Real-Time Spatial Monitoring of Vehicle Vibration Data as a Model for TeleGeoMonitoring Systems

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(ABSTRACT)

This research presents the development and proof of concept of a TeleGeoMonitoring (TGM) system for spatially monitoring and analyzing, in real-time, data derived from vehicle-mounted sensors. In response to the concern for vibration related injuries experienced by equipment operators in surface mining and construction operations, the prototype TGM system focuses on spatially monitoring vehicle vibration in real-time. The TGM vibration system consists of 3 components: (1) Data Acquisition Component, (2) Data Transfer Component, and (3) Data Analysis Component. A GPS receiver, laptop PC, data acquisition hardware, triaxial accelerometer, and client software make up the Data Acquisition Component. The Data Transfer Component consists of a wireless data network and a data server. The Data Analysis Component provides tools to the end user for spatially monitoring and analyzing vehicle vibration data in real-time via the web or GIS workstations. Functionality of the prototype TGM system was successfully demonstrated in both lab and field tests. The TGM vibration system presented in this research demonstrates the potential for TGM systems as a tool for research and management projects, which aim to spatially monitor and analyze data derived from mobile sensors in real-time.

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Table of Contents

Acronyms

CDMA - Code-Division Multiple Access
DGPS - Differential Global Positioning System
FTP - File Transfer Protocol
GIS - Geographic Information System
GPRS - General Packet Radio Service
GPS - Global Positioning System
GSM - Global System for Mobile communications; Groupe Spécial Mobile (Original)
GUI - Graphical User Interface
JAJ - Jarring and Jolting
MANET - Mobile Ad hoc Network
MSHA - Mine Safety and Health Administration
NIOSH - National Institute for Occupational Safety and Health
NMEA - National Marine Electronics Association
PCMCIA - Personal Computer Memory Card International Association
RTK - GPS - Real Time Kinematic Global Positioning System
SMS - Short Message Service
TCP/IP - Transmission Control Protocol/Internet Protocol
TGM - TeleGeoMonitoring
TGP - TeleGeoProcessing
WBV - Whole Body Vibration
XML - Extensible Markup Language

List of Figures

List of Tables

1. Introduction

1.1. Background and Motivation

The initial goal of this research was to address the concern of vibration related injuries experienced by equipment operators in construction and surface mining operations by developing a TeleGeoMonitoring (TGM) system to spatially monitor vehicle vibration data in real-time. As development of the TGM system progressed, the goals of the research expanded. In addition to the focus on equipment vibration, the goals of this research evolved to include the development and demonstration of the TGM vibration system as a prototype model for a TGM system used to monitor and analyze any type of vehicle-mounted or mobile sensors in real-time. For example, the TGM system presented in this research could be used to spatially monitor and analyze tire pressure, dust, noise, speed, etc., or any combination thereof by adding the proper sensors and modifying the client software. The remainder of this subchapter discusses motivations concerning vibration related injuries (whole body vibration and jarring and jolting) as well as the potential for highly customizable TGM systems for real-time spatial monitoring, management, and analysis of sensor-based data.

Whole body vibration (WBV) and jarring and jolting (JAJ) are significant sources of injury for mobile equipment operators in surface and underground mining operations (Biggs and Miller 2000; Cross and Walters 1994; Wiehagen et al. 2001). Literature relevant to this thesis discusses the effects of vibration from several different points of view. Retrospective statistical studies identify JAJ and WBV as major sources of operator injury and express the need to remedy this problem (Cross and Walters 1994;

Wiehagen et al. 2001). Studies from biological mechanics disciplines have used human body models to study the effects of WBV and JAJ (Huang and Huston 2001). Others have introduced and tested engineering mechanisms to reduce the adverse effects of vibration on equipment operators (Mayton et al. 1997; Mayton et al. 1998). Vibration studies at surface mines also find motivation from an economic standpoint. Thomson, Visser, et al. demonstrate the potential savings in operating and maintenance costs, which can be achieved by using a real-time management system that relies on road vibration signature analysis (Thompson et al. 2003).

Regardless of the approach to vibration studies, research indicates that vibration related injuries are a significant risk for mobile equipment operators. As long as a risk exists, there is room for improvement in the systems and mechanisms available to reduce operator injury resulting from vibration.

GIS technology is used widely in other industries, but is under-utilized in the mining industry (Dillon and Blackwell 2003). Advances in mobile computing, GIS, and wireless networks have made real-time GIS a feasible, if not, logical solution for systems which aim to monitor, manage, analyze, and display spatial information in real-time. Development of customized TGM systems could allow for highly specified real-time spatial analysis for research applications, and could lead to customized overall mine management systems. Customized TGM systems reduce reliance on proprietary systems and can provide tailored solutions using readily available software and hardware. At this time, there has been no development of a customizable real-time GIS for monitoring, analyzing, and displaying vehicle mounted sensors in surface mines.

A system used to monitor and display vehicle-mounted accelerometer data in real-time was developed and tested for this research to demonstrate the use of real-time GIS as a tool for further study and reduction of vibration related injuries. The system serves as a prototype model for real-time monitoring, analyzing, and displaying of any data derived from mobile sensors. Additional sensors can be added to incorporate all data, which can be associated with a geographic location (i.e. dust, noise, tire pressure, etc.).

1.2. GIS Overview

The history of Geographic Information Systems (GIS) dates back to the mid 1960s when the Canadian government developed the Canada Geographic Information System to explore Canada's land resources and uses (Longley et al. 2001). Longley and Goodchild et al. note that in 2000 there were over one million core GIS users and possibly five million casual users. Definitions of a GIS vary among users and disciplines. GIS, under this research, is defined as a computer or group of networked computers used to store, analyze, and display data associated with spatial coordinates. Real-time GIS will refer to a GIS, which is automatically updated via external hardware or networked computers. In this research, the external hardware and networked computers are mobile. The term *real-time-GIS* is often used in conjunction with the terms *TeleGeoProcessing* (TGP) and *TeleGeoMonitoring* (TGM). As outlined by Laurini, Servigne, et al. (2001) TGP can be taken as the integration of GIS and telecommunication systems. TGM extends TGP with the addition of a positioning system such as GPS.

Table 1.1 summarizes characteristics of TGM, TGP, and GIS systems. This nomenclature referring to the union of GIS and telecommunications is used throughout this thesis and the system described herein can be considered as a TGM system used to monitor vehicle derived vibration data.

Table 1.1 Layers of organization between TeleGeoProcessing and TeleGeoMonitoring (Laurini et al. 2001)

3. TeleGeoMonitoring
Decision Support System & RTDSS
Real Time Database
Real Time Acquisition Process
Real Time Transmission Process
Real Time Visualization/Mapping
2. TeleGeoProcessing
Telecommunications
Federated databases
System engineering
1. GIS
Information system
Spatial databases
Mapping

Regarding the term *real-time*, it should be noted that with systems sending data via wireless networks there should be a measurable lag between transmittal and receive time. This should be particularly true with systems, which require significant data processing prior to transmittal. In this paper the term *real-time* will refer to transactions taking up to several seconds. The term *near real-time* will be used to describe systems taking several minutes for data transfer.

1.3. GPS Overview

The Global Positioning System is a navigation system based on satellite radio signals, which can provide a four-dimensional navigation solution (X, Y, Z, & Time).

Development of GPS began in 1972 with the creation of NAVSTAR and GPS Joint Program Office (JPO), which included U.S. Navy, Army, and Air Force personnel (Kintner 1999). After years of development and testing it was announced that the system was officially operational in 1995. In 1996 GPS became available, internationally, for civilian use.

The following description of the GPS is a summary of Kintner's (1999) work. 24 operational satellites make up the Space Segment of the GPS (Figure 1.1). The Control Segment is responsible for controlling satellite orbits and operations. Receivers make up the User Segment, which calculates the navigation solution. Relationships between the three segments are shown in Figure 1.2.

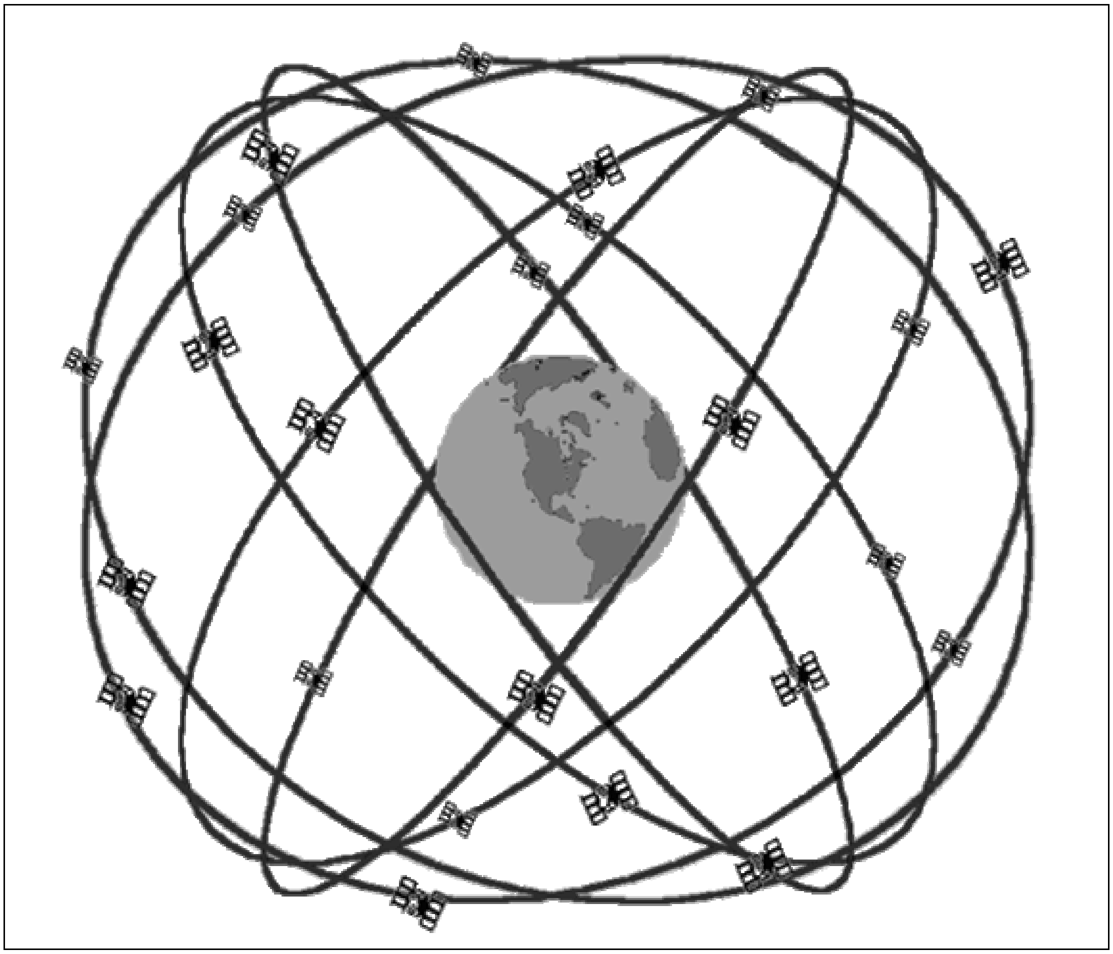

Figure 1.1 Space segment of Global Positioning System - 24 satellites in 6 orbital planes, 4 satellites in each plane (Dana 1998)

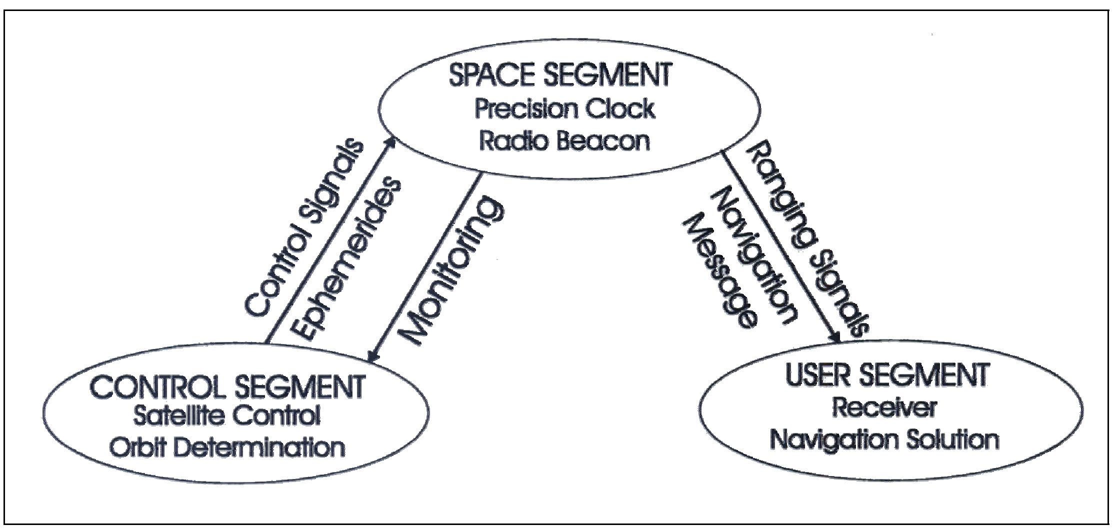

Figure 1.2 The three segments of GPS and their interrelationships (Kintner 1999)

An in-depth technical description of the GPS is beyond the scope of this paper, but a note regarding the accuracy of the navigation solution is included as it relates to the future of this research project. Each GPS satellite transmits information on two frequencies called L1 and L2, which are modulated with pseudorandom noise (PRN) codes unique to each satellite. One of the PRN codes called the Coarse Acquisition (C/A) code modulates only the L1 frequency, where as the PRN code called the Precise (P) code modulates both the L1 and L2 frequencies. However, the P code is encrypted by the Department of Defense (DoD) so that civilian users may not use it. This translates into a navigation solution with a positional error of around 10 meters for civilian users as opposed to 0.5 centimeters if the P code were used on both L1 and L2.

The goal of this research is to prove the concept of using a TGM system to monitor vehicle data derived from mobile sensors. High GPS accuracy is unnecessary at this point in the research. However, for the future extensions of this research accurate GPS location data may be crucial. To significantly increase the navigation solution accuracy Differential GPS (DGPS) or Real-Time Kinematic GPS (RTK-GPS) can be used. Both systems rely on a stationary receiver of known location, which broadcasts timing corrections to mobile receivers. Sub-meter accuracy can be achieved with DGPS and centimeter accuracy can be achieved with RTK-GPS. Refer to Chapter 5 for GPS related recommendations for the future of the TGM system.

1.4. Wireless Network Overview

The origin of wireless computer networking can be traced back to 1968, when development of the ALOHANET began at the University of Hawaii (Abramson 1985).

Abramson's ALOHA system was developed to share computer information between the university's main campus and satellite campuses located on other islands using radio communications. After ALOHANET, wireless technology continued to improve for both voice and data communication. Currently, there are a significant number of wireless standards. However, the TGM system in this research was tested on only 3 wireless network types. Two specifications of the 802.11 standard were used in the lab setting and a Code-Division Multiple Access (CDMA) network was used in the field tests of the TGM system.

802.11, developed by a member group of the Institute of Electrical and Electronics Engineers (IEEE), refers to a group of specifications for wireless local area networks (IEEE 2005). The two specifications used by the TGM system described in this thesis are 802.11b and 802.11g. Both 802.11b and 802.11g operate in the 2.4 MHz band and can operate at speeds of up to 11 and 54 Mbps, respectively (Gast 2002). Hardware (cards, routers, repeaters) to setup an 802.11 network are readily available and easy to setup.

CDMA is a digital communication technique with U.S. military roots dating back to the 1940s (CDG 2005). It was not until the early 1990s that CDMA cellular techniques were used for civilian communication. Currently, the majority of CDMA use is for voice communication, however, CDMA as a means of data transfer is increasing. Several major communications companies in the U.S. and abroad offer access to CDMA networks via commonly available cell phones, modems, and computer devices.

1.5. Research Objectives and Approach

The goal of this research is to demonstrate the use of GIS, GPS, and wireless networks to monitor, analyze, and display data from vehicle mounted sensors in real-time. The prototype system developed for this research focuses on monitoring vibration experienced by vehicle operators. In addition to developing a tool for study of vehicle vibration as it relates to operator safety, this research aims to demonstrate the potential of TGM systems as customizable tools for a variety of surface mine applications not necessarily related to vibration.

The prototype system was divided into three components: (1) Data Acquisition Component, (2) Data Transfer Component, and (3) Data Analysis Component. After development of the system, it was tested both in a lab setting and in a mobile environment. The goal of testing the system was to verify that GPS and vibration data were successfully acquired by the mobile client, sent to the server, and properly displayed via a web interface. Although network lag from the client to the server was either unnoticeable or reasonably small it should be noted that data transfer time was not considered as a parameter for testing the system. It should also be noted that the signal to noise ratio for the vibration data acquired from the accelerometer needs improvement if the TGM system is to be used outside the testing environment. Again, this research aimed to develop a TGM system for spatially monitoring vibration data derived from a vehicle-mounted accelerometer, and to verify the system's functionality. Suggestions regarding the signal to noise ratio and other recommendations for future work are included in Chapter 5.

2. Literature Review

Literatures discussed in this chapter reflect a wide range of disciplines and most do not explicitly discuss real-time vibration monitoring and surface mining equipment. However, there are many similarities between the systems discussed in the included literature and the prototype system presented in this thesis. The research discussed in Chapter 2.1 involves systems, which monitor, track, or analyze spatial data from either static or dynamic sources in real-time. Chapter 2.2 discusses proprietary systems relevant to this research. Research related to vibration is included in Chapter 2.3.

2.1. Real-Time TGM Systems

2.1.1. Emergency Response and Management Systems

Integrating GIS, GPS, and GSM (a specification for cellular communication used worldwide) technologies Derekenaris, Garofalkis, et al. (2001) discuss a comprehensive ambulance management system, which was proposed as a solution to the emergency and ambulance management problem in the prefecture of Attica in Greece. The system was designed to replace ambulance routing and districting based on paper maps and personal experience. The design allows for GPS derived ambulance location, sensor data, and voice messages to be sent via the GSM network to a communication server. Data concerning previous incidents, hospital capabilities, available equipment and expertise for each ambulance, and regularly updated traffic information would be available to the GIS in a database server to allow for criteria based decisions. Ultimately, the ambulance management system will track and display ambulance locations, assign ambulances to certain areas, find incident locations based on addresses given during an emergency calls, assign the appropriate vehicle to handle the incident, route the ambulance to the incident and to the best suited hospital, and log incident statistics to the database server. A diagram of the system described by Derekenaris, Garofalakis, et al. is shown in Figure 2.1.

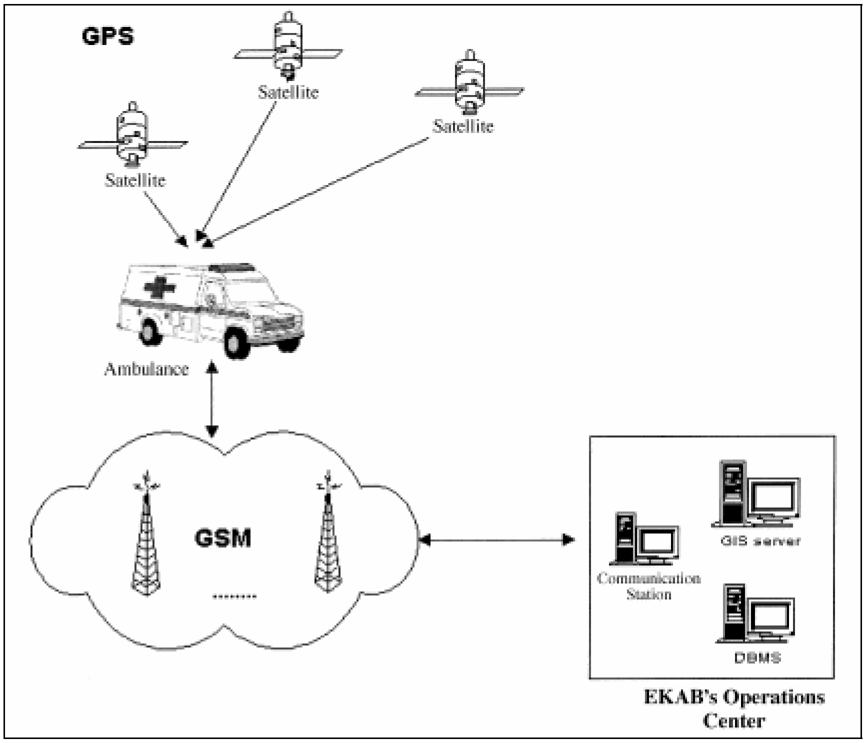

Figure 2.1 Overall integrated ambulance management system (Derekenaris et al. 2001) (Copyright Elsevier 2001)

A system similar to that of Derekenaris et al. was proposed for the Atlanta Police Department in Georgia to reduce emergency response time (Tsai et al. 2002). The research identified three areas for improvement in order to decrease response time: (1) reliable locations of vehicles, hospitals, fire stations, and incidents, (2) integration and collaboration of related agencies, and (3) fast and reliable distance and route calculation. The framework of the proposed system, which includes GPS equipped vehicles, an unspecified means of telecommunication, and a GIS, is shown in Figure 2.2.

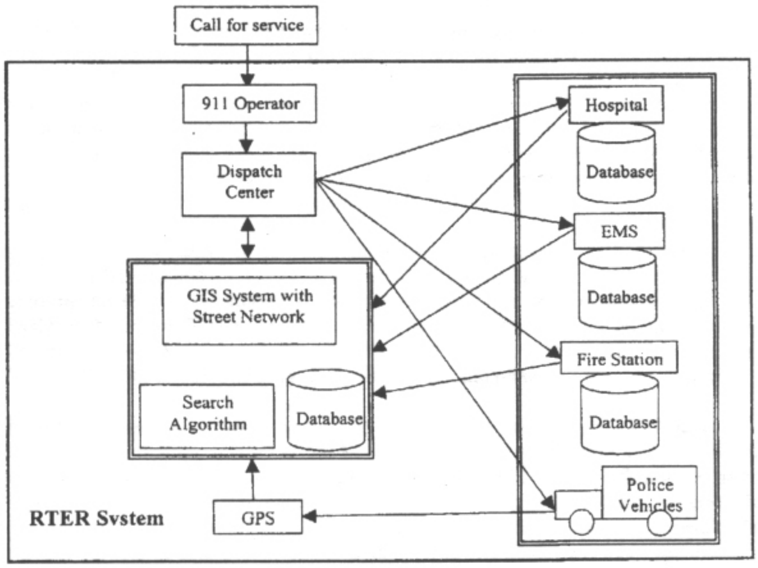

Figure 2.2 Framework of Real-time Emergency Response (RTER) System (Tsai et al. 2002) (Copyright ICTTS 2002)

The prototype system developed by Tsai, Wang, et al. using Microsoft's Access and Visual Basic 6.0 and ESRI's MapObjects and NetEngine, was tested in a simulation setting. Upon receipt of an emergency call the system would locate the incident and, using simulated moving vehicles, calculate point-to-point and shortest network distances to the incident from each simulated vehicle. The authors envision the system as a real-time police dispatching and tracking system capable of reducing response time.

2.1.2. Tracking, Mapping, Monitoring, and Map Delivery Systems

Relating to the vibration component of the TGM system in this research, Rouillard (2002) describes a system to monitor, across a network, shocks and vibrations experienced by transport vehicles. Rouillard discusses means of signal analysis and compression to allow for small packets of data, which accurately describe shocks, vibrations, and associated locations, but can easily be transmitted over a network at regular intervals or as requested. Once the data are received and stored by the host computer they can be retrieved by the end user for post-processing as shown in Figure 2.3.

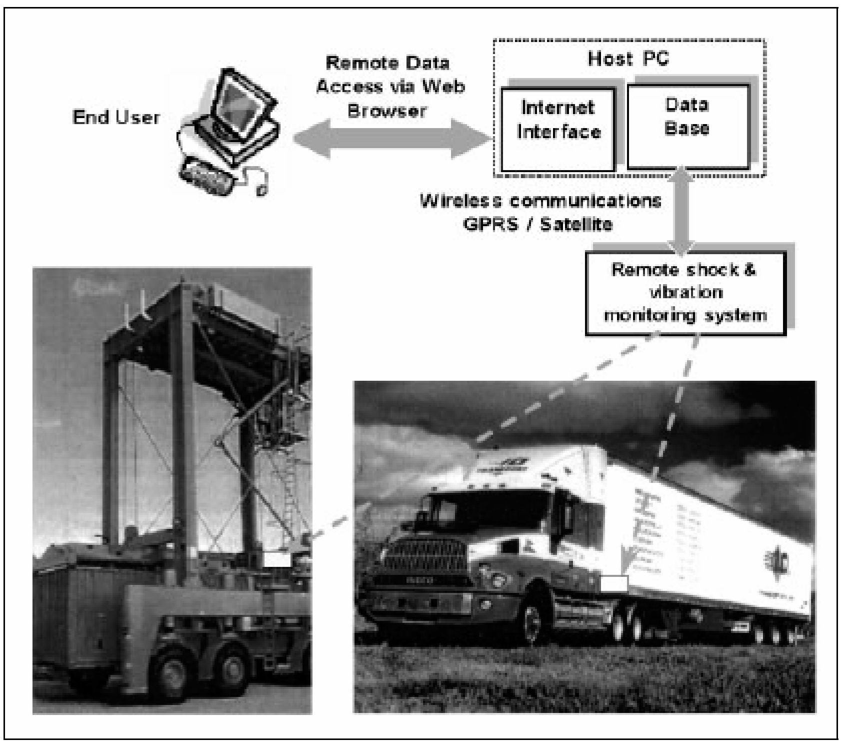

Figure 2.3 Principle of remote monitoring (Rouillard 2002) (Copyright John Wiley & Sons 2002)

Although Rouillard seems interested in providing raw data to the end user his system could be modified to incorporate a real-time GIS. Rouillard's discussion and application of compression of the vibration signals without loss of meaningful information is of particular interest to the future of this research where accurate, but small packets of vibration information are crucial.

The "G^3" surveillance system was proposed by Lin et al. (2003) to track vehicles and low flying aircraft on a digital map in real-time. The G^3 system makes use of GPS, GIS, and General Packet Radio Service (GPRS), which is a wireless data communication technique based on GSM technology. The client part of the system relies on custom hardware and software to receive GPS messages and to relay them to the server via a GPRS network. Testing of the G^3 system included verification of transmitted data for different transmission periods (3 to 120 seconds) and transfer time tests (average: 750 milliseconds).

In an effort to reduce haul truck run-over accidents and dumpsite-edge or ramp related roll-overs Nieto and Dagdelen (2003) developed and tested "VirtualMine". VirtualMine is a server independent system based on GPS, wireless networks, and virtual boundaries defined by vehicle positions and edges. Running on an in-cab tablet PC VirtualMine provides a three dimensional GUI based on the Virtual Reality Modeling Language (VRML). The vehicle operator can monitor his or her position in real-time in relation to other vehicles equipped with VirtualMine. Nieto and Dagdelen envision an automatic warning system based on the overlapping of vehicle "safety spheres", which describe a user defined boundary around a vehicle. In addition to proximity warning, VirtualMine aims to allow for on-demand contour modeling by making use of logged vehicle positions. VirtualMine was tested in a survey field and an operational surface mine with regards to GPS accuracy, proximity, and precision.

Although map delivery and personal tracking systems may have different motivations and application goals when compared to the TGM system presented in this paper, they both rely on similar technology and processes. Casademont, Lopez-Aguilera, et al. (2004) present a system by which sections of maps can be wirelessly downloaded on a contingency basis to Personal Digital Assistants (PDA). Using PDAs equipped with GPS receivers users can track their location in real-time. This client-server system was tested successfully using several different wireless protocols. Of particular interest to the future of the prototype system in this paper is the way Casademont, Lopez-Aguilera, et al. handle differential GPS corrections. If a more accurate GPS-derived location is required a user can send a request via Short Message Service (SMS) to the server and receive an SMS message with the appropriate GPS correction.

A system proposed by Karimi and Krishnamirthy (2001) focusing on the use of GIS and GPS for real-time routing in Mobile Ad hoc Networks (MANET) is included here for its suggested use of a real-time GIS and MANETs. A MANET is a dynamically self-organizing wireless network, which lacks fixed infrastructure and is comprised of mobile nodes (Conti 2003; Toh 2002). The network will repair itself when nodes move out of range or fail and can therefore be considered as self-healing. Karimi and Krishnamirthy outline the potential use of a GIS as part of a packet routing strategy, which considers node location, direction of movement, terrain and other factors. Integration of a GIS with a MANET can be described as a hybrid MANET because it relies on some fixed infrastructure (i.e. GIS workstation and server). Using stored terrain data and dynamic node data it may be possible to use real-time GIS to predict new locations of mobile nodes in the hybrid MANET (Figure 2.4).

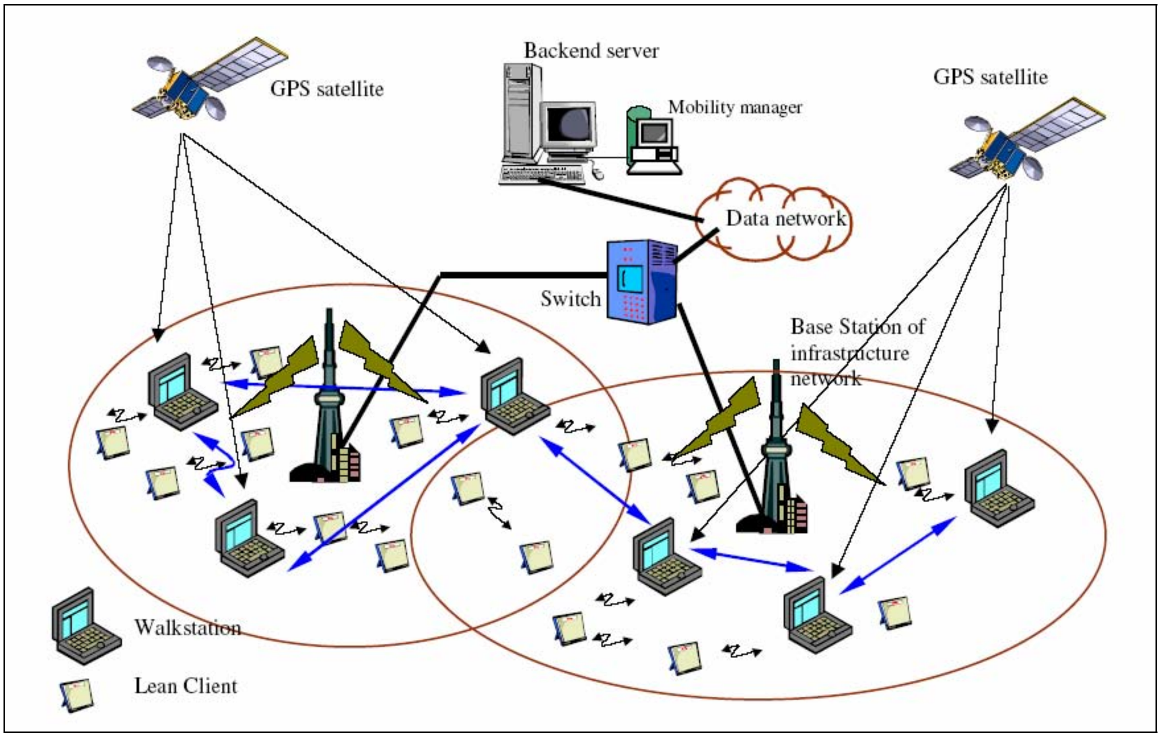

Figure 2.4 A hybrid ad hoc-infrastructure based topology (Karimi and Krishnamurthy 2001) (Copyright IEEE 2001)

2.1.3. Non-Mobile Sensor Monitoring and Highly Localized Systems

Systems, which use data from fixed, but remote sources in real-time for monitoring and analysis are based on architecture similar to the prototype system in this research and face related challenges. Al-Sabhan et al. (2003) discuss the development of a real-time web based watershed analysis tool for flood prediction. The system relies on in-field rain gauges, a wireless network, database server, and a GIS model. A Java based web interface provides the end user with access to near real-time data and provides several tools for modeling, analysis, and prediction. The architecture of the hydrological modeling tool is shown in Figure 2.5.

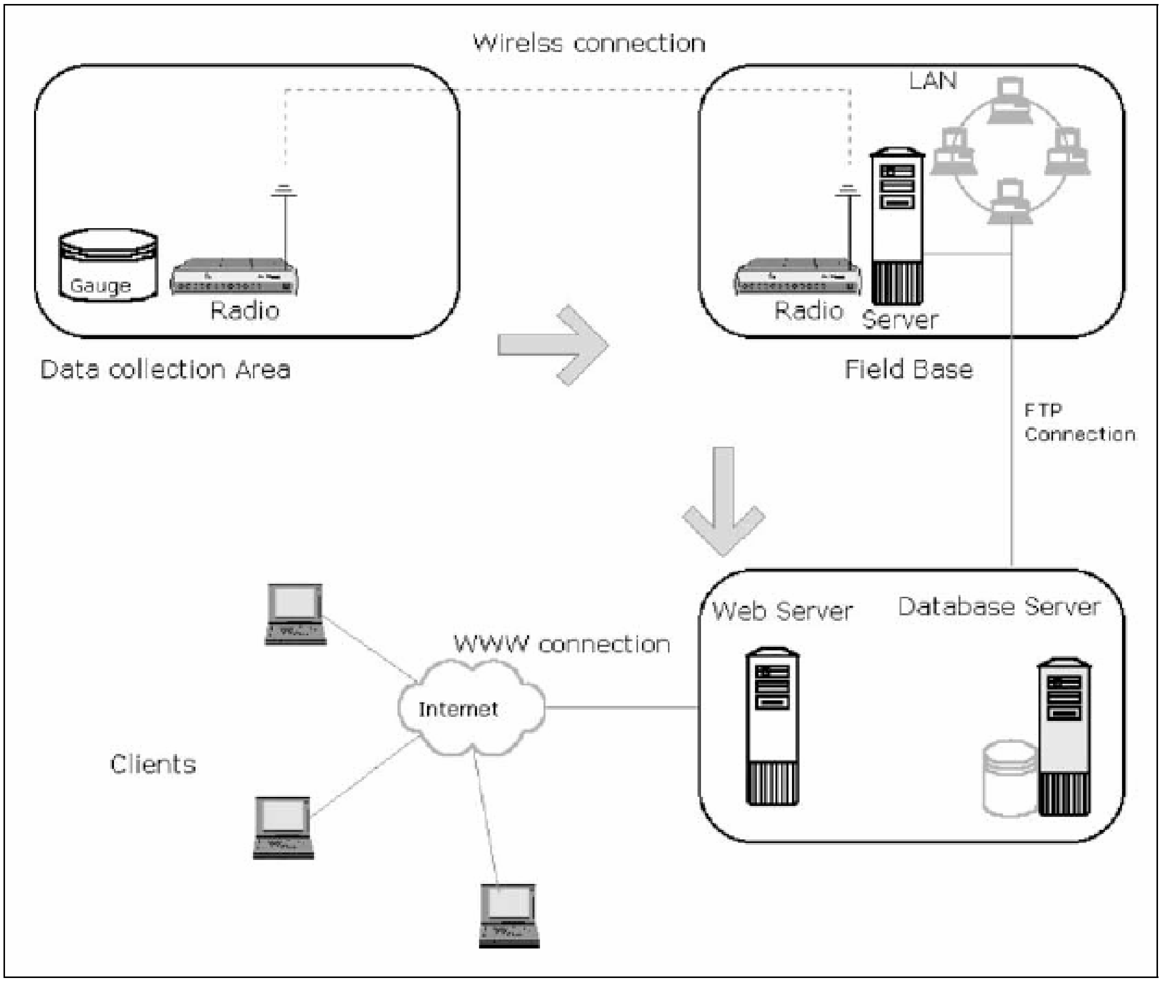

Figure 2.5 Project architecture (Al-Sabhan et al. 2003) (Copyright Elsevier 2003)

Using fixed cameras along highway routes, a telecommunications network, and a GIS Yeh, Lai, et al. (2003) proposed a near real-time traffic monitoring solution with architecture resembling the flood prediction system developed by Al-Sabhan et al. The system is envisioned as an in-cab tool to warn drivers of approaching traffic congestion and therefore save time and money with regards to transport. Figure 2.6 shows the configuration of the traffic monitoring system, which can deliver updated traffic information to the end user with a lag of less than 5 minutes. The end user display of the proposed system, which includes a dynamic traffic map, video feed, and basic traffic statistics is shown in Figure 2.7.

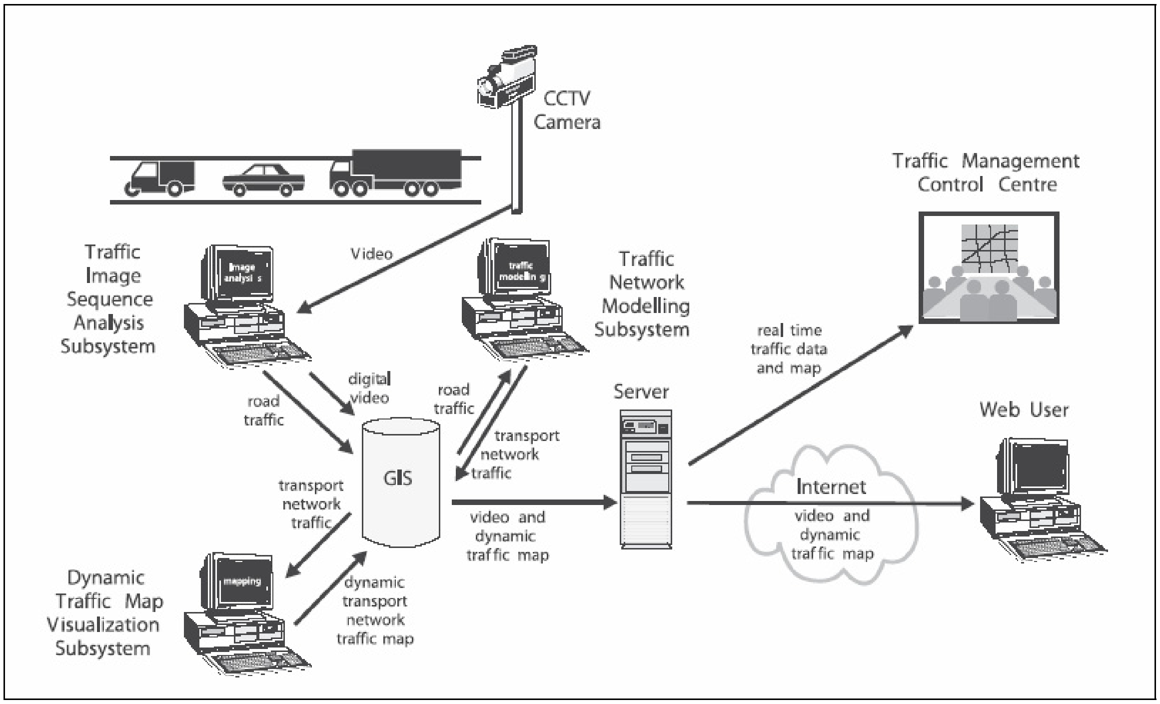

Figure 2.6 Proposed configuration of a real-time traffic multimedia Internet geographic information system (GIS) (Yeh et al. 2003) (Copyright Pion Ltd. 2003)

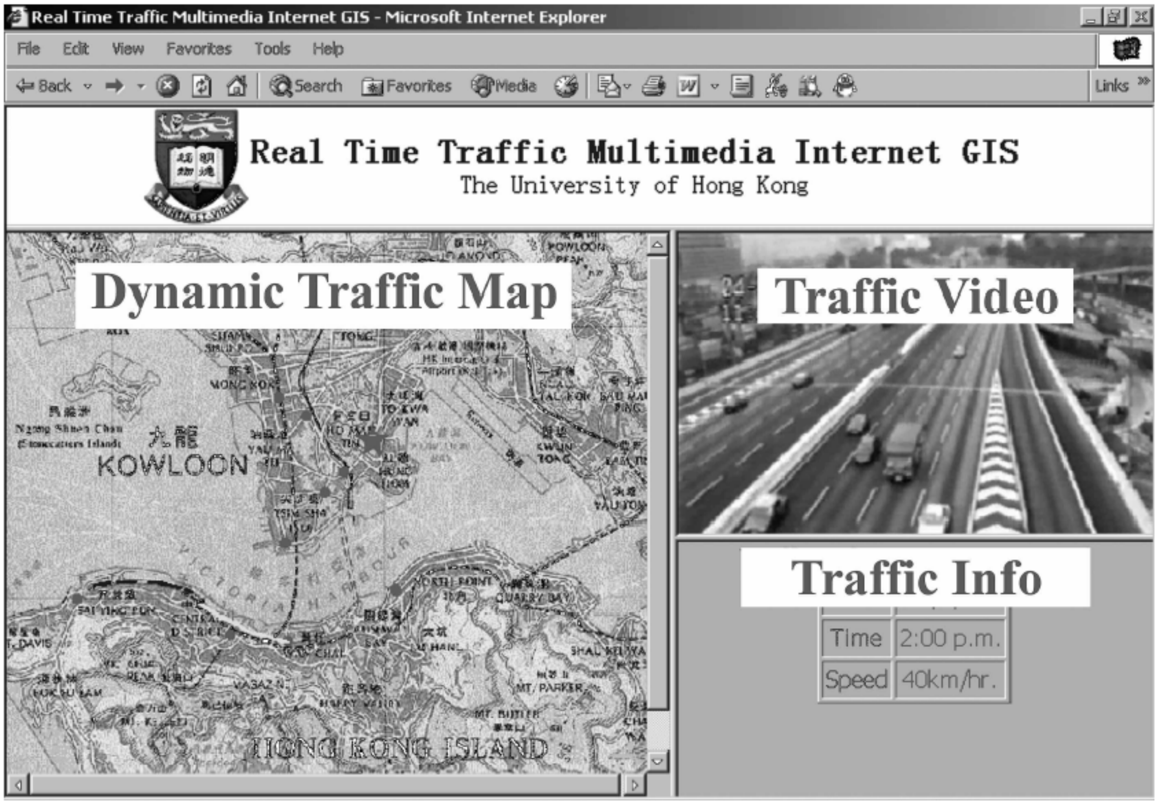

Figure 2.7 Web display of the dynamic traffic map, traffic video, and information of the proposed system (Yeh et al. 2003) (Copyright Pion Ltd. 2003)

Systems not concerned with real-time monitoring of remote sensor derived data may be getting further away from the scope of the TGM system described in this thesis, but still include tangible concepts. Built with a localized 802.11b network, several GPS equipped PDAs, and a central GIS server a system was used to test the feasibility of using the aforementioned technology for environmental monitoring and management (Tsou 2004). Equipped with mobile PDAs, the users surveyed a park region for changes in plant life such as new locations of invasive plants. Updated shape files were then transferred to the GIS server via the wireless network using File Transfer Protocol (FTP). Another system used to wirelessly update a GIS was used at a construction site in Tokyo Japan to map, in real-time, an underground water pipe (Arai et al. 2003). Using RTK-GPS and a data cell phone, pipe coordinates were sent to the GIS server in real-time.

2.2. Proprietary Mine Tracking Management Systems

Caterpillar's MineStar system includes a series of components geared towards maximization of production and profit. Components of the system provide fleet scheduling, production management, equipment health information, material and equipment tracking, mine planning, drilling management, in-cab earthmoving planning, and overall system monitoring. The Health component of the MineStar system uses a Vital Information Management System (VIMS), which acquires equipment health information and makes it available wirelessly in real-time (Caterpillar 2004). The goal of the MineStar Health system is to allow for remote analysis of equipment health and to aid in preventative maintenance (Jarosz and Finlayson 2003). Although VIMS data may be accessed via proprietary software as part of the MineStar system, it may be possible to access VIMS data independently for customized purposes as suggested by Thomson et al. (2003). Integration of original equipment manufacturers' (OEM) VIMS with the TGM system described in this paper could be a powerful tool for customizable real-time spatial analysis and overall mine management using real-time GIS.

Similar to MineStar, Wenco's Mine Management System (MMS) uses equipment-mounted sensors to monitor and manage production in real-time (Wenco 2004). The system provides capabilities comparable to MineStar such as fleet scheduling, drilling management, etc. (Jarosz and Finlayson 2003). Again, the purpose of the production and efficiency oriented Wenco system differs from that of the TGM system in this research, but the system architecture is similar.

A third proprietary mine management system that includes remote monitoring of vehicle mounted sensors is Modular's IntelliMine (Modular 2004). IntelliMine has basically the same capabilities of MineStar and Wenco's MMS. The components of IntelliMine dealing with remote analysis of equipment health are called MineCare and Dispatch. MineCare and Dispatch allow for real-time remote monitoring and management of equipment health for preventative maintenance.

2.3. Vibration at Surface Mines

The motivation for this research includes the development of a prototype system to spatially monitor vibration experienced by equipment operators in real-time as a model for TGM systems used to spatially monitor data derived from any vehicle mounted sensor. This is in response to a number of studies concerning vibration related injuries.

2.3.1. Vibration Related Injuries

Serious injuries resulting from JAJ remain a significant issue for mobile equipment operators. Biggs and Miller note that over a 9 year period starting in 1986 truck drivers accounted for nearly 63 percent of the fatalities and 60 percent of the lost-time injuries for truck haulage in surface mines (Biggs and Miller 2000). They further mention that "very little research has been done related specifically to shock trauma injuries, that is, jolting and jarring injuries caused by surface mine haulage trucks, nor to the development of engineering controls to reduce such injuries".

Table 2.1 summarizes injuries by type for dozer operators based on a NIOSH study using MSHA injury data from January 1988 to December 1997 (Wiehagen et al. 2001). Jarring and jolting related injuries make up for 70 percent (597 of 855) of the serious injuries and 39 percent (7 of 18) of the fatalities.

Table 2.1 While operating a dozer: serious injuries and lost workdays by operator impact (fatalities in parentheses) (Wiehagen et al. 2001)

Operator Impact	Serious Injuries	%	Days Lost	Average days lost[1]
Jolted/jarred	436	50	17,630	40.4
Jolted/jarred - struck against	142	16	5,388	37.9
Jolted/jarred - landed outside cab	26(7)	3	906	47.7
Musculoskeletal injury (MSI)	155	18	5,656	36.5
Struck by object	78	9	1,733	22.2
Burned/contact with a hot object	10(1)	1	324	36
Asphyxiated	4(4)	<1	—	—
Drowned	3(3)	<1	—	—
Crushed/run over by dozer	3(3)	<1	—	—
Other	16	2	249	15.6
Total	873(18)	100	31,886	—

[1]For the 855 lost-time injuries

A similar research by Cross and Walters (1994) examined compensation claims in the mining industry of South Wales, Australia, over the course of 4 years. Of 28,306 claims, 8,961 related to the head, back, and neck. Of the 8,961 claims 11% (986) were attributed to vehicular jarring. 53% of the vehicular jarring injuries described in the claims involved underground transporters and shuttle cars. Vehicular jarring injuries while operating surface loaders, dozers, and dump trucks made up 29% of the claims. Figure 2.8 shows a comparison of causes of head, neck, and back injuries for equipment operators as indicated by the compensation claims analyzed by Cross and Walters. Jarring makes up for 36 percent of the injuries.

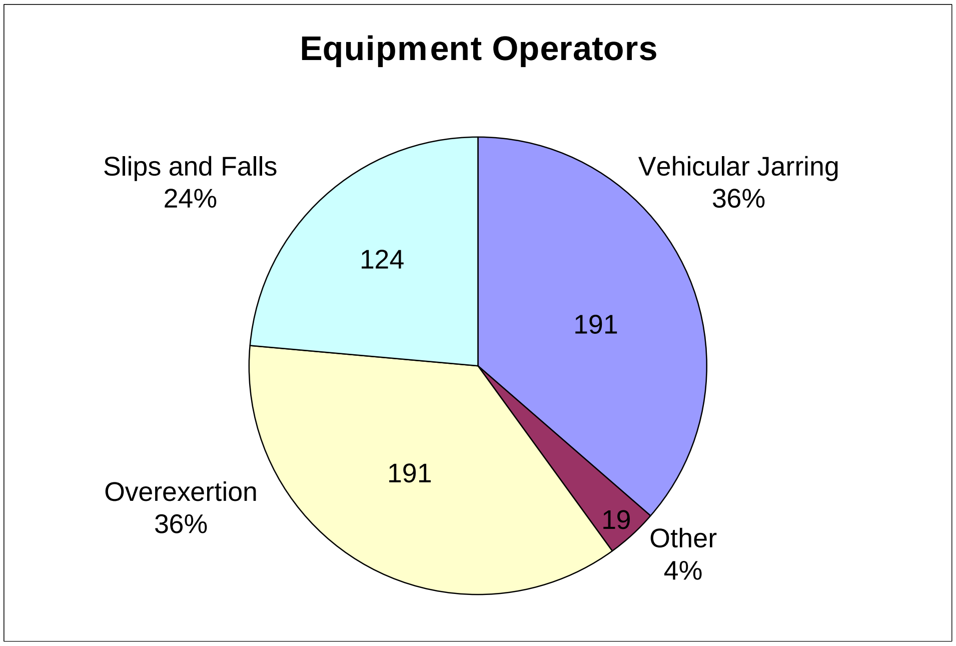

Figure 2.8 All head, neck and back injuries (Chart was recreated for inclusion here) (Cross and Walters 1994) (Copyright Elsevier 1994)

In addition to retrospective analysis of injury claims relating to JAJ, studies have been conducted to investigate such injuries from mechanical, simulative, and responsive standpoints. Wilder et al. (1996) reference many articles concerning whole body vibration and jolting and go on to discuss the mechanics of the lower back and suggest possible solutions to vibration and jolt injuries. The proposed solutions include operator seat and cab modifications to isolate the operator from or to reduce his or her exposure to jolting and vibration. Using a 17 member human-body model, Huang and Huston (2001) studied the model's response to WBV and JAJ. They compare their findings to experimental data and conclude that multi-member models can be effectively used for studying WBV and JAJ. It is worth noting that when compared to accident victim simulation data Huang and Huston mention that "there is relatively little data available for WBV [whole body vibration] and JAJ [jolting and jarring]". A study by Mayton et al. (1998) identified jarring and jolting as a serious problem for low-coal shuttle car operators. They investigated the use of ergonomic seats and viscoelastic foams for isolating an operator from jolts and jars and used their findings to design a seat, which was well received in underground mine trials.

2.3.2. Vibration and Haul Road Management

An article by Thompson et al. (2003) proposes a real-time mine road maintenance management system to significantly reduce maintenance and operating costs. Using data from onboard accelerometers and GPS based truck locations they were able to differentiate between types of road defects based on vibration signatures. The article suggests the use of these signatures in combination with OEM systems to monitor truck vital signs and GPS to direct road maintenance in real-time as opposed to ad-hoc or scheduled maintenance.

3. System Design and Development

3.1. System Overview

The TGM system developed for this research can be divided into 3 components as shown in Figure 3.1: (1) Data Acquisition Component, (2) Data Transfer Component, and (3) Data Analysis Component. The Data Acquisition Component is responsible for acquiring GPS and vibration data, establishing and maintaining a connection to the server, and sending data messages to the server. Responsibilities of the Data Transfer Component include managing incoming data messages and delivering the data as requested by the end user. The Data Analysis Component consists of the tools provided to the end user to monitor and analyze the data stream in real-time. A simplified flow sheet outlining the functions of each component is shown in Figure 3.2. It should be noted that the flow sheet represents the action of acquiring only one set of GPS coordinates with corresponding vibration data and sending it to the server for distribution. While running the TGM system, each component can be thought of as a separate continuous loop whose state is dictated by user commands.

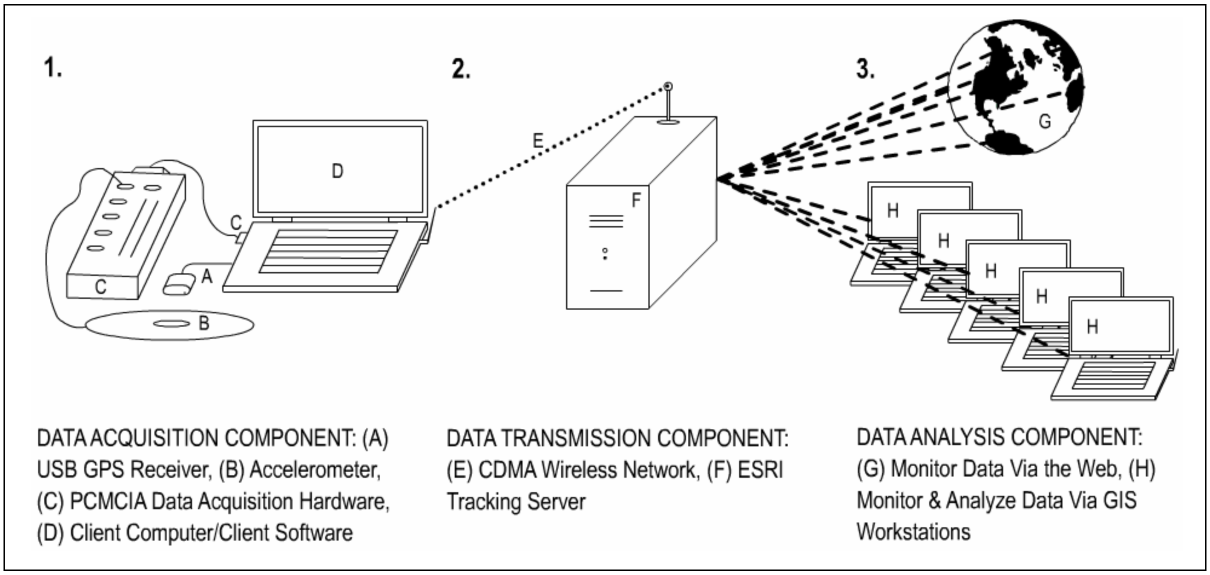

Figure 3.1 The three components of the Telegeomonitoring System

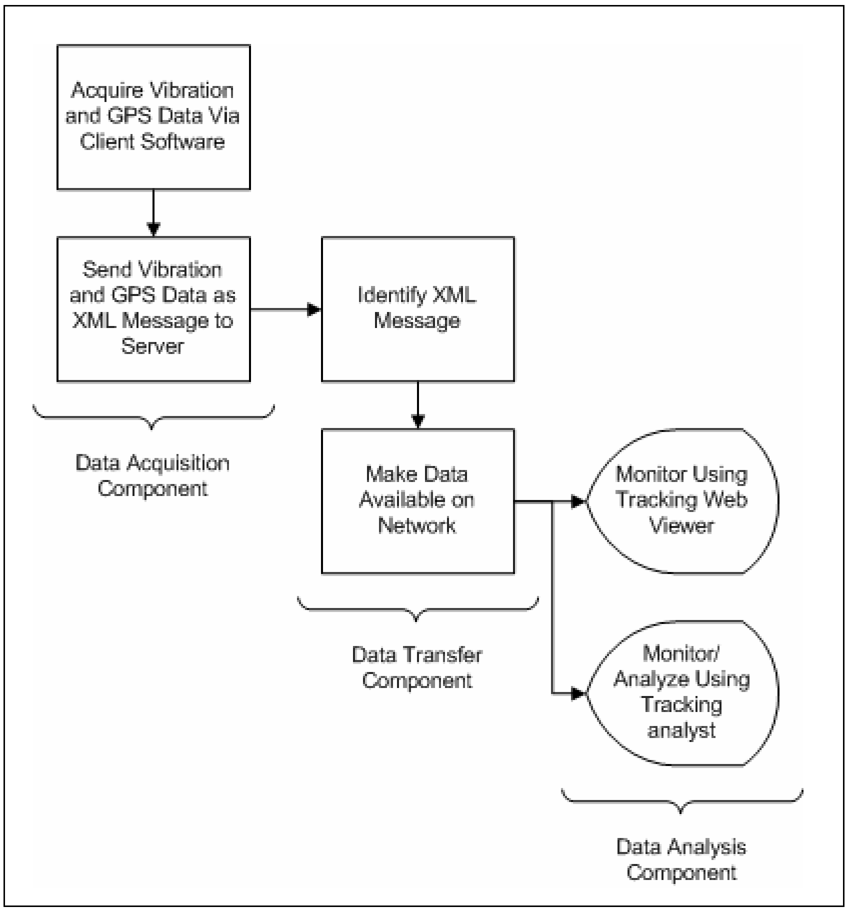

Figure 3.2 Simplified flow sheet for overall TGM system

3.2. Data Acquisition Component

The Data Acquisition Component consists of a mobile PC, data acquisition hardware, GPS receiver, accelerometer, wireless networking hardware, and custom software. Details on the component hardware are shown in Table 3.1.

Table 3.1 Hardware summary for Data Acquisition Component

Hardware	Details
Laptop	Sony Vaio (PCG-GR270P)
Processor	*Intel Pentium III (750 MHz)*
RAM	*512 MB*
Operating System	*Windows XP Pro*
GPS Receiver	Rayming TripNav (TN-200)
Interface	*USB (Virtual COM)*
Data Acquisition	National Instruments DAQCard-6024E
Channels	*16 single-ended; 8 differential*
Sample Rate	*200 kS/s*
Interface	*PCMCIA*
Connector Block	*BNC Block (NI BNC-2110)*
Accelerometer	PCB Triaxial ICP Accelerometer (356B40)
Sensitivity (± 10%)	*100 mV/g*
Measurement Range	*± 10 g pk*
Network Adapters	
T1	*Integrated Ethernet Adapter*
802.11 b, g	*PCMCIA Card (Lynksys WPC54GS)*
CDMA (Sprint Network)	*Samsung Cell (VGA-1000)*

Figure 3.3 shows connection types used in the Data Acquisition Component and Figure 3.4 shows a picture of the hardware. The laptop, powered through a cigarette lighter adapter, runs the client software, which manages all incoming and outgoing data. Towards the bottom right of Figure 3.4 is the connector block used for connecting to the accelerometer, which is the disc-like part located above the box. The connector block is

connected to the laptop via the PCMCIA data acquisition card. A close-up of the accelerometer, data acquisition card, and connector block is included in Figure 3.5. The cell phone, located above the accelerometer in Figure 3.4, is connected to the laptop via a USB port, which is treated like a virtual COM port by the client software. A second USB interface acting as a virtual COM port is used by the GPS receiver, whose cord can be seen trailing up to the roof of the vehicle. A close-up shot of the GPS receiver is shown in Figure 3.6.

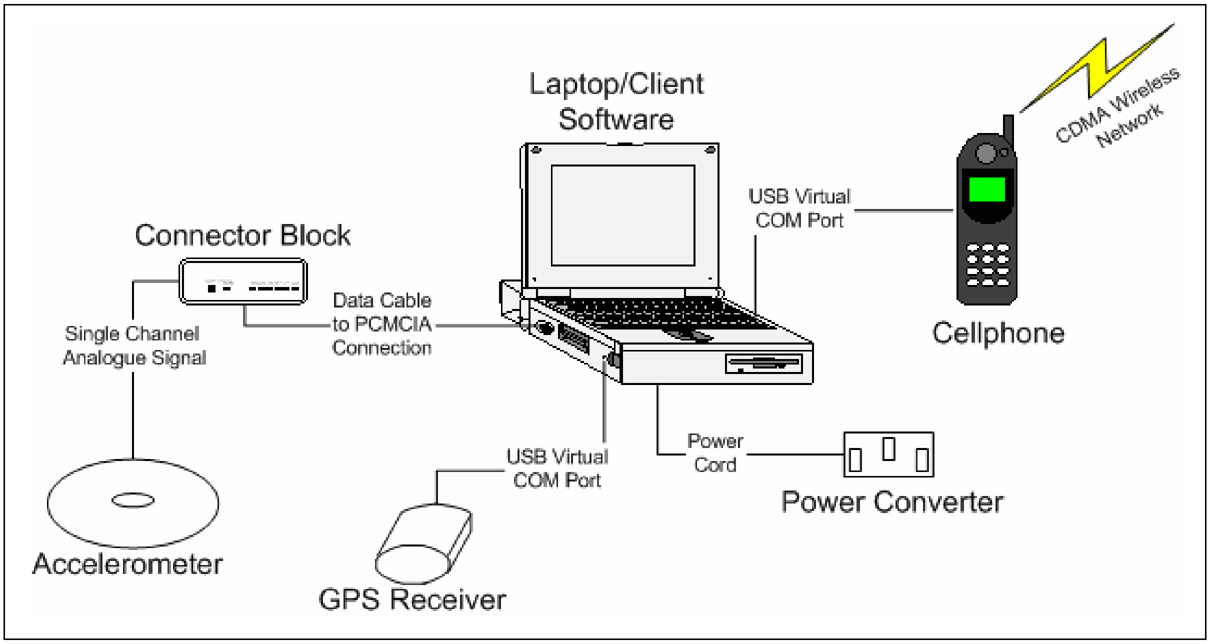

Figure 3.3 Connection types used in the Data Acquisition Component

Figure 3.4 Hardware of the Data Acquisition Component

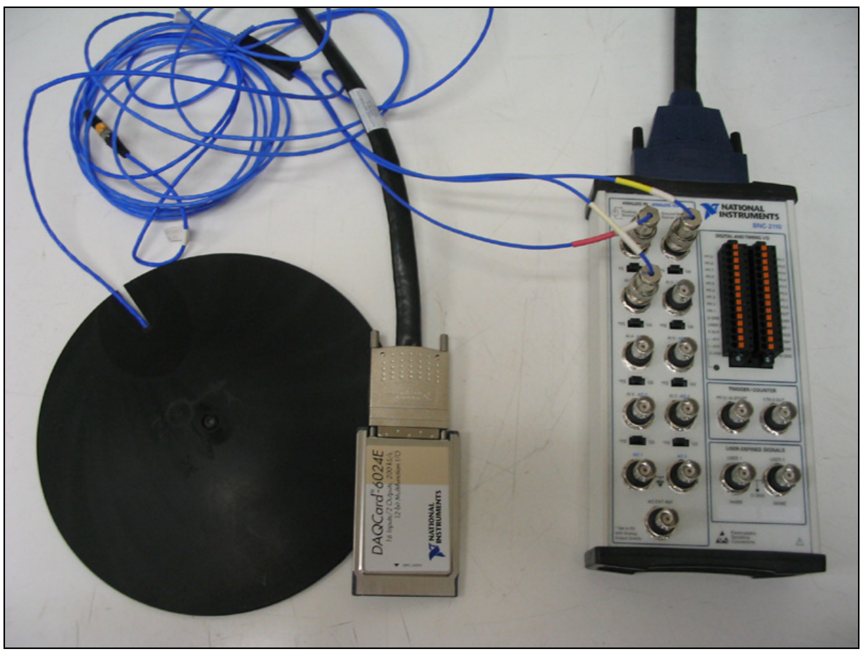

Figure 3.5 Close-up of accelerometer, PCMCIA data acquisition card, and connector block

Figure 3.6 Close-up of magnet-mounted GPS receiver

The client software is the heart of the Data Acquisition Component and is responsible for controlling and managing both incoming and outgoing data streams. National Instrument's LabView 7.1 software, a graphical development environment used primarily for data acquisition, analysis, and display, was used to develop the client software for the TGM system (National Instruments 2005).

A simplified flow sheet illustrating the functions of the client software is shown in Figure 3.7. The GUI for the client software is shown in Figure 3.8. For the full client software block diagram, refer to Appendix A. When the user executes the program, a connection to the server is initiated by the client software. To establish a server connection, only the server IP address and port number, as entered by the user in the client GUI, are required. The client software can work with any network protocol, which enables access to the internet or a connection to the server via a local area network. For the field test, the TGM system used a cell phone to transmit data over Sprint's CDMA network. A PCMCIA wireless card and integrated Ethernet adapter were used separately in the lab setting to send data over 802.11g, 802.11b, and T1 networks. Upon successful connection with the server the client software attempts to read in data from both the GPS receiver and the accelerometer according to user-defined parameters set using the client interface (Figure 3.8). GPS and accelerometer data are then processed simultaneously as separate threads.

The current client GUI shows information which may be superfluous for in-cab applications. In particular, the real-time vibration wave form, processed vibration data, GPS data, and outgoing data message are included in the display for debugging purposes and need not be included in future builds of the client software. Reducing the client display to only user-controlled parameters might make it possible to use a much less powerful computer such as a PDA.

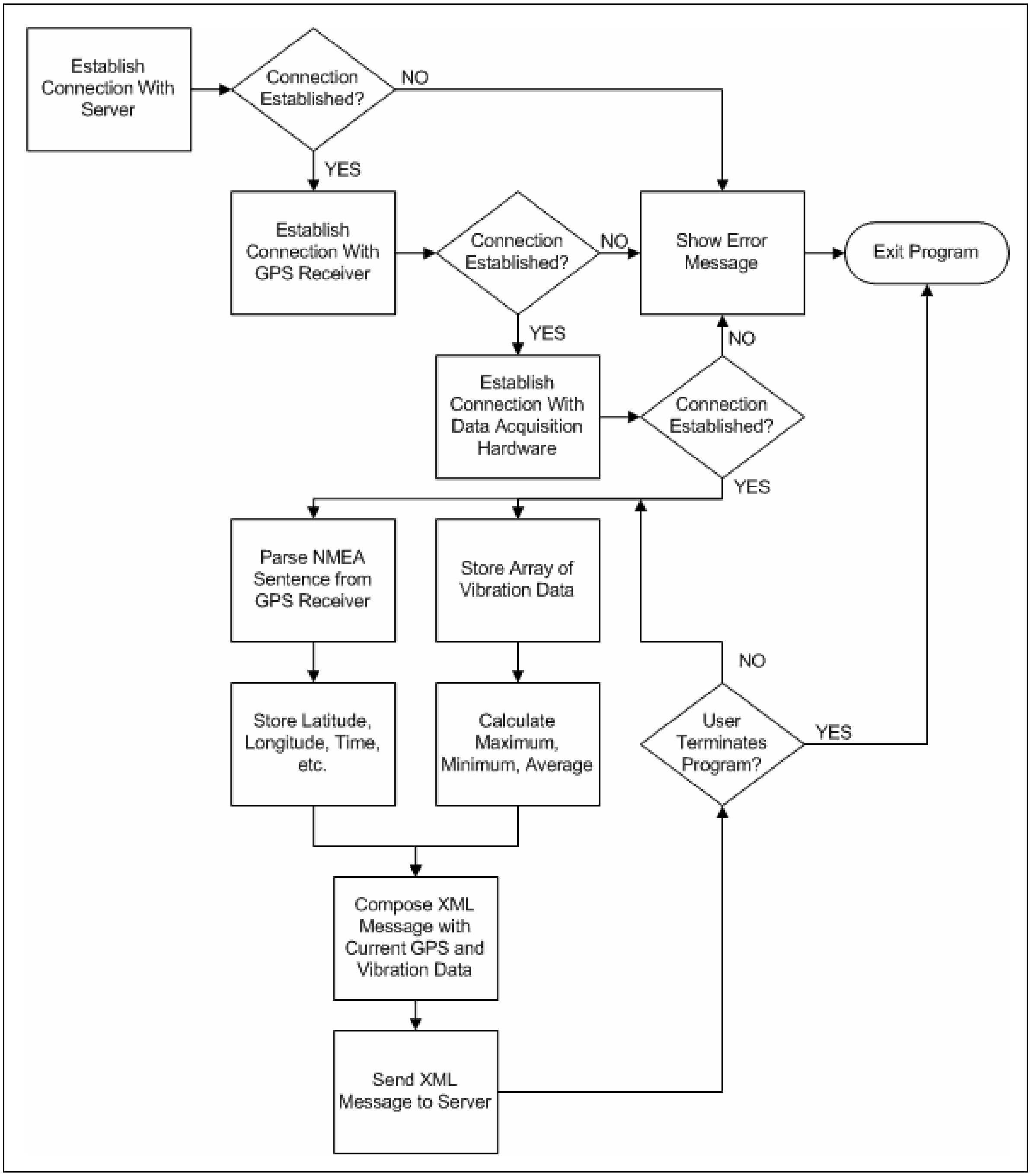

Figure 3.7 Simplified flow sheet of client software

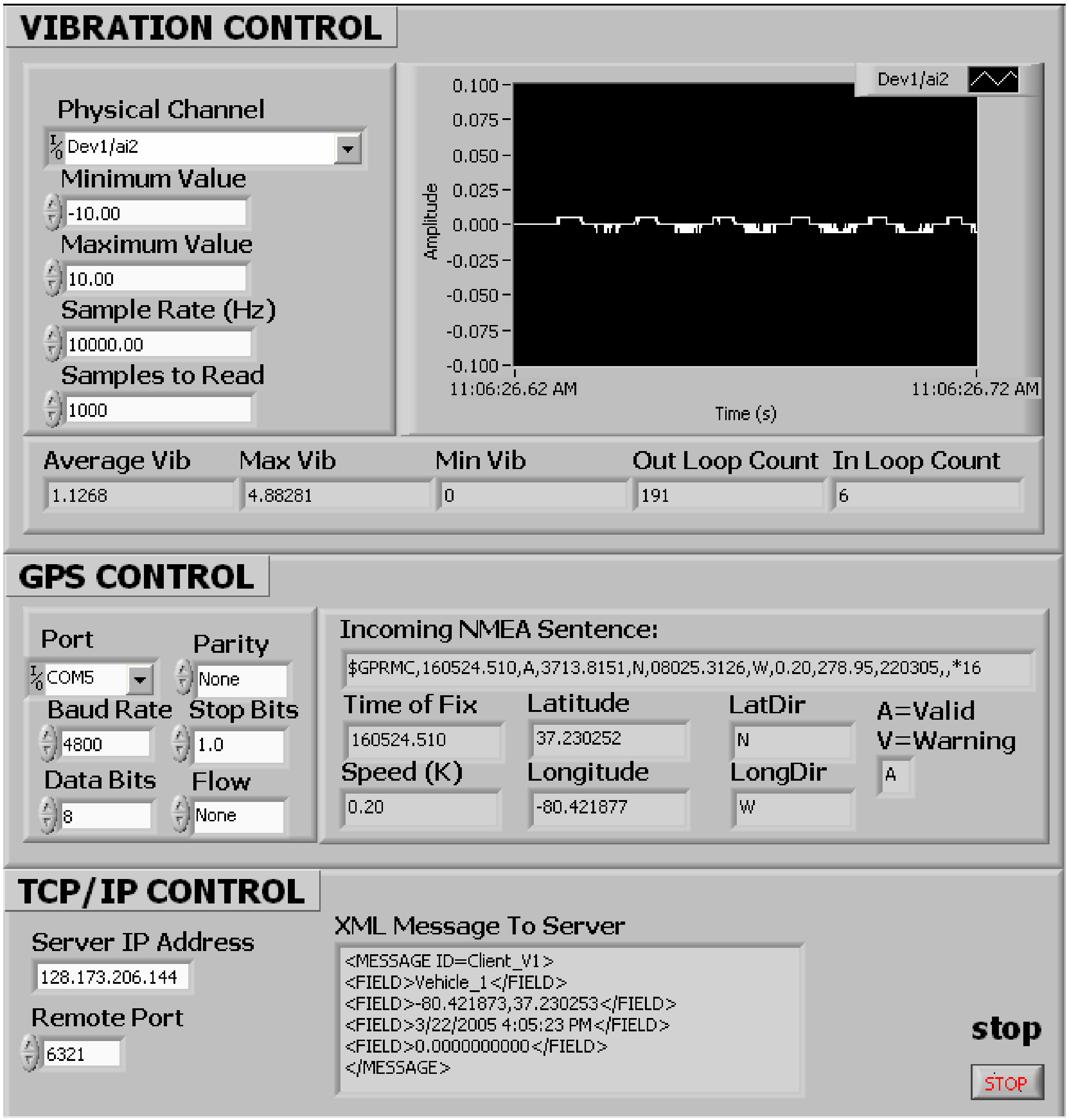

Figure 3.8 Client Software Graphical User Interface

The GPS receiver sends data to the client software as National Marine Electronics Association (NMEA) sentences. NMEA is a non-profit organization focused on marine electronics (NMEA 2003). The NMEA standard refers to a standard protocol for communication between marine equipment. Several different data-types included in the NMEA standard are sent in each transfer. The client software filters out unwanted data-types and stores only the desired information. In this case, the *Recommended Minimum Specific GPS/TRANSIT Data* (RMC) data-type is used because the TGM system requires only location and time information from the GPS receiver. The following is an example of an RMC formatted NMEA sentence:

`$GPRMC,123519,A,4807.038,N,01131.000,E,022.4,084.4,230394,003.1,W*6A` (DePriest 2005)

This NMEA sentence is broken down and explained in Table 3.2.

Table 3.2 Explanation of RMC data type NMEA sentence (DePriest 2005)

Sentence Part	Explanation
RMC	Recommended Minimum sentence C
123519	Fix taken at 12:35:19 UTC
A	Status A=active or V=Void.
4807.038,N	Latitude 48 deg 07.038' N
01131.000,E	Longitude 11 deg 31.000' E
022.4	Speed over the ground in knots
084.4	Track angle in degrees True
230394	Date - 23rd of March 1994
003.1,W	Magnetic Variation
*6A	The checksum data, always begins with*

After retrieving the RMC formatted string the client software parses the string into the following substrings: time of fix, status, latitude, latitude direction, longitude, longitude direction, and speed. The time of fix (hhmmss.sss) and system date are then formatted into a timestamp format (MM/DD/YYYY hh:mm:ss) to be included in the outgoing EXtensible Markup Language (XML) formatted message to the server. XML is a standard created by the World Wide Web Consortium (W3C) (2005) for describing data with user-defined tags. Latitude and longitude are received in the formats *ddmm.mmmm* and *dddmm.mmmm*, respectively. In other words, latitude and longitude are received as a string of degrees, minutes, and decimal minutes. In order to use these coordinates in the GIS environment they are converted to the format of decimal degrees (dd.dddddd). The sign of the coordinates are assigned based on the latitude and longitude direction. North (N) and East (E) are positive and South (S) and West (W) are negative. For example, take the received latitude as *3713.8147 N*. Since latitude is in the format *ddmm.mmmm* the first 2 characters are taken as degrees. Reading the remainder of the string from an offset of 2 gives *13.8147* (mm.mmmm). The remaining string, *13.8147*, is then divided by *60* to yield decimal degrees (13.8147/60 = .230245). Degrees are then added to decimal degrees to give *37.230245.* Since the direction is *N* the sign is positive. This procedure is also used to convert the longitude coordinate with the exception that the first 3 characters are taken as the degrees (**ddd**mm.mmmm) instead of the first 2. After reformatting the incoming latitude and longitude coordinates they are included in the current outgoing XML message in the format *longitude, latitude,* corresponding to *x,y*.

The accelerometer used to measure vibration is triaxial, where each direction of motion (x, y, and z) has its own channel over which an analogue voltage is sent. However, the prototype system in this research is concerned only with vertical motion (z). Using the pull-down menus on the client GUI the user specifies the channel corresponding to motion in the z direction in addition to minimum and maximum values, sample rate, and number of samples. The sample rate refers to the rate at which the data acquisition card samples the analog input signal. *Samples to Read* dictates the number of samples to read from the buffer and affects the smoothness of the waveform representation of the vibration data. The signal from the accelerometer is continuously sampled so the buffer is continually refreshed. Every 2 to 3 seconds an array of vibration data from the buffer is used to calculate minimum, maximum, and average vibration. Although the client GUI displays all current vibration calculations, only the maximum vibration value is included in the XML message to the server.

Although the vibration section of the Data Acquisition Component stands to improve in the future of this research, it is adequate for the purpose of proving the concept of the TGM vibration system.

When GPS coordinates, vibration maximum, and timestamp for a given moment are included in the XML message the message is sent to the server. An example of an outgoing XML message is as follows:

```
<MESSAGE ID=Client_V1>
<FIELD>Vehicle_1</FIELD>
<FIELD>-80.421873,37.230253</FIELD>
<FIELD>1/31/2005 2:39:27 PM</FIELD>
<FIELD>0.8564123</FIELD>
</MESSAGE>
```

In the first line *Client_V1* tells the server to which message definition this message conforms. *Vehicle_1* identifies the vehicle running the client software. If the Data Acquisition System were installed on additional vehicles the second line would be changed to *Vehicle_2, Vehicle_3,* and so on for each vehicle. No other adjustments to any part of the TGM system would be required to accommodate additional vehicles. The third, fourth, and fifth lines are vehicle location, timestamp, and vibration, respectively. The final line, *</MESSAGE>*, marks the end of the XML message. More on the format of the XML message and the server-side message definition are discussed in Chapter 3.3.

3.3. Data Transfer Component

The Data Transfer Component of the TGM system includes a server and network. Details of the Data Transfer Component's hardware are shown in Table 3.3.

Table 3.3 Hardware Summary for Data Transfer Component

Hardware	**Details**
Server	Dell GX110
Processor	*Pentium III 600 MHz*
RAM	*512 MB*
Operating System	*Windows 2000*
Server Software	*ESRI Tracking Server Pre-Release**
Servlet Container	*Apache Tomcat 5.0*
Java Platform	*Sun J2SE 1.4.2*
HTTP Server	*Apache HTTP Server 2.0.52*
Lab Setting Network #1	T1
Interface	*Integrated Ethernet Card*
Router	*Linksys WRT54GS*
Lab Setting Network #2	802.11b
Routers/Repeaters	*Virginia Tech's Integrated Wireless Net*
Lab Setting Network #3	802.11g
Router	*Linksys WRT54GS*
Field Setting Network #1	Sprint CDMA Network
Phone	*Samsung Cell (VGA-1000)*

*(Tracking Server is a product of Northrop Grumman Corp. Copyright 2005. All rights reserved.)

3.3.1. Server Section

ESRI's Tracking Server Pre-Release software is the main part of the Data Transfer Component (Tracking Server is a product of Northrop Grumman Corp. Copyright 2005. All rights reserved). It is a tool for accepting real-time data and transferring them to web clients or GIS workstations running Tracking Analyst (ESRI 2005). As it functions in the

Data Transfer Component, Tracking Server accepts XML messages from the client software in the Data Acquisition Component. The incoming XML messages are compared to user-defined message definitions, which indicate the data type for each field of a message. In other words, the message definition tells TS what to expect in each field of an incoming XML message that conforms to the message definition. Multiple message definitions can be used to allow different formats for incoming messages. However, the TGM system in this research uses only one message definition. After associating an incoming XML message with a message definition, conditional actions may be applied to the data in the message. For example, if the value of a certain field in a single message meets particular criteria than the message can be tagged in order to alter the symbology associated with the message or filtered for exclusion. Once applicable actions are applied to an incoming message the data may be distributed to the Tracking Server Web Viewer or Tracking Analyst. Figure 3.9 shows a simplified flow sheet for the processes in the Data transfer Component.

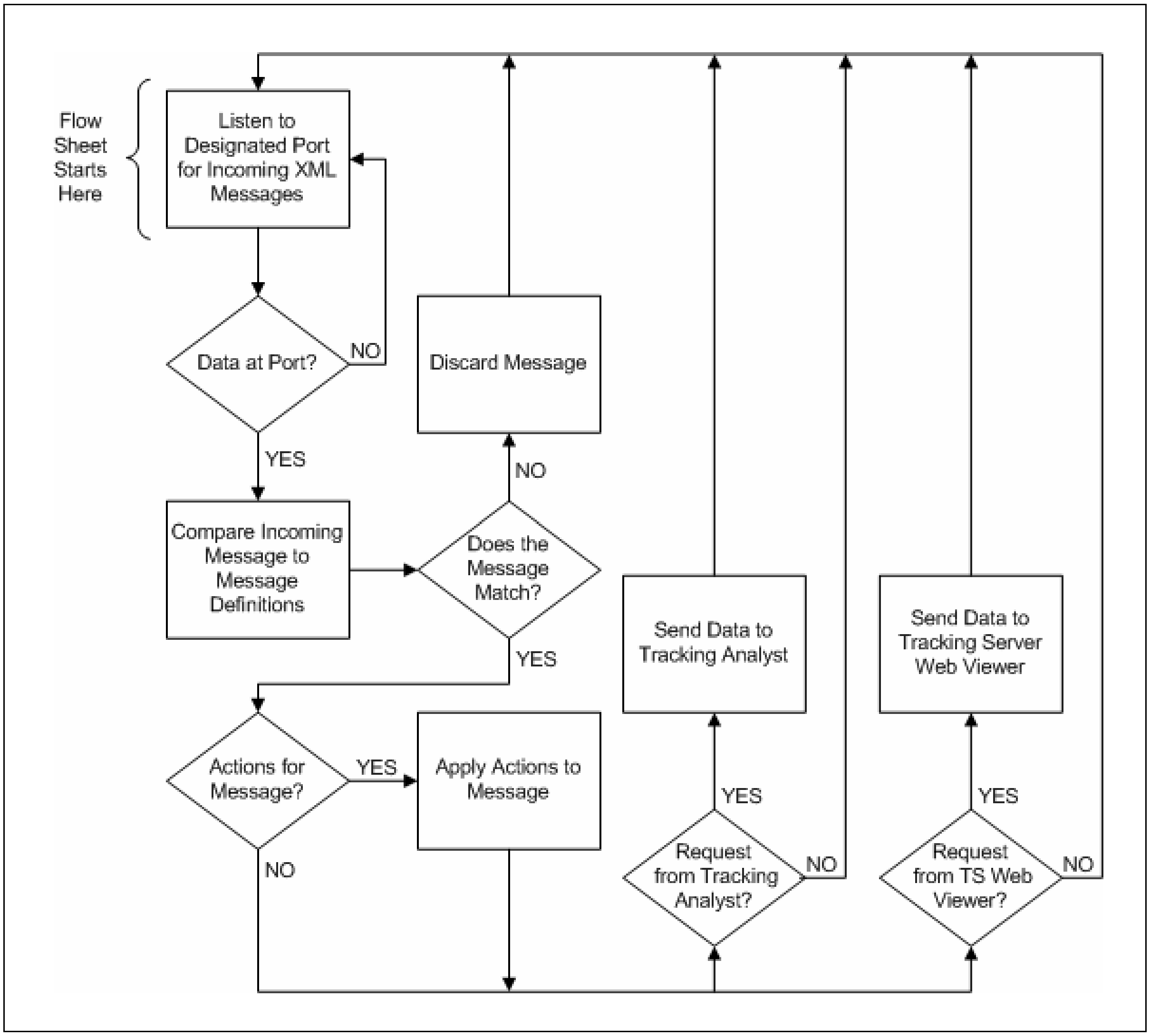

Figure 3.9 Simplified flow sheet of the Data Transfer Component

Tracking Server includes several *data links*, which can receive or transmit data, manage Tracking Server settings, or perform a combination of these routines (ESRI 2004b). The packaged data link used by the TGM system is called the Generic Input. Using TCP/IP protocols, the Generic Input data link can listen on a user-specified port for incoming XML messages. Referring to the Tracking Server nomenclature, the client software of the Data Acquisition Component is considered to be a *server connection.*

The first step in the process of setting up Tracking Server for the TGM system was to create the message definition. Figure 3.10 shows the Message Definition Editor window in Tracking Server Manager. The name of the message definition was set to "Client_V1", the message definition ID was generated by Tracking Server, and the Data Time Zone and coordinate system were set accordingly. The fields of the message definition are shown in the bottom window of Figure 3.10. *ID*, *Loc*, *TStamp*, and *Vibration* refer to the vehicle identification, vehicle location, message time stamp, and maximum vibration value, respectively.

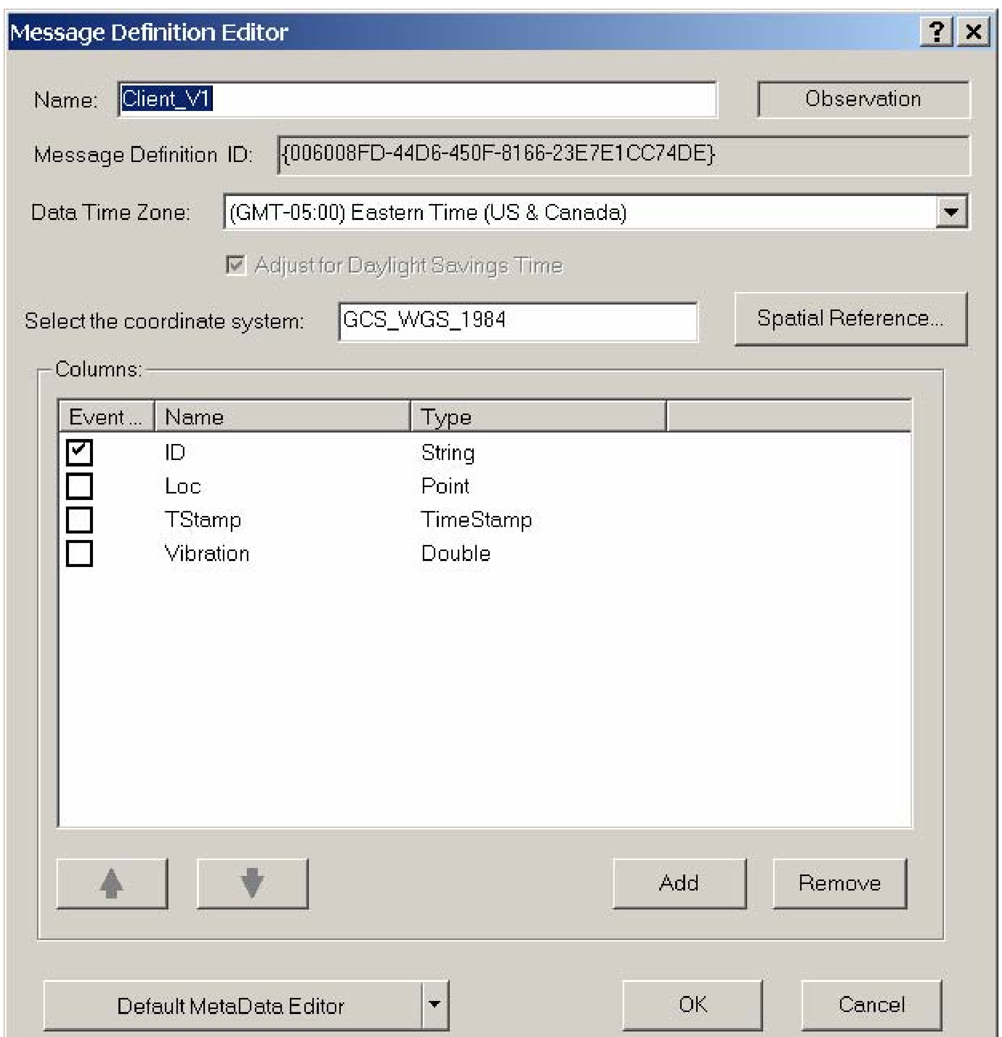

Figure 3.10 Tracking Server Message Definition Editor Window

For reference, the example of an incoming XML message is included again here:

```
<MESSAGE ID=Client_V1>
<FIELD>Vehicle_1</FIELD>
<FIELD>-80.421873,37.230253</FIELD>
<FIELD>1/31/2005 2:39:27 PM</FIELD>
<FIELD>0.8564123</FIELD>
</MESSAGE>
```

The first line tells Tracking Server that this message complies with the message definition called “Client_V1”.

The second step for configuring Tracking Server for the TGM system was to set up a *tracking service* for the Client_V1 message definition. Clicking “New” on the “Tracking Services” tab of Tracking Server Manager opens the window shown in Figure 3.11. The Tracking Service Name was set to “ClientV1”, the type was set to “Simple”, and the Client_V1 message definition was selected for observation from the pull-down menu.

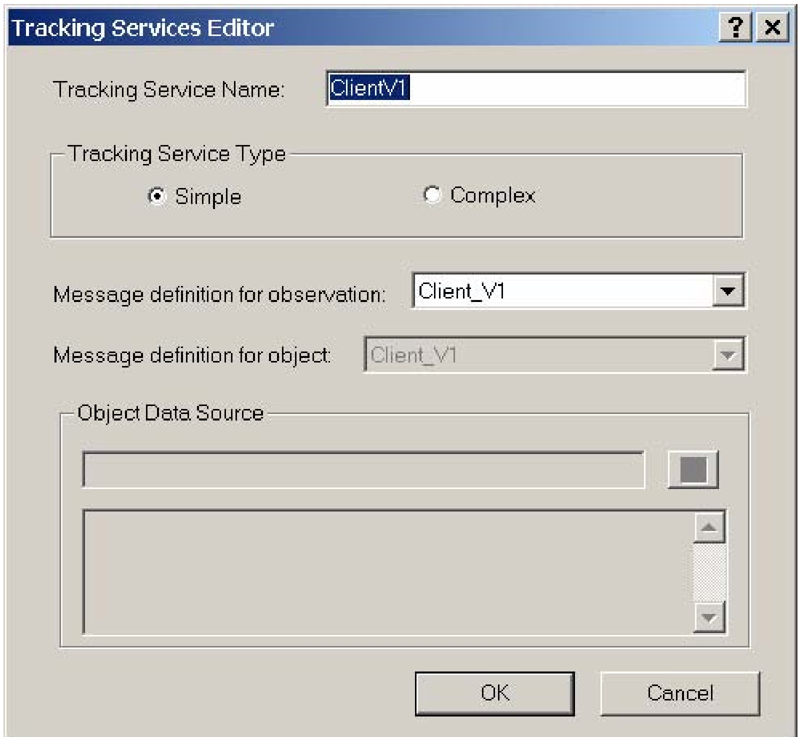

Figure 3.11 Tracking Server Tracking Services editor window

The next step was to enable the new Tracking Service for distribution by the Tracking Server Connector data link, which was packaged with Tracking Server. The Tracking Server Connector is responsible for transferring data to the web viewer and Tracking Analyst. By double-clicking "Tracking Server Connector" on the "Data Links" tab of Tracking Server Manager (Figure 3.12) the Tracking Server Connector Properties window is opened as shown in Figure 3.13. The box corresponding to the ClientV1 tracking Service was checked to enable service distribution.

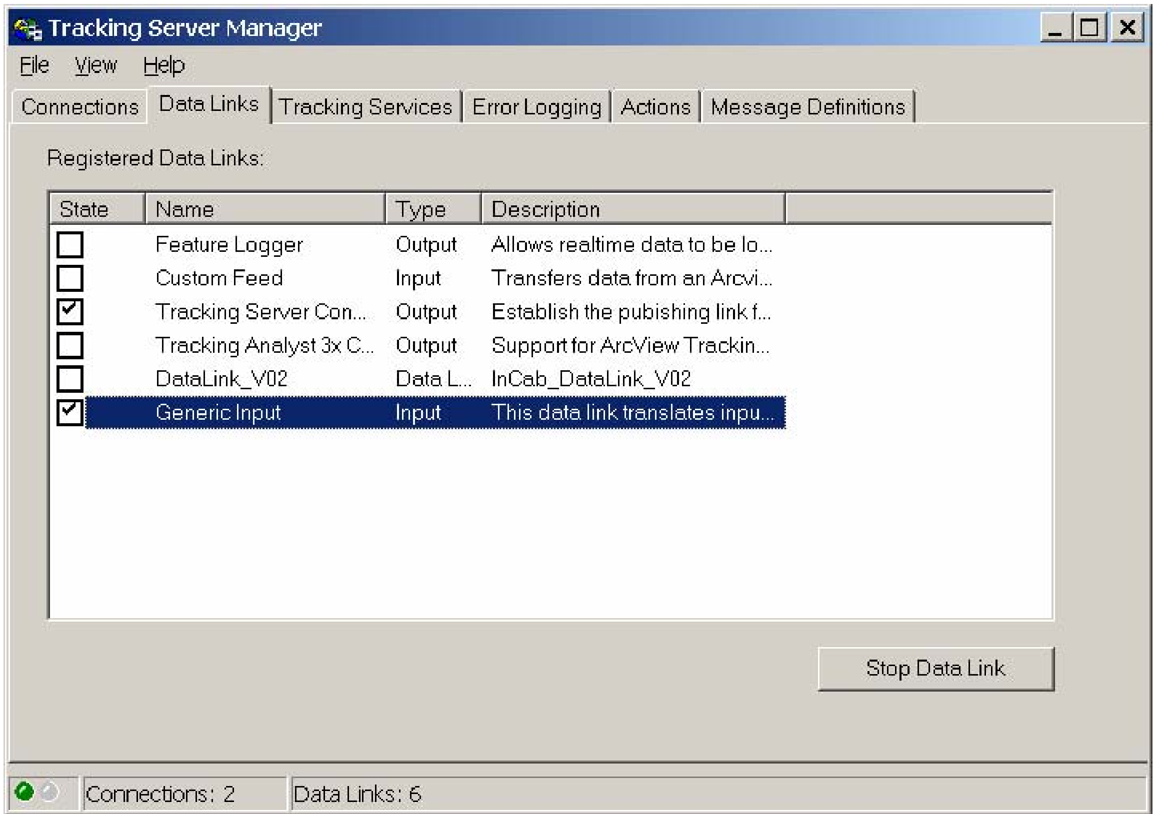

Figure 3.12 Tracking Server Manager main window Data Links tab

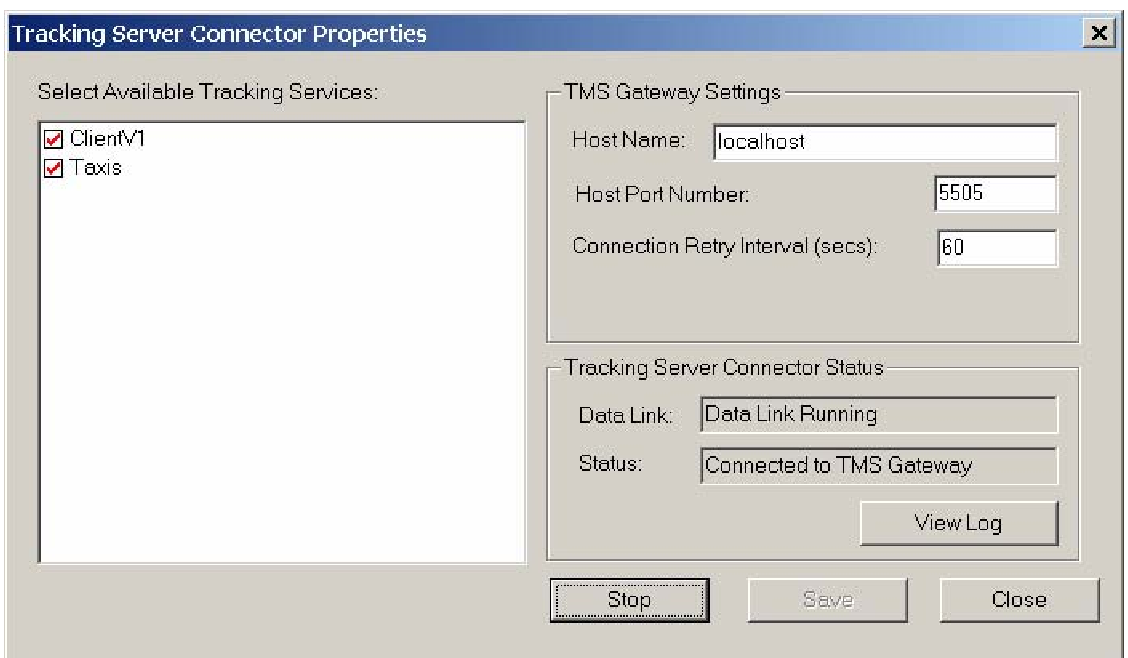

Figure 3.13 Tracking Server Connector Properties window

After enabling the ClientV1 service, Tracking Server was capable of distributing incoming data to a Tracking Viewer website or Tracking Analyst. To allow for condition-based symbology (i.e. flashing red dot) on the Tracking Viewer website a Tag action was applied to the Client_V1 message definition. A Tag action applies a textual tag to a data message if a certain condition is met. The tag can be used to alter the symbology corresponding to the tagged message when viewed via the Tracking Viewer website. Tags are used by the TGM system to flash a large red dot in place of the normal symbol when a vibration value greater than 4 is received in a message. To create a tag action the “New Action” button was pressed in the “Actions” tab in Tracking Server Manager. A name was given to the action and it was defined as a Tag action. After naming the action the Tag Action Parameters window opens as shown in Figure 3.14. The Tag Text was specified as “HighVibration” and the action was set to be triggered by an attribute query.

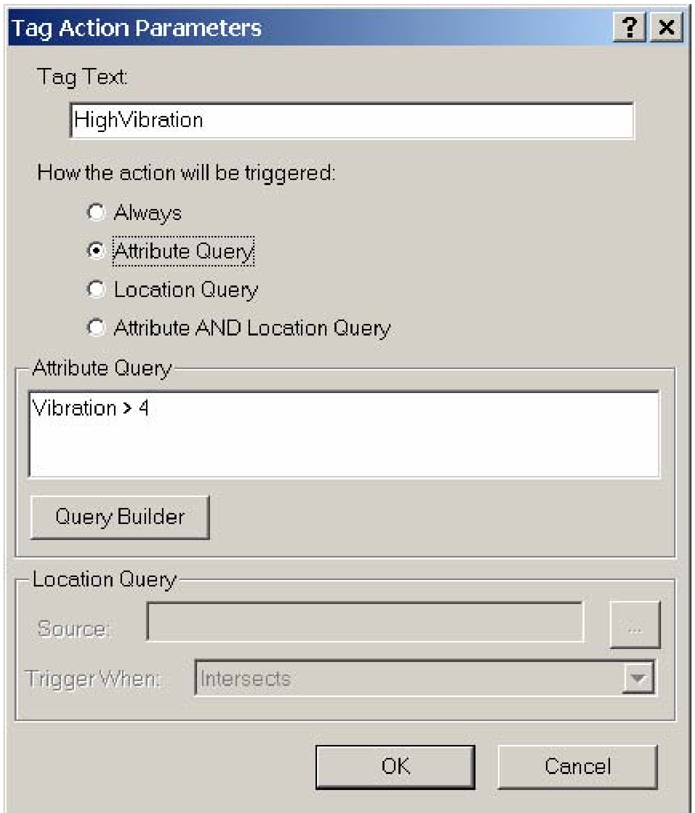

Figure 3.14 Tracking Server Tag Action Parameters window

Pressing the "Query Builder" button opens the Query Builder window as seen in Figure 3.15. The query was defined as "Vibration > 4". This translates to the following: when the value of the "Vibration" field of an XML message conforming to the Client_V1 message definition is greater than 4, then apply this action.

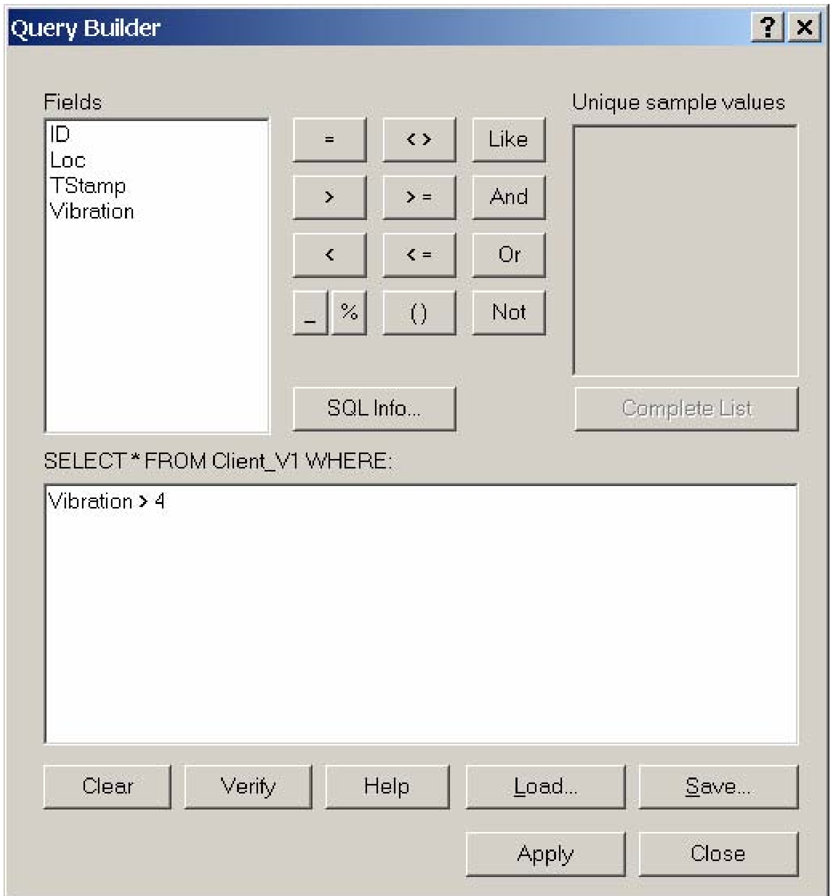

Figure 3.15 Tracking Server Query Builder window

3.3.2. Network Section

The server is connected, through a router, to Virginia Tech's T1 network. A connection to the server can be established both within the server's local area network and externally. Using the local area network, the client software can connect to the server via the router's 802.11g network or by plugging directly into the router. Externally, the client software can connect to the server using any network protocol, which provides a connection to the internet. In the lab setting, an external server connection is made using Virginia Tech's integrated 802.11b wireless network. Sprint's CDMA network is used in the field to establish a connection to the server. All incoming Tracking Server port requests originating from an external source first reach the router and are then forwarded to the server.

3.4. Data Analysis Component

The Data Analysis Component provides tools to the end user to monitor and analyze data from the Data Acquisition Component in real-time. The two methods for accessing data distributed by Tracking Server are the Tracking Viewer website and Tracking Analyst on a GIS workstation. After completing the server setup as outlined in Chapter 3.3.1, no further server-side modifications are necessary for using Tracking Analyst. After making a connection to Tracking Server via Tracking Analyst a real-time layer representing data from the Data Acquisition Component may be added to the data frame in the same fashion as adding a static layer. This is demonstrated in Chapter 4. The remainder of this chapter will focus on the development of the Tracking Viewer website.

The tools used to build the Tracking Viewer website are ESRI's ArcIMS, Tracking Server Author, and Tracking Server Designer. ArcIMS is used to distribute maps and GIS data via the web (ESRI 2004a). For this research, it was used as an image service to provide the background map of Blacksburg for the Tracking Viewer website. Tracking Server Author and Designer are wizard-style tools included with Tracking Server for building the Tracking Viewer website.

The first step was to create the map for the image service using ArcIMS. As shown in Figure 3.16, shape files of Blacksburg were used to build the map for the Blacksburg image service in ArcIMS Author. The process of adding data and adjusting symbology in ArcIMS Author is virtually the same as when using ArcMap, ESRI's desktop GIS software. The Blacksburg map includes shape files representing roads, buildings, and corporate limits. After adjusting the properties of the Blacksburg map it was saved as an *.axl* file, or map configuration file.

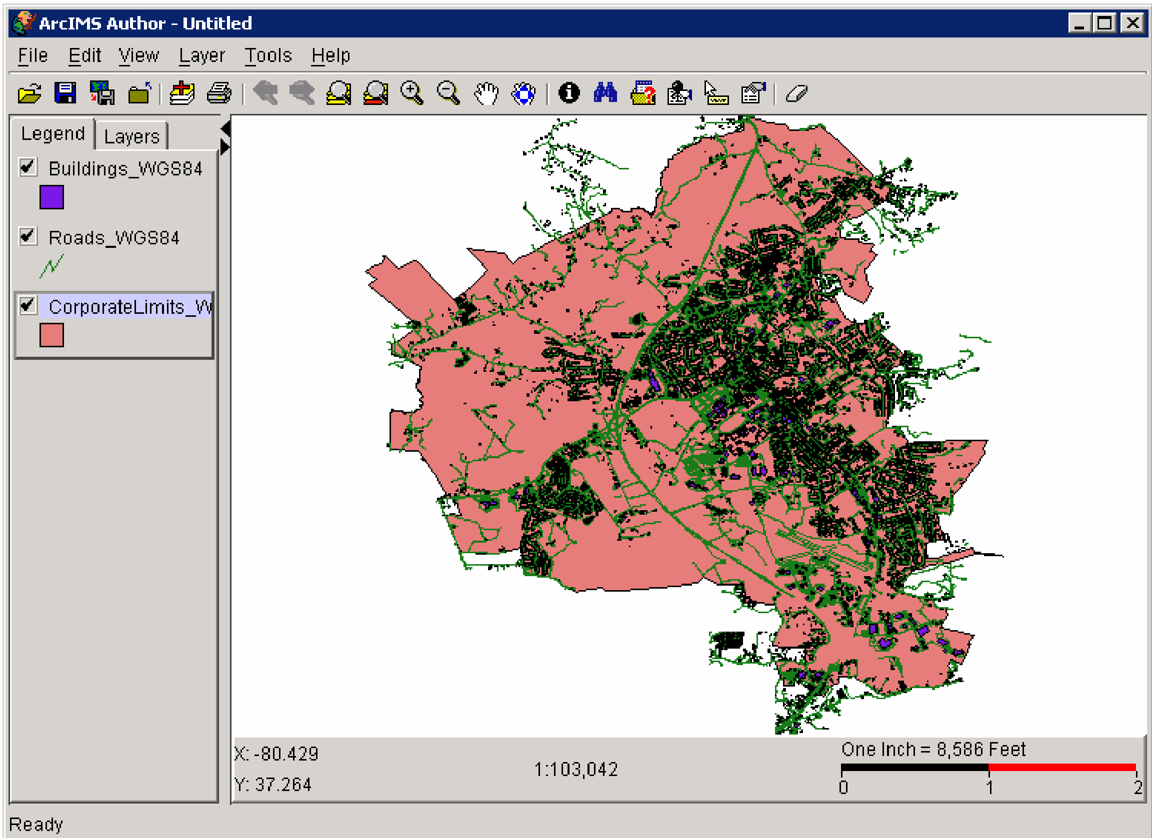

Figure 3.16 ArcIMS Author - Blacksburg map

Using ArcIMS Administrator as shown in Figure 3.17 the Blacksburg image service was created. First, "Services" was selected in the left panel of the window and the "New Services" button was selected to open the New Service dialogue box. The name "TS_BBurg_WGS84" was given to the service and the Blacksburg map configuration file was selected as the map file. After saving the configuration the Blacksburg image service was ready for use.

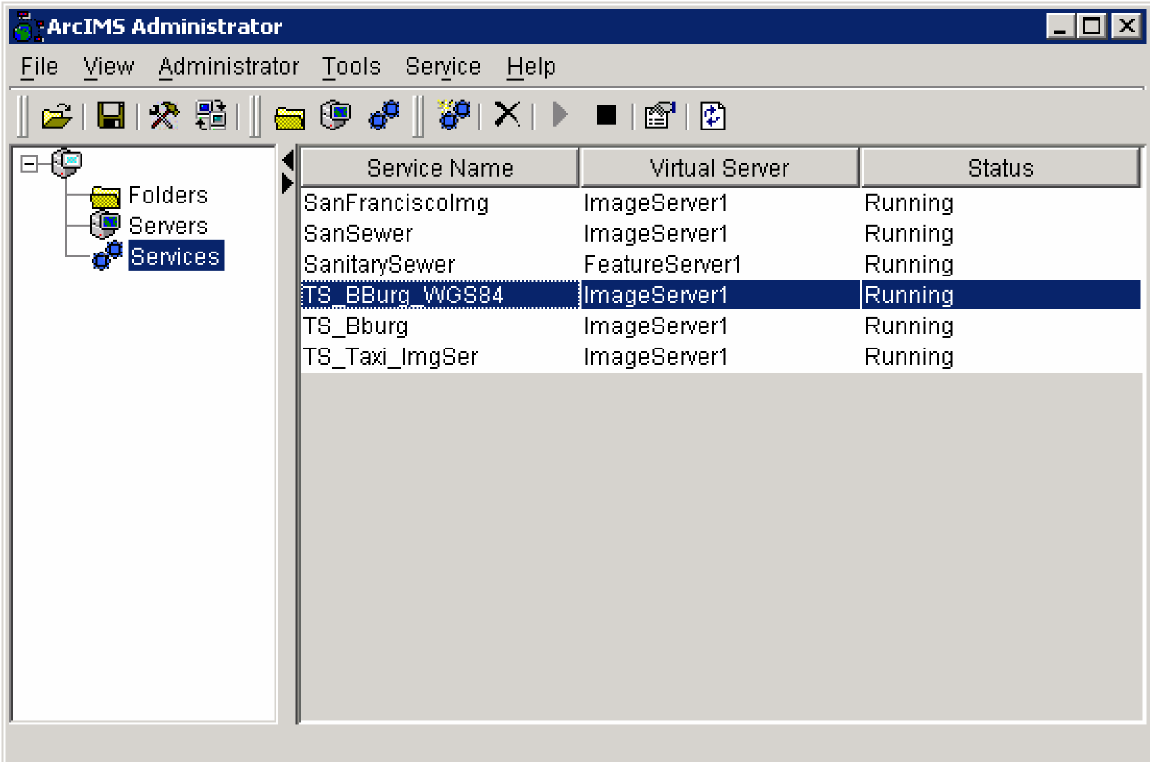

Figure 3.17 ArcIMS Administrator window

The next step in building the Tracking Viewer website was to create a tracking symbology file for the Client_V1 tracking service. This symbology file resembles an XML file and contains the settings, which describe how the real time data will be displayed in the Tracking Viewer. After opening Tracking Server Author, the Client_V1 service was selected and the main window was displayed. Figure 3.18 shows the symbology tab in Tracking Server Author. In this window the field to be displayed is selected in addition to symbol size, shape, and color. For the TGM system in this research the symbology was set up to show the last 30 seconds of travel by adjusting the color of the symbols based on their occurrence (Figure 3.18). The last step in building the tracking symbology file was to enable the Tag action discussed in Chapter 3.3.1. By clicking on the “Actions” tab in Tracking Server Author, available actions were displayed. The high vibration action as defined in Tracking Server Manager was enabled by clicking the check box next to it. Additionally, the shape, color and size of the symbol to be displayed when the action is applied were defined in this window as well. After completing the settings for the tracking symbology file it was saved as a *.txl* file (see Appendix D) to be used with Tracking Designer.

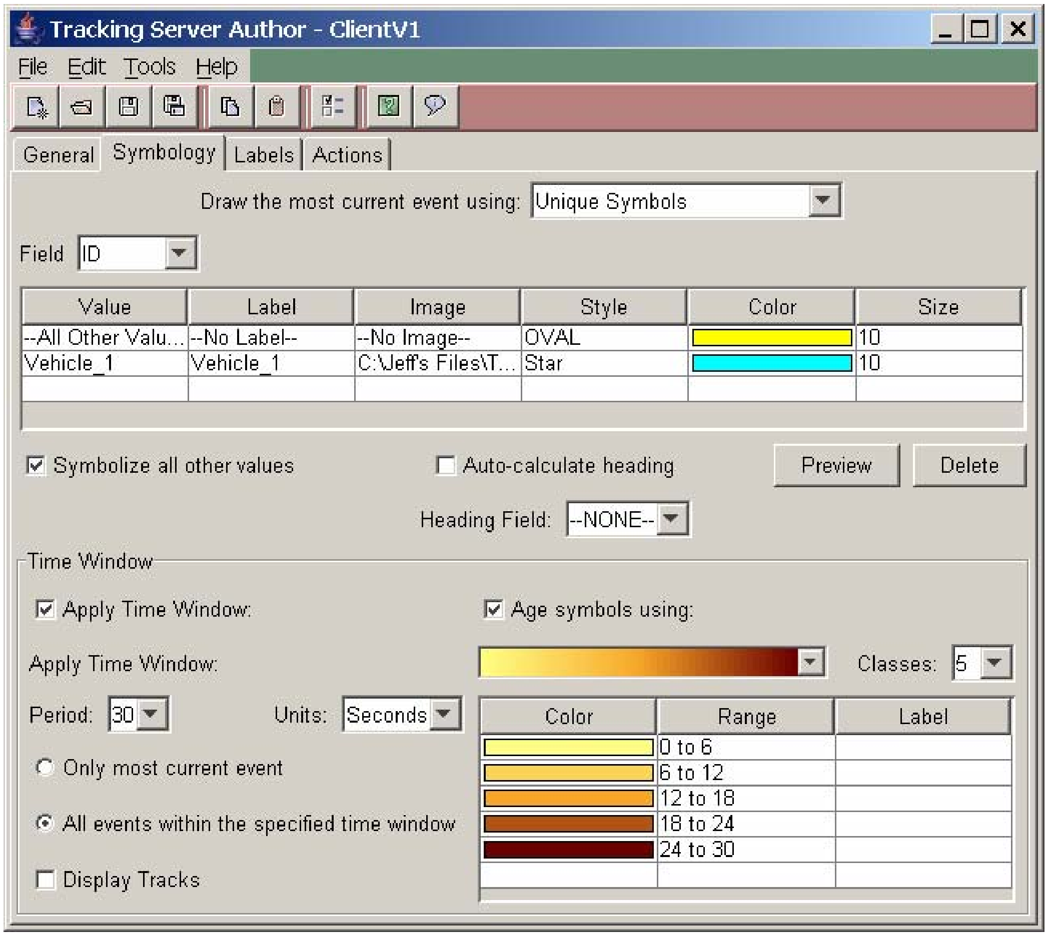

Figure 3.18 Tracking Server Author Symbology tab

Tracking Server Designer is a simple 8-step wizard used to build a Tracking Viewer website. Figure 3.19 shows each window of the 8-step process of Tracking Server Designer. Directory location and web site title are specified in the first window. The second screen connects to a user-specified ArcIMS server and lists the available image services. In the case of this research, the Blacksburg image service was hosted by a dedicated IMS server located at Virginia Tech's Center for Geospatial Information Technology (CGIT). After selecting the Blacksburg image service, the location of the tracking symbology file is specified in the third window. Appearance settings (title display, logo, color, fonts, etc.) for the Tracking Viewer website are selected in window 4. In the fifth window settings are made to enable the end user to toggle layers on and off. The initial extent of the Tracking Viewer website is set to match that of the ArcIMS image service, as shown in window 6. Window 7 enables common GIS tools (zoom, pan, information, etc.) for the website. Finally, the Tracking Server Designer process is completed by selecting "Finish" in window 8. After building the Tracking Viewer website, it was necessary to deploy the site in order to make it available on the web.

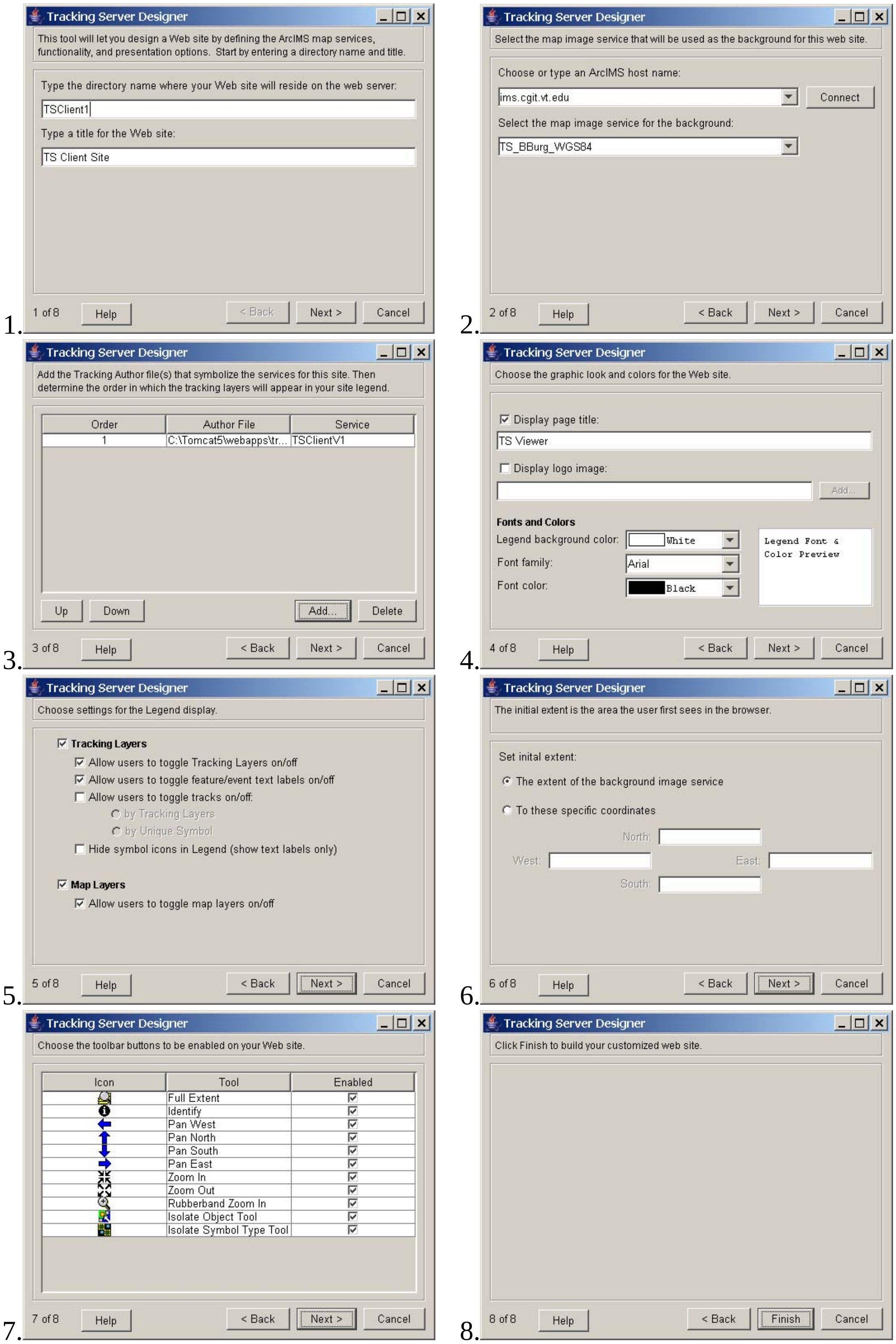

Figure 3.19 Tracking Server Designer steps for building a Tracking Viewer website

Using the local Tomcat Manager page, as shown in Figure 3.20, the website created in Tracking Server Designer was installed and made available on the web.

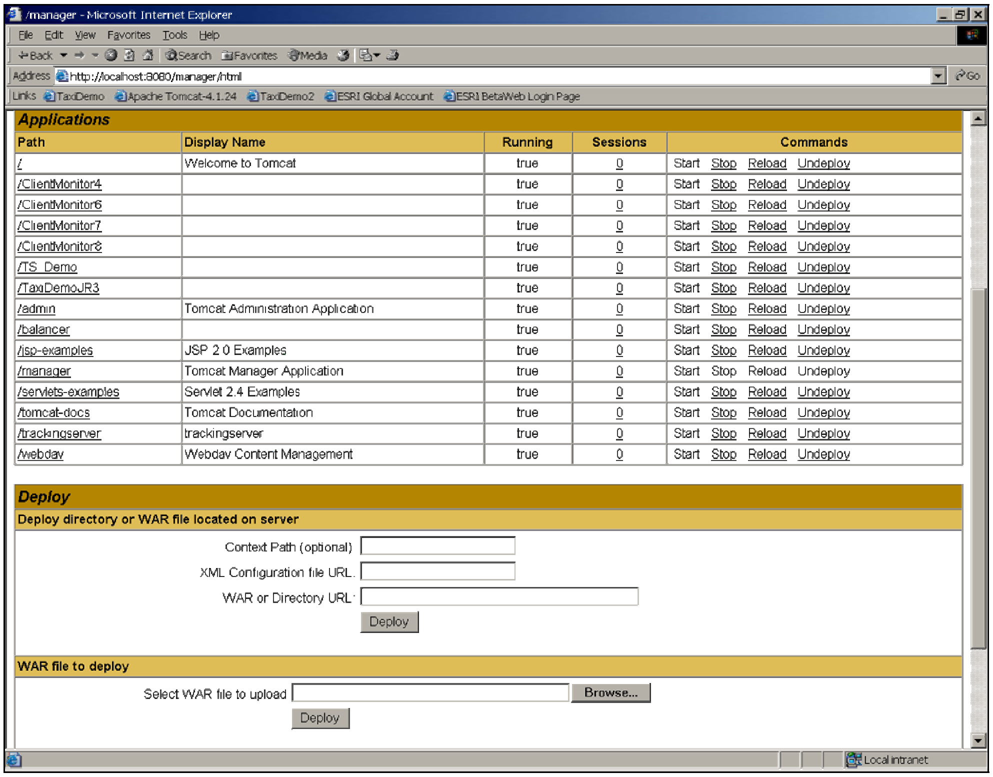

Figure 3.20 Tomcat Manager page

4. System Testing and Proof of Concept

Testing of the TGM system in the lab setting began with the development of a Client Simulator used to send XML messages to the server. Using the Client Simulator the functionality of Tracking Server, the Tracking Viewer website, and Tracking Analyst were verified. During the lab testing phase the client software was tested by verifying its connection to the server and control and management of the data acquisition hardware and GPS receiver. Full testing and proof of concept of the TGM system involved placing the Data Acquisition Component in a vehicle, driving around Blacksburg, and verifying its functionality by monitoring vehicle data via the Tracking Viewer website.

4.1. Client Simulator/Server Testing - Lab Setting

The Client Simulator, developed with LabView 7.1, was used for debugging and testing the server settings and Tracking Viewer website. The simulator operates in the same fashion as the full Client software in that it is a server connection, which initiates a connection to the server and sends XML messages. The Client Simulator GUI is shown in Figure 4.1 and the full block diagram can be seen in Appendix B. The user specifies the IP address and port number of Tracking Server and runs the program. Vehicle location coordinates are read from a CSV text file (See Appendix C), which contains previously logged GPS coordinates from a drive around Blacksburg. The timestamp field is created by accessing the system time of the computer running the Client Simulator and formatting it accordingly. A random number between 1 and 4 is used to simulate the vibration field. After accessing the CSV file, generating the timestamp, and simulating the vibration value, an XML message is composed and sent to the server. This process is repeated continuously to send XML messages in one second intervals.

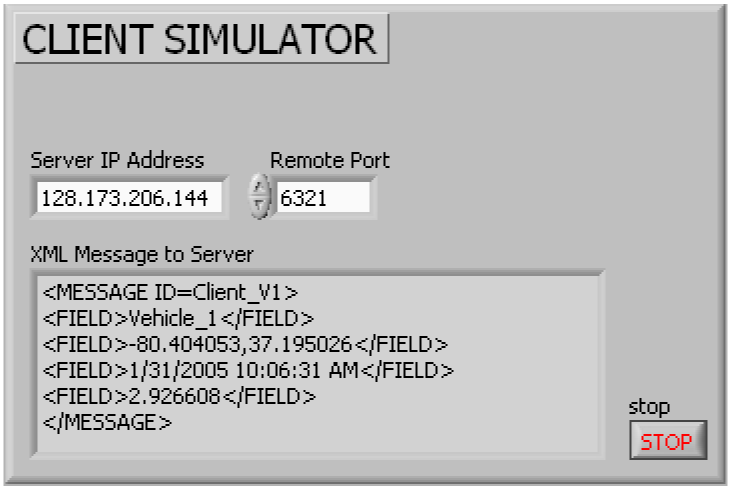

Figure 4.1 Client Simulator GUI

The Client Data Viewer, a tool supplied with Tracking Server, was used to verify that incoming data were accurately read and distributed by the serv. Figure 4.2 shows the Client Data Viewer window. The left panel shows information about the selected tracking service and the right panel shows the data distribution stream of Tracking Server. Once the messages were properly displayed in the Client Data Viewer it was fair to assume that the data should be accessible using the Tracking Viewer website and Tracking Analyst.

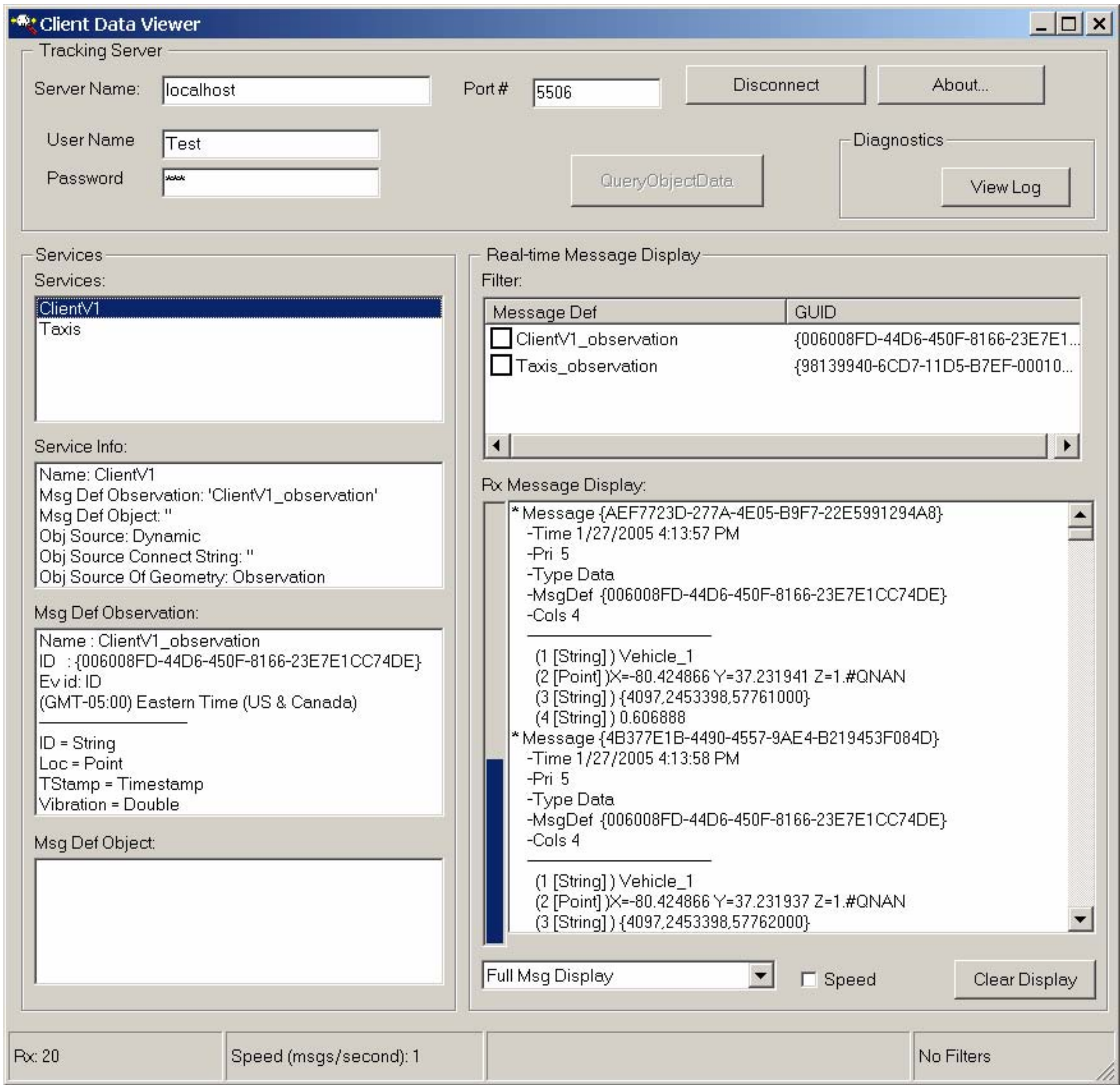

Figure 4.2 Client Data Viewer window

After observing that messages were properly received and distributed by Tracking Server the Tracking Viewer website was used to monitor the Client Simulator data as shown in Figure 4.3. The left panel shows the map layers, which can be toggled on or off by the user. The map is automatically updated as data is received. Again, the vehicle data is symbolized to show the last 30 seconds of travel as indicated by the *time window* legend in the left panel. A high vibration tag is indicated by a large red dot, which appears on the map for a few seconds.

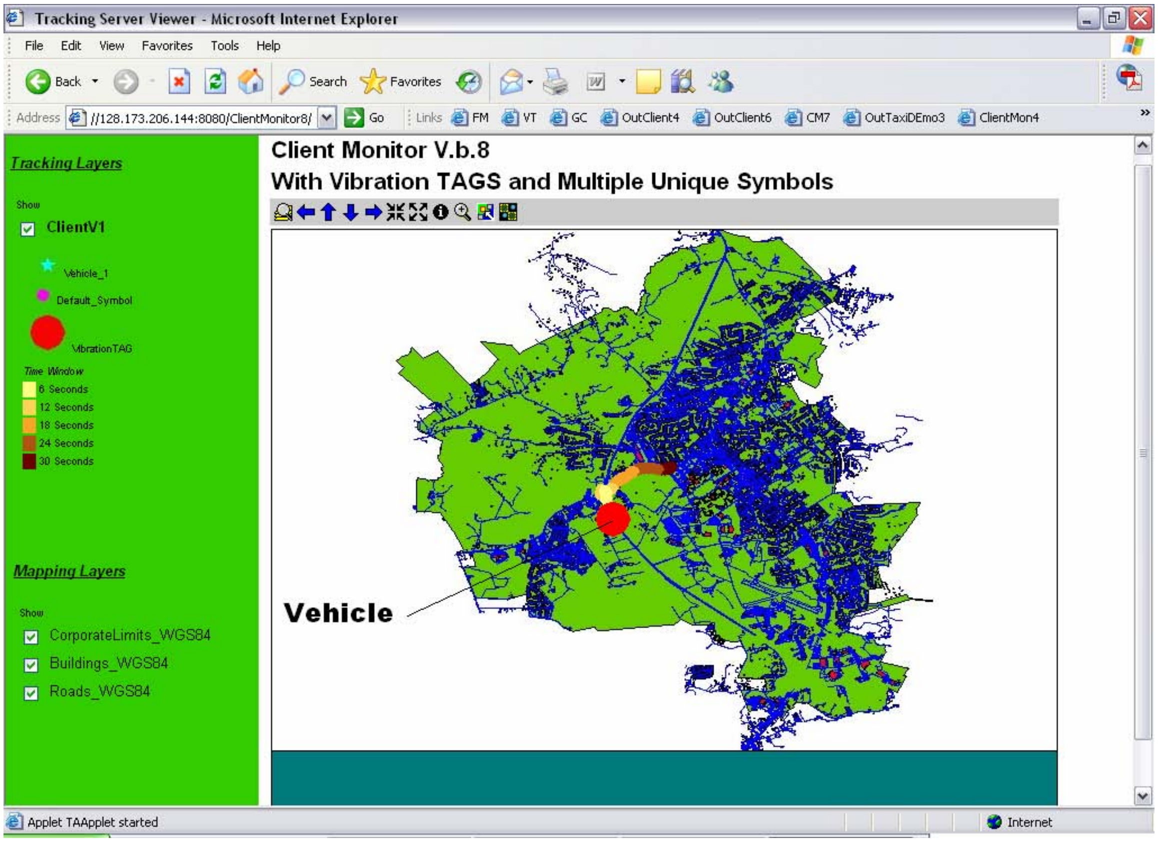

Figure 4.3 Tracking Viewer website showing Client Simulator data

Figure 4.4 shows Client Simulator data as viewed in Tracking Analyst. After establishing a connection to Tracking Server, data from the Client_V1 service may be viewed and treated as a typical layer in the GIS. Although a connection to the IMS server could have been established with Tracking Analyst to show the Blacksburg image service, locally stored Blacksburg shape files were used instead (Figure 4.4).

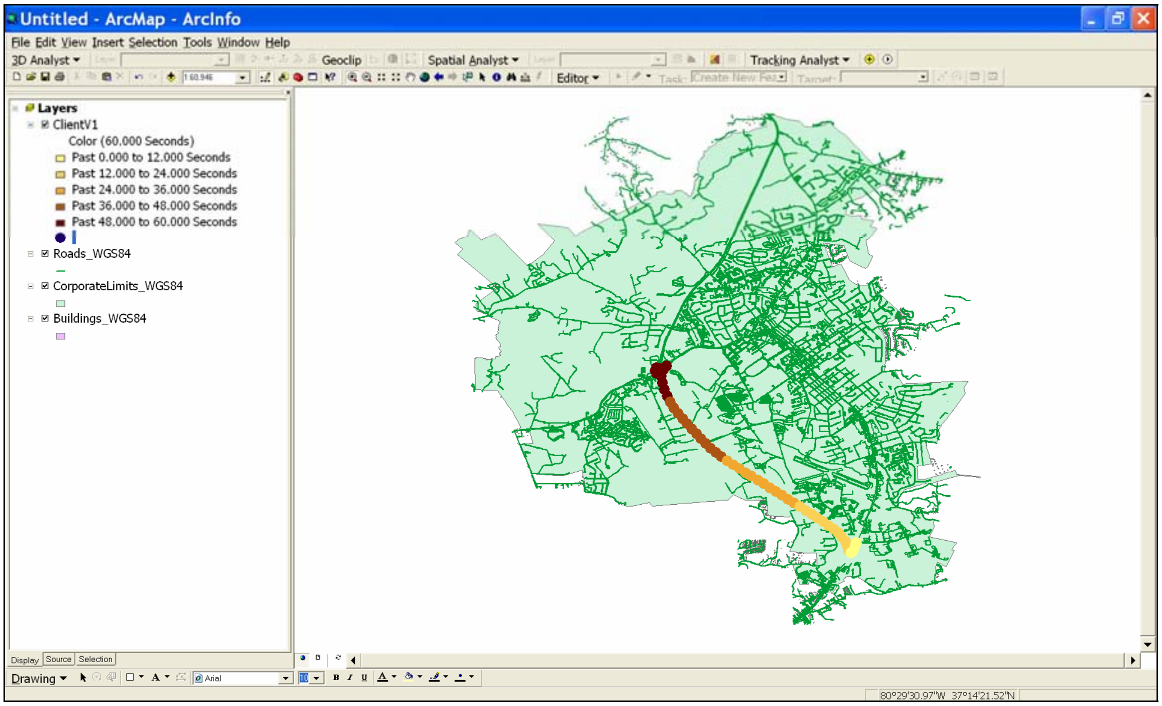

Figure 4.4 Using Tracking Analyst to view Client Simulator data

Using the *Identify* tool in ArcMap the user can click on a symbol representing the vehicle to show data corresponding to that point (Figure 4.5). The *Identify Results* window shows all information sent by the Client Simulator in addition to ID information generated by ArcMap.

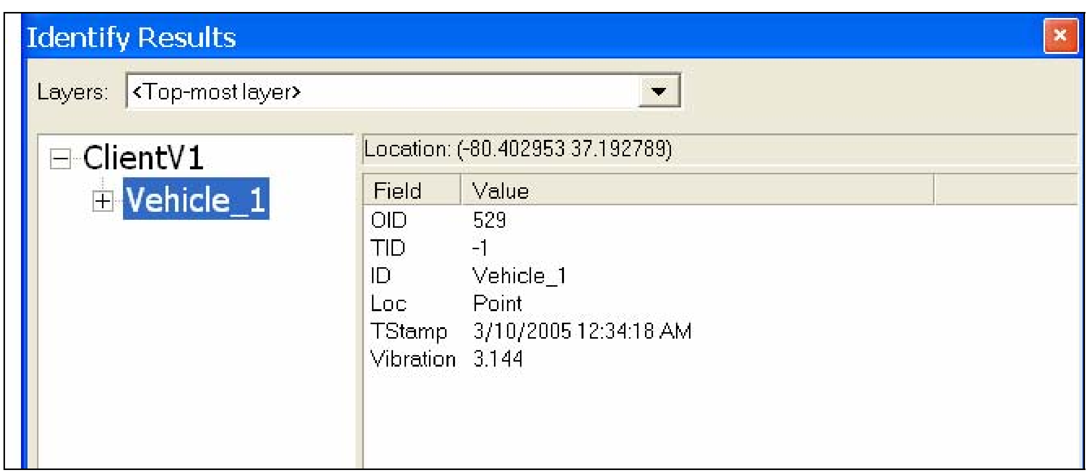

Figure 4.5 Point attributes shown using the Identify tool in ArcMap

Attributes of all the points sent by the Client Simulator can be seen by right-clicking the Client_V1 layer in the data frame in ArcMap and opening the attributes table as shown in Figure 4.6.

Attributes of ClientV1

OID	TID	ID	Loc	TStamp	Vibration
184	-1	Vehicle 1	Point Z	3/10/2005 12:28:11 AM	0.337
185	-1	Vehicle 1	Point Z	3/10/2005 12:28:12 AM	4.878
186	-1	Vehicle 1	Point Z	3/10/2005 12:28:13 AM	0.832
187	-1	Vehicle 1	Point Z	3/10/2005 12:28:14 AM	4.450
188	-1	Vehicle 1	Point Z	3/10/2005 12:28:15 AM	1.297
189	-1	Vehicle 1	Point Z	3/10/2005 12:28:16 AM	1.500
190	-1	Vehicle 1	Point Z	3/10/2005 12:28:17 AM	3.023
191	-1	Vehicle 1	Point Z	3/10/2005 12:28:18 AM	2.151
192	-1	Vehicle 1	Point Z	3/10/2005 12:28:19 AM	0.926
193	-1	Vehicle 1	Point Z	3/10/2005 12:28:20 AM	0.282
194	-1	Vehicle 1	Point Z	3/10/2005 12:28:21 AM	4.197
195	-1	Vehicle 1	Point Z	3/10/2005 12:28:22 AM	4.329
196	-1	Vehicle 1	Point Z	3/10/2005 12:28:23 AM	2.193
197	-1	Vehicle 1	Point Z	3/10/2005 12:28:24 AM	4.720
198	-1	Vehicle 1	Point Z	3/10/2005 12:28:25 AM	1.897
199	-1	Vehicle 1	Point Z	3/10/2005 12:28:26 AM	1.318
200	-1	Vehicle 1	Point Z	3/10/2005 12:28:27 AM	2.609
201	-1	Vehicle 1	Point Z	3/10/2005 12:28:28 AM	3.918
202	-1	Vehicle 1	Point Z	3/10/2005 12:28:29 AM	1.333
203	-1	Vehicle 1	Point Z	3/10/2005 12:28:30 AM	0.594
204	-1	Vehicle 1	Point Z	3/10/2005 12:28:31 AM	3.766
205	-1	Vehicle 1	Point Z	3/10/2005 12:28:32 AM	2.894
206	-1	Vehicle 1	Point Z	3/10/2005 12:28:33 AM	1.235
207	-1	Vehicle 1	Point Z	3/10/2005 12:28:34 AM	3.963
208	-1	Vehicle 1	Point Z	3/10/2005 12:28:35 AM	1.582
209	-1	Vehicle 1	Point Z	3/10/2005 12:28:36 AM	0.994
210	-1	Vehicle 1	Point Z	3/10/2005 12:28:37 AM	4.718
211	-1	Vehicle 1	Point Z	3/10/2005 12:28:38 AM	0.384
212	-1	Vehicle 1	Point Z	3/10/2005 12:28:39 AM	4.970
213	-1	Vehicle 1	Point Z	3/10/2005 12:28:40 AM	1.038
214	-1	Vehicle 1	Point Z	3/10/2005 12:28:41 AM	0.252
215	-1	Vehicle 1	Point Z	3/10/2005 12:28:42 AM	4.158
216	-1	Vehicle 1	Point Z	3/10/2005 12:28:43 AM	1.894
217	-1	Vehicle 1	Point Z	3/10/2005 12:28:44 AM	3.874
218	-1	Vehicle 1	Point Z	3/10/2005 12:28:45 AM	1.499
219	-1	Vehicle 1	Point Z	3/10/2005 12:28:46 AM	3.192
220	-1	Vehicle 1	Point Z	3/10/2005 12:28:47 AM	0.148
221	-1	Vehicle 1	Point Z	3/10/2005 12:28:48 AM	0.480
222	-1	Vehicle 1	Point Z	3/10/2005 12:28:49 AM	1.981
223	-1	Vehicle 1	Point Z	3/10/2005 12:28:50 AM	4.409
224	-1	Vehicle 1	Point Z	3/10/2005 12:28:51 AM	3.252
225	-1	Vehicle 1	Point Z	3/10/2005 12:28:52 AM	0.646
226	-1	Vehicle 1	Point Z	3/10/2005 12:28:53 AM	3.180
227	-1	Vehicle 1	Point Z	3/10/2005 12:28:54 AM	1.783
228	-1	Vehicle 1	Point Z	3/10/2005 12:28:55 AM	0.268

Record: 1 Show: All Selected Records (0 out of 944 Selected.) Options

Figure 4.6 Attributes table for the real-time Client_V1 layer

Just as actions were defined and applied in Tracking Server Manager for use with the Tracking Viewer website, actions may be created in Tracking Analyst and applied to the incoming data stream. Figure 4.7 shows the process of setting up an action tag in Tracking Analyst. The procedure is virtually the same as defining an action in Tracking

Server Manager. In this case, the action was set to tag a record when the corresponding vibration exceeds a value of three. Figure 4.8 shows a close-up view of the Client Simulator data in Tracking Analyst after actions were applied. Star symbols on the map represent vehicle locations where the vibration value was greater than three.

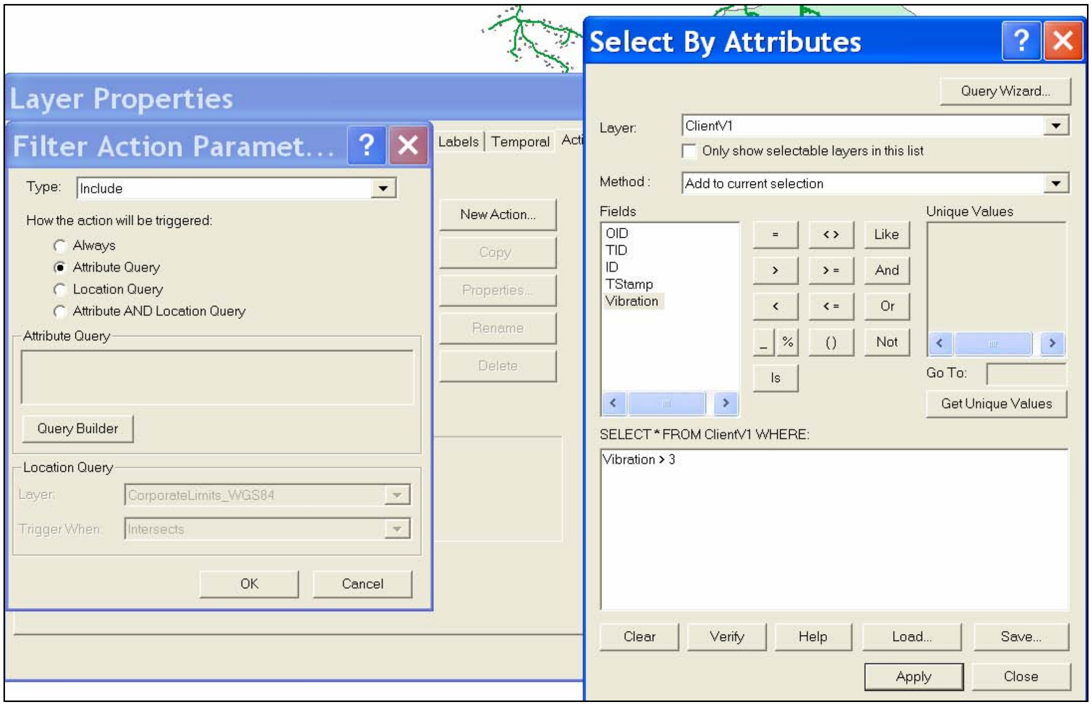

Figure 4.7 Applying actions in Tracking Analyst

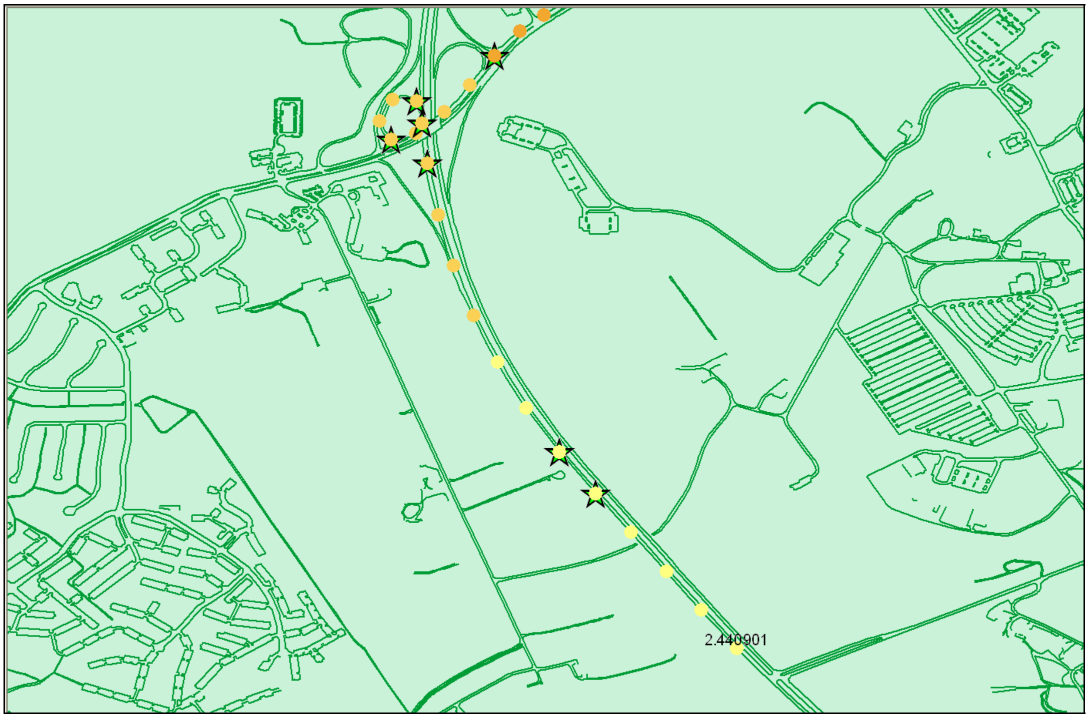

Figure 4.8 Close-up of real-time tagged data in Tracking Analyst

After successful demonstration of the Client Simulator, Tracking Viewer website, and Tracking Analyst it was assumed that the latter two were ready for use with the full client software, provided XML messages were properly sent to Tracking Server.

4.2. Client Testing - Lab Setting

Client testing in the lab was limited mostly to verifying the format of the incoming messages received by Tracking Server and debugging the client software accordingly. Although a GPS signal was unobtainable in the lab, the receiver could be used to send the last known set of coordinates, which would allow for a stationary dot to appear on the Tracking Viewer website or Tracking Analyst. Once the client software and Data Acquisition Component seemed to be functioning properly with Tracking Server the system was tested in the field.

4.3. Proof of Concept - Field Setting

The proof of concept field test was carried out by placing the Data Acquisition Component in a vehicle (Figure 4.9), driving around Blacksburg, and monitoring the vehicle's location and vibration data via the Tracking Viewer website (Figure 4.10).

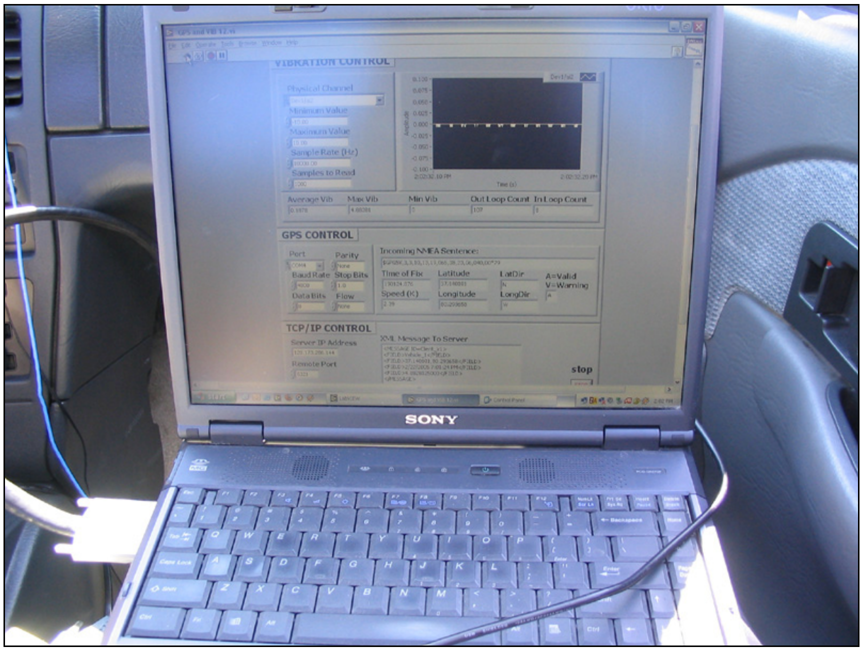

Figure 4.9 Data Acquisition Component operating during the field test

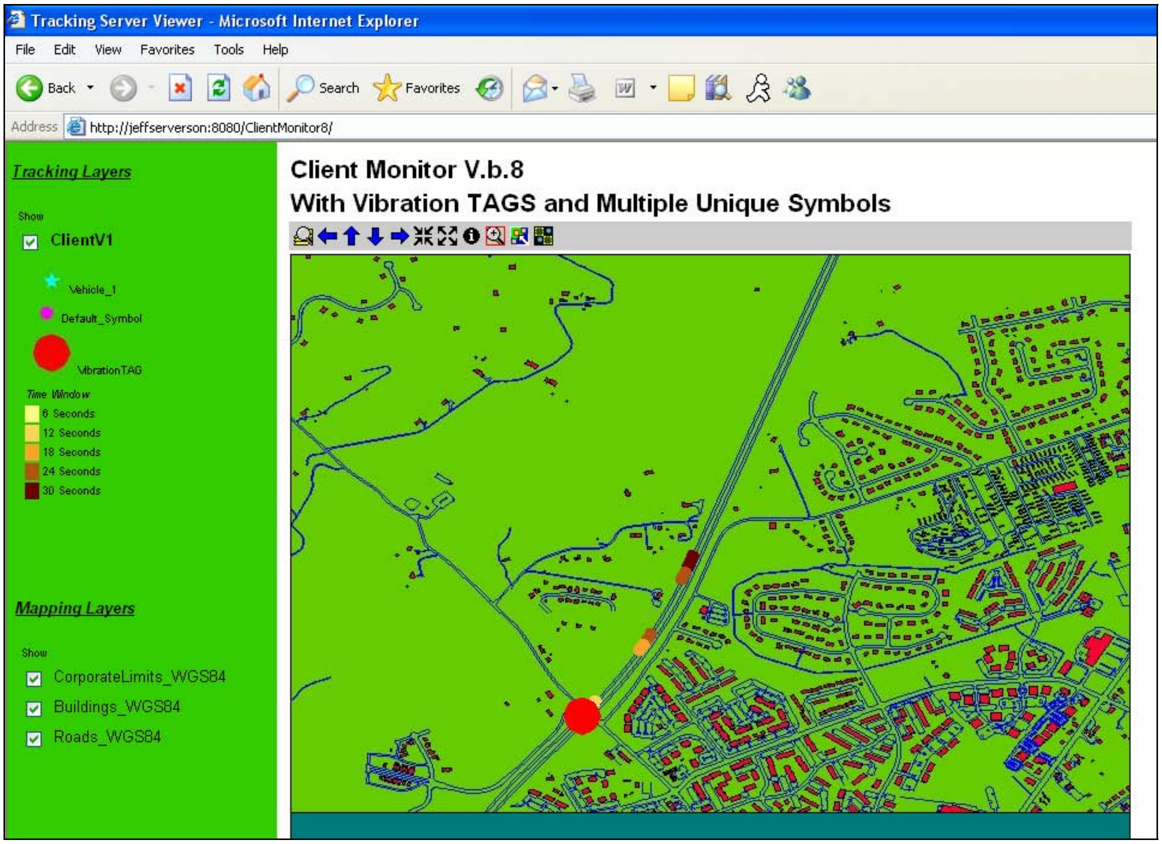

Figure 4.10 Real-time field test data shown on the Tracking Viewer website

Using an additional cell phone for voice communication, the vehicle's location was verbally verified at several points in the trip with someone observing the Tracking Viewer website. Included in Appendix E with the hard copy of this thesis, is a video of the second TGM system field test, which shows the vehicle's trip as seen on the Tracking Viewer website and simultaneous clips of the Data Acquisition System in operation.

5. Conclusions and Recommendations

5.1. Conclusions

A TeleGeoMonitoring (TGM) system to spatially monitor and analyze vehicle derived vibration data in real-time was developed. This system serves as a prototype model for a customizable TGM system capable of monitoring and analyzing data derived from any type of vehicle-mounted or mobile sensor in real-time. Although it is built with proprietary hardware and software, the architecture of the TGM vibration system is open for modification or custom tailored solutions, which aim to spatially monitor and analyze remotely derived data in real-time. The TGM vibration system was demonstrated by verifying that data were consistently acquired in a mobile environment, successfully sent to the Tracking Server, and properly displayed on the Tracking Viewer website. This research achieved its goal of proving the concept of a TGM system to spatially monitor vehicle vibration in real-time. However, many improvements and extensions are envisioned for the future of the TGM system and its related research.

5.2. Recommendations

Immediate recommendations (enumerated below) include improvements to the TGM vibration system. The (1) introduction of RTK-GPS or DGPS corrections could significantly improve the accuracy of the vehicle's location coordinates. A feasible option to improve GPS accuracy is to send corrections from Tracking Server to the client software via a custom data link. The (2) signal to noise ratio of the vibration data could improve with the application of appropriate amplifiers and filters to the Data Acquisition Component. Also, as mentioned by Rouillard (2002), the TGM system could benefit from (3) data compression with minimal loss. Regarding the client GUI, (4) several parts could be removed to improve performance. Display of the dynamic vibration waveform is both processor intensive and unnecessary from a functionality point of view. Simplification of the client software display could make possible the use of small tablet PCs or PDAs instead of the laptop, which is currently used.

Ultimately, it is envisioned that the TGM vibration system developed in this research could evolve into a powerful research tool or comprehensive mine management solution. As a research tool, variations of the TGM system could benefit health and safety studies, equipment diagnostic studies and tests, tire research, haul road studies, etc. Bringing real-time data layers into an already powerful GIS environment could aide mine management and planning by allowing for decisions based on the mine status at that moment. If the TGM system were used at a surface mine it is likely that an alternative means of transferring data would have to be considered. Surface mines are often located remotely and may contain obstructed views of communication satellites. A Mobile Ad Hoc Network (MANET) may be a suitable option for establishing a mine-wide wireless data network. As mentioned earlier, a MANET lacks fixed infrastructure and is comprised of mobile nodes (i.e. vehicles). Data may *hop* from one node to the next until it reaches its destination. A MANET would remove the need for an outside data network (i.e. CDMA) and would reduce the amount of equipment required to establish a network. Figure 5.1 illustrates a variation of the TGM system as envisioned at a surface mine operation. The dashed lines in Figure 5.1 represent GPS data and the dotted lines represent a MANET.

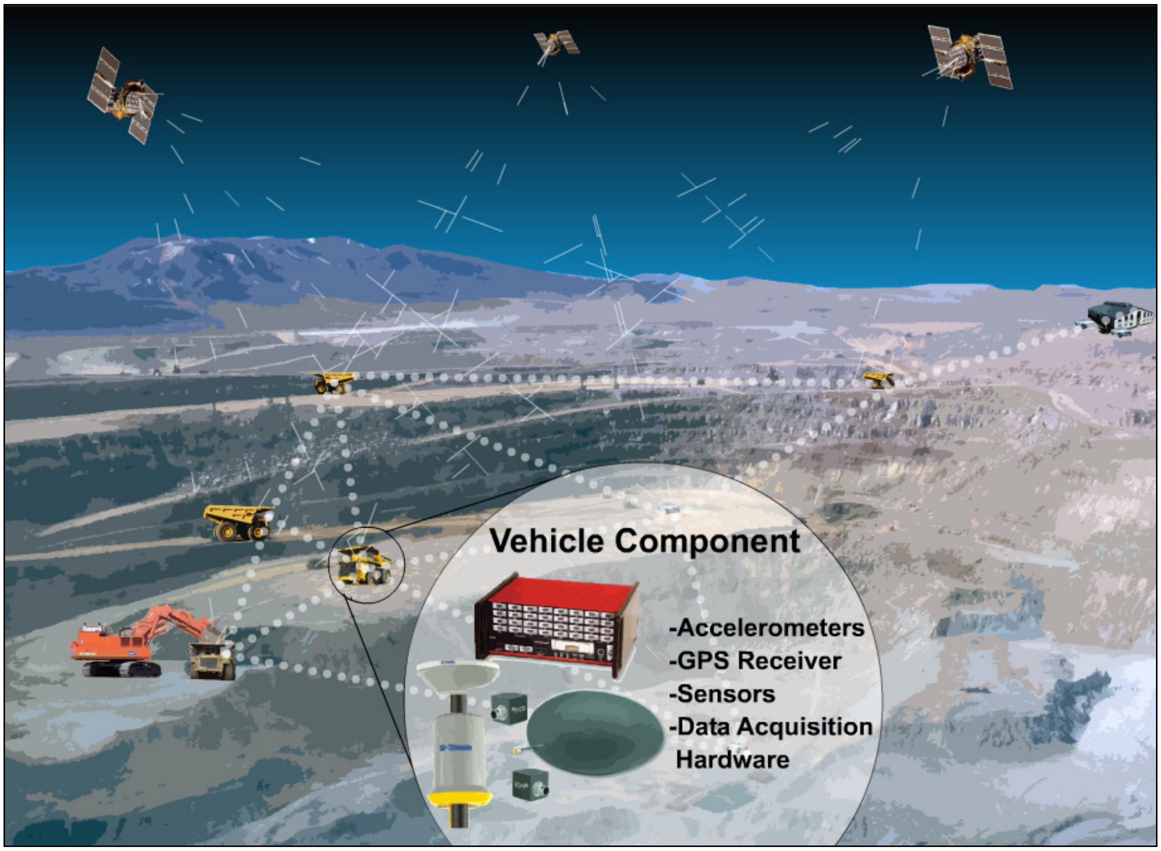

Figure 5.1 Envisioned TGM system installed on an equipment fleet at a surface mining operation

Whether for research or management, TGM systems prove to be a powerful option where customized solutions for monitoring and analyzing real-time vehicle-derived data are required.

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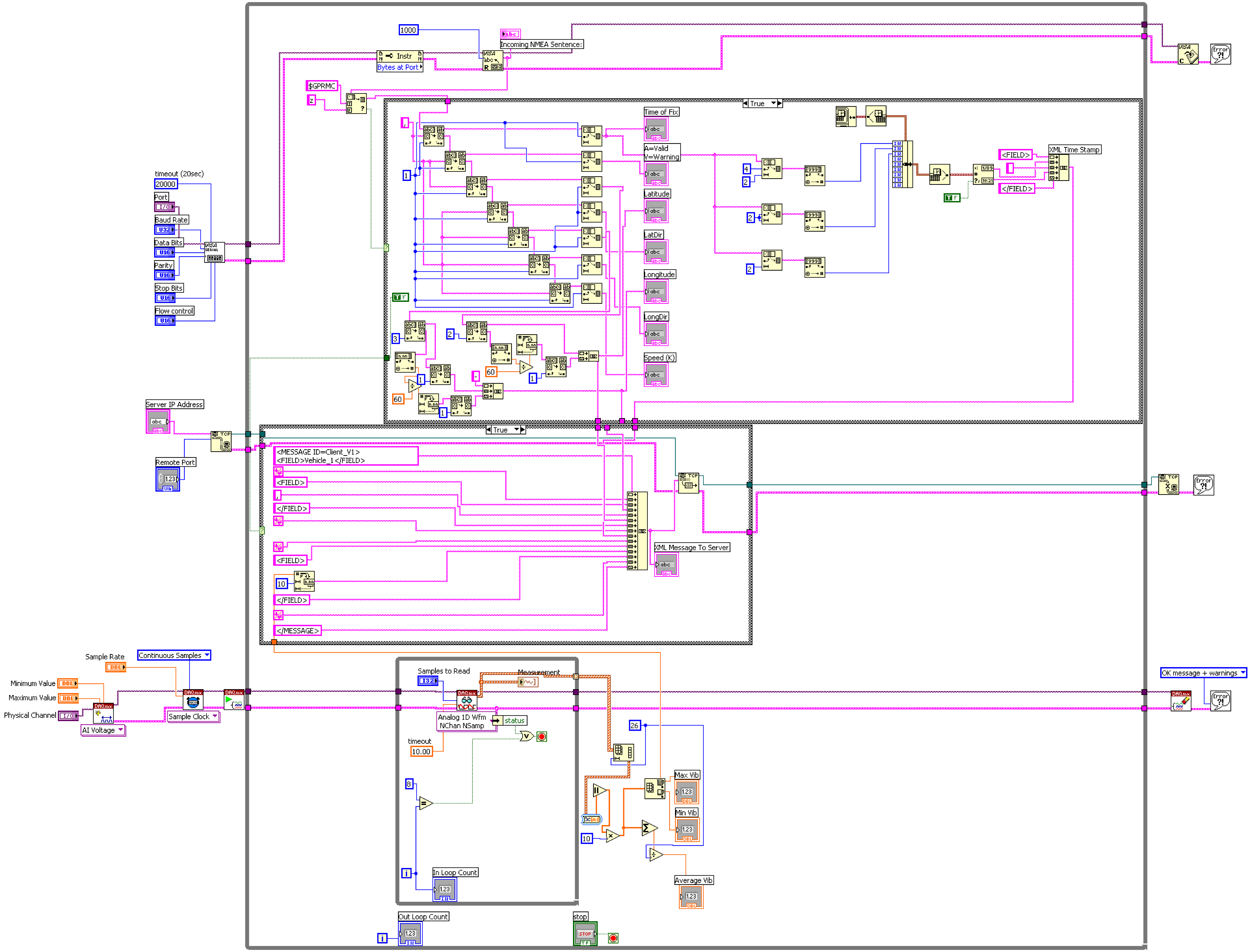
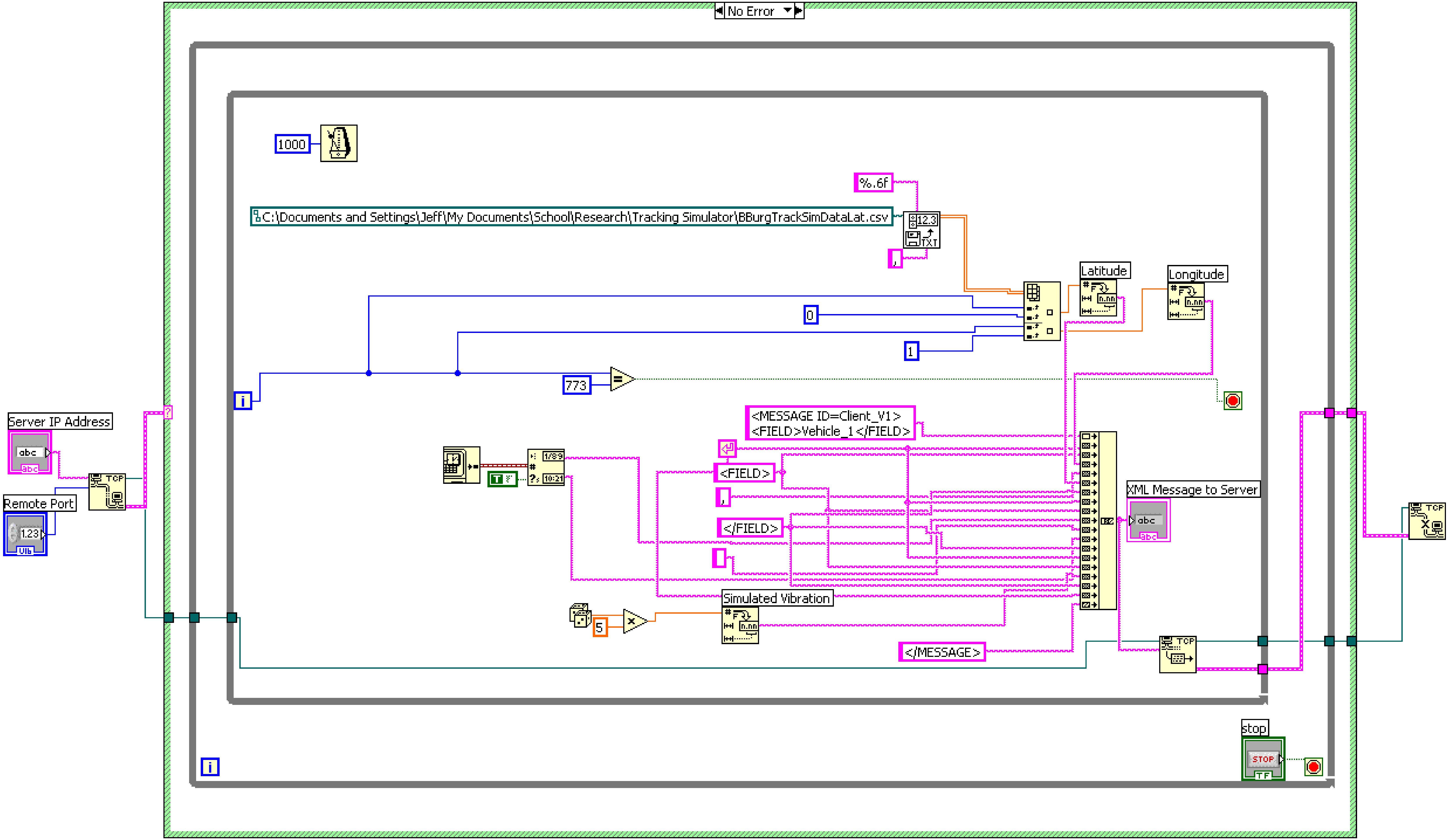
Appendix A: Client Block Diagram



Appendix B: Client Simulator Block Diagram



Appendix C: Blacksburg Simulator Data

```
37.232731,-80.421205,0,0
37.232788,-80.421194,0,0
37.231895,-80.425185,612.558777,0.136509
37.231918,-80.425076,593.481873,0.147522
37.231938,-80.42493,568.821533,0.076036
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37.232083,-80.425089,600.17688,7.446686
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37.231957,-80.428103,606.585388,34.225414
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37.231465,-80.429656,614.6828,43.087696
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37.230553,-80.436385,613.640137,64.959465
37.230067,-80.437161,613.972656,60.343327
37.229675,-80.437783,613.84314,40.004028
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37.230988,-80.422919,603.247375,5.173684
37.230974,-80.422863,602.841248,2.799567
37.230941,-80.422815,603.640564,4.300826
37.230903,-80.422752,604.091003,4.955735
37.230867,-80.422681,604.989868,5.339124
37.230833,-80.422607,605.737549,5.471367
37.230807,-80.422529,607.523743,5.39356
37.230771,-80.422462,607.046204,5.150097
37.230716,-80.422429,607.043579,5.047721
37.23066,-80.422428,605.622498,4.789346
```

Appendix D: Tracking Symbology File


```
<?xml version="1.0"?>
<TRACKING_ANALYST_SYMBOLOGY>
      <TRACKING_SERVICE_ITEMS version="1.0" name="" type="" id="">
            <TRACKING_SERVICE version="1.0" name="ClientV1" type="Point"
id="0">
                  <ACTION_ITEMS>
                        <ACTIONS_ENABLED>true</ACTIONS_ENABLED>
                        <ACTION tag="HighVibration" version="1.0"
name="VibrationTAG" type="Tag" id="{006008FD-44D6-450F-8166-
23E7E1CC74DE}">
                              <SHAPE>Circle</SHAPE>
                              <COLOR>FF0000</COLOR>
                              <SIZE>30</SIZE>
                              <ENABLED>true</ENABLED>
                        </ACTION>
                  </ACTION_ITEMS>
                  <LABEL_ITEMS type="type1">
                        <LABEL_ITEMS_ENABLED>off</LABEL_ITEMS_ENABLED>
                        <INCLUDE_FIELD_NAMES>off</INCLUDE_FIELD_NAMES>
                        <LABEL version="1.0" name="New" type="type1"
id="0">
                              <LABEL_FIELD_NAME>ID</LABEL_FIELD_NAME>

      <INCLUDE_FIELD_NAME>off</INCLUDE_FIELD_NAME>
                              <LABEL_ENABLED>off</LABEL_ENABLED>
                              <LABEL_PLACEMENT>SE</LABEL_PLACEMENT>
                              <SYMBOL_LABEL_FONT version="1.0" name=""
type="" id="">
                                    <FONT_SIZE>10</FONT_SIZE>
                                    <FONT_STYLE>Times New
Roman</FONT_STYLE>
                                    <FONT_COLOR>000000</FONT_COLOR>
                              </SYMBOL_LABEL_FONT>
                        </LABEL>
                  </LABEL_ITEMS>
                  <SYMBOLOGY_LEVELS>
                        <SYMBOLOGY version="1.0" name="Many" type="Many"
id="0">

      <AUTO_CALCULATE_HEADING>off</AUTO_CALCULATE_HEADING>

      <USES_DEFAULT_SYMBOL>on</USES_DEFAULT_SYMBOL>
                              <ACTIVE>on</ACTIVE>
                              <HEADING_FIELD>--NONE--</HEADING_FIELD>
                              <MOLE_FIELDS>
                                    <MOLE_STRENGTH>--NONE--
</MOLE_STRENGTH>
                                    <MOLE_FIELD>--NONE--</MOLE_FIELD>
                                    <MOLE_NAME>--NONE--</MOLE_NAME>
                                    <MOLE_QUANTITY>--NONE--
</MOLE_QUANTITY>
                                    <MOLE_IMAGE_SIZE>--NONE--
</MOLE_IMAGE_SIZE>
                                    <MOLE_RATING>--NONE--</MOLE_RATING>
                                    <MOLE_SPEED>--NONE--</MOLE_SPEED>
                                    <MOLE_TYPE>--NONE--</MOLE_TYPE>
                                    <MOLE_PARENT>--NONE--</MOLE_PARENT>
                              </MOLE_FIELDS>
                              <TIME_WINDOW>
                                    <AGE_SYMBOLS>on</AGE_SYMBOLS>
                                    <UNITS>Seconds</UNITS>
```

```
<DISPLAY_TRACK>off</DISPLAY_TRACK>
<EVENT_TYPE>ALL_EVENTS</EVENT_TYPE>
<PERIOD>30</PERIOD>
<ENABLED>on</ENABLED>
<AGING>
<CLASSES>5</CLASSES>
<AGING_CLASS_ITEMS>
<AGING_CLASS id="0">

<TIME_RANGE>6</TIME_RANGE>

<AGING_COLOR>FFFF84</AGING_COLOR>
<AGING_LABEL>--No
Label--</AGING_LABEL>
</AGING_CLASS>
<AGING_CLASS id="1">

<TIME_RANGE>12</TIME_RANGE>

<AGING_COLOR>FBD357</AGING_COLOR>
<AGING_LABEL>--No
Label--</AGING_LABEL>
</AGING_CLASS>
<AGING_CLASS id="2">

<TIME_RANGE>18</TIME_RANGE>

<AGING_COLOR>F7A629</AGING_COLOR>
<AGING_LABEL>--No
Label--</AGING_LABEL>
</AGING_CLASS>
<AGING_CLASS id="3">

<TIME_RANGE>24</TIME_RANGE>

<AGING_COLOR>B15315</AGING_COLOR>
<AGING_LABEL>--No
Label--</AGING_LABEL>
</AGING_CLASS>
<AGING_CLASS id="4">

<TIME_RANGE>30</TIME_RANGE>

<AGING_COLOR>6B0000</AGING_COLOR>
<AGING_LABEL>--No
Label--</AGING_LABEL>
</AGING_CLASS>
</AGING_CLASS_ITEMS>
</AGING>
</TIME_WINDOW>
<FIELD_SYMBOL_MAPPING version="1.0"
name="" type="" id="">
<MAPPING_ITEMS>
<MAPPING name="" id="0">
<LABEL>Vehicle_1</LABEL>
<FIELD_VALUE_ITEMS
type="AND">
<FIELD_NAME_VALUE
id="0">

<FIELD_VALUE>Vehicle_1</FIELD_VALUE>

<FIELD_NAME>ID</FIELD_NAME>
```

```
      </FIELD_NAME_VALUE>
                                                            <FIELD_NAME_VALUE
id="1">
      <FIELD_VALUE>Vibration</FIELD_VALUE>
      <FIELD_NAME>Vibration</FIELD_NAME>
      </FIELD_NAME_VALUE>
                                                            <FIELD_NAME_VALUE
id="2">
      <FIELD_VALUE>--Field Value--</FIELD_VALUE>
      <FIELD_NAME>--NONE--</FIELD_NAME>
      </FIELD_NAME_VALUE>
                                                      </FIELD_VALUE_ITEMS>
                                                      <SYMBOL version="1.0"
name="" type="Point" id="">
      <SHAPE>Star</SHAPE>
      <LABEL>Vehicle_1</LABEL>
      <FILL_COLOR>00FFFF</FILL_COLOR>
                                                            <IMAGE>--No Image-
-</IMAGE>
      <LINE_COLOR>00FFFF</LINE_COLOR>
                                                            <SIZE>10</SIZE>
                                                      </SYMBOL>
                                                </MAPPING>
                                          </MAPPING_ITEMS>
                                    </FIELD_SYMBOL_MAPPING>
                                    <SYMBOL version="1.0"
name="Default_Symbol" type="Point" id="">
                                          <SHAPE>OVAL</SHAPE>
                                          <LABEL>--No Label--</LABEL>
                                          <FILL_COLOR>FF00FF</FILL_COLOR>
                                          <IMAGE>--No Image--</IMAGE>
                                          <LINE_COLOR>FF00FF</LINE_COLOR>
                                          <SIZE>10</SIZE>
                                    </SYMBOL>
                              </SYMBOLOGY>
                        </SYMBOLOGY_LEVELS>
                  </TRACKING_SERVICE>
      </TRACKING_SERVICE_ITEMS>
</TRACKING_ANALYST_SYMBOLOGY>
```

Appendix E: CD Supplement

CD Contents:

- Client Virtual Instrument (.vi)
- Client Simulator Virtual Instrument (.vi)
- Blacksburg simulator data (.csv)
- Tracking Viewer website symbology file (.txl)
- Video of second field test (.wmv)
- Digital version of this thesis (.pdf)