SWIFT

Seattle Wide-area Information For Travelers

Communications Study

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EXECUTIVE SUMMARY

This document discusses the rationale, procedures, results, discussion and conclusions of the Seattle Wide-area Information for Travelers (SWIFT) *Communications Study* evaluation that was conducted for the Washington State Department of Transportation (WSDOT). Included are background explanations of the issues involved in researching, planning and conducting the coverage testing that was conducted as part of this evaluation. For the purposes of this report, testing was accomplished using the SWIFT High Speed Data System (HSDS) as it was deployed in the Seattle, WA area by Seiko and configured to provide traffic incident, speed/congestion and real-time bus position information to test participants during the SWIFT field operational test evaluation.

The SWIFT system was designed to provide traffic incident, speed/congestion and real-time bus position information, among other information (e.g., personal paging and general information messages) to three receiving devices designed to use the Seiko HSDS FM sub-carrier system. These three devices, the Seiko MessageWatch, the Delco in-vehicle navigation device and the IBM or Toshiba portable computer with Remote Receiver Module (RRM), were distributed to test participants for their use during the evaluation phase of the field operational test. To help document the SWIFT operational test and evaluation, the *SWIFT Consumer Acceptance Study* evaluation provided user "helpdesk" support and implemented questionnaires and focus group meetings that resulted in the collection of substantial data about how well the user devices worked, when and where users experienced problems receiving messages or pages and other information about how personally useful the SWIFT system was to them. The records of these meetings included comments and suggestions on how the system could be improved and what features they wanted to see in the future. In addition to these efforts, there were several discrete SWIFT evaluation tasks aimed at addressing architecture, communication, deployment cost and institutional issues. The specific task discussed in this document evaluates the communications coverage aspects of the Seiko HSDS system used to support the SWIFT project in the Seattle area.

There were four (4) objectives of the *SWIFT Communications Study* testing in Seattle: (1) determine the basic capability of the HSDS subcarrier to deliver ITS information; (2) assess Received Signal Level (RSL), Bit Error Rate (BER) and Packet Completion Rate (PCR) at pre-selected field-test sites; (3) determine the existence of multipath radio signals due to reflection(s) off surrounding terrain and structures; and (4) assess in-building message-receipt probability. The reason items 2-3 were assessed was to determine possible causes of missing messages or delays in receiving them (i.e., low signal level, multi-path interference and in-building attenuation).

In order to select the most productive subset of test locations, the results of the a survey question asking where users experienced communications-coverage problems and the problem reports logged with the SWIFT Hotline were used as major inputs to this process. In addition, information previously gathered by the firm of Hatfield & Dawson, Consulting Engineers, during their earlier (1995) tests for FM channel interference by the Seiko messaging system, were also a factor in the decision process. Although H&D were primarily concerned with measuring the distortion induced into the FM entertainment channel by the Seiko HSDS messages, they also noted a number of locations that exhibited high levels of multi-path distortion in the HSDS signal.

The *SWIFT Communications Study* field tests were conducted during the week of July 28 to August 2, 1997 and data was collected at eight (8) field test locations using Seiko MessageWatch and RRM devices to receive pre-determined messages from the Seiko HSDS system. A number of methods were used to measure the coverage/performance of the SWIFT system at the test sites. In order to obtain both technical and operational measurements, the test suite included both the SEIKO MessageWatches and two laptop portable computers with RRM adapters. Test instrumentation included:

- An HP-8965E Spectrum Analyzer, which was used to provide accurate, calibrated measurements of received signal level (RSL) from the FM transmitters at each of the test sites. It was also used to measure the 'noise-floor' adjacent to the transmitter's channel. This measurement was used to calculate a signal/noise (SNR) measurement from a specific transmitter, which can be correlated to the bit error rate (BER), as well as the packet completion rate (PCR). The spectrum analyzer was also used to measure the variation in the signal level as a function of time. Large variations in received signal level, greater than 3-4 decibel (dB), are an indicator of multi-path signal propagation.
- The TREQ Monitor is a piece of portable Seiko test instrumentation, used by their field technicians to measure and evaluate the reception characteristics at a site. In use, it is locked to the frequency of one of the transmitters in the system, and consequently doesn't employ the channel selection algorithms incorporated in the Message Watch and RRM. For each transmitter, the unit records the RSL, BER, PCR and level of error correction that was necessary. This information is presented on a monitor, and can be saved as snapshot images for further analysis. The TREQ was the major source for technically detailed information on the reception performance for each channel and the calculation of BER/PCR rates.
- At each location global positioning system (GPS) information, received signal levels (RSL), delta RSL, bit-error-rates (BER), packet completion rates (PCR), base-band spectrum levels, and noise levels as well as test message data from 2 RRMs, 6 Seiko MessageWatches and a Seiko TREQ monitor system were collected. This information was recorded for each of the seven (7) HSDS broadcast stations supporting the SWIFT program in the Seattle area.

Detailed analysis of the user questionnaires and focus group reports indicated that the majority of SWIFT users, approximately 93%, reported no communications problems with the SWIFT HSDS. Thus, the Seiko HSDS worked quite effectively for the purposes of the SWIFT FOT evaluation.

Analysis of communications problem reports indicated that there were concentrations of areas where SWIFT message-reception problems existed. Four geographic locations (i.e., Downtown

Seattle, University District, Redmond and SeaTac) contained concentrations of reported in-building message-receipt problems, while three areas (i.e., Everett, Federal Way and Tacoma) contained the greatest concentrations of outside message-receipt problems. In-building message-receipt problems were localized at the University of Washington in the University District and at Microsoft in Redmond.

Field testing was conducted at eight outdoor sites that were previously identified as possible locations where there may be message-receipt problems. One outdoor test site (i.e., Everett) was the same as one of the three primary locations were SWIFT participants reported problems receiving messages. Otherwise, indoor testing was also conducted at one site (i.e., Shoreline). Summary results for on-site testing indicated that for Site #1 (Bellevue), the BER and PCR were extremely good except for the most distant stations, KAFE and KBTC. Site #2 (West Seattle) faired much poorer, being able to receive messages from only one station, KCMS, which was directly across the water from the test site. Site #3 (SeaTac) exhibited reasonable BER and PCR performance from four out of seven HSDS signals, while Site #4 (Everett) was assessed to have an extremely harsh multi-path environment which could be mitigated somewhat by using a directional antenna to reduce reflected off-axis signals. Site #6 (Shoreline) exhibited problems with all but one station, KCMS where it was believed that the closeness to the transmitter resulting in a high RSL caused the devices to immediately lock onto this station. This could also explain the good performance experienced with KCMS at site #7 (Downtown Seattle), which was somewhat closer to this station and without obstructions than any of the other stations. Data collected at site #5 (South Seattle) through #8 (Puyallup) showed typical results, based on the area topography and confirm the user reports of problems. Thus, sites #4 (Everett) and #6 (Shoreline) were probably the worst performers of the lot.

The RSL measurements made as part of these tests tracked reasonably well with the predicted contours produced by Seiko. While the predicted levels were sometimes higher that those measured, the correlation was strong enough to support using the RSL contours for HSDS system coverage planning and transmitter site selection. Plots of BER and PCR as a function of RSL, produced from the test results, indicated that the error rate and minimum signal level quoted in Seiko's specifications were valid. There was, however, a strong suggestion that while sufficient RSL is necessary to successfully transmit messages at a particular location, it is not by itself a sufficient indicator of message-delivery success.

At least two sites were found to have a significant impact of the BER/PCR due to multi-path interference. In an area topographically prone to the creation of multi-path interference, such as Seattle, the use of RSL predictions alone were determined to be an inadequate measure of ultimate system performance. In other words, while a predicted RSL contour may indicate that a receiver should be able to lock onto several available HSDS signals, multi-path may render many unusable, despite more than an adequate RSL.

In building tests showed a significant overall drop off in RSL for locations A and D, this measured reduction in RSL of greater than 50 dB results in a corresponding decrease in PCR from 100% to approximately 65%, as well as a serious increase in BER from 10-6 to 10-2. What is even more important about the outcome of this test series is that the HSDS station (KCMS) used for this test is approximately 1.8 miles Northwest of the TSMC facility and has an extremely strong signal.

The SWIFT FOT was a success from a communications point of view. Analysis of user-reported problems with receiving messages indicated that the HSDS performed within predicted estimates provided by Seiko. That is, approximately 93% of all users reported that they experienced no problems receiving messages. In addition, field measurements of RSL, BER and PCR confirmed that the system performed within specifications, although the receipt of messages in some test locations appeared to be influenced by multi-path factors. In particular, the existence of multi-path appeared to degrade slightly the receipt of messages and measured BER and PCR levels at two sites. Finally, in-building receipt of messages was impacted by the distance a receiving device was located inside a building. Nonetheless, in-building degradation of message-receipt is a normal performance characteristic of an HSDS and one in which the environmental factors (e.g., building structures, antenna design) contributing to this effect are not completely known.

In summary, the *SWIFT Communications Study* documented the successful performance of an HSDS that was fielded in conjunction with a deployed ATIS in the Seattle, WA area. This conclusion is supported by the data that was collected during the conduct of this evaluation.

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1. INTRODUCTION

The United States (U. S.) Congress passed the Inter-modal Surface Transportation Efficiency Act (ISTEA) in 1991. The purpose of this legislation was to re-invigorate the country's transportation infrastructure by providing needed repairs to the highway system, encouraging the development of inter-modal transportation facilities and applying information technology (IT) solutions to transportation problems.

The Intelligent Transportation Systems (ITS) initiative grew out of ISTEA's interests to apply IT solutions to transportation problems. Specifically, the U. S. Department of Transportation (USDOT) developed the *National Program Plan for ITS* (1994) in order to guide the deployment of ITS around the country. The goals of the USDOT ITS program are to:

- Improve the safety of surface transportation
- Increase the capacity and operational efficiency of the surface transportation system
- Enhance personal mobility and the convenience and comfort of the surface transportation system
- Reduce the environmental and energy impacts of surface transportation
- Enhance the present and future productivity of individuals, organizations and the economy as a whole
- Create an environment in which ITS can flourish

Operational tests present opportunities to develop, deploy and evaluate specific implementations of ITS. According to the Federal Highway Administration (FHWA) document, *Generic ITS Operational Test Guidelines* (1993), prepared by The MITRE Corporation, an ITS Field Operational Test (FOT) is a "joint public/private venture, conducted in the real world under live transportation conditions..." that "...serve[s] as [a] transition between Research and Development (R&D) and the full-scale deployment of [ITS] technologies." Thus, FOTs represent a significant step in accelerating the deployment of ITS in North America.

Conducting FOTs results in feedback from the public regarding the viability and perceived usefulness of a specific ITS implementation. This information can be used by the public and private organizations involved to determine the best approach toward full-scale implementation after the FOT is completed. Also, lessons are learned during the conduct of an FOT that will enable the Federal, State and Local governments in partnership with industry and non-profit, academic institutions to bear, conceive, design, develop and deploy an ITS that provides the best possible services to the traveling public.

1.1. SWIFT Project

On September 8, 1993, the Federal Highway Administration (FHWA) published a request for ITS FOTs. The concept for the SWIFT project was submitted in response to this request on January 6, 1994 by the SWIFT Project Team. The SWIFT Project Team proposed to partner with the FHWA to perform an operational test of a wide-area ITS communications system in the

Seattle area. The proposed system incorporated a flexible FM sub-carrier High Speed Data System (HSDS) that had been developed and commercially deployed in the Seattle area by one of the SWIFT Project Team members. The HSDS would be used to transmit traveler information to three receiving devices provided by other SWIFT Project Team members. It was anticipated that the SWIFT Operational Test would provide valuable information regarding the viability of these devices for traveler information systems. SWIFT Project Team members included:

- Delco Electronics Corp., a subsidiary of General Motors Corporation (Delco)
- Etak, Inc. (Etak)
- Federal Highway Administration (FHWA)
- International Business Machines, Inc. (IBM)
- King County Department of Metropolitan Services (Metro Transit)
- Metro Traffic Control, Inc. (Metro Traffic Control)
- Seiko Communications Systems, Inc. (Seiko)
- Washington State Department of Transportation (WSDOT).

On April 6, 1994, the SWIFT proposal was accepted by the FHWA contingent upon the filing of a signed Memorandum of Understanding (MOU) by all SWIFT Project Team members and a Teaming Agreement between the Washington State Department of Transportation (WSDOT) and the FHWA. The SWIFT MOU was signed on October 18, 1998 and the SWIFT Teaming Agreement was completed on January 10, 1995. Following the fulfillment of these requirements by the SWIFT project team, construction of the SWIFT system was initiated.

In addition to guiding the signing of the SWIFT MOU and Teaming Agreements, WSDOT also negotiated separate contracts with the University of Washington (UW) and Science Applications International Corporation (SAIC) to participate in the SWIFT project. The University of Washington was retained to provide data gathering and fusion services for the project, while SAIC was retained as the independent evaluator. In this regard, SAIC signed their contract with WSDOT on September 13, 1994 and UW on November 17, 1994.

As part of the their contract with WSDOT, the University of Washington also developed and demonstrated a dynamic ride-share matching system called Seattle Smart Traveler (SST). SST used the UW Intranet to match ride requests with drivers. Participants registered and requested/offered rides using a web-like page, and riders would be notified of pending rides by email. The project also used 65 SWIFT Seiko MessageWatchs, or pagers, to let riders know where to call to set up a ride. These SST users also participated in SWIFT and received traffic incidents and general information messages. A separate evaluation of SST was conducted by the Texas Transportation Institute and, thus, the SWIFT evaluation did not address the SST project.

1.2. SWIFT System Description

An overview of the SWIFT system is shown in Figure 1-1, while Table 1-1 lists the primary types of information that were delivered by SWIFT. Each SWIFT receiving device regularly scanned the FM airwaves to identify, retrieve and display the information/messages intended for it.

The SWIFT system was divided into five (5) data components:

- Generation— gathering of the information to be transmitted
- Processing— formatting of the information to be transmitted
- Transmission— broadcast of the information to travelers
- Reception— receipt of the transmitted information by SWIFT devices
- Interpretation— use of the transmitted information by operational test participants.

Each of these are described in the following sections.

Table 1-1. Information Delivered by SWIFT.

Device/Information Received	Traffic Incidents, Advisories, Scheduled Events and Road Closures	Route Guidance	Traveler-Service Information	Freeway Loop-Sensor Information	Bus Locations and Schedules	Time and Date, Personal Paging and General Information Messages
Seiko MessageWatch	Yes	--	--	--	--	Yes
Delco In-vehicle Navigation Device	Yes	Yes	Yes	--	--	Yes
SWIFT Portable Computer	Yes	--	Yes	Yes	Yes	Yes

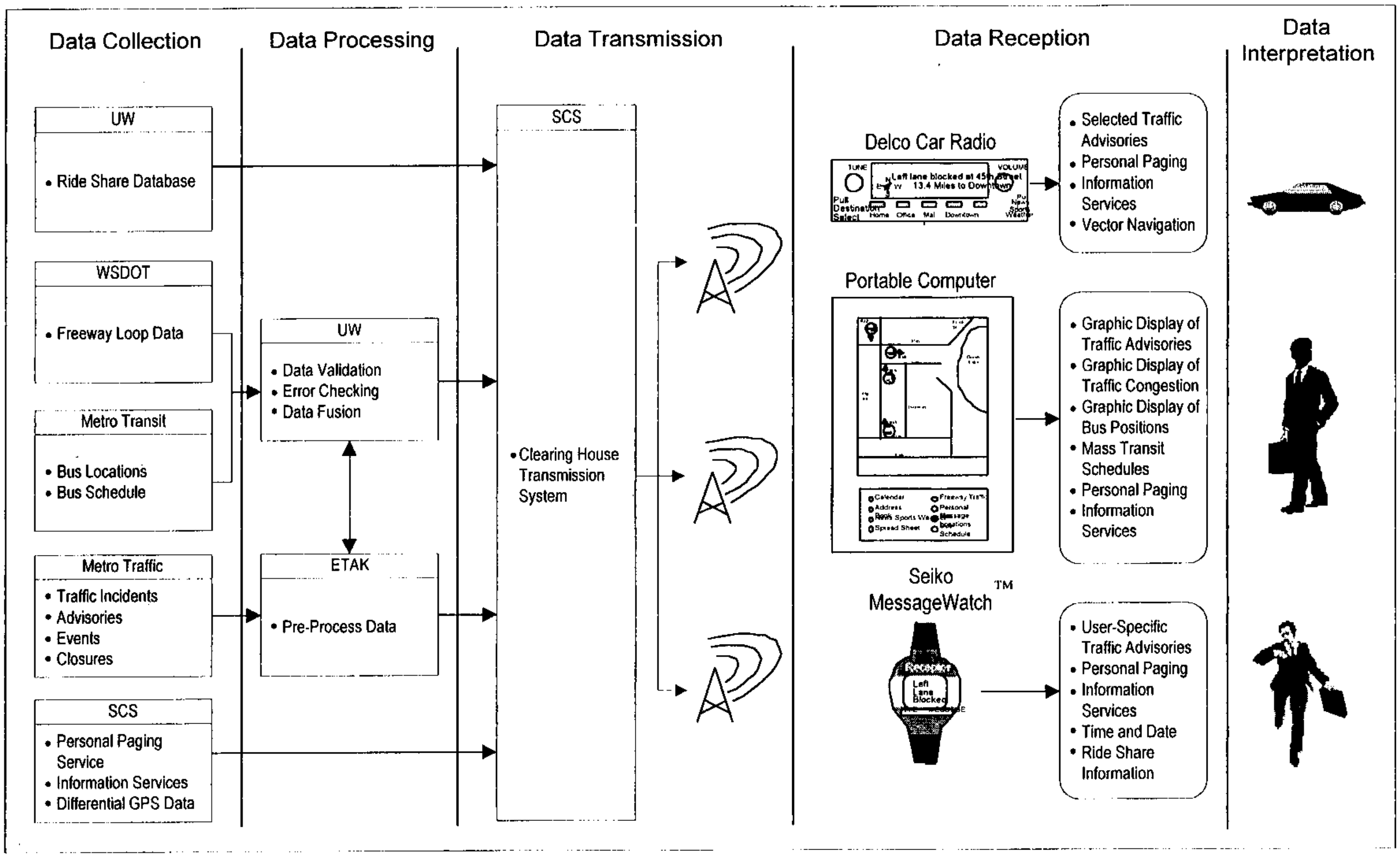


Figure 1-1. SWIFT System Description.

1.2.1. Generation

Table 1-2 provides a listing of the information that was provided to SWIFT FOT participants. This information was generated by Metro Traffic Control, Etak, Delco, WSDOT, Metro Transit and Seiko.

Table 1-2. SWIFT Data Generation.

Data Generator	Data Generated
Metro Traffic Control, Inc.	Traffic Incidents, Advisories, Scheduled Events and Closures
Delco and Etak	Route Guidance
Etak	Traveler-Service Information
WSDOT	Freeway Loop-Sensor Information
Metro Transit	Bus Locations and Schedules
Seiko Communications Systems, Inc.	Time and Date, Personal Paging and General Information Messages

Traffic Incidents, Advisories, Scheduled Events and Closures

This information was generated by Metro Traffic Control personnel who routinely compiled incident information for use in traffic reports delivered to several Seattle-area radio stations. Information, consistent with the International Traveler Information Interchange Standard (ITIS), was entered into a Traffic Work Station (TWS) developed by Etak, Inc. The TWS located the incident and the operator added descriptive information about the incident, such as "truck overturned" or "right lane closed." The TWS then formatted the message for transmission and forwarded it to Seiko.

Route Guidance

As part of the in-vehicle device they developed for the SWIFT project, Delco supplied a route-guidance system that assisted local drivers by providing a directional pointer to pre-selected destinations. This system incorporated a Global Positioning System (GPS) antenna that was placed on the roof of the SWIFT FOT participant's vehicles that participated in this portion of the test, and was tied into a Geographic Information System (GIS) that Etak supplied. Users would select destinations from an "Etak Guide" which contained the latter's geographic coordinates. Users could also enter latitude/longitude coordinates as destinations, save the current positions of their vehicles as destinations and select to receive estimated time of arrival (ETA) information based upon the current speed of their vehicles. The route guidance provided by the directional pointer was static— no turn-by-turn directions were provided, only an arrow pointing in the direction the driver needed to go to reach the destination.

Traveler-Service Information

As indicated, the in-vehicle device for SWIFT provided traveler-service information (i.e., Etak Guide) to its users. This same information was also presented as a "Yellow Pages" directory on the SWIFT portable computers. Users could select the name of local-area businesses or organization by category (e.g., service stations, restaurants, colleges and universities, tourist destinations, etc.) and receive a display of the appropriate address and telephone number in order to guide their travel. Portable computer users could also select to have the locations of their selections presented on the map of Seattle that accompanied the SWIFT application.

Freeway Loop-Sensor Information

Traffic congestion information was derived from the existing WSDOT freeway management system in Seattle. Vehicles were detected with a network of 2,200 standard traffic loops, and UW used the loop information to estimate speeds, which were then expressed as a percentage of the posted speed limit. The speed information was compared to freeway bus speeds to detect any errors. Congestion information was then packaged into a format that could be directly transmitted and sent to Seiko via the Internet.

Bus Locations and Schedules

Bus location and schedule information was provided by King County Metro Transit. Their Automatic Vehicle Location (AVL) system uses small roadside transmitters, wheel (distance) sensors and pattern matching to locate buses in the system. Each location was updated about once every minute and a half. Raw data from Metro Transit's system were sent to UW, where each coach location was converted into latitude and longitude. The UW then generated all of the information including the route and trip number into a format ready for transmission, which was sent to Seiko via the Internet. The SWIFT project included all the fixed routes that Metro Transit operates, or up to 900 buses during peak periods.

Time and Date, Personal Paging and General Information Messages

All SWIFT devices also received and displayed information services currently available to Seiko MessageWatch customers. These included time and date, weather reports, financial-market summaries, sports scores, ski reports and lotto numbers. All SWIFT devices could also function as a personal pager.

1.2.2. Processing

Data generated by WSDOT, Metro Transit, and UW were collated at UW, where it was validated, converted, corrected and fused. Once these activities had taken place, the data were processed into standardized data packets in order to facilitate ultimate transmission over the HSDS. Information provided by Metro Traffic Control was preprocessed on the TWS. All data from UW and Metro Traffic Control were transmitted to Seiko via the Internet.

1.2.3. Transmission

SWIFT data transmission involved sending the processed data to Seiko which formatted the data packets for transmission over the HSDS transmission network. Once formatted by Seiko, the data were transmitted over an FM subcarrier at a rate of 19,000 bytes per second (19 Kbps). In order to increase the certainty of reception by Seiko MessageWatches, double-level error correction and multiple transmissions were used. Otherwise, asynchronous (or broadcast) message sent to the Delco in-vehicle navigation device and the portable computers were sent only once.

Seiko High Speed Data System

The SWIFT project was based upon the HSDS that is currently used to deliver paging and information services to Seiko MessageWatch customers. The HSDS signal is added to standard FM broadcast transmissions in the form of digital data modulated at a frequency 66.5 khz higher than the standard, or "nominal," FM audio signal. No portion of an FM signal, audio or otherwise, is broadcast below the nominal frequency. FM radio signals are usually broadcast in three frequency groups between the nominal frequency and 55 khz above this frequency. Thus, the SWIFT HSDS signal was presented at a frequency that did not interfere with nominal, or standard FM audio, transmissions.

SWIFT HSDS receivers were "frequency agile," which means they could receive messages from any HSDS-equipped FM station. Seven Seattle-area radio stations transmitted the HSDS protocol to SWIFT devices. Consequently, information was sent from all stations in the area which nearly guaranteed reception of important paging messages.

SWIFT information was transmitted three times (once every 1.87 minutes) from each station for the Seiko MessageWatch. Otherwise, for the portable computers and Delco in-vehicle navigation device, congestion information was transmitted every 20 seconds, incident information every 30 seconds and bus information every 90 seconds. This feature of the Seiko HSDS provided information redundancy which further ensured that SWIFT FOT participants were receiving the most current information provided by their receiving device.

SWIFT Message Formats

All SWIFT information was encoded into a version of the International Traveler Information System (ITIS) message-formatting convention. The North American version of ITIS, which was developed by the Enterprise group, is based on message formats used by the European Radio Broadcast Data System (RBDS). The ITIS codes conserve bandwidth by sending incident and congestion information in a compact form. Some customization of the ITIS formats was necessary for SWIFT in order to adjust for HSDS packet size, which is longer than the RBDS packet. Message formats were also developed to send the SWIFT bus location and speed/congestion data, which are not available in the RBDS.

SWIFT traffic-incident information received by the Delco in-vehicle navigation device was integrated with Global Position System (GPS) location and time/date information received by the same device. The latter capability provided the incident-direction/distance information and the current time of day information presented by the Delco in-vehicle navigation device.

Information transmitted to the three receiving devices used in the SWIFT project is presented below:

- Seiko MessageWatch— incident type/direction, roadway affected and closest intersection. Example: A level 3 incident (i.e., accident) on Southbound I-5 is located near the Mercer intersection.

- Delco In-vehicle Navigation Device— incident type/direction, description, roadway/intersection affected, duration and vehicle-reference (in miles) description. Example: An accident blocking the two outside lanes of Northbound I-5, expected to last for the next 15 minutes, is located 16 miles to the Northwest.
- SWIFT Portable Computer— icon display/text description (including incident type, roadway affected, direction, closest intersection, backup and duration) of incidents, icon display of real-time bus position, timepoint schedule information, icon display of speed information (i.e., closed, 0-19, 20-34, 35-49, 50+ and no data) and speed icon location description. Example: Vehicles are traveling at 50% of normal speed at the Mercer speed sensor.

1.2.4. Reception

Three types of HSDS-capable receiver devices, each developed and manufactured by private entities through consultation with their SWIFT team members, provided SWIFT FOT participants with incident information, traffic speed/congestion information, bus information, informational messages (e.g., forecast weather, sports scores, stock-market information) and personal pages, depending upon the device. The devices were:

- Seiko MessageWatch
- Delco In-Vehicle Navigation Device
- SWIFT Portable Computer

Figures 1-2, 1-3 and 1-4 show examples of the three receiving devices used for SWIFT. Operational features of each of these devices are described in the following sections.

Seiko MessageWatch

These devices are commercially available and widely used in the Seattle area to deliver personal-paging services and "information service" messages. Current information-service messages include weather forecasts, financial market summaries, local sports scores and winning lotto numbers. SWIFT traffic messages were featured as an added information service.

SWIFT test participants who used the Seiko MessageWatch supplied information to the Evaluator about the usual routes, directions, days and times of the day they traveled. Traffic messages indicating the location and severity of traffic problems that the user might encounter were sent based on the resulting travel profile. Because the Seiko MessageWatch stored eight messages, only traffic problems that resulted in substantial delays were sent.

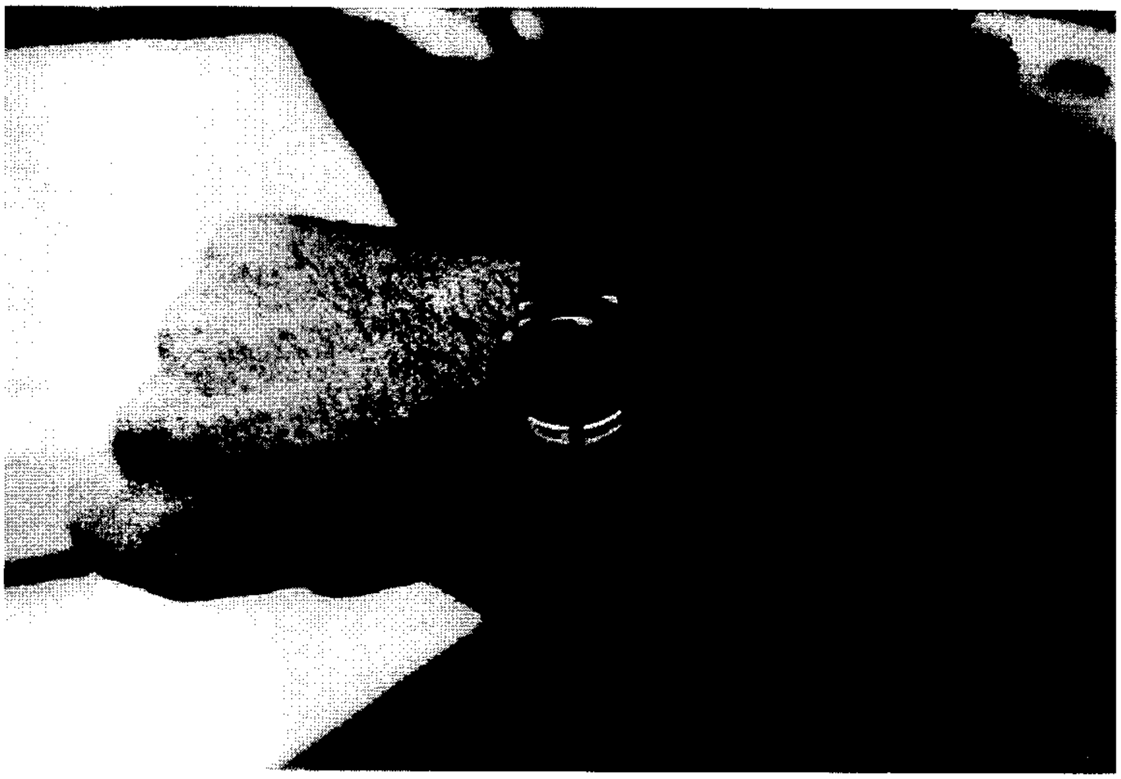


Figure 1-2. Seiko MessageWatch.

Delco In-Vehicle Navigation Device

This device incorporated a route-guidance component, GIS, GPS receiver and the speakers of a radio/compact disc player to present real-time traffic information to users. The whole package was placed into one of four vehicle types: 1995 or newer Buick Regals, Oldsmobile Cutlass Supremes and Saturns, and GMC Rally Vans.

The Delco device included the capability to select destinations from a "Yellow Pages" directory of local landmarks, hotels, restaurants, businesses and street corners selected by the user. The GPS provided the current location of the vehicle and a directional display associated with the route guidance system indicated the direction (relative to the vehicle) and distance to the selected destination. The stereo speakers were used to announce received messages.

Real-time traffic-incident information was transmitted over the Seiko HSDS. The HSDS receiver was built into the Delco in-vehicle navigation unit filtered out any messages that were outside a pre-defined distance (e.g., 20 miles) from the current location of the vehicle. The navigation unit also decoded upon demand the SWIFT traffic messages from text into a "voice" that provided incident details to the driver. Although messages were retransmitted every minute, only new or modified messages were announced to the driver.

Figure 1-3. Delco In-vehicle Navigation Device.

SWIFT Portable Computer

The SWIFT project primarily used IBM Thinkpad and Toshiba Satellite portable computers. Some Dauphin sub-notebook computers were distributed before they were discontinued due to negative user feedback. The Thinkpads were 486 machines, used Windows 3.1, had a built-in, "butterfly" keyboard and presented information on an active matrix, SVGA color display. The Satellites were Pentium 100 machines, used Windows 95 and also presented information on SVGA color displays.

A separate HSDS receiver unit was attached to the SWIFT portable computer's serial port. This unit had approximately the same footprint as the portable computer and was often attached to the portable computer via Velcro tape. Primary SWIFT information presented on the portable computer included real-time traffic incident, speed/congestion and bus-location information.

All of the traveler information for SWIFT portable computers was displayed using Etak Geographical Information System (GIS) software to show the location of each piece of data. The software allowed the user to select the type(s) of information (i.e., traffic incident, speed/congestion or transit-vehicle location) to be displayed on a map of Seattle. A "Yellow

Pages" directory was also installed and linked to the GIS software to show the location of a selected business or point of interest. SWIFT portable computers also offered transit schedule information from static database tables inside the computer.

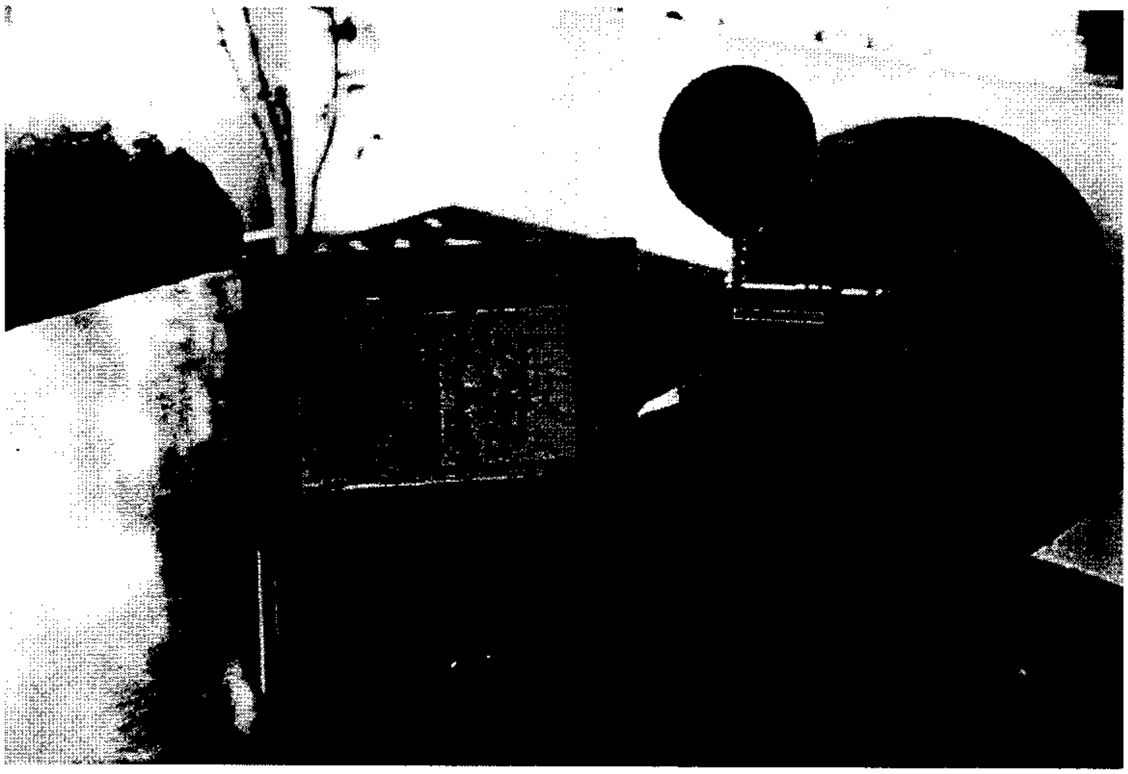


Figure 1-4. SWIFT Portable Computer and RRM.

1.2.5. Data Interpretation

The data interpretation portion of the SWIFT system involved hypothesized processes that affected how users were able to interact with the system. Among those user perceptions that were addressed were the following :

- Data Reception— whether SWIFT information was received
- Data Timeliness— whether SWIFT information was received in a timely fashion
- Data Reliability— whether SWIFT information was regularly received
- Data Display— whether SWIFT information was displayed appropriately
- Data Fidelity— whether SWIFT information was accurate
- Data Validity— whether SWIFT information affected travel behavior.

1.3. SWIFT Field Operational Test Evaluation

Once the SWIFT system was completed, an FOT was conducted with approximately 690 users who were recruited from the community in order to assess the system. With the majority of the SWIFT system completed by June 30, 1996, the SWIFT FOT evaluation was conducted from

July 1, 1996 through September 20, 1997. The goals of the SWIFT FOT evaluation, listed in order of priority, were to evaluate:

1. *Consumer Acceptance, Willingness to Pay and Potential Impact on the Transportation System* – determine user perceptions of the usefulness of the SWIFT receiving devices, how much consumers would be willing to pay for such devices and services and assess how SWIFT-induced changes in users' driving behavior might impact the Seattle transportation network if the SWIFT system was fully deployed.
2. *Effectiveness of the HSDS Transmission Network* – determine how well the SWIFT HSDS communications system functions.
3. *Performance of the System Architecture* – determine how well the various SWIFT components work singularly and together.
4. *Institutional Issues That Affected the Operational Test* – identify how institutional factors associated with the SWIFT public-private partnership affected the FOT, with emphasis on implications for deployment.
5. *Deployment Costs* – estimate how much money it would take to deploy and maintain a SWIFT-like system.

Five evaluation studies were conducted as part of the SWIFT FOT evaluation. These studies paralleled the five SWIFT FOT evaluation goals and were implemented at various times during the 15-month test. Table 1-3 provides a summary of SWIFT evaluation information.

As part of the conduct of the SWIFT FOT evaluation, the Evaluator was responsible for user recruitment. This involved the recruitment of approximately 1,200 individuals before selection of the 690 FOT participants was made. The final breakout of SWIFT participants is shown in Table 1-4.

Table 1-3. SWIFT Evaluation Information.

Study/ Activity	Study Leader	Test Plan Completion Date	Primary Data Collection Periods	Primary Data Collection Methods	Final Report Completion
Consumer Acceptance	Jeff Trombly	August 19, 1997	Spring, Summer and Fall, 1997	Questionnaires, Telephone Surveys, Focus Groups	March 31, 1998
Communications	Jim Murphy	August 19, 1997	Fall, 1997	Field Tests	June 29, 1998
Architecture	Hesham Rakha	August 19, 1997	Spring, 1997	Data logging and Field Tests	March 31, 1998
Deployment Cost	Mark Jensen	August 19, 1997	Summer, 1997	Data Collection	March 31, 1998
Institutional Issues	Bruce Wetherby, Principal Investigator	August 19, 1997	Spring and Fall, 1997	Questionnaires and Semi-structured Interviews	March 31, 1998

Table 1-4. SWIFT Participant Breakout.

Device/Condition	Existing	New	Metro Transit Van Pool	SST	Total
Seiko MessageWatch	50	400	--	70	520
Delco In-vehicle Navigation Device	--	65	25	--	90
Portable Computer	--	80	--	--	80
Total	50	545	25	70	690

Selection criteria for each category of SWIFT user varied, primarily depending upon the assumed operational requirements for each device type. As a result, three types of Seiko MessageWatch users (i.e., existing [i.e., those who owned their own watches], new [i.e., those who were given a Seiko MessageWatch for the first time] and SST [i.e., those who participated in the SST program] and two types of Delco in-vehicle navigation device users (i.e., new [i.e., SOV commuters] and Metro Transit Van Pool [i.e., HOV commuters] were recruited. The majority of the eighty (80) SWIFT portable computer users were bus riders with mode-choice options.

The SWIFT FOT Evaluator was also responsible for the following activities:

- Device configuration/software installation
- Device distribution/installation scheduling
- Training/instruction on device usage
- Travel profile entry/maintenance
- SWIFT Help Desk
- User problem analysis/feedback to team members
- Device collection/de-installation
- SWIFT newsletter (writing, publication and mailing; WSDOT responsible for editing and breadboarding)

1.4. Purpose of SWIFT Communications Study

The purpose of the *SWIFT Communications Study* was to evaluate the communications coverage of the Seiko HSDS that was used as the wireless communications for the SWIFT FOT. The focus of this evaluation was to assess the appropriateness of using FM subcarrier technology for disseminating traveler information.

1.5. Objectives

The objectives of the *SWIFT Communications Study* were to:

- Measure the interoperability, or capability of the SWIFT HSDS to perform without interfering with commercial information transmission.
- Determine the delay associated with the receipt of SWIFT messages.
- Assess the adequacy of the communications coverage provided by the SWIFT HSDS.

In the end, the first two objectives were not addressed by the *SWIFT Communications Study* because the interoperability of the SWIFT system was not a reported concern of the Fmstations providing the infrastructure for the SWIFT HSDS, and because SWIFT message delay was assessed by the *SWIFT Architecture Study*. Otherwise, the sub-objectives of the *SWIFT Coverage Field Test*, which was designed to assess the adequacy of the HSDS message transmission within the SWIFT coverage area, were:

- Determine the capability of the HSDS subcarrier to deliver ITS information
- Assess Received Signal Level (RSL), Bit Error Rate (BER) and Packet Completion Rate (PCR) at pre-selected field-test sites.
- Assess the existence of multi-path
- Determine in-building message-receipt probability

The methods and findings of the *SWIFT Communications Study* are presented according to these sub-objectives.

Initially, the *SWIFT Communications Study* was also going to assess (1) the interoperability of the SWIFT system and (2) the delay associated with the receipt of SWIFT messages. The interoperability test, which was designed to assess the character of any self-induced interference caused by the HSDS sub-carrier signal on the FM entertainment signal in the same 100 KHz baseband spectrum, was canceled due to the substantial number of studies which have already been performed as well as the lack of perceived FM signal degradation observed and/or reported during the SWIFT operational test period of more than a year. The delay test, which was intended to characterize the throughput delay of known message traffic from the Seiko network operations center (NOC) to the three test devices, was cancelled because this activity was subsequently performed by the *SWIFT Architecture Study*.

2. METHODOLOGY

This section provides an overview of *SWIFT Communications Study* test procedures. Four coverage tests are addressed: (1) how the overall capability of the SWIFT HSDS to deliver ATIS information was determined and how field-test sites were selected; (2) how RSL, BER and PCR field-test measurements were obtained; (3) how multi-path assessments were derived and (4) how in-building message-receipt probability was measured. More detail regarding individual site test setup procedures is presented in Appendix A.

2.1. Independent HSDS Assessment and Selection of Test Sites

The purpose of the independent HSDS assessment was to determine the capability of the SWIFT system to provide ATIS information. First, user-generated responses to questions were used to identify the percentage of users that reported coverage problems. Second, the user responses were used along with signal-strength plots to identify test field-site locations that were likely to have poor reception so that the nature of the problems could be studied.

The following steps were used to conduct an assessment of the adequacy of the SWIFT HSDS to provide ATIS information:

- Step 1: Obtain composite HSDS coverage maps from Seiko indicating RSL contours for the two end-user devices (i.e., Seiko MessageWatch and SWIFT portable computer) being used for field testing
- Step 2: Ask SWIFT FOT participants to report areas of SWIFT communications difficulty with their devices. This was done for *SWIFT Consumer Acceptance Study* Questionnaire #1
- Step 3: Perform content analysis and summarize SWIFT FOT participant-reported areas of poor information reception. Groupings of reported areas of communications coverage problems, in particular, were noted and identified
- Step 4: Determine reported areas of communications problems that were outside the HSDS coverage map and eliminate them as possible test sites
- Step 5: Calculate percentage of SWIFT FOT participants who reported no communications problems, or were otherwise satisfied with SWIFT HSDS coverage
- Step 6: Determine concentrations of areas where SWIFT FOT participants reported indoor and outdoor problems with receiving messages

The following steps were used to determine the field-test site locations that should be used to test the adequacy of SWIFT HSDS coverage:

- Step 1: Obtain 1:500,000 scale USGS map of Washington State and plot locations of seven (7) SWIFT HSDS stations

- Step 2: Review SWIFT questionnaire, focus group and help-desk reports information to isolate areas of reported communications difficulty. Plot these areas on a 1:500,000 scale USGS map of Seattle
- Step 3: Compare reported areas of SWIFT communications difficulty to composite and individual-station HSDS RSL contours for MessageWatches and portable computers as supplied by Seiko
- Step 4: Compare reported areas of SWIFT communications difficulty to the locations of HSDS tests performed during a previous study commissioned by Seiko (i.e., Hatfield and Dawson, 1995)
- Step 5: Factor in different receiver sensitivities for MessageWatches and portable computers
- Step 6: Overlay individual-station HSDS RSL contours on the USGS 1:500,000 map of the Seattle to identify/confirm possible areas of potential weak RSL for each HSDS station
- Step 7: Select "problem" areas of coverage for field testing by identifying weak individual-station RSLs and comparing them to user-reported problem areas

Initially, ten (10) areas with coverage problems were selected to be tested, but only eight (8) sites were actually tested.

2.2. RSL, BER and PCR Testing

The purpose of this testing was to measure the Received Signal Level (RSL), Bit Error Rate (BER) and Packet Completion Rate (PCR) at locations identified through analysis of predicted RSL and user reports of poor or no message reception. These tests were performed using the equipment configuration shown in Figure 2-1. A calibrated test antenna and spectrum analyzer were used to sample and record the RF spectrum in the FM band for each of the seven (7) HSDS stations in the Seattle area. In addition, a TREQ monitor system (supplied by Seiko) was employed to simultaneously measure and log the PCR statistics for known test messages injected into the SWIFT system specifically for this test. Six (6) MessageWatches and two (2) SWIFT portable computers were used to receive these actual test messages.

The approach used for this series of tests was to have Seiko send repeated messages to the end-user devices being employed for this test. Receipt of SWIFT messages by Seiko MessageWatches was tested by mounting these devices on a large, wooden dowel. This dowel was fastened to a light-duty tripod in such a way as to allow it to be oriented vertically or horizontally. During testing, the watches were deployed on the test fixture in each of three orientations: North/South, East/West and vertically. They typically remained in each orientation for about two (2) hours, and were checked approximately every 45 minutes to determine if any messages were missing/not received. A log was kept for each watch, for each test orientation. Figures 2-2 and 2-3 show the two configurations (i.e., horizontal and vertical) that were used to test the Seiko MessageWatches.

Testing message-reception performance of the watch was somewhat problematical. Although Seiko was able to generate test messages to the watches with an incrementing index, these messages were sent to the watches at approximately six-minute intervals. This relatively low repetition rate meant that the use of a single watch would mandate an exceptionally long test period in order to collect a statistically relevant number of sample points. To reduce the duration of the watch test, six watches were included in the test configuration. By allowing the test to run for an hour or more, about ten measurement points per watch, or sixty total, were collected.

Receipt of messages by SWIFT portable computers (i.e., Toshiba Satellites) was measured at each site by using RRMHOST software supplied by Seiko. Typically, both units were initially placed outside the data-collection van, with one unit oriented in the North/South horizontal direction and the other in the East/West horizontal direction. The units were checked frequently to ascertain if they locked onto one of the seven HSDS stations. If either unit was in a slow-scan mode, a fast scan was initiated. Otherwise, the RRMHOST software, which was modified by SAIC technicians to record the receipt of information at one-second intervals, logged the receipt of all information by writing it to a harddisk "logfile" for later analysis. Finally, both portable computers and RRMs were powered by using two DC to AC inverters plugged into the rear cigarette lighter jack in the back of the van used for testing.

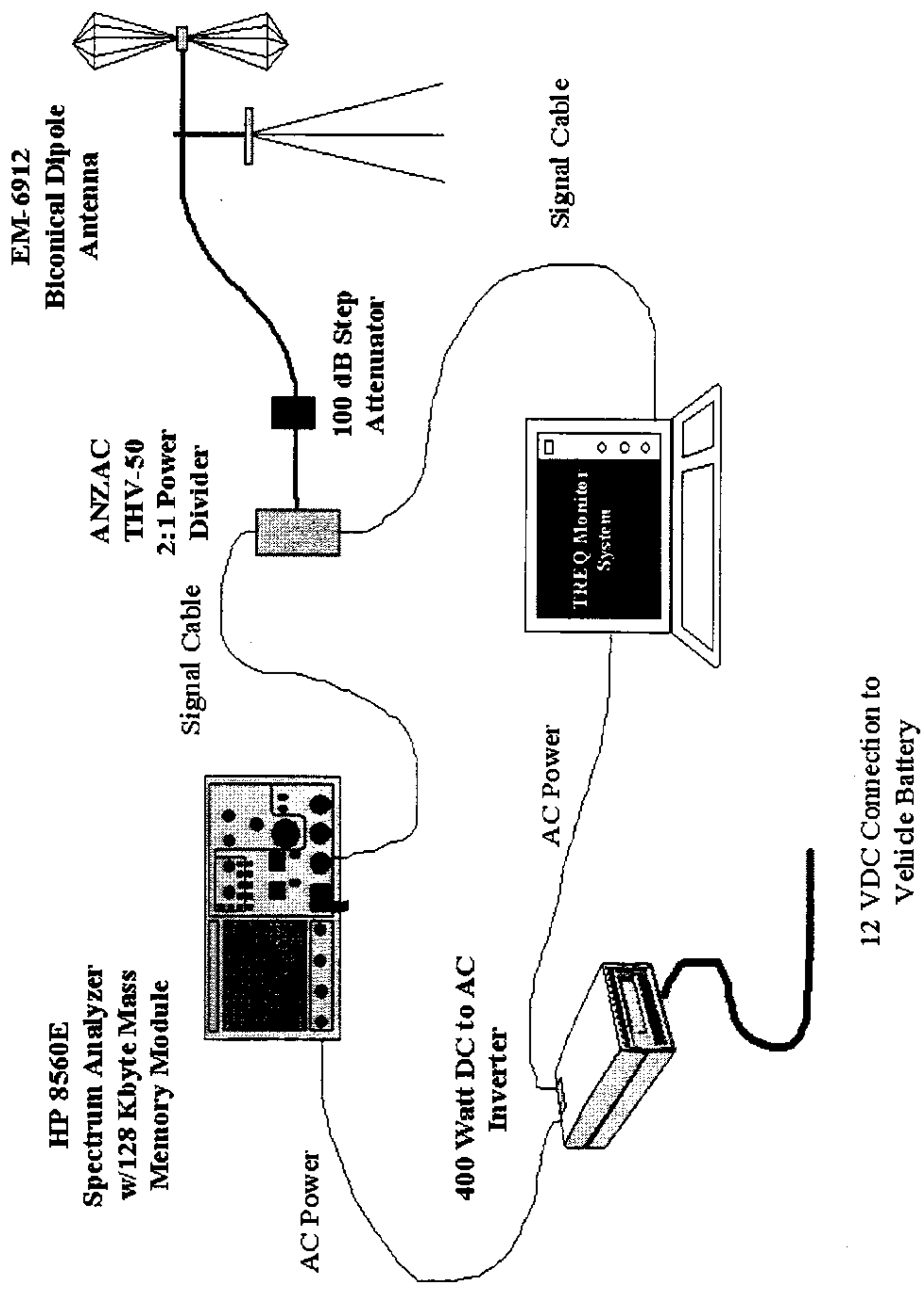


Figure 2-1. Coverage Test Equipment Configuration Diagram.

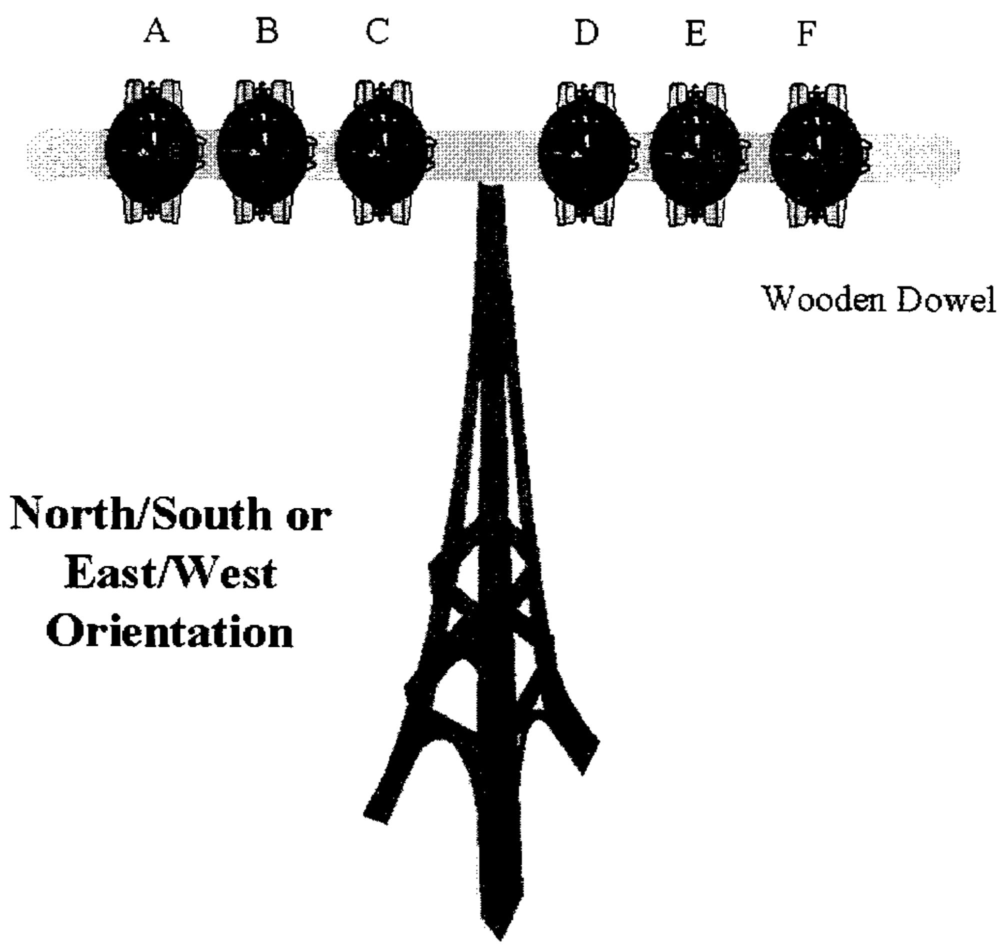


Figure 2-2. Drawing of Seiko MessageWatch Horizontal Test Configuration.

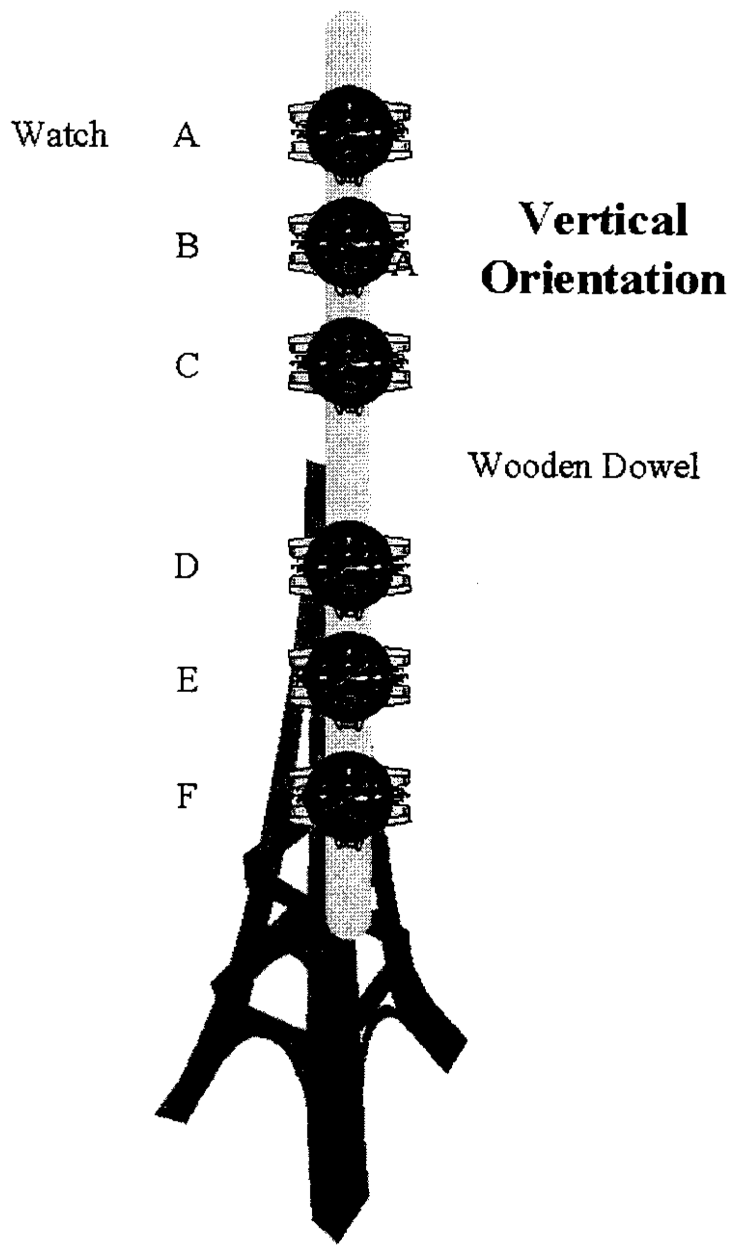


Figure 2-3. Drawing of Seiko MessageWatch Vertical Test Configuration.

Figure 2-4 shows an example of the raw data collected by the RRMHOST software. The local timestamp for each sample was indicated by the 'T:' entry in the log. Messages starting with "A:05" were time-synchronization messages sent by the system that were used by the analysis script to mark the approximate 'wall-clock' time when messages were lost. For the purposes of determining message reception error rate, Seiko arranged to have messages sent to the test RRM's at approximately one-minute intervals. The content of these messages was an index number that increased by one with each new message generated. If reception of a message was missed, the sequence of received index numbers would be broken and there would be a gap of one or more index numbers. Also, the difference between the time stamps of successive messages received by the test RRM's, given the known constant messages injection rate, was used to measure the inter-message arrival time, and make some preliminary inferences concerning delay and capacity. The index test messages generated by SEIKO were preceded by a "A:06" in the log excerpt, with the information field containing a hexidecimally encoded version of the ASCII digits of the index number.

To accomplish the necessary extraction and processing of messages from the log file, a script was written in MAWK. MAWK is a public domain, DOS-based version of the widely used UNIX AWK utility. It is an extremely powerful text-processing tool that can operate on large files very rapidly. The script detects gaps in index number messages, using these to generate a message-reception rate based on the number of messages that should have been received, and the number of messages lost. It also records the message inter-arrival times, producing a statistical distribution analysis of the inter-arrival times which included Max/Min values, mean, mode and standard deviation. A copy of the output produced by the MAWK script is shown in Figure 2-5.

Measurement of RSL, BER and PCR was accomplished at each site by using an omni-directional antenna, a spectrum analyzer and TREQ monitor. In particular, a calibrated, bi-conical dipole antenna, Model # EM-6912, manufactured by Electro-Metrics Corp., was used for most of the measurements done with the spectrum analyzer and TREQ monitor utilizing an ANZAC power splitter and associated 50Ω coaxial cabling. This is a highly omni-directional unit that has published calibrations between its apparent received signal level and a reference "isotropic" antenna (dBi). For SWIFT, it was oriented vertically and deployed using an accompanying bracket which was supported by a heavy-duty tripod.

```
T:867122230
A:C0 0A 0A 66 41 42 40 6B 55 55 7A 78 5E 6C
A:C0 7F 51 45 7A 66 47 71 5D 4E 40 40 79 7A
A:C0 40 6B 55 65 72 78 66 53 40 6E 51 68 66
A:C1 0A 12 02 B8 84 3A 27 43 98 86 80 3E 82 C6
A:C1 0A 38 80 07 8A DA 37 70 00 00 00 00 00 00
A:C1 0A 55 0B 98 8E 88 23 10 00 00 00 00 00 00
A:C1 0A 25 89 17 AE AC 03 53 98 45 88 87 84 FE
T:867122231
A:C0 45 71 5D 47 40 40 76 66 4E 71 52 45 78
A:C0 66 41 42 40 6B 55 79 75 78 42 6C 7F 51
A:C1 0A 3E C0 08 8E CA 31 31 1C 00 08 D3 E3 0E
A:C1 0A 11 C3 38 80 62 11 73 98 98 88 73 C1 E9
A:C1 0A 3E C0 08 0A D8 3D 03 EC 10 78 30 03 C2
A:C1 0A 12 41 28 03 D2 26 C3 E4 09 88 87 85 67
A:C1 0A 3F C4 78 07 14 2E B3 A4 00 08 4D 04 2F
A:C1 0A 3F 44 47 86 6E 1F D3 F4 00 88 DB E3 0A
A:C1 0A 11 C0 00 8D 3A 30 F4 48 02 09 0A 04 A4
A:C1 0A 0A 45 27 05 8A 2D C5 50 73 8A 2B 63 06
A:C1 0F 00 00 00 00 00 0D C7 DF 7D FD FE 61 C0
T:867122232
A:C1 0A 55 0B 58 A1 94 13 E3 98 98 88 74 41 E9
A:C0 6A 66 46 47 58 68 7F 61 5F 57 79 78 4E
A:C1 0A 3C 01 00 8A E8 22 44 48 22 78 DC 43 E3
A:C1 0A E6 00 08 04 F8 27 15 E4 55 80 B0 62 77
A:C1 0F 01 E3 F1 B8 DC 6F F7 1B 80 00 BC 5C 36
A:C1 0A 4E 81 17 0A D2 27 63 98 98 88 74 81 E9
A:C1 0F 03 03 8E 06 03 EE 3F 1F 8F FF E3 7D FF
A:C1 0F 04 DF FF F8 1F FF C7 FB 71 68 1F E0 00
```

Figure 2-4. Example of Raw Data collected by RRMHost Log File.

```
######################################################################
TEST ANALYSIS RESULTS
######################################################################

TEST START TIME STAMP =  867122229
FIRST TIME MESSAGE RECEIVED =  970730122716WE

TOTAL RRM MESSAGES RECEIVED =  48
TOTAL LOST RRM MESSAGES =  1
PERCENT RRM MESSAGES RECEIVED = 98.0

LAST TIME MESSAGE RECEIVED  =  970730131615WE
TEST STOP TIME STAMP  =  867125180

TEST DURATION =   2951 (sec.)   or        0.82 (Hrs.)

####################################################################
MESSAGE INTER-ARRIVAL TIME STATISTICS
####################################################################

MEAN = 58
STANDARD DEVIATION (å) = 24
2-SIGMA (2å) = 48

MIN. VALUE (Sec) = 14                 MAX. VALUE (Sec) = 154
MODE (Most Common Value, to Nearest 10 Sec. Increment) = 60

 14 <Å  ÅS  Å  ÅMÅ  Å  SÅ  Å  Å  Å  Å  Å  > 154

 14 <Å  Å  Å  ÅÛÅ  Å  Å  Å  Å  Å  Å  Å  > 154

   [ M = MEAN          S = Std. DEVIATION(å)       Û = MODE ]
[ Tick Marks Start at Next 10 Sec. -- Tick Increment = 10 Sec. ]
```

Figure 2-5. MAWK Script Output File.

The Spectrum analyzer (Model # HP 8540E) used for *SWIFT Communications Study* testing, which was purchased for subsequent WSDOT use, was incorporated to provide accurate, calibrated measurements of RSL from the FM transmitters at each of the test sites. It was also used to measure the 'noise-floor' adjacent to the transmitter channel. This measurement was used to calculate a signal/noise (SNR) measurement for a specific transmitter, which could be correlated to BER as well as PCR. Measurement of the adjacent channel noise-floor was also intended to address the issue of whether an unusually high noise environment might be the cause of reception problems at a specific site. The spectrum analyzer was also employed to measure the variation in the signal level received from the transmitters as a function of time, via the "Delta-Marker" function provided. Large variations in received signal level, greater than 3-4 decibel (dB), are usually an indicator of multi-path signal propagation.

The Seiko-supplied TREQ monitor is a portable computer with a Windows-95 based application called RPA. This application permits monitoring several quantities associated with the operation of the Seiko HSDS sub-carrier and was designed and is ideally suited for this type of testing. The TREQ was used to monitor and record the following data at each site for all seven Seattle-area stations: (1) RF spectrum received signal levels, (2) the baseband received signal levels, (3) the packet-completion rate and (4) a sampling of the data stream, and subsequent bit-error rate, being transmitted.

The TREQ Monitor is operated by manually locking to the frequency of one of the transmitters in the system, and consequently doesn't employ the channel-selection algorithms used in the MessageWatch and RRM. Nonetheless, for each transmitter, as indicated above, the unit records the RSL, BER, PCR and level of error correction that was necessary. This information was written to the screen and could be saved as a snapshot, Graphical Image File (GIF) for further analysis. Figure 2-6 shows the information that was presented on the TREQ monitor.

At all SWIFT field-test sites, two GPS units, one Garmin and one Trimble, were employed during to ensure that accurate position was recorded for each test location. The Garmin unit was able to provide distance and bearing information from each test site to the seven transmitter locations. The Trimble unit, which was powered from the vehicle's electrical system, was used for backup purposes in the event that the Garmin unit failed. The Garmin unit proved very useful and easy to use, although it took a significant amount of time to acquire the fix the channel each time it was powered up, owing to the fact that it was only a one-channel unit. Conversely, if it was left on for an extended period of time, the battery life was severely shortened.

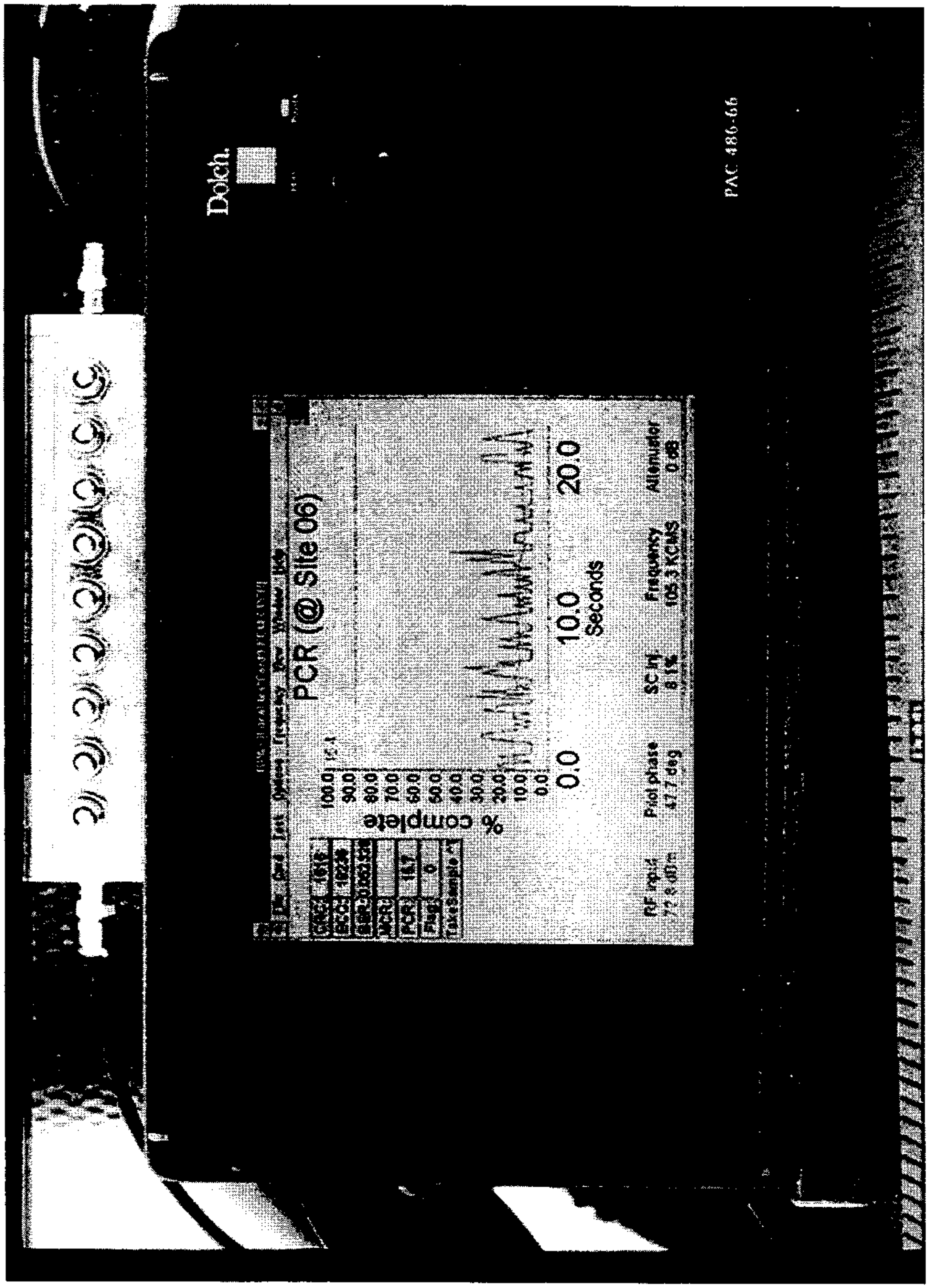


Figure 2-6. Photograph of TREQ Monitor Screen Output.

Since most of the *SWIFT Communications Study* test equipment was A/C powered, it was necessary to accommodate this requirement using a combinations of D/C to A/C inverter systems. The Toshiba/RRM systems each utilized a 125 Watt inverter to power each unit. The spectrum analyzer initially used the HP portable power supply, but since the connections to the vehicle battery was accomplished using a heavy-duty jumper cable, connecting both the HP and TREQ Monitor units simultaneously became problematic. It was verified that the 400 Watt Tripp-Lite DC to AC Inverter unit could provide power to both the spectrum analyzer and the TREQ monitor systems and was used for that purpose most of the time.

In summary, the following steps represent the set of test and measurement procedures that were used to assess RSL, BER and PCR at each of the *SWIFT Communications Study* test sites:

- Step 1: Upon arrival at test site, the equipment cabling was connected, the power supply system was checked, the antenna system(s) deployed and the measurement devices were powered-up, checked out and calibrated.
- Step 2: Geographic fix (i.e., latitude/longitude/altitude), distance and magnetic bearing to each of the seven HSDS stations was determined by using a GPS system.
- Step 3: The watches were set to "fast scan" mode and allowed to lock onto the strongest HSDS station. A manual log of the test messages received on each of the six watches was maintained, including the time of receipt (to 1 minute resolution). Particular attention was paid to missed messages.
- Step 4: Similarly, the RRM/laptop systems were allowed to lock onto the strongest HSDS station and an automated log of all messages was collected with one-second timestamps. This message log was post-processed during the analysis portion of the task.
- Step 5: Using the TREQ monitor, a logfile for each station included: Baseband spectrum, RF spectrum, Packet Completion Rate and Bit-Error-Rate.
- Step 6: Using the Spectrum Analyzer, RSL, BER and PCR data was taken for all seven stations and traces stored in the instrument memory module for later retrieval for plotting. In addition, noise "floor" measurements were taken in order to characterize the testing site.
- Step 7: Observations of the 19 KHz pilot signal were made to give an indication of the potential for multi-path. If this signal indicated that there were problems receiving test messages, multi-path testing was performed as described in Section 2.3.
- Step 8: A manual log of all test equipment settings, locations and physical environments was maintained for all sites tested.

2.3. Multi-Path Interference Test

The purpose of this test was to characterize, as qualitatively as possible, the severity of the multi-path present at each SWIFT HSDS test location. This analysis was especially important at locations where the RSL was shown to be adequate for proper receptor device operation and there were end-user observations to the contrary. Thus, the objective of this test was to measure values of RSL in several off-azimuth directions for each of the Seattle HSDS stations. Additionally, by observing the variations of the 19 KHz pilot, a reasonable indication of the severity of the multi-path problem could be postulated.

Multi-path testing is based on the hypothesis that where there were significant amplitude variations in the FM signals, both pilot and carrier, there was a reasonable likelihood that a multi-path environment existed. In addition, with the existence of significant multi-path, there is the potential for loss of HSDS phase lock and hence missed messages.

The effects of multi-path interference are typically caused in the real world by objects such as buildings, watertowers, hilly terrain and, in some instances, moving vehicles or airplanes. These objects reflect FM signals like a mirror and create an especially bad environment for all FM systems, including the SWIFT HSDS. Seattle, with its hilly terrain and tall buildings, is considered to be one of the more challenging urban areas for multi-path problems. Multi-path in the FM world causes ghosting in a TV picture or loss of stereo on an FM radio, and is the result of the same signal arriving at the receiving antenna at different times and from different directions because of the reflections off other objects. At any given location, only the reception of the broadcast station experiencing multi-path is affected. Otherwise, multi-path parameters such as amplitude, phase and direction are difficult to identify and measure, particularly in an urban environment where many reflective objects may cause a host of separate reflected signals to impinge on the antenna.

For the purposes of the *SWIFT Communications Study* testing, a simple technique was employed to detect the presence of multi-path interference using the TREQ monitor system. This system was capable of being locked to a specific HSDS station. At test locations where poor reception was found, but where there was adequate RSL, a multi-path situation may exist. Since the azimuth (bearing angle) from the test location to the specific transmitter was known in advance, it was possible to replace the omni-directional test antenna with a directional antenna pointed directly at the transmitter. By using this method, one can compare the two sets of measurements and observe changes in the BER and PCR from the particular station. In cases where significant multi-path was indeed present, the directional antenna technique greatly improved receiver performance. In addition, experimental measurements were also made a varying off-azimuth bearings up to ± 25°. This method can help identify if there is more than one multi-path signal and generally from what direction(s) they are being received. However, due to the fairly wide pattern of this directional antenna, exact measurements were not able to be taken.

A Winegard Directional FM antenna, Model # CA-6065, was used during the testing to isolate observed signal degradation possibly caused by multi-path environments. This antenna, designed with 10 dB of gain, was mounted on a 5 foot 1¼" steel mast which was supported with a 3' roof-mount tripod. The beam-width of this antenna across the FM band was 60 degrees or less, with a fast drop-off in received signal level beyond this point. Consequently, when this antenna is aimed at a station, the level of multi-path will be significantly reduced if the received signal is originating from angles greater than +/- 30 degrees. An improvement in BER/PCR over that measured with the OMNI antenna configuration strongly suggests that the cause of poor performance may be multi-path interference. Further details regarding directional antenna use for multi-path testing are presented for each test site in Appendix A.

A Tektronix 2430A digital oscilloscope was also used in conjunction with a Sansui TU-919A synthesized FM receiver to allow further investigation into the severity of any multi-path problems. Use of this technique was based upon the assumption that multi-path signals received by the directional antenna would broaden, or widen, the bandwidth of the signal displayed by the oscilloscope. Should the width of this signal be decreased, however, by pointing the directional antenna in a different direction, then the postulated existence of multi-path would be reduced and thereby perhaps provide some insight into the conditions contributing to the detection of multi-path at a localized test site. Figure 2-7 shows the equipment configuration used during this test.

In summary, the following steps were implemented at the test sites where there was a significant indication of the presence of multi-path:

- Step 1: Upon arrival at test site, the equipment cabling was connected, the power supply system was checked, the antenna system(s) deployed and the measurement devices were powered-up, checked out and calibrated.
- Step 2: A geographic fix was recorded using the GPS system, including Latitude/Longitude/Altitude.
- Step 3: Using the TREQ monitor, a logfile for each station was created that included: Baseband spectrum, RF spectrum, PCR and BER.
- Step 4: Once measurements were made with the omni-directional antenna, the directional antenna was used to determine if the increased suppression of multi-path signals would improve the BER/PCR at the receivers. The signal from the directional antenna was padded down to be equivalent to that from the Omni-directional antenna, to allow for a comparison at comparable signal levels. The directional antenna was first pointed at a specific station, then pointed at 45-degree increments to either side of the station. Measurements of BER/PCR in each configuration were made and recorded in the data sheet for the site. Figure 2-8 shows a picture of the directional (on left) and Omni-directional (on right) test antennas fully deployed for testing.
- Step 5: In locations where significant indications of multi-path were in evidence, additional testing procedures were employed to characterize these effects. These included the following:
- Step 5A: Deployment of a directional FH antenna, which was used to determine if by pointing it directly at the station, the RSL, BER and PCR could be improved significantly
- Step 5B: By pointing the directional antenna "off-axis" in incremental steps, determining if there was another direction at which the RSL, BER and PCR was also significantly improved

- Step 5C: Use the directional antenna with a Sansui FM receiver and a Tektronix 3036A oscilloscope to measure the amount of detected audio present in the suspect signal
- Step 6: A manual log of all test-equipment settings, locations and physical environments was maintained for all sites tested.

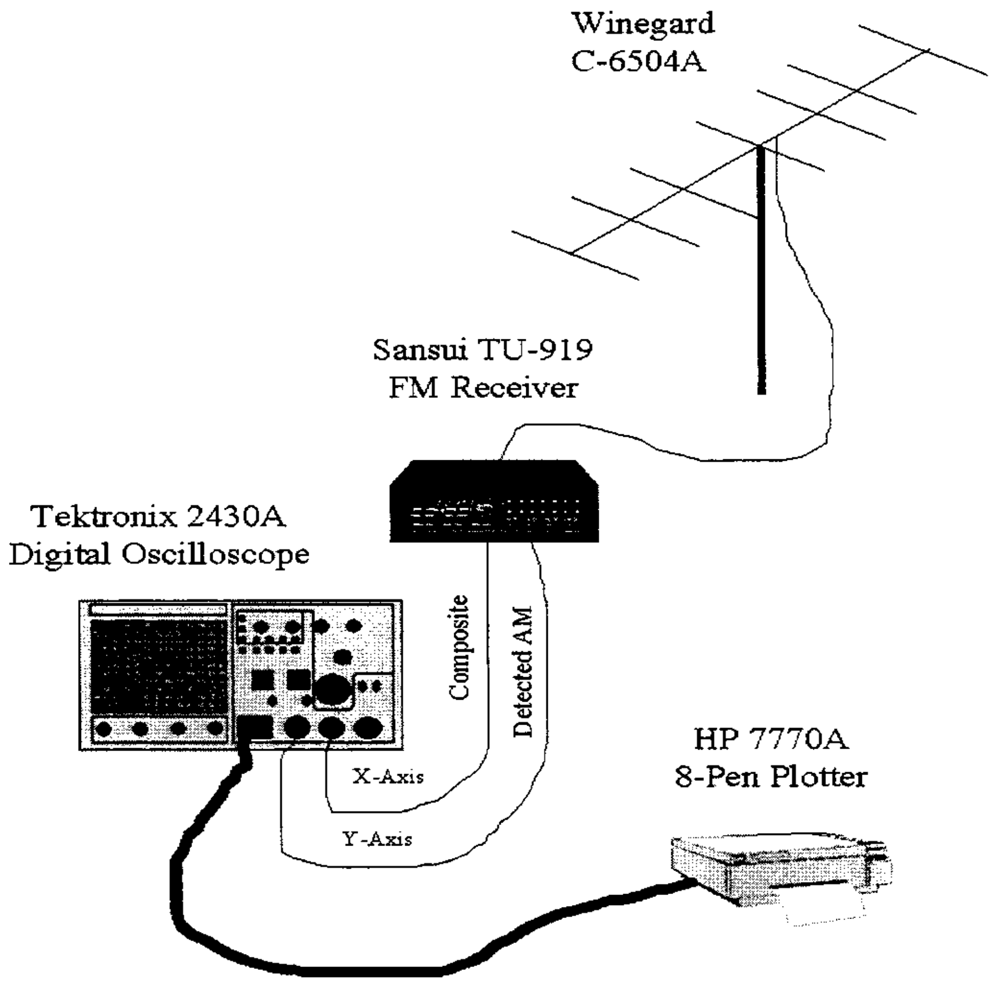


Figure 2-7. Multi-path Test Configuration Diagram.

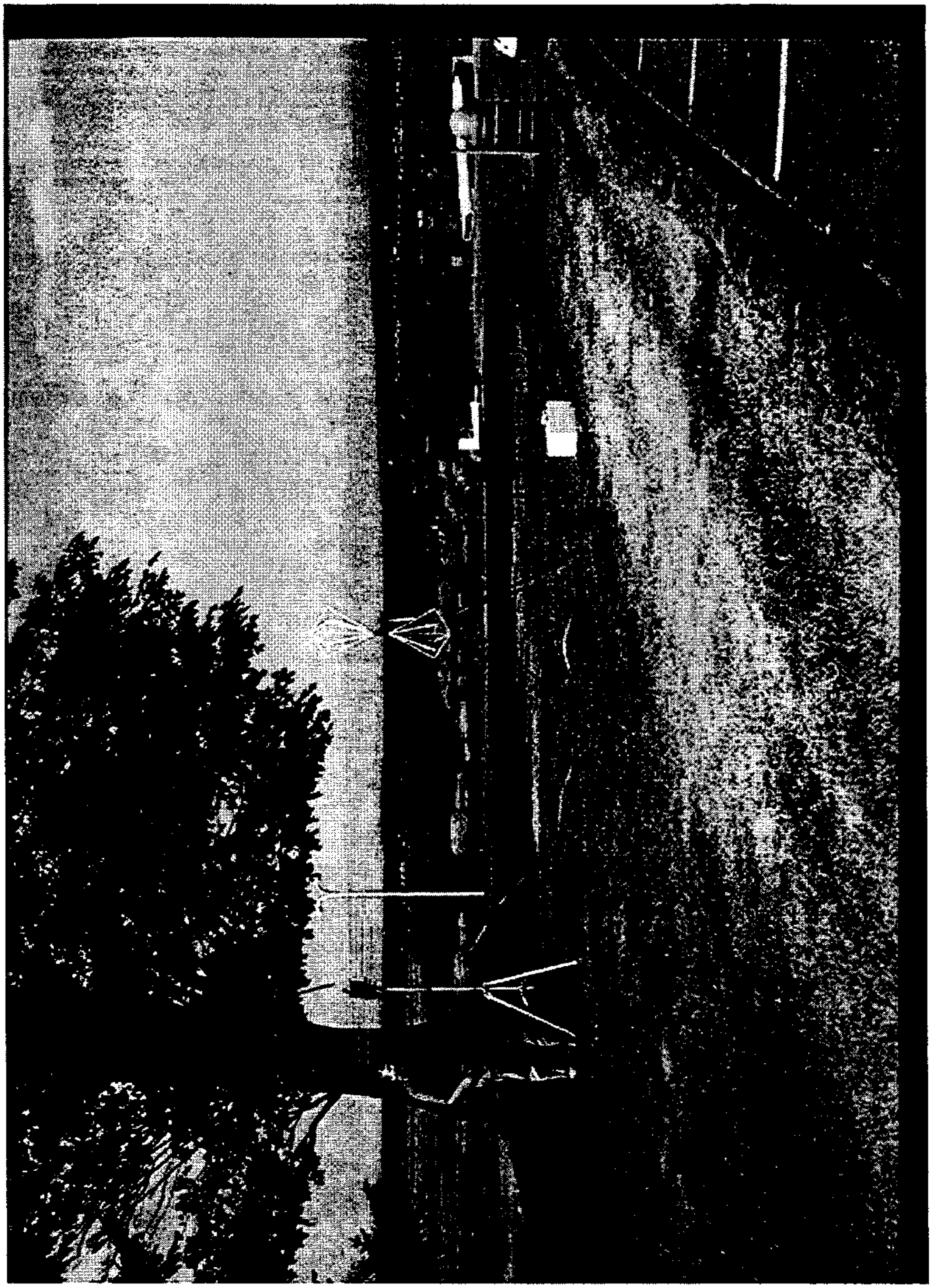


Figure 2-8. Photograph of Antennas Used for SWIFT Communications Study Testing.

2.4. In-Building Reception Sensitivity Test

The purpose of this test was to characterize the RSL at the various test locations with respect to the signal attenuation measured as the instrumentation was moved from an on-street position to an in-building position where measurements were taken at convenient intervals into the particular building and away from the wall. In particular, this test addressed those user reports which indicated that problems receiving messages occurred when they were inside a building at work, but otherwise did not have reception problems. In a fashion similar to RSL testing, this test utilized the calibrated antenna, spectrum analyzer and TREQ monitor.

As indicated on the floorplan of the WSDOT Traffic Systems Management Center (TSMC) shown in Figure 2-9, there were four in-building measurement locations. These were designated 6A, 6B, 6C ands 6D. Location 6 as noted on was used as a reference and was measured outside the TSMC facility.

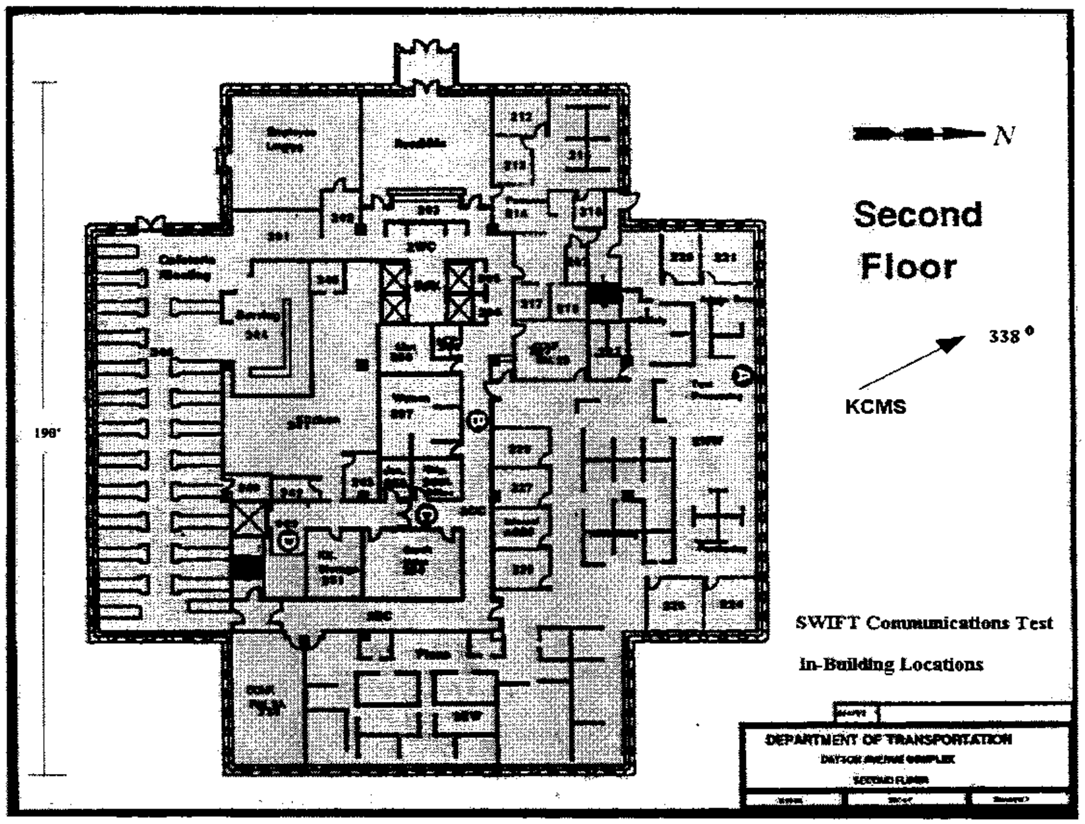


Figure 2-9. TSMC Floorplan Showing Inside Building Measurement Locations.

The following steps represented the set of test and measurement procedures that were performed for SWIFT in-building tests. Each of the following measurement steps were performed for a subset of the seven SWIFT HSDS stations:

- Step 1: At each in-building test location, the equipment cabling was connected, the power supply system was checked, the antenna system(s) deployed and the measurement devices were powered-up, checked and calibrated.
- Step 2: Using the TREQ monitor, a logfile collected for each station will included: Baseband spectrum, RF spectrum, PCR and BER.
- Step 3: Using the Spectrum Analyzer, RF spectrum measurements representing RSL for station KCMS were made and stored to instrument memory for later retrieval for plotting.
- Step 4: Measurements were conducted at four different locations by moving the antennas inside the target structure in increments while maintaining a bearing of 33 degrees to station KCMS. Measurements at any particular location were repeated until the RSL and/or PCR/MCR became low enough to prohibit the reception of SWIFT messages.
- Step 5: A manual log of all SWIFT test equipment settings, locations and physical environments was maintained for all the in-building locations tested.

3. RESULTS

Results of *SWIFT Communications Study* testing are presented in the following sections.

3.1. HSDS Assessment and Site Selection

Review of SWIFT FOT participant responses to a question in the first *SWIFT Consumer Acceptance Study* questionnaire inquiring about locations of HSDS coverage problems indicated that approximately 93% of SWIFT participants did not report communications-coverage problems. To be identified as a coverage problem, missed messages would need to be reported in an area that was within the SWIFT RSL contour. Thus, reported HSDS effectiveness among SWIFT Seiko Messagewatch and portable-computer users corroborated Seiko's estimates of at least 90% message-receipt probability within the SWIFT coverage area.

Of the 43 (7%) of Seiko MessageWatch and portable computer users who reported SWIFT coverage problems, 20 (47%) reported locations within buildings while 23 (53%) reported problems with receiving messages in outside locations. Upon analysis, four geographic locations were the sites of all reported in-building message-receipt problems: Downtown Seattle (8), Redmond (5), University District (4) and SeaTac (3). At the Redmond and University District sites, buildings on the Microsoft Campus and the University of Washington, respectively, appeared to be the source of the majority of complaints. Although detailed information regarding the type of building within which SWIFT participants reported problems receiving messages was not obtained from all respondents, the majority of those who did provide this information reported that they worked within concrete building structures. Three outside locations received the greatest number of complaints: Everett (4), Federal Way (4) and Tacoma (4).

Given that reported SWIFT message-receipt probability by SWIFT Seiko MessageWatch and portable-computer users was shown to be within the bounds predicted by Seiko, further analyses were done to determine ten (10) "problem" locations at which HSDS field testing could occur. The purpose of identifying these sites would be to enable *SWIFT Communications Study* field testing to occur at sites that would highlight, or show, possible difficulties in communications coverage in order to more completely describe the operational features of the SWIFT HSDS.

Composite, predicted RSL for Seiko MessageWatchs is shown in Figure 3-1, while the same information is presented in Figure 3-2 for SWIFT portable computers. These data, derived from information supplied by Seiko, indicate that a 90% RSL is predicted for both devices across the majority of the SWIFT HSDS coverage area. Also provided by Seiko, on a 1:250,000 scale, were individual RSL contour plots (calibrated to the Seiko MessageWatch) for the seven HSDS stations in the Seattle area.

The above analysis resulted in the selection of ten (10) candidate sites for field testing in the Seattle area. Figure 3-3 shows the actual test locations that were used for the *SWIFT Communications Study* evaluation. They were: (1) Bellevue, (2) West Seattle, (3) SeaTac, (4) Everett, (5) South Seattle, (6) Shoreline, (7) Downtown Seattle, and (8) Puyallup. Olympia and Redmond were not tested. One of these test locations (i.e., Everett) was corroborated by reports of outdoor problem-coverage areas provided by SWIFT FOT participants.

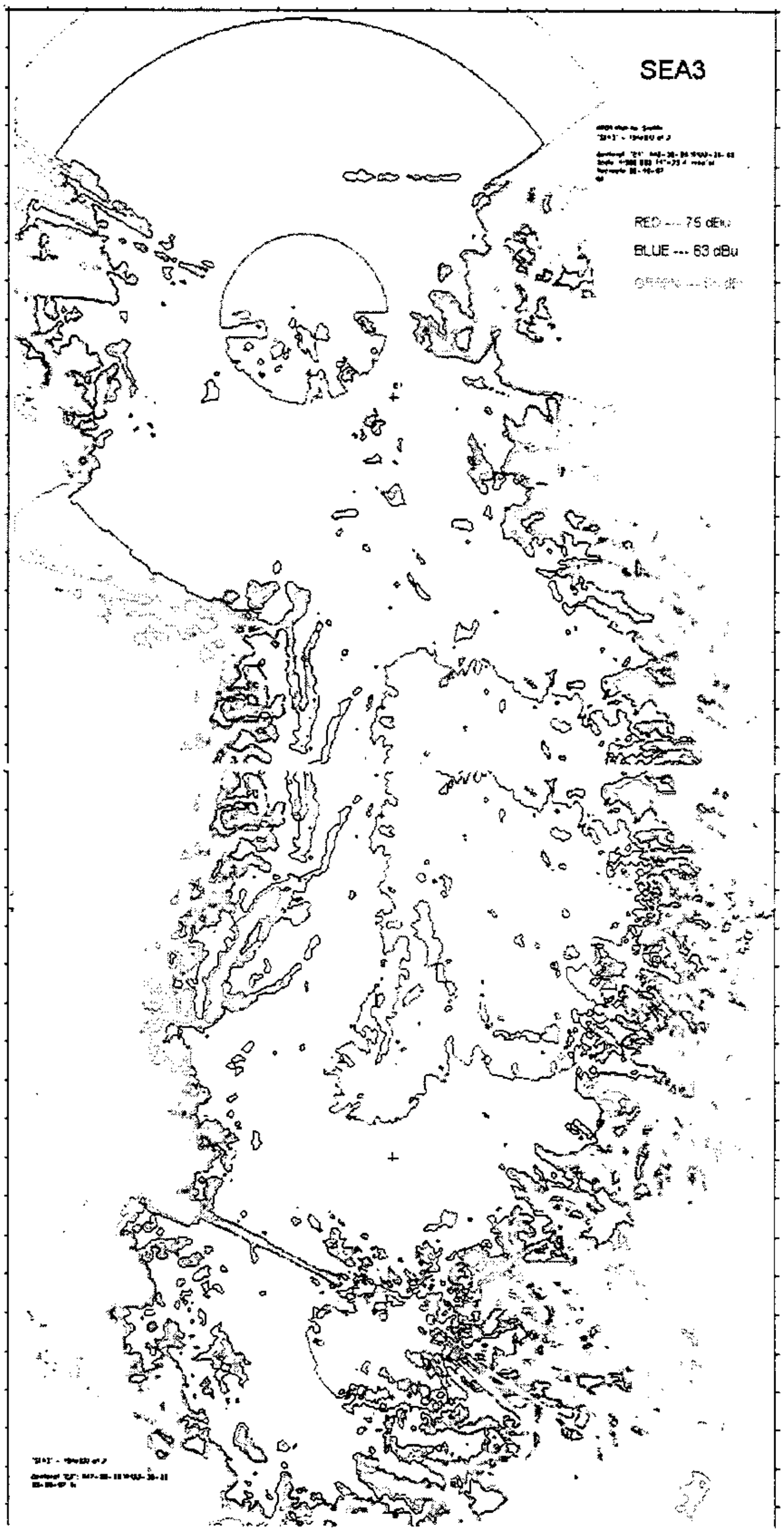


Figure 3-1. Composite Predicted Received Signal Levels for Seiko MessageWatch.

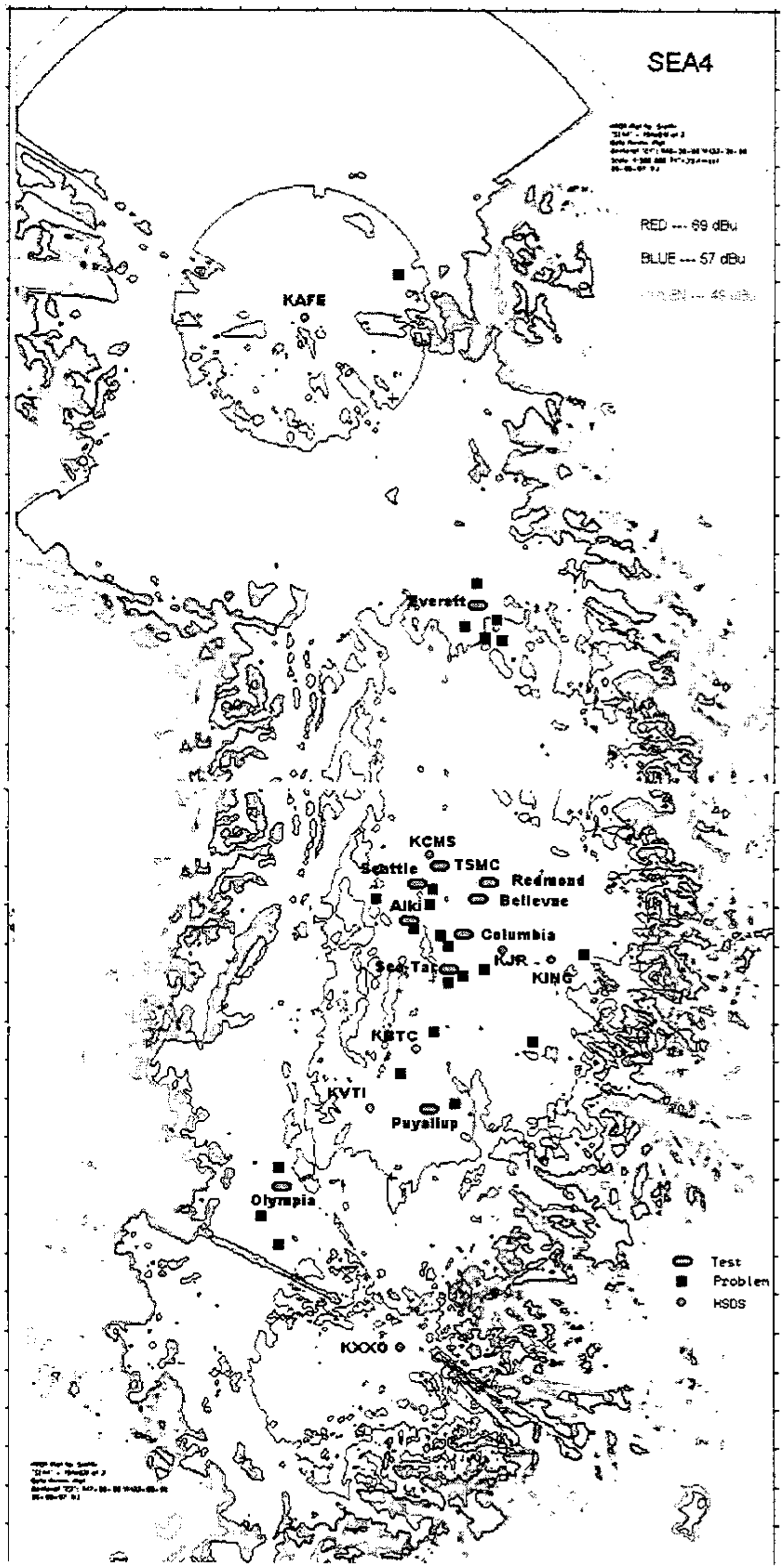


Figure 3-2. Composite Predicted Signal Levels for Remote Receiver Module.

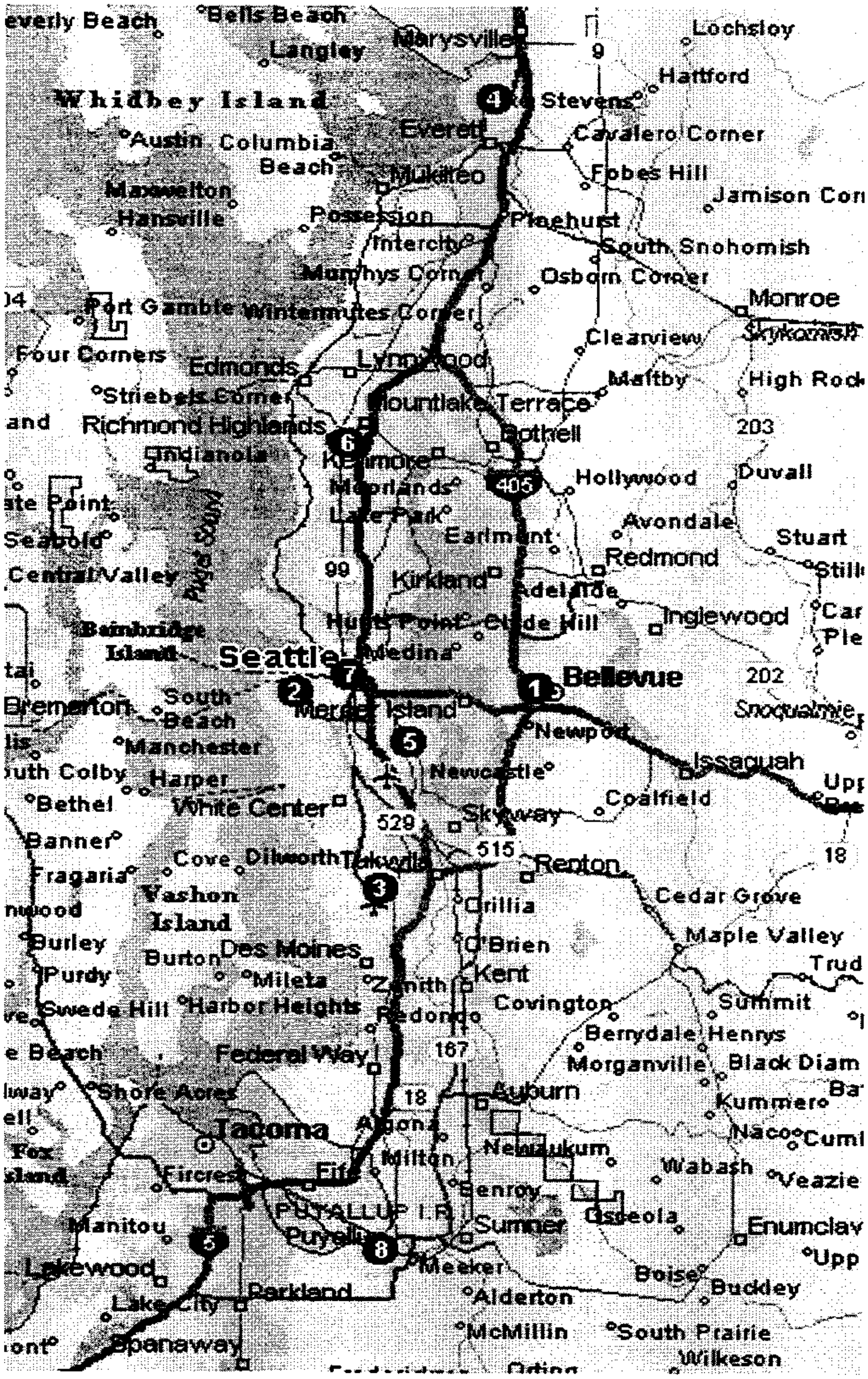


Figure 3-3. Seattle-Area Map Showing Actual SWIFT Test Locations.

3.2. RSL, BER and PCR MEASUREMENTS

This section presents the detailed, site-by-site analysis of Received Signal Level (RSL), Bit Error Rate (BER) and Packet Completion Rate (PCR) measurement results. To re-iterate, the purpose of *SWIFT Communications Study* testing was to assess the coverage of the Seiko HSDS system as it was deployed for use during the SWIFT program. It was suggested by early analysis of the problems encountered with FM sub-carrier systems that failure mechanisms are not strictly related to received signal levels. As a result, further investigation prompted data collection and analysis of not only RSL data, but BER, PCR, background noise level, and indirect indications of multi-path interference.

A separate analysis was performed to determine to what extent the very hilly terrain, present in the Seattle area, might have on the received signal levels received by the equipment at the individual test locations. This effort was used in the test-site selection process and for the purposes of his report, this simple determination of the terrain profiles between the seven HSDS transmitters and the eight test locations was used to enhance the understanding of the RSL results discussed elsewhere in this section.

The results collected during the on-site testing were organized into an Excel Workbook, a summary of which in shown in Figure 3-4. This facilitated the analyses presented in this report, and provides a vehicle for future extended analysis by SAIC, WSDOT or other parties. The workbook was structured with a sheet for each site, with each sheet divided into sections for the collected TREQ, spectrum analyzer, RRM and watch data. Where appropriate, this data was configured in the spreadsheet with separate rows for each station in the system. Correction factors for cabling and antenna loss were automatically applied to raw measured signal levels to yield calibrated values. Due to the voluminous amount of RRMHost data, only the results of the MAWK analysis routine are shown in the spreadsheets. Relevant excerpts from the spreadsheets are presented as part of the summary results and site-specific discussions that follow.

The RSL measurements made as part of these tests track reasonable well with the simulation contours produced by Seiko. While the simulated signal levels were sometimes higher than those measured, the correlation was strong enough to support using Seiko's simulation as a tool for system coverage planning and transmitter site selection. Plots of BER and PCR as a function of signal level produced from the test results indicated that the error rates and minimum signal levels quoted in Seiko's HSDS specifications are valid. In particular, it should be noted that all SWIFT field-test sites except Everett (Site #4) had at least one station with a reception rate of 99%, indicating probable reception of messages. Copies of these curves are presented in the following sections.

HSDS Station	Site 1 - SAIC				Site 2 - ALKI				Site 3 - SeaTac				Site 4 - Everett			
	RSL	BER	PCR	Phase	RSL	BER	PCR	Phase	RSL	BER	PCR	Phase	RSL	BER	PCR	Phase
KVTI	-63	1.0E-05	100%	358.0	-68	5.0E-01	0%	358	-67	4.0E-02	1%	50	-75	5.0E-01	0%	358
KBTC	-36	5.0E-01	0%	358.0	-72	5.0E-02	16%	60	-63	1.0E-01	99%	61.5	-75	5.0E-01	0%	358
KJR	-12	1.0E-06	100%	66.2	-58	5.0E-01	0%	358	-39	1.0E-06	100%	66.3	-78	5.0E-01	0%	358
KXXO	-57	1.0E-06	100%	358.0	-64	6.0E-02	8%	56	-63	2.0E-02	0%	65	-61	5.0E-02	0%	358
KING	-37	1.0E-05	100%	59.7	-60	4.0E-02	21%	63	-43	1.0E-06	100%	65	-63	5.0E-01	30%	118
KAFE	-69	5.0E-01	0%	358.0	-76	5.0E-01	0%	358	-61	5.0E-01	0%	358	-70	5.0E-01	0%	358
KCMS	-35	8.0E-04	100%	68.3	-52	1.0E-03	99%	60	-7	8.0E-07	100%	65	-58	5.0E-01	0%	358

HSDS Station	Site 5 - Columbia				Site 6 - TSMC				Site 7 - Seattle				Site 8 - Puyallup			
	RSL	BER	PCR	Phase	RSL	BER	PCR	Phase	RSL	BER	PCR	Phase	RSL	BER	PCR	Phase
KVTI	-78	5.0E-01	0%	358.0	-73	5.0E-01	0%	358	-68	4.0E-03	0%	358	-63	5.0E-02	24%	59
KBTC	-79	5.0E-01	0%	358.0	-78	5.0E-01	0%	358	-49				-53	7.0E-05	89%	53
KJR	-49	1.0E-02	82%	62.0	-69	5.0E-01	0%	358	-74	5.0E-01	0%	358	-60	8.0E-02	0%	70
KXXO	-82	5.0E-01	0%	358.0	-63	6.0E-02	0%	62	-75	5.0E-01	0%	358	-76	5.0E-01	0%	358
KING	-46	1.0E-06	100%	60.0	-69	5.0E-01	0%	358	-66	5.0E-02	37%	107	-59	5.0E-02	49%	93
KAFE	-75	5.0E-01	0%	358.0	-63	5.0E-02	23%	55	-78	5.0E-01	0%	358	-62	5.0E-01	0%	358
KCMS	-58	4.0E-03	97%	60.0	-60	3.0E-04	100%	59	-52	1.0E-03	99%	66	-75	5.0E-01	0%	358

Figure 3-4. Summary of Individual Site Analysis Results.

Site1 (Bellevue)

The individual analysis of SWIFT coverage at site #1 is shown in Figure 3-5. BER and PCR performance was excellent except for KBTC, which although being only 24 miles from the test location, may have been affected by terrain blockage. KAFE, while showing poor message receipt behavior, may be more affected by excessive path losses than terrain effects, since it is located almost 80 miles from the test site. The reader is reminded that the intent of this type of testing was not meant to identify those candidate locations where reception was perfect, but rather to select locations where the predicted or historical data indicated marginal to poor reception. Data collection using the RRM systems was not accomplished at this location due to the fact that although A/C power was available on the rooftop, there were not enough receptacles to perform simultaneous testing. With respect to the Seiko MessageWatches, 100% of the messages sent specifically to the six test watches was received. This occurred independent of the N-S or E-W orientation of the test fixture. Only when the watches were oriented in the vertical position was there a slight degradation in message performance to 98%.

Site 2 (West Seattle)

This test location was interesting because even with its close proximity to downtown Seattle, all but one of the station's radial azimuths were occluded by the terrain profiles. KCMS was the one exception, being about 13 miles distant at an over-water bearing of 353°, almost due North. Because this station was available, with a very strong -58 dBm signal, both RRM devices and six watches continued to receive messages flawlessly during the entire length of the testing. Figure 3-6 shows the performance analysis spreadsheet for test location #2.

Site 3 (SeaTac)

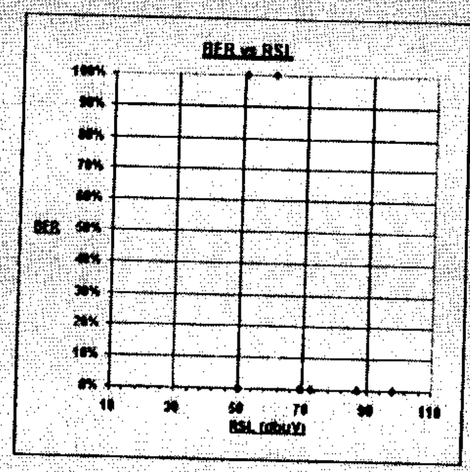
SeaTac airport was identified as a problem area because of numerous reports of lack of message reception, particularly with the watches. Although testing in the vicinity of the airport did not result in suggesting that this area has poor coverage, test participants who worked inside metal hanger-type buildings were the source of the majority of the poor-reception reports. Another possibility as to the cause of poor reception could be elevated electrical noise levels in the airport area due to aircraft operations. From the test location, near the airport fire station, measurements of background noise did not suggest any particular problems.

After a review of the terrain profiles for each station azimuth, there seemed to be a case for suggesting terrain blockage as the culprit. Interestingly enough, the only stations that exhibited very good performance were those about 20 miles distant. KING, KJR and KBTC performed very well, allowing virtually 100% of the messages to be received on the two RRMs and six watches. BER data from the TREQ for station KCMS was also very low, but PCR information was either lost or not saved during the data-collection experiments. This BER data suggests that KCMS was probably the best station, signal and bit error-wise, at this location, although the RRMs remained locked onto KJR. A review of the BER and PCR statistics for location #3 indicated in Figures 3-7 and 3-8 shows the effect of artificially introducing signal attenuation to lower the received signal level from KBTC and therefore reducing the SNR. This method allows recording the performance characteristics to enable an understanding of expected behavior under varying signal conditions. Figure 3-9 provides the performance spreadsheet for test location #3.

STATION/GPS POSITION DATA				SPECTRUM ANALYSER DATA						TREQ ANALYSER DATA							
STATION	FREQ.	RANGE (MILES)	BEARING (MAG.)	S/A RAW RSL - (dbuV)	S/A CORRECTED RSL (dbuV)	RSL (dbm)	DELTA RSL (dbuV)	NOISE FL. (dbuV)	SNR (db)	TREQ RAW RSL (dbm)	CORRECTED RSL (dbm)	CORRECTED RSL (dbuV)	BER	PCR	ECC	CRC	PILOT ANG. (DEG)
KVTI	90.9	36.7	190	44	50	-57	5	11	33	-69	-63	44	0.0E+00	100%	0	0	358
KBTC	91.7	24	184	54	60	-47	2	10	44	-42	-36	71	1.0E+00	0%	0	0	358
KJR	95.7	6.5	126	90.5	98	-9	2	11	79.5	-20	-12	95	0.0E+00	100%	0	0	66.2
KXXO	96.1	69.4	172	80	87	-20	4	10	70	-64	-57	50	0.0E+00	100%	0	0	358
KING	98.1	12.9	110	66	73	-34	1	12	53	-45	-37	70	1.0E-06	100%	33	0	59.7
KAFE	104.3	79	318	44	51	-56	3	10	34	-76	-69	38	1.0E+00	0%	0	0	358
KCMS	106.3	126	304	62	69	-38	2	11	51	-42	-35	72	8.0E-04	100%	387	5	68.3

RRM DATA ANALYSIS									
RRM#	MSG's SENT	MSG's MISSED	% RCVD	INTER MSG TIME MEAN	INTER MSG TIME MEDIAN	IMT MODE	IMT STD	IMT MIN	IMT MAX
1									
2									

WATCH DATA ANALYSIS				
AXIS	START #	STOP #	TOTAL MISSED	PERCENT RCVD
N - S	32	42	0	100
E - W	42	52	0	100
VERT.	53	64	1	98



CABLE LOSS (db)	5
OMNI CORR. (db)	
KVTI	0.94
KBTC	0.94
KJR	2.25
KXXO	2.23
KING	2.73
KAFE	2.02
KCMS	2.02

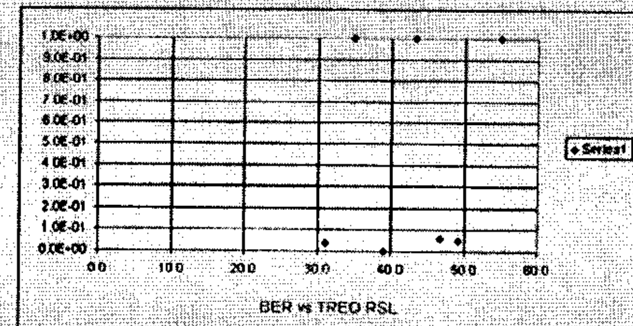
Figure 3-5. Performance Analysis Spreadsheet for Test Location #1.

STATION/GPS POSITION DATA				SPECTRUM ANALYSER DATA						TREQ ANALYSER DATA							
STATION	FREQ.	RANGE (MILES)	BEARING (MAG.)	S/A RAW RSL - (dbuV)	S/A CORRECTED RSL (dbu)	RSL (dbm)	DELTA RSL (dbuV)	NOISE FL. (dbuV)	SNR (db)	TREQ RAW RSL (dbm)	CORRECTED RSL (dbm)	CORRECTED RSL (dbuV)	BER	PCR	ECC	CRC	PILOT ANG. (DEG)
KVTI	90.9	29.9	175	24	30	-77	11	12	12	-74	-68	39	1.0E+00	0%	0	0	358
KBTC	91.7	19	158	22	28	-79	9	12	10	-78	-72	35	6.0E-02	16%	15622	1331	60
KJR	95.7	14.5	80	38	45	-62	20	11	27	-65	-68	49	1.0E+00	0%	0	0	358
KXXO	96.1	65.2	163	19	26	-81	10	10	9	-71	-64	43	6.0E-02	8%	20250	1620	56
KING	98.1	21.2	85	28	36	-71	12	12	16	-68	-60	47	4.0E-02	21%	11948	1199	63
KAFE	104.3	78.6	326	11	18	-89	N/A	10	1	-83	-76	31	1.0E+00	0%	0	0	358
KCMS	105.3	13.4	353	42	49	-58	7	11	31	-59	-52	55	1.0E-03	99%	740	40	60

RRM#	CHANNEL LOCKED	MSG's RCVD	MSG's MISSED	% RCVD	INTER MSG TIME MEAN	IMT MODE	IMT STD	IMT MIN	IMT MAX
1	105.3	76	0	100	59	70	34	12	253
2	105.3	90	1	99	61	30	41	13	211

CABLE LOSS (db)	5
OMNI CORR. (db)	
KVTI	0.94
KBTC	0.94
KJR	2.26
KXXO	2.23
KING	2.73
KAFE	2.02
KCMS	2.02

AXIS	START #	STOP #	TOTAL MISSED	PERCENT RCVD
N - S	80	97	0	100
E - W	69	80	0	100
VERT.	93	109	0	100



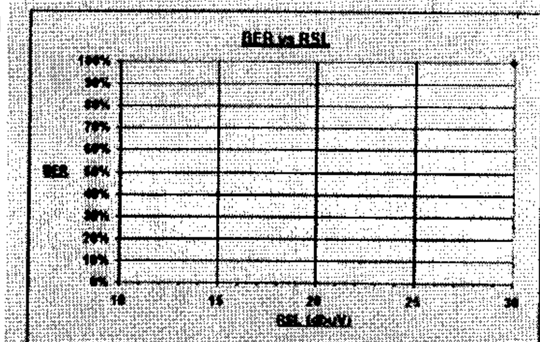


Figure 3-6. Performance Analysis Spreadsheet for Test Location #2.

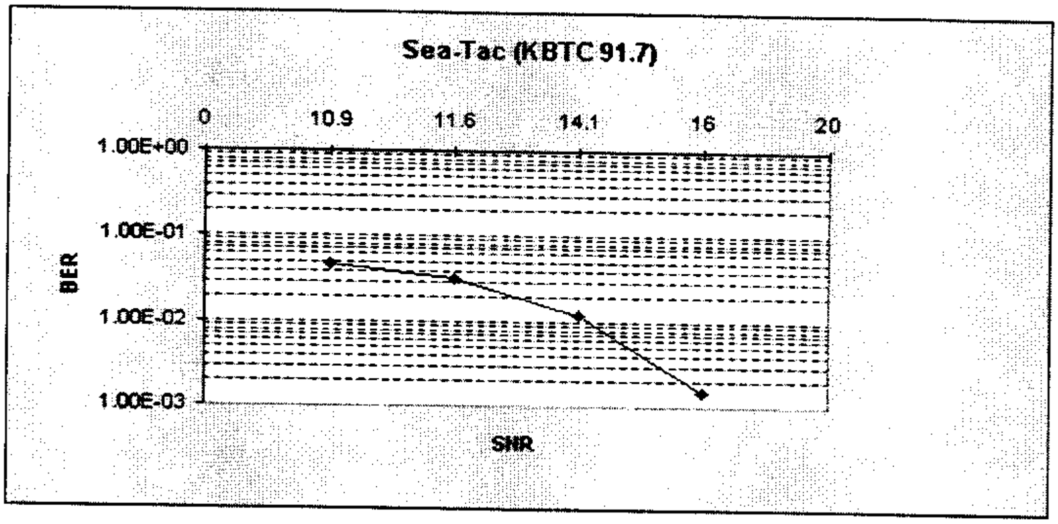


Figure 3-7. BER performance versus SNR for KBTC Signal at Location #3.

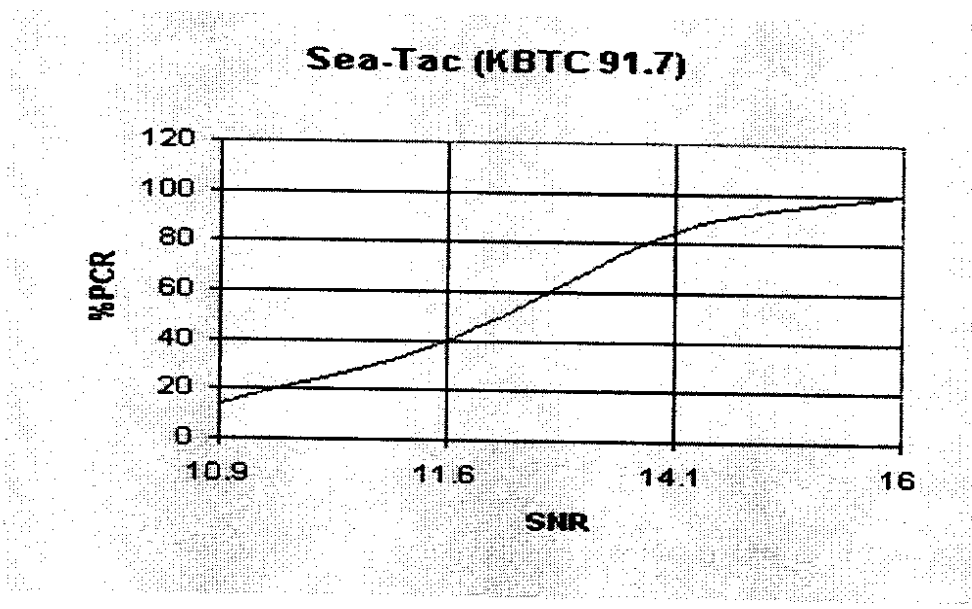


Figure 3-8. PCR Performance versus SNR for KBTC Signal at Location #3.

STATION/GPS POSITION DATA				SPECTRUM ANALYSER DATA						TREQ ANALYSER DATA							
STATION	FREQ.	RANGE (MILES)	BEARING (MAG.)	S/A RAW RSL - (dbuV)	S/A CORRECTED RSL (dbuV)	RSL (dbm)	DELTA RSL (dbuV)	NOISE FL. (dbuV)	SNR (db)	TREQ RAW RSL (dbm)	CORRECTED RSL (dbm)	CORRECTED RSL (dbuV)	BER	PCR	ECC	CRC	PILOT ANG. (DEG)
KVTI	90.9	23.9	194	26	32	-75	10	12	14	-73	-67	40	4.0E-02	1%	4385	311	50
KBTC	91.7	11.1	184	35	41	-66	10	12	23	-69	-63	44	1.0E-03	99%	609	12	61.6
KJR	95.7	11.1	35	55	62	-45	15	11	44	-46	-39	68	0.0E+00	100%	0	0	66.3
KXXO	96.1	56.9	169	34	41	-68	7	10	24	-70	-63	44	2.0E-02	0%	2088	156	65
KING	98.1	15.7	57	54	62	-45	8	12	42	-51	-43	64	0.0E+00	100%	0	0	65
KAFE	104.3	88.5	324	15	22	-86	N/A	10	5	-68	-61	46	1.0E+00	0%	0	0	358
KCMS	105.3	22.1	334	35	42	-65	8	11	24		7	114	8.0E-07				

RRM DATA ANALYSIS

RRM#	CHANNEL LOCKED	MSG's RCVD	MSG's MISSED	% RCVD	INTER MSG TIME MEAN	IMT MODE	IMT STD	IMT MIN	IMT MAX
1	95.7	48	1	98	58	60	24	14	154
2	95.7	72	0	100	57	60	22	14	127

WATCH DATA ANALYSIS

AXIS	START #	STOP #	TOTAL MISSED	PERCENT RCVD
N - S	41	51	0	100
E - W	51	61	0	100
VERT.	61	71	0	100

CABLE LOSS (db)	5
OMNI CORR. (db)	
KVTI	0.94
KBTC	0.94
KJR	2.25
KXXO	2.23
KING	2.73
KAFE	2.02
KCMS	2.02

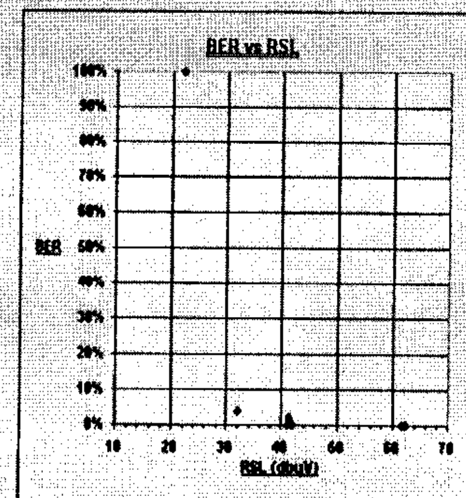


Figure 3-9. Performance Analysis Spreadsheet for Test Location #3.

Site 4 (Everett)

At this test location, the initial data-collection effort was flawed by an apparent loss of Seiko test messages. A review of the seven terrain profiles revealed signal occlusions from every station except KING. Interesting enough, KING with a significant signal level of -63 dBm, still performed very poorly at approximately 30%. The BER and PCR performance curves are show in the Figures 3-10 and 3-11, respectively. Also, please refer to the performance analysis spreadsheet for test location #4, shown in Figure 3-12. This outcome appeared to be the best indication so far of severe multi-path interference. Similarly, the two RRM devices were locked onto KING at 98.1 MHz, but their message performance was poorer than normal in the 70% range. The analysis and discussion of the multi-path experiment at this location is discussed elsewhere in this section.

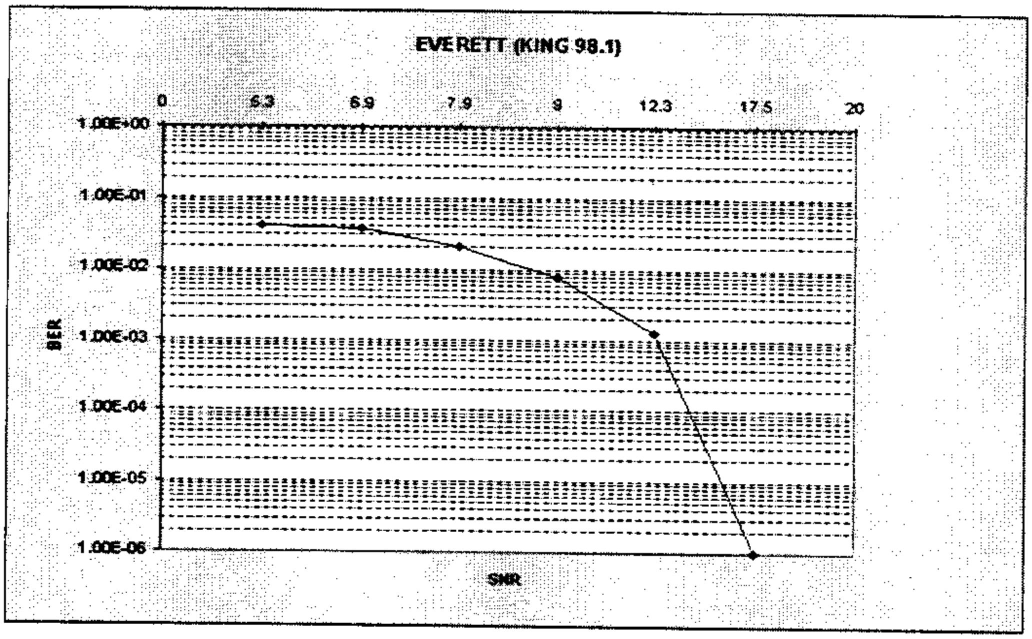


Figure 3-10. BER versus SNR Performance at Location #4 Using A Directional Antenna.

Site 5 (South Seattle)

Test location #5, in South Seattle, exhibited good performance from three close-by stations, KJR, KING and KCMS. The lack of strong enough signals from the remaining four stations was attributed to a combination of excessively long distances together with terrain blockage.

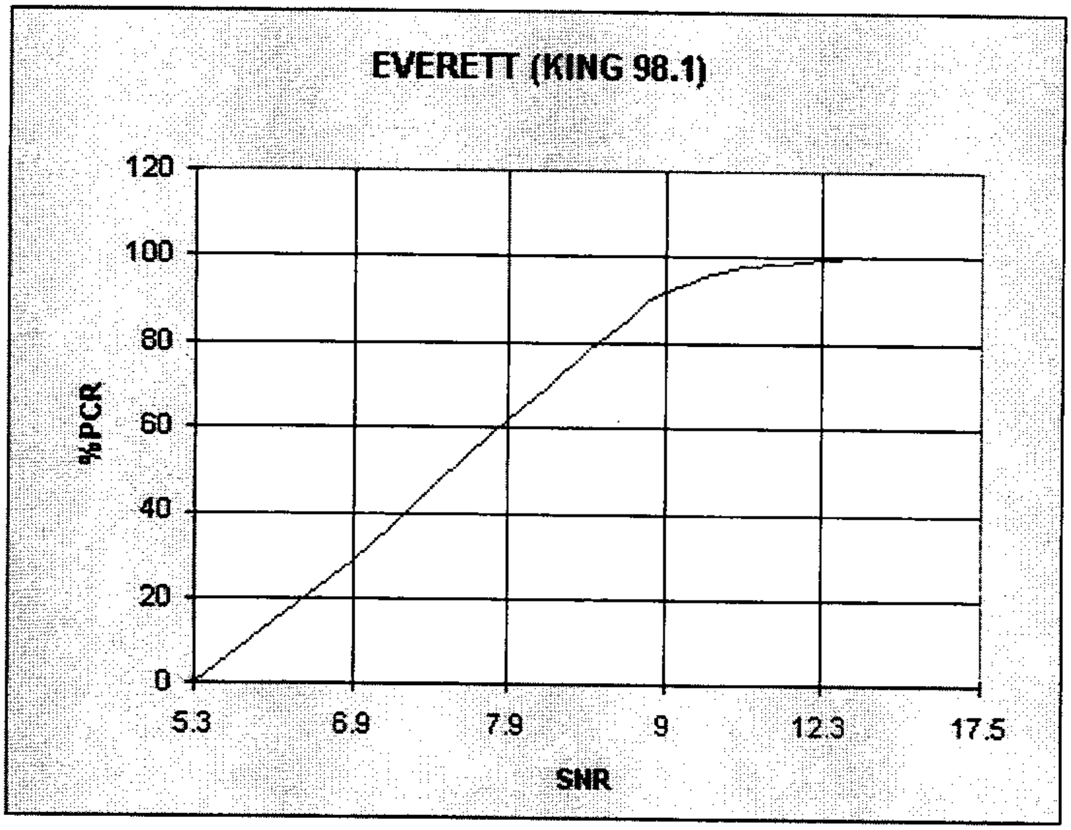


Figure 3-11. PCR versus SNR Performance at Location #4 Using A Directional Antenna.

The message performance data collected from the two RRMs was not surprisingly identical, regardless for their antenna orientation. The six watches similarly performed without errors at 100%. The BER curve for location #5 is shown below in Figure 3-13. It was developed using error rate data from an attenuated signal from station KCMS. Similarly, the PCR performance curves for locations is shown in Figure 3-14, with the performance analysis spreadsheet shown in Figure 3-15. These measurements were performed using a reasonable strong signal from KCMS of -62 dBm and introducing attenuation in steps until both quantities were affected. By adding attenuation in increments, such 10 dB, until performance started to fall of and then adding smaller, 3 dB, increments, the data points for these two curves were developed.

STATION/GPS POSITION DATA				SPECTRUM ANALYSER DATA						TREQ ANALYSER DATA							
STATION	FREQ.	RANGE (MILES)	BEARING (MAG.)	S/A RAW RSL - (dbuV)	S/A CORRECTED RSL (dbuV)	RSL (dbm)	DELTA RSL (dbuV)	NOISE FL. (dbuV)	SNR (db)	TREQ RAW RSL (dbm)	CORRECTED RSL (dbm)	CORRECTED RSL (dbuV)	BER	PCR	ECC	CRC	PILOT ANG. (DEG)
KVTI	90.9	61.7	177	18	24	-83	3	11	7	-81	-75	32	1.0E+00	0%	0	0	358
KBTC	91.7	50.1	171	13	19	-88	2	11	2	-81	-75	32	1.0E+00	0%	0	0	358
KJR	95.7	33	153	31	38	-69	2	12	19	-85	-78	29	1.0E+00	0%	0	0	358
KXXO	96.1	96.3	168	21	28	-79	2	11	10	-68	-61	46	1.0E+00	0%	0	0	358
KING	98.1	37.1	144	36	44	-63	2	12	24	-71	-63	44	5.0E-02	30%	19213	1499	118
KAFE	104.3	64.3	308	30	37	-70	1	12	18	-77	-70	37	1.0E+00	0%	0	0	358
KCMS	105.3	18.6	182	39	46	-61	3	12	27	-65	-58	49	1.0E+00	0%	0	0	358

RRM DATA ANALYSIS

RRM#	CHANNEL LOCKED	MSG's RCVD	MSG's MISSED	% RCVD	INTER MSG TIME MEAN	IMT MODE	IMT STD	IMT MIN	IMT MAX
1	98.1	57	32	64	63	60	26	14	141
2	98.1	52	10	84	60	70	11	28	84

WATCH DATA ANALYSIS

AXIS	START #	STOP #	TOTAL MISSED	PERCENT RCVD
N - S	48	48	N/A	N/A
E - W	41	48	11	74
VERT.	48	97	N/A	N/A

CABLE LOSS (db)	5
OMNI CORR. (db)	
KVTI	0.94
KBTC	0.94
KJR	2.25
KXXO	2.23
KING	2.73
KAFE	2.02
KCMS	2.02

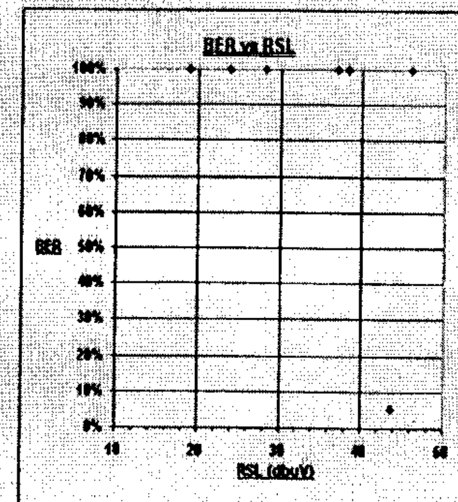


Figure 3-12. Performance Analysis Spreadsheet for Location #4.

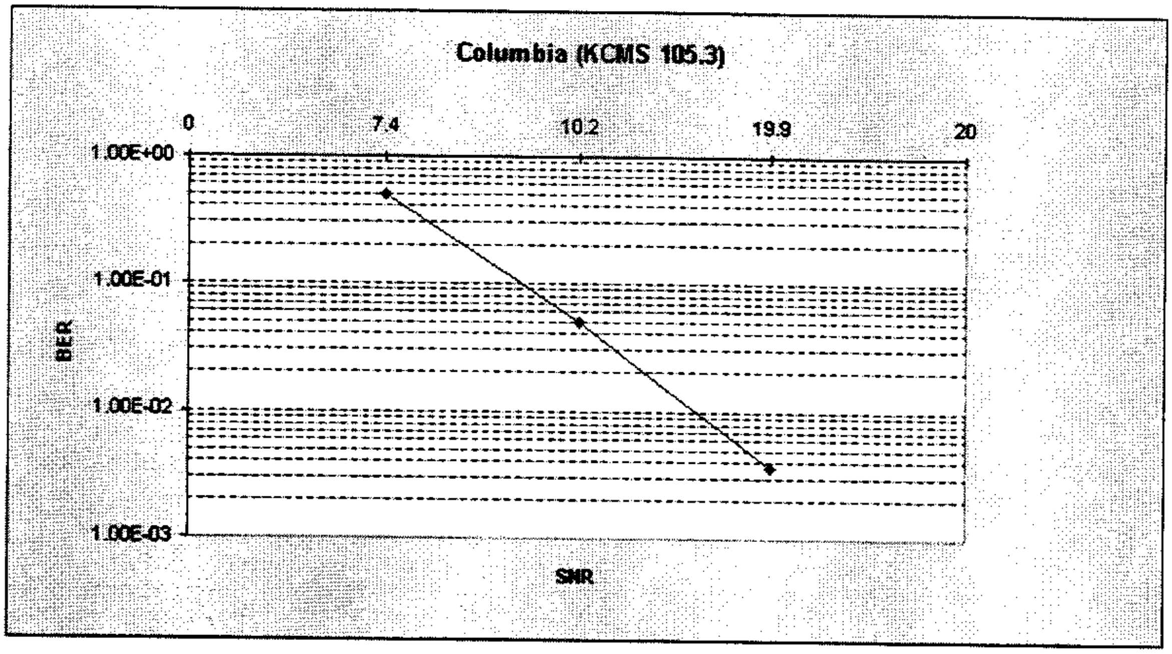


Figure 3-13. BER versus SNR Performance Curve at Location #5.

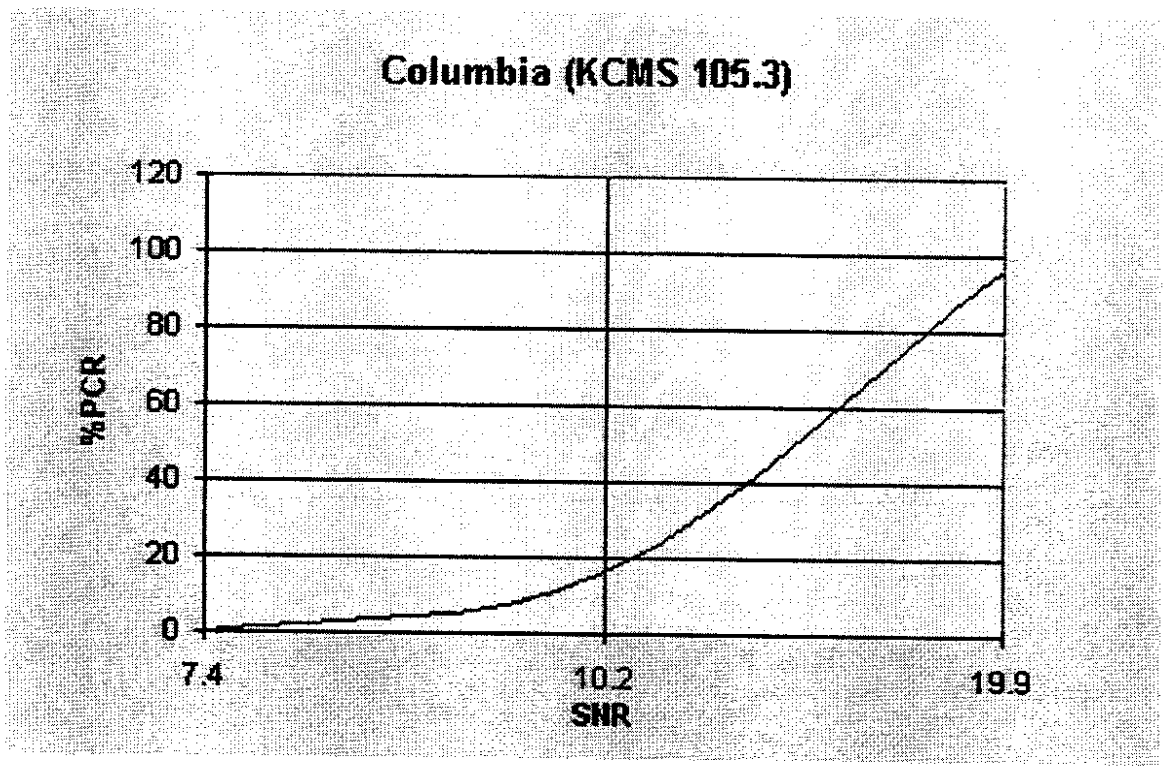


Figure 3-14. PCR versus SNR Performance Curve at Location #5.

STATION/GPS POSITION DATA				SPECTRUM ANALYSER DATA						TREQ ANALYSER DATA							
STATION	FREQ.	RANGE (MILES)	BEARING (MAG.)	S/A RAW RSL - (dbuV)	S/A CORRECTED RSL (dbuV)	RSL (dbm)	DELTA RSL (dbuV)	NOISE FL. (dbuV)	SNR (db)	TREQ RAW RSL (dbm)	CORRECTED RSL (dbm)	CORRECTED RSL (dbuV)	BER	PCR	ECC	CRC	PILOT ANG. (DEG)
KVTI	90.9	31.9	185	16	22	-85	11	12	4	-82	-76	31	1.0E+00	0%	0	0	358
KBTC	91.7	19.7	174	13	19	-88	9	12	1	-85	-79	28	1.0E+00	0%	0	0	358
KJR	95.7	9.2	86	47	54	-53	20	11	36	-56	-49	58	1.0E-02	82%	7013	471	62
KXXO	96.1	66	168	14	21	-86	10	10	4	-89	-82	25	1.0E+00	0%	0	0	358
KING	98.1	16	90	51	59	-48	12	12	39	-54	-46	61	0.0E+00	100%	0	0	60
KAFE	104.3	80	322	14	21	-86	N/A	10	4	-82	-75	32	1.0E+00	0%	0	0	358
KCMS	105.3	13.2	329	38	45	-62	7	11	27	-65	-58	49	4.0E-03	97%	8892	565	60

RRM DATA ANALYSIS

RRM#	CHANNEL LOCKED	MSG's RCVD	MSG's MISSED	% RCVD	INTER MSG TIME MEAN	IMT MODE	IMT STD	IMT MIN	IMT MAX
1	95.7	129	1	99.2	60	60	17	13	112
2	98.1	123	1	99.2	60	70	16	14	112

WATCH DATA ANALYSIS

AXIS	START #	STOP #	TOTAL MISSED	PERCENT RCVD
N - S	133	144	0	100
E - W	123	133	0	100
VERT.	134	145	0	100

CABLE LOSS (db)	5
CORR.	
KVTI	0.94
KBTC	0.94
KJR	2.25
KXXO	2.23
KING	2.73
KAFE	2.02
KCMS	2.02

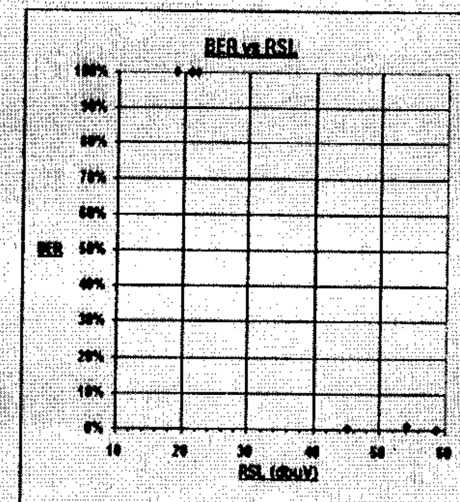


Figure 3-15. Performance Analysis Spreadsheet for Location #5.

Site 6 (Shoreline)

Conditions at this test location initially indicated that a multi-path environment might be the cause of the inability to take data from six out seven FM stations. After reviewing the transmission path terrain profiles, the results suggested that all but two had significant terrain blockages and six of seven were at a distance of about 20 miles or more. KCMS, unlike any other test was very close, 1.8 miles, with a -20 dBm signal which overwhelmed the RRMs and watches, causing them to lock on hard to the 105.3 MHz frequency. Manually forcing the watches to scan did not change the results. The only other station for which data was able to be collected on the TREQ was KAFE, with an RSL of -70 dBm. Figures 3-16 and 3-17 illustrate the BER and PCR curves for test location #6, respectively, while Figure 3-18 shows the performance analysis spreadsheet for location #6.

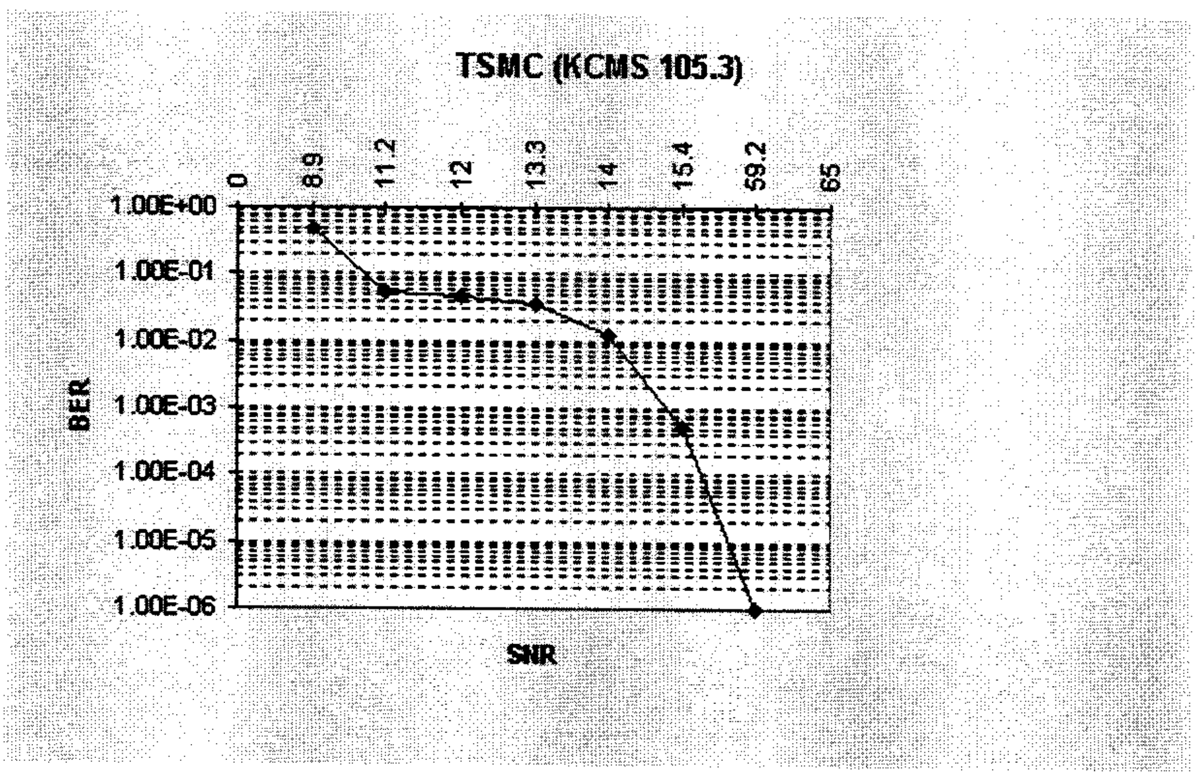


Figure 3-16. BER versus SNR Performance Characteristics for Location #6.

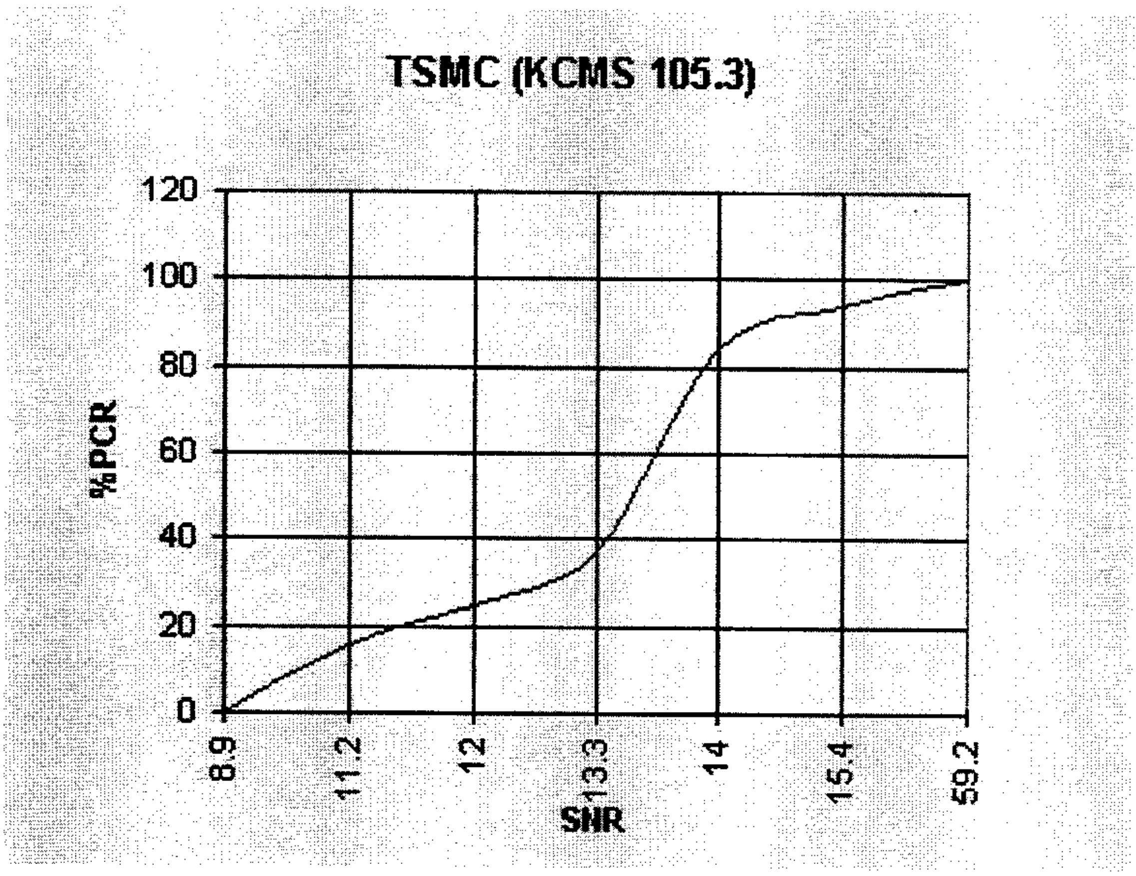


Figure 3-17. PCR versus SNR Performance Characteristics Measured at Location #6.

Site 7 (Downtown Seattle)

This downtown Seattle test location was probably among the worst from a terrain blockage point of view, being obscured on all sides except the North, where KCMS, being about 11 miles away, was able to provide the single station needed to provide good reception. The six watches performed very well, all recording a 100% score, but the two RRM devices scored 60% and 81% respectively, with the system having an N-S orientation out-scoring the other E-W direction. Figures 3-19 and 3-20 present the BER and PCR curves versus SNR for measurements taken using KCMS. Figure 3-21 shows the performance analysis spreadsheet for data collected at site #7.

STATION/GPS POSITION DATA				SPECTRUM ANALYSER DATA						TREQ ANALYSER DATA							
STATION	FREQ.	RANGE (MILES)	BEARING (MAG.)	S/A RAW RSL - (dbuV)	S/A CORRECTED RSL (dbuV)	RSL (dbm)	DELTA RSL (dbuV)	NOISE FL. (dbuV)	SNR (db)	TREQ RAW RSL (dbm)	CORRECTED RSL (dbm)	CORRECTED RSL (dbuV)	BER	PCR	ECC	CRC	PILOT ANG. (DEG)
KVTI	90.9	41.6	175	21	27	-80	3	11	10	-79	-73	34	1.0E+00	0%	0	0	358
KBTC	91.7	30.4	164	15	21	-86	1	10	5	-84	-78	29	1.0E+00	0%	0	0	358
KJR	95.7	17.8	121	54	61	-46	3	12	42	-76	-69	38	1.0E+00	0%	0	0	358
KXXO	96.1	76.7	165	30	37	-70	1	11	19	-70	-63	44	6.0E-02	0%	18888	1465	62
KING	98.1	24.1	114	46	54	-53	3	12	34	-77	-69	38	1.0E+00	0%	0	0	358
KAFE	104.3	68.6	321	30	37	-70	2	11	19	-70	-63	44	5.0E-02	23%	22203	2022	56
KCMS	105.3	1.8	338	80	87	-20	2	11	69	-67	-60	47	3.0E-04	100%	548	9	59

RRM DATA ANALYSIS

RRM#	CHANNEL LOCKED	MSG's RCVD	MSG's MISSED	% RCVD	INTER MSG TIME MEAN	IMT MODE	IMT STD	IMT MIN	IMT MAX
1	95.7	208	1	99.5	63	60	33	13	323
2	98.1	205	1	99.5	63	60	33	14	323

WATCH DATA ANALYSIS

AXIS	START #	STOP #	TOTAL MISSED	PERCENT RCVD
N - S	47	59	0	100
E - W	37	47	0	100
VERT.	59	70	0	100

CABLE LOSS (db)	5
OMNI CORR. (db)	
KVTI	0.94
KBTC	0.94
KJR	2.25
KXXO	2.23
KING	2.73
KAFE	2.02
KCMS	2.02

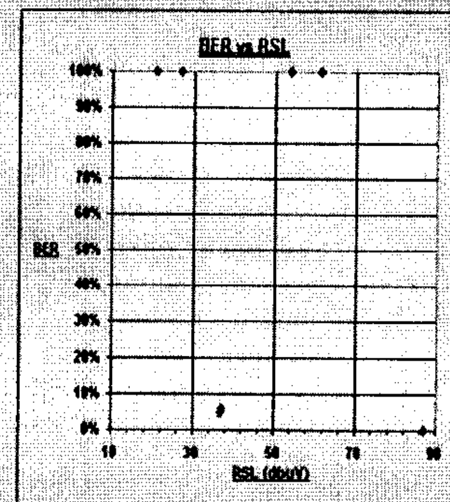


Figure 3-18. Performance Analysis Spreadsheet for Location #6.

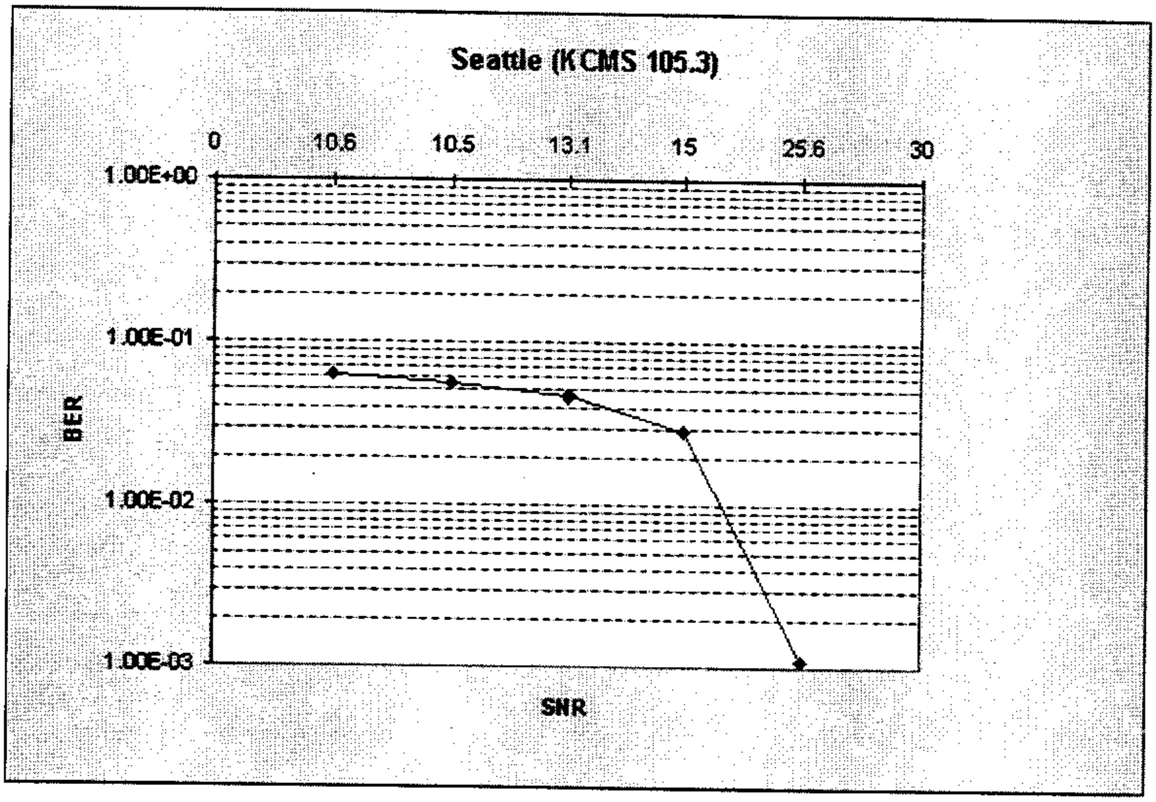


Figure 3-19. BER versus SNR Performance data Collected at Location #7.

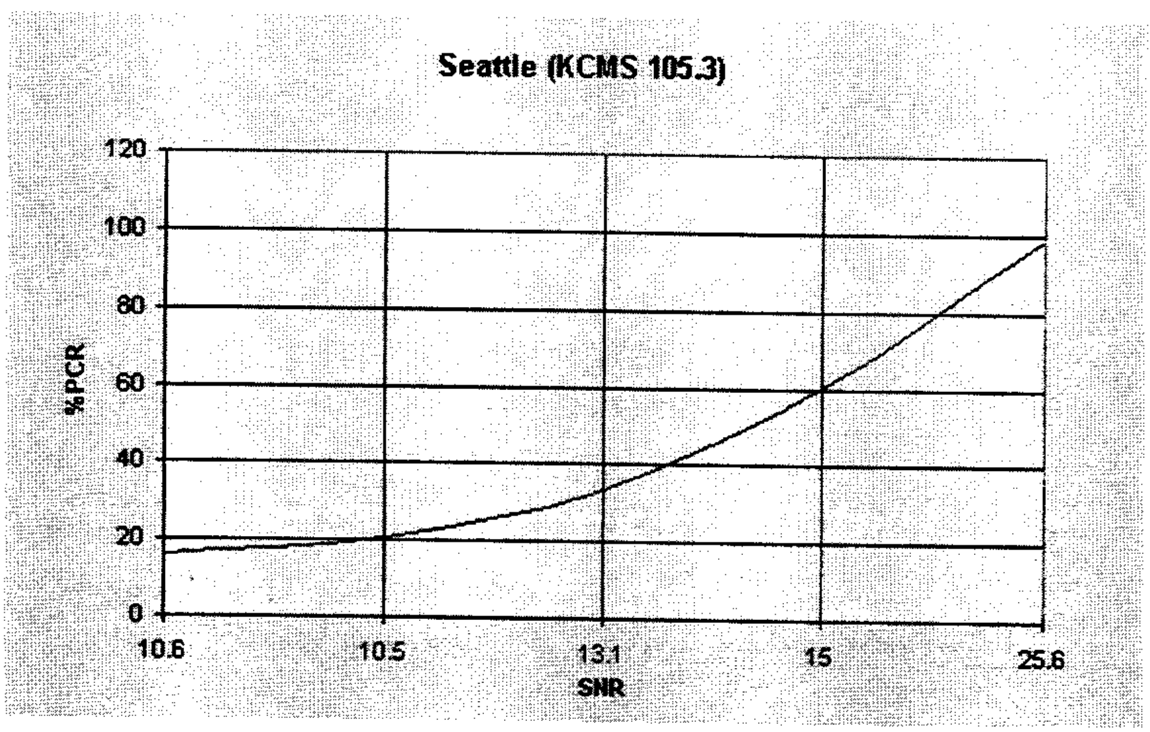


Figure 3-20. PCR versus SNR Performance data Collected at Location #7.

STATION/GPS POSITION DATA				SPECTRUM ANALYSER DATA						TREQ ANALYSER DATA							
STATION	FREQ.	RANGE (MILES)	BEARING (MAG.)	S/A RAW RSL - (dbuV)	S/A CORRECTED RSL (dbuV)	RSL (dbm)	DELTA RSL (dbuV)	NOISE FL. (dbuV)	SNR (db)	TREQ RAW RSL (dbm)	CORRECTED RSL (dbm)	CORRECTED RSL (dbuV)	BER	PCR	ECC	CRC	PILOT ANG. (DEG)
KVTI	90.9	32.8	180	26	32	-75	3	12	14	-74	-68	39	4.0E-03	0%	241	12	43
KBTC	91.7	21.2	167	21	27	-80	2	12	9	-55	-49						
KJR	95.7	11.8	93	35	42	-65	2	12	23	-81	-74	33	1.0E+00	0%	0	0	358
KXXO	96.1	67.5	166	24	31	-76	2	12	12	-82	-75	32	1.0E+00	0%	0	0	358
KING	98.1	18.6	93	31	39	-68	2	12	19	-74	-66	41	5.0E-02	37%	25310	1972	107
KAFE	104.3	77.5	323	14	21	-86	N/A	12	2	-85	-78	29	1.0E+00	0%	0	0	358
KCMS	105.3	11.1	338	44	51	-56	2	13	31	-59	-52	55	1.0E-03	99%	679	35	66

RRM DATA ANALYSIS

RRM#	CHANNEL LOCKED	MSG's RCVD	MSG's MISSED	% RCVD	INTER MSG TIME MEAN	IMT MODE	IMT STD	IMT MIN	IMT MAX
1	105.3	112	27	81	69	60	19	14	125
2	105.3	64	42	60	58	60	16	14	85

WATCH DATA ANALYSIS

AXIS	START #	STOP #	TOTAL MISSED	PERCENT RCVD
N - S	127	137	0	100
E - W	115	127	0	100
VERT.	137	149	0	100

CABLE LOSS (db)	5
OMNI CORR. (db)	
KVTI	0.94
KBTC	0.94
KJR	2.25
KXXO	2.23
KING	2.73
KAFE	2.02
KCMS	2.02

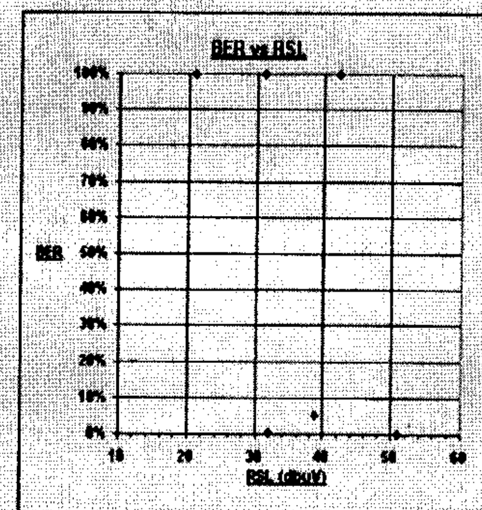


Figure 3-21. Performance Analysis Spreadsheet for Location #7.

Site 8 (Puyallup)

Test location #8, in a fashion similar to site #7, was the victim of significant terrain blockage. Only KBTC was able to provide an 89% message completion rate. An interesting observation was made when one RRM2 (E-W orientation) successfully received 100% of the messages, but RRM1 (N-S orientation) received only 35%. To further confuse the issue, all six watches performed at nearly 100%, regardless of their orientation.

It is also interesting to note that after the test had been running for approximately one hour, RRM1 appeared to be lost in the sense that it did not or could not recognize the full and proper set of Seattle area HSDS frequencies to scan. This information supporting this assertion is presented in Table 3-1. This unit scanned only one of the Seattle stations, KAFE on 104.3 MHz, but did not lock onto it due to a low RSL of -61 dBm. It should also be noted that the other frequencies, highlighted in bold in Table 3-1, were not scanned. RRM2, on the other hand, turned in a good score of 89%.

Figures 3-22 and 3-23 illustrate the BER and PCR versus SNR performance exhibited by signals received from KBTC. In addition, Figure 3-24 shows the summary performance analysis spreadsheet for data collection efforts made at test site #8.

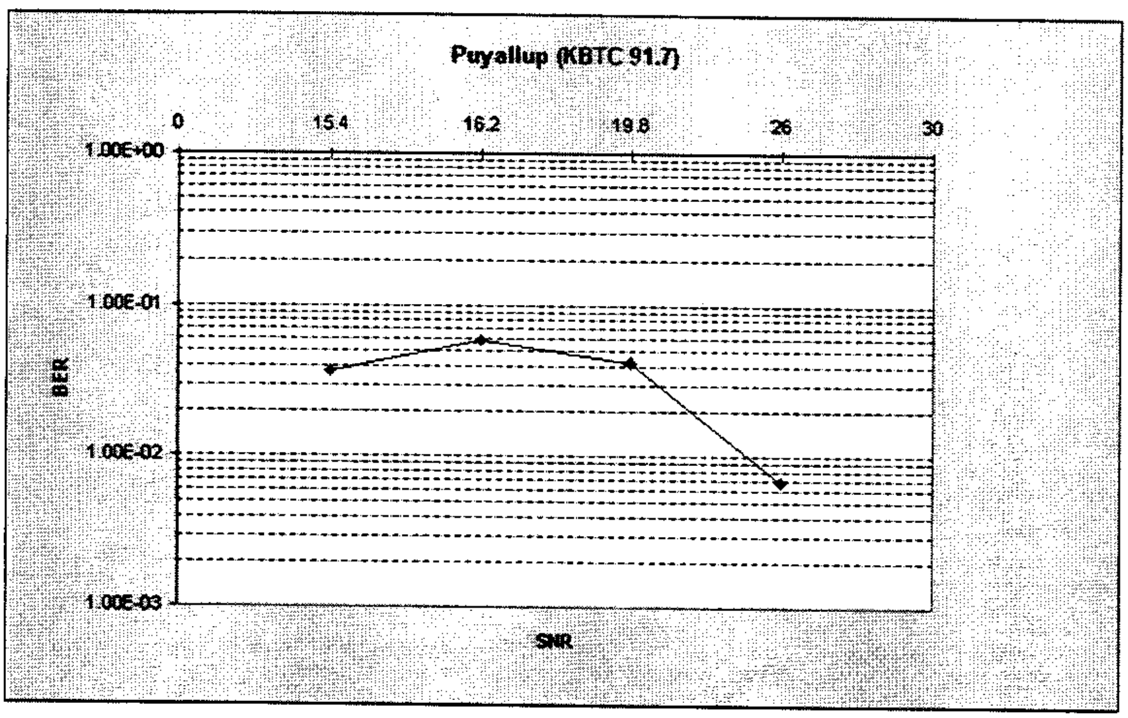


Figure 3-22. BER versus SNR Performance for KBTC at Site #8.

Table 3-1. RRM1 Scanned Frequencies without Successful Lock at Site #8.

Frequency	Lock	Frequency	Lock
87.5	No	87.9	No
88.3	No	88.7	No
89.1	No	89.5	No
89.9	No	90.3	No
90.7	No	**90.9 (KVTI)**	Not Scanned
91.1	No	91.5	No
91.7 (KBTC)	Not Scanned	91.9	No
92.3	No	92.7	No
93.1	No	93.9	No
94.3	No	94.7	No
95.1	No	95.5	No
95.7 (KJR)	Not Scanned	95.9	No
96.1 (KXXO)	Not Scanned	96.3	No
96.7	No	97.1	No
97.5	No	97.9	No
98.1 (KING)	Not Scanned	98.3	No
98.7	No	99.1	No
99.5	No	99.9	No
100.3	No	100.7	No
101.1	No	101.5	No
101.9	No	102.3	No
102.7	No	103.1	No
103.5	No	103.9	No
104.3 (KAFE)	No	104.7	No
105.1	No	**105.3 (KCMS)**	Not Scanned
105.5	No	105.9	No
106.3	No	106.7	No
107.1	No	107.5	No
107.9	No		

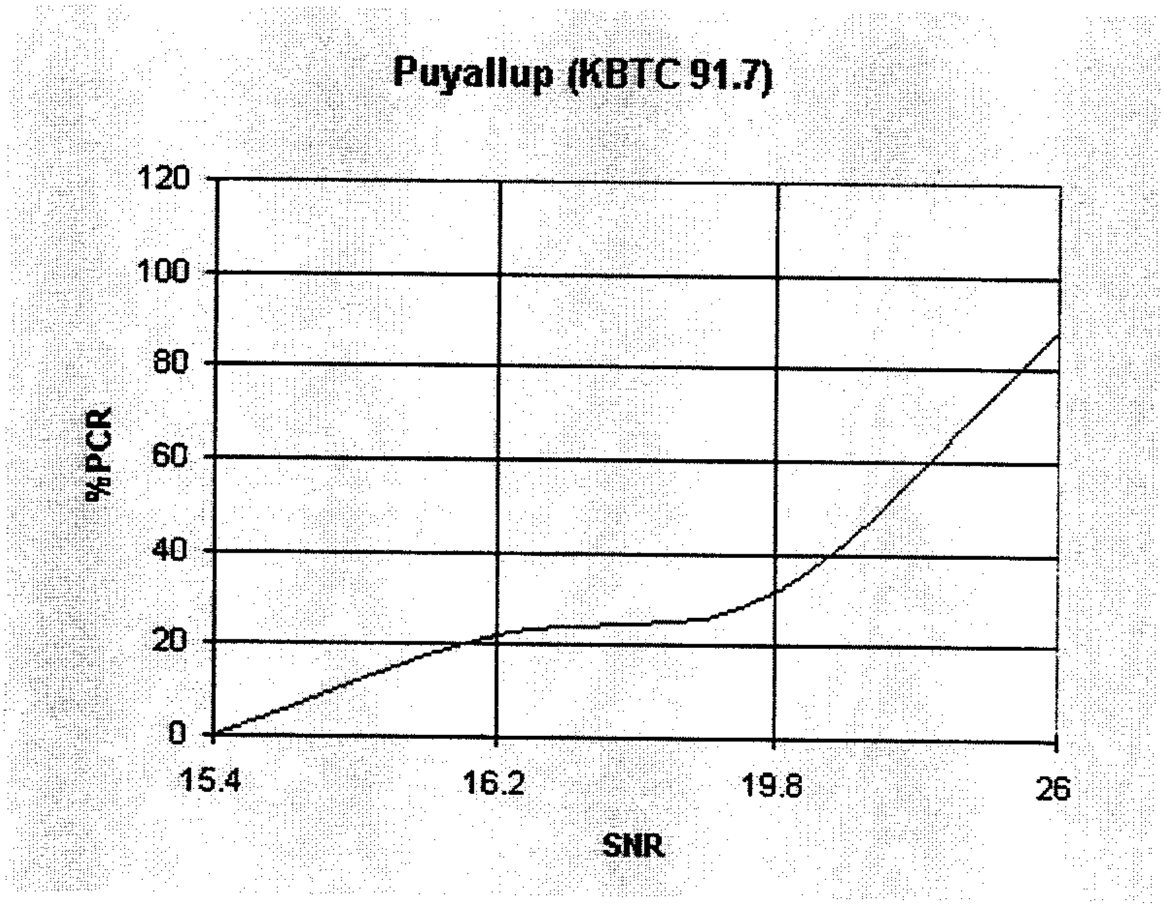


Figure 3-23. PCR versus SNR Performance for KBTC at Site #8.

In most cases, throughout the analysis, the inter-arrival time analysis indicated that the mean arrival time was fairly consistent at approximately 60 seconds, with a standard deviation (spread) value of about 20-30 seconds. However, a number of sites showed maximum values in the hundreds of seconds. This could be a reason for reports of untimely traffic incident message reception. This should be further addressed by Seiko to determine if it was caused by an artifice of the test configuration, or indicative of possible operational message delays.

STATION/GPS POSITION DATA				SPECTRUM ANALYSER DATA						TREQ ANALYSER DATA							
STATION	FREQ.	RANGE (MILES)	BEARING (MAG.)	S/A RAW RSL - (dbuV)	S/A CORRECTED RSL (dbuV)	RSL (dbm)	DELTA RSL (dbuV)	NOISE FL. (dbuV)	SNR (db)	TREQ RAW RSL (dbm)	CORRECTED RSL (dbm)	CORRECTED RSL (dbuV)	BER	PCR	ECC	CRC	PILOT ANG. (DEG)
KVTI	90.9	13.7	244	37	43	-64	2	12	25	-69	-63	44	5.0E-02	24%	16536	1391	59
KBTC	91.7	9.7	309	46	52	-55	2	12	34	-59	-53	54	7.0E-05	89%	4600	368	53
KJR	95.7	26.3	359	34	41	-66	4	11	23	-67	-60	47	8.0E-02	0%	17183	982	70
KXXO	96.1	38.9	173	23	30	-77	1	12	11	-83	-76	31	1.0E+00	0%	0	0	358
KING	98.1	26.6	14	41	49	-58	3	12	29	-67	-59	48	5.0E-02	49%	40350	2518	93
KAFE	104.3	106	327	39	46	-61	4	11	28	-69	-62	45	1.0E+00	0%	0	0	358
KCMS	105.3	40.4	337	19	26	-81	1	12	7	-82	-75	32	1.0E+00	0%	0	0	358

RRM DATA ANALYSIS

RRM#	CHANNEL LOCKED	MSG's RCVD	MSG's MISSED	% RCVD	INTER MSG TIME MEAN	IMT MODE	IMT STD	IMT MIN	IMT MAX
1	?	36	67	35	60	60	12	42	98
2	98.1	89	0	100	59	60	15	15	98

WATCH DATA ANALYSIS

AXIS	START #	STOP #	TOTAL MISSED	PERCENT RCVD
N - S	54	62	0	100
E - W	62	69	1	98
VERT.	69	78	0	100

CABLE LOSS (db)	5
OMNI CORR. (db)	
KVTI	0.94
KBTC	0.94
KJR	2.25
KXXO	2.23
KING	2.73
KAFE	2.02
KCMS	2.02

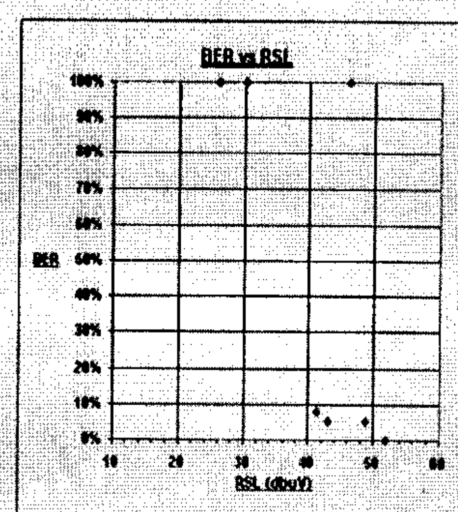


Figure 3-24. Performance Analysis Spreadsheet for Site #8.

3.3. Multi-path Measurement Results

SWIFT Communications Study Coverage Test results for multi-path measurements are presented in the following sections.

Site 1 (Bellevue)

There was no indication of the presence of a multi-path environment at this location.

Site 2 (West Seattle)

There was no indication of the presence of multi-path interference at this location.

Site 3 (SeaTac)

There was an indication of multi-path problems from KCMS at this test location. The method used to determine if this interference could be mitigated was change receiver antennas on the TREQ system from the calibrated omni-directional dipole to the more directional FM antenna. By adjusting the signal attenuation to equalize the difference in gain between the two antennas, approximately 10 dB the effective directional pattern might reduce the sidelobe signals enough to improve the measured performance. Figure 3-25 shows the PCR performance for station KCMS, as measured by using the omni-directional antenna.

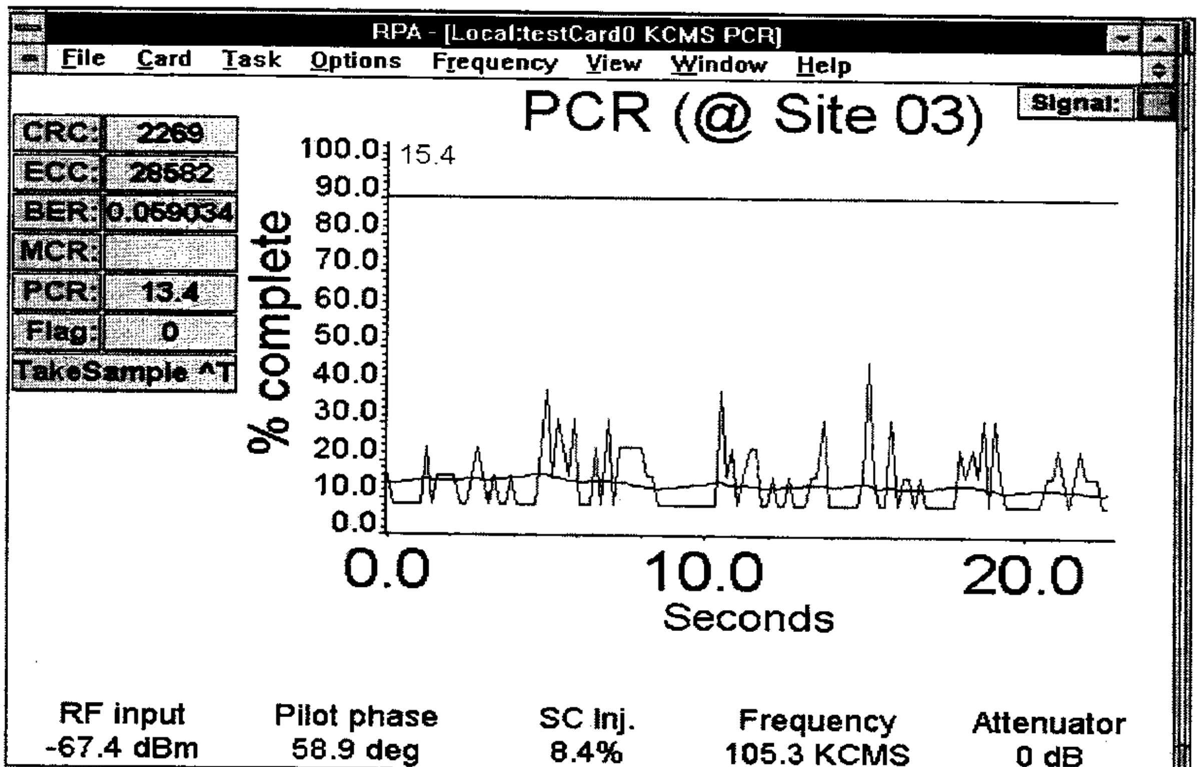


Figure 3-25. Suspected KCMS Multi-path Signal Measured at Site #3 with Omni Antenna.

The data recorded here is PCR and is shown to be about 10%, the effective BER is 5.9E-2. When the directional antenna is connected to the TREQ signal input, the resulting improvement in PCR and BER reasonably suggests that the signal shown in Figure 3-25 was subjected to significant multi-path interference. This result is shown in Figure 3-26, below.

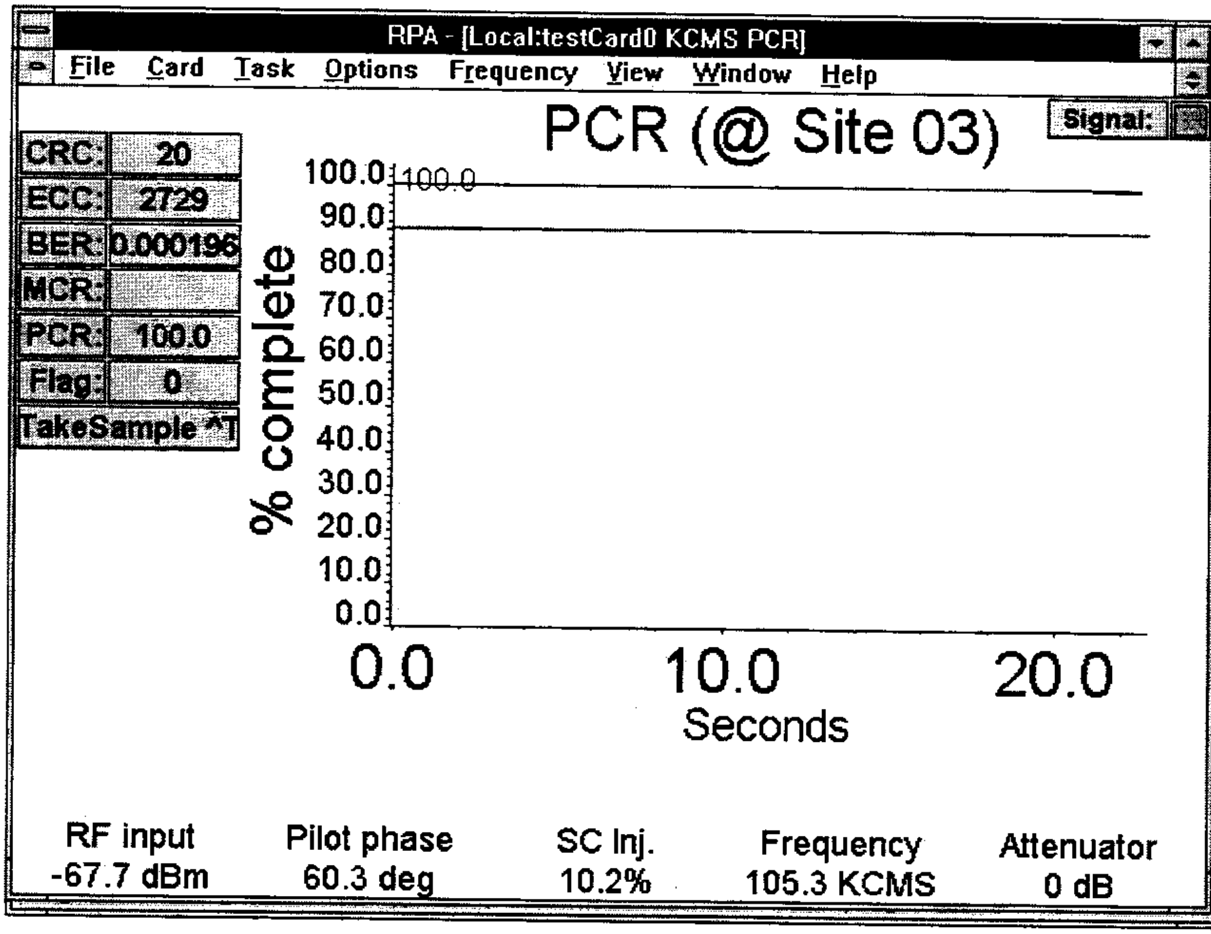


Figure 3-26. Same KCMS Multi-path Signal Measured at Site #3 with Directional FM Antenna.

This result indicates the KCMS signal shows a greatly improved PCR, approaching 90% with the directional antenna. In addition, the resulting BER has now been reduced to an exceptionally low value of 1.9E-4.

Site 4 (Everett)

Test location #4 also had a strong suggestion of the presence of multi-path interference from a very strong station, KING. The same technique was employed to attempt to mitigate the multi-path effects, and was used with similar success, as shown in Figures 3-28 and 3-29.

The PCR was varying between 20% and 30% and the BER was measured to be 5.8E-2 in this example.

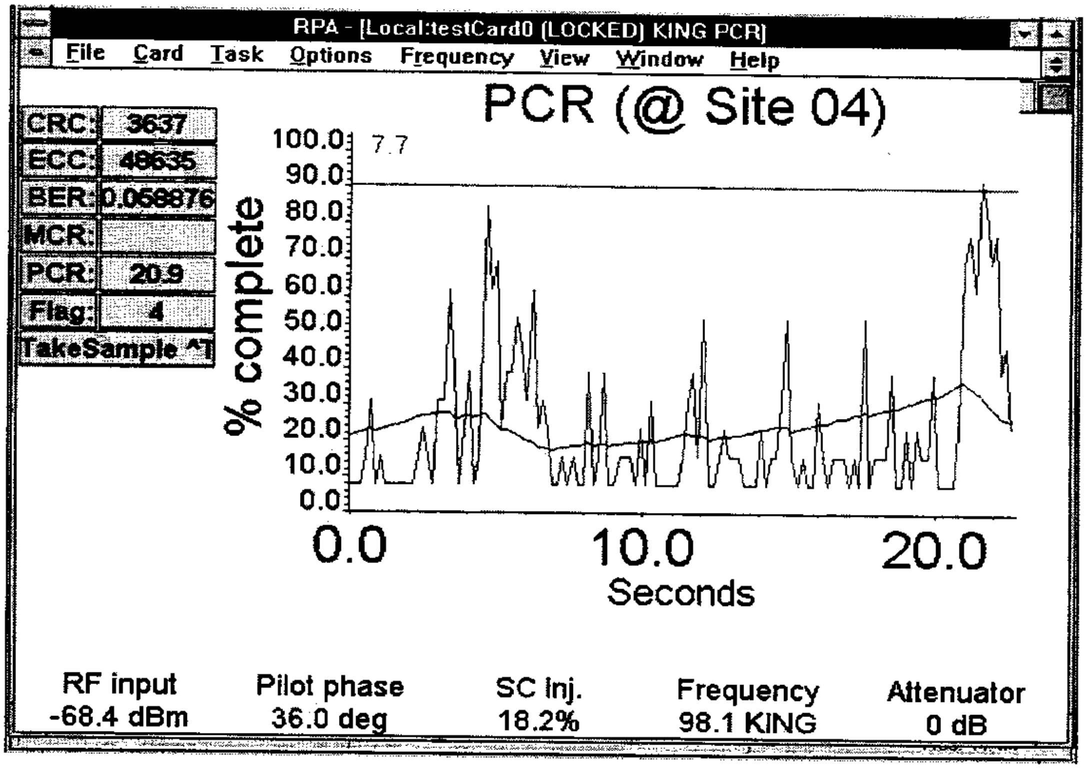


Figure 3-27. Suspected KING Multi-path Signal Measured at Site #4 with Omni Antenna.

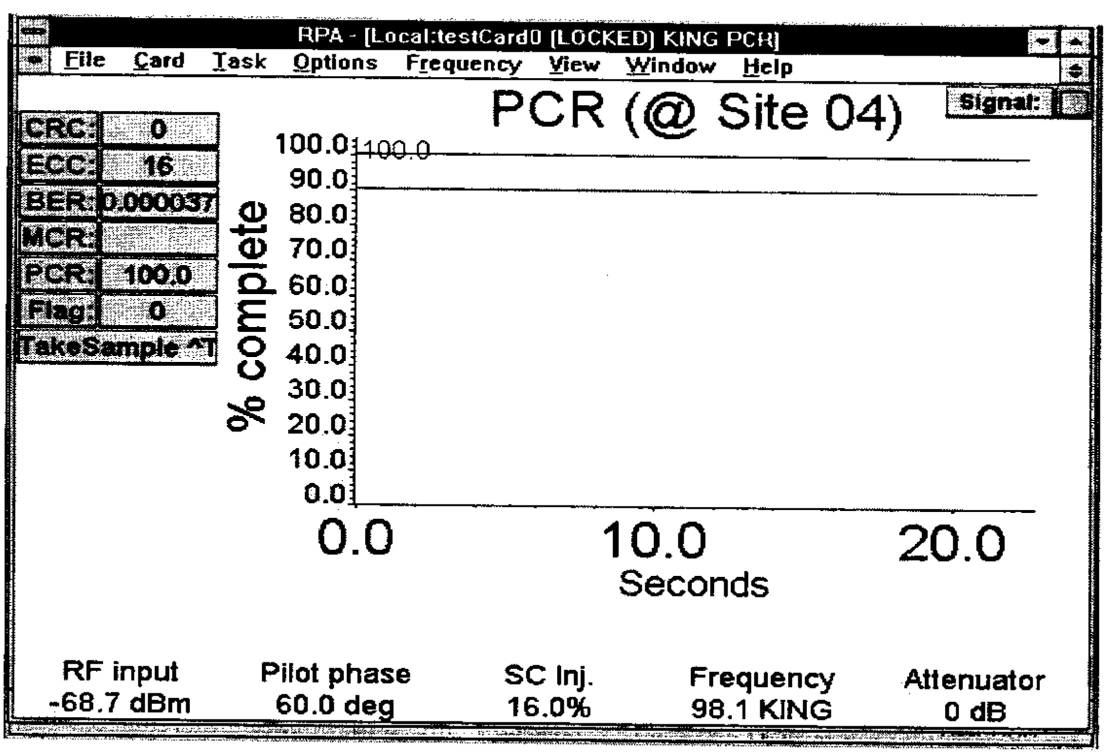


Figure 3-28. Same KING Multi-path Signal Measured at Site #4 with Directional Antenna.

Site 5 (South Seattle)

There was no indication of the presence of a multi-path environment at this location.

Site 6 (Shoreline)

There was no indication of the presence of a multi-path environment at this location.

Site 7 (Downtown Seattle)

There was no indication of the presence of a multi-path environment at this location.

Site 8 (Puyallup)

There was no indication of the presence of a multi-path environment at this location.

The effect of multi-path on BER is to increase the measured amount. While the RSL simulation plots may indicate that a receiver should be able to lock onto three or four possible SWIFT transmitters, multi-path may render several of these transmitters unusable, despite more than adequate signal levels. This can reduce the overall diversity to the point where only one or two transmitters are viable for a lock. In this case, a receiver which is in a signal null from the few available transmitters could be completely cut off from message service. In areas where multi-path is measured or expected, the coverage indicated by the simulation RSL plots need to be "derated," according to the level of multi-path.

Discussions with Seiko have indicated that their simulation program has been enhanced to provide more indications of multi-path effects. This was used in the planning for the NYC system, due to the number and size of the skyscrapers. It is suggested that, if possible, the multi-path-enabled version of the simulation should be run for the Seattle configuration. This may help to corroborate current findings, and isolate areas that were not tested and that may have comparable multi-path problems. This information could be used by Seiko to fine-tune their configuration and minimize the extent of the poor reception areas.

Seattle's terrain consists of a number of hills running generally in a North-South direction. Elevations range from sea level to 500 feet in the city and up to 1,100 feet along the Eastern edge of the HSDS coverage area. In addition, both the downtown areas of Seattle and Bellevue have several tall buildings ranging up to 72 stories. Because of these factors, the Seattle area is generally recognized to be prone to multi-path interference.

Ultimately, given the terrain of Seattle and despite the best efforts of the system designers, there will always be some locations that cannot obtain reliable reception. Analysis of the factors can make these areas arbitrarily small, but they will still occur. Strangely, the RRM-equipped laptops seemed to experience more isolated blackout areas than the watch, despite the RRM's greater signal sensitivity. A strong explanation is that the watches lower signal sensitivity put some of the multi-path interference below the receiver threshold, analogous to the effect of the directional antenna used with the TREQ.

3.4. In-Building TSMC Test Results

Figures 3-29, 3-30 and 3-31 show the measurements taken at increasing distances inside WSDOT's TSMC building for RSL, BER and PCR, respectively. These curves confirm that the RSL, BER and PCR is degraded as distance inside the building increases.

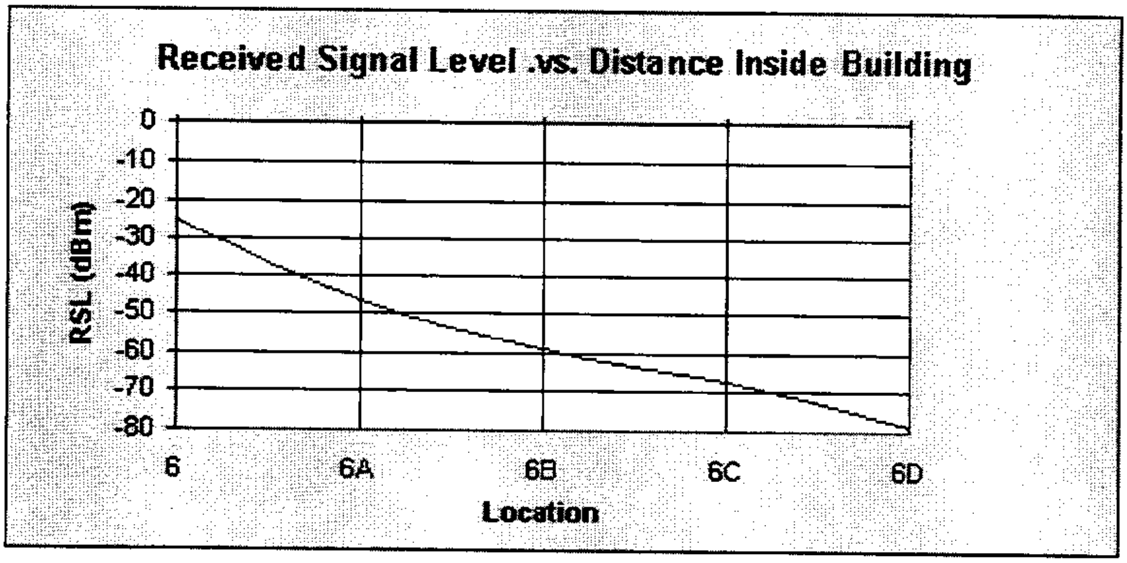


Figure 3-29. TSMC Inside Building Measurement of RSL at Four Locations.

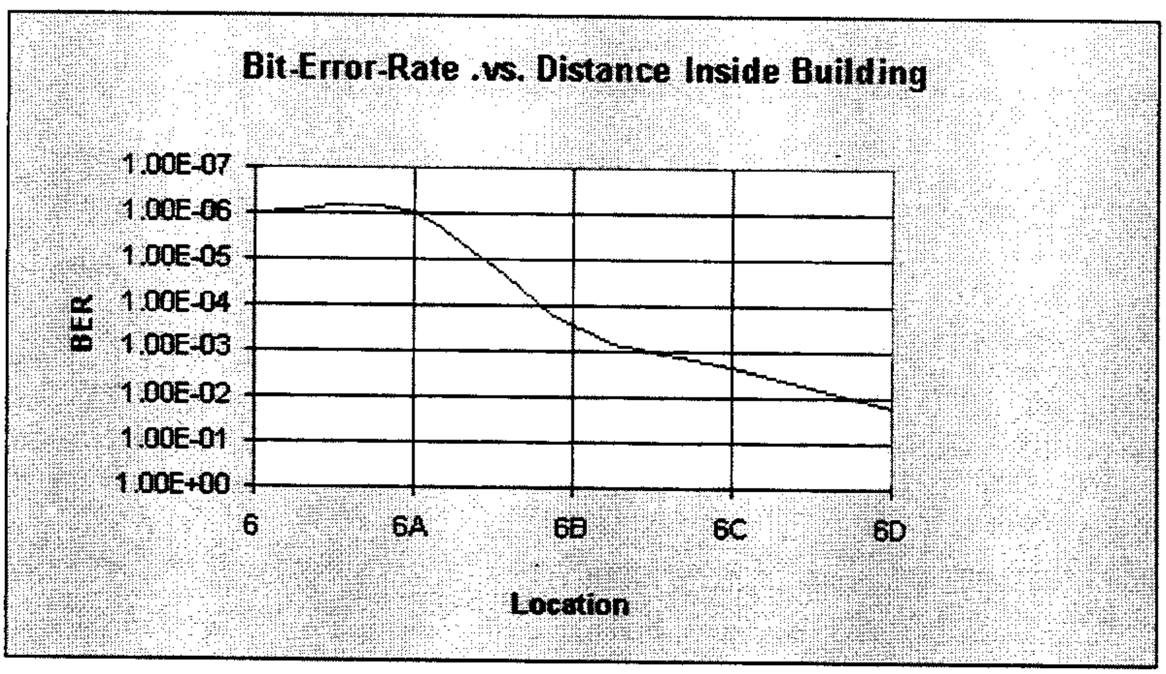


Figure 3-30. TSMC Inside Building Measurement of BER at Four Locations.

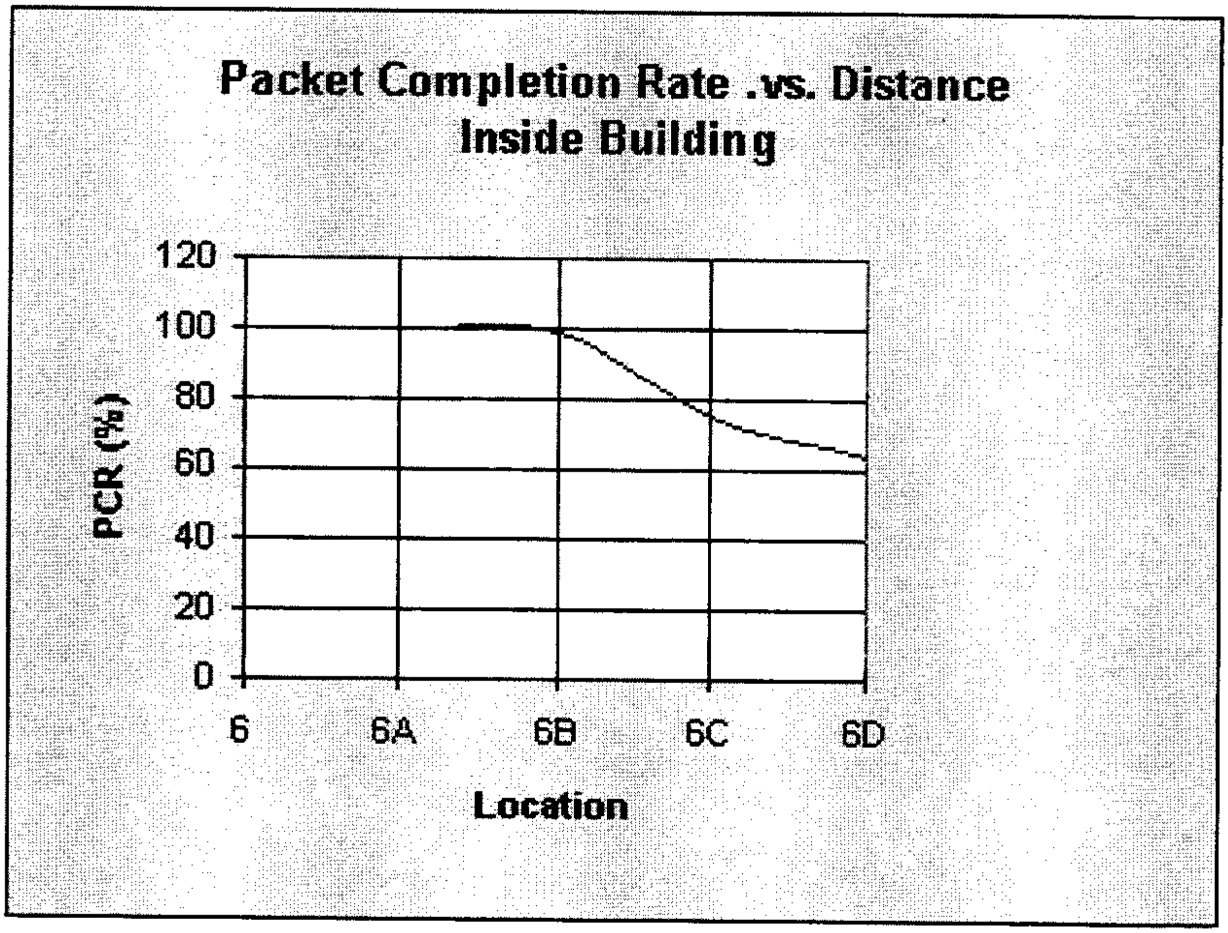


Figure 3-31. TSMC Inside Building Measurement of PCR at Four Locations.

These test measurements are useful in a general sense for predicting the effects of reductions in signal strength as the receiver is moved deeper into the building, away from the exterior walls. There are, however, many other variables which might influence this signal attenuation phenomenon. They are: building construction techniques and materials, frequency of signals being received, number, size and placement of windows, to name a few.

4. DISCUSSION

During the conduct of the *SWIFT Communications Study* evaluation, several interesting observations were made. These included:

- Overall performance of the SWIFT system from a coverage point of view was very good— i.e., approximately 93% of participants reported no reception problems
- Six (6) of eight (8) suspected "problem" sites still had adequate reception to deliver SWIFT messages
- The RSL measurements made as part of these tests tracked reasonable well with the simulation contours produced by Seiko
- Plots of BER as a function of signal-to-noise ratio (SNR) level produced from the test results indicated that the error rate and minimum signal level quoted in the Seiko specifications were valid
- The receiver/antenna sensitivity specifications for the Seiko watches remains a good estimate of device performance
- Unlike the watch, whose performance seemed to be independent of the orientation of its loop antenna, the performance of the RRM, using the paddle antenna, appears to be somewhat dependent on antenna orientation
- Reduction in the ability of the SWIFT devices to receive messages was due to a significant multi-path environment
- At two sites there appeared to a significant impact on BER/PCR due to multi-path signal interference
- There was substantial signal attenuation for in-building locations, even in the presence of an otherwise strong HSDS signal

Concerning the fact that RSL measurements tracked reasonable well with the simulation contours produced by Seiko, while the simulated signal levels were sometimes higher than those measured, the correlation was strong enough to support using the simulation as a tool for system coverage planning and transmitter site selection. In particular, plots of BER and PCR as a function of signal level produced from the test results indicated that the error rates and minimum signal levels quoted in the Seiko specifications were valid.

The test results strongly suggest that while sufficient RSL is necessary for adequate reception at a site, it is not by itself a sufficient indicator of message delivery success. At two sites a significant impact on BER/PCR due to multi-path signal interference was found. In an area geologically/ topographically prone to the creation of multi-path, such as Seattle, there has to be more emphasis placed on this effect when coverage areas are predicted. In essence, multi-path interference reduces the effective spatial/frequency diversity at a given location.

In general, the HSDS system worked well in most locations, including 6 of 8 suspected problem spots. Some user-reported problem areas were difficult assess due to the non-technical nature of these reported incidents as well as the fact that testing was not able to be performed at all problem locations. In other areas, problems with the HSDS were very apparent. These included the effects of severe multi-path interference, low RSL due to antenna orientation issues and possible problems caused by excessively high RSL in locations very close to an HSDS transmitter.

Despite the HSDS's problems with terrain blocking and multi-path, it appeared that the mitigating strategies of using multiple towers, sending messages three (3) times to the Seiko MessageWatch and frequent updates of "broadcast" traveler information adequately compensated for the FM subcarrier's imperfections. This was demonstrated by the 93% of SWIFT participants who reported no problems with receiving messages and the nearly perfect reception by the MessageWatch at 6 of the 8 suspected problem sites.

Excellent performance of the SWIFT HSDS in the Seattle metropolitan area, however, does not mitigate the severe impact that non-reception may have upon individual users. Some SWIFT test participants, for example, who reported that they were not able to receive SWIFT messages at either home or work, reported that these difficulties essentially rendered the SWIFT system useless at least 50% of the time. Thus, any assessment of HSDS effectiveness needs to address the myriad of environmental factors contributing to the receipt of messages by end-user devices (e.g., building type, terrain, multi-path).

Use of extremely high power FM stations may, in some instances, subject the HSDS to the occurrence of multi-path interference, particularly in hilly/mountainous areas. Ultimately, given the terrain of Seattle and despite the best efforts of the system designers, there will always be some locations that cannot obtain reliable reception. Analysis of the factors can make these areas arbitrarily small, but they will still occur. Strangely, the RRM equipped laptops seem to have more isolated blackout areas than the watch, despite the greater signal sensitivity of the RRM. Our only explanation is that the watches lower signal sensitivity put some of the multi-path interference below the receiver threshold, analogous to the effect of the directional antenna used with the TREQ.

Even though the Seiko HSDS system performs reasonably well in the Seattle area, there are some regions where significant variations in terrain severely affect coverage. When this situation is found to be the case, it is recommended that more rigorous multi-path analyses and testing be performed in advance of system deployment. For example, where multi-path interference was observed in the tests, it was always associated with two/three high power stations. It is suggested that this multi-path problem might be mitigated by using a larger number of local, lower-power stations instead of higher-powered ones. A recommendation is made that further analysis into this issue be conducted and although it is uncertain how this may effect system costs, it is believed that coverage problems in these specific areas can likely be improved. Figure 4-1 illustrates one of several possible multi-path mechanisms.

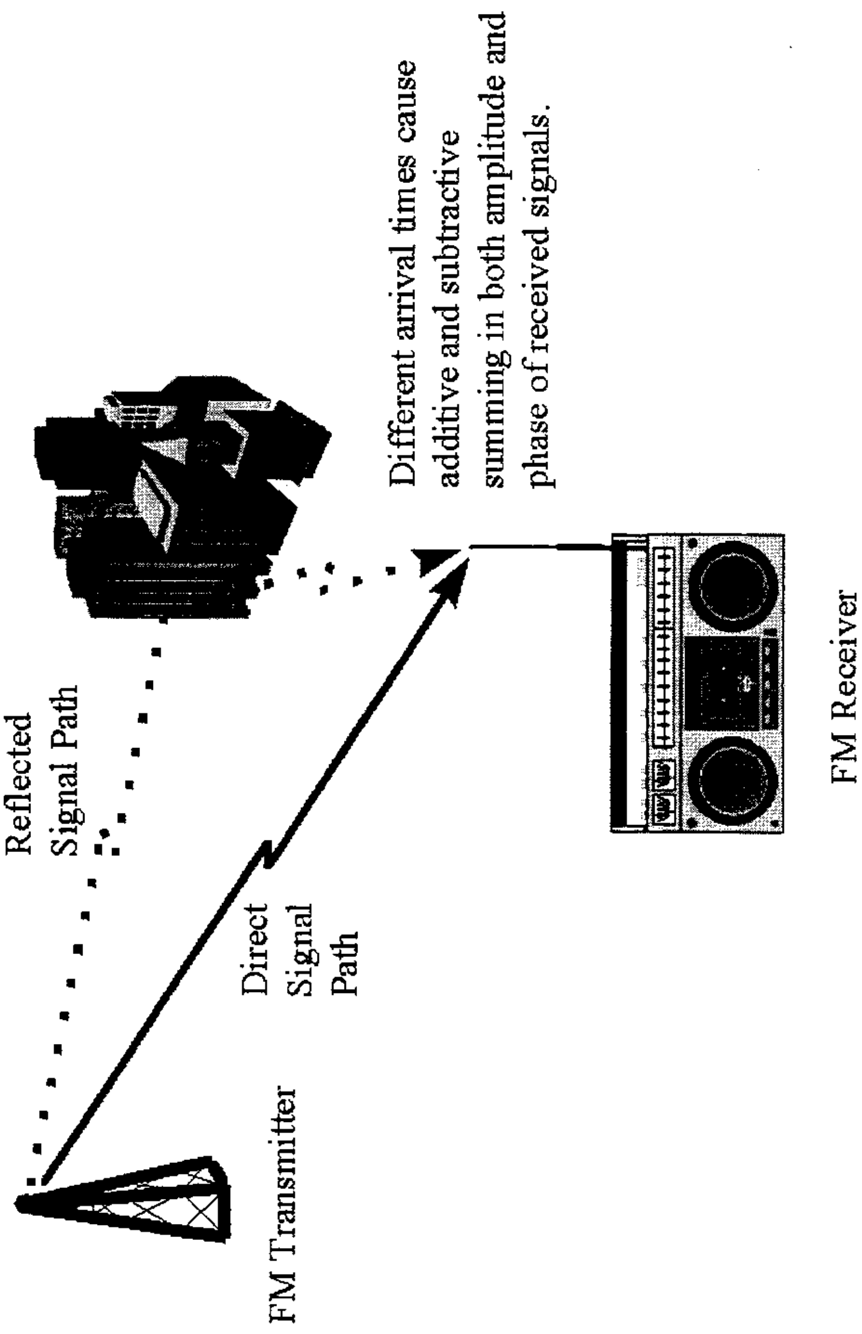


Figure 4-1. Example of Multi-path Propagation Mechanisms.

Other HSDS performance increases can be made by improving the spatial diversity of the stations. For instance, adding a site West of Puget Sound would cover many of the shadow areas in the Downtown Seattle or Everett areas. Nonetheless, such a site does not presently exist. Thus, the near total cutoff of a signal by high terrain would also greatly limit any FM subcarrier in a mountainous rural environment unless a system of repeaters is implemented.

From observations and measurements made outside and inside at the TSMC as well in Downtown Seattle (i.e., Location # 7), the issue of message reception inside buildings, parking garages, downtown canyons, etc. is a significant one. Although in-building locations near windows are less likely to experience significant problems, interior locations are certainly much more prone to low RSL and the resulting low PCR, characteristics of lost messages. In-building attenuation is dependent on factors such as: building type, construction materials, size, number and placement of windows. In general there is no effective method to characterize building attenuation in general terms. This, together with recognizing that antenna orientation both with the MessageWatch and the RRM influenced the number of messages received, suggests that there are an indeterminate number of environmental situations that influence HSDS message-receipt effectiveness.

In conclusion, the results of the limited data collection/analysis effort accomplished during this *SWIFT Communications Study* suggest the following:

- SWIFT users were generally satisfied with the communications performance of the HSDS— reported coverage problems were concentrated in certain areas and overall performance of the system fit the coverage profiles distributed by Seiko
- The Seiko HSDS FM sub-carrier system works well in an urban environment where there are several commercial FM stations available and willing to install the HSDS equipment.
- Seiko has done a good job at predicting the signal level contours in the Seattle area, but in terrain intensive areas like Seattle, Denver and New York City could improve the prediction process by developing techniques that mitigate multi-path interference problems that will significantly improve message reception.
- Increased receiver sensitivity coupled with better antennas may improve in-building message reception.

5. SUMMARY AND CONCLUSIONS

Relative to the objectives of the Communication Study, the SWIFT FOT was a success. Analysis of user-reported problems with receiving messages indicated that the HSDS performed within predicted estimates provided by Seiko. That is, approximately 93% of all users reported that they experienced no problems receiving messages. In addition, field measurements of RSL, BER and PCR confirmed that the system performed within specifications, although the receipt of messages in some test locations appeared to be influenced by multi-path factors. In particular, the existence of multi-path degraded the receipt of messages and measured BER and PCR levels at two sites. Finally, in-building receipt of messages was impacted by the distance a receiving device was located inside a building. Nonetheless, in-building degradation of message-receipt is a normal performance characteristic of an HSDS and one in which the environmental factors (e.g., building structures, antenna design) contributing to this effect are not completely known.

In conclusion, this *SWIFT Communications Study* has documented the successful performance of an HSDS that was fielded in conjunction with a deployed ATIS in the Seattle, WA area. Message-receipt probability was excellent for the majority of SWIFT participants, and field measurements of RSL, BER and PCR indicated that information transmission was good, but the existence of multi-path at some locations suggested that significant future attention should be given to the analysis of multi-path interference mechanisms. This conclusion is supported by the data that was collected during the conduct of this evaluation.

6. REFERENCES

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APPENDIX A: INDIVIDUAL SITE TEST SETUP PROCEDURES

This appendix describes the specific procedures that were used to perform SWIFT Coverage Test activities at each of the eight (8) test sites. Ten (10) prospective test sites were initially selected after an analysis of SWIFT user problem reports and coverage contour analyses, but actual testing was only conducted at these sites after it was determined upon arrival in Seattle that these were the best places to collect data. In particular, the following sections summarize the activities at each of the SWIFT test sites visited during the week of July 28th through August 2nd and report any unique conditions or observations found while the testing was underway. For the record, the weather during the entire week of testing was sunny and cool.

The pre-arranged plan with Seiko Communications in Beaverton, OR was to transmit addressed pager messages containing an integer number to each of the eight (8) test devices, six (6) MessageWatches and two (2) portable computers with RRMs. Because the watch messages are repeated three times, the fastest transmission rate for unique watch messages was 5.8 minutes. Similarly, because the RRM messages are only transmitted once, the fastest transmission rate was approximately 15 seconds. These so called "test message" numbers were reset to one (1) at the beginning of each day, which ran from 6:00 AM to 9:00 PM from Monday 7/28/97 through Saturday 8/2/97.

Finally, the testing which was accomplished at each site also seemed to generate a substantial amount of public interest. In all, there must have been three (3) dozen people who asked questions about what type of experiment was going on. Most on them were knowledgeable about the SWIFT project. The greatest degree of interest was at the SeaTac airport due to security concerns about exactly what the test van was doing so close to the airport.

<u>*Site 1:*</u> *Roof top @ SAIC/TransCore Building, Bellevue, WA*

Please refer to the map illustration in Figure A-1 for detailed site location information. Setup and testing began at approximately 3:30 PM on Monday 7/28/97. The rooftop is located on the 2nd floor of the building and is accessible via a door located directly across from the rear elevator which is outside the SAIC/TransCore office door. There was adequate AC power available outside on the roof and the DC to AC inverter was not used for these tests.

The spectrum analyzer, TREQ monitor and calibrated Bi-conical dipole were deployed. A GARMIN 38 GPS receiver was used to establish a fix of the test location as well as distances and bearings were also recorded to each of the 7 HSDS stations. RRMs were not used during this test because this location does not have a history of SWIFT message reception problems and the transmission of unique test messages to these 2 devices could not be assured until the following morning.

Approximately 2½ hours of data were collected at location #1.

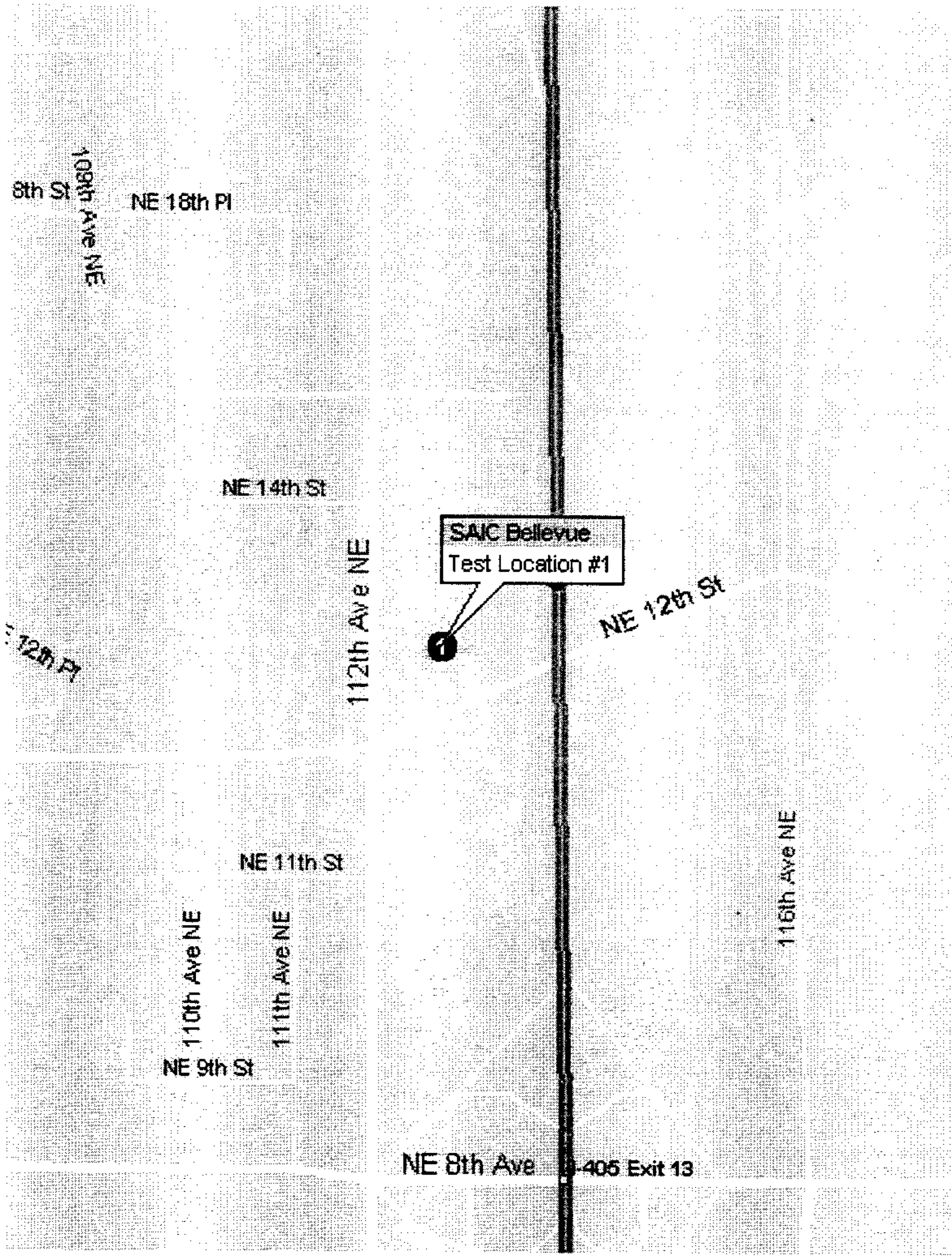

Figure A-1. Map of Bellevue Test Location #1.

Site 2: *On-Street @ ALKI Avenue & 64th Street, West Seattle, WA*

Please refer to the map illustration in Figure A-2 for detailed site location information. Testers were onsite at approximately 12:15 PM on Tuesday 7/29/97. This location is on a well traveled street due to its proximity to the beach. The on-street parking is unusual because of a bicycle lane nearest to the sidewalk which prevents parking close to the curb. Although the HP portable power supply is rated to power the spectrum analyzer, it was found that connecting the 500 watt inverter directly to the battery terminals with a set of heavy-duty jumper cables provided the best power configuration.

The terrain of West Seattle, which is actually a peninsula, is very hilly at its center. This fact seemed to cause significant reductions in the received signal strength from all but one of the Seattle stations, namely KCMS. Both RRMs were almost immediately and solidly locked onto this station at 105.3 MHz. The modified Seiko routine name RRMHost3 was used to collect and log message data on the two RRMs and even a forced "fast-scan" did not result in locking onto any other station. At this location there was little or no indication of multi-path signals.

Approximately 4¾ hours of data was collected at this location.

After testing was finished it was determined that an appropriate test location in downtown Seattle should be identified, one similar to that which the Hatfield & Dawson study had used. After riding around for some time, a location at Alaskan Way & Pike Street, across the street from Pier 59, looked most accessible. A cursory trial using the watches, indicated a potential problem area due to the fact that every watch seemed to be losing a significant number of messages. This short test lasted about 1½ hours. It was decided that full testing should be accomplished at this location later in the week. Since there was enough daylight left, the location where the Hatfield & Dawson had made measurements in NW Seattle was found. At a location diagonally across the street from 4226 Sixth Avenue NW a simple test using the watches was conducted. At this location the watches functioned normally and during the limited test period of approximately one hour there were no messages lost on any of the six devices.

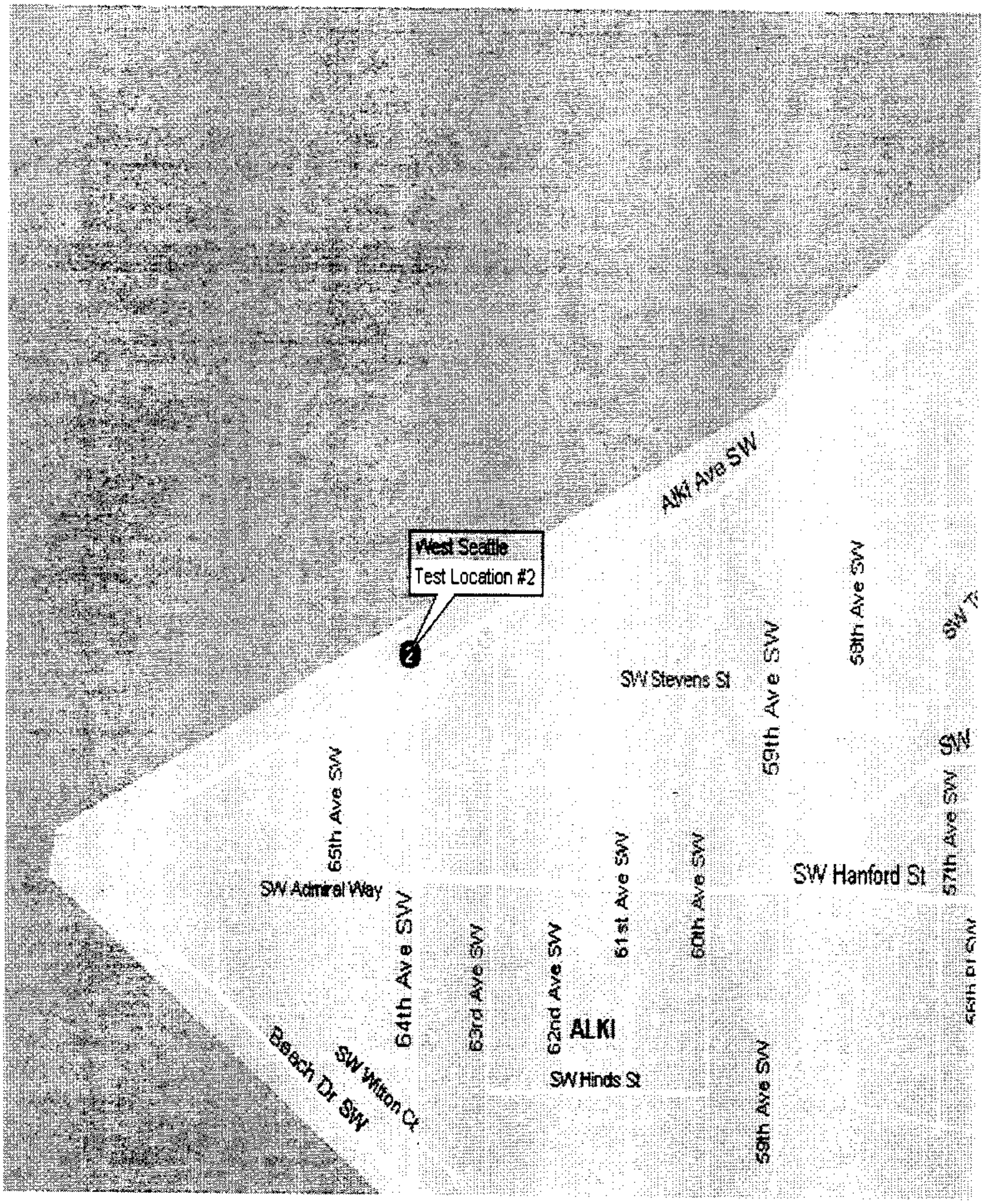

Figure A-2. Map of West Seattle Test Location #2.

Site 3: *Lot near main fire station @ Seattle-Tacoma Airport, SeaTac, WA*

Please refer to the map illustration in Figure A-3 for detailed site location information. Testers were onsite and setup for testing at approximately 10:00 AM on Wednesday 7/30/97. This test location was a gravel parking lot near the main SeaTac airport fire station on the NE side of the field. The terminal building was west of the site about a ¼ mile distant. This location was interesting because of the possibility of multi-path interference from two HSDS stations, KCMS (105.3) and KXXO (96.1). Both RRMs locked and held on KJR (95.7) for the duration of the test.

Several sets of measurements were made using the directional FM antenna to determine if improvements in the RSL, BER & PCR could be realized by pointing this antenna directly at the suspect station and also by using the directionality to see if a signal from another direction might prove equally useful. Additionally, measurements were taken using the Sansui TU-919 FM receiver and Tektronix 3640A oscilloscope to determine magnitude of the observed multi-path environment. The test & measurement process at this location lasted about 7 hours.

On the way back to Seattle, a survey of the area in Southeast Seattle was made. This area exhibited a substantial number of problem reports. A preliminary test, of about one (1) hour in duration, was made in the city park (Seward) located on the Bailey Peninsula on Lake Washington. Using the six watches, there was no indication that this was a problem area and another potential site on Rainier Avenue was judged to be a better location.

Site 4: Parking Lot @ West Marine Drive, Everett, WA

Please refer to the map illustration in Figure A-4 for detailed site location information. Testers were onsite at approximately 10:30 AM on Thursday 7/31/97. This site is located on the northern tip of the point that forms Everett. The terrain to the south is somewhat hilly and the location is not an exceptionally strong one for good message reception. Not long after arriving, it was noticed that all six watches began losing messages and at about 11:00 AM no new messages were being received.

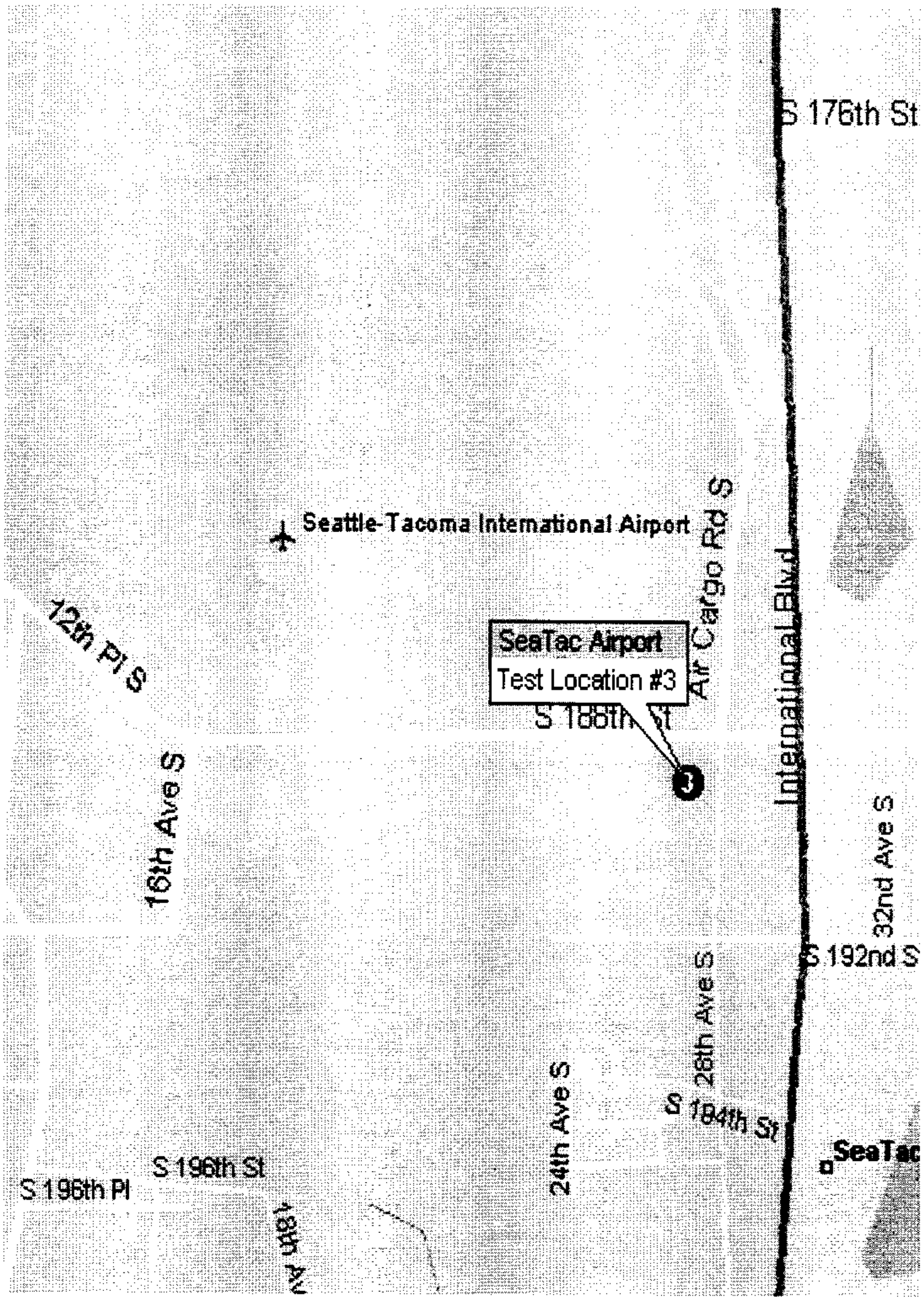

Figure A-3. Map of SeaTac Airport Test Location #3.

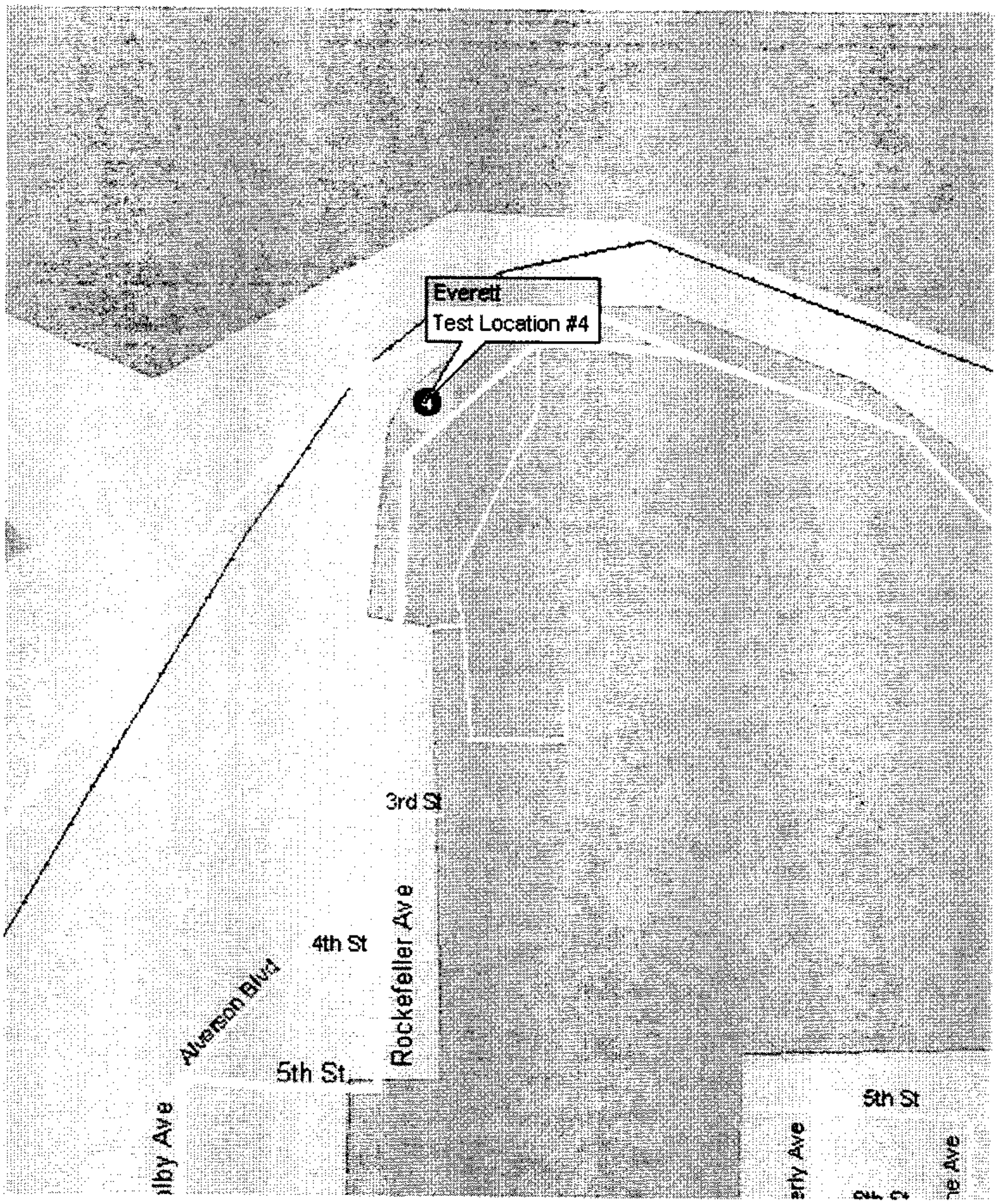

Figure A-4. Map of Everett Test Location #4.

A call was placed to Seiko to determine if their system was down. The operations manager could not provide this information, so a subsequent call/voice-mail to Seiko alerted them to these symptoms but they reported that the HSDS was performing satisfactorily. It wasn't until about 2:00 PM that test messages were seen again, but three of the watches began receiving messages about ½ an hour before the remaining three. This is peculiar since all the test messages are transmitted specifically to these six watches and each repeated three times.

At this location there was a strong indication of multi-path from KING (98.1). Additional testing with the directional antenna was performed. The RRMs locked and held on KING (98.1) for the duration of the testing. About 5 hours of on-site testing was accomplished at this location.

<u>Site 5</u>: *In Parking Lot @ S. Rainier Avenue & Bayview Street, South Seattle, WA*

Please refer to the map illustration in Figure A-5 for detailed site location information. Testers arrived onsite at approximately 6:15 PM on Thursday 7/31/97. This location was judged to be among the quietest sites in this busy section of SE Seattle. Although that location did not appear to exhibit any multi-path characteristics, the RRMs seemed to be having problems with a solid lock. After approximately an hour of remaining locked onto KING (98.1) RRM system #1 switched lock to KJR (95.7) and remained there for the duration. of the testing. The test duration at this location lasted approximately 2 hours.

<u>Site 6</u>: *Parking Lot @ Dayton Avenue & 160th Street NW, Richmond, WA*

Please refer to the map illustration in Figure A-6 for detailed site location information. Testers were onsite at approximately 8:35 AM on Friday 8/1/97. This location was in the parking lot of the WSDOT TSMC and less than 2 miles from KCMS (105.3). Both RRMs initially locked onto KJR (95.7) began skipping around between KCMS (105.7) and KJR (95.7). By introducing 20 dB of signal attenuation into the RRM2 receiver, lock on KCMS (105.3) was almost instantly obtained. Similarly, 10 dB was added to the RRM1 receiver and lock on KCMS (105.3) was also obtained, but only after a longer period of scanning. This results indicates that very strong signals may overload the receivers front-end and actually cause it to continue scanning even in the presence of a high RSL. Approximately 5 hours of testing was accomplished at this location.

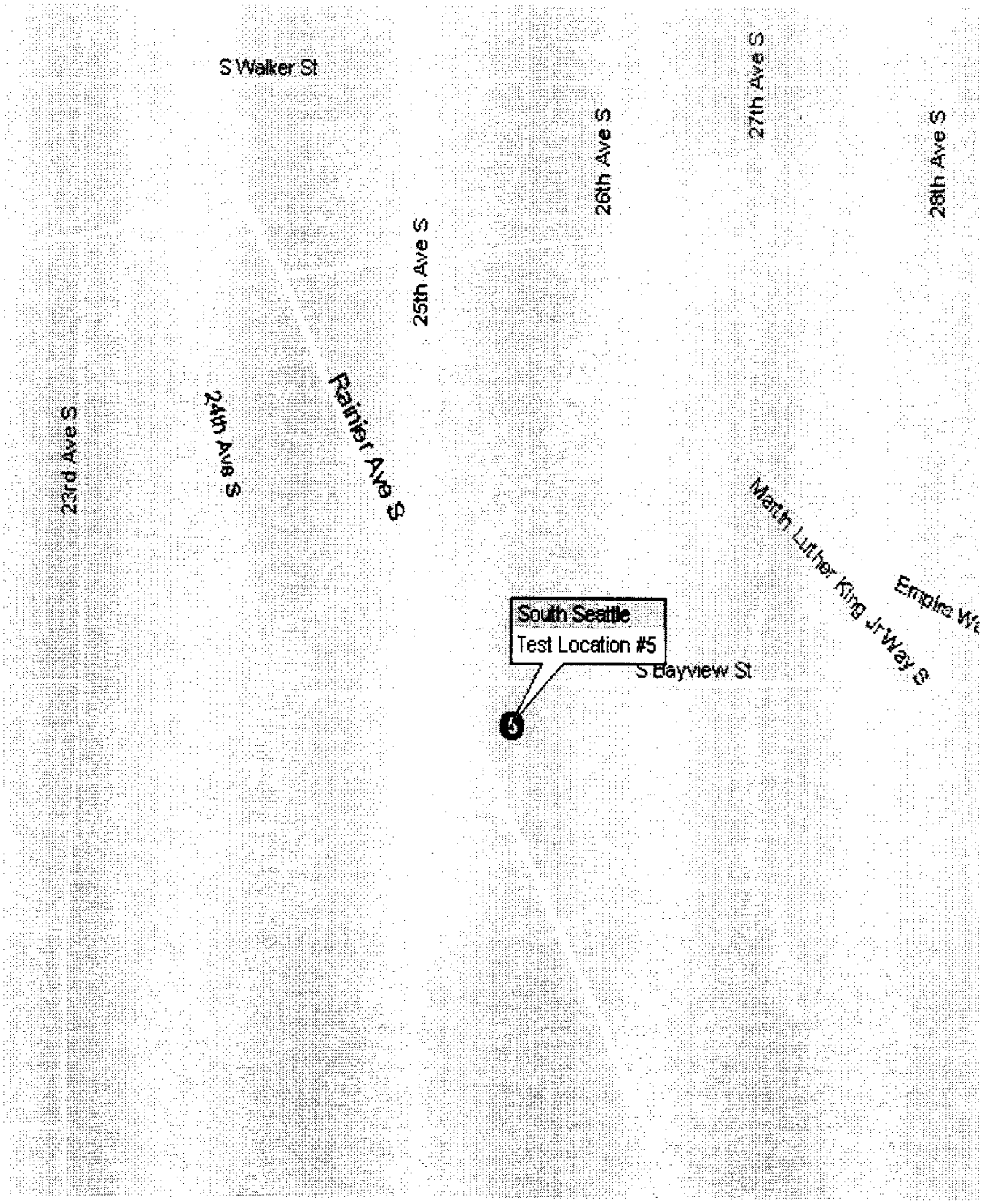

Figure A-5. Map of South Seattle Test Location #5.

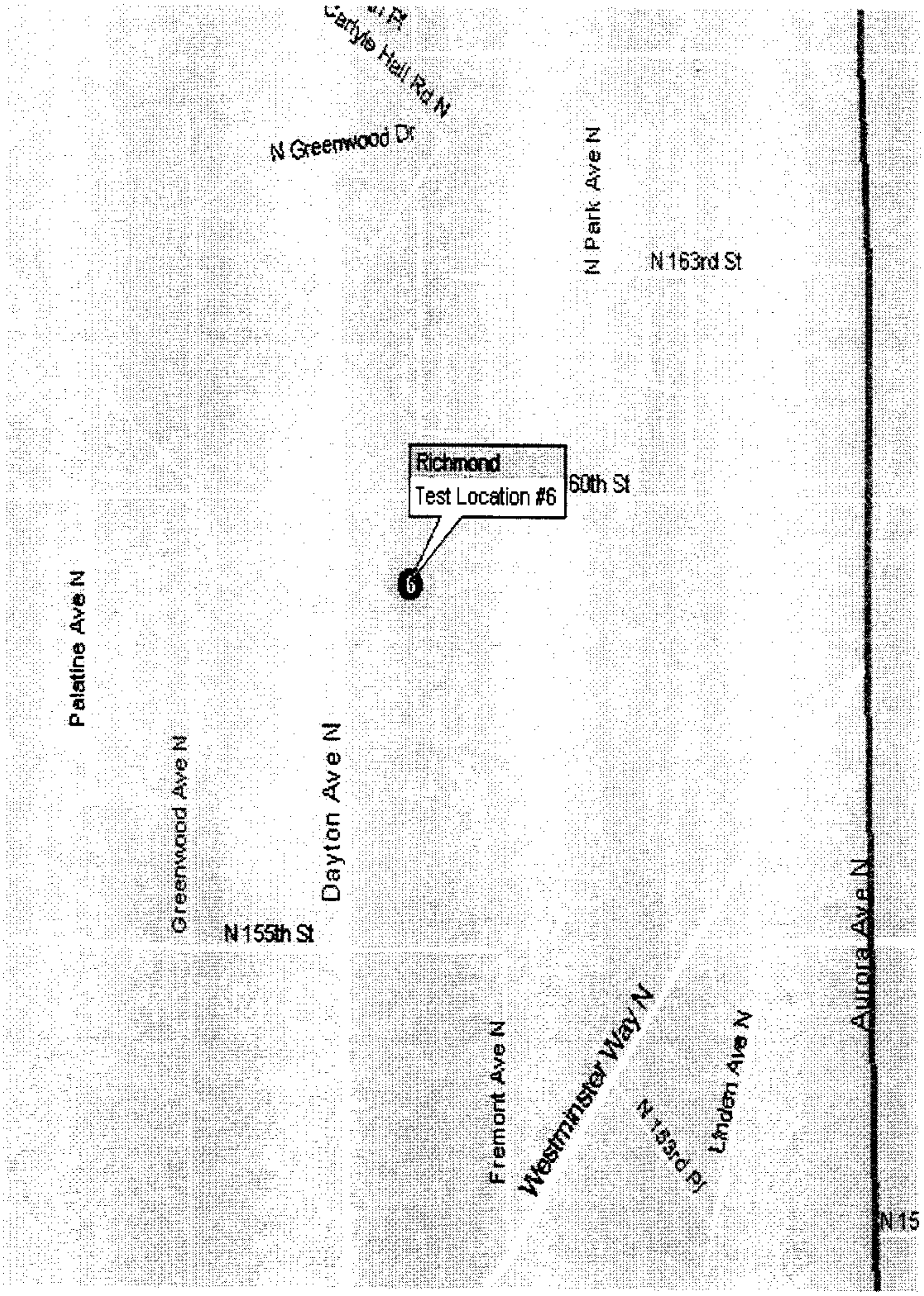

Figure A-6. Map of the Shoreline Test Location #6.

Site 6A: *In Building @ Dayton Avenue & 160th Street NW, Shoreline, WA*

Figure 2-9 shows a drawing of the floorplan of the 2nd floor of the TSMC facility which is located on a hill North of Seattle. This location was first of four conducted inside the TSMC at varying distances from the North end of the building and generally in a line of constant bearing (338°) to KCMS (105.3). This location was approximately 20 feet inside an exterior window/wall at the North end of the building. During these in-building tests, all of the other station frequencies were monitored without success.

Site 6B: *In Building @ Dayton Avenue & 160th Street NW, Shoreline, WA*

This second test site was located in an interior corridor approximately 60 feet inside the North exterior window/wall.

Site 6C: *In Building @ Dayton Avenue & 160th Street NW, Shoreline, WA*

This location was third of four conducted inside the and was approximately 100 feet inside the North exterior window/wall, near the elevator and kitchen

.*Site 6D*: *In Building @ Dayton Avenue & 160th Street NW, Shoreline, WA*

This location was last of four conducted inside the and was approximately 130 feet inside the North exterior window/wall.

The duration of these in-building tests at the TSMC lasted approximately 2 hours.

Site 7: *In Parking Lot @ Alaskan Way & Pike Street, Downtown Seattle, WA*

Please refer to the map illustration in Figure A-7 for detailed site location information. This location had been identified earlier in the week and arrival was about 5:30 PM on Friday 8/1/97. This location is notable due to the proximity to both Puget Sound and the elevated highway called State Route 99. To the East, there are many tall buildings and this location is also on the water at the foot of many of the hills on the city of Seattle is built. RRM1 whose antenna was oriented N/S obtained almost immediate lock on KCMS (105.3). RRM2 whose antenna orientation was E/W also appeared to obtain lock on KCMS (105.3) but continued to scan. After about two full hours of testing, RRM1 maintained lock but RRM2 would never really lock onto any other station, including KCMS (105.3). The duration of this test totaled approximately 2½ hours.

Site 8: *Parking Lot @ 9th Avenue & 4th Street, Puyallup, WA*

Please refer to the map illustration in Figure A-8 for detailed site location information. Testers arrived onsite about 11:15 AM on Saturday 8/2/97. This location was in a vacant parking lot near the county fairgrounds. This area was located in a valley with hills on the East and West. RRM1 was oriented N/S and RRM2 oriented E/W as usual. RRM1 had trouble locking onto any station, but RRM2 acquired lock on KING (98.1) very quickly. When RRM1 was re-oriented to an E/W configuration, lock was almost immediately obtained. It was thought to be interesting that RRM1 oriented in the N/S direction was always in the "fast scan" mode, but this process of scanning did not include all of the HSDS station in the Seattle area. The following is a list of those frequencies scanned. It was recorded by observing many repetitions of the fast scan cycle. The HSDS frequencies have been noted in Figure A-9, as well as the fact that lock was never acquired. It is reasonable to surmise that in locations where RSL is low, antenna orientation and/or antenna sensitivity plays an important role in the successful reception of messages.

Data collection was concluded after about 3 hours of testing.

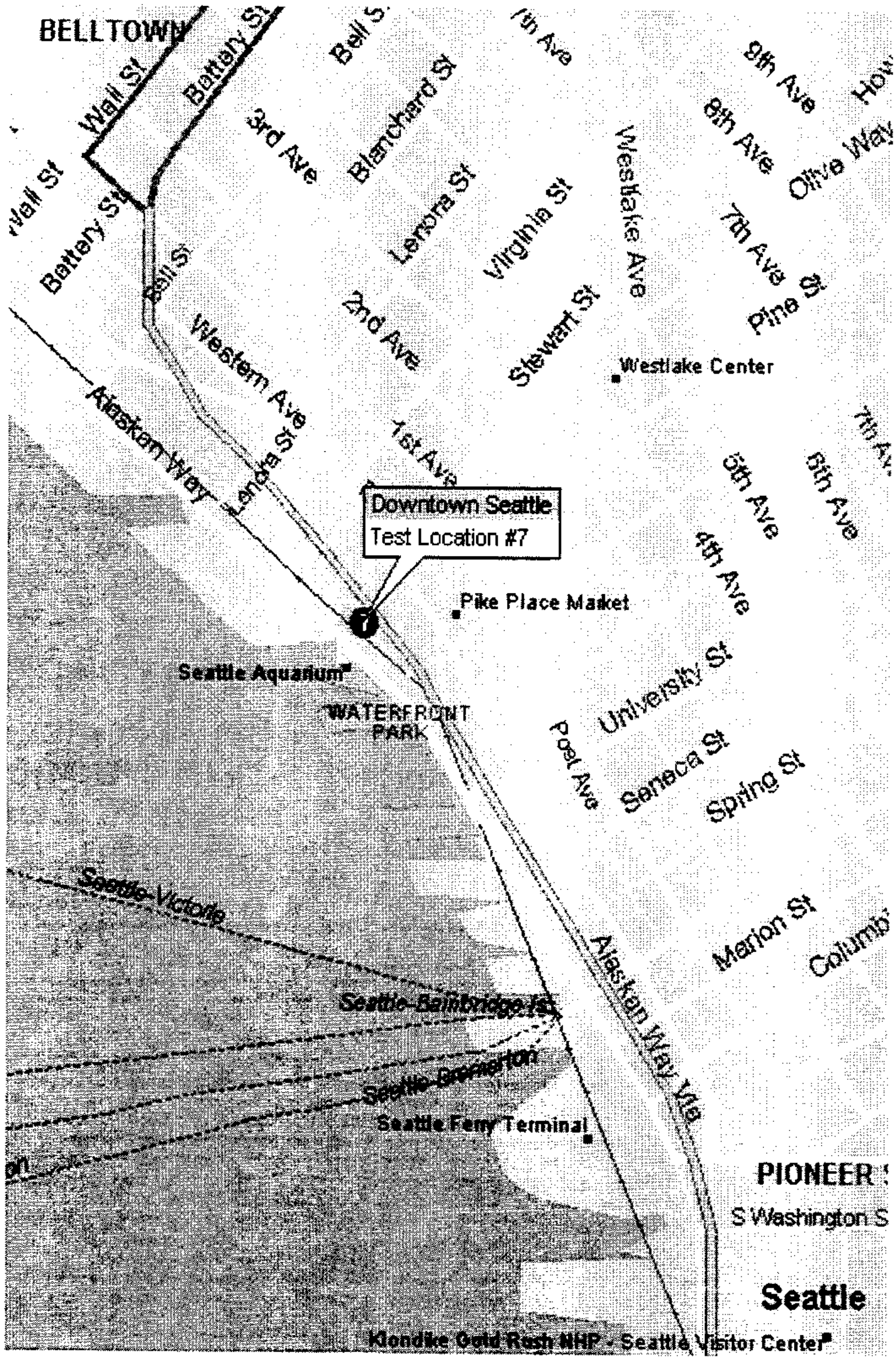

Figure A-7. Map of Downtown Seattle Test Location #7.

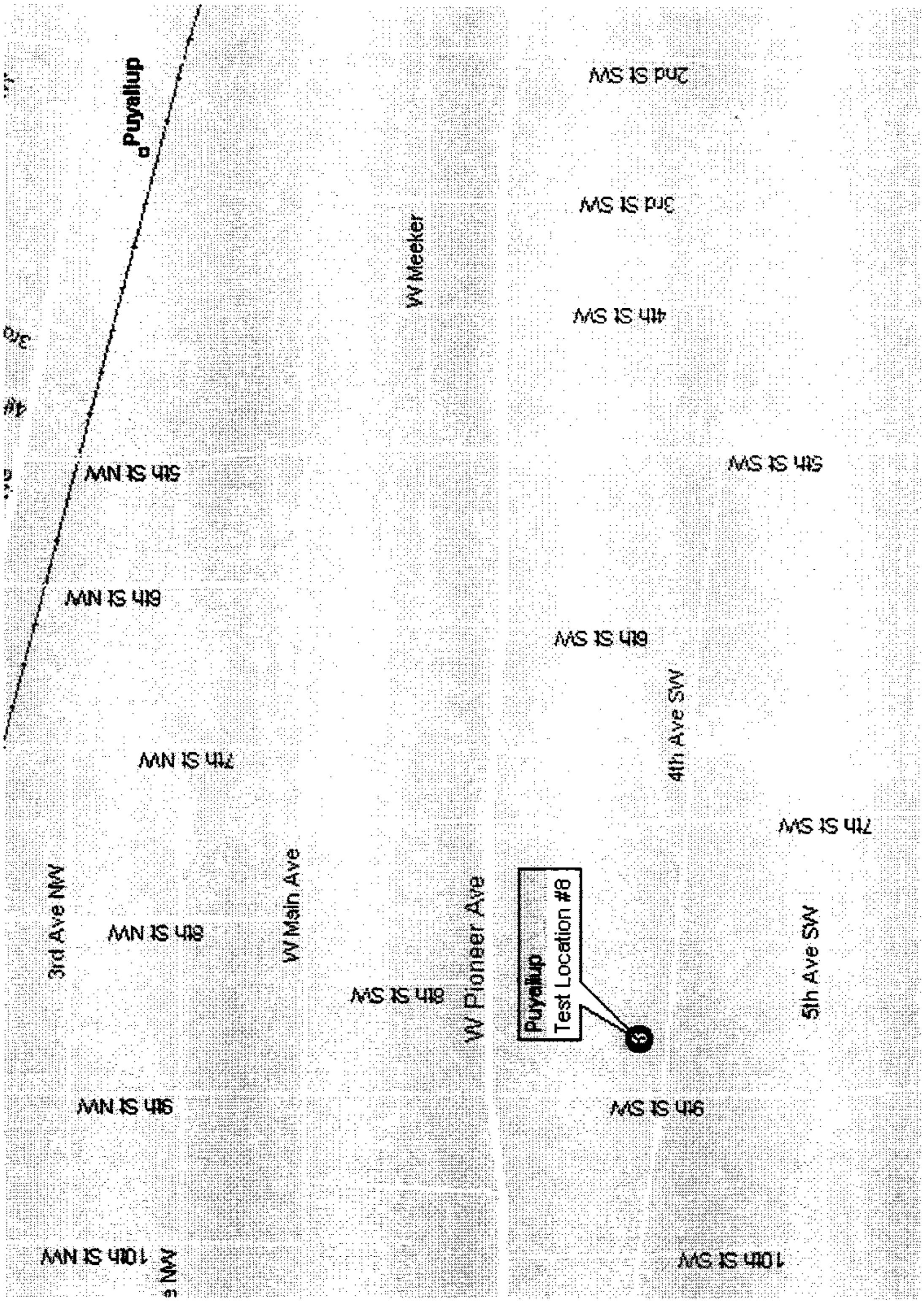

Figure A-8. Map of Puyallup Test Location #8.