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INTELLIGENT TRANSPORTATION SYSTEMS

Remote Passive Road Ice Sensor System (RPRISS)

Jack Reed and Blair Barbour
Nichols Research Corporation

Report of Investigation

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Jack Reed, Blair Barbour

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Nichols Research Corporation
1725 Jefferson Davis Highway, Suite 1103
Arlington, Virginia 22202

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RPRISS is a passive infrared (IR) imaging system that can detect the presence of even very thin layers of ice on a paved surface. The system can also accurately estimate road surface temperature and provide television-like surveillance of traffic in the area. It may have applications as a replacement or supplement to visible-light video surveillance systems in ice-critical areas. It may also have mobile applications as an environmental sensor mounted on anti- or de- icing operation vehicles. The sensor measures the polarization properties of IR radiation from the roadway and clearly delineates iced areas on a video display screen.

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This investigation was completed as part of the ITS-IDEA Program, which is one of three IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in surface transportation. It focuses on products and results for the development and deployment of intelligent transportation systems (ITS), in support of the U.S. Department of Transportation's national ITS program plan. The other two IDEA programs areas are TRANSIT-IDEA, which focuses on products and results for transit practice in support of the Transit Cooperative Research Program (TCRP), and NCHRP-IDEA, which focuses on products and results for highway construction, operation, and maintenance in support of the National Cooperative Highway Research Program (NCHRP). The three IDEA program areas are integrated to achieve the development and testing of nontraditional and innovative concepts, methods, and technologies, including conversion technologies from the defense, aerospace, computer, and communication sectors that are new to highway, transit, intelligent, and intermodal surface transportation systems.

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EXECUTIVE SUMMARY

Nichols Research Corporation (NRC) is currently developing an innovative infrared (IR) imaging system. The sensor measures the polarization properties of the IR radiation from the objects contained within a scene that can then be fused into a single RPRISS detection image. Under this IDEA project NRC has been adapting this technology, which was developed under internal research and development (IR&D) funding, as a possible solution to the problem of detecting (and predicting) icing conditions on roadways. The system under development is referred to as Remote Roadway Passive Ice Sensor System (RPRISS).

RPRISS will be an imaging infrared system to detect the presence of ice on the road surface viewed by the system and will detect very thin layers of ice, including "black ice", undetectable by other non-contacting systems. The system will also be able to accurately estimate the road surface temperature and provide television-like surveillance of the road and traffic scene. It will have application as a supplement or replacement for current video traffic surveillance systems in ice-critical locations, adding the ice detection and temperature estimation capabilities. RPRISS will also have mobile application as an environmental sensor mounted, perhaps, on quality survey vehicles to ascertain the road quality after anti- or de-icing operations, or on the application vehicle itself to alert the operator to adjust his treatment based on real time observed conditions. This capability could also be incorporated on larger truck tractors to provide the operators an additional indication of upcoming hazardous road surface conditions.

Benefits include cost savings made by reduced maintenance crew call-outs, reduced use of mitigation product (thereby providing savings in environmental costs by avoiding excessive product use), and accident avoidance with "black ice" detection.

The system has been tested in the laboratory using various pavement materials, and successfully completed a limited winter field test in Minnesota and developmental fieldwork in Colorado and Alabama. Examples of the data collected are illustrated in Figure 1. The system is currently operating a second-generation prototype sensor and is primarily a scientific data collection and analysis system. A third-generation prototype sensor, designed as an operational sensor rather than a scientific data collection sensor, is currently under development with delivery anticipated by September 30, 1997. Implementation and fielding plans include continuing field collection of data during actual winter weather events. State Departments of Transportation and airport authorities have expressed interest in hosting field demonstrations. Initial contacts are in place with the IR camera community and have been initiated with remote and surveillance vehicle systems integrators.

REMOTE PASSIVE ROAD ICE SENSOR SYSTEM (RPRISS)

IDEA Project

Jack Reed, Nichols Research Corporation, Arlington, VA
Blair Barbour, Nichols Research Corporation, Huntsville, AL

IDEA PRODUCT

The RPRISS is a remote, non-contacting system that detects the presence of ice and snow on roadways and provides this information to the end user through video-type images in which the ice or snow is shown in red. RPRISS has the ability to detect very thin layers of ice, including "black ice" which is undetectable by other non-contacting system sources. RPRISS is built around an innovative passive infrared imaging system and does not require illumination. Additionally, the system can accurately estimate the road surface temperature through conventional infrared means.

The RPRISS system may be implemented in a number of configurations. One configuration is illustrated in Figure 2 and is a fixed-location roadway monitoring system. The sensor engine would be pole-mounted such that it views ice-critical sections of roadway. Processing and control electronics would be mounted at the base of the pole or in a nearby electronics shack such as utilized by Mn/DOT. The sensor engine measures the infrared data and transmits it to the processing electronics where its polarization signature is analyzed and evaluated for the presence of ice. An image is generated showing the location of ice as red overlays on an infrared image and it is transmitted to the appropriate end user via conventional video lines. Such a system could be used as a supplement to existing video surveillance systems or it could replace them entirely. RPRISS will also have mobile application as an environmental sensor, mounted perhaps, on quality survey vehicles to ascertain the road quality after anti- or de-icing application or on the application vehicle itself to alert the operator to adjust his treatment based on real time observed conditions. This capability could also be incorporated on larger truck tractors to provide the operators an additional indication of upcoming hazardous road surface conditions. See Figure 3.

CONCEPT AND INNOVATION

The IR polarization signature of the infrared radiation emitted by an object is dependent on the material of which it is made as well as the temperature of the object. Thus the polarization signatures of ice, snow, water, asphalt, concrete, etc., are all unique. The RPRISS system utilizes a proprietary infrared sensor technology, developed by NRC, to determine the polarization signature of the various objects in a scene. The various signatures are evaluated to determine if ice is present. The location of ice within a scene is indicated, for example, by placing a red colored overlay on top of the infrared image.

The RPRISS system consists of an infrared camera system with custom optics that allows the polarization data to be collected for each pixel of the sensor. This data is then analyzed using proprietary algorithms that determine whether ice is present on a pixel-by-pixel basis. The results are fused into a single RPRISS image in which the regions containing ice are colored red.

PROJECT INVESTIGATION AND PROGRESS

The RPRISS Investigation will be discussed in the following four areas:

- Operational considerations affecting the usefulness of an ice sensing system.
- Theory.
- Development of the RPRISS instrument and its supporting algorithms.
- Laboratory and field work testing and data collection.

OPERATIONAL CONSIDERATIONS

Operational requirements describe the characteristics the RPRISS must demonstrate under what conditions to provide useful information to the transportation system. The issues include identifying who uses the information, where the ice is to be detected, how much ice is significant (both thickness and surface area), how quickly ice must be detected, and the relative concerns of probability of detection with associated probability of false alarm.

We established initial contacts with the operational users at Minnesota DOT (Mn/DOT), the Metropolitan Washington Airports Authority (responsible for Dulles Airport and its 17 mile access road), and the Virginia DoT Northern Virginia Traffic Management System (TMS). Each of these users considered the ice problem in different ways as each represented significantly different communities. At one level, the common requirement is friction control – the traction between the vehicle (be it auto or airplane) and the pavement surface – rather than ice control. For example, an initial estimate for ice significant to airport surface operations, exclusive of runways, is that a patch 10m by 10m *should* be detected, and a patch 20m by 20m *must* be detected. These are the characteristic wheelbase sizes of the large commercial airplanes critical to the major airport operators. For roadway operations, patches smaller than 1m square are probably not significant but patches larger than 3m by 10m (a couple of car-lengths in a lane) certainly are. Time estimates are similarly varied. For fixed site surveillance, detection and revisit times on the order of 5 to 10 minutes seem acceptable. In applications such as on–vehicle road condition assessment, for example monitoring contractor plow operations or adjusting mitigation chemical mixes to match road conditions, real-time operations supporting a 10 to 15 mph speed would be required. The size of the area to be monitored also varies. Fixed sites include critical overpasses and intersections, bridges of different lengths, and larger airport surface areas. These characteristic sizes must be used to trade off and establish instrument component and site considerations.

Additional requirements that emerged from the discussions include surface temperature monitoring. Other users were contacted at the Eastern Winter Road Maintenance Symposium who were approaching winter event operations from a preventive anti-icing perspective rather than a de-icing perspective. The anti-icing techniques are effective in keeping the roads open as long as the maintenance operators are able to stay ahead of the winter event. However, if the event overwhelms the anti-icing strategy, then there must be an immediate change from anti-icing to ice mitigation strategies, as continued anti-icing application can, under some conditions, worsen the road hazard. For these operators, detecting any ice formation seems critical. This may require the RPRISS implementation to have varying detection policies, as "missed detections" are more significant to these users than "false alarms" of smaller ice patches. As in any sensor system, the probability of detection and the probability of "false alarm" are dependent on one another. When a very high detection probability is specified for a given system its false alarm rate will also be higher. In this case, the system needs to detect smaller ice patches. In the more "normal" surveillance applications, false alarms causing callout of a mitigation crew may be more significant than missing, for a while, a few patches of ice right at the threshold.

Yet another perspective was identified during demonstration. The user representative indicated a desire to classify the form of ice as ice, packed snow ice, slush, snow, frost, etc. The kind of ice is a major factor in determining the treatment required.

We have developed an initial spread sheet calculator to assist in matching the available instrument requirements to site locations. We have also developed initial infrared modeling and analysis (IRMA) simulation implementations for some typical road and large (Dulles International) airport locations. The IRMA is a detailed, engineering level simulation currently used for defense systems analysis. We can incorporate the relevant RPRISS innovations and use these systems to model ice detection scenarios to establish the particular instrument parameters to display and iteratively define any particular user's needs.

Theory

All electro-magnetic radiation has certain polarization properties. These can range anywhere from being completely un-polarized, linear polarized, circular polarized, or any combination of the three. Additionally, the polarization properties are modified as the radiation is reflected or transmitted through an interface of two different indices of refraction.

In the general case any radiation can be described using two orthogonally, but otherwise arbitrary, polarized components. Thus when considering IR radiation that is incident on a surface at some angle it can be described in terms of a component that is polarized parallel to the plane of incidence and one which is perpendicular to the plane of incidence as illustrated in Figure 4. The transmission and reflection coefficients of the two components will be different. Thus the transmitted beam, as well as the reflected beam, will have polarization properties different from the incident beam. This effect can be quantitatively evaluated using Fresnel's equations (also illustrated in Figure 4). As can be seen in these equations the reflection and transmission components depend on the angle of incidence as well as the indices of refraction of the two media.

The polarization signatures of IR radiation emitted by ice, snow, asphalt, etc., are unique. This can be explained as follows. The radiation that is emitted by the object originates just below the surface. This radiation is generally unpolarized but can be described by two equal and orthogonally polarized components. As the light propagates through the surface of the road (or ice) the intensity of the two orthogonal transmitted components are different due to Fresnel's laws. The degree to which they vary depends on the material type and the angle from which the object is viewed. As asphalt and ice are very different materials their optical properties, specifically their indices of refraction, are different and consequently they produce different polarization signatures. RPRISS exploits this effect to detect the presence of ice on roadway surfaces.

The *RPRISS* Instrument and Algorithms

NRC has been developing innovative infrared sensors under IR&D programs. The RPRISS system is built around this innovative sensor technology. Photographs of the various sensors are shown in Figure 5. Figure 5(a) is a second-generation sensor and operates in one IR region of the spectrum. Figure 5(b) is a second-generation device that operates in a second IR region of the spectrum. Figure 5(c) is the third-generation device currently under development by NRC.

The second-generation sensors have been designed as scientific laboratory devices and not as operational units. They are used to collect data on various targets and to evaluate their polarization signatures. This generation of sensors, specifically the one shown in Figure 5(a) was used for the laboratory and field data collection described in the next section. The data collected with this camera, along with operational issues such as portability, ease of operation, sensitivity to infrared signatures, ruggedness, size, etc., have been used in the on-going design of the third-generation prototype device.

The third-generation sensor is currently under development and is designed for operational use rather than scientific use and will be smaller, lighter, faster than its predecessors. For example, this generation device will be about the size of a hand-held video camera, and it will collect and process data significantly faster than the second-generation devices. Delivery of a prototype third-generation device is anticipated by September 30, 1997.

A typical RPRISS system would consist of a third-generation infrared sensor, control electronics, and software. One implementation is illustrated in Figure 2. It consists of a fixed, pole-mounted sensor with limited on-board electronics. A communications link would transmit the data from the camera to an electronics package at the base. The electronics package is then responsible for implementing the ice detection algorithms and generating the RPRISS image. The RPRISS image, along with any appropriate warning, is then forwarded to the appropriate operator via standard video lines.

Currently, NRC has been developing these sensors around 3-5 μm indium-antimonide (InSb) technology. Detectors based on this technology are relatively expensive and require cryogenic cooling. However, a new class of sensors has been developed that potentially possesses the ability to decrease the cost of an RPRISS sensor. This class of sensor uses uncooled micro-bolometer technology and is sensitive to long-wave (8-12 μm) IR radiation. The cost of a basic microbolometer system is approximately half that of an InSb system. NRC is also developing polarimetric sensors around this technology and currently has one second-generation 8-12 μm polarimetric sensor. As the popularity of this sensor technology increases, and the corresponding production rate, the cost of these sensors will begin to decrease.

Software algorithms are also being developed to process the infrared signature information and to display an RPRISS image in which ice and snow can be differentiated from the roadway surface. Currently, the algorithms generate an image and display it on a computer monitor. The images are such that a human operator can readily determine the presence of ice or snow on a roadway surface. Future versions of the algorithms will be able to autonomously detect the presence of ice or snow and provide images in which the ice and snow are colored red and/or generate the appropriate warning without human intervention.

RPRISS Laboratory and Field Work

The first phase of the RPRISS project centered around demonstrating that the IR polarization signatures of ice, snow, asphalt, concrete, etc., are unique and that these IR signatures could be used to differentiate ice and snow from roadway surfaces. Roadway samples were obtained from a number of sources (Mn/DOT, Federal Highway Administration (FHWA), and Washington Metro Airport Authority). Ice was formed on the various samples by placing them in laboratory freezer. The samples were analyzed using one of NRC's second-generation phenomenological IR imaging sensors (which are the camera systems that RPRISS will be based on). The results are illustrated in Figures 6-9. The ice cannot be distinguished from the asphalt in the conventional IR image because they are at the same temperature. The ice is easily seen in the RPRISS polarization image due to the difference in the optical properties of ice, asphalt, and cement. These images clearly demonstrate that the NRC sensor can differentiate between ice/snow and roadway surfaces and that an RPRISS system built around this sensor technology could be utilized to monitor road conditions and advise the appropriate officials of the onset of icing conditions.

In addition to simply ascertaining whether or not the infrared polarization signatures could be used for differentiation of ice, snow, and roadway surfaces the laboratory experiments were designed to evaluate the affect of the look angle (the angle of the roadway surface relative to the sensor). This portion of the experiment demonstrated that the signatures were sufficient for detection of ice over a wide range of look angles. These results are shown in Figure 10. As the look angle approaches 0° (i.e. looking straight down on the road) the signatures disappear. It is worth noting that this phenomenon is in agreement with theory. The optimum look angle, as demonstrated by the laboratory data, is approximately between 30° to 60°.

The next phase of the project was to evaluate the RPRISS sensor's ability to detect ice and snow in a real world environment. A section of roadway was to be monitored before, during, and after a snow or ice storm. The primary test was to be performed in Minneapolis, Minnesota. Secondary tests were to be performed, at NRC discretion and as time and weather permitted, while NRC personnel were in Denver, Colorado for testing of an aircraft ice detection system. These secondary tests were to be completed prior to the Minnesota test. Data from these two tests were then to be the used for the further development of ice detection algorithms that would enable the system to autonomously (i.e. no human operator would be required to continuously monitor the data) detect ice and provide the appropriate warnings.

NRC personnel were on-site in Minneapolis, MN to monitor a section of roadway in the Maple Grove, MN area from 5 March 1997 to 10 March 1997. The trip was timed to coincide with the anticipated arrival of a major weather system, which was expected to provide substantial snowfall and freezing rain. With the assistance of Mn/DOT personnel NRC set up the RPRISS sensor to monitor the roadway. The weather front disintegrated, however, and no precipitation fell during the entire time that NRC was on site. NRC opted to move the sensor into a mobile van and set up in the parking lot of a nearby hotel that still had substantial ice and snow on the ground from earlier storms. This enabled the collection of limited data on naturally formed ice and snow. This data is more representative of the actual operating environment than data collected in a laboratory setting and will be used in the further development of ice detection algorithms.

Examples of the data collected are shown in Figures 11-13. Each of these figures contains (a) a visible image, (b) a conventional IR image, and (c) the RPRISS image. As with the laboratory data, the ice is not distinguishable from the asphalt in the IR image because they are of the same temperature. The ice is clearly visible, however, in the RPRISS polarization image. These images demonstrate that the ice and snow are much more evident in the RPRISS image than in either visible or conventional IR images. A human operator could determine the presence of ice or snow with a very high probability of detection and very low rate of false alarms.

PLANS FOR *RPRISS* IMPLEMENTATION

NCR, under R&D funding, is continuing to work with the infrared community to increase the RPRISS technology base to support implementation of an RPRISS system. The initial RPRISS product penetration is anticipated to be in the fixed critical site application. Here the system would be pole or tower mounted to view known critical icing areas to provide early warning of surface temperatures for preventive effort followed by immediate detection of any ice formation. The benefits include the ability to accurately determine the presence of ice and its extent thereby eliminating false remediation crew callouts and allowing an accurate estimate of the effort and product mix required to mitigate the situation. This will provide economies in both product and product environmental impact and the initial labor distribution. If an anti-icing strategy is used, the system will provide immediate indication if an event has overwhelmed the anti-icing strategy, indicating that the strategy must change to mitigation and de-icing to avoid exacerbating the potentially deleterious effects of improperly continued anti-icing. Large cities might have ten or more critical points warranting an RPRISS fixed system. Smaller municipalities may have one to five such areas. Large airports would likely require only one or two systems because of the higher mounting location and larger minimum detection requirements. An initial market would likely be 1000-1500 systems over the first five years.

The next anticipated application area is mounting units on inspection and remediation vehicles. The benefits here are product mix optimization and improved utilization, with results similar to fixed applications. Initial market would likely be one per larger region and municipality, or 500 systems. This may be pessimistic, as the system may have additional applications in more routine road inspection and maintenance which has not yet been explored.

The final application is in large trucks and critical material (explosives, gasoline, dangerous chemicals, etc.) vehicles. Principal benefit in this arena is increased safety from early detection of otherwise undetectable black ice. Other benefits may include automatic obstacle detection in some kinds of fog and at night, etc. Penetration into this market will require two orders of magnitude reduction in the cost of the basic infrared system. However, indications are that the basic IR industry is developing many applications designed to drive this cost down. An initial estimate is 5000 units, about the minimum that might interest the vehicle manufacturers.

The individual project requirements will dictate exactly how the system will be implemented. Before considering specific applications, however, additional field tests should be performed. At a minimum, NRC should return to Minneapolis, MN, or other suitable locations, during the upcoming winter season and monitor a section of roadway in accordance with the original plan. If possible multiple locations should be monitored. This will provide the opportunity to test preliminary ice detection algorithms under development that use data obtained from the laboratory and field tests performed to date.

A second field test also to be considered is to install an RPRISS sensor, at an appropriate site, along with the necessary data storage capability, for the duration of the winter season. This will provide a more complete database, allow the ice detection algorithms to be refined, and give a better understanding of the operational requirements of the sensor system. Additionally, a long duration test will help to answer questions such as the following:

- Should the system should be autonomous and provide a warning when ice is detected or should it simply provide enhanced images for human operators to evaluate?
- How often should the RPRISS update the operator?
- Should the RPRISS be fixed-mounted, mobile, or a combination of both, etc.?

At the conclusion of the additional field tests, recommendations concerning implementation of an RPRISS system will be made.

CONCLUSIONS

NRC is currently heavily involved in developing innovative infrared imaging systems. Under this contract NRC has evaluated the feasibility of adapting one of these systems to address the problem of detecting ice on roadways. Preliminary laboratory tests show that the unique infrared signatures of ice, snow, and roadway surfaces may be used to detect the presence of ice on roadways. Plans to monitor a section of roadway as icy conditions developed were hampered due to weather. Limited field data was collected on ice and snow which was already present at a hotel parking lot near the proposed test site. This data is still being evaluated but preliminary results indicate that ice can be detected on roadway surfaces in an operational environment. Additional field trials should be pursued before actual implementation of a complete RPRISS system. These tests will provide the experience base necessary to develop the operational requirements needed before a complete system can be fielded.

INVESTIGATOR PROFILE

Mr. Blair Barbour received his B.S. in Physics from Marshall University in 1984. He received his M.S.E.E. in Electro-Optical Engineering from the University of Dayton in 1986. Br. Barbour has over 14 years of direct experience in optical device testing, the development of new IR spatial phase sensor technologies, and advanced optical systems and innovative optical sensors. Mr. Barbour is currently employed at Nichols Research Corporation where he is the Director of the System Development and Evaluation Center. He is the inventor and program manager on the passive IR spatial phase sensor.

Dr. Michael W. Jones received his B.S. in Electrical Engineering from the University of Memphis in 1986. He received his M.S.E.E. in 1993 and his Ph.D. in 1996 from the University of Alabama in Huntsville (UAH). His work while at UAH focused on the development of novel 3-D display architectures. Dr. Jones is currently employed at Nichols Research Corporation where his primary research activity is the development of advanced infrared imaging sensors.

Mr. Jack Reed received his B.S. in Electrical Engineering from Clemson University in 1967. He received his M.S. in Mechanical Engineering from the University of Texas, El Paso, in 1976, and his M.S. in Systems Management. from the University of Southern California in 1979. Mr. Reed has more than 25 years experiences developing, operating, and supporting complex systems.

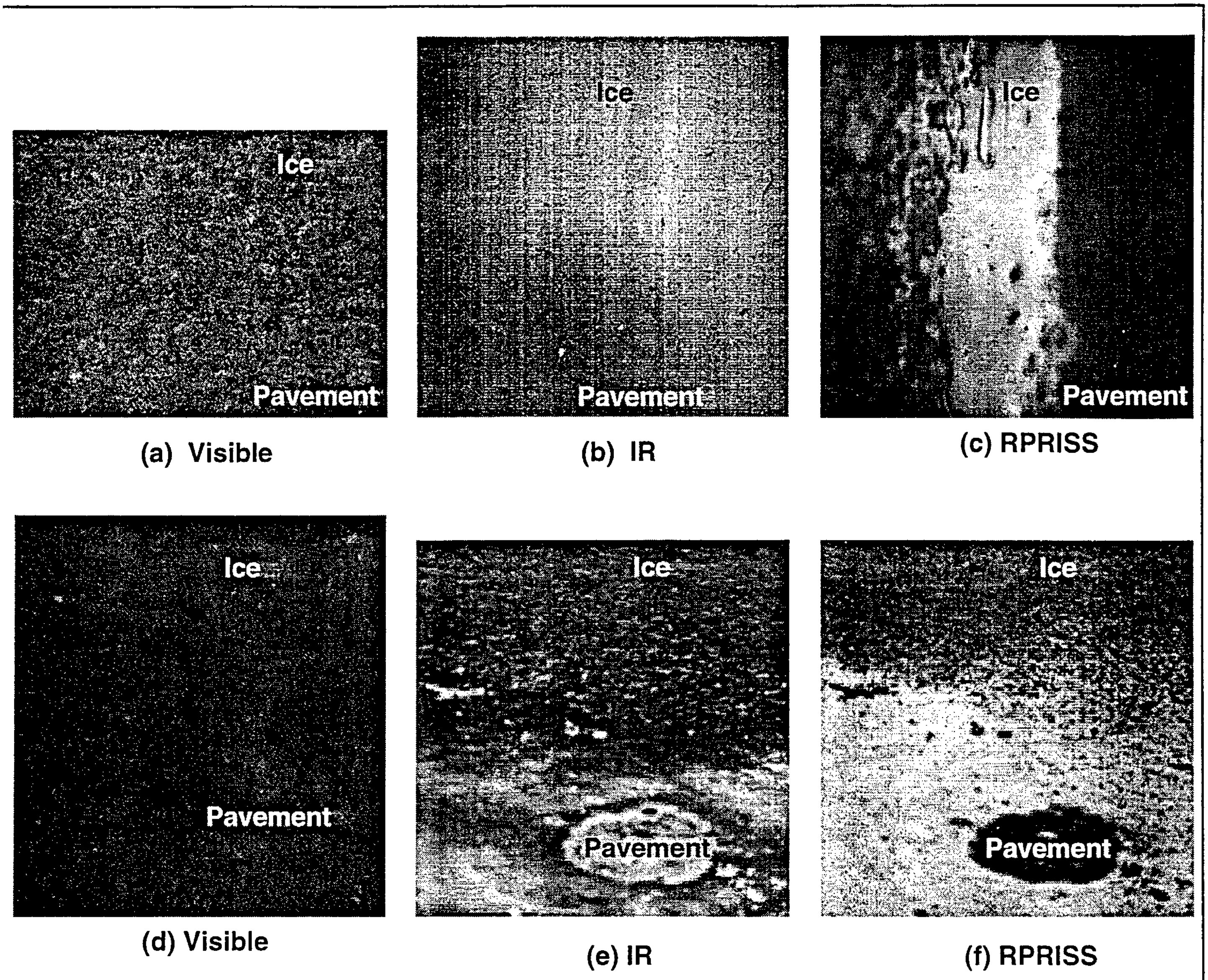


Figure 1. Examples of data collected using RPRISS sensor. (a)-(c) Images obtained in laboratory of ice on roadway sample, (d)-(f) Images obtained in the field of ice on asphalt surfaces.

FILE: FIG. 1
ADOBE ILLUSTRATOR

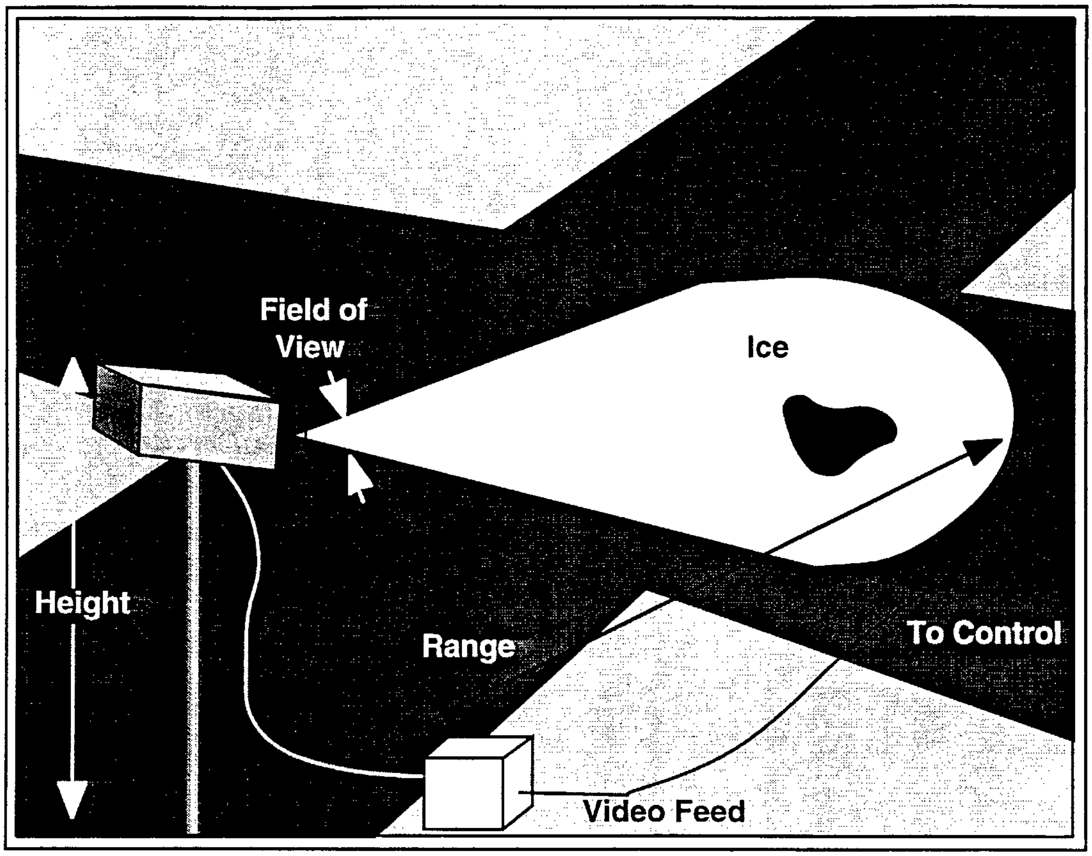


Figure 2. REPRISS Concept.

FILE: ~~Fig2R~~ Fig2rps.word

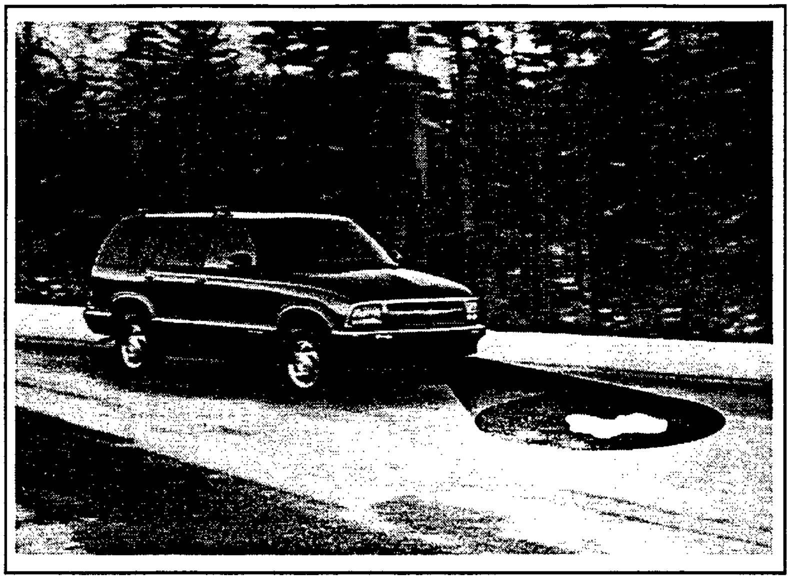
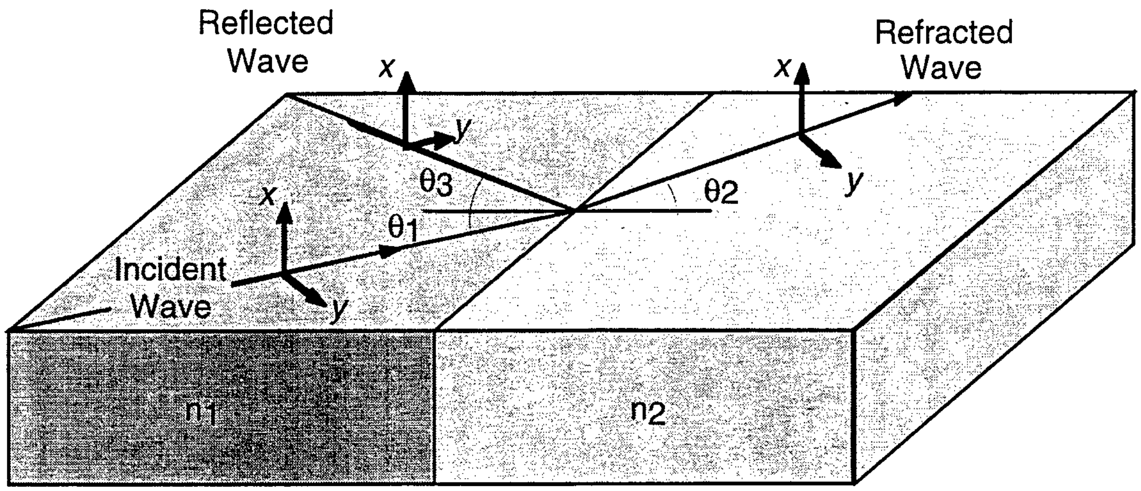


Figure 3. Vehicle-mounted RPRISS system.

FILE: Fig. 3
word file



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$r_x = \frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_1 \cos\theta_1 + n_2 \cos\theta_2} \qquad r_y = \frac{n_2 \cos\theta_1 - n_1 \cos\theta_2}{n_2 \cos\theta_1 + n_1 \cos\theta_2}$$

$$t_x = 1 + r_x \qquad t_y = 1 - r_y$$

Figure 4. Reflection and refraction at a dielectric interface.

FILE NAME: Fig. 4

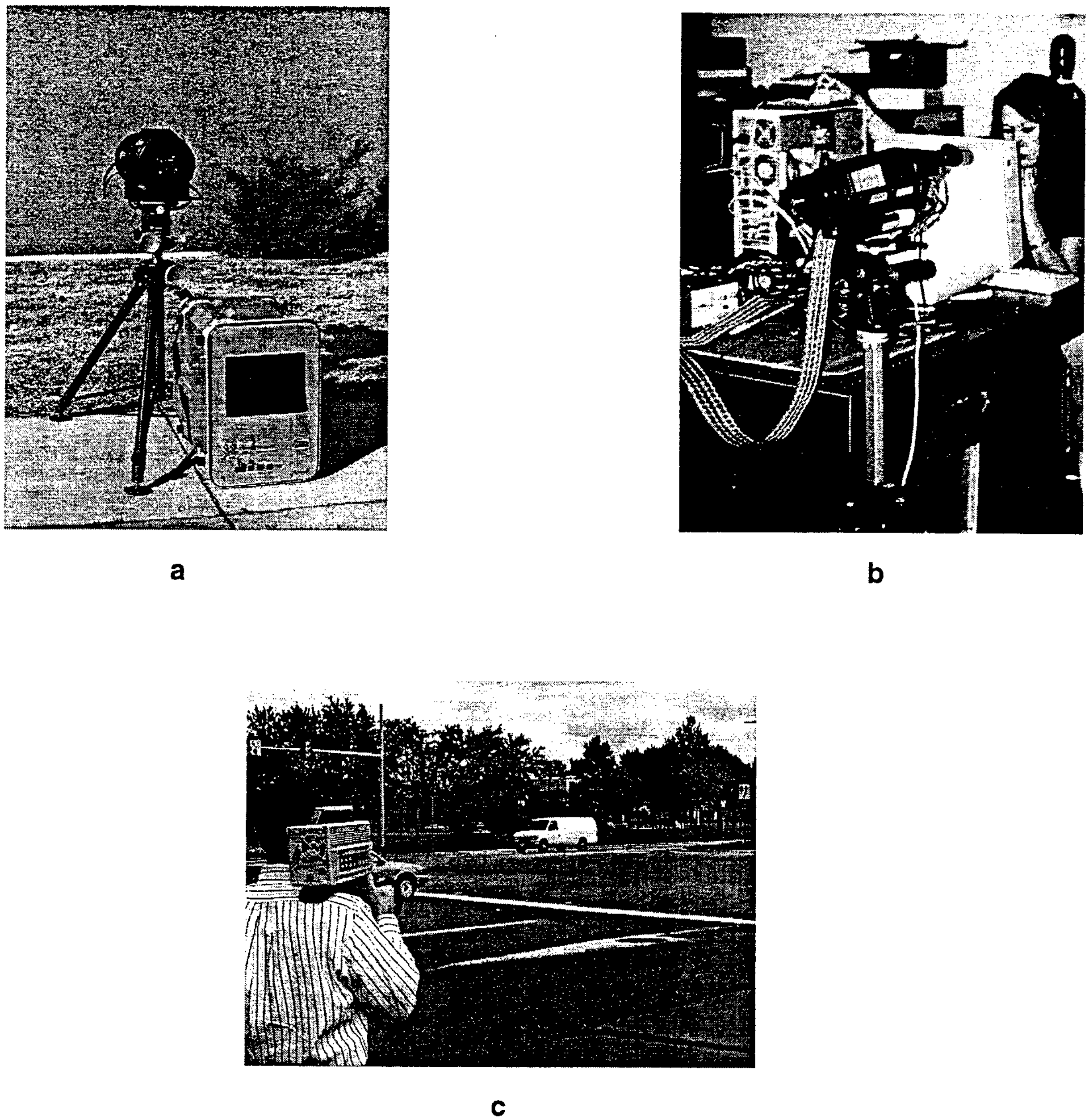


Figure 5. Photographs of NRC's various infrared sensors. (a) second-generation3-5 μm sensor, with increased signal to noise performance, (b) second-generation 8-12 μmsensor, (c) third-generation 3-5 μm sensor.

FILE: Fig. 5
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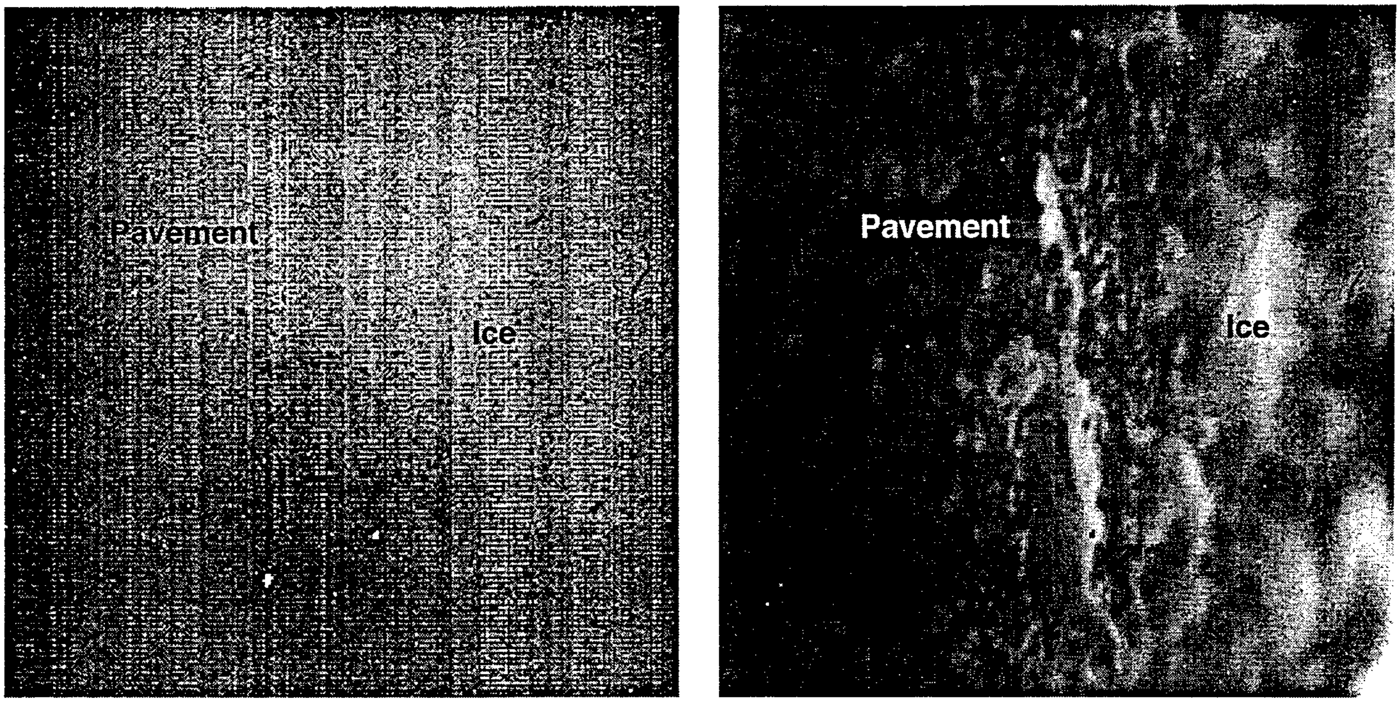
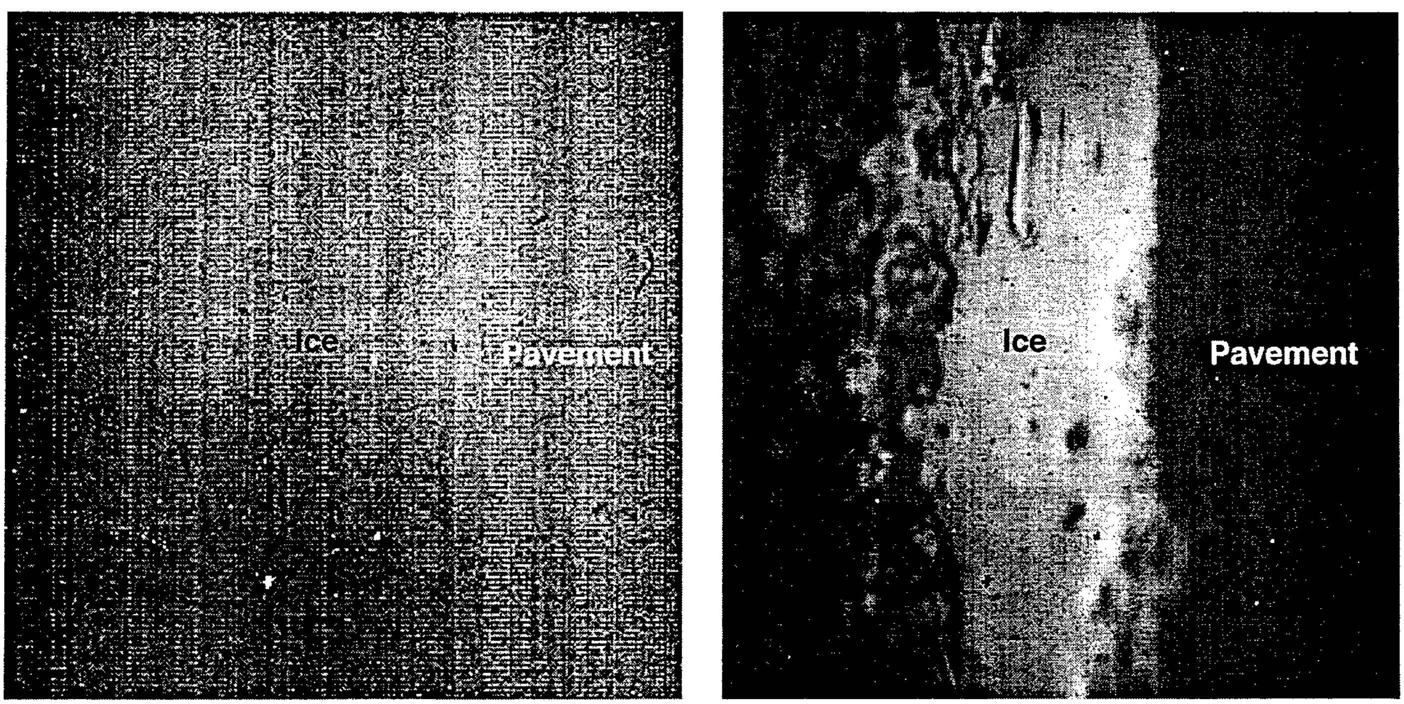


a b

Figure 6. Laboratory data of ice on an asphalt surface
(a) Conventional IR image (b) RPRISS image.



a b

Figure 7. Laboratory data of ice on an asphalt surface
(a) Conventional IR image (b) RPRISS image.

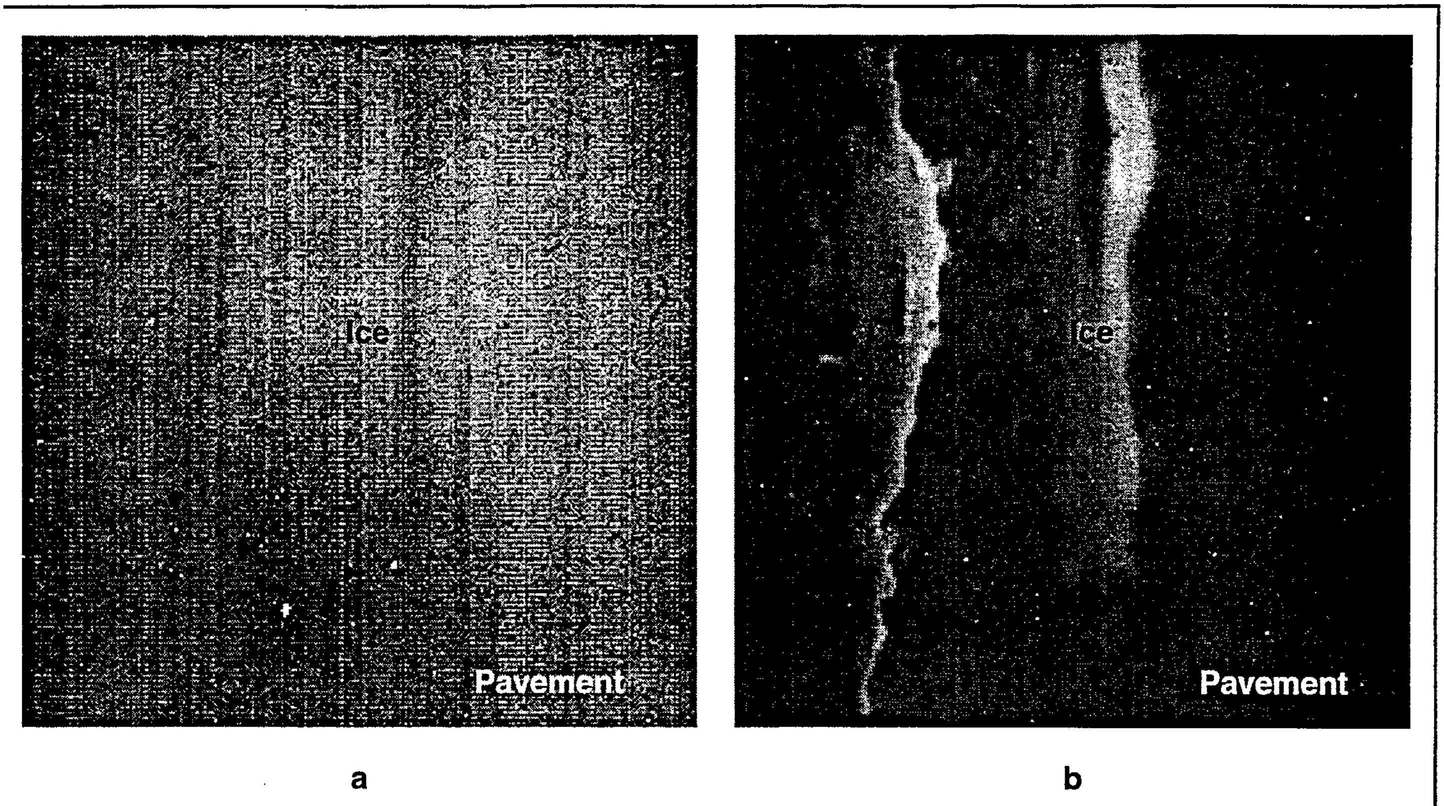


Figure 8. Laboratory data of ice on a grooved cement surface.
(a) Conventional IR image (b) RPRISS image.

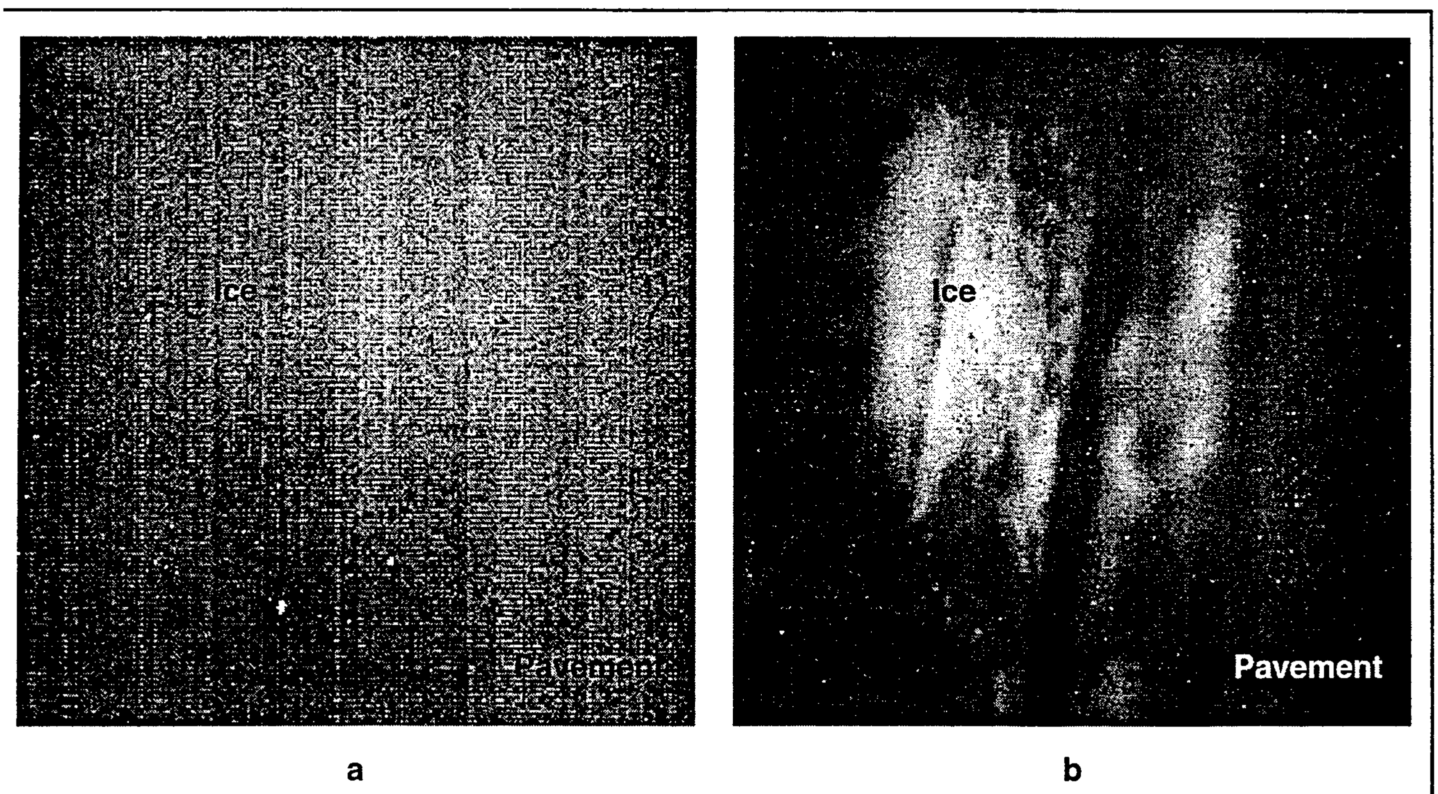


Figure 9. Laboratory data of ice on a cement surface.
(a) Conventional IR image (b) RPRISS image.

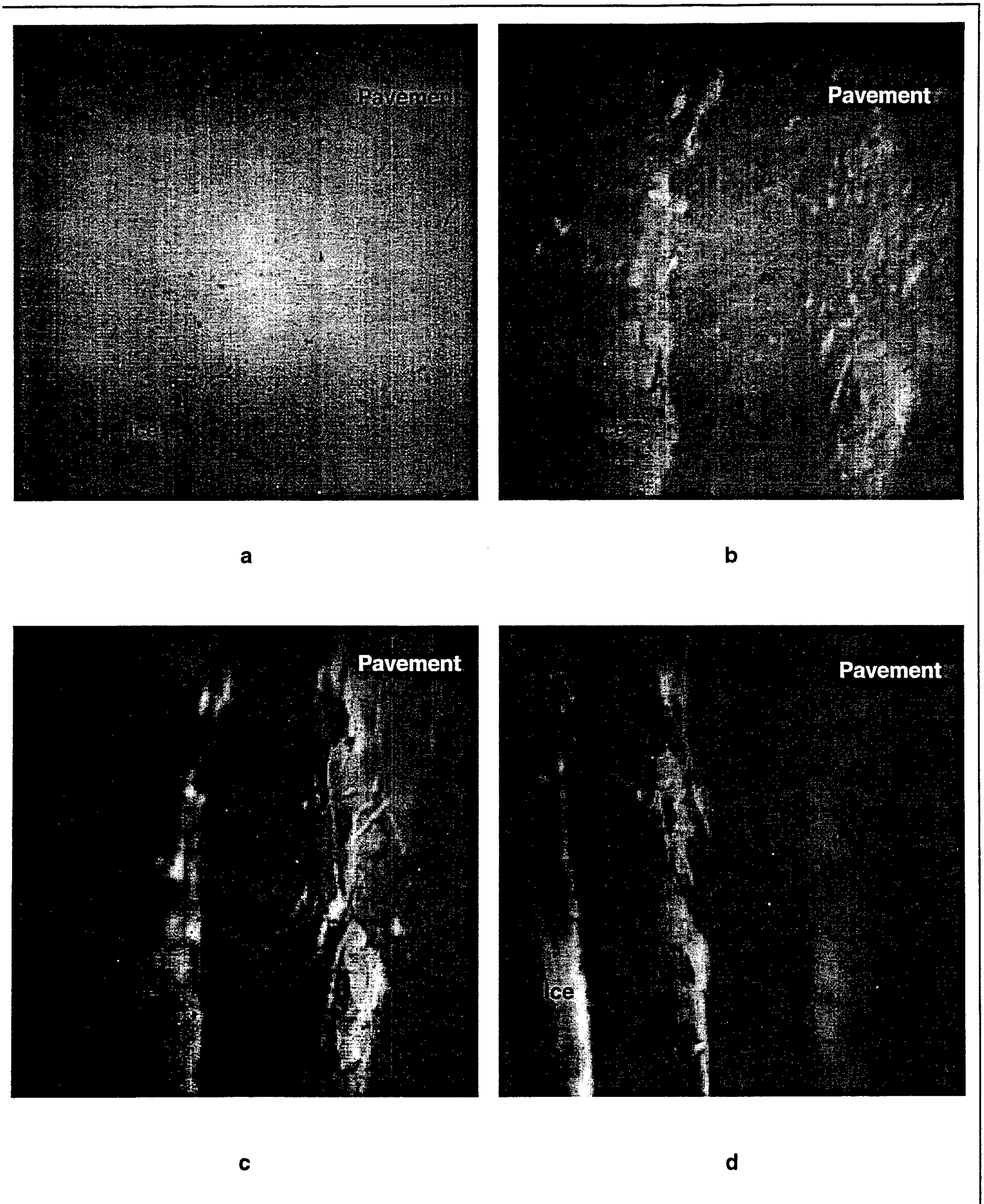


Figure 10. RPRISS image as a function of angle. (a) 0°, (b) 25°, (c) 45°, and (d) 60°

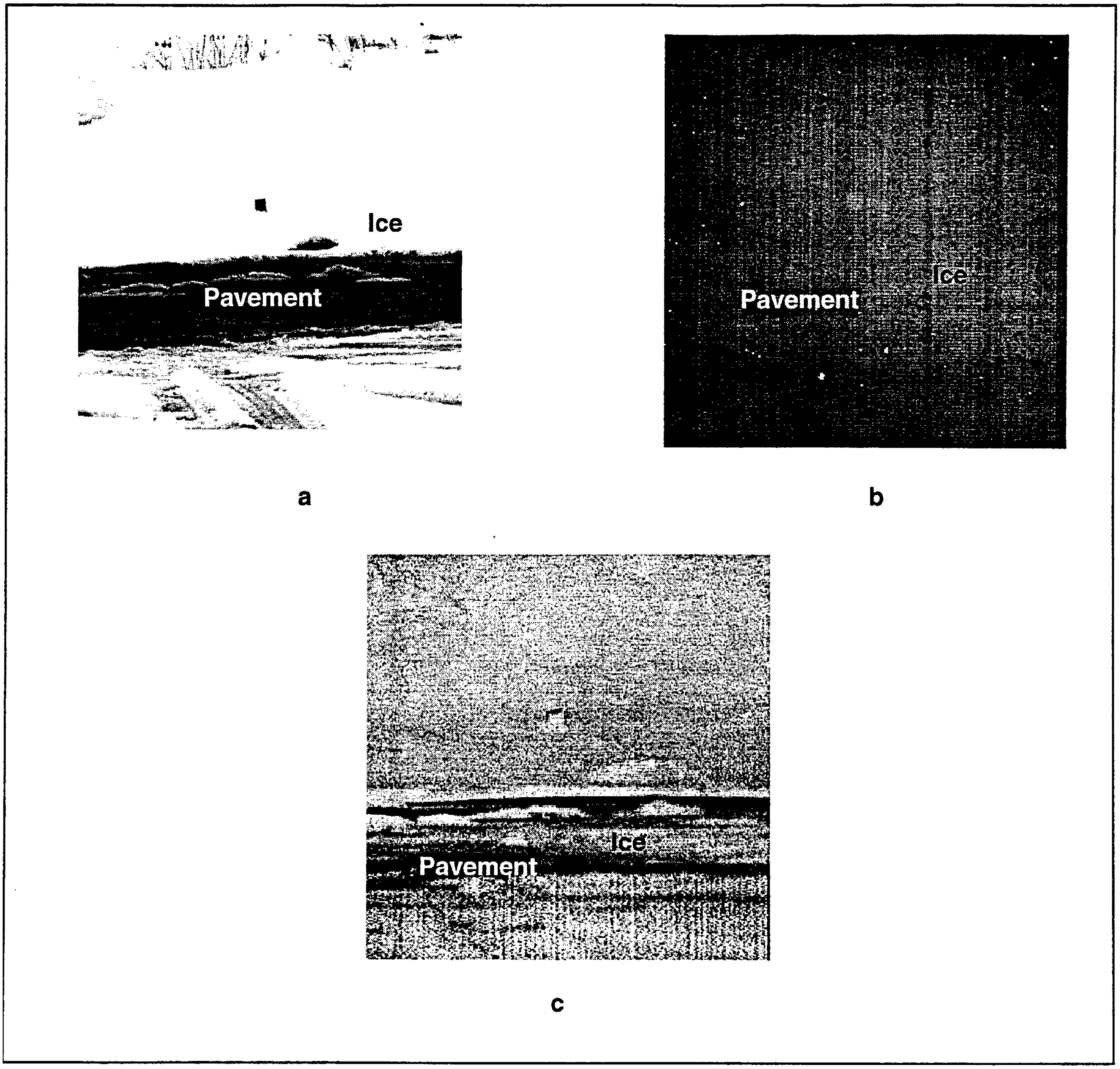


Figure 11. Field data of ice on an asphalt roadway surface. (a) Visible image (b) Conventional IR image, (c) RPRISS image

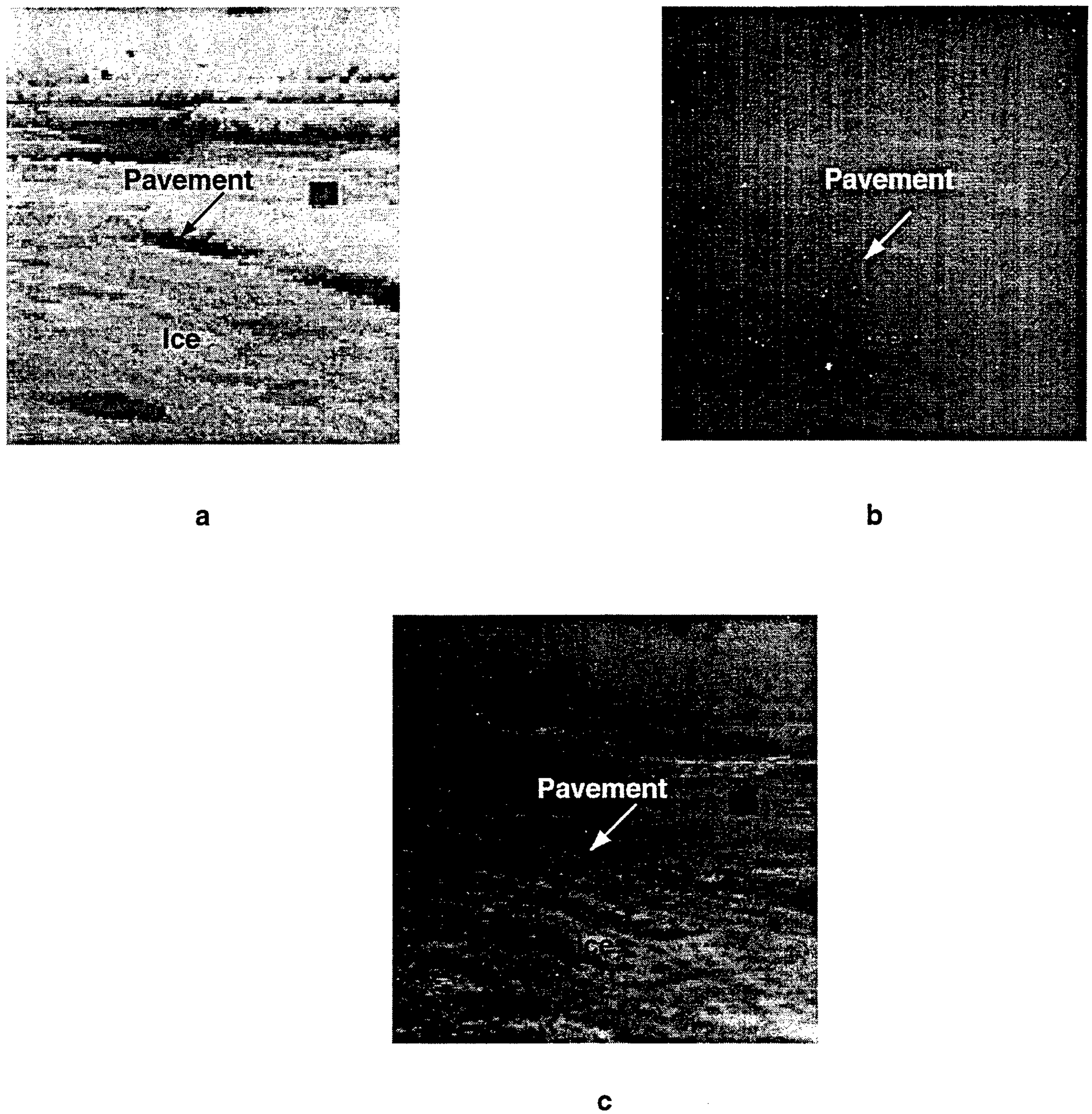


Figure 12. Field data of ice on an asphalt roadway surface. (a) Visible image (b) Conventional IR image, (c) RPRISS image

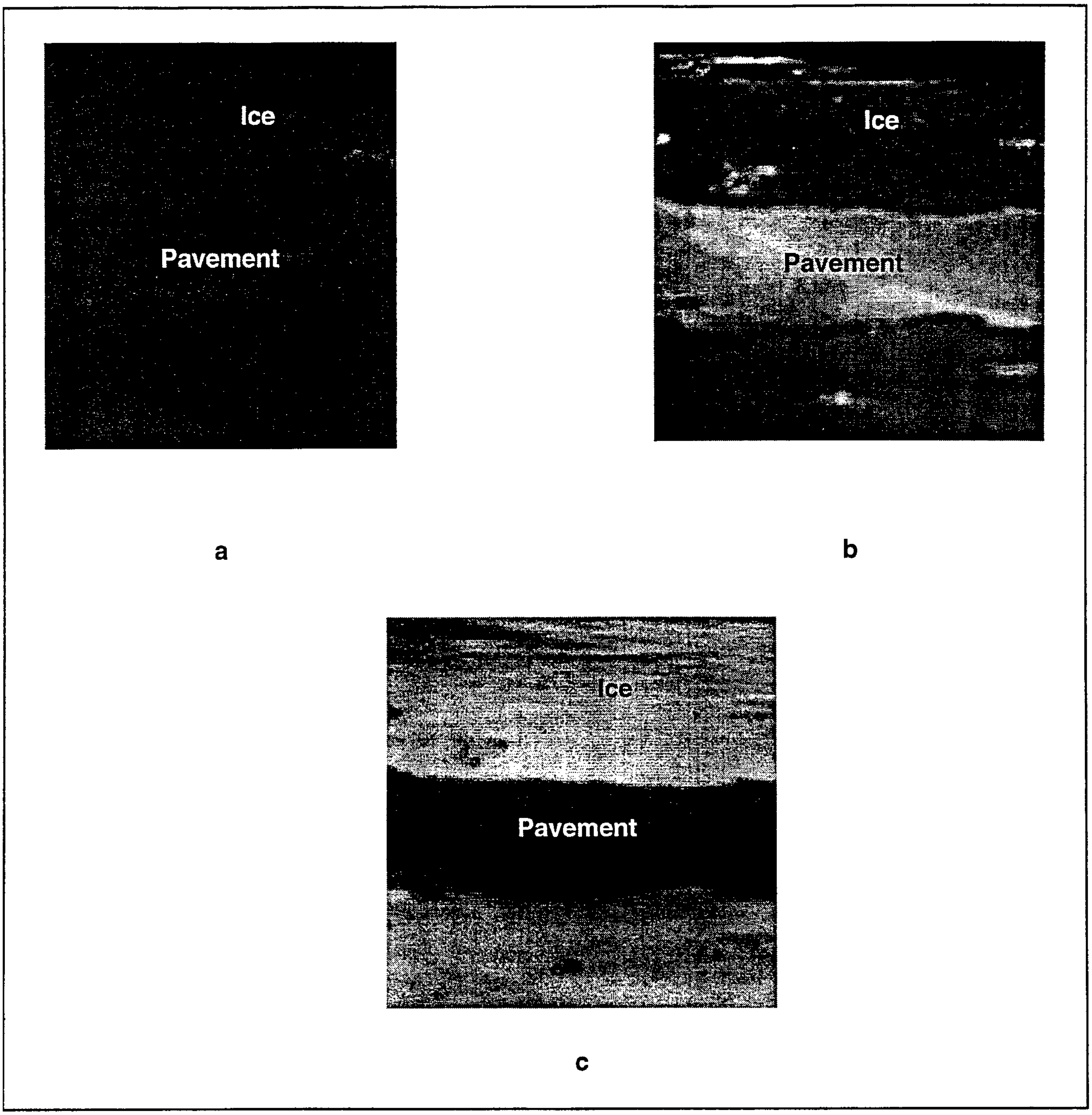


Figure 13. Field data of ice on a parking lot asphalt surface. (a) Visible image (b) Conventional IR image, (c) RPRISS image