Quantitative Radiation Thermometry Using Commercially Available High-Speed Video Cameras

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Outline

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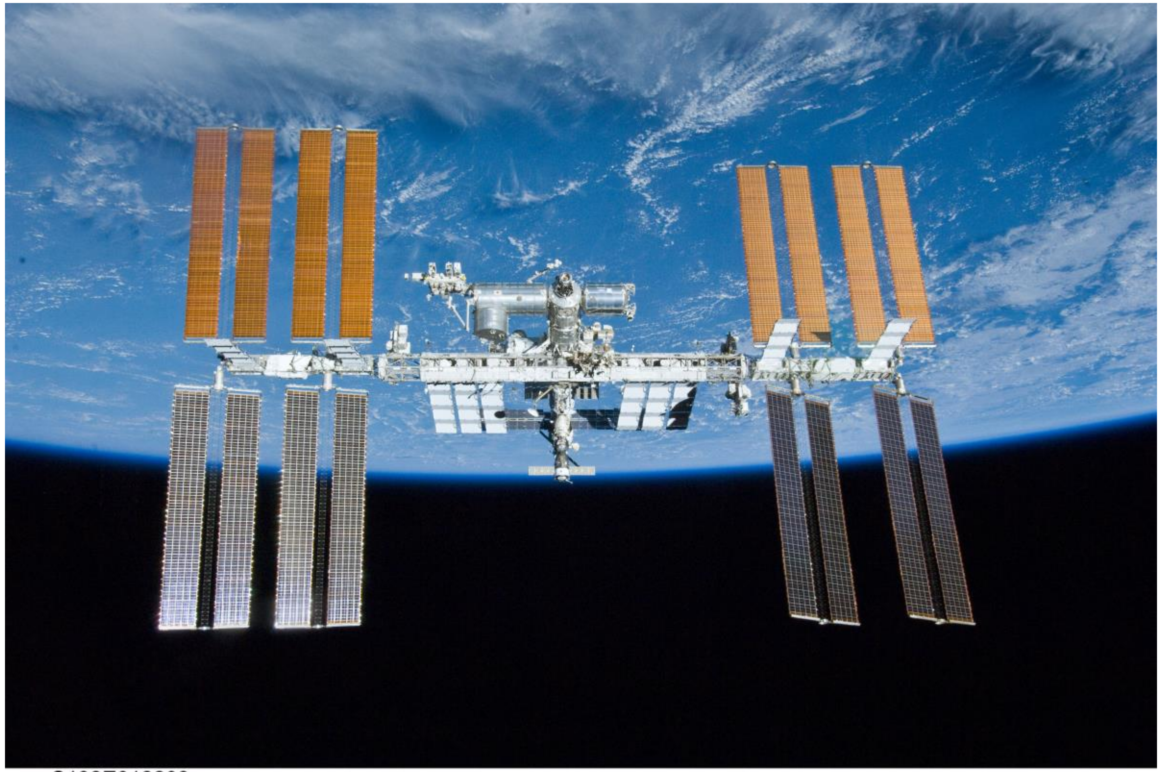
Motivation for the work (1/2)

- Certain critical components on the ISS can have problematic restarts after shutting off, making deenergizing the circuit highly undesirable
- Therefore, the ISS team wanted to perform a hot-swap of certain electrical components, most severe condition being 82A / 30V over 0.055 sec
- NASA assessment initiated to evaluate the hazard posed to astronauts if an arc were to occur due to tool or FOD shorting the exposed electrodes
- The Air Force Research Lab (AFRL) had recently performed a series of arc tests at lower pressures, but not vacuum
- AFRL videos clearly showed liquid metal ejected from arcs down to 0.1 torr

International Space Station (ISS) in orbit



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Motivation for the work (2/2)

- At ISS pressures (≈5×10^{-6} torr) question as to whether discharge would take the form of classic arc discharge, glow discharge, dark discharge, and whether hot ejected particles would be generated
- Therefore, the team determined that arc testing at representative pressures and electrical configuration needed to be performed with the ability to measure the count, size, speed, and temperature of potentially molten metal particles along their trajectory using high speed videos in a stereopsis configuration

Initial System Requirements

- Measurement system requirements were generated from two sources:
  - High speed videos from AFRL low-pressure electrical arc tests
  - Theoretical predictions of maximum potential particle temperatures
- Observation Goal: track a 0.5 mm diameter particle with 10 pixels across, ejected from the arc in any direction at 6.7 m/s (22 ft/s) with a field of view (FOV) 50 mm (2 in) on either side of the arc, and 1 pixel of blur
  - Spatial Resolution: 0.05 mm/pixel (0.002 in/pixel)
  - Temporal Resolution: 20,000 fps, exposure time < 50 μs
- Therefore, needed camera/lens combination that resulted in 300-2,000 pixels across a 10-cm (4-in) FOV

- Theoretical predictions of maximum particle temperatures spanned the melting points up to the vaporization points for the metals of interest (given varying assumptions)
- Therefore substantial energy emitted in **visible and infrared spectra**

Measurement Options Evaluated

- Initial evaluation of commercially available IR cameras was that no systems could satisfy the combination of frame rate, FOV, and spatial resolution requirements
- Due to predicted particle temperatures the team considered conventional high-speed video cameras (HSV)
- Two different pairs of commercially available HSV were used
  - Photron FASTCAM SA-Z [Photron, Tokyo, Japan] (hereafter "Photrons")
  - Vision Research Phantom v311 [Vision Research Inc., Wayne, NJ] (hereafter "Phantoms")
- Camera Configurations (using f32, 200-mm Nikon Nikkor)
  - Photrons: 20 kfps, 1024 x 1024 pixels, 5 μs exposure, 91-cm (36-in) standoff, 27 mm (1.06 in) DOF
  - Phantoms: 6 kfps, 800 x 600 pixels, 8 μs exposure, 138-cm (54.5-in) standoff, 61.3 mm (2.41 in) DOF

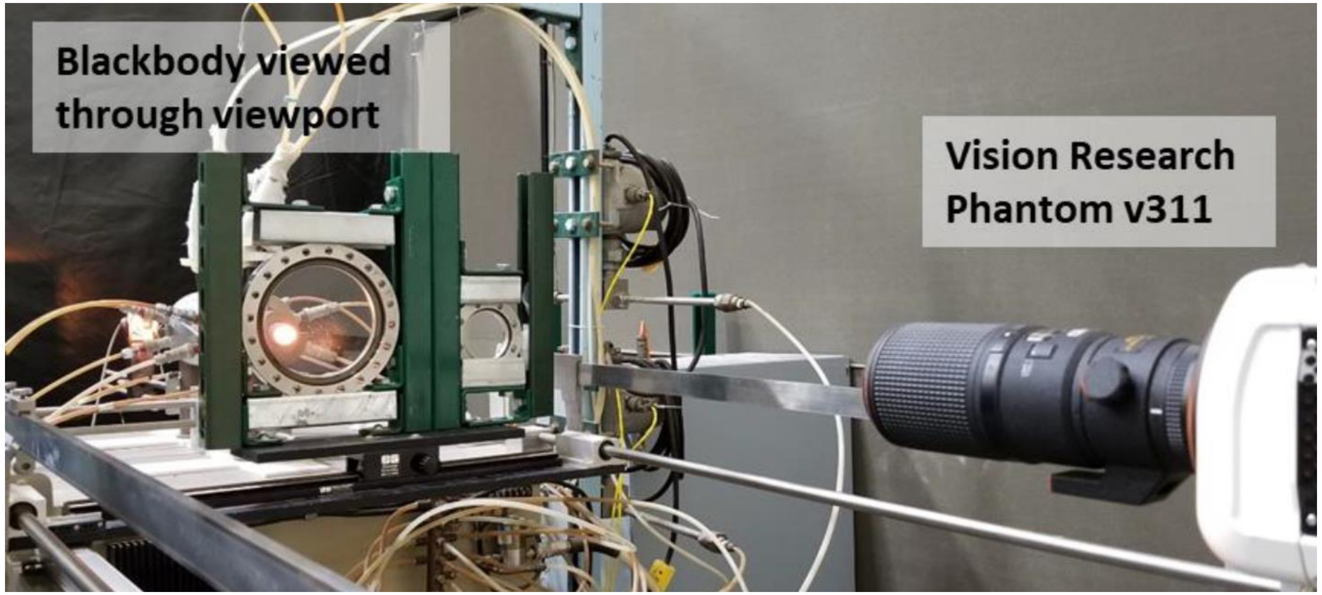
Measurement Method

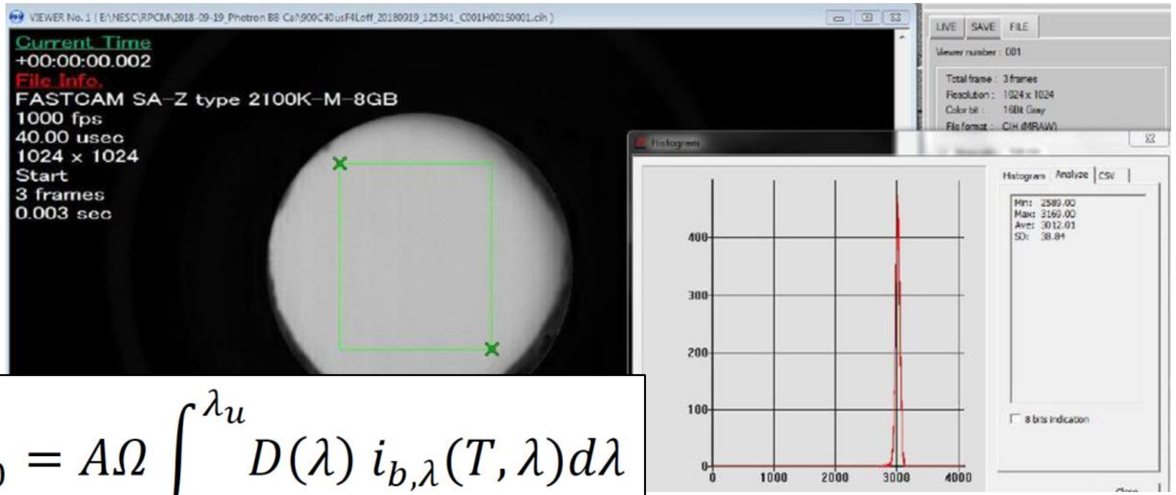
Measurement method consisted of three parts:

1. Performing a blackbody calibration of the camera/detector using the same optical path as each test setup (including transport of viewport windows)
2. Obtaining the characteristic 12-bit grayscale value for the particle from a high-speed video frame were no effect of participating vapor was present
3. Converting that grayscale value to a temperature using the calibration curve and analytical tools

Measurement Method: Calibration Method

- Thermo Gauge Model 48-kW furnace blackbody was used as a calibrated light source for the cameras
- Viewport windows from each test setup, specific to each camera, were installed at the same separation distances
- Calibration used same aperture, frame rate, exposure time settings for cameras as during test
- 12-bit grayscale values used were the average over the area of the blackbody – characteristically narrow distributions (shown)
- Signal generated by the detector for a given temperature used the spectral response curve and equation shown





$$I_0 = A\Omega \int_{\lambda_l}^{\lambda_u} D(\lambda)\, i_{b,\lambda}(T,\lambda)\, d\lambda$$

Measurement Method: Temperature Determination

Pathfinder testing to evaluate optical parameters → Freeze optical parameters and perform test program → Perform blackbody calibration → Extract particle grayscale values (use peak value)

↓

Determination of approximate detector signal (use grayscale value, calibration curve) → Choose T and iterate to obtain particle temperature using the material-specific spectral emissivity, as shown: → *Optional*: repeat Steps 5, 6 using a range of grayscale values to evaluate measurement uncertainty based on what the particular grayscale distribution looks like

$$I_0 = A\Omega \int_{\lambda_l}^{\lambda_u} \varepsilon_\lambda \, D_i(\lambda) \; i_{b,\lambda}(T,\lambda) d\lambda$$

Measurement Method: Sources of Error and Uncertainty

- Uncertainties and errors can be divided into two categories:
  - Measurand considerations
  - Measurement system considerations
- Measurand considerations:
  - Spatial and temporal variations in temperature relative to exposure time and image resolution
  - Spectral emissivity uncertainty
  - Ambient/environment light sources and attenuation sources
- Measurement system considerations:
  - Detector noise
  - System sensitivity to uncertainty in emissivity
  - Detector repeatability

Spatial Variation, Spectral Emissivity Uncertainty

Spatial Variation of Grayscale

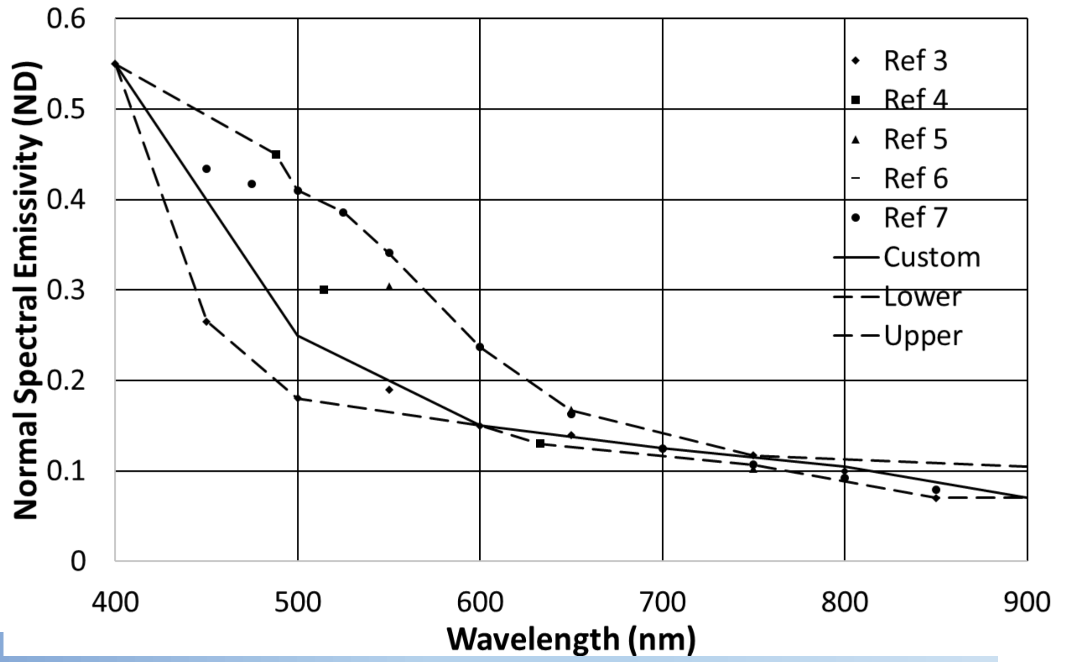
- Consistently manifested as a peak value monotonically decreasing to particle edge
- Incident radiation proportional to cosine of angle between surface normal and focal plane, so expectation is decreasing toward boundary
- Therefore, peak value used as measurement

Prefs	547	548	549	550	551	552
311	0	0	0	0	0	0
312	0	0	0	32	0	0
313	0	0	409	680	409	0
314	0	59	798	971	649	0
315	0	234	902	913	467	0
316	0	50	553	470	0	0
317	0	0	0	0	0	0

Screenshot from the ImageJ Pixel Inspection Tool (United State National Institutes of Health open-source software), including pixel row and column indices shaded in gray.

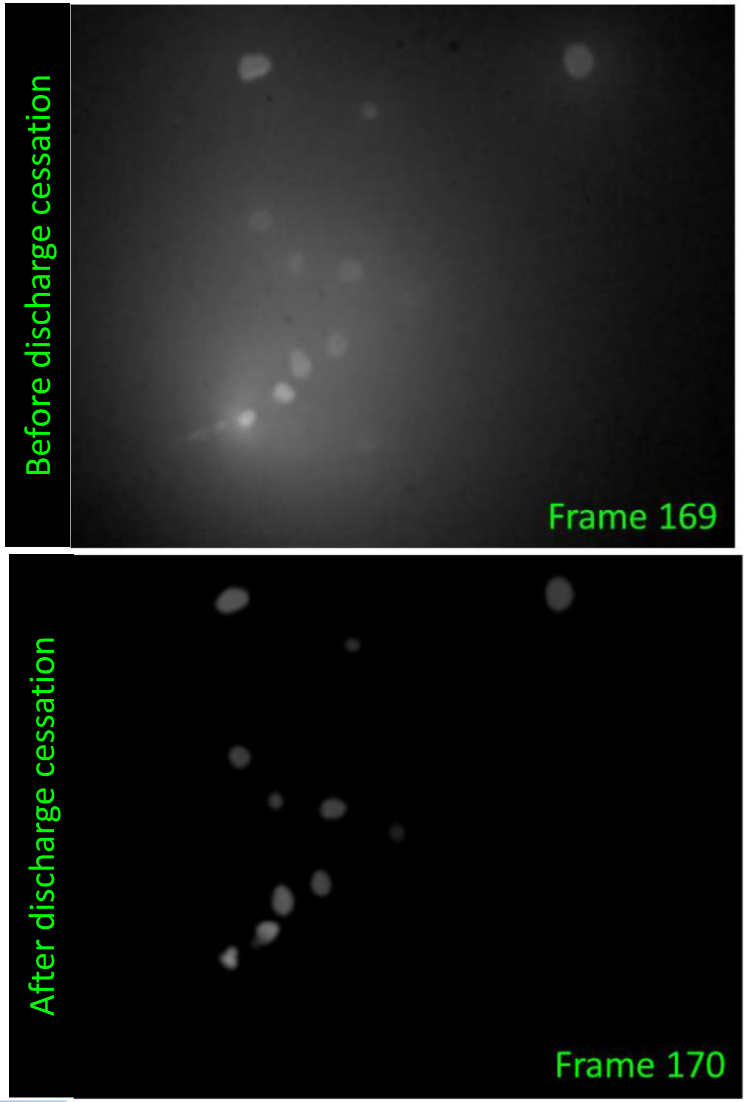
Spectral Emissivity Uncertainty

- Exact data (material, temperature range, spectral range) not available
- Values obtained from interpretation of available data proved sufficient



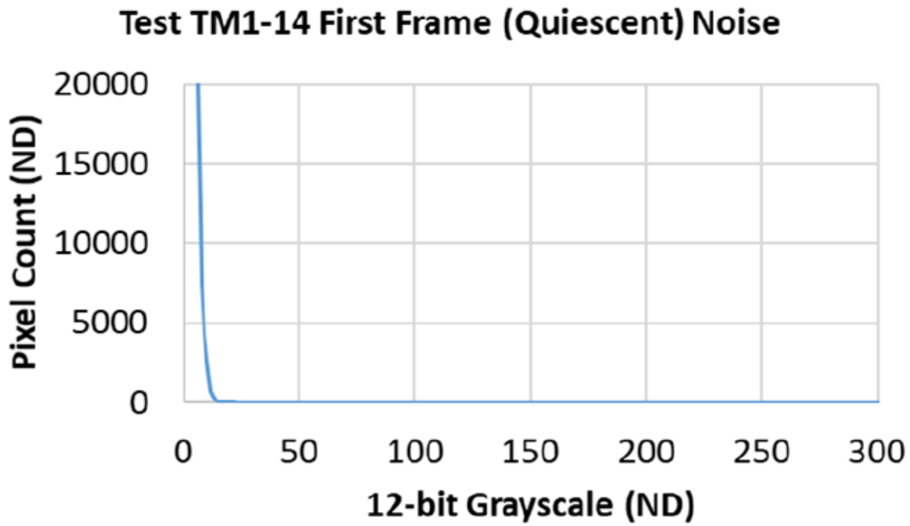
Ambient/Environment Light Sources and Attenuation (1/2)

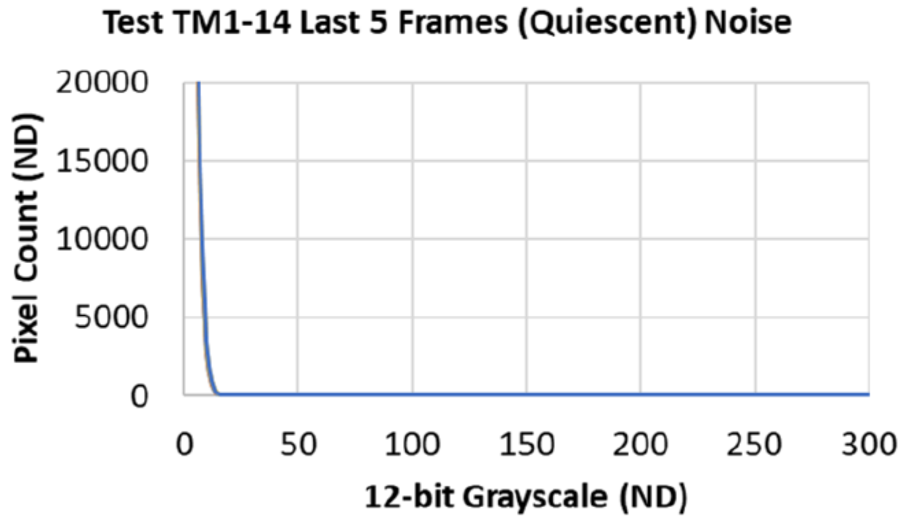
- Detector can have ambient light incident on it, as well as attenuation of the signal emitted from the particle and traveling to the detector
- Attenuation: negligible due to the use of visible wavelengths over short distances, and entirely compensated by replicating the optical path during blackbody calibration
- Ambient/Environment Light Sources – thermal emission from the particles was not the only source of light during testing
- Metal vapor generated around the superheated liquid metal filament tip and ejected particles participated in the electrical energy discharge and became luminous
- The emission from the metal vapor stopped when the electrical discharge stopped, thus enabling evaluation of the thermal emission



Ambient/Environment Light Sources and Attenuation (2/2)

- In addition to the light coming from the test setup, there were ambient sources of light as well (overhead fluorescent lights)
- Detector noise due to ambient light sources was evaluated three different ways
  - Detector grayscale distribution before/after detector zeroing ("shading") operations, with/without lens cap on
  - Detector grayscale distribution for blackbody @ 773 K
  - Quiescent frames before/after an electrical discharge event
- Resulting Signal to Noise Ratio (SNR)*
  - Photrons: 5-164 (average: 36)
  - Phantom: 0.5-52 (average: 13), 94% > 2





*The vast majority of pixels were zero for both 1MP cameras

System Sensitivity to Emissivity Uncertainty

- The measurement system sensitivity to surface emissivity uncertainty will either attenuate or magnify into an uncertainty in temperature based on the wavelength of light being used by the system
- Evaluated two different ways: monochromatic detector assumption (closed form solution), numerical evaluation of actual wideband detector
- Monochromatic detector assumption
  - Uses Wien's approximation
  - For 2300 K, 700 nm, ε_λ=0.1±0.02 (20%), 51 K (2.2%) uncertainty
  - For mid-wave infrared detector using 4-µm wavelength ≈17% (391 K)

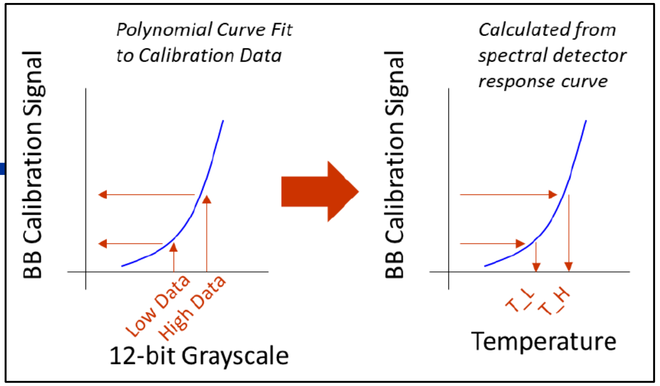
$$\frac{d \ln T}{d \ln \varepsilon_\lambda} = -\frac{\lambda T}{C_2}$$

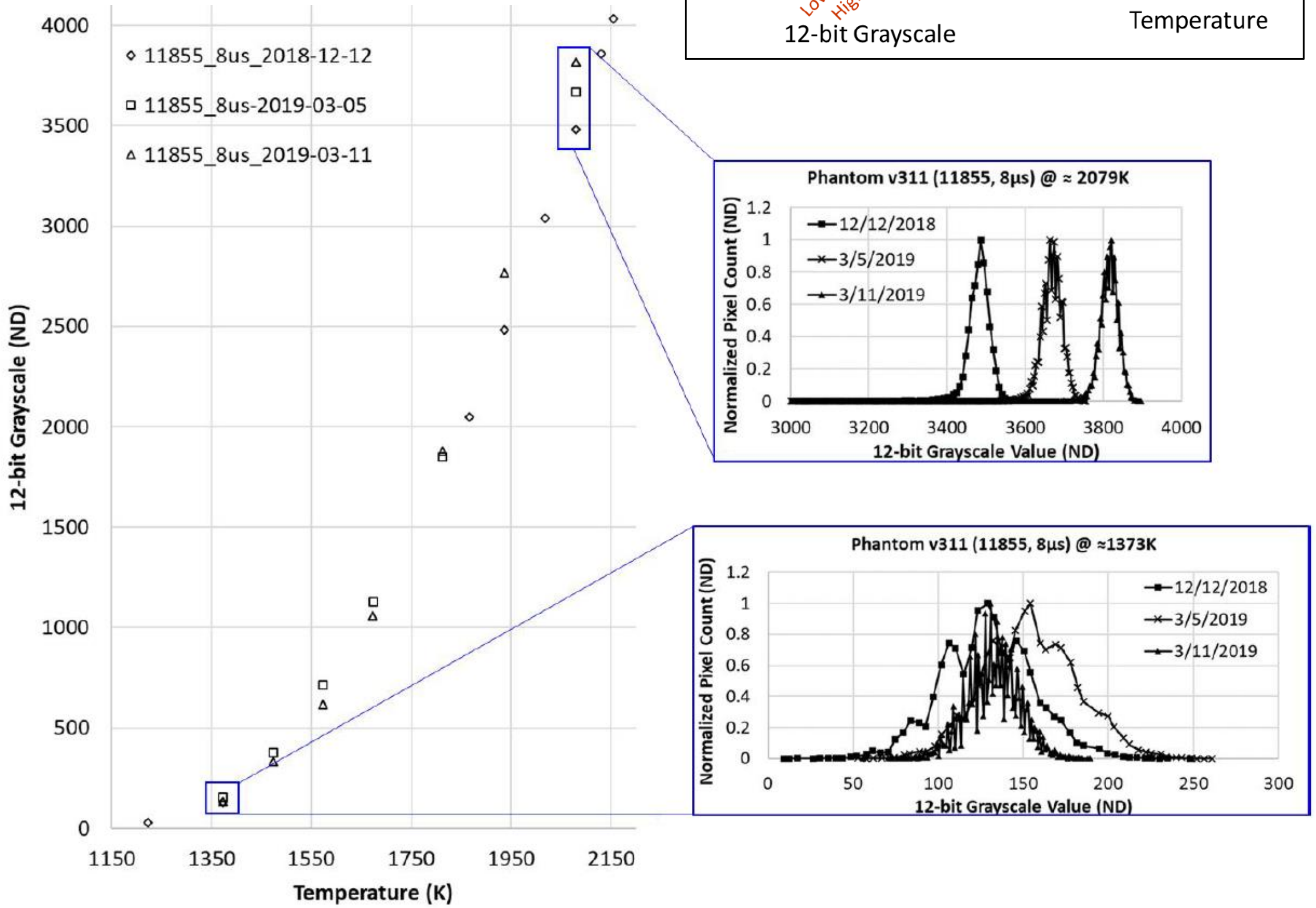
C_2 = 14,388 μm-K

- Wideband numerical evaluation
  - ±20% spectral emissivity profiles for aluminum were used to calculate corresponding temperature uncertainty range
  - Result was ±2% temperature variation about measurement using nominal profile

Detector Stability

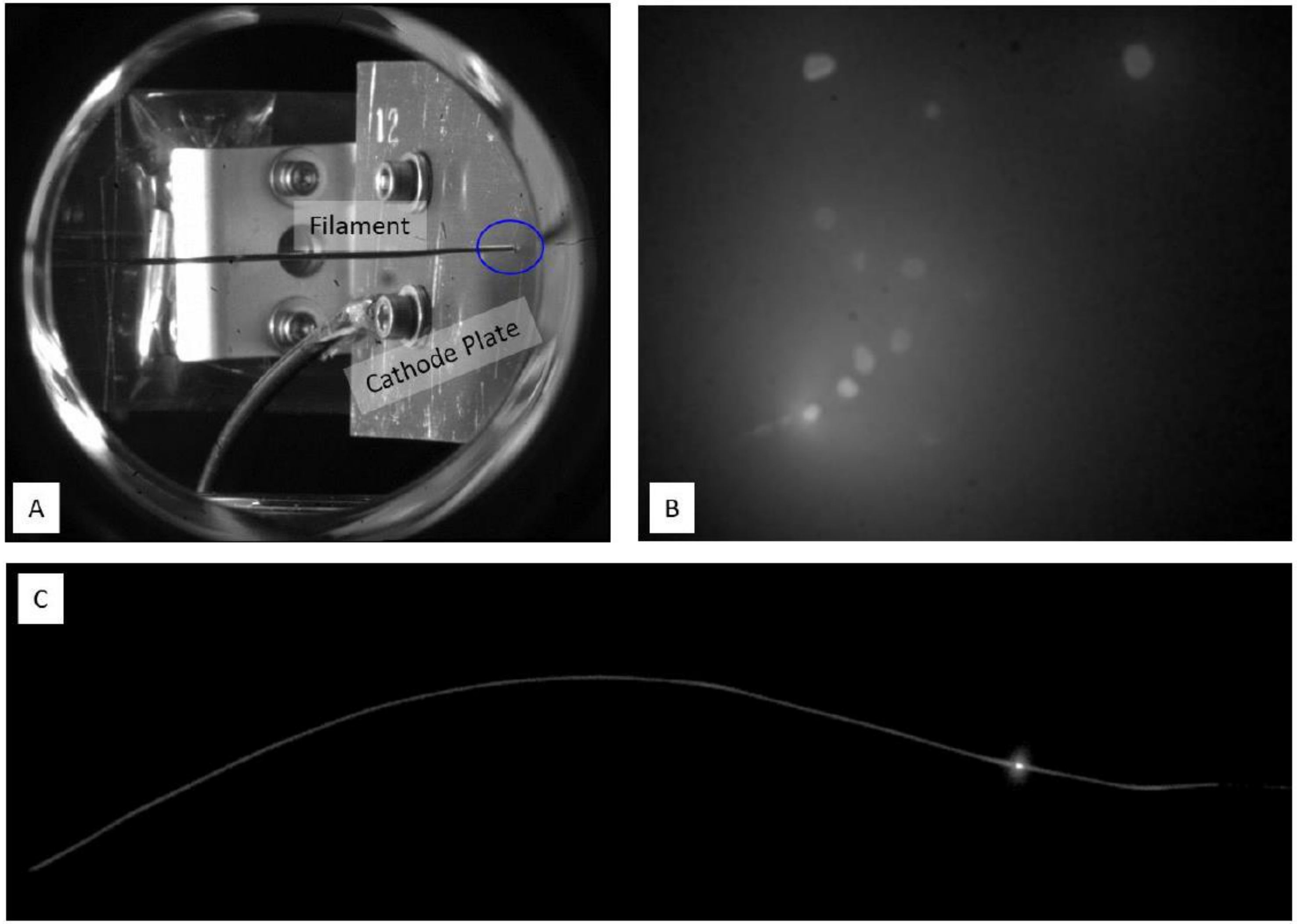
- Long-term stability of the detector was important due to calibrations taken a month or more after testing
- Calibration data taken over several months, highly correlated
- Figure shown is one camera, typical of the other three
- 2079 K calibration data spread equates to -1.6% to +0.3% errors in temperature when converted to blackbody values, widest spread in the data
- 1373 K calibration data spread equates to 3.85% to 4.22% errors in temperature





Validation Opportunities

- Typical arc events resulted in the filament tip touching the cathode plate (A) during the test and ejecting particles in every direction (B)
- A few tests (C), the filament tip fused to the cathode plate, joule heated, and fell apart
- These tests, known to be at/near melting point, served as built-in validation cases
- Photrons: SS near melting temperature (1673-1723 K) measured at 1743 K
- Phantoms: SS tests with temperature measurements 1650-1750 K



Measurement System Characterization Results

- Measurement systems and methods were proven to provide radiometric temperature measurements that satisfied project requirements
- The temperature measurement ranges for the three subject materials, in the application-specific optical configuration (aperture, exposure time) are provided in the table below

	Aluminum		Copper		Stainless Steel	
	Low	**High**	**Low**	**High**	**Low**	**High**
Photron FASTCAM SA-Z	1874	2791	1843	2653	1605	2424
Vision Research Phantom v311	1741	2872	1734	2763	1521	2362

***Low assumes a 12-bit grayscale value of 1 and High assumes a value of 4095**

****Photrons: 5μs exposure, Phantoms: 8μs exposure)**

*****Temperature Limits in Kelvin**

Conclusions

- Commercially available high speed (VIS) video cameras were shown to be capable of being used for high speed quantitative thermal imaging of molten metals in the temperature range of 1500-2900 K (depending on material) with high spatial resolution
- The errors and uncertainties in the measurement were investigated, and demonstrated sufficient accuracy for the subject application
- Measurements were validated with unplanned, physically-defined events that occurred during testing (i.e. joule-heated filaments at/near melting point)

Recommendations for further work

- Evaluate measurement system limits (upper and lower) given max/min exposure times, apertures to fully understand the temperature ranges able to be measured with these cameras under the right conditions
- Evaluate other cameras in agency inventory

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