Analog Diffractive Optics on Flat and Non-Flat Substrates: Electron-Beam Fabrication and Applications

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Outline

I. JPL E-beam capabilities

II. Fabricationo fanalog- reliefd iffractiveoptical element s

III. Blazedgrating sonn on-flats ubstrates

- *Compactimagi ngspectro meters*

IV. Computer-generated holograms

- *Transient-eventimagi ngspect rometers*

V. Beam-shaping diffractiveoptic s

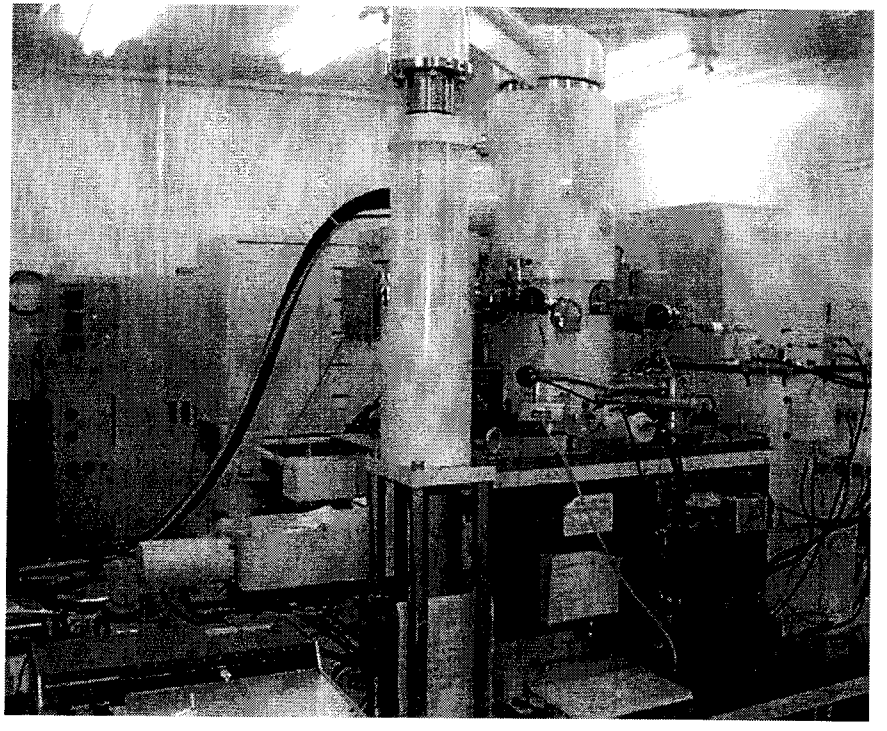
- *Particlevelocim etry /flow characterization*

VI. Gray-scaleoc cultings pots

- *Coronagraphs for Terrestrial Planet Finder*

I. Electron-Beam Lithography atJP L

JEOL JBX-9300FS



Currently the mostadvancedE-beam lithographysyst em(EBLS) in thew orld

Parameter	***JEOL JBX-9300FS***
Voltage	100 kV 50kV
MinimumSp otSize	4 nm 7n m
BeamC urrentf or:1 00n msp ot	175 nA 125n A
10n msp ot	10 nA 4n A
FieldSize	500 μm 1000 μm
PatternG eneratorSp eed	25 MHz
FieldSt itchingAccu racy	20n m
Write Area	9in sq
WaferS ize	12 ind ia
WritingGrid	1 nm 2n m
Electron Source	ZrO/WField Emissio nGu n
DeflectionSyst em	DualD eflector Low-speed1 9-bitD AC High-speed1 2-bitD AC Dynamicf ocus Dynamica stigmatism
Fine-Pitch Control	±5%
HeightC ontrol	White-lightme asurement Auto-correctiond irect-write, ±0.2mm Manualvia Jo bdeck, ±2mm
Cabling	Ethernet
Computer Control	LocalSma rts - 3In ternal DECAlp haC PUs

II. E-BeamFa bricationof Ana log-Relief Diffractive Optics

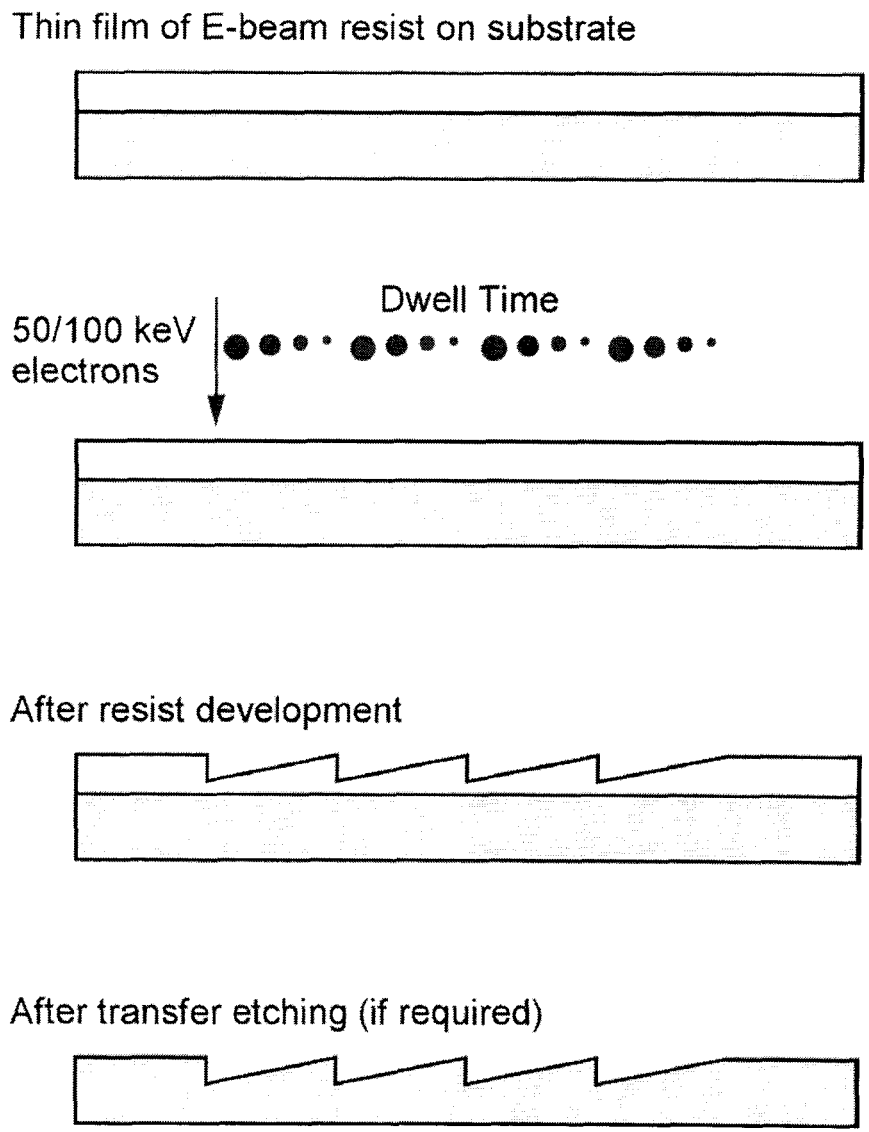
E-BeamFa bricationofAn alogDiffractive Optics

FabricationM ethod

- Thin filmof e-beam resist(PMMAor PM GI) spunonsubst rate
- Direct-write analog-doseelectr on-beam lithography
- Electron beambr eaks bondsin the resist- increases solubilityt odeveloper
- Developeret chesex posed resistt oproduce surfacereliefpat tern
- Transfer ofpatt ernsinto substrate is possiblebut diff icult

Advantages

- Well controlled analogdept h (< 5%er ror)
- Arbitrarypatt erns
- Excellentf eaturealignment (st itching)
- Prototypeelement sare efficientlyf abricated

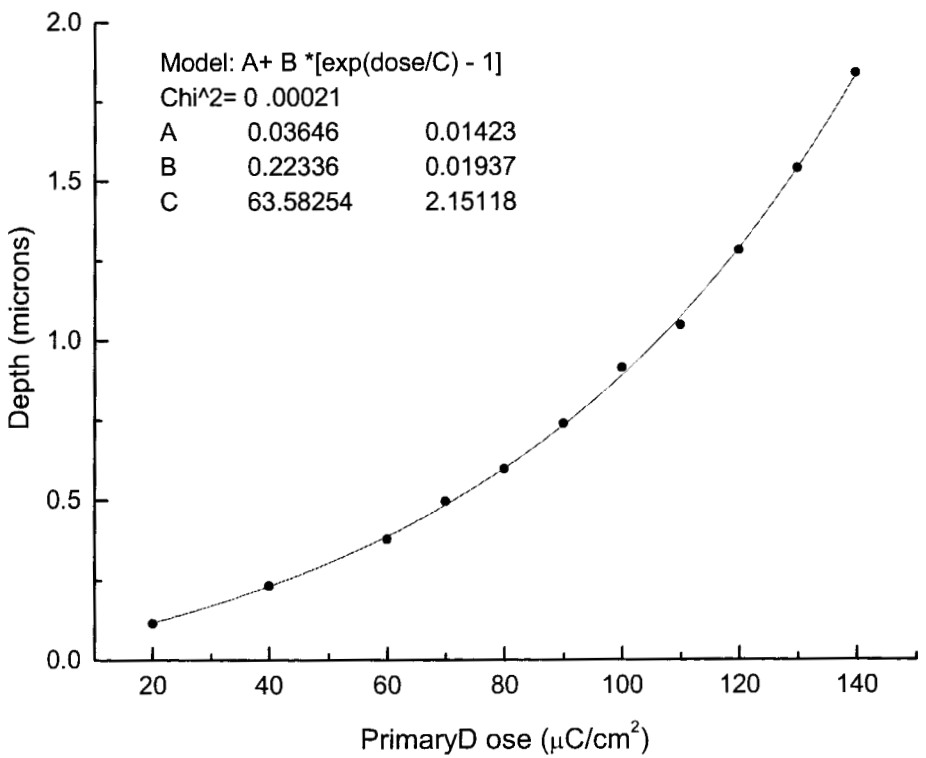


E-BeamFa bricationofAn alogDiffractive Optics

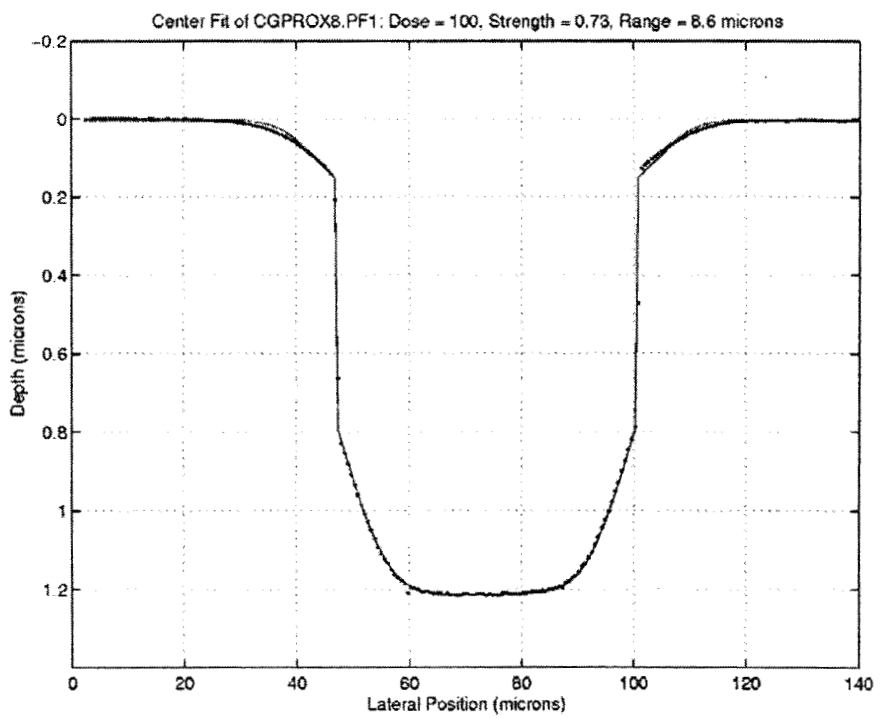
Pattern Preparation

1. Desiredsur facer eliefpatt ernis represented as square pixels(50nm - 2.5 μmt yp.)
2. Pixel depthsar econver tedt oE-beam dosesusingt hem easurednonlinear dose response of PMMA
3. Fourier deconvolution isusedt opr e-compensatet hepatter n fort hebackscatt ered electrondose "proximity effect"(~1/3 of the totaldose, 1/e Gaussian radius ~ 10 μm)

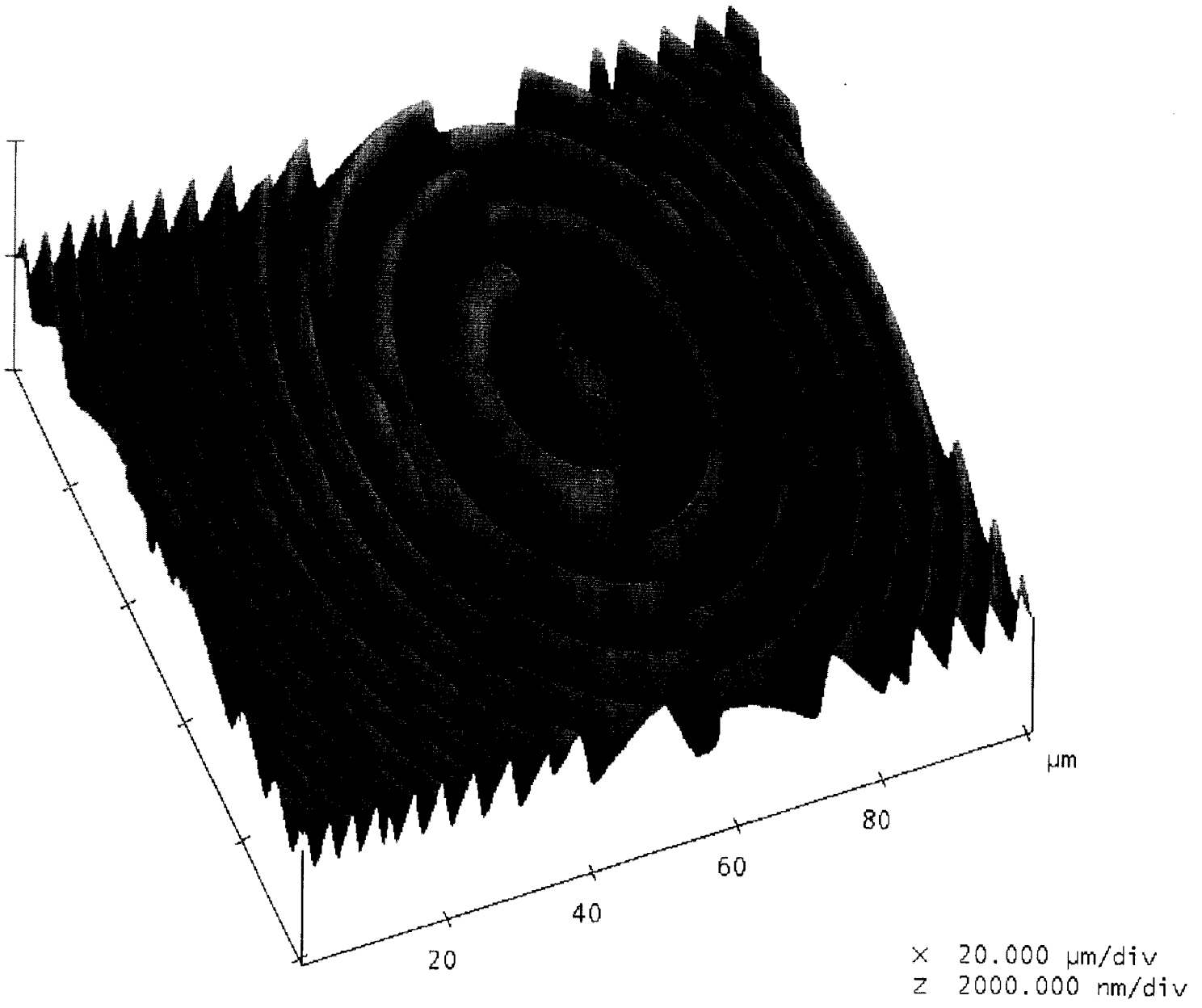
NonlinearDepthvs . DoseRes ponseofR esist



DepthC ross-SectionofaUni formDoseR ectangle (showsproxim ityeffect)



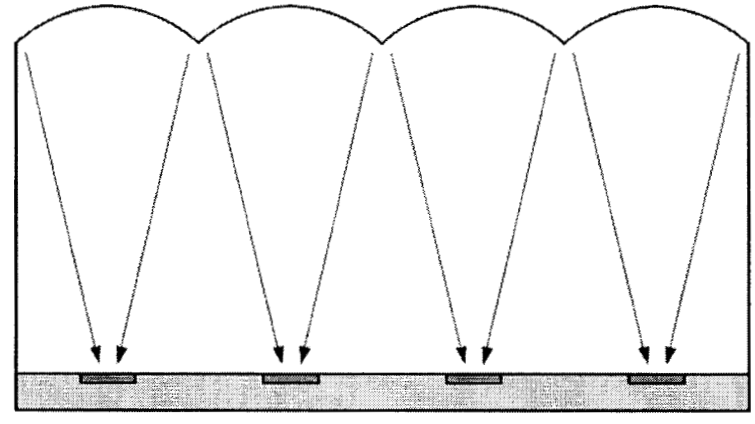
Analog Diffractive Lenses



Microlensesf or Focal Plane Arrays

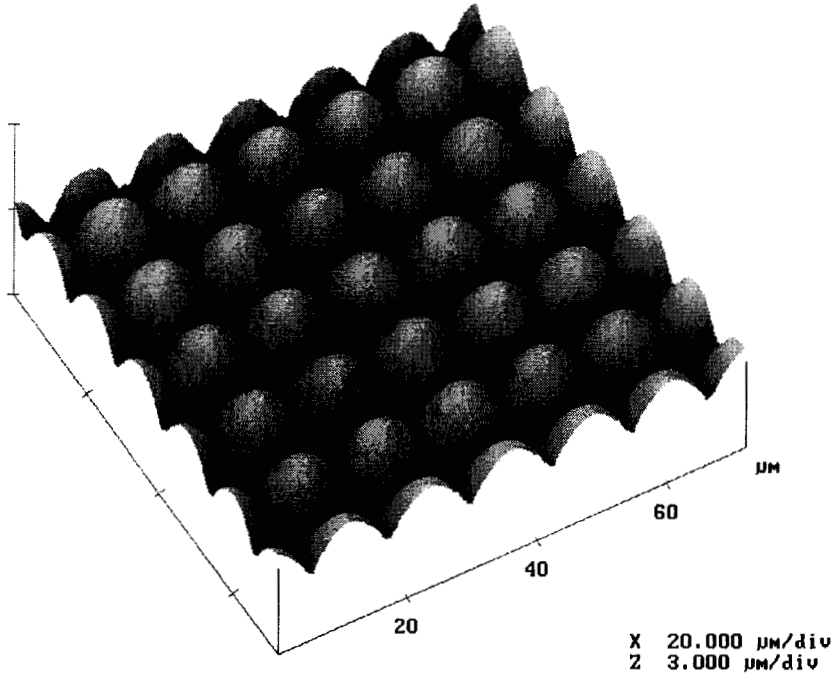
- Microlenses canimpr ove thef illfact orof focal planear rays(CCDs,C MOS active pixel sensors)
- Lenses fabricatedby direct-writeel ectron-beam lithographyinPM MAon thinquar tz substrate
- Lensar rayalignedandbondedt odetec tor

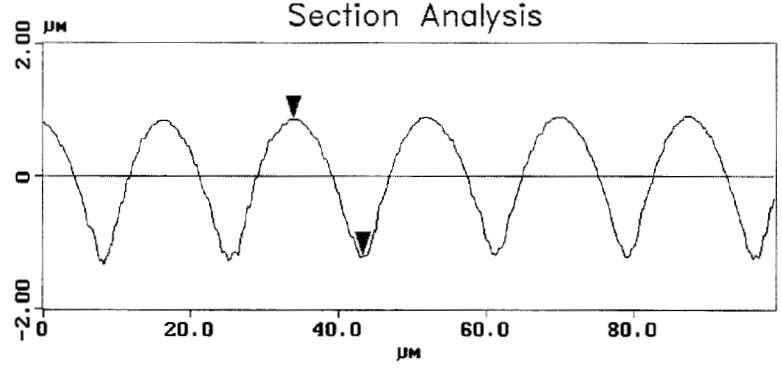
Microlens Array

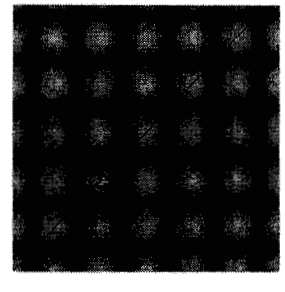


Focalp lane arrayw ith<1 00%fi llfa ctor

SurfaceProfil eof M icrolens Array



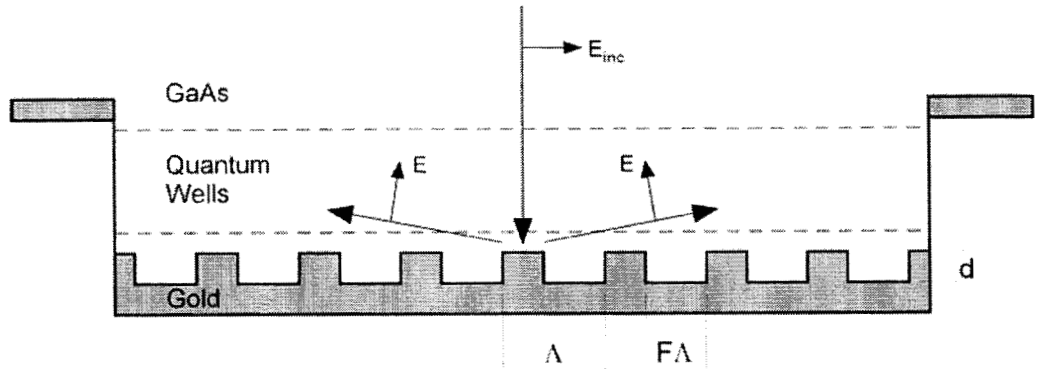




Horiz	9.563 µM	Desired
Vert	2.066 µM	2.01
Angle	12.193 deg	

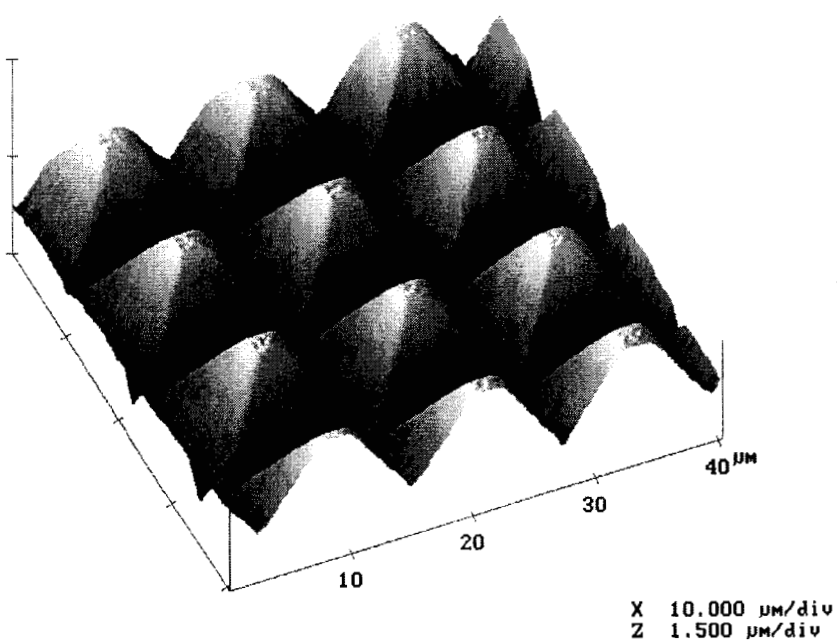
Optical Coupling Structures forQWIP s

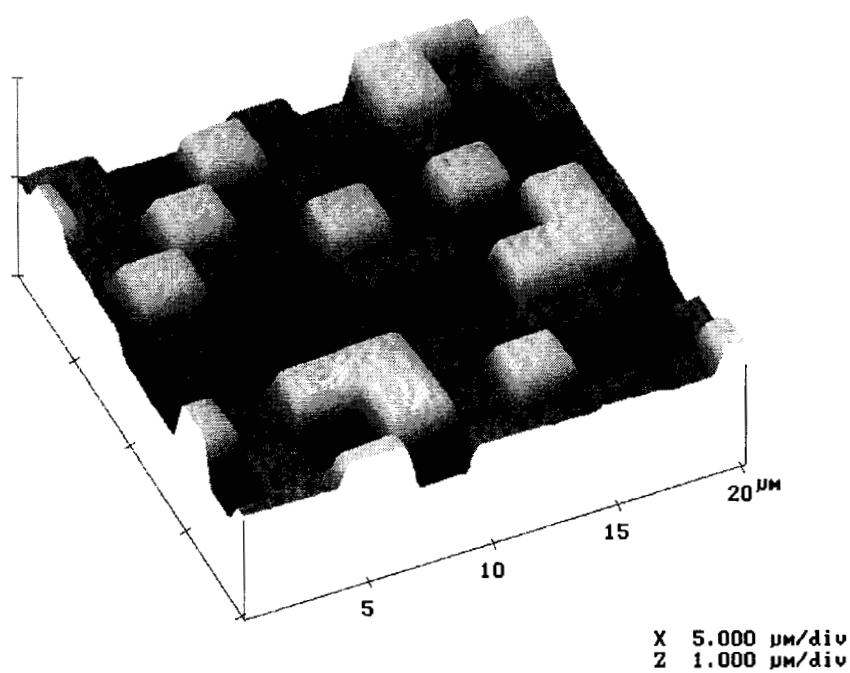
- Quantumw ellinfr aredphotodetect ors (QWIPs)r equirethat li ghtpropagate parallel to quantumw ell layers to be absorbed



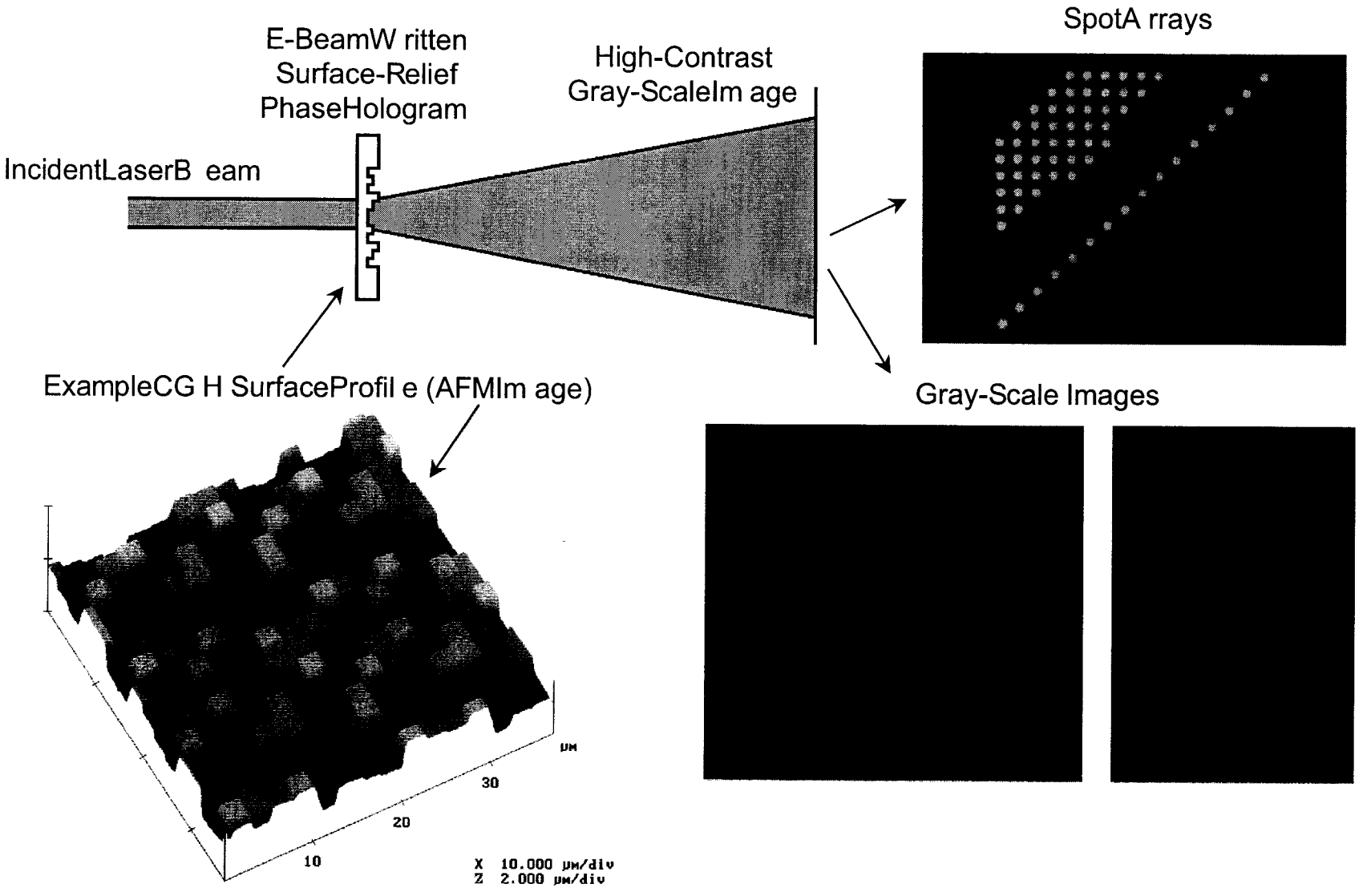
Pyramidstructurerefl ectsi ncidentl ight horizontallyinsidepy ramids

Achromaticrandom refl ectoris desi gnedtohave zero normal-incidence reflectivityat2w avelengths





Computer-Generated Holograms



III. Blazed GratingsonNo n-FlatS ubstrates

Application: Compact imaging spectrometers

Collaborator:
Pantazis(Zako s) Mouroulis (JPL Section387)

Need for Blazed Gratings - ImagingSp ectrometry

ImagingSpectr ometry

1. Measuret he spectra ofallpixelsina scene
2. Analyzethe spectrat oobt ain usefulinfor mation aboutt hescene

Applications

<u>RemoteS ensing</u>

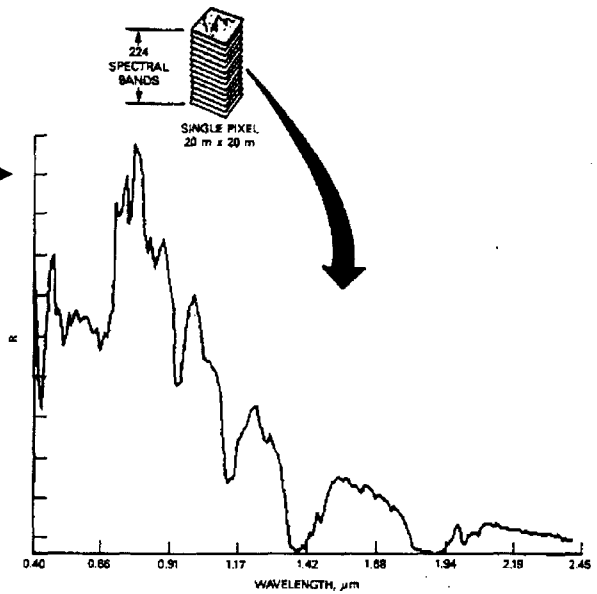
- Mineralexplorat ion
- Hazardousw astem onitoring
- Crop/forestheal th
- Fire/Wetlands monitoring

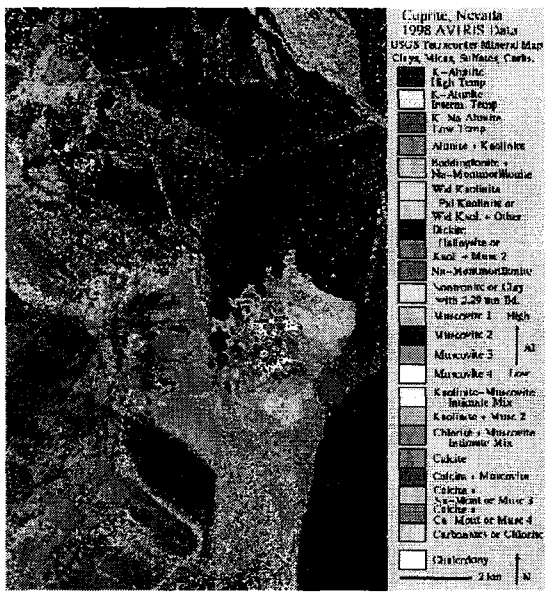
<u>Defense</u>

- Targetident ification
- Chemicalw arfare warning

<u>Biology/Medicine</u>

- Abnormal tissue identification
- Fluorescence studies ofc ellularpr ocesses





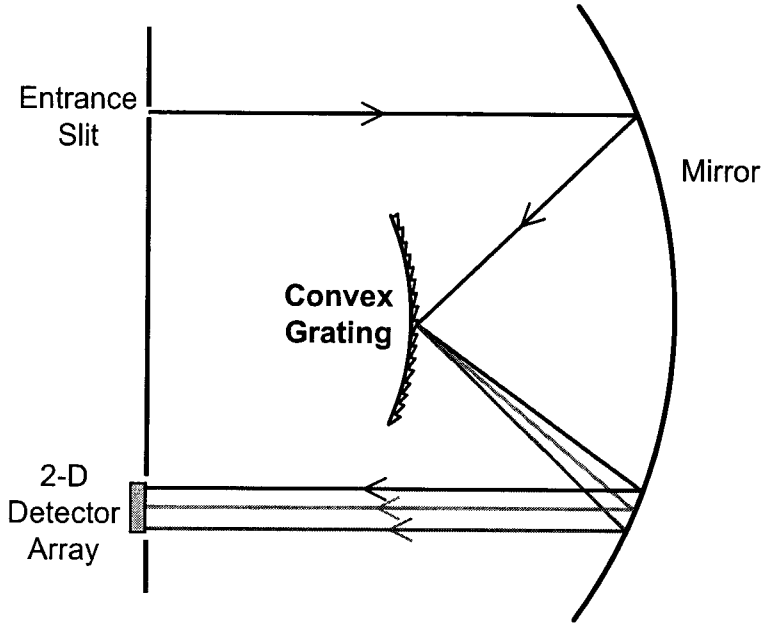
AVIRISD ata ofC uprite,N evada

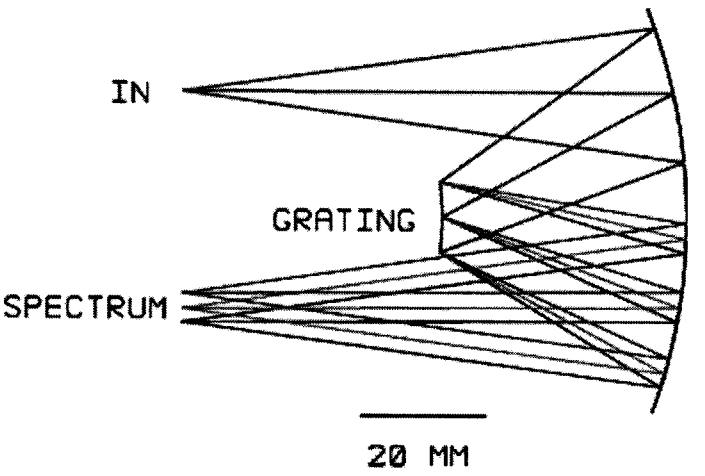
Slit Imaging Spectrometer

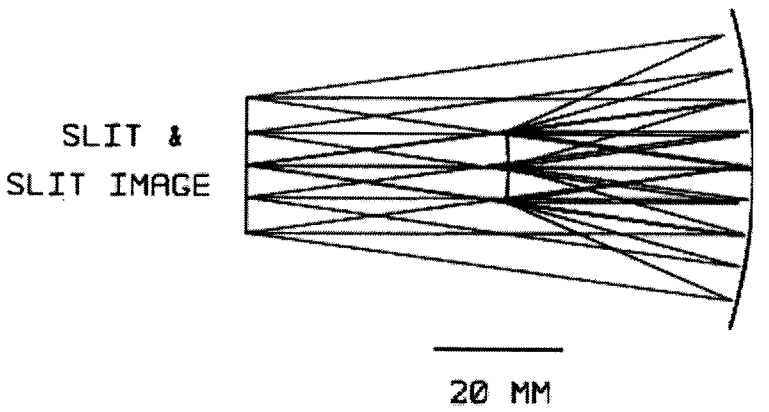
- Spectrometer measures spectra for all points along a slit. System mounted on a scanning platform (aircraft or spacecraft) to collect spectra for a 2D area ("pushbroom scanning")

Need for Non-Flat BlazedGra tings

Sliti magingspectr ometerbasedont heO ffner concentrict wo-mirror design





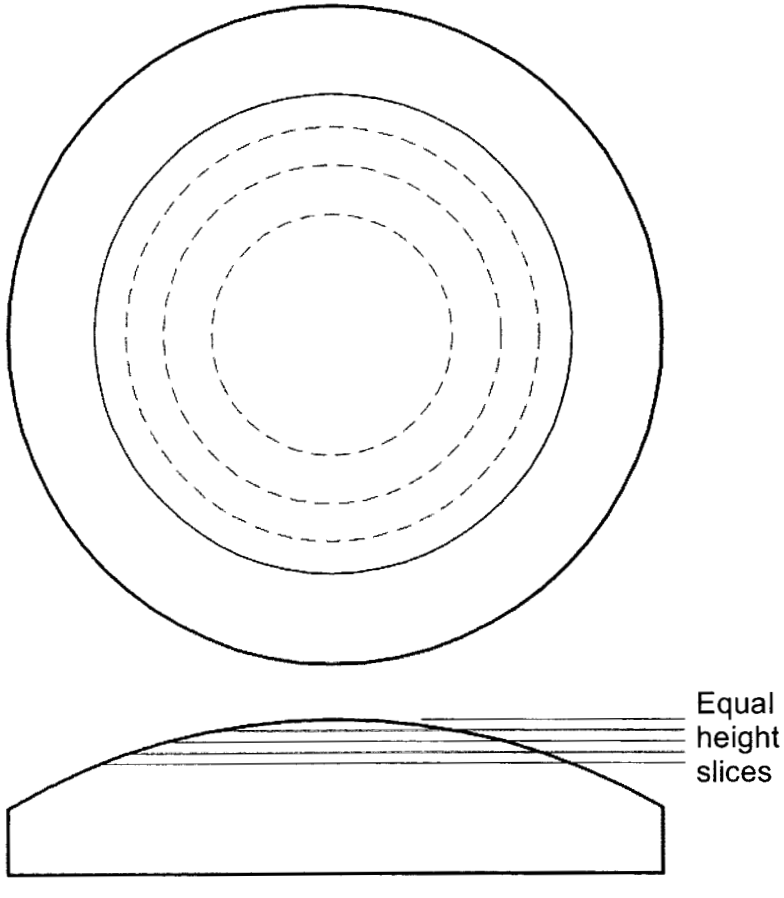


- Can bedesigned to have *verylow slit-image distortion*
  - Minimizespixelc rosstalk
  - Greatlysimplifiesc alibration of the spectrometer
- Canbe verycom pactandlightw eight
- Requires a convex grating (blazed for high efficiency)

BlazedGra tings onCo nvex Substrates

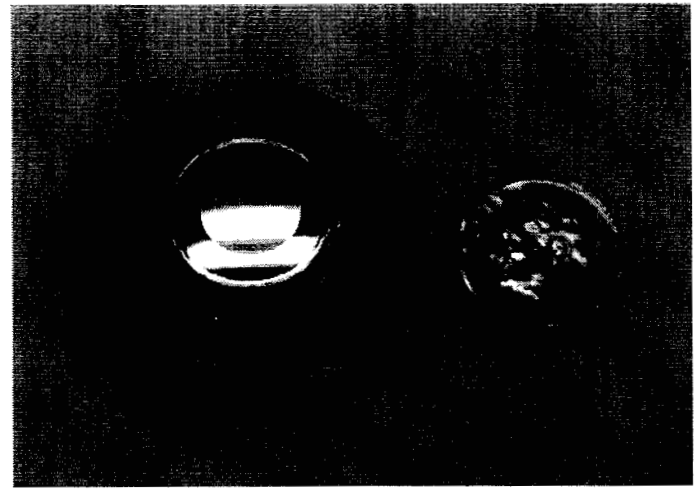
Convex GratingFabricat ion

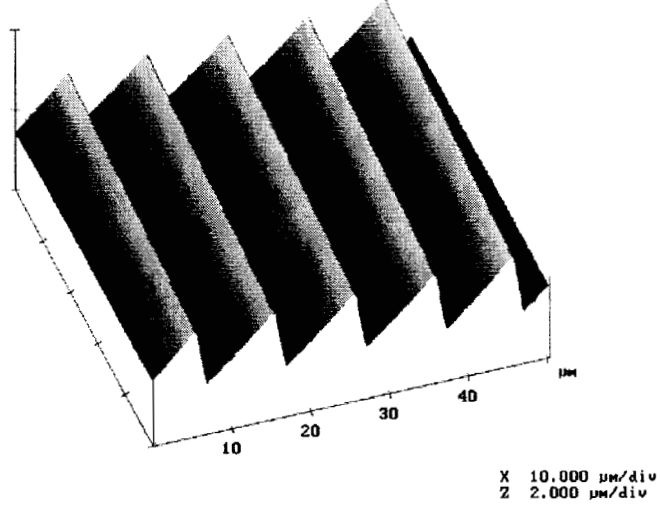
- Patternis brokenintoan nularsecti onsthatcov er equalheights tepsof ~5 0m icrons(E-beam depth of field)
- E-beam *focus,defl ectorgai n,androta tion* are correctedforeach annul arpattern



Single-blazegratingon aluminums ubstrate for *NASA NewMi lleniumEO-1 M ission*

- Selected overdiam ond-ruledandhol ographic gratings basedonm easurementsof efficiency, scattering, and wavefront quality





Flight InstrumentC onvex Gratings

Typical ConvexG rating Specifications

- TRW Hyperion (onboardN ASA New MilleniumEO- 1spac ecraft)
- Spectrometer1 and Spectrometer2

Specificationsa ndp erformance off light-instrument gratings

Grating	Diameter	Period	Blaze Angle	Substrate Sag	Wavelength range (order)	Peak Efficiency†, Wavelength (order)	Ghosts, Scatter‡
Hyperion VNIR	14 mm	17.4 μm	0.55 deg	0.23 mm	0.4 – 0.85 μm (-1)	92% @ 490 nm	0.025%
Hyperion SWIR	14 mm	17.4 μm	2.27 deg	0.23 mm	1.13 – 2.55 μm (-1)	92% @ 1450 nm	0.16%
Spect. 1 Dual-band	29 mm	35.7 μm	1.19 deg	1.27 mm	0.5 – 0.85 (-2) 1.0 – 2.45 (-1)	91% @ 0.63 μm (-2) 93% @ 1.26 μm (-1)	0.05%
Spect. 2 MWIR	36.6 mm	103.6 μm	1.12 deg	0	3 – 5 μm (-1)	Not Meas.	Not Meas.

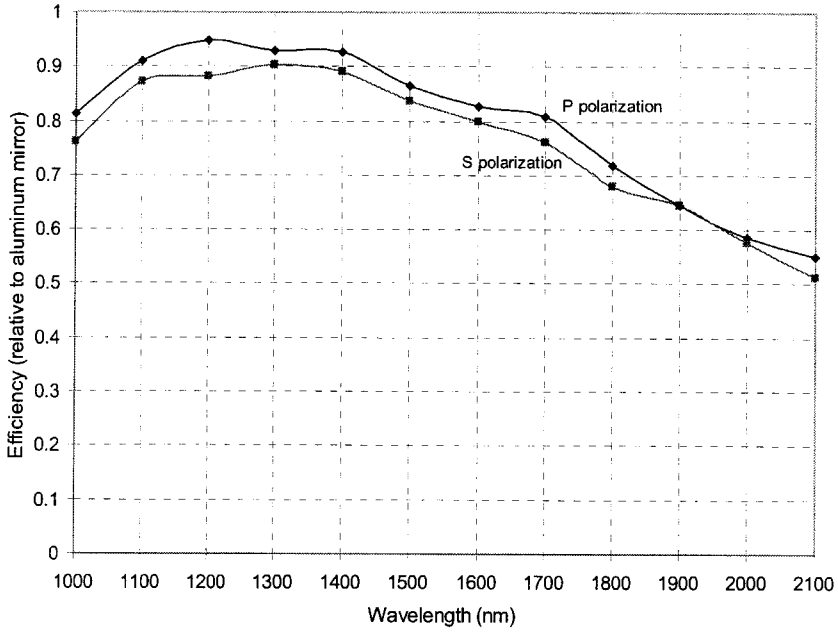
† - relative to an aluminum mirror

‡ - compared to the brightest order at 633 nm, in all cases ghosts dominated over diffuse scatter

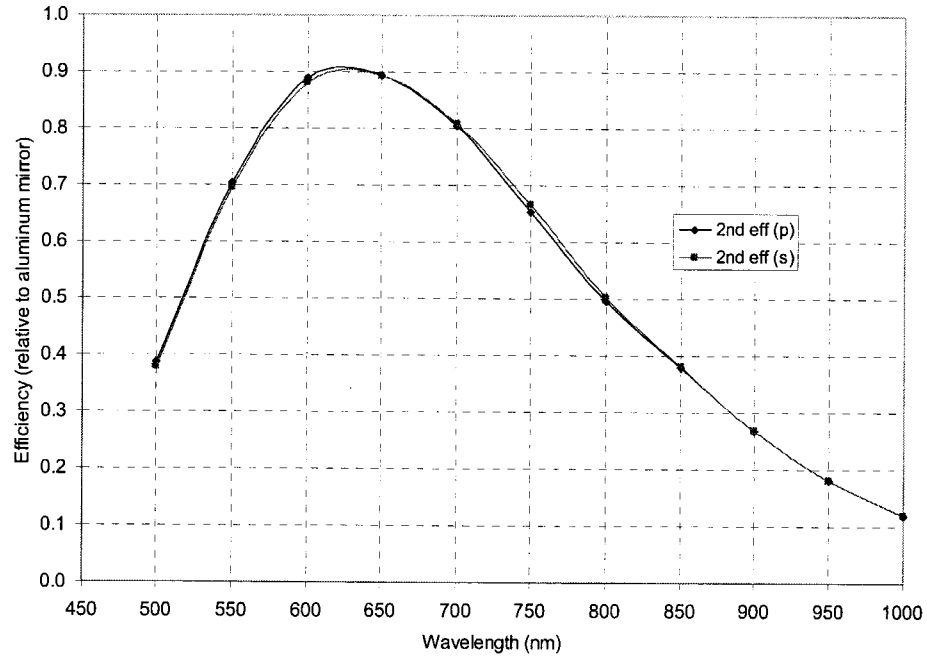
- Just delivered: 4 gratings for the APL CRISM spectrometer (Mars Reconnaissance Orbiter)

Convex GratingDiffraction Efficiency

Spectrometer1G rating (1st Order)



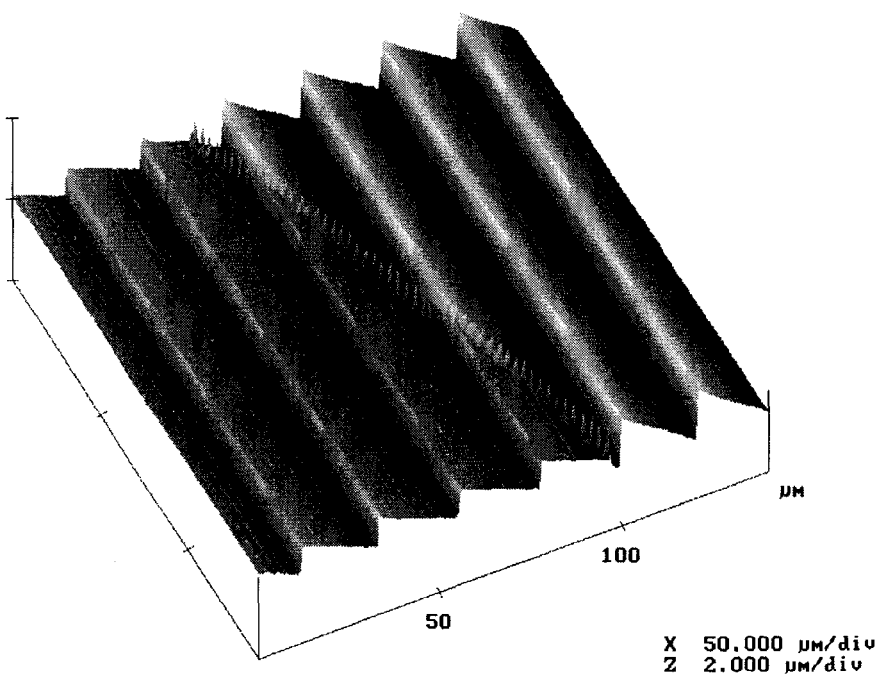
Spectrometer1G rating (2nd Order)



Dual-Blaze Gratings

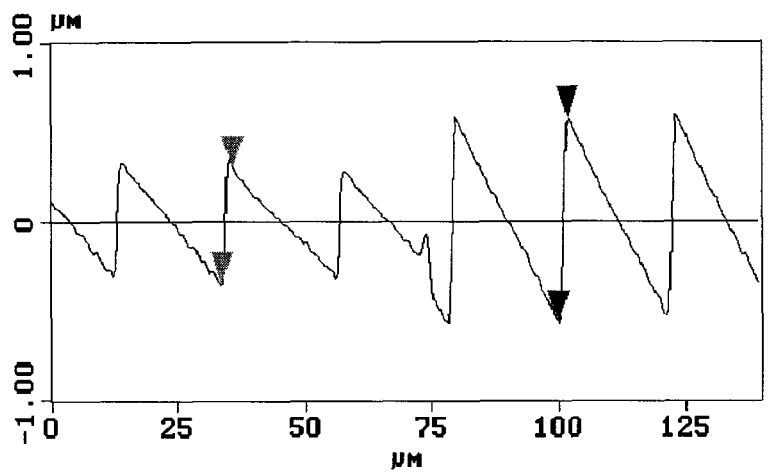
Dual-BlazeC onvexG rating

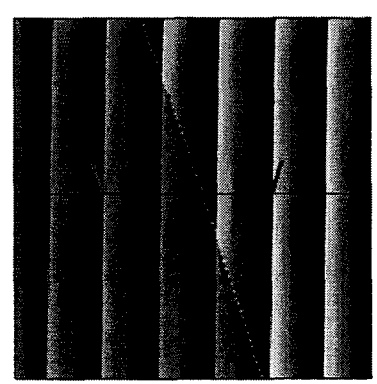
- Constantper iod overent irear ea
- Twoblaze angles:
  - centerc ircleblazed forv isible
  - outer annulus blazedf or infrared
- <u>HighEff iciencyf orbot hVisibl e andl nfrared</u>
- Provides flatandhigh signal to noise ratio.



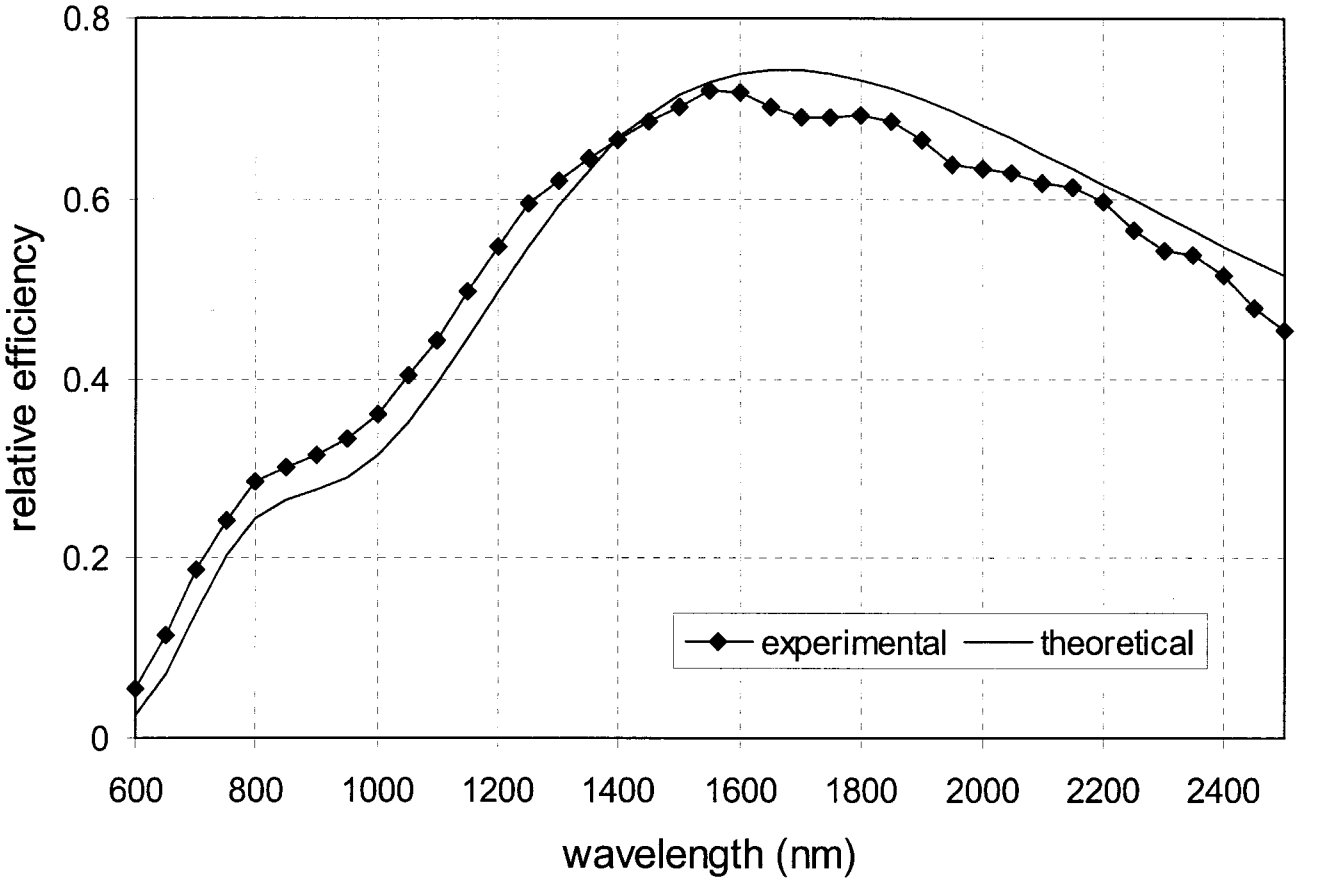
AFM profileof a dual-blaze convex grating showing blaze-anglezone boundary

- Average-depthsar eal ignedt ominimize opticalaber ration at boundary





Dual-Blaze Grating Efficiency



IV. ComputerGe neratedH olograms

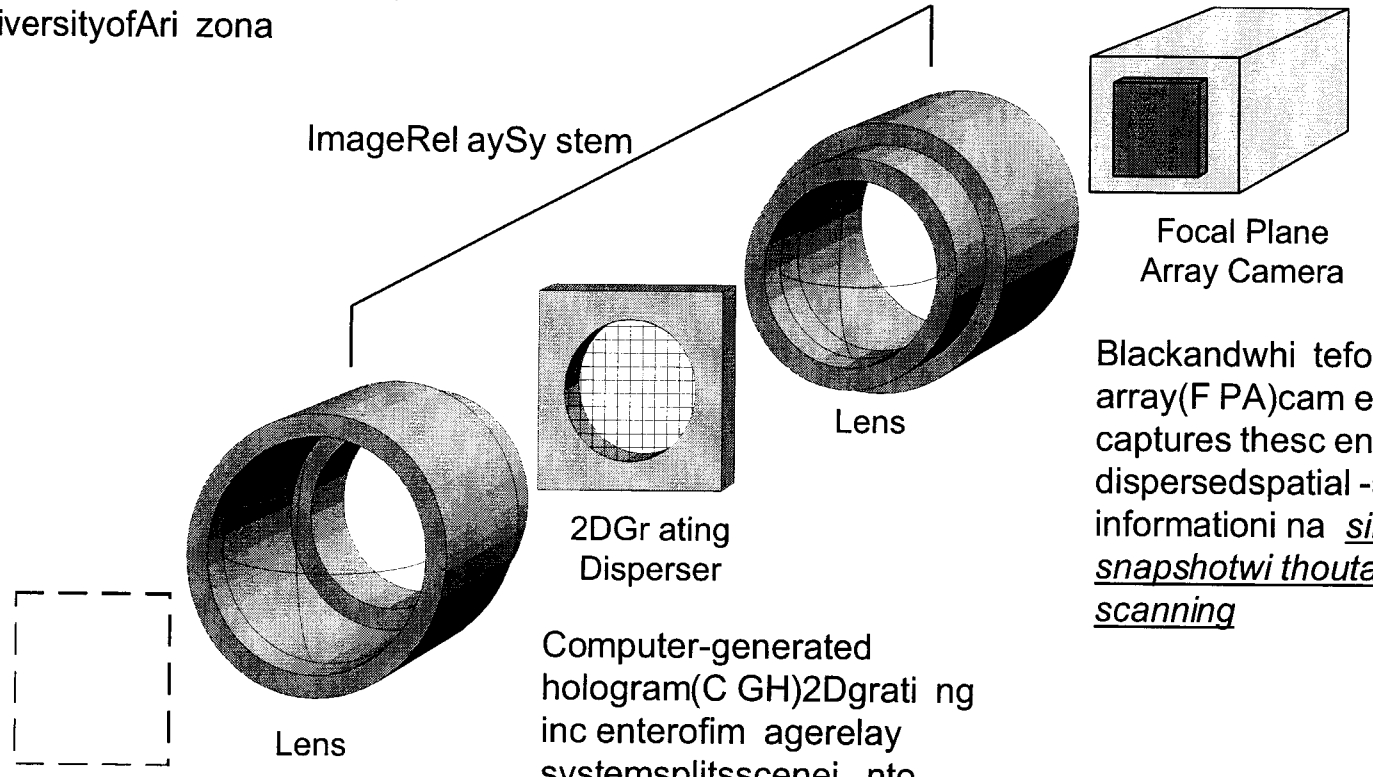
Application: Transient-event imaging spectrometers

Collaborators:
Greg Bearman (384)
Profs.M ichael Descour andEu staceD ereniak (U.A rizona)

Computed-Tomographyl maging Spectrometer (CTIS)

Noveli nstrumentthat *enablestr ansient-eventm ulti-spectralimaging* by capturing spatialand spectralinfor mation in asingl esnapshot , withnom oving parts.

- Initialdem onstrationby
  M.D escour andE .Dereniak ,
  UniversityofAri zona



Blackandwhi tefocalplane array(F PA)cam era captures thesc ene's dispersedspatial -spectral informationi na *single snapshotwi thoutan yty peof scanning*

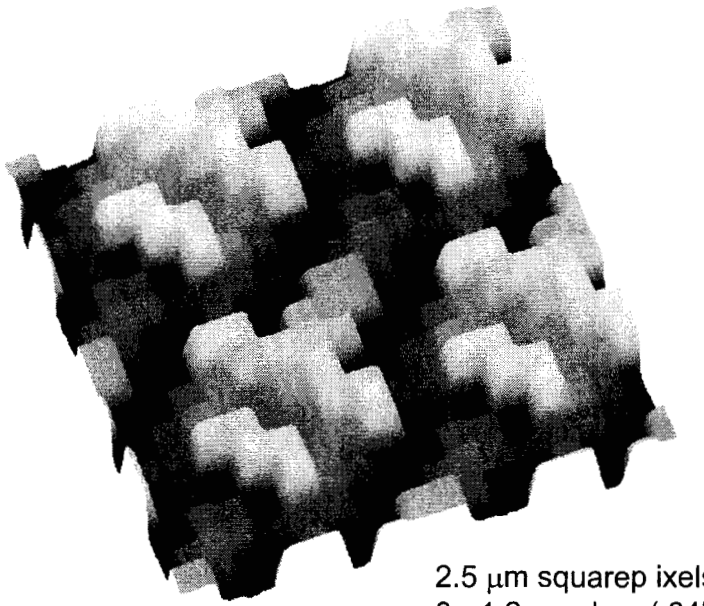
Computer-generated hologram(C GH)2Dgrati ng inc enterofim agerelay systemsplitsscenei nto multiples pectrally-dispersed images.

Primaryim agingsys tem (notshow n)form s imageof asc ene.

- Tomographic reconstruction computations yield the spectrum for every pixel in the scene

Computer-GeneratedHo logram2D Grating

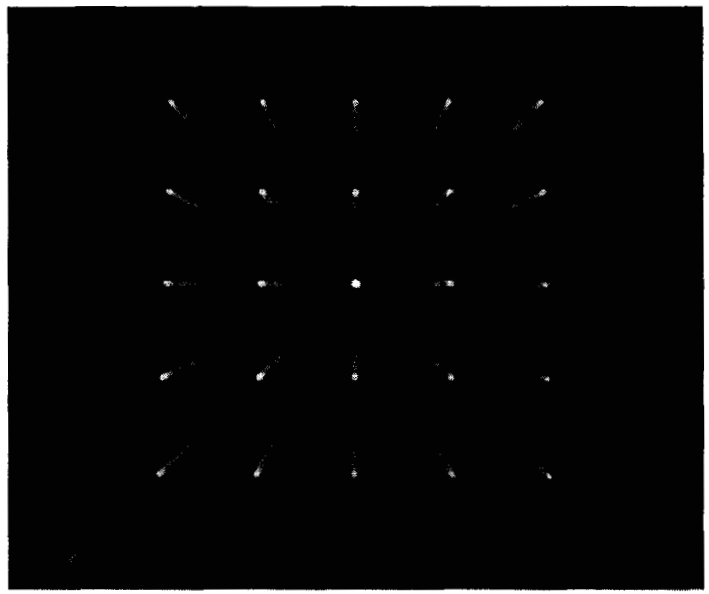
SurfaceProfi le of2D G rating (1.7 cmdi a.)



2.5 μm squarep ixels
0- 1.2 μm deep(64le vels)

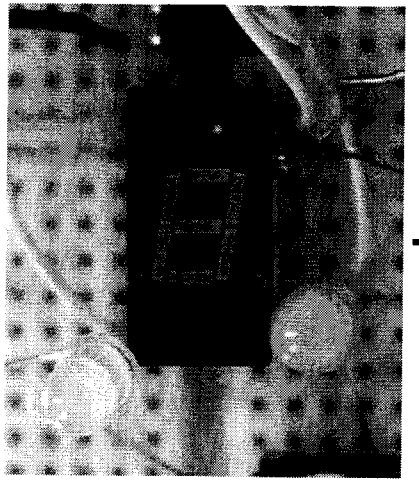
- E-beamexposure andacet one development creates surface relief pattern
- Filmt hicknessvariat ionc auses transmittedlig htt o bedi ffractedin toa 2Dpatt ern
- JPL's diffractiveoptics fabricationand design techniques enable high performance CTISoper ation

White-Light Pointl maged Through Grating



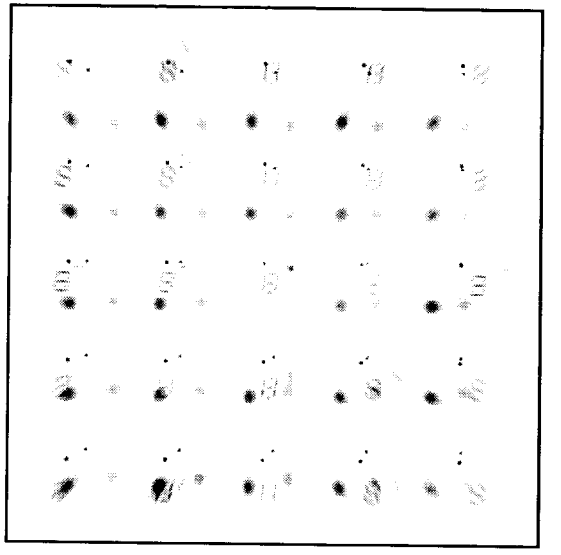
- Gratingw as designedt opr oducea5x5 array oforders
- Fabricated grating demonstrated equal intensity orders,balan cedcolor dispersion, andhigh efficiency

CTIS Principleo fO peration



Scenecom posedof
LEDs andlas erspots

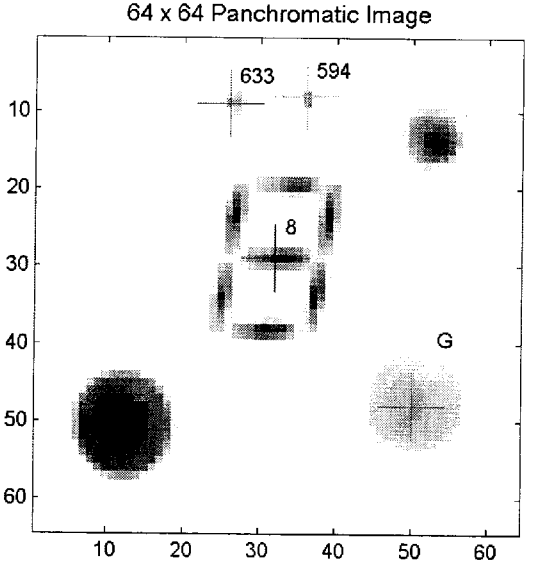
CTIS

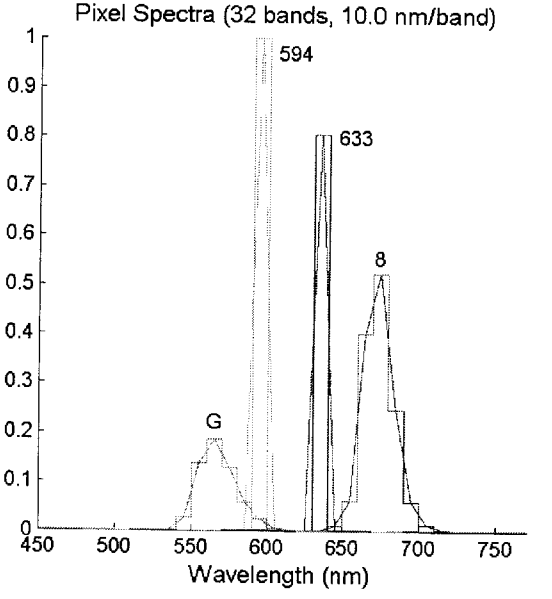


Imagec apturedbyC TIS
focalplanearray (darkam bient)

Tomographic
reconstruction
algorithm

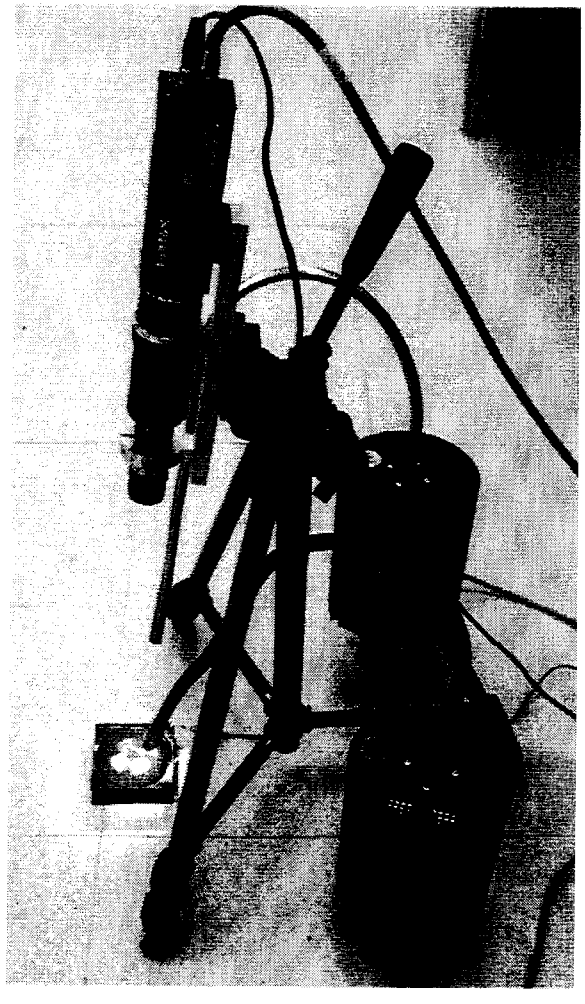
Spatial-spectral
informationi nthescene

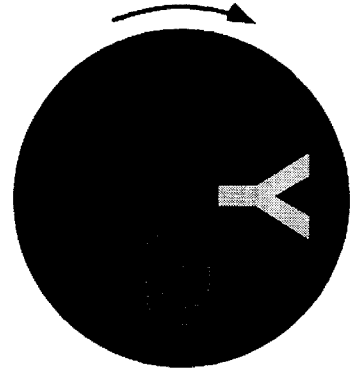




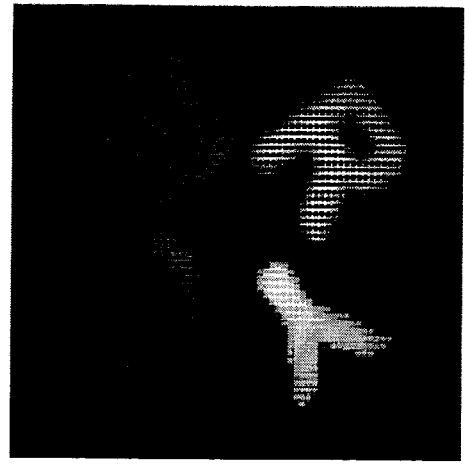
PortableCT IS System

Spinning LaboratoryTarget

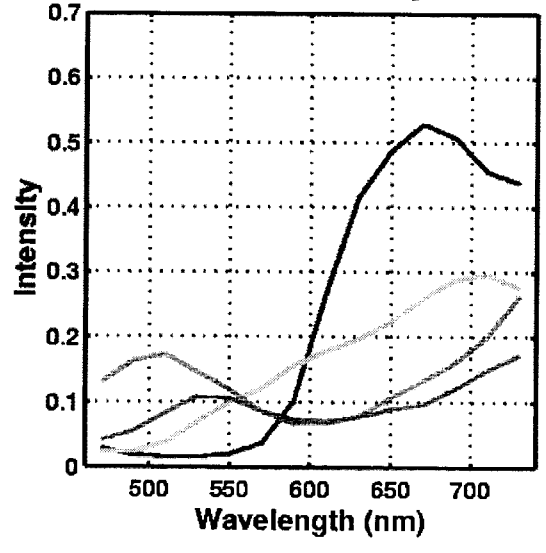




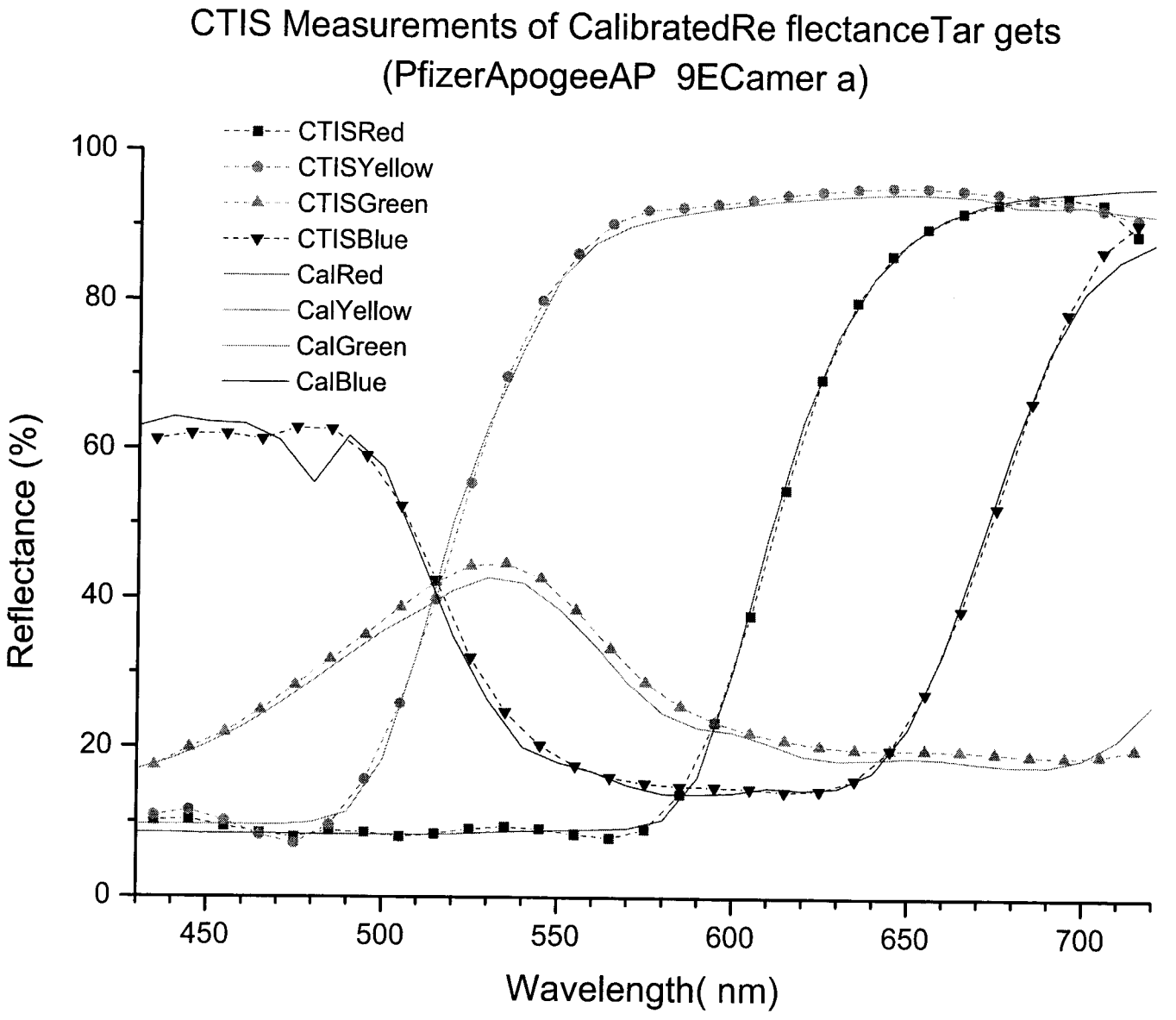
62 x 72 Spectrally Classified Image



Common Spectra of Bright Pixels



CalibratedR eflectance TargetSp ectra



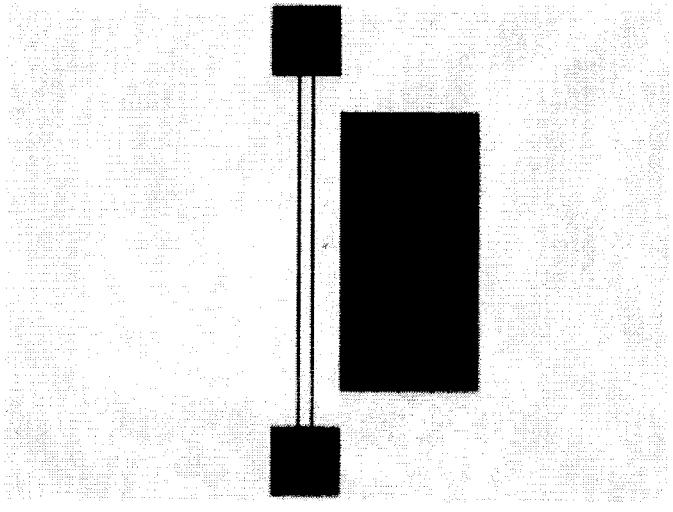
V. Beam-ShapingDiff ractiveEle ments

Application: Particle velocimetry / flow characterization

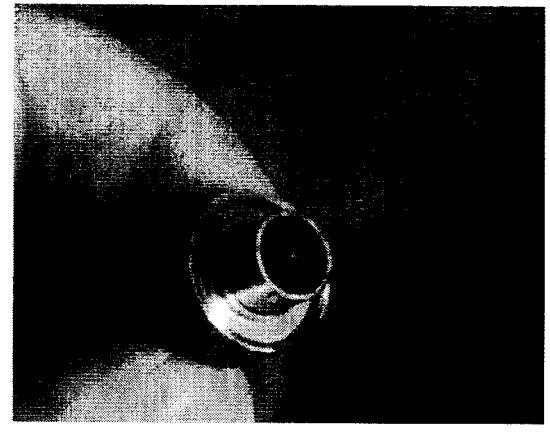
Collaborators:
Prof.M ory Gharib (Caltech)
D. Modarress, D. Fourguette, etal .(V ioSenseC orp.)

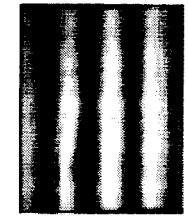
Diverging-FringeS hear-StressSen sor

Top SideCh romeP attern (slitsan dwin dow)

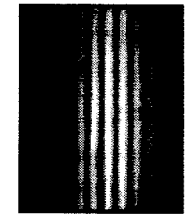


PackagedSen sor

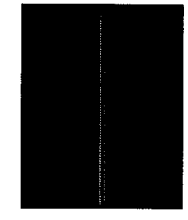




150 μm from surface

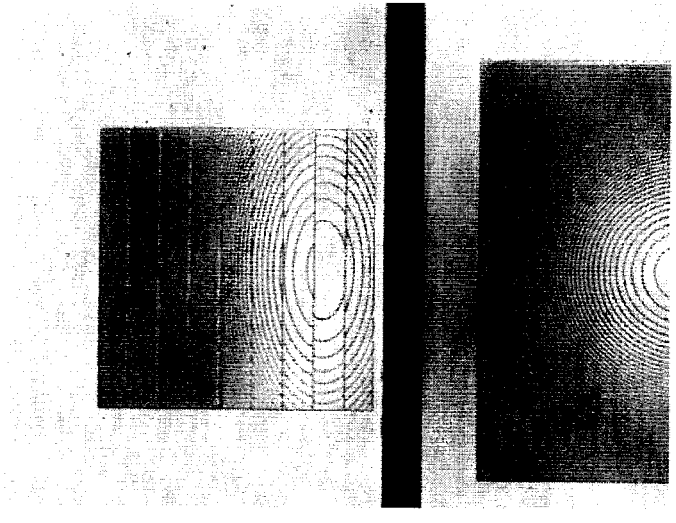


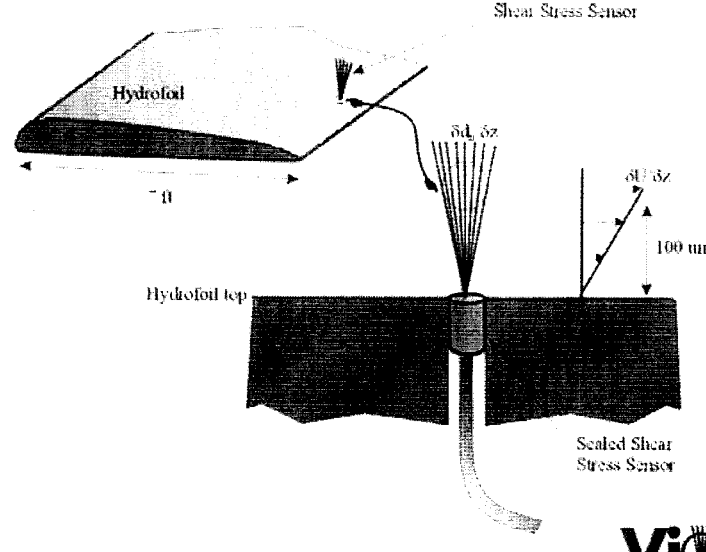
50 μm from surface



Slits

BackS ideDiff ractiveOp tics (dual-linefo cusl ens,i solations lot,r eceiverlen s)

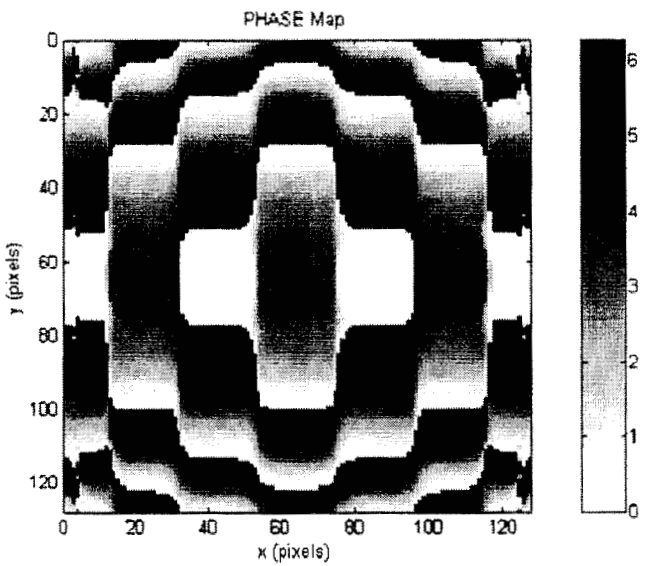




ViaSense Corporation

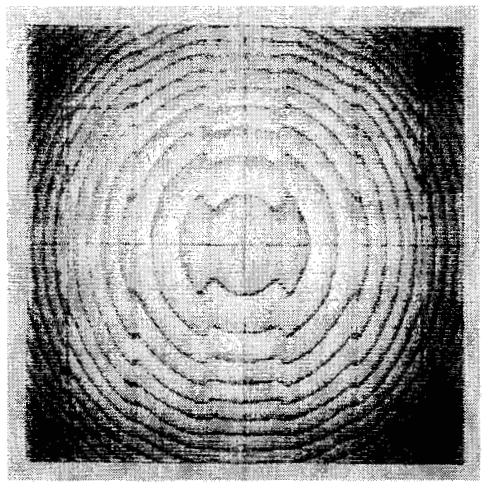
Two-Spot Velocimeter

Beam-ShapingDOE Ph aseM ap (withoutlen sp hasefu nction)

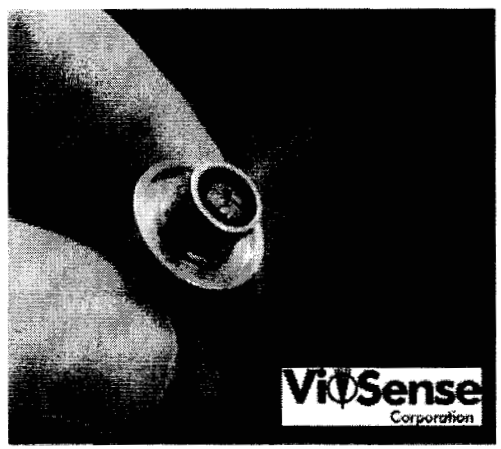


- Can bedesigned t o produce arbitrary shape diffraction-limited patterns

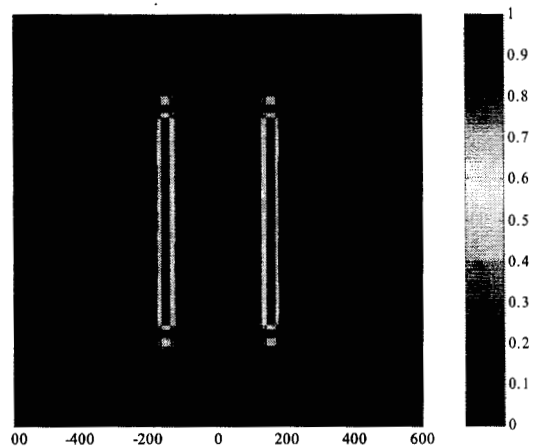
FabricatedD OE (includinglen s phase function)



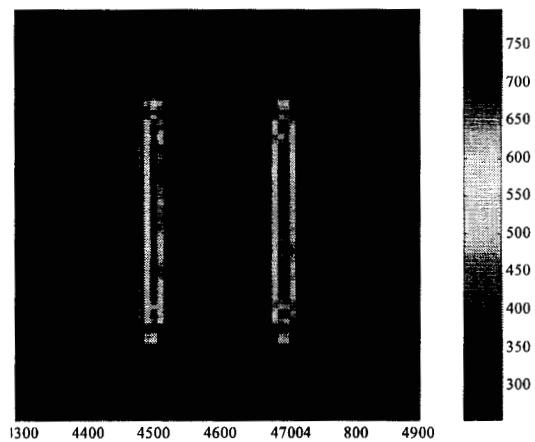
Packaged"M icroV"



SimulatedIn tensity



Measured Intensity



Status

- Two-spot velocity sensor has been fabricated, packaged, and tested
- Scattered signal-to-noise ratio was greater than 50

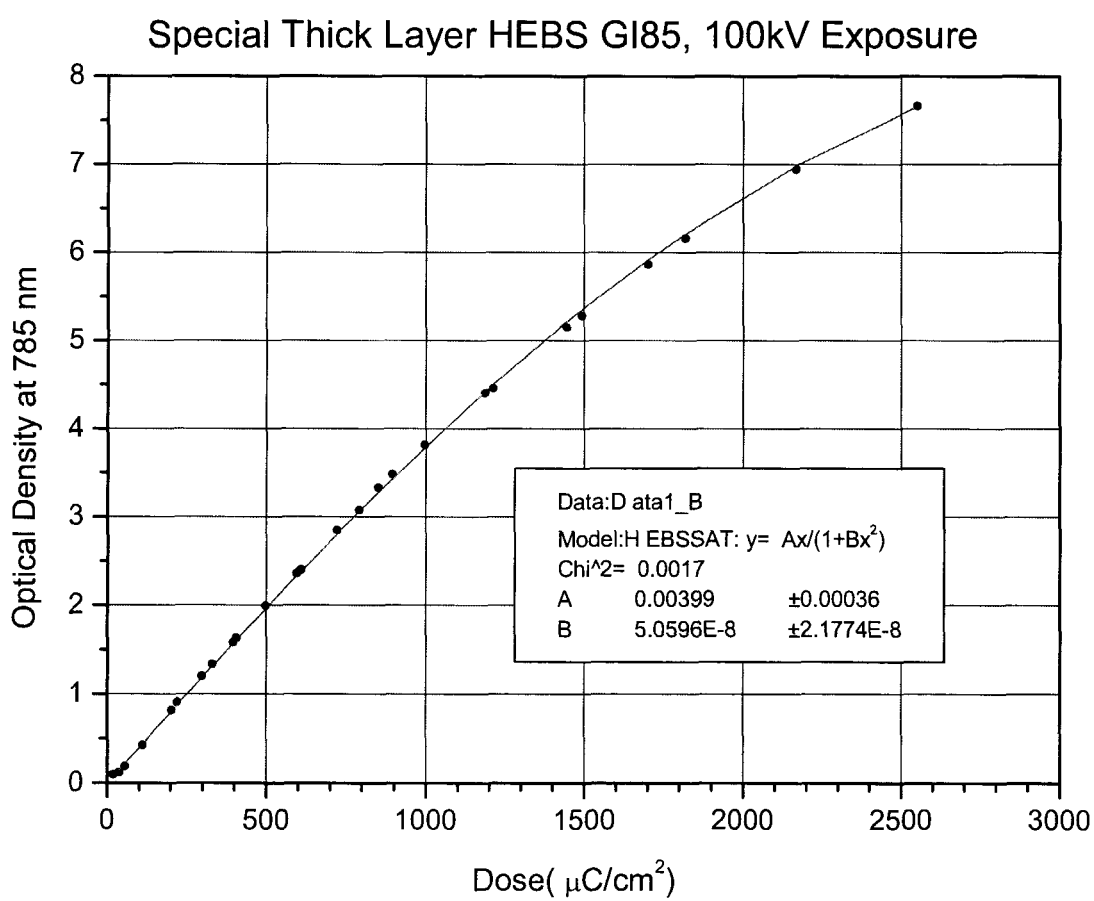
VI. Gray-ScaleO ccultingS pots

Application: Coronagraphs for Terrestrial Planet Finder (Goal is to image planets around nearby stars)

Collaborators:
JohnTraug er (JPL Section3262),Ton y Hull (JPL Section387)

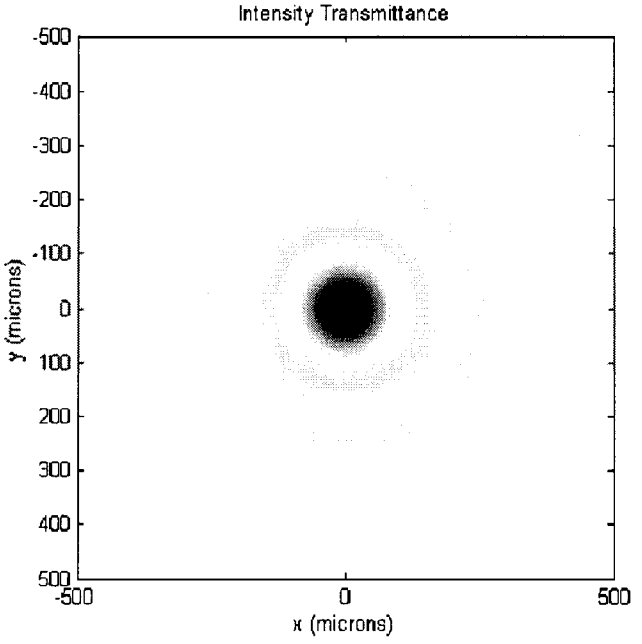
Occulting Spots inH EBS Glass

- Coronagraphdesigns for TPF require gray-scaleoccultingspot sto reducediff raction inthe planetaryr egion aroundt he star
- Spot must be extremely darkat center (opticaldensi ty> 8,t ransmittance <10^{-8})
- Canyon Materialsm akesH EBS (highener gy beam sensitive) glass that graysw ith E-beamexposure.

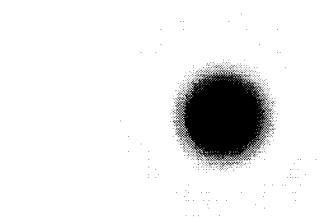


Gray-ScaleAp odized OccultingSp ot

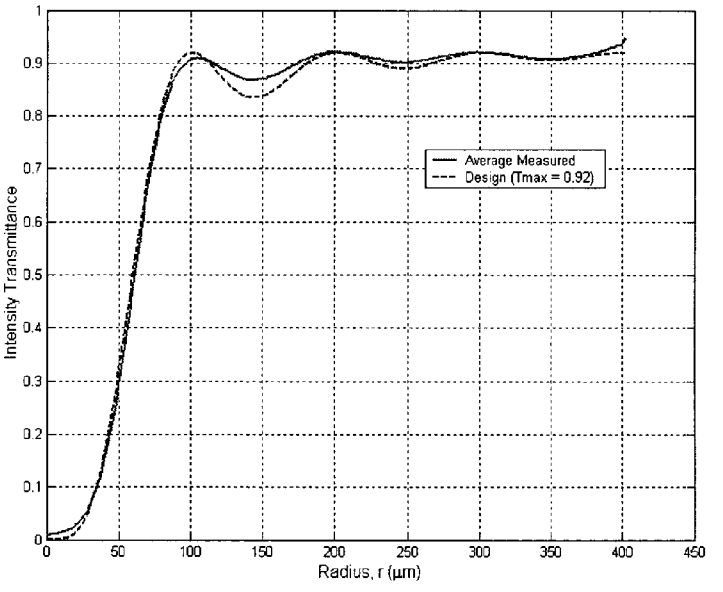
Design



Fabricated



- Differencesbet ween design andm easured transmittance areduet oE-beam proximity effect
- Wehav enow char acterizedpr oximityeff ect in HEBS
- Newpr oximity-corrected spots havebeen fabricated andar e undergoingt esting



Summary

Analog Surface-Relief E-BeamFab rication Capability

Pixel sizes	0.1to2 .5 μm
E-beamdose s	1024
Depth	Atl east 8 microns <5%a ccuracy,t ypical
Non-flatsub stratesag	3.5 mm maximum
E-beamwri tingtim e	~1ho ur/ cm ^{2} ofare a