Expectations for future curved and flat CMOS photon detectors to mature scientific CMOS

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Expectations for future curved and flat CMOS
EIROFORUM June 2018

Talk outline

I.) Typical scientific astronomical detectors (CCD)

II.) Expectations for flat scientific CMOS

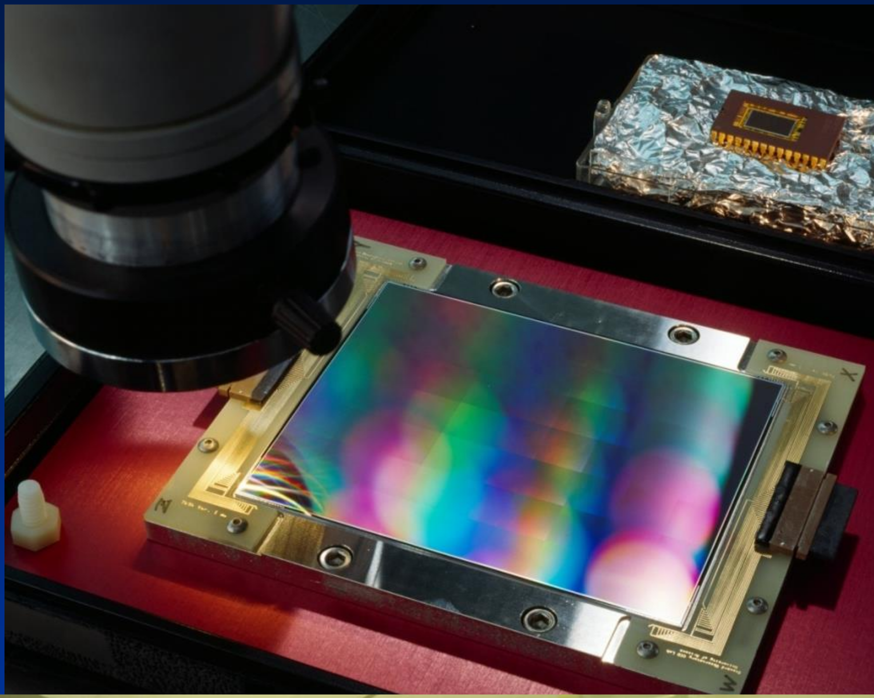
III.) Curved detectors development status

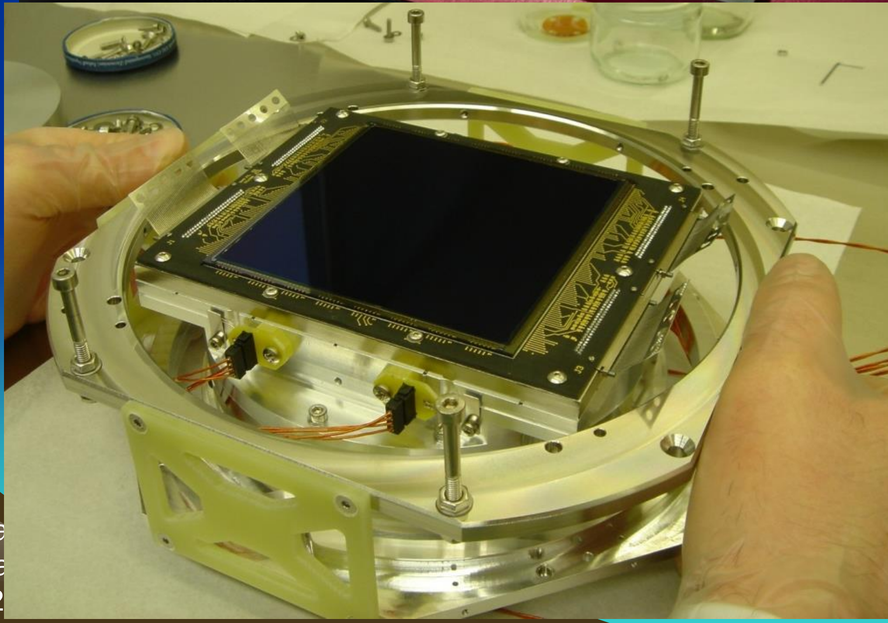
I.) Typical scientific astronomical detectors

(Flat) Scientific CCD:

- No CMOS –
- now State-of-the-Art
- No AO >> see Mark's talk tomorrow
- Large format, monolithic ~ 95 x 95 mm^2
- Low noise
- Monochrome / no colour filters
- No motion video rate
- Cooled to ~ - 120 C in vacuum
- Exposure time minutes to hours
- ALWAYS:
- Thinned silicon, backside illuminated

- Imaging, spectroscopy





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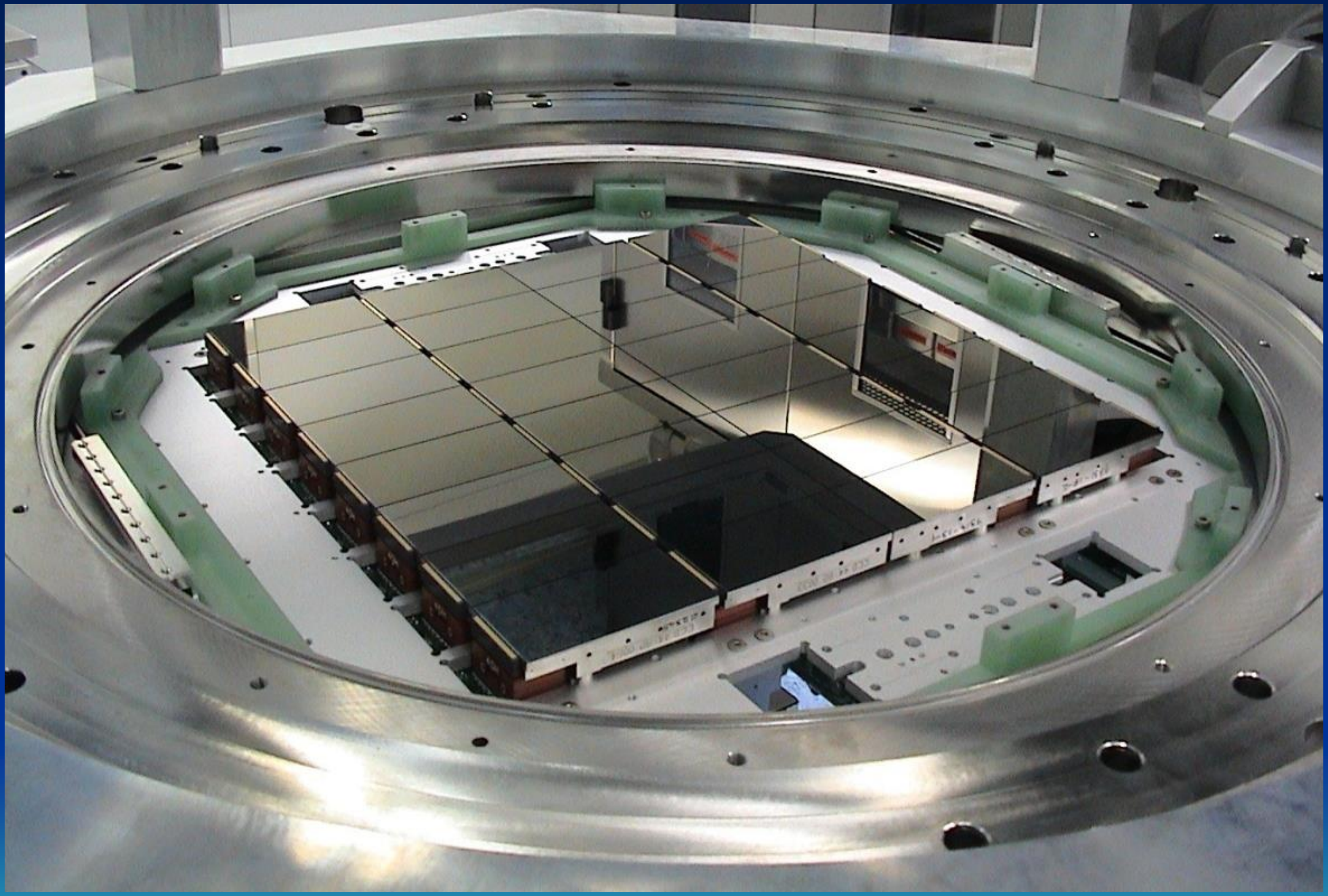
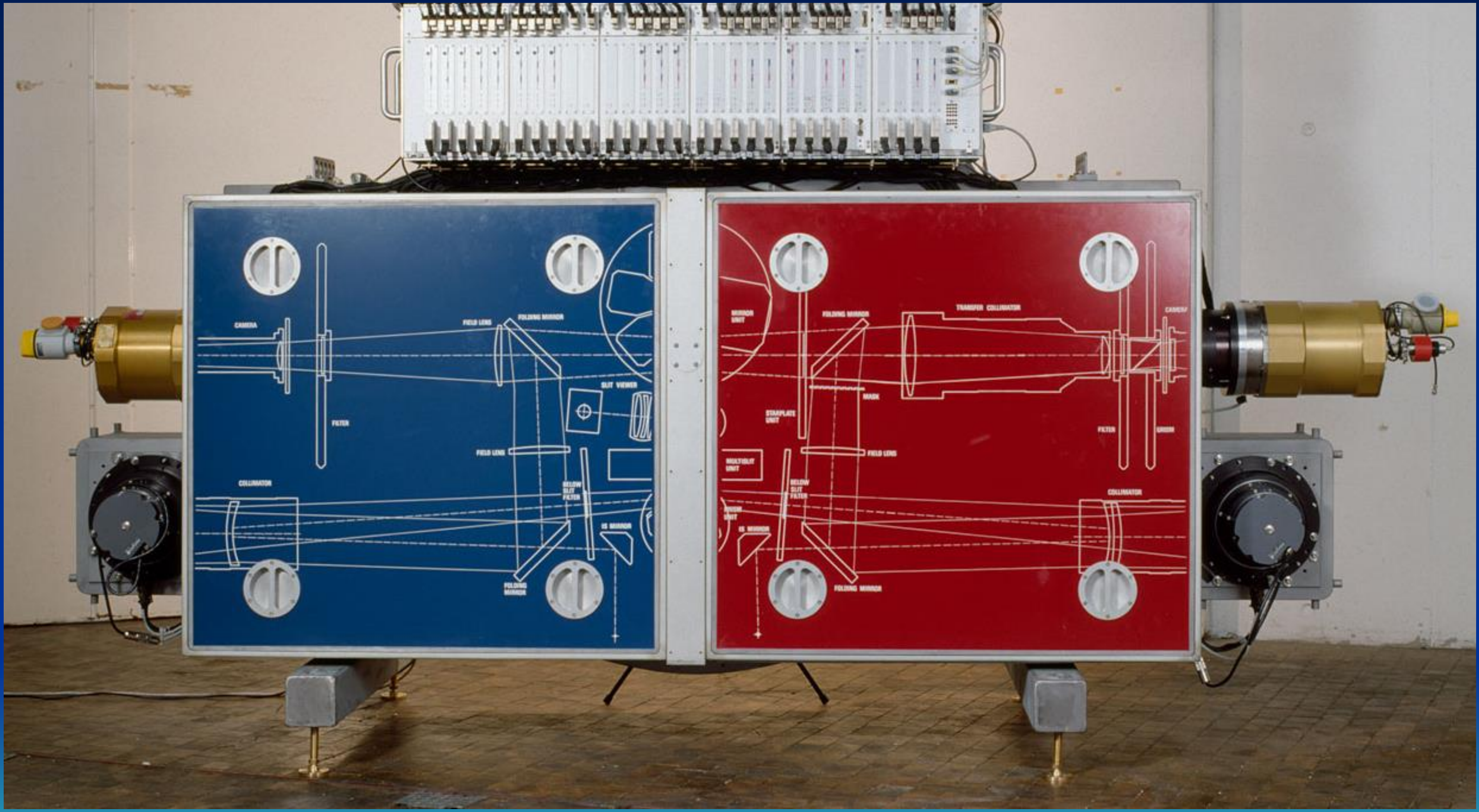
Imaging: Detector Mosaic - wide field of view



ESO OmegaCAM CCD mosaic 268 M Pixel, 32 CCDs, ~ 24 x 24 cm^2 light sensitive area

Spectroscopy: Faintest signal, high stability
(e.g. ESPRESSO)

Imaging & Spectroscopy: Blue / Red optimized



I.) CCD versus CMOS in our application:

CCD technology context:

- **Scientific detectors are core components of any astronomical instrument**
- **Often one of the most expensive single component of an (ESO) instrument**

- **Users have highest requirements in:**
  - **pixel fill factor 100 % (CCD)**
  - **backside illumination (all)**
  - **maximized Q.E over the visible to near infrared wavelength range (80-90 %)**
  - **Different Si thickness and R (15um blue, 40 um red, 250 um near IR)**
  - **lowest dark current for low light level imaging < 0.5 e- / (pixel hour)**
  - **cooled state-of-the-art CCD detectors ~153 K**
  - **typical pixelsize of 10 to 24 µm >> optics**
  - **monolithic physical size up to ~ 95 x 95 mm^2**
  - **typical readout noise of < 2….3e^- at ~ 100 kpix/sec,**
  - **On-chip binning capability to improve S/N**

- ***Currently CCD image quality is unparalleled for this application, where readout speed or parallel colour capture are not the main drivers.***

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I.) CCD versus CMOS in our application:

CMOS technology context:

- **Contrary to CCDs the commercial imaging world uses mostly CMOS detectors**
- **e.g., SONY, largest commercial CCD supplier, terminated CCD production 2017**

- **Although CMOS requirements in commercial applications are demanding,**
- **e.g., pixel sizes below 1 µm, integrated colour filters, high speed video readout rate, integrated image processing or memory capability, on-chip digitization (column parallel ADCs), and low-cost mass production,**

- **CMOS developments largely run counter to most astronomical applications.**

- ***Due to this missing link to the scientific application, currently none of the commercial devices is usable for any ESO instrument to replace a large scientific CCD.***

II.) Expectations for flat scientific CMOS

The up-coming dilemma:

CCDs:

++: CCD devices enable perfect image quality

- - : Less overall demand / no significant investments into new developments
a small number of manufacturers and R&D labs left
expensive compared to CMOS production / niche market
cost of keeping dedicated CCD production facilities operational increases

Contrary to that, CMOS world:

++: Detector design and manufacturing lines are typically separate enterprises working on a variety of new technologies.
Customer has freedom to choose the best and most economic technology within a growing portfolio.

- - : Despite many advantages (see below) CMOS is without further R&D not suitable to replace a CCD for ESO's application and will not make the progression from commercial to scientific CMOS - an evolution the CCD technology underwent about 15 to 20 years ago.

What we would like to see:

Possible Synergies and a joint R&D Program for ‘pure’ scientific CMOS with the following goals:

- CMOS replacement for large size, state-of-the-art CCDs, focussed onto:
  - backside illuminated CMOS detector, with
  - very best achievable CMOS pixel <u>optical</u> performance (few T’s):
    - in all parameters of large pixels (10 – 24 μm)
    - <u>except</u> readout speed, and
    - <u>except</u> high integration with peripheral circuitry.
- <u>Instead</u> the fundamental pixel design should have as little functionality / circuitry as possible, for:
  - best broadband Q.E. / highest fill factor (backside and bussing optim.), optimized photodiode size & shape (lag / sens. / PSF), lowest noise performance, but potentially allow binning - required in most science cases.
- All video processing shall be done off-chip (heat, noise, fill factor)
- Emphasis on modular design scaleability
- PURISM for best performance – (analogy high end stereo)

Other drivers of this CMOS development are:

- **Lower per-pixel cost for large devices**
- **Standard and high resistivity variants possible (blue / red enhancement)**

- **Overcome fixed size barrier of 6-inch wafers for CCDs with current suppliers**
- **CMOS 12…20 inch wafer size**
- **Mosaicking with large devices, resulting in really large 'affordable' focal planes, compared to current standard**

- **New readout modes for instruments, e.g.:**
  - **built-in on-chip exposure meter, non-destructive (repetitive) readout to reduce read noise, active guiding / on-chip tracking, now enabling active instruments (e.g., real-time flexure compensation) with much reduced cost for instruments' mechanical stability, thermal control, total mass, etc.**
- **Faster readout as conventional CCDs, reducing overhead**

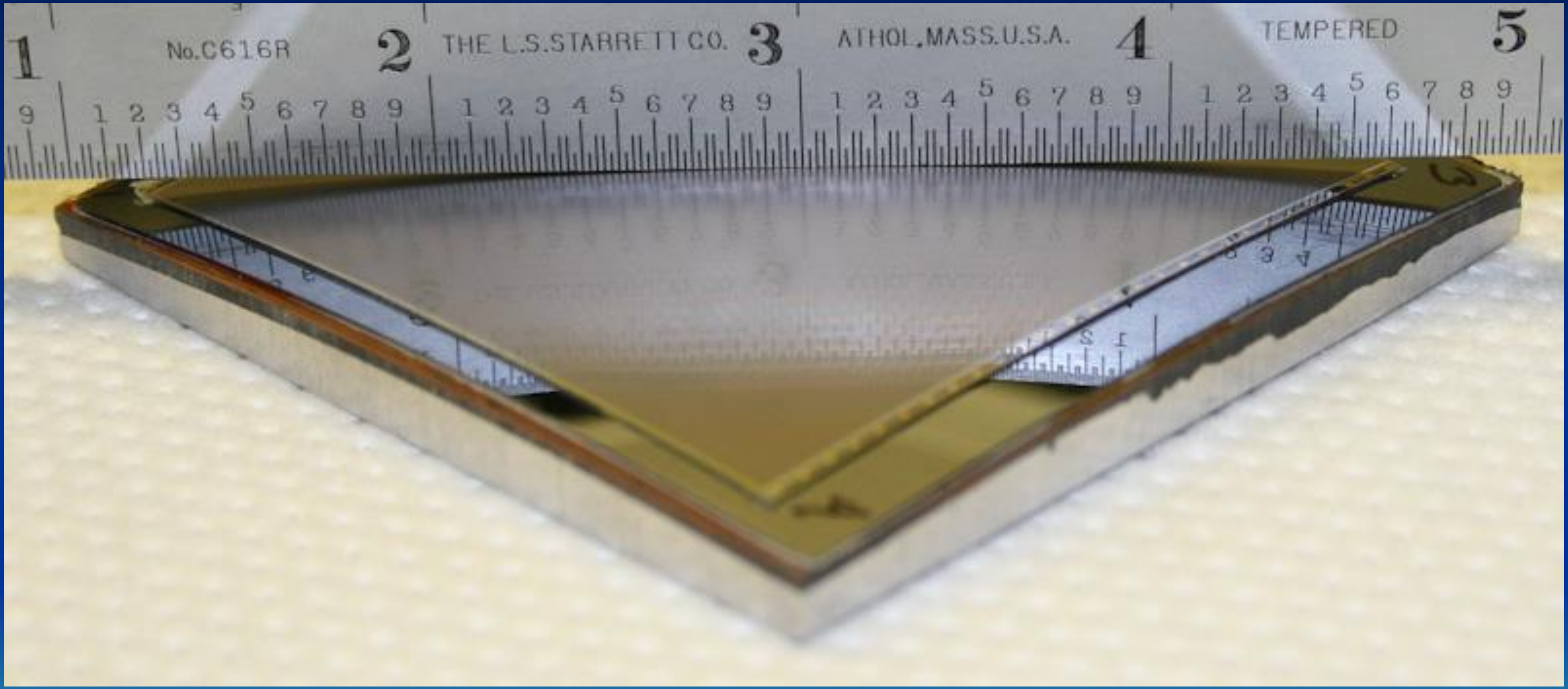
- **Improved detector cosmetics without CTE issues**
- **Less cooling effort due to lower intrinsic power consumption**
- **Possibly operation without any mechanical shutter (A9)**

Interested in collaboration / synergies ?
Please let us know…..

III.) Curved Detectors Development Status

Curved Detectors (3D) – Status

Olaf Iwert, ESO



Skeptic about curved detectors ?

A participant from SPIE 2013, Edinburgh:

"….Are these guys crazy ??

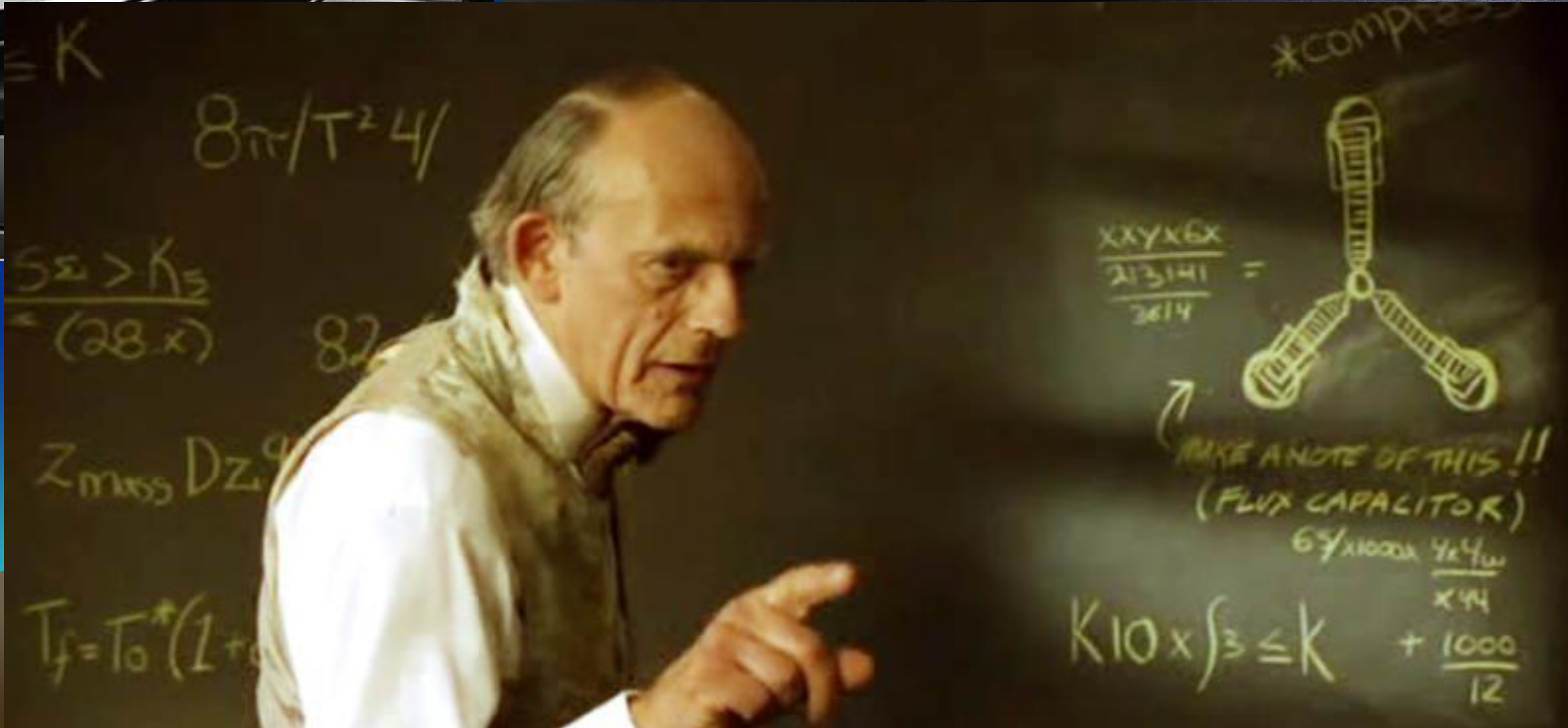
(IR)Detectors are complex

enough already !

We should stop this development….."

But what about Progress ?

BACK TO THE FUTURE



It takes a looong time from

the first idea to the

actual product…..

(ALWAYS), but some examples how long:

A.) Solid State Imagers:

- **What is the first time you came into touch ?**
- **What were your thoughts at that time on their future for the impact on our daily life ?**
- **What do you think the astronomers / engineers replied, whom I talked to ?**

1975: FIRST Digital Camera (Kodak)

Kodak's inventor of the first digital camera has revealed how bewildered company executives couldn't understand why anyone would ever want to look at images on a TV screen when he first proposed the idea of a 'filmless camera' to them in 1975.

Patent US4131919A

Analog <> Digital Camera (large format) :

- “Digital wonderbricks” now everywhere since ~ 2003, but not in 60 mm x 60 mm, which was the medium format standard
- Largest commercially offered medium format detectors now have ~ 60 mm x 40 mm, but no backside illumination
- Hubble “Trigger” for all scientific CCD work !

B: CCD versus CMOS:

Talk by M. Loose SDW 2005, Taormina:

“CCDs are dead / dinosaurs >> CMOS is the future”

2017:

- **Commercial poducts (OK)**
- **Scientific products (no way yet…)**
- **e.g. ESPRESSO CCD detectors 90 x 90 mm State-of-the-Art), plus required binning**

C: 1961 - COMPUTER MOUSE / GUI

SRI Stanford Research Institute - now Stanford Research International, owned by Sarnoff

~ 1985 again by Apple; early 90's widespread

Google also : 'Mother of all presentations, Engelbart

FLASHBACK TO SDW 2013:

Curved detectors: Where did we stop ?

In a nutshell: Curved Detector KEYPOINTS

- Optical advantages of system performance
- Curved detectors plus simplified optics >> not really elaborated this time in detail >> Zwicky ?
- Advantages as f (Field, speed, vignetting, resolution)
- Fixed / modulated curvature
- Cryogenic / non-cryogenic curvature
- Curving thin or thick detectors ?
- Theory of tensile stress versus practical experiment
- High curvature / low curvature with small / large detectors
- Curvature shape with high / low accuracy
- Commercial world: Mirrorless cameras / cellphones

Milestone developments 2013 (1) JPL modulated curvature on the fly, relying on thinning

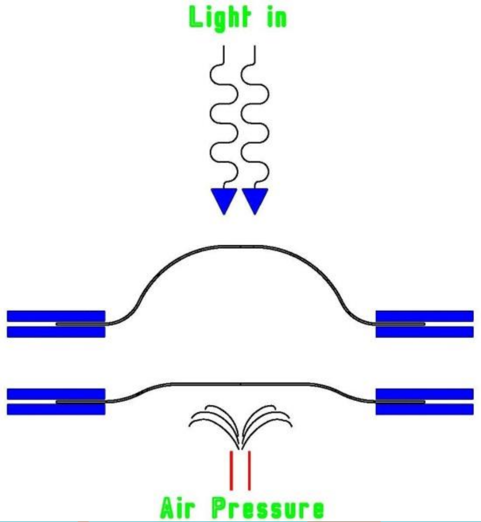
Unsupported, frame thinned, curvature modulated on the fly during imaging:

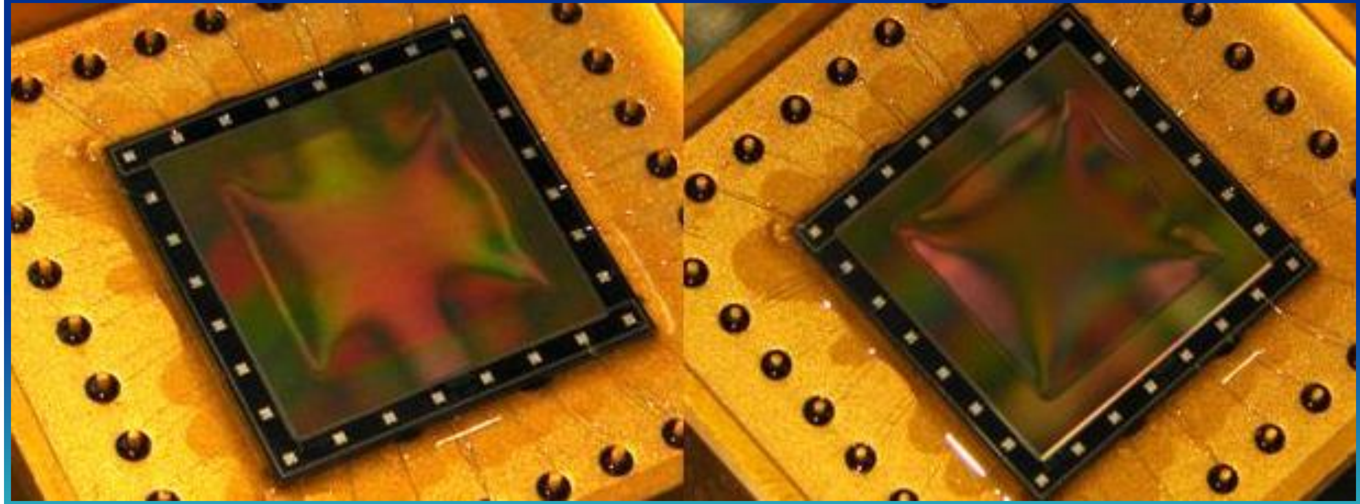
Shouleh Nikzad, JPL, USA: CCD of 12 x 12 mm^2,

Device curvature modulation - 250 mm … + 250 mm radius on the fly

Operated at room temperature without obvious performance loss,

but not fully characterized >> *talk to Shouleh*

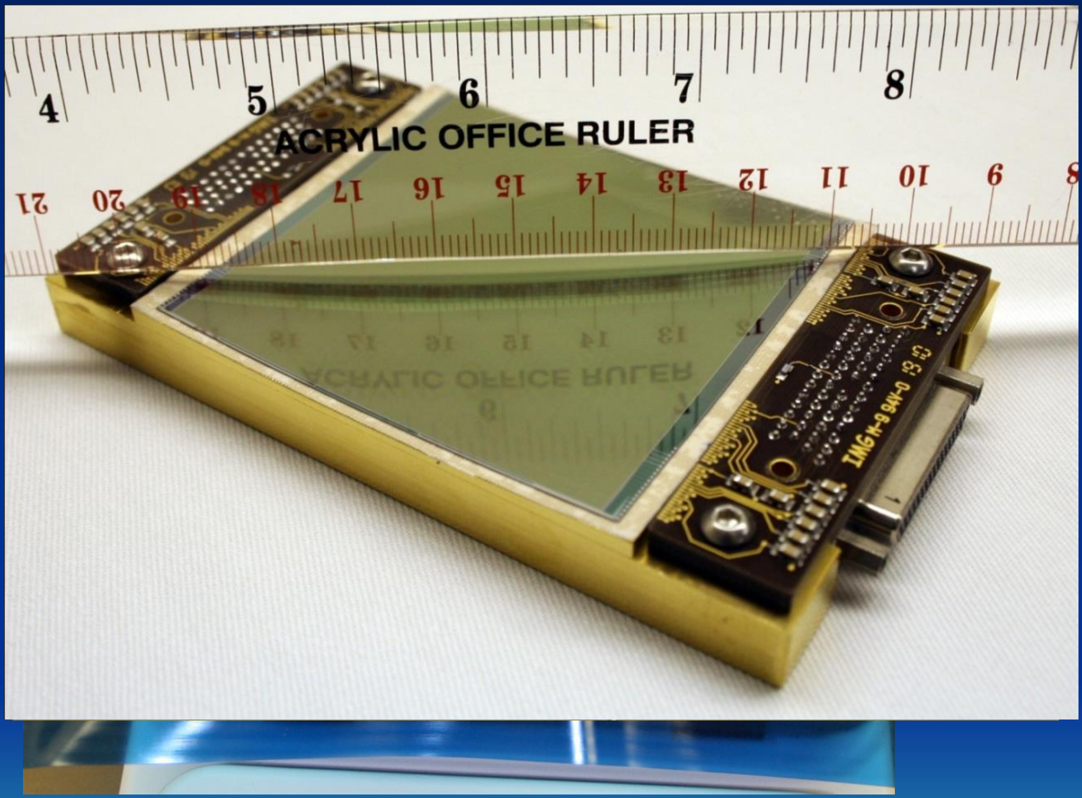




Images courtesy of S. Nikzad, JPL

Milestone developments 2013 (2)

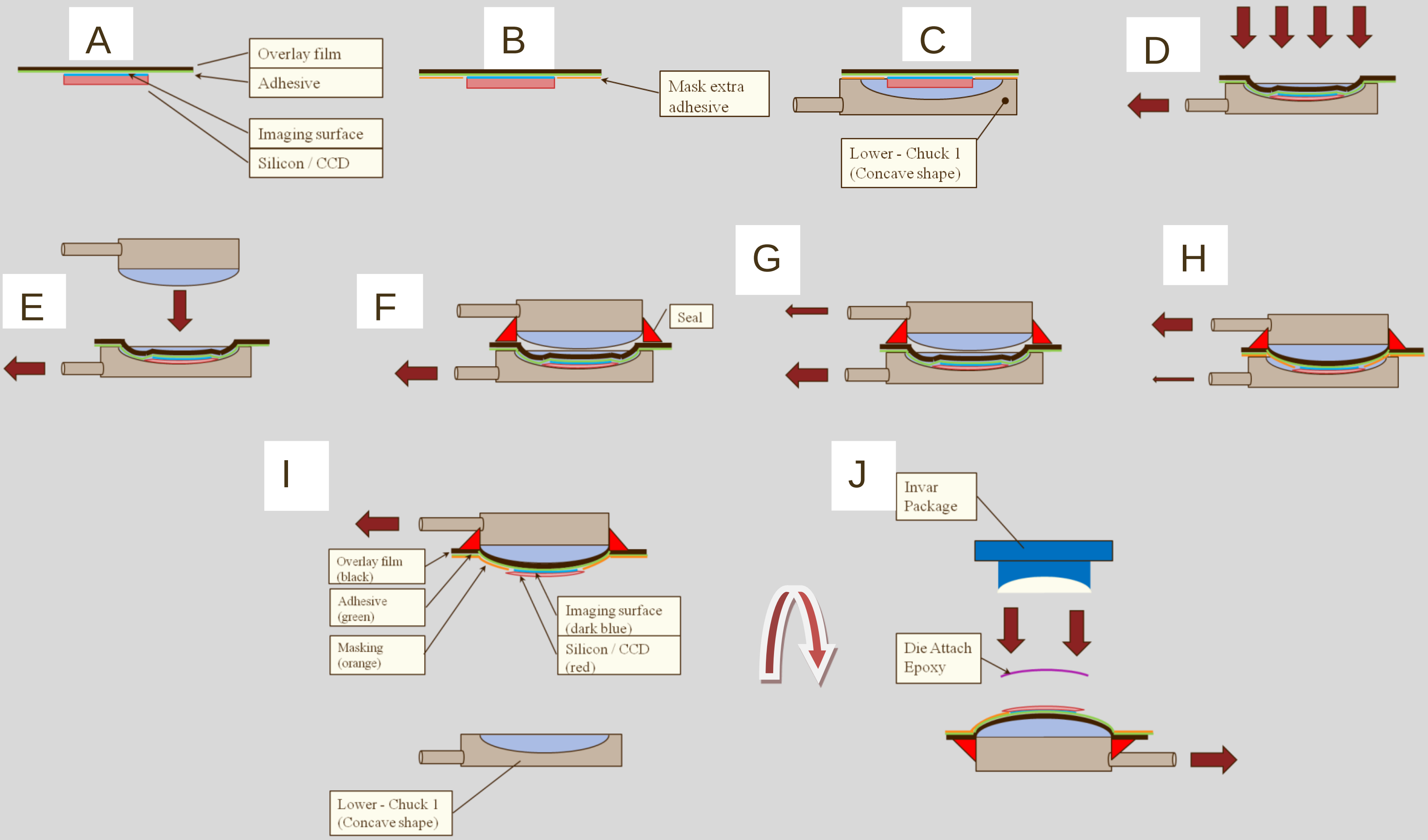
ESO / ITL 1st Curved Astronomical detector, 4k x 4k, 15 um detector



- **1st curved large detector**
- **~ 200 um thick, frontside**
- **Limit of curvature ?**
- **500 mm curvature radius**
- **Concave, fixed**
- **Cryogenically cooled**
- **Characterized before & after curvature with similar result**
- **Curved above known theoretical limit**
- ***>> Talk to Mike Lesser, me***

ESO / ITL curving process: 2 Vac

Overview of process steps:

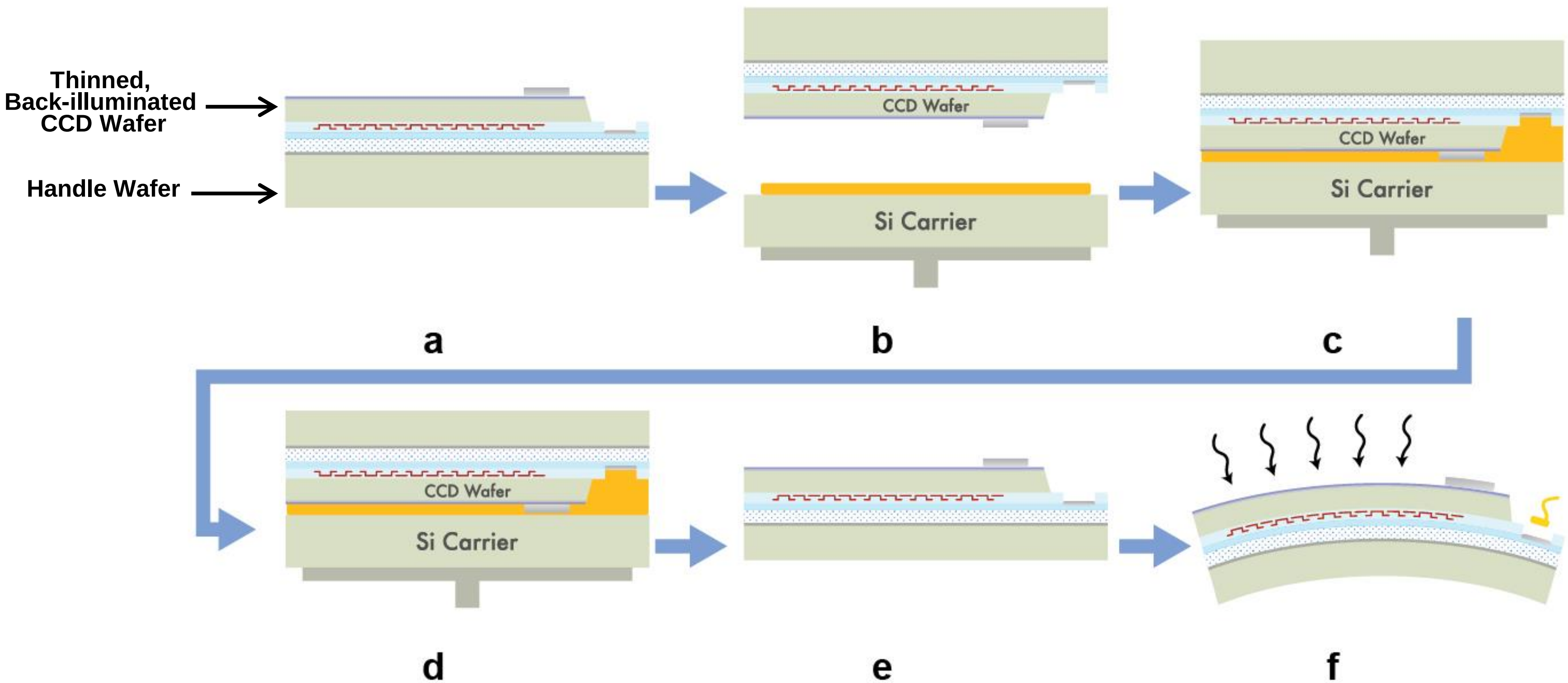


Milestone developments 2013 (3)

MIT / LL SST Telescope (3.5 m, F1) designed for individually curved detectors in a mosaic

- **6 x 2 detectors of 2k x 4k, 15um each**
- **Not a prototype – pioneering a very courageous decision, independent of anyone else**
- **Convex, 5.44 m curvature radius**
- **Extremely accurate curvature ~3 um for combined curvature across mosaic**
- **Now a second mosaic built for 2nd telescope**
- ***>> Talk to Vyshi S., Barry Burke***

Processing of Curved CCD to Completion



- Mount back-illuminated, functional CCD wafer (a) to carrier wafer (b+c)
- Thin handle wafer (d)
- Remove from platen (e)
- Dice wafer and deform CCD to spherical shape (f)

Milestone developments 2013 (4)
It's not a Trick – it's a SONY Patent
Optics for Curved Detector

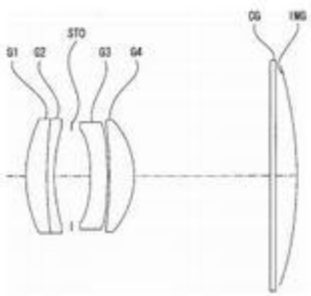
Sony 35mm F1.8 Curved Imager の特許 [光学技術・レンズ設計]

ソニーがフルサイズミラーレスに対応する35mm F1.8をはじめとする数本のレンズのを出願中です。湾曲した撮像素子を前提とすることで、少ないレンズ枚数ながら収差の極めて少ない光学系に仕上がっているようです。

【追記】ミラーレスと書いた理由は、バックフォーカスが短いことを強調したかったのであって、レンズ交換式か非交換式かを議論したかったわけではありません。

Curved detector:

4 lenses



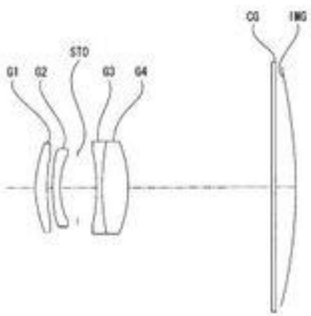
patent: 35mm f/1.8 (full-size mirror-less)

Already built with flat detector:

>= 8 lenses (Nikon, Olympus)

Curved detector:

4 lenses

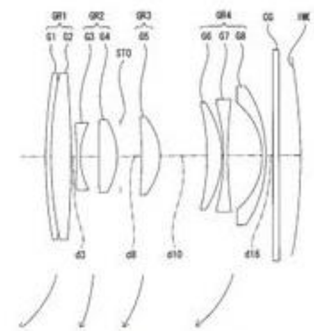


>= 7 lenses

(Olympus)

patent: 35mm f/2.8 (full-size mirror-less)

Sony patent 2013-61476 in Japan



patent: 10-25mm f/2.8-5.6 (1inch mirror-less)

Back focal distance minimized

Not possible with flat det.

+ ZOOM in connection with lens shift and curvature modification

CURVED DETECTORS SINCE SDW 2013

ESO DEVELOPMENTS (1)

A.) Broaden the interest base / inform the community

B.) MOS instruments – demand as seen e.g. in 4MOST

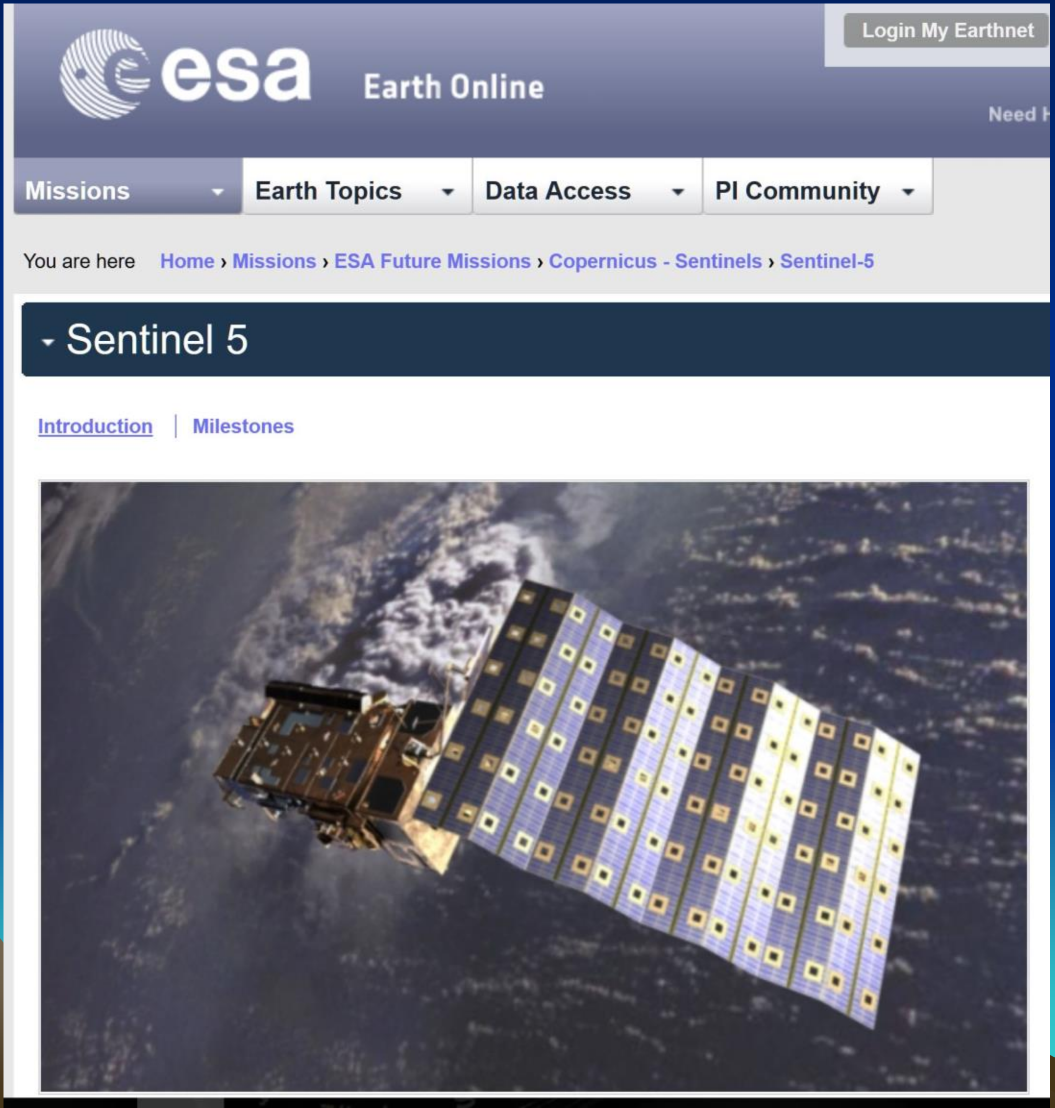
C.) Open exchange with LAM and co-operating to see what is a common basis to push this forward for scientific detectors

D.) ESA/ESO collaboration with support from highest level:

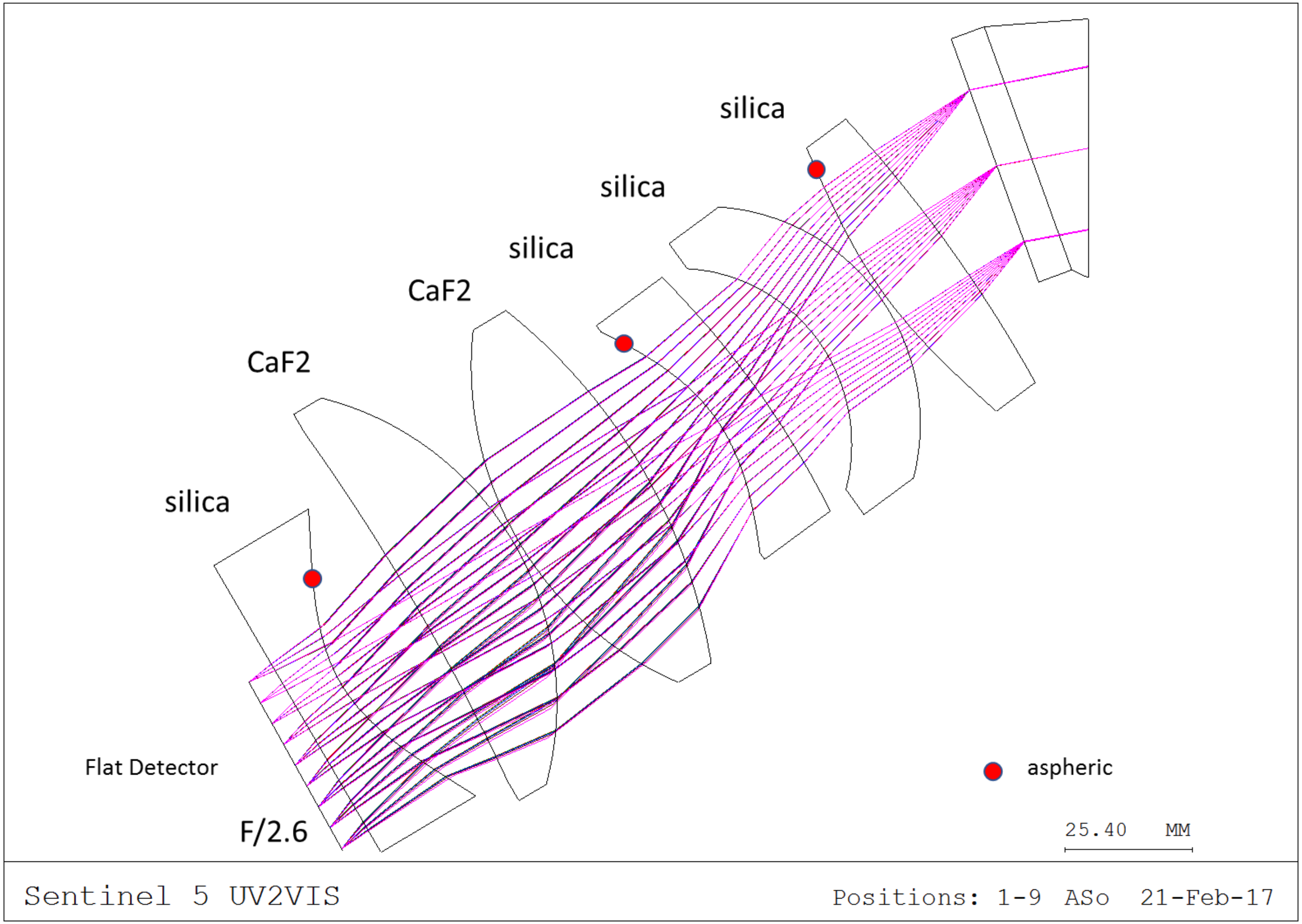
Space projects : better image quality,
weight reduction,
alignment insensitivity

ESO / ESA CURVED DETECTOR

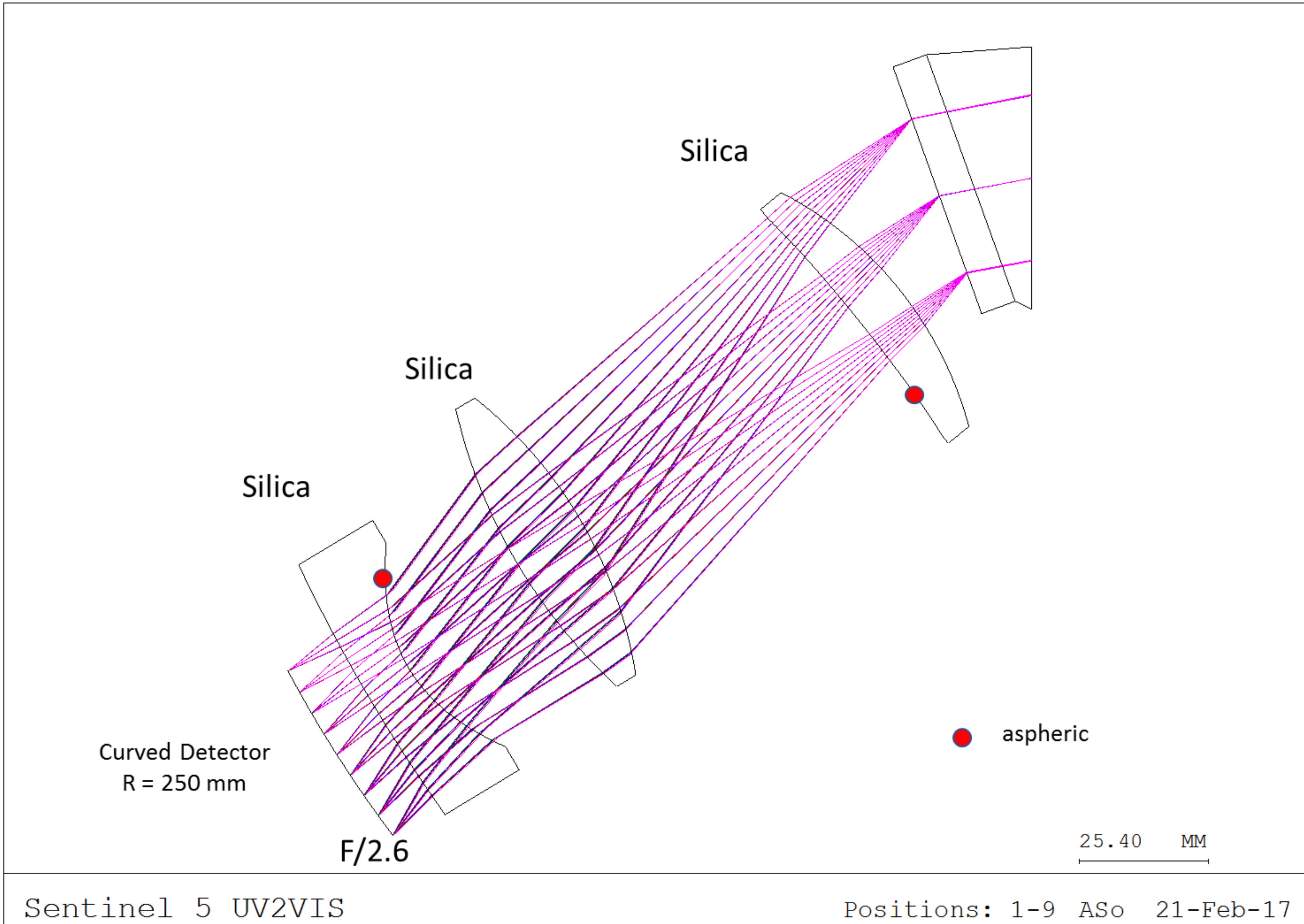
Example of an optical system simplification
Study done on Sentinel 5 UV2VIS camera



Original Optical Design Sentinel V



New Design with a curved detector



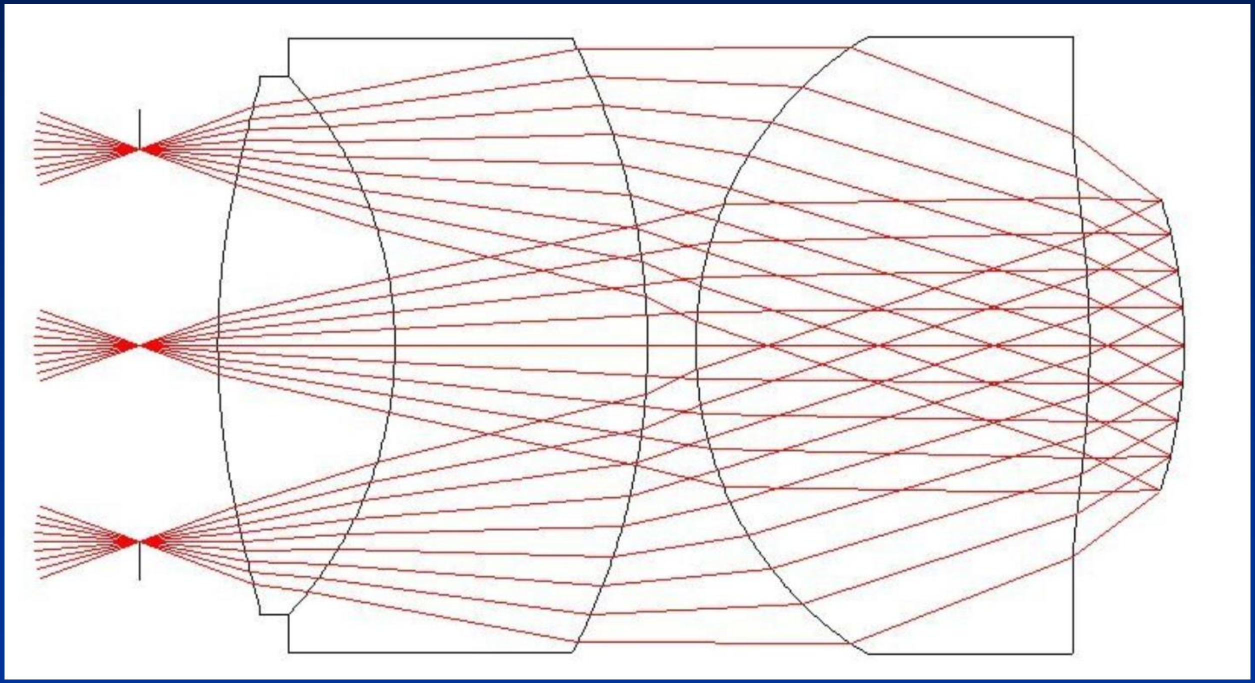
ESO DEVELOPMENTS (2)

Plans for novel Spectroscopic telescope facility

- L. Pasquini et al.: New telescope designs suitable for massively multiplexed spectroscopy, SPIE Digital Library 2016 & 2017
- L. Pasquini et al.: ESO spectroscopic Facilty, IAU Symposium 331, 2017

- **Large 10 – 12 meter dedicated new spectroscopic telescope combined with**
- **Larger FOV (~ 5 square degrees) – survey**
- **Massively multiplexed spectroscopy (~ 5000 fibres)**
- **Matched sampling telescope – instrument**
- **Fast cameras (~F1) and matched pixel size**
- **Several hundred standardized spectrographs with curved detectors 4k x 4k 15 um, R~ 250 mm**

ESO DEVELOPMENTS (2a)



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JPL DEVELOPMENTS

- **Continued on curvature development with thick detectors**
- **Confidential: Medical developments**
- **19 mm curvature radius** ***>> Talk to Shouleh Nikzad***

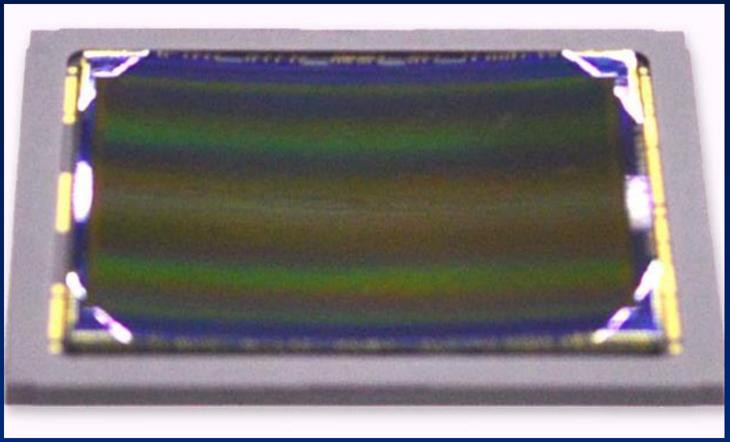
MIT DEVELOPMENTS

- **Continued on curvature development**
- **2nd focal plane built, with even better performance**
- **Confidential developments (defense), high curvature**
- ***>> Talk to Vyshi S., Barry Burke***

SONY DEVELOPMENTS

Kazuichiro Itonaga: A Novel Curved CMOS Image Sensor Integrated with Imaging System

2014 Symposium on VLSI Technology Digest of Technical Papers



- **2014: About 100 backside illuminated 3D curved CMOS sensors fabricated in both smartphone and 35mm format (24 mm x 36 mm) as R&D project**
- **Process developed in house, intention for mass production, reliability testing done**
- **Huge commercial interest for mirrorless FF cameras, & compacts and others (later)**
- **Detector and System tests with special optics done – no absolute numbers, but ….**

SONY DEVELOPMENTS (2)

$$\text{Field curvature}\,(A_{fc}) \propto \frac{D^2}{F_n}$$

F_n : F number

D : *Diameter* of image circle ...*(Eqn. 1)*

$$J_d = \frac{-qW}{2\sqrt{\tau_{p0}\tau_{n0}}}\sqrt{NcNv}\times\exp\left(-\frac{E_g}{2kT}\right)$$

$$\tau_{n0} \equiv \frac{1}{v_n s_n N_t} \qquad \tau_{p0} \equiv \frac{1}{v_p s_p N_t}$$

J_d : Dark current

E_g : Energy band gap

W : Depletion layer width

N_t : Trap site density

v_n, v_p : Thermal velocity (n-type, p-type)

s_n, s_p : Capture cross section (n-type, p-type)

N_c : Conduction effective state density

N_v : Valence effective state density ...*(Eqn. 2)*

Fig. 1 A equation of field curvature of lens

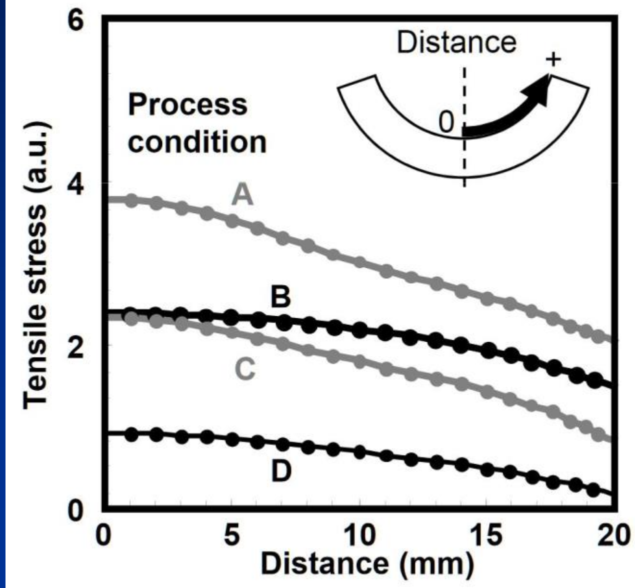


Fig. 2 Normalized tensile stress within image circle as a function of curving process condition A to D. (Conditions : Material and temperature were varied.)

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SONY DEVELOPMENTS (3)

with a blight lens.

(Conditions : Material and temperature were varied.)

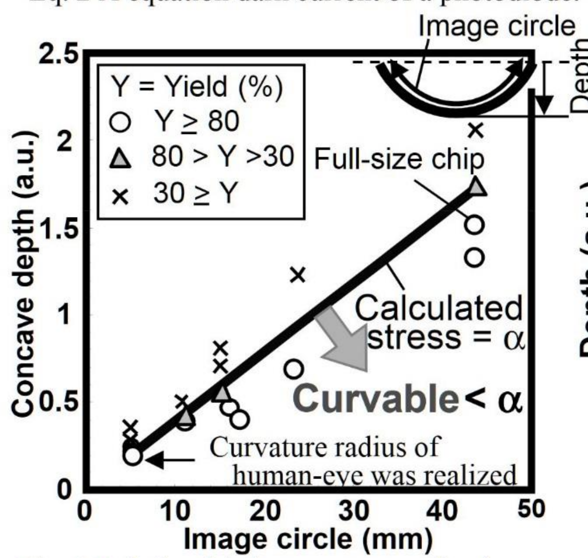


Fig. 3 Relationship between normalized a concave depth and a diameter of image circle.

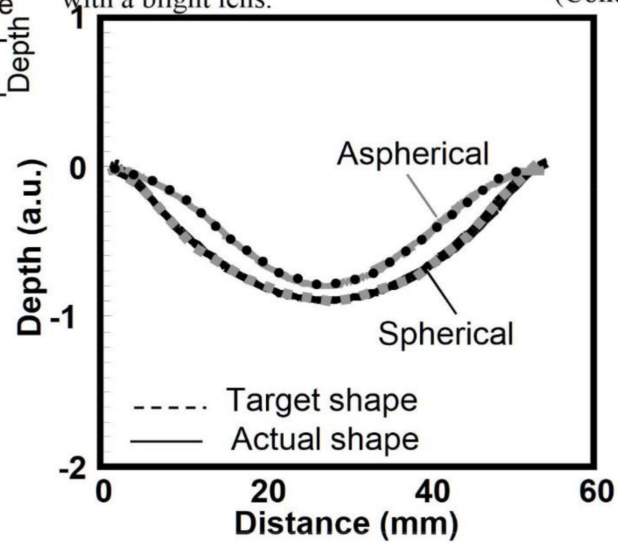


Fig. 4 The surface shape of a curved CIS.

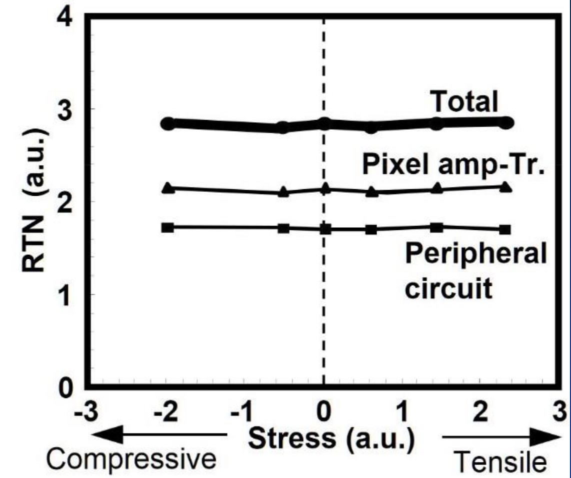


Fig. 5 Normalized random telegraph noise (RTN) as a function of normalized sensor stress.

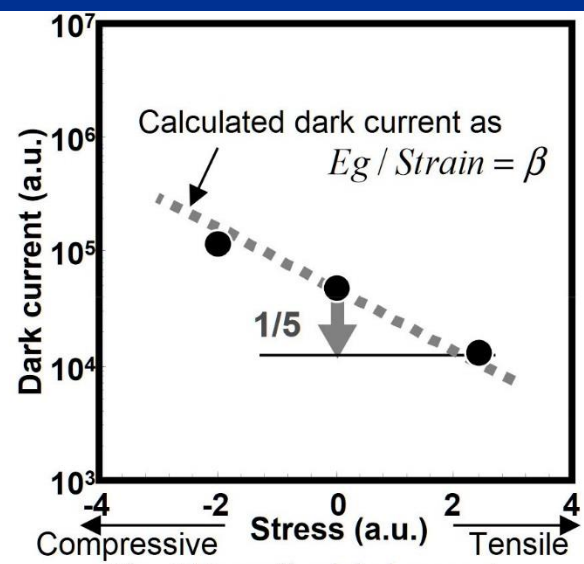


Fig. 6 Normalized dark current as a function of a sensor stress.

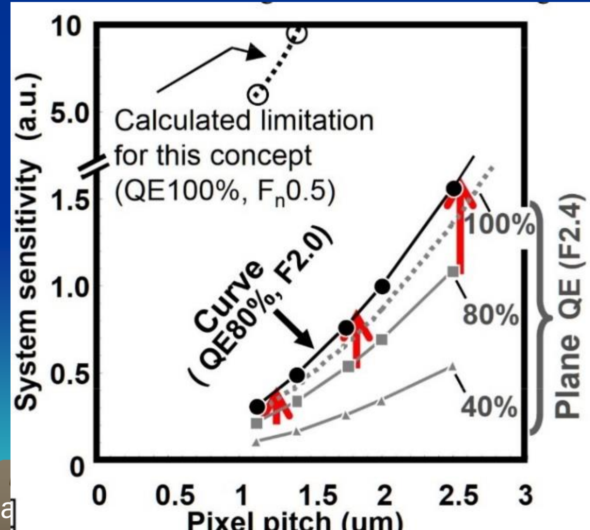
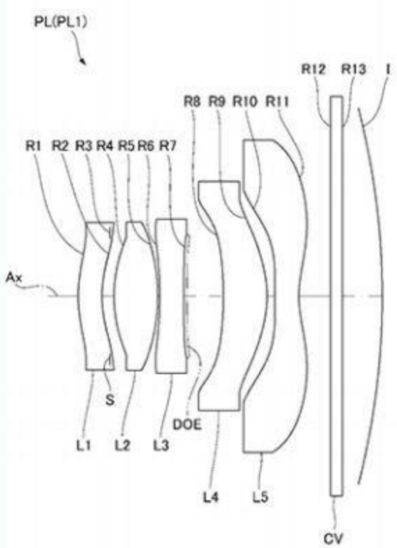


Fig. 11 Relationship between pixel pitch and normalized system sensitivity. A large improvement in *system sensitivity* has been obtained.

NIKON DEVELOPMENTS

2016 bottom / 2017right



(57) **Abstract**: An imaging lens (PL) which has an image surface (I) curved so that a concave surface faces the object side comprises five lenses including both positive lenses and negative lenses. At least one of the negative lenses included in these five lenses is disposed next to a positive lens near an image side. The pair of a positive lens and a negative lens disposed next to the positive lens near the image side wherein the combined refractive power thereof is the maximum positive refractive power satisfies the following conditional expression: $0.5 < fc / f < 1.2$ where fc represents a combined focal length of the positive and negative lenses wherein the combined refractive power thereof is the maximum positive refractive power, and f represents a focal length of the imaging lens.

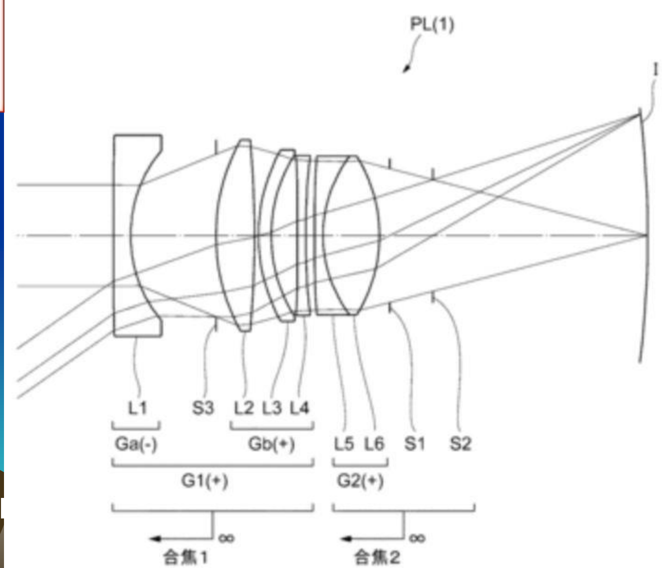
(57) 要約:　物体側に凹面を向けるように像面（Ｉ）が湾曲した撮像レンズ（ＰＬ）であって、正レンズおよび負レンズの両方を含む５枚のレンズからなり、これら５枚のレンズに含まれる負レンズのうち少なくとも１枚は、正レンズの像側に並んで配置されており、前記正レンズおよび前記正レンズの像側に並んで配置された前記負レンズの組のうち、合成屈折力が最大の正屈折力となる前記正レンズおよび前記負レンズの組において、以下の条件式を満足する。　０．５＜ｆｃ／ｆ＜１．２　但し、ｆｃは前記合成屈折力が最大の正屈折力となる前記正レンズおよび前記負レンズの合成焦点距離、ｆは前記撮像レンズの焦点距離。

Wide-angle lens for curved 35mm full-frame sensor from NIKON [Pantent]

が湾曲センサ用広角レンズの特許を申請しています。
has applied a patent of wide-angle lens for curved 35mm full-frame sensor.

【公開番号】特開2017-125904(P2017-125904A) click here for the application document
【公開日】平成29年7月20日(2017.7.20)
【発明の名称】撮像レンズおよび撮像システム

【第1実施例の諸元データ Specifications】
f=35.0 mm
FNO=2.0
ω=35.0°
像高=21 mm
センサが湾曲しているため、平面センサに比べて画角がすこし広くなっています。



第1実施例に係る撮像レンズのレンズ構成図 **Optical system design**

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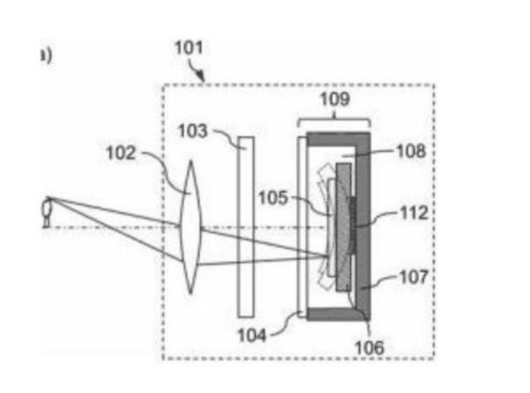
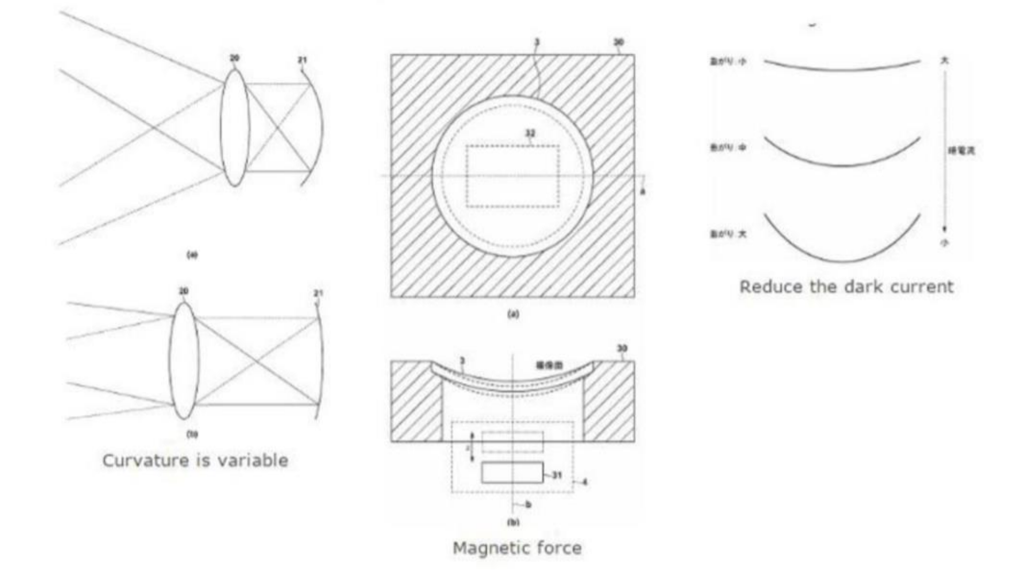
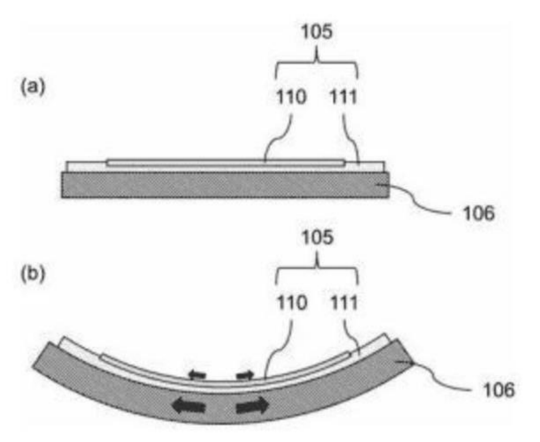
CANON DEVELOPMENTS

- At least 4 different recent patents on curved sensors: 2016-173496; 2016-197603; 2016-201425; 2016-213571
- Modulation of the curvature on-the-fly (magn./piezo)
- Reduction of dark current







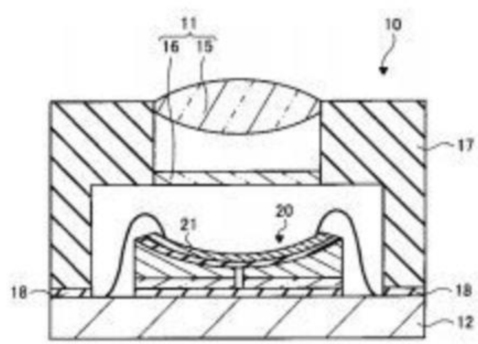
TOSHIBA DEVELOPMENTS

Toshiba Curve Image Sensor For Smartphones - Patent

By admin, on June 27th, 2016

Toshiba working on a curve sensor module for smartphones to drag out maximum image quality from available light. A curve sensor mimic human eye and its capacity to capture light remains constant throughout the sensor plane.   You may also surprise to know that curve sensor requires less optical elements compared to traditional flat sensor, hence less obstacles in the path of light.

Take a look at the patent details below



Complete camera module

Patent details – Description, self-interpretation of the patent literature

- Patent Publication No. 2016-76543
    - Published 2016.5.12
    - Filing date 2014.10.3

TELEDYNE Hybrid IR DEVELOPMENTS

Internal R&D project, team led by Majid Zandian:

- **Substrate removed HgCdTe array that is being bent in one (two) axis in a cylindrical / 3D shape – hybridized with multiplexer**
- **Array size: 640 x 480 pixels, 15 micron pixel pitch**
- **A special new process was developed to enable this type of flexible IR array to be made**
- **Production Process for curvature is ITAR controlled and a Teledyne trade secret**
- **Proof of concept is shown, no damage of the array observed**
- ***>> Talk to Majid Z. / Jim B.***

Video Teledyne

No redistribution of this video please !

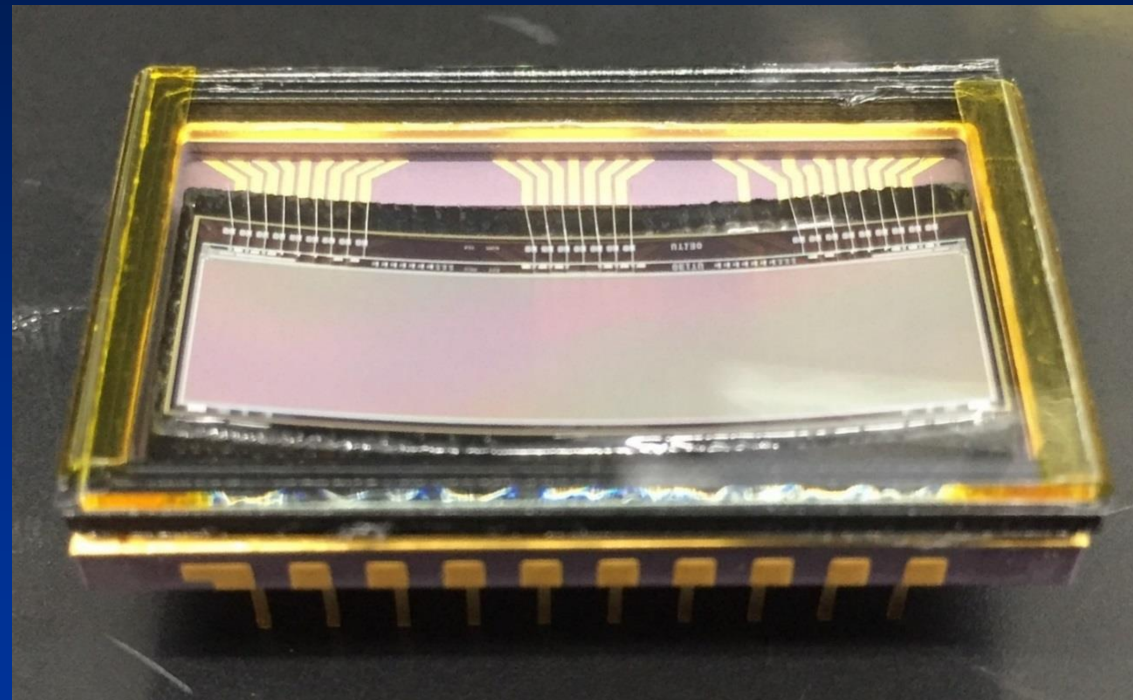
E2V DEVELOPMENTS

Minimum scope demonstrator:

- **CCD30-11, frontfaced,**
- **thinned to 150 um**
- **[1024 X 256; 27 * 7 mm]**
- **Ceramic package with curved insert**

- **Cylindrical Curvature exclusively**
- **Curvature Radius = 7 cm**

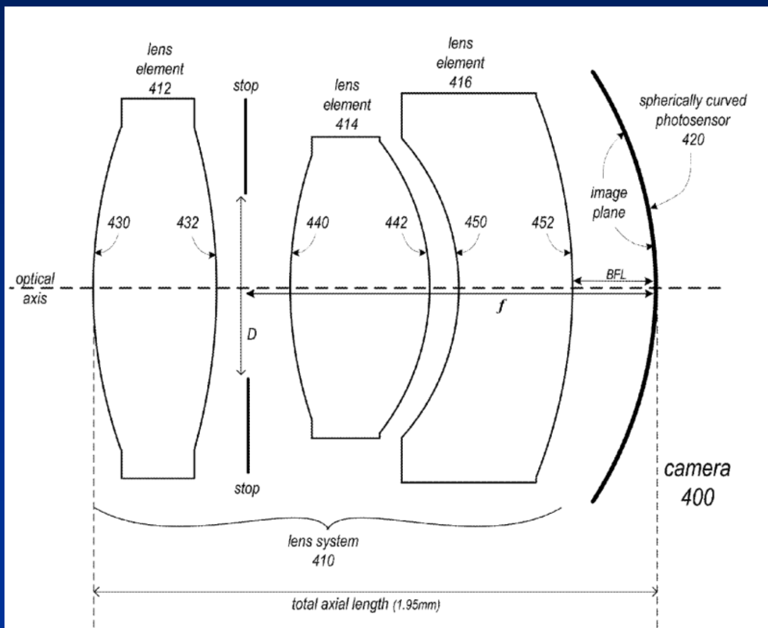
- **Several devices have been made,**
- **More deliverable devices in progress;**



Very much appreciated that e2v / Teledyne work experimentally on this, but we really need 3D Curvature for all our examined applications

APPLE DEVELOPMENTS

(12) **United States Patent** (10) **Patent No.: US 9,244,253 B2**
Chen et al. (45) **Date of Patent: *Jan. 26, 2016**



optical surface	radius of curvature (RoC)	thickness	conic constant	4th-order aspheric coefficient	6th-order aspheric coefficient	8th-order aspheric coefficient	10th-order aspheric coefficient
lens element 412, surface 430	1.169	0.424	0	-0.264	-0.519	-0.316	0
lens element 412, surface 432	-3.407	0.102	0	-0.223	-0.215	0.155	-0.122
Stop	infinity	0.161	0	0	0	0	0
lens element 414, surface 440	1.421	0.479	-2.072	0	0.376	-3.144	2.462
lens element 414, surface 442	-0.876	0.100	0	0.468	-2.332	0.261	0
lens element 416, surface 450	-0.866	0.394	0	0.300	-1.584	-9.225	22.116
lens element 416, surface 452	-1.524	0.291	0	0.321	-0.400	-0.676	1.425
image plane (photosensor 420)	-1.364	-	0	0	0	0	

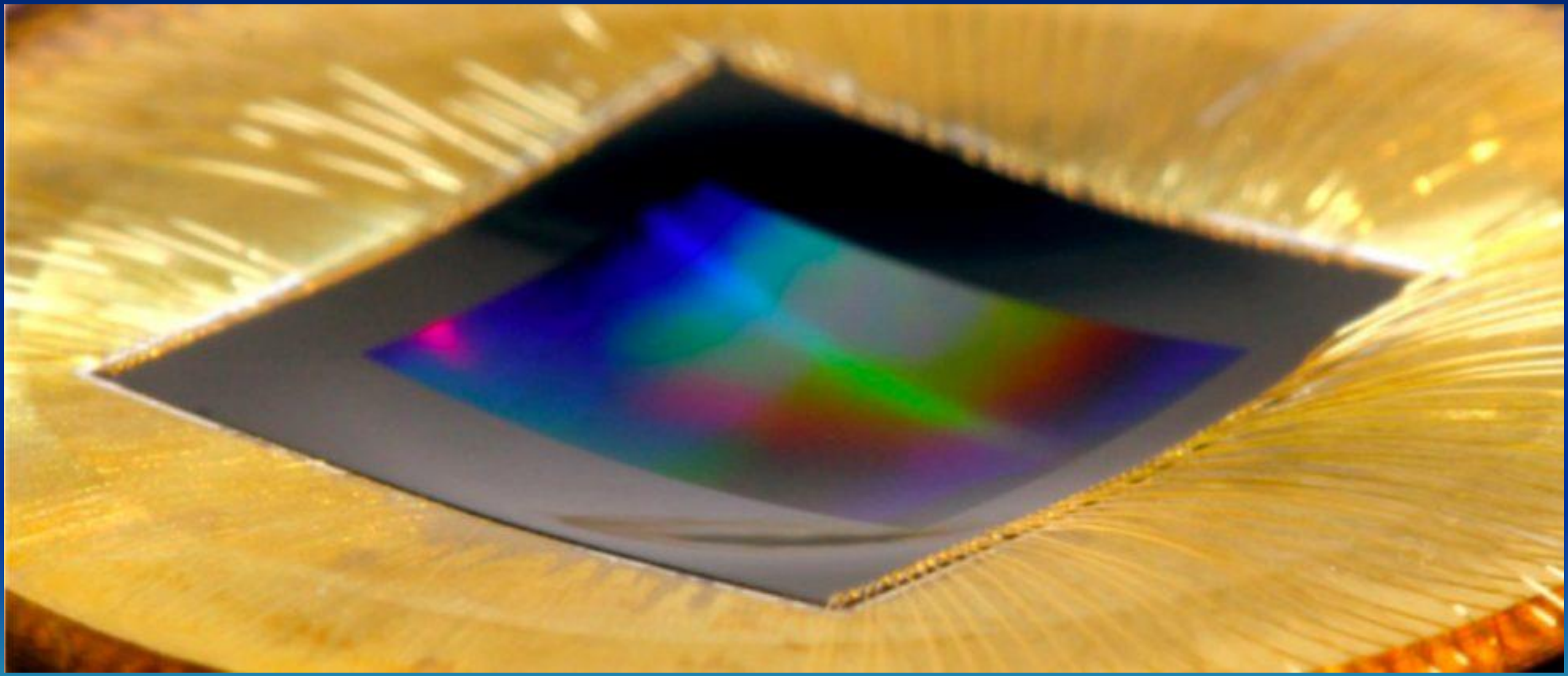
Flat camera design: smartphones, laptops, tablets
Focal length within ~ 20 % of Radius of Curvature of detector

Olaf Iwert
European Southern Observatory (ESO)

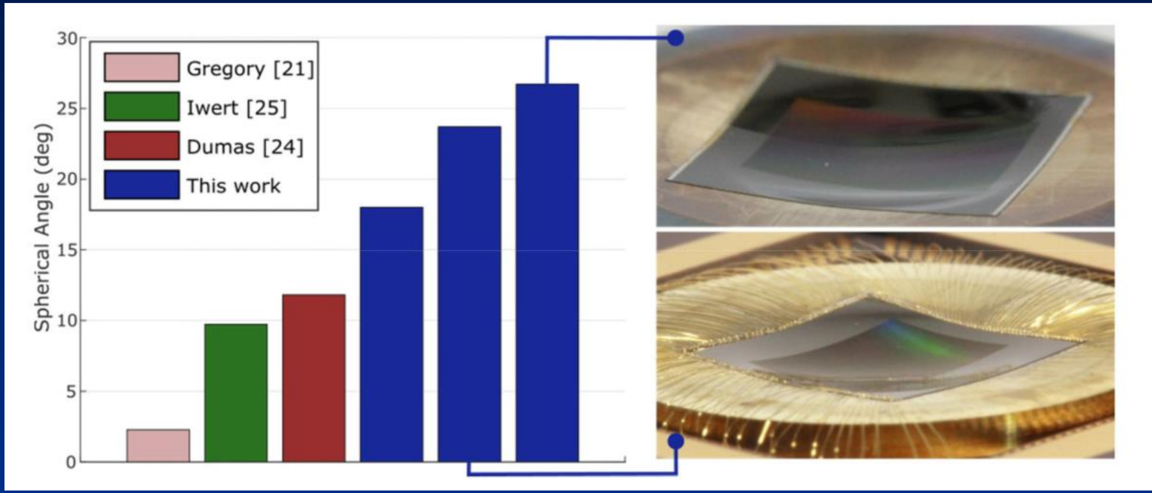
MICROSOFT / HRL* DEVELOPMENTS

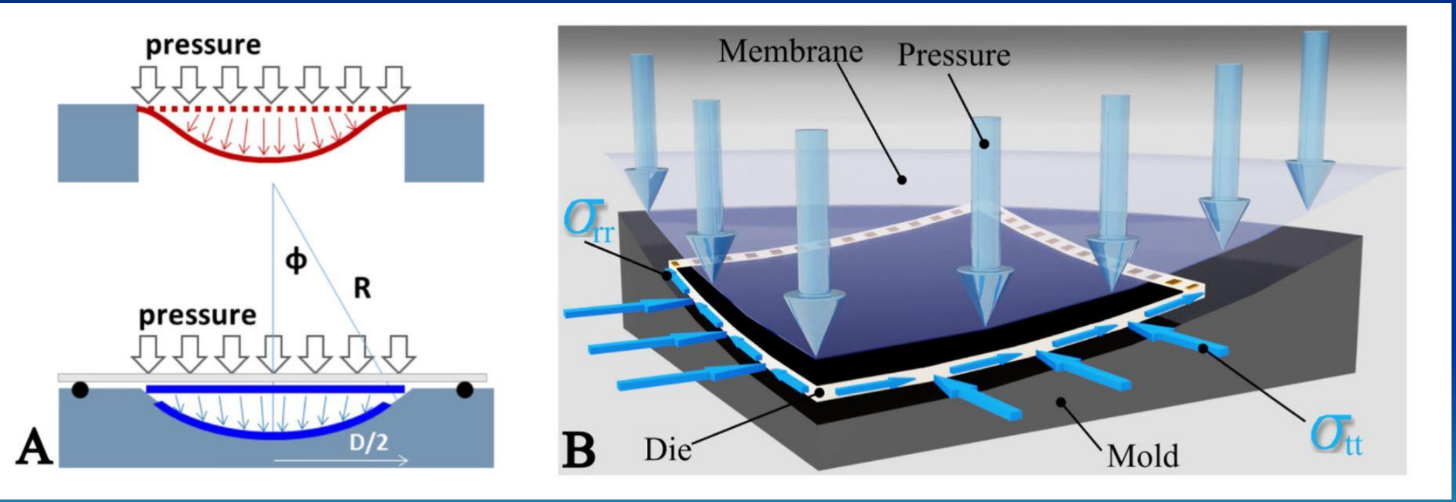
(originated from Hughes Research Laboratories)

Brian Guenther et al.: Highly curved image sensors: a practical approach for improved optical performance, June 2017, Optics Express



MICROSOFT / HRL DEVELOPMENTS (2)





Olaf Iwert
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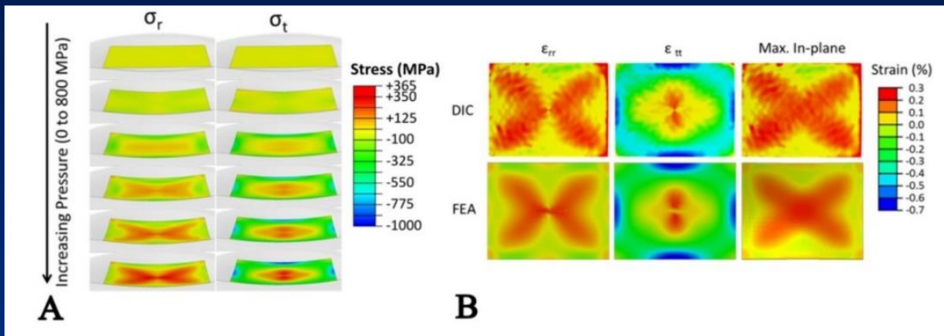
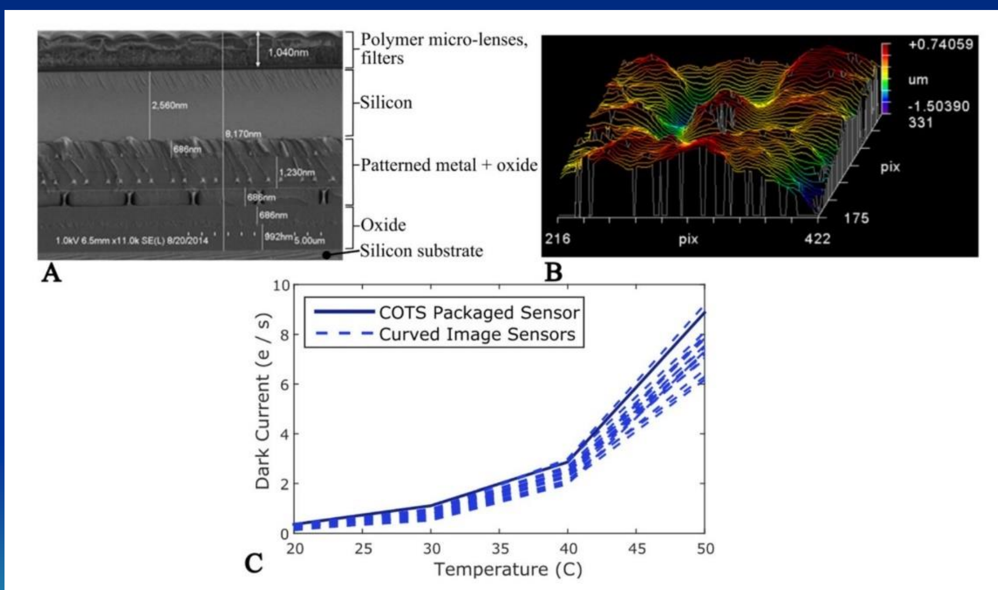
Expectations for future curved and flat CMOS
EIROFORUM June 2018

MICROSOFT / HRL DEVELOPMENTS (3)





CMOS back side illuminated 18 megapixel CMOS sensor (Aptina AR1820HS)

1.25 µm pixel; the light sensitive area 6.1 x 4.6 mm. thinned to 16 µm

General curvature radius between 24.6 and 16.7 mm,

18.74 mm radius for camera

dies bondig to mold surface using an epoxy adhesive / solder,

Deviations from the targeted radius of curvature of 0.3 µm RMS and 2.2µm peak to valley, measured interferometrically

MICROSOFT / HRL DEVELOPMENTS (4)

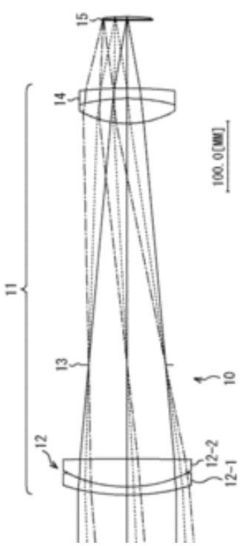
- Have done “their homework” to compare to literature and results, theoretically and practically
- High curvature and high accuracy
- New process wih movable die edges, such as to surpress tensile stress, rather foster compression
- Optical System performance measured in comparison with Canon 1Ds with 50mm / F 1.2 (FF) with small curved sensor and special optics: Vignetting and sharpness especially in corners are outperformed (!)
- Claim that proess is scaleable to any die size nd curvature at high curvature accuracy and mass production compliant.

SONY “ASTRO” DEVELOPMENTS (1)

【公開番号】特開2017-102189(P2017-102189A)
【公開日】平成29年6月8日(2017.6.8)
【発明の名称】撮像装置、および電子装置
【課題】民生用として最大級のサイズを有する撮像素子と、光学的により明るく、より簡素なレンズ構成の単焦点レンズとを備える撮像装置を提案する。
【解決手段】(前1文省略)。本開示は、例えば、天体観測用途の光学機器に適用できる。

【実施例1の主な仕様】
f(焦点距離) =387mm
F(開口数) =2.8
ω(半画角) =5.0deg
H(レンズ全長) =679mm

FIG. 1



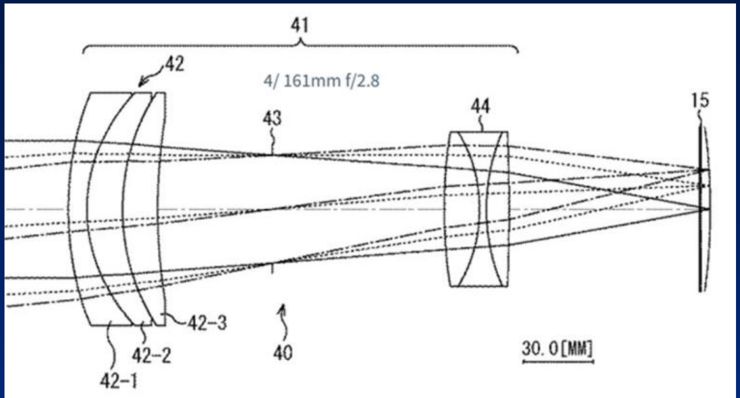
第1の実施の形態である撮像装置10の構成例を示す図

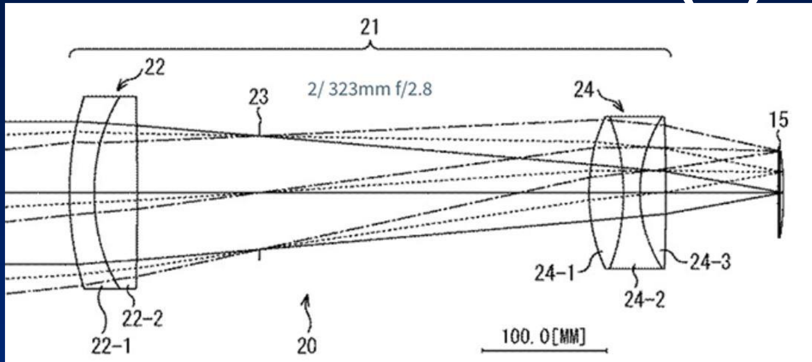
Japanese patent 2017-102189:

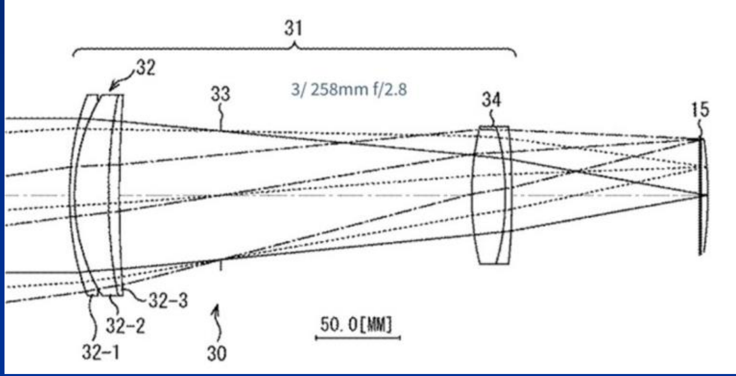
- **Sony 400mm f/2.8 lens and whole lens family designed for a curved medium format sensor for real 6 x 4.5 format.**
- **High MTF, highest resolution, simple lens design, for high resolution curved detector.**
- **The patent mentions industrial, astronomical and photography.**
- **Sony clearly thinks about the possibility to make a medium format mirrorless system camera with curved sensor.**

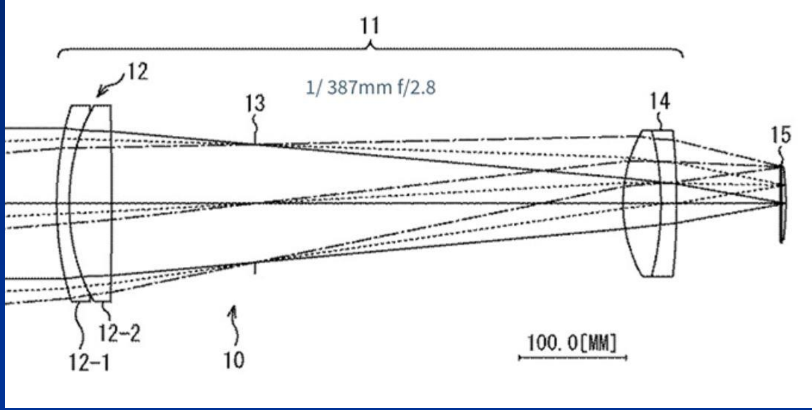
Olaf Iwert
European Southern Observatory (ESO)

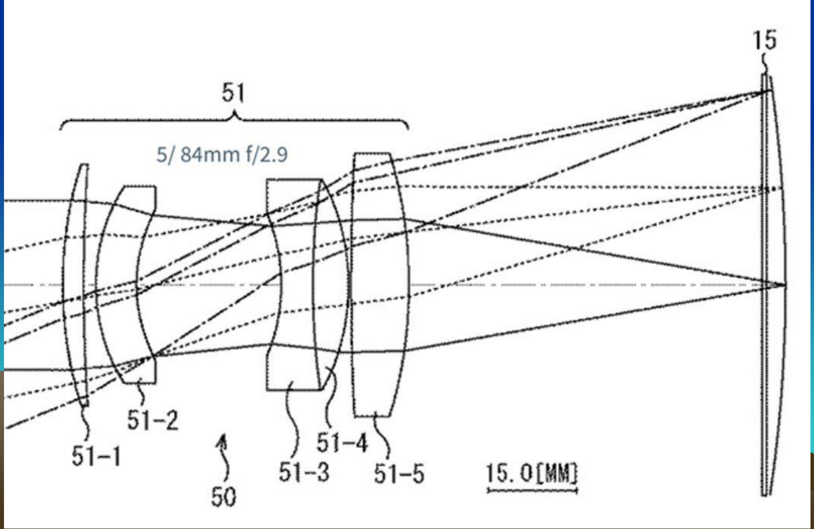
SONY "ASTRO" DEVELOPMENTS (2)



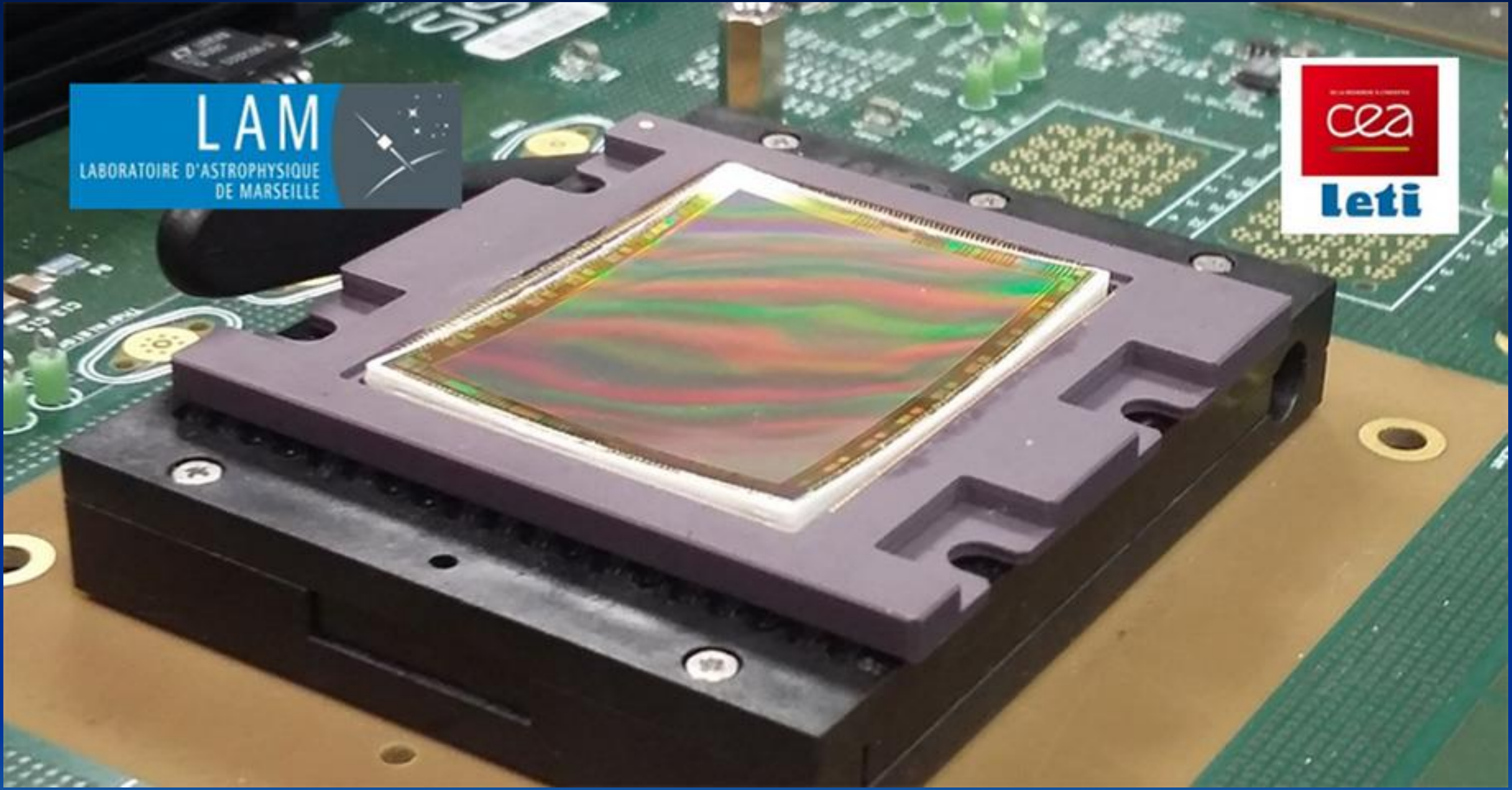








LAM / CEA / LETI DEVELOPMENTS



Emmanuel Hugot - extra talk

CONCLUSION / OUTLOOK

Please think out of the box for

SYSTEM Performance

Large size CMOS

and

Curved sensors are just around the corner – everywhere:

Commercial products / Scientific Use

Sooner or later…

Thank you for your attention !

Olaf Iwert
European Southern Observatory (ESO)

Interested in collaboration / synergies ?
Please let us know…..