Supercontinuum-based VIS-SWIR light source for the STARR II gonioreflectometer

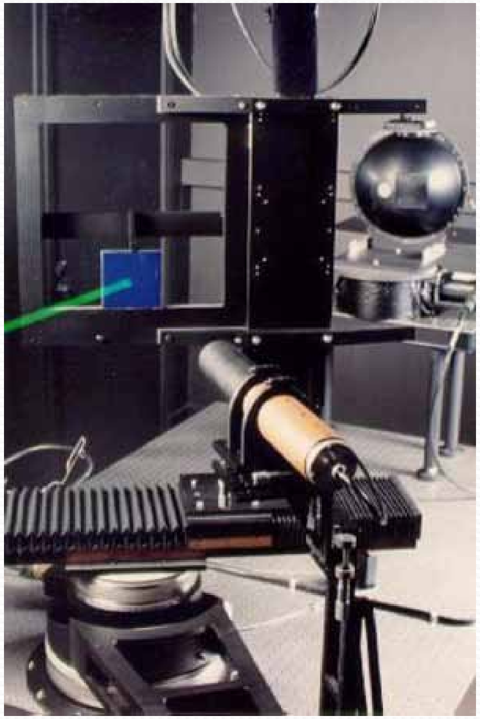
Heather Patrick and Clarence Zarobila
NIST

Introduction

- What is STARR II?
- BRDF and climate science satellite support
- BRDF light source requirements
- A brief introduction to supercontinuum sources
- Supercontinuum characteristics
- Tuning and beam delivery
- Outlook and Conclusions

STARR II

- New instrument for bidirectional reflectance distribution function (BRDF) and reflectance
- 250 nm – 2500 nm spectral range
- Builds upon capabilities of existing STARR facility, the national reference instrument for spectral reflectance measurements



The current STARR facility

GOSI, an example out-of-plane goniometer

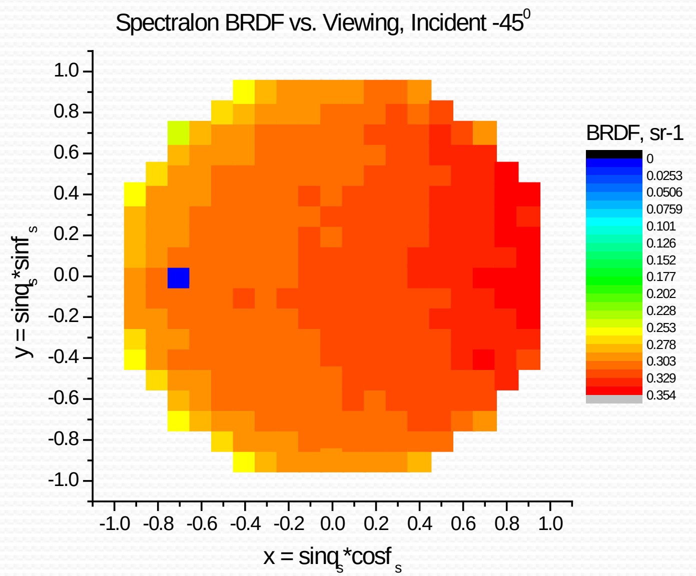
STARR II features

- Increased source flux to improve speed and accuracy
- New goniometer to enable out-of-plane measurements
- Increased sample size and scanning capability

BRDF Measurements

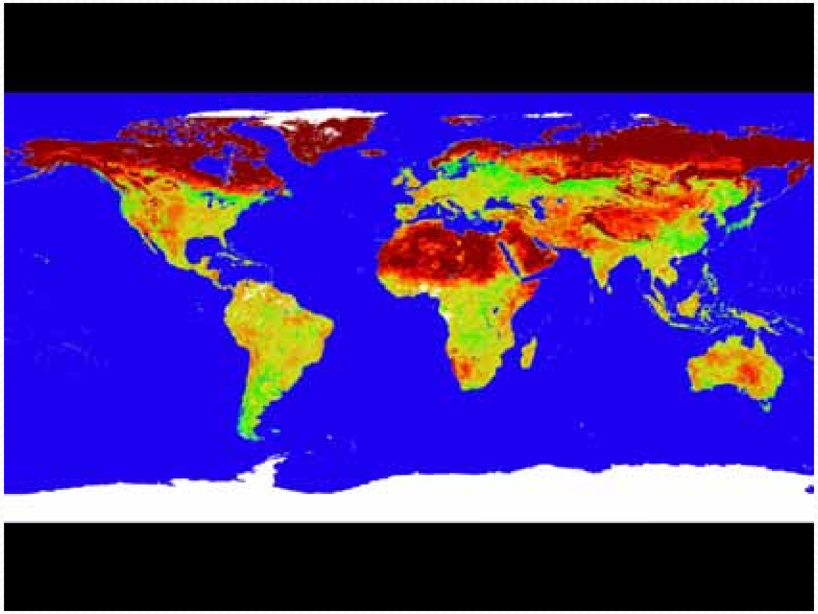
- BRDF is a *function* describing reflectance of a target vs. illumination and viewing geometry
- Objects look different when viewed from different angles and illuminated differently
- Lambertian sample should have BRDF = 1/p but even best Lambertians (like spectralon) exhibit deviations, especially with non-normal illumination

BRDF map vs. viewing angle measured on a spectralon sample S-polarized incident



BRDF and climate science

- Many current and future satellites employ spectralon or other type solar diffusers (MODIS, LDCM, CLARREO…)
- Diffuser illuminated by sun; compare earth radiance to diffuser radiance (use BRDF)
- Often employ standard sources or other means to monitor solar diffuser stability
- Diffuser panels also widely used in pre-launch calibrations, example irradiance to radiance calibrations using illuminated diffuser panel



Courtesy nasaimages.org

Climate satellites produce maps of the earth's albedo, or reflectance, as shown here. Solar diffusers on board the satellites help to calibrate the radiometric scale of these images.

On-board diffuser example: MODIS

Sunlight in

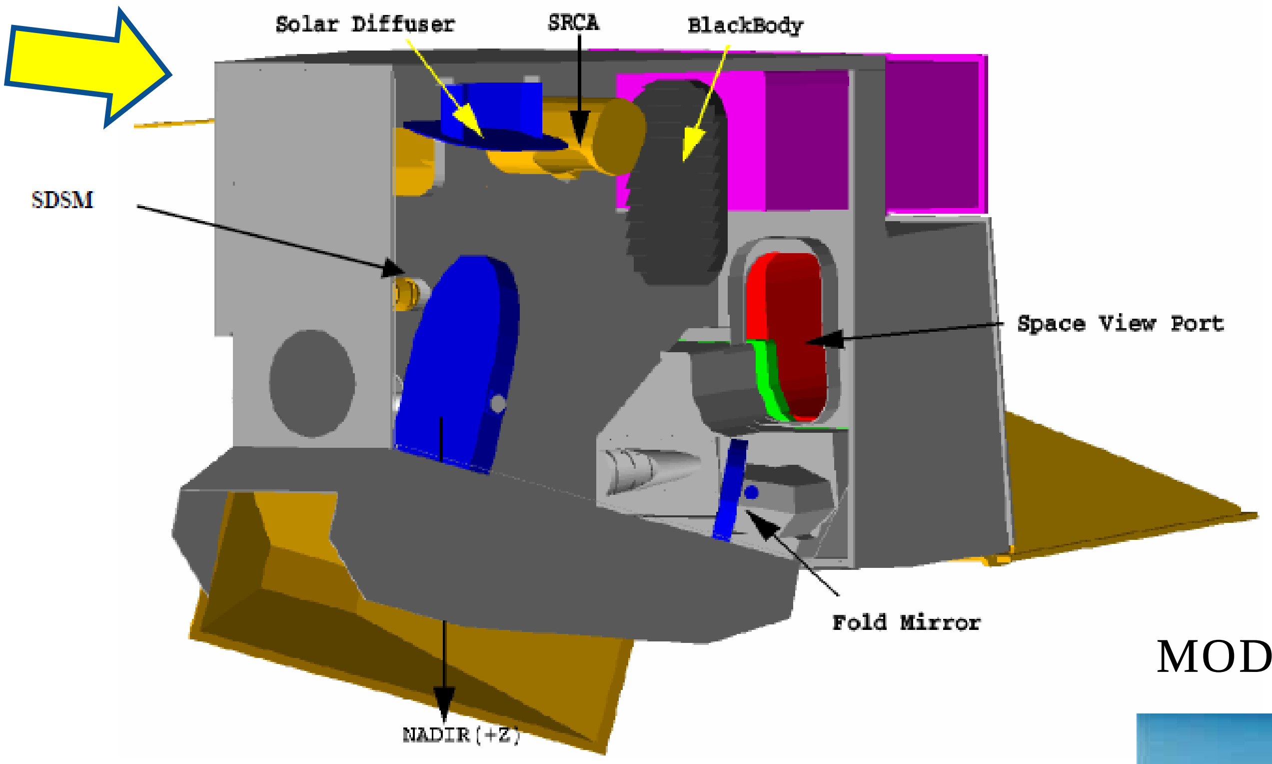


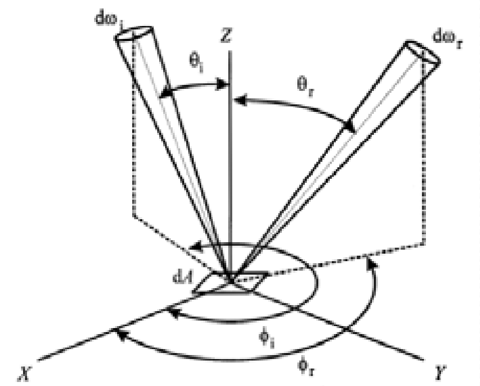
Figure 1 MODIS scan cavity and on-board calibrators.

- MODIS scan module backside view
- Note out-of-plane viewing of diffuser!

MODIS solar diffuser

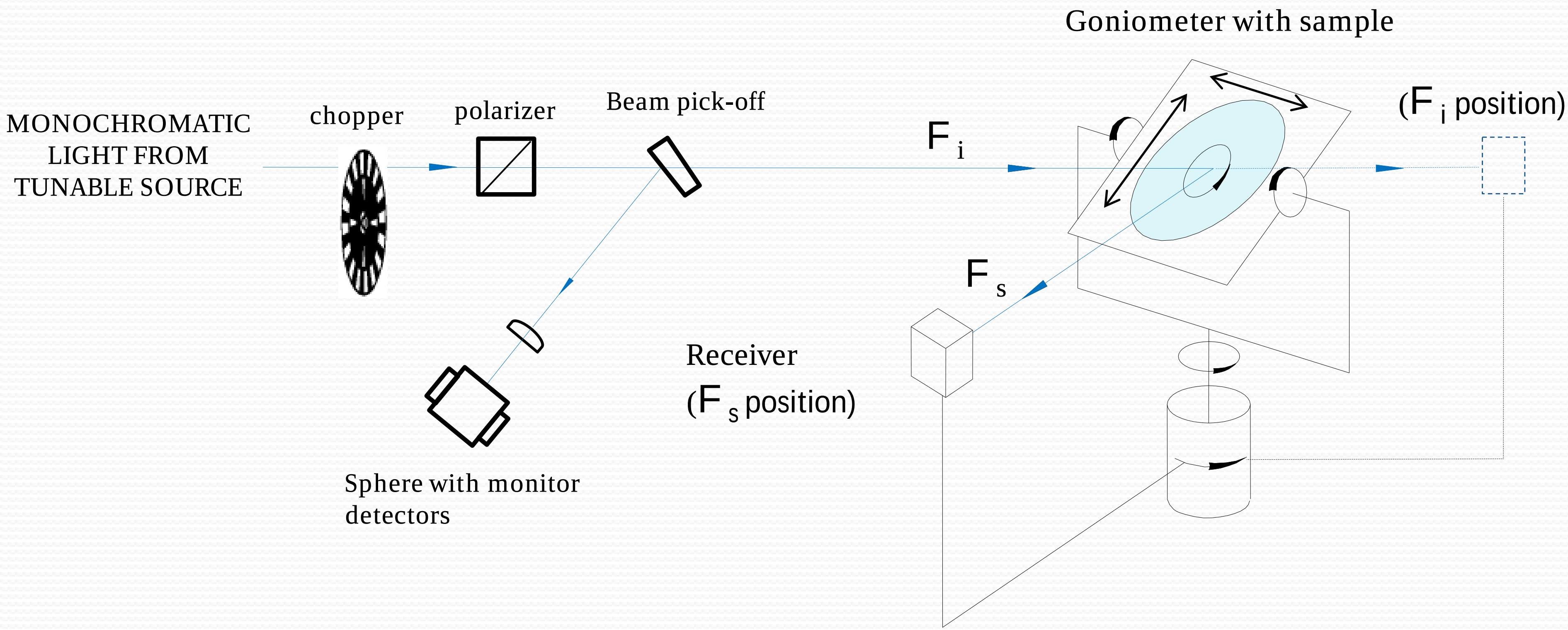
Diffuser measurement requirements

- BRDF into SWIR!
  - SWIR bands on VIIRS, LDCM OLI, CLARREO etc.
  - Current SWIR traceability through directional-hemispherical measurements; BRDF extrapolate?
- Flexibility in BRDF geometries
  - Out-of-plane measurements
  - Ability to survey diffuser surface



- High accuracy
  - 0.5% over full solar band and a range of incident/scattering angles
  - Challenging in UV and SWIR, and for out-of-plane

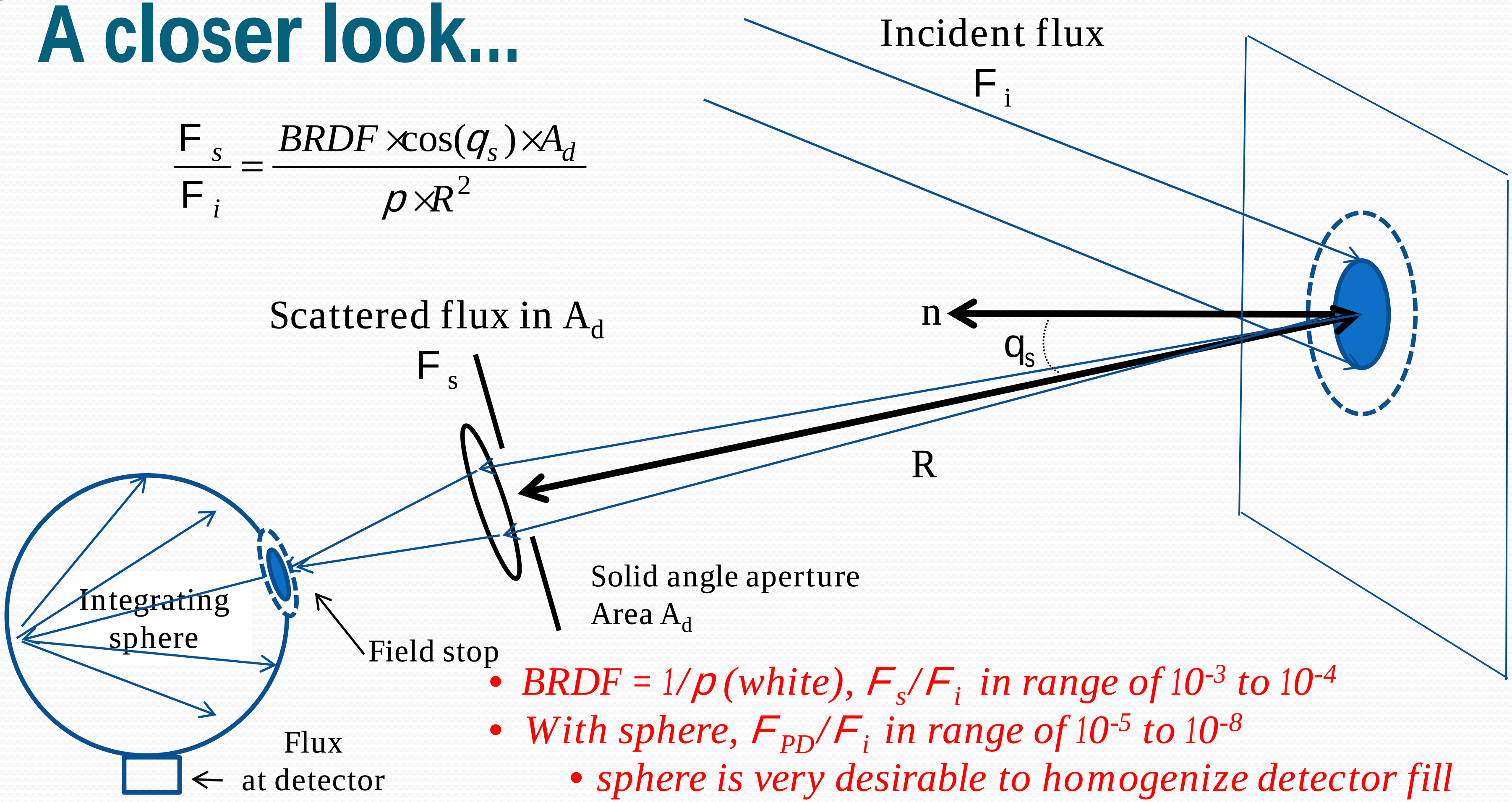
Proposed STARR II Layout



- Receiver measures incident flux (F_i) directly; no reference sample needed
- Goniometer allows arbitrary incident, scattering angles
- Plan for incident/scattering angles up to 80°
- Samples up to 32 cm on a side; detector arm around 750 mm
- Spot projected to sample not to exceed 1 cm diameter at sample
- Possible to scan sample surface

A closer look…

$$\frac{F_s}{F_i} = \frac{BRDF \times \cos(q_s) \times A_d}{p \times R^2}$$



- *BRDF = 1/p (white), F_s/F_i in range of 10^{-3} to 10^{-4}*
- *With sphere, F_{PD}/F_i in range of 10^{-5} to 10^{-8}*
  - *sphere is very desirable to homogenize detector fill*
- *Lamp-based source F_i ~ 100 nW at 2500 nm*
- *If F_i ~ 100 nW F_{PD} in 1 fW to 1 pW range!*
- *At these levels, F_{PD} can easily be lower than detector NEP*
- *Need to improve source power!*

Supercontinuum (SC) Fiber Laser Source

"As broad as a lamp, as bright as a laser"

- 450 nm – 2500 nm spectrum
- Broadband output through nonlinear conversion in fiber, up to 6W total output
- Quasi-cw, typical pulse repetition 10 MHz – 80 MHz
- Laser-like, diverging beam output from fiber

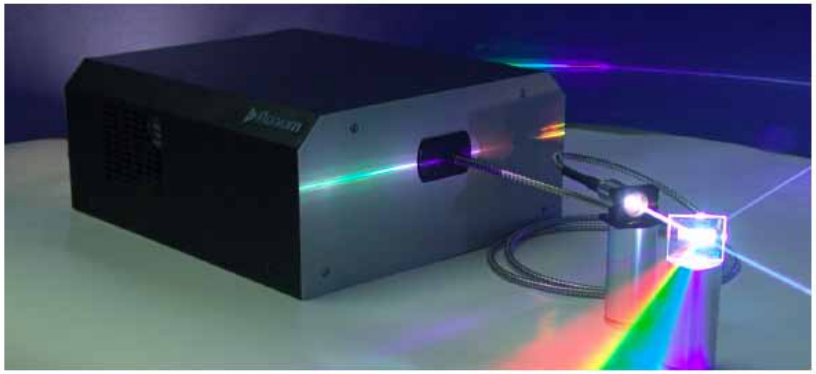


*image www.fianium.com

Photonic Crystal Fiber

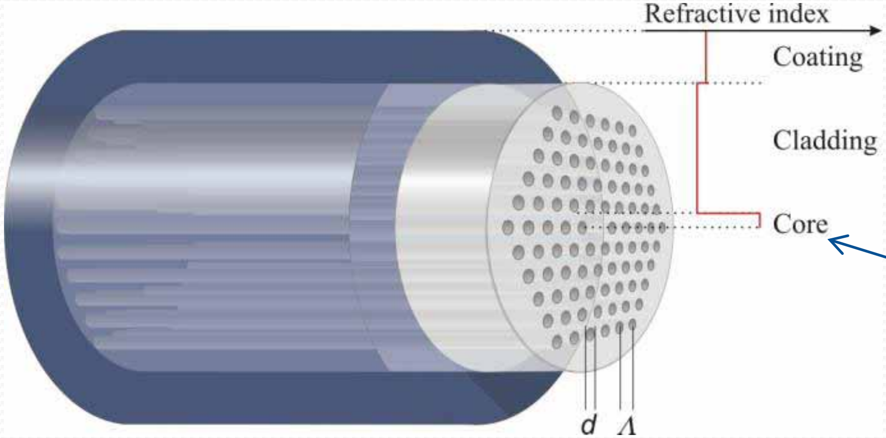


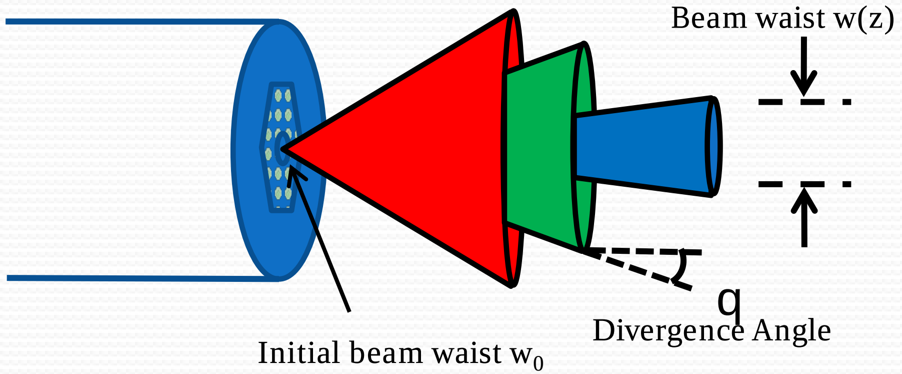
*image www.nktphotonics.com

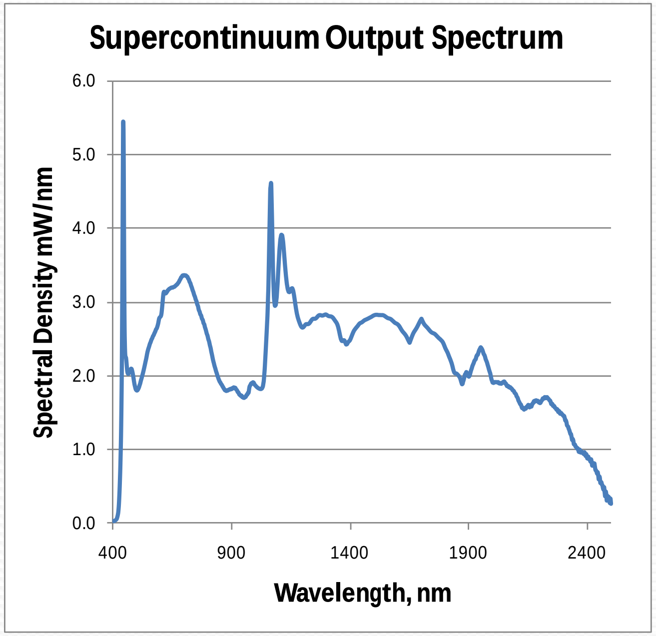
Hole pattern in cladding engineered for single mode operation at all wavelengths

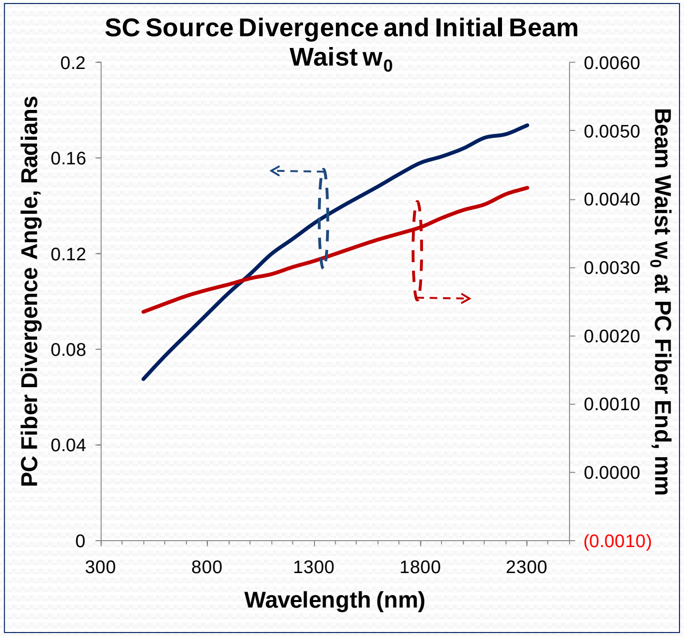
All light is guided in core region of several mm diameter

SC Spectrum and NA characterization

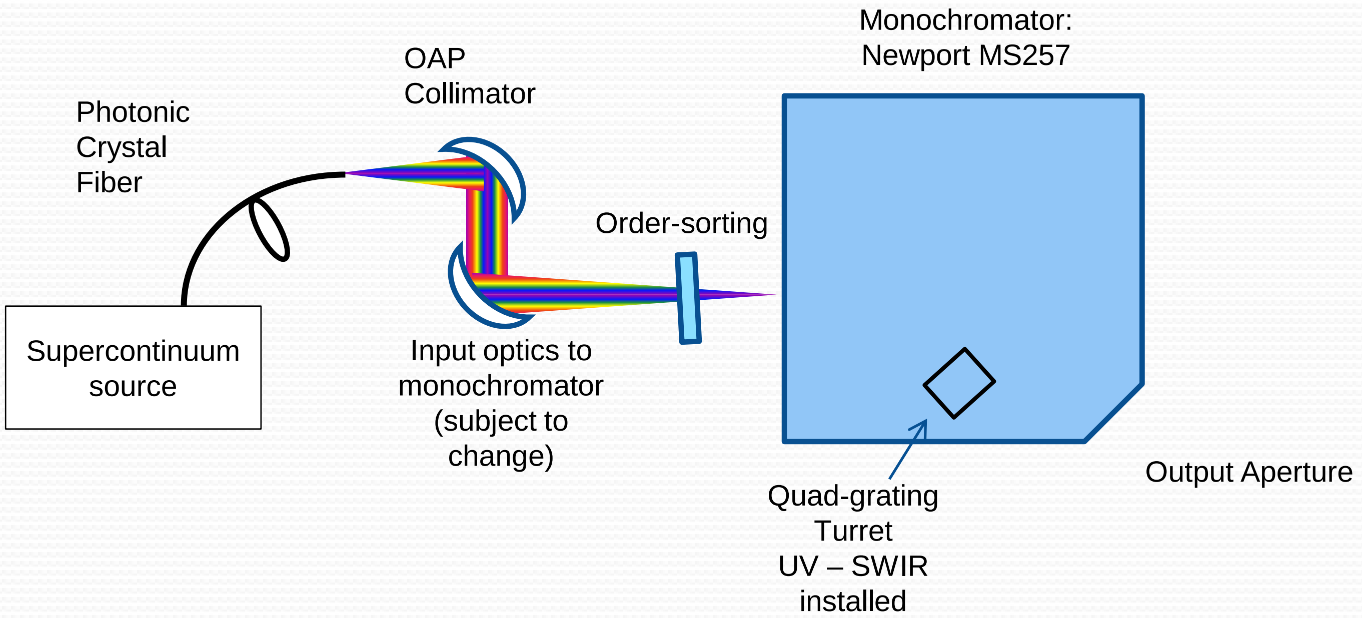
- SWIR-enhanced SC source
- > 0.3 mW/nm at 2500 nm
- Laser-like output; diverges from gaussian waist at fiber end
- Collimation demonstrated with OAP
- NA vs. wavelength measured; important for beam coupling







SC + Monochromator Tunable Source



- Couple SC to monochromator using reflective or refractive optics
  - Use NA info to avoid overfilling monochromator optics
  - Very efficient coupling due to directional source
  - Refractive optics also demonstrated; may be preferable to tune NA to fill optics at desired output wavelength
- Quad-grating turret gives UV-SWIR operation

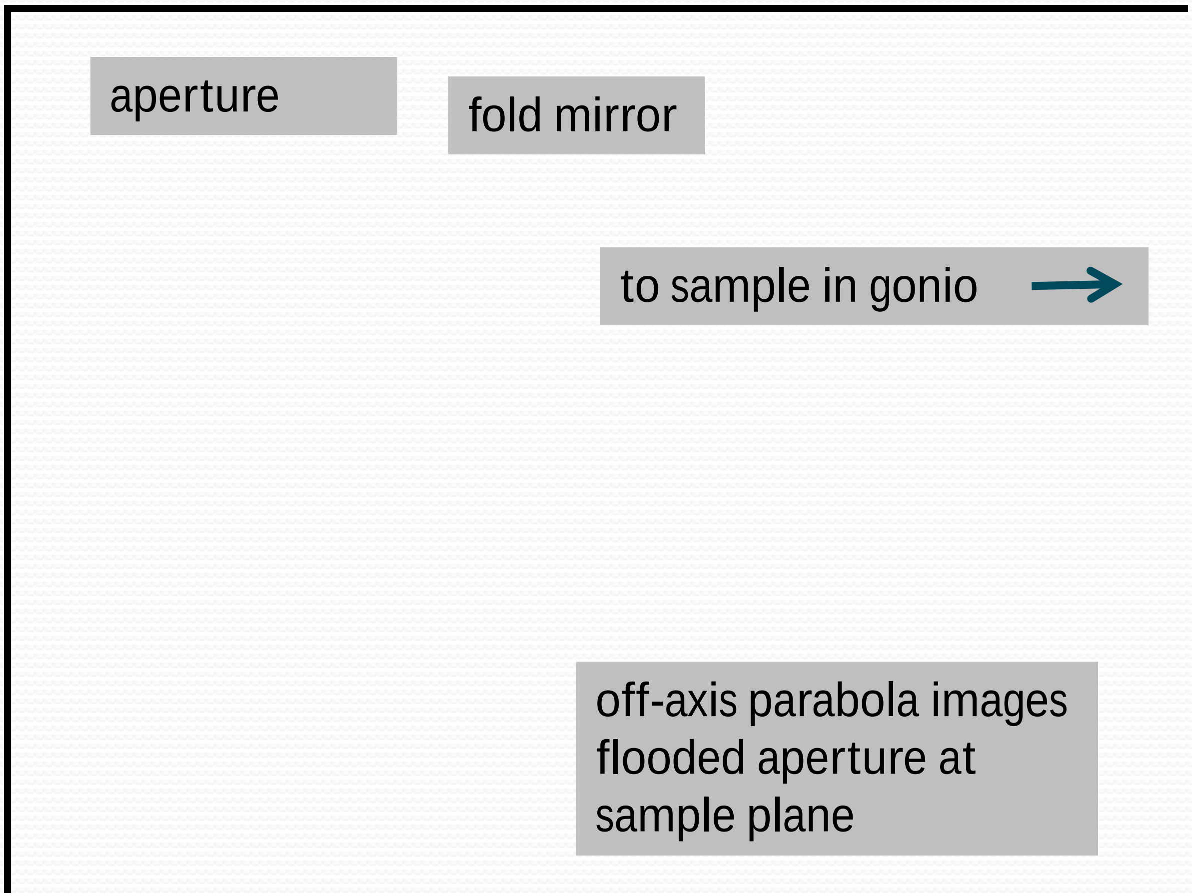
Initial Tunable Power Results

Set Wavelength (nm)	Power (mW)
500	2.83
600	3.75
700	6.89
800	6.05
900	5.96
1000	7.39
1100	14.23
1200	8.84
1300	12.64
1400	19.58
1500	22.62
1600	18.58
1700	14.12
1800	13.34
1900	11.18
2000	9.78
2100	7.72
2200	6.55
2300	4.24
2400	2.35
2500	1.39

- Measured at 2 mm circular exit aperture
- Unpolarized
- Quasi-monochromatic output in 11-12 nm BW
- > 1 mW out to 2500 nm

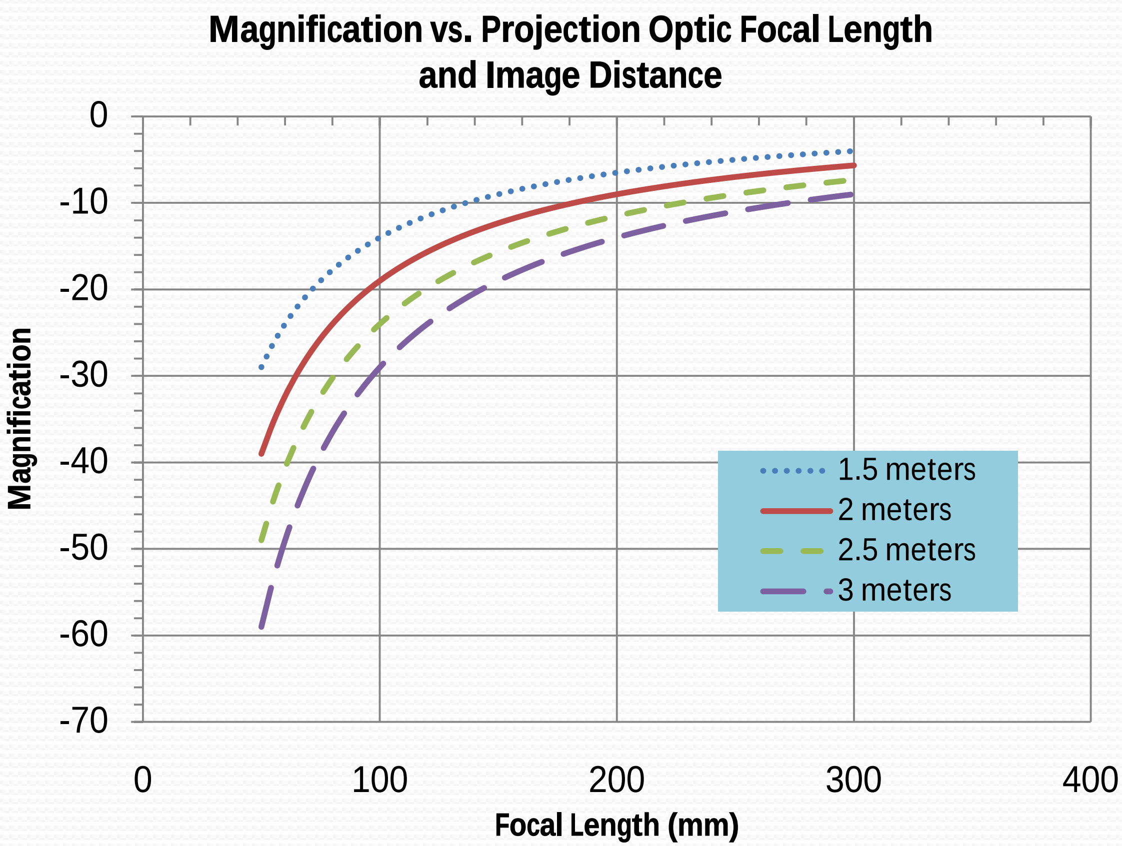
Initial coupling and power results are promising. But, good power at exit slit is not enough! Want to project uniform, or at least symmetric, illumination to sample.

Light Projection to Sample



- Off-axis parabola used to collect light flooding an aperture and to image aperture
- Focal length determined by image distance and required magnification…
- Desire illumination of aperture to be as uniform as possible

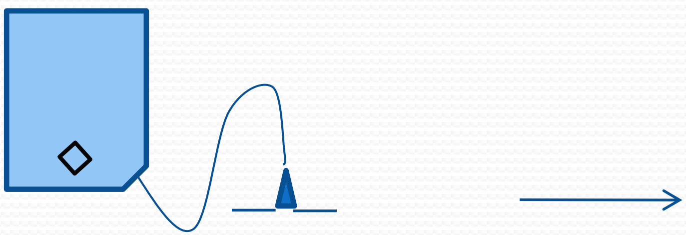
Magnification (M) and Focal Length (FL)



- 1 – z'/FL = M
- z' is image distance
- Ex: 2 meter image distance and magnification of -20 requires a FL = 95 mm
- M = -20 requires aperture of 0.5 mm diameter if 10 mm spot is desired at image plane

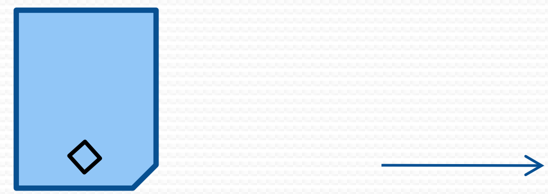
How to illuminate the aperture?

1. Use fiber at monochromator exit, flood aperture at distil end



- Demonstrated to 2300 nm with 1.8 mm core silica fiber
- > 300 mW at sample up to 2200 nm
- Projected spot can depend on fiber orientation
- Precipitous power drop past 2200 nm due to absorption in glass
- Considering fluoride fiber, transmits to 3500 nm but smaller core diameter => more loss

2. Image monochromator output aperture directly



- Use round exit aperture for monochromator
- Difficulty: light at exit aperture is more line-like, aperture *not* generally uniformly illuminated
- Zemax modeling can be used to guide how to defocus input to make output more uniform (requires translating input optics)
- May be power loss issues due to defocus

Movie!

Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
Fianium SC450-6
Projected to Specimen
Unknown DVD
Title 1
Chapter 1
00:04
DVD

Status and Outlook

- Supercontinuum-based light source in development
  - 6 W SC source with output to 2500 nm procured
  - Monochromator coupling demonstrated
  - Tunable output with 11-12 nm BW from 500 nm – 2500 nm
- Two options to project light to sample from aperture
  - Fiber-based
  - Free-space
  - Evaluating spot quality at sample plane
- Goniometer is in early stage of procurement
  - Leveraging existing expertise with GOSI