Leveraging High Performance Hyperspectral Sensors for the Conservation of Masterworks

NATO SET-277

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Done in partnership with the US National Gallery of Art

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OUTLINE

- NVESD Mission Statement
- History of Collaboration with NGA
- Motivation
- Thermal Radiometry
- LWIR Spectral Imaging Examples
- Conclusions
- Thanks & Bibliography

CCDC C5ISR NVESD MISSION

Research and Development in Advanced Sensors -Military Specific Technology-

- EO/IR Imagers (Focal Plane Arrays, Optics, Real Time Image Processing)
- Tactical Lasers
- Sensor Architectures
- EO/IR System Modeling, Characterization & Specification
- Tactical Augmented Reality
- Countermine/Counter-IED

~ $150M Research + Development + Producibility = Transition of Affordable Technology to Soldiers, and War Support During Wartime

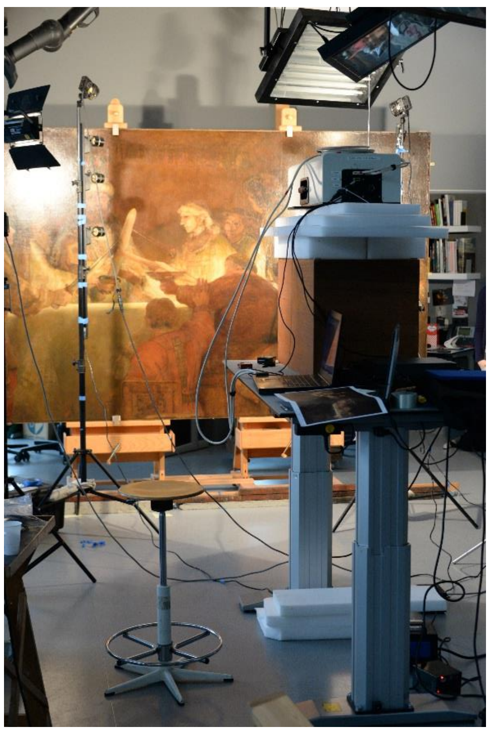
Provide leap-ahead sensor technologies to our Soldiers providing situational understanding in all environments and improving rapid decision-making

So, how did the US Army get involved with Art???

(special thanks to Dr. John Delaney, K. Dooley, others)

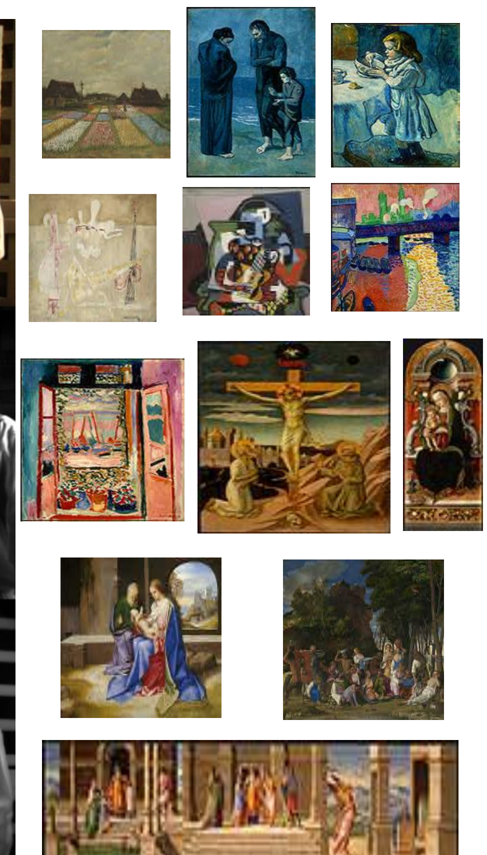
NGA COLLABORATION

- NVESD's former director (A.F. Milton) was on the board at a number of foundations and provided the introduction and permitted us to use our time on a limited basis.
- NVESD has the sensors and NGA & friends have the art!
- Some artists worked on thus far: DaVinci, Picasso, Manet, Rothco, Pasellino, Bellini, Matisse, Delacroix, Derain, Bellows, Kirchner, Duccio, Giorgione, Rembrandt, more…
- Semi-annual field tests occur at the Gallery (or elsewhere) with NVESD instruments (subject to mission availability).



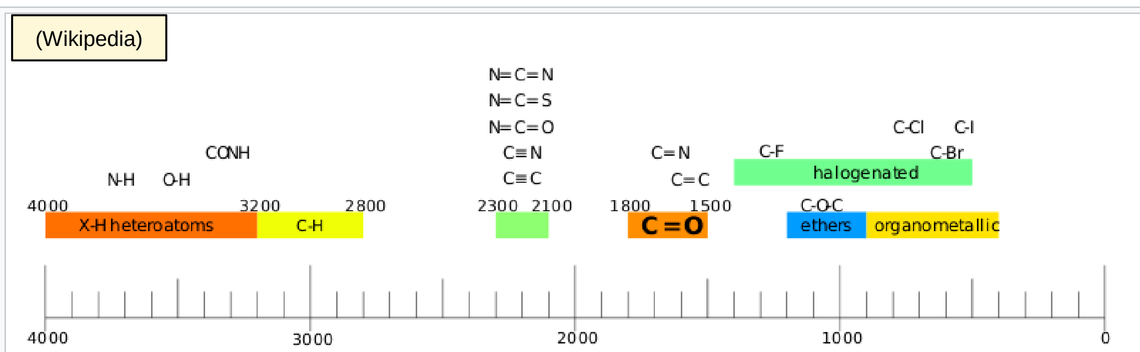
The Mauritshuis

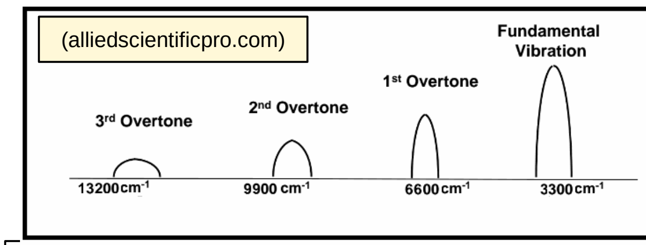
The Rijksmuseum

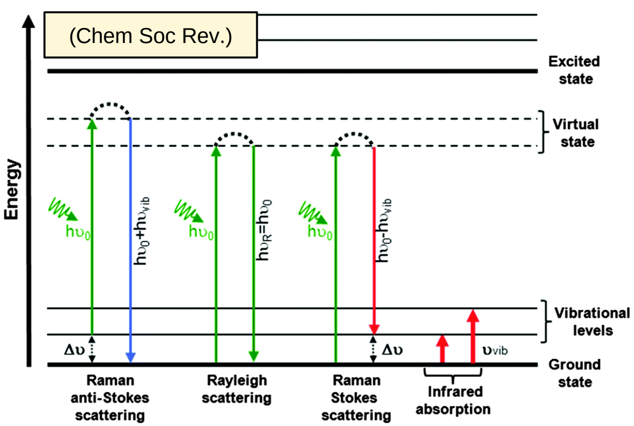


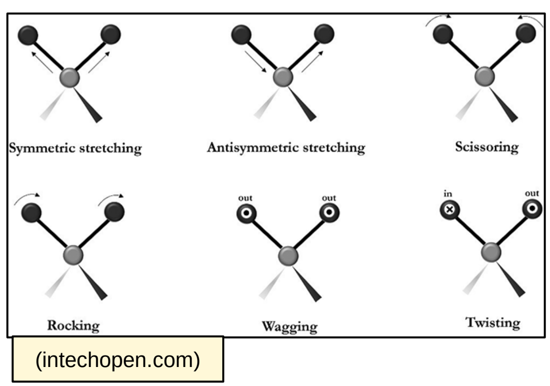
LWIR SPECTRAL IMAGING MOTIVATION

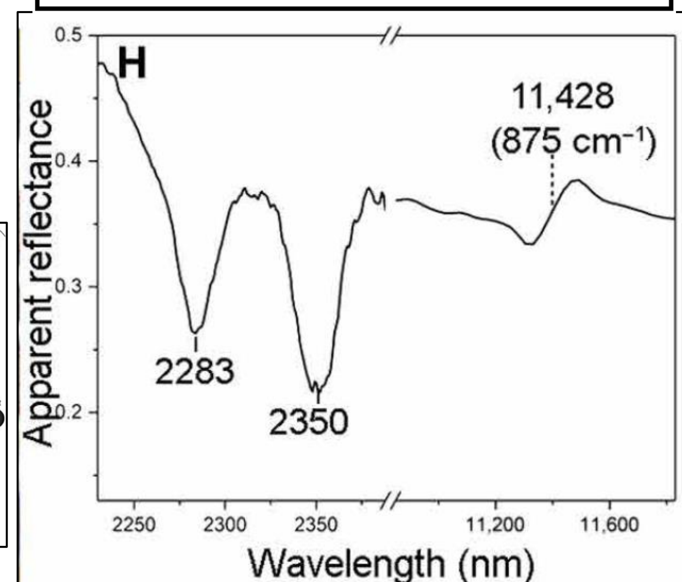
- Diffuse spectroscopy has been used for decades in the reflective bands to examine color, and to study overtones and combination bands of vibrational modes of chemical bonds
- The "Mid-IR" (2.5-25um) is rich in spectral features that allow the specific identification of many chemical functional groups contained in artists' materials such as pigments, binders, fillers, and degradation products
- The Mid-IR has been harder to do in a non-destructive standoff geometry until recent advances in thermal channel HSI instruments.





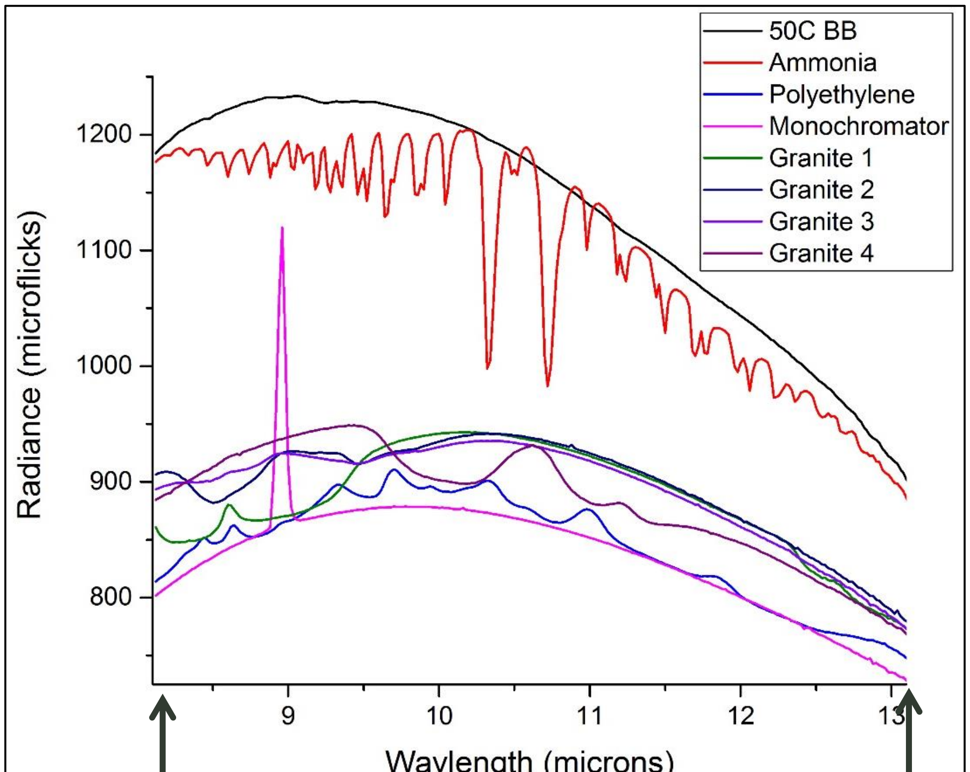






THERMAL SPECTRAL IMAGING

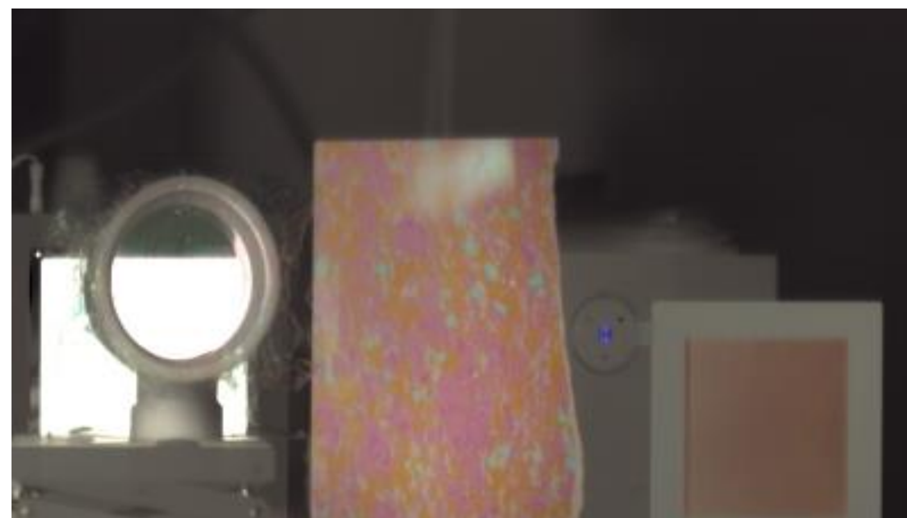
- Many historical paints are based on ground up minerals with an organic based binder. Both the minerals and binders have observable signatures.
- By observing reflectivity vs. λ in the MWIR & LWIR spectral bands the chemical composition of the pigments and/or binder can be determined non-destructively.



1234 cm^{-1}

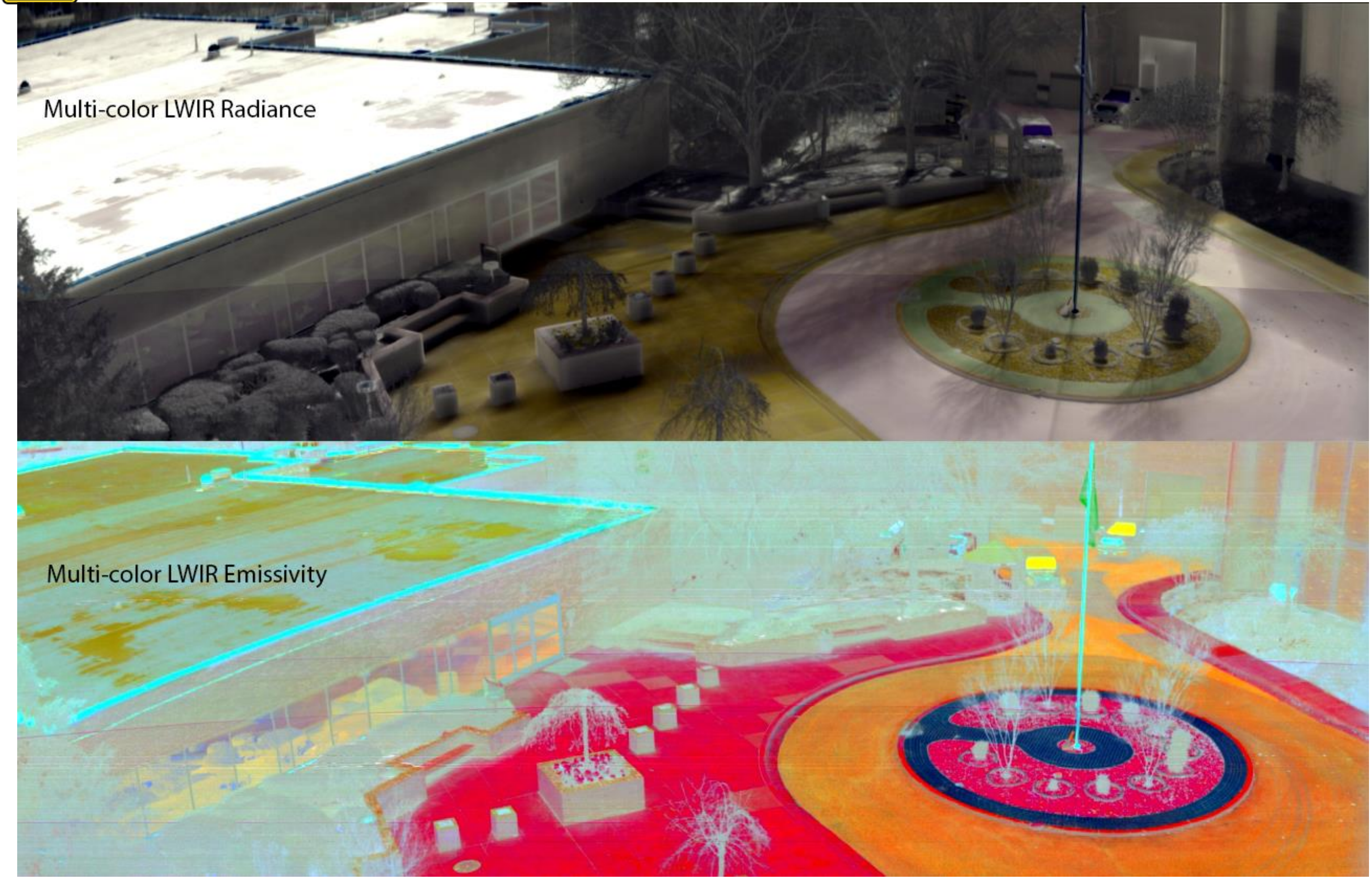
763 cm^{-1}

8.1 um to 13.1 um / 1234 cm^{-1} to 763 cm^{-1} (~250 images)

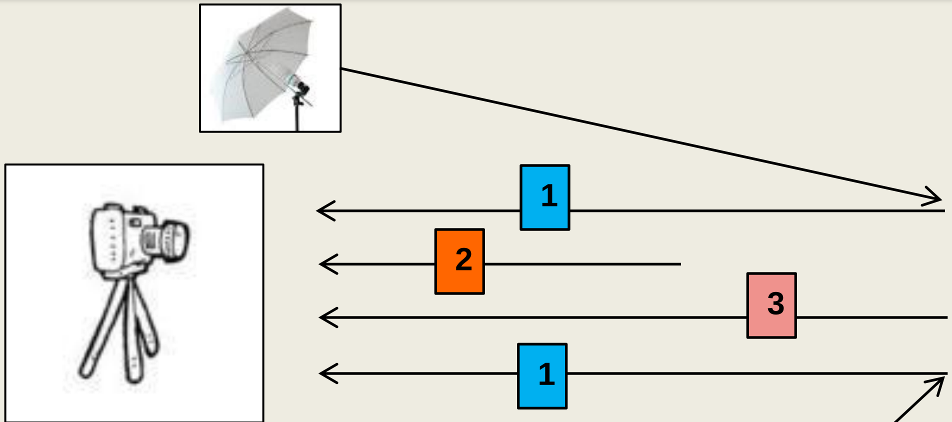


Blue=8.96um, Green=9.52um, Red=11.02um

THERMAL SPECTRAL IMAGING



Thermal Radiative Transfer (National Gallery Version)



$$L = (1-\varepsilon)\,(L_{lamp} + L_{Room})\,\tau_{atm} + L_U + \varepsilon\, L_{TGT}\,\tau_{atm}$$

Case #0: Painting is same temp as room, no ‘heat’ lamp

$$L_{TGT} = L_{Room},\ L_{lamp} = 0 \quad \Rightarrow \quad L = L_{Room}\,\tau_{atm} + L_U$$

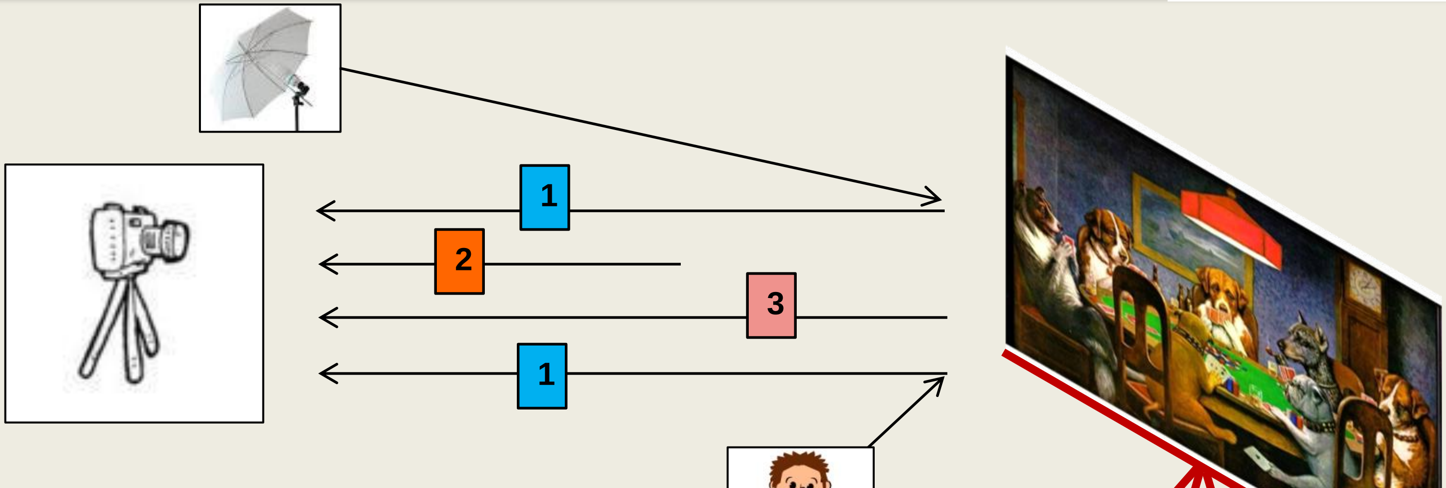
No ε left in the equations! Not very useful.

Therefore, we have two (not entirely separated) choices:

(1) Create a difference between L_{Room} and L_{TGT} (heat the painting or cool the room)

(2) Apply some directed light source, L_{lamp}. (Turn on a lamp, or take the painting outside…)

Thermal Radiative Transfer (National Gallery Version)



$$L = (1-\varepsilon)\,(L_{lamp} + L_{Room})\,\tau_{atm} + L_U + \varepsilon\, L_{TGT}\,\tau_{atm}$$

Case #1: Painting is some ΔT warmer than rest of room.

$$L_{TGT} > L_{room},\; L_{lamp} = 0 \;\Rightarrow\; L = \tau_{atm}\, L_{Room} + L_U + \varepsilon\,\tau_{atm}\,(L_{TGT} - L_{Room})$$

Case #2: Painting same T as rest of room, but external illumination applied.

$$L_{TGT} = L_{room},\; L_{lamp} > 0 \;\Rightarrow\; L = \tau_{atm}\, L_{Room} + L_U + (1-\varepsilon)\,\tau_{atm}\, L_{Lamp}$$

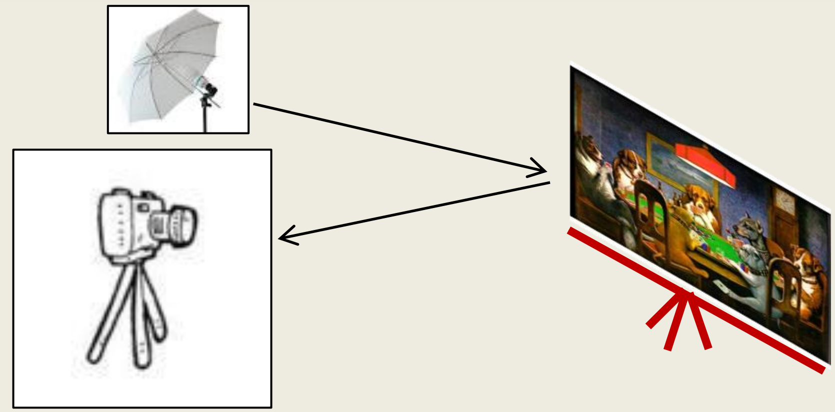
Since typically ε>0.9 we get the same ΔL with a small ΔT between painting & room, as with a large emitted flux heat lamp.

But… you can pay a price with image sharpness & MTF, as transient heating effects tend to blur edges & fine detail.

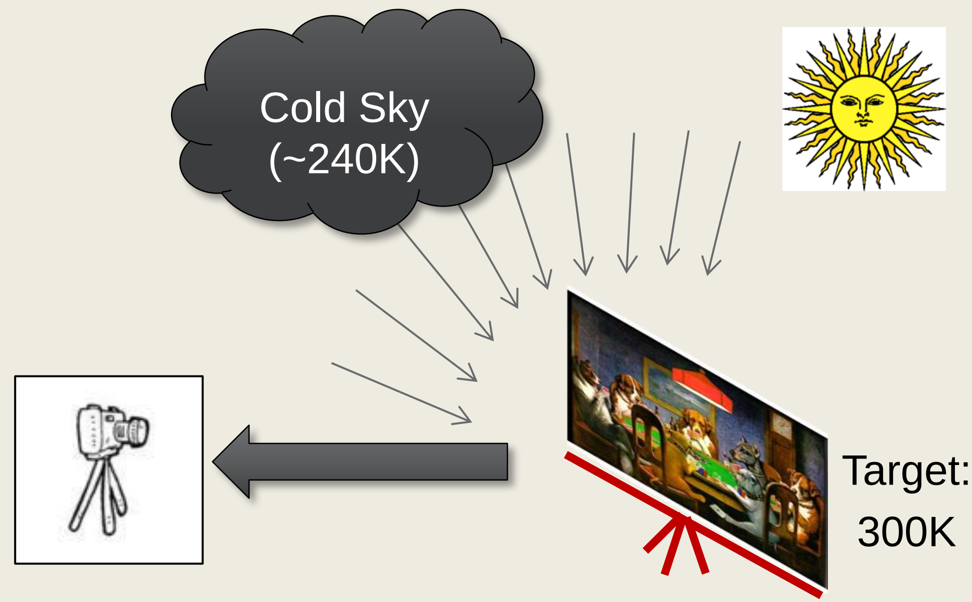
Thermal Imaging Considerations

Tips for Best Reflective Thermal Imaging

- Most paints are highly specular in the MWIR & LWIR. Specular reflection produces a large signal, but tends to be highly non-uniform for point source lighting. A very narrow BRDF leads to hot spots on the target.
- Non-specular illumination is much more uniform, but will need to put lots of light on the target.



- Ideally, what we would want is a large extended Lambertian source with significantly different ΔT than the target. That's easy! Take the painting outside on a clear blue sky day!
- Cold sky on a clear day provides a very effective delta radiance and produces nice images



SO DID WE REALLY TAKE MASTERWORKS OUTSIDE?!?!

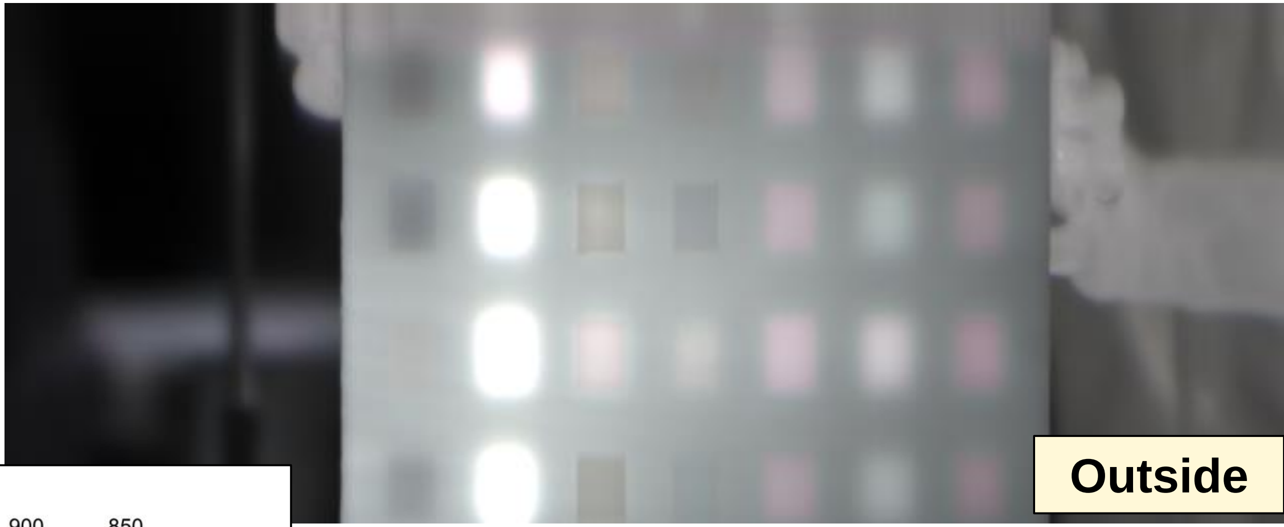
Kind of…

We took out test panels and a mockup using period appropriate paints.

REFLECTIVE VERSUS EMISSIVE SENSING (RADIANCE SPACE)

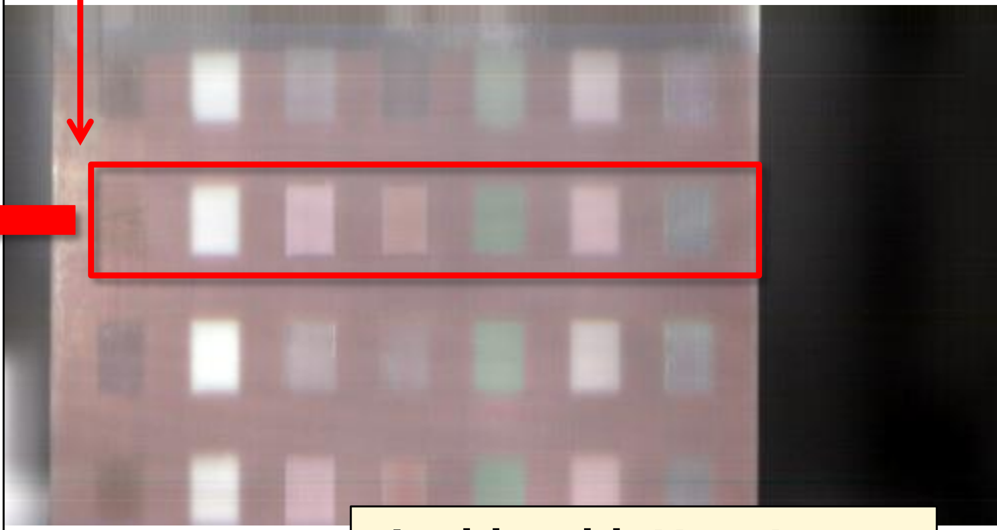
- Large Planck blackbody spectrum dominates all signals and must be removed before doing any meaningful analysis

Non-uniform spatial illumination from heat lamp creates hot spots and reflections

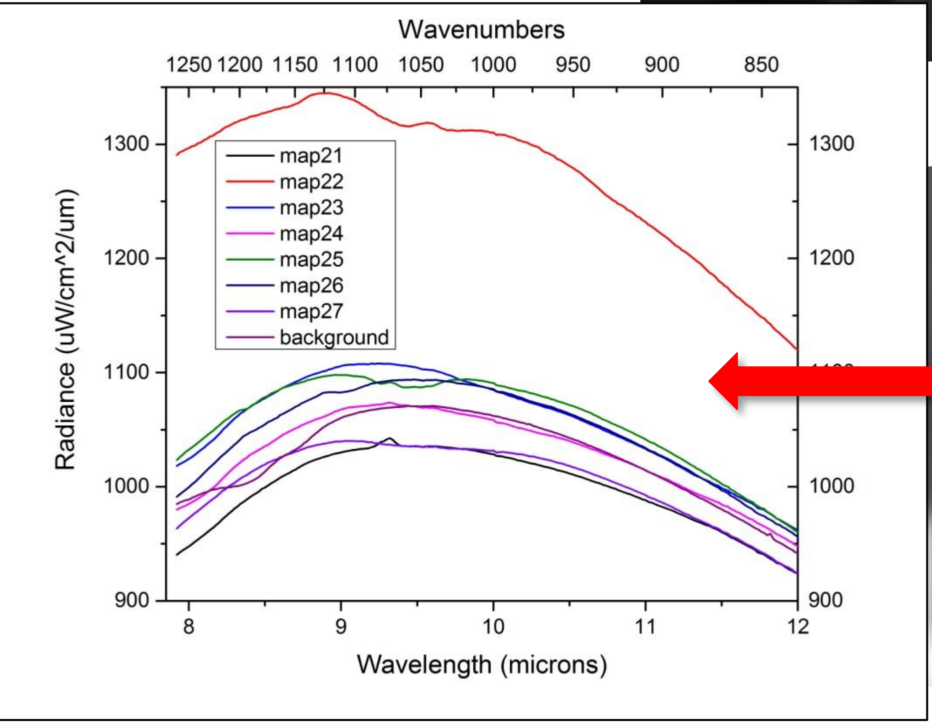


Outside

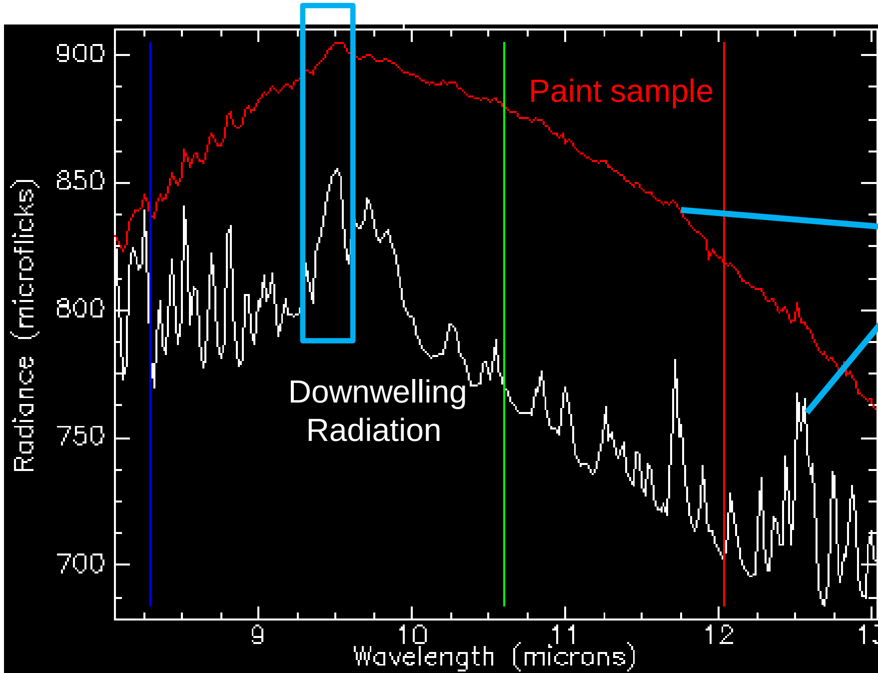
Specular reflection ↑ Emissive Reflective ↓

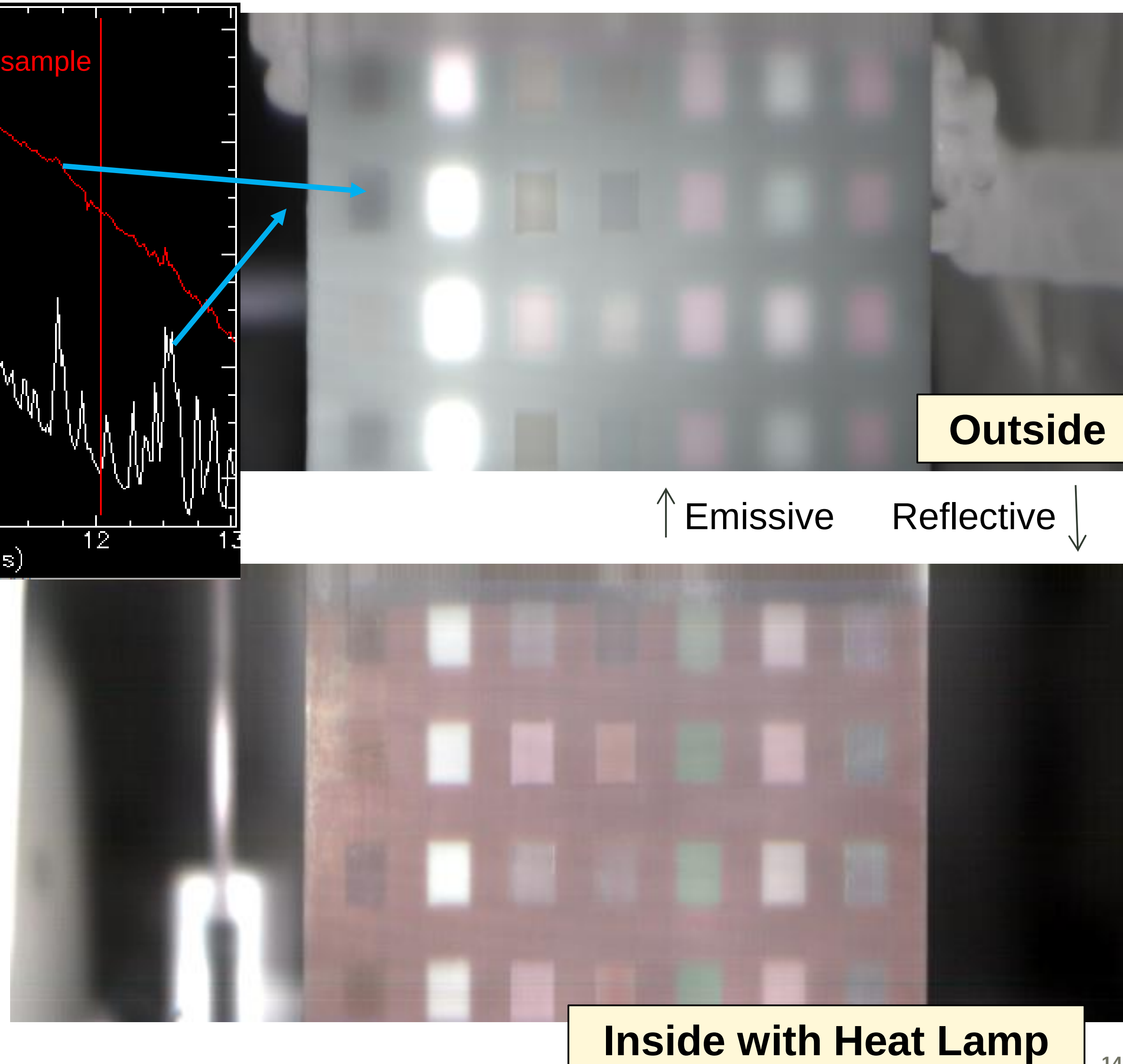


Inside with Heat Lamp



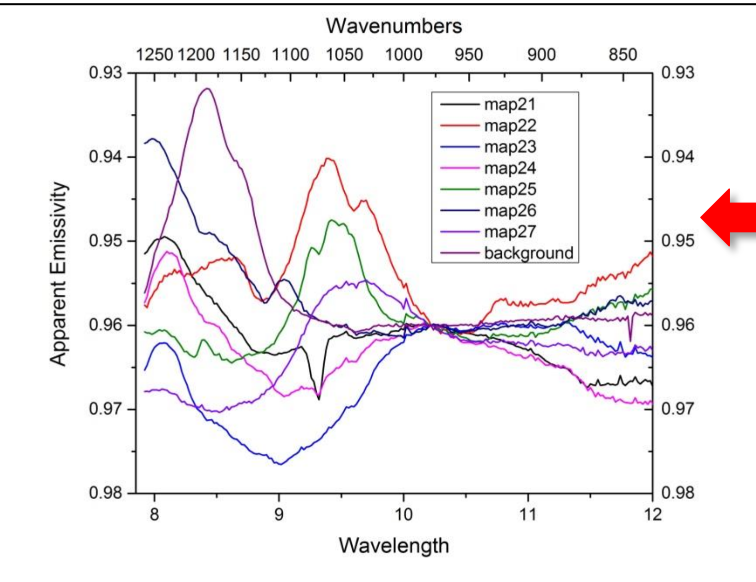
REFLECTIVE VERSUS EMISSIVE SENSING (RADIANCE SPACE)

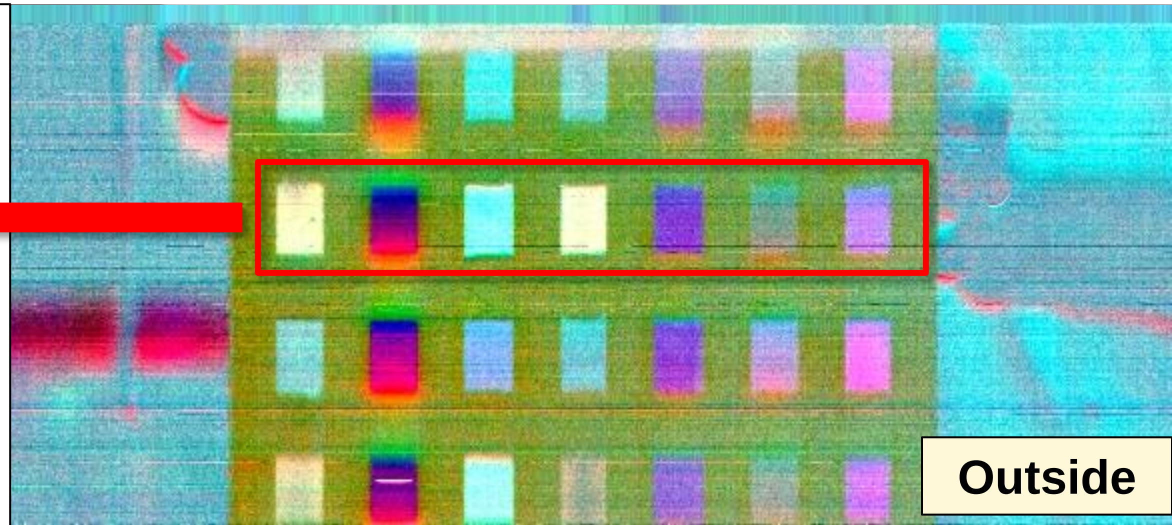




- Outdoor imaging suffers from spectrally non-uniform illumination due to the many atmospheric absorption lines
- Looking for small features among a forest of other large spectral features is a challenge.

REFLECTIVE VERSUS EMISSIVE SENSING (AFTER TEMPERATURE / EMISSIVITY SEPARATION)

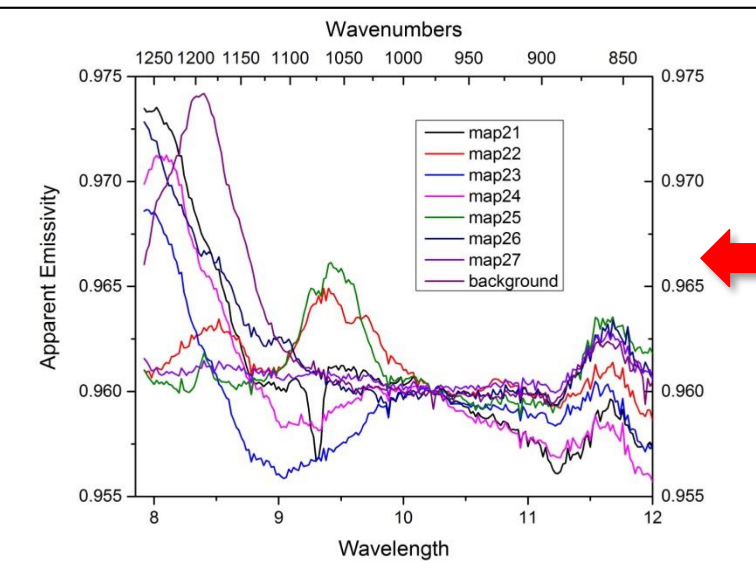


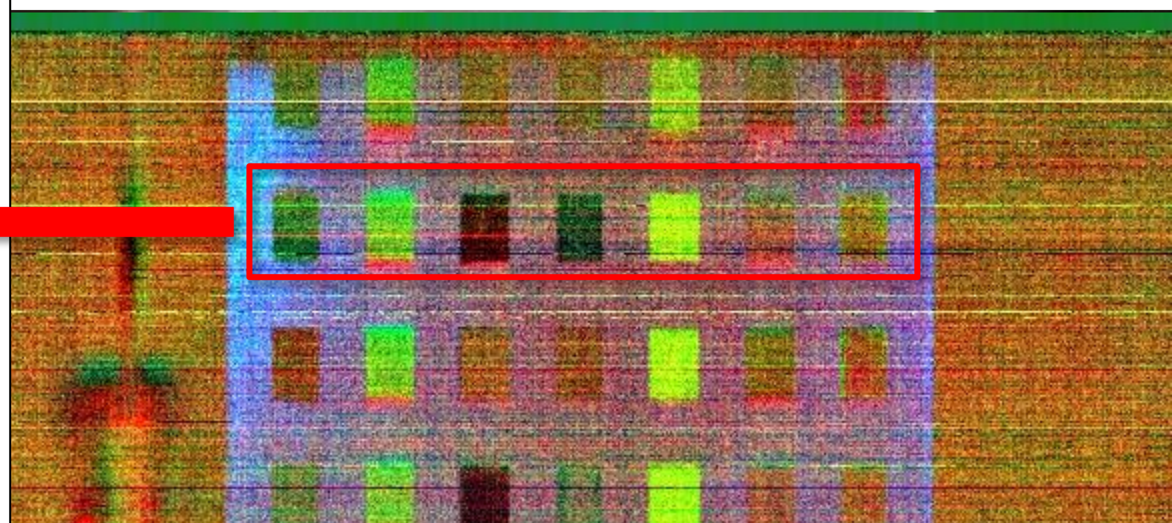


Converted to ε space

↑ Emissive

Reflective ↓

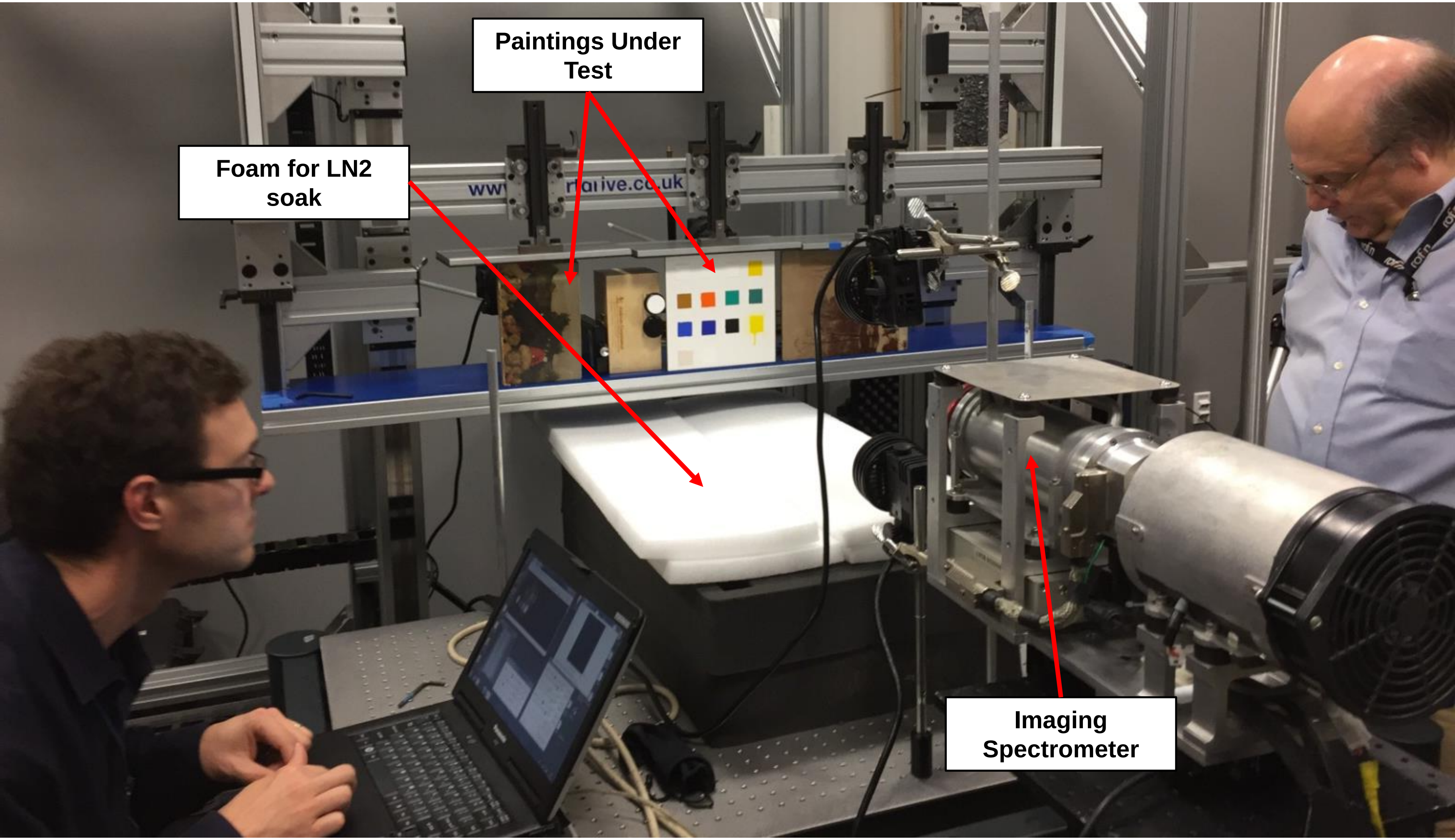




Inside with Heat Lamp

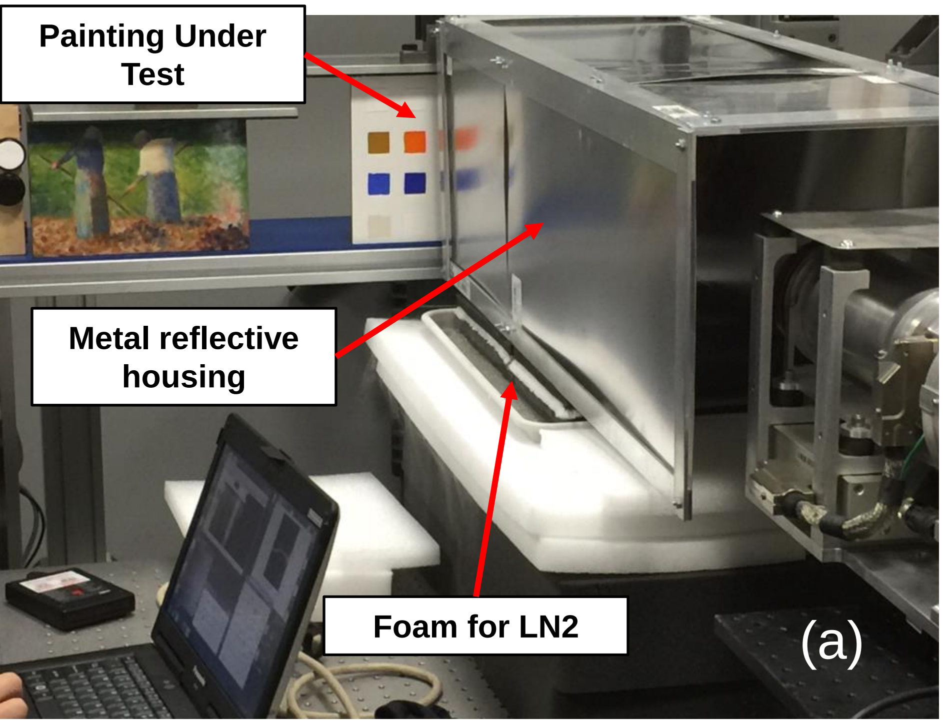
NEXT STEP: MAKE AN INDOOR COLD SKY

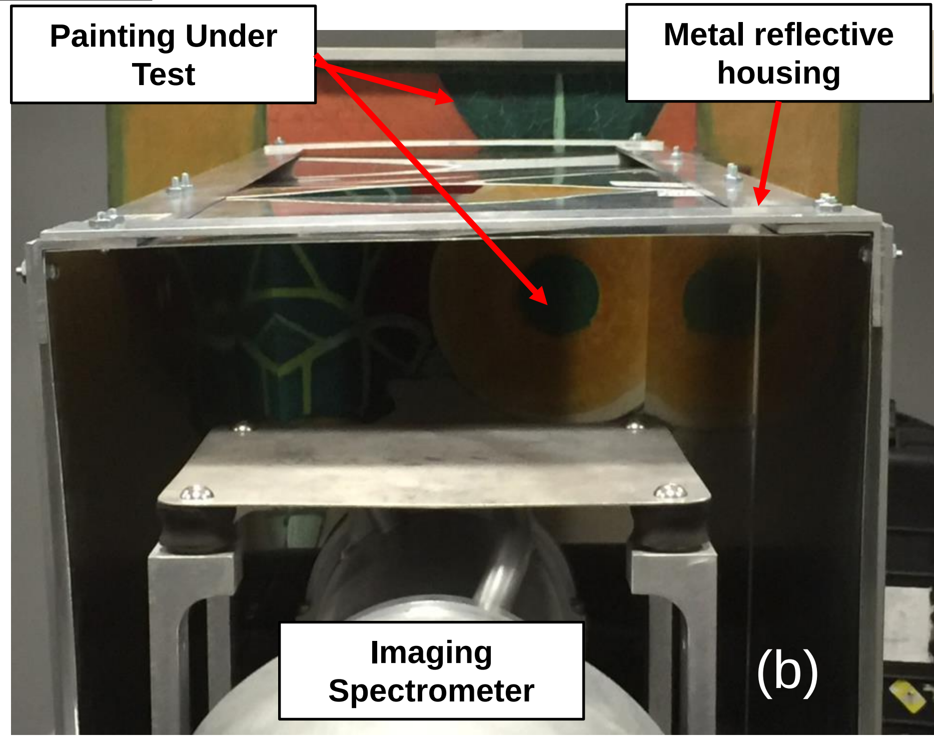
Goal: Image in "emission" mode ($T_{sky} << T_{painting}$), but with a Lambertian, cold, & spectrally flat "sky".

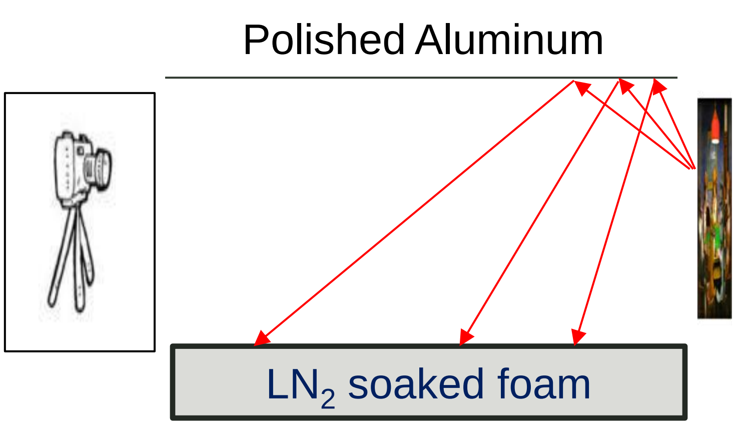


NEXT STEP: MAKE AN INDOOR COLD SKY

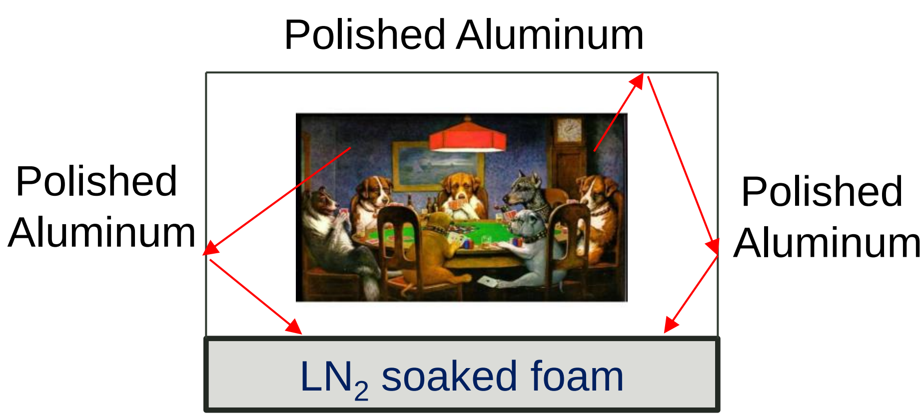
"Cold Tunnel"





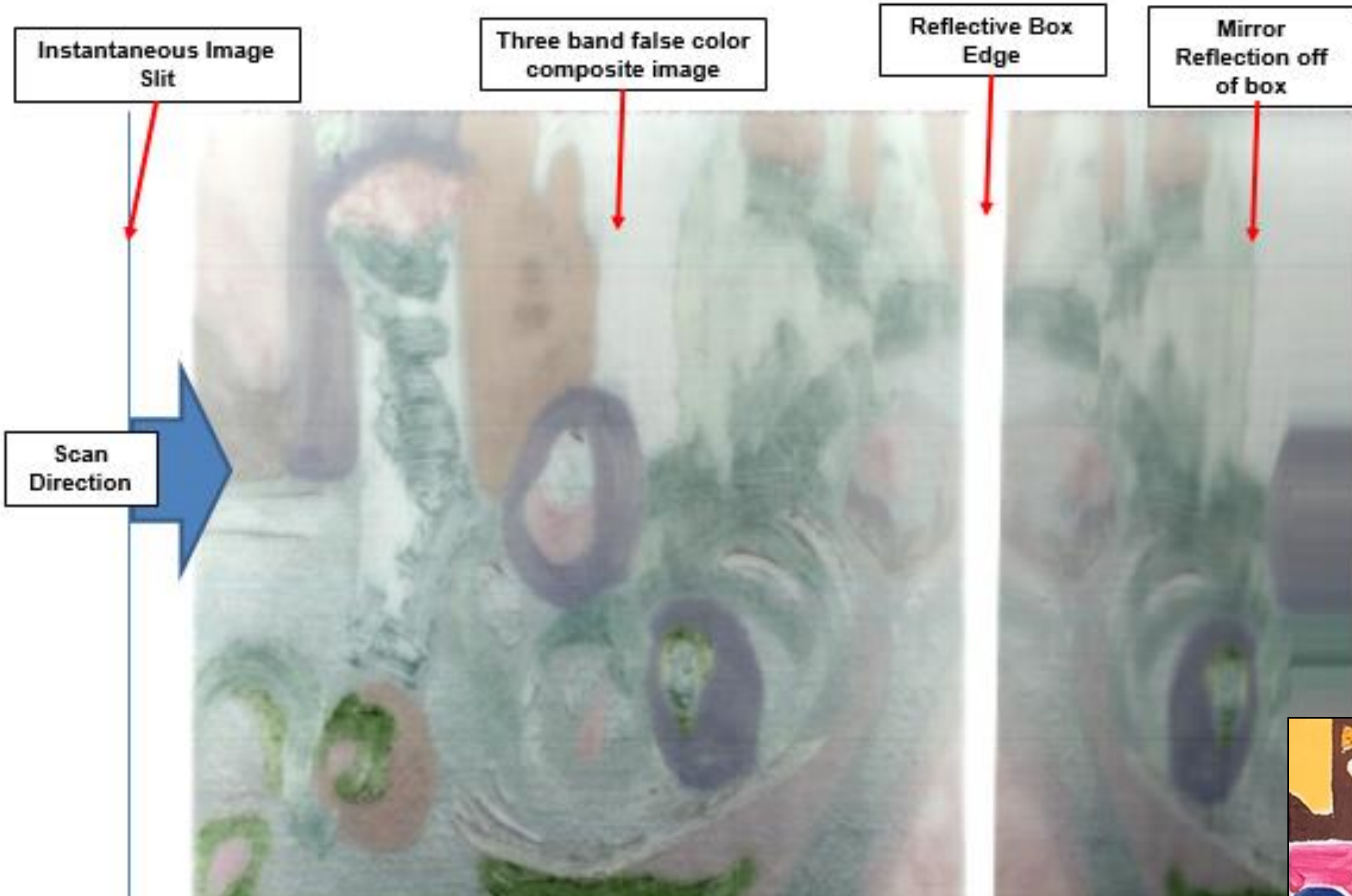


Side view



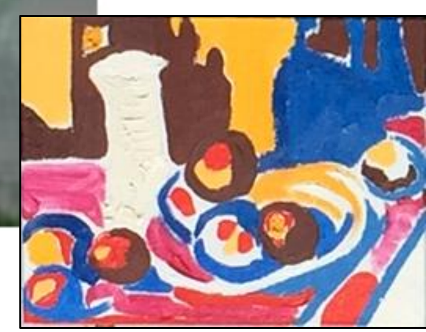
End view

SAMPLE INDOOR “COLD SKY” LWIR HSI IMAGERY USING COLD TUNNEL

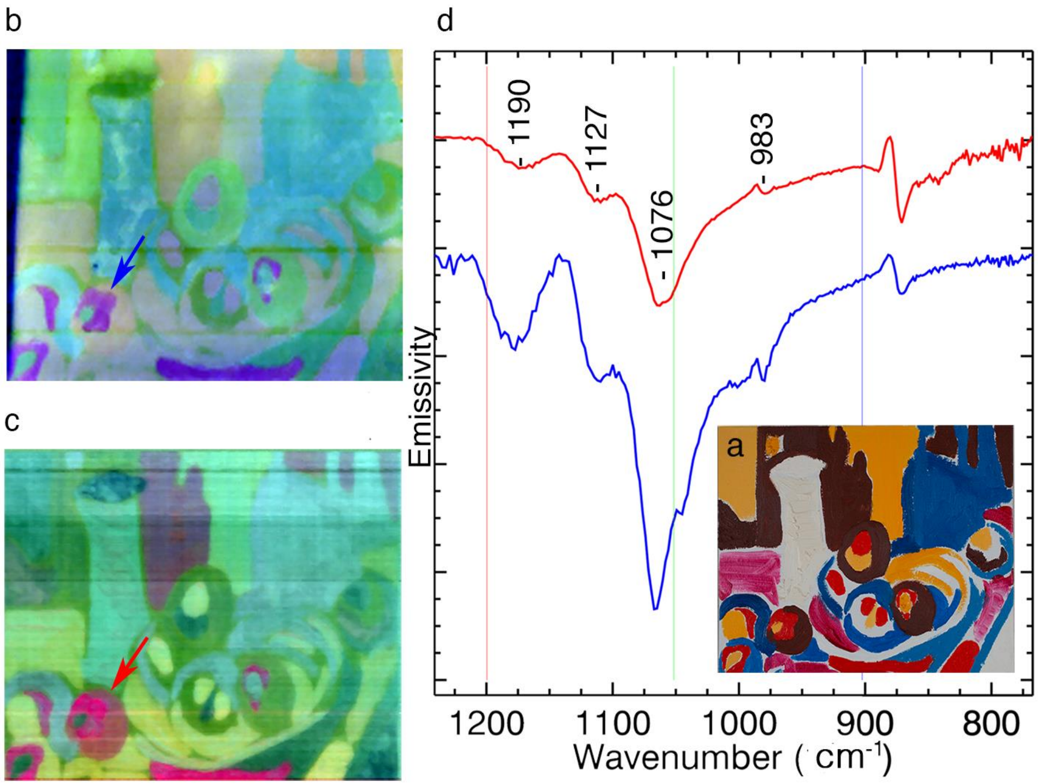


RED: 11.56um, GREEN: 10.15um BLUE: 9.45um

RED: 865cm^{-1}, GREEN: 986cm^{-1} BLUE: 1058cm^{-1}

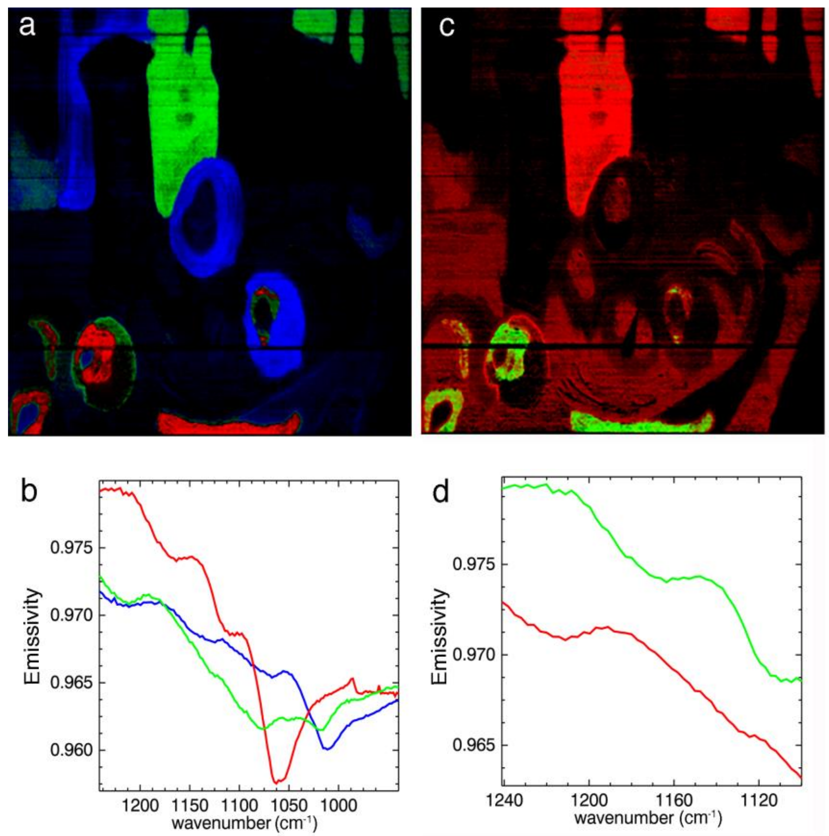


LWIR SPECTRAL IMAGING RESULTS



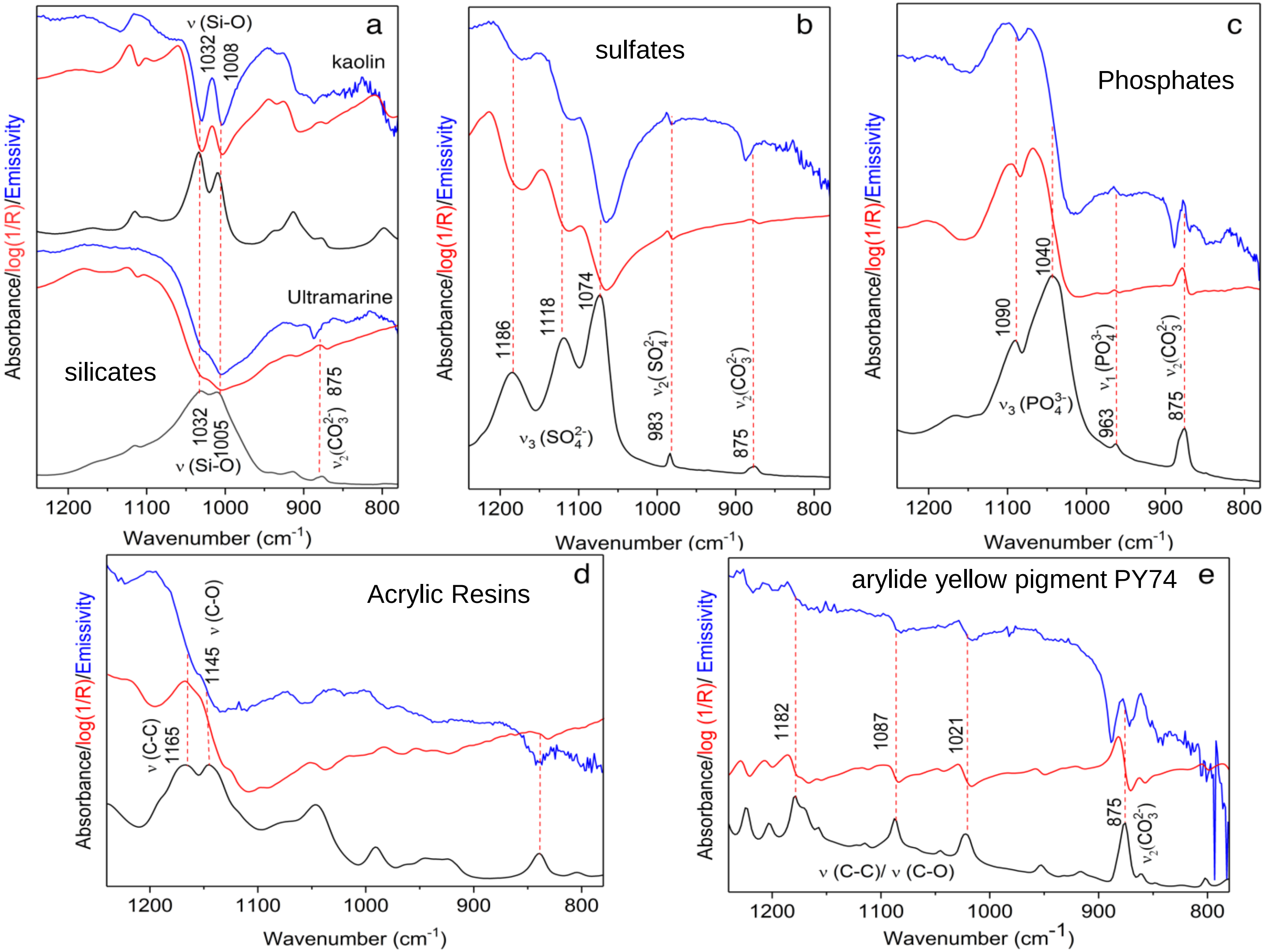
(900, 1050, 1200 cm^{-1})

Emissivity spectra (outdoors=blue, indoors-cold-tunnel=red) from cadmium red paint sites (indicated with corresponding colored arrows



Material map & corresponding spectral endmembers of $BaSO_4$ in oil and alkyd paints (red), silicate in oil and alkyd paints (blue), and silicate in acrylic paints (green).

CORRELATION OF THREE DIFFERENT INSTRUMENTS

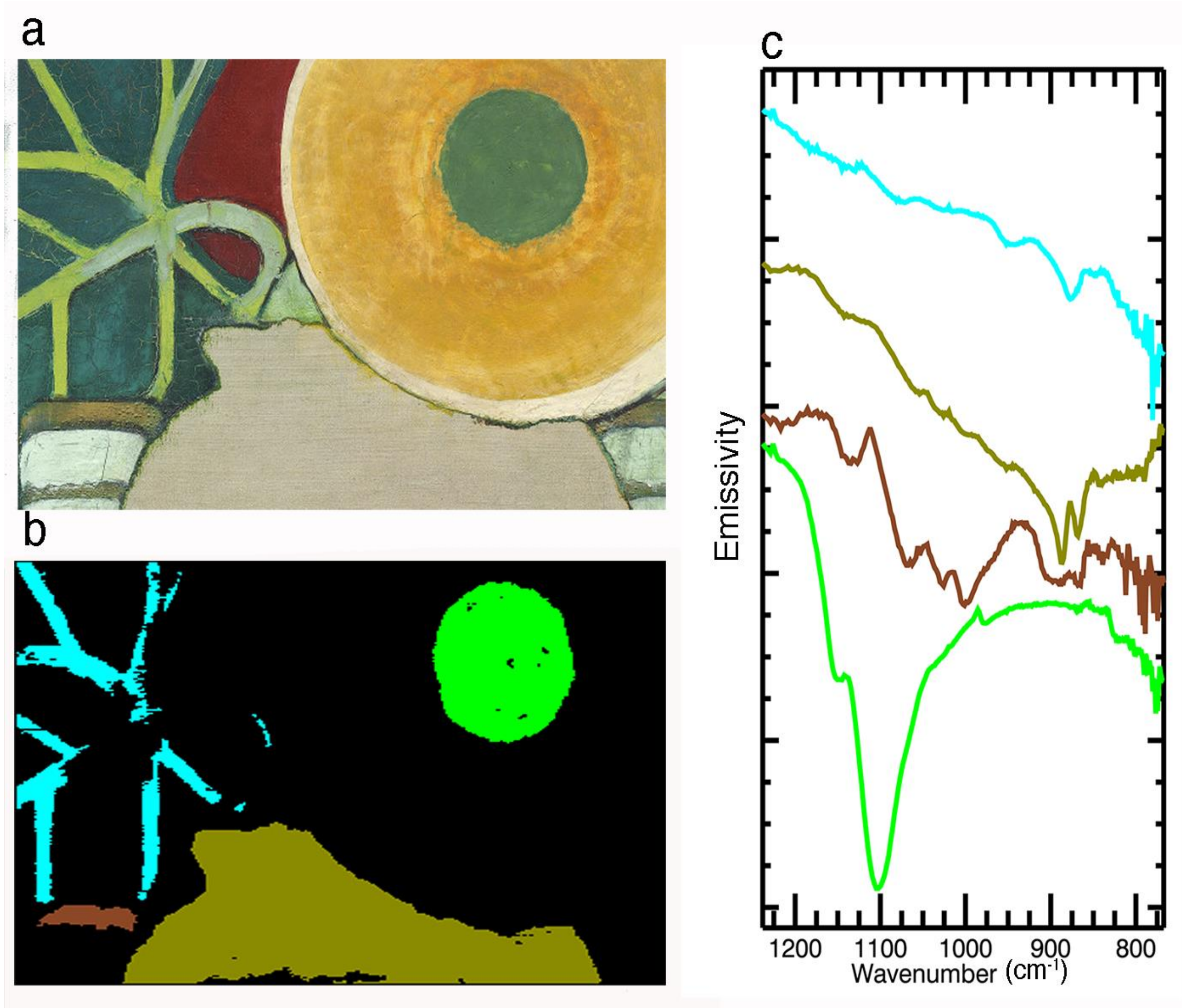


Black: sampled with benchtop μFTIR spectrometer

Red: contact point FTIR spectrometer

Blue: LWIR HSI instrument

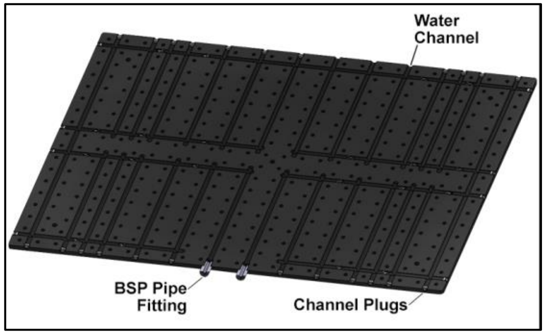
EDWARD STEICHEN'S *STUDY FOR "LE TOURNESOL"*

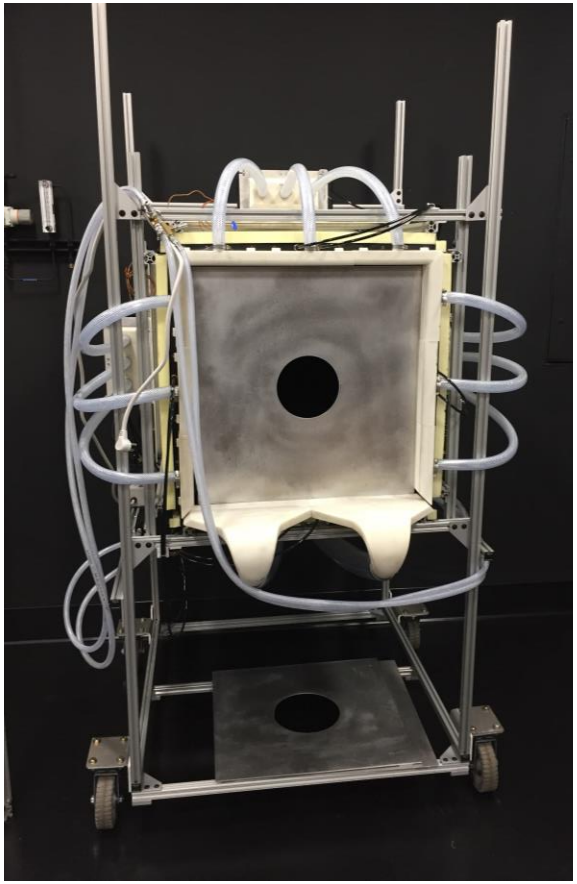


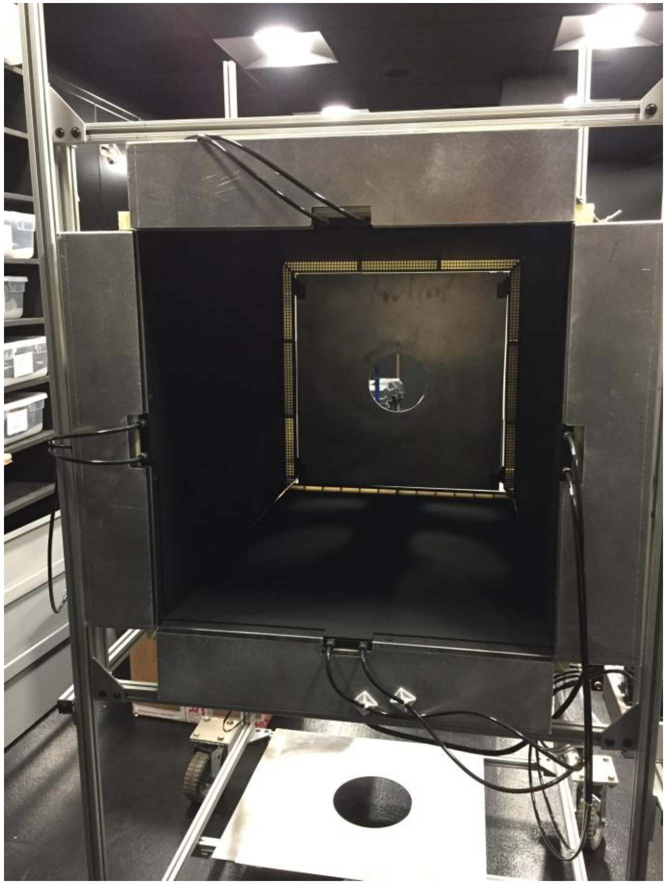
Color detail of Edward Steichen's *Study for "Le Tournesol (The Sunflower)"* (a); gift of Joanna T. Steichen © Estate of Edward Steichen, and map (b) of the spectral endmembers (c).

IMPROVED INDOOR "COLD SKY"

- Instead of using LN_2 and reflective Al, new version uses a series of eight chilled Thorlabs breadboards with highly emissive paint surfaces affixed on each side.
  - A high capacity chiller pumps refrigerated glycol through all four sides
  - Chilled, dry air passes over each side via laminar flow to prevent frost from forming on walls
  - Reflective enclosure reflects light from target back from around camera lens
- Initial tests show up to 30C delta between high emissivity walls and room temperature target side. This setup also achieves steady state.







CONCLUSIONS

- NVESD & NGA have been collaborating on Masterwork spectral imaging for over a decade.
- Investigations using Army spectral cameras have covered many spectral bands and sensing modalities.
- Many publications and presentations have resulted thus far from this collaborative work.
- Much has been learned about significant Masterworks that will aid in the study and conservation of these pieces for future generations.
- New sensors and laboratory equipment now make possible phenomenology investigations in the 'Mid-IR'.

THANK YOU TO SET-240

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