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Demonstration of Dual-Band Infrared Thermal Imaging at Grass Valley Creek Bridges

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Demonstration of dual-band infrared thermal imaging at Grass Valley Creek Bridges

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ABSTRACT

We demonstrated dual-band infrared (DBIR) thermal imaging at the Grass Valley Creek Bridges near Redding CA. DBIR thermal imaging is an enabling technology for rapid, reliable, bridge deck inspections while minimizing lane closures. The bridge-deck inspections were conducted from a mobile DBIR bridge inspection laboratory during November 2-3, 1995. We drove this self-contained unit at limited highway speeds over 0.4 lane miles of bridge deck. Using two thermal IR bands, we distinguished delaminations from clutter. Clutter, or unwanted thermal detail, occurs from foreign materials or uneven shade on the bridge deck surface. By mapping the DBIR spectral-response differences at 3-5 μm and 8-12 μm, we removed foreign material clutter. By mapping the deck diurnal thermal inertia variations, we removed clutter from uneven shade. Thermal inertia is a bulk deck property, the square root of thermal conductivity x density x heat capacity. Delaminated decks have below-average thermal inertias, or above-average day-night temperature excursions. Compared to normal decks areas, delaminated deck areas were typically 2 or 3 °C warmer at noon, and 0.5 °C cooler at night. The mobile DBIR bridge inspection laboratory is currently undergoing extensive testing to examine bridges by the Federal Highway Administration.

Key Words: Dual-Band Infrared, Thermal Imaging, Nondestructive Evaluation, Bridge Deck Inspections

1. BACKGROUND

To date, most bridge inspections rely on human interpretation of surface visual features or chain dragging. These methods are slow, disruptive, unreliable and raise serious saftey concerns. Single-band infrared (SBIR) thermal imaging, often referred to as thermography, is a technique with a promising potential. This technique has been used previously to detect delaminations within bridge decks. [1-4] However, it is difficult to distinguish subsurface delaminations from surface features on SBIR images. To locate and identify subsurface delaminations, we must first remove the mask from surface clutter (or unwanted detail on the IR images). Clutter is often introduced by foreign materials on the roadway, shadows, and reflected IR backgrounds.

Previous investigators have used video cameras, first to identify and then to remove surface-object clutter. Unlike thermal signals produced by subsurface delaminations, clutter signals vary with IR wavelength. To take advantage of this important spectral difference, the Lawrence Livermore National Laboratory (LLNL) applies dual-band infrared (DBIR) thermal imaging for bridge inspections. DBIR thermal imaging allows precise, temperature measurement to reliably locate bridge deck delaminations by removing wavelength-dependent emissivity variations due to surface clutter.

The LLNL has successfully demonstrated the patented DBIR thermal imaging method[5,6] for a variety of applications. By removing spatially varying emissivity noise, DBIR methods typically improve temperature accuracy and precision by an order of magnitude compared to SBIR methods. In addition to precise temperature maps, DBIR methods provide emissivity-noise maps which clarify interpretation of heat flow anomalies from subsurface features, e.g., underground objects and structural deficiencies. Previously reported applications of DBIR imaging depicted:

- Geothermal aquifers under 6 to 60 meters of dry soil,[7,8]
- Cemetery walls, trenches and a building foundation under 80 cm of asphalt and debris[9]
- Buried mines, rocks and objects under 1 to 20 cm of disturbed sand, soil, or sod,[9-15]
- Airframe material loss from corrosion under 1 or 2 mm of exposed aluminum skin[15-23]
- Synthetic bridge-deck delaminations, 5 and 10 cm deep, in concrete and asphalt-concrete slabs [22-25]

2. FEASIBILITY STUDY USING SURROGATE BRIDGE DECKS

In this section, we summarize a feasibility study, conducted during 1994, which demonstrated the applicability of dual-band infrared thermal imaging to bridge decks. [22-25] We constructed small-scale surrogate bridge decks using concrete and asphalt-concrete slabs. Two nearly identical concrete test slabs were cast in January 1994. The slabs were 1.8 m (6 feet) square by 19 cm (7.5 inches) thick. During March 1994, one of the slabs was paved with a 5-cm (2-inch) thick layer of asphalt.

The synthetic delaminations were constructed with five 5-cm (2-inch) deep embedded pieces of Styrofoam cut to various square sizes and thicknesses. The Styrofoam pieces formed synthetic delaminations, at a depth of 5 cm in the unpaved concrete slab and 10 cm in the paved concrete slab. We placed objects on the slabs which produced surface clutter. During April 1994, we mapped surface temperature differences for paved and unpaved concrete slabs. Later, we developed image-processing methods to unmask synthetic delaminations and remove surface clutter. The temperature images were processed using the VIEW computer code developed at LLNL. [22-25]

We developed emissivity-corrected surface temperature maps to depict heat flow anomalies produced by subsurface delaminations and to remove surface clutter. Clutter is unwanted thermal detail. Clutter often occurs from foreign deck materials. Clutter sometimes occurs from uneven shade on the bridge deck surface. Clutter may also occur from unseen chemical differences in concrete which respond differently at the two IR wavelengths measured with the dual-scanner system. By mapping the DBIR image differences at 3-5 μm (SW), and 8-12 μm (LW), we identify and remove foreign material clutter.

By mapping the bridge deck thermal inertia, or resistance to diurnal temperature change, we distinguish substantial defects (e.g., subsurface delaminations) from superficial surface features (e.g. shaded deck areas). Thermal inertia is a bulk deck property, i.e., the square root of thermal conductivity x density x heat capacity. Deck areas with synthetic delaminations have below-average thermal inertias and above-average day-night temperature excursions relative to normal decks areas. Typically, delaminated surrogate deck areas were 2 or 3 °C warmer at noon, and 0.5 °C cooler at night, than their surroundings.

We used the IR dual-scanner system mounted on a tower platform to measure the thermal responses and emissivity differences which distinguish normal from cluttered and delaminated surrogate bridge decks. We used precisely-calibrated, contact-thermistors and DBIR thermal imaging methods for precise, temperature measurements. The slab temperature data taken in January and April were used to evaluate the best measurement times, with the largest thermal contrast, for unmasking bridge deck delaminations. These times were from 1200 hrs to 1500 hrs during clear days, and from 2200 hrs to 0600 hrs at night.

Near midday, for several clear days in April 1994, the concrete-slab surface above a 23-cm (9-inch) square, 5-cm (2-inch) deep Styrofoam piece, was on the average about 3 °C warmer, and at night 0.6 °C cooler, than the surrounding concrete-slab surface. For actual bridge deck inspections taken during November 1995, delaminated areas were typically 2-3 °C warmer than normal areas at 1200 hrs, and 0.5 °C cooler than normal areas at 2200 hrs. We discuss the actual bridge deck results in greater detail in a later section. Suffice to say, the tower-platform tests of surrogate (small-scale) bridge decks helped us plan effective measurement times for the actual bridge deck inspections which were conducted after the initial feasibility study.

We discovered a strong correlation between the defect volume, and the temperature signal which it produced. The daytime (above-ambient) minus nighttime (below-ambient) IR temperature-difference signals varied linearly with the volume of the embedded Styrofoam pieces which produced the temperature differences. We predict delaminated bridge decks with large volumes of damaged concrete will produce larger temperature excursions from those of normal concrete than delaminated bridge decks with small volumes of damaged concrete. To date, we were only able to "predict" delaminated deck areas. It would be most interesting to confirm our predictions with "bridge truth". Bridge truth is well-documented visual, photographic, and video-tape observations, which record the location and amount of damaged concrete while the bridge deck is rehabilitated.

The tower-mounted demonstration successfully depicted the 5-cm deep synthetic delaminations for 10-cm or larger Styrofoam pieces embedded in concrete slabs. The concrete slabs had delaminated concrete volumes which ranged from 33 to 165 cm^3 (2 to 10 cubic inches). The tower-mounted demonstration also depicted 10-cm (4-inch) deep synthetic delaminations for 23-cm (9-inch) Styrofoam pieces embedded in the asphalt-covered concrete slab. The small-scale surrogate bridge deck delaminations had areas from 103 to 523 cm^2 (16 to 81 square inches). Typical bridge delaminations, which we describe later in this paper, encompassed 10 to 30 % of a 1 m by 3 m bridge-lane image. Their areas ranged from 0.3 to 0.9 m^2 (3 to 10 square feet).

3. DUAL-BAND INFRARED THEORY APPLIED TO BRIDGE DECKS

We adapted our patented[5,6] DBIR thermal imaging method for concrete bridge deck inspections.[22-25] This method acquires images simultaneously at two infrared wavelength intervals: 3-5 μm and 8-12 μm. A power law model explains how infrared signals vary as a function of the surface emissivity and the surface's absolute temperature:[26]

$$I_\lambda \sim e_\lambda \, T^{50/\lambda} \tag{1}$$

where I_λ is the intensity at a given wavelength, e_λ is emissivity at that wavelength, **T** is the temperature in Kelvin, and λ is the wavelength in μm.

We can obtain temperature alone by computing the ratio

$$R = \frac{I_5}{I_{10}} = \frac{e_5 \; T^{50/5}}{e_{10} \; T^{50/10}} = \frac{e_5}{e_{10}} T^5 \tag{2}$$

For a graybody, $e_5 = e_{10}$ and $R \sim T^5$.

Emissivity is a numeric whose value lies between the limits of zero for a nonradiating source and unity for a blackbody. The emissivity is given by the ratio of the radiant emittance of the source to the radiant emittance of a blackbody at the same temperature. Three types of sources can be distinguished by the way that the spectral emissivity varies:[27] (1) a blackbody or Planckian radiator, for which emissivity is one; (2) a graybody, for which emissivity is a constant less than one; and (3) a selective radiator for which emissivity varies with wavelength.

We can obtain the emissivity ratio for various types of sources by computing

$$\frac{(I_{10})^2}{I_5} = \frac{(e_{10})^2 (T^5)^2}{e_5 \; T^{10}} = \frac{(e_{10})^2}{e_5} \qquad (3$$

This ratio is sensitive to surface objects that have different emissivities at 5 μm and 10 μm (most metal surfaces). We then compute the normalized ratios to obtain temperature and emissivity-ratio (E-ratio) maps:

$$(T/T_{av})^5 = (SW/SW_{av}) \, / \, (LW/LW_{av}) \tag{4}$$

$$\text{E-ratio} = (LW/LW_{av})^2 \, / \, (SW/SW_{av}). \tag{5}$$

where **SW** is the short-wavelength intensity (e.g., I_5), SW_{av} is the average value of the pixels in **SW**, **LW** is the long-wavelength intensity (e.g., I_{10}), and LW_{av} is the average value of the pixels in **LW**.

For bridge decks, it is important to distinguish surface temperature variations (associated with a deep delamination) from emissivity variations (associated with wavelength-dependent reflective responses for deck materials). In practice, the DBIR signal intensities are not accessible, whereas the calibrated temperature differences are assessible. Thus, we could not use Eqs. (4) and (5) to distinguish emissivity noise variations (associated with surface clutter) from temperature differences (associated with subsurface delaminations).

Consequently, we developed an alternative method to locate and remove clutter. The alternative method turned out to be about as effective for distinguishing delaminations from surface clutter. It is simpler, more direct, and easier to use. We use the average of the longwave and shortwave calibrated temperature images in place of Eq. (4). We use the spectral differences for the longwave and shortwave calibrated temperature images to replace the emissivity-ratio map of Eq. (5).

We simply compare the temperature difference at two deck locations, to determine if it is the same for the two bands. Temperature differences for the host concrete deck material, with subsurface delaminations, are identical at 3-5 µm and 8-12 µm. We use the average of the longwave (LW) and shortwave (SW) calibrated temperature images for the corrected DBIR temperature-image map. The average temperature map shows temperature variations from surface-only features and from subsurface features such as delaminations.

We map the spectral differences between the LW and SW temperature maps to depict surface clutter from foreign materials which reflect differently and have different emissivities at the two wavelength bands. Emissivity variations differ at 3-5 µm and 8-12 µm, for selective radiators, which have anomalous resonances in one of the DBIR bands. By subtracting (LW - SW) temperature images, calibration errors stay the same, and emissivity differences stand out. The resultant spectral-difference map serves a similar purpose to the E-ratio map of Eq. 5. Unlike the average temperature map, which depicts surface clutter and subsurface delaminations, the spectral-difference map depicts only surface clutter. We tag clutter which has the same location, size and shape on the average DBIR temperature, LW temperature, SW temperature and spectral-difference maps. We tag subsurface delamination sites which do not correspond to clutter sites on the average DBIR, LW or SW temperature maps.

Subsurface bridge deck delaminations are gaps in the concrete filled with air, corrosion products and debris. The presence of the gap causes the concrete above the gap to be warmer at midday and cooler at midnight than the surrounding undamaged concrete. Single-band thermal imaging, is widely used by the thermography community to evaluate spatially-varying temperatures. However, in practical bridge deck situations — with large spatially-varying emissivity changes — SBIR thermal imaging has limited temperature accuracy and sensitivity. SBIR methods do not allow spectral separation of emitted IR signals at delamination sites from reflected IR signal backgrounds at clutter sites.

The DBIR method achieves the needed sensitivity by separating the effects of spatially varying, wavelength-dependent emissivity for deck materials which behave like selective radiators, from the effects of surface temperature according to Equations 1 through 5. When access to **SW** and **LW** intensity values is limited, we map LW - SW calibrated IR temperature values which are small and constant for the host deck material, but larger and variable at clutter sites with contamination or compositional differences which behave like selective radiators.

4.0 MOBILE DBIR LABORATORY FOR BRIDGE INSPECTIONS

We designed, built, tested and applied a mobile DBIR thermal imaging laboratory for bridge inspections.[28,29] This work was sponsored by the Federal Highway Administration (FHWA) Nondestructive Evaluation Research and Development Program. Results from our surrogate bridge deck demonstration guided the design of the mobile bridge-inspection system shown in Figure 1. The Agema 900 dual scanners, which had 40° lenses, were mounted on a telescoping mast about 4 meters (13 ft) above the roadway. The system controls, 12-bit digital image processor, and high-speed recording hard drives were inside the modified 27-foot motor home. The IR cameras scanned the reinforced-concrete bridge deck for subsurface defects called delaminations. The mobile DBIR laboratory is currently undergoing extensive testing to examine bridges by the FHWA.[29]

We drove the self-contained mobile laboratory to the Grass Valley Creek Bridges near Redding, California where we acquired bridge-deck thermal images. Using thermal image analysis, we distinguished subsurface delaminations (concrete gaps), from surface materials and clutter (e.g. paint, patches, hinges and shaded areas). Shaded areas have thermal responses similar to subsurface delaminations during the day, but different thermal responses compared to subsurface delaminations at night.

To distinguish delaminated decks from normal decks, decks with surface material differences, and clutter, we imaged the delamination site: (1) size, shape, volume, depth and location; (2) thermal inertia (or daytime minus nighttime temperature differences) relative to ambient deck sites; (3) daytime and nighttime temperatures, relative to ambient deck sites; and (4) spectral (or LW - SW) image differences, relative to deck sites with surface material differences and clutter.

During the day, delaminated deck sites were masked by variable shade from hills, trees, or cloud-cover. At night, delaminated deck sites were 0.5 °C cooler than normal deck sites, and shade was not a problem. Shade presents a special type of unwanted detail, or surface clutter. Shade affects the interpretation of bridge inspections, when the bridge is deep within a canyon and surrounded by hills and trees. Thermal inertia responses (i.e. daytime above-ambient minus nighttime below-ambient thermal difference patterns) distinguish delaminated deck sites with bulk material damage from shaded, but undamaged, deck sites.

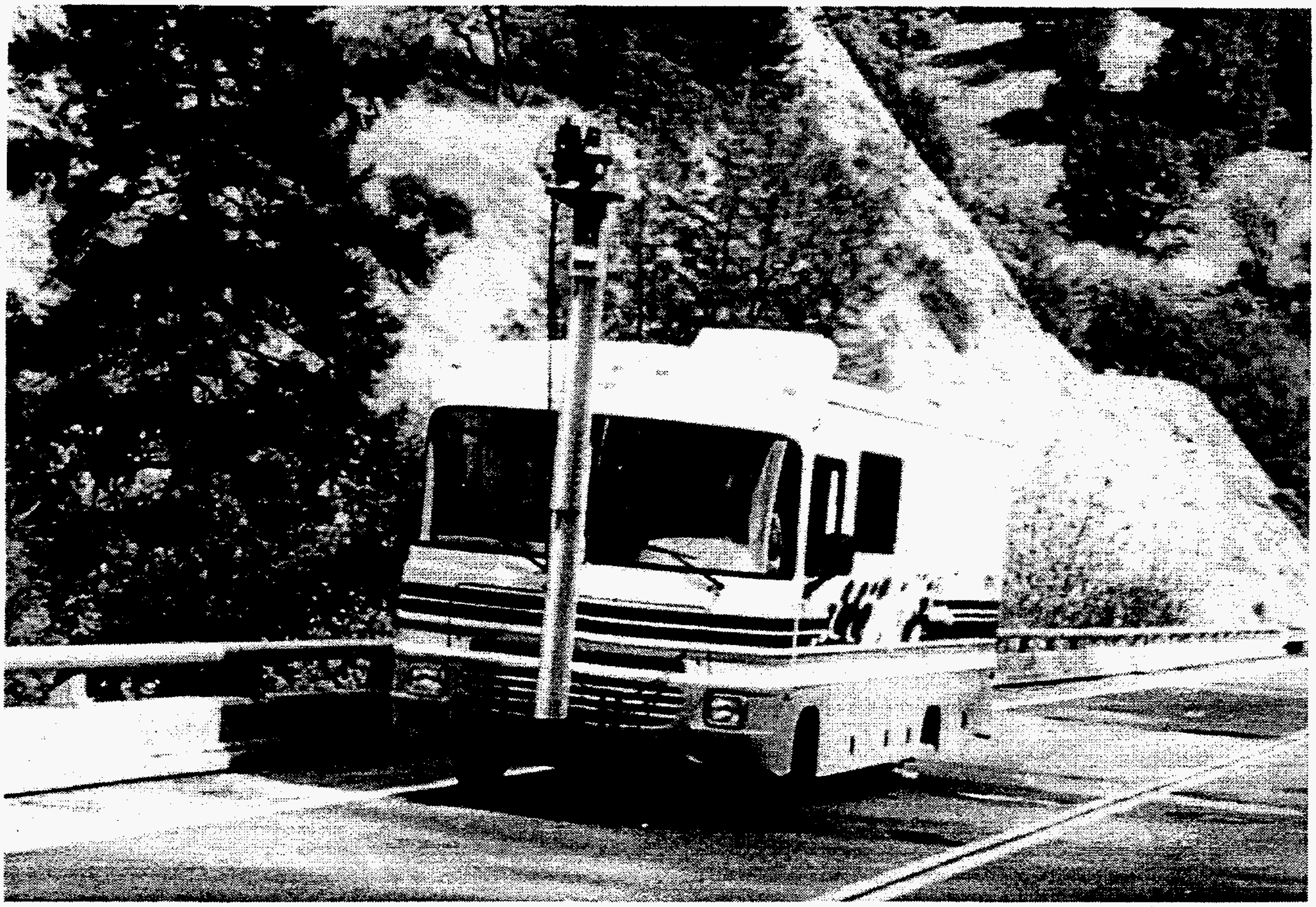

Figure 1. View of the mobile dual-band infrared (DBIR) thermal imaging laboratory as it inspects a Grass Valley Creek bridge near Redding California. The DBIR laboratory's cameras are mounted on a telescoping mast about 4 m (13 ft) above the roadway. They scan the reinforced-concrete bridge deck for defects called delaminations.

5.0 DISTINGUISHING DELAMINATIONS FROM CLUTTER

To distinguish delaminated decks from normal decks, decks with foreign materials, and shaded decks, we studied the Grass Valley Creek bridge-deck images recorded on the Agema 900 System 12-bit digital image processor. We show examples of a delaminated deck site, which had an area of 8.2 square feet, in Figures 2 and 3; a patched deck site in Figure 4, and a deck site with shaded areas which looked like delaminations on the daytime images, but had thermal inertias unlike delaminations on the nighttime images in Figure 5. The bridge deck images shown in Figures 2-5 were recorded during daytime, at 12:04 hrs on November 3 1995, and nighttime at 22:14 hrs on November 2 1995.

Coregistered LW, SW, and LW - SW images allow us to distinguish bridge decks which are normal from bridge decks which have subsurface delaminations, foreign surface materials and clutter (unwanted detail associated with surface features). We map thermal images on LW, SW, or DBIR maps which average the LW and SW thermal features. These maps depict subsurface delaminations plus foreign surface materials and clutter from deck sites with uneven shade. The LW - SW emissivity-noise maps depict only surface features (or non-thermal IR reflectance anomalies for surface materials). The daytime, nighttime, and day - night temperature-difference maps depict thermal-inertia responses which distinguish shaded from delaminated-deck sites.

To achieve high-definition delamination maps for bridge-deck evaluation, we must identify and remove surface features from the DBIR thermal maps. We developed highly-effective, automatic defect-recognition algorithms (e.g., to quantify corrosion defects in aging aircraft) which are not discussed in the context of this paper. Using similar, rules-based automatic defect-recognition algorithms, we could produce a reliable, high-definition, evaluated-delamination map for bridge deck evaluation.

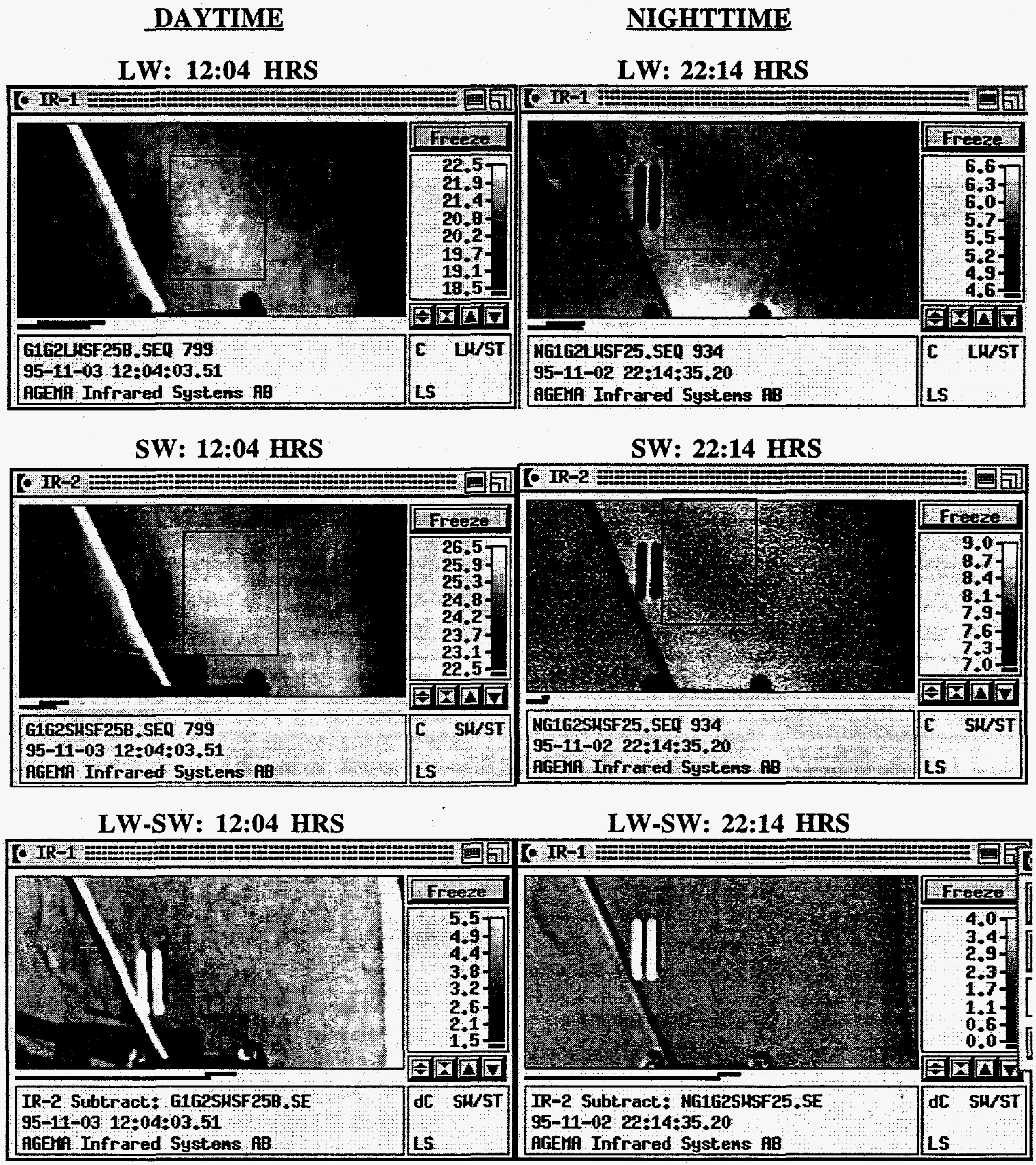

Figure 2. Grass Valley Creek bridge-deck delamination sites (boxed areas) were warmer than ambient at 12:04 hrs on November 3, and colder than ambient at 22:14 hrs on November 2. The LW-SW maps depicted only surface features, such as the expansion joint, aluminum markers, camera mount, painted shoulder line, and deck sites shaded from direct sunlight.

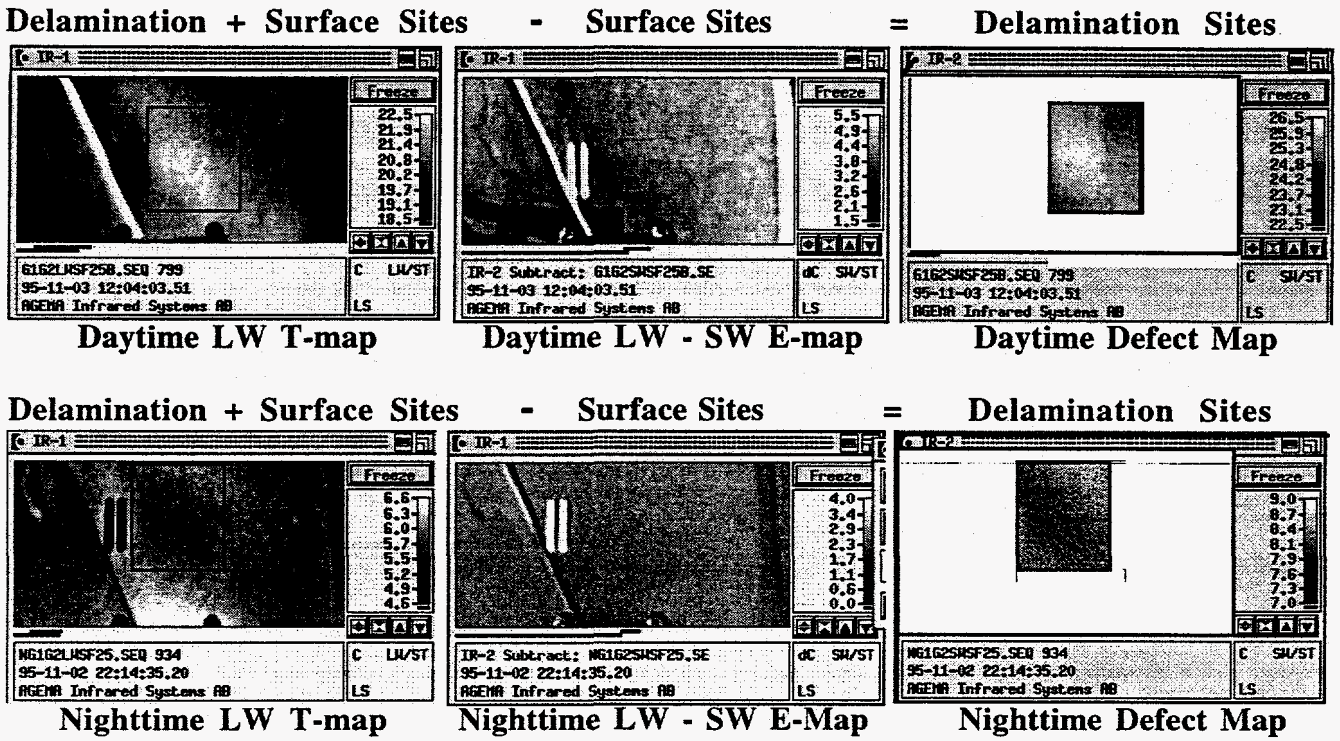

Figure 3. The LW temperature maps depict subsurface delaminations and surface clutter. The DBIR spectral-difference maps depict only surface clutter. We tag surface features on the DBIR spectral-difference, emissivity maps (E-maps). We remove surface features from the temperature maps (T-maps), to produce the delamination defect maps. The delaminated concrete was 1.9 °C warmer than ambient on November 3 at 12:04 hrs. It was 0.4 °C cooler than ambient on November 2 at 22:14 hrs.

In Figure 3, we display images shown in Figure 2 which highlight the thermal and spectral response differences between surface and subsurface deck features. The boxed areas are 1.9 °C warmer than ambient on the daytime LW temperature map, called the T-map, and 0.4 °C cooler than ambient on the nighttime LW T-map. There is a warmer by day, and cooler by night thermal polarity change for delaminated deck sites, compared to normal deck sites. This behavior is a thermal inertia effect related to the volume, depth, and fill debris associated with the concrete gaps within the delaminated deck.

Also, in Figure 3, we note the shaded area depicted on the daytime LW - SW emissivity-noise map, called the E-map, which we do not see depicted on the nighttime LW - SW E-map. This shaded area occurs because we did not use a solar filter to remove SW background signals, from reflected sunlight at 2 to 4 μm, for the Figure 2 SW daytime T-map. Deck areas which were not shaded by the scanner mount on the SW T-map have larger (apparent) temperature signals than the LW T-map signals, since the longwave 8-12 μm region is insensitive to IR backgrounds from reflected sunlight. When used on a clear, sunny day, the solar filter aids interpretation of bridge-deck defects. When used at night, or on an overcast day, the solar filter produces SW T-maps with more noise and less thermal contrast, which impedes interpretation of bridge-deck defects.

Figures 2-5 demonstrate the power of DBIR thermal imaging, to characterize subsurface delaminations. The DBIR method allows us to remove the mask from foreign surface materials and clutter, which has unique spatial, spectral, thermal, thermal inertia, emissivity and temporal responses, unlike those of subsurface defects. DBIR temperature maps, and daytime minus nighttime temperature-difference maps depict thermal inertia differences to distinguish defective from normal bridge decks. DBIR thermal imaging provides an efficient and effective tool to identify delaminations by removing surface clutter (e.g., from painted lanes, patches, pavement contamination, expansion joints, pavement materials with compositions which differ from the host deck material, and uneven shade from hills, trees and cloud-cover).

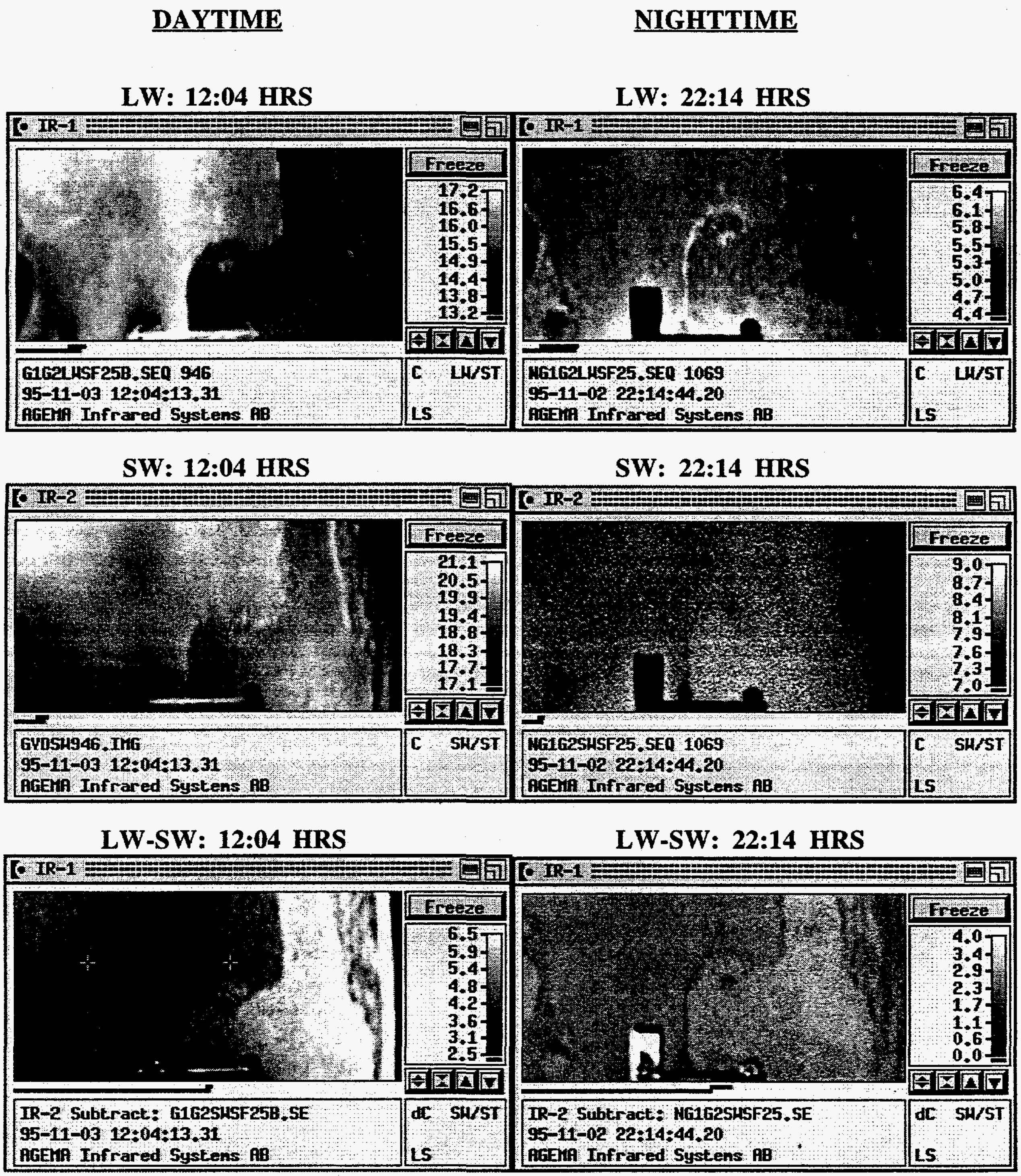

Figure 4. Grass Valley Creek bridge-deck patch site. The patch is a curved structure right of center. The daytime and nighttime LW and SW temperature maps and the LW - SW spectral-difference maps depict mostly surface features, such as the painted shoulder line, camera mount, aluminum marker, concrete patch, and noontime shade.

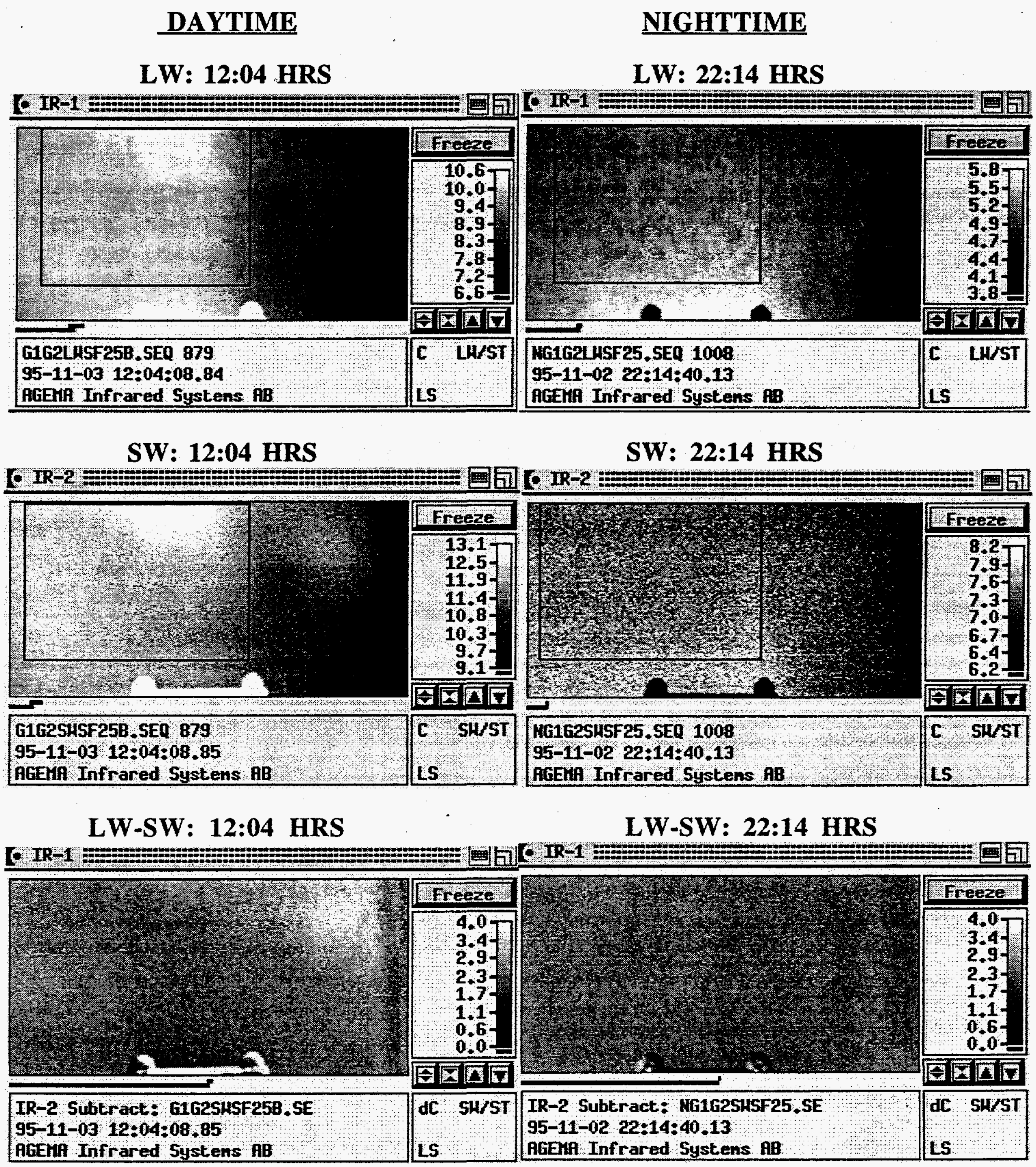

Figure 5. A Grass Valley Creek bridge-deck area with uneven shade. Deck sites with uneven shade have above-ambient daytime temperatures, like the boxed sunlit areas (left column). However, delaminated deck sites have below-ambient nighttime temperatures unlike the boxed areas (right column). Therefore, the daytime deck temperature patterns were produced by uneven shade from hills, trees and cloud-cover.

6.0 SUMMARY AND CONCLUSION

We designed and fielded a mobile DBIR bridge inspection laboratory. We drove this self-contained unit at limited highway speeds over 0.4 lane miles of Grass Valley Creek bridge decks. The distinction between defective deck sites (with structural damage from subsurface delamination) and normal but cluttered deck sites (with foreign surface materials or uneven shade) was based on their respective spatial, spectral, thermal, thermal inertia, emissivity and temporal responses.

We depicted foreign surface materials which had the wavelength-dependent emissivity behavior of a selective radiator source. Examples of these foreign surface materials include: painted lanes, aluminum-tape markers, pavement contamination, patches, expansion joints, and materials with compositions unlike the host deck material. These surface features were clearly depicted on LW (8-12 μm) minus SW (3-5 μm) spectral difference maps. Once identified, these surface features are removed from the LW and SW apparent temperature maps to clearly identify delaminations.

The DBIR method replaces human speculation about bridge deck emissivity behavior, based on visible observation, with spectral measurement. This allows identification and subsequent removal of unwanted surface features to clarify interpretation of bridge deck delaminations. By clarifying interpretation of delaminations, we improve bridge inspection reliability.

To distinguish delaminated deck sites from deck sites shaded by hills, trees and cloud-cover, we conducted daytime and nighttime inspections. Delaminations are bulk volume effects which modify bridge-deck thermal inertias. Uneven shade is a surface effect which modifies bridge-deck temperatures. Delaminated, and shaded deck sites each had about 2 or 3 °C warmer than ambient deck temperatures during the day. Only the delaminated deck sites had about 0.5 °C cooler than the ambient deck temperatures at night.

The 2.9 °C $\pm$ 0.4 °C average day-night temperature difference for delaminated deck areas studied at the Grass Valley Creek bridge deck, is comparable to the 3.6 °C $\pm$ 0.6 °C day-night temperature difference, for the 9-inch square, 1/8-inch thick, synthetic delamination in the surrogate deck reported previously. The synthetic and natural delaminations had about the same thermal inertia, or resistance to temperature change, which was less than the thermal inertia for normal, undamaged decks.

We demonstrated the power of DBIR thermal imaging to inspect the Grass Valley Creek bridge decks by removing the mask from surface clutter which obscures interpretation of subsurface defects. Surface clutter is unwanted detail on the DBIR images from foreign surface materials or uneven shade. DBIR temperature and thermal inertia maps provide an efficient and effective tool to identify and quantify the volume and areal extent of subsurface delaminations which affect the bridge-deck integrity.

Automatic defect recognition, display, and evaluation of bridge delaminations would facilitate interpretation and clarify bridge-deck inspections. This requires developing VIEW macros to interpret DBIR digital image data for bridges, based on the methods we developed for another application of DBIR thermal and thermal inertia imaging (e.g., to quantify corrosion defects in aging aircraft). This procedure would produce a single, composite-DBIR, evaluated-defect map of bridge-deck delaminations.

To summarize, The DBIR thermal imaging method provides an enabling technology for rapid, reliable, bridge deck inspections, while minimizing lane closures. The DBIR method can indicate the fractional area of the bridge that is delaminated as well as locate and characterize the volume of damaged regions. This technique is expected to help bridge managers prioritize bridges for repair and then to direct the repairs to specific locations for timely maintenance and repairs. The mobile DBIR bridge inspection laboratory is currently undergoing extensive testing to examine bridges by the Federal Highway Administration.

7. ACKNOWLEDGMENTS

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