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Optical Fabrication, Testing, and Metrology III

**Angela Duparré
Roland Geyl**
Editors

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Jacques Mangin, Université de Bourgogne (France)

Optical system design reliance on technology development

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WELCOME

**Firstly, thanks goes to SPIE,
the organizing committee, Chairs
and Co-Chairs of the Conference
for acceptance of this presentation**

INTRODUCTION

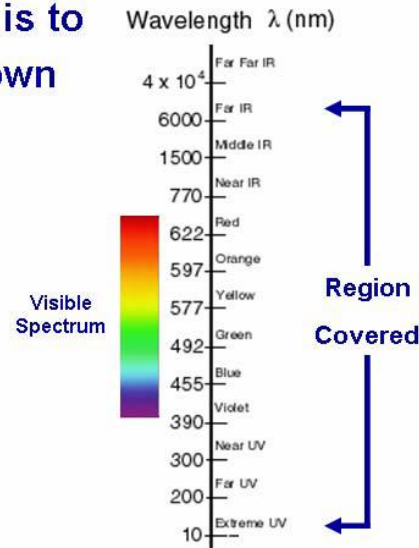
Before commencing with an outline of the presentation an explanation of the the definitions used throughout is given

DEFINITIONS

- ① Technology development is the progression over time of manufactured optical components:
 - Materials \approx optical substrates
 - Coatings \approx multi-layer thin films
 - Surfaces \approx optical surface profiles
- ② Optical design software is a tool to apply technology
- ③ Optical designer 'creates' the optics portion of the of the optical system design utilizing optical design software to apply technology
- ④ FOV is Field of View & NA is Numerical Aperture

DEFINITIONS (Cont'd)

- ⑤ Object is to the left and Image is to the right unless otherwise shown
- ⑥ Three wavebands discussed:
 - Infrared $\approx 0.7\text{-}1.5, 3\text{-}5$ & $8\text{-}13\mu\text{m}$
(700-1500, 3000-5000 & 8000-13000nm)
 - Visible $\approx 0.435\text{-}0.656\mu\text{m}$
(435-656nm)
 - Ultraviolet $\approx 0.434\text{-}0.013\mu\text{m}$
(434.4-13.4nm)



OUTLINE

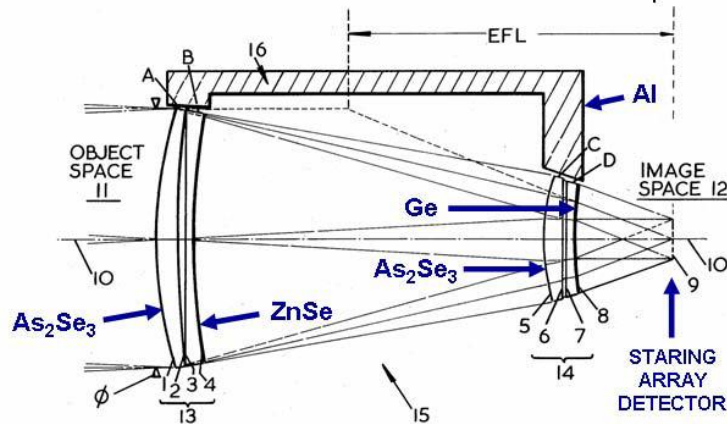
- By way of mainly the US Patent database, examples are given to illustrate the reliance of optical system design on key technology
- The examples are categorized by waveband of operation and partly chronologically
- Performance characteristics are not discussed but all examples may be considered high performance for their intended applications

WAVEBAND 1 INFRARED

EXAMPLE 1.1

PETZVAL OBJECTIVE – SECURITY

Passively Athermalized System
EFL=51mm F/1.5 FOV \varnothing =5° Waveband=8-13 μ m

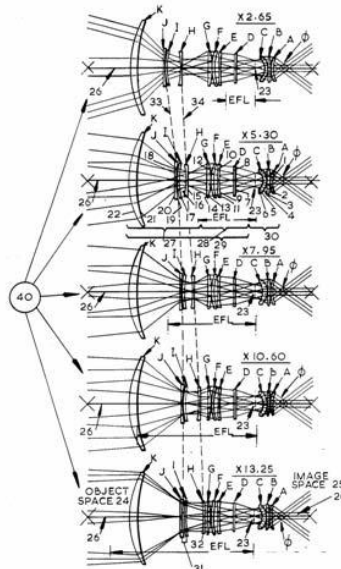


US Pat. No. 4,505,535 A1 I.A.Neil Mar. 19, 1985

KEY TECHNOLOGY	
✓	MATERIAL
	COATING
	SURFACE
BENEFITS	
SOLID STATE	
ROBUST	
ISSUES	
TOXIC MATERIAL	
MATERIAL QUALITY	

EXAMPLE 1.2a

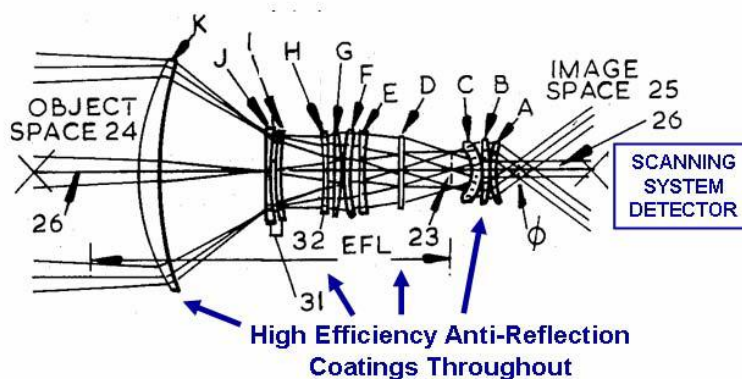
ZOOM TELESCOPE – SECURITY



EXAMPLE 1.2b

ZOOM TELESCOPE – SECURITY

Compact Mechanically Compensated Zoom System
Zoom Ratio=5x Exit Pupil \varnothing =10mm & FOV \varnothing =72° Waveband=8-13 μ m

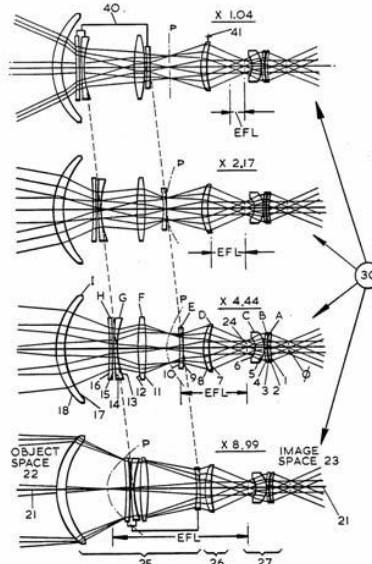


KEY TECHNOLOGY	
	MATERIAL
✓	COATING
	SURFACE
BENEFITS	
	COMPACT
ISSUES	
	NONE

US Pat. No. US4,659,171 A1 I.A.Neil Apr. 21, 1987

EXAMPLE 1.3a

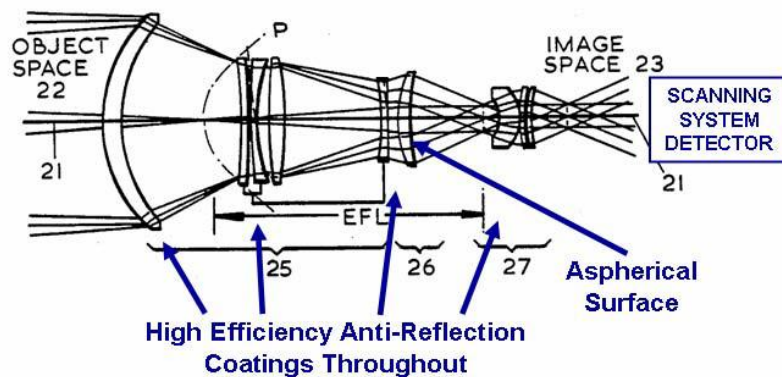
ZOOM TELESCOPE – SECURITY



EXAMPLE 1.3b

ZOOM TELESCOPE – SECURITY

Compact Optically Compensated Zoom System
Zoom Ratio=9x Exit Pupil \varnothing =14.4mm & FOV \varnothing =60° Waveband=8-13 μ m



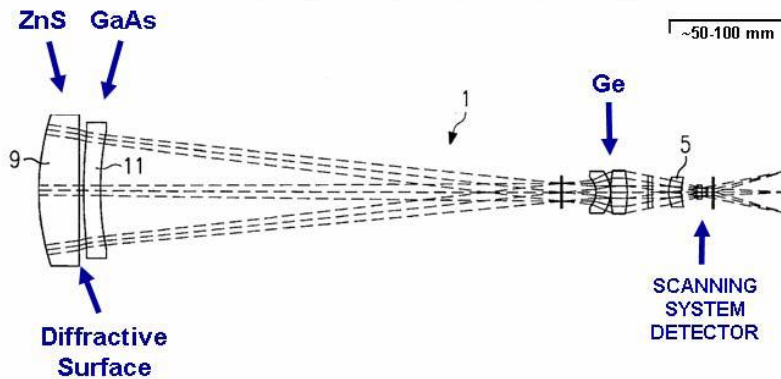
US Pat. No. 4,632,498 A1 I.A.Neil Dec. 30, 1986

KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
COMPACT	
SIMPLE MECHANICS	
ISSUES	
FOCUS DRIFT THROUGH ZOOM	
ASPHERE COST	

EXAMPLE 1.4

OBJECTIVE – SECURITY

Passively Athermalized & Color Corrected Air Spaced Doublet
with Diffractive Surface
Waveband=8-13 μ m (possibly 3-5 μ m depending on materials)

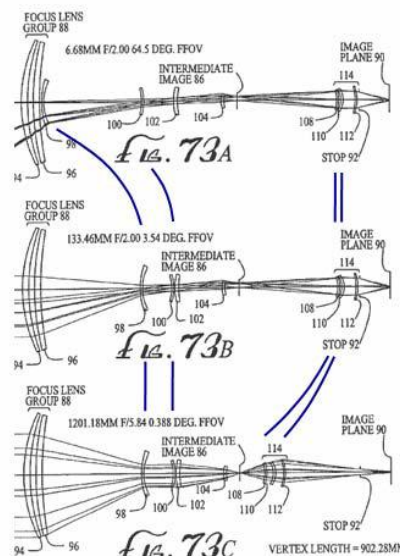


US Pat. No. 5,504,628 A1 J.F.Borchard Apr. 2, 1996

KEY TECHNOLOGY	
✓	MATERIAL
	COATING
✓	SURFACE
BENEFITS	
	SOLID STATE
	ROBUST
ISSUES	
	SECONDARY COLOR
	LONG LENGTH

EXAMPLE 1.5a

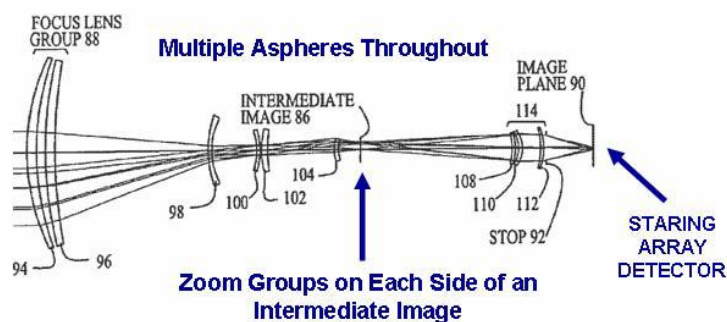
ZOOM OBJECTIVE – SECURITY



EXAMPLE 1.5b

ZOOM OBJECTIVE – SECURITY

Compound Zoom System
 Zoom Ratio=180x EFL=6.7-1201mm F/2-5.84 FOV \varnothing =64.5-0.4°
 Wavebands=3-5 μ m or 8-13 μ m



KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
HIGH ZOOM RATIO	
ISSUES	
COMPLEX MECHANICS	
IMAGE F/NO VARIES	
ASPHERE COST	

US Pat. No. 7,224,535 B2 I.A.Neil May 29, 2007

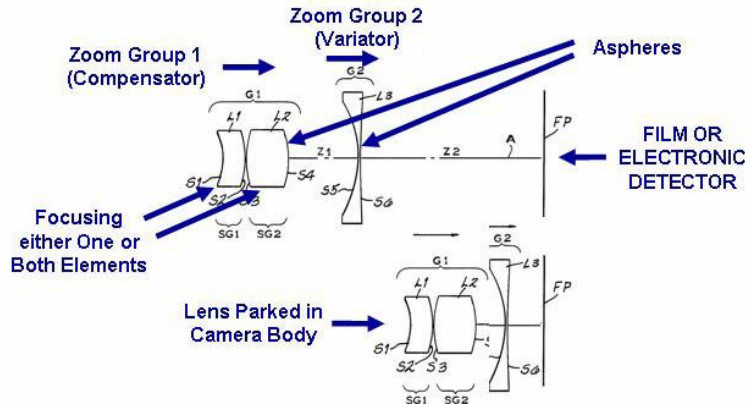
WAVEBAND 2

VISIBLE

EXAMPLE 2.1

COMPACT CAMERA ZOOM OBJECTIVE – PHOTOGRAPHIC CONSUMER

Zoom Objective System with 2x Zoom Ratio
EFL=35.7-68.5mm F/3.5-6.8 ImageØ=43.2mm Waveband=Visible



US Pat. No. 4,936,661 A1 E.I.Betensky, M.H.Kreitzer & J.Moskovich Jun. 26, 1990

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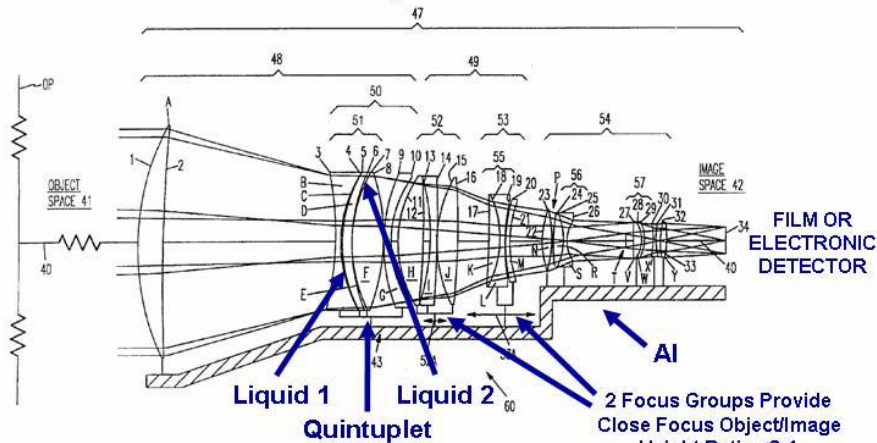
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KEY TECHNOLOGY	
	MATERIAL
	COATING
✓	SURFACE
BENEFITS	
	SIMPLE
	COMPACT
	LOW COST
ISSUES	
	MOLDED ASPHERES

EXAMPLE 2.2a

TELEPHOTO OBJECTIVE – PHOTOGRAPHIC CINE

Passively Athermalized & Color Corrected System with Liquid Elements
EFL=693mm F/2.75 ImageØ=28.9mm Waveband=435-656nm



US Pat. No. 5,638,215 A1 I.A.Neil Jun. 10, 1997

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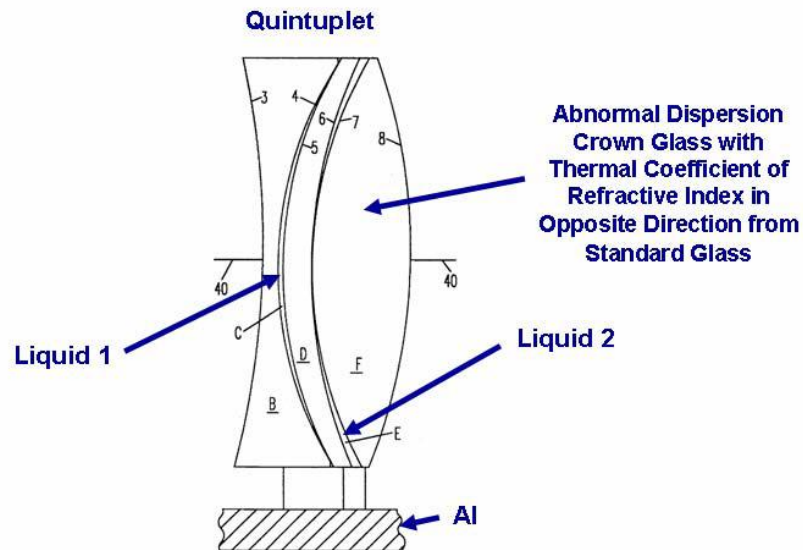
Glasgow, Scotland, United Kingdom – 2nd September 2008

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KEY TECHNOLOGY	
✓	MATERIAL
✓	COATING
	SURFACE
BENEFITS	
	LOW COST GLASSES
	COMPACT
ISSUES	
	LIQUID DISCOLORATION
	LOW TEMPERATURE

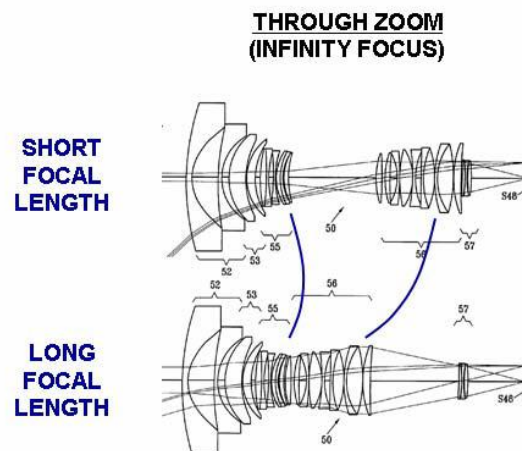
EXAMPLE 2.2b

TELEPHOTO OBJECTIVE – PHOTOGRAPHIC CINE

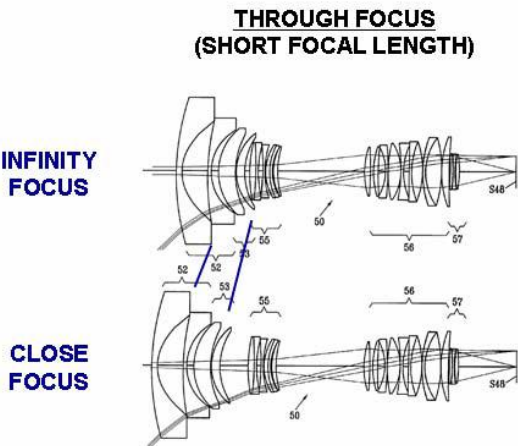


EXAMPLE 2.3a

MACRO FOCUS ZOOM OBJECTIVE – PHOTOGRAPHIC CINE



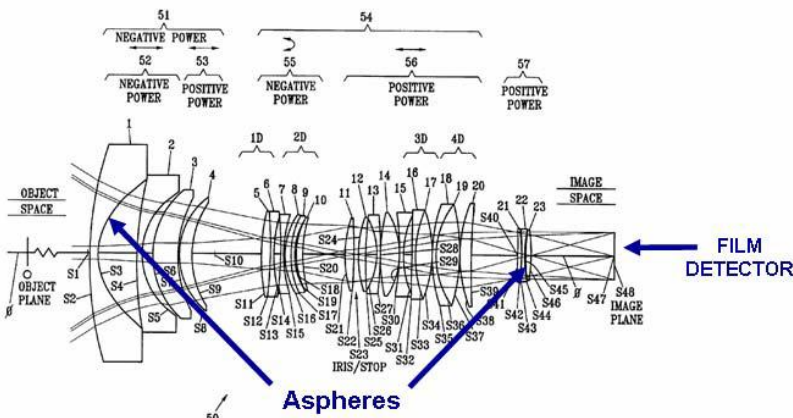
EXAMPLE 2.3b
MACRO FOCUS ZOOM OBJECTIVE
– PHOTOGRAPHIC CINE



Close Focus Object/Image Height Ratio = 2.5:1 (At Long Focal Length)

EXAMPLE 2.3c
ZOOM OBJECTIVE – PHOTOGRAPHIC CINE

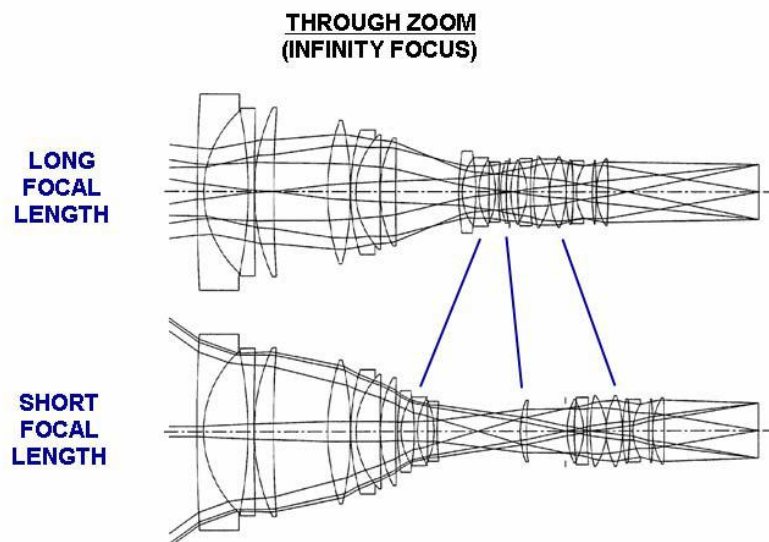
Macro Focus Zoom System with 3.5x Zoom Ratio
EFL=14.5-50mm F/2.2 ImageØ=28.9mm Waveband=455-644nm



KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
VERSATILE	
FIXED FOCAL LENGTH OPTION	
ISSUES	
COMPLEX MECHANICS	
ASPHERE COST	

EXAMPLE 2.4a

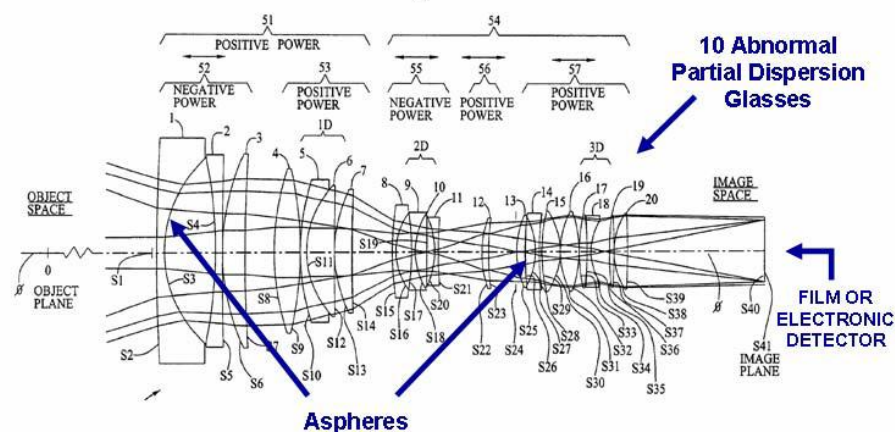
ZOOM OBJECTIVE – PHOTOGRAPHIC CINE



EXAMPLE 2.4b

ZOOM OBJECTIVE – PHOTOGRAPHIC CINE

Compact Zoom Objective System with 4.7x Zoom Ratio
EFL=19-90mm F/2.7 ImageØ=27.8mm Waveband=455-644nm



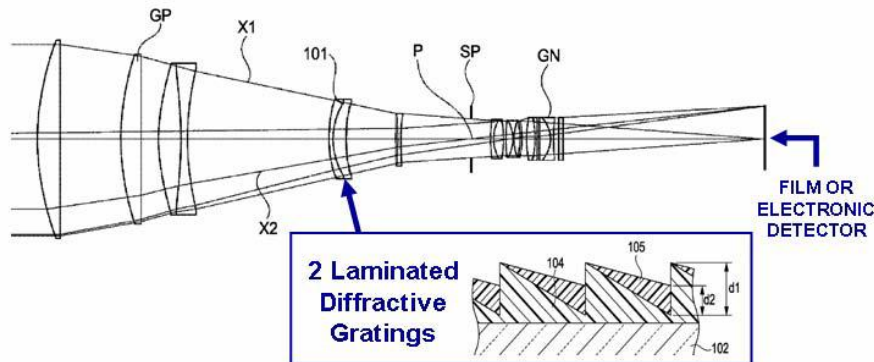
US Pat. No. 7,123,421 B1 J.Moskovich, I.A.Neil & T.Yamanashi Oct. 17, 2006

KEY TECHNOLOGY	
✓	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
COMPACT	
VERSATILE	
FIXED FOCAL LENGTH OPTION	
ISSUES	
COMPLEX MECHANICS	
ASPHERE COST	

EXAMPLE 2.5

OBJECTIVE – PHOTOGRAPHIC PROSUMER

Telephoto System with Diffractive Surface
EFL=780mm F/5.8 ImageØ=43.2mm Waveband=435-656nm



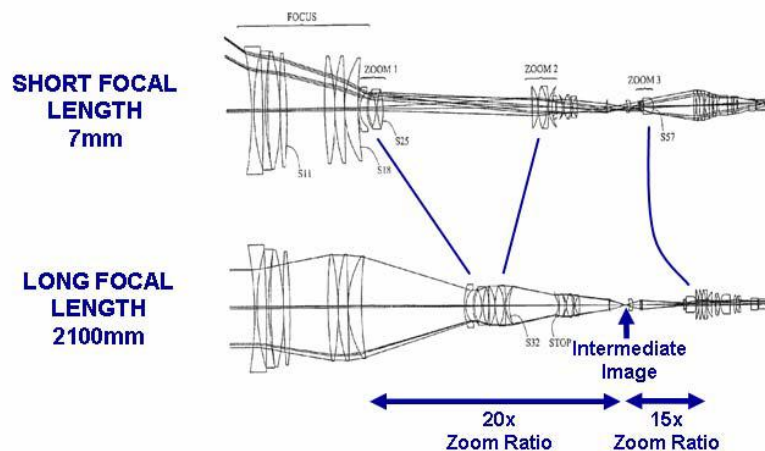
KEY TECHNOLOGY	
✓	MATERIAL
	COATING
✓	SURFACE
BENEFITS	
	COMPACT
	COLOR CORRECTED
	REDUCED NO. OF EXOTIC GLASSES
ISSUES	
	FLARE

US Pat. Pub. No. 2008/0088950 A1 H.Endo Apr. 17, 2008

EXAMPLE 2.6a

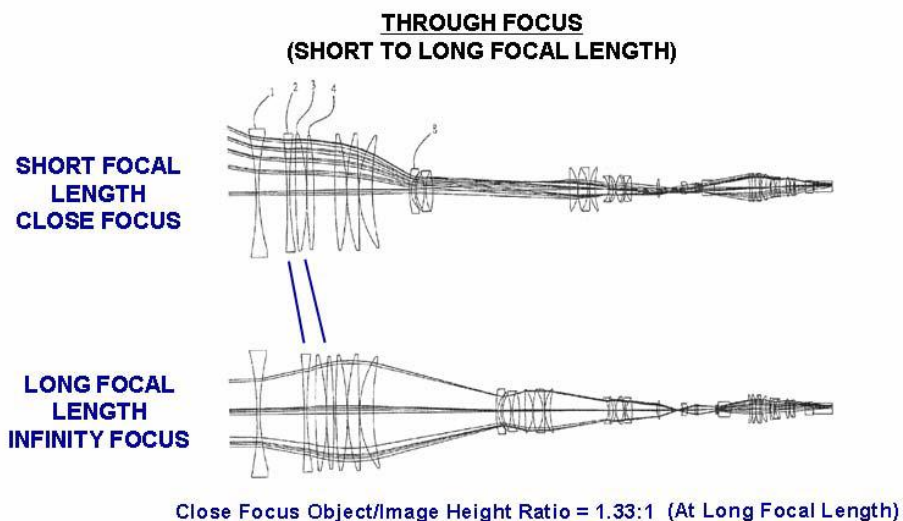
ZOOM OBJECTIVE – PHOTOGRAPHIC HDTV

**THROUGH ZOOM
(INFINITY FOCUS)**



EXAMPLE 2.6b

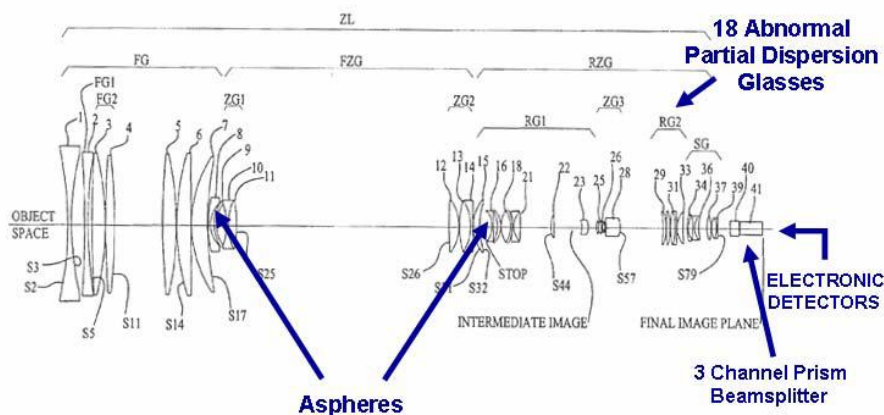
ZOOM OBJECTIVE – PHOTOGRAPHIC HDTV



EXAMPLE 2.6c

ZOOM OBJECTIVE – PHOTOGRAPHIC HDTV

Compound Zoom System with 300x Zoom Ratio
EFL=7-2100mm F/2-13 ImageØ=11mm Waveband=Visible



US Pat. No. 6,691,188 B2 E.I.Betensky, J.B.Caldwell, I.A.Neil & T.Yamanashi Nov. 1, 2005

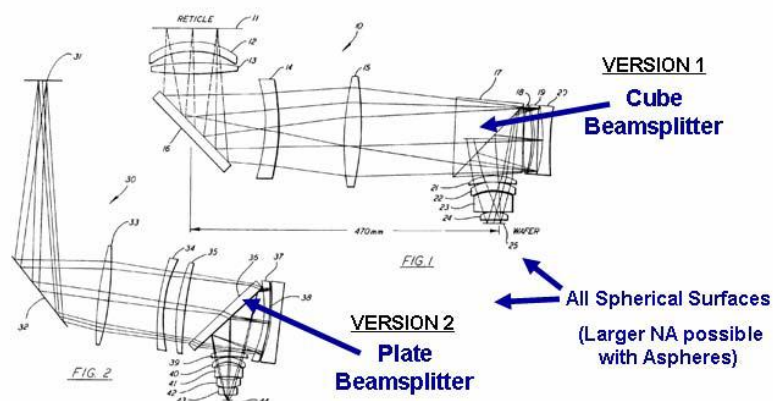
WAVEBAND 3 ULTRAVIOLET

30

EXAMPLE 3.2

PROJECTION RELAY LENS – MICROLITHOGRAPHIC

Refractive/Reflective Projection System
RELAY=4:1 NA=0.45 ImageØ=30mm Wavelengths=240-256nm



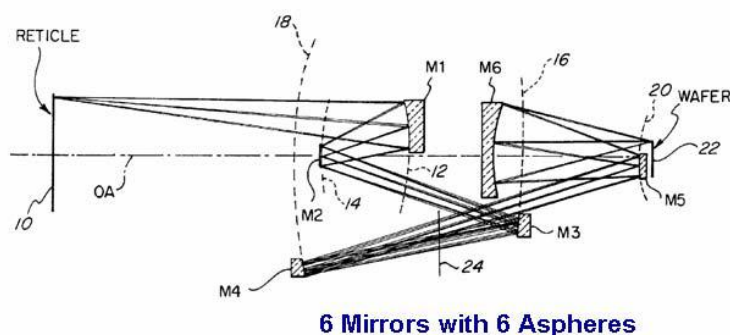
KEY TECHNOLOGY	
✓	MATERIAL
✓	COATING
	SURFACE
BENEFITS	
RESOLUTION	
ISSUES	
ALIGNMENT	

US Pat. No. 4,953,960 A1 D.M.Williamson Sep. 4, 1990

EXAMPLE 3.3

PROJECTION RELAY OPTICS – MICROLITHOGRAPHIC

All Reflective Projection System
RELAY=4:1 NA=0.25 ImageØ=31mm Wavelengths=13.4nm & <200nm



KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
HIGH RESOLUTION	
ISSUES	
@13.4nm <10% TRANSMISSION WITH COATINGS	
ASPHERE COST	
ALIGNMENT	

US Pat. No. 5,815,310 A1 D.M.Williamson Sep. 29, 1998

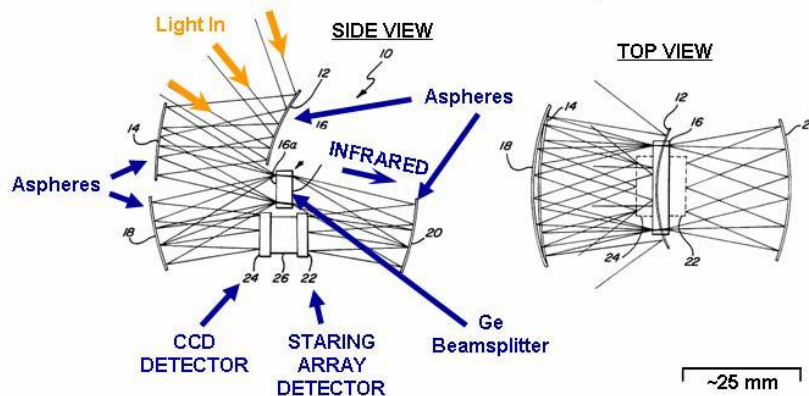
WAVEBAND 4 MULTIPLE

EXAMPLE 4.1 OBJECTIVE – SECURITY

Dual Waveband System

F/4.5(elev), F/1.5(azim) & F/2.3(average) FOV \varnothing =40°(elev.) & 53°(azim.)

Wavebands=Visible & 8-13 μ m



KEY TECHNOLOGY	
	MATERIAL
✓	COATING
✓	SURFACE
BENEFITS	
COMPACT	
SOLID STATE	
ROBUST	
ISSUES	
ASPHERE COST	

US Pat. No. 5,847,879 A1 L.G.Cook Dec. 8, 1998

EXAMPLE 4.2a

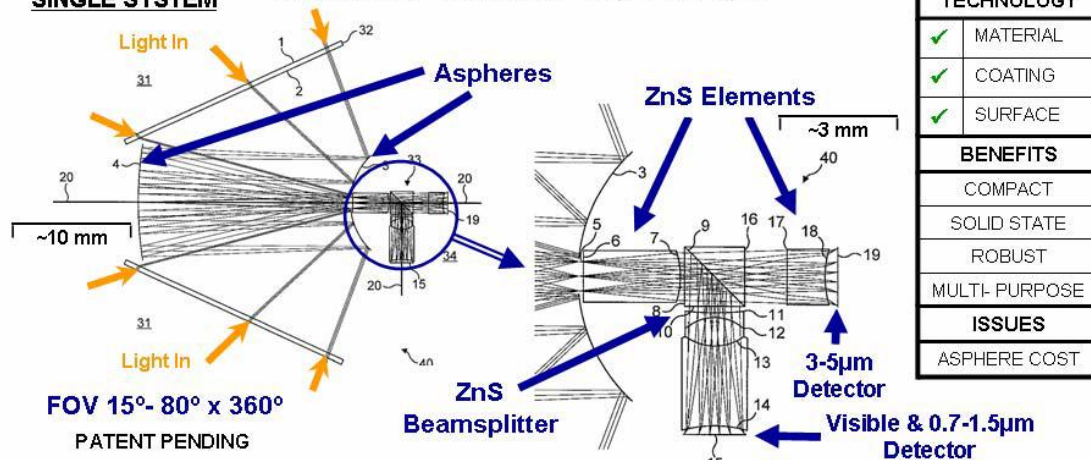
OBJECTIVE – SURVEILLANCE

Compact Multi-waveband Wide Angle Objective

FOV 15°- 80° x 360°

Wavebands=Visible, 0.7-1.5µm & 3-5µm

SINGLE SYSTEM



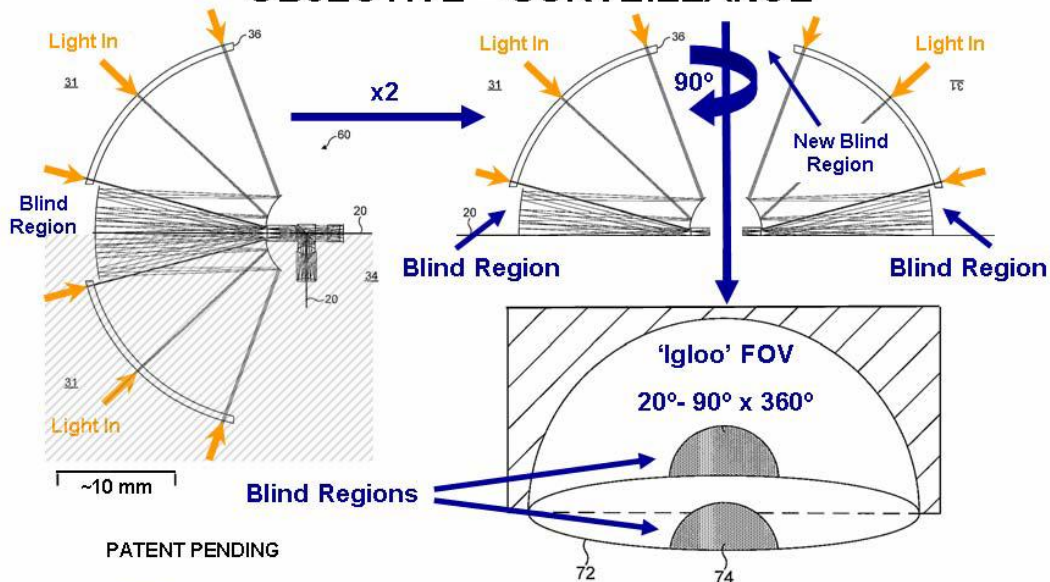
SPIE Europe
Optical Systems Design

Glasgow, Scotland, United Kingdom – 2nd September 2008

35

EXAMPLE 4.2b

OBJECTIVE – SURVEILLANCE



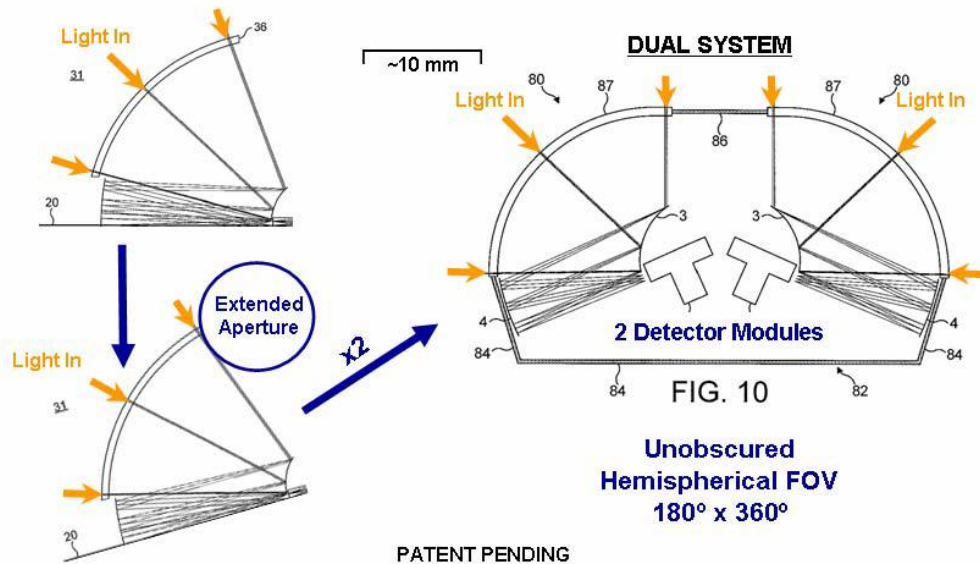
SPIE Europe
Optical Systems Design

Glasgow, Scotland, United Kingdom – 2nd September 2008

36

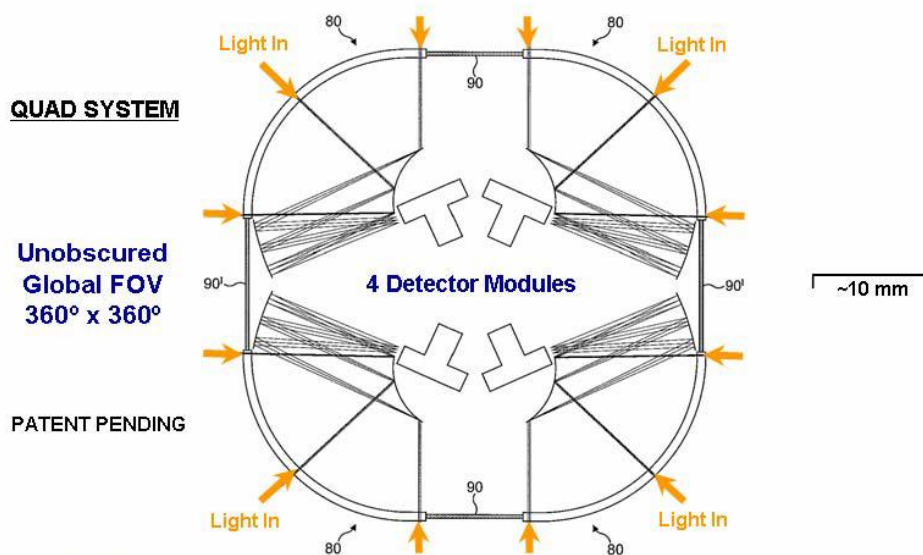
EXAMPLE 4.2c

OBJECTIVE – SURVEILLANCE



EXAMPLE 4.2d

OBJECTIVE – SURVEILLANCE



KEY TECHNOLOGY SUMMARY

	WAVE BAND															
	INFRARED					VISIBLE						ULTRAVIOLET			MULTI	
EXAMPLE	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	4.1	4.2
CIRCA	80's	80's	80's	90's	00's	90's	90's	00's	00's	00's	00's	90's	90's	90's	90's	00's
MATERIAL	✓			✓			✓		✓	✓	✓		✓			✓
COATING		✓	✓		✓		✓	✓	✓		✓	✓	✓	✓	✓	✓
SURFACE			✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓

CONCLUSION

- Usually technology provides 'improvements' but occasionally it is 'disruptive' in that it dramatically changes the optical system design such as enabling a new form of design
- In the specific case of disruptive technology this usually appears to happen separately in either materials, coatings or surfaces
- No apparent trend in technology development except:

"Necessity is the mother of invention"

Plato c. 400 BC

ACKNOWLEDGEMENTS

**Thanks goes to the following individuals
for contributions to this presentation**

David W. Samuelson

David M. Williamson

Andy Wood





A Perspective on the Design of Head-Worn Displays

Jannick Rolland with

Ozan Cakmakci, Florian Fournier, and Sophie Vo

CREOL, The College of Optics and Photonics
the University of Central Florida

<http://odalab.ucf.edu>
jannick@odalab.ucf.edu



Highlights

Introduction

Applications

Prior Work

Early work at ODALab

Current Technologies under Development

Head-mounted Projection Displays (HMPD)

Eyeglass Head-Worn Displays (HWD)

Why Head-Worn Displays?

Assuming HWDs can be designed aesthetically (which is not a given) to meet with social acceptance:

- **Mobility**

- **Privacy**



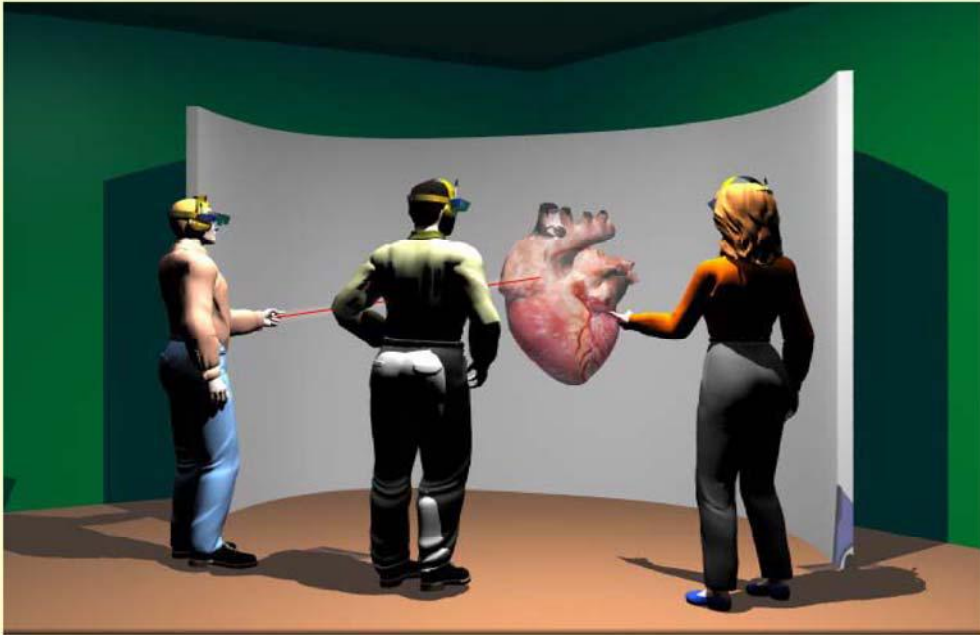
- **Constancy:** Provides the basis for novel user interfaces that are available constantly (on a demand basis) to the user

Science Fiction Sets Expectations of Where we Aim to Be Going!



* Goldman, A. (1998). Lost in Space. New Line Cinema

Medical Rooms of the Future



Telemedicine: Face to Face Teleportal



Fig 1. Vision of "see-thru-my-eyes" capability. (1) Doctor in local control room guides (2) remote treatment via stereoscopic see-thru headset worn by emergency technician.



Fig.2. Vision of mobile "Face-to-Face" interaction (1) remote team member wearing 3D face recording system talk in to (2) team leader in control center.

Courtesy of Frank Biocca, MSU



Wearable Displays: **A Range of Possibilities**

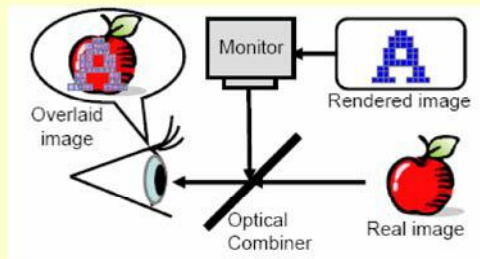
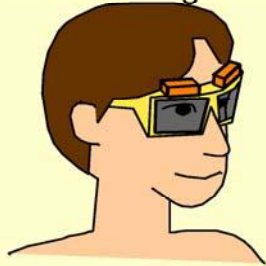
Their future lies in large part in their “seamless” integration with tangible interfaces around us

**Augmented Reality
/ Mixed Reality
Vs. Virtual Reality (full immersion)**

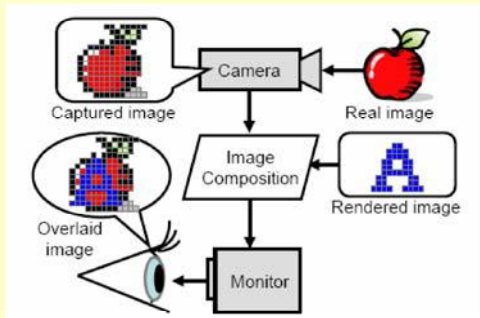
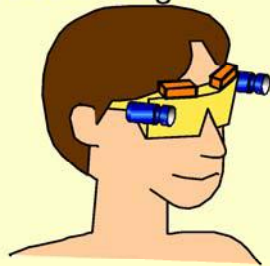


Augmented/Mixed Reality

Optical See-through

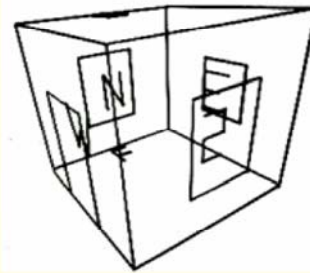


Video See-through



Historical Notes

First graphics-driven HWD was developed by Ivan Sutherland in the 1960s.



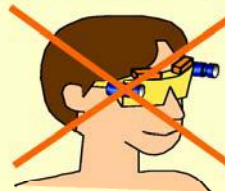
Augmented Reality Displays

Early (first?) stereoscopic VST-HMD

- HMD-mounted stereo cameras with custom-designed lenses compensate for display distortion (Biocca & Rolland, Presence 1998)



Some applications call for
optical see-through
capability



Highlights from Past Development

- U.S. Army first to fly a helmet-mounted sighting system on the Cobra helicopter.
- IHADSS (Integrated Helmet and Display Sighting System) was then deployed by the U.S. Army for the AH-64 Apache Helicopter.

IHADSS, while monocular, greatly contributed to the proliferation of all types of HMDs.

The success of HWD design is most likely to occur when developed

- In the context of the users and
- Targeted at specific applications

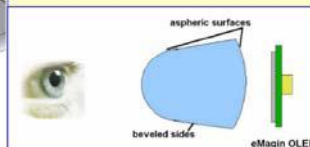
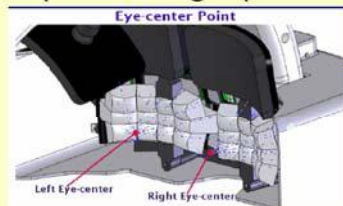
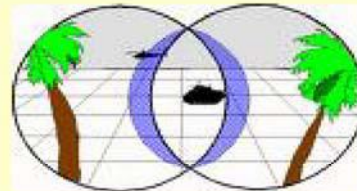
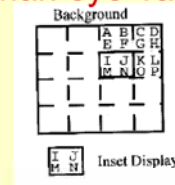
A Main Design Trade-off

FOV vs. Resolution - Currently limited by microdisplays

Angle subtended by a pixel = $\frac{FOV}{\# \text{ of pixels}}$ **Human eye 1 arcmin**

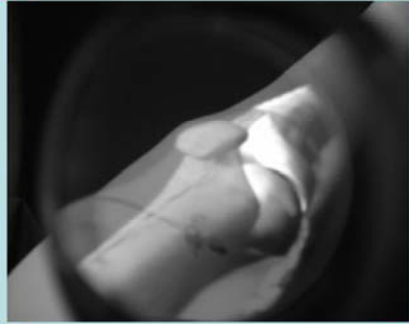
Approaches:

- 1) High-resolution area of interest or inset
- 2) Partial binocular overlap ("Luning")
- 3) Optical tiling (Kaiser, Sensics)



Recent developments by Sensics.

Driven by Medical Visualization: VRDA Tool “Virtual Reality Dynamic Anatomy”

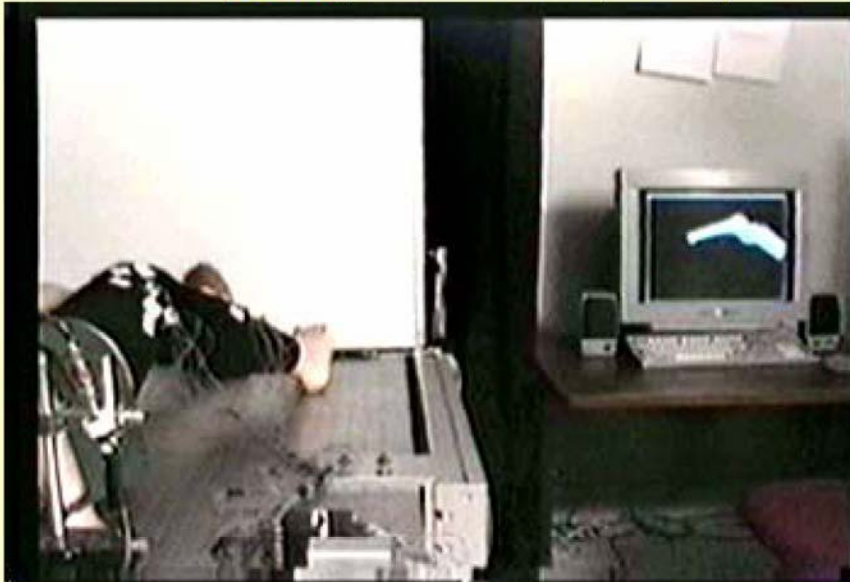


NIH - First Award 1997-2002

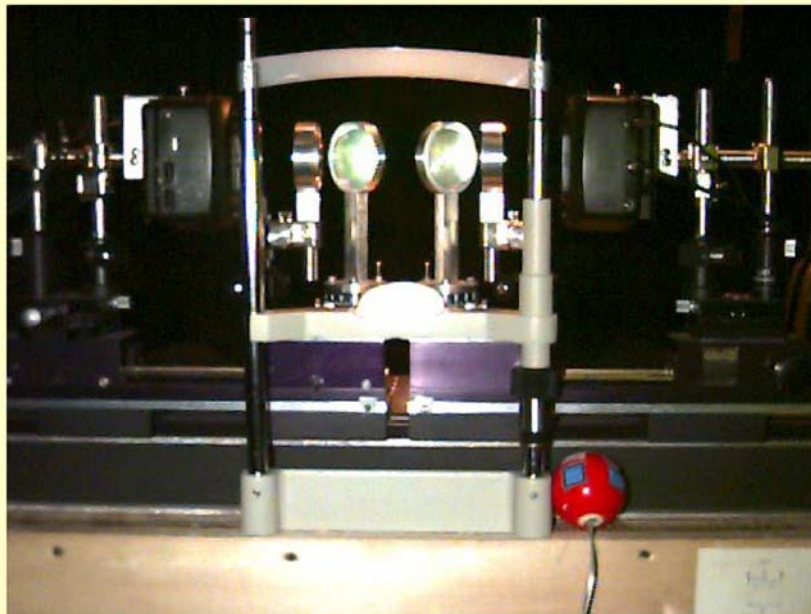
Methods Optics, Computer Vision, and Graphics



Development of a Kinematic Model of Joint Motion ([Baillot](#), Rolland et al., 2000)



Early Feasibility Experiments



First results in dynamic optical superimposition on an optical bench system

Featured in *Scientific American*, April 2002

Baillet et al., *Presence* 2000; Argotti et al., *Computers & Graphics* 2002



Visualization (Head-Worn Displays)

Cakmakci Ozan, and Jannick Rolland, Head-worn displays, *IEEE/OSA Journal of Display Technology*, 2(3) (September 2006).

C. Fidopiastis, L. Davis, J. Covelli, L. Nguyen, R. Martins, O. Cakmakci



Students: F. Hamza-Lup, A. Santhanam

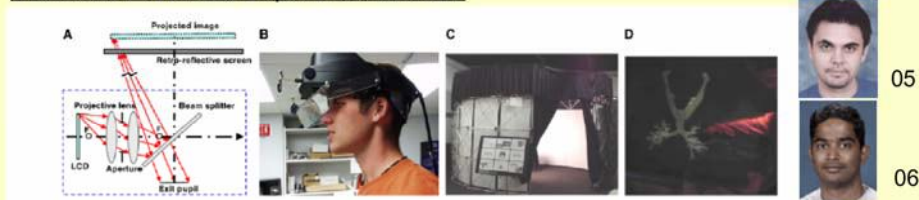




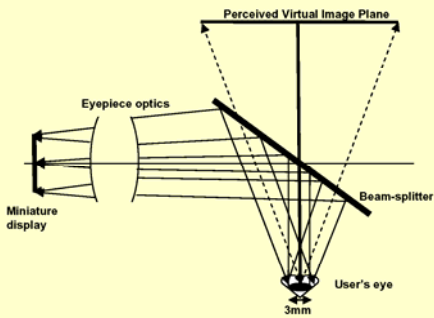
Fig. 5 HMPD in use in a deployable Augmented Reality Center (ARC): (A) Schematic of the HMPD optics; (B) user wearing a HMPD; (C) the ARC; and (D) user interacting with 3D models in the ARC. (View this art in color at www.dekker.com.)



Eyepiece versus Projection HMDs

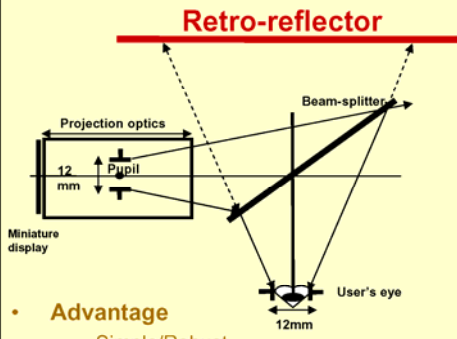


Eyepiece Optics (HWD)



- Advantage**
 - Simple/Robust
 - Color
- Challenge**
 - Optical weight scales with FOV
 - Distortion (electronic comp)
 - Illumination limited (miniature display)

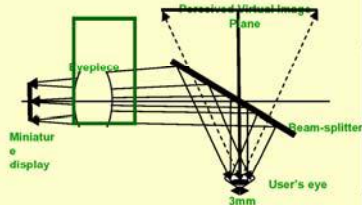
Head Mounted Projection Display



- Advantage**
 - Simple/Robust
 - Color
 - Optics size does not scale with FOV
 - Lightweight
 - Distortion free
 - Lower aberrations than eyepiece design
- Challenge**
 - Illumination limited by microdisplays
 - Screen type and location

Review of “Large FOV” Eyepiece Optics Design

Rolland and Hua, 2005
Encyclopedia of Optical
Engineering (Marcel Dekker)

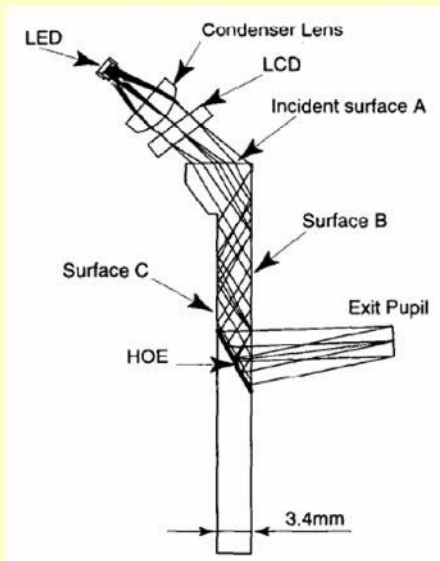


Picture	Specification	Lens Form	Specification
	FOV 70 EFL 100 H. Erfle 1478704		FOV 70 EFL 100 Michael D. Missig 5446588
	FOV 33 EFL 34 J. D. Robinson C. M. Schor P. H. Muller W. A. Yankee eyepiece 5696521		B. S. Fritz HMD using Mangin Mirror combiner 5638490
	FOV 40-60 EFL 100 Takayoshi Togino Eyepiece with DOE 6181475 5959780		FOV 40 15.2x12.3 MicroDisplay F#1.7 J. G. Droessler Honeywell Inc. Morristown, NJ 6147807
	FOV 50x60 J. G. Droessler D. J. Rotier Tilted Cat Ocular 1989		FOV 120 C. Anier Jean-Blaise Migozzi Holographic Binocular Helmet Visor 5124821
	FOV 50-60 color Helmet visor display B. Chen Off-axis Design 5526183		FOV 60 color 1.3" diagonal CRT J. P. Rolland Off-axis Design 100C94, OE 2000

Direct View

See-through

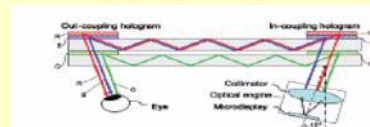
Related Work



Kasai. Int. Symp. Wearable Computers '00.



Resolution ~2 arcmins
FOV ~30 degrees
10 mm pupil [Lumus]



H. Mukawa et al. In Proc.
Society of Information
Display, 2008.

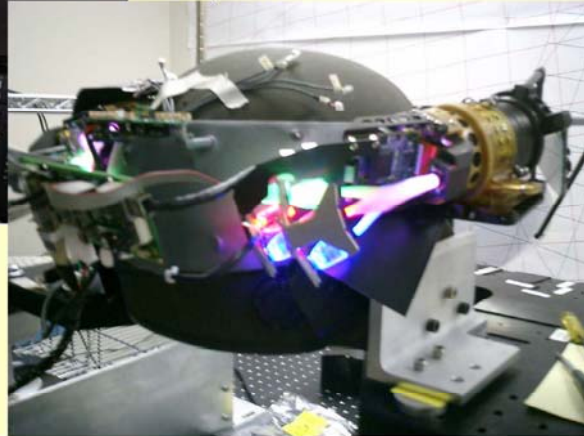
SONY

AHMD (Advanced HMD) Ultrawide FOV, off-axis design



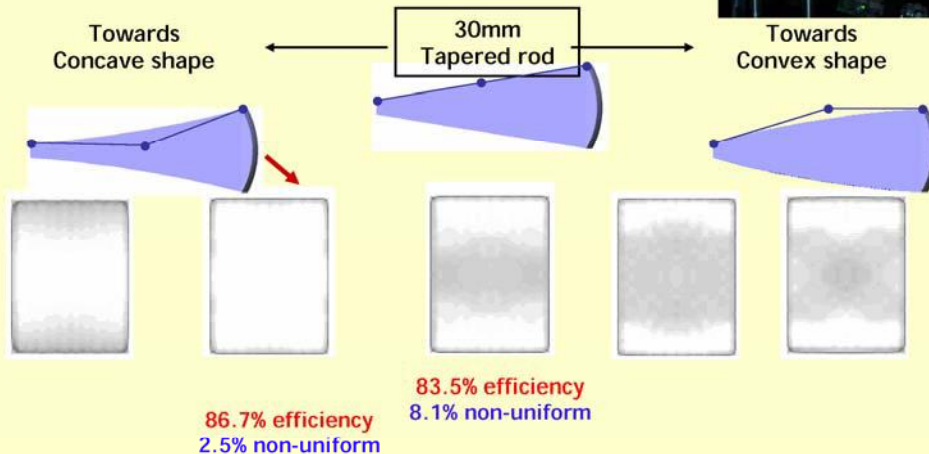
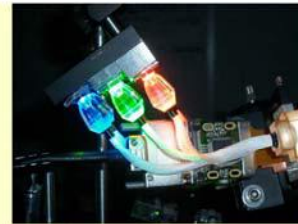
Courtesy of LINK/ZYGO and
Optical Research Associates
Early 2000

AHMD Specifications	
Helmet compatibility	HGU-56P, HGU-55P all sizes
Center of gravity	Balanced
Eye relief	> 50 mm
Exit pupil	15 mm
Transmissivity	> 60%
Field-of-view	100° H x 50° V
Binocular overlap	30°
Resolution	1280 x 1024 per eye



Spatial Uniformity Behavior with Freeform Bezier Shapes

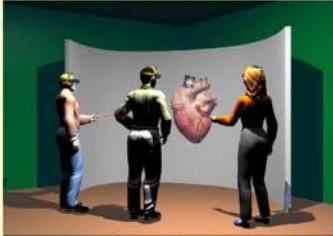
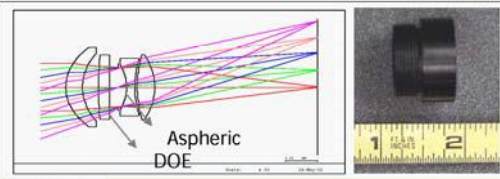
Fournier et al., Appl. Opt. 47 (2008) & OL 33(11) (2008)



Changing the concavity of the shape can improve uniformity
without sacrificing efficiency

Deployable Technology 1st Generation HMPD

with VGA LCD microdisplays
Hua, Ha, and Rolland, Appl. Opt. 42 2003



Fisher, 96 Patent

Miniaturization of
the Optics

Deployable Rooms



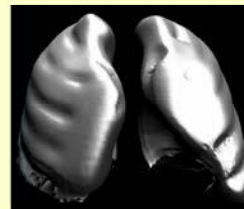
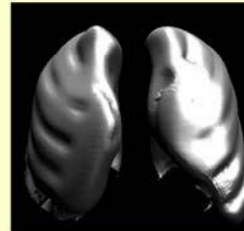
3D Visualization of the Upper Airway for Training Medics in Emergency Intubation Procedures

Augmented Reality Visualization

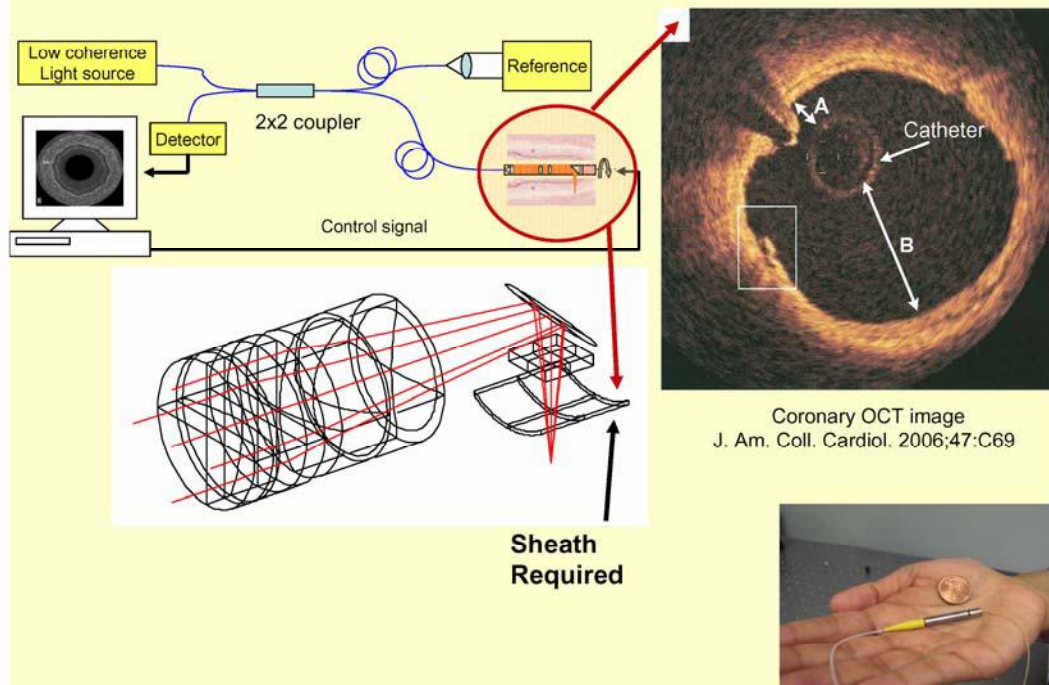


Lung Dynamics

Anand Santhanam, PhD 06



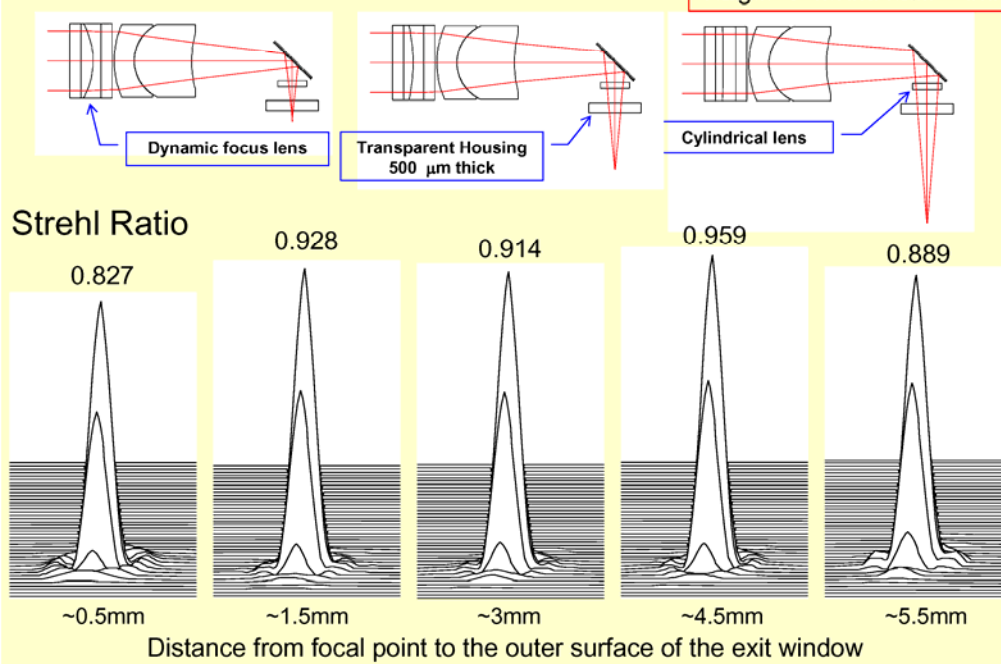
Imaging: Extended Depth of Focus Needed in Catheters



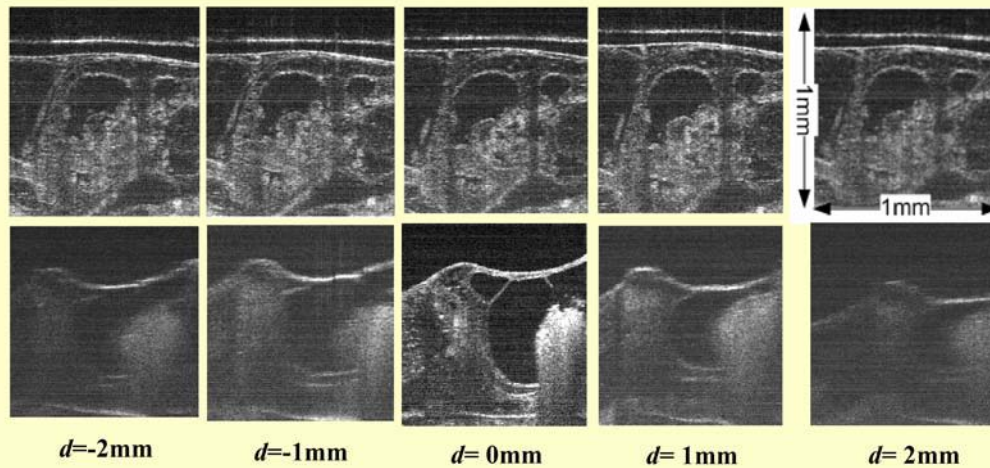
PSF through Working Range

Meemon et al., AO 2008

Target → Strehl ratio > 0.8



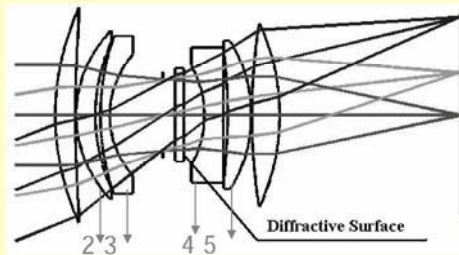
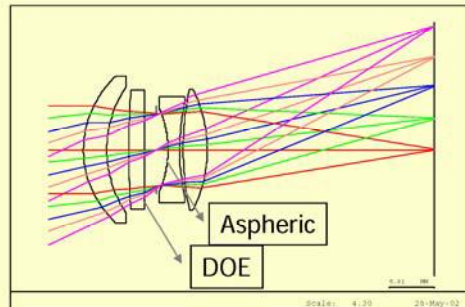
Bessel Beam vs. Conventional



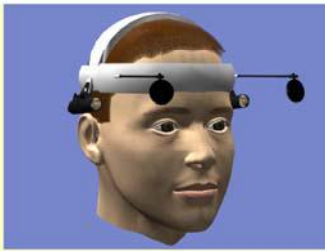
First Images of biological tissue acquired with a microlens axicon in a double pass OCT : Images of African frog (*Xenopus Laevis*) tadpole located at relative axial distances d from each medial position of its depth of focus.

K. Lee and J. Rolland Optics Letters 33 (2008)

52 deg. Lens / 8g per eye



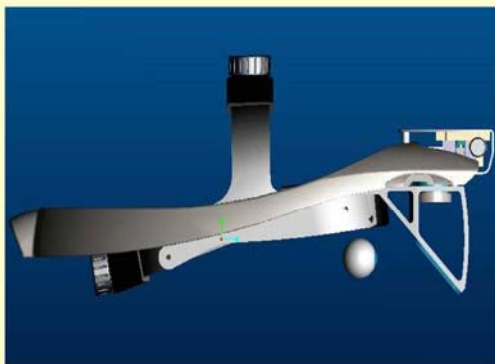
Teleportal Display UCF/MSU



Reddy et al., CVPR'04

42° FOV HMPD

Lightweight 595 grams - 2nd Generation HMPD using 800x600 OLED

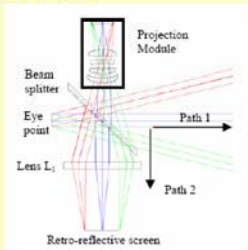


Optical Design done in the ODALab and
HMPD Optomechanical design done by Nvis Corporation
under SBIR program 2004-2005 with the US ARMY

M-HMPD - Fabric-free, Mobile

Martins, Optics Express 15(22), 2007

See-through, Outdoor
42° FOV



A recent experiment with the MD
Anderson Cancer Center Orlando
to appear in JDT, Dec08



Comparison of the ARC system with the 2D display system

To appear in Special Issue of JDT, Dec 08

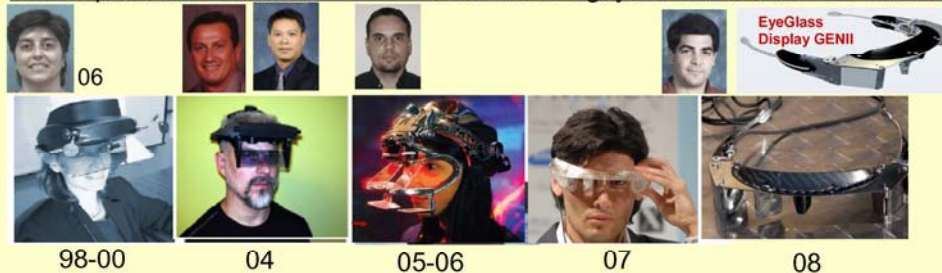
Subject	Average time (sec) Experiment 1		Average time (sec) Experiment 2		Average time (sec) Experiment 3	
	ARC	2D monitor	ARC	2D monitor	ARC	2D monitor
Expert 1	0	2.55	0.75	11.05	1.05	13.05
Expert 2	0	0.95	1.05	8.95	0.95	11.0
Expert 3	0.45	4.05	0.95	12.05	1.55	15.05
Expert 4	0	3.95	0.55	14.95	1.05	14.05
Expert 5	0.55	2.55	1.45	8.0	0.9	16.0
Expert 6	0	3.45	1.40	9.0	1.55	13.0
Average	0.2	2.9	1.0	10.7	1.2	13.7

The individual dose beams are delivered to a patient in 30-40 seconds, Thus, a 10 second delay in decision making is highly significant

Visualization (Head-Worn Displays)

Cakmakci Ozan, and Jannick Rolland, Head-worn displays, IEEE/OSA *Journal of Display Technology*, 2(3) (September 2006).

C. Fidopiastis, L. Davis, J. Covelli, L. Nguyen, R. Martins, O. Cakmakci

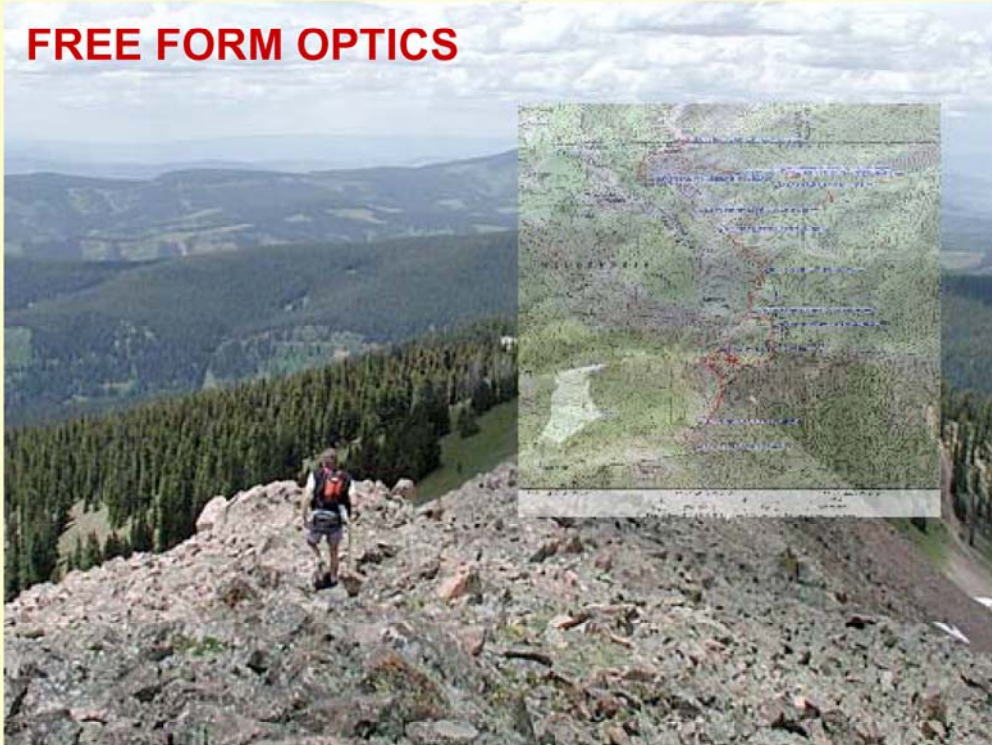


Students: F. Hamza-Lup, A. Santhanam



Fig. 5 HMPD in use in a deployable Augmented Reality Center (ARC): (A) Schematic of the HMPD optics; (B) user wearing a HMPD; (C) the ARC; and (D) user interacting with 3D models in the ARC. (View this art in color at www.dekker.com.)

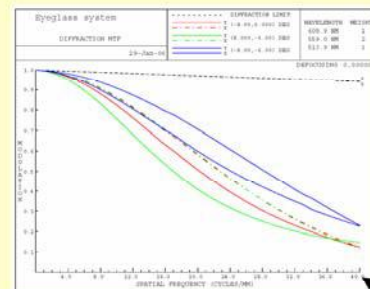
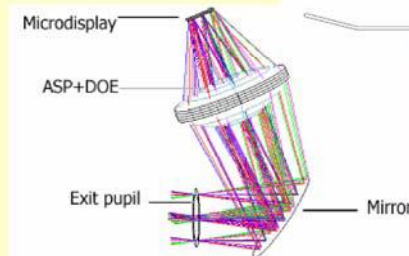
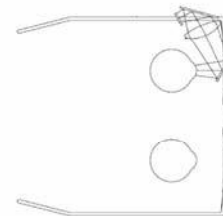
FREE FORM OPTICS



Eyeglass Display

Ozan Cakmakci, Kidger Scholarship 05

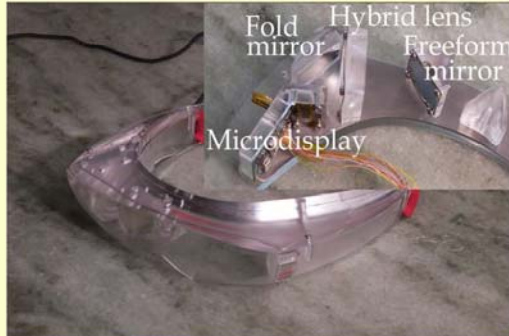
Cakmakci & Rolland, *Journal of Display Technology*, (2006).



Dual-element Solution



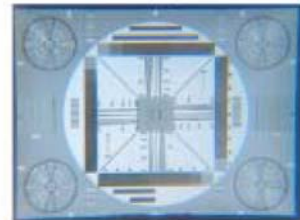
Cakmakci & Rolland, OL 32(11), 2007



Field of view: up to 25 FOV diagonal
 Resolution: ~1.5 arcminutes
 Exit pupil size: up to 12mm
 Eye clearance: >15 mm
 Distortion: <4%
 Wavelengths: 450-650nm



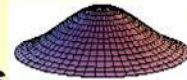
(a)



(b)

Fig. 2. (Color online) Photograph through the fabricated dual-element system of (a) a color target and (b) a black and white target.

We Propose to Design Freeform Optical Surfaces whose Representations use **Local Basis Functions** (as Opposed to Global Polynomials)

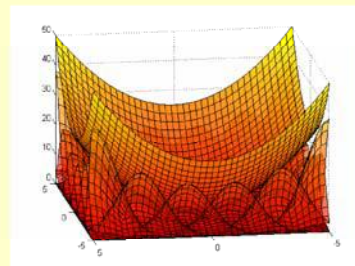


- An optical surface can be represented as a sum of basis functions

$$z(x, y) = \sum \phi_i(x, y)w_i$$

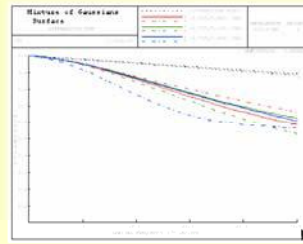
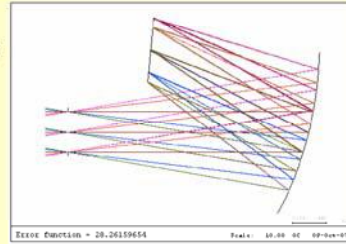
- In matrix form

$$z = \Phi w$$



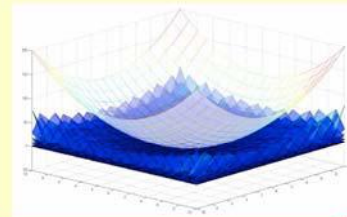
- To be invertible, Φ must be positive definite. equivalent to having positive eigenvalues.

Results



Surface type	Average MTF	Max. Distortion
Anamorphic asphere	26.5%	3.8%
X-Y polynomial	43.6%	2.65%
Zernike polynomial	42%	3.74%
Lin. Comb. of Gaussians	60.5%	3.6%

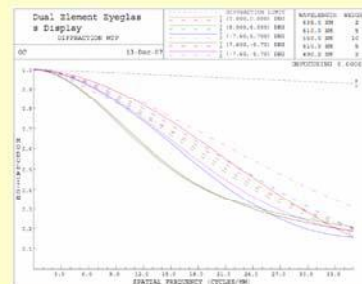
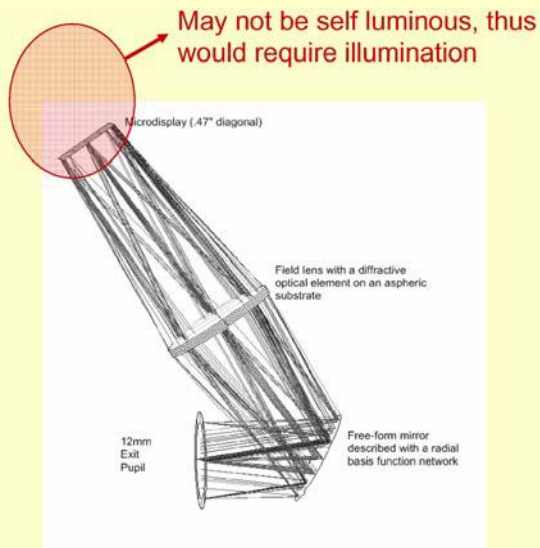
40 cycles/mm



Cakmakci et al., Optics Express 16(3) (2008)

Revisiting the Dual-Element Design: Pupil Size Expansion

Cakmakci et al. OL (April 2008)



Using a 16x16 set of basis functions.



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The EyeGlass Display



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- NASA
- Florida Photonics Center of Excellence
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