HUMANIZING THE DIGITAL EXPERIENCE

TDK Developers Conference 2018

TDK InvenSense EPCOS tronics microsystems Chirp MICRONAS

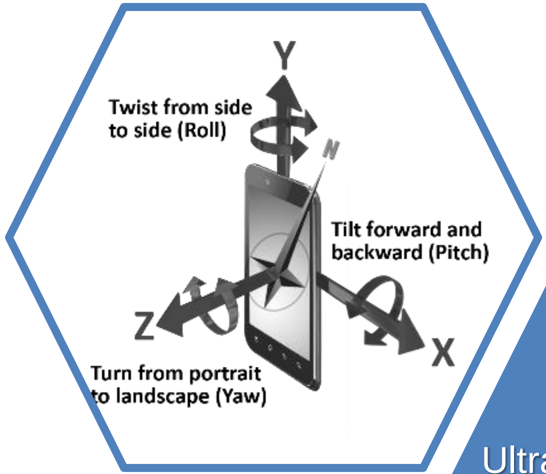
Smartphone Imaging Trends I:

How Optical Image Stabilization and Camera Module Innovations Push the Limits of Optics and Physics

Lars Johnsson, Senior Director Product Marketing, Motion & Pressure Business Unit, InvenSense

TDK Developers Conference
September 17-18, 2018
Santa Clara Marriott

CORONA Motion Sensor Applications



Motion Sensors in Smartphones
Movement, Navigation
Orientation, Gestures
Fitness, AR/VR
Image Stabilization,

Augmented & Virtual Reality
Ultrasonic & Motion sensors for 6 DoF Movement, Orientation Tracking, Object overlay

Robotics & Autonomous Motion
Internet of Moving Things requires motion sensing for Stabilization, navigation, autonomous control

Image Stabilization
Optical Image Stabilization, camera modules, OIS controllers, EIS Video Stabilization, Computational Image Stabilization

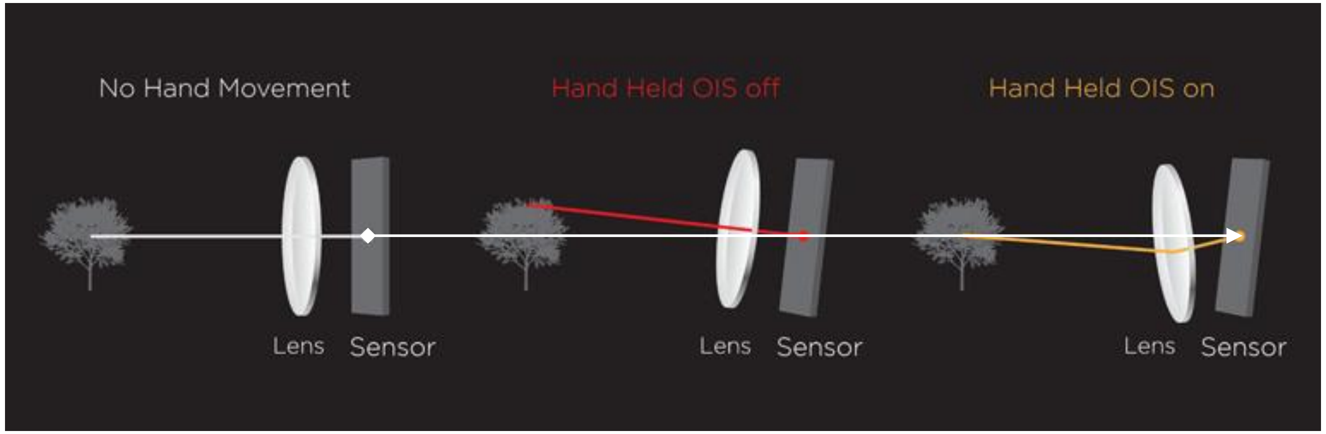
Wearables
Internet of Wearable Things
Smart Watches, Health, Fitness & more

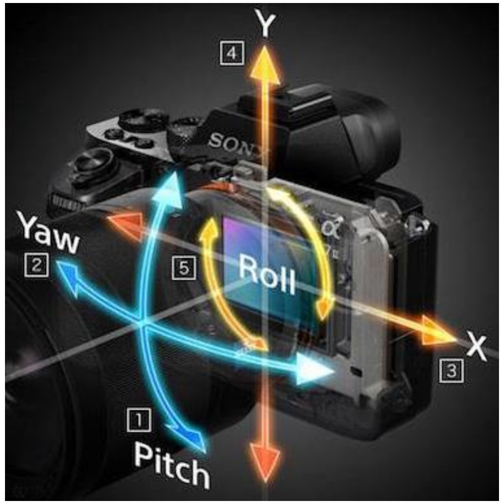

Capturing Light – the essence of photography

Leading Smartphones stabilize their Images

- In low-light conditions the only way to get enough light on the pixels is by keeping the shutter open long enough (>>50ms), which creates pixel blur from inadvertent camera shake.

- OIS solutions use motion sensors to measure camera shake and then tilt the lens to counter act the camera motion, which allows the shutter to stay open longer and capture more light





Awesome Smartphone Cameras I: Born in the USA

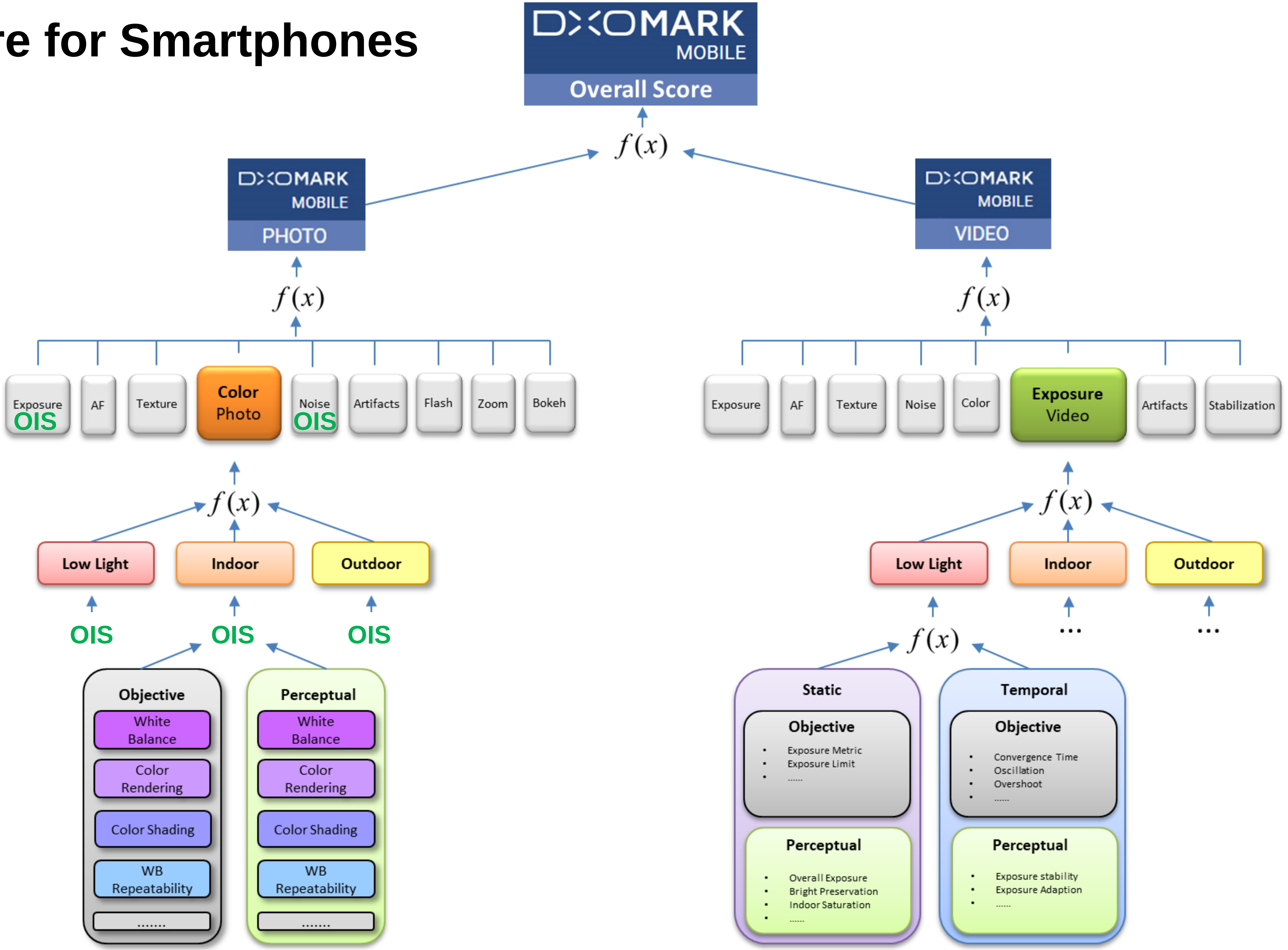
Google Pixel 2 XL	Single Lens: 12.2 MP (f/1.8) with **OIS**
Apple iPhone X	Dual Lens: 12 MP (f/1.8) with **OIS**; 12 MP telephoto (f/2.4) with **OIS**

- The DXOMARK score is the sum of many attributes that indicates a Smartphone camera's quality

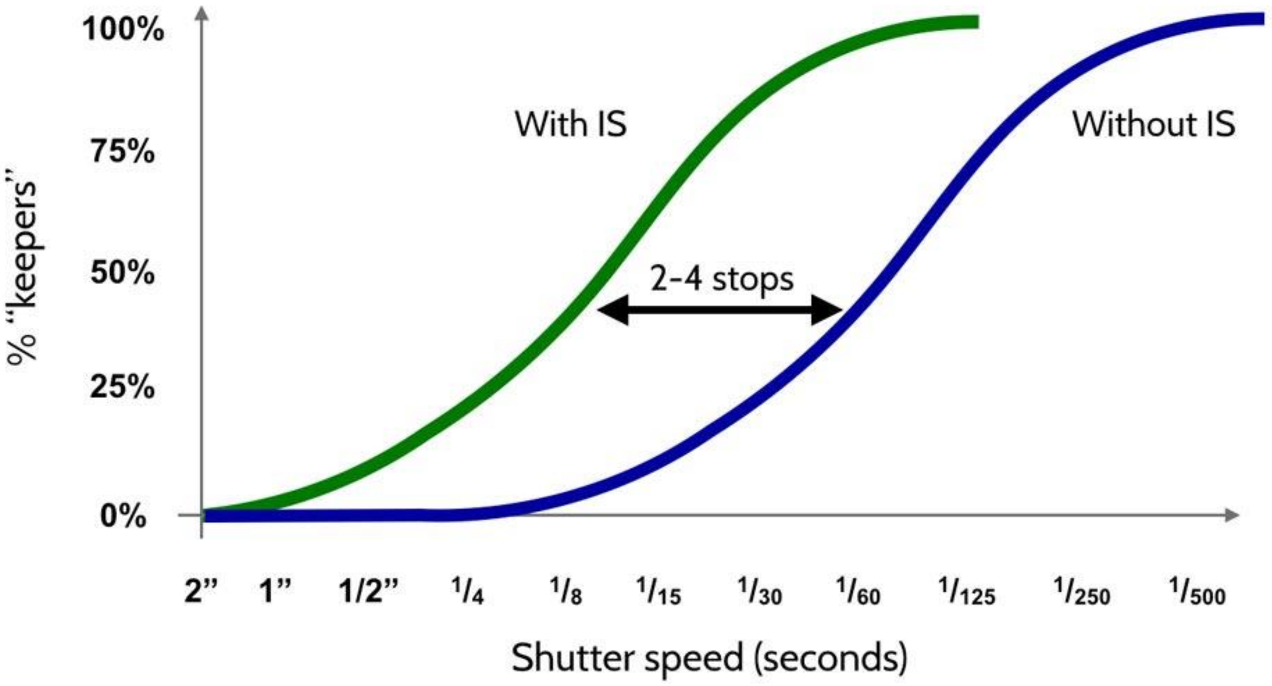
DXOMARK Score for Smartphones

- The DxOMark score for Smartphones evaluates the Photo and Video quality separately, and then combines them into an Overall score

- It's complicated, but **OIS** is everywhere ...



Optical Image Stabilization



- OIS solutions use motion sensors to measure camera shake and then tilt the lens to counter act the camera motion, which allows the shutter to stay open longer and capture more light
- When done right OIS solutions can improve the light capture by 2-4 aperture stops, but what's an aperture stop

What’s in an Aperture Stop

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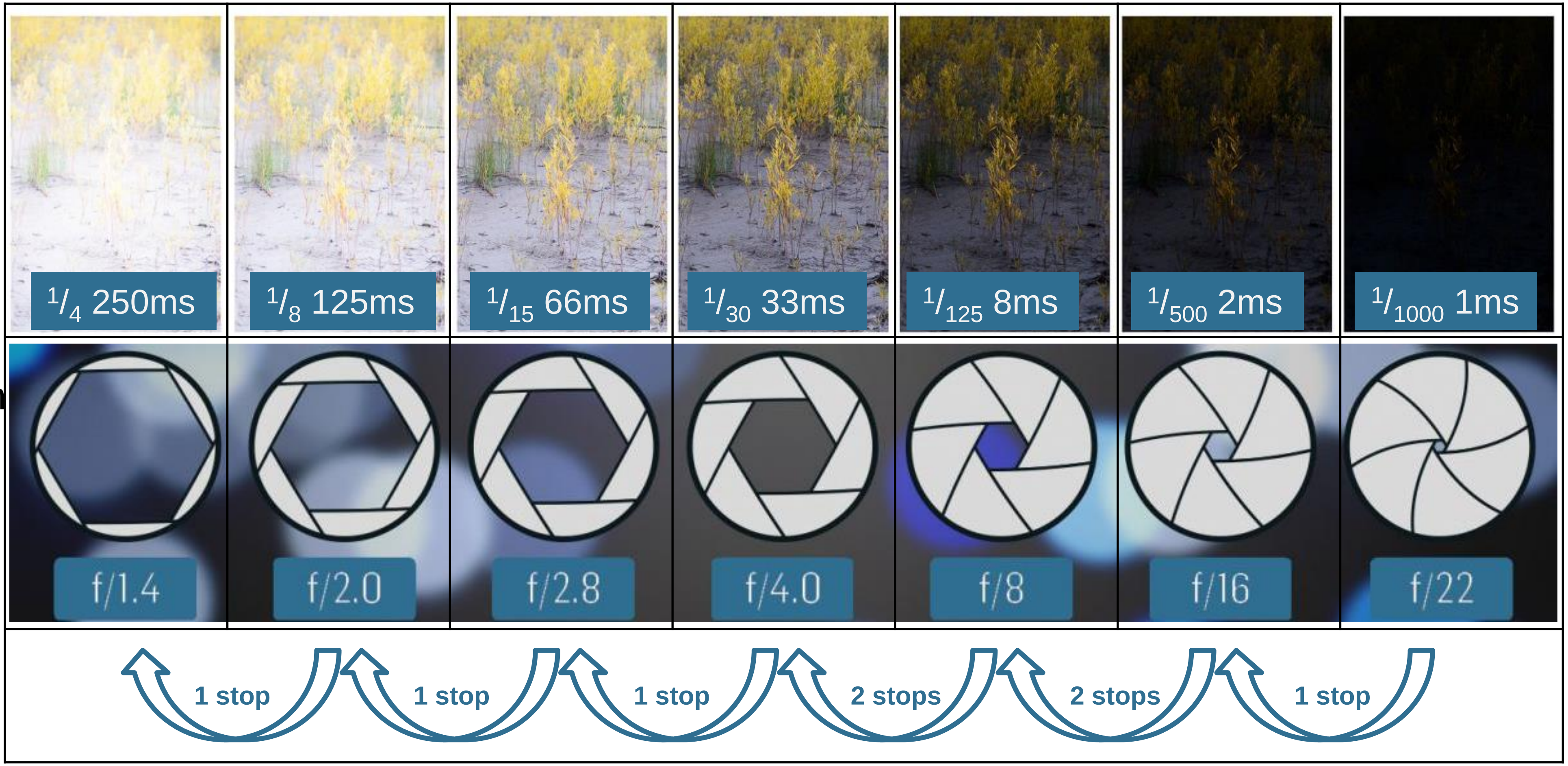
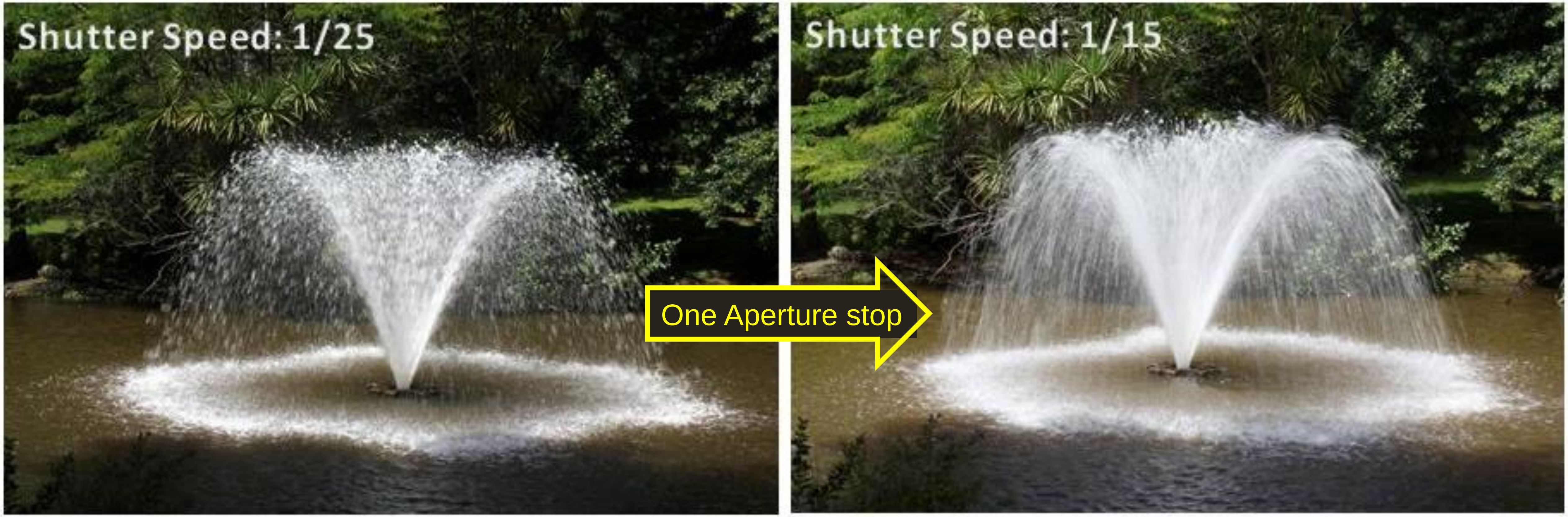
- Sunny Pasture shot with fixed Aperture (f/2.0) and different Exposure Settings
- Same light collection can be realized with fixed Exposure ($^1/_{30}$) and different Aperture Settings
- Aperture Stop Changes



- Capturing more light can be accomplished through a bigger lens/aperture or longer exposure time
- In Smartphones only the exposure time can be varied given the size and cost of a variable aperture lens

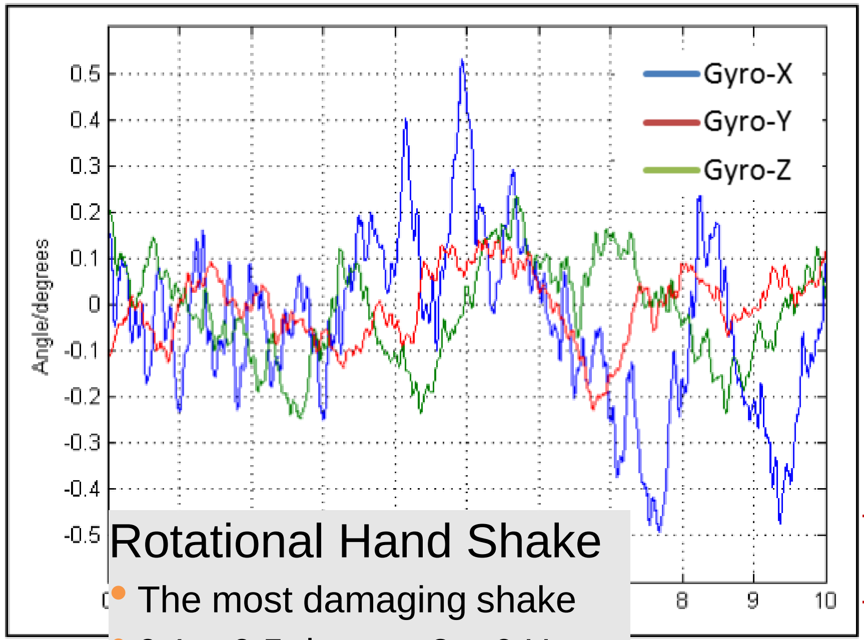
One Aperture Stop is all it takes …



- One aperture stop may not sound like much, but it is essential to capture enough light to create high-dynamic range images with recognizable detail in shaded areas, while also allowing ‘motion blur’ of the water droplets to create a stunning fountain effect …

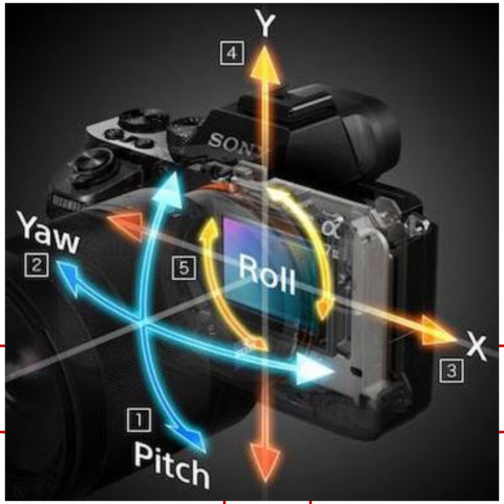
The images are for illustrative purposes, to show impact of a single aperture stop on image quality.

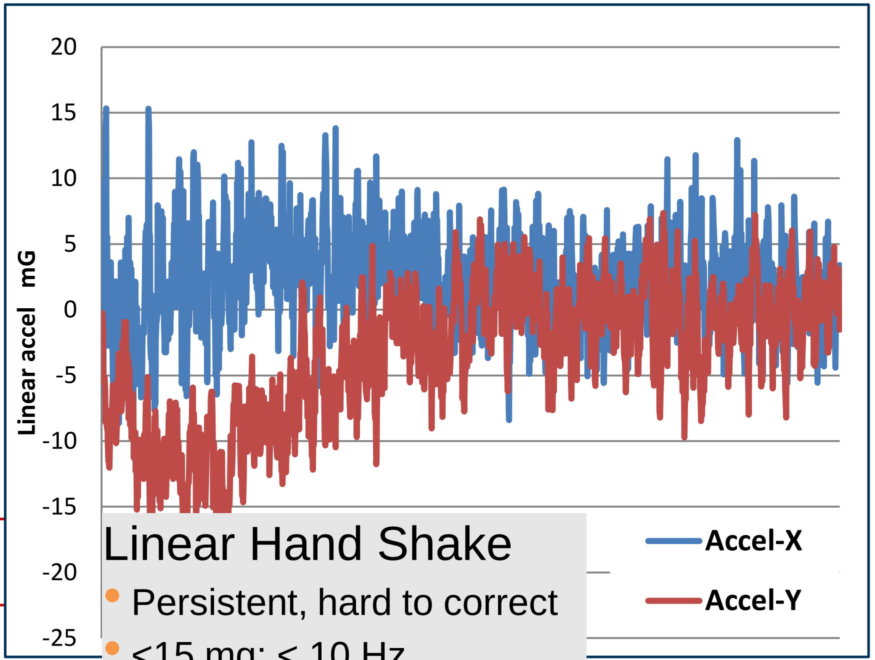
Hand Shake – without OIS it would be all a blur



Rotational Hand Shake

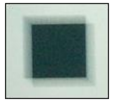
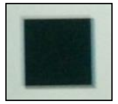
- The most damaging shake
- 0.1 ~ 0.5 degree; 2 ~ 6 Hz



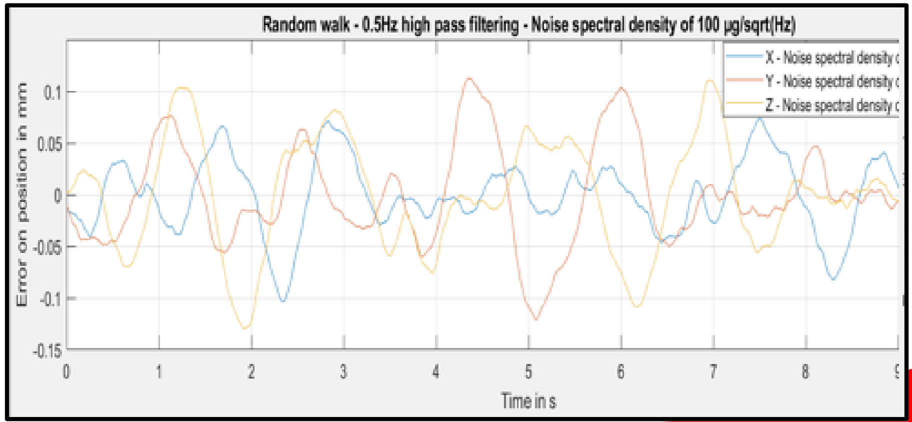


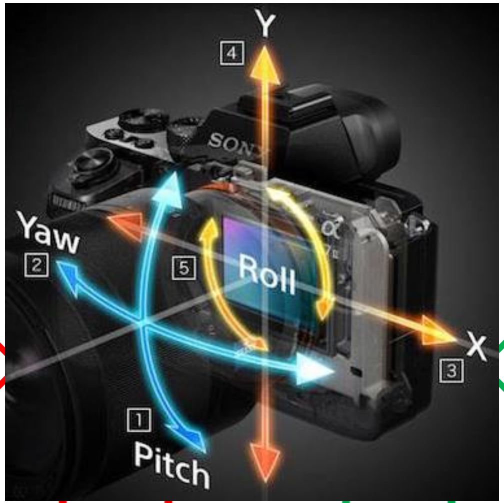
Linear Hand Shake

- Persistent, hard to correct
- <15 mg; < 10 Hz

Image "blur" scale						
Suppression Ratio	0 dB	6 dB	12 dB	18 dB	24 dB	30 dB
'Aperture Stops'	0 stops	1 stop	2 stops	3 stops	4 stops	5 stops
	No OIS			**Poor OIS**	**OK OIS**	**Great OIS**

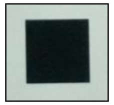
Noisy Sensor = Fake Motion = Poor OIS
TDK Sensor = only Real Motion = Great OIS





Noisy Accel 100 ug/rtHz
Basic Gyro 3.8 mdps/rtHz
Poor temp stability 15 mdps/C
High sensitivity error 1%

ST LSM6DSM

		
18 dB	24 dB	30 dB
3 stops	4 stops	5 stops
Poor OIS	**OK OIS**	**Great OIS**

Clean Accel 60 ug/rtHz
Great Gyro 2.8 mdps/rtHz
High temp stability 5 mdps/C
Low sensitivity error <0.5%

TDK ICM-42622

One Aperture Stop is all it takes …

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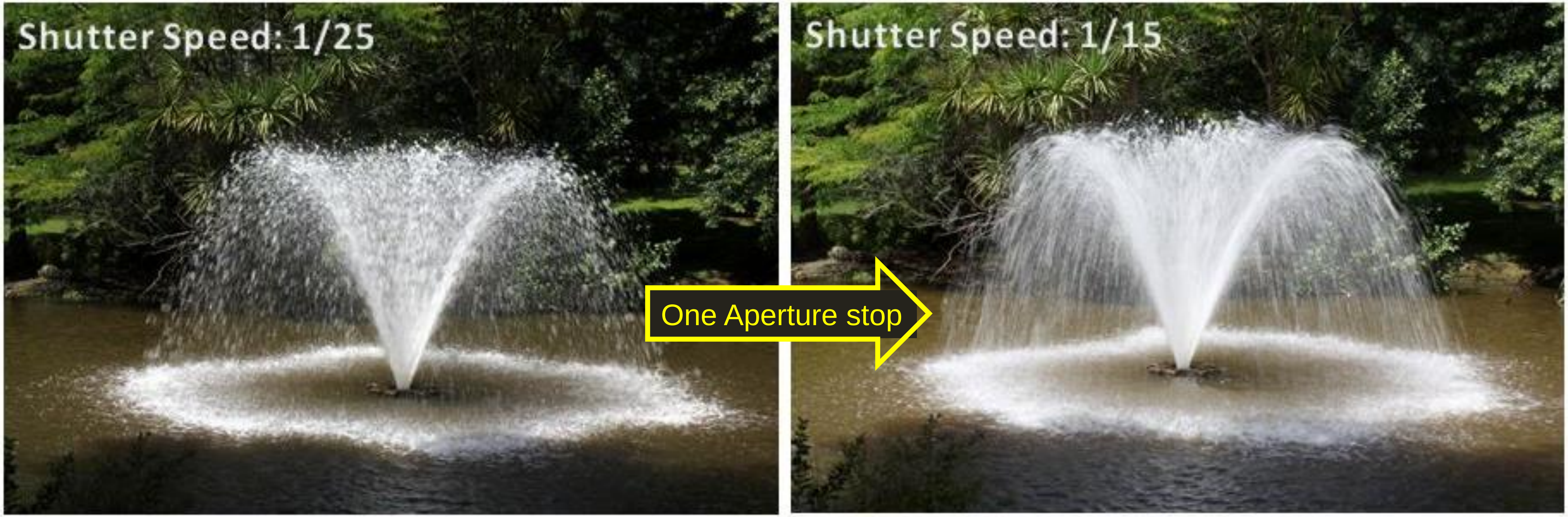

OIS performance with ST 6DSO Motion Sensor

OIS performance with TDK ICM-42622 Motion Sensor

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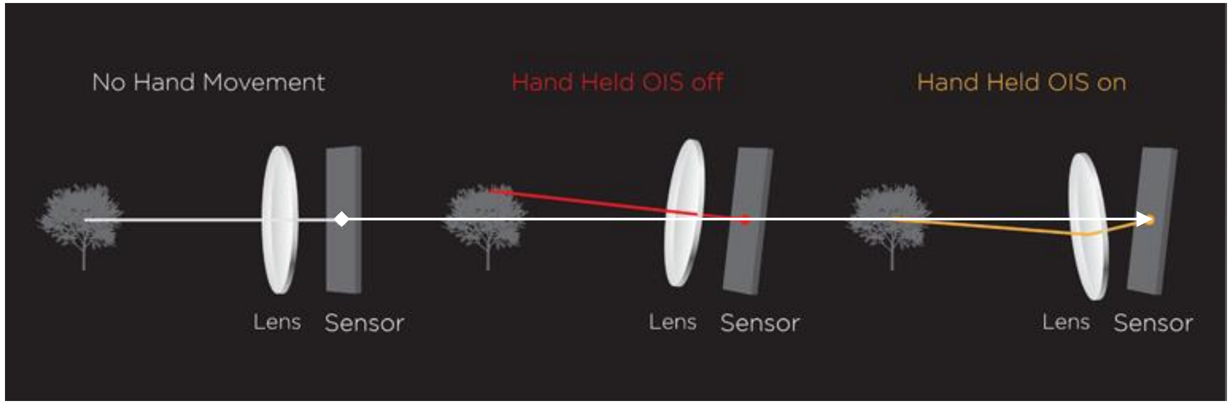
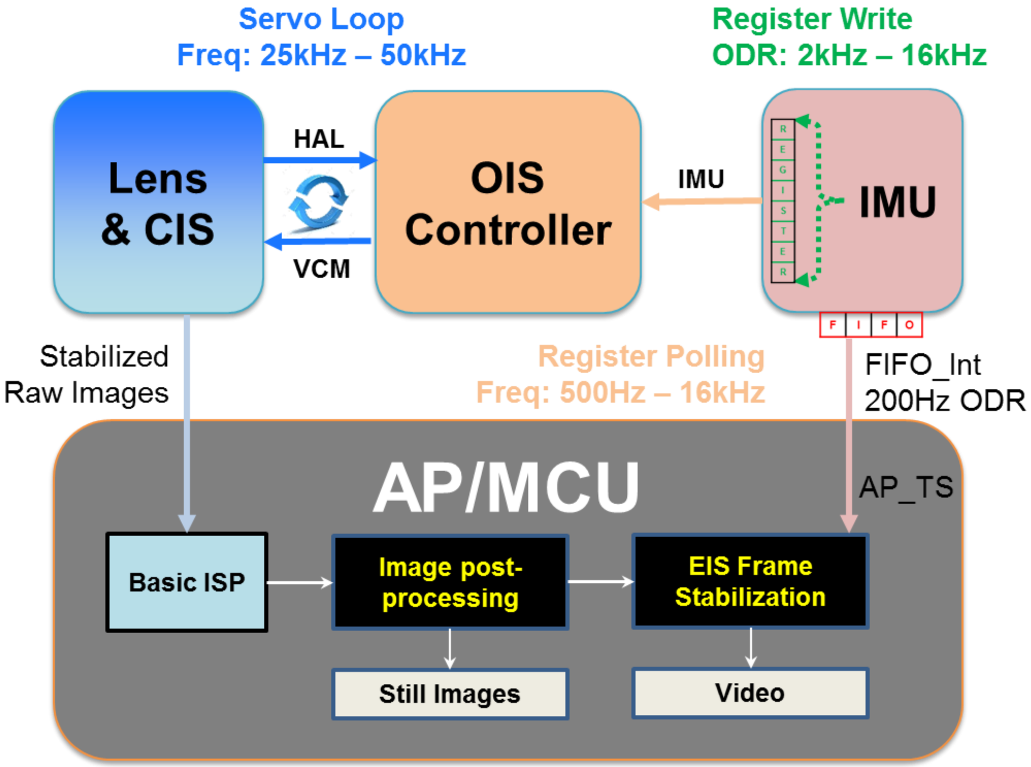
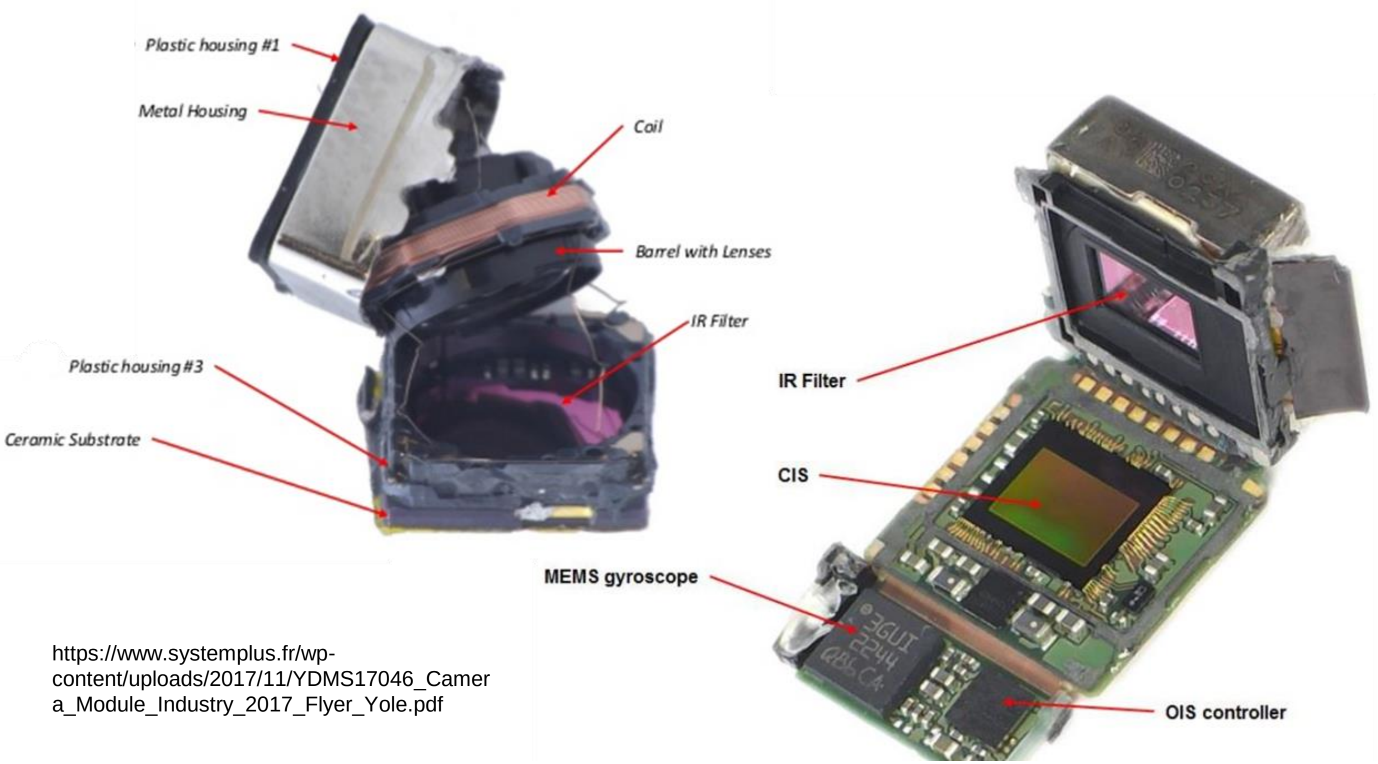
The images are for illustrative purposes, to show impact of a single aperture stop on image quality.
These images were taken with a DSLR camera that did not use either ICM-42622 nor ST 6DSO

The Moving Pieces that make OIS work

- The principle of OIS
- The hardware for OIS
- The logic behind OIS



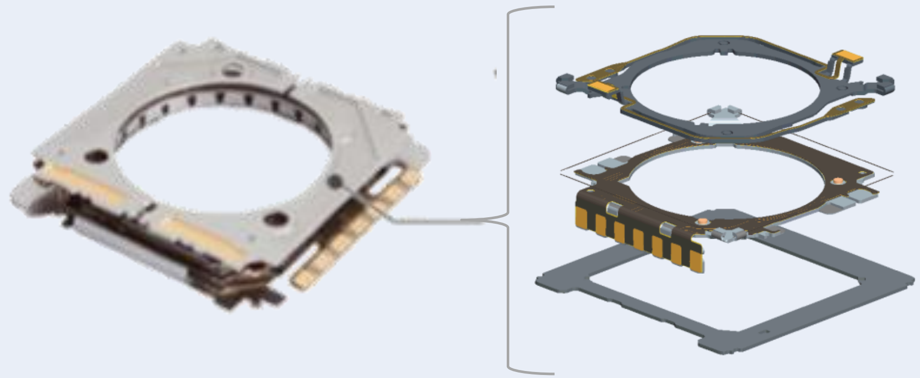
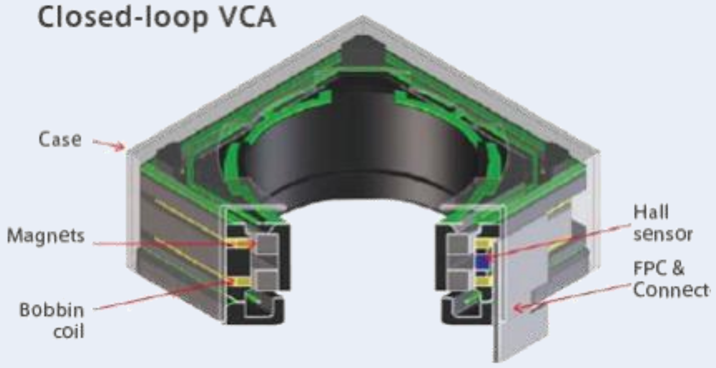




https://www.systemplus.fr/wp-content/uploads/2017/11/YDMS17046_Camera_Module_Industry_2017_Flyer_Yole.pdf

SMA – the "new HW kid" on the OIS block

SMA & VCM achieve similar OIS suppression ration

	SMA OIS	VCM OIS
		
Pros & Cons	• 2-5x lower power consumption than VCM • Smaller solution (0.3mm z, 10% smaller x-y) • No magnet field/interference • Higher stability and shock resilience • Can support larger/heavier lens assemblies • Slow control loop enables integrated controller • Potential for lower cost architectures	• Proven performance, large scale technology

Optical Image Stabilization – VCM & SMA what's next

- OIS will continue to grow in importance, especially in Flagship Smartphones, since OIS allows more light to hit the pixels, which is critical for "low-light" and "HDR" imaging
  - OIS will also be a key component in dual-rear camera Smartphones, and for cameras with optical zoom
- Wider OIS adoption is challenged by the significant cost adder and size of current OIS solutions
- SMA-OIS has a lot of promise to reduce size and cost of OIS, eliminate magnetic interference concerns and enable the movement of larger lenses

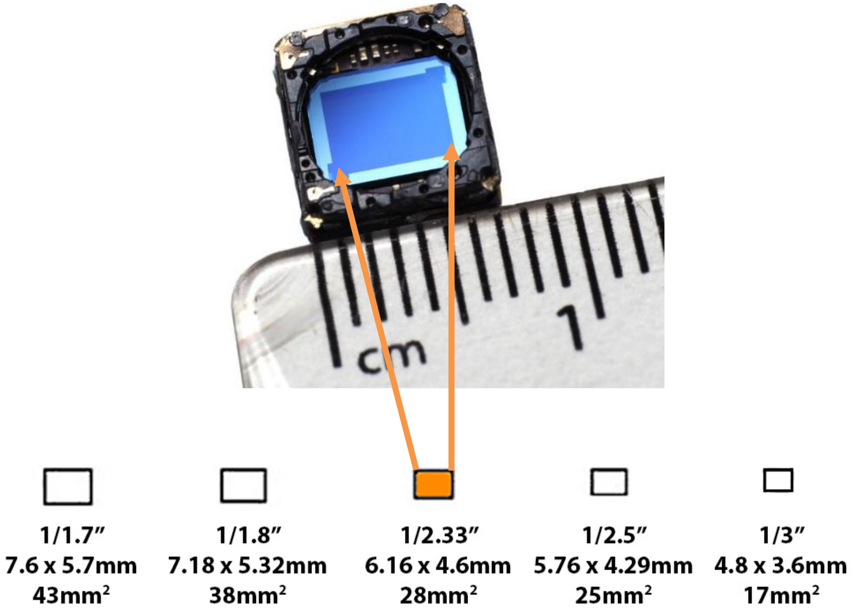
- Either way, OIS remains a key ingredient for Flagship Smartphone cameras, and the accuracy and temperature performance advantages make the ICM-42622 the best choice for any OIS solution

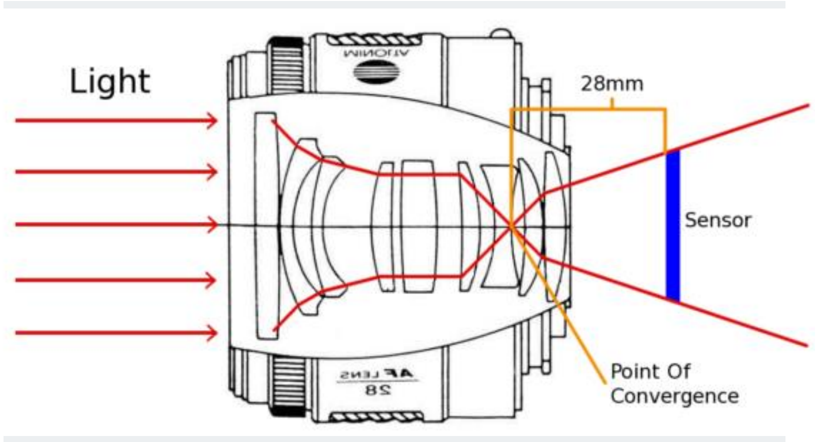
How else can a Smartphone camera capture more light

- If keeping the shutter open longer is not an option due to cost savings or space imitations, what else can be done to capture more light:
  - Increase the size of the pixel on the image sensor
  - Increase the size of the image sensor inside the camera module
  - Increase the size of the aperture
  - All of the above (hard to do one without the other)

Capturing more light: fundamental challenges

Option	Advantage	Comment
Image Sensor: pixel size	• Typical image sensor: 1/2.6 sensor with 1.4um pixel (Pixel 2)	• Used in high-end camera modules shipping today
Image Sensor: pixel resolution	• Typical image sensor: 1/2.6 sensor with 12MP resolution (Pixel 2)	• 16:9 aspect ratio = 8.3MP • 4:3 aspect ratio = 12.5MP
Aperture: f/1.8	• Typical aperture size for wide-angle camera (focal length / lens diameter)	• Larger apertures with wide openings create complex lens assemblies given the limited available Z-height
Dual camera and sensors	• Are two better than one?	• Two capture more light • Two are more complex • Two are bigger than one • Two cost more than one



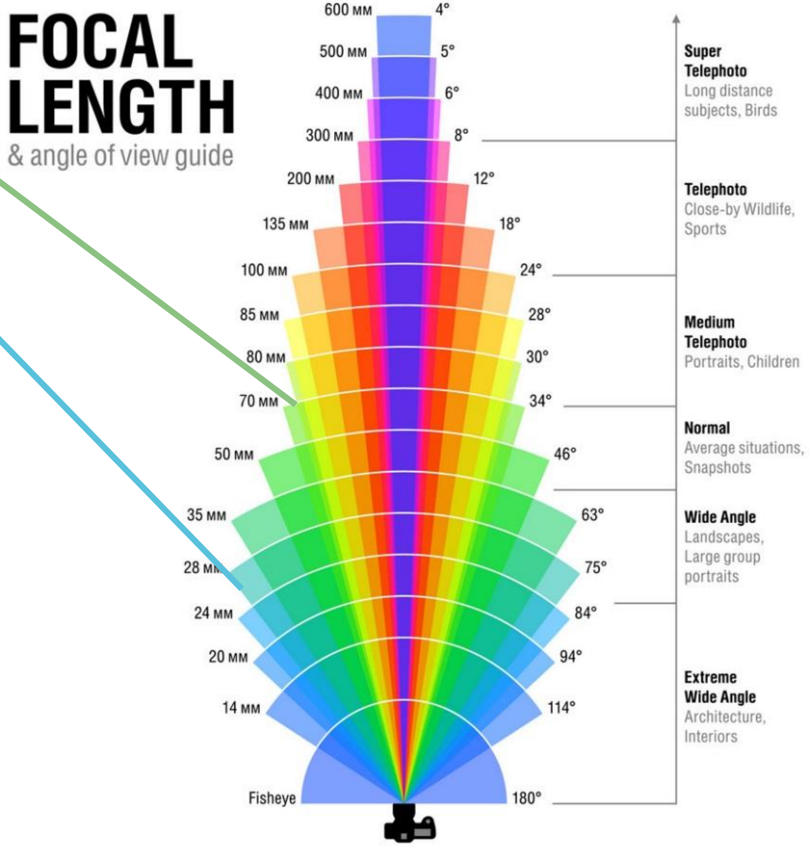


Smartphone Aperture-Lens-Sensor Dependencies

Dual-camera Imaging in Smartphones – Corephotonics

- Corephotonics is a dual-camera innovator with a variety of different dual-camera approaches

Dual wide-angle cameras couple one color sensor with a monochromatic sensor: The monochromatic sensor captures 2.5 times more light and thus reaches better resolution and signal-to-noise ratio (SNR). By fusing the images coming from both cameras, the output image has better resolution and SNR, especially in low light.



Dual Optical Zoom cameras couple a 'wide field of view' camera with a telephoto 'narrow field of view' camera:
In this case, image fusion improves the SNR and resolution from no zoom up to the point the telephoto camera field-of-view is the dominant one. In this low zoom factor range, the fused image is comprised from 1 pixel from the wide pixel and number of pixel from the Tele, resulting in better SNR and higher resolution.

- Source: http://corephotonics.com/inventions/image-fusion/

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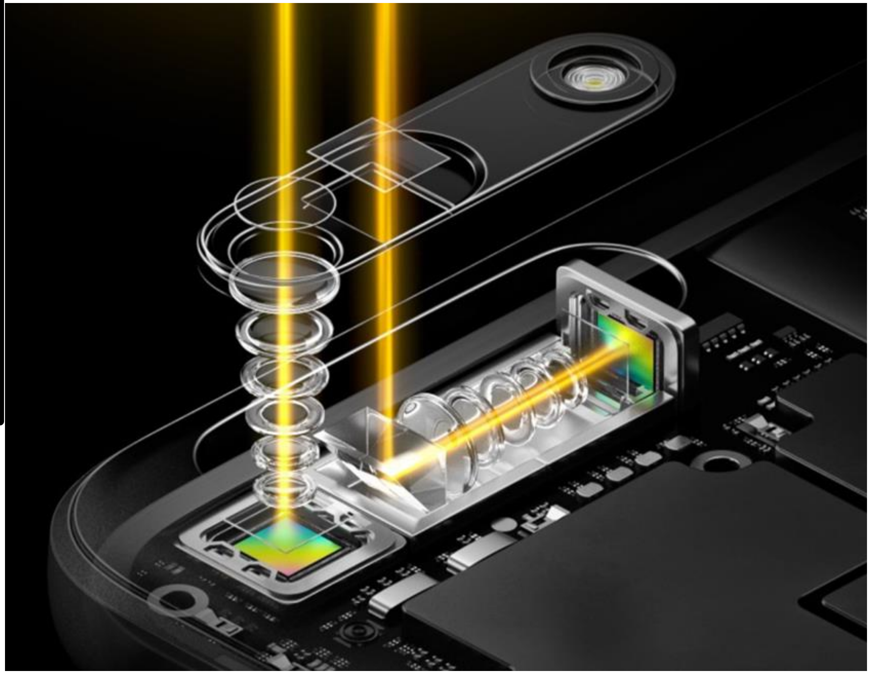

5X Optical Zoom employs a folded camera system that has very low module Z-height and provides optical image stabilization, resulting in unmatched optical zoom performance.

- Source: http://corephotonics.com/inventions/image-fusion/

iPhone X with dual-camera & dual-OIS

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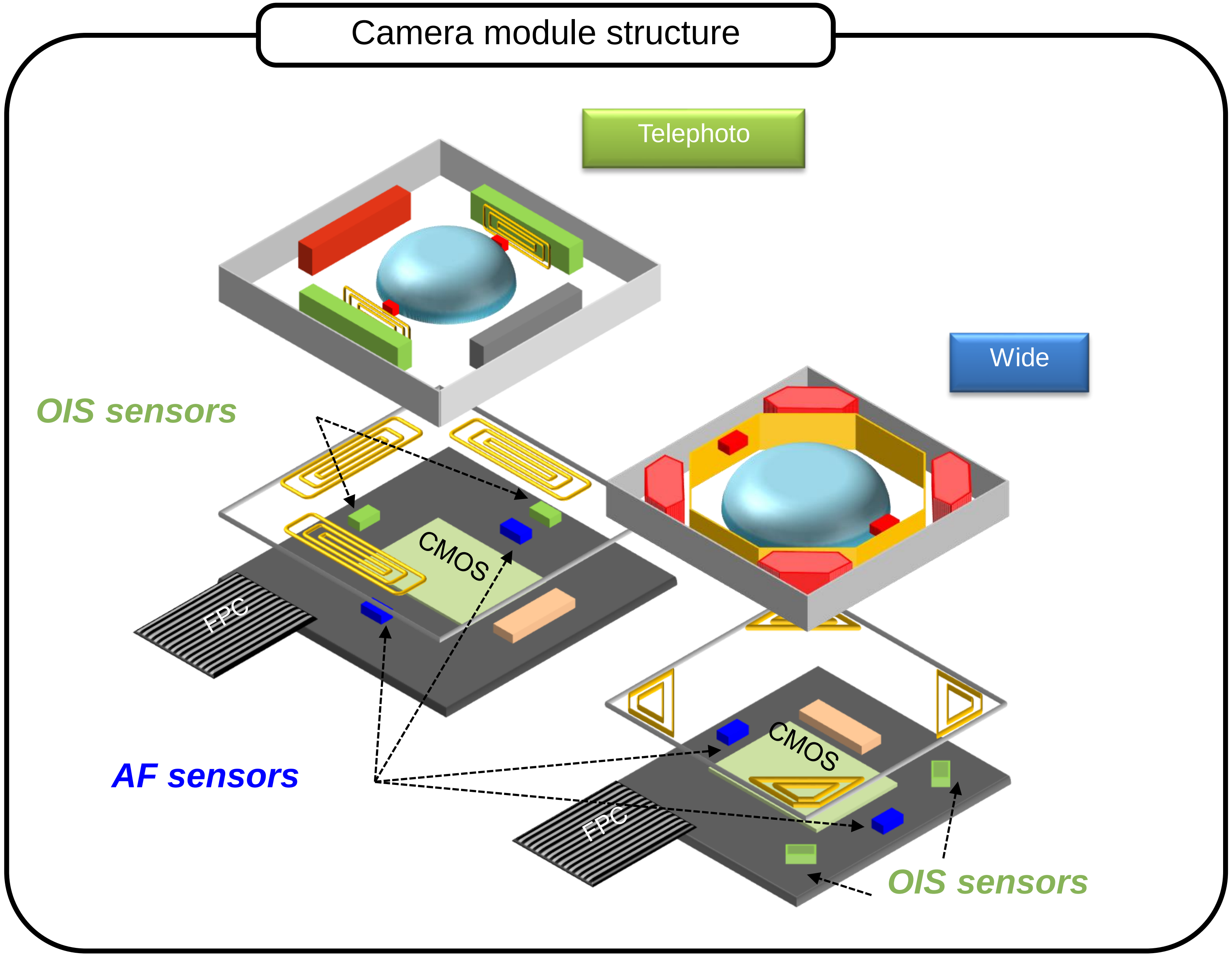
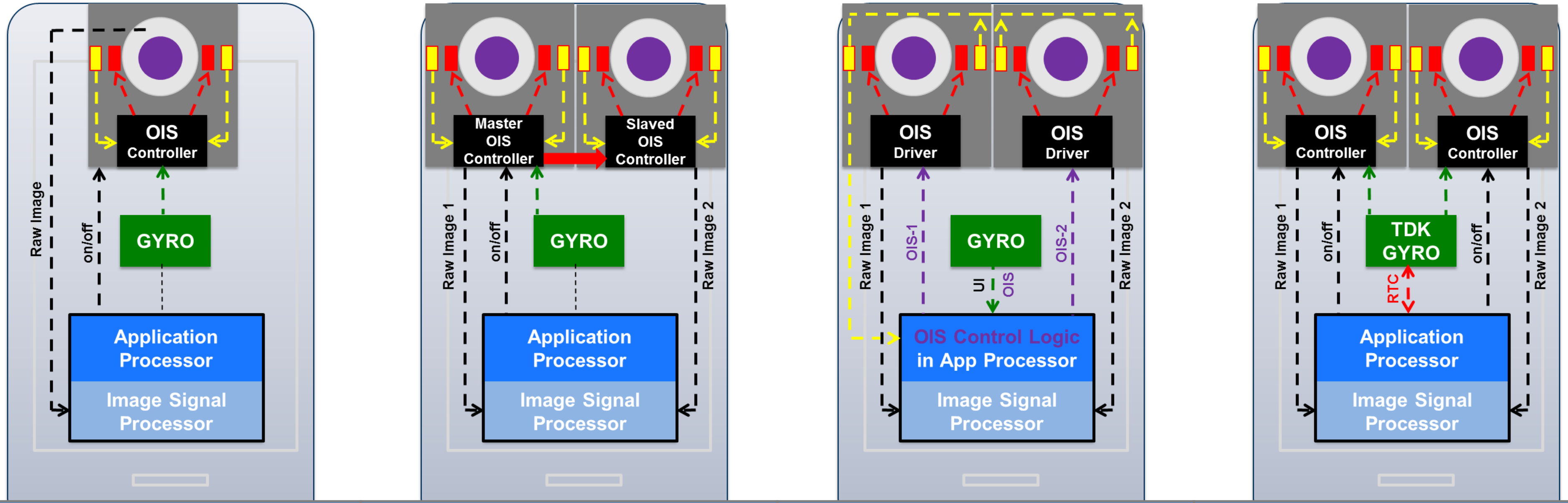
iPhone X Camera

- 12MP wide-angle f1.8 aperture plus 12MP telephoto with f2.4 aperture & dual-OIS
- 7MP front camera



Mainboard OIS Architecture Evolution



	Mainboard OIS	Complex Dual OIS	AP controlled OIS	Synchro Dual OIS
Pros & Cons	• Lower cost than camera-module with built-in Gyro	• Highest quality at higher price/power • AP independent control	• High quality but AP CPU cycle/latency dependent • Great for hybrid EIS/OIS	• Affordable, high quality when synchronized • Great for front/back OIS
Motion Sensor KPIs	• Gyro/Accel sensitivity error & temp stability • Gyro/Accel noise, bias & temp stability	• “Mainboard OIS” KPIs • Single OIS Aux interface	• “Mainboard OIS” KPIs • UI&OIS data share single I3C interface	• “Mainboard OIS” KPIs • Dual OIS Aux interface • Real-time Clock synch
TDK Advantage	• Superior Gyro OIS KPIs	• Superior Gyro OIS KPIs	• Superior Gyro OIS KPIs • Clock-synch option	• ICM-42600; only Gyro with dual OIS & RTC
Examples	• Flagship Phones	• Samsung Galaxy S9	• iPhone X	• Coming soon

Dual-camera Xiaomi: it doesn't just look like an iPhone

Xiaomi uses Sunny Optical's dual-aperture camera module (with Corephotonics IP)

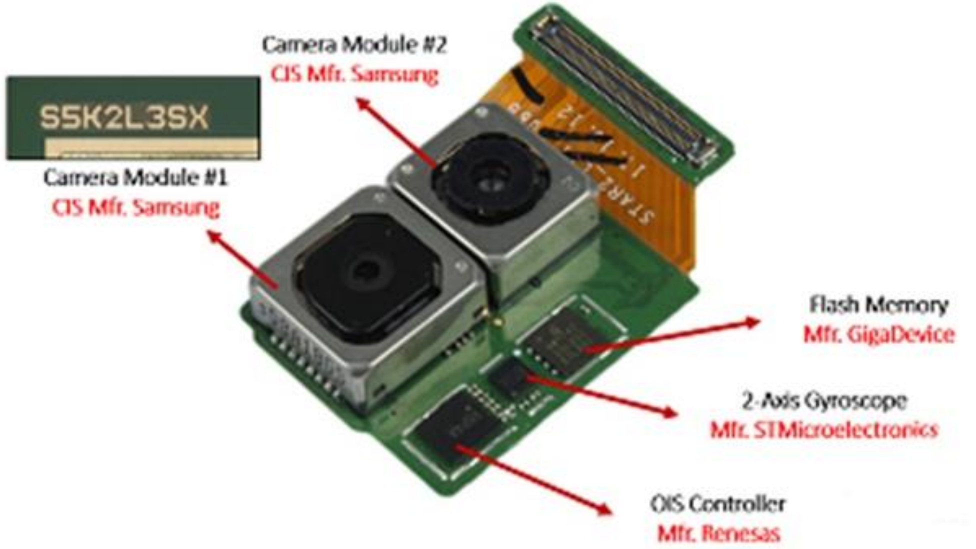
DXOMARK MOBILE

99	Xiaomi Mi 8	•	€360
98	Google Pixel 2	•	€870
97	Apple iPhone X	•	€1000
97	Huawei Mate 10 Pro		
97	Xiaomi Mi MIX 2S		
94	Apple iPhone 8 Plus		
94	Samsung Galaxy Note 8		
92	Apple iPhone 8		
90	Asus ZenFone 5	•	€370
90	Google Pixel		

- The camera on the Mi 8 is no Me Too.
  - The rear-facing camera module features twin 12Mp cameras, one a wide-angle with a 1/2.55-inch size sensor, 1.4µm pixels, and an f/1.8-aperture lens, and the other a short telephoto with a slightly slower f/2.4 aperture. Other features include phase detection autofocus, 4-axis optical image stabilization (OIS) on the wide-angle module, and an LED flash.
  - The Mi 8 The main camera uses a 1/2.55" Sony IMX363 Sony sensor with a 1.4µm pixel size, F1.8 aperture lens and a 4-axis optical image stabilization system. The longer lens offers approximately a 2x zoom factor. The sensor comes with smaller 1.0µm pixels, and at F2.4 the aperture is not quite as fast as the main camera's.

Pricing as of June 6 2018: https://www.gsmarean.com

Dual-camera Galaxy S9+ with dual-aperture ‘night mode’



DXOMARK MOBILE	
99	Samsung Galaxy S9 Plus
99	Xiaomi Mi 8
98	Google Pixel 2
97	Apple iPhone X
97	Huawei Mate 10 Pro
97	Xiaomi Mi MIX 2S
94	Apple iPhone 8 Plus
94	Samsung Galaxy Note 8
92	Apple iPhone 8
90	Asus ZenFone 5
90	Google Pixel

- The Galaxy S9+ is the first smartphone on the market to offer a variable-aperture camera
  - Dual camera with dual-OIS and variable aperture with a 12MP wide-angle dual-pixel sensor with variable f1.5/f2.4 aperture and a 12MP telephoto dual-pixel sensor with f2.4 aperture
- The Galaxy S9+ captures nighttime adventures with stunning clarity. With the F1.5 aperture mode and multi-frame noise reduction, the rear camera ensures the photos you take in the dark come out clear and bright, no fine-tuning required. (Night-mode available in F1.5 aperture mode only).

Source for variable aperture images: https://tech2.org/galaxy-s9-camera-how-a-variable-aperture-works/

Triple-camera Huawei P20 Pro with AI ‘night mode’

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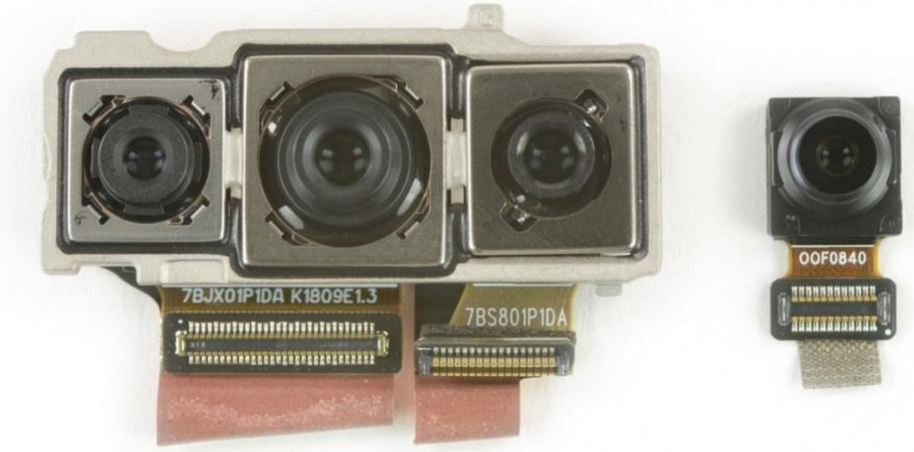

DXOMARK MOBILE

109	Huawei P20 Pro
103	HTC U12+
102	Huawei P20
99	Samsung Galaxy S9 Plus
99	Xiaomi Mi 8
98	Google Pixel 2
97	Apple iPhone X
97	Huawei Mate 10 Pro
97	Xiaomi Mi MIX 2S
94	Apple iPhone 8 Plus
94	Samsung Galaxy Note 8
92	Apple iPhone 8
90	Asus ZenFone 5
90	Google Pixel

- The Huawei P20 Pro is the first smartphone on the market to offer a tri-camera with AI
  - a 40MP telephoto sensor (f/1.8) that captures the colors in the scene and Light Fusion combines data from 4 pixels to generate a 10MP photo where each pixel is much bigger than the ones Google Pixel 2
  - a 20MP monochrome sensor (f/1.6) for depth and texture when combined with the 10MP image from the 40MP sensor
  - a standard 8MP image sensor (f/2.4) with 3x optical zoom, which features OIS support
- The P20 Pro features “Artificial Intelligence Stabilization (AIS)”, that combines multiple short exposure frames for low-light capture and enhanced dynamic range, culminating in a stunning night mode with 3 to 4 second exposure, that combines a sequence of 5-8 variable exposure images for added dynamic range.

Awesome Smartphone Cameras II: Optimised in China

Google Pixel 2 XL	Single Lens: 12.2 MP (f/1.8) with **OIS**
Apple iPhone X	Dual Lens: 12 MP (f/1.8) with **OIS**; 12 MP telephoto (f/2.4) with **OIS**
Huawei P20 Pro	Triple Lens: 40 MP (f/1.8); 20 MP monochrome (f/1.6); 8 MP telephoto (f/2.4) with **OIS**

Huawei P20 Pro with Artificial Image Stabilization

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- In low light situations the P20 Pro's Night Mode and AIS kick in, delivering a considerable a larger amount of light and dynamic range than iPhone X and Pixel 2XL.

just right

too dark

too yellow

In Conclusion: inconclusion

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- OIS will continue to grow in importance, especially in Flagship Smartphones, since OIS allows more light to hit the pixels, which is critical for “low-light” and “HDR” imaging
  - OIS will also be a key component in dual-rear camera Smartphones, and for cameras with optical zoom

- The accuracy and temperature performance advantages make the ICM-42622 the best choice for any OIS solution

- For an in-depth look at the strength, weaknesses, opportunities and threats that ‘computational/artificial’ image stabilization provide we’d appreciate your return at 1:30pm, for the 2nd half of our Smartphone Imaging Trends: How Computational Imaging and Artificial Intelligence shed Light on the Invisible …

Smartphone Imaging Trends II:

How Computational Imaging and Artificial Intelligence shed Light on the Invisible

Lars Johnsson, Senior Director Product Marketing, Motion & Pressure Business Unit, InvenSense

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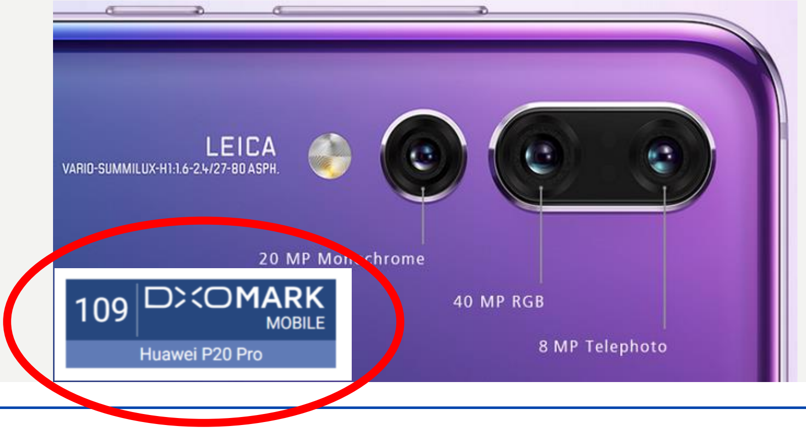
Huawei P20 Pro	Triple Lens: 40 MP (f/1.8); 20 MP monochrome (f/1.6); 8 MP telephoto (f/2.4) with **OIS**	

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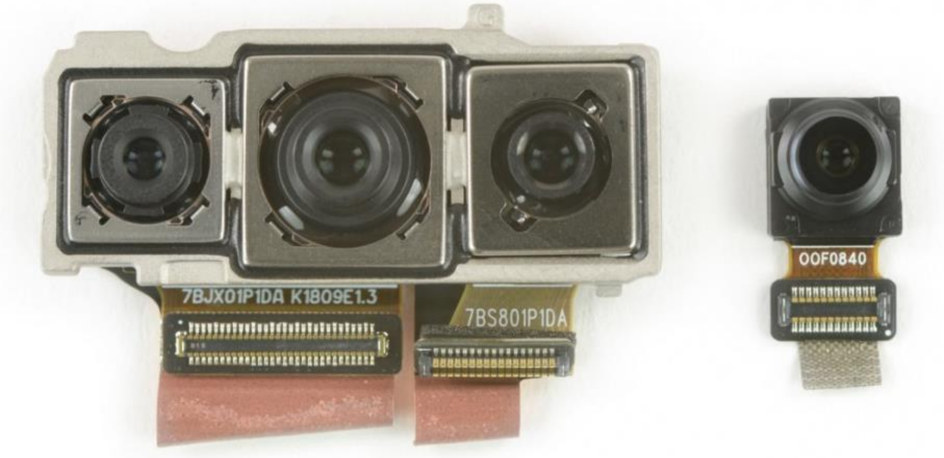

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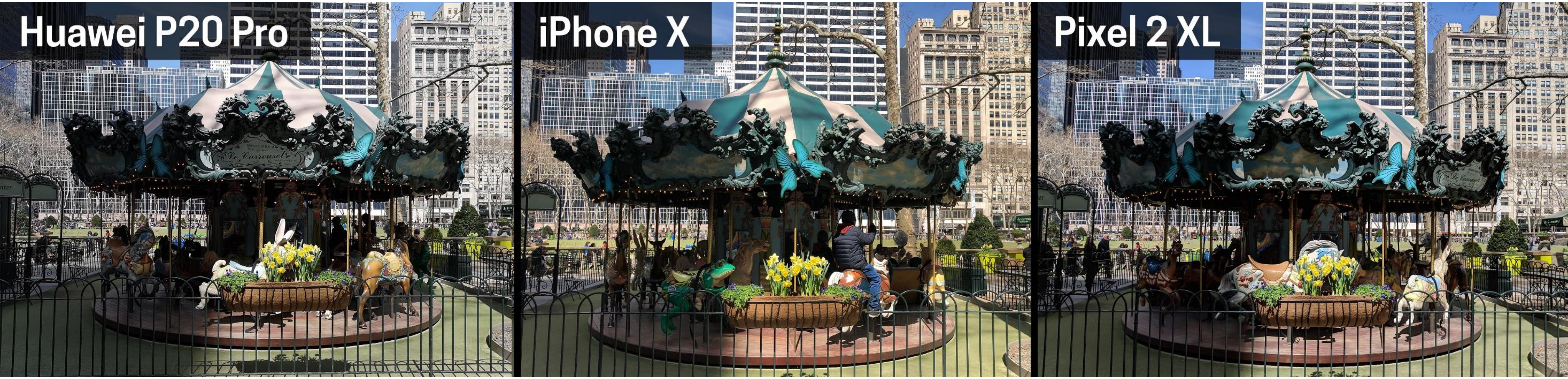
TDK

https://www.tomsguide.com/us/huawei-p20-vs-pixel-2-vs-iphone-x-camera,review-5324.html

Huawei P20 Pro with Artificial Image Stabilization

- In HDR scenarios the P20 Pro cuts a much shallower graduation between the highlights and lowlights than iPhone X and Pixel 2XL.



too dark

Really rich

Just right

https://www.tomsguide.com/us/huawei-p20-vs-pixel-2-vs-iphone-x-camera,review-5324.html

Computational Imaging in Smartphones 2016

- Computational Image Stabilization starts out by capturing a burst of images with short exposure times. It then combines the frames to reduce the noise and build up a stable, properly lit image.
- High Dynamic Range photography starts out by capturing a burst of images with different exposure times. It then uses pixel analysis to understand the contrast difference between frames before combing the frames to build up an image with optimal exposure in different object regions.
- An important challenge for CIS and/or HDR photography is that any movement between successive images will impede combining them afterwards, unless the ISP is capable to compensate the pixel shift, or use frame motion analysis to estimate the pixel shift between frames before combining them.
- Google's original HDR continuously streams images and keeps up to 10 in dedicated memory, all very underexposed so that bright areas like blue skies don't wash out. When the shutter is pressed it picks the best of a given sequence, weeding out blurry ones, combining only the sharp images to build up a contrast rich image with high dynamic range.

Computational Imaging in Smartphones 2017

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- The Pixel 2 adds optical image stabilization (OIS) capability, meaning the camera counteracts camera shake by physically moving optical elements, giving the Pixel 2 a better foundation for the improved HDR+. "With OIS, most of the frames are really sharp. When we choose which frames to combine, we have a large number of excellent frames”. (Tim Knight, head of Google's Pixel camera engineering team)

Computational Imaging in Smartphones – Morpho

- Morpho analyzes and combines multiple images to brighten, sharpen, enhance and stabilize pictures

Increase brightness and contrast by combining two or more images to reduce pixel noise. Ideal for low-light

Increase sharpness + resolution of a picture by combining and integrating two or more images. Ideal for focus and zoom

HDR enhances the dynamic range of a picture by combining and integrating multiple images at different exposure levels. Ideal for mixed light

Remove pixel blur from ‘long exposure’ by combining multiple ‘short exposure’ images. Ideal for image stabilization during low-light conditions or when the camera is in motion

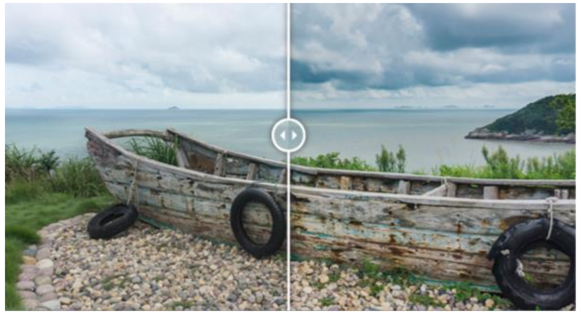
- Source: http://www.morphoinc.com/en/technology

Computational Imaging in Smartphones – Arcsoft

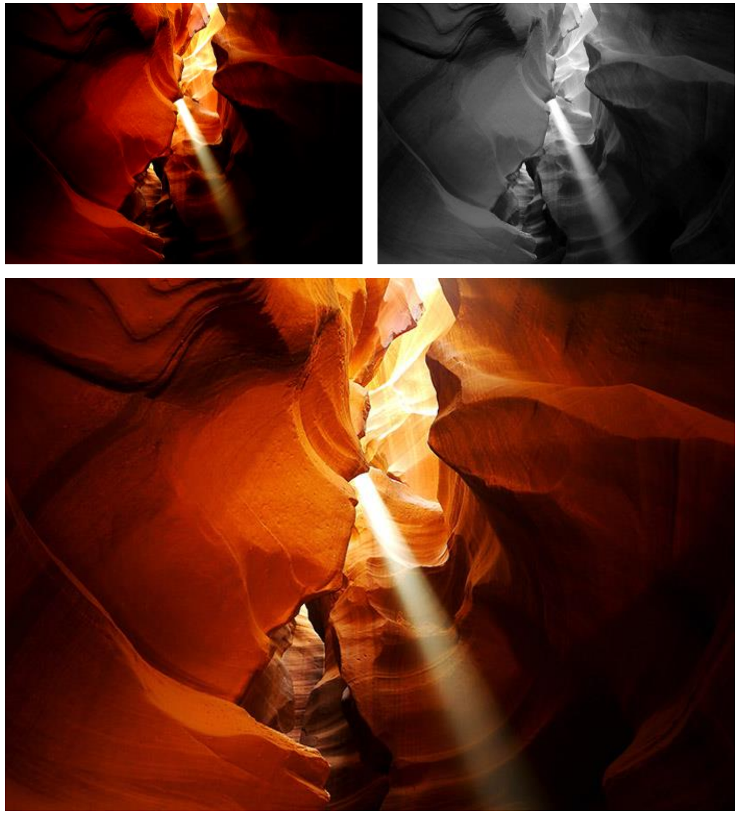
- Arcsoft deploys a variety of computational image processing techniques to brighten, sharpen, enhance and stabilize pictures

Low-Light Technology uses the characteristics and noise distribution of the image from various camera sensors to optimize noise-reduction. This results in a high-brightness, low-noise, real-color, sharp image, similar in quality to one with ISO levels 2-3 stops lower

Image stabilization performs intelligent analysis of lighting conditions to increase shutter speed. Imaging algorithms prevent blurriness caused by hand-shake and are suitable for devices with or without OIS, and can integrate with gyro sensors



HDR smart detection algorithms detect regional brightness within the image, used to ensure that bright and dim areas all receive optimal exposure, allowing for dynamic adjustment of up to 2-3 stops. This results in an image with clearer details, distinct light levels and stunning color.

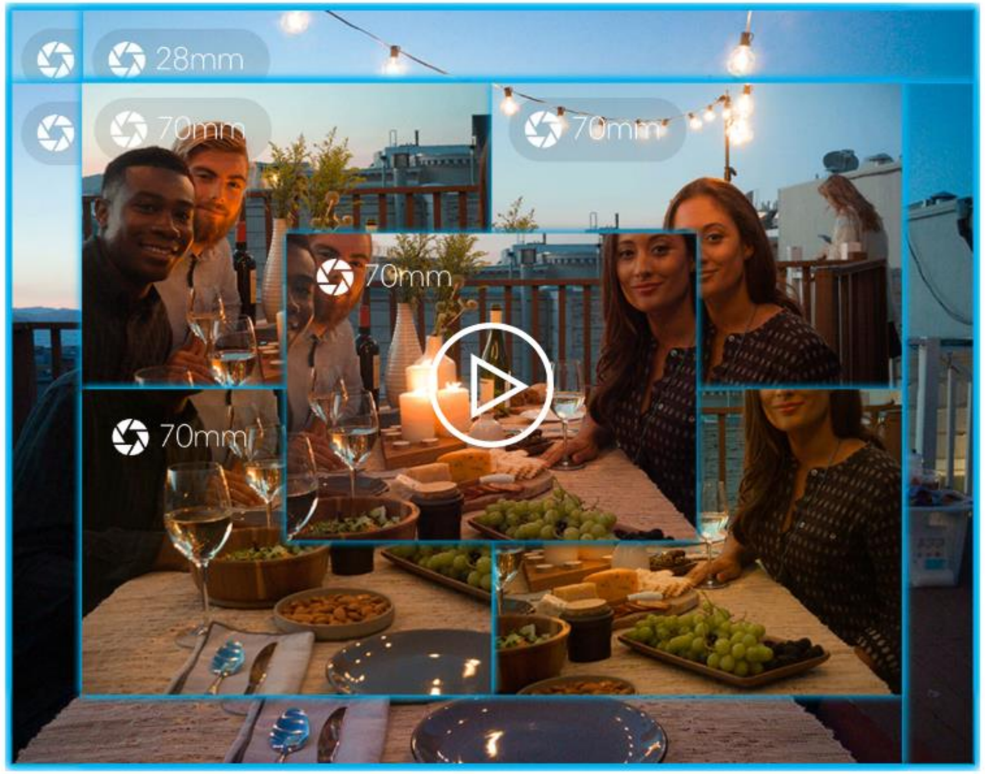


RBG & mono dual-cameras combine the color information collected by the RGB camera with the brightness and details information provided by the mono camera, to greatly enhances image quality in terms of noise, brightness, color, details

- Source: http://www.arcsoft.com/technology/low-light.html

Computational Imaging – seeing the Light

- When the L16 takes a picture, 10 or more cameras fire simultaneously, capturing slightly different perspectives of the same scene. The L16 intelligently chooses a combination of its 28mm, 70mm, and 150mm modules to use in each shot, depending on the level of zoom. These individual shots are then computationally fused together to create an incredibly high-resolution 52MP photograph.
- No OIS, no problem, but it takes 3-custom ASICs and a $2,000 ASP to do all the math and see the light …



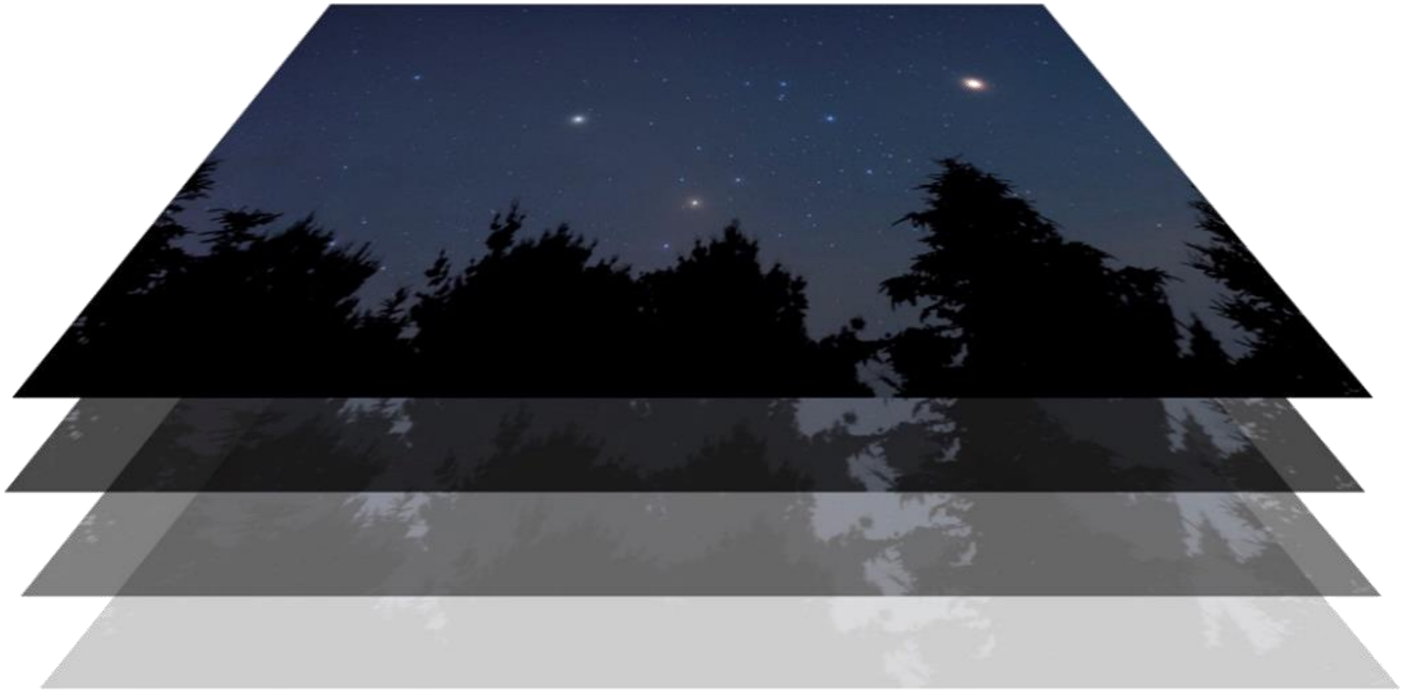
The Light shines bright, even at night

- L16 low light capture (longer exposure, multiple shots).
  - Light pictures achieve their exposure, resolution and quality through the combination of adjacent views stitched together ‘panorama style’, sometimes combined with a rapid successions of images overlaid to increase brightness and enhance dynamic range. The possibilities are endless, the math is complex …
  - When the L16 senses a scene with dim lighting, it will capture multiple images consecutively, much like burst mode. The major difference with the L16’s stacked capture is just how many total images it captures. Each L16 photo is already comprised of 10 or more images—which means that a stacked capture photo may contain as many as 40 combined images. The result of capturing so much data is much less noise and much more detail.
- The L16 uses our ICM-20690 6-axis to accelerate the computational imaging

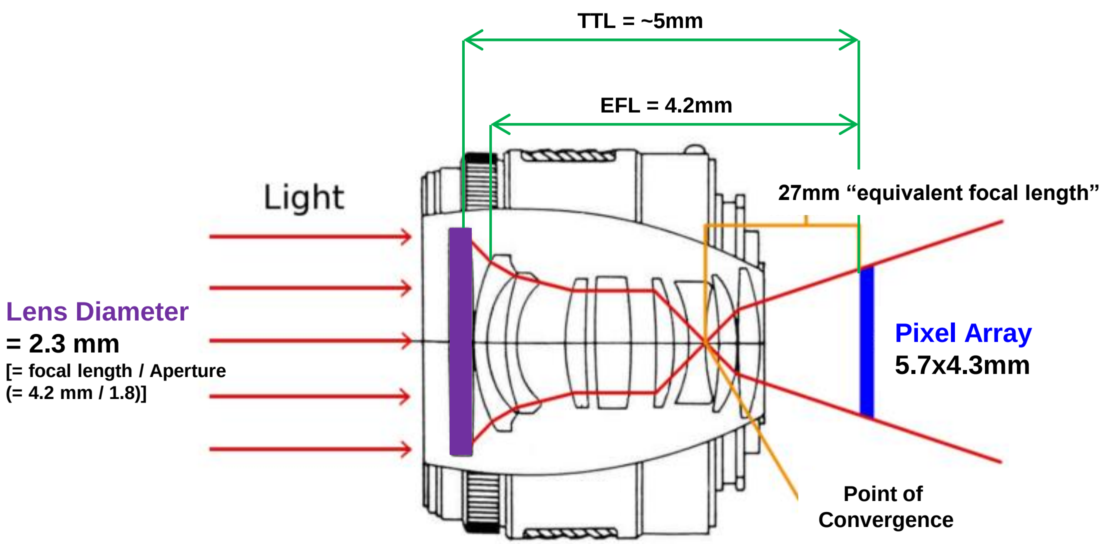
- Source: http://www.arcsoft.com/technology/low-light.html

Computational Imaging – the math would be much easier if things wouldn't move

- Combining 2 frames exposed in short succession still leaves the possibility that things (pixels) have shifted, opening the door to significant pixel blur
- Before the frames can be combined the amount of pixel shift between the frames has to be determined
- Contrast rich pixel-patches are identified and then their location on the pixel-map is compared between the different frames
- Once a quality pixel-patch-match has been identified, and its shift has been analyzed, a 'motion vector' is computed and applied to shift all other pixels accordingly
- Creating motion vectors from pixel-patch matching somehow doesn't sound right …

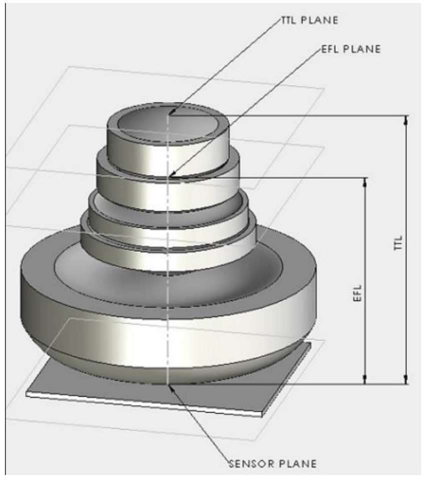


Where the photon hits the pixel

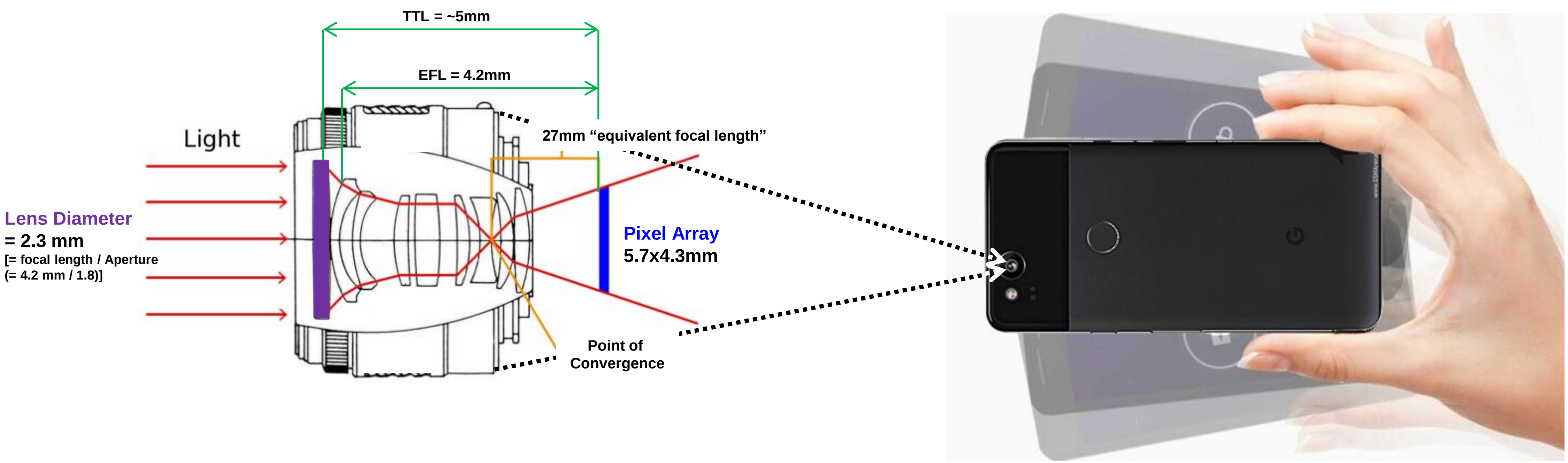


	Sensor Specs	Comment
Pixel size	• 1/2.6" sensor with 1.4um pixel (Pixel 2, iPhone X)	• F/1.8 Aperture used in Pixel 2 (and iPhone X)
Sensor resolution	• 12MP resolution (Pixel 2, iPhone X)	• 16:9 aspect ratio = 8.3MP • 4:3 aspect ratio = 12.5MP
Sensor array	• 5.73 x 4.3 mm	• 4k resolution @ 4:3 aspect ratio = 4096 x 3072 pixels

- A typical wide angle lens assembly with a F/1.8 aperture and 27mm "equivalent focal length" has an Effective Focal Length "EFL" of 4.2mm and is based on a stack of five or six lens elements in the lens barrel. This results in a Total track Length "TTL" of about 5mm and module height of 5.8mm.
- For a 12MP sensor with 4:3 aspect ratio and 1.4um pixel size the sensor size is 5.73 x 4.30 mm



When the photon hits the wrong pixel



- The same hand jitter that would lead to "blurred pixels" if it wasn't for OIS solutions, will lead to significant "pixel shift" from frame-to-frame during HDR/burst imaging.
- Since the hand shake can be measured with a good motion sensors, the question is if the "pixel shift" can be projected accurately enough such that the computational pixel-patch matching can be accelerated

The 6-degrees of Pixel Shifting – Visualized

- Hand shake is unpredictable
- It takes a great 6-axis motion sensor to figure it out

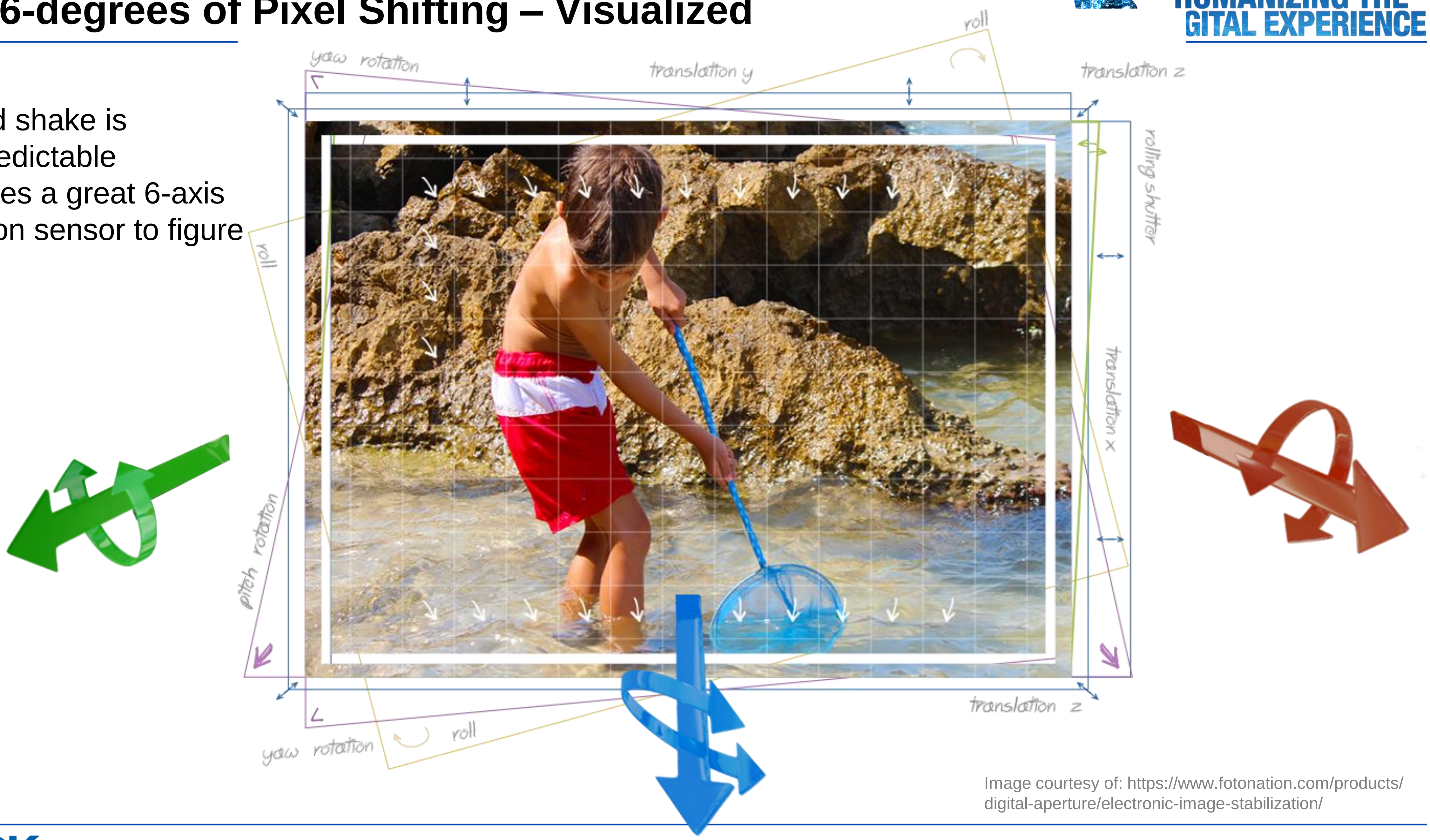
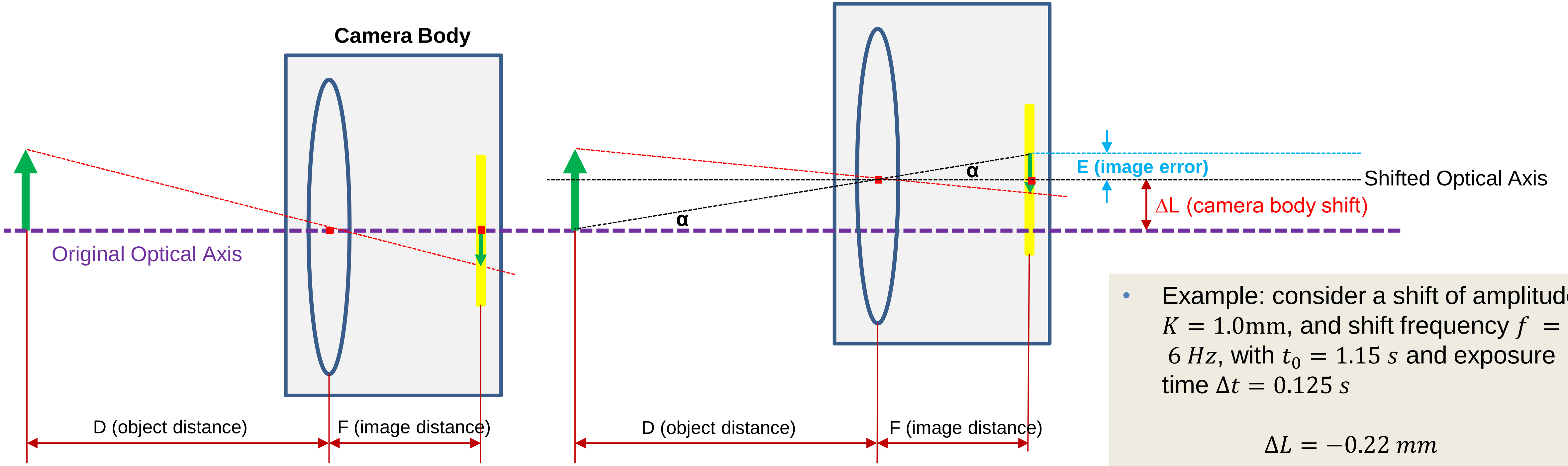


Image courtesy of: https://www.fotonation.com/products/digital-aperture/electronic-image-stabilization/

Pixel shift from lateral shift



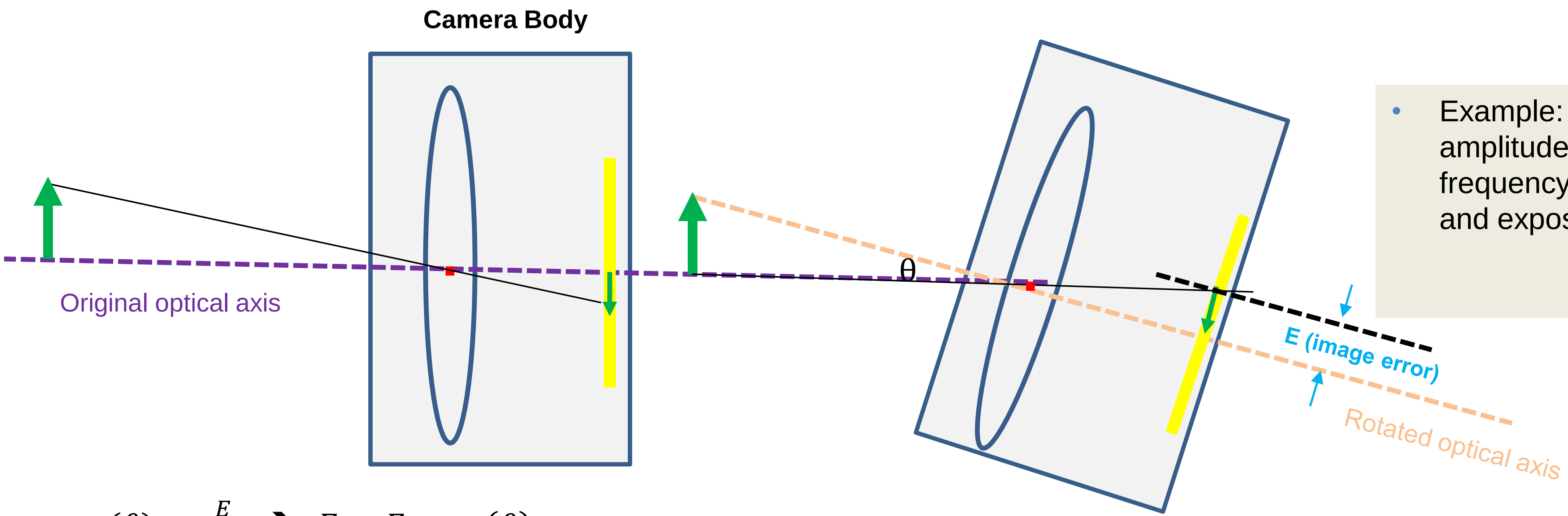
- Example: consider a shift of amplitude $K = 1.0\text{mm}$, and shift frequency $f = 6\ Hz$, with $t_0 = 1.15\ s$ and exposure time $\Delta t = 0.125\ s$

  $$\Delta L = -0.22\ mm$$

- $\tan(\alpha) = \frac{\Delta L}{D} = \frac{E}{F}$ ➔ $E = \frac{F * \Delta L}{D}$
- Let Δp be the pixel shift due to shift ➔ $\Delta p = \frac{E}{pixel\_size} = \frac{F * \Delta L}{D * pixel\_size}$
- Eg: Assume $\Delta L = 0.22\ mm$ / Effective focal length $F = 4.2mm$ /Object distance $D = 100mm$ / Pixel size $pixel\_size = 1.4\ um$

$$\text{Pixel shift } \Delta p = \frac{4.2 * 0.22}{100 * 1.4 * 10^{-3}} = 6\ pixels$$

Pixel shift from rotational shake



- Example: consider a rotation shake of amplitude $B = 0.7^{\circ}$, and shift frequency $f = 6\,Hz$, with $t_0 = 3.2\,s$ and exposure time $\Delta t = 0.125\,s$

  $$\Delta\theta = 0.45^{\circ}$$

- $\tan(\theta) = \frac{E}{F}$ ➔ $E = F * \tan(\theta)$
- Let Δp be the pixel shift due to shake ➔ $\Delta p = \frac{E}{pixel\_size} = \frac{F * \tan(\theta)}{pixel\_size}$
- Example: Assume Effective focal length $F = 4.2mm$ / rotation angle $\theta = 0.33^{\circ}$ / Pixel size $pixel\_size = 1.4\,um$

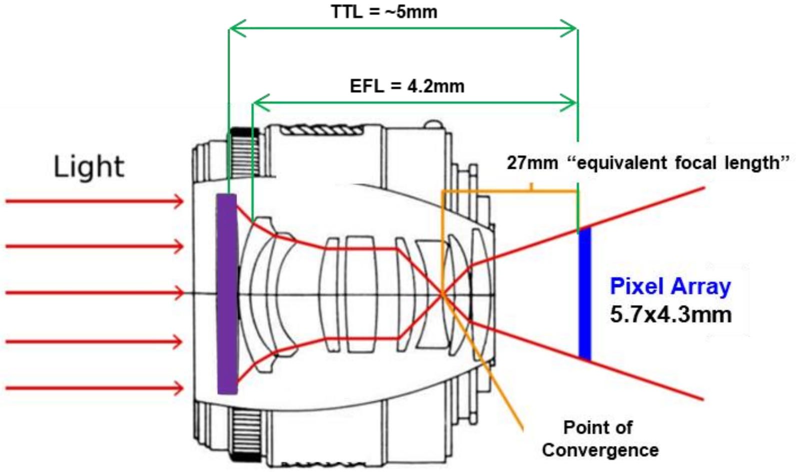
Pixel shift $\Delta p = \frac{4.2 * \tan(0.45)}{1.4 * 10^{-3}} = 24.37\ pixels$

Frame-to-frame pixel-patch shift: all over the map

HUMANIZING THE DIGITAL EXPERIENCE

- Pixel-patch shift due to camera movement, for different exposure times
- Scenario: 27mm focal length, 77° angular field of view, 1.4um pixel

Δt	Shake @ 0.7° 6Hz	Shift @ 0.5mm 6Hz	Total Pixel shift from Shake & Shift
30ms	3.08	4	7.08
60ms	39.94	19.79	59.73
125ms	64	18.90	82.9
250ms	74.14	28.53	102.67



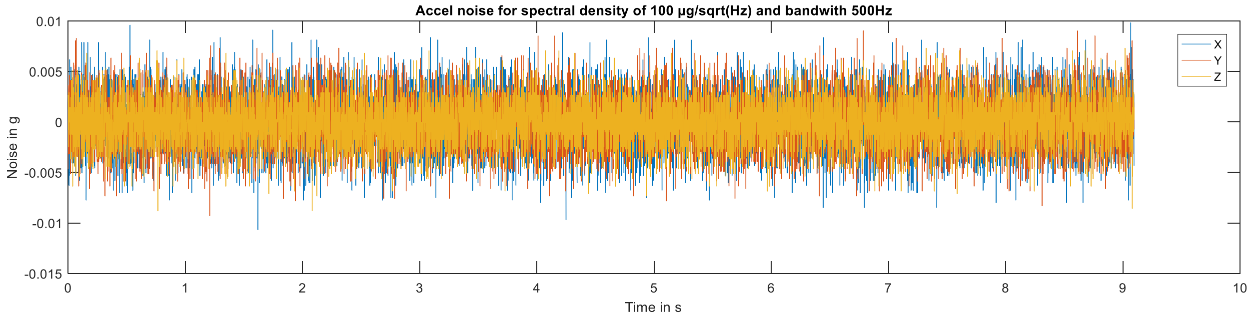
- Only one axis (the X-axis "horizontal axis") is considered for Shift.
- The shake column account for the rotational shake and shift due to the off-center rotation.
- The object distance D is set to 100 mm
- Tables show the absolute values of the pixel shifts, and the Shake & Shift column is a simple addition between of Shake and Shift column

So we can project the pixel shift, but can we measure it

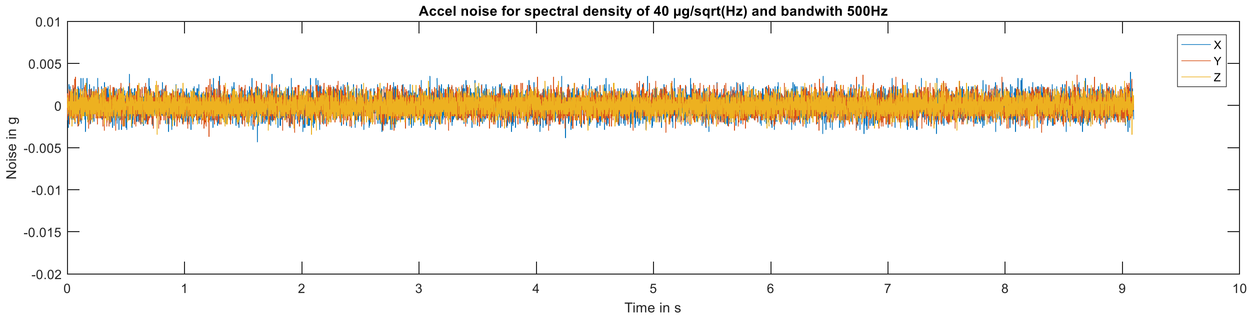
HUMANIZING THE DIGITAL EXPERIENCE

- Noise is the enemy of motion sensor accuracy, leading to “fake motion” when there isn’t any

Accelerometer with **100ug/rtHz** noise density

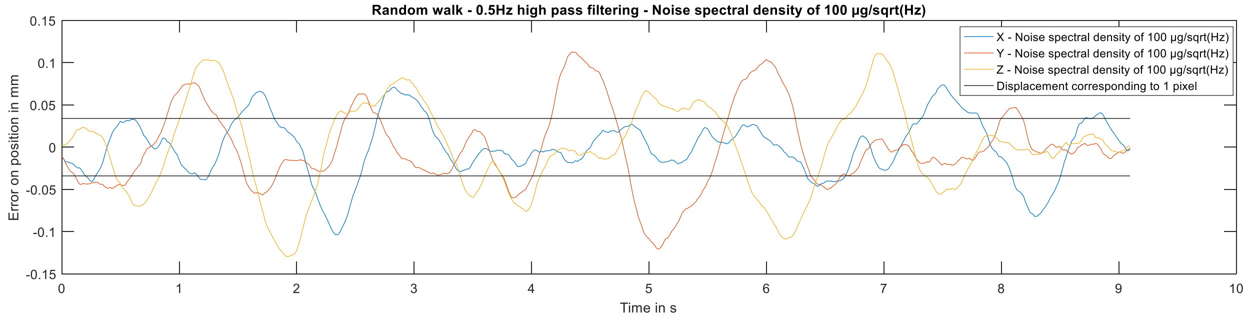


Accelerometer with **40ug/rtHz** noise density

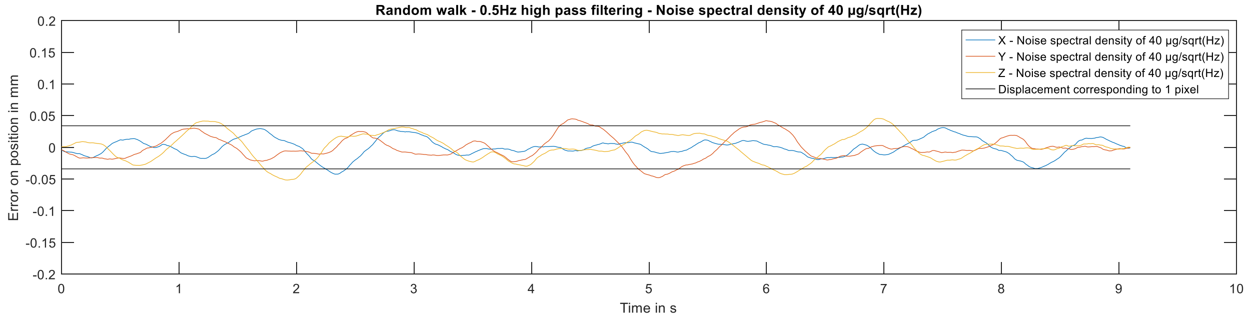


- Random walk as a function of noise density, with 0.5Hz HPF applied

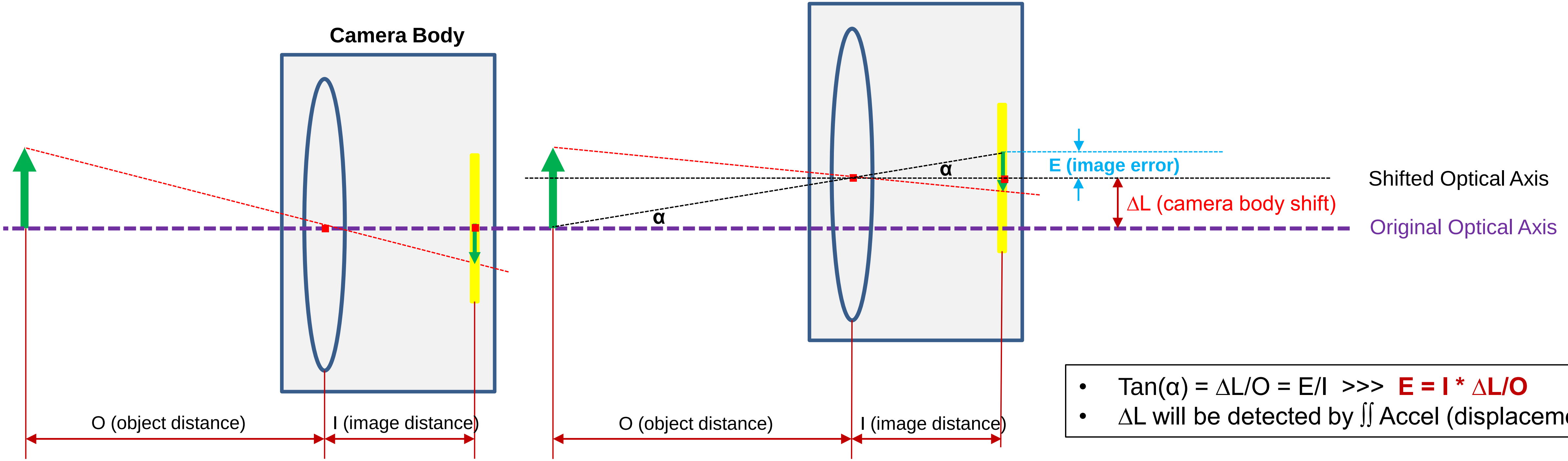
Position error that results from **100ug/rtHz** noise density



Position error that results from **40ug/rtHz** noise density



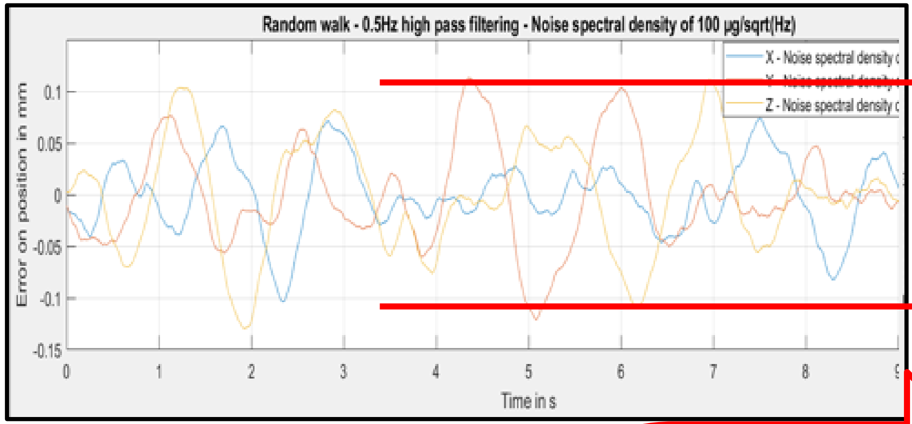
Relationship between Pixel, Lens and Displacement



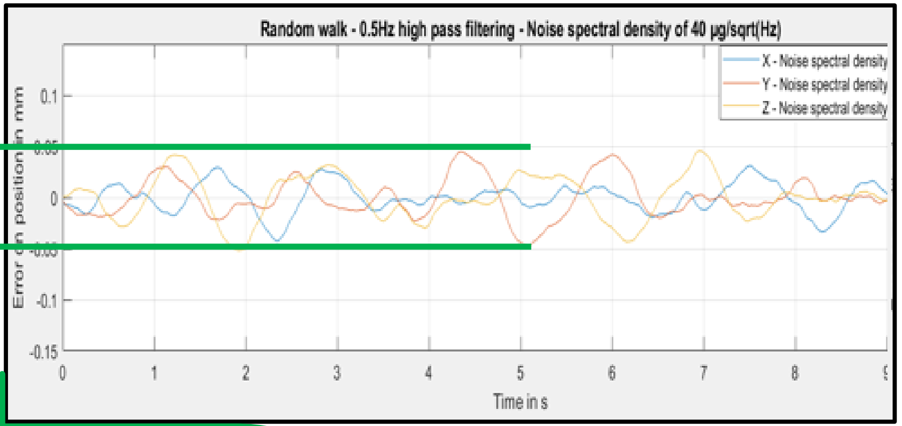
- Tan(α) = ΔL/O = E/I >>> **E = I * ΔL/O**
- ΔL will be detected by ∬ Accel (displacement).

Accel	Noise density (ug/sqrt(Hz))	HPF	Fake ΔL^ from Accel Noise (um), RMS	Pixel shift error from Fake ΔL (Accel Noise)
ICM-42622	40	0.5Hz	32	**2.5**
		1Hz	12	**1**
LSM6DSO	100	0.5Hz	71	**5.7**
		1Hz	28	**2.3**

Position Estimation Error from Motion Sensor Noise



- False position change based entirely on motion sensor noise figure



Noisy Accel 100 ug/rtHz
Basic Gyro 3.8 mdps/rtHz
Poor temp stability 15 mdps/C
High sensitivity error 1%

Noisy Sensor = large position error

Clean Accel 50 ug/rtHz
Great Gyro 2.8 mdps/rtHz
High temp stability 5 mdps/C
Low sensitivity error <0.5%

TDK ICM-42622 = small position error

Bad Sensor = Excess Motion = Poor Pixel Match

TDK Sensor = Precise Motion = Great Pixel Match

Noisy Accel 100 ug/rtHz
Basic Gyro 3.8 mdps/rtHz
Poor temp stability 10 mdps/C
High sensitivity error 1%
1% Clock error

large position error = poor 'night mode'

small position error = great 'night mode'

Clean Accel 50 ug/rtHz
Great Gyro 2.8 mdps/rtHz
High temp stability 5 mdps/C
Low sensitivity error <0.5%
RTC eliminates clock error

ST6DSO Sensor = large position error

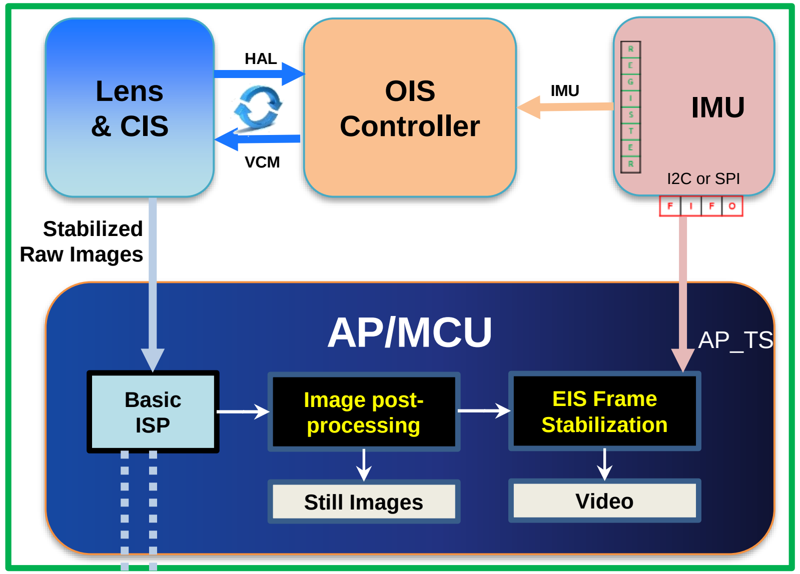
TDK ICM-42622 = minimal position error

Computational Imaging & Stabilization- what's next

- AI Imaging is awesome and unstoppable, automatic object/scene detection with corresponding exposure/focus adjustments are enriching amateur photography to advanced DSLR levels
- OIS will continue to be important, especially in Flagship Smartphones, since OIS allows more light to hit the pixels, critical for "low-light" and "HDR" imaging, key Smartphone camera use cases
- OIS will also be important for Smartphones cameras with optical zoom, as small movement causes larger pixel blur at higher focal length, and optical zoom is a growing trend in Smartphones
- AI Image stabilization works well and will drive better imaging into the mid-tier market. Moore is on the side of AIS, but good motion sensors used in the right way can play an important role to accelerate this trend
    - TDK is working closely with leaders in the Computational Image Stabilization field, to accelerate the adoption of computational imaging in mid-tier Smartphones, where compute resources are at a premium
- Imaging remains a key battleground for Smartphone OEMs, and the intersection of OIS and AIS provides TDK-InvenSense a great opportunity to differentiate with high-performance motion sensors

InvenSense Motion Sensors at the Center of Smartphone Imaging

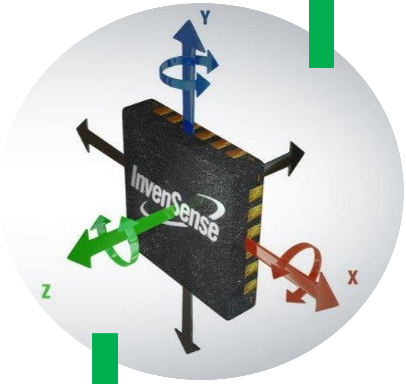
O I S



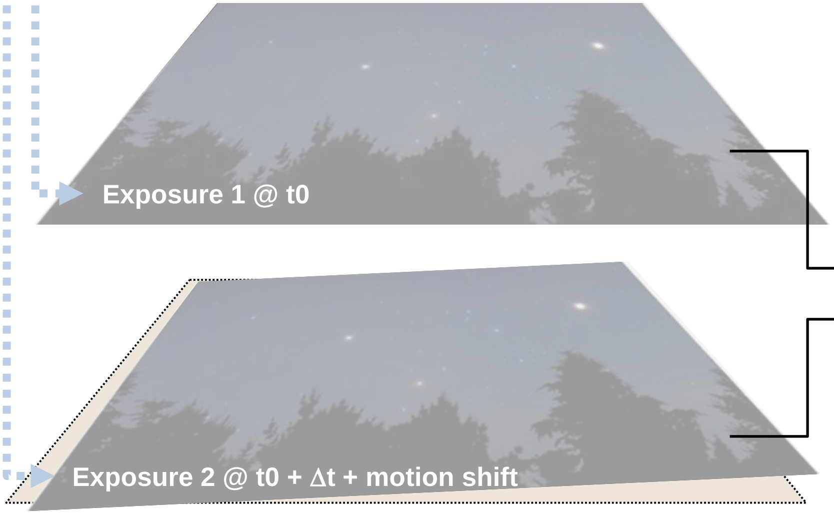
Motion Suppression

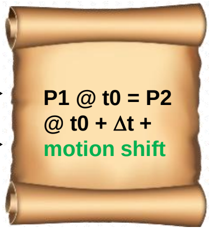
18 dB	24 dB	30 dB
3 stops	4 stops	5 stops
Poor OIS	OK OIS	Great OIS

Precise motion vectors enable more accurate OIS lens control, thereby minimizing pixel blur and extending exposure time by 1 stop!

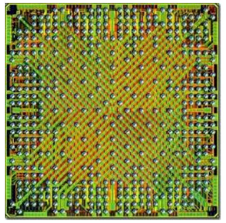


C I S





Global Pixel Map Registration



Multi Exposure Image Fusion

Precise motion vectors enable faster registration and better fusion results at lower complexity, enabling low-light Images with high-dynamic-range!

Thank You!