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Comparison of Infrared Cameras for Concrete Bridge Deck Scanning:

- Vol.2 Field Test at Haymarket Bridge -

NEXCO-West USA, Inc.

1015, 18th Street, NW, Suite 504

Washington, DC, 20036

Tel: 202-223-7040

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1. Infrared cameras and IrBAS software

In this research project, three infrared cameras with different specifications manufactured by FLIR Systems, Inc., (shown in Table 1) were compared for effectiveness in application to bridge deck scanning from a moving vehicle. As shown in Table 1, the T420 and T640 models have the same type of detector (uncooled microbolometer) and have similar thermal sensitivities, but their imaging resolutions are different. The model T640 and SC5600 have around the same imaging resolution, but their thermal sensitivities, spectral ranges, and detector types (as the SC5600 has a higher quality "InSb" type installed) are different. The results obtained by these three different cameras were compared to show how each's specifications have evident effects on the degree of accuracy in the detection of delaminations within concrete bridge decks.

Table 1: Three infrared cameras used in this research and their primary specifications

Infrared Camera	T420	T640	SC5600
			
Thermal sensitivity/NETD	<0.045℃ at 30℃	<0.03℃ at 30℃	<0.02℃
IR resolution	320 × 240 pixels	640 × 480 pixels	640 × 512 pixels
Spectral range	7.5 - 13 μm	7.5 - 14 μm	2.5 - 5.1 μm
Detector type	Uncooled microbolometer	Uncooled microbolometer	InSb

A report by the Second Strategic Highway Research Program 2 (SHRP2) (Gucunski, 2013) attempted to test the efficacy of infrared technology for deck application in respect to the timing of inspections. They found that the results varied greatly depending on the time of day. Though the thermal image data is difficult to discern due to the fact that it was collected by technicians who were unfamiliar with infrared, it is still widely used for reference.

In this report, a specialty software developed by NEXCO named IrBAS (see Figure 1) was utilized, and a more in-depth, realized analysis was completed. It is not always possible to detect concrete delaminations only from the color variation of raw infrared imagery, since the concrete structure itself tends to have a temperature gradient depending on location and orientation with respect to the sun (Matsumoto et al., 2013). This software, as shown in Figure 2, has an automatic damage classification system that can classify damaged concrete areas into three categories:

1. Indication: delamination exists within 4cm depth from the concrete surface; currently satisfactory,
2. Caution: delamination exists within 2cm depth from the concrete surface; close monitoring is recommended,
3. Critical: delamination is reaching the concrete surface; immediate action is required. Raw IR image data is filtered and rated into three categories by the software to indicate and evaluate the severity of subsurface defects in concrete structures as shown in Figure 1.

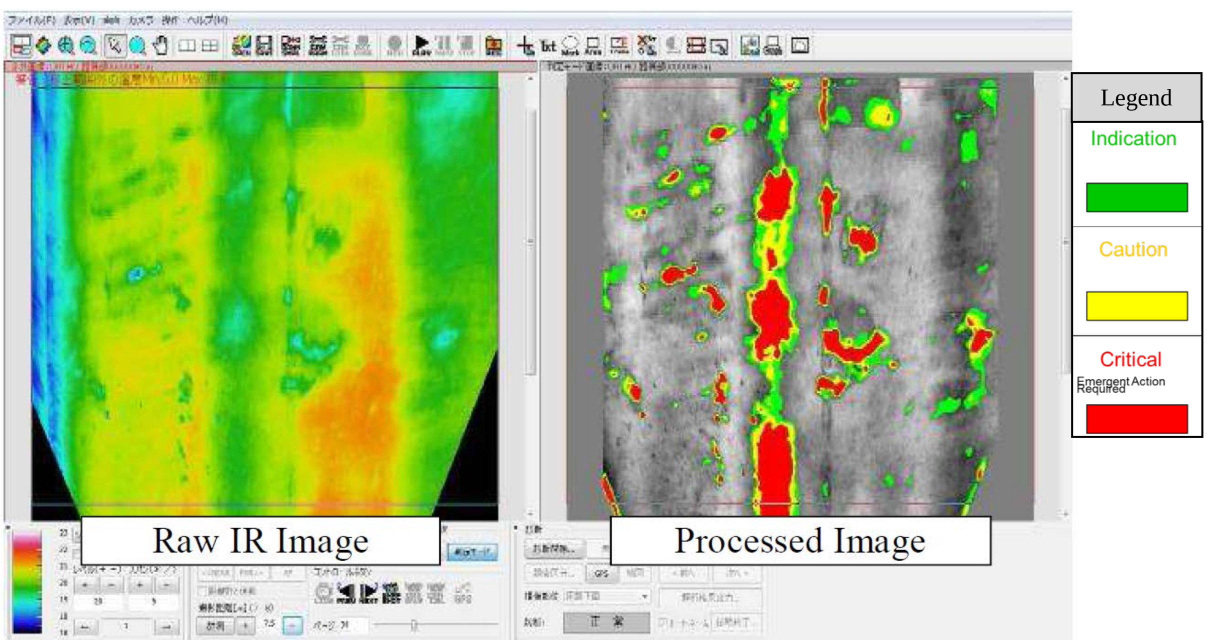

Figure 1: Example of IrBASS software output

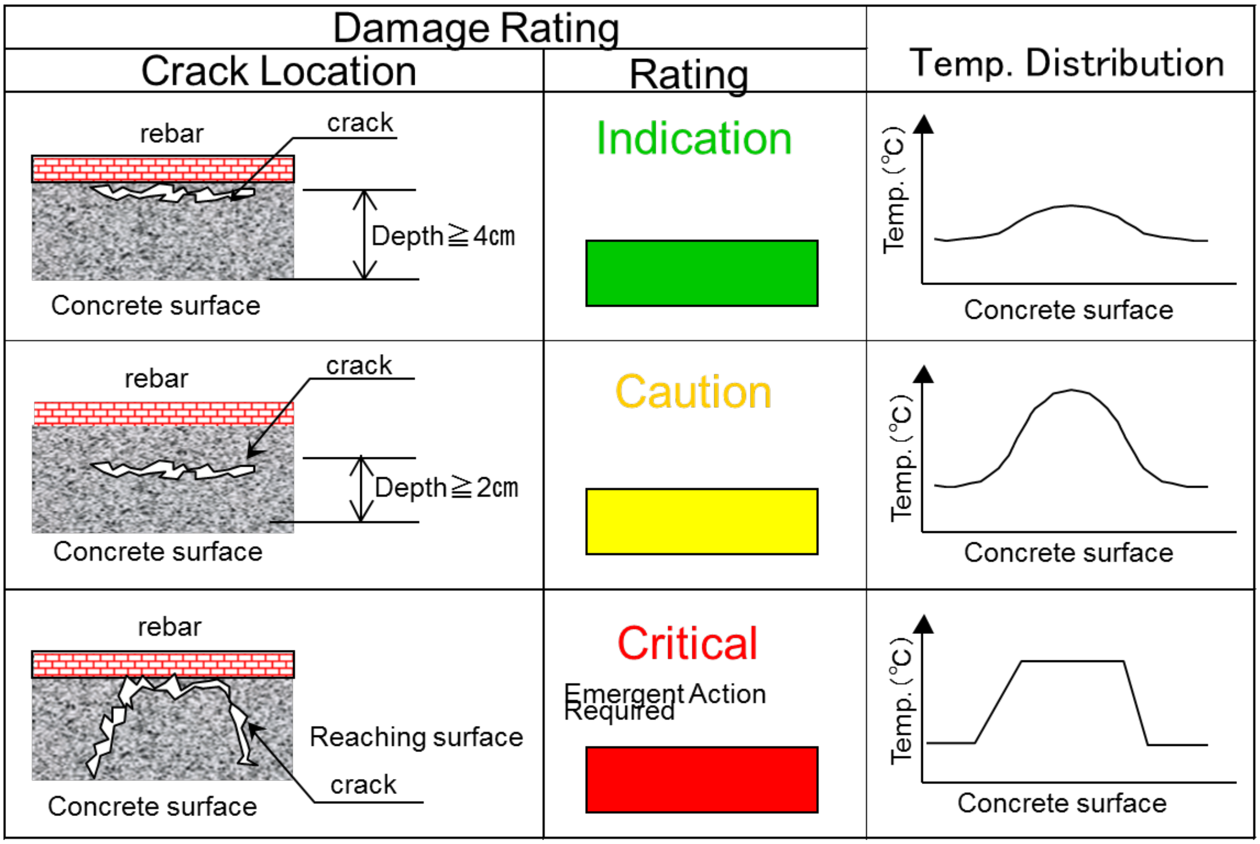

Figure 2: Damage classification by IrBAS Software

2. Testing and comparison between other kinds of NDT in Haymarket, VA

The field test was carried out on Haymarket Bridge, which is part of VA Route 15 running over Interstate 66 in Haymarket, Virginia. The specific testing location was the bridge's southbound shoulder. The bridge was built in 1979 and consists of a steel main girder, a reinforced concrete deck, and two spans. Its deck is almost 8 inches thick, and deterioration on the surface can be clearly observed through a visual inspection from the deck top. SHRP2 has used this sample bridge in order to test multiple kinds of NDT in their report (Gucunski, 2013). In Figures 4 and 5, the report's GPR and hammer sounding/chain dragging analyses are displayed respectively. Figure 6 displays a visual overview of the site taken by NEXCO. Major delaminations were detected in the five rectangular and circularly noted locations. Previous to any NDT experimentation, the locations of damaged areas were known and subsequently confirmed, making the site ideal for further verification and research. Therefore, it was possible to adequately detect differences in capability between the three different types of cameras used.

Figure 3: Haymarket Bridge. Route 15 over I-66 in Haymarket, VA.

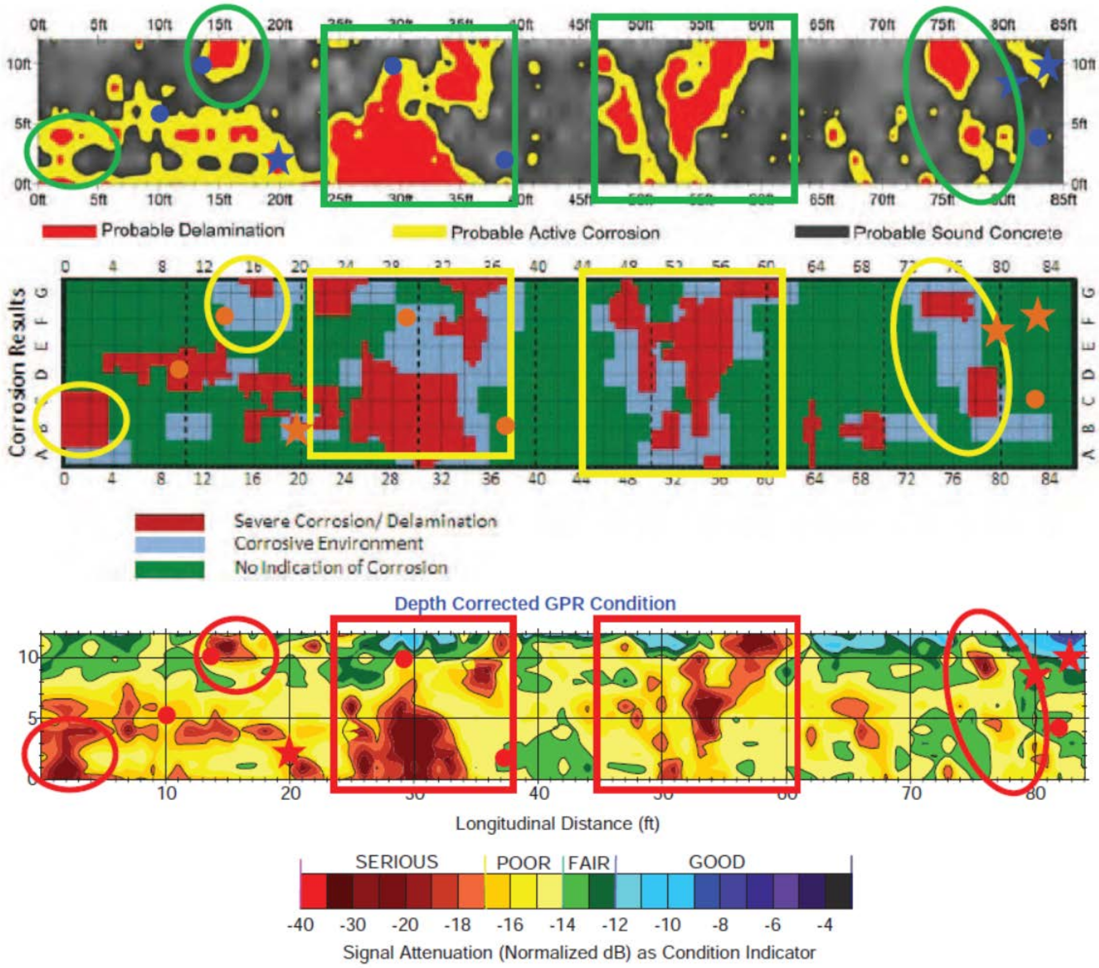

Figure 4: SHRP2 GPR damage rating

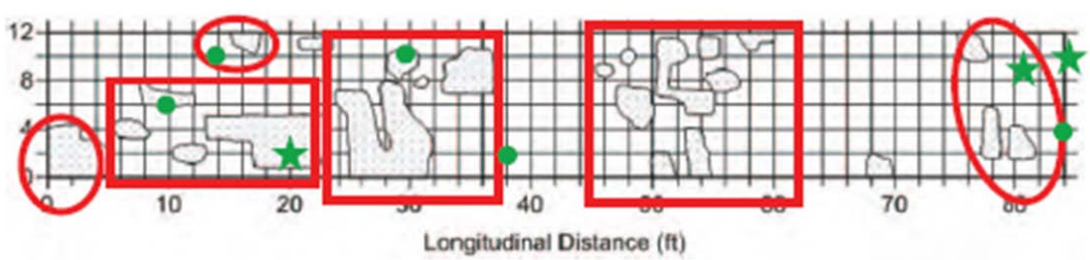

Figure 5: SHRP2 hammer sounding and chain dragging results

Figure 6: Scanned visual image taken by NEXCO

Firstly, photography with the SC5600 was carried out and compared with SHRP2's GPR results (Figure 7). Though the shapes of the two analyses do not match exactly, the areas in which delaminations were detected are mostly the same. In other words, the outcome obtained by infrared scanning is comparable to conventional methods, and can specifically identify areas of concern in bridge decks to an unprecedented degree.

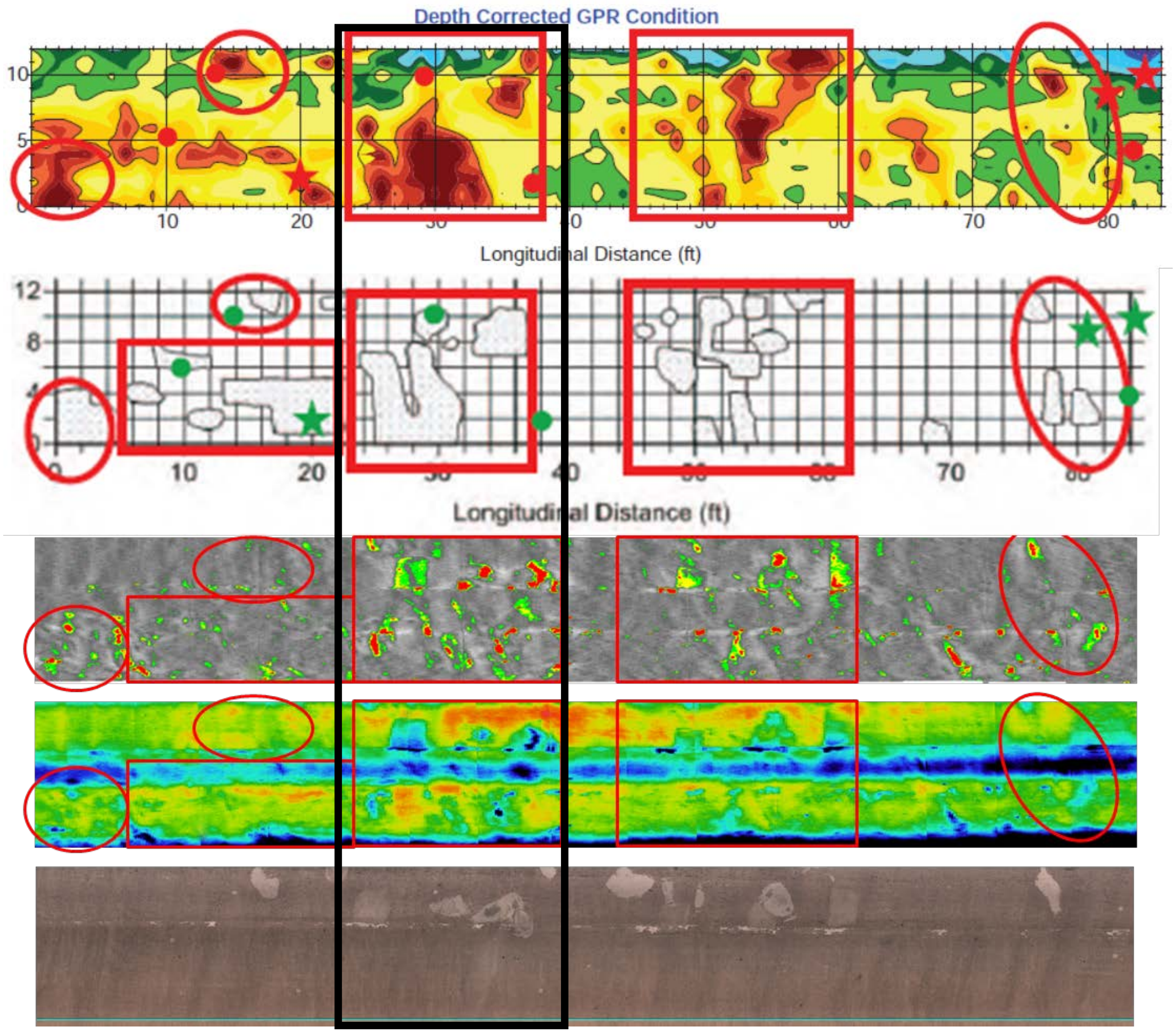

Figure 7: SHRP2 GPR, hammer sounding/chain dragging, and infrared results comparison (infrared data collected by the SC5600 camera)

3. Scanning methodology

Judging from the GPR readings in SHRP2's report, an area with a large group of delaminations was selected and analyzed with the three camera types. The selection is outlined in Figure 7 with a black rectangle. Each camera's detection accuracy of delaminated areas was put to the test. The cameras were mounted on a vehicle and connected to three separate computers, each running IrBAS. The scans were taken at the same time of day at a speed of 30mph.

Figure 8: Infrared system setup

IR photography was performed on October 10th 2014 after sunset. The stable weather and temperature conditions allowed for suitable data.

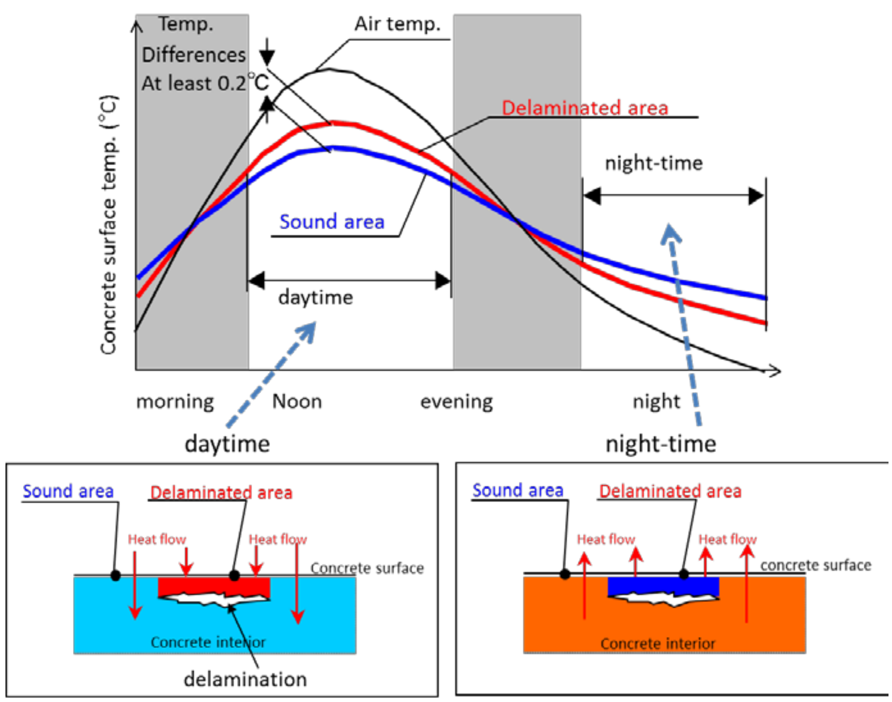

Figure 9: Concept of infrared inspection by temperature differential

4. Patented concrete test piece（thickness = 3cm）setup

In a parking lot near the test site, the same test piece used in Vol. 1 (laboratory test) of this report was set up to provide both a control for the temperature of delaminated areas and a temperature log. The temperature of ambient air and concrete was taken in both the waning sunlight and the shade (Figures 10 and 11).

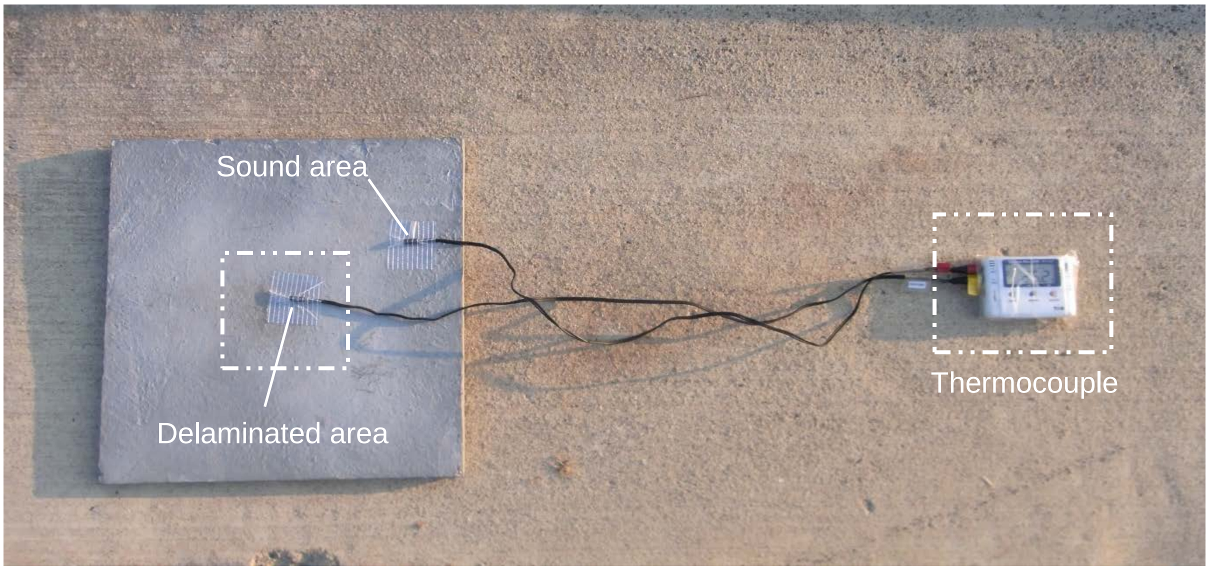

Figure 10: Concrete test piece setup (thickness = 3cm)

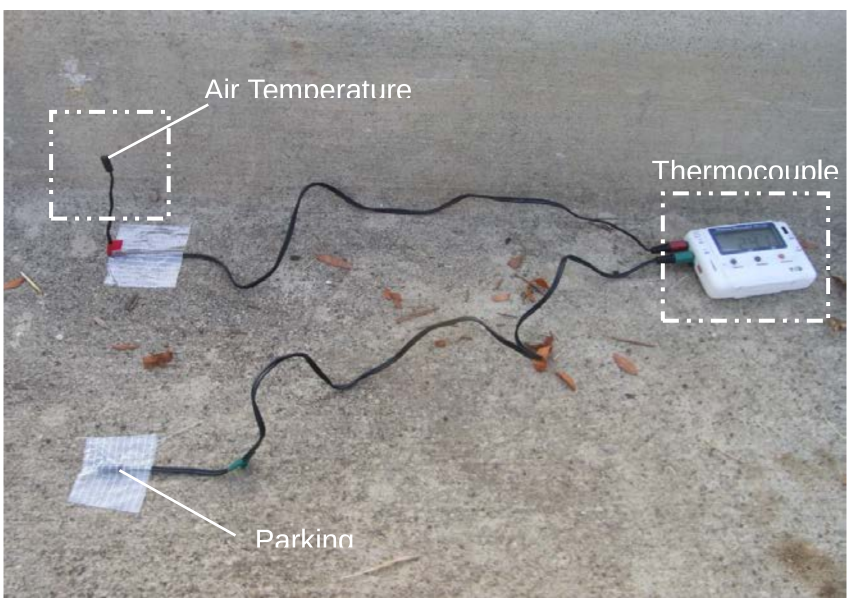

Figure 11: Atmospheric temperature log setup

In Figure 12 below, the entire temperature log for the controls and the ambient temperature is displayed. As described in Vol. 1, “Sound area” and “Delaminated area” refer to the sound and artificially delaminated portions of the concrete test piece.

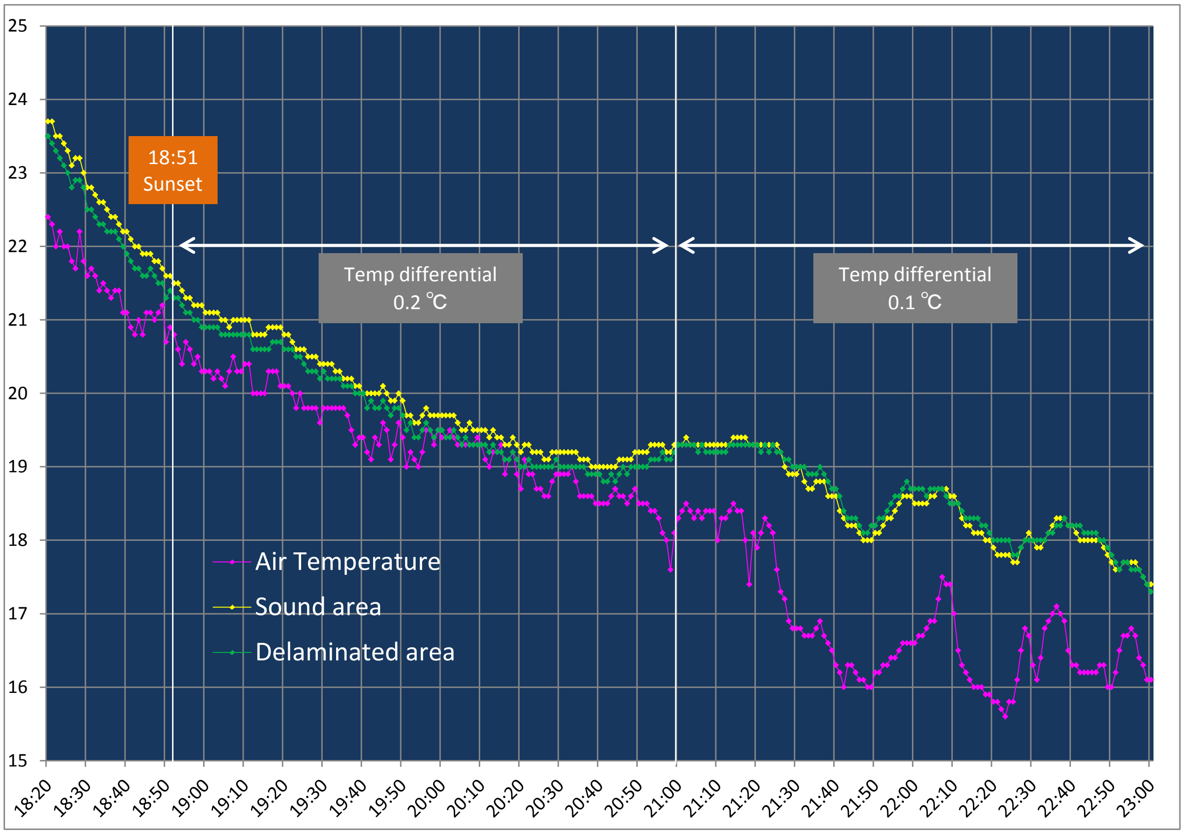

Figure 12: Temperature historical record throughout testing

After a 6:51PM sunset, the temperature slowly declined at a steady rate, and a 0.2℃ temperature differential between the sound and unsound portions of the test piece was observed. Afterwards, though the ambient temperature fell sharply at 9:00PM, the differential remained at around 0.1℃ or lower. Based on the labolatory testing performed in Vol. 1, the SC5600 was able to clearly detect delaminations when the differential was 0.2℃ or greater, but its functionality decreased as the differential fell to 0.1℃ or lower. Naturally, finding temperature discrepancies within a smaller gap becomes more difficult, and the data becomes more challenging to interpret. These conditions provided grounds for two separate investigations, those being two separate comparisons between the SC5600 and the T-series at a reasonable differential, and one which pushes the technology to its absolute limit.

5. Test results

5.1 Test piece (thickness = 3cm) readings at a temperature differential of 0.2℃ or greater

The temperature during the time period in which the sound and artificially delaminated portions of the test piece were at a gap of 0.2℃ or greater is shown on the first half of the graph below. The red line indicates the time at which the sample in Figures 14-16 was taken.

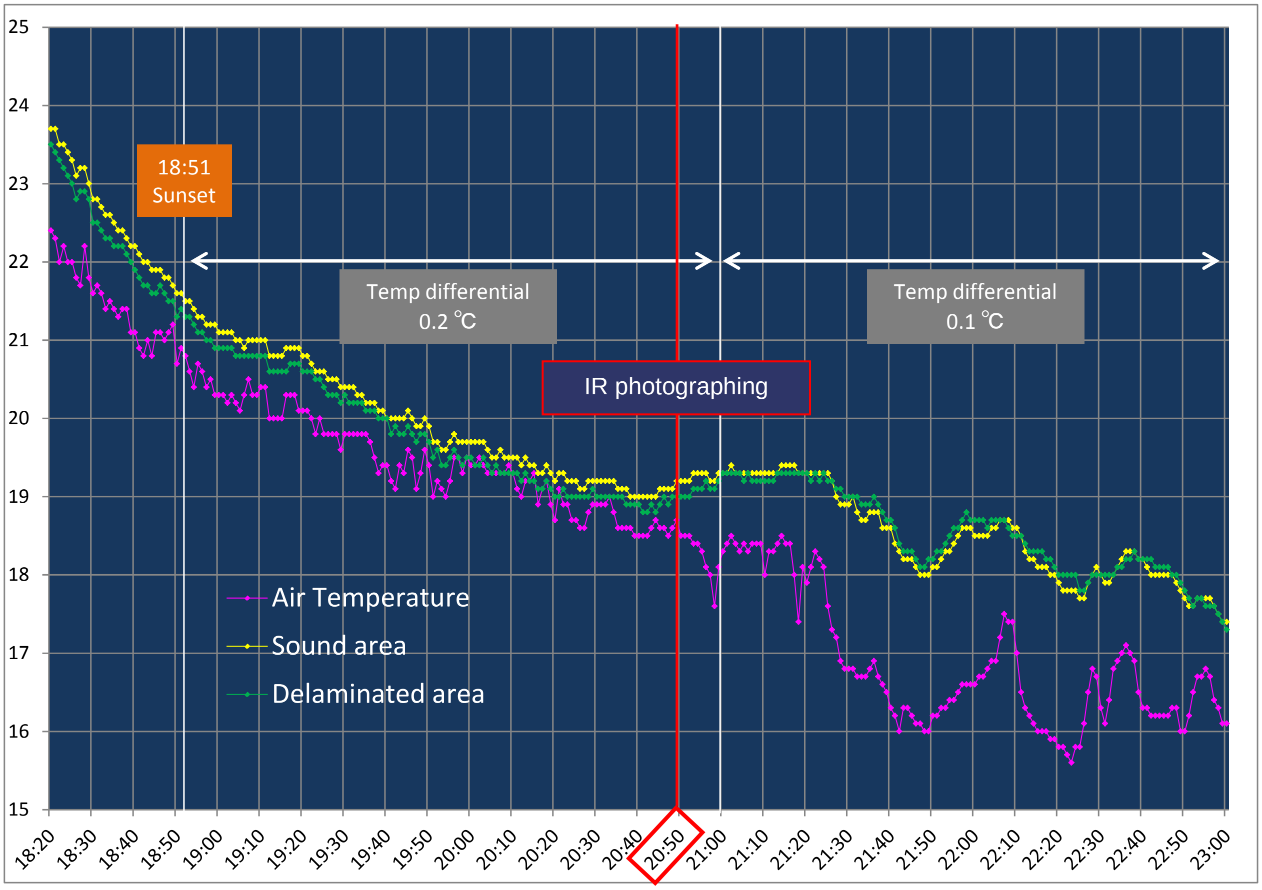

Figure 13: Temperature historical record during photography

In Figures 14-16, a sample of the results for the SC5600, T640, and T420 are shown respectively. The SHRP2 findings are also shown on the side for a clear, direct comparison. Detected delaminations on the deck are circled in white, delaminations within patched areas are highlighted by a white rectangle, and false detections are highlighted by a yellow rectangle. The dotted shapes represent a failure in detection. Since the SC5600's results turned out to be the most reliable, it was used as a benchmark for comparison. With the SC5600, the difference between delaminations within patched areas and other slab delaminations can be recognized, but due to their insufficient exposure times, this difference cannot be reliably discerned with the T640 and T420. With blurred images, post analysis becomes difficult. While the T640 was able to detect one delamination within a patched area and one in the upper portion of the deck, it missed five other instances detected by the SC5600. Only one instance (the upper patched area delamination) was correctly detected by the T420. False detections occurred in both the T series' results. See Table 2 for a description of individual results.

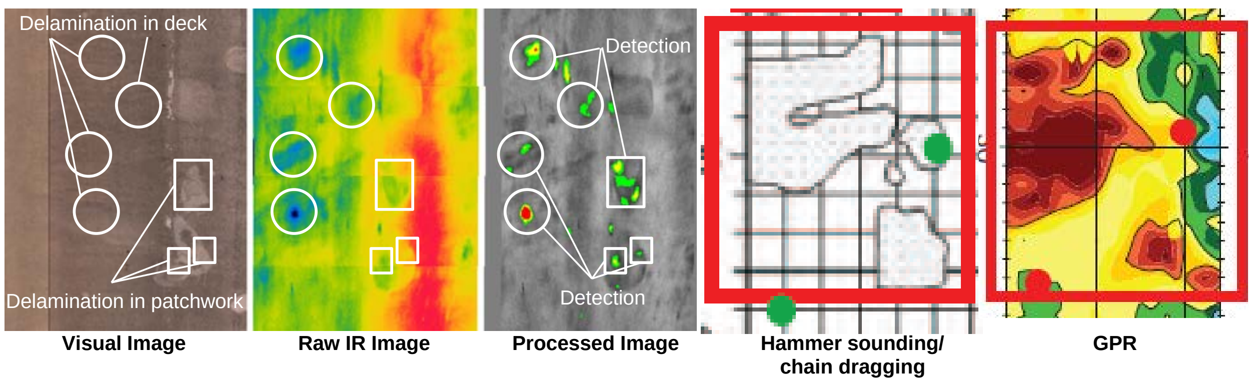

Figure 14: SC5600 results when temperature differential is 0.2℃（20:50）

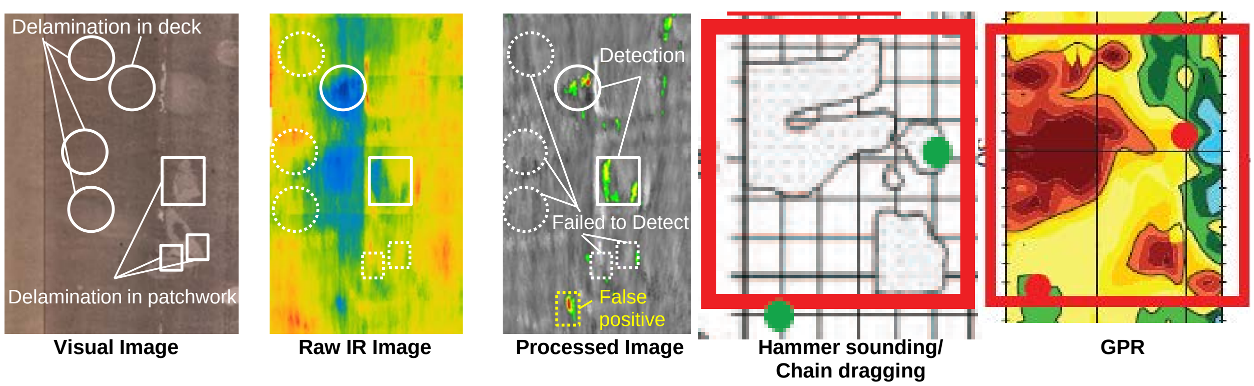

Figure 15: T640 results when temperature differential is 0.2℃（20:50）

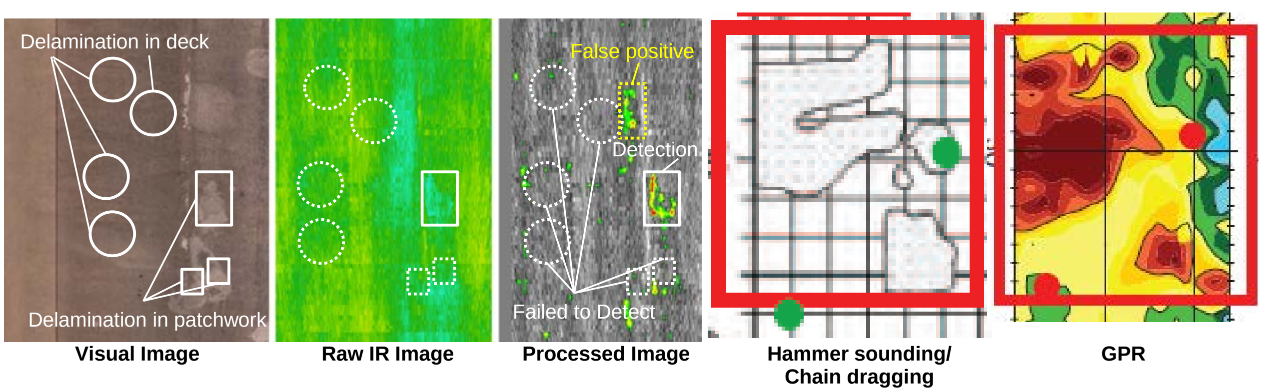

Figure 16: T420 results when temperature differential is 0.2℃（20:50）

Table 2: Summary on delamination detection (when temperature differential is 0.2℃)

Infrared Camera	Deck top delaminations: 4 in total	Patchwork delaminations: 3 in total	False detections due to image quality
SC5600	4 detected	3 detected	none
T640	1 detected (3 failed to detect)	1 detected (2 failed to detect)	few
T420	0 detected (4 failed to detect)	1 detected (2 failed to detect)	many

5.2 Test piece（thickness = 3cm） readings at a temperature differential of 0.1℃ or less

Next, the temperature during the time period in which the sound and artificially delaminated portions of the test piece were at a gap of 0.1℃ or less is shown on the second half of the graph below (Figure 17). The red line indicates the time at which the sample in Figures 18-20 was taken.

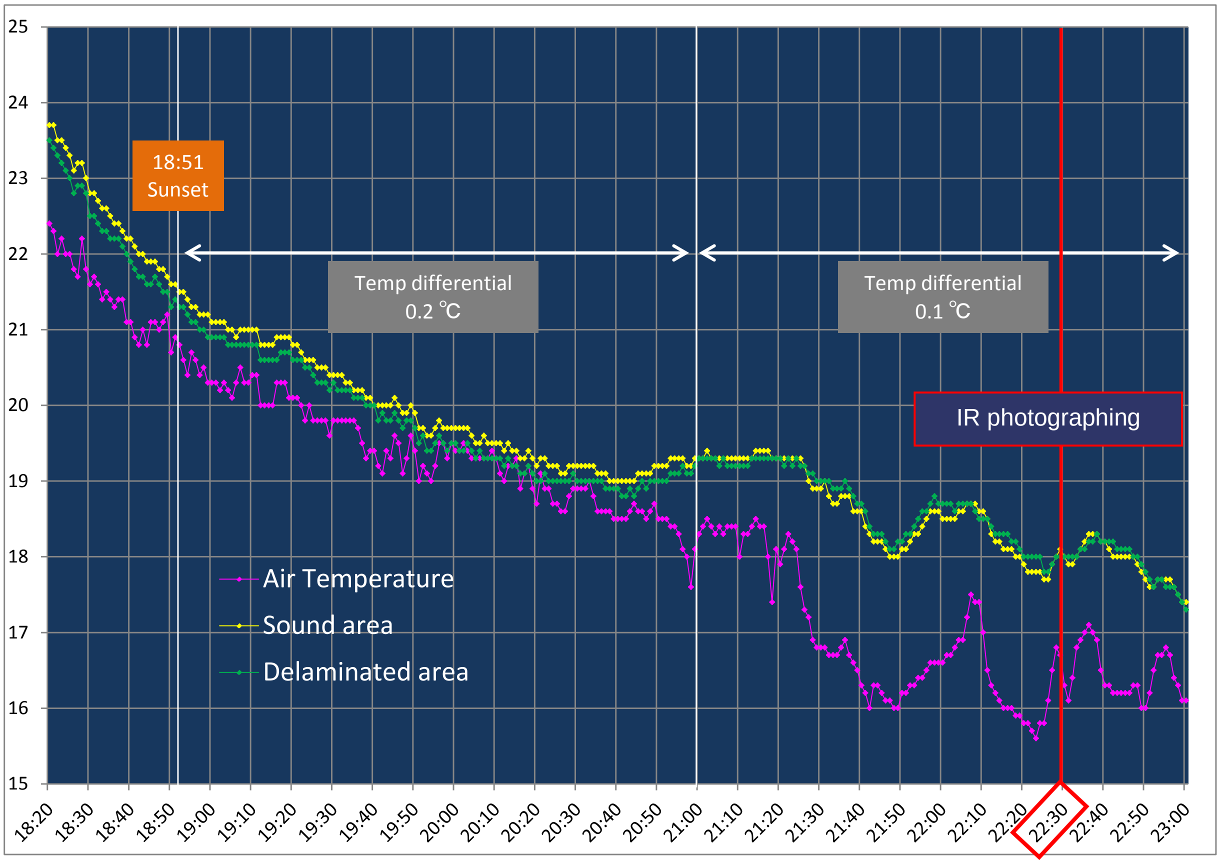

Figure 17: Temperature historical record during photography

In Figures 18-20, the same sample (taken 2 hours later) of the results is shown in the same manner as above. Delaminations and false detections are also marked in the same manner.

Although the temperature differential is smaller and provides more challenging, condition for delamination detection, the SC5600 successfully found the delaminated areas with little change. Given the longer exposure time and a lack of environmental settings, the images for the T series changed drastically compared to the earlier time period. Most notably, many false detections and a general lack of definition were observed. For both T series cameras, the second delaminated patch and all of the four previous deck delaminations went unseen. See Table 3 for a description of individual results.

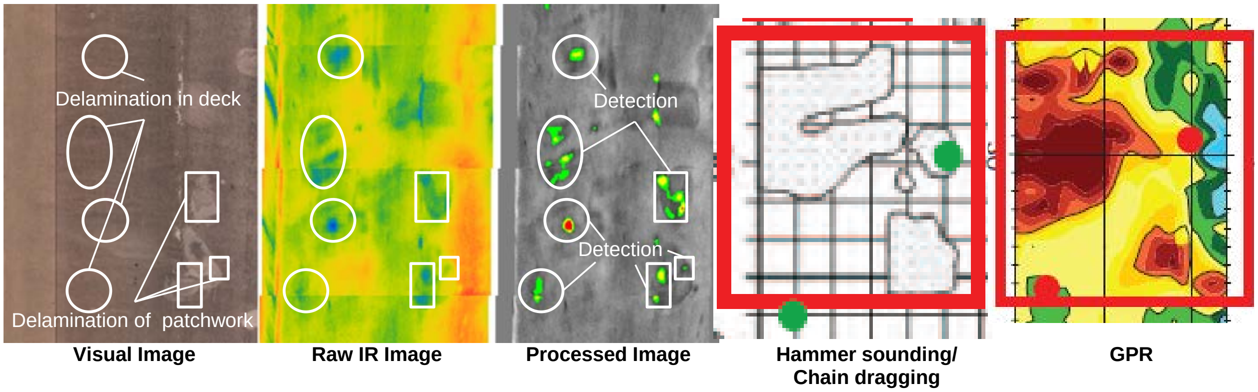

Figure 18: SC5600 results when temperature differential is 0.1℃ (22:30)

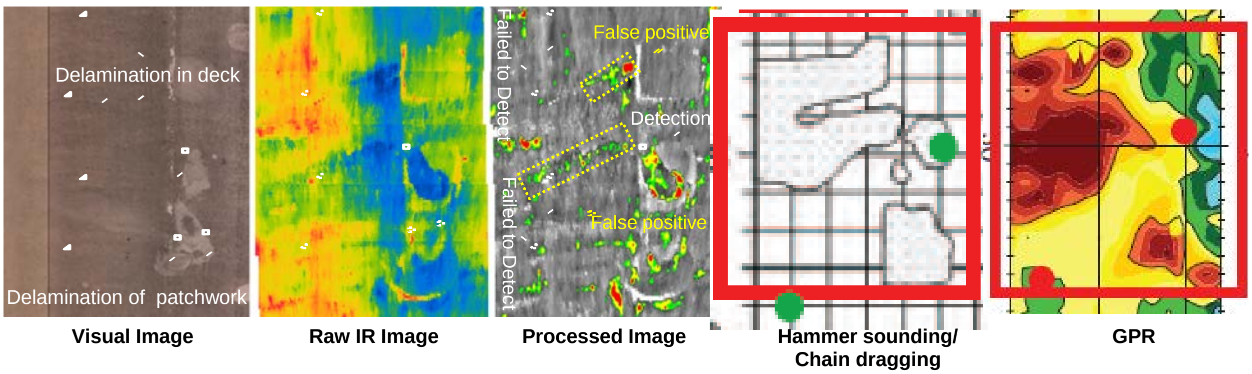

Figure 19: T640 results when temperature differential is 0.1℃ (22:30)

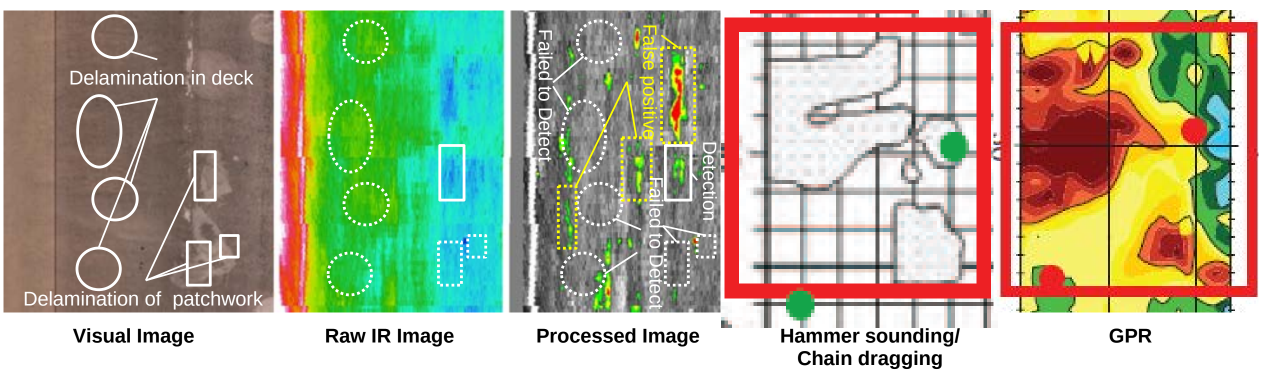

Figure 20: T420 results when temperature differential is 0.1℃ (22:30)

Table 3: Summary on delamination detection (when temperature differential is 0.1℃)

Infrared Camera	Deck top delaminations:4 in total	Patchwork delaminations:3 in total	False detections due to image quality
SC5600	4 locations detected	3 locations detected	none
T640	1 detected (3 failed to detect)	1 detected (2 failed to detect)	few
T420	0 detected (4 failed to detect)	1 detected (2 failed to detect)	many

6. Conclusions

In general, when infrared inspection is done in the evening, it is best to observe temperature differentials when ambient temperature drops a few hours after sunset and heat flows from the concrete interior. Following this time period, the heat flow from the concrete decreases gradually, and the temperature gap between sound and unsound portions of the concrete becomes slim. As more heat and radiation within the concrete is released, the gaps become more subtle, and detecting delaminated areas becomes more challenging. In this test, the SC5600's finely tuned ability to detect these subtle instances – at a meager 0.1℃ differential – was confirmed. In both phases of the test (though especially during the 0.1℃ or less portion), the T series demonstrated some failure in detection and/or false detection in concrete delamination. The cause lies with the cameras' relatively longer exposure time, and less sensitivity. While the SC5600 can capture data at 10μs～5ms, the T640 only can do so at 10ms, the T420 at 12ms. Note that there is actually no given "exposure time" for the T series, though they operate on a similar "time constant" (the term is used here for simplicity's sake). Since cameras with lower shutter speed are exposed to the subject for a longer timeframe, the resulting image will be more blurred when motion comes into play. As an instrument to be used on the highway bridges, the SC5600 is built to counteract this. Its fast exposure time allows it to take images with clear resolution at speeds of 50mph and above. Taking into account this test was performed at a mid-range speed of 30mph, it not only discounts the T series ability to capture data of practical accuracy at highway speeds, but at slow speeds as well. Had the test been carried out at the SC5600's normal photography speed of 50mph, the T series' images would have been more blurry and challenging to analyze.

Above all else, it can be said that for highway infrared inspection, the SC5600 is far superior to other commonly implemented models, and a high exposure rate is critical in preventing things like blurred imagery and subsequent false detections. Moreover, the SC5600 effectively doubled the window of time in which inspections can be carried out. During both the 0.2℃ and 0.1℃ timeframes, the SC5600 could suitably spot delaminations, but the T series was unable to do so during the 0.1℃ timeframe. The ideal timeframe in this case was the first half (0.2℃), from 6:50PM to 9:00PM, around 2 hours and 10 minutes. The second half (0.1℃) lasted from 9:00PM till 11:00PM. It is possible to get clear data over a longer period of time mostly in thanks to the installation of an InSb detector and a closed cycle rotary cooler which stabilizes the camera's internal temperature and filters out noise. The T series does not have a cooling system, and their ideal field work timeframe was shortened to just two hours. Judging from this instance, the SC5600 doubled the day's workable hours, and essentially doubled productivity.

By raising work efficiency and precision using cooled models, there are many benefits. Reduction of field work hours leads to further reduction in field data collection costs. False detections and blurry images will be minimized, and with the processing power of IrBAS and its database, the user gains much more intelligent data at a much faster rate. Firms which utilize the cooled models can expect not only more trustworthy results, but also long term compensation and a return on investment.

7. References

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