Comparison of In-Pavement Versus Non-Invasive Pavement Sensor Technologies

AKA

The Lesser of Two Evils

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Part I

- Goals Statement
- Test Design Parameters
- State of the Art
- Background Needs Definition
- Non-Invasive Pavement Sensor, (NIPS), Theory Of Operation
- Software Development

The Goal Of The Investigation

- **This is an investigation into the applicability of currently available Non-Invasive Pavement Sensors, NIPS, technology to replace In-Pavement Sensors, IPS, within the Caltrans D02 ITS infrastructure. The primary goal is to determine if NIPS can replace IPS by proving in actual wintertime traveled highway conditions that they can report pavement status as reliably or better than IPS.**

- **With the secondary goal of determining if NIPS technology is accurate enough to be used in place of IPS in automated warning systems.**

What This Evaluation Includes

- This evaluation is primarily a comparison of surface status reporting of NIPS to the currently deployed IPS; it is not a laboratory evaluation of absolute quantities of the measured values.
- To that end we have defined <u>interesting events</u> as those where the IPS and NIPS <u>reported status is not the same</u>. Where all sensors report the same there is no conflict and the NIPS is considered equal to IPS.
- Our analysis will center on isolating those events where there are <u>differences</u> and <u>analyze</u> those incidents and identify <u>which reports were more accurate to the actual conditions</u>.
- In order to meet the goals of this evaluation it was necessary to generate a clear understanding of the underlying principals of operation of NIPS technology.

Current State of the Art

- **The state of the art for some time has included <u>both IPS and NIPS</u> with varying capabilities to detect and <u>report pavement surface temperatures.</u>**

- **These sensors, again to varying degrees, are also capable of determining the <u>covering of the pavement with water, ice, snow, and de-icing chemicals</u>, which are <u>then translated into a pavement surface condition</u>, such as wet, dry, ice or snow watch, ice or snow warning <u>and of late road surface friction or level of grip has been included.</u>.**

Why search for an alternative to IPS?

- **The primary reason for this evaluation was due to two limitations of IPS technologies.**
  - **The first was the difficulty in finding a practical and reliable method to calibrate IPS once installed in the pavement.**
  - **The second is the difficulty in maintaining IPS in good working order.**

In Pavement Sensor Calibration Issues

- **Many attempts have been made to find methods to evaluate the accuracy, calibrate, and test IPS once they have been installed in the pavement but <u>none have proven both practical and effective</u> at the same time.**

- **The various methods attempted usually involve lane closures, installing thermocouples or other temperature sensors on or near the IPS, then using ice to cool the sensor and surrounding pavement to some predetermined stable temperature. Along with various methods of applying water and deicing chemicals and measuring the response. <u>The success has been mixed at best.</u> [1,2,3,4,5]**

Lufft "Calibratable IPSs"

- A proposed method of calibrating and replacing IPS has seen various incarnations over the years the latest of which is produced by Lufft and included the IRS 21 and the IRS 31 series of IPS.
- These are representative of a class of IPS that include a separate housing and electronic insert that can be removed for calibration or replacement. In our district we experienced a failure rate of up to 40% with these IPS for various reasons but mostly water intrusion.
- Investigation revealed in some cases the rubber O-Ring was undersized for the recesses such that even with proper torqueing of the retaining screws the seal is insufficient.

Lufft Puck Failure Rate

The table at the right shows the raw failure rate of the Lufft version of IPS with the removable electronics. Of the failed IPS in this chart 2 have been refurbished and returned but not installed and "road tested" yet.

Lufft IPS Failure Count

RWIS Location	# Pucks	# Failures	# Replacements	# Failed Replaceemnts
Sims Road	4	1		
North Weed	4	4	4	2
Vollmers	4	0		
Perez	3	1		
Anderson Grade	8	4	4	1
Dunsmuir	3	0		
Totals	26	10	8	3
	Orignal		Replacement	
	Failure Rate	38%	Failure Rate	38%

Total	
Failure Rate	38%

Galvanic Corrosion

Example of a Lufft IRS 21 IPS with <u>galvanic corrosion</u> disassembled for inspection. Note the two holes in the white plastic body have corroded to become larger than the electrodes that protrude from the interior to the external surface of the well.

Grind Out and Saw Cut Damage.

To the right is an example of a location that has had multiple IPS failures in this case note the grinding out of the cabling.

Sensor Lead in Sealant Deterioration

One failure mode is when the <u>pavement wears near the edge of the saw cut</u> and exposes the edges of the sealant to tire traffic. This either breaks hardened epoxy or pulls out sticky sealants which <u>leaves the cable exposed to being damaged</u>.

Pavement Expansion and contraction

Another failure mode is the contraction and expansion of the pavement especially the contraction phase where the pavement pulls away from a hard epoxy breaking the pavement to epoxy seal and leaving the epoxy free to work up and out.

Yet Another Failure Mode

Another failure mode is using a sealant that never hardens enough. The problem here is the <u>sealant remains pliable enough to allow the cabling to pump up through the sealant.</u>

Direct Snow Plow Damage to the Sensor

This type of damage can be exceptionally difficult as it most often occurs when the pavement is inaccessible due to weather conditions like snow on the road and remaining on the shoulders making it impossible to repair. In addition the personnel who usually are needed to assist with the repair are busy with other wintertime duties.

Direct Pressure Damage to the Sensor

Another failure mode for IPS is direct pressure from heavy vehicles <u>especially when tire chains are used</u>.

Difficulties in Repairing Damaged IPS

Some of the difficulties affecting repairs of IPS include coordinating the personnel and equipment to facilitate lane closures, make the saw cuts, core the holes for the replacement sensor, procuring the materials. Trying to coordinate these resources during winter operations can leave a system in a compromised state for prolonged periods during the critical time they are intended to be operational. $☺$☺$

D02 Created IPS Installation Procedure

After researching the root causes for the aforementioned failure modes of IPS installations it was decided some of the failures could be avoided by a more detailed installation procedure that took steps designed to mitigate the known failure modes.

- **<u>Deeper and narrower </u>saw cuts**
- **Proper <u>cleaning and drying</u> before applying sealants or epoxies**
- **Proper sealants elastomers and epoxies**

Why Re-Evaluate NIPS Technology

The evaluation of NIPS technology is intended to address issues uncovered in earlier studies that brought into question the reliability of the reported data from the NIPS systems. NIPS technology has undergone numerous improvements since those early studies, enough so that later laboratory studies indicate the accuracy has improved to the point they should be considered a viable component of an ITS system. [7,8,9,10]

NIPS Theory of Operation

NIPS sensors are composed of <u>two separate infrared sensor types</u>; one for measuring the temperature of the road surface and one for measuring the surface condition. They operate on different principals <u>one passive measuring emitted IR, one active measuring reflected IR.</u>

Remote Infrared Temperature Sensing Basics

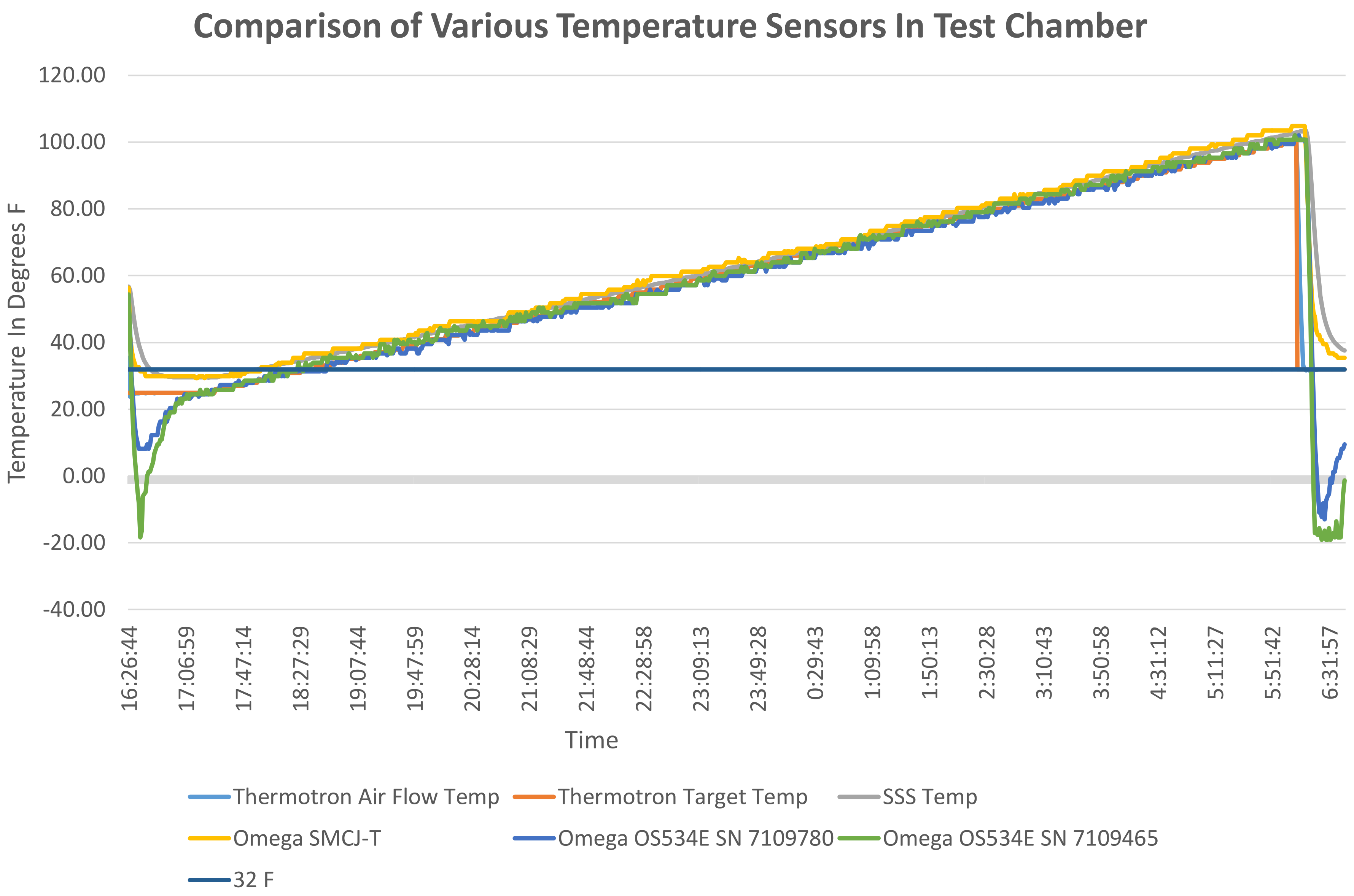
IR temperature sensors <u>detect the level of IR radiation</u> at a specific wavelength <u>emitted by the target and then also from the internal temperature sensor</u>. Then <u>compare the IR emitted from the sensor to the IR emitted by the target</u> and by <u>knowing the temperature of the sensor</u> element one can infer the temperature of the target. <u>The ratio of IR emissions should match the ratio of temperatures.</u>

Remote Infrared Temperature Sensing Limitations

- The IR comparison has limitations in that the sensor itself must be within the range of the comparator that compares the sensor to the target IR emissions or the accuracy of the measurement can be dramatically skewed.
- IR radiation from other sources can reflect off the target surface and skew the comparison.
- Water droplets or fog in the path between the target and sensor can emit IR and skew the comparison.
- The graph on the next slide shows how the Omega IR sensors reacted to large temperature changes of the target value in a short period of time and the time it took for the IR sensors to acclimatize to the change.

[12]

Remote Infrared Temperature Sensing Error



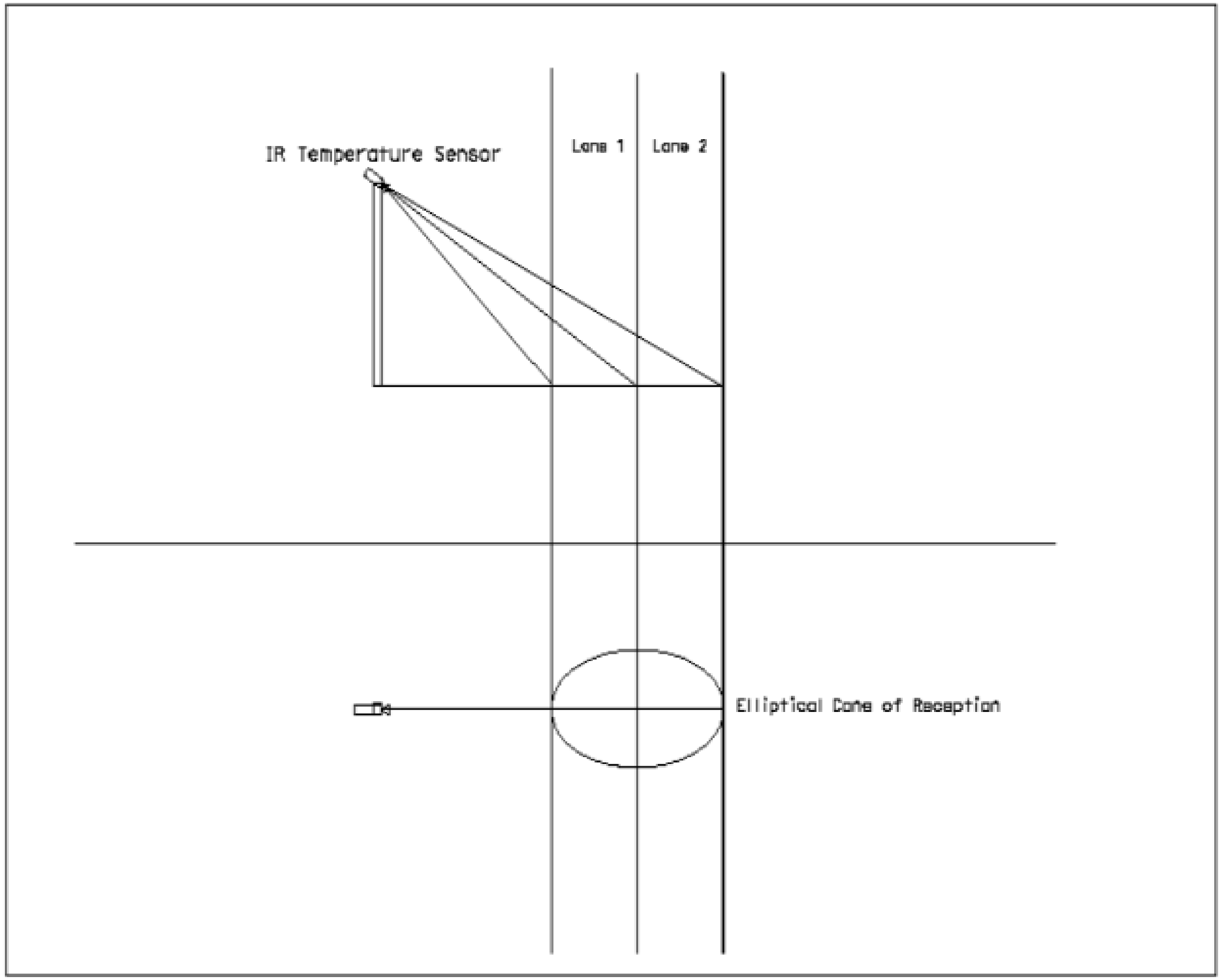
IR Temperature Sensing & Emissivity

- **Surface emissivity is another concern, perfect black body radiation has an emissivity of 1 most objects encountered have a emissivity of 0.95 and most IR temperature sensors are calibrated to 0.95.**

- **IR tapes with specified emissivity are used in laboratory calibrations, at least by Vaisala.**

IR Temperature Sensing & Area Averaging

- IR temperature sensors average the temperature over large area. The sensor has a lens that focuses the IR emissions from the pavement onto the sensor. The field of view of the lens, usually measured in degrees from the centerline of view, determines the field of view of the sensor and the temperature measured is an average of the entire field of view. This in effect defines a cone of reception which becomes an ellipse when projected on the pavement surface.
- Knowing the dimensions of the cone of reception for the IR temperature sensor is critical to being sure the temperature measurement is measuring the road surface and not the shoulder or median.



IceSight Infrared Temperature Sensor Field of View as a Function of Distance
All Distances in feet.

Height	Lateral Distance	Total Distance 10'-33' Asphalt 10'-50' Concrete	Cone of Reception Diameter & Ellipse Minor Axis	Ellipse Major Axis	Look Angle From Road to IceSight in Degrees (30-85)	Look Angle From Road to IceSight in Radians
10	10	14.1421356	3.6602534	5.3589541	45	0.78539816
10	15	18.0277564	4.665925878	8.90462397	33.690068	0.5880026
15	10	18.0277564	4.665925878	5.74919818	56.309932	0.98279372
15	15	21.2132034	5.4903801	8.03843115	45	0.78539816
15	20	25	6.470475	11.3197765	36.869898	0.64350111
15	25	29.1547595	7.545805692	15.6752196	30.963757	0.5404195
20	10	22.3606798	5.787368779	6.61123639	63.434949	1.10714872
20	15	25	6.470475	8.30924681	53.130102	0.92729522
20	20	28.2842712	7.3205068	10.7179082	45	0.78539816
20	25	32.0156212	8.28625106	13.8699278	38.659808	0.67474094
20	30	36.0555128	9.331851756	17.8092479	33.690068	0.5880026
20	35	40.3112887	10.43332744	22.5926294	29.744881	0.51914611
25	10	26.925824	6.968914851	7.65703804	68.198591	1.19028995
25	15	29.1547595	7.545805692	9.00853137	59.036243	1.03037683
25	20	32.0156212	8.28625106	10.9165398	51.340192	0.89605538
25	25	35.3553391	9.1506335	13.3973852	45	0.78539816
25	30	39.0512484	10.10720505	16.4726489	39.805571	0.69473828
25	35	43.0116263	11.13222612	20.1696504	35.537678	0.62024949
30	10	31.6227766	8.184575417	8.79372105	71.565051	1.24904577
30	15	33.5410197	8.681053168	9.91685459	63.434949	1.10714872
30	20	36.0555128	9.331851756	11.4983964	56.309932	0.98279372
30	25	39.0512484	10.10720505	13.5476618	50.194429	0.87605805
30	30	42.4264069	10.9807602	16.0768623	45	0.78539816
30	35	46.0977223	11.93096638	19.1012898	40.601295	0.70862627
35	10	36.4005494	9.421153807	9.98204469	74.054604	1.29249667
35	15	38.0788655	9.855533897	10.9431284	66.801409	1.16590454
35	20	40.3112887	10.43332744	12.2943892	60.255119	1.05165021
35	25	43.0116263	11.13222612	14.0416448	54.462322	0.95054684
35	30	46.0977223	11.93096638	16.1924817	49.398705	0.86217005
35	35	49.4974747	12.8108869	18.7563393	45	0.78539816

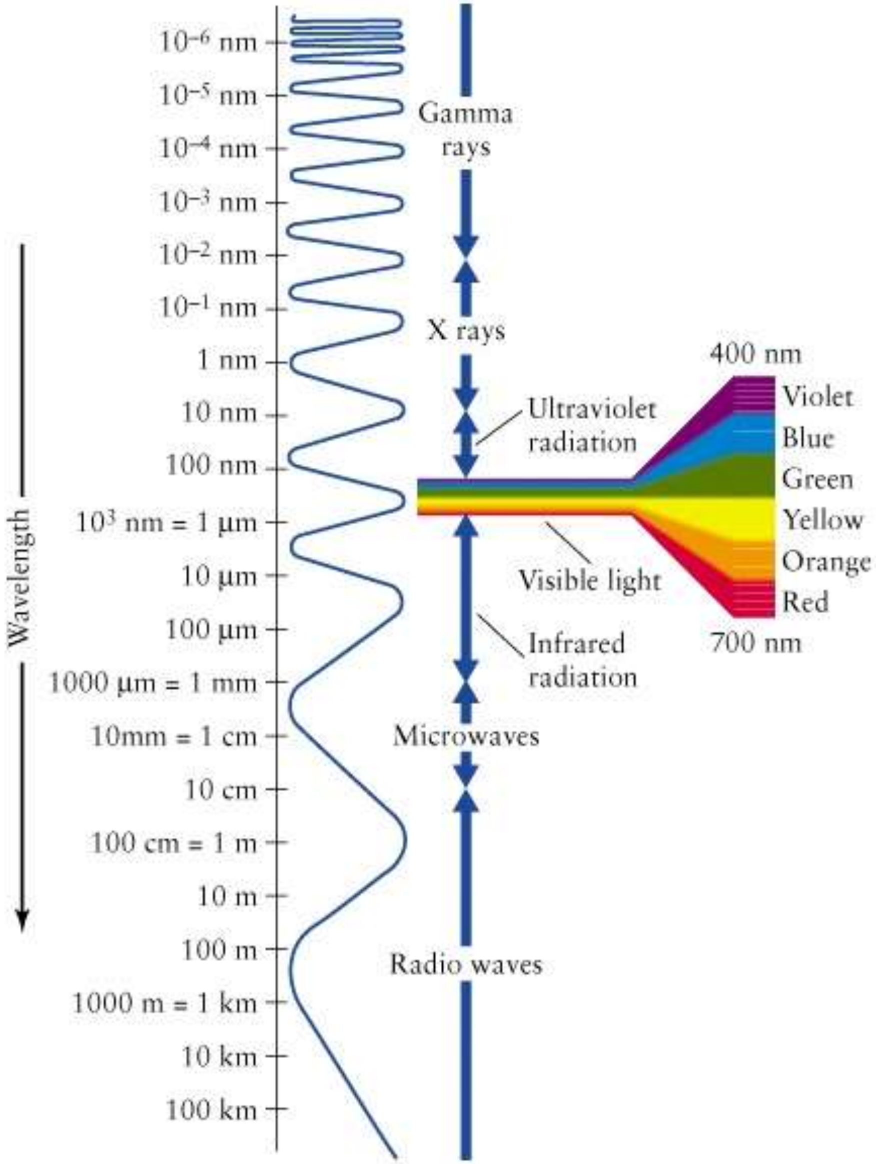
NIPS Reflected Infrared Spectral Analysis Basics

- **NIPS use <u>a limited form of IR spectral analysis</u> to determine road surface condition. <u>Measurements of the reflection/absorption</u> of IR energy <u>at differing wavelengths to</u> determine the presence of water, ice, or frost.**
- **The process involves laser emitters at wavelengths of 850?, 1350?, and 1550? nanometers and a <u>sensor to measure the reflected IR energy</u>.**
- **The IR sensor <u>measurements are made with all the lasers off and then in turn while each laser is on.</u> The <u>difference in intensity</u> of the IR radiation <u>between the off and on</u> state measurements for each laser indicates the extent that the surface is reflecting or absorbing at each wavelength.**
- **<u>Measurements of each wavelength are averaged</u> and in some cases use a sliding window averaging and may also exclude outlier readings.**

Infrared Spectral Analysis Basics

- **The USGS Spectroscopy Lab has created a library of charts depicting the spectral absorption/reflection as a function of wavelength in the IR spectrum for different forms of water. For more in-depth information see 13 in bibliography.** [13]
- **In the NIPS the IR analysis is accomplished by comparing the reflected IR radiation at the predetermined wavelengths to spectral charts for water ice and snow. It's almost like comparing colors in the visible spectrum: I see you're wearing a 475nm shirt today☺. See the following charts.**

Electromagnetic Spectrum



Wavelength image from Universe
By Freedman and Kauffman.
http://science-edu.larc.nasa.gov/EDDOCS/Wavelengths_for_Colors.html

Chart of H2O IR Absorption

At the right is a chart from the USGS website Reflectance spectra of solid carbon dioxide, CO_2, and water, H_2O, from Clark *et al*. (1986).

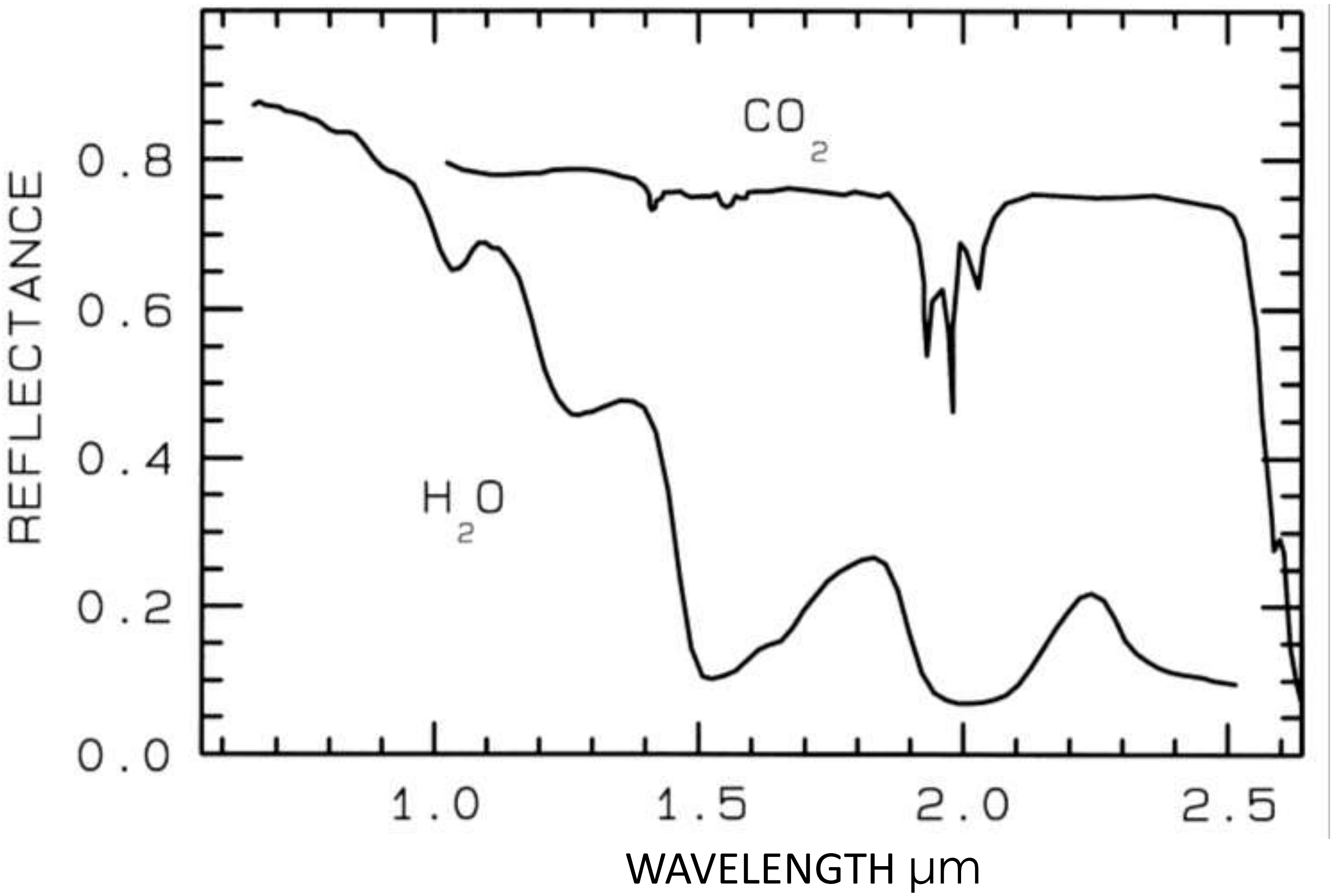


Chart of H2O Ice IR Absorption

At the right is a chart from the USGS website showing H2O ice reflectance as a function of wavelength.

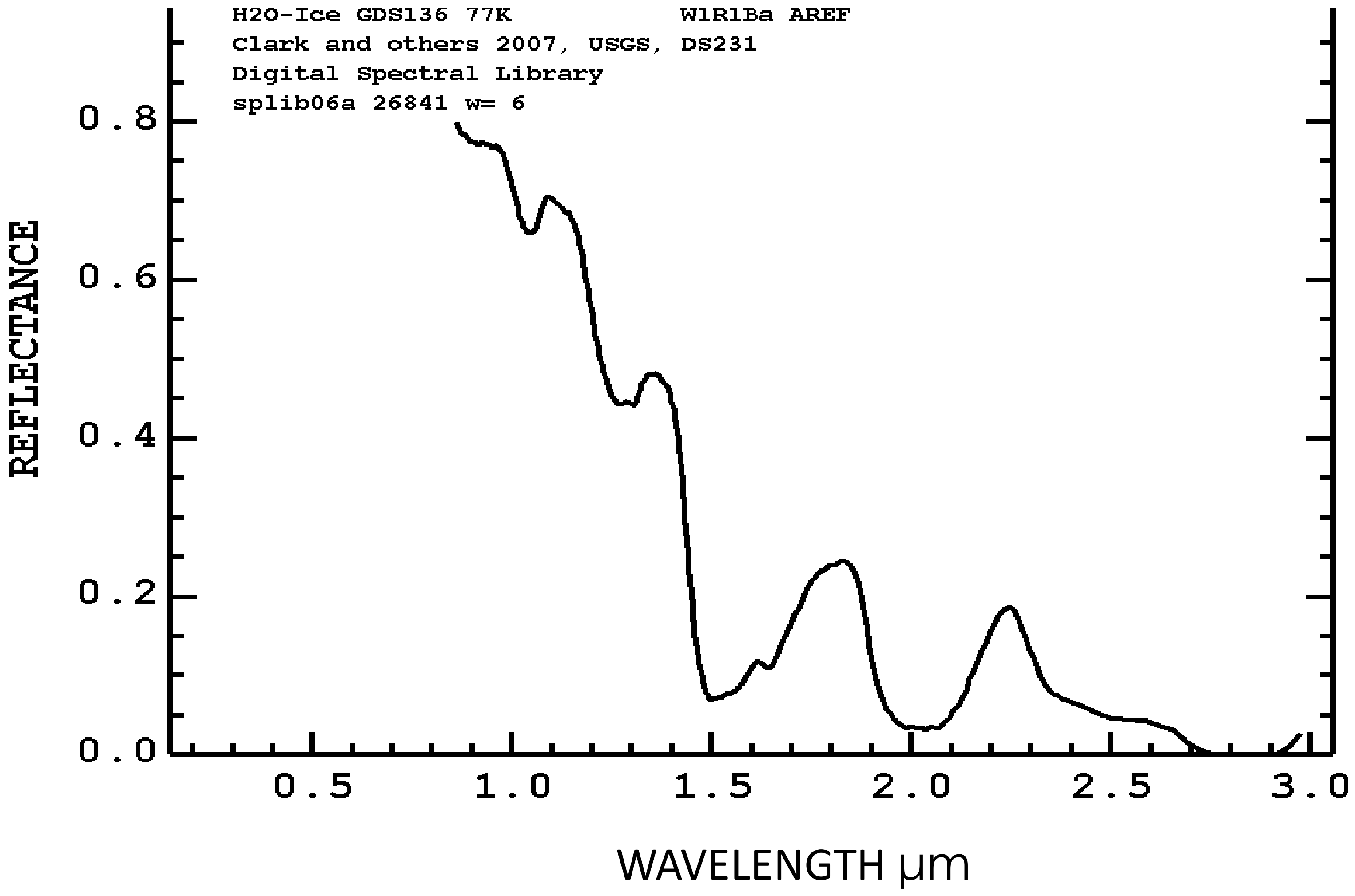


Chart of Frost IR Absorption

At the right is The near-infrared spectral reflectance of A) a fine grained (~50 µm) water frost, B) medium grained (~200 µm) frost, C) coarse grained (400-2000 µm) frost and D) an ice block containing abundant microbubbles. The larger the effective grain size, the greater the mean photon path that photons travel in the ice, and the deeper the absorptions become. Curve D is very low in reflectance because of the large path length in ice. The ice temperatures for these spectra are 112-140 K. From Clark *et al*. (1986).

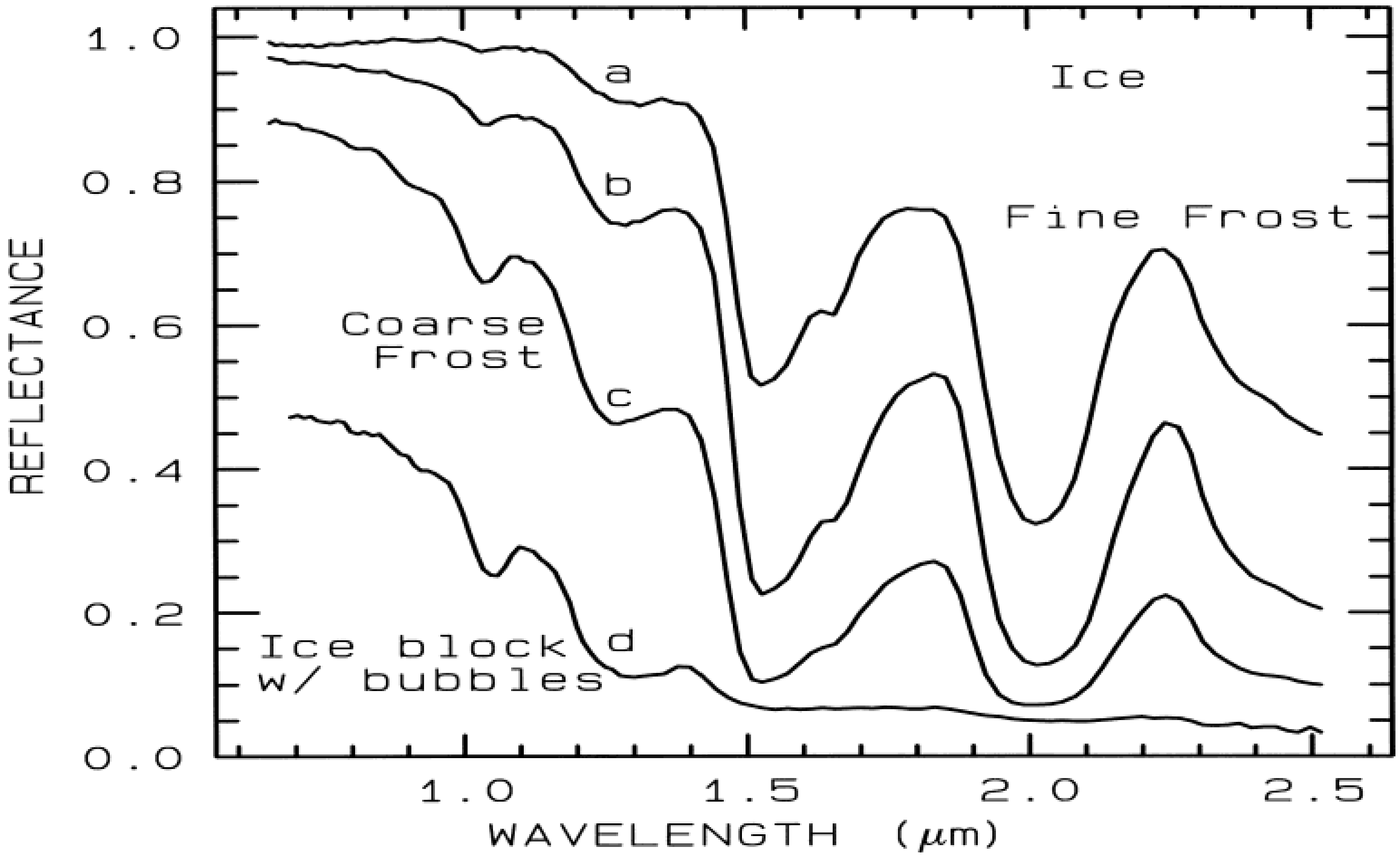
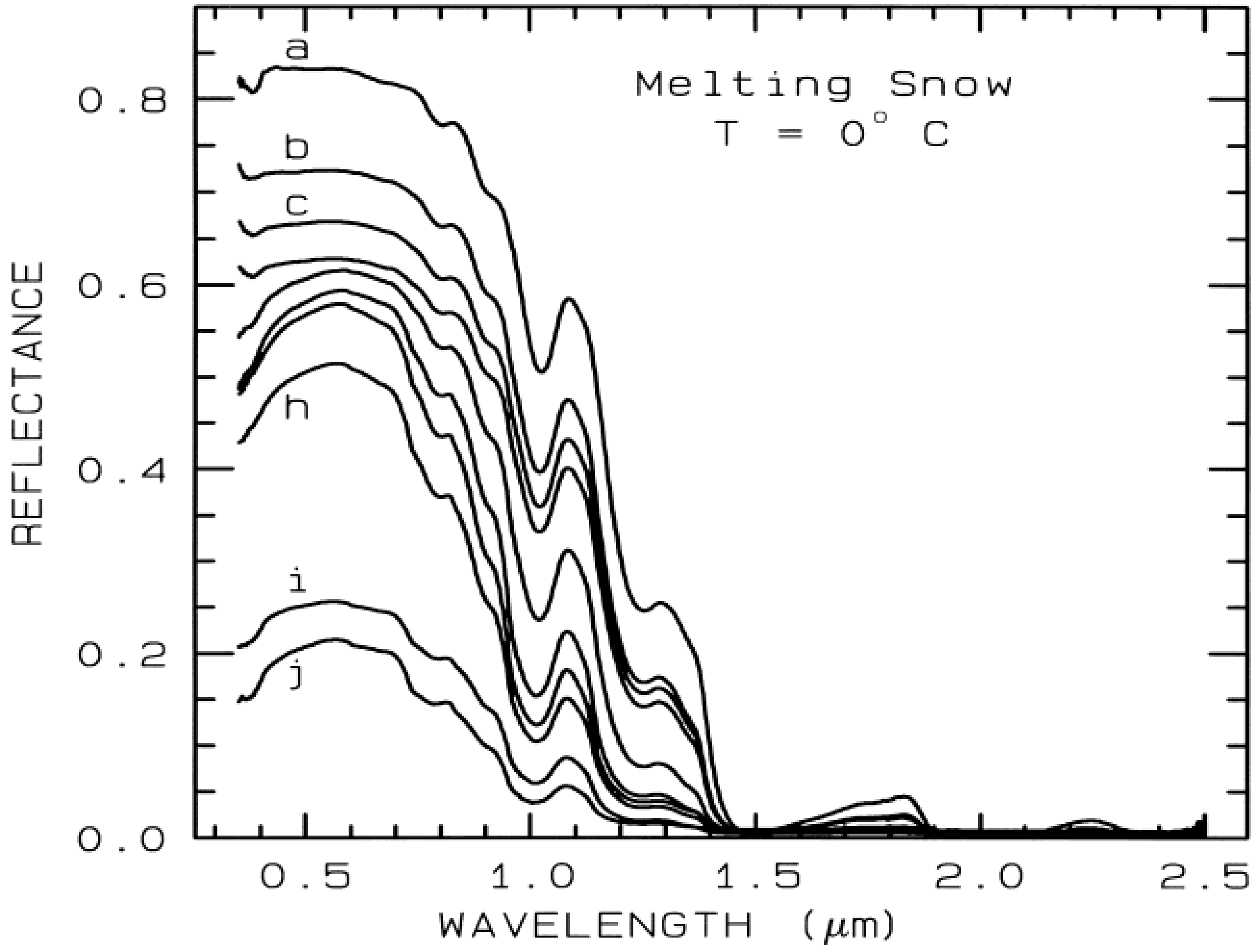
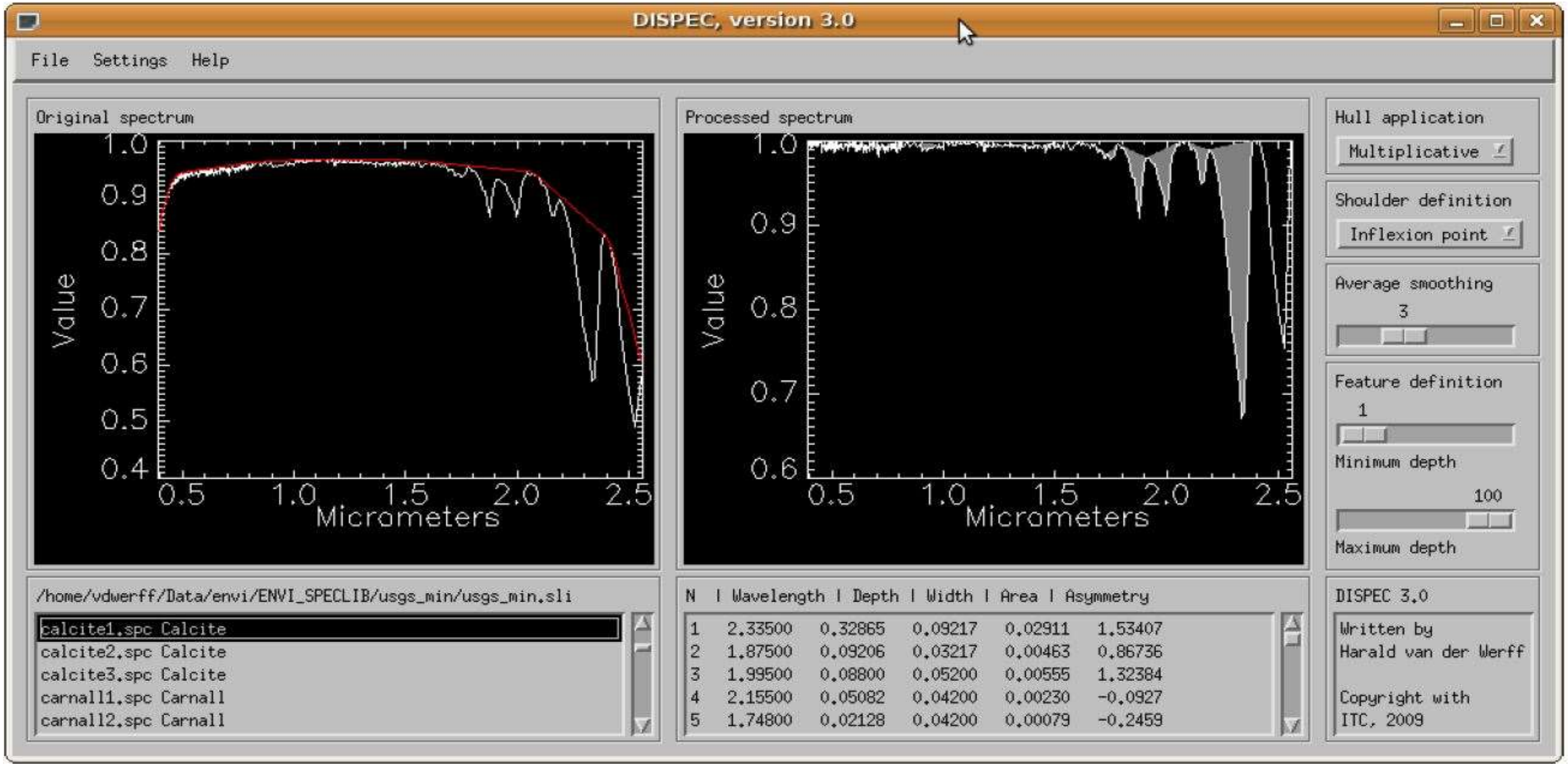


Chart of Melting Snow IR Absorption

A series of reflectance spectra of melting snow. The top curve (a) is at 0o C and has only a small amount of liquid water, whereas the lowest spectrum (j) is of a puddle of about 3 cm of water on top of the snow. Note in the top spectrum, there is no 1.65-µm band as in the ice spectra in figure 22a because of the higher temperature.. The 1.65-µm feature is temperature dependent and decreases in strength with increasing temperature (see Clark, 1981a and references therein). Note the increasing absorption at about 0.75 µm and in the short side of the 1-µm ice band, as more liquid water forms. The liquid water becomes spectrally detectable at about spectrum e, when the UV absorption increases. Spectra from Clark, King and Swayze, in preparation



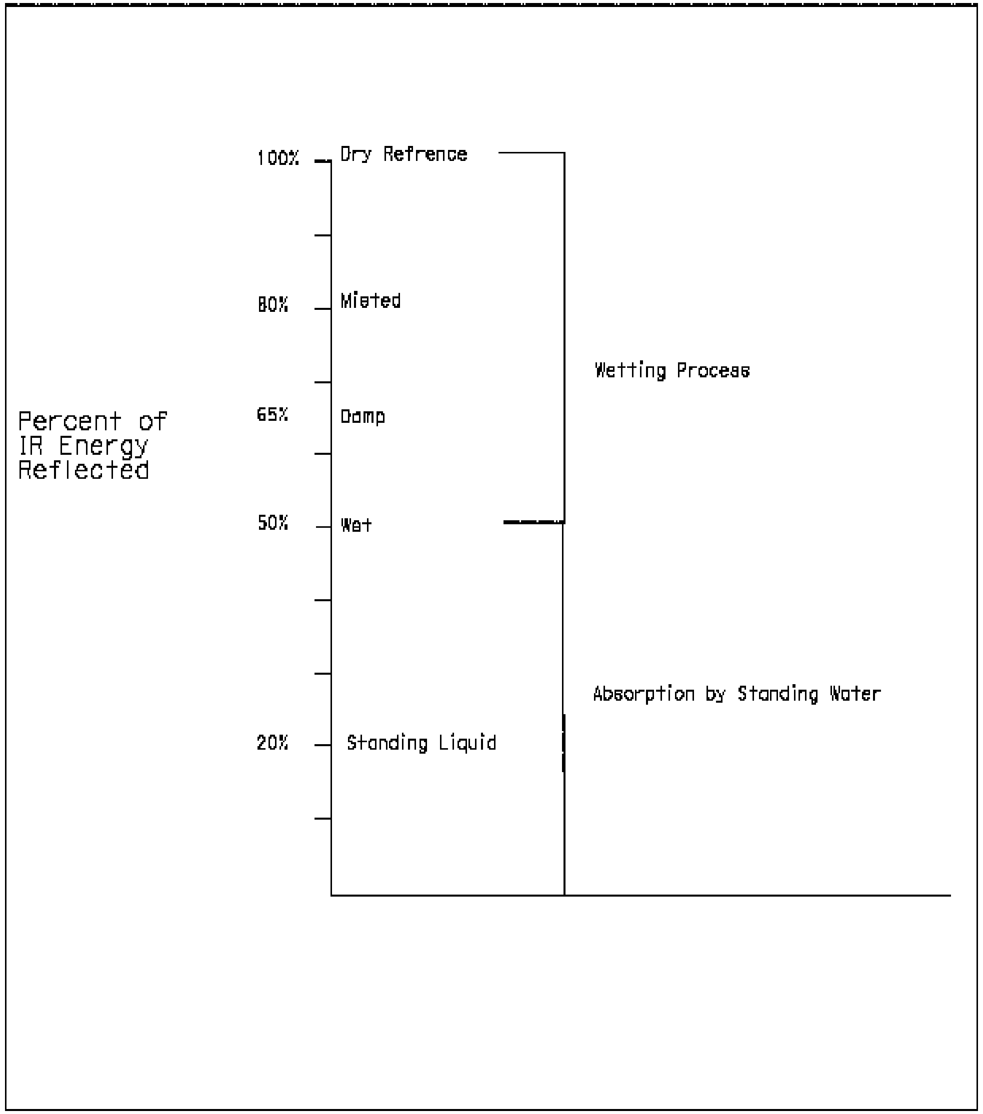
Continuum Removal



Continuum Removal is a mathematical process whereby the contour of the characteristic charts can be normalized to produce a clear spike identifying the characteristic of the material under examination. Image from [14]

Chart of NIPS Calibration Principal

Surfaces can be classified as being <u>"Wettable" or "Non-Wettable".</u> A wettable surface will soak up water at first like paper or dry concrete and is <u>characterized as a darkening of the surface</u>. A <u>non-wettable</u> surface will not absorb water such as glass or plastic the water will simply <u>bead up or runoff.</u> This chart describes the "wetting process" which is responsible for the trace moisture readings that can translate to either frost or trace moisture under the right circumstances. This helps in understanding how <u>important it is that NIPS calibration be done on absolutely dry pavement</u>.



Perceived limitation of NIPS ability to detect lowered freezing point.

- **Initially there was a concern that NIPS technology might not be able to detect lowered freezing point when de-icing chemicals were present, which could exclude NIPS from correctly identifying water in liquid form at temperatures below freezing.**
- **It turns out not to be an issue because the reliability of IR spectroscopy to detect ice crystals is so well established that predicting the freezing temperature offset due to de-icing chemicals is unnecessary. NIPS can directly detect ice and frost.**

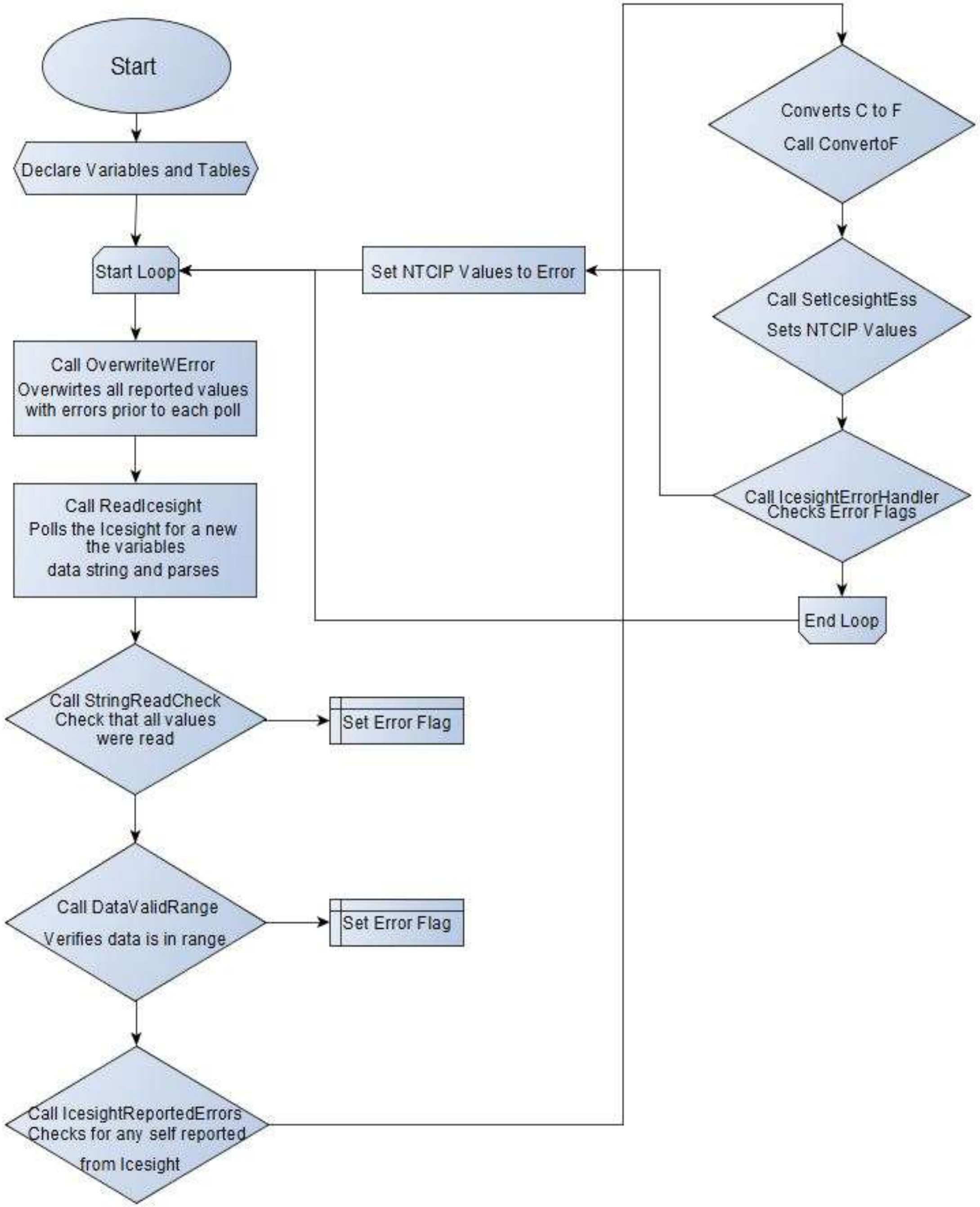
NIPS Software Development for the Campbell Scientific CR1000 Datalogger

- ►Campbell Scientific, (CS), provided sample code for both NIPS products we tested CR1000 datalogger.

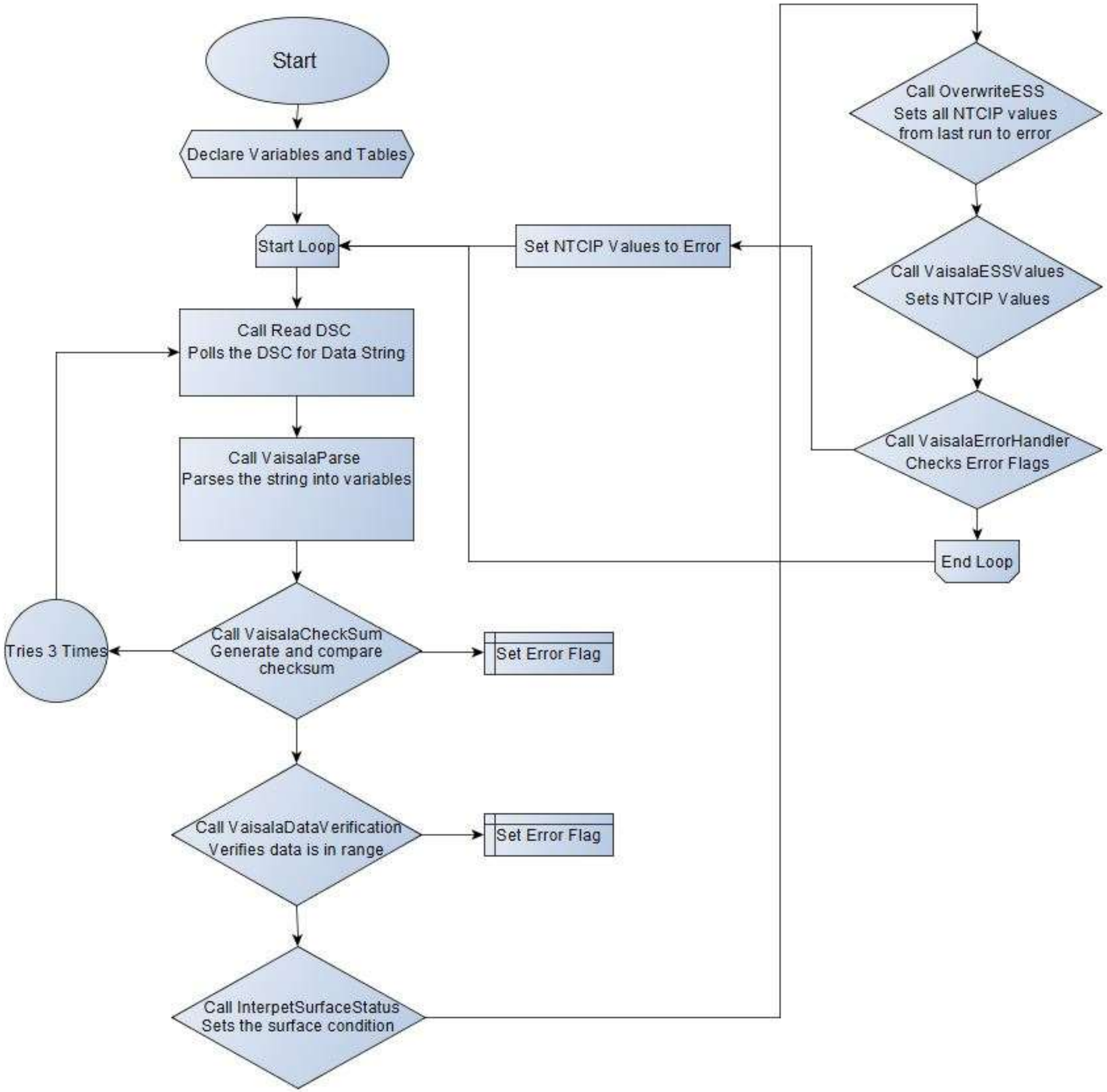
- ►Numerous versions of code were developed over the course of the evaluation and the final versions of the code for each NIPS are and are available on request.

CR 1000 Code Flow Chart for the Icesight.

Note: There is a critical wait state in the ReadIcesight subroutine that is necessary in the polling process.

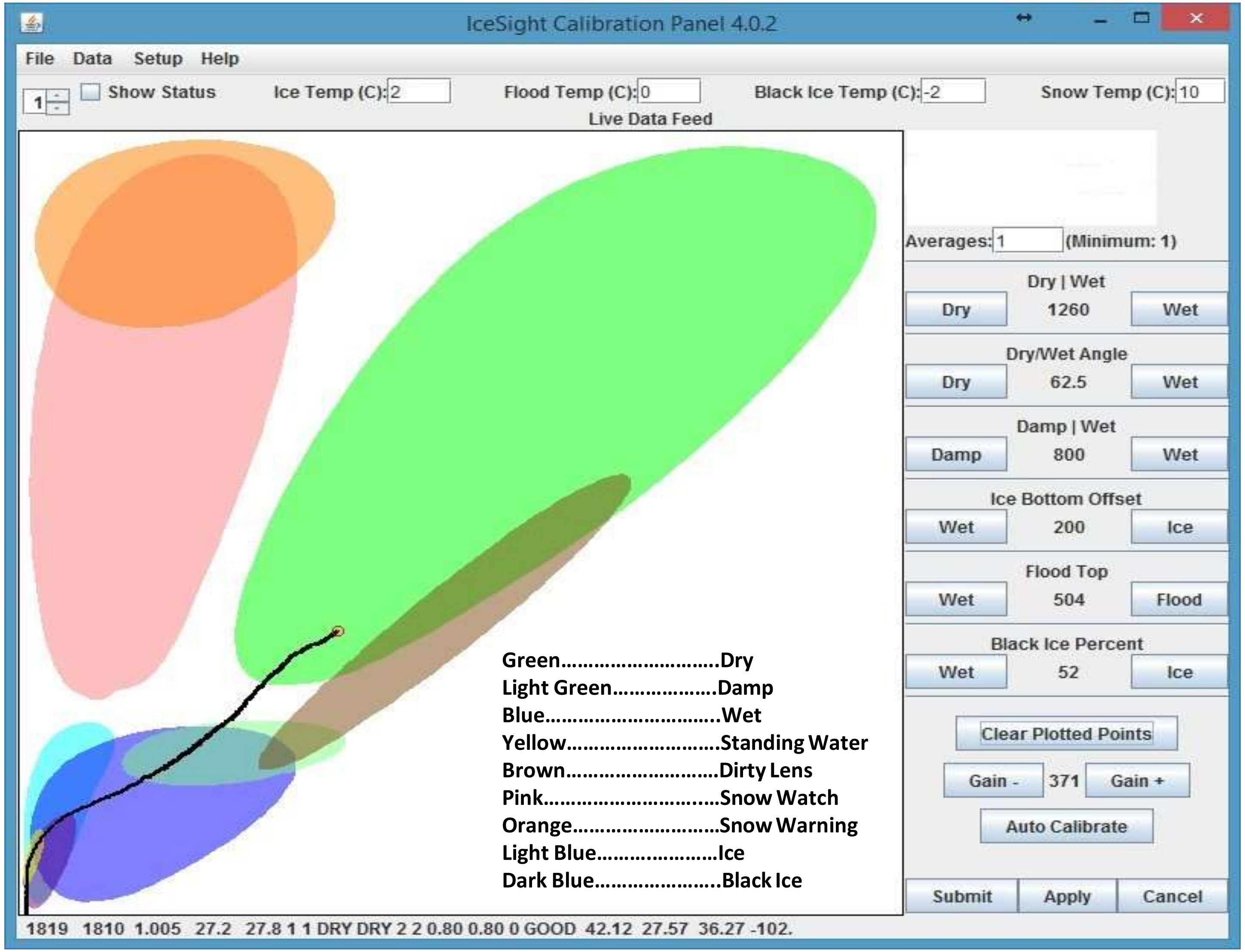


CR 1000 Code Flow Chart for the Vaisala Note the Inclusion of the checksum test.



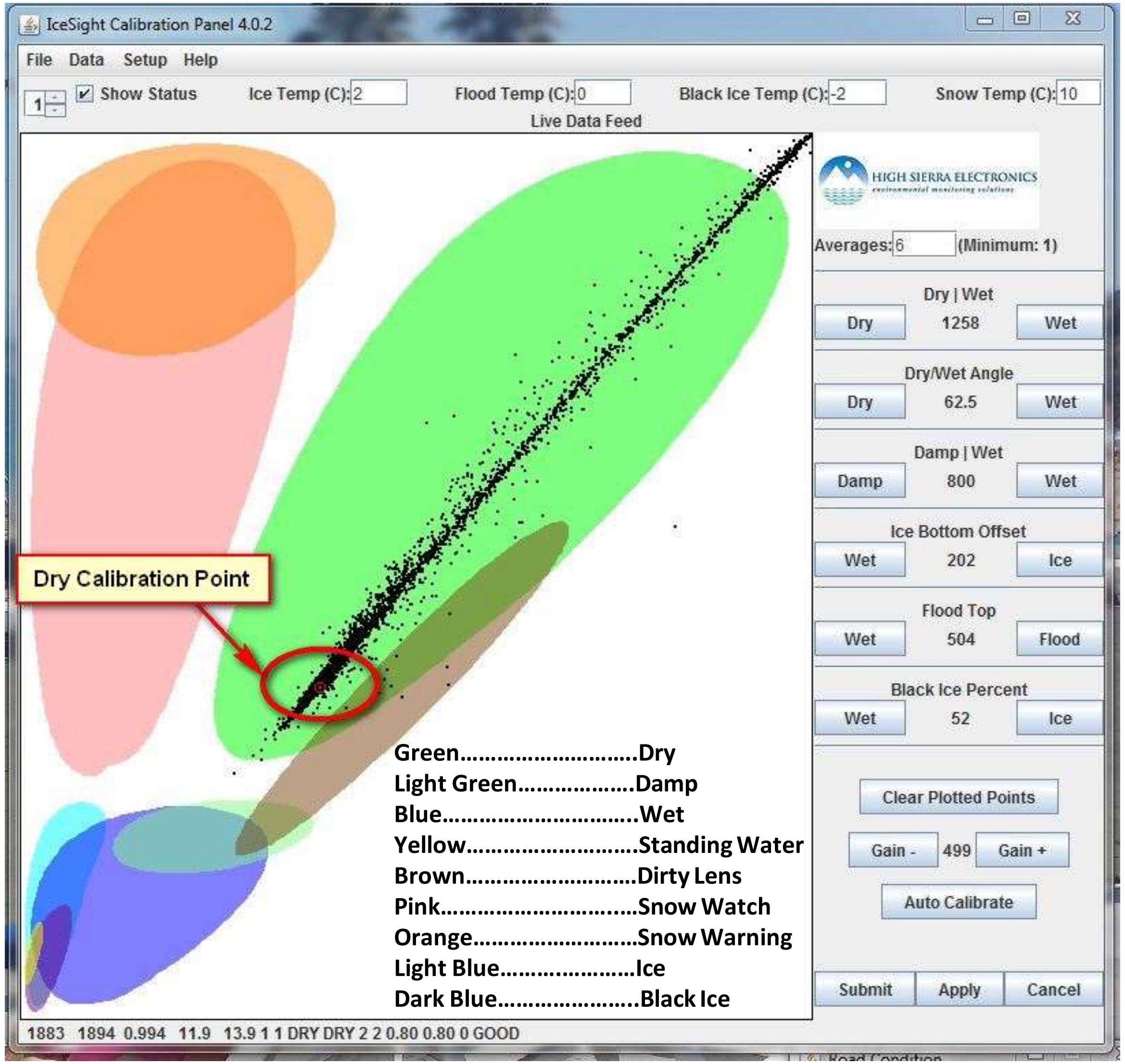
Icesight Calibration in Office

At the right is a Java window used to access live Icesight reporting from the field. This utility allows the Icesight to act as a stand alone sensor without the need for a full RWIS. This graph shows an overnight curve created in my office during code development. This curve depicts a block of concrete frozen to -20º F and covered with ice. The block was placed in the field of view and left to acclimatize to room temperature and dry overnight. The resulting curve is an ideal curve showing the transition from ice, to wet to dry.



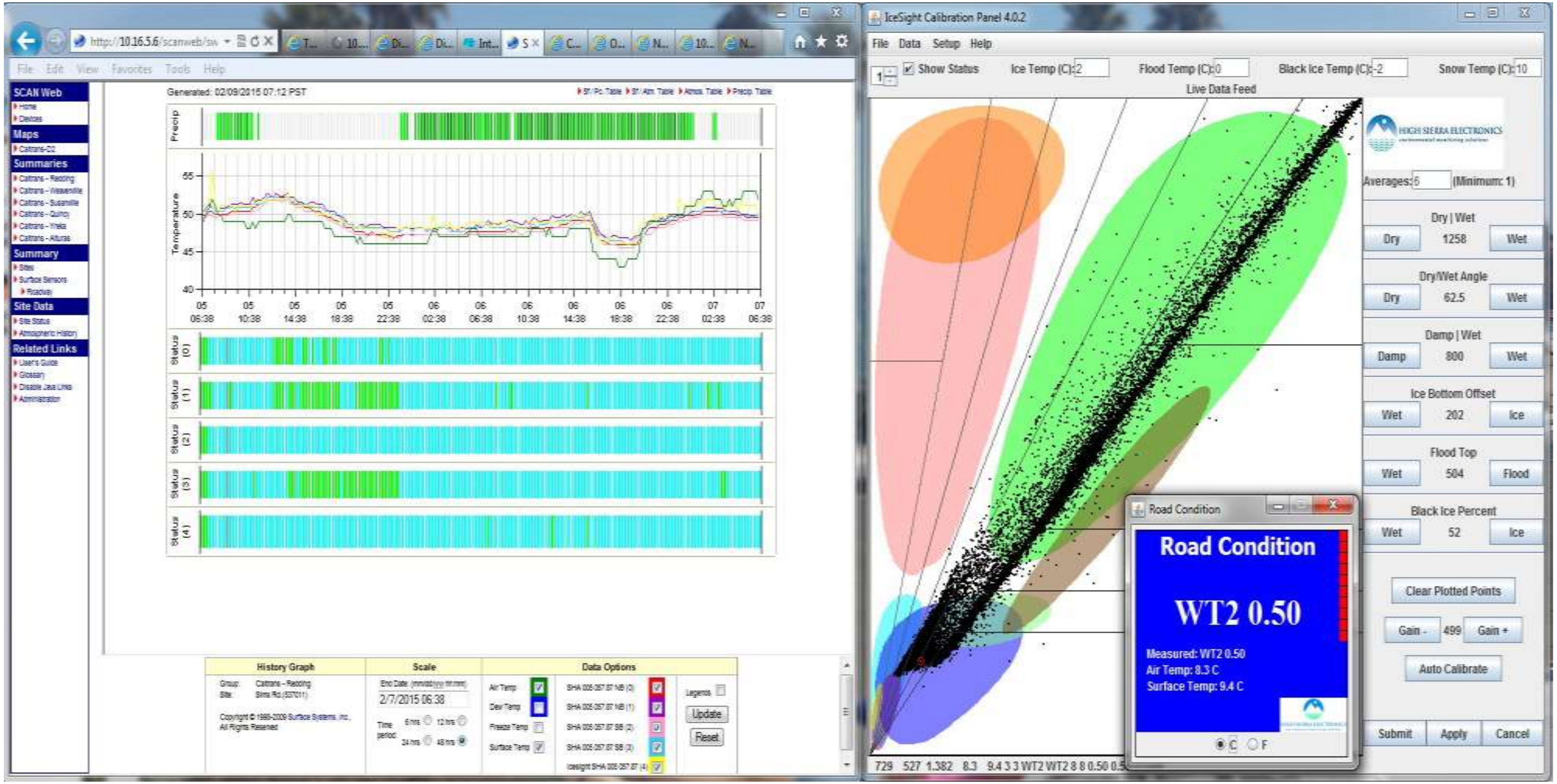
Icesight Calibration in the Field

At the right is a <u>calibration curve created in the field</u> at Sims road. This curve depicts the dry calibration process where the Icesight is calibrated to dry pavement in a live traffic environment. Note the grouping of reading around the dry calibration point and the line of readings projecting up to the upper right corner. The line leading to the upper right are vehicle interference reads and need to be averaged out in normal operation.



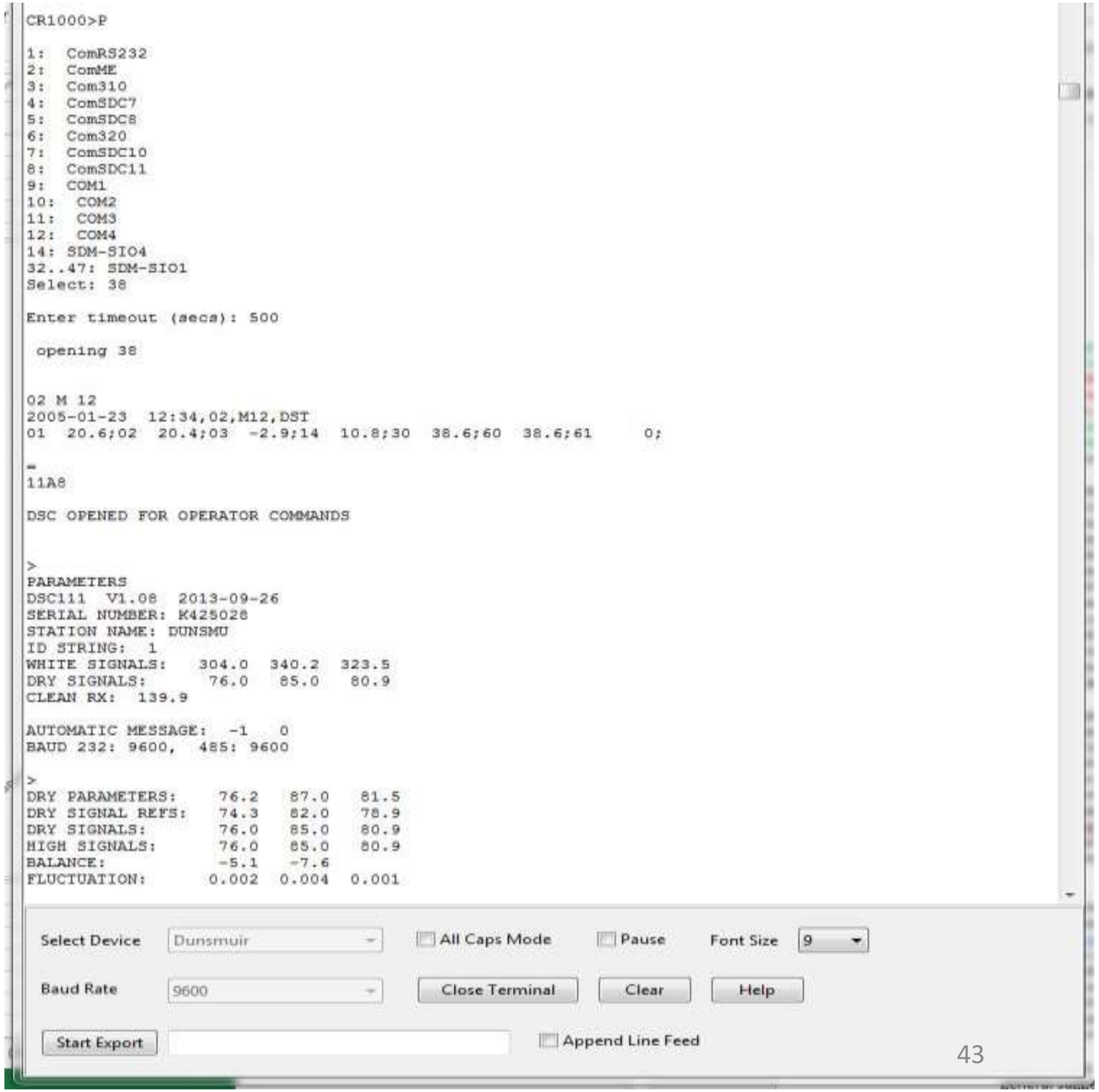
Monitoring Icesight with Live Traffic in a Storm

At the right is a long term monitoring curve created in the field at Sims road. This curve depicts a storm with live traffic. Again notice the amount of reads that need to be averaged out.



Setting Dry Calibration on the Vaisala

- The calibration of the Dry Parameters on the Vaisala DSC is detailed in the Vaisala manual and can be performed remotely through the Loggernet program.
- Loggernet is a separate software package from Campbell Scientific for administering and programming the CS dataloggers.
- At the right is a log of viewing the Current Dry Parameters setting on the Vaisala using the Pass through command in the CS 1000 Loggernet Programs terminal emulator.



Dry Calibration Tracking on the Vaisala

- **The calibration of the Dry Parameters on the Vaisala DSC sets the *Dry Parameters* value to match the reflected signal strength of dry pavement at that time.**

- **As time progresses and the pavement surface changes a value called *Dry signal refs* is set to new values that track the reflected signal strength changes over time due to changes in the pavement surface condition.**

- **The higher of the two values is then used in making pavement status evaluations and "Tracks" the pavement changes over time.**

- **The tracking value may be lost on a reset of the DSC and can result in considerable changes in reported status till enough cycles of dry status have accumulated.**

- **This then in effect is an un-calibrated system and is the reason I do not recommend deploying a automated system with a single IPS sensor.**

Vaisala Configuration Panel

At the right is a Vaisala configuration panel listing the current settings and showing how to change setting 7 below, here showing turning ECHO off on the 485 line. Note the item 48 VisLimit this setting is discussed later in the presentation and sets the visibility limit below which the Vaisala goes into error mode due to low visibility.

```
BEL
>conf

VER: DSC111  V1.08  2013-09-26 SN:K425028
CONFIGURED PARAMETERS, SIMSDSC
 1 Mode         1.000,  2 HIST intv    10.00,  3 Rosa ID     0.000
 4 Slave A      2.000,  5 Slave B      0.000,  6 Slave C     0.000
 7 ECHO 485     1.000,  8 Heat PWR T   2.000,  9 Heat PWR R  2.000
10 Heat VBlow   12.00, 11 Tbox SC0   -271.00, 12 LowSignal   0.005
13 SlushSlope   0.050, 14 Dryli        0.010, 15 SumDryli    0.400
16 Wetli        0.020, 17 Snowli       0.030, 18 SumSnowli   0.450
19 WaterSc      0.160, 20 IceSc        0.150, 21 SnowSc      1.600
22 Grip0        0.050, 23 Grip1        0.050, 24 GripSlush   0.270
25 GripMin      0.090, 26 GripDry      2.100, 27 IceDry      2.100
28 Aqua        200.00, 29 FrLim1       0.600, 30 FrLim2      0.400
31 AlfaX        1.000, 32 AlfaY        1.000, 33 fast noise  0.200
34 fast min     30.00, 35 slow noise   0.050, 36 slow min    5.000
37 Dry wht      4.000, 38 Clean Rx    132.79, 39 Warn Rx     0.600
40 Alarm Rx     0.300, 41 Dirt dT      0.000, 42 Auto Dry    0.200
43 Dry adjust   0.980, 44 Grip SC1     1.000, 45 FOG offset  0.000
46 FOG base   1000.00, 47 TA DSC      -2.000, 48 VisLimit   250.00
49 VisTimeout 150.00, 50 MESO CSUM     3.000, 51 DryStoLim   0.030

>conf 7 0
```

Specifications: NIPS Temperature Accuracy

- **The Icesight specifies the surface temperature accuracy as:**

  +/- 0.8°C or +/- 1.44°F from -5°C to +5°C

  +/- 3.3°C or +/- 5.94°F from -40°C to +55°C

- **The Vaisala DST specifies a surface temperature accuracy as:**

  +/- 0.3°C or +/- 0.50°F

  <u>As long as the difference between the device and the surface is less than 10°C</u>.

Part II
Testing In Live Highway Environment

When and Where
Fall 2014 through Spring 2016

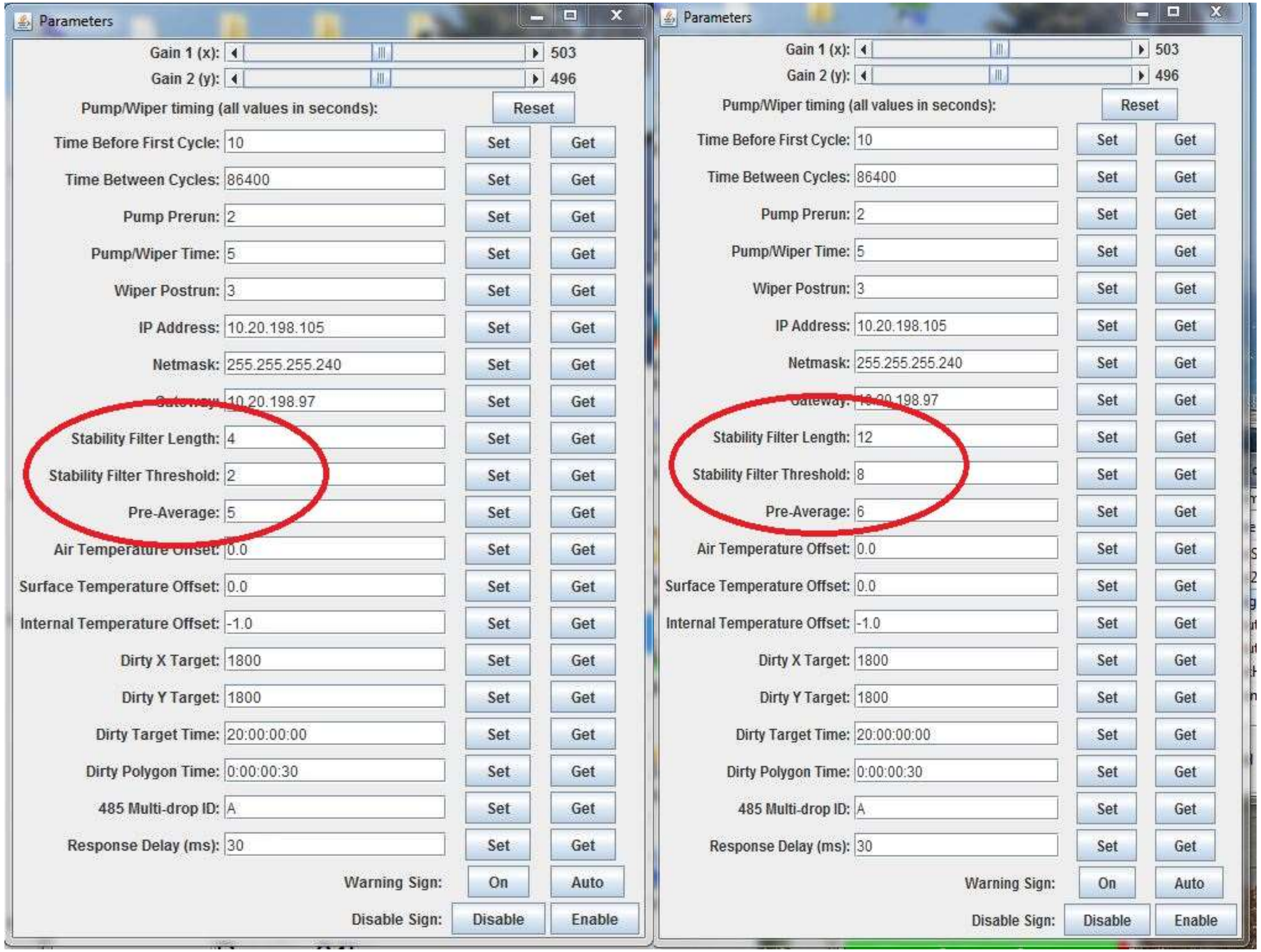
- ►This evaluation took place over two winters from the fall of 2014 through the spring of 2016.
- ►The winter of 2014/2015 the first test system was deployed at Sims Road and I-5 there was not enough inclement weather to complete the investigation, but it did provide a couple of interesting incidents. In addition this site gave us a comparison to the Lufft IRS 21 IPS.
- ►The winter of 2015/2016 the equipment under test was moved to two locations; Snowman Summit on highway 89 to compare with FP2000 IPS and then to I-5 in Dunsmuir to compare with Lufft IRS 31 Pro IPS.

Sims Road Experience Gathered

- The first important discovery was that running the Icesight in a live highway environment multiple reads by the IR spectral analysis system are interrupted by vehicles and errors were reported which had to eliminated by changing the averaging parameters.
- The one interesting snow event we had we were not able to analyze as thoroughly as we would have liked because we didn't have a complete enough image archive to go along with the sensor data, the need for a good image archive became apparent.

Sims Vehicle Interference Errors

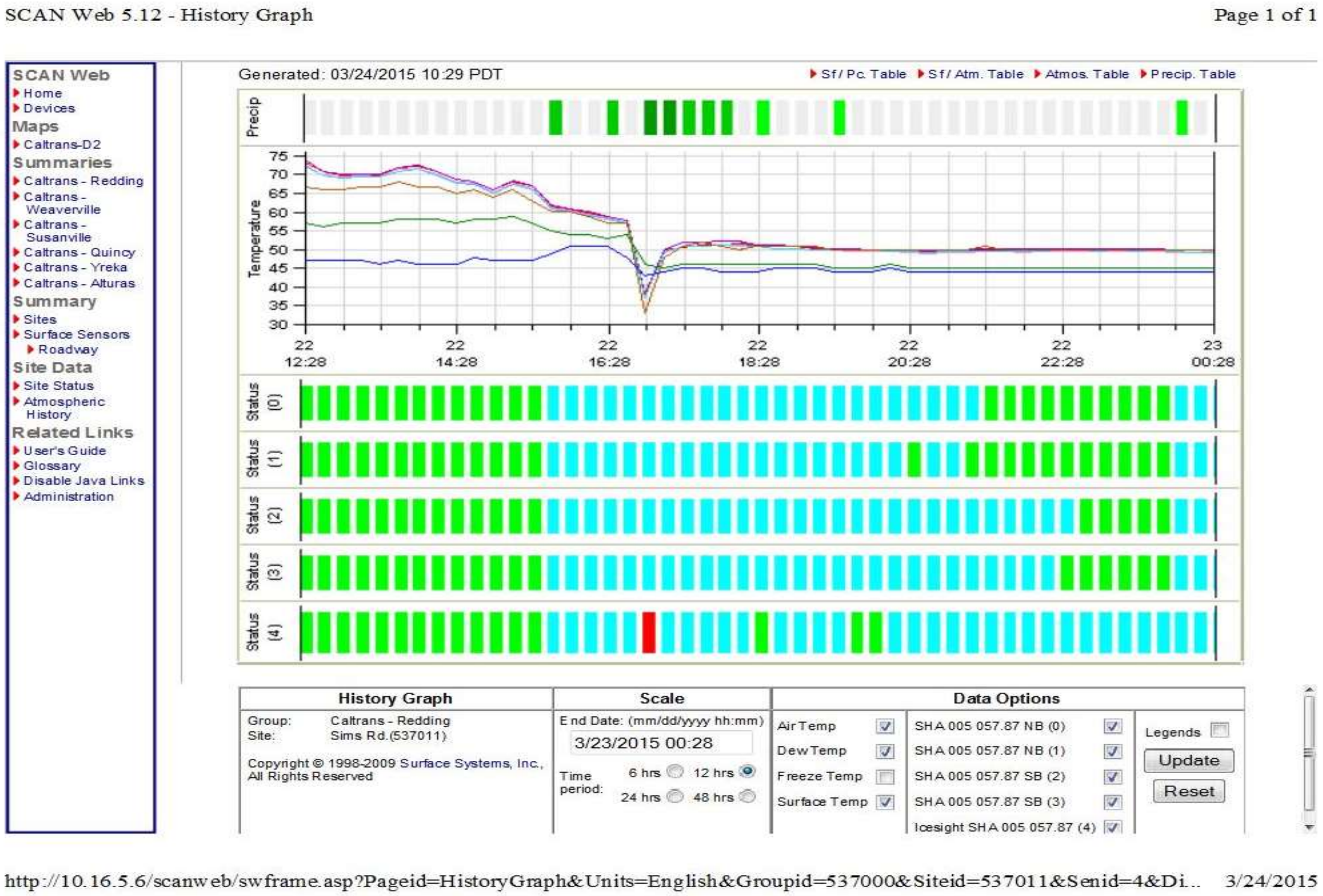
Each time a vehicle is in the Icesight's line of view to the pavement the values returned by the lasers rise to a maximum, which corresponds to a pavement condition of "Error." The averaging values in the Parameters screen of the configuration utility were set too low for a live traffic environment. Researching the settings and setting up a live logging routine to monitor the error occurrences while increasing the averaging values the vehicle read errors were eliminated.



First Activation of Ice Warning

This was our first interesting event, a Scanweb report showing an <u>ice warning event reported by the Icesight</u> which the IPS did not capture.

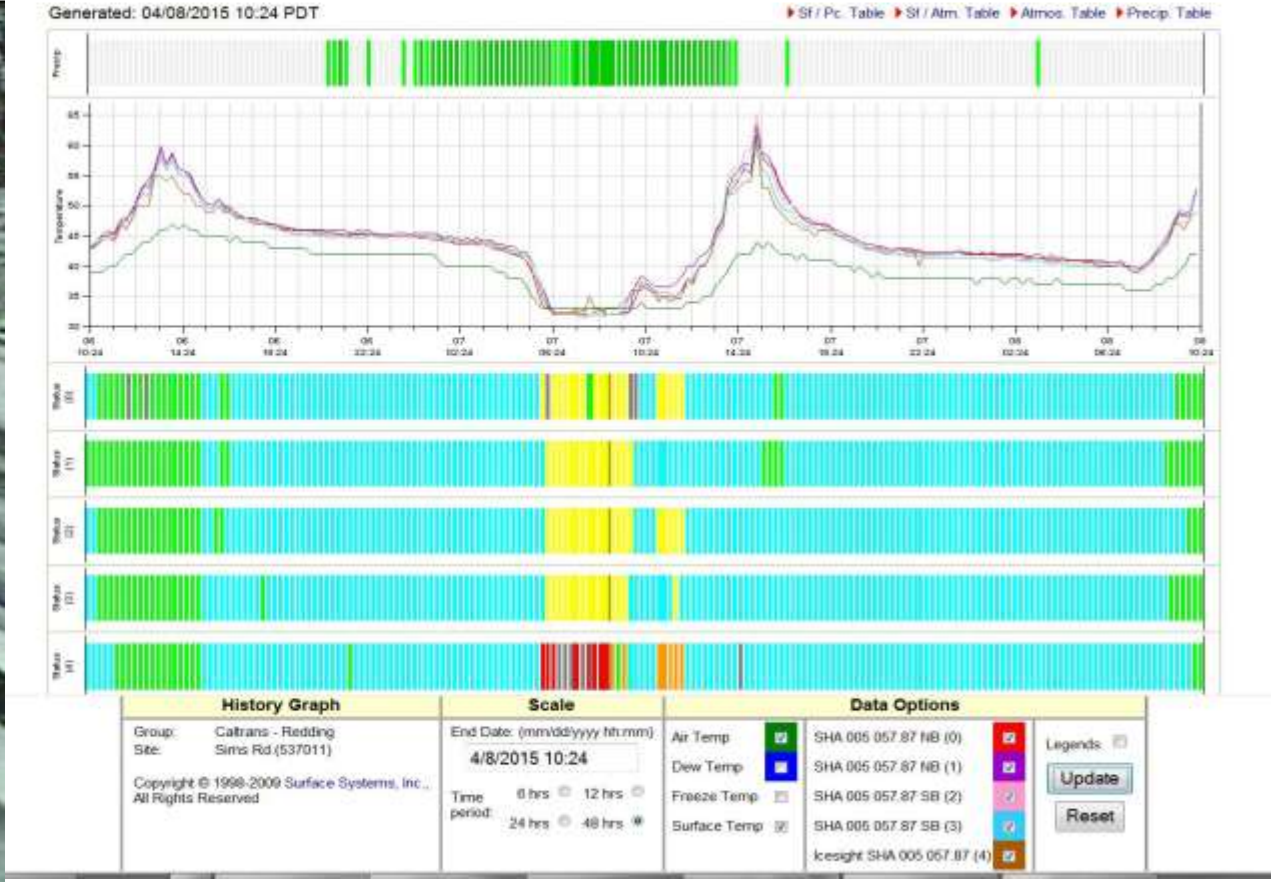
It is also worth noting the <u>indications of dry by the Icesight shortly after the hailstorm which may indicate fog</u> that evening, but again this points out that without an image archive it's nearly impossible to arbitrate conflicting reports between sensors.



Hailstorm Investigation

Investigation of the ice warning revealed a hailstorm as root cause. In an interview with the local truck stop owner he stated there was a significant hailstorm with what he called almond size hail, and he further reported that traffic was pulling off the freeway and waiting the storm out. So we have confirmation of the incident reported by the Icesight as a condition of Ice Warning as a significant incident impacting traffic flow. At the right is an image on the aftermath of the hailstorm showing the remnants of hail on the shoulders.

Activation of Snow Warning



At the right is the Scanweb report of the <u>snow warning and watch in April of 2015</u>. In this incident the IPS reported only chemically wet but the indicates a <u>snow warning was a more correct</u> characterization of the actual pavement condition. It is also worth noting the indications of dry and error by the Icesight may indicate fog or low visibility during the incident. Yet again this points out an image archive is indispensable in pavement condition analysis.

I-89 at Snowman’s Summit

Installing the out of pavement sensors at the Snowman’s Summit RWIS October 2016.

Snowman Summit Pavement Sensors Both In and Out

Installation of the out of pavement sensors at Snowman Summit with in pavement FP2000 sensors in the road below. The NIPS were installed 20’ up and 25’ from ETW on a wood box beam sign post. <u>Note one of the IPS is in the soft median.</u>

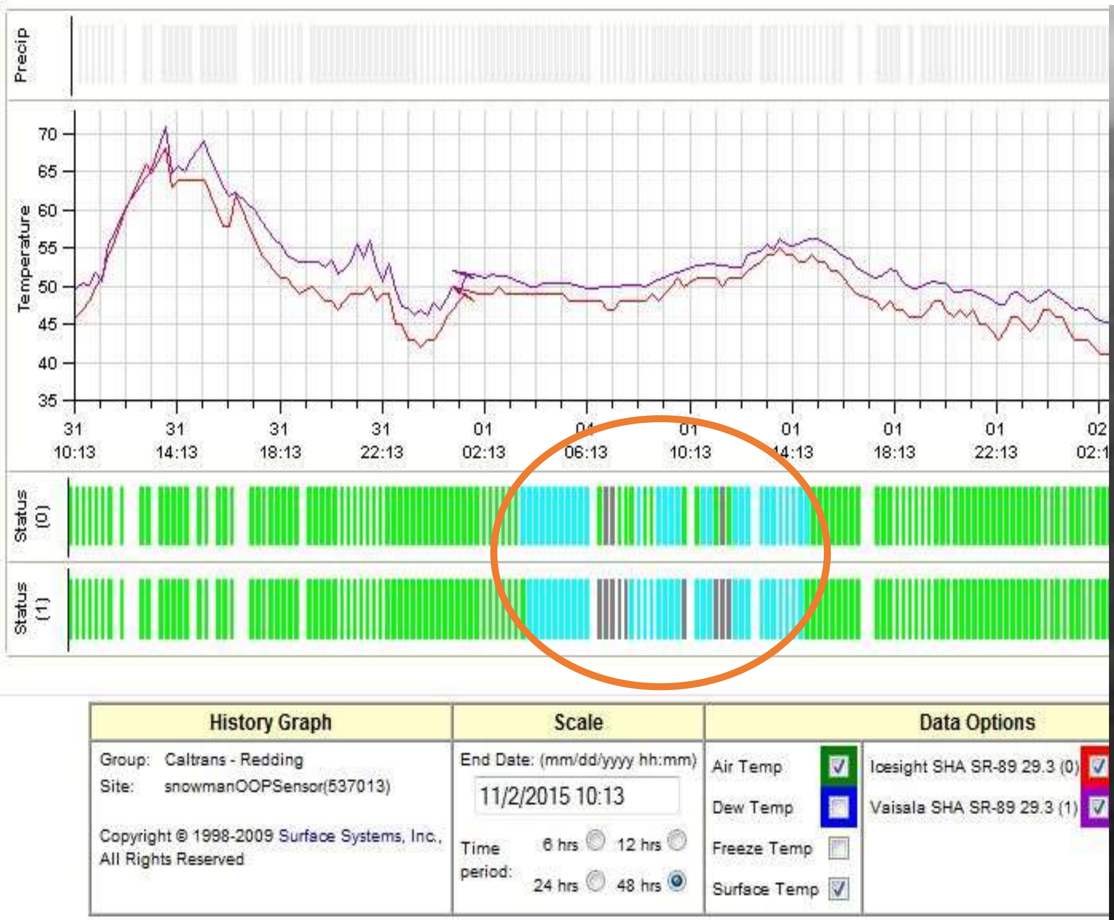
Snowman Install details

- **Proper aiming of the NIPS was observed to include the <u>lanes only in the IR temperature sensors cone of view</u>.**
- **Setting IR spectral surface sensors to not interfere with each other. Care was taken to aim each of the NIPS about 8 feet on each side of the in pavement sensors to ensure the <u>laser emissions from one NIPS would not interfere with the other NIPS.</u>**
- **The look angle of sensors from the pavement up to the NIPS was calculated to be approximately <u>40° elevation well within the manufacturers specifications</u>.**

Snowman Datalogger Installation

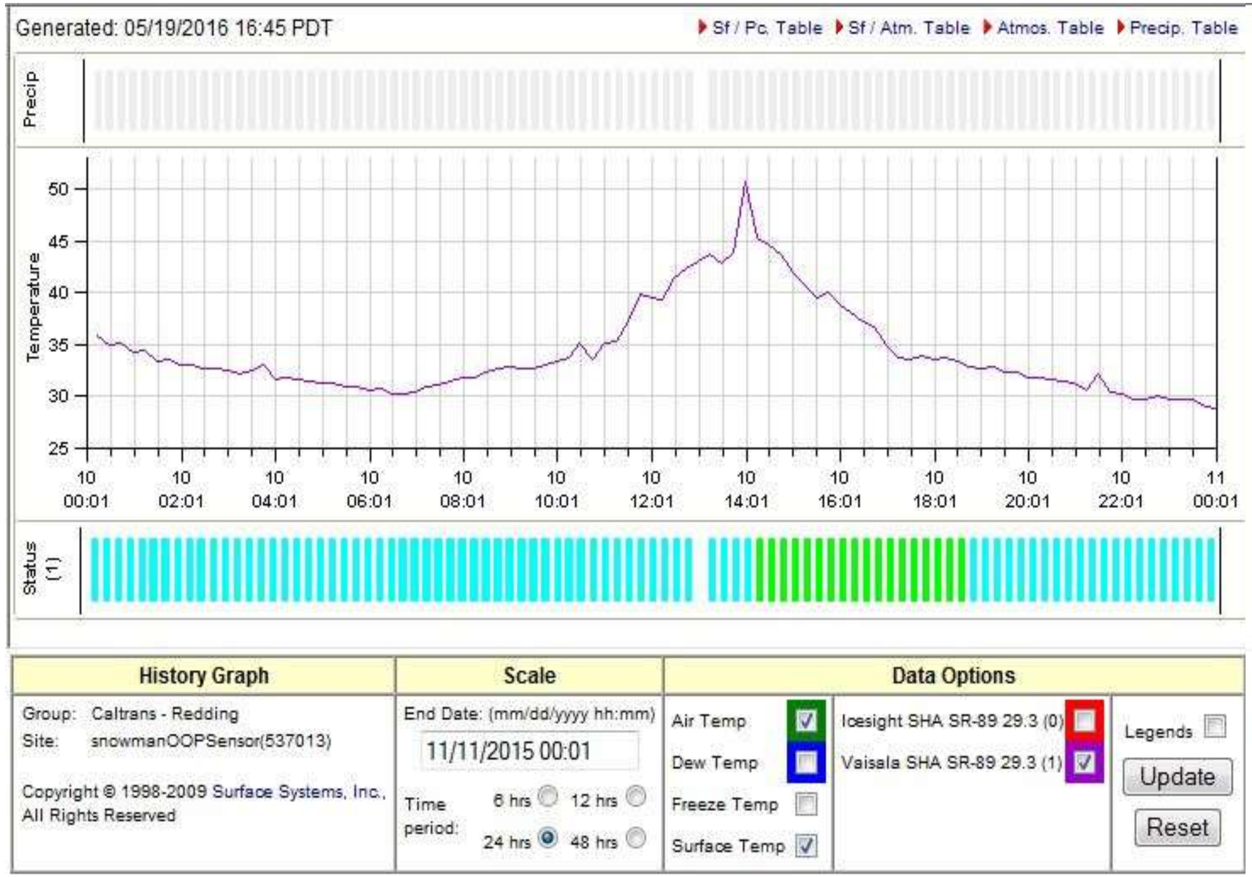
A separate datalogger had to be installed at the Snowman site as this site has a SSI RWIS that would not support the NIPS. This meant we had to have two instances of ESS at the Snowman location in Scanweb. <u>So when we see images of Scanweb captures later in the presentation they are compilation's of the two instances of the ESS Scanweb at the Snowman location.</u>

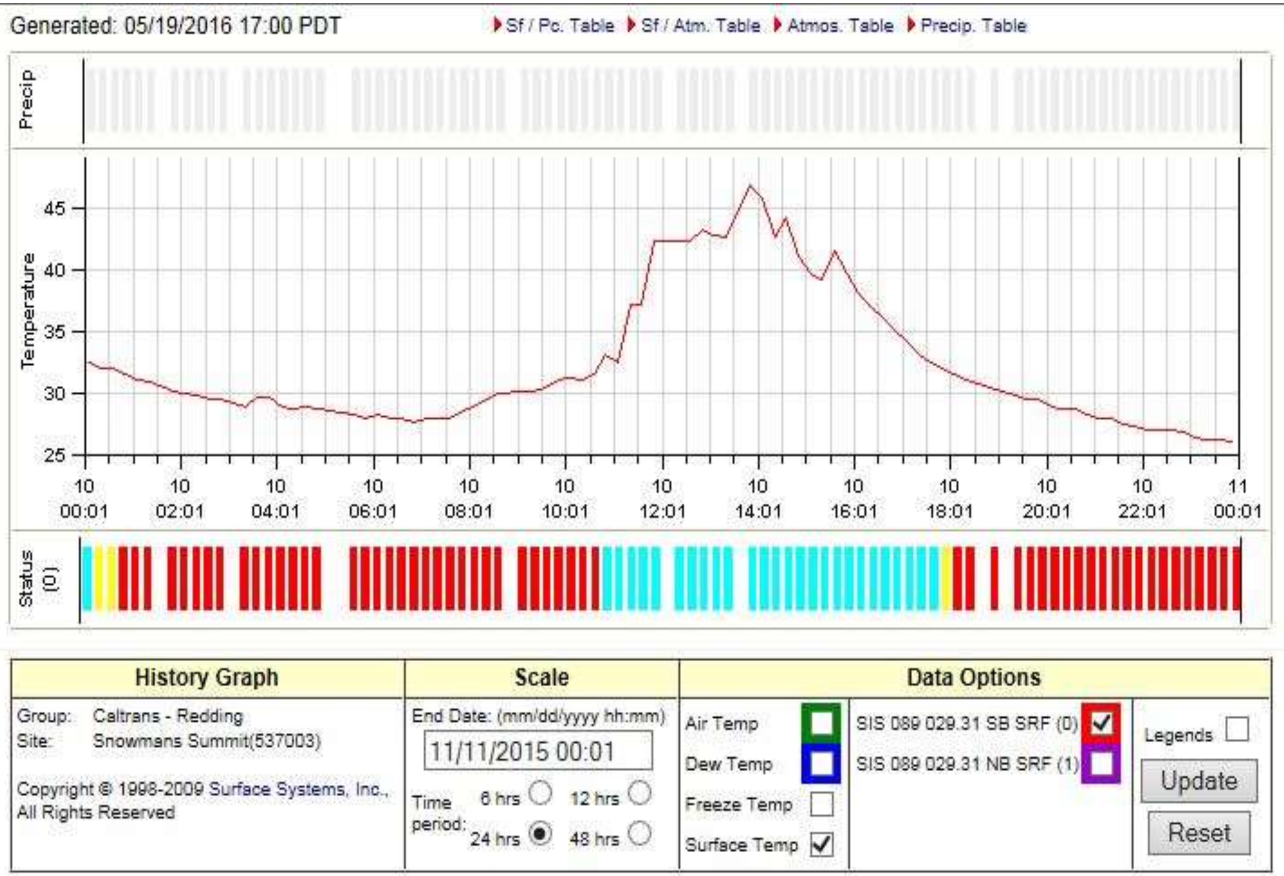
Interesting Event Due to Fog November 1, 2015



The video shows the visibility conditions during <u>error and erroneous dry reports from the NIPS</u> sensors. This fog incident lead me to contact both vendors which resulted in both vendors coming up with methods to report this condition as either fog or low visibility. By the time we got the updates it was too late in the test cycle to fully evaluate the updates. In addition the Vaisala product can be ordered with a visibility option which will report this condition without modification.

Interesting Event Nov. 10th 2015 IPS Reports Ice NIPS Trace Moisture





The right Scanweb report shows the IPS where the Vaisals NIPS is aimed. The left Scanweb report shows the Vaisala NIPS. See next slides for graphs and video of the conflicting reports.

IPS Ice Warning

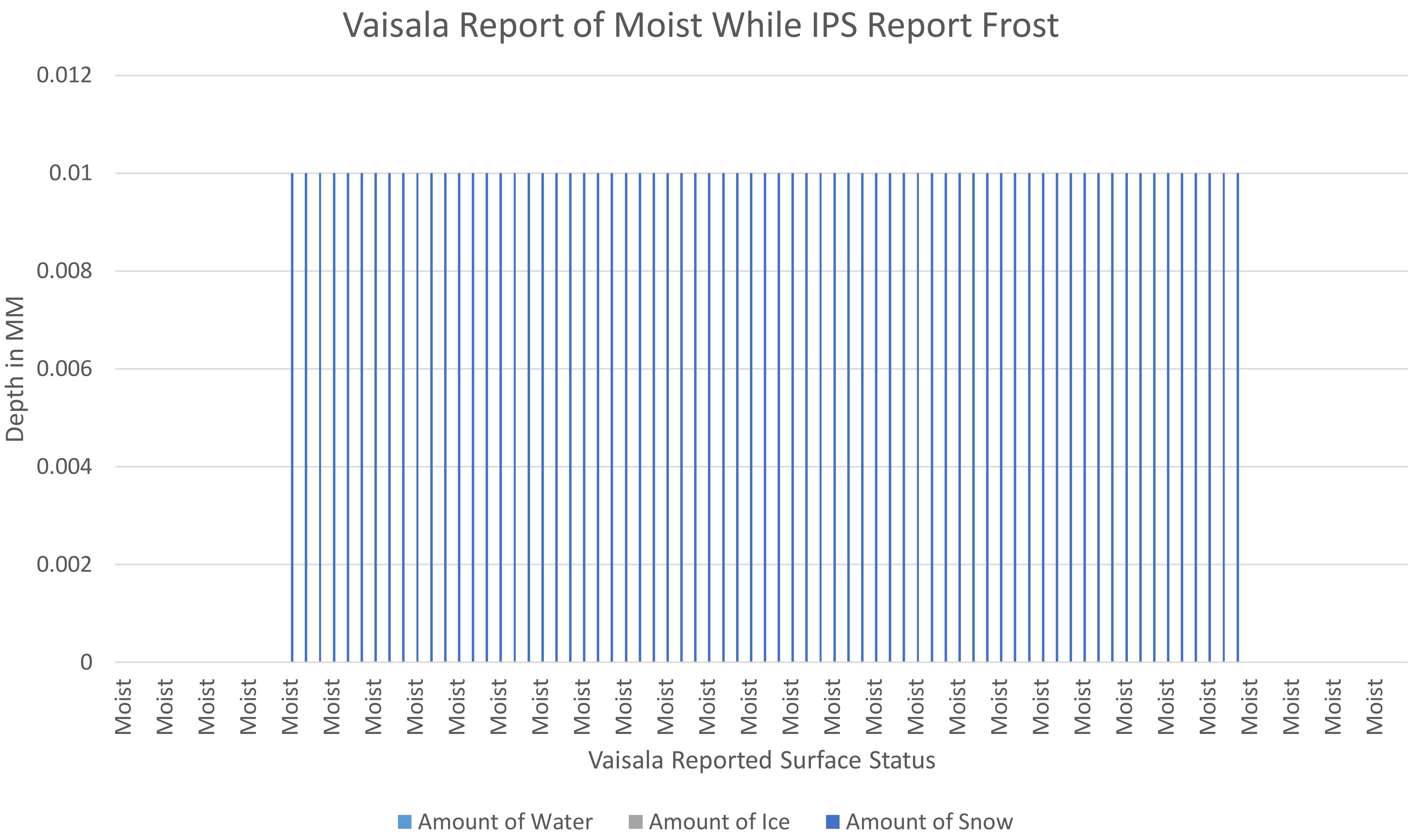
This video covering the daylight hours of November 10th 2016 we compare conflicting reports from the IPS and NIPS. From 1:00 A.M. till 10:20 A.M. the IPS reports ice warning while the NIPS reports trace moisture. It appears the ice warning from 8:30 from on is incorrect.

This incident was one that initiated the addition of an HD capable camera to the post with the NIPS. This is also a reason to recommend a best practice of installing a camera and lighting with any type of pavement sensor.

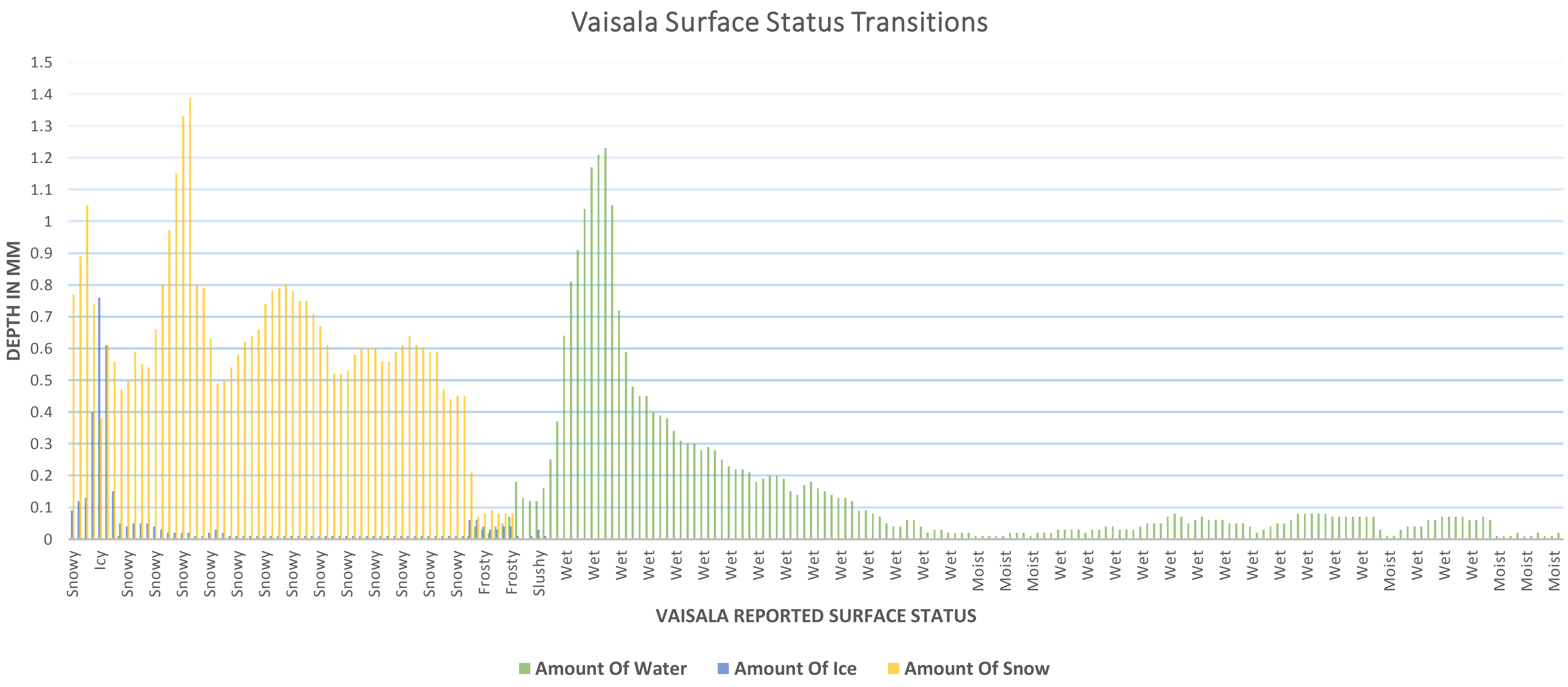
For further analysis we look at the raw data from the Vaisala on the following slides.

NIPS Moist Vs. IPS Frost Data Evaluation

At the right is a graph of the surface covering reported in the Vaisala data logs. Which shows an extremely shallow layer of snow on the pavement 1/100th of a mm which Vaisala has chosen to report as moist. On the next slide for comparison is a similar graph showing a incident where the Vaisala NIPS transitioned through snow, to ice, to snow to wet and finally to moist.



Vaisala Surface Status Transitions Example



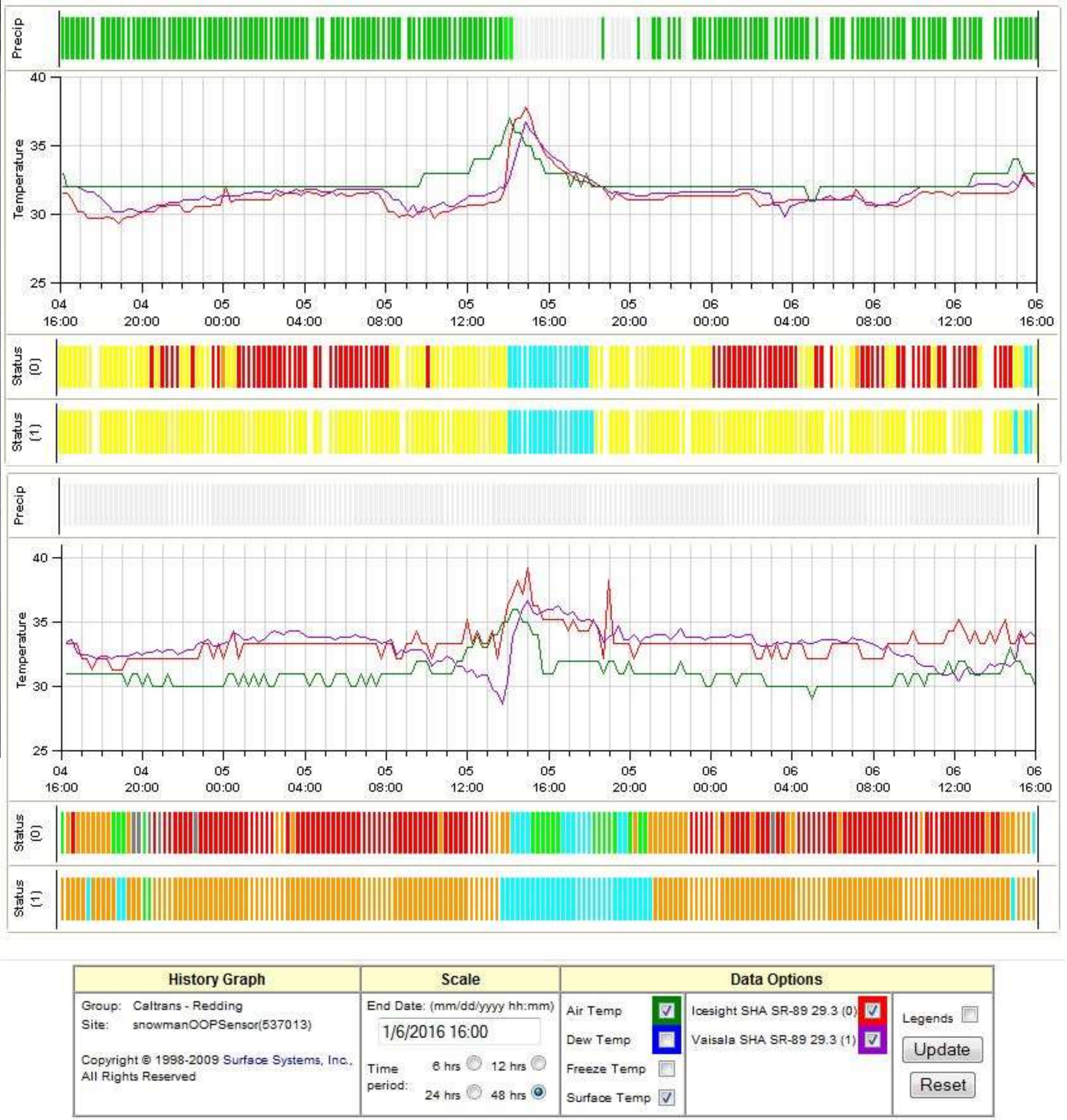
Snow Event At Snowman Summit Nov. 24th 2015.

The video to the right shows a snow event where the <u>IPS is showing chemically wet while the NIPS shows snow watch</u>. Again resolving the conflict in surface status reports is difficult but clearly there are times when the pavement surface is covered in snow yet the IPS reports chemically wet. This is attributed to the well having trapped chemical solution not representative of the roadway in general.

Also note the dry and error reports from the NIPS. This points out that in some locations where fog is a common occurrence IPS or a combination of IPS and NIPS may be a preferred solution.

Images of Cinder, Salt and Water mixture in IPS Well

This depicts a failure mode that has been observed numerous times in our evaluation and noted other evaluations where the well remains full of material that is not representative of the pavement in general. I made several trips to the site during these events and confirmed that the well in the IPS was full of a paste mixture of cinders, salt and water. With several onsite observations confirming this and collecting data from the maintenance logs on when de-icing chemicals were applied this failure mode was confirmed under certain conditions to persist for prolonged periods.



The above video taken with the HD camera installed on the same post as the <u>NIPS shows a snow incident where the IPS is reporting chemically wet</u>, the NIPS is showing snow watch or snow warning and in this case there is <u>no doubt the snow watch/warning is correct</u>. This also points out the value of the HD camera in arbitrating the actual surface condition

I-5 SB at Dunsmuir CA

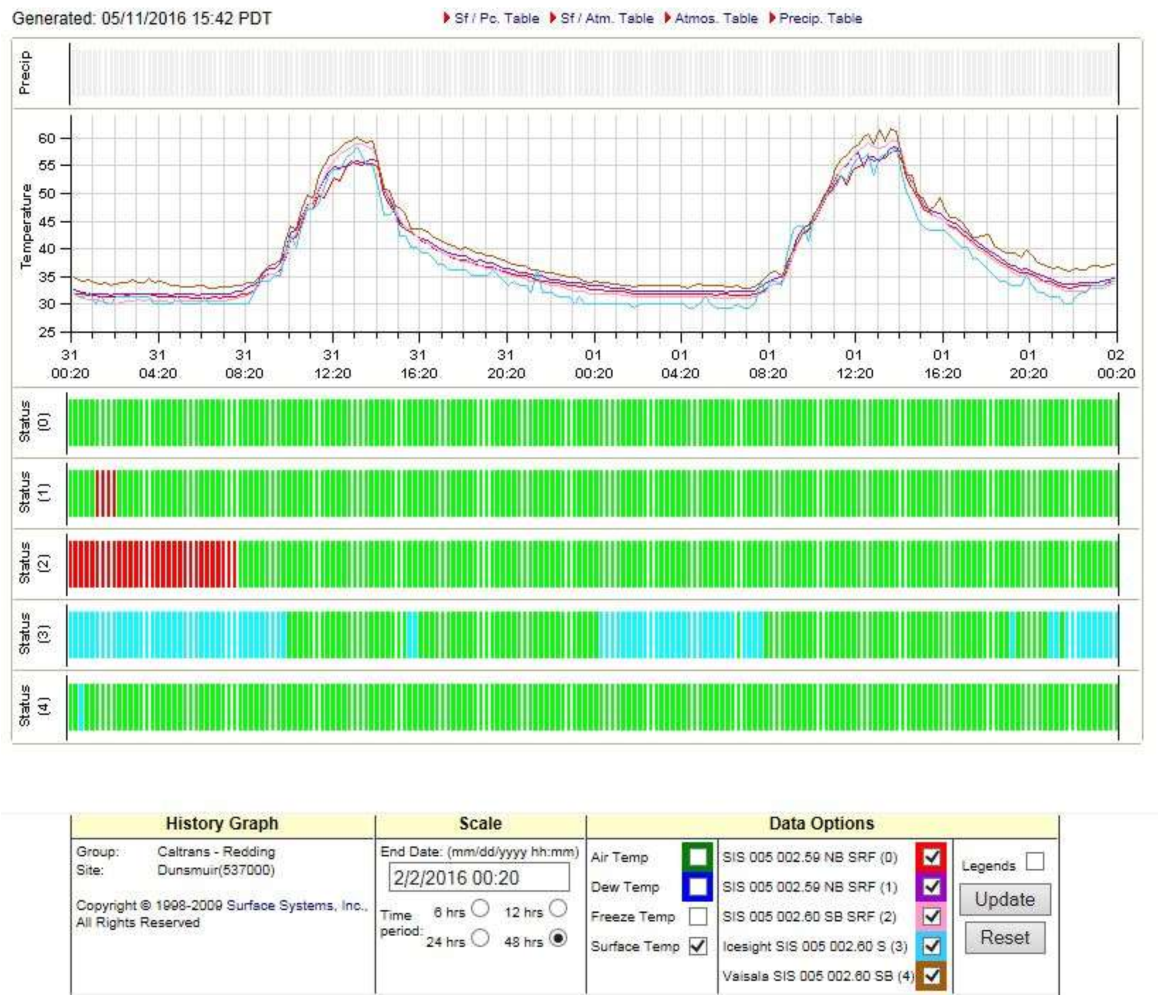
Installing the NIPS at Dunsmuir Installed 20’ up on a wood box beam sign post 26’ from ETW. With Lufft IRS31 Pro in the lane.

I-5 SB at Dunsmuir CA

Aiming the NIPS near the IPS, at this site we aimed the NIPS much closer to the IPS as further investigation of the principals of operation and discussions with the vendors identified the cone of reception for the IR sensing component to be much smaller than first anticipated.

Interesting Event At Dunsmuir January 31st

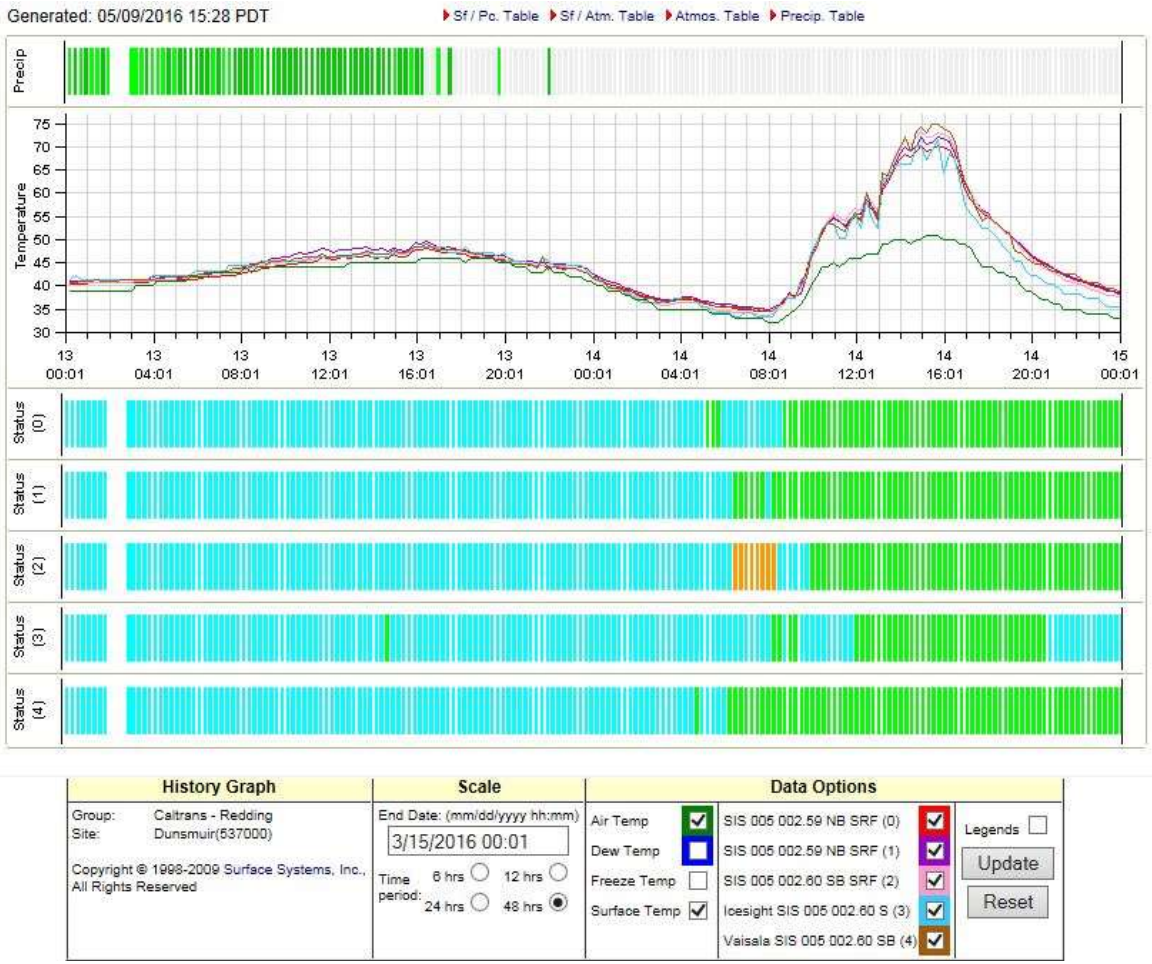
At the right is a Scanweb presentation of an event where the IPS is showing Ice Warning through 8:30AM and one NIPS is showing trace moisture and the other is showing dry. In this case the videos on the following slide show trace moisture was the most correct. The interesting thing to note is the IPS was reporting the correct response for the general atmospheric conditions not the pavement conditions as shown by the wide shot video showing the roadside. Note the logs form the Vaisala DSC showed no water, ice or snow during this period.



Interesting Event At Dunsmuir January 31st

Note the embedded time stamp in the video to the left reverted to eastern time when moved from Snowman to Dunsmuir.

Interesting Event At Dunsmuir March 14th, 2016



In this case the <u>IPS in the lane with the NIPS was showing Snow Watch while all other sensors were showing dry or trace moisture</u>. In this case the video shows the <u>trace moisture was more correct</u>. Looking at the temperature readings from the IPS reveals this puck was reading a temperature down to 33.8° F while the other pucks were reading over 34° F. This is a good example of how important the accuracy of temperature measurements are; a few tenths of a degree make the difference between a correct and an incorrect status report. <u>In a automated system this could be a critical error and again points to the need for multiple sensors in an automated system</u>.

Part III

Summary
Experience Gathered
Results
Recommendations
Looking Forward

Summary

- **The evaluation involved acquiring two representative Commercial Off the Shelf, COTS, NIPS, Install them collocated with in COTS IPS sensors and compare the surface status reporting between the technologies.**

- **Examined a representative cross section of the published information regarding the principals of operation, correlate the principals of operation to the to the results of the data examined.**

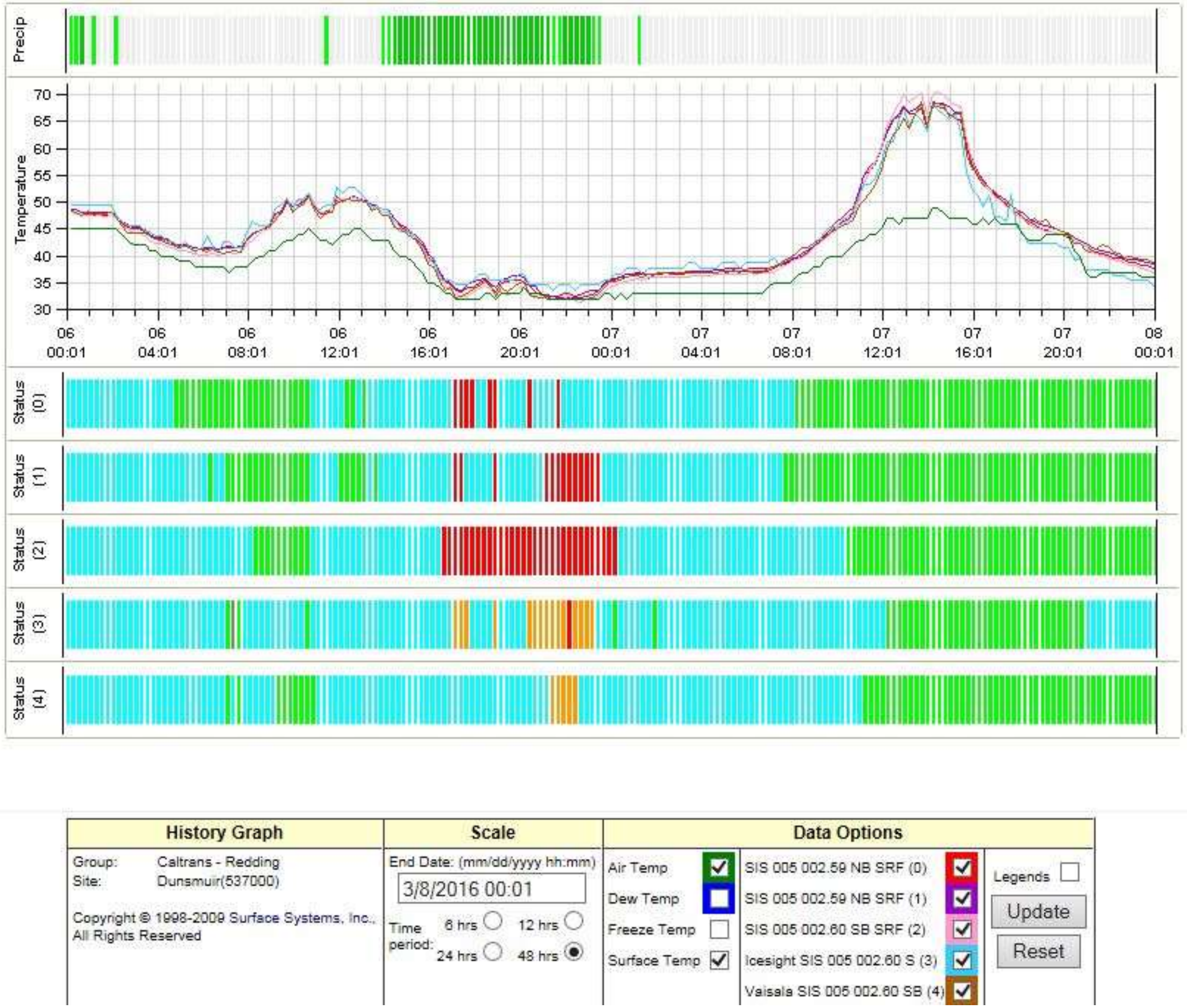
- **The capabilities observed indicate NIPS technology is as capable as IPS technology for deployment in traveled roadway conditions in both temperature and surface condition sensing, low visibility excepted.**

Experience Gathered

- ►Calibration of NIPS is critical the slightest variation from calibrated values on clean dry pavement results in large variations in reporting especially in the transition of states, like dry to moist or moist wet.
- ► The need to calibrate and maintain calibration records is a must for NIPS. Power loss can reset calibration settings, the calibration records may be necessary to bring a NIPS back into service if that happens. This could constitute a failure mode in an automated system.
- ►These devices are small computers with software and firmware that is very complex and like any computer system "save your work before you shutdown".
- ►In heavy traffic or with parked vehicles on the shoulder interference reads due to vehicles in the view of the sensors is a concern that needs to be understood in site surveys and configuration.
- ►The need for high quality video to arbitrate the interesting events became so important that it should be considered a standard practice to include a CCTV and lighting with all surface sensor installations. When in doubt looking at images is the go to solution.
- ►IR temperature sensors can be very sensitive to variations between the sensor and target temperatures, this is particularly important during calibration.

Problems with Data Analysis

The Scanweb capture to the right shows a incident that we were not able to arbitrate. The incident was in the evening and there was not sufficient lighting for the camera images to be useful. So in this case we take the general trend between 4:00 P.M. and midnight to be there was an agreement between the sensor classes there was in fact a snow incident. This points out a reason a single sensor should not be relied upon; even among similar or even the same model of sensor the variability in pavement conditions even over a few feet and the variability of the calibrations contribute to a level of uncertainty that characterizes the state of the art. Thus again the lesser of two evils.



Comparison of Sensor Failure Modes

- The comparisons indicate differing modes of failure for the two IPS types:
  - At the Snowman and Sims sites with IPS with wells, it is evident the wells in the sensors create their own environment that persists through even severe snow incidents and give false readings of chemically wet when in fact snow warning or snow watch are indicated.
  - At the Dunsmuir site with IRS31 Pros they are good at detecting the prevailing conditions in general but in some cases not necessarily the pavement conditions specifically.
- At both locations the NIPS displayed an error condition or dry when in fact the conditions could not be determined by a IPS due to low visibility.

Results

- Both classes of sensors are valid for reporting surface conditions, the incidents noted in this presentation were not the norm they were the exceptions.   Our original question "can NIPS replace IPS?" for general RWIS applications is answered in the affirmative.
- The answer to the secondary question "can NIPS be used for automated systems" is less clear. I would not recommend a single NIPS be relied upon for automated systems deployment, and the automated system must be able to handle a low visibility report.
- NIPS technology has reached a level of accuracy in reporting that matches or exceeds IPS for determining the surface condition of traveled highways. However it is merely the lesser of two evils neither technology is perfect.
- NIPS technology is not fire and forget it requires ongoing maintenance and calibration to be reliable and accurate.

Results Continued

- ►In fog or other low visibility situations the Icesight has a tendency to report "DRY" mixed in with errors resolutions for this error mode have been proposed but too late in our evaluation to be tested.
- ►In fog or other low visibility situations the Vaisala reports an error that can be translated to low visibility.
- ►IPS with wells have a tendency to create their own environment that may persist for days and not be indicative of the general pavement status.
- ►Of the two NIPS tested the Vaisala DSC111 is more robust, accurate, and it's feature set is more inclusive than the Icesight, however the ability to deploy an Icesight sensor as a stand alone sensor without the need for a full blown RWIS is a significant advantage for that device and may prove useful in the long run.
- ►The findings point out that the earlier quest for a method to calibrate IPS was a valid quest, and further points out that NIPS not only CAN be calibrated it is an ongoing requirement for accurate reporting.

Recommendations

- ►Always clean the lenses and re-calibrate in the fall PRIOR to rain and moisture the surface should be absolutely dry when calibrated.
- ►Back up or record the calibration settings both factory calibrations and on-site calibrations.
- ►Install a CCTV and lighting in conjunction with any pavement sensor.
- ►Don’t rely on a single sensor.
- ►Don’t deploy out of pavement sensors in areas prone to fog.
- ►Site Surveys should include full day sunlight reflection and shadow evaluation.
- ►Don’t install in an area where vehicles can park and interfere with the line of sight to the pavement.

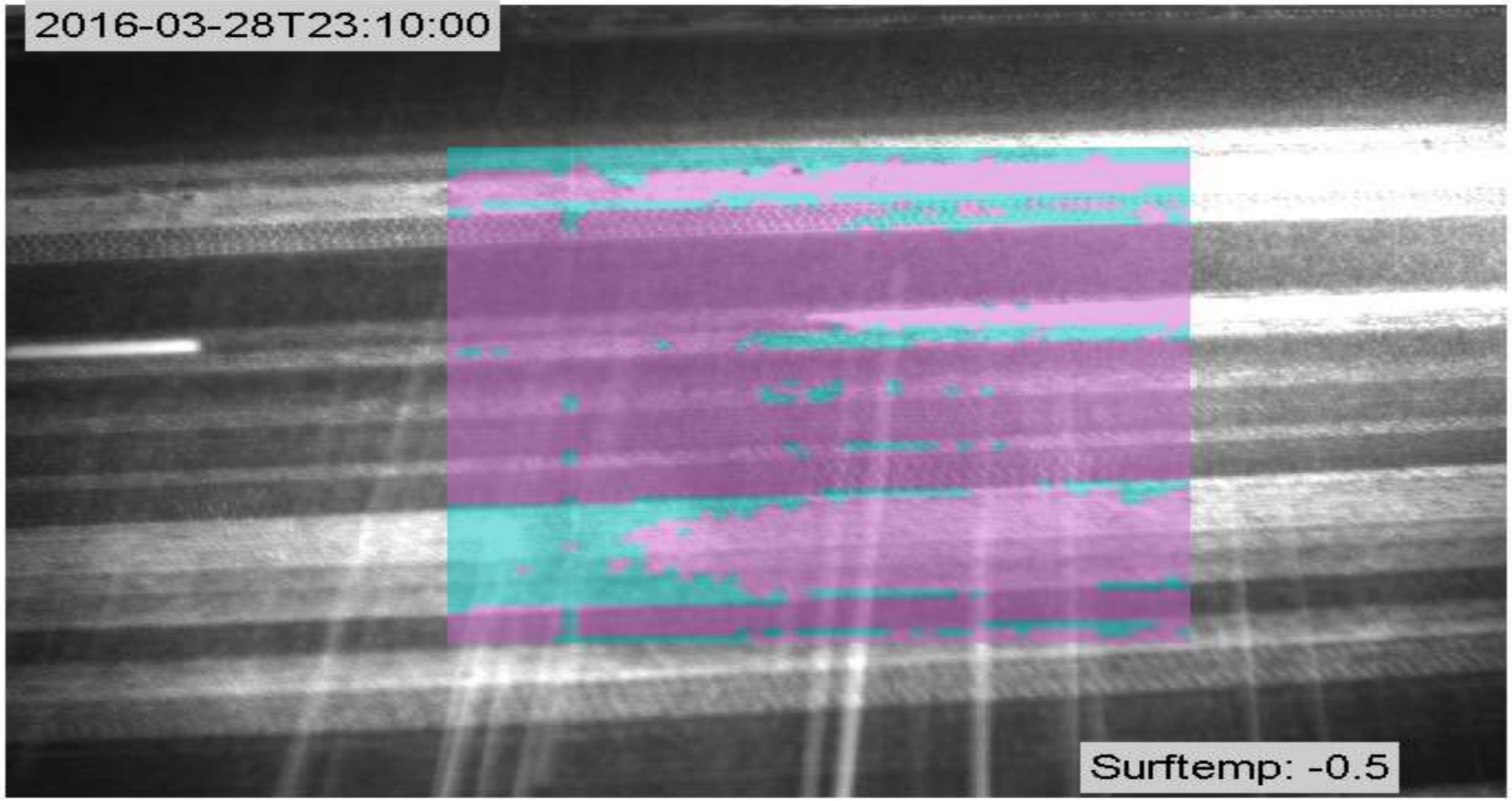
Locating Pavement Sensors at the "First to Freeze and Last to Thaw" Location

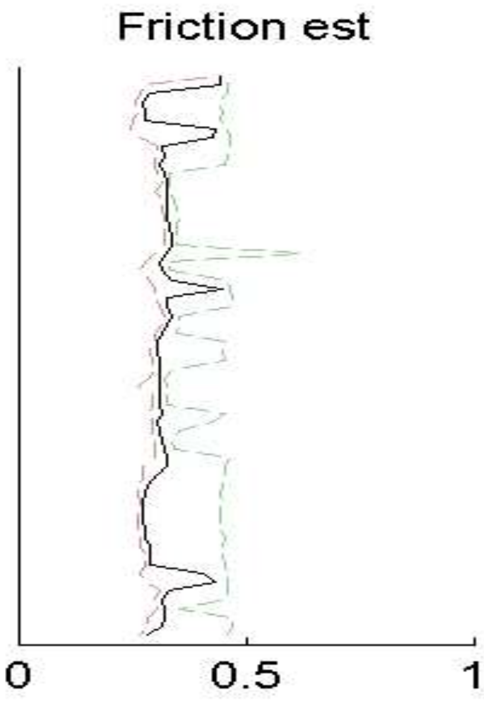
- **Finding the "First to Freeze and Last to Thaw" location is complicated by changing factors in the environment the known factors are as follows:**
- **Sun position as a function of yearly movement of the earths pole position, i.e. shade from trees or other objects have a large impact on the "First to Freeze and Last to Thaw" location and as the winter progresses some shaded areas come and go or move up and down the road with associated change in the angle of the sun.**
- **Snow banks on the shoulder and changes in the shoulder slope effect how water is forced onto the pavement and can cause migration of the "First to Freeze and Last to Thaw" location by changing where the water is forced on the pavement.**

Looking Forward

- ►There are interesting potentials for improvements, dual wavelength IR Temperature sensing, full roadway based sensors for large area coverage, see images next slide, mobile NIPS or MARWIS, etc.
- ►The results of this investigation show there has been a continuous stream of improvements made in COTS NIPS and IPS.
- ►There is ample room for more improvements in pavement sensing technology in general and an expectation that we are far from the limits of pavement sensing technology, as such we should expect the current products replaced with new more capable products.
- ►We should also expect that the new products that enter the marketplace will have their own growing pains.

Full Roadway Sensor Images





Images of a 2D pavement surface sensor with Friction as a function of lane position. 2DRoad road temperature sensor, a world first for road temperature classification, which has been manufactured for fixed and mobile installations to monitor road condition over a 6x6m area, providing the road user with a detailed visualization of the road condition. Images courtesy MetSense.

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