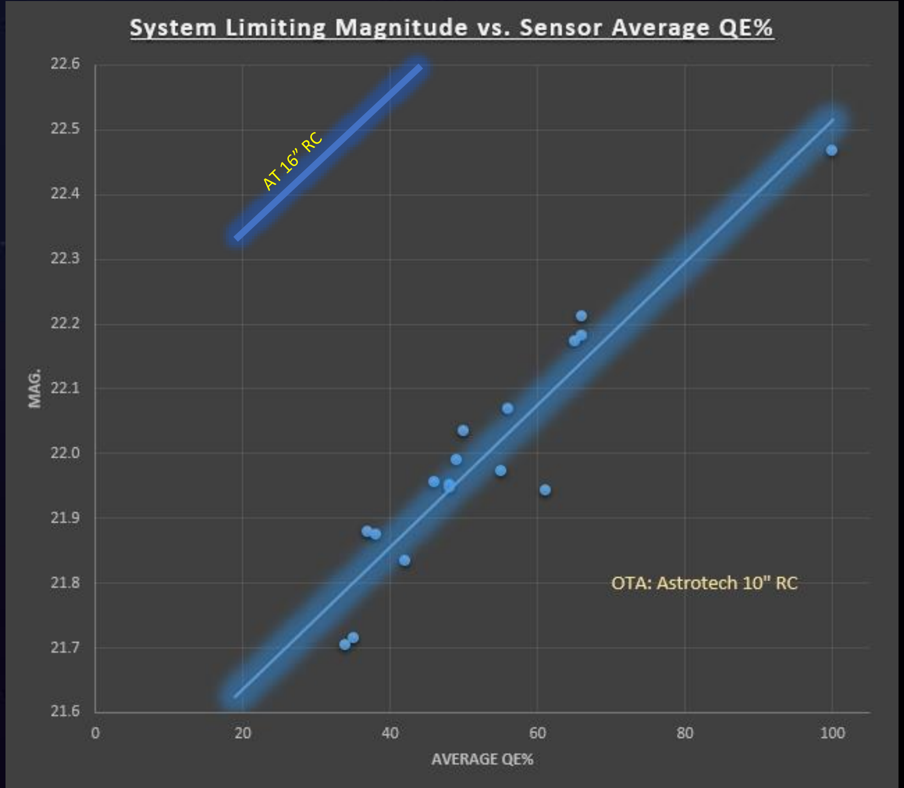
There is a strong correlation and dependence between the system sensitivity and the average imager QE. This holds true across mfg. technologies and manufacturers.

In the example of 10” RC OTA shown, this dependence is approximately 0.011 magnitudes for each % of average QE, but this will generally apply to other OTAs for the same target.

The main contributing factor to the scatter is the camera read noise. For example, the older KAF1602E chip has higher read noise of 15e as compared to ~3e for modern CMOS APS sensors, lowering its limiting magnitude by about 0.1 mag from theoretical.

Altair	Atik	MI	Orion	QHY	QSI	SBIG	ZWO	Sensor	Diag mm	avg QE%	LM
								Perfect	N/A	100	22.468
		C4-16000				AC2020BSI		Gsense 2020BSI	18.8	66	22.211
						CCD47-10(mb)		CCD47-10	18.8	66	22.182
						AC4040BSI		Gsense 4040BSI	52.1	65	22.173
						SBIG ST-8XE		KAF1602E	16.6	61	21.943
Hycam115M			G10-M	QHY294M			ASI294MM-P	IMX492	23.1	56	22.070
					QSI 632	CCD3200		KAF3200ME	17.9	55	21.974
						AC4040FSI		Gsense 4040FSI	52.1	50	22.034
	ChemiMOS	MI C3-26000					ASI533MM	IMX533M	16.0	49	21.990
Hycam 26M		C3-26000	G26-M	QHY268M			ASI2600MM	IMX571M	28.2	48	21.947
		C5A-100M					ASI461MM	IMX461	54.8	48	21.952
	490EX				QSI 690	CCD814		ICX814	16.0	46	21.955
		C3-61000		QHY600M			ASI6200MM	IMX455	43.3	42	21.834
	VS60			QHY461PH	QSI 660	CCD694		ICX694	16.0	38	21.875
		C2-12000A						IMX304	17.5	37	21.879
	Atik 16200				QSI 6162	STXL-16200M		KAF16200	34.6	35	21.715
	383L+				QSI 683	ST/STF8300		KAF8300	22.5	34	21.705


System Limiting Magnitude for Various Sensors


System Limiting Magnitude vs. Sensor Average QE%

Conditions:

OTA: Astro-Tech 10” RC

Sky: 20MPAS, 2 arc-sec Seeing

Target: K0 Stellar Class

Exposure: 1hr. / 60s SUBs

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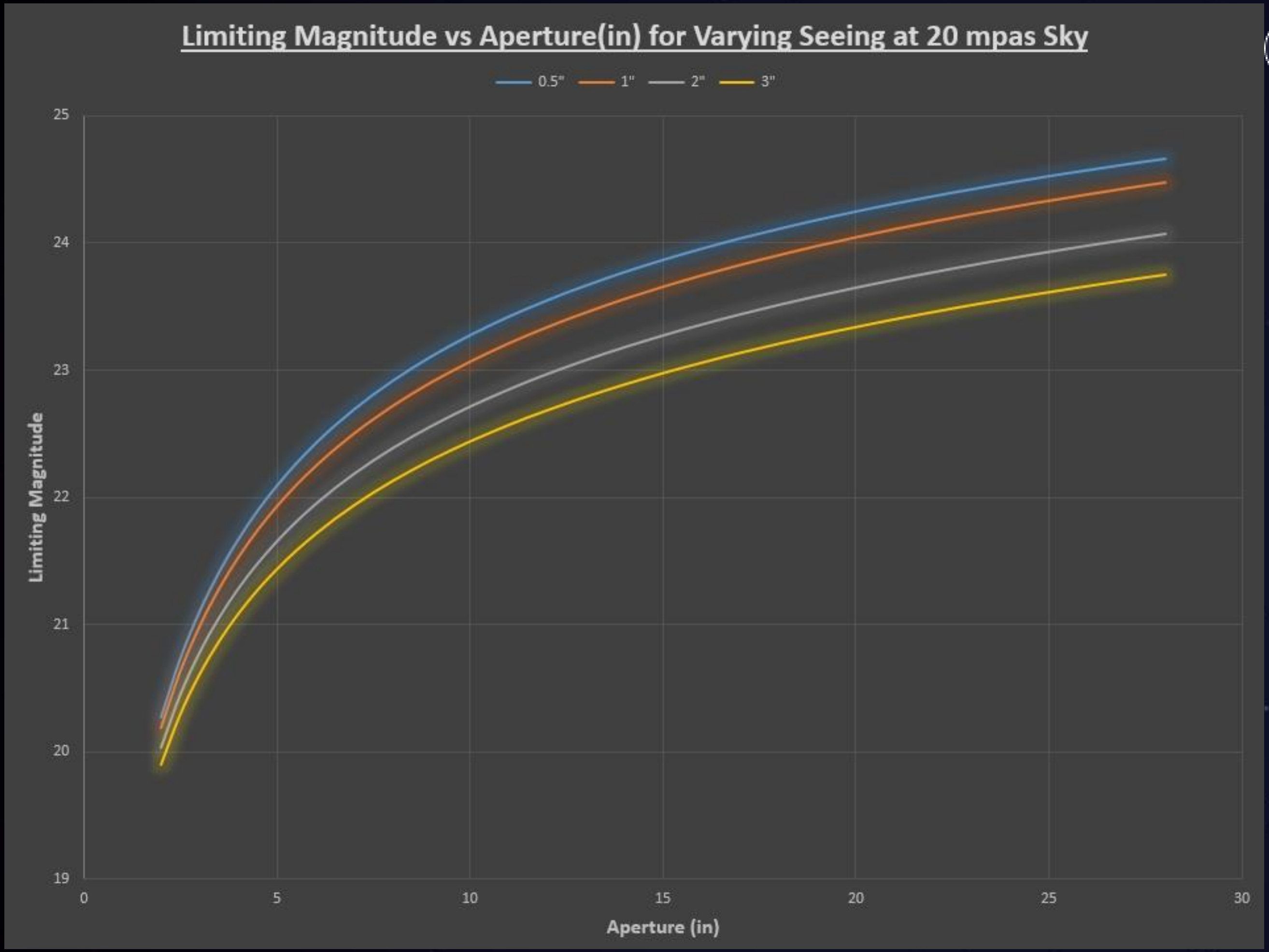
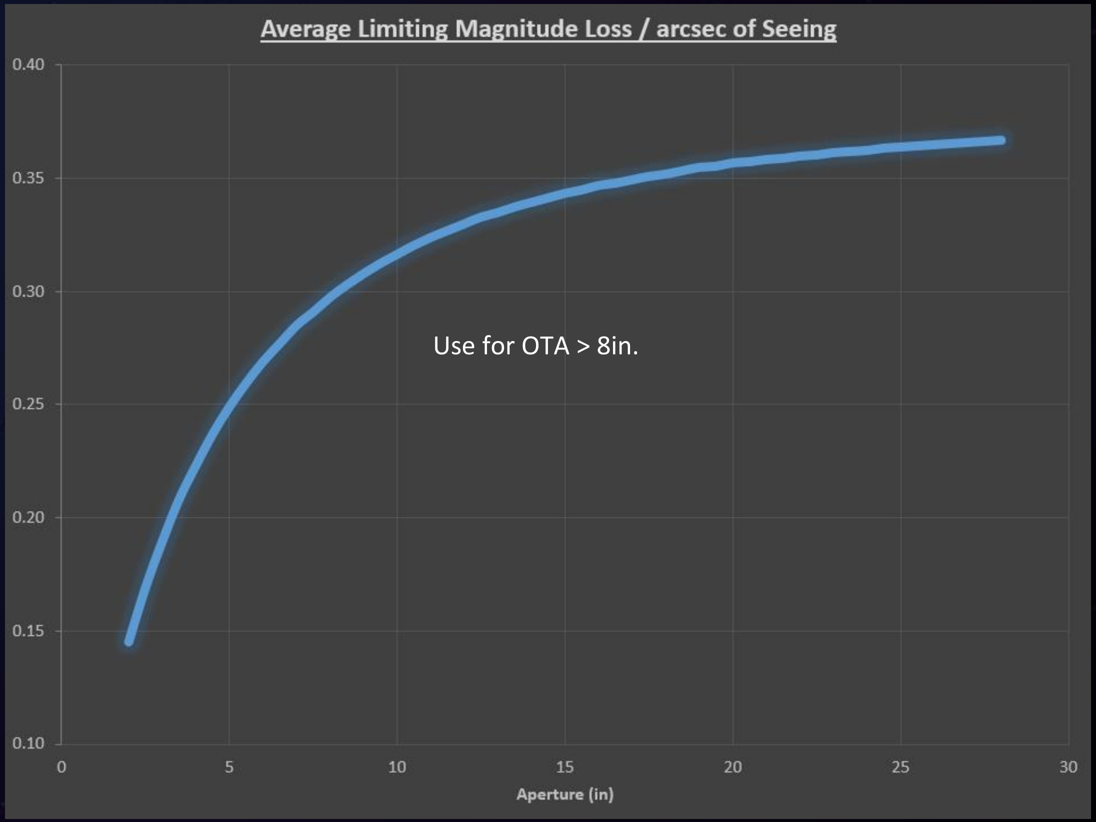
IMPACT OF SEEING

In vacuum of space, star angular diameters are infinitely small. Atmospheric turbulence induced light refraction causes starlight to rapidly bend/deflect on its way towards the telescope, causing a blurry image. This causes the star image on the sensor to be larger than diffraction limit prescribes, and be more spread on the imager. Thus individual pixels get less target light, but the same amount of background from the sky glow (light pollution).


Limiting Magnitude vs Aperture(in) for Varying Seeing at 20 mpas Sky


Average Limiting Magnitude Loss / arcsec of Seeing

Use for OTA > 8in.

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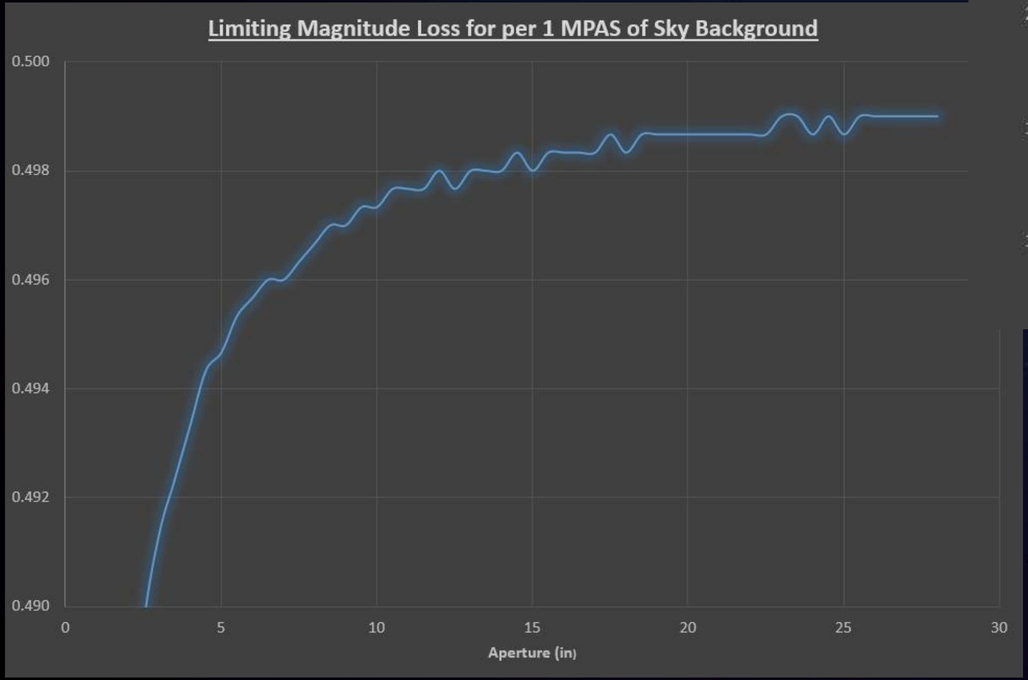
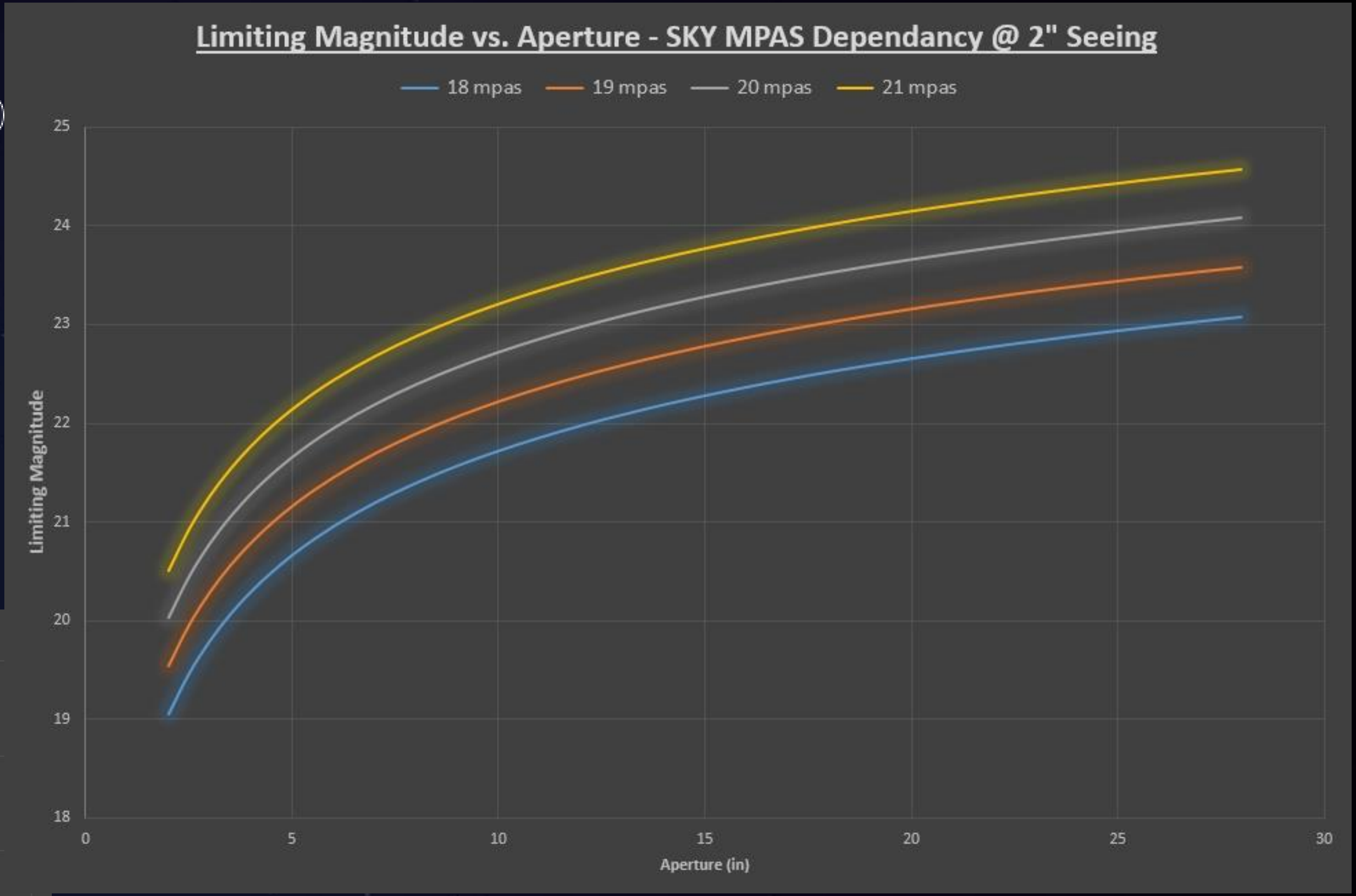
LIGHT POLLUTION IMPACT

Without exception, we all have to contend with it to some degree. Although the background light can be subtracted, the noise it generates cannot. This noise will equal square root of the background photon flux.

So, 10,000 photons will create noise of 100, which is a problem if you are trying to detect an object with 100 photons. However, if the background is only 1,000 photons, resulting noise of 33 photons will allow for SNR=3, thus a detectable object.

The above is a very simplistic presentation, and in reality things are much more complicated.


Limiting Magnitude Loss for per 1 MPAS of Sky Background


Limiting Magnitude vs. Aperture - SKY MPAS Dependancy @ 2" Seeing

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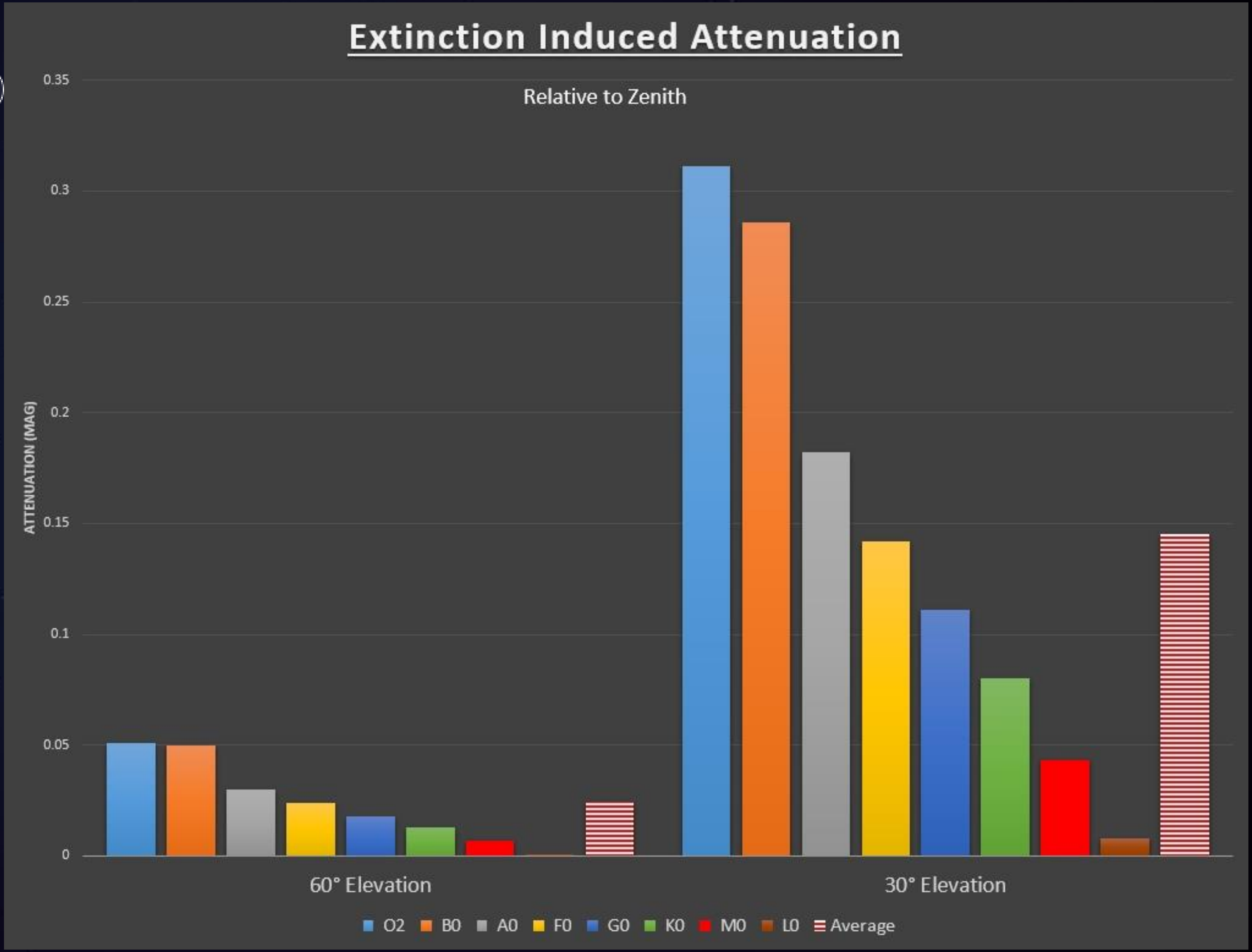
EXTINCTION EFFECTS

Atmospheric extinction is the reduction in brightness of stellar objects as their photons pass through our atmosphere. This reduction is wavelength dependent, and affects shorter wavelengths much more.

Extinction is modeled by calculating the Rayleigh scattering, Aerosol Scattering (haze) and the Ozone extinction. Extinction heavily depends on the target star elevation, low to the horizon stars being very heavily affected. The observing site's altitude is also a factor, since higher the observer, less atmosphere there is to impact the light.

This chart shows calculated extinction values for different stellar class targets. Hot blue stars are the most heavily affected.

Extinction increases almost exponentially below 30 degrees of elevation, and is almost negligible above 60 degrees.



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PUTTING IT ALL TOGETHER - ESTIMATING ASTROPHOTOGRAPHY SYSTEM LIMITING MAGNITUDE

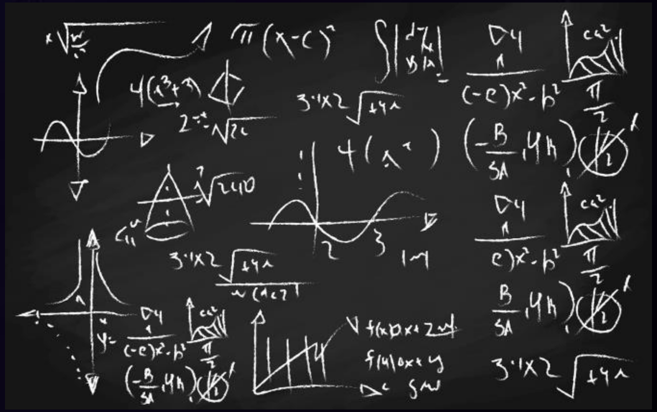
To estimate limiting magnitude of any system (LM), start with the theoretical magnitude of a perfect system (TM), from the earlier chart. It shows what is achievable by a given aperture for a perfect system at 20MPAS sky glow, and 2 arc-sec Seeing:

- Subtract OTA type attenuation (0.063 for SCT)
- Subtract attenuation due to all relevant optics (for SCT that is mirrors, corrector and the camera window)
- Subtract camera attenuation for selected stellar type bearing in mind sensor peak QE% (Only KAF sensor data is provided here).

This will give you an estimate at 20 MPAS sky glow and 2" Seeing. If your sky is different:

- Add/Subtract 0.5mag x difference from 20MPAS
- Add/Subtract 0.32mag x difference from 2 arc-sec of Seeing

The resulting Limiting Magnitude estimate will be within ∓0.15mag. More accurate results require far more complex analysis and more in-depth and comprehensive treatment.



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