OPTICAL AND DETECTOR DESIGN OF THE OCEAN COLOR INSTRUMENT FOR THE NASA PACE MISSION

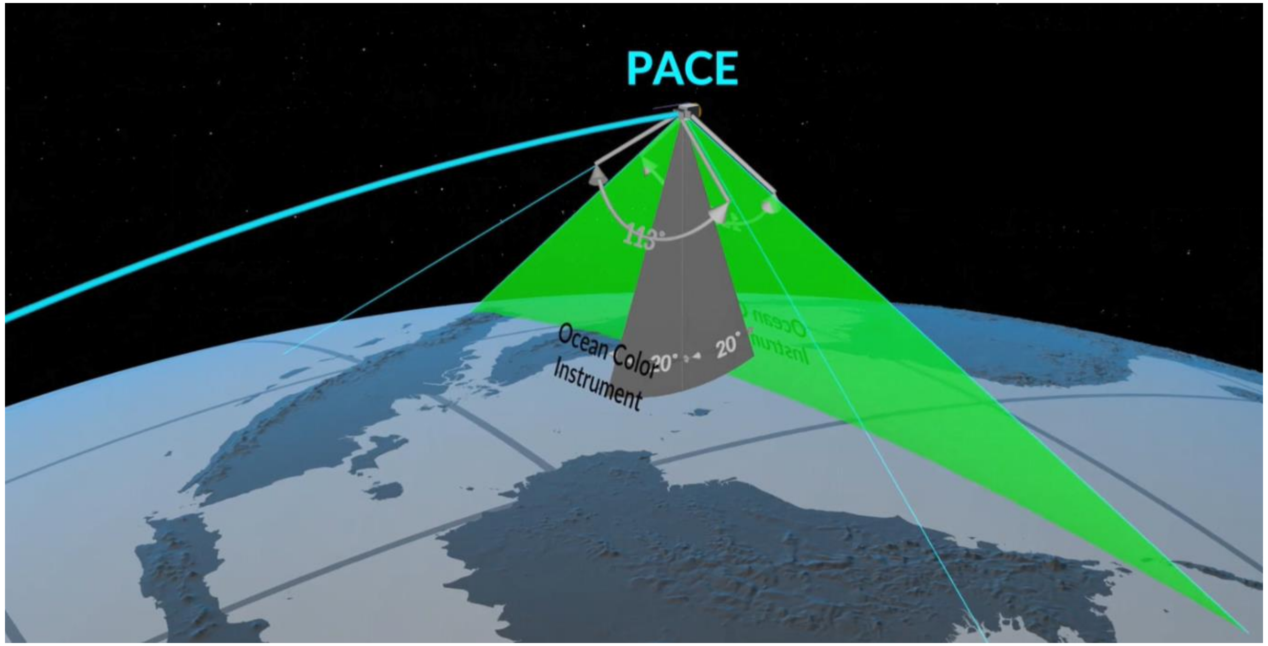
IGARSS 2023, Pasadena, CA

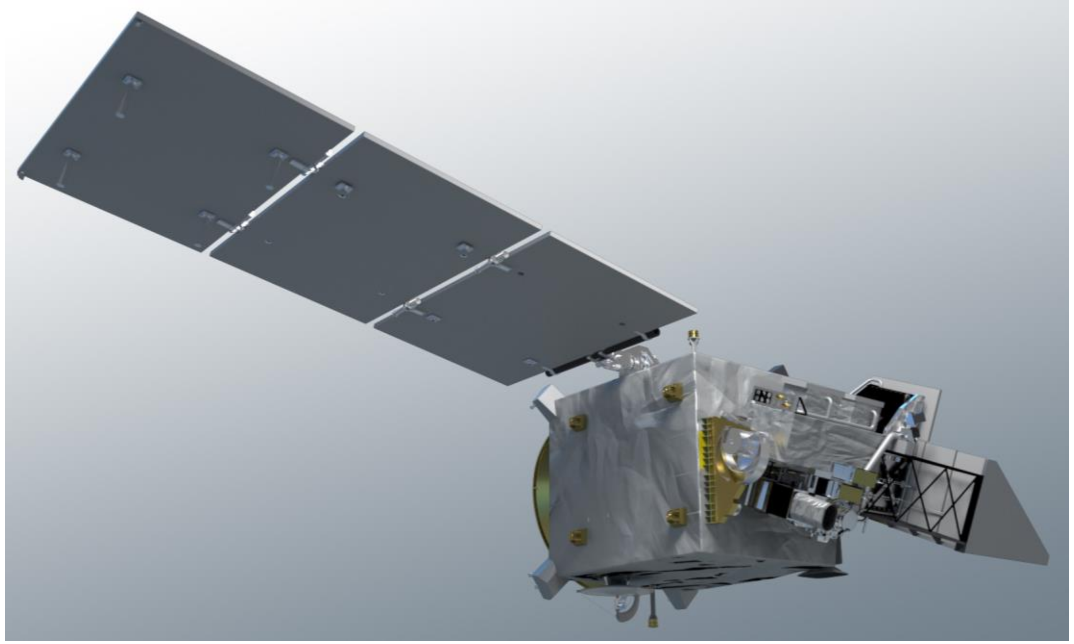
July 20, 2023

U. Gliese[1], D.A. Kubalak[2], Z. Rhodes[3], C.R. Auletti[4], S.R. Babu[2], B. Blagojevic[2], K. Boggs[5], R.R. Bousquet[6], G. Bredthauer[5], G.L. Brown[2], N.T. Cao[7], T.L. Capon[2], J. Champagne[3], L.H. Chemerys[7], F.N. Chi[7], B.L. Clemons[8], J. Cook[3], W.B. Cook[2], N.P. Costen[2], K.R. Dahya[4], P.V. Dizon[2], R. Esplin[3], R.H. Estep, Jr.[2], A.R. Feizi[9], S.H. Feng[2], E.T. Gorman[8,10], J.A. Guzek[11], O.A. Haddad[12], C.F. Hakun[2], L.B. Haynes[9], M.J. Hersh[2], C.S. Hill[13], D.G. Holliday[1], L.A. Ramos-Izquierdo[2], K.S. Jepsen[7], E. Kan[2], B.P. Kercheval[7], S. Kholdebarin[9], J.J. Knuble[2], A.T. La[2], E.D. Laurila[14], M.R. Lin[2], W. Lu[15], A.J. Mariano[2], L.A. Meier[16], G. Meister[2], B. Monosmith,[8,17], D.B. Mott[8], M.M. Mulloney[1], Q.V. Nguyen[18], T.J. Nolan[7], M.A. Owens[18], J. Peterson[3], M.A. Quijada[2], K.A. Ray[7], K. Squire[3], C.P. Stull[19], J. Thomes[2], E. Waluschka[20], Y. Wen[8], M.E. Wilson[1], and P.J. Werdell[2]

1. KBR Inc, 2. NASA GSFC, 3. Space Dynamics Laboratory, 4. Aerodyne, 5. Semiconductor Technology Associates, 6. Genesis Engineering Solutions, 7. SSAI, 8. Formerly of NASA GSFC, 9. AK Aerospace Technology, 10. Quantum Space, 11. Design Interface, 12. Ingenion, 13. Aurora Engineering, 14. Peraton, 15. Telophase, 16. Conceptual Analytics, 17. Newton, 18. Florez Engineering, 19. Lentech, 20. Stellar Solutions

Introduction to PACE and OCI



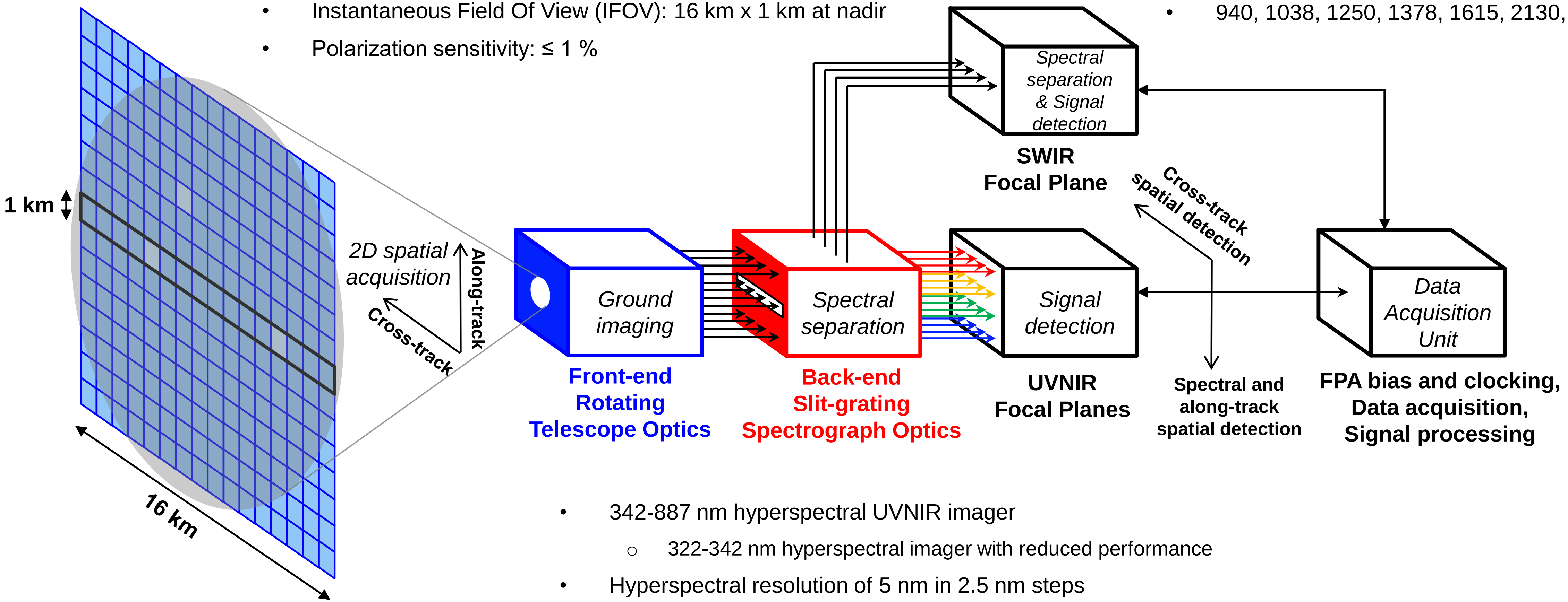


- **Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission:**
  - Orbit: ~676.5 km altitude, polar, ascending, 98° inclination, sun synchronous, 13:00 local equatorial crossing
  - Mission life: 3-year design life with 10-year propellant
  - Instrumentation: OCI (hyperspectral UVNIR radiometer), SPEXOne (narrow swath, 5-angle, hyperspectral UVNIR polarimeter), HARP2 (wide swath, hyper-angular, 4-band VISNIR polarimeter)
- **Ocean Color Instrument (OCI):**
  - Hyperspectral UVNIR imager and 7-band SWIR imager with a spatial resolution of 1 km^2 at nadir
  - Scanning telescope spinning at 5.77 Hz with ±56.6° angular view range resulting in 2663 km ground swath-width
  - 2-day global coverage
  - ±20° tilt to avoid sun-glint
  - Daily on-board solar calibration and twice monthly lunar calibration

OCI Imaging System

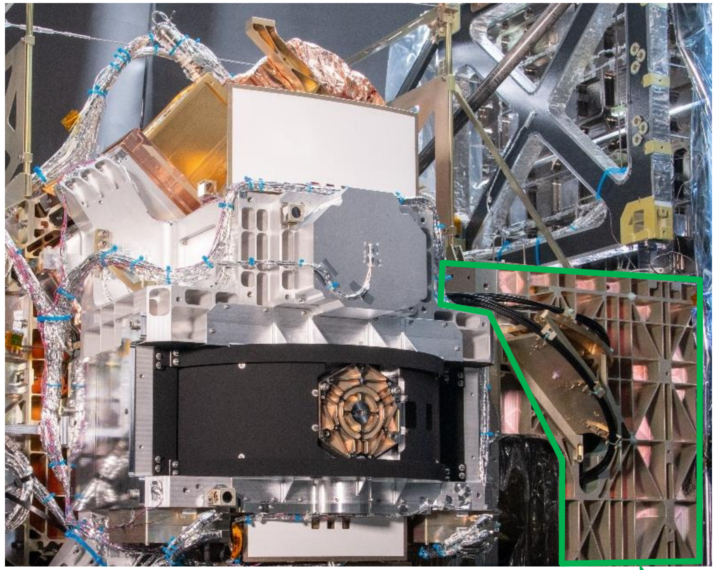
- Spatial resolution of 1 km x 1 km at nadir
- Instantaneous Field Of View (IFOV): 16 km x 1 km at nadir
- Polarization sensitivity: ≤ 1 %

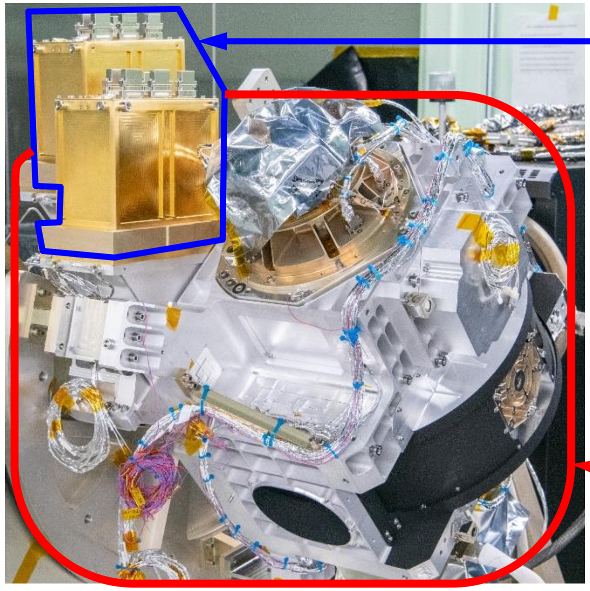
- 7-band SWIR imager
- 940, 1038, 1250, 1378, 1615, 2130, 2260 nm

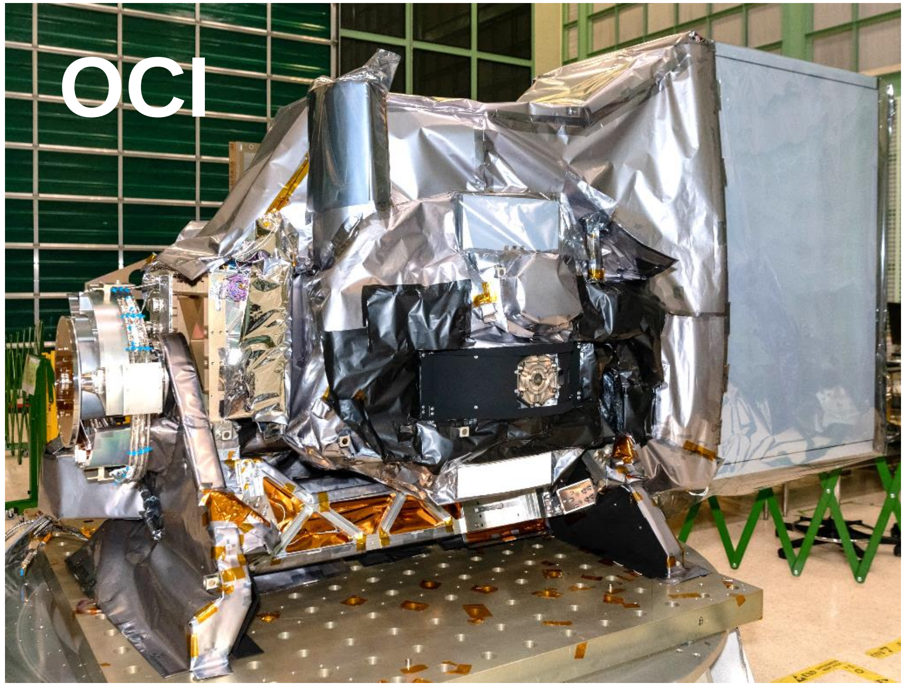


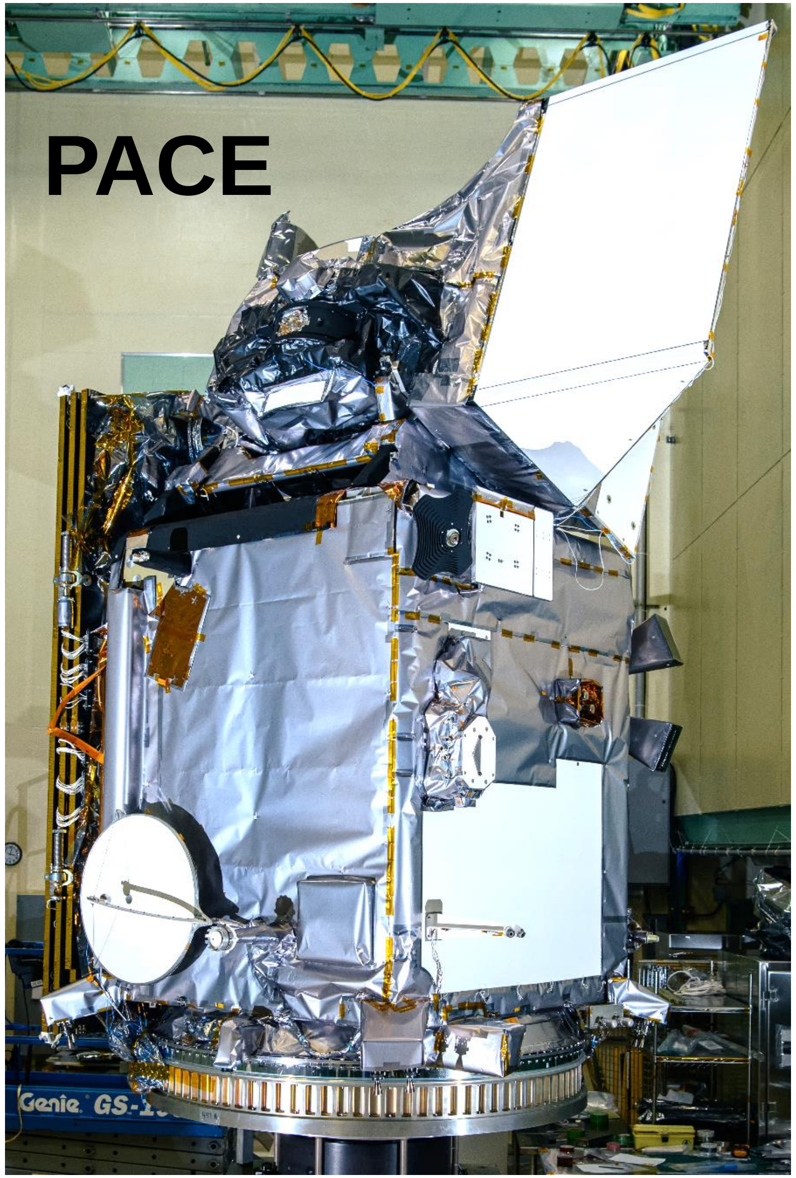
- 342-887 nm hyperspectral UVNIR imager
  - 322-342 nm hyperspectral imager with reduced performance
- Hyperspectral resolution of 5 nm in 2.5 nm steps
- Signal-to-Noise Ratio (SNR) of 260-1920 (in 5 nm optical bandwidth at typical ocean spectral radiance levels)
- Dynamic Range (DR): 4800:1-5900:1 (max-detectable signal to 1-sigma noise)
- Radiometric gain stability: ≤ ±0.1 %,
- Spatial image striping artifact level: ≤ 0.1 %

OCI Hardware







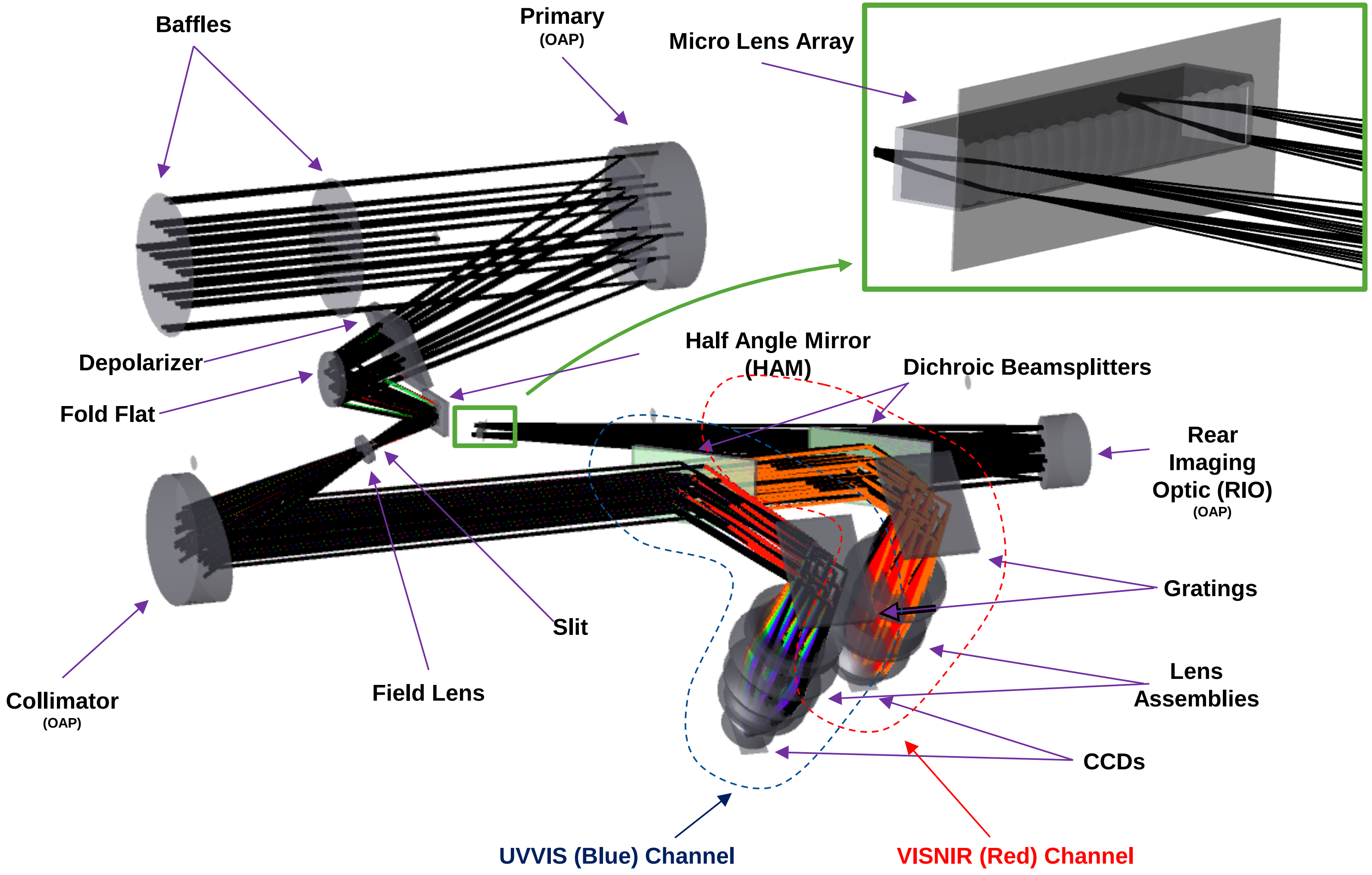


Fiber-Coupled 7-Band SWIR Detection System

Hyperspectral UVNIR Detection System

Hyperspectral Optical System

OCI Optical System



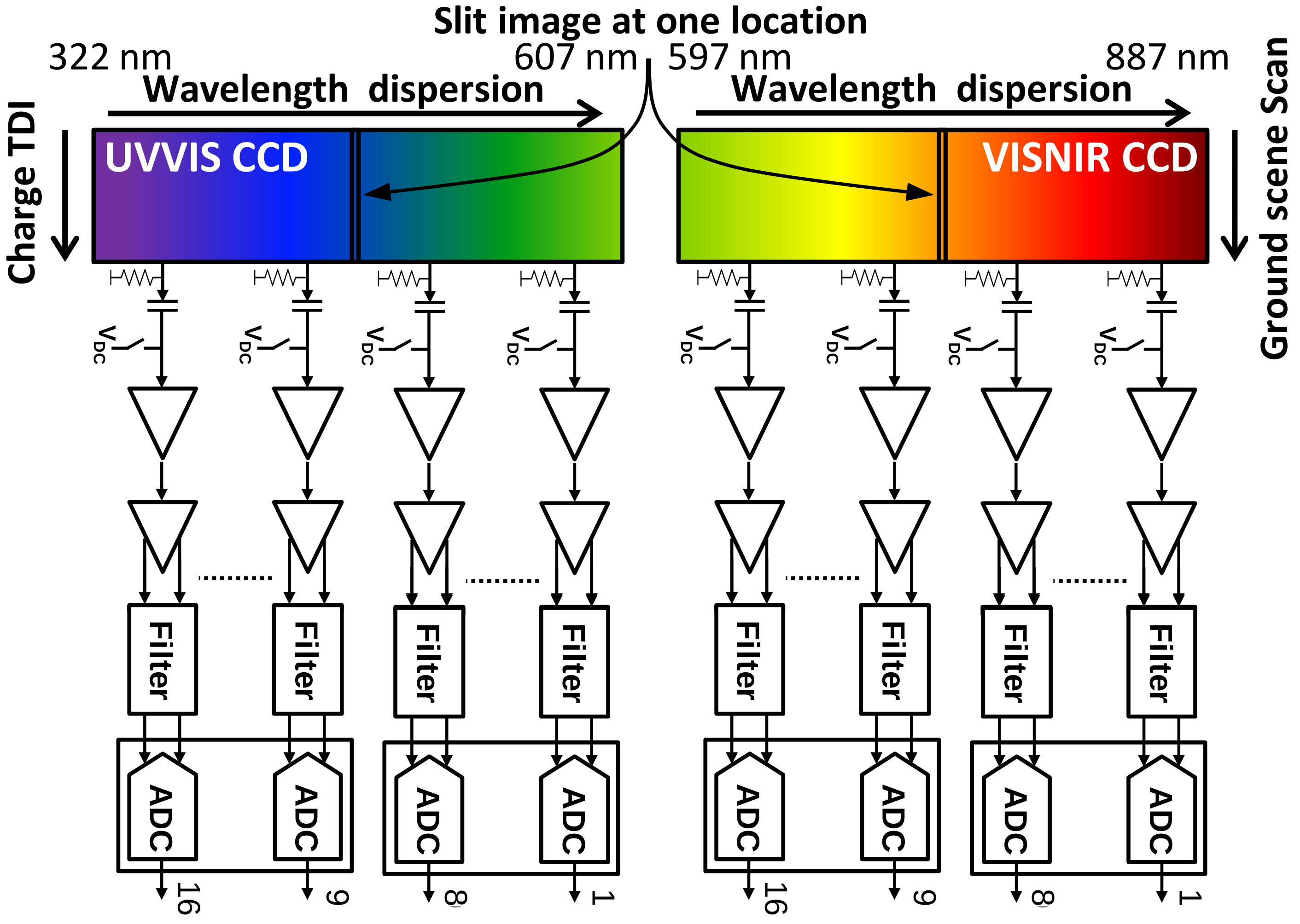
Optical System Performance

- Throughput
  - ≥ 0.4 at ≥ 360 nm
  - 0.3 at 340 nm
- f-number
  - 1.2
- Polarization sensitivity
  - ≤ 1 %
  - ≤ 0.4 % at ≥ 360 nm
- Point Spread Function (PSF)
  - ≤ 46 µm (80 % encircled energy)
- Modulation Transfer Function (MTF)
  - ≥ 0.95 (Nyquist)
- Spectral sampling
  - 0.625 nm
- Out-Of-Band Response Ratio (OOBRR)
  - ≤ 0.05 (integrated out-of-band to in-band ratio for 5 nm resolution full-width 1 %)

Optical System – Key Challenges

- Achieved performances demanding for the design and involved optical technologies
- Front-end optical system has to work over the entire 322-2260 nm wavelength range with high throughput to achieve high SNR
- Back-end hyperspectral spectrographs require a challenging very low f-number
- Maximizing throughput over such a broad wavelength range with so many surfaces is difficult and requires very careful design
- Unique coatings for both the reflective and transmissive optics developed to extend performance into the UltraViolet (UV)
- Low f-number, broad spectral range, UV requirements, IFOV and widely dispersed image rays, leads to a very difficult back-end design
- Careful choice of lens materials made in order to maximize throughput
- Number of elements and element radii carefully balanced to meet requirements without causing ghosting
- Essential that spinning of primary mirror sub-system and half-angle mirror are closely synchronized
- Movement of ground scene through slit and across CCDs precisely synchronized with TDI charge movement in CCD
- High precision motors and encoders developed
- Precision phase-locked loop motor control designed to track the CCD charge movement clock

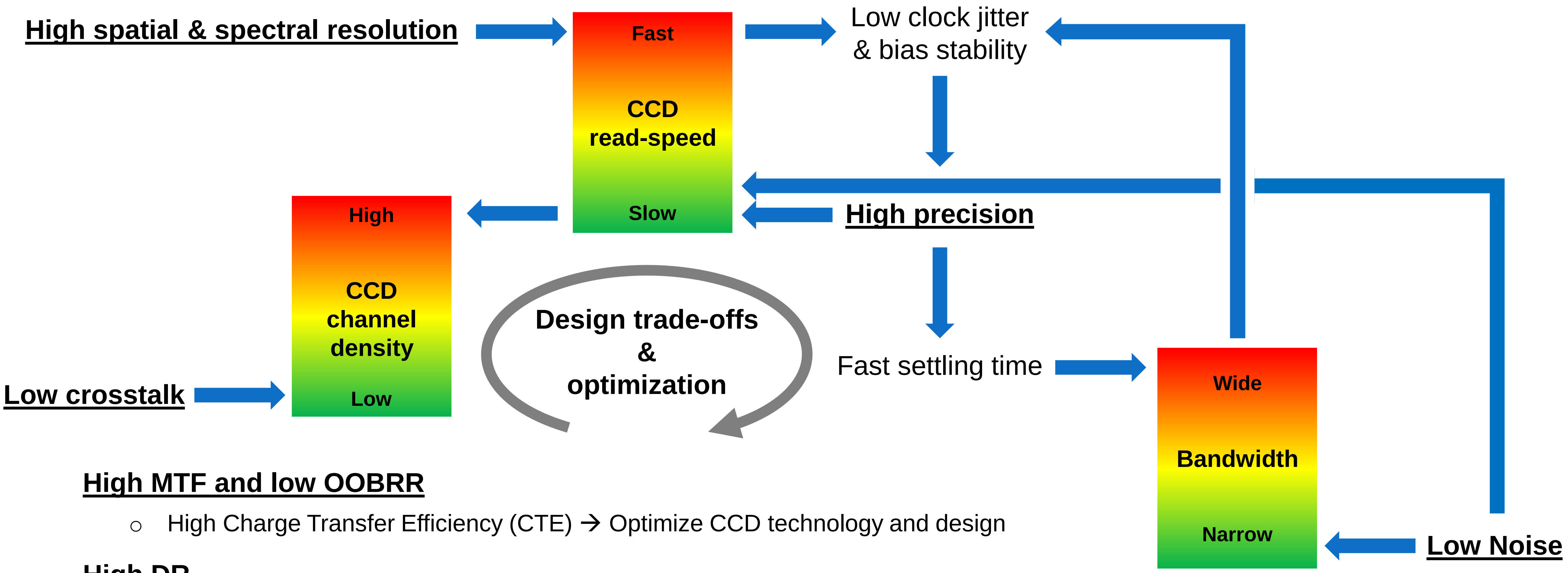
OCI Hyperspectral UVNIR Detection System



Hyperspectral UVNIR detection system performance

- QE
  - ≥ 0.4 (315 nm), ≥ 0.97 (460 nm), ≥ 0.91 (605 nm)
  - ≥ 0.94 (600 nm), ≥ 0.97 (680 nm), ≥ 0.67 (890 nm)
- Full well capacity
  - ≥ 750 ke-
- Read speed
  - 8.5 MHz with 17 MHz CDS
- Gain
  - 22, 33 and 55 DN_{14}/ke- (depending on channel)
- Noise
  - ≤ 3 DN_{14} 1-sigma
- Precision
  - ≤ 0.1 %
- Channel-Channel (Ch-Ch) Crosstalk
  - ≤ $1.3 \cdot 10^{-4}$
- Dynamic Range (DR)
  - 4800:1-5900:1 (max-detectable signal to 1-sigma noise)
- Step recovery precision (max → min)
  - ≤ 0.25 % within 1 Science Pixel (SP)

Hyperspectral UVNIR Detection System – Key Challenges



High MTF and low OOBRR

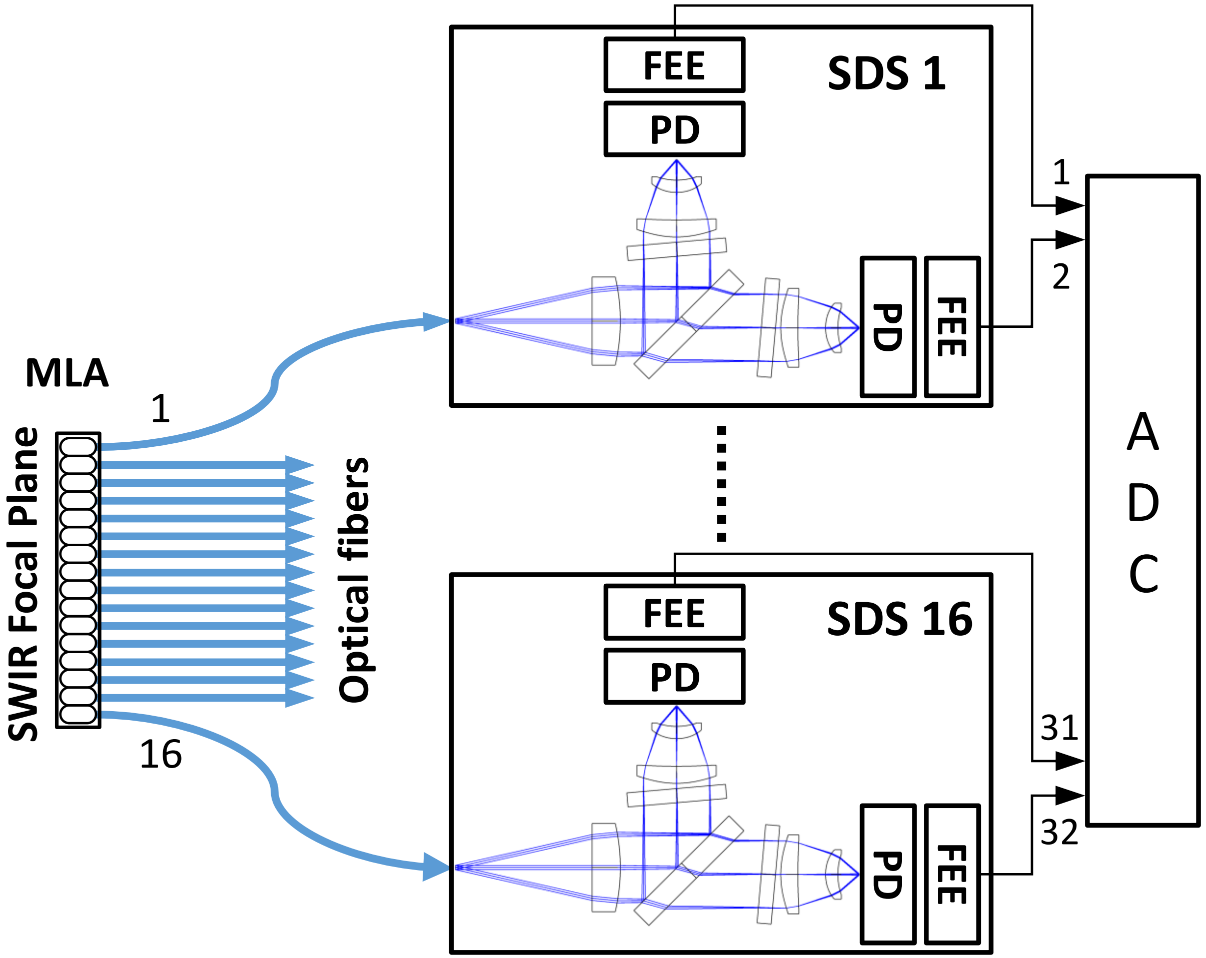
- High Charge Transfer Efficiency (CTE) → Optimize CCD technology and design

High DR

- Large CCD well and sense node capacity → Optimize CCD technology and design
- Compact and fast 14 bit ADC → Qualify commercial ADC technology for space flight use

CCD and electronics carefully designed to accomplish required instrument performance

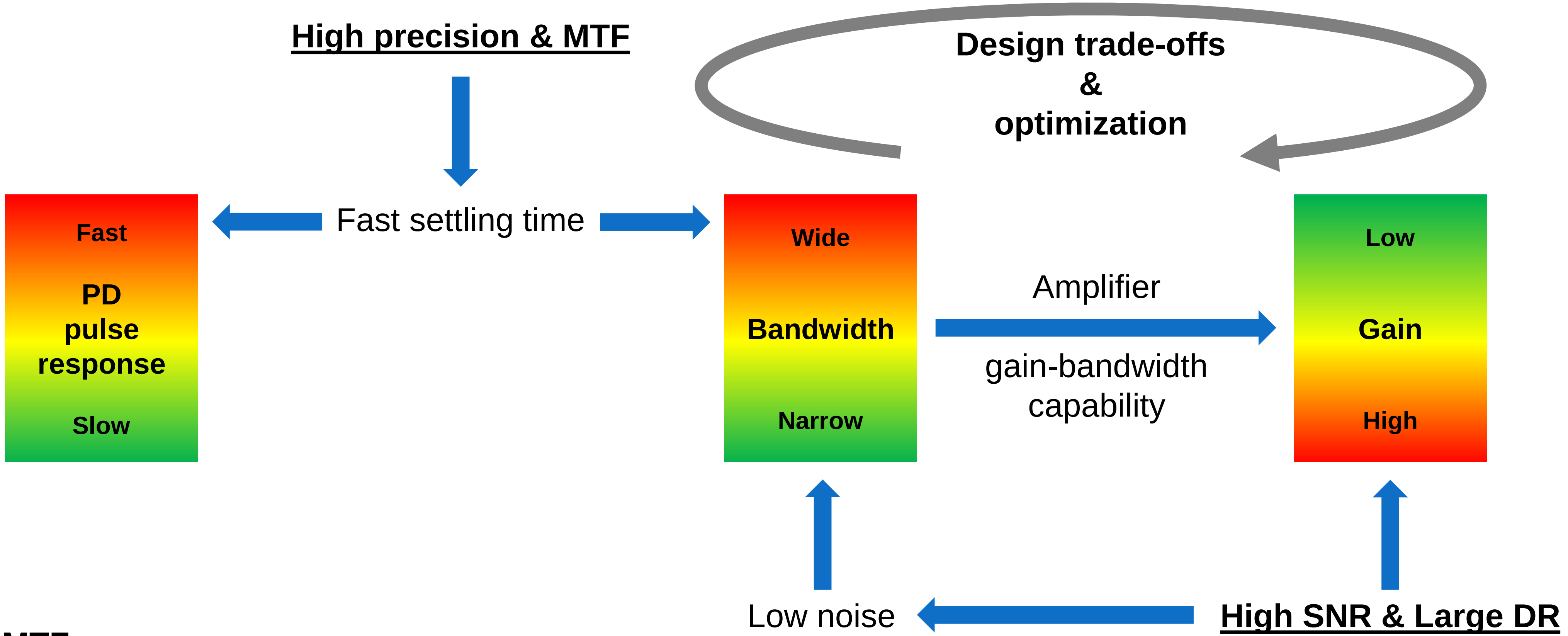
OCI 7-Band SWIR Detection System – Design



7-Band SWIR Detection System Performance

- QE
  - ≥ 0.8
- Gain
  - $5.24 \cdot 10^5$ – $5.38 \cdot 10^5$ DN_{16}/µW (depending on channel)
- Noise
  - ≤ 6.3 DN_{16} 1-sigma
- Precision
  - ≤ 0.2 %
- Dynamic Range (DR)
  - 9600:1-20000:1 (max-detectable signal to 1-sigma noise)
- Pulse response (max → min)
  - ≤ 1 % within 3 Science Pixels (SPs)

7-Band SWIR Detection System – Key Challenges



High MTF

- Low leakage between lens elements in MLA → Development of special fabrication techniques

Electronics optimized to trade-off SNR, DR and MTF to accomplish required instrument performance

PD pulse response and amplifier gain-bandwidth capability ultimately limits achievable precision and MTF

Conclusion

- Developed 322-887 nm UVNIR 5 nm hyperspectral resolution radiometer with 7 940-2260 nm SWIR bands
- Outstanding radiometric performance
- Pushes boundaries of several state-of-the-art technologies
- Wide range of technology developments and design optimizations needed to achieve performance
- UV & two 2-µm bands realize several atmospheric improvements over heritage instruments
- No other current or planned hyperspectral radiometer provides 1-2 day global coverage
- Significant advancement over previous banded imaging platforms
- Set to enable quantitative evaluation of separate plankton species from space for the first time