A Dual-Mode GPS Real-Time Kinematic System for Seamless Ultrahigh-Precision Positioning and Navigation

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BIOGRAPHIES

Donghyun Kim is a research associate in the Department of Geodesy and Geomatics Engineering at the University of New Brunswick (UNB), where he has developed the UNB RTK (real-time kinematic) system for a gantry crane auto-steering system. He has a B.Sc., M.S. and Ph.D. in geomatics from Seoul National University. He has been involved in GPS research since 1991. Currently, he carries out research related to ultrahigh-performance RTK positioning at up to a 50 Hz data rate, with application to real-time deformation monitoring, Internet-based moving platform tracking, and machine control.

Richard Langley is a professor in the Department of Geodesy and Geomatics Engineering at UNB, where he has been teaching since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. Prof. Langley has been active in the development of GPS error models since the early 1980s and is a contributing editor and columnist for GPS World magazine.

ABSTRACT

A variety of broadband wireless access technologies were investigated for improving the performance of GPS RTK systems. Compared with UHF radio modems, broadband wireless access technologies provide great advantages for RTK applications. For example, the line-of-sight condition for a radio link is not required any more except for "last mile" wireless connection (*i.e.*, wireless connection of end-user devices to wired networks). This potentially improves the available performance of an RTK system, especially in medium and long-baseline applications. Also, network-based global RTK applications and diversified location-based services integrated with RTK and multimedia are feasible. These advantages are mainly thanks to broadband access connectivity from the core infrastructure network to end-user devices. As end-user devices and GPS resources such as permanent (or localized) reference stations become available more and more on the network, we can expect more practical and fully operational RTK systems. In this paper, we introduce the UNB RTK system which was initially developed for a rubber-tired gantry crane (RTGC) auto-steering system and discuss recent upgrades to improve the availability of the RTK system by using broadband wireless communication.

INTRODUCTION

As is typically the case for most RTK applications, machine-control applications such as an RTGC auto-steering system require positioning accuracies better than a few centimetres with extremely high reliability in a real-time and kinematic mode. However, unlike many other RTK systems, this emerging RTK-based RTGC auto-steering system requires positioning solutions at a high update rate; *e.g.*, 10 Hz or higher. Downlink (from base station to the cranes) RTK data rates required for this application can reach up to 69 Kbps at a 10 Hz update rate. Data uplink (from the cranes to a monitoring center) was not considered for the initial system design. Later on, however, the capability of a data uplink can be easily implemented in the system. As a result, the overall RTK data rate could be higher than 100 Kbps when a full data link (down- and up-link) is established. This requirement prevents the system from using conventional UHF radio modems for real-time data communication. As an alternative, a variety of broadband wireless access technologies were investigated for the system.

The UNB RTK system, initially designed for the RTGC auto-steering system, is able to provide navigation solutions in real time at a 10 Hz or higher update rate, commensurate with the dual-frequency data rate. The system works in conjunction with a GPS receiver and the Institute of Electrical and Electronics Engineers (IEEE) 108.11b compatible 2.4 GHz wireless local area network (WLAN) master unit at an RTK base station and two dual-frequency GPS receivers with WLAN adapters installed on RTGCs [Kim *et al*., 2002; Kim and Langley, 2002; Kim *et al*., 2003; Kim and Langley, 2003a; Kim and Langley, 2003b]. In the initial implementation of the system at a port container terminal in South Korea, seven RTGCs operating simultaneously communicate directly with the RTK base station and each other on a peer-to-peer level (or ad hoc mode) sharing a given cell coverage area. This type of network is often formed on a temporary basis and is commonly referred to as an ad hoc network. It is mainly used to quickly and easily set up a WLAN where no wired network (core infrastructure) is available; *e.g*., at a port container yard, mine, construction site and so on.

In many instances, an ad hoc network may contain an access point (AP). The main function of an AP is to form a bridge between wireless and wired LANs. The AP is analogous to a base station used in cellular phone networks. When an AP is present, stations do not communicate on a peer-to-peer basis. All communications between stations (or between a station and a wired network client) go through the AP. An AP is not mobile and forms part of the wired network infrastructure. An ad hoc network in this configuration is said to be operating in the infrastructure mode. Customer premises equipment access gateways, such as an AP in wired networks and a base station in cellular phone networks, provide broadband access connectivity from the core infrastructure to end-user devices using one or more broadband communication technologies.

We have explored the capabilities of the UNB RTK system in new GPS applications. Recently, tests of this system for deformation monitoring have been carried out at Highland Valley Copper Mine in British Columbia, Canada. Also, tests to investigate the performance of the software under long-baseline situations including on-land and offshore environments are being conducted. Spread spectrum wireless radios using the 900 MHz frequency band, dual-mode WLAN (IEEE 802.11b and 802.11a using the 2.4 GHz and 5 GHz frequency bands, respectively) and wired LAN have been used for real-time testing. From the initial investigations for new RTK applications, a second generation of the UNB RTK system has been developed which improves system performance for different applications by improving broadband access connectivity from the core infrastructure to end-user devices.

BROADBAND ACCESS TECHNOLOGY

Broadband communication consists of the technologies and equipment required to deliver packet-based digital voice, video, and data services to end users. Broadband affords end users high-speed, always-on access to the Internet while affording service providers the ability to offer value-added services. Due to the growth of the Internet, there has been tremendous build-up of high-speed, inter-city communication links that connect population centres and Internet service providers around the world. This build-up of the backbone (core) infrastructure network has occurred primarily via optical communication technologies. Broadband access connectivity from the core infrastructure to end-user devices (e.g., PCs, personal digital assistants (PDAs), telephones, television sets, digital cameras, *etc*.) is provided by customer premises equipment access gateways via one or more home networking technologies. Figure 1 shows how broadband access connectivity is extended from the core infrastructure to end-user devices.

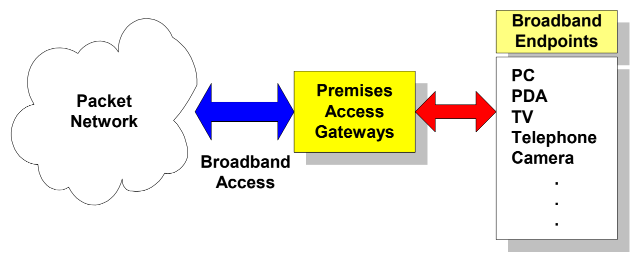

Figure 1: Broadband access connectivity.

Broadband access technologies are evolving to remove the bandwidth bottleneck for the "last mile": *i.e*., the connection of homes and small businesses to the core infrastructure. As illustrated in Figure 2, there are many competing broadband access technologies to improve last-mile connectivity such as twisted pair, fiber/coax, all fiber and wireless (see more details in IEC [2003a-d]).

Twisted-pair telephone lines are the access media used by the vast majority of individual residential subscribers today. Over time, a number of technologies have been introduced to provide faster data speeds over this medium; *e.g*., voiceband modems, integrated services digital network (ISDN) digital subscriber line (DSL), and other DSL approaches. Fiber/coax systems were originally introduced for video-broadcast applications; *e.g*., cable TV hybrid fiber/coax (HFC) systems, bidirectional HFC systems, and switched digital broadband (SDB) systems. Because these systems are inherently broadband, techniques have been developed to use this advantage to provide high-speed data transmission, principally for residential Internet access. The predominant access systems for business users are optical-fiber synchronous optical network (SONET) and synchronous digital hierarchy (SDH) systems. In the future, passive optical network (PON) systems are expected to become an all-fiber access medium for residential users as well. At present, several broadband wireless technologies are used to provide Internet access such as terrestrial broadcast, cellular, wireless Ethernet and satellite broadcast.

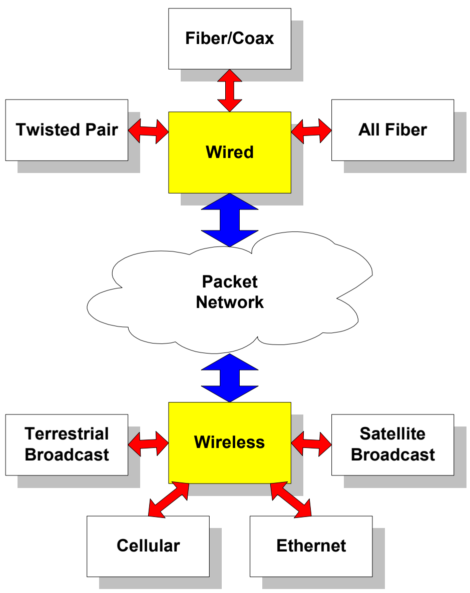

Figure 2: Broadband access alternatives.

UNB RTK SYSTEM

The UNB RTK system was initially developed for an RTGC auto-steering system in commercial operation at Korea International Terminals' Kwangyang Port in South Korea. For real-time data communication, an ad hoc network was built using an IEEE 802.11b compatible 2.4 GHz WLAN. Seven RTGCs operating simultaneously communicate directly with the RTK base station and each other in peer-to-peer mode sharing a given cell coverage area (Figure 3).

The performance of the RTK-based RTGC auto-steering system was demonstrated at the port in May 2002. Since then, we have explored the capabilities of the system in new GPS applications such as local deformation monitoring at an open pit mine and long-baseline RTK in on-land and offshore environments. From the initial investigations for new RTK applications, a second generation of the UNB RTK system has been developed which improves system performance for different applications. One of the main features of the new system is dual-mode communication which can switch between WLAN and 900 MHz spread spectrum wireless radio (hereafter SSWR) automatically if either communication link is not available. As a result, dual-mode communication increases availability of the RTK system and hence, it is able to provide seamless RTK services for clients moving through different environments.

In most instances, the performance of an RTK system relies on the availability of real-time data communication. Therefore, establishing stable broadband access connectivity was important for us and turned out to be one of the biggest challenges in developing the system. We have tried to increase the availability of the system by implementing several broadband wireless access technologies into the UNB RTK system.

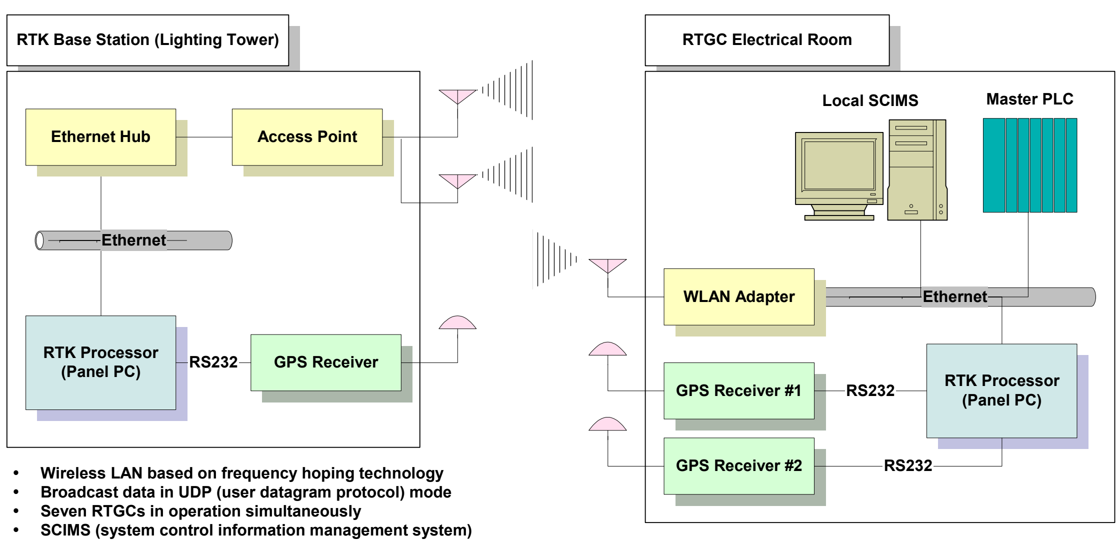

Figure 3: Sketch of the RTGC auto-steering system based on an ad hoc network using WLAN.

Wireless Ethernet

To expand the use of wireless Ethernet in the UNB RTK system, several standards developed by the IEEE 802 Working Groups were investigated. The current standard for wireless LAN is 802.11b (WLAN, also known as Wi-Fi). It offers 11 Mbps transmission rates in the 2.4 GHz frequency band. The 802.11a variant of the standard operates in the 5 GHz frequency band and offers transmission rates up to 54 Mbps. A recent addition to the 802.11 standard is 802.11g which offers transmission rates up to 22 Mbps in the 2.4 GHz frequency band [IEEE 802, 2003a]. While Wi-Fi is mainly fit for indoor broadband wireless access, the emerging standard of the IEEE 802.16 is being developed for wireless metropolitan area networks (WMAN), also known as WiMAX. It focuses on the efficient use of bandwidth between 10 and 66 GHz [IEEE 802, 2003b]. Another emerging standard of the IEEE 802.20 is being developed for mobile broadband wireless access (MBWA) networks operating in licensed bands below 3.5 GHz. It supports various vehicular mobility classes up to 250 km/h [IEEE 802, 2003c]. Currently, the UNB RTK system operates with the standards of the IEEE 802.11. Meanwhile, the standards of the IEEE 802.16 and 802.20 are still evolving and might provide a great advantage to the RTK system developers and users in near future.

Establishment of the UNB RTK Base Station

The UNB Fredericton campus provided an ideal environment to carry out research on improving the availability of real-time data communication for RTK applications. First, the campus network is well established and provides broadband access connectivity to the core infrastructure network. Therefore, end-user devices on campus and the core infrastructure network can be connected via one or more wireless networking technologies. Accessibility to the end-user devices via the campus or the core infrastructure network loosens the line-of-sight requirement typical of most conventional wireless technologies. Second, the WLAN is not available everywhere on campus. As illustrated in Figure 4, several Wi-Fi hot spots are available on campus. Even at hot spots, however, the signals picked up outdoors are so weak that RTK applications are very limited. If WLAN is the only available broadband wireless access technology for us, RTK solutions may not be available most of the time. This situation motivated us to look for an alternative (e.g., SSWR using the 900 MHz frequency band). Third, campus terrain imposes a challenging situation on the RTK base station. The campus sits on a hill and looks down on the downtown area of the city. To get the better coverage of broadband wireless signals, we set up the RTK base station on a building located at the top of the hill. A base station server computer was installed at Gillin Hall at the foot of the hill (about 1 km away from the base station) where the GPS research laboratory is located. This situation required us to develop procedures to access and control the RTK base station remotely.

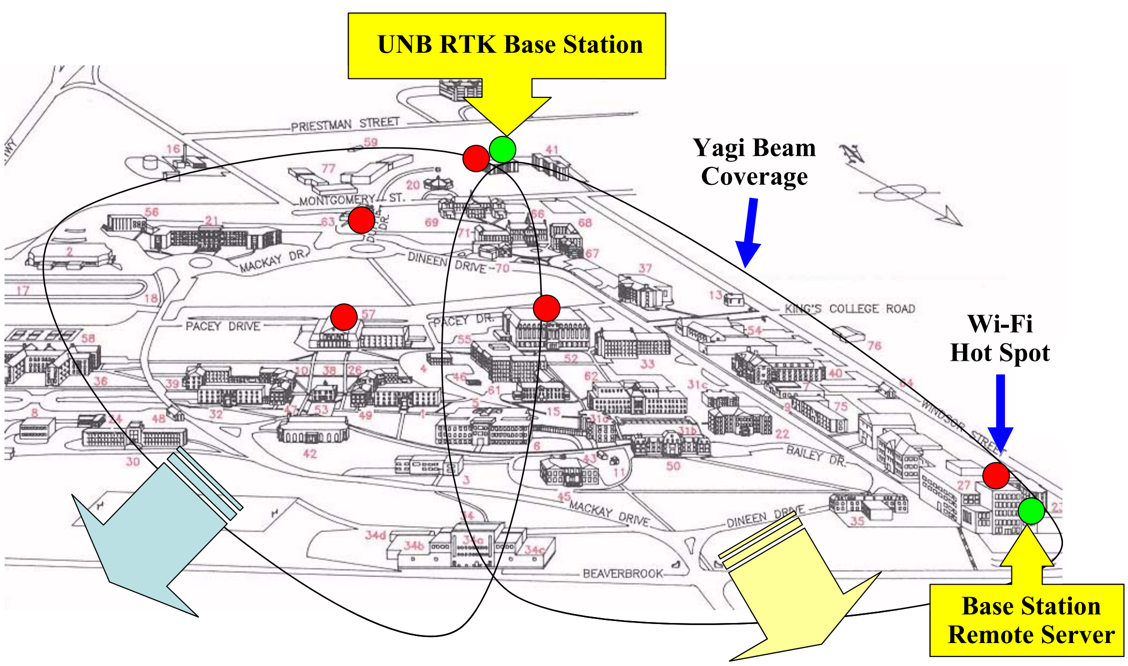

Figure 4: UNB RTK base station and broadband signal coverage.

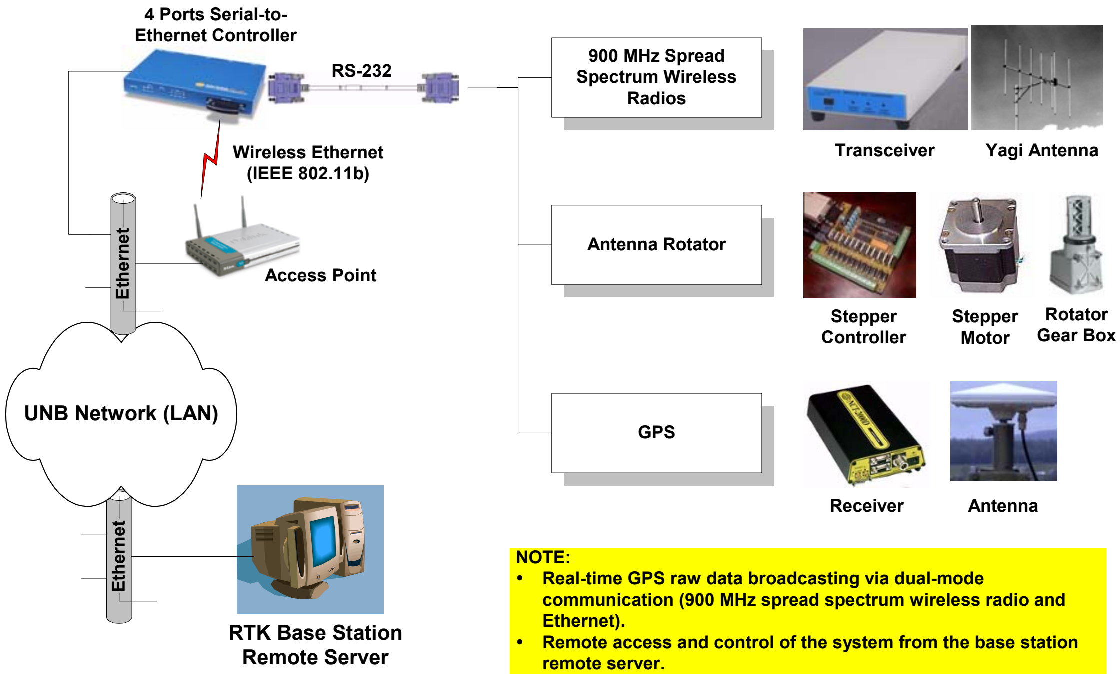

Figure 5: UNB RTK base station system components.

Figure 5 shows the UNB RTK base station system components. The RTK base station remote server is connected with a 4-port serial-to-Ethernet controller via the campus network (wired or wireless LAN). The 4-port serial-to-Ethernet controller provides broadband access connectivity from the network to the end-user devices (*i.e.*, a GPS receiver, SSWR and stepper motor controller). Such a system configuration enables the RTK base station server to access and control the end-user devices remotely. Another interesting aspect of the base station system components is the Yagi-antenna rotator. We have built it using a stepper motor, stepper controller and gear box. Horizontal and vertical beamwidths of the Yagi-antenna are 45 and 55 degrees, respectively. To get a line-of-sight connection with a moving platform, we have to rotate it from time to time as depicted in Figure 4. This can be done by sending commands from the RTK base station server to the stepper motor controller.

UNB RTK Software

To establish an RTK processor using a single CPU (central processing unit) and handling multiple end-user devices simultaneously, a time-division multiple processing scheme (*i.e.*, multi-tasking) must be used. This can be accomplished by several threads (independent routines for handling end-user devices) and events (for time synchronization) in Visual C/C++. As illustrated in Figure 6, the UNB RTK software has three independent threads sending (or receiving) data (or commands) to GPS receivers, SSWRs, and wired and wireless LANs. Multimedia processing modules are compiled with the RTK processor as a DLL (dynamic library link) under the Windows operating system. Each thread receives data from an individual end-user device and saves them in a ring buffer. Therefore, three ring buffers hold data from the devices until they are processed. For RTK processing, data extracted from GPS and SSWR (or WLAN) ring buffers should be coupled and synchronized with GPS Time. The UNB RTK software searches for coupled and synchronized data in GPS and SSWR ring buffers. If no such data exists, it automatically starts to search for data in the GPS and WLAN ring buffers, and vice versa.

The UNB RTK software provides three processing modes – base, remote and monitor. In the base mode, the RTK processor receives GPS data from the base station. It checks data qualities and then broadcasts them via SSWRs and the wired/wireless LAN. In the remote mode (Figure 7), the RTK processor receives GPS data from the GPS receivers mounted on the rover platform and saves them in the GPS ring buffer. It also receives the data broadcast from SSWRs and the wired/wireless LAN and saves them in the SSWR and WLAN ring buffers, respectively. After that, the RTK processor starts to process the data for RTK solutions and, for machine control applications, sends the solutions to the machine's programmable logic controller (PLC). It also broadcasts the RTK solutions via SSWRs and the wired/wireless LAN. In the monitor mode, the RTK processor receives the RTK solutions broadcast from SSWRs and the wired/wireless LAN. Then it passes them to any monitoring system for further processing and integration.

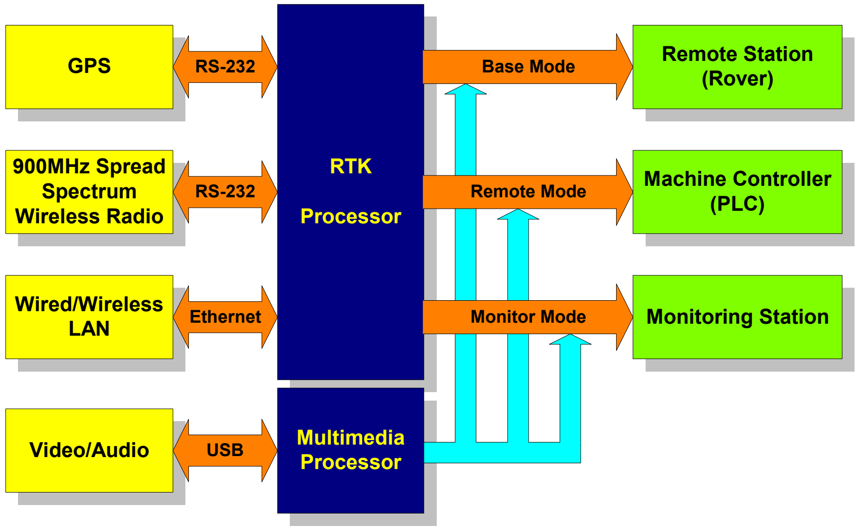

Figure 6: UNB RTK software block diagram.

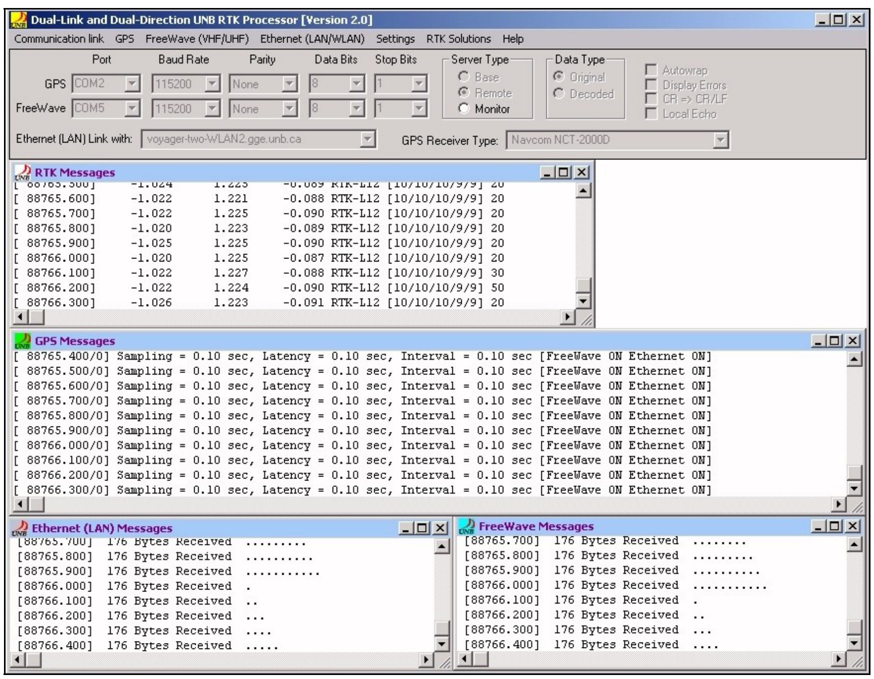

Figure 7: UNB RTK software operating in the remote mode.

GEO-SPATIAL FUSION DEMONSTRATION

As we finished developing a second generation of the UNB RTK system, we demonstrated the performance of the system at the GPS laboratory and on the UNB Fredericton campus. The main goal was to attain stable broadband access connectivity via dual-mode communication (SSWR and WLAN). Integration of the RTK solutions and multimedia data (video and audio) with other geo-spatial fusion technologies (*e.g.*, digital maps, satellite or airborne images, etc.) was another goal to accomplish through the demonstrations. Figure 8 illustrates the system configuration for the geo-spatial fusion demonstration. In this figure, the flows of GPS raw data, RTK solutions and multimedia data are indicated by the arrows.

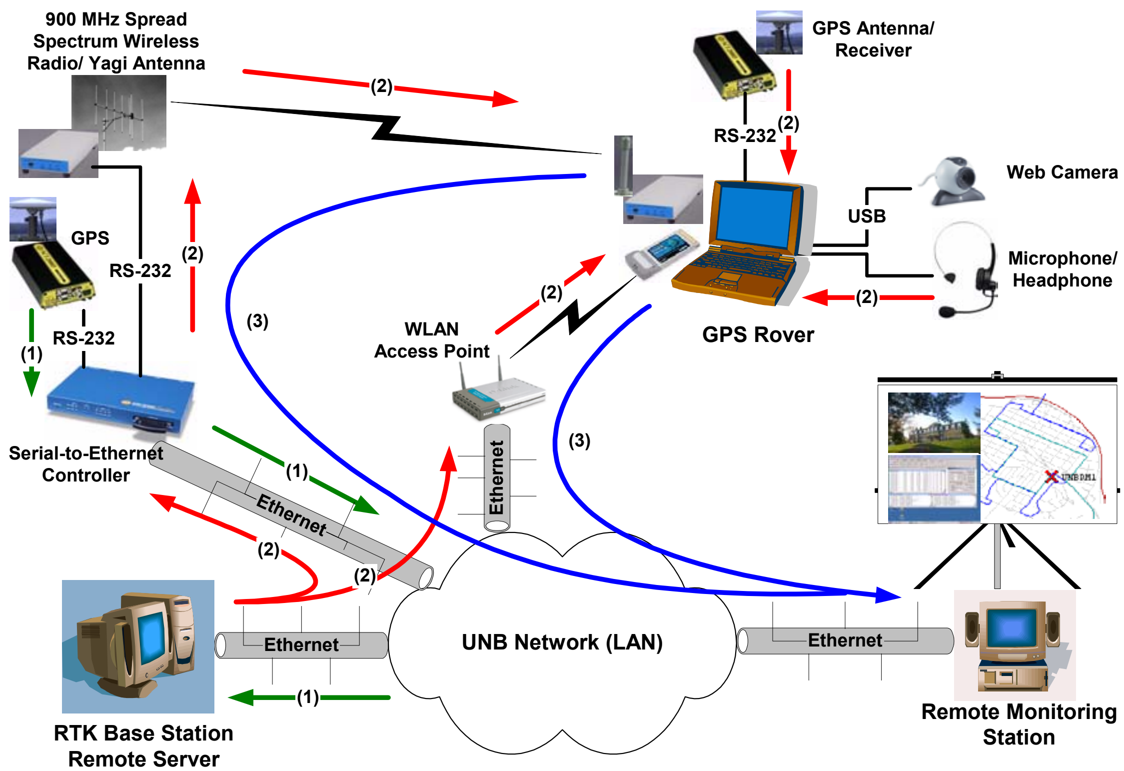

Figure 8: UNB RTK system configuration for Geo-spatial fusion demonstration.

The demonstration conducted at the GPS laboratory (left picture in Figure 9) was a simulation of real situations on campus. All system components were set up in the same way as in Figure 8. We also simulated a campus patrol person and vehicle (middle and right pictures in Figure 9) on campus. An example of the display during the demonstration is presented in Figure 10. During the demonstration, dual-mode communication provided stable broadband access connectivity and increased the availability of the RTK system. As a result, we successfully integrated the geo-spatial fusion technologies with the GPS RTK solutions and multimedia data. In Figure 10, the campus patrol vehicle was located in the parking lot of the Wu Center building at the top of the campus, about 1 km away from the RTK base station. The monitoring station was temporarily set up at the Head Hall Auditorium where high school students met to see the demonstrations. The screen picture of Figure 10 was captured from the monitoring station during the demonstration.

Figure 9: Geo-spatial fusion demonstrations: GPS laboratory (left), campus patrol person and vehicle (middle and right).

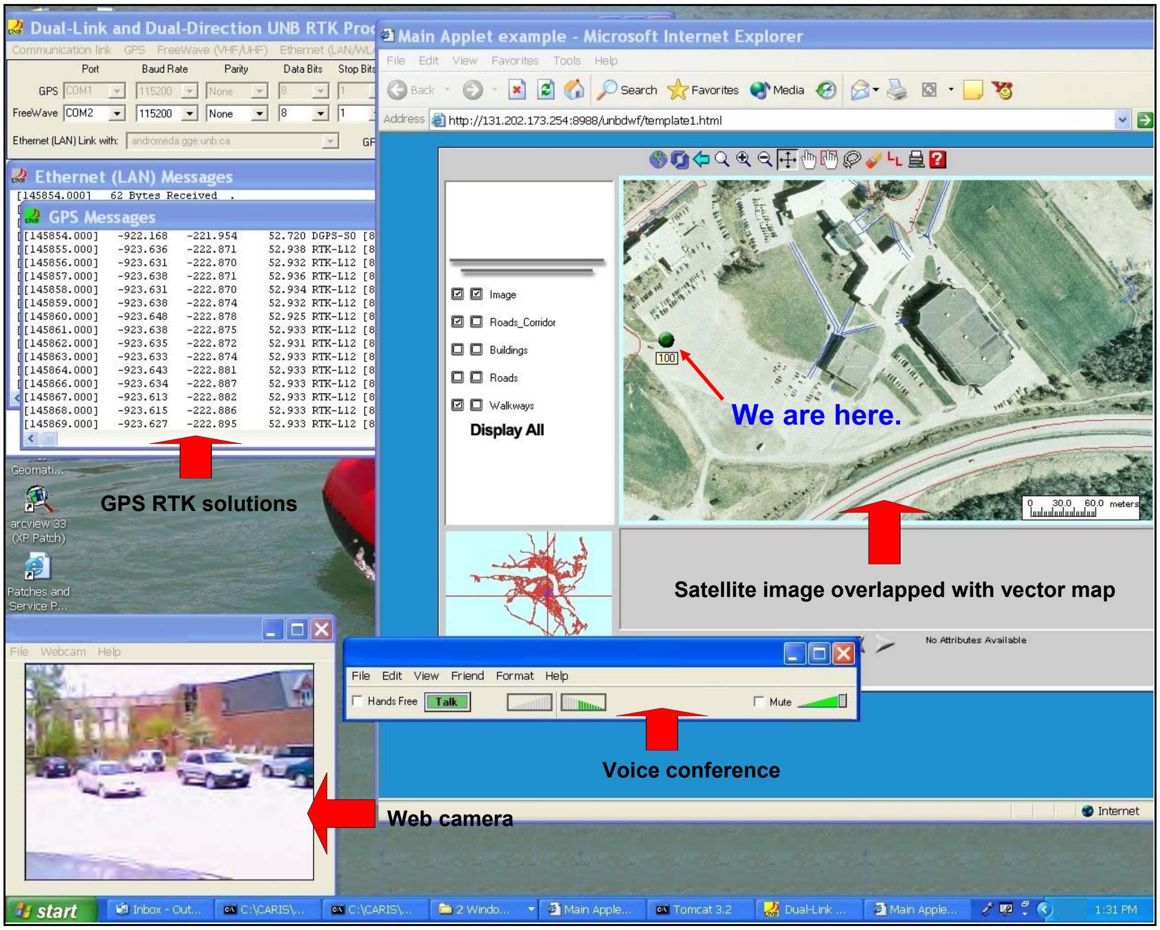

Figure 10: Integration of geo-spatial fusion technologies with GPS RTK and multimedia.

CONCLUDING REMARKS

In most GPS RTK applications, our first interest is to resolve the integer carrier-phase ambiguities because it is possible to achieve a-few-centimetre-level high-precision positioning solutions once the ambiguities are fixed correctly. Therefore, there is no doubt that the first requirement for a practical and fully operational RTK system is the reliability of ambiguity resolution. Since an RTK system is used in real-time applications, the system should process data and provide RTK solutions very quickly. Therefore, the second requirement must be the (computational) efficiency of ambiguity resolution. If the performance of the RTK system in terms of these two requirements is not satisfactory, we had better spend more time to improve the reliability and efficiency of the system rather than anything else. In this respect, the UNB RTK system is well designed and achieving excellent results.

Unlike many other RTK systems, the UNB RTK system can use broadband wireless access technologies for real-time data communication. Since the system was initially designed for the RTGC auto-steering system which requires navigation solutions at a 10 Hz or higher update rate, the RTK data rate can reach up to 69 Kbps. Conventional narrow-band UHF radio modems cannot deliver such high capacity data. Using broadband wireless access technologies has provided several advantages such as:

- alleviation of a line-of-sight condition for the radio link:
  Except for “last mile” wireless connection (i.e., wireless connection of end-user devices to the core infrastructure network), the line-of-sight condition for the radio link is not required any more. This allows the RTK system to be used for medium and long-baseline applications.
- network-based global RTK applications:

Since end-user devices and GPS resources such as permanent (or localized) reference stations are available more and more on the network, it is feasible to globalize RTK applications.

- diversified location-based services with RTK and multimedia:
  As broadband communication aims to deliver packet-based digital voice, video, and data services to end users, diversified location-based services could be provided. Such an example might be the integration of geo-spatial fusion technologies with RTK and multimedia.

Currently, broadband wireless access technologies are evolving rapidly to provide satisfactory services to end users. The wireless metropolitan area networks (WMAN or WiMAX, IEEE 802.16) and mobile broadband wireless access networks (MBWA, IEEE 802.20) might provide a great advantage to the RTK system developers and users. New generation cellular services (3G or higher) are also expected to provide a great advantage to the RTK community.

For a while, we have mainly concentrated on "last mile" broadband wireless connectivity in our RTK system development. Since we are still some years away from the widespread deployment of the emerging broadband wireless access technologies, we need to keep looking for alternative approaches under given operating situations. Dual or multiple-mode communication to access on the core infrastructure network seems a good approach at this stage for a more practical and fully operational RTK system.

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