Enhancing deep cavity detection using orthogonal measurement techniques NLV-030-20, Year 2 of 3

Cleat Zeiler, Michael Howard, Heather Howard, Reagan Turley

This work was done by Mission Support and Test Services, LLC, under Contract No. DE-NA0003624 with the U.S. Department of Energy and supported by the Site-Directed Research and Development Program. DOE/NV/03624--1206.

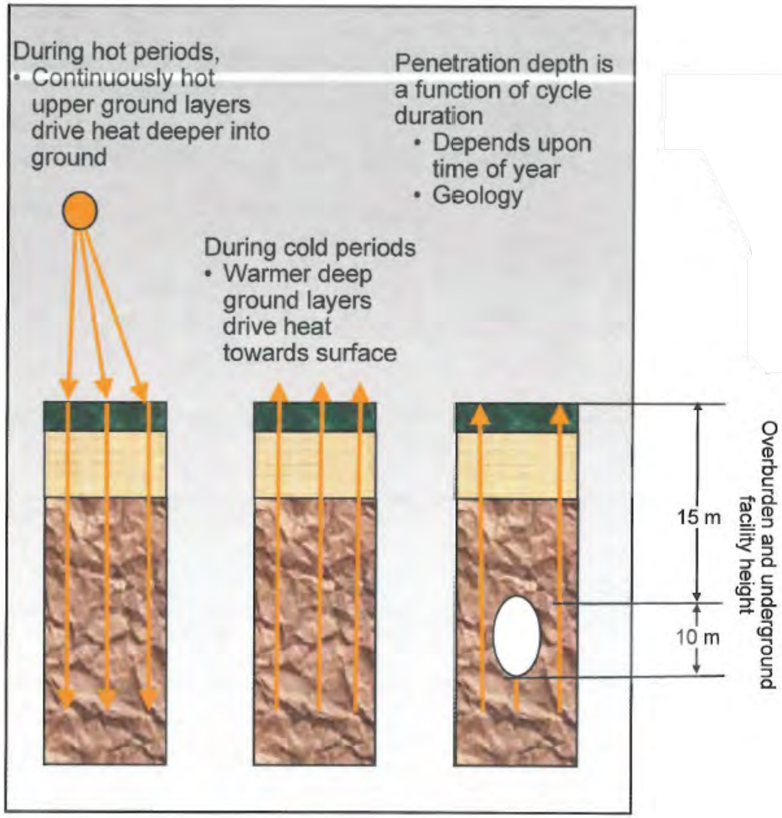
Reviewed for Classification
Paul P. Guss, MSTS, 1302
September 20, 2021
Export Control
EAR99 – No License Required

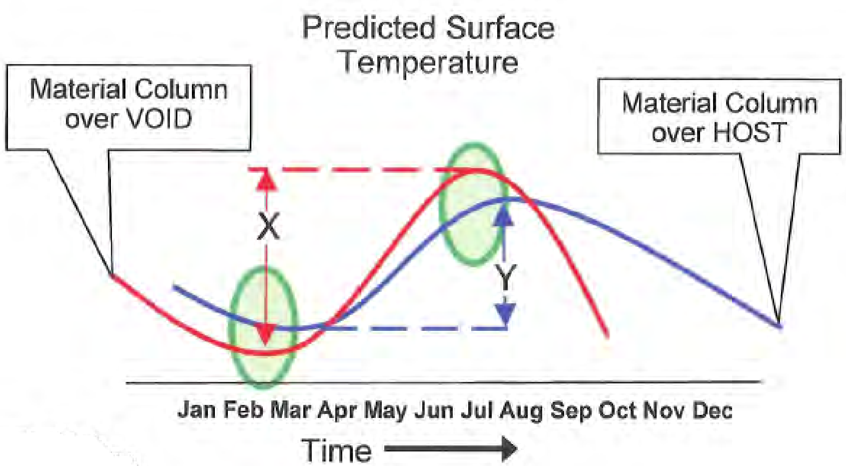
Challenge

- Thermal inertia modeling has been able to detect voids in the subsurface for shallow voids. Can you detect deeper voids?
- Can you characterize the footprint of an underground facility using thermal imaging techniques?
- What are the depth and size of a void that can be detected using thermal modeling?
- By combining geophysical parameters, can you enhance or improve the interpretation of the thermal imaging?
- A key target is having a remote capability to detect underground facilities and understand the scope and size of activities.
  - Example: When the government of North Korea stated that it destroyed the entrance to its underground testing facility, did it really collapse the whole complex, or was there only a surficial impact?

Innovation

- Thermal imaging measures radiation in the mid- to long-wave infrared spectral ranges
- Differences in subsurface composition and structure will express in the spatial distribution of surface temperature
- An underground void will result in a lower thermal inertia
- Combining thermal inertia modeling with the Geologic Framework Model (GFM) will provide resolution enhanced signature recognition
  - Geophysical surveying and parameters
  - Orthogonal measurement techniques
  - Airborne thermal imaging
  - Ground truth measurements during overflights

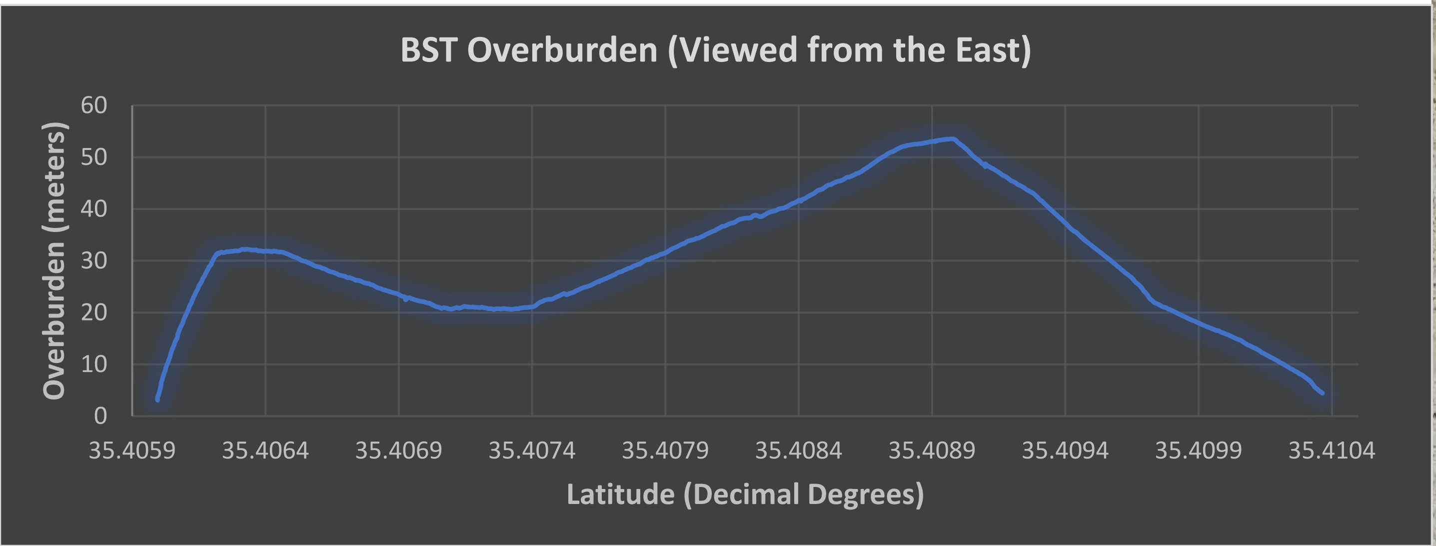


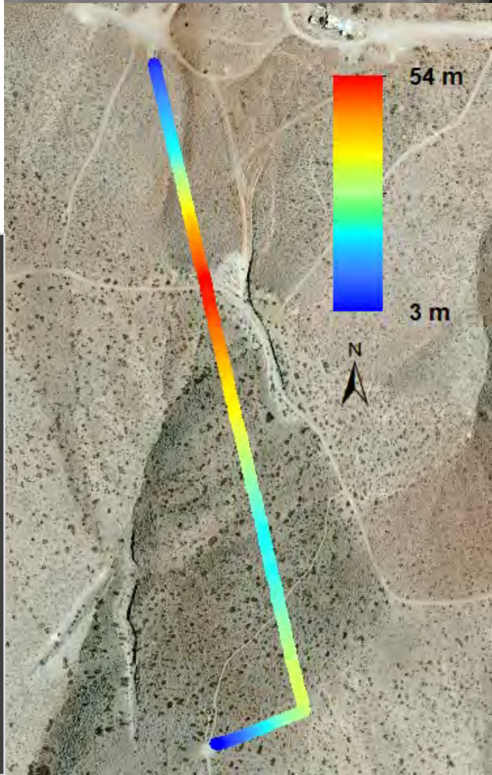


Graphic from Durek, J., 2008, Underground Tunnel and Facility Detection Using Temporal Dual-Band Infrared Computed Tomography (TDICT).

Experiment Site – Burro Schmidt Tunnel (BST)

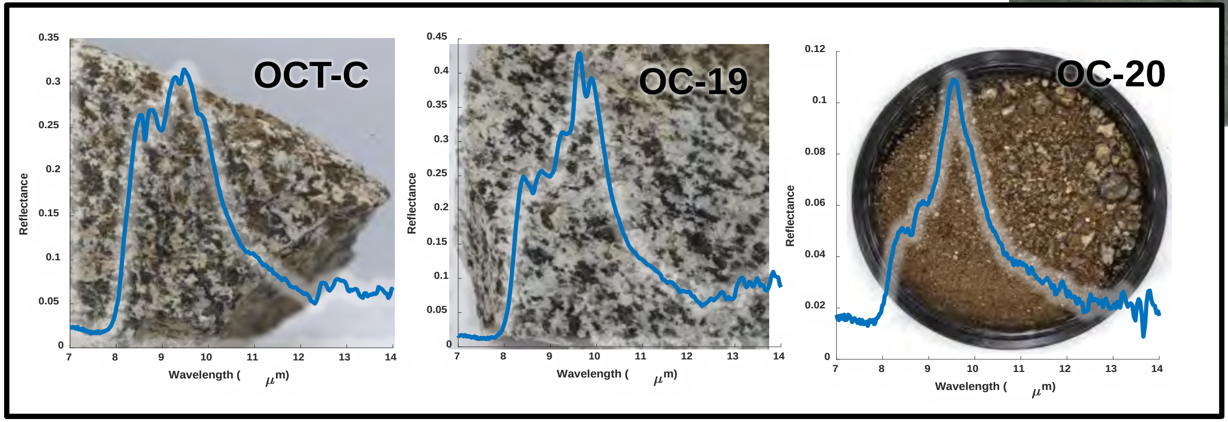
- Historic site in the El Paso Mountains
  - Variable overburden offers multiple depth scenarios at a single testbed
  - Uniform geologic host material with sparse surface vegetation
- Partnered with Lawrence Livermore National Laboratory (LLNL) to arrange thermal HSI data collections over BST
  - Spectral range 7.5–13 µm
  - 249 spectral channels
  - Flown at an altitude of around 5,500 ft
- Partnered with Custom and Border Agency (CBP) to collect parametric and overburden data of BST

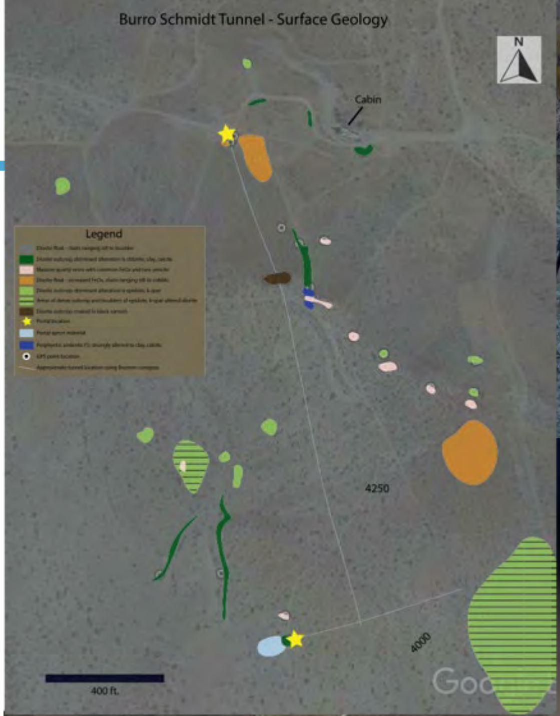


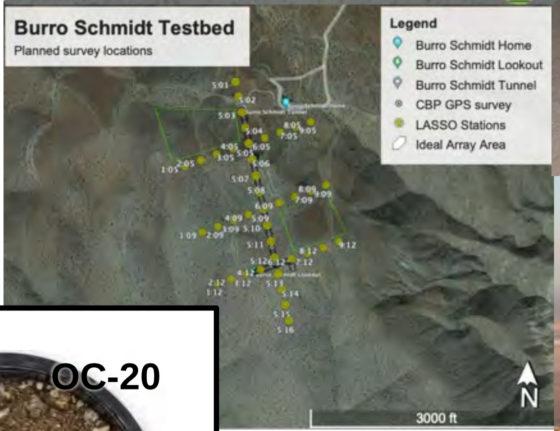


Ground Surveys of BST

- Radiometric measurements
  - Series 3–5 µm and 8–12 µm radiometers to measure radiometric temperature of surface materials
  - Mobile radiometers – Measured temperature variability on surface and interior tunnel walls
  - Weather station – Standard meteorology plus upwelling and downwelling solar irradiance
- Geological survey of area
  - Outcrop shown to be diorite (previously assumed granite)
  - Selected samples were sent to Dynalene Laboratory Services for measurement of thermal conductivity, thermal diffusivity, and specific heat
  - Samples were also measured for density

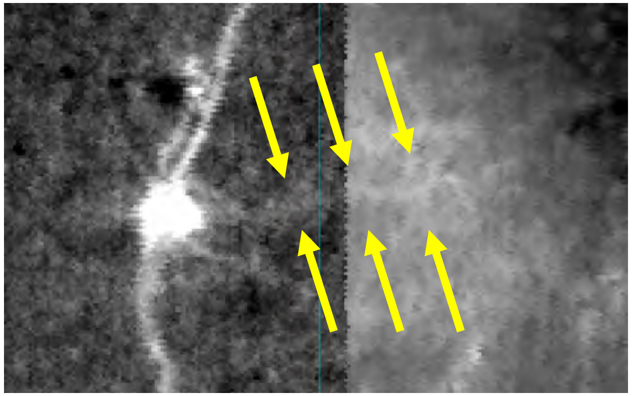


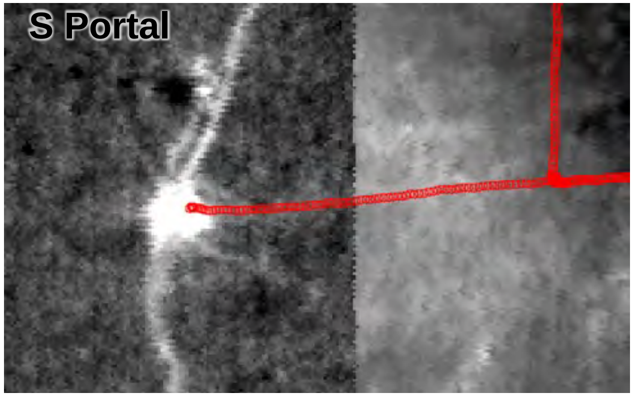




Preliminary Analysis of LLNL Data

- LLNL LWIR HSI over BST during pre-dawn on July 19, 2021
- Image data had significant vibration caused by a malfunctioning cryo-cooler
  - Severely reduced utility of data for detecting subtle thermal features
  - Cryo-cooler has been repaired for the next collection
- It rained around 9 PM the night before the pre-dawn collection for about 30 minutes as measured by an on-site weather station
  - Any moisture will severely impact the signal strength in the infrared spectral region.
- A portion of the tunnel is visible in the decorrelation-transformed image data





MASI/TASI Integration into B350

- MASI/TASI mounting plate for forward hole in B350
  - A mounting plate was designed and constructed to hold the 300+ lb MASI/TASI sensor assembly, including a stabilized mount
  - The plate adapts to the existing pressure tub spacer, which was certified to mount to the pressure dome mounting plate for other sensor configurations
  - Avcon was contracted to certify the mounting plate – STC completed 9/8/2021
- Power draw – On-site engineering required to separate power draw from the cryo-coolers and ICU to different mission power circuits
- Controller electronics – All supporting electronics were integrated into existing standard 19-inch racks with prior certification

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
STATEMENT OF COMPLIANCE WITH AIRWORTHINESS STANDARDS

AIRCRAFT OR AIRCRAFT COMPONENT IDENTIFICATION

2. MAKE	3. MODEL NO.	4. TYPE (Airplane, Radio, Propeller, etc.)
Textron Aviation	B300 S/N FL-1190	Airplane

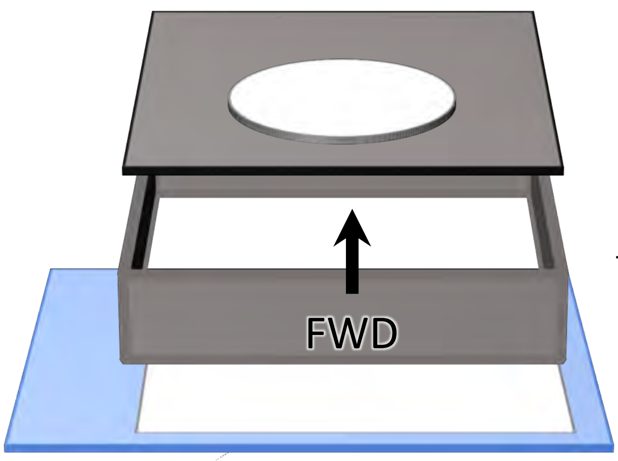
LIST OF DATA

6. IDENTIFICATION	7. TITLE
DRAWINGS	
DR-AMS-DTL-2010 Rev B Dated 07/12/2021	MASI/TASI – GSM 4000 MOUNTING PLATE
DOCUMENTS	
SR193520 REV IR Dated 08/25/2021	STRUCTURAL ANALYSIS FOR MASI/TASI – GSM 4000 MOUNTING SERIES

NOTES

	MASI 600	TASI 600
FOV (Deg)	40	40
Frame Rate (Frames/Sec)	63	200
Integration Time (ms)	15.9	5
Spatial Pixels	640	600
Spectral Bands	64	32
Spectral Wavelength (microns)	3 – 5	8 – 11.5
GSD at 3500 feet AGL (ft)	4	4.25

B350 Itres MASI/TASI Installation Sequence Schematic



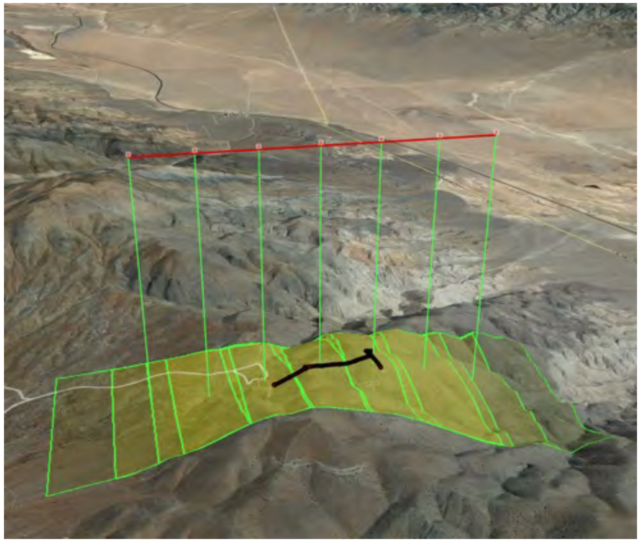
MASI/TASI –GSM4000 Mounting Plate (New)

RSL/BN Pressure (Scanner) Tub Spacer Segment

Pressure Dome Mounting Plate (1877421)

MASI/TASI HSI Mission Planning

- Acquisition parameters
  - BST can be covered in one flight line with the Itres systems from 3500 feet AGL
  - GSD will be approximately 4 feet
  - The aircraft will be limited to 150 knots in order to maintain equal pixel size in flight and cross-track directions
  - Aircraft roll will be restricted to 15 degrees for the entire flight directory to ensure optimum GPS satellite lock and geometry
  - Data will be collected during pre-dawn hours (~1 hour before sunrise) and around solar noon
  - Photogrammetric system will acquire stereo imagery for extraction of digital terrain model
- Anticipated challenges
  - Many fires are burning in the vicinity and data quality will be impacted by smoke interference – Recon flight on 9/14/2021 showed significant smoke
  - There have been multiple rain events leading up to the airborne collection
  - Extended technical integration timeline of MASI/TASI expected due to Itres support limited to remote communications due to international COVID travel restrictions.



Airborne collections currently scheduled from 9/20 to 9/30
Model predicts detection in the 2–4 m and 7–8 m overburden.

Summary of Results, Path Forward

- Summary of results
  - Thermal HSI data collected with LLNL sensor
  - Preliminary analysis of LLNL data shows tunnel detection at the south portal
  - Ground-based temperatures, weather, and radiance collected during LLNL overpasses
  - Geologic survey conducted to characterize bedrock and surface cover
  - Itres MASI/TASI sensor suite integrated into B350 for primary thermal HSI collections – late summer 2021
  - Mission planning complete for MASI/TASI image acquisition surveys
- Path forward
  - Conduct MASI/TASI airborne HSI data collections of BST and calibration sites
  - Collect simultaneous radiometric ground truth with MASI/TASI overpasses
  - Conduct seismic survey of BST and extract bedrock properties
  - Improve accuracy of surface energy balance
  - Improve geologic map coverage using spectral signatures of rocks

Impact

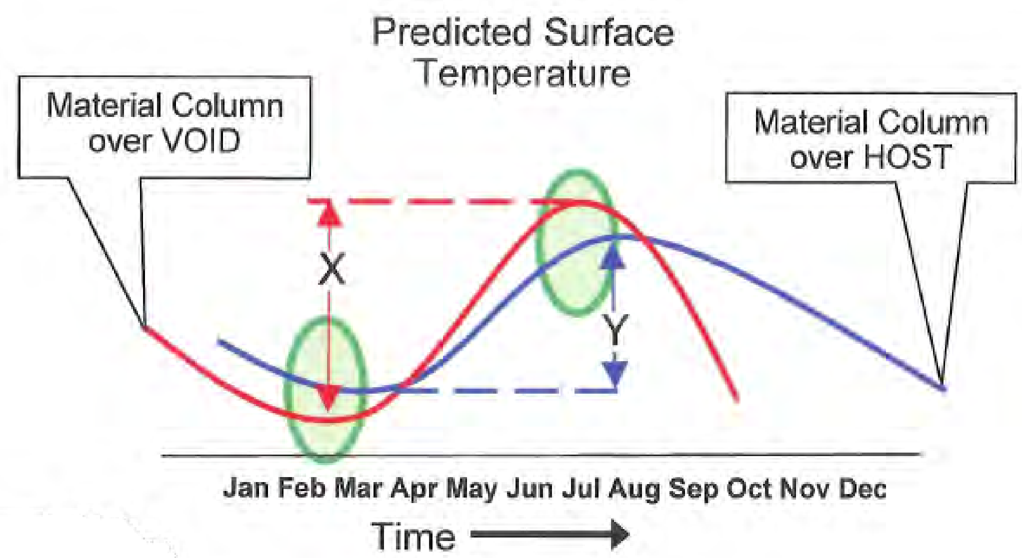
- Collaborations were develop between RSL and LLNL
  - RSL was able to provide performance information for LLNL for their newly developed HSI sensor
  - RSL was able to use the HSI data acquired over the experiment site
- Ongoing collaborations with CBP mission partners
  - CBP was able to use BST as an additional testbed for their taskforce assessment and testing requirements
  - RSL was able to use the results from their tunnel survey using their subterranean inertial navigation system to map BST
- New interest is currently being developed as a new interagency work group with DTRA and Geo-Temp (Nancy Del Grande)

Backup Slides

Technical Approach – Modeling

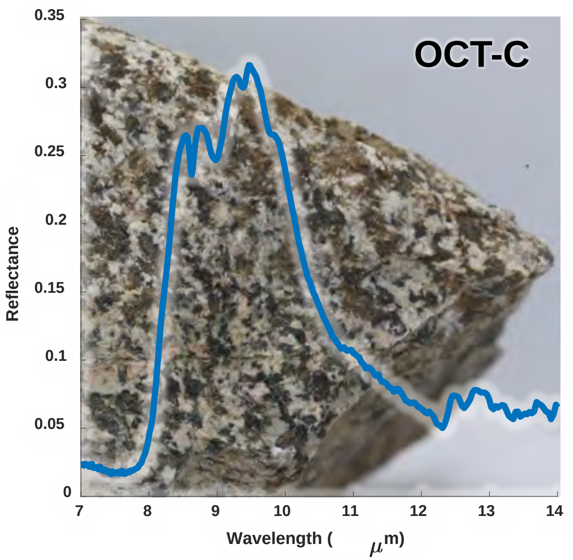
Modeling the Surface Energy Balance

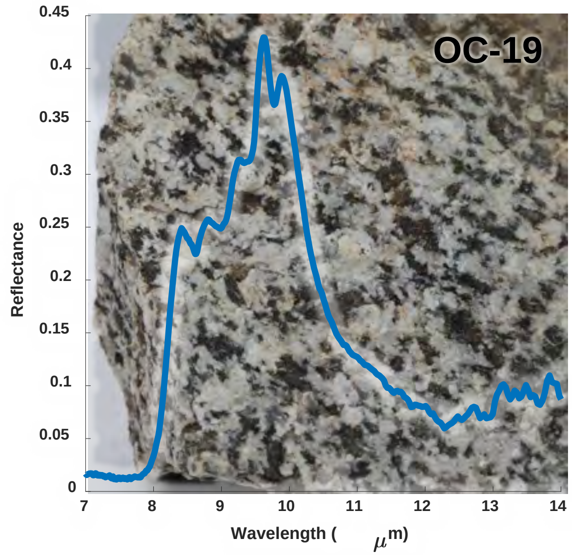
- A heat flow model was developed to estimate the surface energy balance and determine the temporal impact to surface temperature due to the presence of subsurface voids
- The model is used to determine when in the annual cycle the subsurface void will exhibit the highest contrast to the host material at the surface, enabling the detection, location, and spatial extent mapping of the void by airborne thermal imaging
- Overhead thermal imaging is conducted at the predicted optimum times to include several diurnal and seasonal cycles

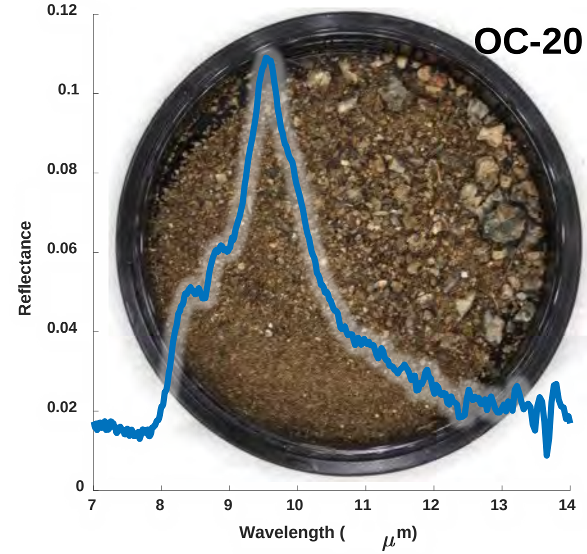


Graphic from Durek, J., 2008, Underground Tunnel and Facility Detection Using Temporal Dual-Band Infrared Computed Tomography (TDICT).

Thermal Analysis of BST Host Material







OCT-C

K = 2.39 W/m/K
k = 0.86 mm²/s
ρ = 2.78 g/mL
c_p = 1.00 J/g/K
ε = 0.87

OC-19

K = 1.89 W/m/K
k = 0.54 mm²/s
ρ = 2.90 g/mL
c_p = 1.20 J/g/K
ε = 0.85

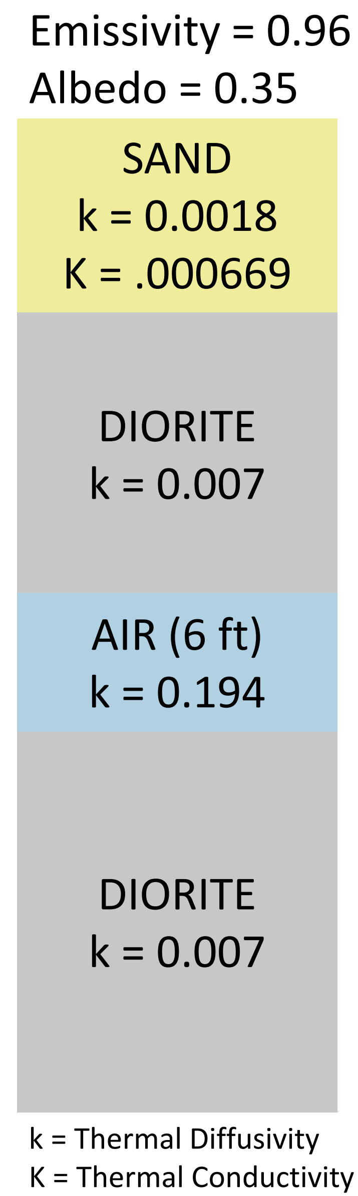
OC-20

K = 0.28 W/m/K
k = 0.18 mm²/s
ρ = 1.57 g/mL
c_p = 0.96 J/g/K
ε = 0.96

K = Thermal conductivity
k = Thermal diffusivity
ρ = Density
c_P = Specific Heat
ε = Emissivity

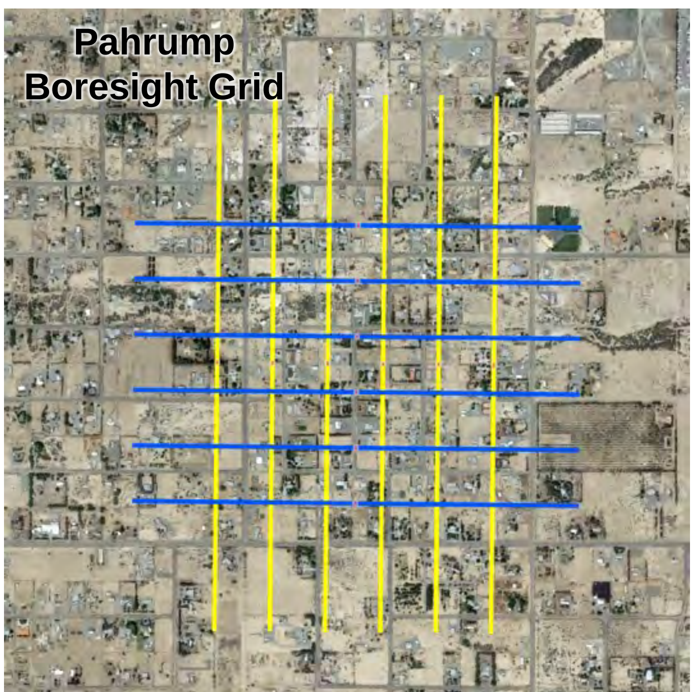
Modeling Burro Schmidt Tunnel (BST)

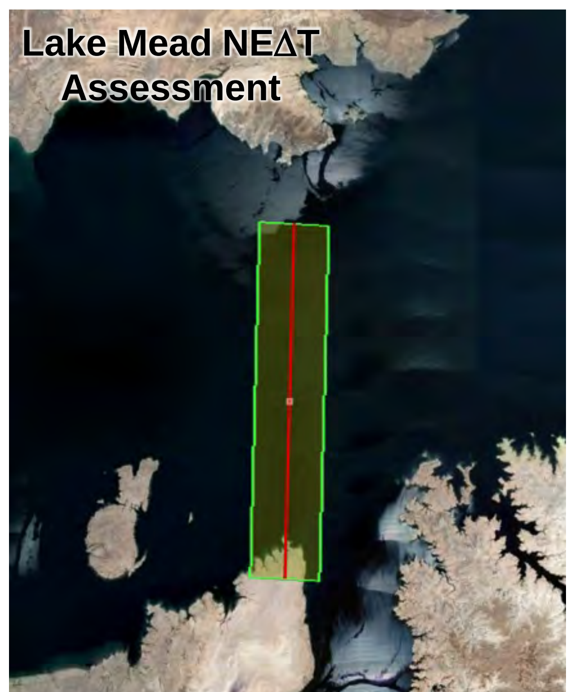
- The BST was modeled with the 1D simulator to estimate optimum imaging times
- Since the overburden of the tunnel varies along its trajectory, as seen with the CBP data, multiple depths were simulated
- Meteorological inputs were needed for an entire year; therefore, weather was obtained from NOAA's Rapid Refresh model
- The tunnel height was estimated to be 6 feet
- Host material was identified by the geological survey to be diorite
  - Thermal properties for the surface were obtained from the OC-20 sample
  - Thermal properties for the bedrock diorite was an average of the OCT-C and OC-19 samples

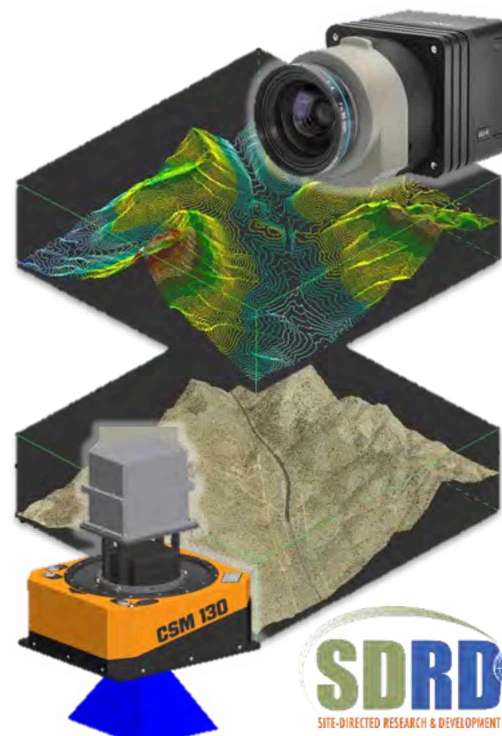


MASI/TASI HSI Mission Planning

- Supporting collections
  - A boresight alignment collection will be made to align the inertial measurement unit with the imaging sensors focal plane
    - Required for accurate georectification
    - A set of 6 lines with 80% side overlap in perpendicular headings
    - Pahrump chosen to avoid flight restriction
  - Image collection over Lake Mead will assess noise across the full frame and give an estimate of in-air NEΔT
  - Photogrammetric system will acquire stereo imagery for extraction of digital terrain model that will be used to orthorectify the thermal imagery







SDRD
SITE-DIRECTED RESEARCH & DEVELOPMENT