



Study title:

**High Accuracy Dynamic Highway Mapping Using
a GPS/INS/CCD System with On-The-Fly GPS
Ambiguity Resolution**

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16. Abstract A high-precision land-based integrated mapping system was developed at the Ohio State University to support road centerline mapping operations at the Ohio Department of Transportation District 1 Office. The system represents a transition from the traditional mobile mapping paradigm towards a highly automated and autonomous design following the trends of modern geoinformatics. The two key components of the custom-designed system are a high-precision integrated GPS/INS navigation system and a fully digital and automated imaging subsystem. The van-based mapping system was designed to deliver the road centerline positions at sub-decimeter accuracy in a highly automated manner with limited human interaction in near real-time. The final report presents the system's concept and design, followed by a performance evaluation, including road test results, representing an operational environment, and then the operating instruction part closes the document.					
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Disclaimer

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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Chapter 1: Introduction

Conventionally, the road centerline surveys have been performed by the traditional survey methods, providing rather high, even sub-centimeter level of accuracy. The major problem, however, that the Departments of Transportation face, is the safety of the survey crew and the disruptions to the traffic flow, and to a large extent – even inaccessibility of some highways to the surveys crews due to safety hazard. The survey cost also becomes an issue, as due to the traffic and other environmental constraints, these surveys are relatively expensive, while the rate of production is slow, and therefore, frequent updates (re-surveys) are not feasible. This prompted the Ohio Department of Transportation, District 1, to replace the conventional survey by an automated mobile mapping system, which would collect the data while moving at the traffic speeds, ensuring at the same time the safety of the survey personnel. The mapping system, based on GPS/INS (inertial navigation system) integration for vehicle positioning and image georegistration, is designed specifically for centerline monitoring, and is capable of providing the platform positioning accuracy at 2-4 cm level under good GPS constellation, and the centerline location accuracy at 4-10 cm level, depending on the quality of GPS, image quality and image processing accuracy. This system collects data at speeds of up to 35 mph (or 65 mph if lower accuracy can be accepted), and thus, much higher than the conventional methods, and collects virtually continuous log of position coordinates along the centerline, as compared to about 30-35-meter sampling rate provided conventionally. At this rate of production, approximately 60 lane miles of highway can be surveyed and processed in a day, while the survey methods yield only ~2 lane miles a day (including the pavement inspection). Preliminary comparison of the characteristics of the conventional and the new centerline survey methods indicate that the person/hour productivity is over than 20 times higher for the mobile mapping system, compared to a total station and a level survey. The number of points collected along the centerline increased seven to ten times. Even though the accuracy of MMS might be lower as compared to the conventional methods, the increased safety of the survey crew and road accessibility any time is a crucial factor. Moreover, the images provide the instantaneous information about the pavement conditions, and the almost continuous positioning log provides an excellent basis for the road network GIS. Repeated surveys along multiple highway lanes can provide the information about the crown of the road, and allow determination of the road profile and cross-sections. This information is vital for assessing the rainwater flow patterns.

The mobile mapping system (MMS) presented in this report was designed, developed and tested at the Ohio State University, and delivered to the ODOT District 1 office. Modular and portable design allows for the system's installation in various platforms. It is currently installed in the van, but can be also placed in the vehicle that performs the centerline painting, allowing for efficient and economical integration of two important road maintenance tasks.

Chapter 2: Research Objectives

During the last decade of the 20th Century the concept of Mobile Mapping Systems (MMS) has been established and evolved from rather simple land-based systems to more sophisticated, real-time multi-tasking and multi-sensor systems, operational in land and airborne environments. Mobile Mapping technology has made remarkable progress, notably expanding its use in remote sensing, and surveying and mapping markets. New systems are being developed and built for specialized applications, in support of land-based and airborne imaging sensors, aimed at automatic data acquisition for GIS databases.

The major objective of this project was to design and develop a new GPS/INS/CCD integrated system for precise monitoring of highway center and edge lines. The system was developed at The Ohio State University for the Ohio Department of Transportation. The prototype of the positioning component of the system is based on a tightly integrated GPS/INS (Trimble 4000SSI, Litton LN100), and the imaging component comprises a fast, down-looking, color digital camera from Pulnix (TMC-6700, based on 644 by 482 CCD and acquisition rate up to 30 Hz). The high image rate provides sufficient overlap of the subsequent images at highway speed; therefore stereo data processing can be performed in near real time with the support of a single camera and on-the-fly navigation solution.

In this report, we discuss the design, operational aspects and performance analysis of the system prototype. A new approach to the application of navigation data to real-time processing of the imagery is also presented. A detailed operational manual including the performance analysis is presented.

Chapter 3: General Description of Research

The GPS/INS/CCD Integrated Survey System (GISS) is designed to work as a system of customized and off-the-shelf (COTS) hardware and software for the purpose of collecting global positioning system (GPS) data, inertial navigation system (INS) data and digital imagery (in phase II of the project). The system depends upon precise timing in order to integrate the data to produce highly accurate map information.

Positioning Sub-System



Figure 3. GISS land-based platform.

The system consists of two distinct sub-systems: the imaging sub-system and the positioning sub-system. The positioning system uses GPS and INS data to determine the position and orientation of the platform (land-based vehicle in this case), and subsequently, the imaging component. The GPS data is collected and stored, during the survey, within the GPS receiver. At least one GPS base station must be used for a GISS survey. Additional base stations will provide redundancy and robustness to the system; however, in its current design the processing does not switch to another base automatically. Still, multiple base stations will allow for multiple solutions, and redundancy to assure better coverage. These base stations will be situated over known control points according to accepted surveying practices, and the position and elevation of the phase centers of the antenna will be determined and recorded for post-processing of the GPS data. It is recommended that the mapping vehicle should start the survey job in the vicinity of the base station. Base-rover separation should not exceed 5-10 km to assure proper ambiguity recovery after extended GPS loses of lock that may happen in the highway/road environment (multipath, interference, signal blockage by foliage, etc.). The rover GPS receiver is mounted in the positioning platform with the antenna rigidly affixed to the platform. The positioning platform is

typically a van designed for image data collection (see Figure 1 and 2). The positional offset of the phase center of the rover GPS antenna from the INS should be determined by a precise survey for post-processing of the GISS data. Details about conducting a GISS survey are discussed in Chapter 2.

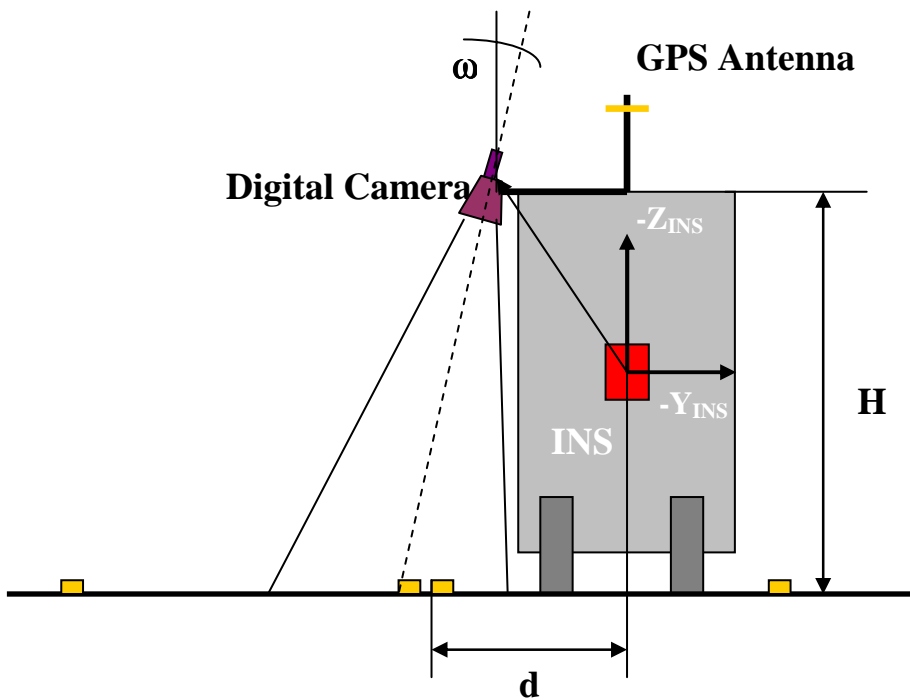
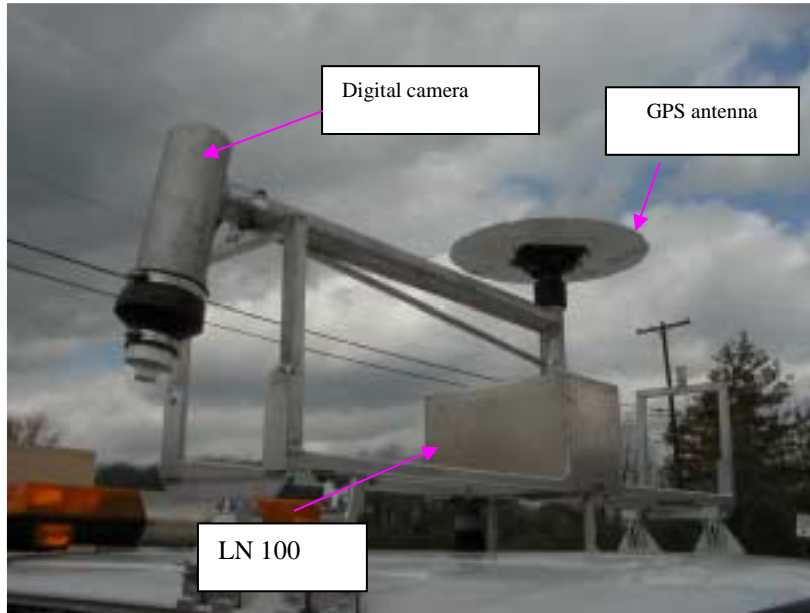


Figure 4. GISS sensor configuration.

The INS is rigidly attached to the positioning platform along with the GPS receiver. The rigidity of this connection is essential, as the orientation of the INS can be resolved to a few arc seconds. Whereas the GPS data is logged within the receivers during the course of the survey, the INS will transfer its data to a specially configured computer. This computer, considered the central part of the GISS positioning system, is equipped with a special interface to communicate with the INS, as well as a highly accurate timing card linked to the GPS time reference and a serial (RS-232) connection to the rover GPS receiver. Raw INS data are transferred at the rate of 400 Hz to the positioning computer.

During the course of a GISS survey, the GPS data are logged to the internal memory of the GPS receivers while the INS data are written directly to the hard drive of the positioning computer. The post-processing of this data involves transferring all of this data to a single host computer where several processing steps are carried out. First, the raw INS data undergo a format conversion and a linking to the GPS time reference (see the System Operating Instructions, Addendum B). Second, the GPS data ambiguities are resolved using kinematic GPS processing OSU-developed software. Finally, all of the GPS and INS data are processed, together with the image log file (see the System Operating Instructions, Addendum B) by an integrated Kalman filter (ODOT) that generates the exterior orientation file for the imagery and also the positioning data of the platform for the entire duration of the survey. There should be no gaps in the solution, as GPS losses of lock are bridged with the INS prediction, whose accuracy depends on the gap duration, and INS calibration time before the lock was lost.

The imaging component of the system consists of a single down looking digital color camera, Pulnix TMC-6700, based on 644 by 482 CCD, with an image acquisition rate of up to 30 Hz (~10 Hz currently used, and the image acquisition rate is automatically controlled based on the vehicle speed). The sensor characteristics are presented in Table 1. The details of the imaging system operational aspects are provided in the System Operating Instructions, Addendum B section.

Figure 3 illustrates the GISS design architecture and data processing flow. Tables 2 and 3 present the initial (average) boresight parameters and the example of the achievable quality on the checkpoints. The boresight parameters presented here should not be treated as constant values, and should be re-estimated any time after any suspected change in location among the sensors, or after the system has been removed and re-installed. The same applies to the accuracy at checkpoints: this will strongly depend on the quality of GPS, which is a single most important factor determining the overall accuracy of the system.

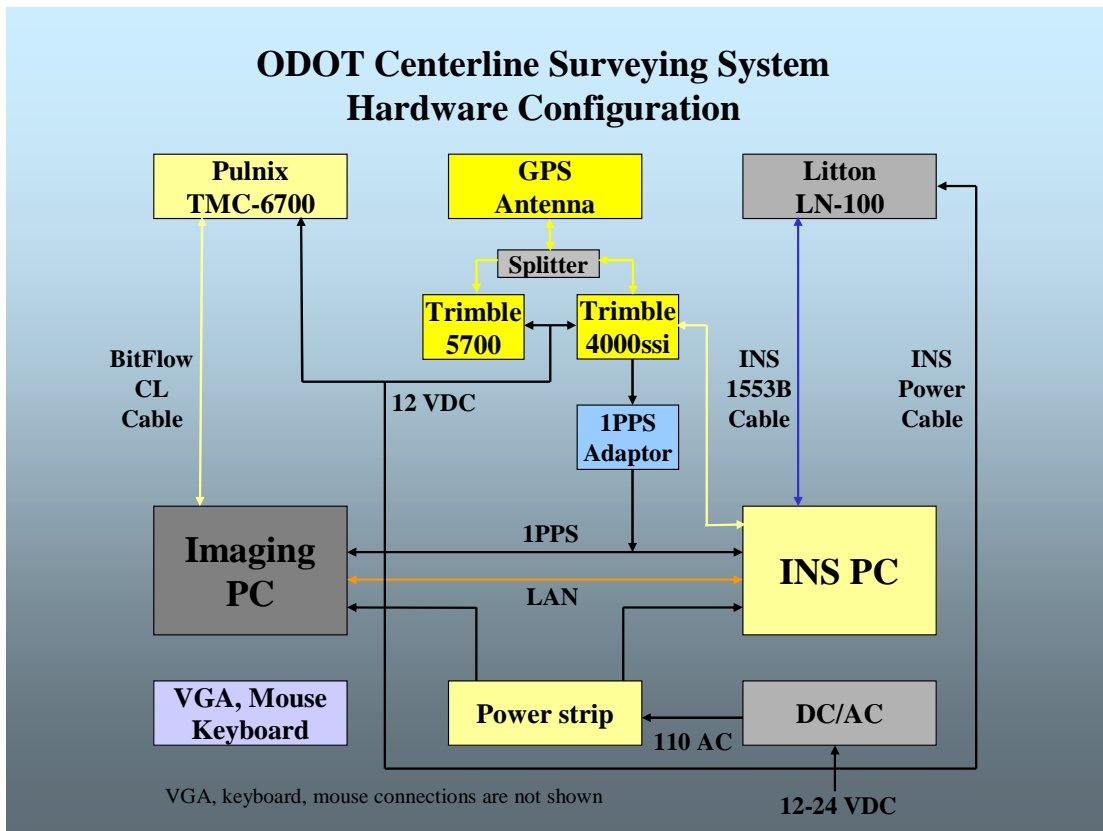


Figure 3. GISS design architecture and data processing flow.

Camera CCD pixel size	9 micron
Camera focal length	6.5 mm
Camera height above road surface	3 m
Image scale	$3/0.0065=461$
Ground pixel size at nadir (no tilt)	4.1 mm
Ground coverage along vehicle	2.68 m
Ground coverage across vehicle	2 m
Maximum speed without overlap at 10 FPS	$2.68/0.1=26.8$ m/s (96 km/h or 60 MPH)
Maximum speed to maintain 50% overlap	$26.8/2$ m/s (48 km/h or 30 MPH)

Table 1. Sensor characteristics and the image acquisition conditions.

Offsets in IMU body frame [m]		Rotation [degree]	
dX	-0.514	ω	-12.0264
dY	-0.019	ϕ	-1.4187
dZ	0.037	κ	-89.0449

Table 2. Average boresight offsets and rotations.

Chapter 4: Results: Performance evaluation

The centerline-mapping vehicle, equipped with all the sensors and data acquisition hardware was ready for preliminary testing in spring 2001, and after an initial fine-tuning, a series of field tests was conducted on and around the OSU Campus, see Figure 4. These surveys were performed at various daylight conditions as well as at different GPS constellations in order to analyze the environmental and hardware limitations. The results of the performance validation and the freeway surveys are discussed in the following section. As it was described above, monocular mode was used in the final testing to assure both high processing speed and robustness. The GPS baselines for all the surveys were relatively short, about 1-2 miles for the Campus surveys and an about 5-10 miles for the freeway tests.

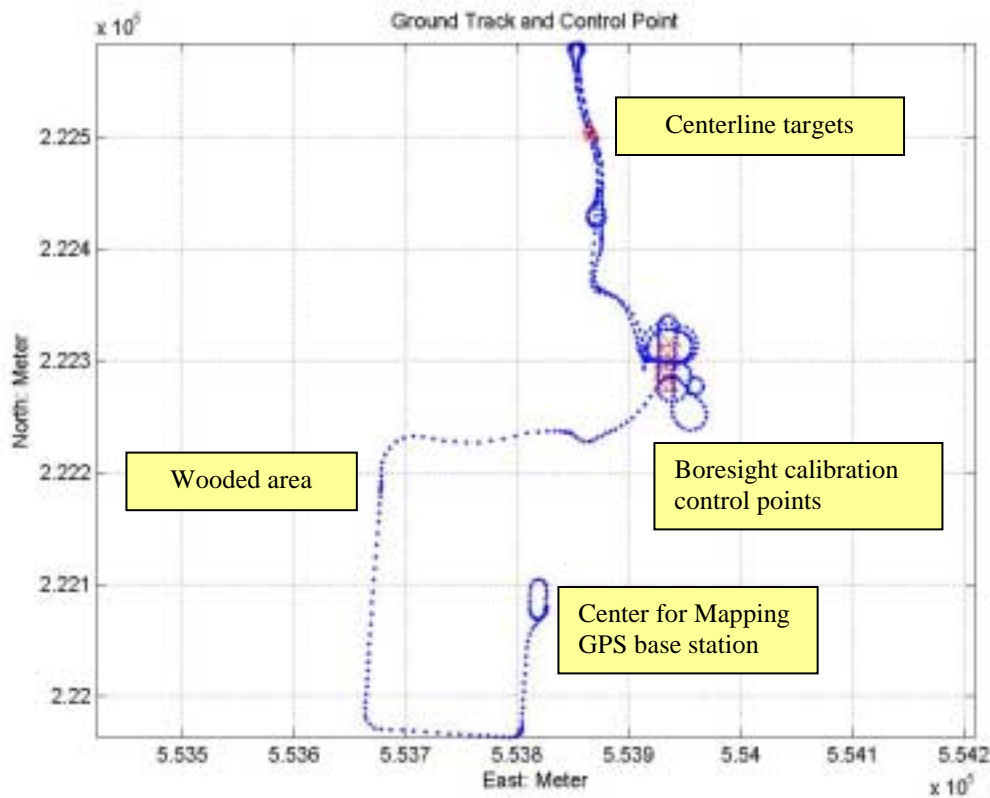


Figure 4. OSU West Campus test survey area

Performance validation tests.

Five ground control points were installed in a road segment on the OSU West Campus, with GPS-surveyed positions at 1-2 cm accuracy, as shown in the upper part of Figure 4. An image of one of the control points placed in the true centerline position is depicted in Figure 5. During the tests, the road segment with the control points was surveyed several times from both directions, and repeated at different times of the day under various light conditions, such as strong sunshine, shadow, or cloudiness. The surveying vehicle speed was in the 25-35 MPH range, representing the legal limit for similar roads. Figure 6 illustrates the centerline points automatically extracted from the images acquired in a three-pass survey, conducted around noontime. Curves were fitted

to the points based on geometrical constraints describing the rate, at which the centerline can change its direction (not discussed here). The points repeatedly extracted from the same direction show a very good match with each other. Actual data analysis indicated an about 2-3 cm 3D variances between the consecutive passes. We should note that due to the similar conditions, the navigation results were comparable to the optimal navigation performance in all the cases tested. The difference between the opposite direction surveys, however, showed a small bias in the range of 8 cm (3D); the separation of the forward and backward lines is very distinct in the close-up in Figure 6. After several tests, it was clearly evidenced that the two reasons for this discrepancy were the boresight error and a sort of a shadow effect. The centerline extraction process produced slightly different locations with or without shadows cast over the centerline. Except for the repeated boresight adjustments, no further corrections were made to the system as repeated tests routinely produced differences between the opposite direction surveys in the 6-8 cm range (3D). In addition, the deviation from the true centerline position seemed to be nearly symmetrical in repeated surveys, and therefore, results fell well within the required sub-decimeter accuracy. Tests showed a rather small number of outliers produced by the imaging subsystem, yet their removal is still important, and therefore an additional line-fitting-based outlier removal was implemented. Based on the point deviations from the first line fitted, the outlier points are removed, and in a second step the line position is readjusted to the filtered points.

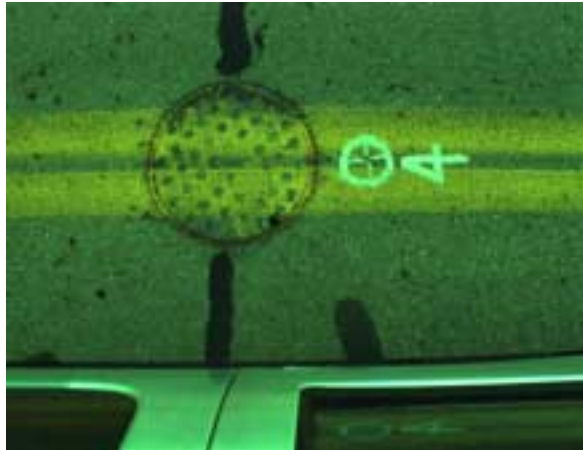


Figure 5. Road centerline control target

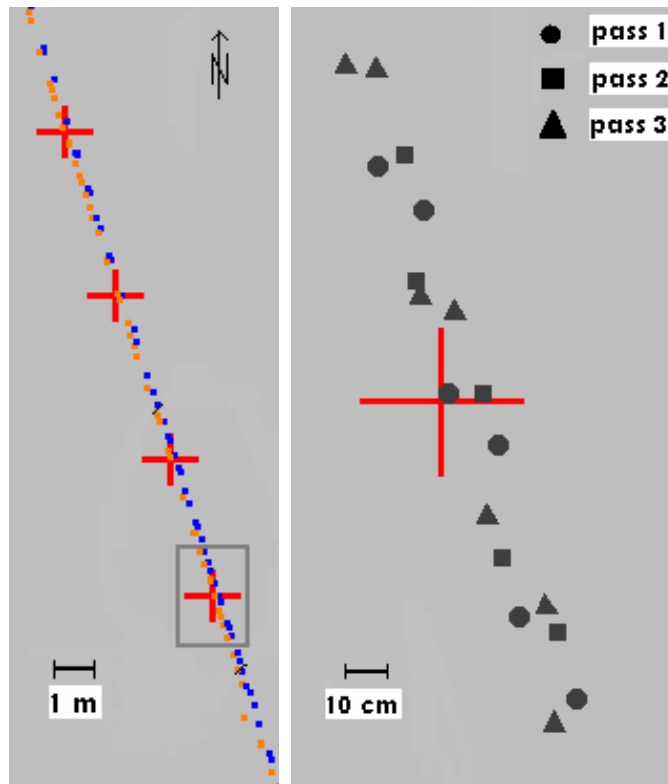


Figure 6. Centerline points measured from several passes

An additional test was performed at the boresight calibration area, see Figure 7. The precisely surveyed points were used as check points during the tests. Table 3 shows the results.

Freeway tests

Several surveys were conducted on a six-lane freeway North of OSU Campus. There was no ground truth available for validation, thus only differential results were obtained from the repeated passes in the same lane. Also, for obvious reasons, lane marks could be only surveyed from one direction. A new aspect of these tests was the higher vehicle velocity, of about 55-65 MPH. Consequently, even with the maximum achievable image rate, the images did not provide a continuous coverage of the road. The data acquisition system could maintain an about 10 FPS sustained image capture rate, resulting in a centerline point extracted every 3 m on average. A more detailed analysis of different surveys indicated about 5-9 cm deviation (3D) between the repeated surveys. An important lesson learned from the freeway tests was that loss of GPS lock could easily happen, and reacquiring the signal may take different times for different receivers. Consequently, an additional Javad Legacy receiver, with tunable tracking loops, more suitable for kinematic application was used. The Trimble 4000SSI, which is integrated into the system in several ways, more importantly it provides the GPS-based timing for the IMU and imaging subsystems, was also used. It should be mentioned that the Legacy receiver provides data with slightly higher noise than the 4000SSI; however, it is capable of maintaining lock even under harsher environmental conditions.

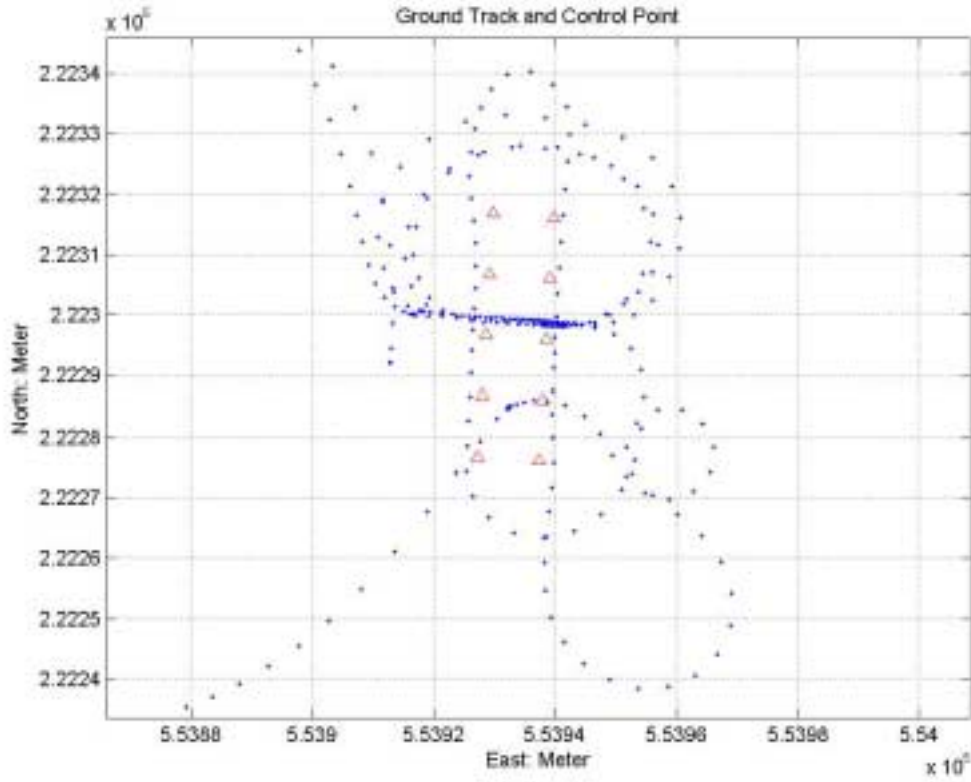


Figure 7. Boresight area points used as check points for testing.

Model Check points	Surveyed Control			Based on DO Images			Difference		
	X	Y	Z	X	Y	Z	X	Y	Z
461									
12_1	553938.517	222296.048	205.736	553938.524	222296.049	205.743	-0.007	-0.001	-0.007
12_2	553938.517	222296.048	205.736	553938.493	222296.065	205.797	0.024	-0.017	-0.061
3	553929.208	222306.817	205.786	553929.196	222306.818	205.853	0.012	-0.001	-0.067
4	553929.873	222316.806	205.614	553929.867	222316.805	205.663	0.006	0.001	-0.049
462									
0	553927.275	222276.767	205.840	553927.261	222276.738	205.961	0.014	0.029	-0.121
12	553938.517	222296.048	205.736	553938.493	222296.039	205.776	0.024	0.009	-0.040
4	553929.873	222316.806	205.614	553929.870	222316.826	205.699	0.003	-0.020	-0.085
45									
12	553938.517	222296.048	205.736	553938.531	222296.020	205.780	-0.014	0.028	-0.044
4	553929.873	222316.806	205.614	553929.881	222316.816	205.642	-0.008	-0.010	-0.028
3	553929.208	222306.817	205.786	553929.193	222306.832	205.880	0.015	-0.015	-0.094
0	553927.275	222276.767	205.840	553927.265	222276.801	205.883	0.010	-0.034	-0.043

Table 3. Checkpoint fit to ground truth (example).

Chapter 5: Conclusions

A state-of-the-art mobile mapping system has been developed and implemented to support ODOT District 1 mapping operations. Several surveys have proved that sub-decimeter accuracy can be achieved under normal conditions. Besides the high positioning performance, the main advantage of the system is the reduced requirement for human interaction, which is primarily limited to the post-processed GPS/IMU navigation computation. The processing of the road images is totally automatic, and requires time comparable to the processing of the navigation solution. For a one-hour survey the totally autonomous processing of the images takes about less than two hours, which is comparable to the time required to download and organize the GPS and IMU data, followed by the processing of the navigation solution. Therefore, the system can be considered near real-time, as the final results are available in a rather short time after the survey is completed.

The tightly coupled GPS/IMU navigation system has shown excellent performance under good to moderate GPS signal reception. 4-7 cm positioning and 10-20 arcsec attitude navigation results have been routinely achieved in numerous road tests. The high-performance IMU can effectively bridge the gaps when the GPS signals are lost. And, for stop-and-go city situations with limited GPS signal reception, the embedded ZUPT module can provide an additional support. As the reacquisition of the GPS signal is very critical, the use of the most recent generation of the advanced GPS receivers is mandatory.

The implemented single camera solution and monocular processing have resulted in a reliable extraction of the centerline points. Several comparison tests have proved that the monocular model could achieve the required performance in a robust and timely way without any human interaction. In addition, this model is invariant with respect to the discontinuities. Repeated results on a test range have shown a consistent performance of 6-8 cm RMS (3D).

For the future developments, a faster image acquisition rate can further improve performance and could potentially open the door for stereo processing, as gaps in the image sequence will disappear. Additional conditions for this to happen are the substantially improved computer resources and the availability of more robust matching schemes.

Chapter 6: Implementation plan

The OSU staff worked in close collaboration with District 1 personnel to assure that all operational aspects of the system's operation are followed during the field procedure. This included test surveys conducted in Columbus, and training of District 1 staff.

The system is fully implemented and installed in the District 1 vehicle, and was passed to the District 1 office in summer 2003. To support daily operations and effective utilization of the system, the User's Manual is included in Appendix 1.

Currently, the system is configured to work only on the left side of the vehicle. With additional effort, the system could be configured to operate on the right side of the vehicle. This, however, would require substantial effort (system calibration, algorithm modification, etc.) and time commitment that goes beyond the scope of this project.

An extra copy of the source code is included on a CD ROM; the operational code is also installed on the two PCs installed in the vehicle, delivered to District 1 in summer 2003.

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Appendix A: **GPS/INS/CCD Integrated Survey System (GISS)**

USERS MANUAL
Version 2.0

Chapter 1: Preparing for the Survey

Survey Planning

Prior to the actual collection of data by the GISS data acquisition system, the area to be surveyed should be carefully examined to determine the location and quality of ground control points needed as GPS base stations, and camera boresight calibration (in phase II of the project). The physical installation of the data acquisition system should be considered carefully. The current configuration of the data acquisition system requires:

- ⇒ a high quality 110v, 60Hz AC power supply be available in the platform,
- ⇒ environmentally (pressure, temperature, shock) controlled location to mount the computer, GPS receiver, INS and associated cabling for the entire system,
- ⇒ a suitably amplified GPS signal from an approved L1/L2 GPS antenna .

Each of these points will be discussed in detail in the following sections.

Ground Control Location

The location, accessibility and coordinates of necessary ground control points must be determined. It is preferable to use accurately known control points if possible, as any error in the control position will translate into positional errors of the mapping platform. First order control points are best suited to the accuracy of the mapping system, as their positional errors are below the advertised positional errors of the GISS, and thus will not adversely impact the error budget for the system. Points of lesser quality may be utilized, but their reduced accuracy will adversely and directly affect the quality of the position derived for the mapping platform.

Base station location

The initialization of the positional system requires that one ground control point be located within a kilometer of the point where the system will be powered up.

A useful tool for locating control points and retrieving their data sheets is a search engine at the National Geodetic Survey. It may be located on the World Wide Web at <http://www.ngs.noaa.gov/datasheet.html>.

Chapter 2: Equipment Set-up

Computer Placement

The largest elements of the data acquisition system are the imaging and the positioning computers. They should be located securely and cushioned against any vibration and shock.

INS Placement

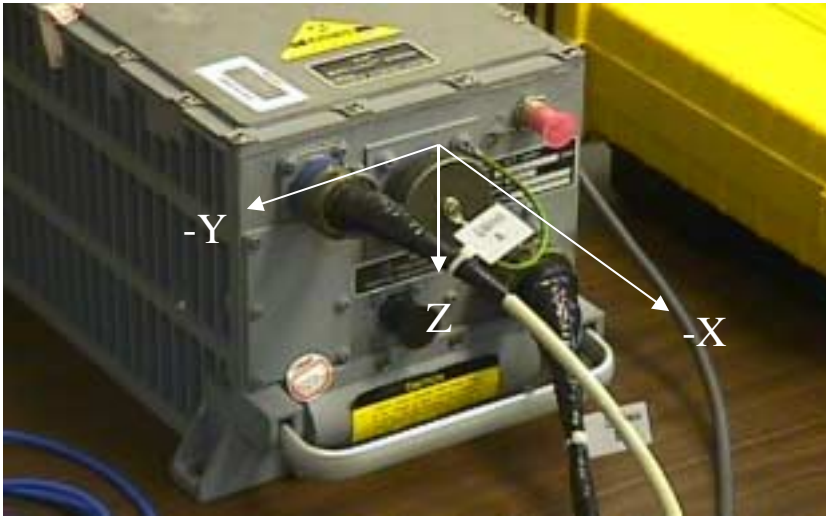


Figure A1. The reference axes of the INS.

The INS must be firmly attached to a rigid platform or directly to the vehicle's floor. This platform should also serve as a mounting point for the camera. The INS has an internal reference frame whose positive x axis should be in the same direction as the direction of the platform's motion (shown in Figure A1). This should be mounted facing towards the front of the vehicle.

Positioning Sub-System Cabling

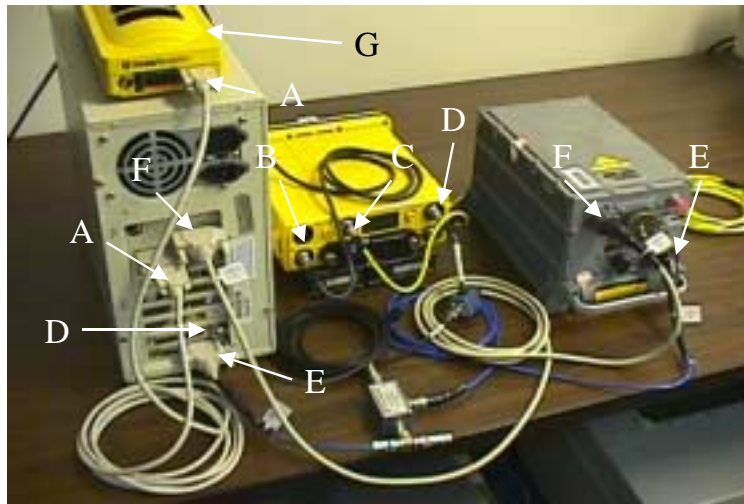


Figure A2. The GISS positioning system cabling configuration.

Figures A2 and A3 show the cabling configuration of the GISS positioning computer, the rover GPS receiver and the INS. In this Figure five major cables are shown. Cable “A” is the RS232 serial communication cable between COM2 of the positioning computer and the serial port of the Trimble 4000SSI receiver. Cables “C” is the GPS antenna connection for the 5700 and 4000SSI receivers, the antenna signal is split and the 4000 receiver powers the GPS antenna. Cable “D” is the RG-58 coaxial cable carrying the one PPS (pulse per second) signal from the 4000SSI AUX output port to the BNC style input port of the positioning computer. A special adapter is attached between these two ports to enable the PPS to be read by the computer. Cable “E”, labeled “LN100 B” and cable “F”, labeled “LN100 A” are communications and power cables for the Litton LN100 INS system.

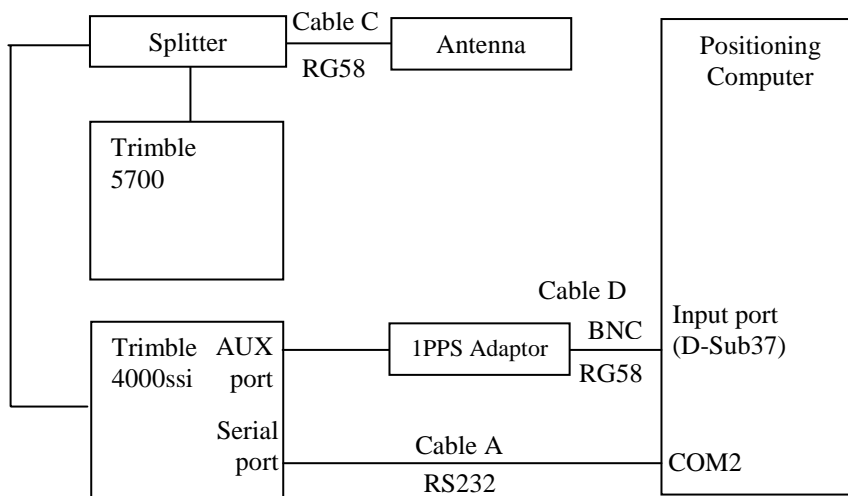


Figure A3. The GISS positioning system cabling configuration.

GPS Configuration

The rover Trimble 4000 GPS receiver is directly powered from the main power module located in the van. To improve GPS reception, a third generation receiver, Trimble 5700 was added as primary GPS data acquisition device. However, the 4000 is still used as it provides the essential timing for the IMU measurements. A nine-pin RS232 serial cable connects the positioning computer to the Trimble 4000.

Trimble 4000SSI receiver should have the following configuration options.

→ Log Data → More → Setup Survey Controls → Modify QuickStart Controls

Elevation Mask = 10 degrees

Meas Sync Time = 1 sec

Store Position = Normally

→ Accept

Setup Survey Controls → Modify QuickStart Controls → More

Continuous Logging = On

Log File Duration = 1200 minutes

→ More → Accept

→ Control → More → More → Baud Rate / Format → Serial Port 1 Settings

Port 1 Baud Rate = 38400

Format = 8-Odd-1

Flow Control = None

→ Control → More → More → More → Masks / Sync Time

Elevation Mask = 10 degrees

PDOP Mask = 7

SV Sync Time = 1 sec

→ Accept

→ Control → More → More → More → More → More → More → 1 PPS Output

1 PPS Output = Enabled (for rover GPS only)

Slope = Negative

Ascii Time Tags = None

→ Control → More → More → More → More → More → More → Event Markers

Event Markers = Enabled (if image data are to be collected also; to be completed in phase II of the project)

Slope = Negative

Event Beep = Always

INS Configuration

With the INS physically secured and electrically connected, the positioning computer must be configured with a proper *location.dat* file. This file contains the start up location for the

INS. This can be obtained from the main position screen of the GPS receiver. For the LN100, the initial latitude, longitude and height should be provided in WGS84 reference system. These units should be converted to radians (semicircles) for latitude and longitude, and meters for height. The following unit transformation may be utilized.

For example, if initial position in **WGS84** is given as follows:

Latitude = 70 deg 6' 32.4 " N
Longitude = 80 deg 30' 43.5" W
Height = 121 US survey feet.

The converted coordinates will read:

Latitude = $(70+6/60+ 32.4/3600)/180$
= 0.3894944444444444 (π)
Longitude = $2 - (80+30/60+43.5/3600)/180$
= 1.55271064814815 (π)
Height = $121*(1200/3937)$
= 36.88087376174752 (m)

The converted data should be entered into text file named *location.dat* located in *c:\art\sw\giss* directory on the positioning computer prior to the start of the INS data collection program. The contents of this text file would appear as follows for the above position.

```
0.38949444444444 1.55271064814815 36.88087376174752
```

Chapter 3: System Operation

System Power On

Please refer to the **System Operating Instructions** for details.

System Initialization: GPS

The rover GPS data collection should begin at this point. This is started by selecting the following option from the 4000SSI display screen:

→ Log Data → Quick Start Survey

The screen should indicate the cumulative time in minutes that the receiver has been logging data. If no such display is seen then the survey should not begin and the user should consult the Trimble 4000SSI user's manual. If the receiver is logging data and it indicates that more than four satellites are being tracked, then the INS initialization & data logging program (*ODOTRT.exe*) should be executed (that is the current approach; it would change once the NT-based system is operational).

The 5700 has a simple user interface.

→ Power On → Log data (if it is not configured for auto recording).

System Initialization: INS

Please refer to the **System Operating Instructions** for details.

Ending the Survey

Please refer to the **System Operating Instructions** for details.

Chapter 4: Processing the Data

Downloading the GPS Data and Format Conversion

Please refer to the **System Operating Instructions** for a short description, while additional details of the programs and processing steps are provided below.

Preprocessing GPS & INS Data

The primary operational steps are performed after the user selects the respective processing buttons in the user interface, as explained in the **System Operating Instructions**. The major GPS/INS data processing modules are presented below. For the details on the image processing modules please refer to the **System Operating Instructions**.

1. *INS Format Conversion*: use BinINS.exe to convert raw, binary file IMU data, INSData.out, into conventional binary format data. The converted files include: IMU.bin (raw IMU data) and Nav.bin (LN100 navigation solution);
2. *Note*: Any INS data collection problems are reported in the ASCII output file, Misc.Dat. Under normal circumstances (no data loss) the file should be empty; otherwise, it contains the time information about the gap, and the amount of IMU data jump during the gap.
3. *GPS Kinematic Solution*: AmbRes.exe computes the rover GPS antenna positions. The outputs include two files: GPSAmb.out (ASCII format) and GPSAmb.bin (binary format). GPSAmb.bin file is used as an input to the integrated Kalman filter. To run:
 - ✓ From the TstAmbRes dialog box select *Load GPS Files* from the File menu
 - ✓ Select the base observation data file, load it
 - ✓ Select the rover observation data file, load it
 - ✓ Select the broadcast ephemeris file or the .SP3 file (at least one)
 - ✓ Select *Ambiguity Resolution* from the Run menu

More details are presented in the **System Operating Instructions**.

Preparing Control Files

Control files for the integrated filter: CONTROL.ALL, KF_INI.DAT should be located in the data processing directory, together with the GPS Rinex base and rover data, initial GPS solution (GPSAMB.bin) from the TstAmbRes.EXE run, as explained below, and the IMU.BIN and NAV.BIN files.

The file location:

1. CONTROL.ALL must be located at the same directory as IMU.BIN and NAV.BIN
 2. GPSAmb.Bin must be located at the same directory as Rover Station data files (*.??O and *.??N)
 3. KfINI.dat is not necessary if we use default parameters. Normally it should be located at the same directory as Control.all
1. The CONTROL.ALL file is used to set the coordinates of the IMU center, rover GPS antenna phase center, and output reference point in the IMU body frame. The body frame is defined as follows: x – negative out the connector surface, z – positive out the mounting feet surface, and y – positive defined by the right hand rule. The WGS84 coordinates of the GPS antenna phase center of the base station are also given in this file. This file has to be updated for every new mission. An example of Control.all file is given below.

```
INSx: 0.0  
INSy: 0.0  
INSz: 0.0  
GPSx: -0.12  
GPSy: -0.15  
GPSz: -1.30  
Outx: 0.0  
Outy: 0.0  
Outz: 0.0  
BaseX: 538779.02950  
BaseY: -5471030.32542  
BaseZ: 3223108.91292
```

INSx, INSy and INSz are normally set to zero, since the reference frame is IMU body-centered. The OUTx, OUTy and OUTz represent the reference output point, which, in the example above, is the IMU center. If the output is expected at the GPS phase center, OUTx, OUTy and OUTz should be the same as GPSx, GPSy and GPSz.

2. The file KF_INI.Dat contains a set of the initial parameters for the Kalman filter. This file should not be modified, except for the cases when the models (or starting conditions) for the state variables change. Under normal circumstances, the current values should be used without any modifications.

Running the Kalman Filter

The details of the running procedure are provided in the **System Operating Instructions**. The user needs to make sure that before the program is run (by clicking on the icon named **ODOT**),

the following files should be available and located in the data processing directories IMU, NAV, BASE, ROVER and EVENTS, respectively, as explained in the **System Operating Instructions**:

1. CONTROL.ALL
2. KF_INI.DAT
3. IMU.BIN
4. NAV.BIN
5. GPSAMB.BIN
6. Rover GPS observation Rinex file (*.02o)
7. Base GPS observation
8. Base navigation Rinex files (*.02n, *.02o) (Rover GPS navigation Rinex file is optional)
9. Image log file(s)

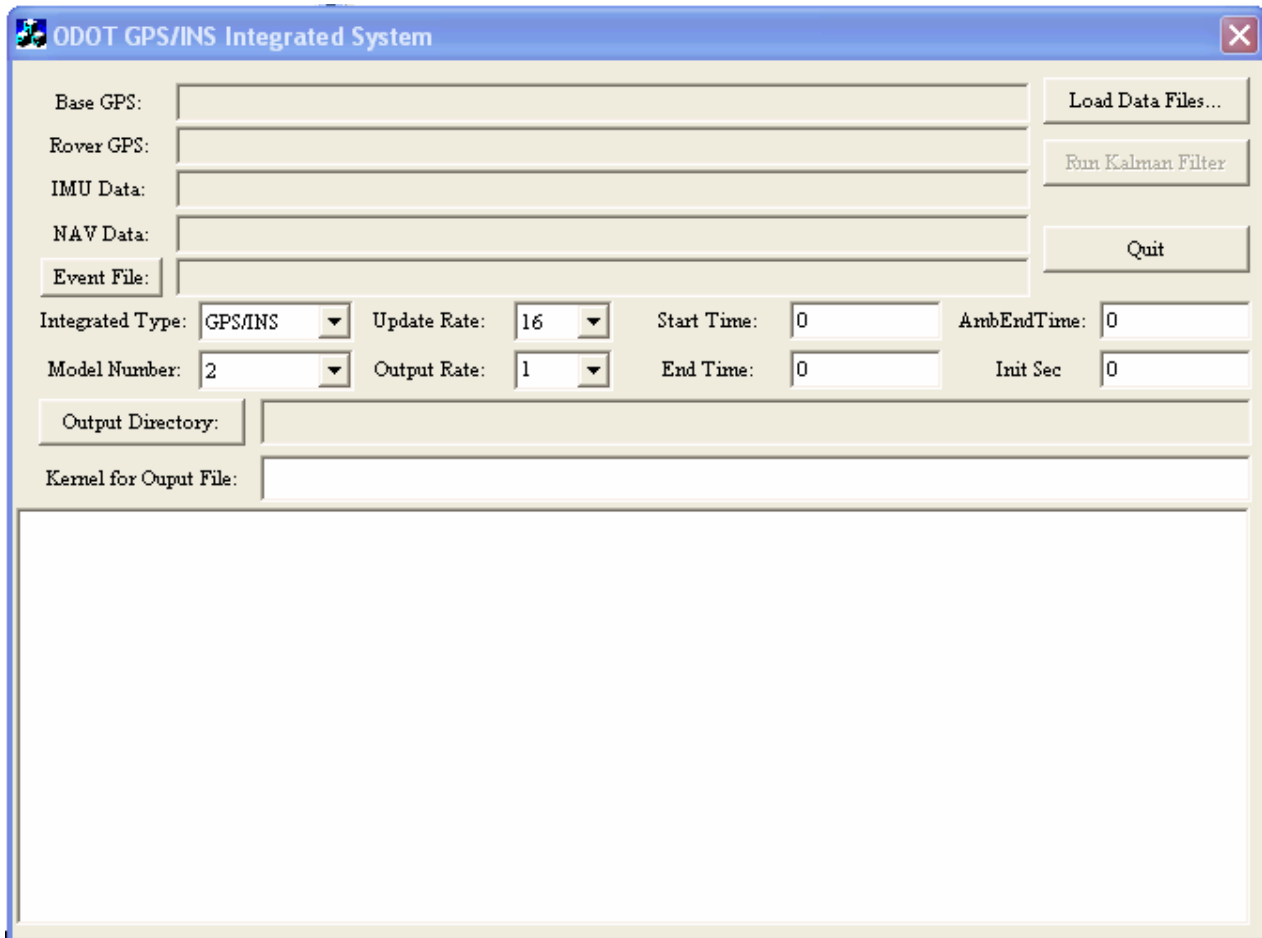


Figure A4. GPSLN100 interface.

The GPSLN100 interface, as shown in Figure A4, allows for data loading, setting run parameters and executing the main application (integrated filter) in the following way:

1. *Load Data Files:*

- Select “Load Data Files...” button to load GPS and INS data.
- Select a base GPS Rinex file. You may choose either navigation file *.02n or observation file *.02o. The program will automatically load another one, if one of them is chosen (provided, they have the same name).
- Select a rover GPS navigation file or observation file.
- Select the IMU.Bin.
- Select the NAV.Bin.
- The program will load GPS files into GPS database.

2. *Set Running Parameters:*

- The program will automatically select default running parameters. The user may change them according to the processing requirements.
- *Start and End-Time.* After the GPS files are downloaded, the dialog box will show the default start-time and end-time, which can be changed accordingly. Out of range time will prompt an error message box, and stop the processing.
- *Running Mode.* GPS/INS Positioning is currently the primary running mode.
- *Model Number:* Currently, three different solution models are provided. Model 1 contains no GPS signal propagation error model; Model 2 contains ionospheric error model; and Model 3 contains both ionospheric and tropospheric error models. Mode 2 is a default.
- *Update Rate:* different update rates can be chosen for the update of the Kalman filter covariance matrix. The default is 16Hz.
- *Output Rate (Hz):* different rates can be selected for the output of the platform’s trajectory. The default is 1Hz.
- *AmbEndTime:* the GPS/INS filter uses the positions given in GPSAmb.Bin to fix ambiguities for the fast start of the Kalman filter. This parameter is used to set the time period during which the positions given in the GPSAmb.Bin are applied. Under the normal circumstances 30-60 sec should suffice. By default, the program will display the maximum available Time from GPSAmb.Bin solution. The user can modify the Ambiguity End Time according to the Start Time, End Time and The Maximum Available Time. If the recommended 30-60 sec+ Start Time is not enough to get a good solution (which may happen for weaker GPS geometry), the user may increase the Ambiguity End Time based on the quality of GPS solution presented in GPSAmb.Bin.
- *Output Directory:* The user can select the directory for the output files (Kfnav.Bin, Kfimu.Bin, ford.zzz and runinfo.txt). The default directory is same as the location of INS data.

- *Kernel for Output Files:* All the output files will add this kernel at the beginning of the filename. For example, if the input name is "Test1" in the text box, then the output files will be Test1_KfNav.Bin, Test1_KfIMU.Bin, Test1_Ford.ZZZ, Test1_RunInfo.Txt.

3. *Run the Program:*

Select the "Run Kalman Filter" button to start the program. During the processing, the prompt area on the screen displays the processing epoch time and all the double-difference residuals (L1 and L2). The level of residuals is expected to be less than 2 cm.

4. Under normal conditions, the filter processes GPS and IMU data to determine 3D position coordinates and orientation of the platform/image sensor. However, during the GPS gaps the processor relies only on the IMU data. Under these circumstances it may be expected that the accuracy of the navigation component will decrease. Therefore, as indicated in **System Operating Instructions**, it is crucial that the GPS is controlled during the survey and if the constellation is weak, or less than 4-5 satellites are available, the system should be put to stop to perform a ZUPT (zero velocity update point). ZUPT supports the calibration of the IMU sensors when GPS is not available. During the post-processing, the program switches automatically to the ZUPT mode to perform system calibration.

5. *Final Results:*

Processing results are stored in four files: KFNAV.Bin (double binary), KFIMU.Bin (double binary), Ford.zzz (ASCII) and RunInfo.Txt (ASCII) (with a selected kernel "Test1," the resulting names will be as follows: *Test1_KfNav.Bin, Test1_KfIMU.Bin, Test1_Ford.ZZZ, Test1_RunInfo.Txt*)

- KFNav.Bin stores the estimated 3D positions (WGS84), velocities (NED) and orientations (heading, pitch, and roll), as well as the standard deviations of these estimates in the same sequence (except for the standard deviations of the attitude components, ordered as follows: sigma pitch, roll and heading). Units are seconds for time, radians for angles, and meters for positions.
- Ford.zzz stores the double-difference residuals for all the satellites. Under normal circumstances, the residuals should be noise-like with values usually being less than 2 cm. A Matlab macro *read_ford.m* can be used to read this file and plot the double difference residuals.
- RunInfo.zzz stores the complete information related to the GPS data, GPS satellite coordinates, partial derivatives, cycle-slip and ambiguity information. This file is designed for testing and debugging purposes, so may not be needed for normal operations.
- KFImu.Bin stores miscellaneous estimates of system and sensor errors at 1Hz rate (double binary). The content of this file may vary depending on the processing model chosen:
 - ⇒ *Model 1:* position errors (3), velocity errors (3), orientation errors (3), accelerometer biases (3), accelerometer scale factor errors (3), gyro drifts (3), gravity disturbances (3), antenna biases (3), and standard deviations of these estimates (standard deviations of navigation parameters are not included in

KF_IMU.BIN. Instead, they are contained in KF_NAV.BIN, as pointed out above).

- ⇒ *Model 2*: The first 24 elements are the same as in Model 1. Then eight estimated ionospheric errors and their standard deviations follow.
- ⇒ *Model 3*: The first 32 elements are the same as in Model 2. Then eight estimated tropospheric errors and their standard deviations follow

NOTE: For the output rate higher than 1Hz the standard deviations for the parameters are not loaded to the binary output files KfNav.bin and KfIMU.bin.

ADDENDUM A

Survey Checklist

1. **Quantity of 2 RG58A/U male to male BNC PPS & Event marker cables**
2. **Quantity of 1 male DB25 to female matrix connector LN100 cable**
3. **Quantity of 1 male DB25 to male matrix connector LN100 cable**
4. **Quantity of ___ male LEMO to male TNC antenna cables**
5. **Quantity of 1 DB9 power-fan-shutter signal cables**
6. **Quantity of 1 male DB9 to female DB25 serial cable for GPS communication**
7. **Quantity of 1 null modem ethernet cable**
8. **Quantity of 2 Trimble external battery harnesses**
9. **Quantity of ___ VGA cable extensions**
10. **Quantity of 1 2-button serial mouse**
11. **Quantity of 2 keyboard extension cables**
12. **Quantity of 1 Trimble PPS signal converter box**
13. **Quantity of 1 keyboard/monitor switch box**
14. **Quantity of ___ Trimble Ground plane antennas**
15. **Quantity of 1 keyboard with ps-2 adapter**
16. **Quantity of ___ power cables**
17. **Quantity of 1 external SCSI cable**
18. **Quantity of ___ Tripods w/ tribrachs**
19. **Quantity of 1 measuring rod for tripod**
20. **Quantity of 1 12v DC – 110v AC power supply**
21. **Quantity of 2 Trimble 4000ssi receivers**
22. **Quantity of 1 Trimble 4000sse receivers**
23. **Quantity of ___ camcorder batteries**
24. **Quantity of ___ Trimble office modules**
25. **Quantity of ___ backup tapes**

ADDENDUM B

System Operating Instructions

Power-on Tasks:

1. Turn on DC/AC inverter main switch (passenger side door)
2. Turn on DC/AC inverter output switch (driver's side of inverter box)
3. Power on **IMU PC** (smaller PC on the left side)
4. After IMU PC boot procedure is complete, power on **Imaging PC** (Dell PC on the right side)
5. Turn on **IMU** power switch (on the rack next to the Dell PC)
6. Turn on **digital camera** power switch (on the rack next to the Dell PC)
7. Turn on **GPS** receivers

Check Data Acquisition PC Systems:

- After the **IMU PC** boot procedure is complete, check the available **disk space** on drive D: – you need approximately 200 Mbyte for every survey hour (disk capacity is about 15 Gbyte). After longer use, either defragment or reformat the disk.
- Check that the rover **GPS receiver** has enough **space** available for the survey. The 2 Mbyte built-in memory can log data for about 2-3 hours. It is a good habit to clear the memory before each survey.
- The **Imaging PC should boot after the IMU PC** has been booted because the D: drive of the IMU PC is shared and therefore must be mounted before the Imaging PC starts the boot procedure.
- Check **disk space** available on the **Imaging PC D: drive**. At maximum capacity, the disk can store images for a one-hour survey, or about 60 mile surveyed distance (the current disk capacity is about 36 Gbyte). Again it is a good habit to clear this disk before each survey.
- If the proper sequence was followed, **drive G:** on the imaging system will be available (the location, where navigation information is passed to the Imaging system during the surveys).
- Run digital camera control software to initialize the camera interface – click on the icon **TM6700_1000CL**. Once the dialog is on, select **CameraLink** and click on **Open**. On the lower status bar, the camera ID will be displayed shortly. At this point, close the dialog; the camera is ready for operations.
- For extreme light conditions, by running the R2View program the camera can be checked for proper settings. Click on the R2View icon, then after two Ok's, select No. A window

will pop up and by clicking on the Trigger icon (a gun) you can take pictures, which will be displayed in the pop-up window. If you adjust the f-stop on the camera, make sure that the exposure time stays in the middle of the range, so the operator or the software can change as the light conditions may vary during the survey.

Start Surveying Tasks:

- Make sure that the **GPS base station is set up and logging**, or there is a permanent base station running nearby with adequate data rate (1 Hz data). Not having base GPS data can have a devastating effect. Remember the base station cannot be farther away than 5-10 km.
- Make sure that there is a **Location.dat** file in the GPS/IMU data acquisition program directory (C:\DEV\TEST). The file should have position data of the starting position to support the IMU initial alignment process (using the information from the GPS receiver is good, see documentation for details).
- Start the GPS/IMU data acquisition program. Click on the **RTINS** icon. Under normal circumstances such as freshly booted system, simply click on the **Start/Stop** button. If the IMU has been already aligned then check on Skip Alignment control before click on the Start/Stop button.
- Watch carefully for the messages displayed in the program's listbox. If there is any problem you will get an error message and the process will abort. Typical problems are: IMU is not turned on or GPS is not connected or 1PPS signal is not available, etc. If something more unusual is happening then power the system down and start from a fresh boot.
- The initial IMU alignment can take a few minutes – there is a progress counter running in the lower status bar. If the IMU is aligned but the program is restarted for some reason, then checking the Skip Alignment before clicking on the Start/Stop button will bypass the alignment process and thus the survey will start shortly after that. As the IMU may accumulate too many errors over time, it is recommended **to realign** it after about **two-three hours of operations**.
- Once the software entered the data-logging mode, a record counter is displayed in the status bar with some additional information. The last two numbers indicate error conditions, so if they start to increase excessively, you may want to stop the survey and check the system, such as realigning the IMU and/or reboot the computer.
- The quality of the GPS reception is continuously monitored during the survey. Please make sure that enough satellites are tracked and the PDOP is within the limit. Availability of **dual frequency** carrier phase data is critical.
- Once the GPS/IMU data acquisition process has started, turn to the Imaging PC and start the digital camera data acquisitions software by clicking on the **SMDigCam** icon. During the initial few seconds, messages are posted in the lower left listbox. Make sure that there are no error conditions reported. Select the triggering and exposure modes and then start the image logging by pressing the **Start/Stop** button. Remember that at maximum, the images are collected at about 30 Gbyte per hour rate.

Monitoring the Surveying Process:

- Always keep an eye on the GPS data acquisition process. If the number of satellites drops, then either slow down or stop the vehicle to allow for reacquiring the satellite signals, and a ZUPT (zero velocity update point), which will support the post processing of the navigation data.
- The RTINS software provides the user with a complete status of both the GPS and IMU data acquisition processes. The GPS is the critical item to watch for as everything else in the system strongly depends on the GPS data quality. For the IMU data logging the record counter is the primary parameter to check on. Then there are two variables displayed as the last two items on the status bar indicating possible error conditions (these two parameters are usually zero and may increase close to a “buffer full” situation; note that the fact that they are not zero, does not necessarily mean that there is any serious problem).
- The monitoring of the imaging PC data acquisition is equally important to the GPS reception quality. Recording low quality images or not recording images will result in unsurveyed segments or complete loss of survey data. As the images are constantly displayed during the survey, maintaining a good image quality is normally not difficult. The only parameter, which can influence this process, is the exposure time that can be controlled either manually or automatically by the program. Besides that, the disk space availability should be monitored periodically. The image acquisition can be suspended any time such as at a traffic stop (it is automatic in speed control mode).

Stopping the Surveying Process:

- Stop the image acquisition process on the imaging PC by pressing first the **Start/Stop** button and once the process has stopped leaving the program by pressing the **Ok** button. Check whether the messages during the process termination indicated any error conditions.
- Stop the IMU data acquisition program on the IMU PC by pressing the **Start/Stop** button. Check the messages in the listbox. The important things to look for are:
 - The INS clock time should be about **64.0064 microseconds** (it may slightly change with temperature).
 - Press the **Time Log File** button to run a check on the timing quality of the survey in term of possible epoch gaps. Usually, it will report zero gaps. Having a small number is still okay. An excessively high number, however, may indicate a major problem (anything larger than 100 is suspicious).
 - As a next step press the **Gap Log File** button, which then will check for missing IMU records. Normally, it should be zero. A small number is okay (if it gets to the thousand range then there may be a real problem with the data).
 - If these tests have passed, then run the time correction by pressing **Process Data** button. After the process is finished check the INS clock value (it must be around the 64.0064 value). If it is not correct, then there is a problem with the data. In case if the original value (the one that was shown after the data acquisition was

stopped) was correct, click on the Keep Time control, and then the **Process Data** button, allowing the correction to be recomputed. If it fails then the data cannot be salvaged.

- **Quit** the IMU data acquisition program.

Data Processing:

There are several steps involved in the data reduction process and many of them can be executed in a parallel fashion. The following description shows a possible sequence, although there are many other possibilities, depending on whether someone optimizes for time or the effort. For example, before making sure that the GPS data is of high quality, it is really pointless to deal with the image processing part. However, starting the centerline image processing at the beginning can save a lot of time provided the navigation solution will be available. The description of the individual programs is omitted from this document; see the system documentation.

- Run the **GPSVan_proc** program (Figure 1) to extract the centerline position from the images on the Imaging PC. Select the log file of the images and start the processing. The approximate processing time roughly equals the data acquisition time (or less, but it is usually not more than the processing of the navigation solution). Selecting options may increase time and requires additional disk space, so do it with an extreme care. The image counter shows the status of the whole process. The output is the image coordinate file, called **Icoord.txt**.
- **Download the GPS data** to the IMU PC. The rover is directly connected; therefore the downloading can start right away. Click on the **GPSLoad** icon to activate the program. Set up some convention on how the data will be organized. Every IMU data acquisition session opens a directory on the D: drive; the directory is named by the date and time (e.g. 20020718_165549). A possible approach to organizing the data is to put all the other navigation data sets under the IMU directory. For example, open a NAV directory and then open three subdirectories in it, such as BASE, ROVER and EVENTS. The base GPS data may come from various sources, such as a base station set up for the job, nearby permanently running GPS station, or some other local permanent station. The downloading process may be different for the various situations. In general, make sure that both Rover and Base GPS receiver data have been downloaded and the data set is converted to Rinex file format.
- For Trimble receivers, use **Trimble Office** to convert **DAT** files to **Rinex format**.
- Once the Rinex files are available, check the data quality, especially the availability of L2 data. If there is any problem with L2, there may not be any acceptable solution, or alternative, more complicated processing option will have to be performed, which may also lead to less optimal quality of your solution. (There is a tool in the AddTool utility for such cases).
- Run **TestINS** program by clicking on its icon on the desktop of the IMU PC. From the dialog select the raw IMU measurement file and the click on the Run button. The process

may take a while for longer surveys. Once the process is complete, check that the **INSTemp.dat** output file shows good values. The third line shows the time scale of the IMU that should be around 1.0001. Any major deviation is a sign of uncorrectable error.

- Obtain control data from the GPS base station. Run the **AddTool** (Figure 2) program to enter the control data into a Rinex format file entry. Select file name and then click on Set to create the file. Open the file just created – it should have two lines in Rinex format. Copy the template **Control.all** file into the current IMU survey directory and then edit it by entering the base station coordinates from the already open Rinex format file. Next open the GPS base station Rinex observation file and replace the two lines with the ones created by the AddTool program.
- Run the **AmbRes** program to preprocess the GPS data. Select and load the GPS files in the following sequence: GPS base observation file, GPS rover observation file and finally any of the GPS navigation files. Upon completion, three files will be created in the ROVER directory.
- In case the AmbRes program fails, there is an optional solution by using Trimble office and Matlab. Run the AddTool to prepare the data. This procedure can sometimes salvage the processing, if no L2 prevents us from reestablishing the ambiguities.
- Bring the image log file(s) from the Imaging PC and place them into the EVENTS directory (e.g., 20020718_165549.log).
- Run the Kalman filter program by clicking on the icon named **ODOT**. Load the data files in the following order: GPS base observation, GPS rover observation and then Imu.bin and Nav.bin. Next, select the image event file from the EVENTS directory. Specify an output file name, for example a project-specific name. Run the filter. Depending on the surveying time, the processing may take a while. The residuals for each processed epoch are displayed in the listbox and can give an immediate feedback on the quality of the solution. If extended periods of zero residuals are visible, this may indicate extended gaps in GPS.
- To convert to the local mapping frame, the solution of the Kalman filter should be further processed. Run the **AddTool** utility and split the filter-produced file (event log file name with the OUT extension) into coordinate (*.COR) and attitude (*.ATT) files.
- Use **Trimble Office** to convert the extracted coordinate file into the choice of your mapping system. There are template files for both import and export operations.
- Use again the **AddTool** utility to merge the coordinates with the attitude data. The freshly created navigation file can be transferred to the Imaging PC.
- On the Imaging PC run the **GPS_coord** program (Figure 3) to compute the centerline points from the image coordinates and the navigation solution. Select the input files in the dialog (navigation file, image coordinate file, which was created by the GPSVan_proc program and is called icoord.txt, and the boresight file). Specify an output file and then run the computation process. The program will report the number of centerlines points created and processed. The output file is ready for importing into any CAD/GIS system.



Figure 1. Image processing program **GPSVan_proc**.

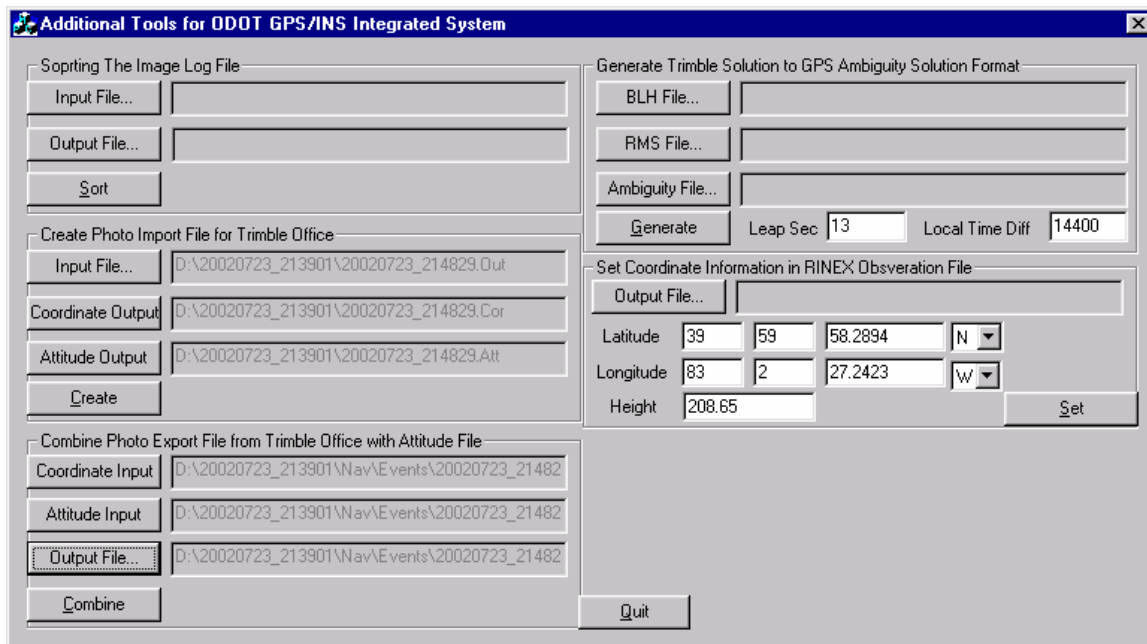


Figure 2. **AddTool** utility program to support various navigation data processing steps.

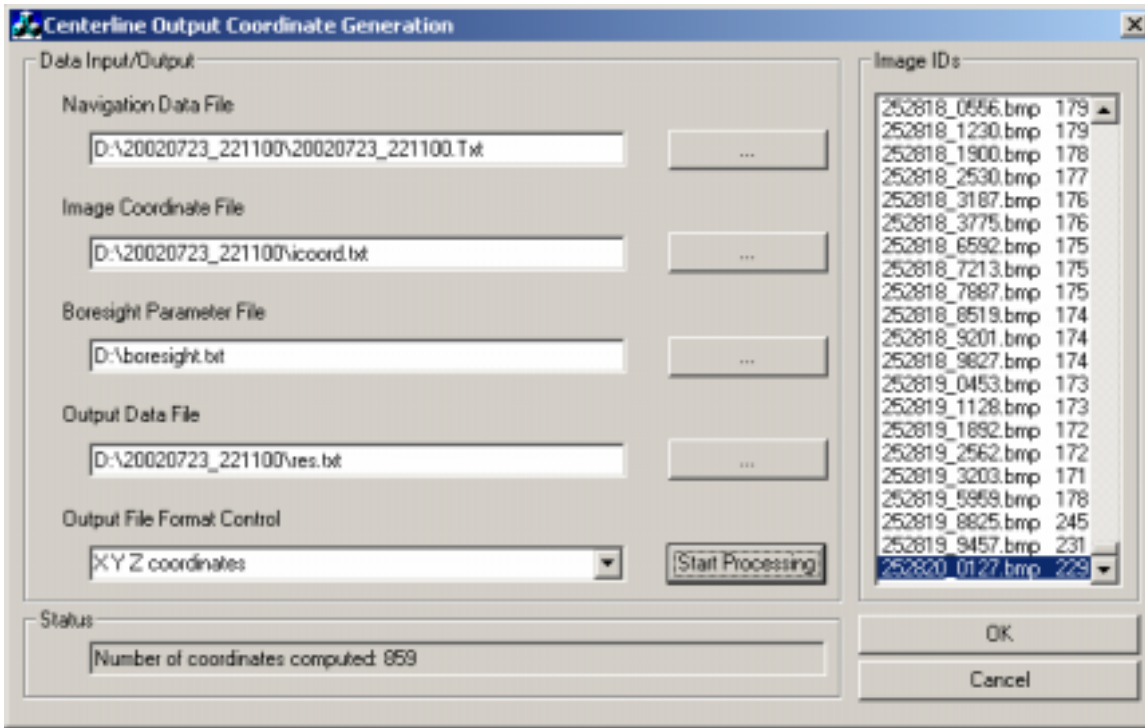


Figure 3. **GPS_coord** program to create centerline coordinates from the navigation solution of the event file and the image coordinate file; requires a valid boresight file.

Power-down Tasks:

- Turn off the **IMU** power switch (on the rack next to the Dell PC), the IMU has a limited lifetime, so make sure that it is always turned off.
- Turn off **digital camera** power switch (on the rack next to the Dell PC)
- Shut down power on **Imaging PC** (Dell PC on the right side).
- Once the Imaging PC is off, shut down the **IMU PC** (smaller PC on the left side).
- Turn on DC/AC inverter output switch (driver's side of inverter box)
- Turn on DC/AC inverter main switch (passenger side door)