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Environmental Performance Test Report

Wireless Laser Communication Performance under Adverse Weather Conditions

VERSION 2

Chapter 1 Introduction

Environmental Performance Test Report

Wireless Laser Communication Performance under Adverse Weather Conditions

Purpose of Test

The performance of wireless communications links, including laser links, may be affected by weather conditions. This test measured the effect of rain and snow on the ICS SkyNet™ 800 4km laser link with OC-3 (155.2 Mb/sec) communications bandwidth.

Description of the Underlying Theory

In a free-space laser link designed with a large divergence transmitter telescope, such as the SkyNet 4 Km Link, the laser beam launched by the transmitter into the atmosphere experiences the following losses:

- Receiver optical and electrical losses
- Atmospheric losses
- Geometrical spreading loss

Receiver optical and electrical losses are internal and accounted for by the specifications, and were outside the scope of this test. The internals of the SkyNet systems were treated as a black box.

For a link, whose wavelength is chosen in one of the transmittance windows in the absorption spectra of the atmospheric molecules, the absorption loss is negligible. Thus, the attenuation of laser power in the atmosphere can be described by the atmospheric losses consisting of only scattering losses,

$$T(R) = 10\log\left[\frac{P(R)}{P(0)}\right] = 10\log\left[e^{-\alpha R}\right] \ dB \qquad (1)$$

where,

T(R) = transmittance at range R,
P(R) = laser power at R,
P(0) = laser power at the source, and
α = *total extinction coefficient, represented here by the scattering coefficient*

The scattering coefficient is approximated by

$$\alpha = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q} \qquad (2)$$

where,

V = *visibility in Km,*
λ = *wavelength in nm, and*
q = *0.585* $V^{1/3}$ *for low visibility (V<6 Km)*
= 1.3 for moderate visibility (6 < V < 60 km)
= 1.6 for good visibility (V > 60 km)

The geometric spreading loss (GSL) is determined by the divergence of the transmitter telescope and the range:

$$GSL = 10\log\left[\frac{Surface\,area\,of\,\,receive\,aperture}{Surface\,area\,of\,\,transmit\,beam\,at\,range\,R}\right] = 10\log\left[\frac{A_R}{\frac{\pi}{4}(\theta R)^2}\right] \text{ dB} \quad (3)$$

where,

A_R = *surface area of the receive aperture* $\left(m^2\right)$

θ = *transmit telescope divergence* $\left(mrad\right)$

R=link range $\left(km\right)$

For the unit tested, θ = 11 mrad and A_R = 36 in^2 = .0232258 m^2.

For a link range of 4 km, the GSL = -48.2 dB.

According to PAV and ICS, the link loss margin at a 4 km range is 28 dB. In other words, at a 4 km range, the link will work satisfactorily if the atmospheric attenuation does not exceed 28 dB. Therefore, the relationship between range R and the maximum attenuation coefficient $\alpha_{\max}$ is given by Equation 4.

$$10\log[(e^{-\alpha_{\max}R})(16/R^2)] = -28 \text{ dB} \qquad (4)$$

Equation 4 can be solved for $\alpha_{\max}$ to give Equation 5.

$$\alpha_{\max} = -(1/R)\ln[(10^{-2.8})(R^2/16)]\ \text{km}^{-1} \qquad (5)$$

From equations 2 and 5, we determine that the 4 km atmospheric loss, at the 915 nm wavelength of the SkyNet unit, does not exceed 28 dB (and the system will work satisfactorily) as long as the visibility exceeds 1.7 km. This discussion assumes that the visibility is uniform over the 4 km path length.

Weather Depth

If atmospheric conditions are not uniform, we must integrate the variable attenuation over the path length. Sometimes most of the attenuation occurs over only a portion of the entire path. For example, a localized cloudburst of rain, perhaps 5-10% of the total path length, can constitute almost the entire attenuation for the link. For such cases, we define weather depth W below.

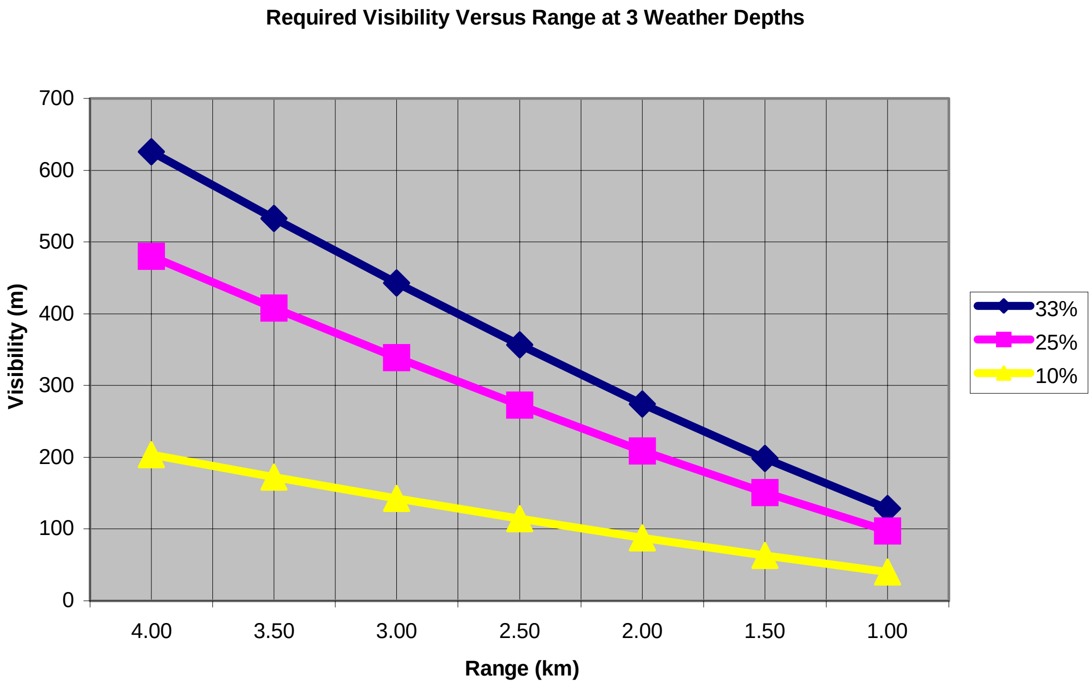
Weather Depth (W) = length of the optical path (as a fraction of the total path length) with the specified attenuation coefficient. The remainder of the path has negligible attenuation.

For a weather depth W, equation 5 can be modified by substituting W$\alpha_{\max}$ for $\alpha_{\max}$ to give equation 6.

$$W\alpha_{\max} = -(1/R)\ln[(10^{-2.8})(R^2/16)]\ \text{km}^{-1} \qquad (6)$$

As an example of a case where use of weather depth is appropriate, consider a weather depth of .25 and a total link range of 4km. Then, equations 2 and 6 indicate that the atmospheric loss at 915 nm will not exceed 28 dB (and the system will work satisfactorily) as long as the visibility exceeds .48 km.

The following figure shows required visibility versus range for weather depths of 10% (W=.10), 33% (W=.33), and 25% (W=.25). Note that the figure gives visibility in meters.


Required Visibility Versus Range at 3 Weather Depths
Visibility (m)
700
600
500
400
300
200
100
0
4.00
3.50
3.00
2.50
2.00
1.50
1.00
Range (km)
33%
25%
10%

Test Methods

In order to provide reproducible test conditions, testing took place inside a climate controlled test chamber. Due to practical size limitations for the test chamber, the placement of the lasers was at a separation of about 10 m. In such a range, almost no geometrical spreading occurs for the launched laser beam. In order to determine the acceptable link range for each atmospheric condition, Telelase used the following two methods:

1) Change the dimension of the clear aperture of the receiver

2) Put neutral density filters in front of the receiver

The following table shows how one can adjust the received laser power by changing the dimension of the receiver clear aperture if the receive telescope has a 6"x6" square aperture.

Table 1. Optical loss introduced by the reduction of the clear aperture of a receiver, which has a 6"x 6" square aperture before adjustment.

Receive Aperture Width (inch)	Loss (dB)
1	-15.6
1.5	-12.0
2	-9.5
2.5	-7.6
3	-6.0
3.5	-4.7
4	-3.5
4.5	-2.5
5	-1.6
5.5	-0.8
6	0.0

A neutral density filter with an optical density of *D* (at the laser wavelength of 915 nm) introduces an optical loss of *D* X 10 dB. Therefore, by choosing appropriate filter and aperture size, we can select the optical channel losses.

What can be measured in the testing is the effect of the weather condition on the laser signal. The weather, rain or snow, will attenuate the beam and increase the likelihood of errors in the received signal. When the signal strength is marginal, a low level of errors is generated. We call this condition I. Let us denote the corresponding channel loss introduced by the filter and reduced receive aperture by T_0. In general, the channel loss can be expressed by

$$T(R) = \frac{P(R)}{P(0)} = G(R)F\,e^{-\alpha R} \quad (7)$$

where,

G(R) = *geometrical spreading loss,*
F = *filter plus aperture loss, and*
$e^{-\alpha R}$ = *atmospheric loss*

For a link range of 10 m, a beam divergence of 11 mrad, and clear air conditions, the above geometric spreading loss and the atmospheric loss are negligibly small and will be ignored[1]. Thus, we obtain

$$T(R) \cong T_o = F \qquad (8)$$

After determining T_0 under clear air conditions, we carried out similar experiments under the following atmospheric conditions:

- Rain
- Snow
- And proof of operation at high temperature

The rate of rain and the snow rate were varied.

In clear air, transmission data errors were measured against a series of filter/aperture combinations to create an error/attenuation curve. The filter/aperture combination was then set at the lowest level of detectable errors. The distinct weather condition was then applied, and data errors measured. The error level from this measurement was then plotted against the error/attenuation curve to find the weather-created attenuation. The attenuation was then used in:

$$F = F' e^{-\alpha R} \qquad (9)$$

Because F, F' and R are known, we can determine the α from equation (9). Next, the available link range R_x under a particular atmospheric condition was determined by solving the following equation.

$$10 \log[(e^{-\alpha R_x})(16 / R_x{}^2)] = -28 \text{ dB} \qquad (10)$$

Note that Eq. 10 is the same as Eq. 4. However, in Eq. 10, we are calculating the link range for acceptable performance at a given value of the atmospheric attenuation coefficient. On the other hand, in Eq. 4 we are calculating the maximum attenuation coefficient that gives acceptable performance at a given range.

The rated range of the SkyNet is set at 4 km. The range is set by the manufacturer to provide sufficient margin of performance to meet availability requirements against an expected set of weather conditions. That is, in clear air, the SkyNet will perform at distances much greater than 4 km. In extremely heavy rain, when 4 km operation is not possible, the system may continue to provide availability if the links were installed at 2 or 3 km.

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[1] The optical pattern of the launched beams has been optimized for ranges between two and four km, and to reduce the effect of scintillation or shimmering. This pattern consists of three bars of laser light, each rotated 120º from each other. Perfect alignment thus consists of an six lobed star shaped pattern of light with lobes at every 60º. At normal installation distances, the lobes are many times the size of the aperture. This is not true under the 10 m test conditions imposed by the chamber size. Alignment, given the narrow apertures to be used and the beam pattern at these close distances, appears to be more critical than in normal operation. Thus, alignments and base conditions were checked before each series of tests, although units installed in the field are normally realigned only on an annual basis.

Chapter

2 Test Equipment

Test Setup and Diagram

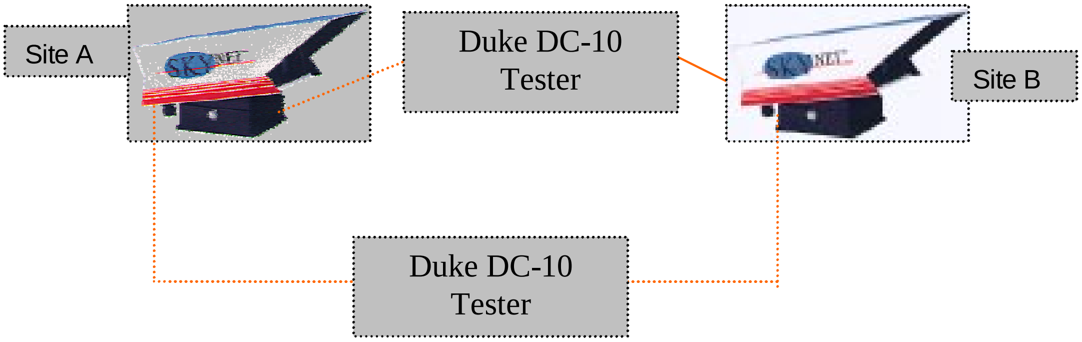
The Test Equipment

The system tested consisted of two SkyNet wireless laser links, equipped with OC-3 (155 Mbit/sec) fiber telecommunications interfaces. Each SkyNet has three 915-nm infrared communications lasers and associated optical systems, and one optical receiver with a similar optical system. The SkyNet units are powered remotely by 18V DC power supplies.

The equipment required to test these systems consisted of two Duke Communications DC-10 ATM/SONET Tester/Simulator/Analyzers, each interfaced to a personal computer for control and data collection. The DC-10s are connected to the SkyNet units via multimode fiber optics cables. Each tester was connected to both SkyNet units, transmitted SONET cells from one transmitter to the receiver in the other unit, and was able to compare the transmitted data to the received data, and log and analyze any errors detected. One tester transmitted from SkyNet A to SkyNet B, the other from SkyNet B to SkyNet A. As beam density and alignment differences resulted in different absolute filter/aperture combinations for a given set of conditions, each direction is analyzed separately.

The SkyNet receiver has a square, 6” X 6” aperture. This aperture was covered by a plate with a 1.5” circular hole, with filters and smaller apertures mounted in front.

Hardware Diagram



- Two SkyNet laser transceivers with Duke DC-10 testers.

The two transceivers are referred to as Site A and Site B, arbitrarily, to maintain data consistency across the testing.

Chapter
3

Test Data

Data from the Test Sequences

Description of Test Environment

Physical Setup

Tests were run against three environmental conditions: Rain, snow and heat. The rain, and heat tests were run in a stainless steel chamber approximately 38 feet by 12 feet by 12 feet. The SkyNet transceivers were located along the length of the chamber, with 10 meters between transceiver lenses. The chamber was equipped with the pumps and nozzles to create rain at up to 9.5 inches/hour and electrical heaters to control the temperature.

The snow generator was too bulky to install within the chamber, and so was located just beyond the chamber door. One SkyNet transceiver was then relocated beyond the door at approximately 25 meters, so the laser light path passed through the snow pattern from the snow generator.

Electrical Setup

The transceivers were provided with 24VDC power from power supplies in the control room, and the DC-10 testers, located in the control room, used optical fiber to exchange data with the transceivers. The 18VDC used by the lasers and receiver was generated from the 24VDC by a power supply within the transceiver housing.

The testers were installed for each to provide its own loop. That is, a tester generated a test pattern, transmitted it via fiber to the input of a SkyNet transceiver (SiteA), which then transmitted it to the other transceiver (SiteB), where fiber optics returned the data to the input of the tester. The other tester drove SiteB transmitting to SiteA.

Operational Setup

In all sequences, the SkyNet transceivers were operated with all three transmitting lasers in operation, each at full aperture. As the power at the receiver at these short distances would be very unrealistic, the power received was attenuated by means of combinations of filters and apertures. The maximum aperture was set at a 1.5-inch diameter circle, as compared to a 6 by 6 inch square in normal applications. The aperture diameters could be reduced by 0.125-inch steps, providing between 0.8 dB and 21.6 dB attenuation. The filter sets included:

Table 2. Filter and Attenuation Factors at 915 nm

Filter	Attenuation in dB
BG-25	-13.6

Filter	Attenuation in dB
BG-38	-33.2
NG-11	-3.8
NG-5	-7.3
NG-4	-9.8

These attenuations are measured at the 915 nm laser wavelength. Combinations of filters and apertures were used to provide total attenuation to simulate geometric spreading (emulating distance) and atmospheric scattering.

Description of Detectable Errors

The SkyNet transceiver pair is being utilized in this application to transmit SONET defined data packets at an OC-3 data rate. SONET is an acronym for Synchronous Optical NETwork. It is a set of standards defining the rates and formats for optical networks specified in ANSI T1.105, ANSI T1.106 and ANSI T1.117.

SONET standard defines the rates and formats, the physical layer, network element architectural features, and network operational criteria. Included in the standard are methods and locations for transmitting and recognizing error conditions, and in fact, over 4% of the signal bandwidth is utilized to contain the framing, timing and error information.[2] The overhead for this information is divided into Section, Line and Path.

The Duke DC-10 tester is capable of detecting a number of these defined error conditions. The errors monitored in this test were:

B3 Errors – B3 is allocated for path error monitoring.

Path FEBE Errors – FEBE (Far End Bit Error) convey the count of interleaved bit blocks that are due to the error conveyed in the B3 byte.

B2 Errors – B2 is allocated for line error monitoring.

Line FEBE Errors – Count of line error blocks conveyed by FEBE.

B1 Errors – B1 is a specified byte that contains section error monitoring information.

Transmit – The number of cells transmitted.

SONET Errors - $SONETError = {\sum (B_2 + B_3 + B_1 + Path + Line)} \big/ Transmit$

There is not a generally accepted figure of merit for measuring SONET overall performance. Telelase has chosen to use the above definition of SONET errors (a SONET error rate) as the most consistent and repeatable figure of merit in this test.

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[2] These definitions are drawn from Worcester Polytechic Institute EE535 course on Telecommunications Transmission Technology, available at http://ece.wpi.edu/courses/ee535/hwk8cd95/dsk1/dsk1.html

Environmental Tests

In all cases, the test sequence began by calibrating the transceiver performance in clear air conditions. The goal was to build a table of attenuation versus error counts. That is, there are four major ranges of received power and communications behavior.

1. Receiver overload and no communications. This condition does not yield useful information and was not investigated.

2. Received power within specifications and error free communications. This is the normal operation case, where geometric spreading has reduced received power to design levels, and atmospheric attenuation has not affected communications.

3. Marginal power and communications. There is a narrow range of received power where communications continue but where measurable errors occur. This region is the region of interest, as the point of interest of the tests is to see and measure the effect of atmospheric conditions on the communications link.

4. Excessive attenuation and no communications. At this point, signal strength has been reduced to the point no bits are received, and the data taken has no value.

The calibration therefore was to discover what range of attenuation placed the results in region 3, with errors but continued operation and communications. The measurement methodology involved:

1. In clear air, starting from region 2 above, perform a series of measurements with closely spaced increases in attenuation. Record error rates vs. filter/aperture settings.

2. Review and plot the series above, and find the attenuation setting with the minimal number of SONET errors greater than zero. This is the best performance within region 3 above.

3. Set the filter/aperture combination to match the attenuation selected in the previous step.

4. Apply the weather condition, and measure the SONET error rate.

5. The error rates were then entered onto the error rate versus power curve drawn in step 2, and the atmospheric attenuation, hence α3, calculated.

From the α, effective visibility and link range for the conditions can be calculated[3], to see if the operating range (1-4 km) of the laser link was maintained under that weather condition.

The following tables give the accumulated errors for the number of cells shown in the Transmit column.

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[3] See the section on Description of the Underlying Theory.

The detailed procedure used to calculate attenuation coefficient α for a measured SONET error is described below.

In order to find an accurate clear air filter loss value corresponding to a given SONET error, we find a linear fit in the form

$$S = mL + b \qquad (11)$$

where S = SONET error and L = filter loss (dB).

Let L_a denote the clear air filter loss corresponding to a given SONET error (from Eq. 11). Let L_x denote the filter loss used in a given rain or snow test. R is the link length occupied by the rain or snow. Then, we calculate the attenuation coefficient α that corresponds to the given rain or snow rate from Eq. 12.

$$L_a = L_x + 10 \log (e^{-\alpha R}) \qquad (12)$$

After α is determined, we can calculate link range R_x from Eq. 10.

Rain

Rain was measured at 1.5-inches/hour, 3 inches/hour, 6.5 inches/hour, and 9.5 inches/hour. No effect on the signal was measured at 1.5 and 3 inches/hour. This test was conducted on November 2, 1999.

Site B Receive

Table 3. Clear air calibration for site B

Filter Loss (dB)	B3 Errors	Path FEBE Errors	B2 Errors	Line FEBE Errors	B1 Errors	Transmit	SONET Error
32.1	1400	1400	1418	1415	1443	1094500	0.6467794
31.3	1507	1507	1534	1534	1563	1210000	0.6318182
30.0	408	408	409	409	418	1254000	0.1636364

Table 4. Rain test data for site B

Rain Rate (in/hr)	Filter Loss (dB)	B3 Errors	Path FEBE Errors	B2 Errors	Line FEBE Errors	B1 Errors	Transmit	SONET Error
9.5	29.7	9	9	9	9	9	1100000	0.04091

Summary of other results:

$$L_a = 29.557 \text{ (clear air, } S = 0.00409)$$
$$m = 0.3601 / dB$$
$$b = -10.6406$$
$$\alpha = 6.908 / Km$$
$$L_x = 1.34 \text{ Km (link length).}$$

Snow

Transceiver A was kept inside the chamber and transceiver B was set up outside the chamber. The snow was produced outside the chamber about 5 ft from transceiver B. When both snow generators were operated, the snow occupied a length of ~10 ft along the optical path. When only one generator was operated, the snow occupied a length of ~7 ft along the optical path.

Clear air calibration tests were carried out both before and after the snow tests.

Site B Receive

Table 5. Clear air calibration data for Site B before snow

Filter Loss (dB)	B3 Errors	Path FEBE Errors	B2 Errors	Line FEBE Errors	B1 Errors	Transmit	SONET Error
20.2	383	383	390	390	392	1276000	0.151881
21.8	131159	131159	135427	135451	135376	1270500	52.62275
21	6888	6889	7016	7016	7052	1265000	2.75581
20.2	594	594	608	608	624	1265000	0.239368
20.2	441	441	450	450	452	1259500	0.177372
20.2	196	196	201	201	204	1259500	0.079238
20.2	328	328	333	334	339	1276000	0.130251

Table 6. Averaged clear air calibration data for Site B

Filter Loss (dB)	SONET Error
20.2	0.155622
21	2.75581

Table 7. Original snow test data at Site B

Snow Rate (in/hr)	Snow Length (ft)	Filter Loss (dB)	B3 Errors	Path FEBE Errors	B2 Errors	Line FEBE Errors	B1 Errors	Transmit	SONET Error
23.3	10	20.2	824	824	849	849	864	1930500	0.218078
10	10	20.2	1254	1162	2175	2095	1308	2029500	0.39389
10	7	20.2	329	329	333	333	337	1628000	0.102027
23.3	10	20.2	1133	1087	2085	1997	1236	2447500	0.307988
5.8	10	20.2	1383	1295	2326	2212	1430	2502500	0.345495

Table 8. **Averaged snow test data for Site B**

Snow Rate (in/hr)	Snow Length (ft)	Filter Loss (9dB)	SONET Error
5.8	10	20.2	0.3455
10	8.5	20.2	0.1774
23.3	10	20.2	0.1047

The SONET errors in this table are counter-intuitive, because the SONET errors decrease with increased snow rate. However, the total number of transmitted cells in snow tests is much more than that in the clear air. In a different approach, let us use comparable number of cells for snow tests, by selecting only the first (approximately) 1265000 cells for the measurement. The errors are cumulative, so the results are valid, and provides a greater degree of normalization between tests than otherwise.

Table 9. **Original snow test data corresponding to approximately 1,250,000 transmit cells.**

Snow Rate (in/hr)	Snow Length (ft)	Filter Loss (dB)	B3 Errors	Path FEBE Errors	B2 Errors	Line FEBE Errors	B1 Errors	Transmit	SONET Error
23.3	10	20.2	479	480	490	490	496	1281500	0.190012
10	10	20.2	514	514	519	519	531	1298000	0.200077
10	7	20.2	173	173	175	175	179	1342000	0.065201
23.3	10	20.2	294	294	299	299	303	1270500	0.117198
5.8	10	20.2	233	233	235	235	237	1281500	0.091533

Table 10. **Averaged snow test data**

Snow Rate (in/hr)	Snow Length (ft)	Filter Loss (dB)	SONET Error	Snow Loss (dB)	α (/Km)
5.8	10	20.2	0.0915	20.2037	0.278
10	8.5	20.2	0.1326	20.2160	1.419
23.3	10	20.2	0.1536	20.2222	1.679

However, the SONET error values in the above (snow) are less than in the earlier table (clear air, filter loss 20.2 dB). Concern for stability of the test setup in the less controlled environment used for snow measurement had led to a repeat of the calibration runs after completion of the snow test. Re-measurement in clear air produced the following set of data is chosen for clear air:

Table 11. **Revised clear air test**

Filter Loss (dB)	B3 Errors	Path FEBE Errors	B2 Errors	Line FEBE Errors	B1 Errors	Transmit	SONET Error
20.2	196	196	201	201	204	1259500	0.079238
21	6888	6889	7016	7016	7052	1265000	2.75581

The corresponding linear fit data are:

$m = 3.346/dB$, $b = -67.504$. *Using these parameters, we obtain the snow loss and the attenuation coefficients given in Table 10.*

Heat

The heat test consisted of setting up the transceivers with a normal operating margin of power levels, then raising the temperature at a rate of 1.5C/minute to a temperature of 65C (150F) while measuring performance.

Normal operating margin means that rather than operating on the verge of failure, filters were removed to provide the expected 24-40-dB margin for clear air, then beginning the heating cycle.

Failure was to be measured by an exceptional increase in SONET errors. The increase was not observed to be exceptional during the heat rise and soak, and normal operation would have continued.

Chapter 4 Results

Results and Conclusions

Local and Link Wide Conditions

As is the case with almost all environmental and stress tests, the conditions encountered during the preceding tests are at the extreme limits of what might be encountered in expected meteorological conditions. As such, error rates and behaviors observed in the test do not directly imply an inability to operate in most climates.

There are a handful of locations on the planet where rain in excess of 9"/hour occur with reasonable frequency. 6"/hour is more commonly found, but still rare.

Snow rates measured in feet/hour are similarly rare.

About the only weather-condition that can be expected to be completely uniform over the two-to-four kilometer (1.2 to 2.5 mile) range for the SkyNet laser transceivers is clear air. This is especially true for weather extremes. Very heavy rain normally is seen in localized shower bursts. Heavy snow often consists of localized heavy falls and drifting.

Experimental values confirm what the equations predict, that the range of the transceivers is a function of observed visibility.

So all the following conclusions are pessimistic, the real-life range of the laser links is in fact longer than that projected when measured against official meteorological data. This is assumed to be due to non-uniformity of weather in real-life locations. Further discussion is found in Weather Depth on page 3.

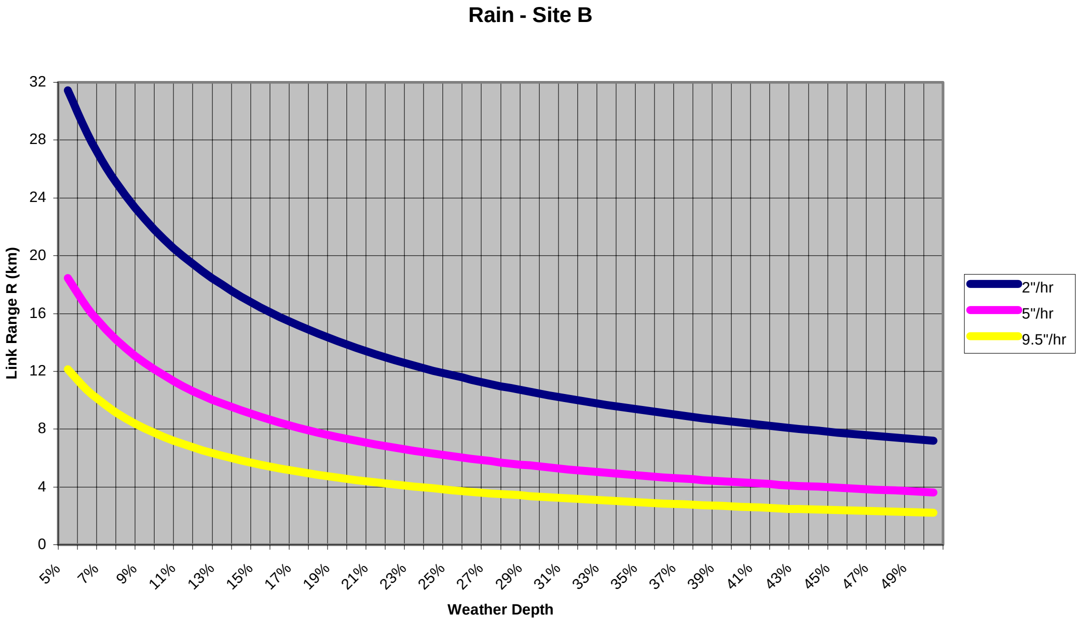
Rain

In the reference, *Infrared Systems Engineering*, R.D. Hudson, Jr., Wiley & Sons, 1969, the following table is given for the effect of rain on infrared transmission. Note that the data from this test is given at 2.5 X 9.5 in/hr, or 23 cm/hr.

Table 12. Transmittance versus rain conditions

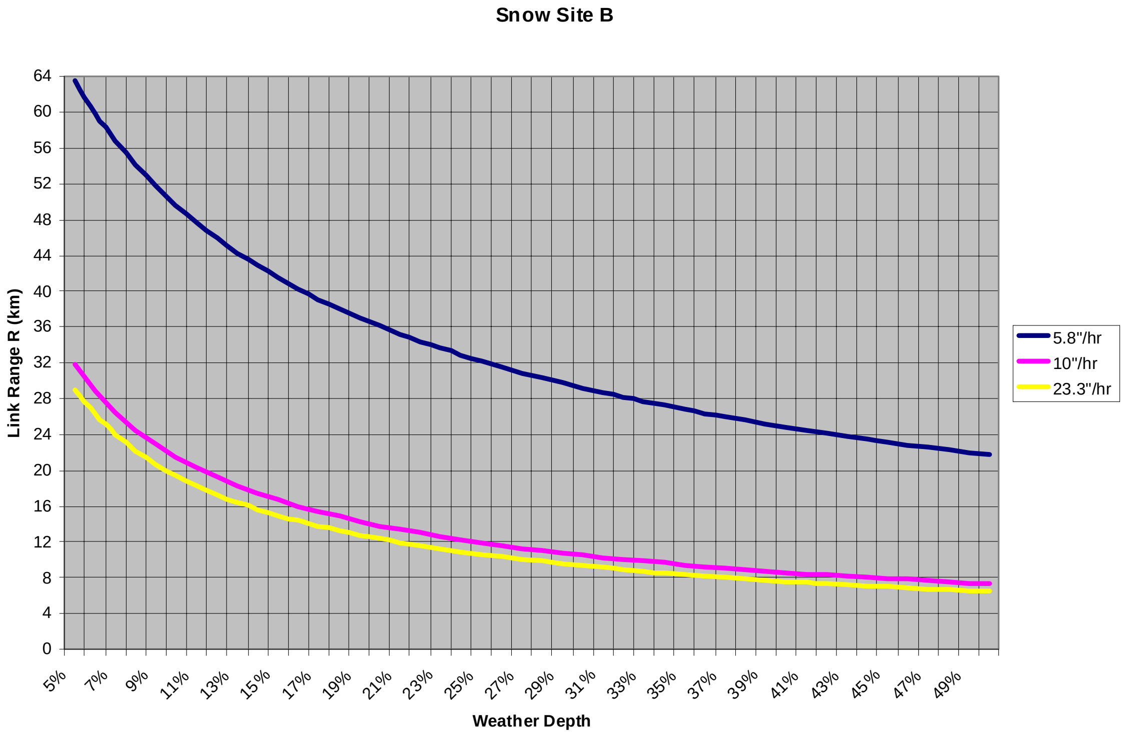
Condition	Rainfall (cm/hr)	Transmittance of a 1.8 km path
Light Rain	0.25	0.88
Medium Rain	1.25	0.74
Heavy Rain	2.5	0.65
Cloudburst	10.0	0.38

The following chart shows the effective Link Range for rain as derived from the measurements taken in these tests over a range of weather depths as discussed earlier. Rain rates of 9.5, 5 and 2-inches/hour rain are plotted, over weather depths of 5-50% of link range. Rainfall effects on lasers are dependent not only on rain rate, but also on droplet size. For purposes of this analysis, 5 and 2-inches/hour results were generated by assuming that α is directly proportional to the rain rate, which is true if the distribution of relative rain drop sizes stays the same for different rain rates.



Snow

The following chart shows the results of the snow tests, giving effective Link Range vs. Weather Depth. As valid data was measured for differing snow rates, no rate effect extrapolations were required.



Heat

As suggested in earlier long-term (30 day) tests in a real-world environment with air temperatures above 100F plus solar loading, satisfactory operation was obtained at temperatures of 65C (150F). While SONET errors increased somewhat (while still acceptable), this may be explained by potential shifting of the transceiver alignment due to the temporary mountings utilized in this test.

Problem Complexity

Actual performance of the SkyNet laser link (or any wireless link solution) in atmosphere has been described by the manufacturer, as at least a five dimensional hyperspace. In this description, the five dimensions are:

- Link distance
- Temperature
- Snowfall rate
- Rain rate

Within this hyperspace, there is a region of high-quality performance of the link, surrounded with a narrow region of sub-optimum performance. This testing is to be carried out within that narrow region of sub-optimum performance, as this is the only region where measurements can be made. However, within each weather regime (rain, snow, heat), only one variable is being controlled, and link distance held constant. The other variables, while not manipulated deliberately, were not controlled.

Therefore, during heat testing, the (damp) chamber started at high humidity and relative humidity fell during the heat cycle

Appendix
A

Calculations

Background Calculations for Filter Glass and Aperture Transmittances

Color Glass Filter Transmittance at λ = 900 nm

Coherent Part Number	Glass Type	Internal τ for d = 1 mm	P	Actual Thickness d (mm)	τ at Actual Thickness	Actual τ (dB)	Quantity	Unit Cost	Telelase Filter Name
26-5728	BG-25	0.3624	0.9131	3	4.35E-02	-13.6	2		FIL3
26-2998	BG-38	0.0219	1.0000	2	4.80E-04	-33.2	8		FIL1
26-3632	NG-11	0.6729	0.9171	2	4.15E-01	-3.8	1		FIL6
26-3582	NG-5	0.4518	0.9208	2	1.88E-01	-7.3	1		FIL5
26-3566	NG-4	0.3371	0.9110	2	1.04E-01	-9.8	1		FIL4
26-6288	NG-3	0.2170	0.9309	3	9.51E-03	-20.2	1		FIL2

x	**BG-25 τ**	**BG-25 ti**	**BG-38 t**	**BG-38 ti**	**NG-11 t**	**NG-11 ti**	**NG-5 t**	**NG-5 ti**	**NG-4 t**	**NG-4 ti**	**NG-3 t**	**NG-3 ti**
850	0.29	0.32	0.02	0.02	0.65	0.71	0.46	0.50	0.34	0.37	0.22	0.23
900	0.32	0.34	0.02	0.02	0.62	0.68	0.42	0.46	0.31	0.34	0.2	0.22
950	0.35	0.39	0.02	0.02	0.60	0.65	0.39	0.42	0.29	0.32	0.19	0.21
1000	0.39	0.43	0.03	0.03	0.58	0.63	0.37	0.40	0.27	0.3	0.19	0.2
m	0.00066	0.00076	6E-05	6E-05	-0.00046	-0.00054	-0.0006	-0.00068	-0.0005	-0.0005	-0.0002	-0.0002
b	-0.273	-0.333	-0.033	-0.033	1.038	1.167	0.965	1.074	0.728	0.758	0.385	0.4
915	0.3309	0.3624	0.0219	0.0219	0.6171	0.6729	0.416	0.4518	0.3071	0.3371	0.202	0.217

	1	2	3	4	5	6	7	8	9	10	11
Filter 1	-33.2	-33.2	-33.2	-33.2	-33.2	-13.6	-20.2	-20.2	-20.2	-13.6	-9.8
Filter 2	-20.2	-13.6	-9.8	-7.3	-7.3	-13.6	-9.8	-3.8			
Filter 3	-7.3	-7.3	-7.3	-3.8		-7.3					
Filter 4											
Filter 5											
Total dB	-60.7	-54.1	-50.3	-44.3	-40.5	-34.5	-30.1	-24.0	-20.2	-13.6	-9.8