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A Sensor for On-orbit Optical Detection of Lethal Non-Trackable Debris; Ground Testing Summary

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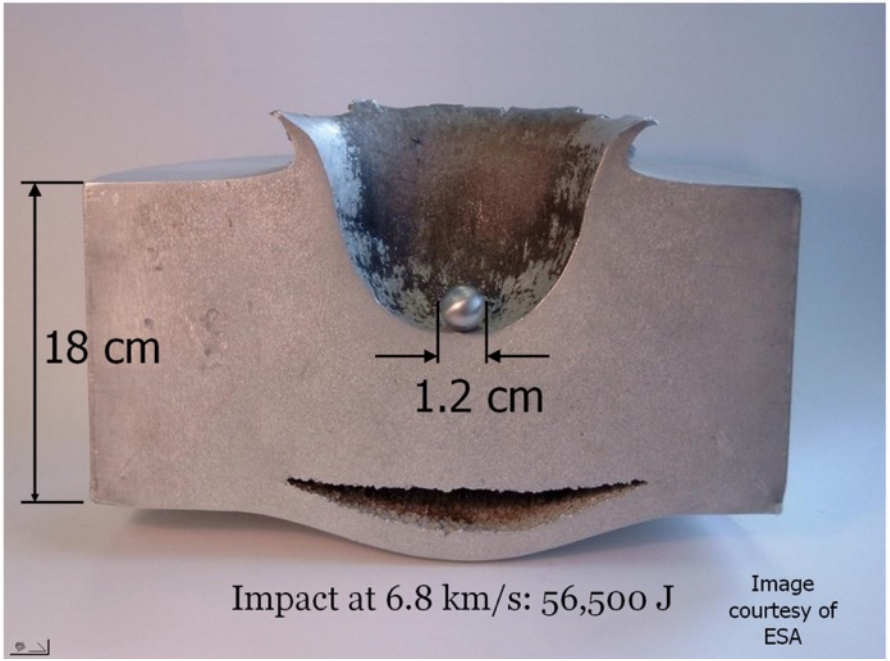
He has been working at the Naval Research Laboratory in Washington, DC for 29 years. He is a civil servant heading the Sensor Development and Applications Section of the Geospace Science and Technology Branch in the Space Sciences Division.

His research includes the development of space-flight hardware to study orbital debris, the upper atmosphere, thermosphere/ionosphere, atmospheric data analysis and modeling.

Motivation



Hypervelocity Impact Testing

Resulting damage to an 18 cm thick block of Aluminum after being impacted by a 1.2 cm Aluminum sphere travelling at 6.8 km/s. *Credit: ESA*

Objects in the size range from fractions of a mm to a few cm have enough kinetic energy to causes serious or catastrophic damage to spacecraft but are too small to be effectively seen from the ground.

LARADO is an on-orbit asset designed to observe this lethal debris population

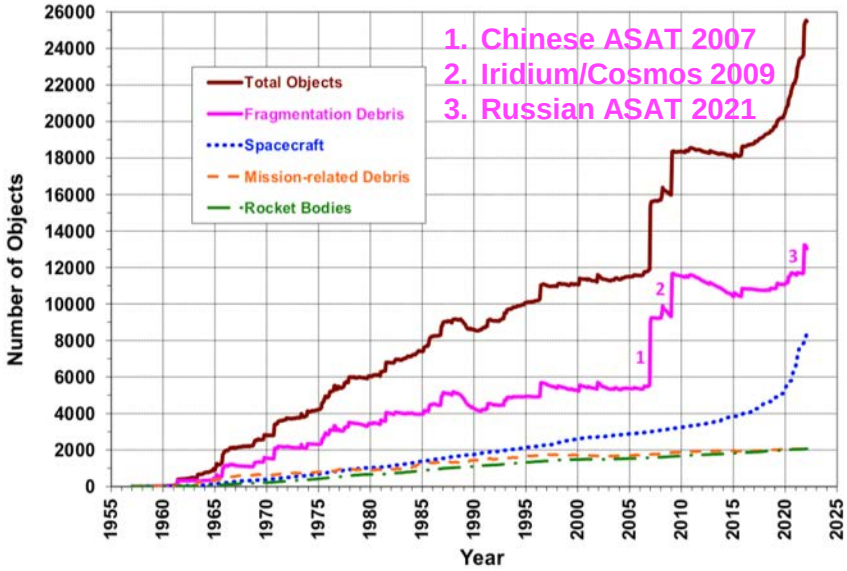
Background

Space debris is a widely recognized, growing problem for all orbiting assets

Current/planned future detection techniques for objects in orbit:

- Ground based radar & optical
- Space based optical
  - All are sensitive to objects >5cm (statistical data down to mm scale)

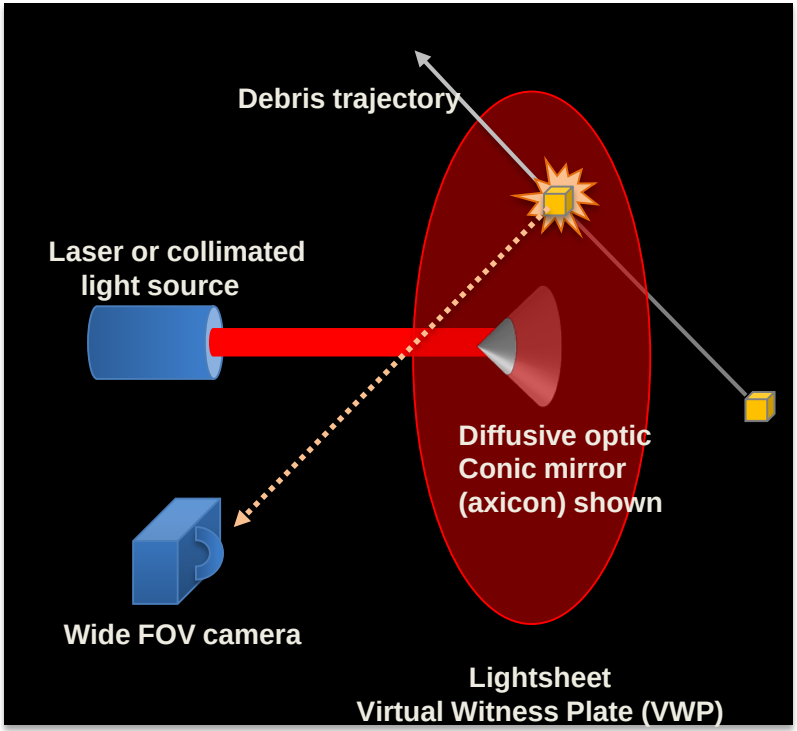
- There are about 750,000 flying bullets about one centimeter in size, such as the one that hit Sentinel 1A, and approximately 150 million objects at around one millimeter



Holger Krag, head of the European Space Agency's Space Debris Office at the Seventh European Conference on Space Debris (April 18-21, 2017)

Laser-sheet Anomaly Resolution and Debris Observation (LARADO)

Objectives: Demonstrate an innovative concept to perform real time, on-orbit, debris detection (10 cm to 1mm with <mm stretch goal), auto-detection.



Description:

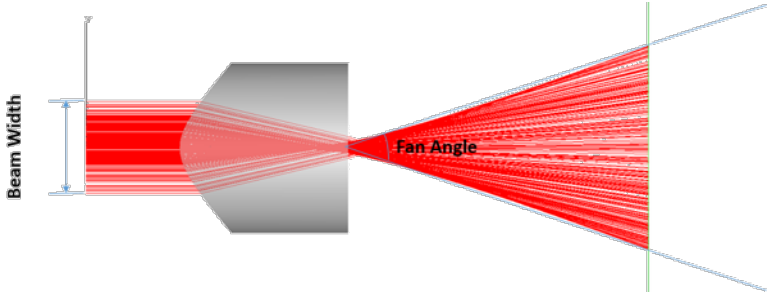
- A light sheet is formed using a collimated light source (e.g. a laser) and a conic mirror, Powell lens or diffuser.
- A camera is used to detect scattered light from objects penetrating the laser sheet.
- System is scalable, more laser power provides increased coverage and better sensitivity
- Desired area x time coverage: $3m^2$*year
  - Reduce errors in models by 50%

Optical Setup Lightsheet

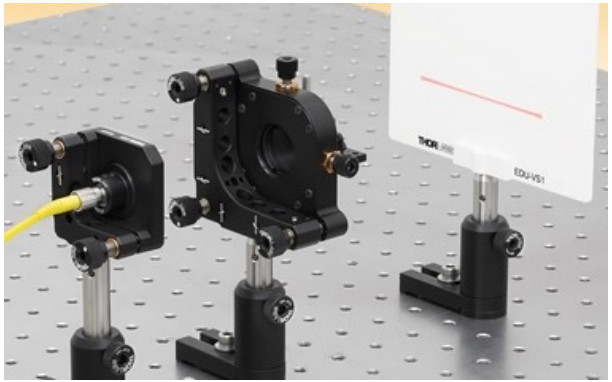
nLight 30 W laser
793 nm (CW)

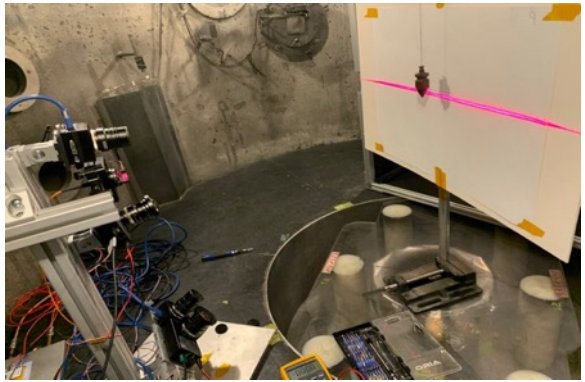
Collimator

Powell Lens



Powell Lens Ray Trace



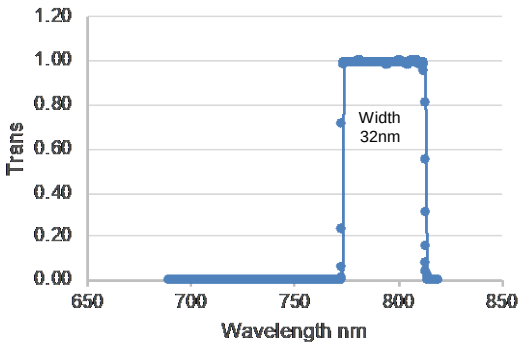


Optical Setup Cameras/Filter

Ximea XiD CCD camera
model MD061MU-SY

- **Traditional Monochrome 6Mp CCD**
- **2752 by 2202 4.5µm Px resolution**
- **Sony ICX814AL sensor (~35% QE at 793nm)**
- **12.5 x 10.0mm chip size**
- **USB 3 interface**
- **8, 10, 12 or 14 bit image depth**
- **ROI readout cropping**

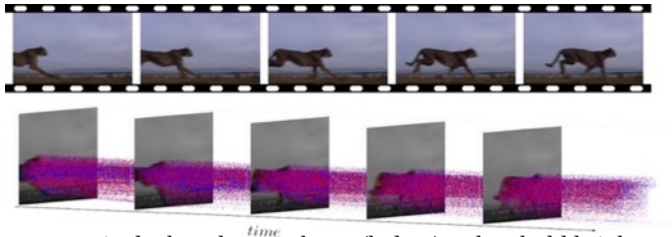
SemRock 794 nm filter



Prophesee camera
Gen 4.1 HD neuromorphic

- **Sony IMX636ES chip**
- **1280 by 720 4.86µm Px res**
- **Optical format: 1/2.5”**
- **Latency at 10kLux: 310 µs**
- **Dynamic Range > 120dB**
- **Min contrast sensitivity 15 %**
- **USB 3 interface**

How a neuromorphic (event-based) camera works



Only reports pixels that change above (below) a threshold brightness. Each pixel is read out independently and asynchronously. Pink (increases) and blue (decreases) dots represent the continuous motion of a cheetah super imposed between frames from a traditional camera.

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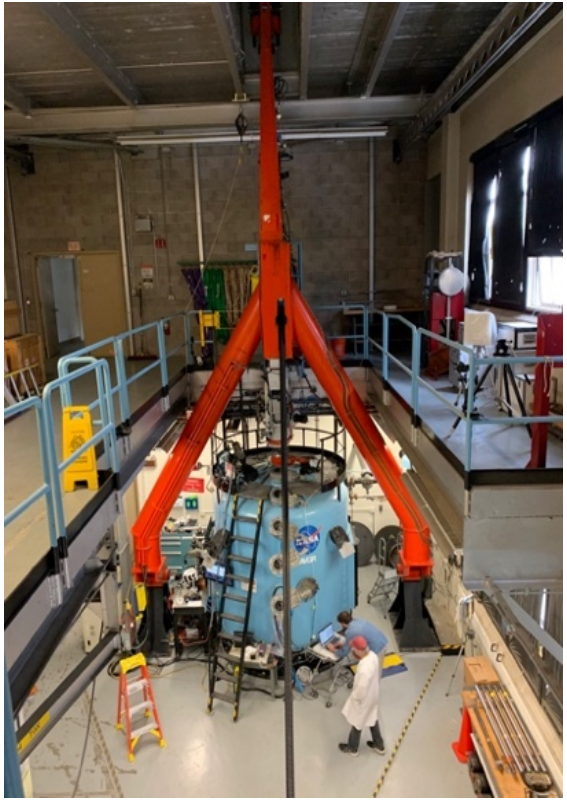
AMES Vertical Gun Range (AVGR)



NASA's premiere hypervelocity impact facility for Planetary Geology and Geophysics research.

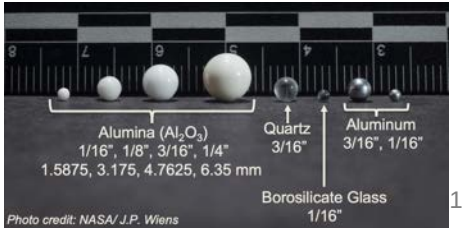
Capabilities:

- 2.5m diameter x 2.75 m chamber
- Impactors can range in size from 1/16" to 1/4" (1.59 - 6.35 mm)
- Launch speeds from 0.5 to 7 km/s
- Can vary the impact angle relative to the gravity vector (15° increments)
- 1m diameter well for targets
- View ports for external instrumentation
- Runs in vacuum (0.5 Torr)

AVGR Trip 2 Shot Test Matrix

Shot #	Gun	Projectile Diameter	Velocity (km/s)	Material
1	PG	1/8" (3.175 mm)	2.33	Alumina
2	PG	1/8" (3.175 mm)	2.37	Alumina
3	PG	1/8" (3.175 mm)	2.3	Alumina
4	PG	1/8" (3.175 mm)	2.31	Alumina
5	PG	1/8" (3.175 mm)	2.31	Alumina
6	PG	1/8" (3.175 mm)	2.37	Alumina
7	PG	1/8" (3.175 mm)	2.31	Alumina
8	PG	1/8" (3.175 mm)	2.32	Alumina
9	PG	1/8" (3.175 mm)	2.32	Alumina
10	PG	1/8" (3.175 mm)	2.27	Alumina
11	PG	1/8" (3.175 mm)	2.33	Alumina
12	PG	1/8" (3.175 mm)	2.3	Alumina
13	PG	1/8" (3.175 mm)	2.3	Alumina
14	PG	1/8" (3.175 mm)	6.27	Alumina
15	LGG	1/8" (3.175 mm)	6.27	Alumina
16	LGG	1/8" (3.175 mm)	6.3	Aluminum
17	LGG	1/8" (3.175 mm)	4.64	Aluminum
18	LGG	1/16" (1.5875 mm)	6.58	Alumina
19	LGG	1/16" (1.5875 mm)	6.42	Aluminum
20	LGG	1/16" (1.5875 mm)	6.49	Aluminum
21	LGG	1/16" (1.5875 mm)	6.41	Aluminum
22*	LGG	various	4.76	Sand
23*	LGG	0.5 mm	4.72	Polyethylene

*Shots 22 & 23 were cup carriers with multiple objects

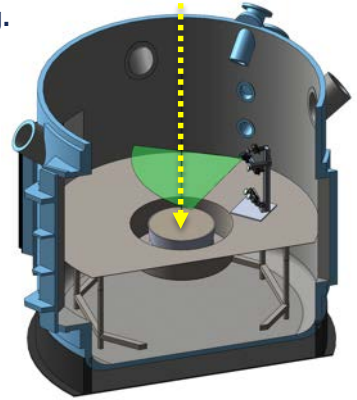


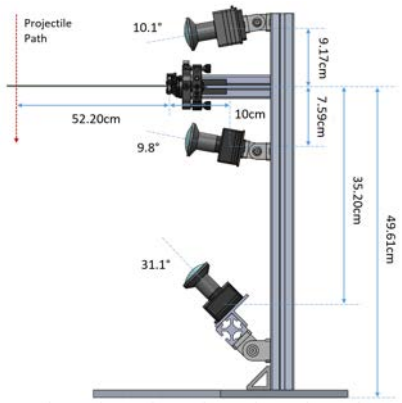
AMES Vertical Gun Range (AVGR) Highlight

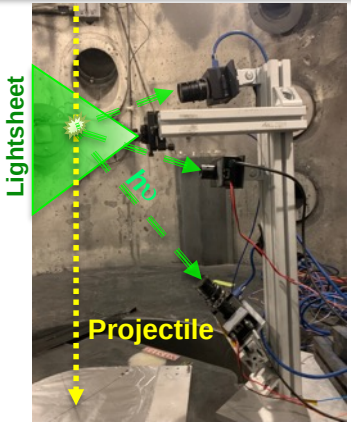
Parallel view data from AMES Round 2 testing.
Good signal observed from both cameras

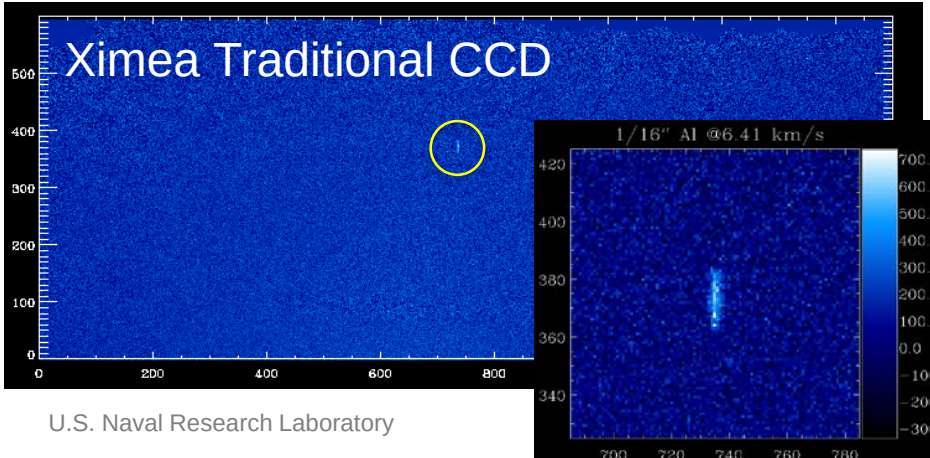
Shot 19 Details:
Light Gas Gun
1/16” diameter (1.5875 mm)
Aluminum @ 6.42 km/s
30W laser output @ 793 nm

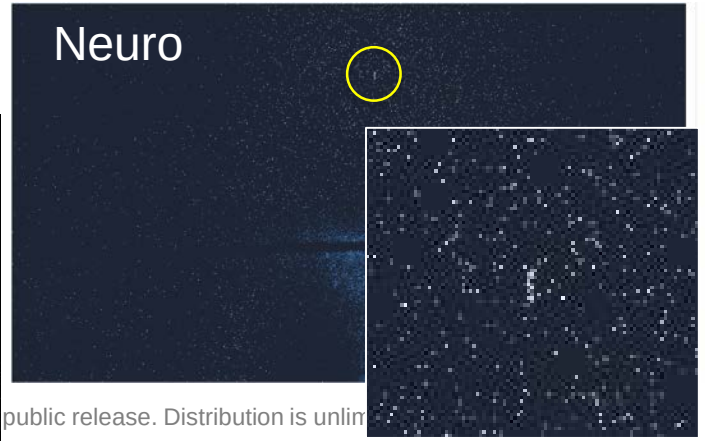
Camera to projectile: 62.88 cm
Along sheet: 52.2 cm
Camera angle: -9.8°



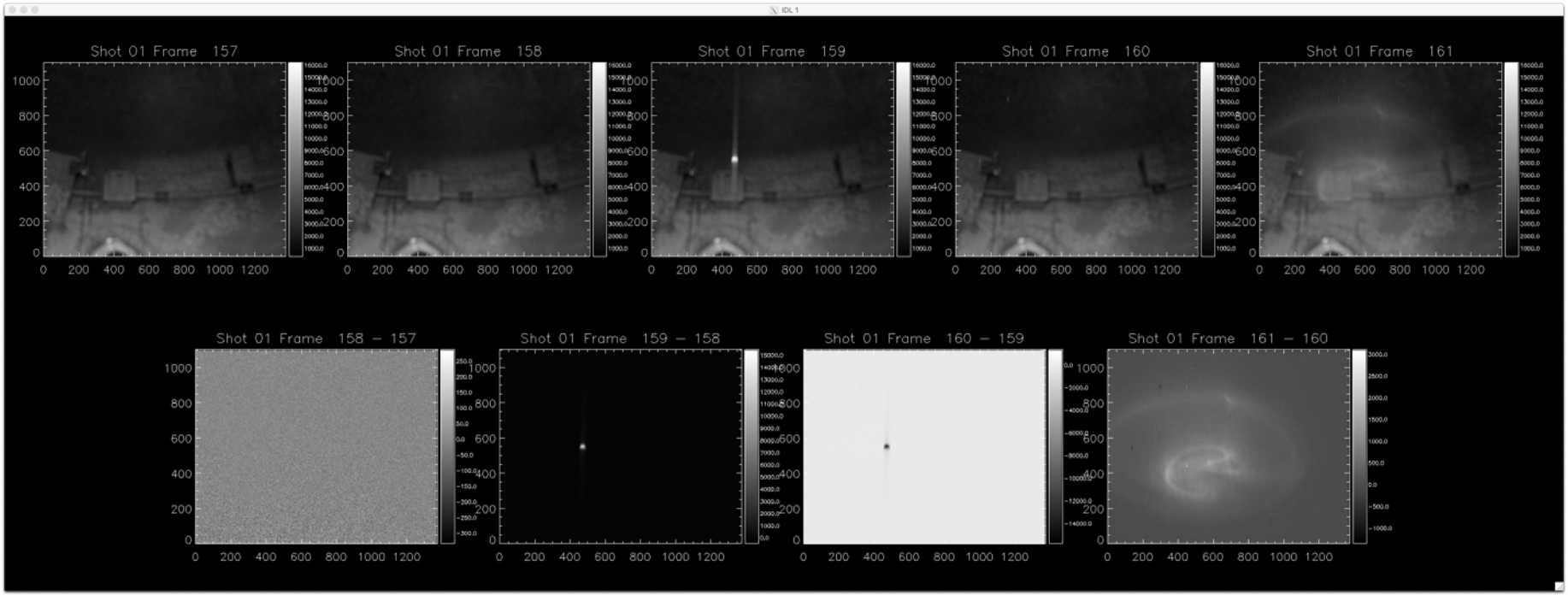








Shot 01 Frame Sequence w/ Diff



AVGR Highlights

Shot 18:

Light gas gun

1/16” Alumina (Al_2O_3)

6.38 km/s

15W @ 793 nm

Ximea:

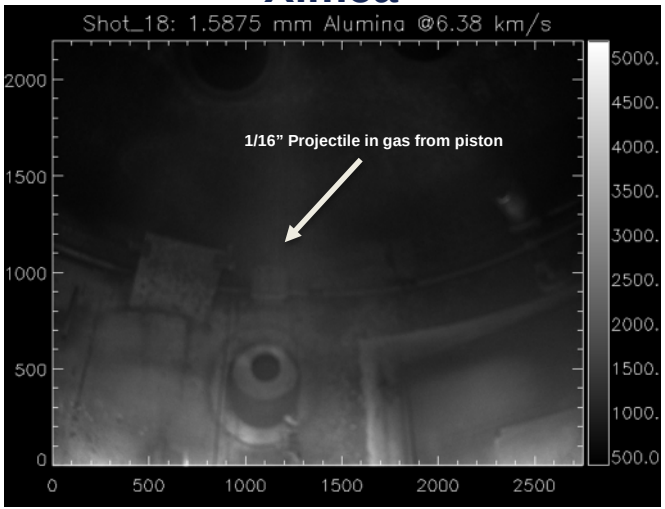
12mm lens, 40 ms exposure

2752 x 2202 pix

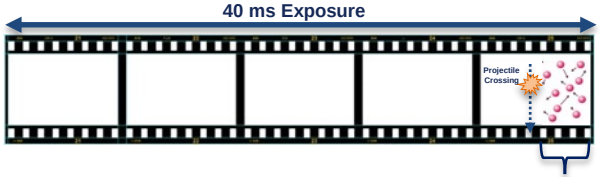
Semrock filter

Neuro: 5mm lens, no filter

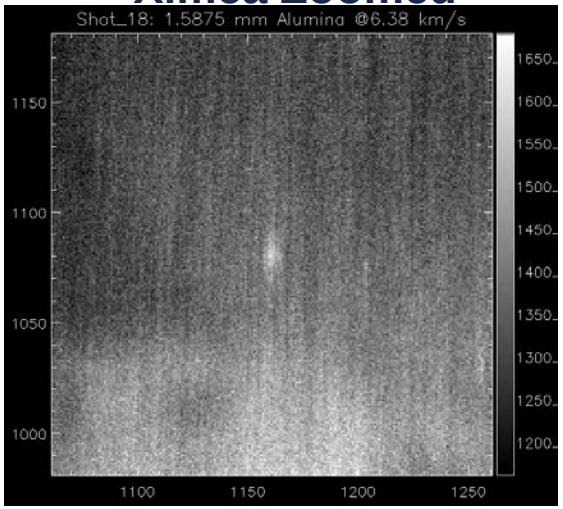
Ximea



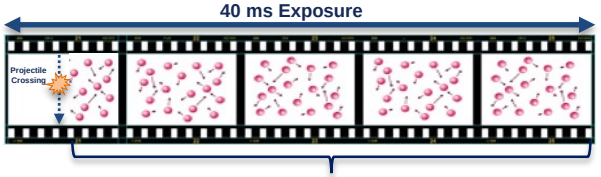
Hydrogen gas enters the scene in the same frame as the projectile. This makes it difficult for auto-detection in this laboratory setting, especially for small fast projectiles.



Ximea Zoomed



In zoomed image from Ximea camera one can clearly identify the projectile, but shows the increased background.



Zoom of differenced Images from Ximea (100x100 px)

Material: Color Tables

Alumina = Greyscale

Aluminum = Blue

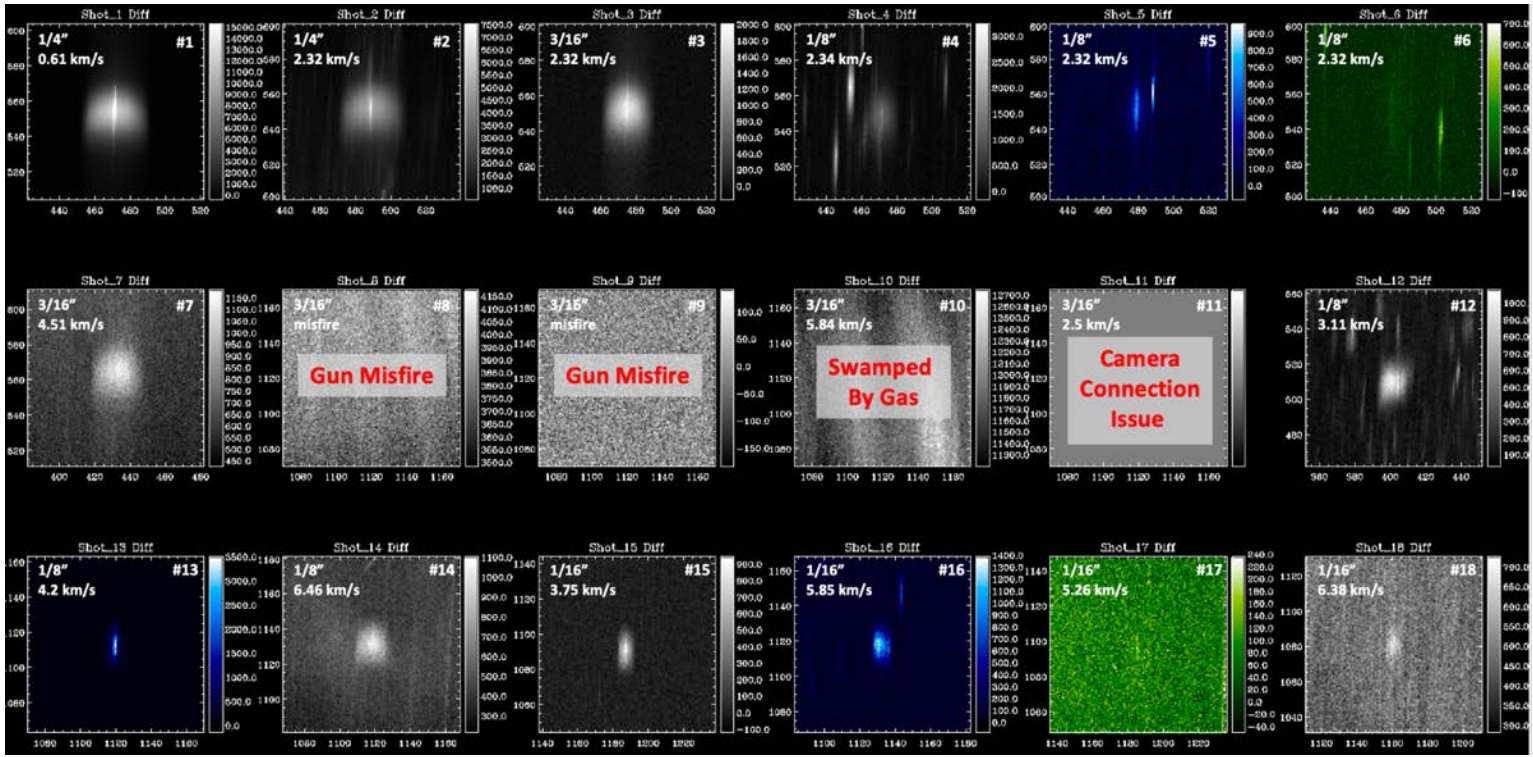
Quartz/Boro = Green

Sizes:

1/4”	6.35 mm
3/16”	4.7625 mm
1/8”	3.175 mm
1/16”	1.5875 mm

Speeds:

0.61 km/s to 6.46 km/s

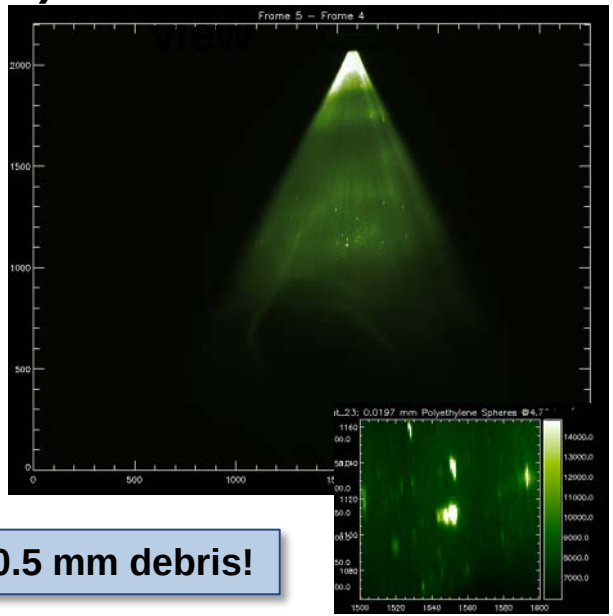


Multiple Debris

Stress test: 0.5 mm dia polyethylene spheres @ 4.72 km/s @ 30W

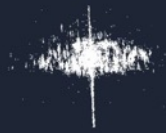
½ mm dia spheres (x50)

Ximea ISO



Successful detection of 0.5 mm debris!

Neuro || view



AVGR Phantom Camera || view

¼" Carrier Cup

Neuro ISO view

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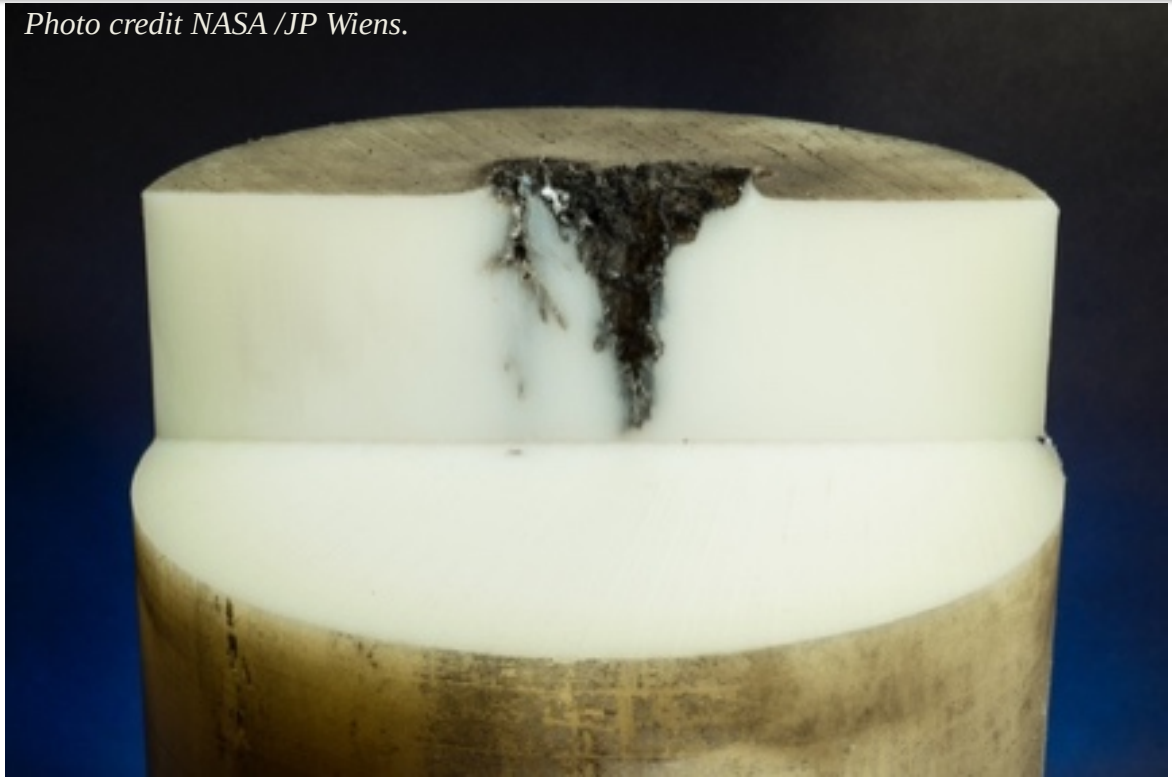
Conclusion & Future Work

- **Successful laboratory testing has been completed at near LEO orbital velocities**
- **TRL of LARADO prototype system has been raised to level 6 (NASA scale)**
  - **Detected single object as small as 1.5875 mm moving at 6.58 km/s**
    - **Group of 0.5mm objects @ 4.72 km/s**
  - **Size characterization was verified.**
  - **SNR is impacted by the random nature of captured frame and background gas in chamber**
  - **Neuromorphic camera shows promise for detection, need to work on bias settings.**

Future Work

1. Continue development of sensor for STPSat-7
2. Modelling: Simulate 2-d image return for each view (|| and iso)
3. Test detection algorithms on simulated image sequences

Questions



A cross-section of the polyethylene backstops taken after multiple shots.

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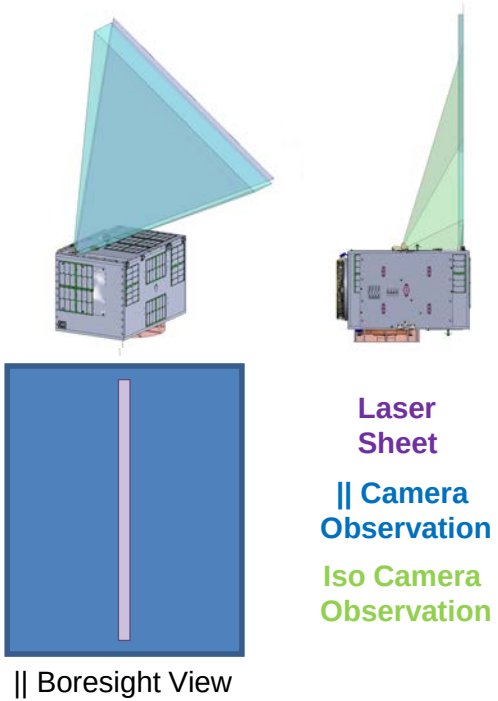
Backup Slides

Implementation on STPSat-7

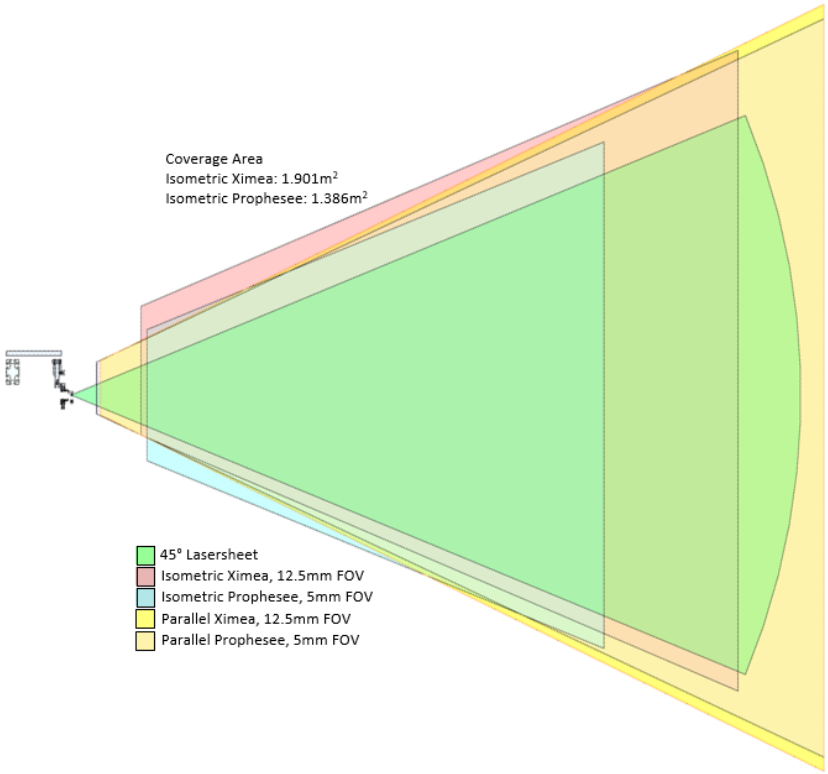
<u>Challenge</u>: There is limited bandwidth on STPSat-7, Unable to downlink all desired LARADO data.

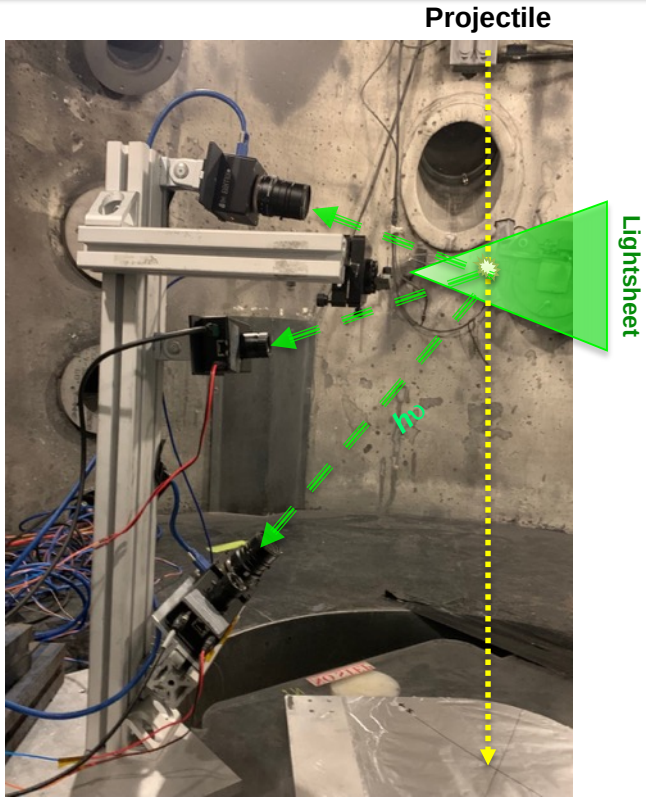
<u>Solution</u>: Change sensor configuration to add a parallel looking viewing (wrt lightsheet) sensor

- Parallel view can be cropped in one direction to ~10-20% of full frame to cover the lasersheet (w/ some buffer).
- This region of interest (ROI) will act as a trigger, when an event is detected in the parallel view the LARADO electronics will flag a # of ISO frames for download with the parallel frame
  - \+ Reduces amount of science data to send to ground
  - \+ Reduces complexity of on-orbit detection algorithms
  - \+ Allows running cameras at a faster cadence
  - \+ 2nd camera allows for discrimination of cosmic rays
  - \+ Avoids sun observation
  - − Adds SWAP for additional camera
  - − Requires time knowledge of the two cameras

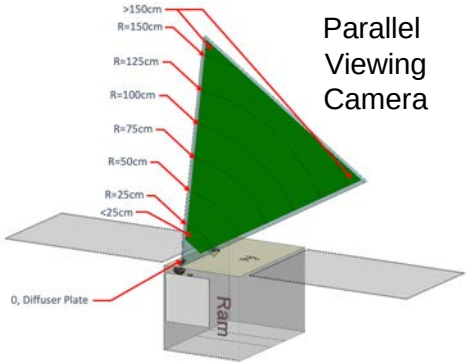


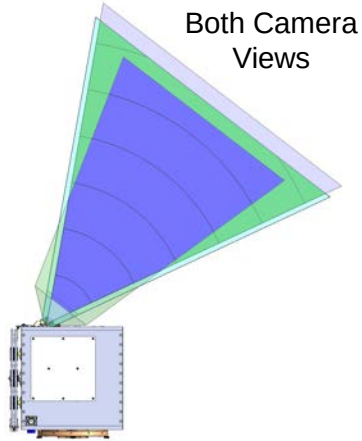
Area Coverage

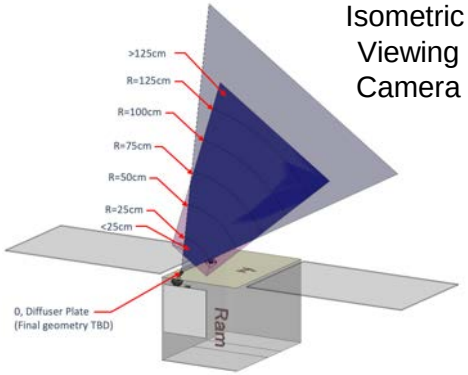


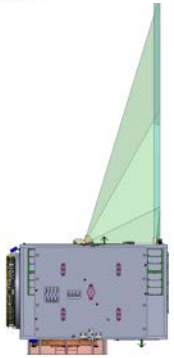


Area Coverage Analysis for STP-Sat7







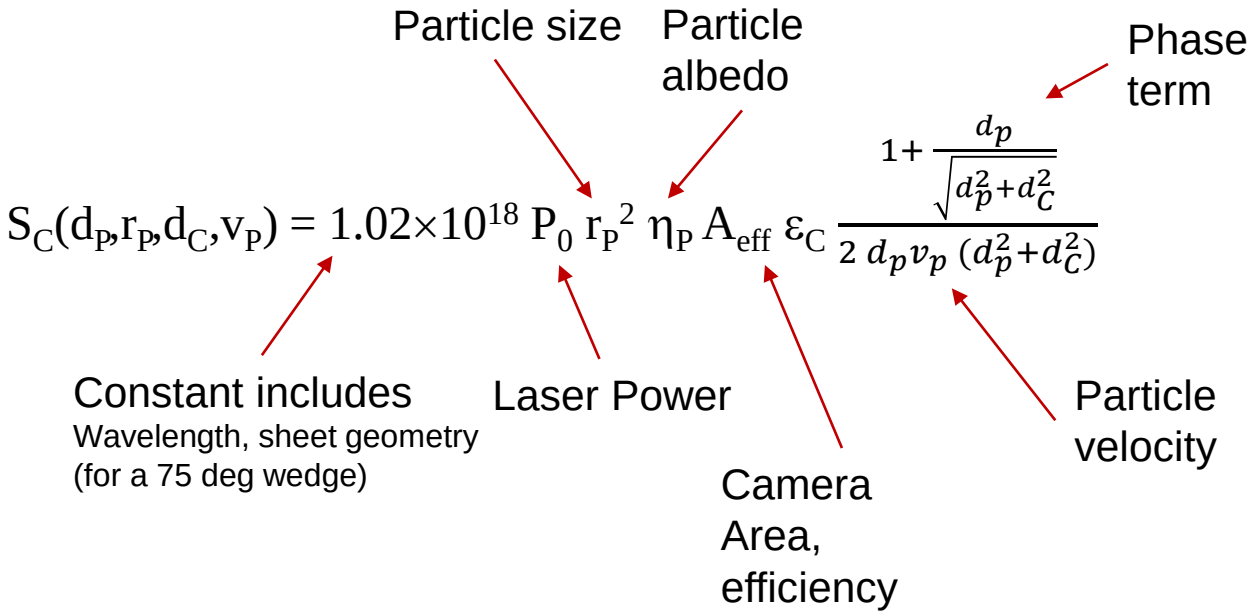


Parallel Viewer				
Radius (cm)	Sep (m)	Range/Radius (cm)	Area (m^2)	∑ Area (m^2)
<25	0.1962	<25	0.0226	0.0226
25	0.3174	25 - 50	0.0927	0.1153
50	0.5667	50 - 75	0.1527	0.268
75	0.8165	75 - 100	0.2127	0.4807
100	1.0663	100 -125	0.2727	0.7534
125	1.3163	125 - 150	0.2952	1.0486
150	1.5018	>150	0.0317	1.0803

Isometric Viewer				
Radius (cm)	Sep (m)	Range/Radius (cm)	Area (m^2)	∑ Area (m^2)
<25	0.4512	<25	0.0254	0.0254
25	0.5114	25 - 50	0.0927	0.1181
50	0.6791	50 - 75	0.1513	0.2694
75	0.8865	75 - 100	0.1922	0.4616
100	1.1116	100 -125	0.2278	0.6894
125	1.3455	>125	0.1448	0.8342
>125	1.4476			

Model

- **Signal from fast-moving FOD (no approximations)**

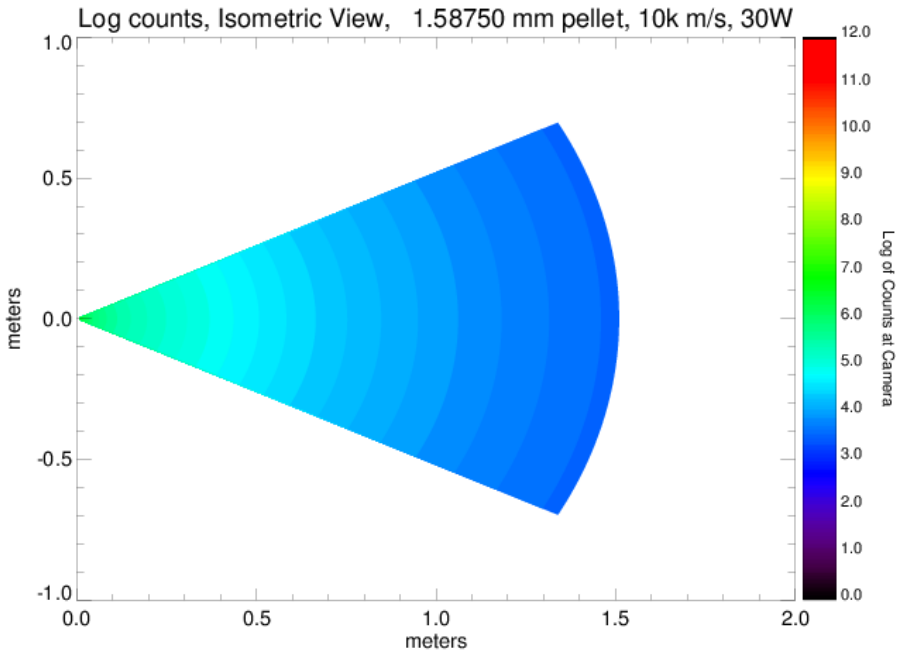


AVGR 1 Counts as a Function of Range

- **Mathematical model (details in paper) predicts the expected counts returned as a function of debris/camera geometry/laser output.**

Inputs:

- **STP Sat-7 Geometry & optics/camera**
- **1.59 cm diameter debris**
- **10 km/s velocity**
- **30 W optical output**
- **Albedo of 1**



Laboratory Test Setup