CEOS WMO-GSICS Workshop
An SI-Traceable Space-based Climate Observing System
NPL, UK
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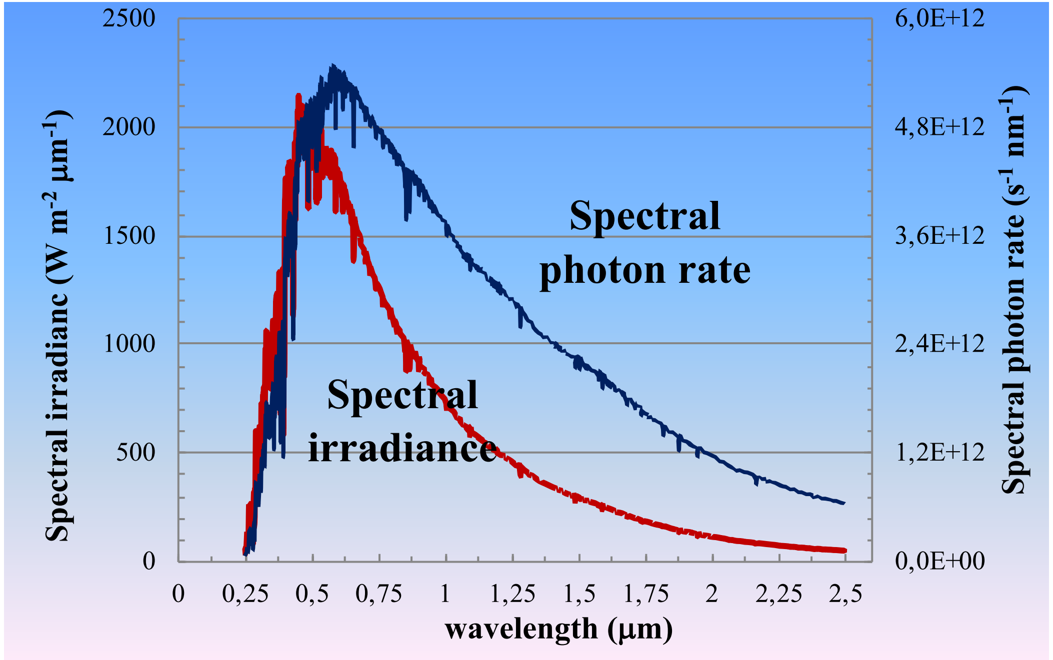
VIS-SWIR solar spectral irradiance radiometry based on Parametric Down-Conversion

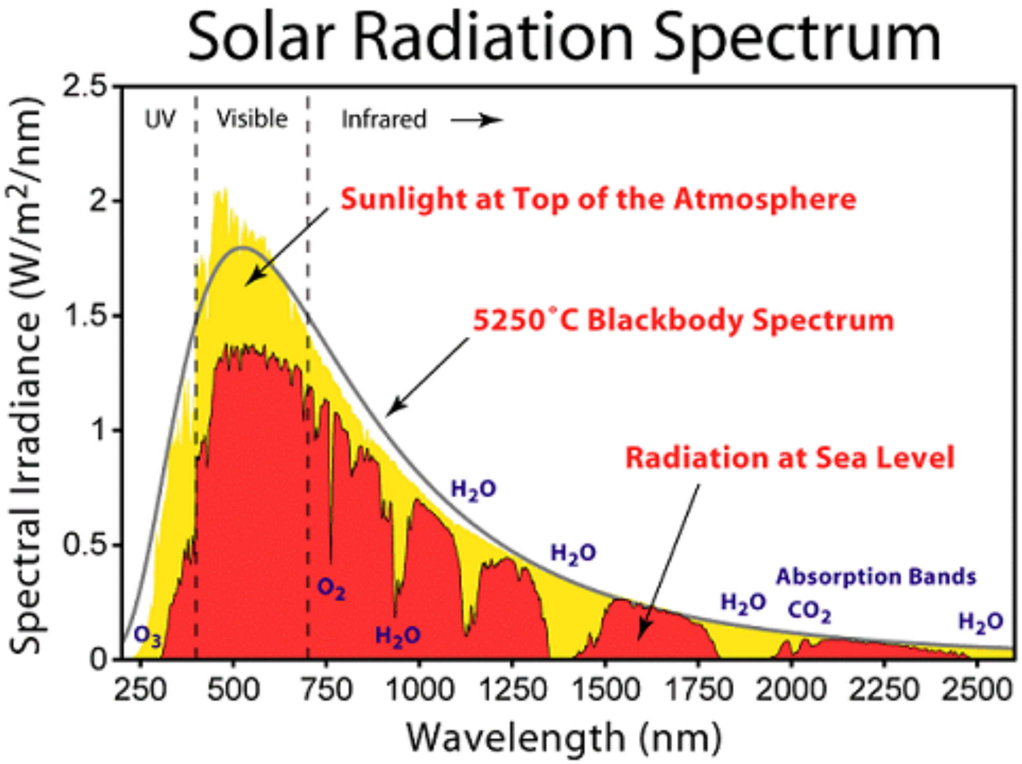
ZHENG Xiaobing
Key Laboratory of Optical Calibration and Characterization, CAS
Anhui Institute of Optics and Fine Mechanics, CAS

Goal

- A space benchmark measuring TOA solar spectral irradiance
- Calibrated with correlated photons
- Uncertainty < 0.3%
- spectrum 380 – 2500 nm
- Resolution 3 – 8 nm
- Current endeavor: lab prototype by 2022

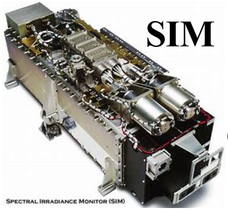


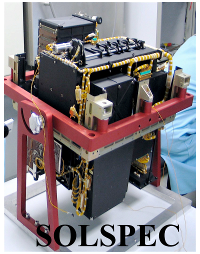
Solar Radiation and Climate Change

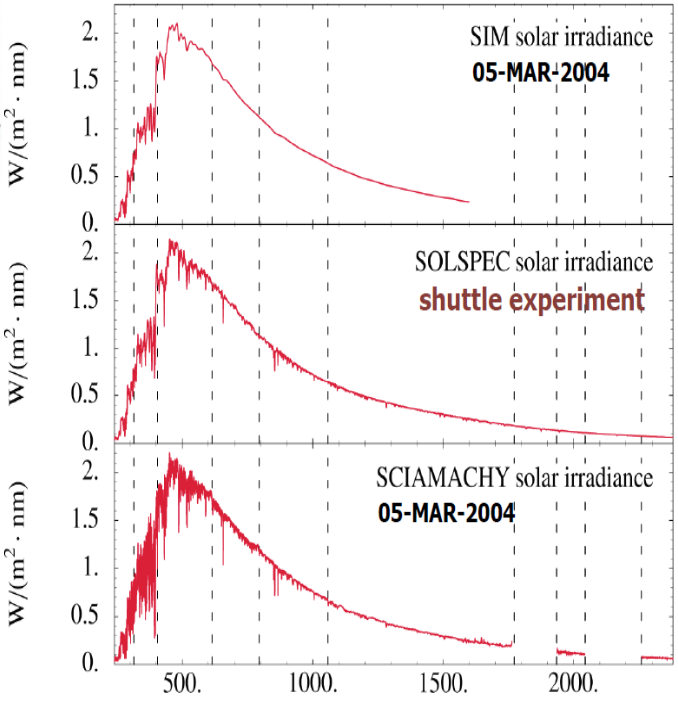


- Solar radiation is the primary incoming energy source of Earth system
- 250 nm – 2500 nm covers 95% solar radiation: visible band, photosynthesis band, atmosphere absorption bands…..
- incident and reflected radiation measurement accuracy 0.05% - 1%

Previous space sensors

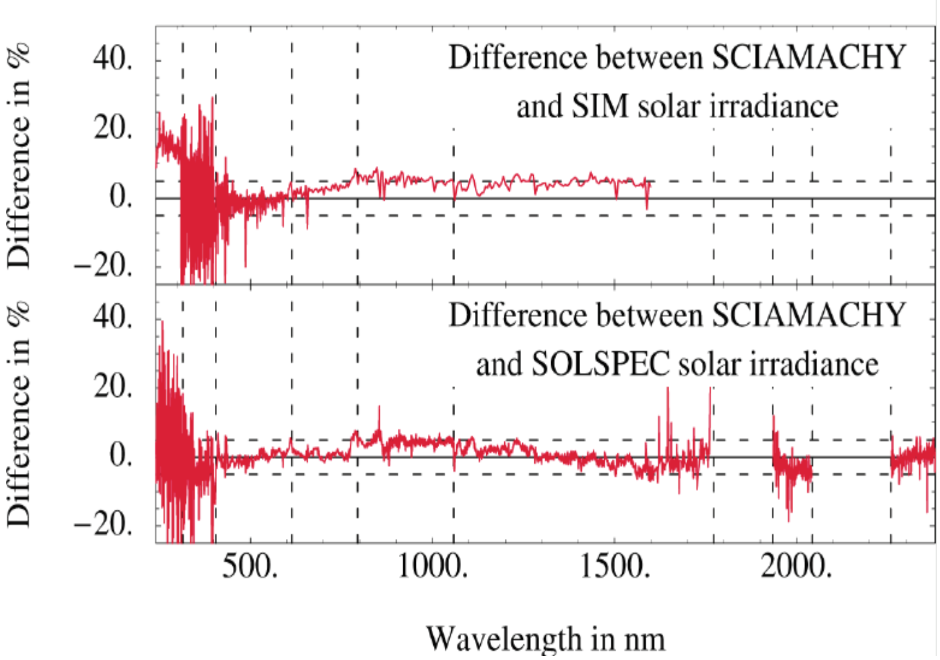






Comparison of SCIAMACHY、SIM、SOLSPEC

~10% (< 500 nm)，~ 3% (500-2500nm)



M. Weber, J. Pagaran, S. Noel, J. Skupin*, K.Gerilowski, and J.P. Burrows, Solar UV/Vis/NIR Spectral Irradiance from SCIAMACHY and GOME, Solar Spectral Irradiance Intercomparison Workshop, Orcas Island, WA, September 19, 2006.
Skupin et al., 2005

Quantum Candela

Definition since 1979

radiation of frequency 540×10^{12} Hz and radiant intensity of **1/683 W/sr** in given direction 。

Proposed definition

photons of frequency 540×10^{12} hertz at a rate of **4.092×10^{15} /s/sr** in given direction.

$$P = Nh\nu$$

Candela realized by counting photon number and linked to power via Plank's constant

J. Y. Cheung, C. J. Chunnilall, E. R. Woolliams, N. P. Fox, J. R. Mountford, J. Wang & P. J. Thomas (2007): The quantum candela: a re-definition of the standard units for optical radiation, Journal of Modern Optics, 54:2-3, 373-396

Realizing quantum candela

Key to realize quantum Candela:
precise counting of photon numbers

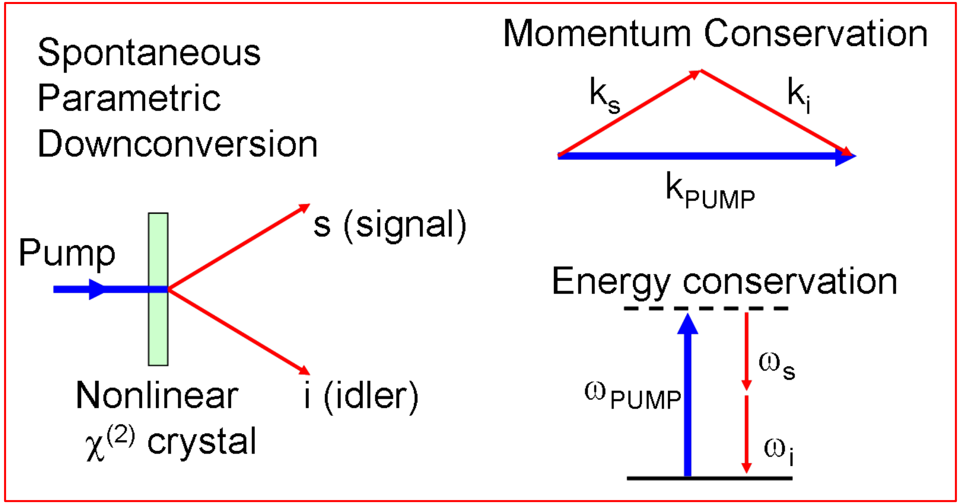
Single photon detectors with calibrated quantum efficiency

Single photon source with controllable statistical properties

Correlated photons generated in parametric down-conversion (PDC)

Photon flow

SPDC（Spontaneous Parametric Down-conversion）

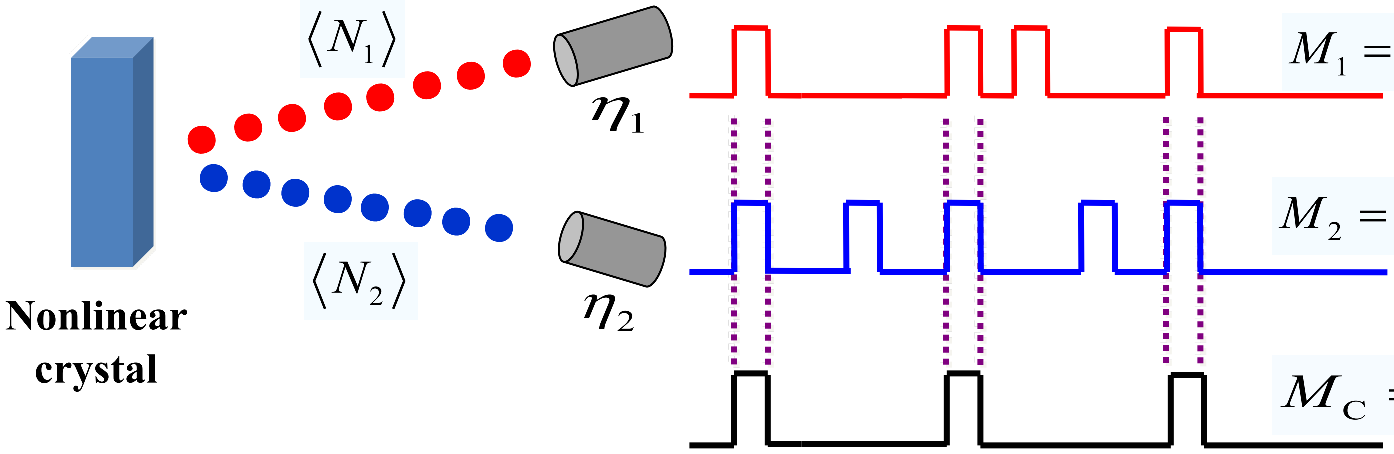


$$\omega_{pump} = \omega_s + \omega_i$$

$$\vec{k}_{pump} = \vec{k}_s + \vec{k}_i$$

- A second order nonlinear effect, predicted in 1960’, proved in 1970’
- A pumping photon will generate a pair of photons (signal and idler) when passing a nonlinear crystal
- Energy and momentum conservation decide wavelengths and directions of photons pairs
- Time correlation of photon pair (simultaneity) can be used to calibrate absolute quantum efficiency of photon counters.

Detector calibration with SPDC



$M_1 = \eta_1 \langle N_1 \rangle$

$M_2 = \eta_2 \langle N_2 \rangle$

$M_C = \eta_1 \eta_2 \langle N_c \rangle$

Twin photons ⇨ $\langle N_1 \rangle = \langle N_2 \rangle = \langle N_c \rangle$

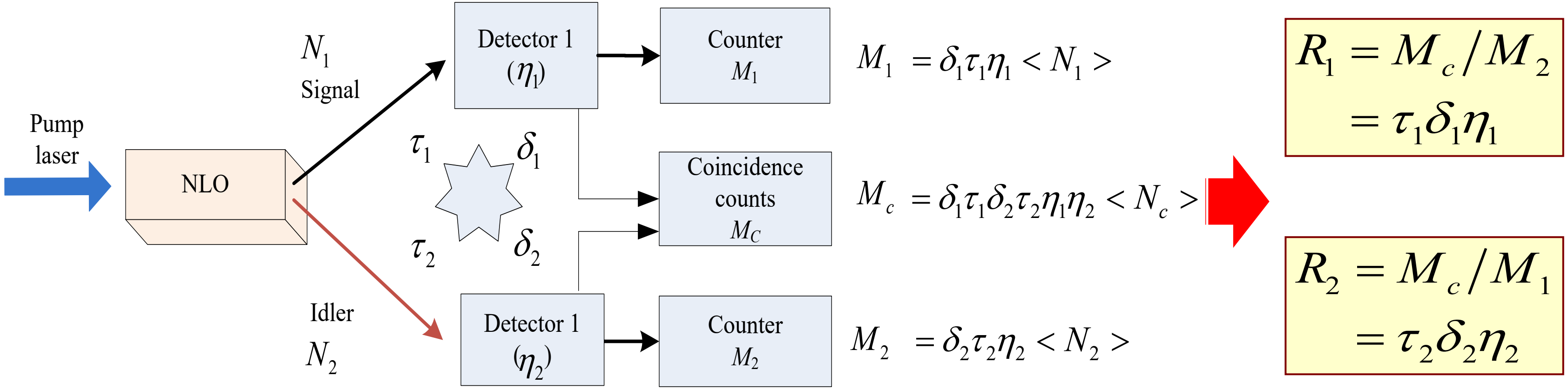
Absolute quantum efficiency ⇨

$$\eta_1 = M_c / M_2$$
$$\eta_2 = M_c / M_1$$

Features of SPDC calibration

★ **Intrinsically absolute, No outer standard needed**

★ **Insensitive to degradation, promising for space benchmark**

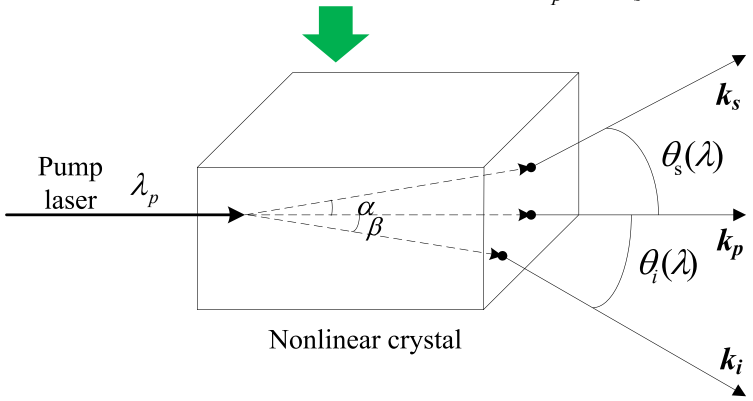


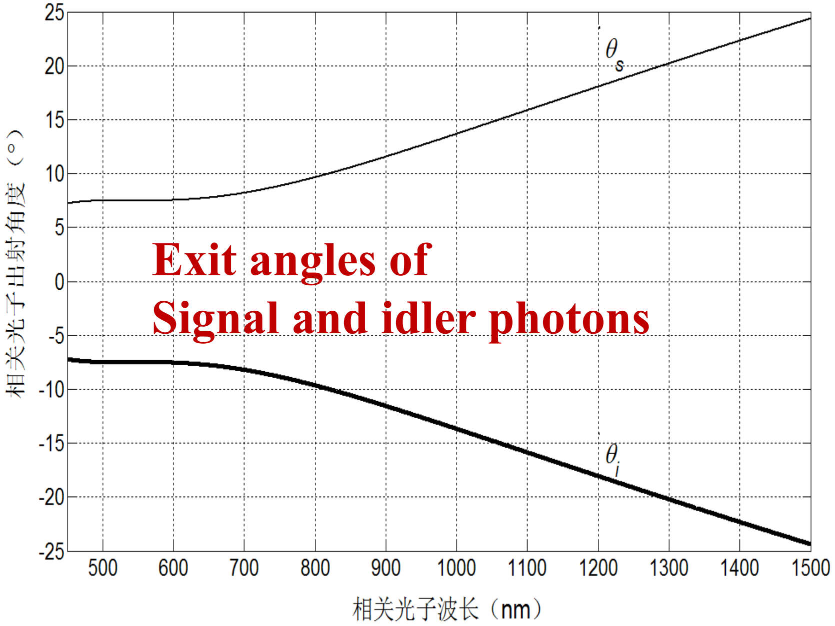
Features of SPDC calibration

★ **Wide working spectrum, pumping frequency to crystal lattice resonant frequency**

Crystal Birefringence for phase matching

$$\cos\alpha = \frac{\left(\frac{n_p^e(\theta)}{\lambda_p}\right)^2 + \left(\frac{n_s^o}{\lambda_s}\right)^2 - \left(\frac{n_i^o}{\lambda_i}\right)^2}{2\frac{n_p^e(\theta)}{\lambda_p}\cdot\frac{n_s^o}{\lambda_s}}$$





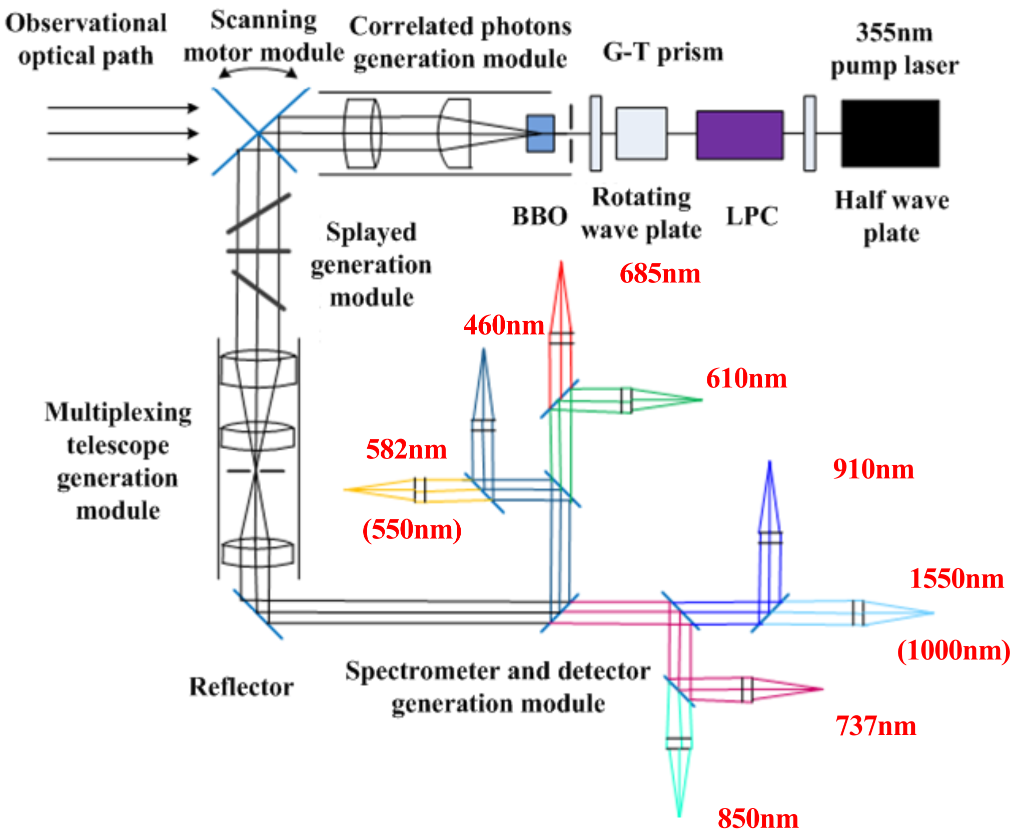
Progress of SPDC calibration

Research team /Time	Pump laser	Crystal	Correlated photons	Detector	**Uncertainty**
Burnham (UK) 1970	He-Cd 325nm 5mW	BBO	633/668.5nm	PMT PMT	**20%**
NIST/IEN 2002	Ar+351.1nm 30mW	KDP	632.8/789nm	APD APD	**0.4%**
J.Y.Cheung (NPL) 2006	Ar+351.1nm 10mW	BBO	702.2/702.2nm	APD APD	**0.36%**
Polyakov (NIST) 2007	Ar+351.1nm	LiIO3	702.2/702.2nm	APD APD	**0.18%**
M S Kang (KRISS) 2008	He-Cd 325nm 5mW	BBO	633/668.5nm	APD APD	**0.2%**
S.Ramelow (IQOQI) 2013	LD405nm	ppKTP	810/810nm	APD APD	**0.3%**

Progress of SPDC calibration (China)

Research team /Time	Pump laser/ Crystal	Correlated photons	Detector	Uncertainty
Institute of Physics, CAS 2003-2006	441.6nm BBO	883.2nm/ 883.2nm	PMT	——
Tianjin University	1544nm Fiber	1550.7/ 1537.4nm	APD/ APD	1.2%
National Institute of Metrology 2012	351.1nm BBO	702.2/702.2nm; 632.8/788.7nm;	PMT/ PMT	0.7%
AIOFM 2015-2017	**355nm BBO**	**8 band @400-1100nm**	**PMT/ APD**	**0.3%**

8-channel radiometer with SPCD calibration



Spectrum: 450-1000 nm

Detectors: 8 APDs (Avalanche Photodiodes)

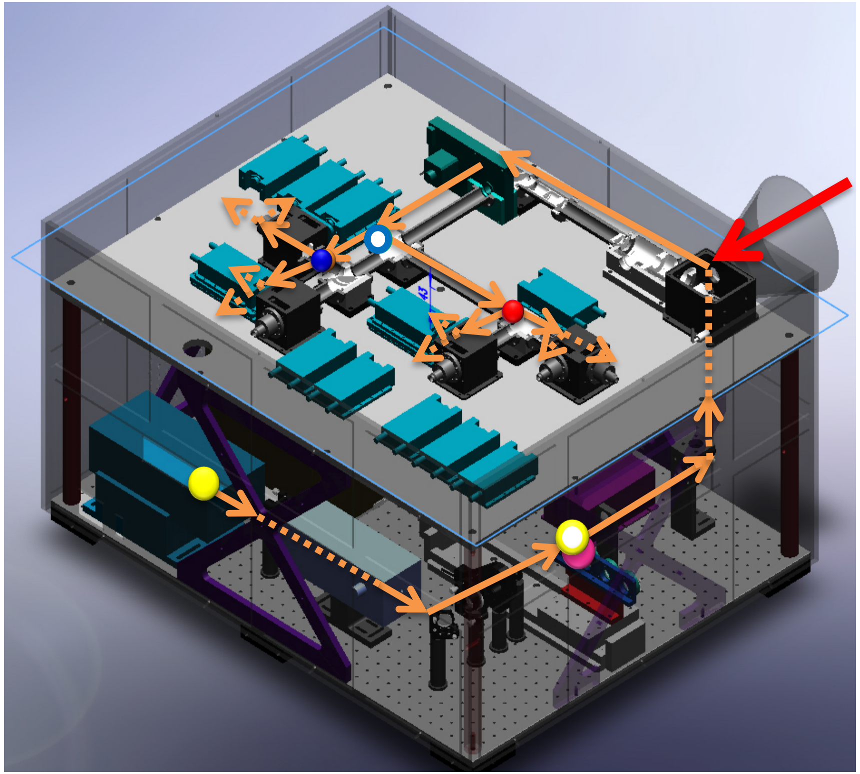
Puming wavelength: 355 nm

Crystal: BBO

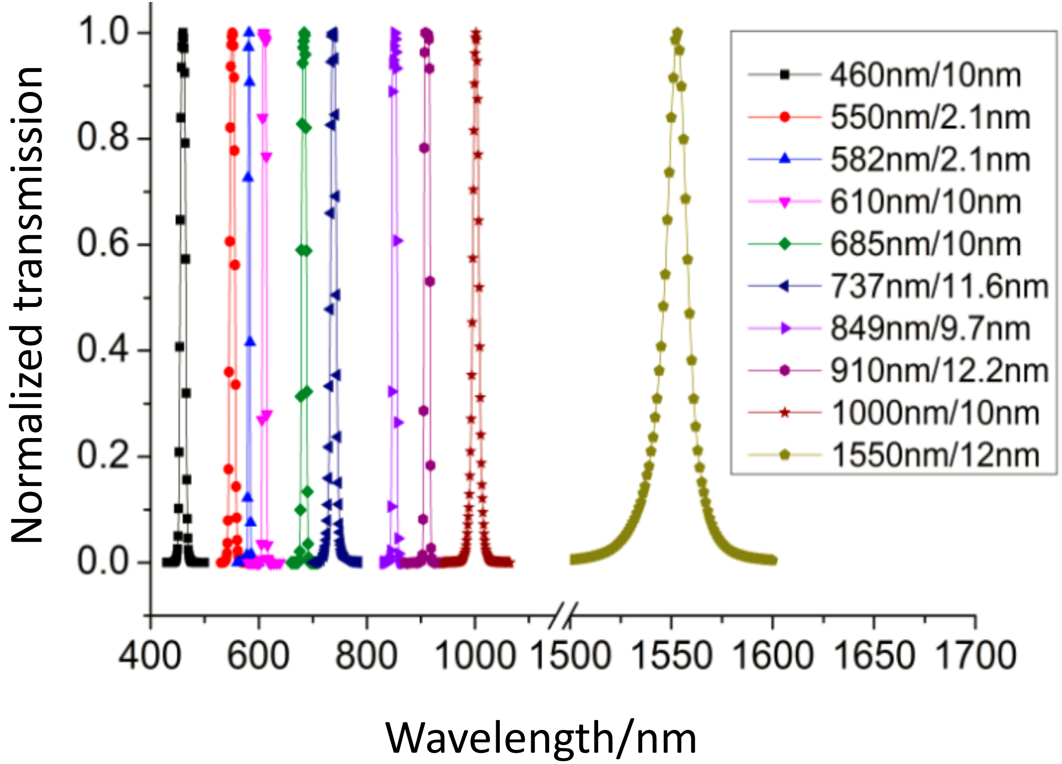
Working modes:

self-calibration + observation

A prototype of 8-channel radiometer

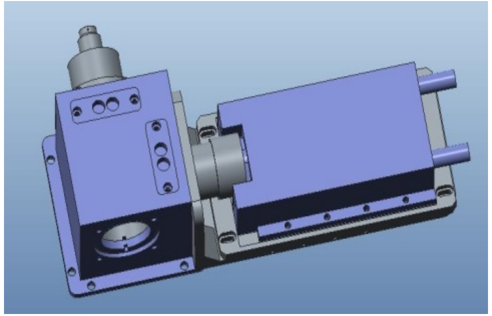


Channel center wavelength and bandwidth



Signal （nm）	Idle（nm）
460 nm	1550 nm
582 nm	910 nm
610 nm	850 nm
685 nm	737 nm

Narrow band interference filters to match twin photon's wavelength and bandwidth



Radiance measurement

Photon rate — Detector count

Incident photon flux

$$\Phi = N \cdot h\nu = \frac{M}{\eta} \cdot \frac{hc}{\lambda} \cdot \frac{1}{\delta}$$

Quantum efficiency — Correction factor

Incident radiance

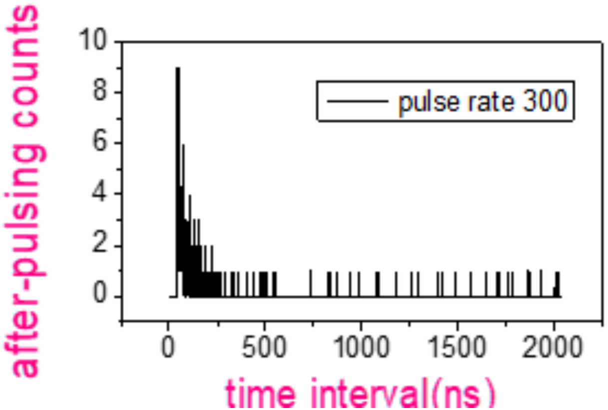
$$L = \frac{\Phi}{\Omega \cdot A}$$

h – Planck's constant
c - light speed
Ω and A – incident solid angle and aperture area
δ - correction factor obtain in self-calibration mode

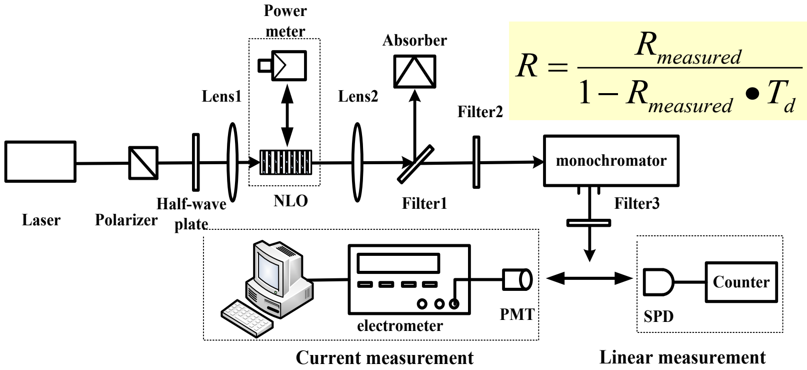
Uncertainty sources of measurements

- **Dark count ~ 10 s^{-1}**
- **Dead time of single photon detectors**
- **Nonlinearity of detector response**
- **After-pulsing probability ~ 1%**
- **Accidental counting**
- **…..**

Dead time measurement



After-pulsing probability



$$R = \frac{R_{measured}}{1 - R_{measured} \bullet T_d}$$

Nonlinearity measurement

Evaluation of radiance measurement uncertainty

Uncertainty source		Measurement results
Combined relative standard uncertainty		**0.29%**
Self-calibration mode	Photon counts	0.2%
	Coincidence counts	
	Background and accident coincidence	
	Nonlinearity of detectors	0.07%
Observation mode	Transmission	0.05%
	Aperture area	0.04%
	Counter accuracy	0.04%
	Solid angle	0.1%
	Observation counts	0.15%

Comparison with cryogenic radiometer

ESR-based radiance

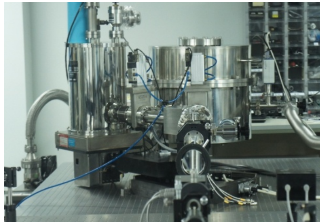
(traceable to cryogenic radiometer)

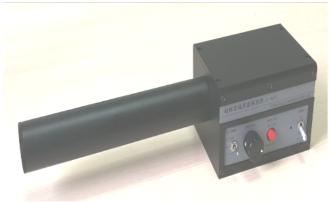
$$E_n = \frac{L_c(\lambda) - L_s(\lambda)}{\sqrt{u_{Lc}^{\ 2} + u_{Ls}^{\ 2}}}$$

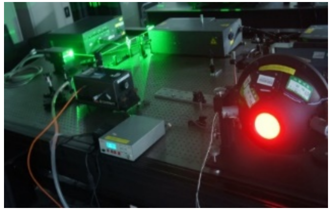
SPDC-based radiance

$\Phi \rightarrow R_{\Phi}(\lambda) \rightarrow R_L(\lambda) \rightarrow L_s(\lambda)$

HACR | Trap detector | Radiance detector | radiance





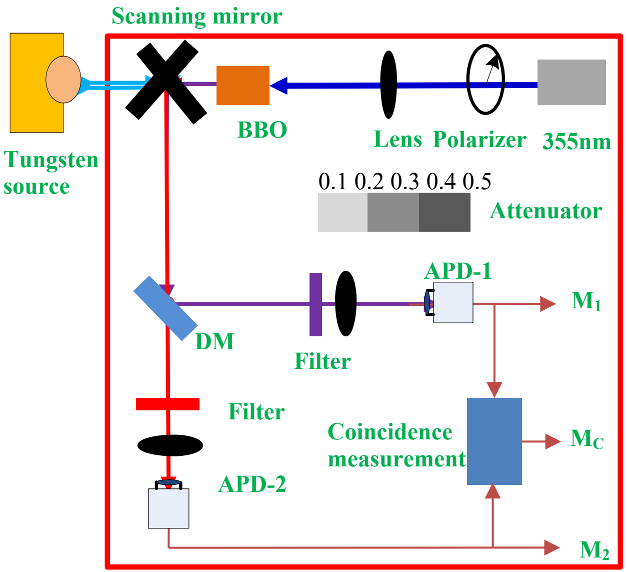


Observation counts

$$L_c(\lambda) = \frac{N_1}{R_1}\frac{hc}{\Omega \cdot A \cdot \lambda} = \frac{N_1}{M_c / M_2}\frac{hc}{\Omega \cdot A \cdot \lambda}$$

Radiance | Coincidence counts | Trigger counts

Prove insensitivity to degradation

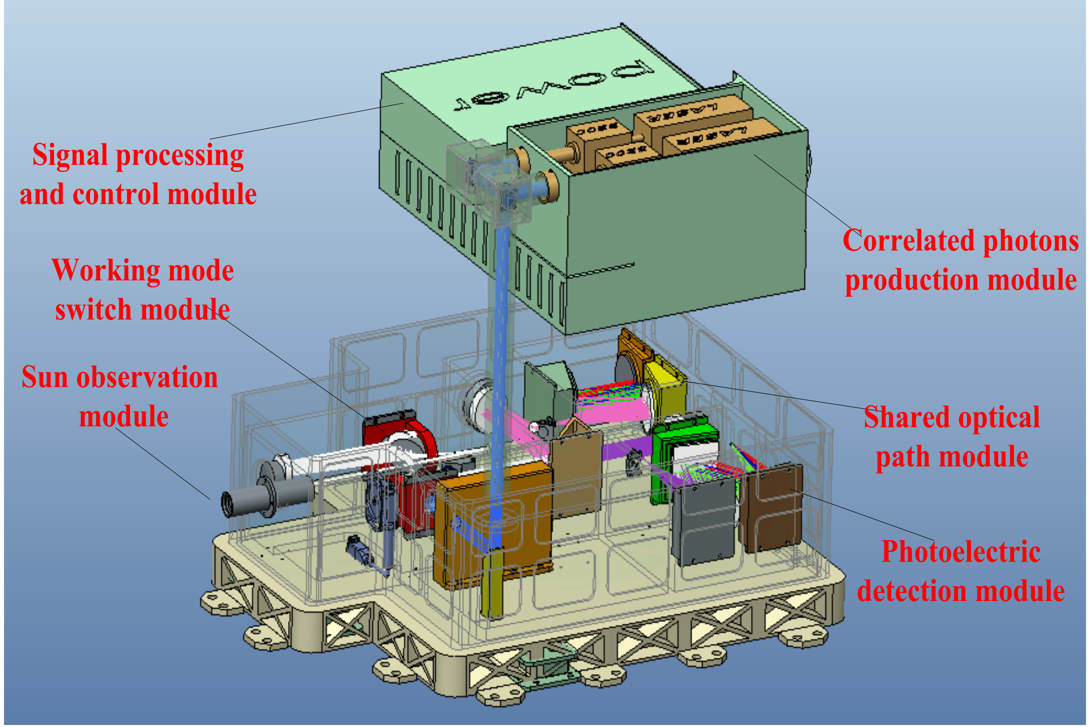


Attenuator No	degradation ratio	Radiance (W/sr·mm²)
1	0.2	2.34×10^{-9}
2	0.3	2.35×10^{-9}
3	0.5	2.34×10^{-9}
4	0.6	2.36×10^{-9}
5	0.7	2.35×10^{-9}
RSD		0.29 %

◆0~70% optical decay， integrating sphere radiance RSD is 0.29%。

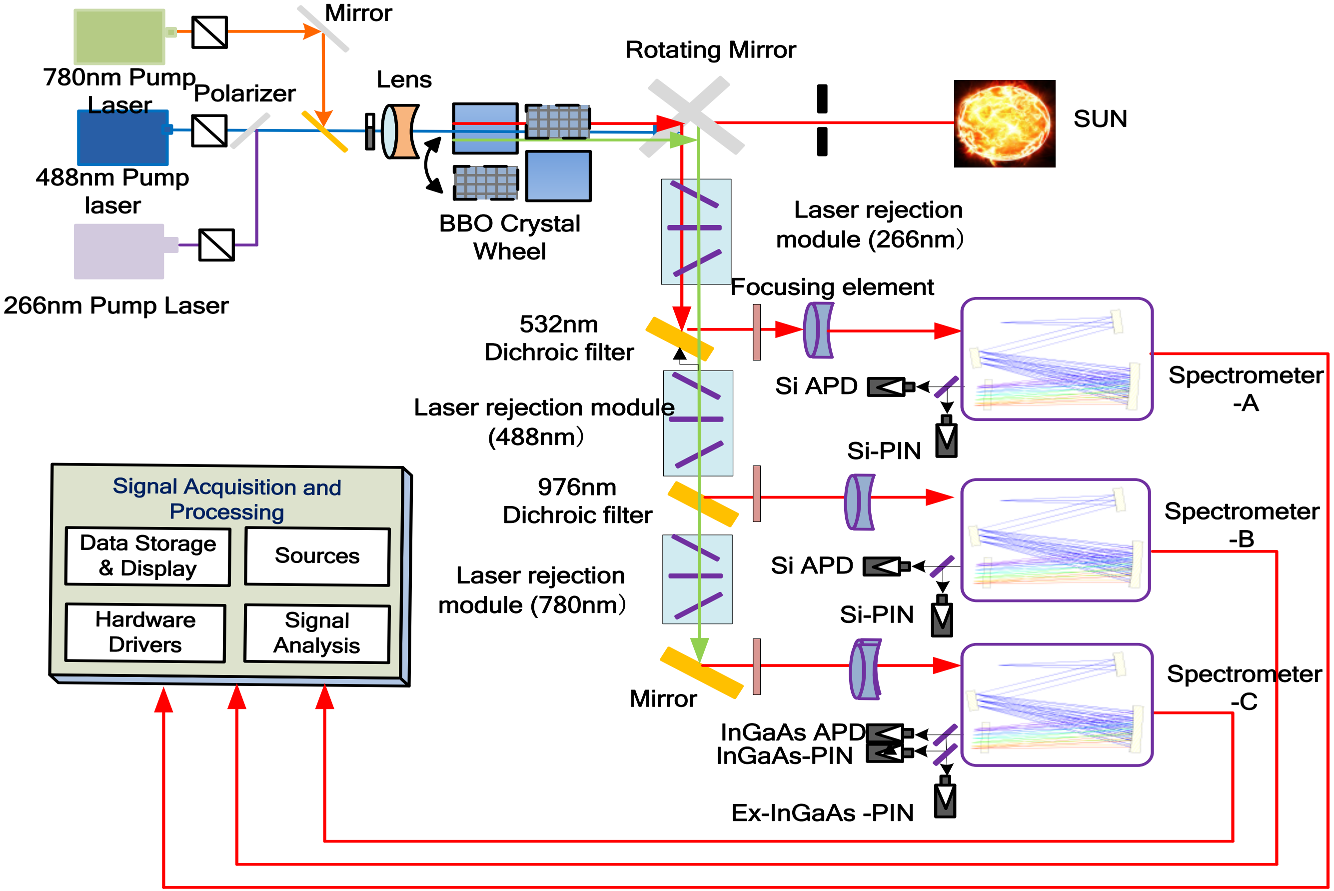
◆0~80% electronic decay， integrating sphere radiance RSD is 0.28%。

Next step: A prototype for space benchmark



- Absolute solar spectral irradiance accuracy: 0.3%
- Spectral range:
  380 nm - 2500 nm
- Spectral resolution:
  3 nm - 8 nm
- A prototype by 2022
- With cooperation of 6 institutes of China

Overall Design



- ✓ 3 pumping lasers @ 266, 488, 780 nm
- ✓ correlated photons @ 380-2500 nm
- ✓ 3 APDs detect correlated photon pairs
- ✓ 4 analog detectors for self-calibration and solar observation

Traceability of solar spectral irradiance

Channel quantum efficiency — $\eta_C(\lambda_s)$

↓ Calibration mode of correlated photons

$$\eta_{DUT} = \frac{M_c - M_{CA}}{M_{A-Valid} - M_{AB}}$$

Spectral power of correlated photons — $P_C(\lambda_s)$

↓ Analog detector measurement

Absolute spectral responsivity — $R_D(\lambda_s)$

$$R = \frac{I_c}{P} = I_c \frac{\lambda \cdot \eta_{DUT}}{N_{\Delta\lambda} hc}$$

↓ Linear measurement and correction

Solar spectral power — $P_D(\lambda_s)$

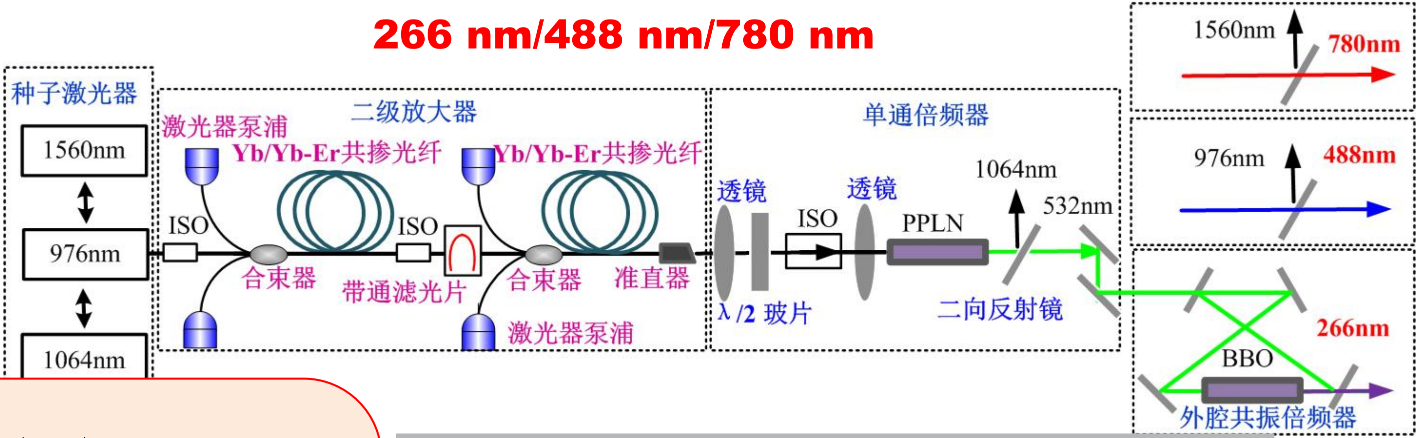
↓ Iris area A, Spectral bandwidth Δ λ

Solar spectral irradiance — $E_\lambda(\lambda_s)$

$$E = \frac{I_{sun} \cdot N_{\Delta\lambda} \cdot \mathrm{h} \cdot \mathrm{c} \cdot (M_{A-Valid} - M_{AB})}{I_c \cdot \lambda \cdot (M_c - M_{CA}) \cdot A \cdot \Delta\lambda}$$

Pumping lasers

266 nm/488 nm/780 nm



Wide spectrum parametric down-conversion

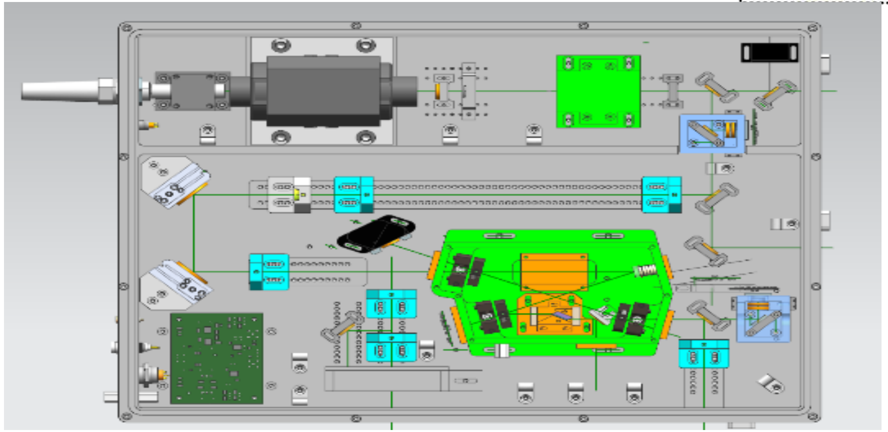
Output:

1.5W@780nm、

1W@488nm、

0.05W@266nm

Stability: 0.3%/3h



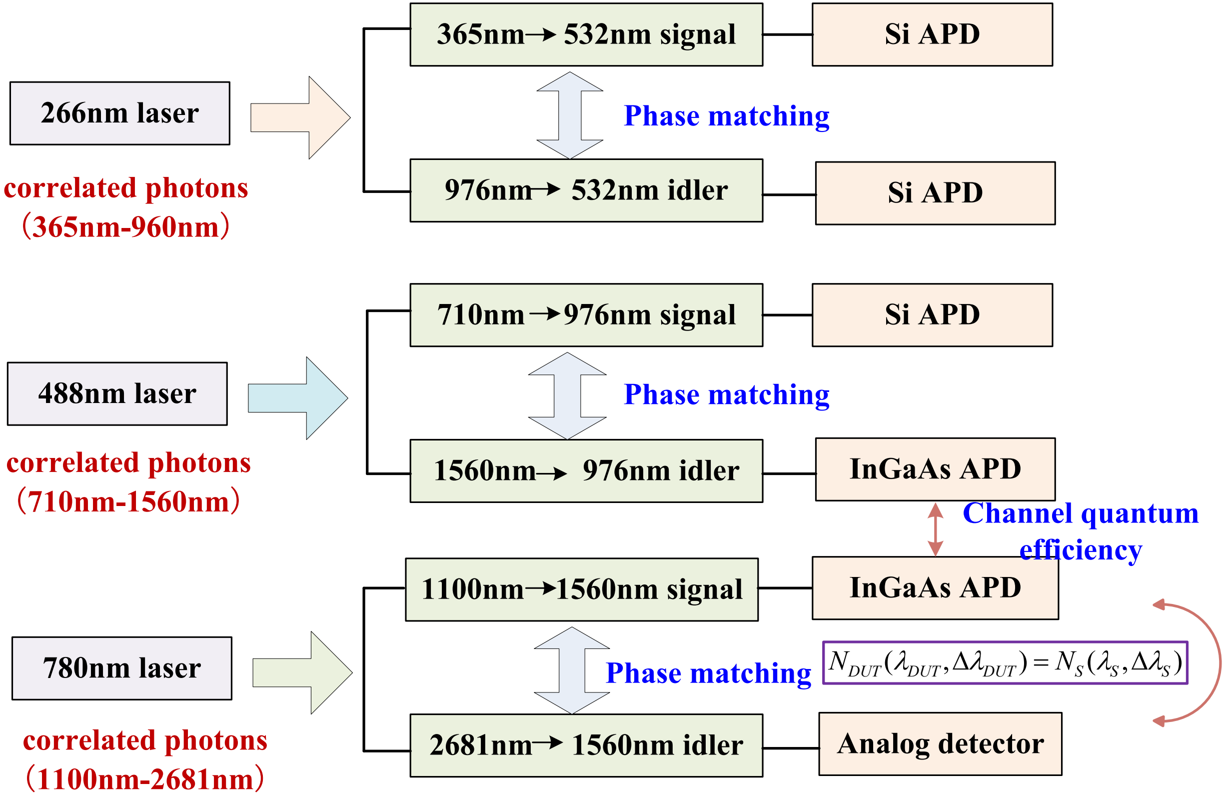
Spectrum matching for correlated photons and detectors

Nonlinear Crystals

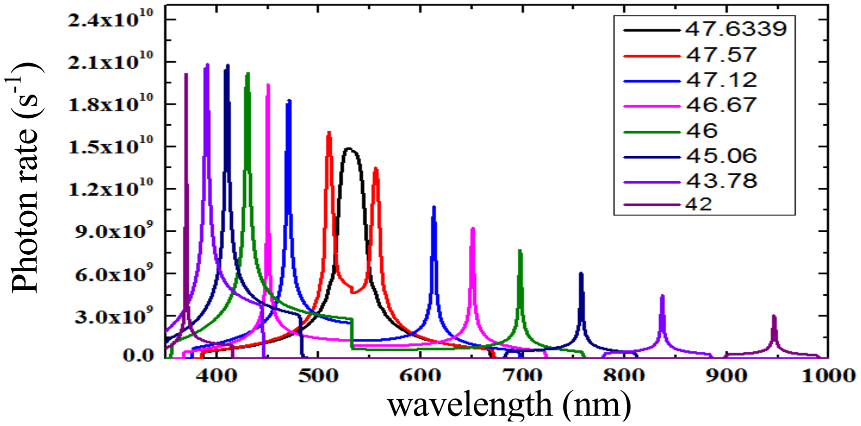
BBO，PPLN (backup)

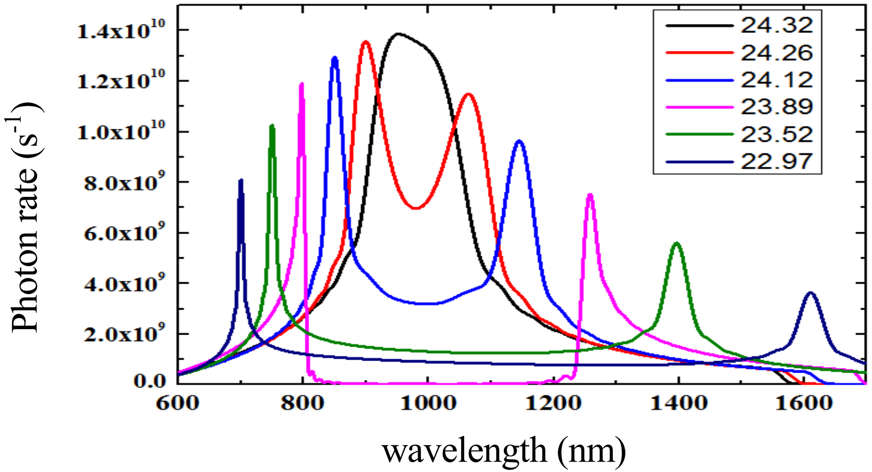
Phase matching mode

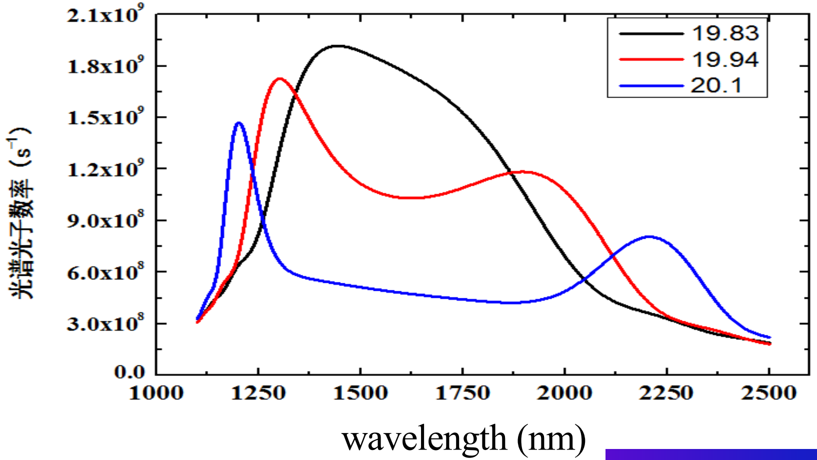
type I collinear (e → o+o)



Phase matching optimizing: spectrum and photon rate

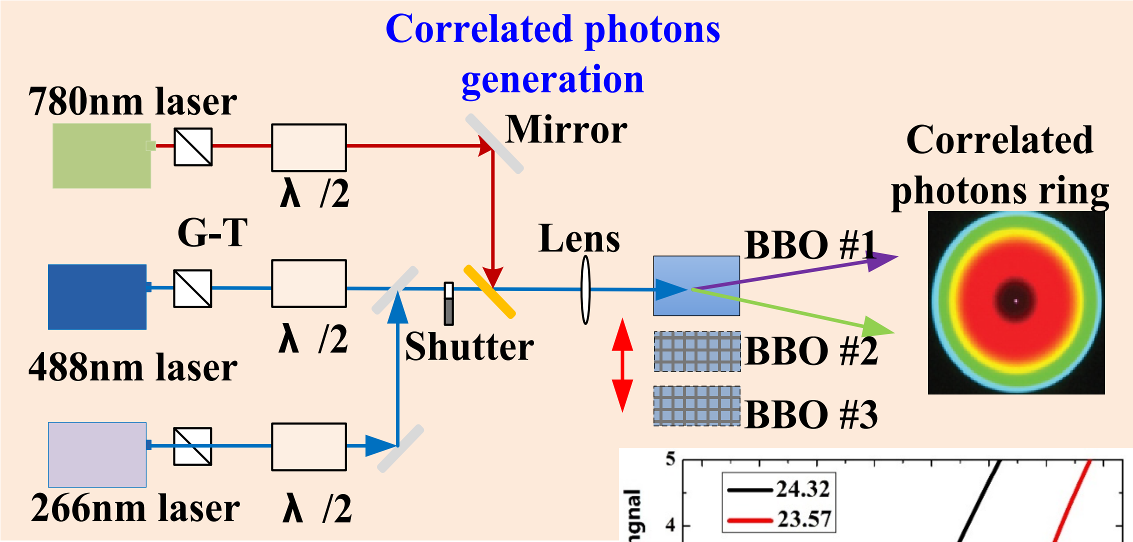


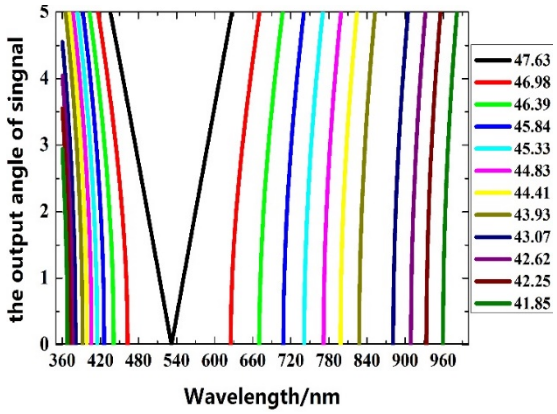




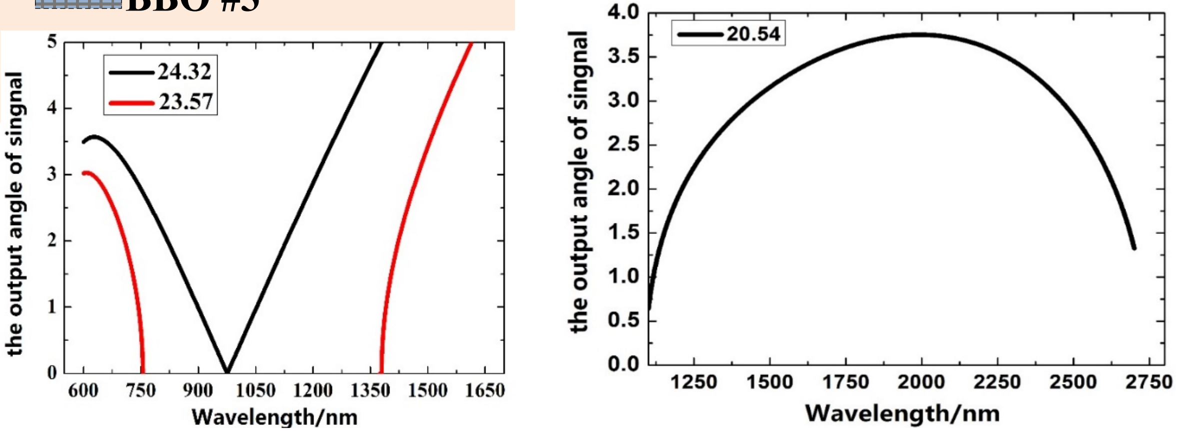
- ~ 7 BBO crystals covering 380-2500nm
- Type I colinear phase matching to balance wavelength coverage, down-conversion efficiency and complexity of optical design

Exit angles of correlated photons



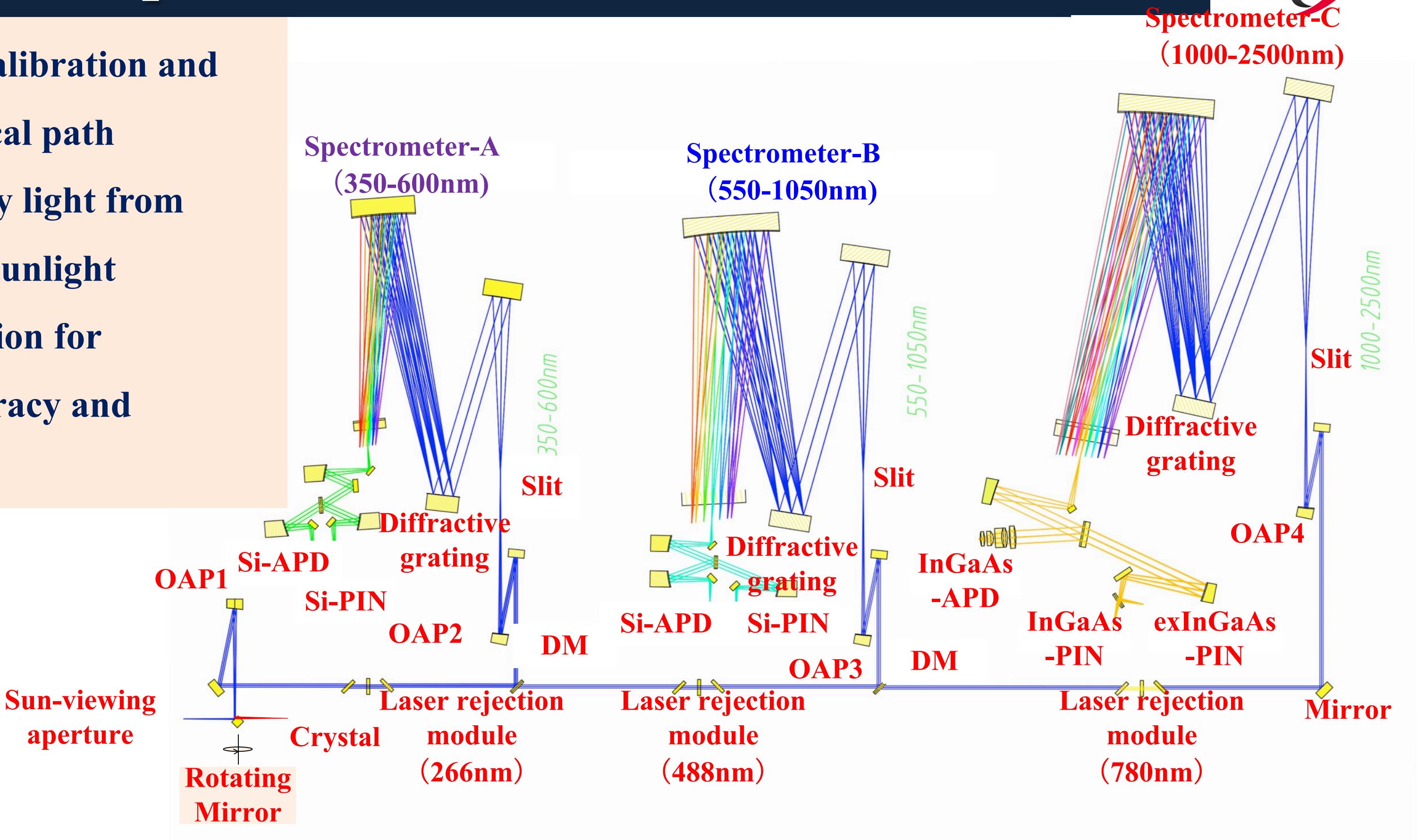


- Correlated photon emission angle < 5°

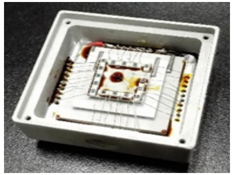


Observation optics

- Equivalence of calibration and observation optical path
- Suppression stray light from pump laser and sunlight
- Spectral calibration for wavelength accuracy and repeatability



Fabrication of single photon detectors

	Si APD	InGaAs APD
		
spectrum	380 nm ~ 1000 nm	1000 nm ~1700 nm
Dark count	<100cps	≤1000 cps
Dead time	~50ns	≤200 ns
Time resol.	800ps	
After-pulsing	<1%	<1%
Overflow rate	>10MHz	≥5 MHz

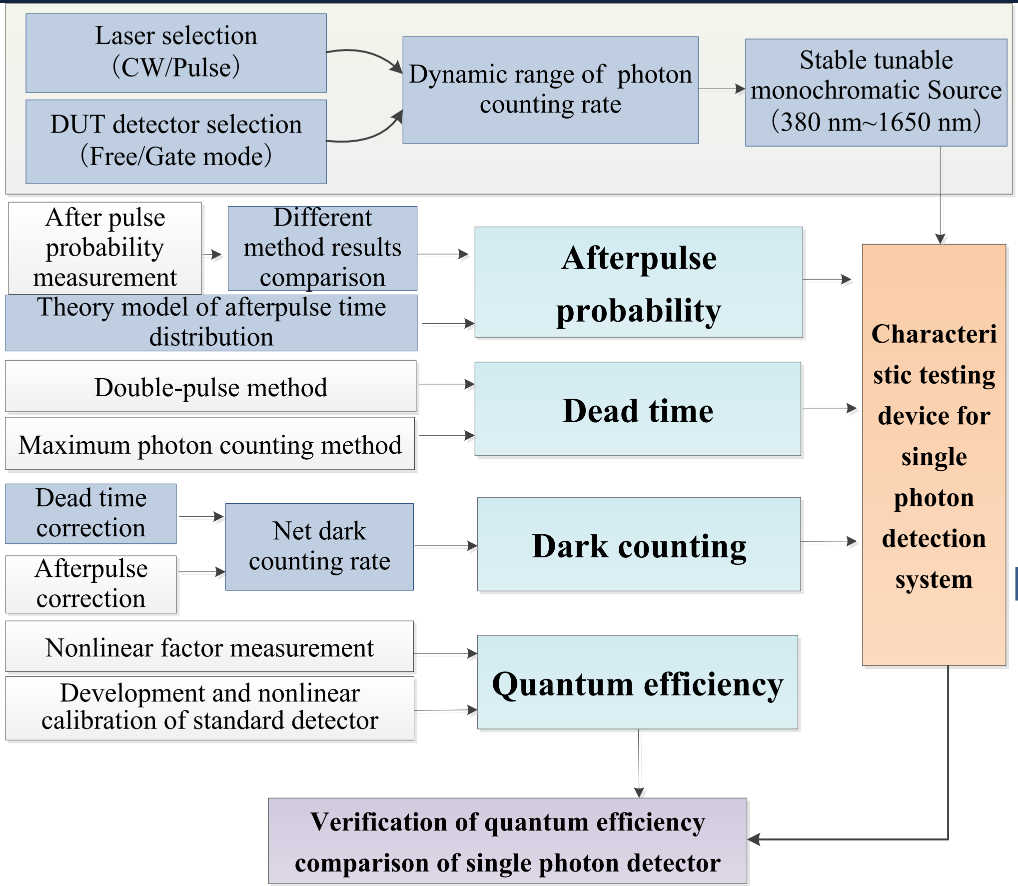
Si-APD、InGaAs-APD

Single element

32×1 linear array

- **low voltage linear power supply**
- **Active quenching**
- **compact cooling and sealing**
- **High transmittance bandpass filter coating**
- **Multi-stage TEC and Sterling cooling**

Characterization of single photon detectors



- **Develop calibration device for SPD parameter character.**
- **Develop testing methods and standards.**
- **Development process method to meet key device performances.**

Spectral range： 380nm~2500 nm；

After-pulse probability： 0.2 %；

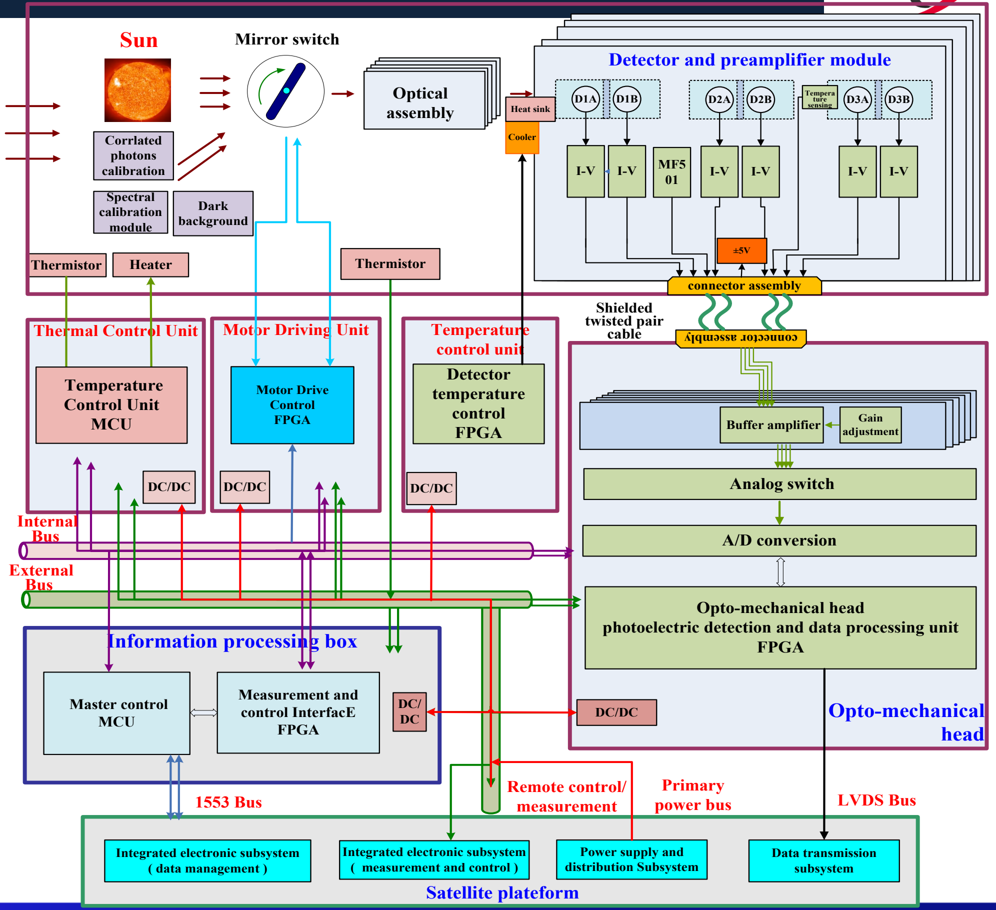
Dead time： 0.2 %；

Dark counting rate： 0.1 %@10^6/s；

Quantum efficiency： ≤0.3%

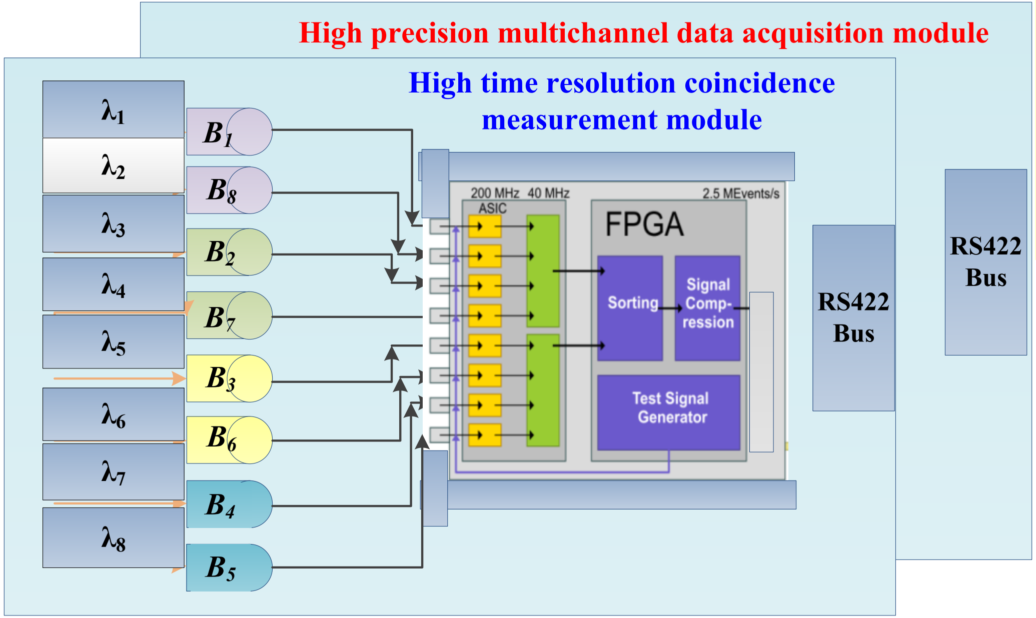
Electronic module

- ➢ Switch between calibration and observation mode
- ➢ Acquisition and processing of coincidence measurement analog signal acquisition and processing
- ➢ Temperature control (Crystal, Detector, Shortwave infrared optical path)



Wideband low noise coincidence detection

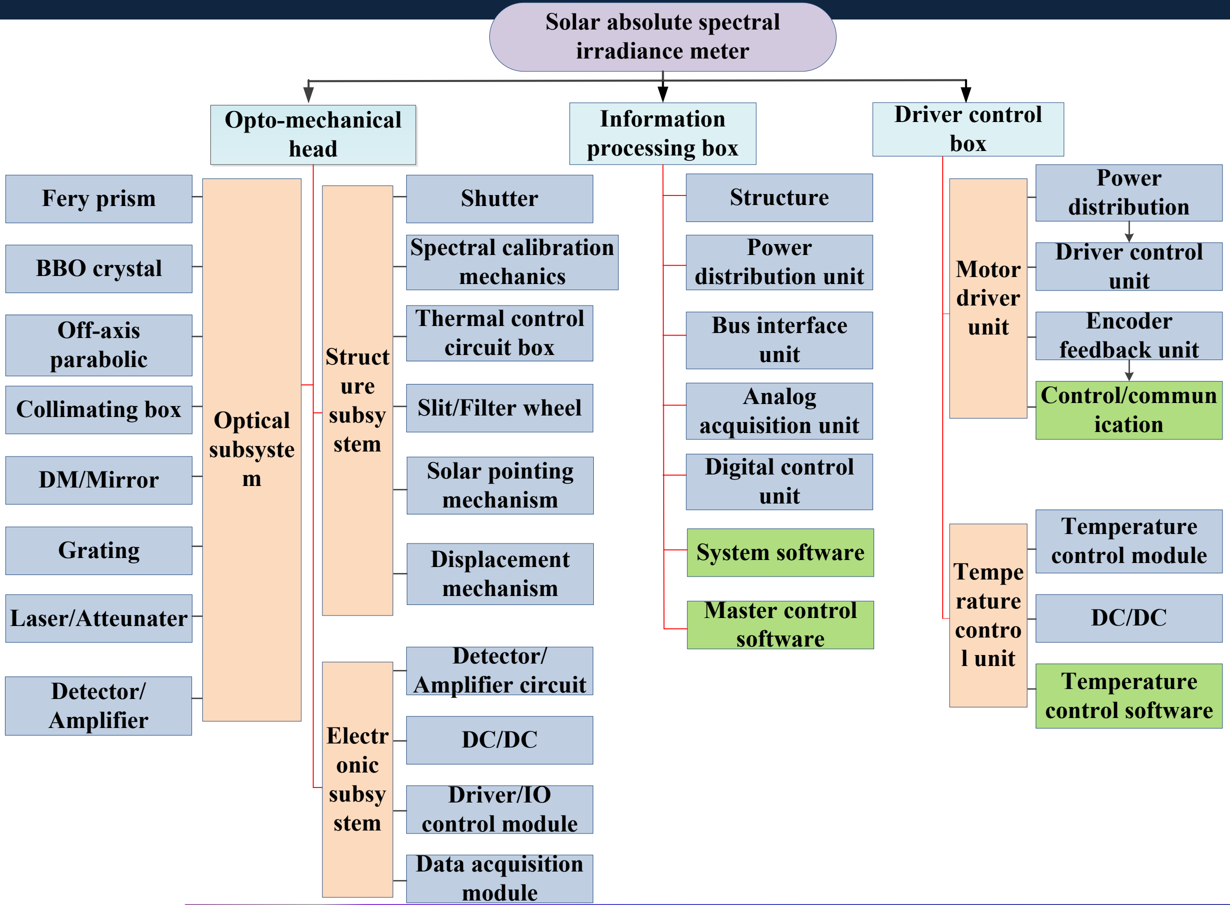
Multi-channel Time-Digit Conversion (TDC)



- 40 MHz counting rate
- ns – ps time resolution
- 0.2% coincidence detection precision
- Minimizing accidental detection
- 32 channel counting synchronizing

Matching solar photon rate and dynamic range

System integration

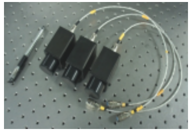


Validation of measurement accuracy

Standard detector method

$$\Phi \Rightarrow R_{\Phi}(\lambda) \Rightarrow R_{E}(\lambda) \Rightarrow E_{s}(\lambda)$$

HACR



Trap detector Filter detector

Laser-induced integrating sphere

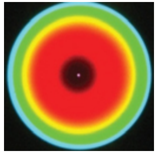
Comparison

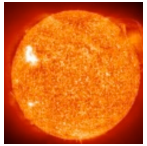
$$E_n = (E_c(\lambda) - E_s(\lambda)) / \sqrt{u_{Ec}^{2} + u_{Es}^{2}}$$

Comparison

Correlated photons method

$$P = \langle N \rangle h\nu \Rightarrow E_c = \frac{I_{sun} \cdot N_{\Delta\lambda} \cdot h \cdot c \cdot (M_{A-Valid} - M_{AB})}{I_c \cdot \lambda \cdot (M_c - M_{CA}) \cdot A \cdot \Delta\lambda}$$

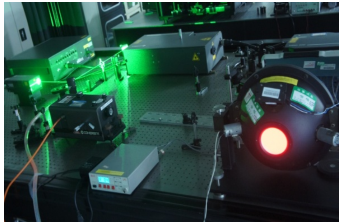


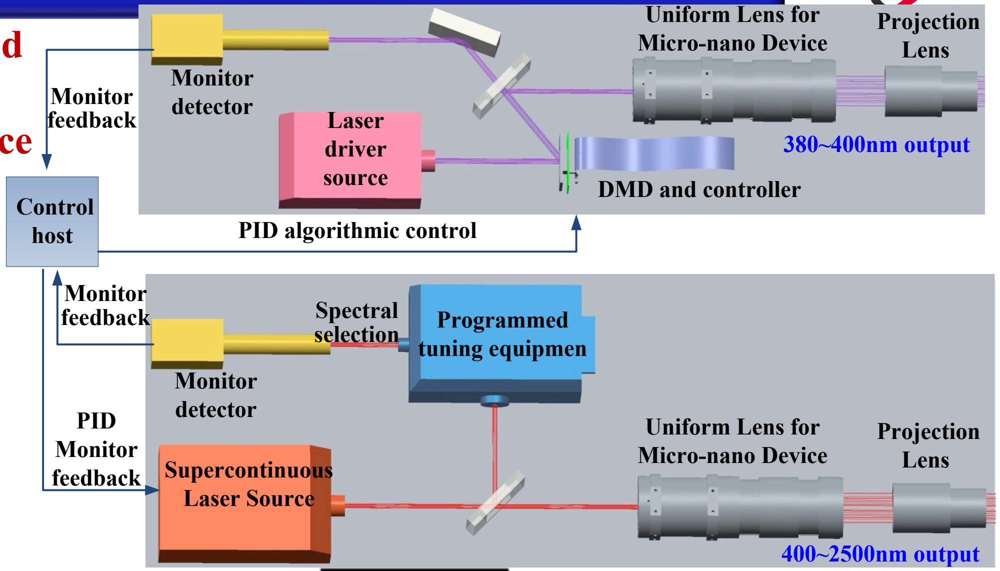


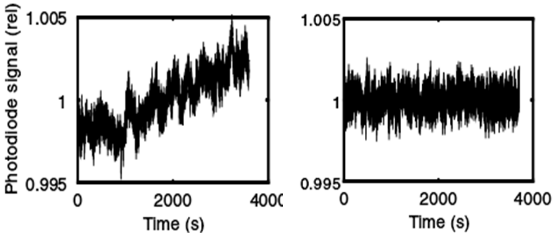
Simulation of solar spectral irradiation

- Verify the accuracy of 0.3% solar spectral irradiance measurement;
- Lab simulation of spectral distribution, stability and uniformity of solar direct radiation at top of atmosphere

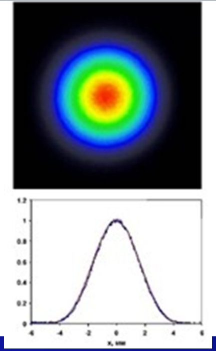
Broadband tuning and high brightness laser calibration source



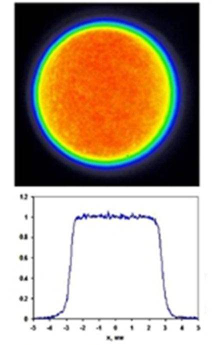




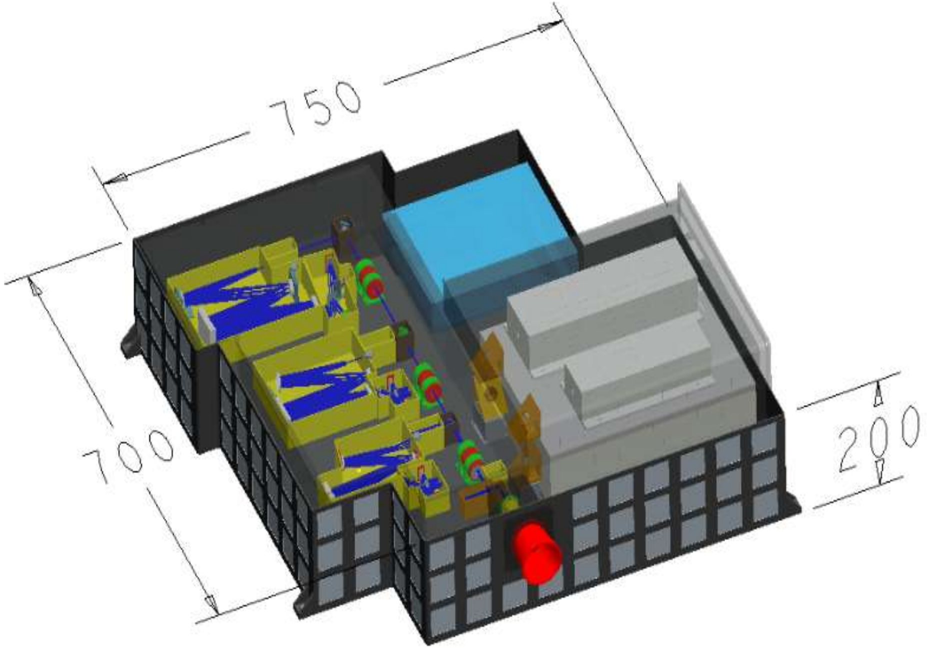
✷ Stability 0.8%➜0.1%



✷ Uniformity 5%➜0.1%



System Specifications



Optical module

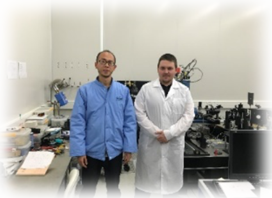
Dimensions	1.2m（L）× 0.6m（W）× 0.8m（H）	
Working modes	Self calibration, observation	
Power	Observation mode	~80W
	Self calibration mode	~200W
Mass	~100 kg	
Orbit	Polar orbiting, 90 deg.	

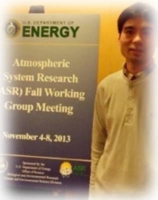
Many more challenges …

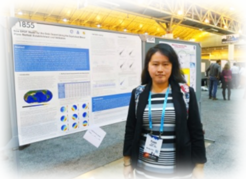
- residual pumping laser suppressed to 10^{-9}
- dynamic range compatibility between calibration and observation modes
- stray light suppression in dispersion optics to 10^{-5}
- suppression of spontaneous emission at SWIR
- nonlinearity correction of analog detectors
- aperture area measurement with uncertainty < 0.1%
- onboard wavelength calibration with accuracy 0.1 nm ~ 0.3 nm
- control of crystal temperature and internal stress
- radiation resistance of single photon detectors

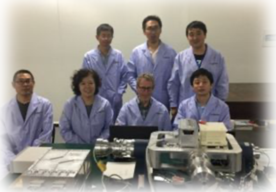
Welcome International Cooperation

- National Physics Laboratory（UK, NPL）
- Physikalisch-Technische Bundesanstalt （DE, PTB）
- World Radiation Center（WRC）
- National Institute of Standard and Technology（US, NIST）
- The All-Russian Research Institute for Optical and Physical （RU, VNIIOFI）
- National Measurement Institute, Australian Government （NMIA）









Thank you.