SWIRP: Compact Submm-Wave and LWIR Polarimeters for Cirrus Ice Properties

National Radio Science Meeting

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- Antenna: Cornelis Du Toit /567
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- Electrical: Michael Coon/555
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- Thermal: Sergio Guerrero/545

TAMU (Ping Yang):
- Ice microphysics simulation

NGAS:
William Deal, Caitlyn Cooke, Kevin Leong, Gerry Mei, Alex Zamora:
- 220 GHz polarimeter (V,H)
- 680 GHz polarimeter (V,H)

William Gaines (NGC)
- BAPTA

U of Arizona:
Russell Chipman, Kira Hart, Adriana Stohn
- LWIR 8-12 um polarimeter (V,H)

NASA Goddard SPACE FLIGHT CENTER · NORTHROP GRUMMAN · College of Optical Sciences, The University of Arizona

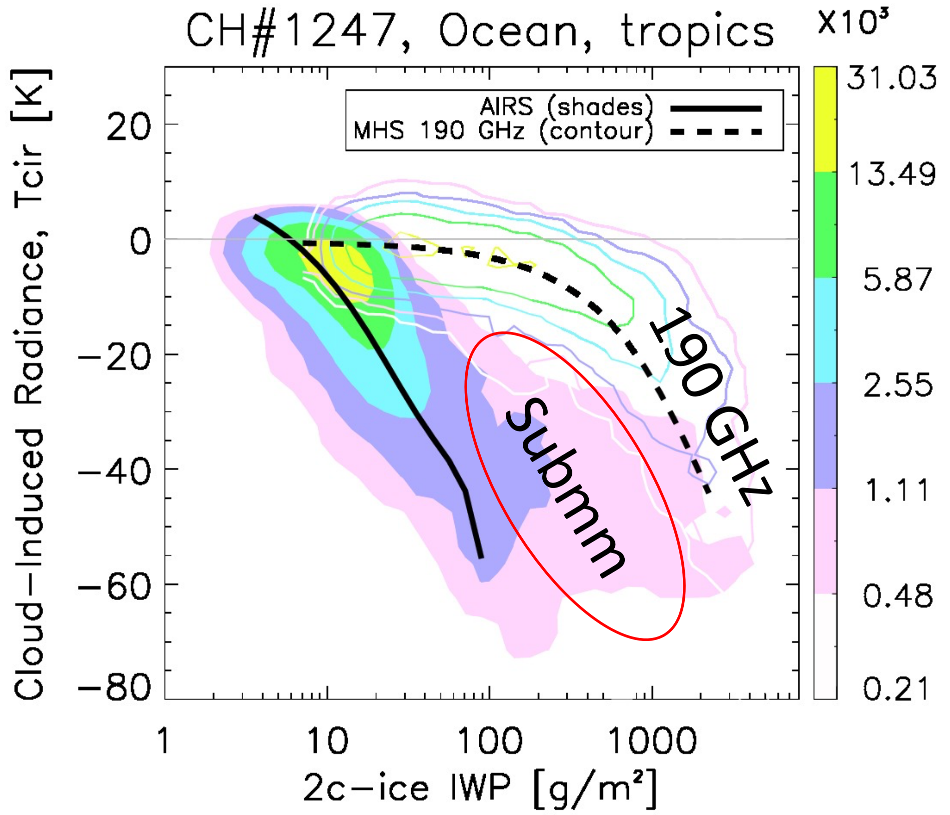
Outline

- Background and Motivation
- Technology Developments and System Requirements
- Observation Geometry
- Current Design
    - Architecture and design highlights
    - Data Handling
    - MiniBAPTA
    - Mechanical Assembly
    - Sub-mm calibration and antenna
    - Sub-mm receivers
    - IR instrument

Background and Motivations

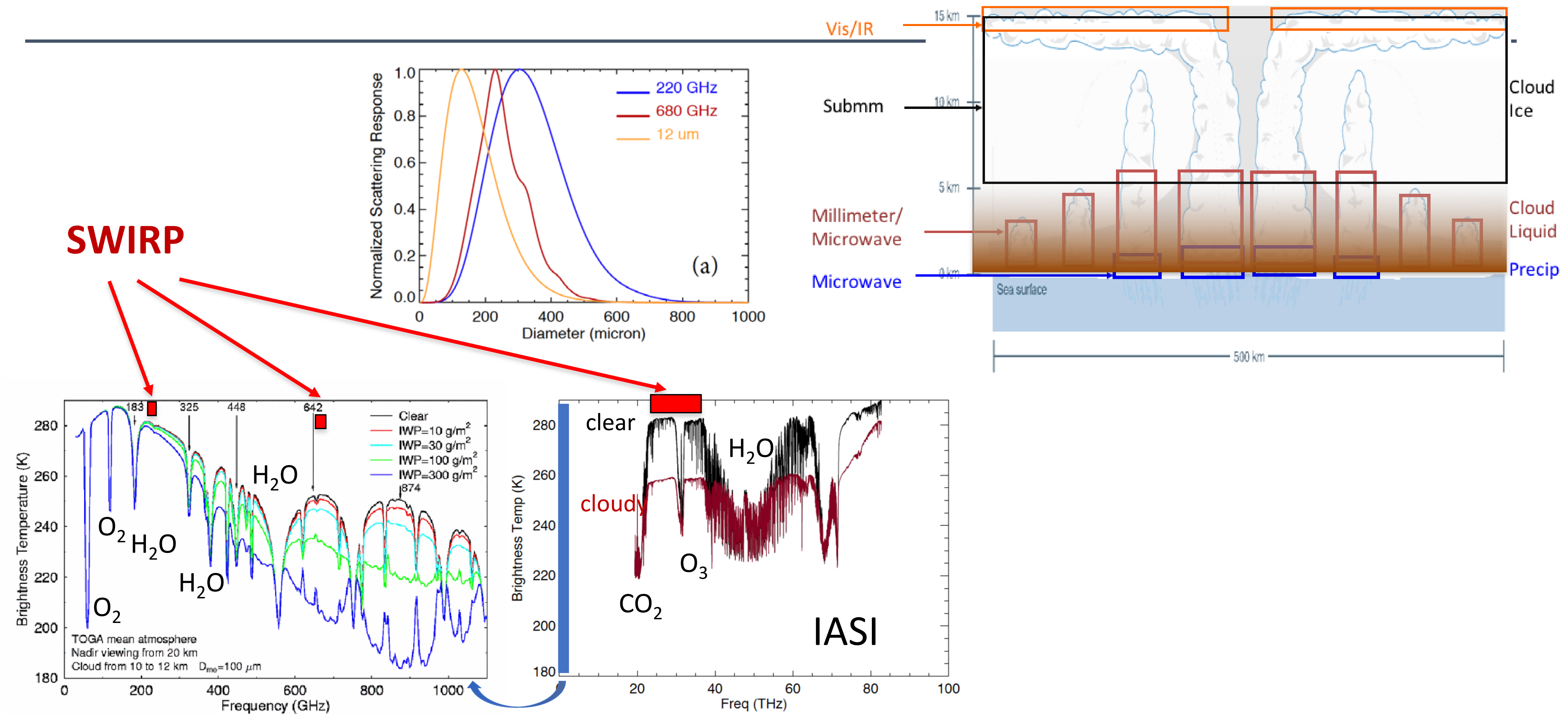
- Clouds, ice clouds in particular, as a major source of uncertainty in climate prediction.
- Some cloud ice is not observed by microwave (MW) and infrared (IR) sensors, and need submm cloud radiometers.
- Cloud microphysical properties (particle size and shape) account for ~200% and ~40% of measurement uncertainty, respectively.
- Combined submm and LWIR polarimeters to provide the sensitivities needed for cloud ice and microphysical property (particle size and shape) measurements over a large dynamic range.

$$T_{cir} = T_b - T_{b\_clear}$$



(Courtesy of J. Gong) Ice Water Path (IWP) from CloudSat/CALIOP

Background and Motivations



Potential SWIRP Contributions to 2017 Decadal Survey (1/2)

Most Important Science Questions

(W-4) Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?

Very Important

(C-6) Improving seasonal to decadal climate forecasts

Important

(W-9) Cloud microphysical property dependence on aerosols and precipitation
(W-10) Cloud impacts on radiative forcing and weather predictability

Potential SWIRP Contributions to 2017 Decadal Survey (2/2)

Set of observation capabilities

- Providing critical information on the make-up and distribution of aerosols and clouds, which in turn improve predictions of future climate conditions and help us assess the impacts of aerosols on human health;
- Addressing key questions about how changing cloud cover and precipitation will affect climate, weather, and Earth's energy balance in the future, advancing understanding of the movement of air and energy in the atmosphere and its impact on weather, precipitation, and severe storms;

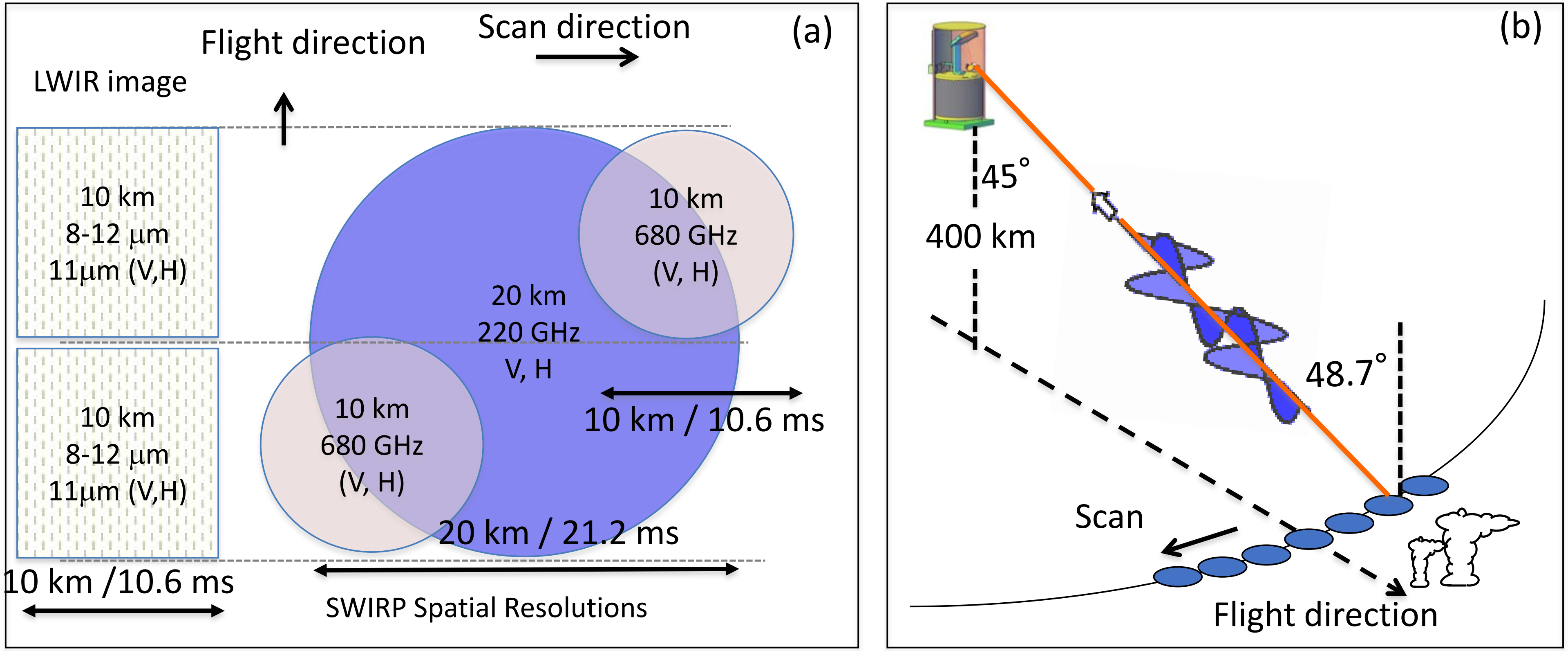
Competitive observational opportunities to address at least three of the following science and applications areas

☐Providing critical insights into the transport of pollutants, wind energy, cloud processes, and how energy moves between the land or ocean surfaces and the atmosphere.

Technology Developments and System Requirements

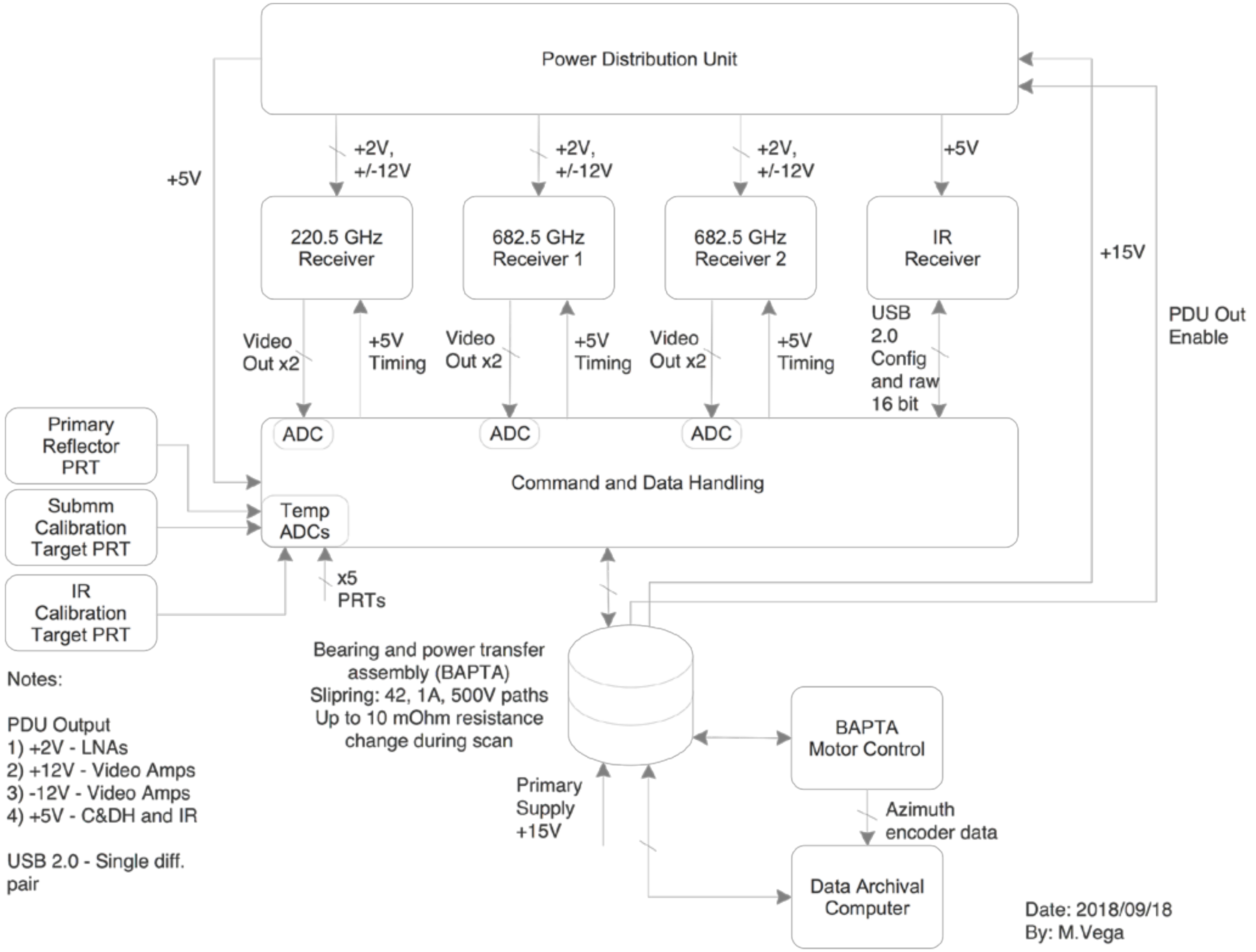
<table>
<tr><th>This Work</th><th colspan="2">Approach</th><th>BW</th><th>NEdT (K) (10.6 ms)</th><th>TRL_{in}</th><th>TRL_{out}</th><th>Power (W)</th><th>Mass (kg)</th><th>Volume Dimensions, Notes</th></tr>
<tr><td rowspan="2">LWIR Polarimeter</td><td><u>Baseline:</u> 3-band spectro-polarimeter with single lens</td><td>8.6μ
11μ
12μ</td><td>0.3μ
1.0μ
1.0μ</td><td>1.0</td><td>3</td><td>5</td><td rowspan="2">0.5</td><td rowspan="2">0.5</td><td>Size: 2 x 2 x 10 cm
polarized channel: 11μ
Single lens for multi-channels</td></tr>
<tr><td><u>Backup</u>: 3-band micro-polarizer array with 4 lenses</td><td>8.6μ
11μ
12μ</td><td>0.3μ
1.0μ
1.0μ</td><td>1.0</td><td>4</td><td>5</td><td>Size: 2 x 4 x 2 cm
polarized channel: 11μ
2 lenses per polarized channel</td></tr>
<tr><td rowspan="3">680 GHz Polarimetric Receivers</td><td rowspan="2"><u>Baseline</u>: 2-element 2-pol array using direct detection</td><td>Receiver</td><td></td><td rowspan="2">0.5</td><td>4</td><td rowspan="2">5</td><td rowspan="3">1.7 / 5</td><td rowspan="3">0.4 / 1</td><td rowspan="2">Size: 2 x 4 x 7 cm each pol rec'r</td></tr>
<tr><td>Filter</td><td>17GHz</td><td>3</td></tr>
<tr><td colspan="2"><u>Backup</u>: 2-element 2-pol array using heterodyne detection</td><td>17GHz</td><td>0.5</td><td>4</td><td>5</td><td>Size: 3 x 3 x 7 cm each pol rec'r;
IFA size: 2 x 4 x 5 cm;
Power: 2.3 W + 2.7 W(DRO);
Mass: 0.5 kg + 0.5 kg (IFA+DRO)</td></tr>
<tr><td rowspan="2">220 GHz Polarimetric Receiver</td><td rowspan="2">Single 2-pol using direct detection</td><td>Receiver</td><td></td><td rowspan="2">0.2</td><td>4</td><td rowspan="2">5</td><td rowspan="2">0.5</td><td rowspan="2">0.3</td><td rowspan="2">Size: 2 x 4 x 9 cm each pol rec'r</td></tr>
<tr><td>Filter</td><td>10 GHz</td><td>3</td></tr>
<tr><td>Small BAPTA</td><td colspan="4">Engineering model for lab prototyping; Based on previous flight design (TRL=9) and adjusted for SWIRP configuration</td><td>3</td><td>5</td><td>2</td><td>2</td><td>Diameter: 6.3 cm
Height: 4 cm</td></tr>
<tr><td>Structure & Calibration</td><td colspan="4">Rotating drum assembly with polarimeters, reflectors and ADC processor; Non-rotating calibration fixture.</td><td>4</td><td>5</td><td>4</td><td>5</td><td>PDU: 3W
Drum diameter: 15 cm</td></tr>
<tr><td>Instrument System</td><td colspan="4">Conical co-scanning LWIR and submm polarimeters with onboard calibration and matched FOVs</td><td>3</td><td>5</td><td><12 / <16</td><td><11 / <12</td><td>Size: < 20 x 20 x 40 cm
Power, mass incl. 30% margin</td></tr>
</table>

Observation Geometry



Current Design – Instrument Architecture

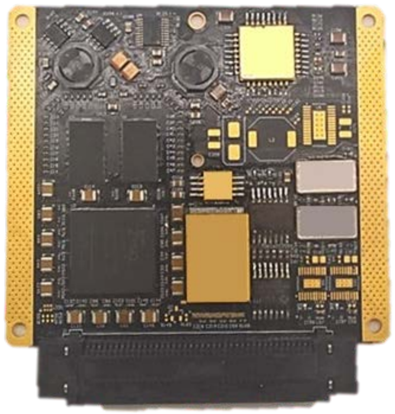
- Relatively high speed interface (78.6 Mbps) from IR camera in raw full frame mode.
- Currently testing FLIR SDK and successfully captured raw 16 bit frame data.
- PDU design underway using unscreened space qualifiable regulators.
- Planning to use Ethernet through slip-rings for instrument data and command handling.
- Slip-ring vendor confirmed prior successful use of Ethernet and provided wiring suggestions.
- MiniBAPTA and sub-mm receiver ICDs received.

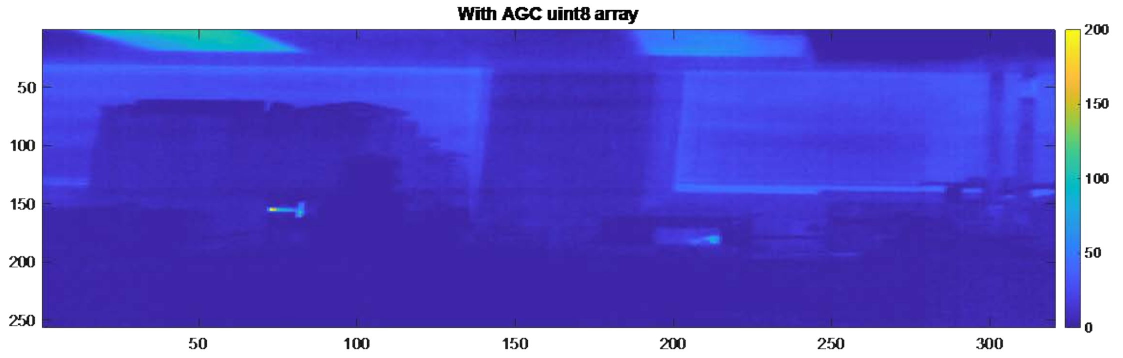


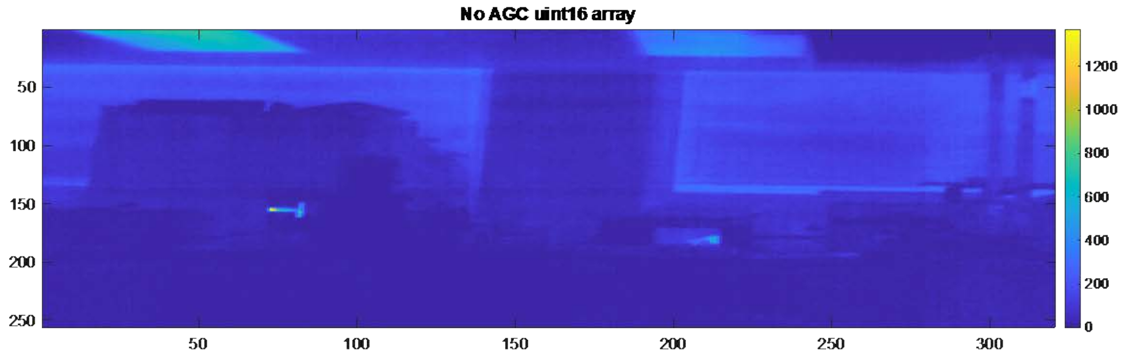
Current Design: Data Handling and IR Camera Interface

- Successfully read raw 16 bit frame data from Boson using Linux laptop in lieu of Space Micro CSP board.
- SDK documentation indicates potential for use of capture command to internal memory and offset read operations
- Pixel selection could happen in this process; leading to reduced data rate into C&DH
- Daughter card to handle thermistor and sub-mm video ADCs.

Space Micro CSP
- Xilinx Zynq-7020
- Dual Arm Core and Reconfigurable 7-Series FPGA Fabric
- 1U cubesat form factor
- 32 Gbit Rad Tol. NAND flash

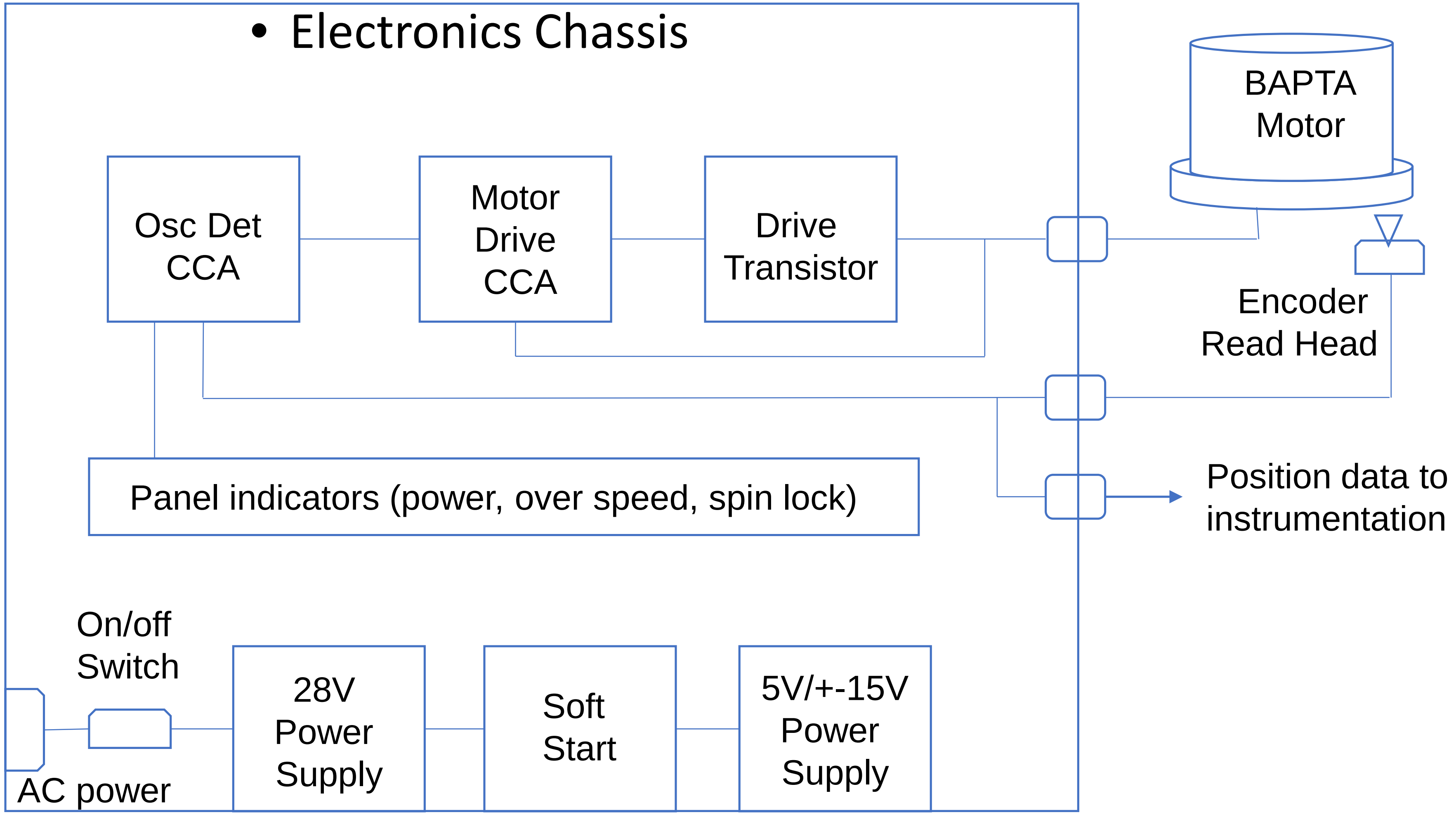




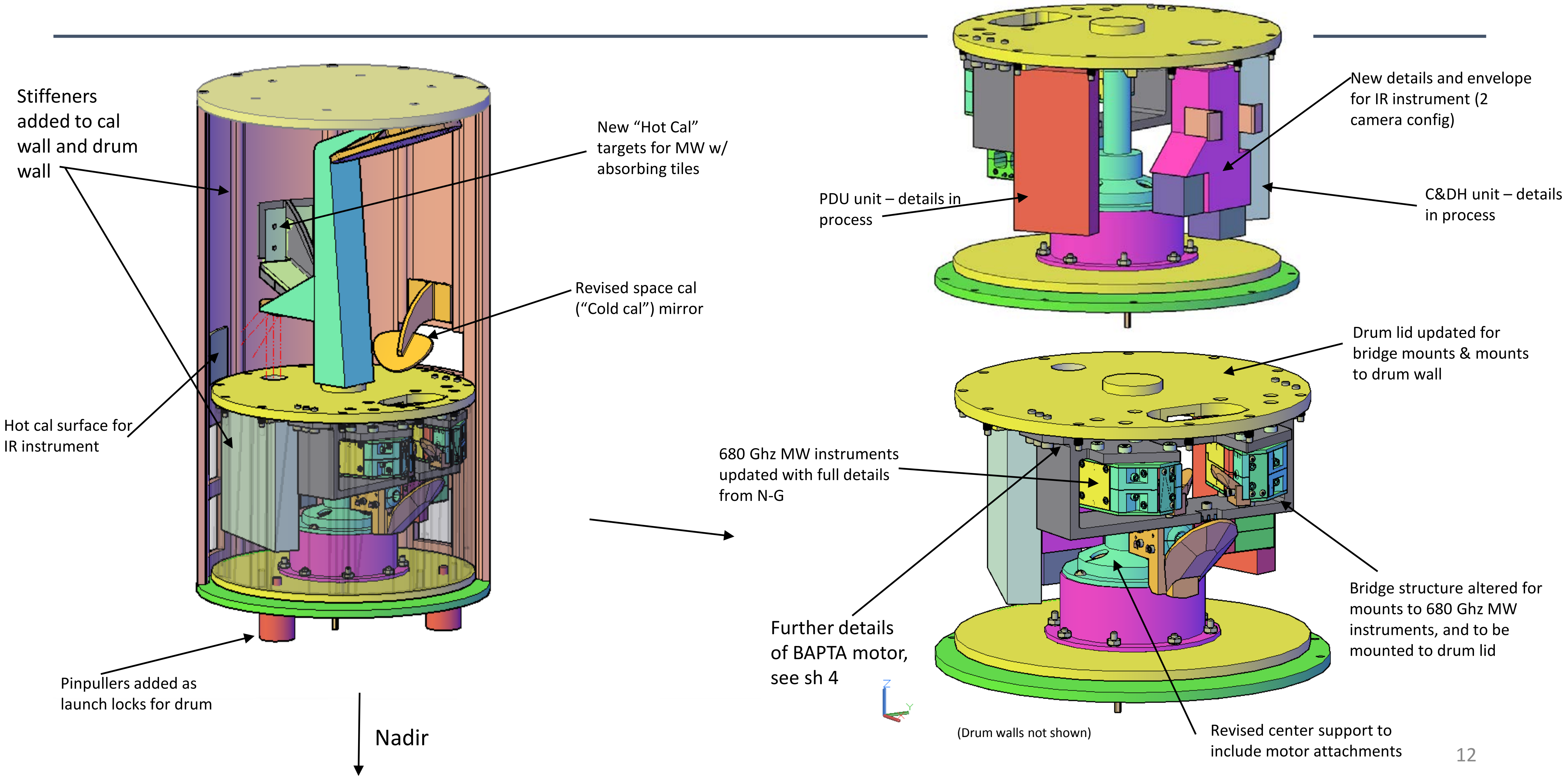


Data capture using FLIR provided SDK (top – 8bit data with AGC On, bottom – 16 bit raw/no-AGC)

Current Design – MiniBAPTA Block Diagram



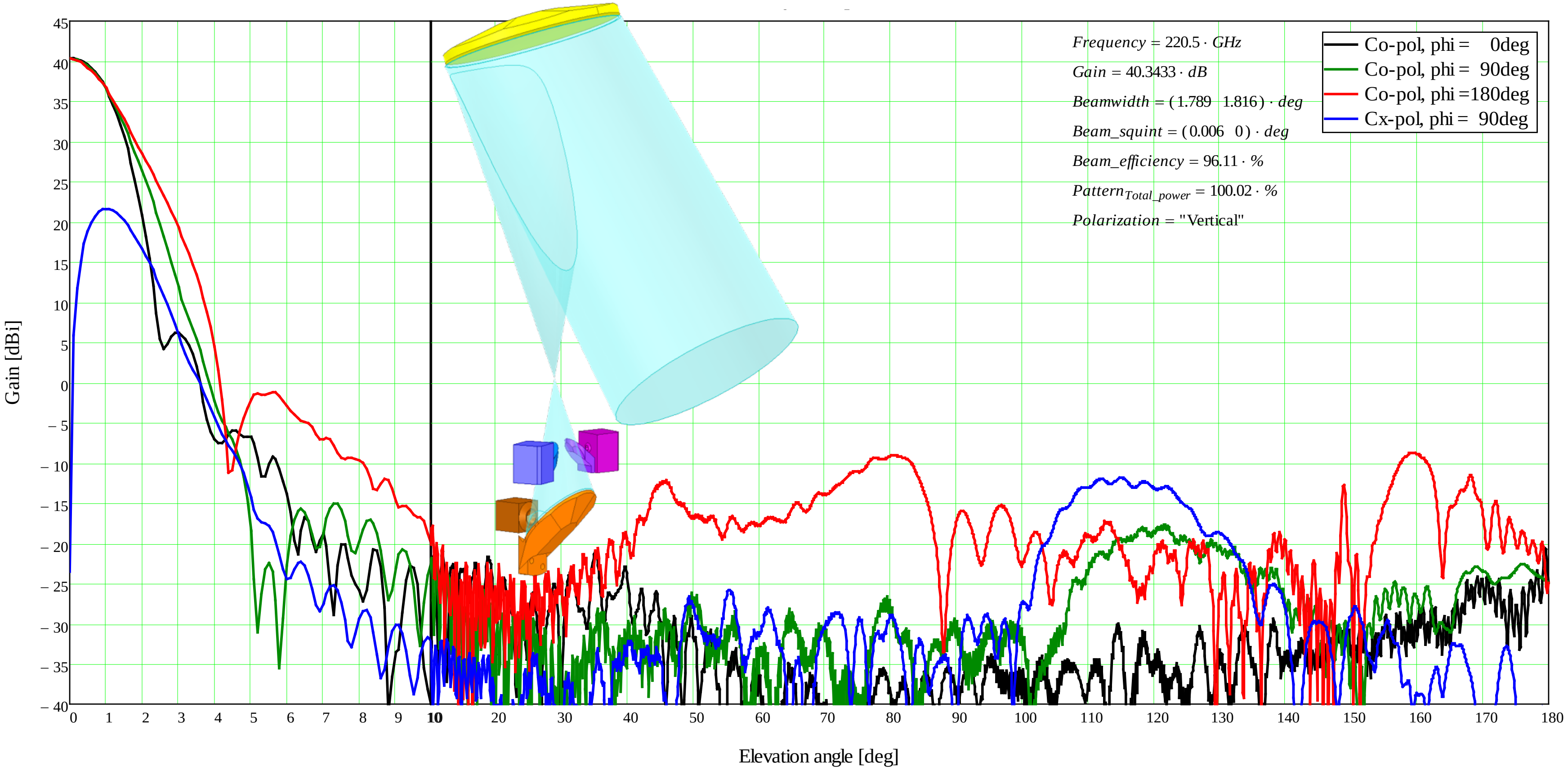
Current Design: Instrument Assembly



Current Design – 220.5 GHz Antenna Model (Vpol shown)

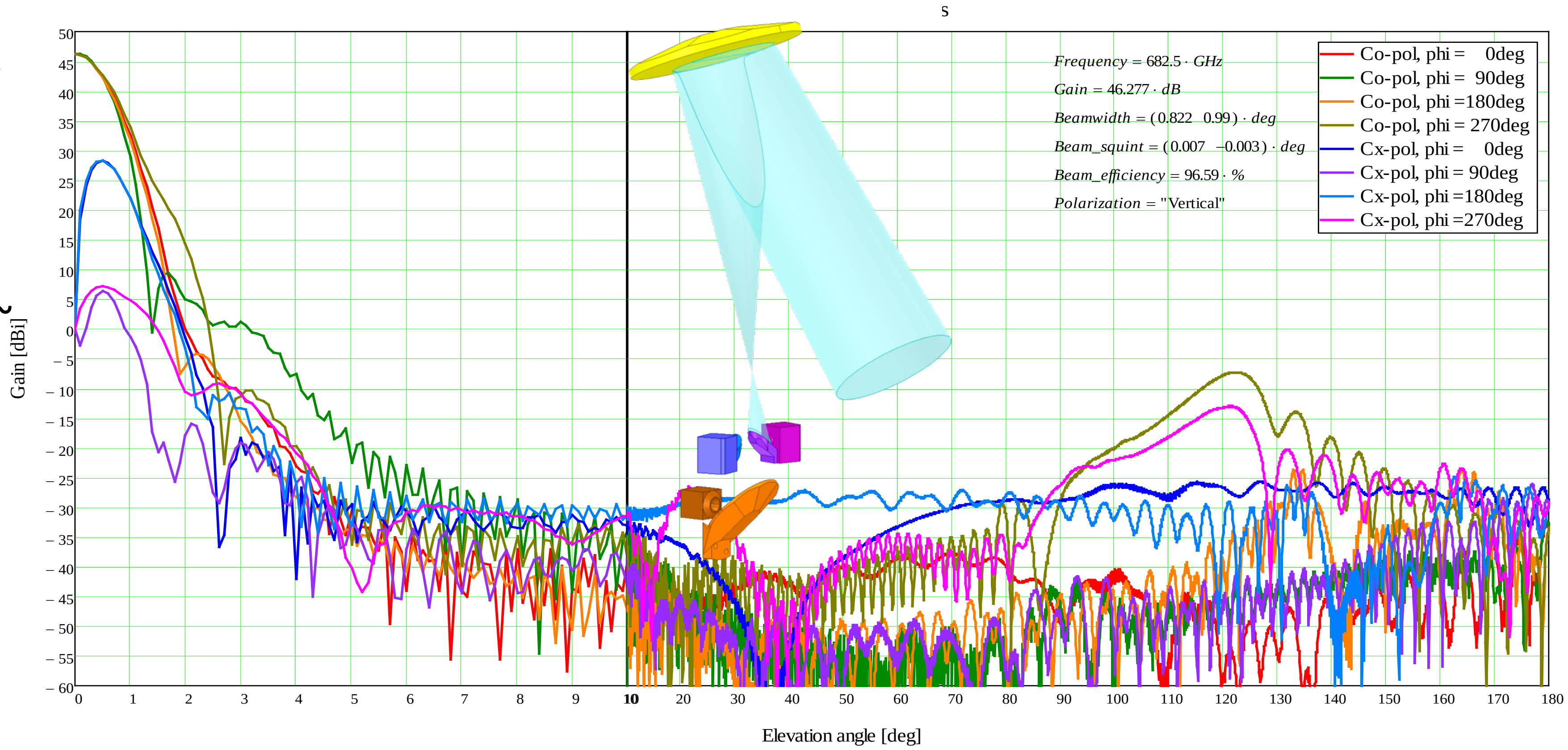
- 220.5 GHz
  - Beamwidth ~ 1.8 deg
  - Gain = 40.3 dBi
  - Beam efficiency ~ 96%
  - Integrated cross-pol ~ 2.0%
- Exiting at 36.2 deg from Nadir
- Earth incidence = 38.9 deg

Cornelis Du Toit



Current Design – 682.5 GHz Antenna Model (Vpol shown)

- 682.5 GHz
  - Beamwidth ~ 1.8 deg
  - Gain = 40.3 dBi
  - Beam efficiency ~ 96%
  - Integrated cross-pol ~ 2.0%
- Exiting at 36.2 deg from Nadir
- Earth incidence = 38.9 deg



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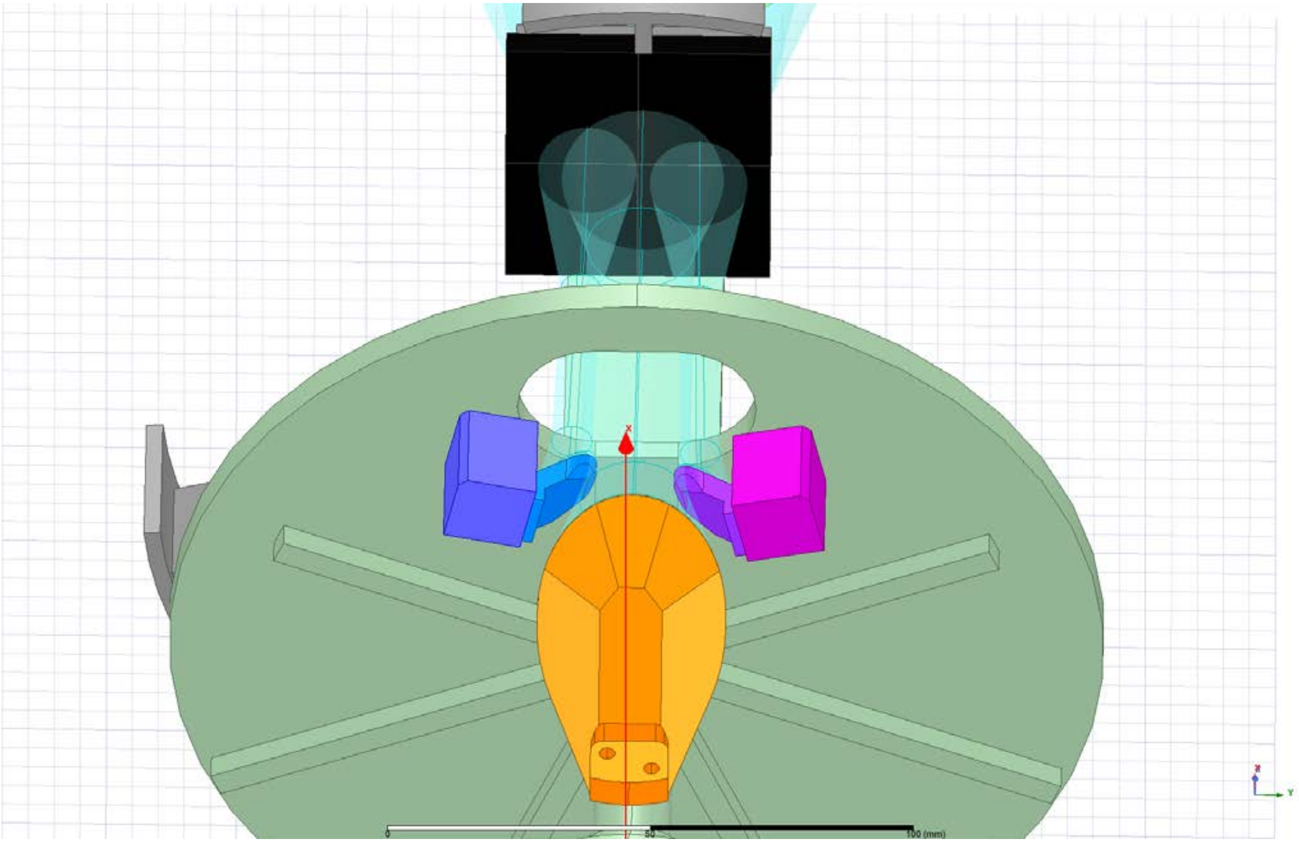
Current Design – Sub-mm Calibration

- **Hot target**
  - Current concept is to intercept beams between primary and secondary reflector.
    - Only requires 4 (1” x 1”) absorber tiles

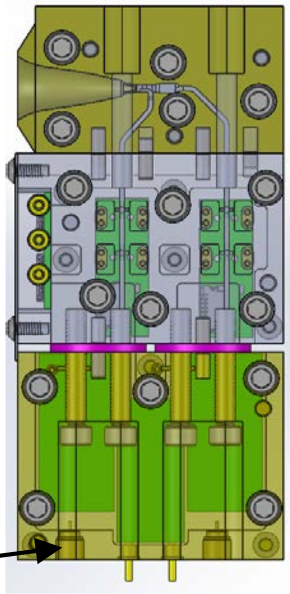


Current Design – 220.5 GHz Direct Detection Receiver

Horn/OMT Module
- WR-4.3 integrated horn, OMT and H/E waveguide twist

BPF Module
- 215-225 GHz Polystrata designed by Nuvotronics

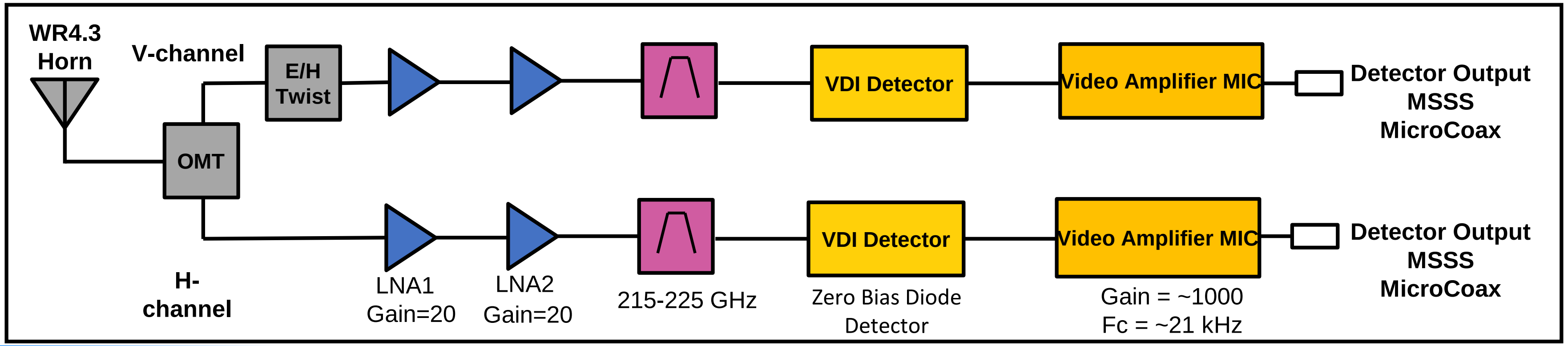
Detector Module
- Virginia Diodes zero bias diode detector



MSSS MicroCoax video output

LNA Module
- Two 215-225 GHz LNA MMICs (per channel)
- Integrated voltage regulator with single +2V bias input
- Switching capabilities for 1/f noise reduction

Video Amplifier
- DC – 21 kHz video amplifier PCB
- Integrated voltage regulator with +/-12V inputs



Current Design – 220.5 GHz Receiver Specs

Receiver Specifications

Parameter	Units	Min	Typ	Max
Receiver Bandwidth	GHz		215.5 – 225.5	
Receiver Center Frequency	GHz		220.5	
Video Bandwidth	kHz		21	
Output Voltage @ 25 C (25 C Target)	mV		1,500	
Operating Temperature Range	C	0		40
Noise Figure @ 25 C	dB		5	
BPF Out of Band Rejection	dB		30	
Passband Gain Variance	dB		1	
OMT H/V Isolation	dB		TBD	
Module Voltages (4)	V		2, 5, 12, -12	
DC Power	mW		360	
Size (WxLxH)	cm		1.5 x 3 x 6.5	
Weight	g		440	

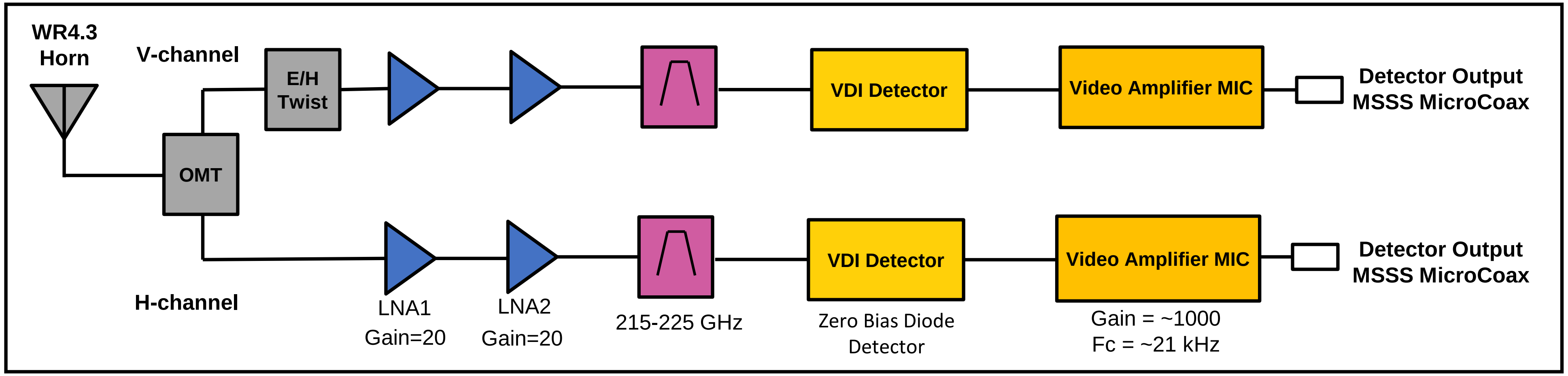
Connector Interface

Connector Description	Connector Type
Video Amplifier Output	MSSS
DC Connectors	DC Feed-thru
GND Connector	Turret

DC Interface

Pin#	Voltage [V]	Current [mA]
1	+12	12
2	-12	12
3	+2	192
4	5	---
5	5V enable	---

Current Design – 220.5 GHz Receiver Cascade Analysis



Cascade assumptions:

- 20 dB LNA gain
- 5 dB LNA NF
- 10 GHz BPF BW
- 2 dB input losses (conservative)

	Target Temp [C]	Target Thermal Noise Power [dBm]	Cascaded NF [dB]	Receiver Input Noise Power [dBm]	Horn/ OMT	LNA1	LNA2	BPF	RF Power @ Det
Gain [dB]	2.0	-83.2	7.0	-76.1	-2.0	20.0	20.0	-15.4	---
Output Power [dBm]	---	---	---	---	-78.1	-58.1	-38.1	-53.6	-53.6

Gain budget assumptions:

- LNA saturation: -20 dBm
- Detector saturation: -25 dBm
- Min. detectable RF power: TBD

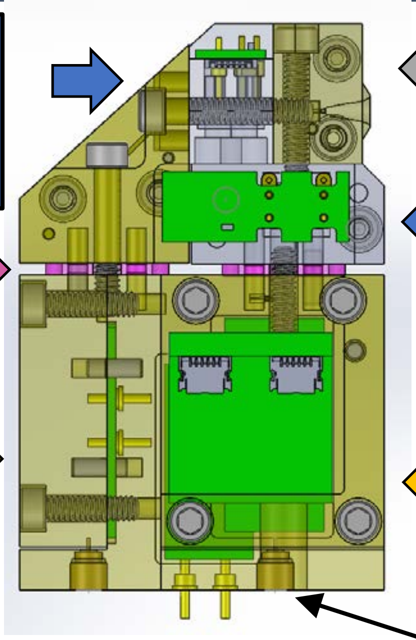
	Target Temp [C]	Target Thermal Noise Power [dBm]	Cascaded NF [dB]	Receiver Input Noise Power [dBm]	Horn/ OMT	LNA1	LNA2	BPF	RF Power @ Det
Gain [dB]	330.0	-61.0	7.0	-54.0	-2.0	20.0	20.0	-15.4	---
Output Power [dB]	---	---	---	---	-56.0	-36.0	-16.0	-31.4	-31.4

Current Design – 682.5 GHz Direct Detection Receiver

H-plane LNA Module
- Two 676-688 GHz LNA MMICs
- Separated E/H plane LNA assemblies for compact design = improved receiver sensitivity

BPF Module
- 676-688 GHz Polystrata designed by Nuvotronics

Detector Module
- VDI zero bias diode detector
- Accommodates LNA regulator and switching PCB

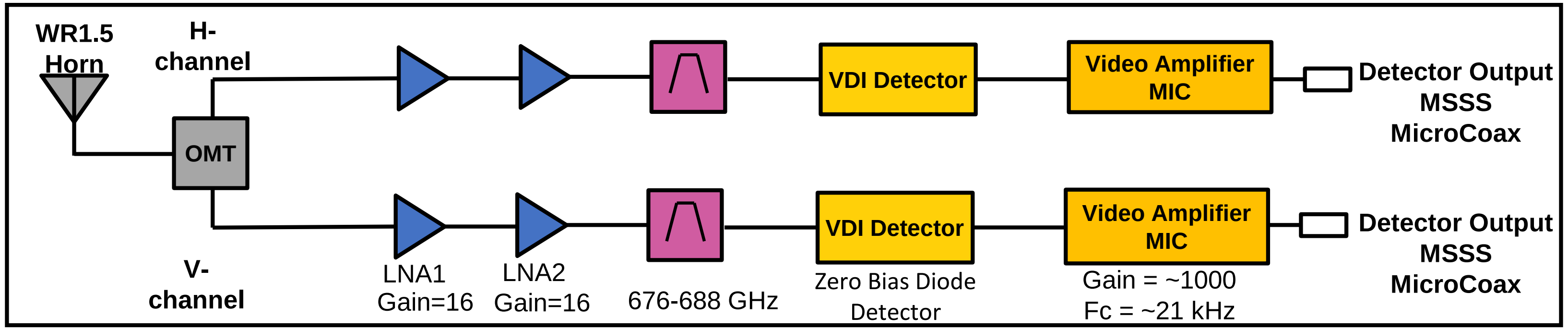


Horn/OMT Module
- WR-1.5 integrated horn, OMT

E-plane LNA Module
- Two 676-688 GHz LNA MMICs
- Integrated voltage regulator and switching capabilities for 1/f noise reduction

Video Amplifier
- DC – 21 kHz video amplifier PCB
- Integrated voltage regulator with +/-12V inputs

MSSS MicroCoax video output



Current Design – 682.5 GHz Receiver Specs

Receiver Specifications

Parameter	Units	Min	Typ	Max
Receiver Bandwidth	GHz		676.5 – 688.5	
Receiver Center Frequency	GHz		682.5	
Video Bandwidth	kHz		21	
Output Voltage @ 25 C (25 C Target)	mV		1,500	
Operating Temperature Range	C	0		40
Noise Figure @ 25 C	dB		11	
BPF Out of Band Rejection	dB		30	
Passband Gain Variance	dB		1	
OMT H/V Isolation	dB		TBD	
Module Voltages (4)	V		2, 5, 12, -12	
DC Power	mW		530	
Size (WxLxH)	cm		1.5 x 3 x 5	
Weight	g		350	

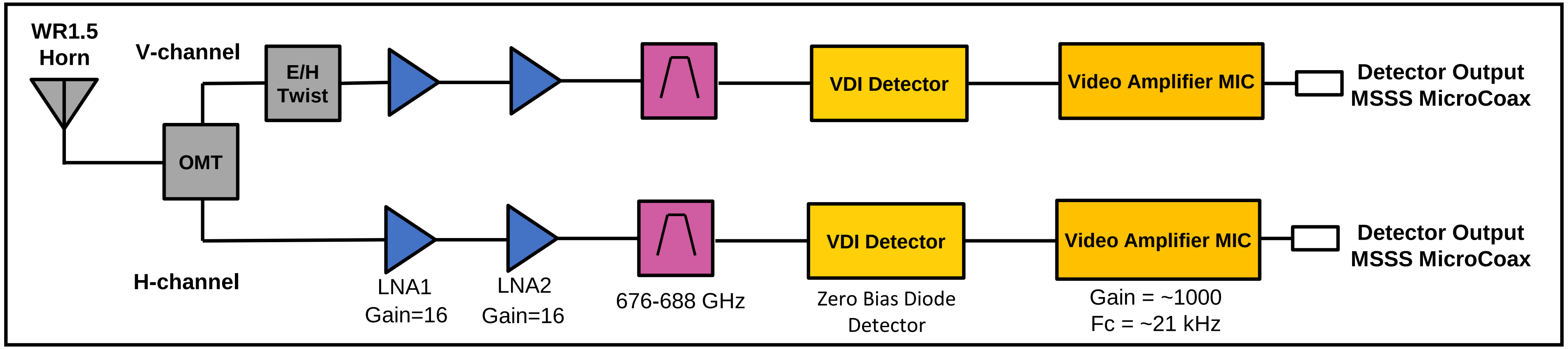
Connector Interface

Connector Description	Connector Type
Video Amplifier Output	MSSS
DC Connectors	DC Feed-thru
GND Connector	Turret

DC Interface

Pin#	Voltage [V]	Current [mA]
1	+12	12
2	-12	12
3	+2	192
4	5	---
5	5V enable	---

Current Design – 682.5 GHz Receiver Cascade Analysis



Cascade assumptions:

- 16 dB LNA gain
- 10 dB LNA NF
- 12 GHz BPF BW
- 2 dB input losses (conservative)

	Target Temp [C]	Target Thermal Noise Power [dBm]	Cascaded NF [dB]	Receiver Input Noise Power [dBm]	Horn/ OMT	LNA1	LNA2	BPF	RF Power @ Det
Gain [dB]	2.0	-83.2	12.1	-71.1	-2.0	16.0	16.0	-14.6	---
Output Power [dBm]	---	---	---	---	-73.1	-57.1	-41.1	-55.7	-55.7

Gain budget assumptions:

- LNA saturation: -20 dBm
- Detector saturation: -25 dBm
- Min. detectable RF power: TBD

	Target Temp [C]	Target Thermal Noise Power [dBm]	Cascaded NF [dB]	Receiver Input Noise Power [dBm]	Horn/ OMT	LNA1	LNA2	BPF	RF Power @ Det
Gain [dB]	330.0	-61.0	12.1	-48.9	-2.0	16.0	16.0	-14.6	---
Output Power [dB]	---	---	---	---	-50.9	-34.9	-18.9	-33.5	-33.5

Channeled Far IR Spectro-Polarimeter Concept

- Objective – measure the flux, degree of linear polarization and angle of polarization from 8.5 – 12.5 microns with at least 0.5 micron resolution
- Primary target is cold clouds measured with a scanning pinhole aperture
- Polarization modulator
  - Quarter wave retarder (QWR) with a fast axis at 45° followed by a CdSe crystal high order retarder (HOR)
  - This combination rotates the angle of incident polarization as a function of wavelength
  - (8*2π at 12.5 μm to 10*2 π at 8.5 μm)
- Following the HOR is a modulation element to separate the 2 polarization channels
  - modulates the transmitted intensity as a function of wavelength with a period of 1 micron
  - opposite polarities in 0 ° and 90 ° channels
  - Measuring both channels enables the distinction of polarization artifacts from spectral artifacts
  - We have 2 different designs which utilize different optical elements to separate channels
    - Wollaston Prism Design
    - 2 Camera Design
- Diffraction grating serves as a spectrometer

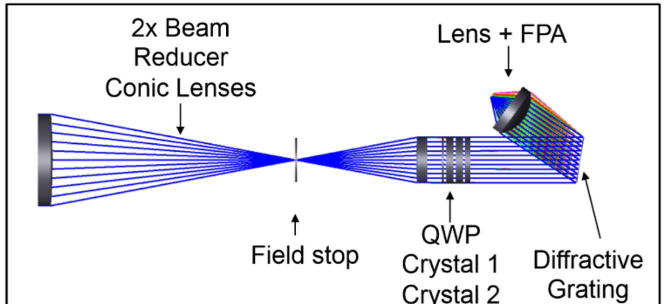
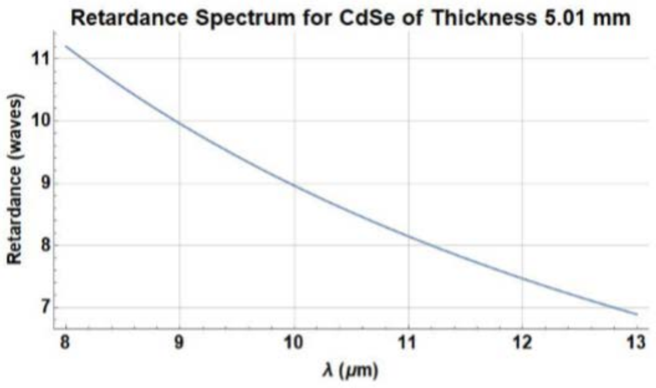


Fig.11. IRCSP Optics

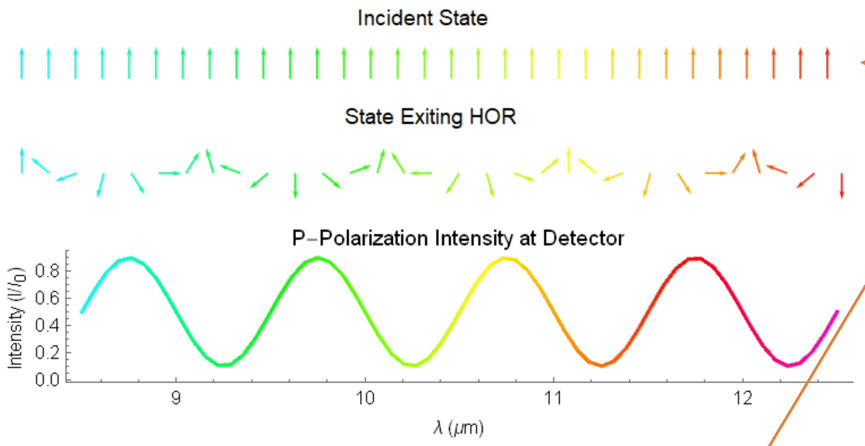
Optical Design from Proposal: the original design only measured 1 polarization output of a linear polarizer



Retardance spectrum for HOR calculated in Polaris-M. The retardance difference δ8.5−12.5 = 4 waves as desired

Channeled Spectro-Polarimeter Concept

- The InfraRed Channeled Spectral Polarimeter IRCSP performs a spectrally-dependent polarization modulation to produce a co-sinusoidal intensity pattern at the detector
- Fringe amplitude is proportional to degree of linear polarization (DoLP), unpolarized light yields no amplitude modulation
- The angle of linear polarization (AoLP) determines the phase of the intensity pattern



Incoming Partially Linearly Polarized Light, DoLP=D

Polarization state is rotated as a function of wavelength

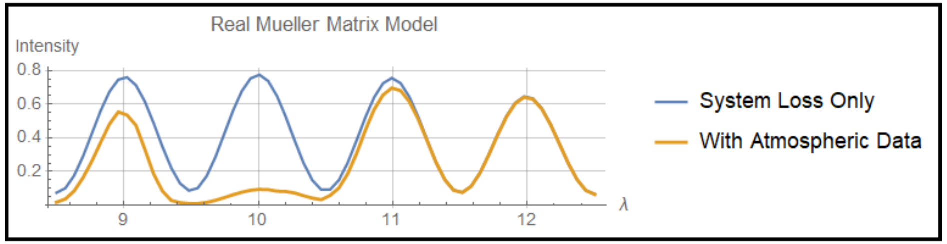
Light intensity modulated at detector
Unpolarized light is unmodulated

Mueller Matrix Model

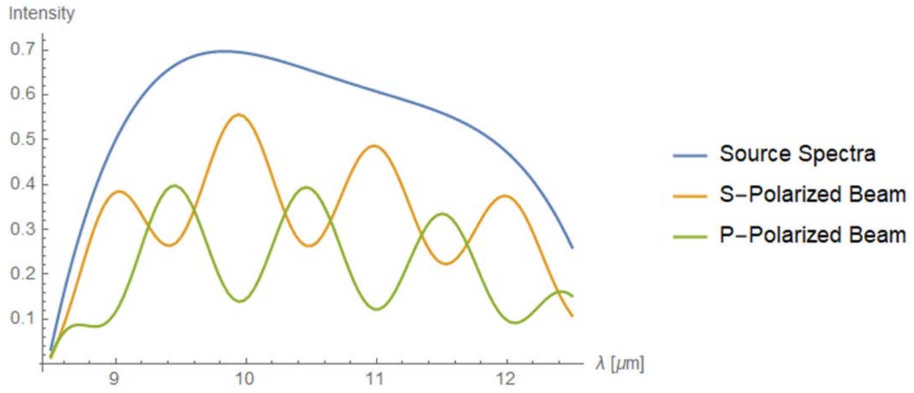
$$\frac{1}{2}\begin{bmatrix}1&0&1&0\\0&0&0&0\\1&0&1&0\\0&0&0&0\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&cos\delta(\lambda)&sin\delta(\lambda)\\0&0&-sin\delta(\lambda)&cos\delta(\lambda)\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&0&0&-1\\0&0&1&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}1\\Dcos(2\theta)\\Dsin(2\theta)\\0\end{bmatrix}=\frac{1}{2}\begin{bmatrix}1+Dsin(\delta(\lambda)-2\theta)\\0\\1+Dcos(\delta(\lambda)-2\theta)\\0\end{bmatrix}$$

Benefit of Measuring Both Polarization Channels

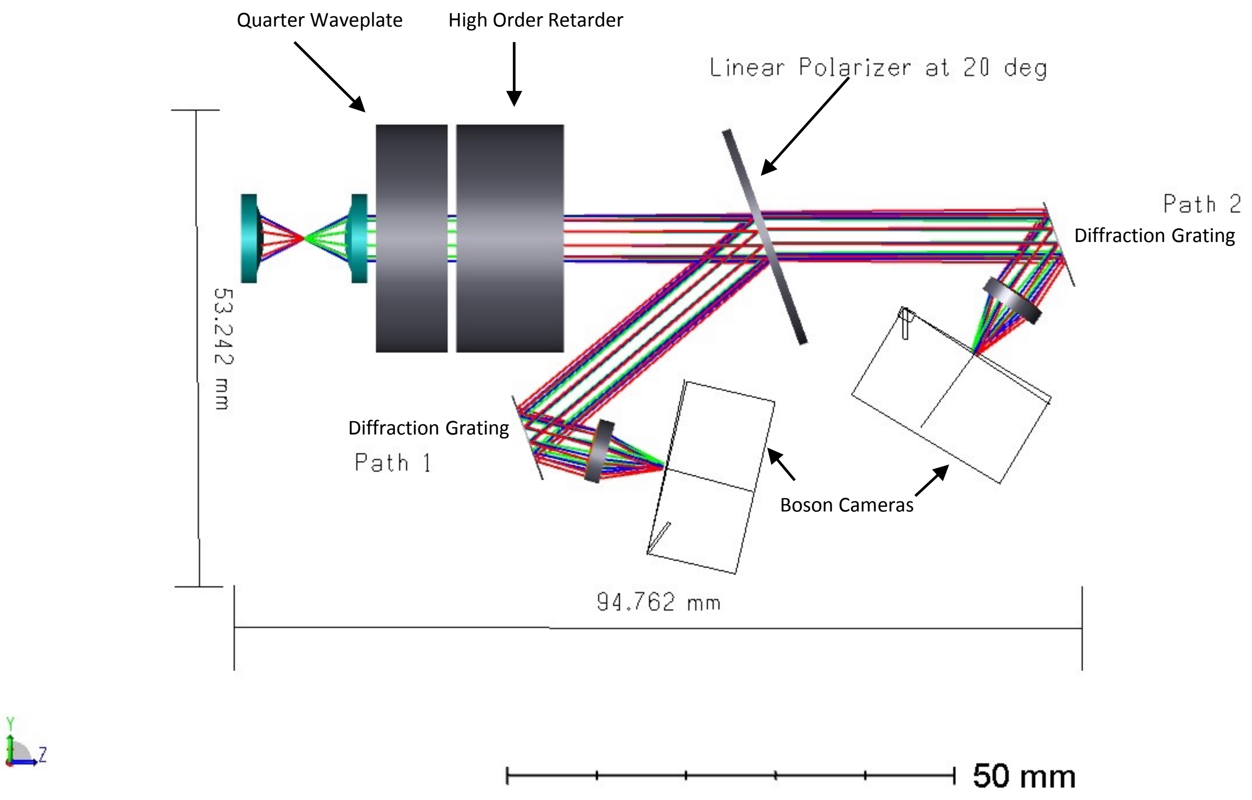
- In the preliminary design, a linear polarizer eliminated the spectral intensity data associated with the polarization state orthogonal to the transmission axis
    - Ambiguous if intensity variations at detector are due to polarization state or source spectrum
    - Ozone absorption causes an artifact on the order of one modulation period
- If all polarization states entering the system are measured at the detector the source spectrum can be measured and corrected for
- Can measure both beams reflected and transmitted by linear polarizer if it is tilted
    - Use the sum of these beams to reconstruct the source spectrum



DOLP=0.8, AOLP =45 Degrees



Miniaturized 2 Camera Design, Plan A



- Collimated light through quarter wave retarder and high order retarder
- 0 and 90° polarizations split at wire grid polarizer to measure flux and polarization
- Two identical diffraction gratings
  - 50 micron period
  - 20 degrees AOI
  - Have grating design with good diffraction efficiency simulated using rigorous coupled wave analysis
- Dimensions of QWP, HOR, and LP housings are shown
- Linear Polarizer operating at maximum angle specified by vendor, Moxtek

Thank you