Pedestrian ITS in Japan

Pseudolites and GPS

Ivan Petrovski, Kazuki Okano, Makoto Ishii, Hideyuki Torimoto, Yusuke Konishi, and Ryosuke Shibasaki

Pseudolites offer one solution to the problem of GPS signal blockage indoors and in obstructed areas. This article describes the efforts of a Japanese team to develop an Intelligent Transportation System for visually impaired pedestrians.

Ivan Petrovski *is the head of R&D for GNSS Technologies Inc. in Tokyo Mercantile Marine University. Previously he worked as an associate professor at the Moscow Aviation Institute and as chief researcher at the GPS division of DX Antenna Co. Ltd.*

Kazuki Okano *is a senior engineer of GNSS Technologies Inc. (Pictured in photo above at left, carrying portable computer during test in Tokyo, Japan)*

Makoto Ishii *is director of marketing at GNSS Technologies Inc.*

Hideyuki Torimoto *is president and CEO of GNSS Technologies Inc. Previously he was general manager of the GPS Division of DX Antenna and executive vice president of Trimble Navigation Japan Ltd.*

Yusuke Konishi *is a Ph.D. student at the University of Tokyo.*

Ryosuke Shibasaki *is a professor of the University of Tokyo, and leader of GIS Project in Japan projects.*

A recurring concern for GNSS applications arises from need for user equipment to have unobstructed reception of the low-power GPS signals, from at least four satellites for code positioning and at least five for carrier-phase positioning. This requirement limits almost every field of GPS implementation: geodesy, navigation, vehicle tracking, construction, and mass markets such as car navigation and wireless communications.

Traditionally, GPS manufacturers and users have coped with this problem in two ways: by incorporating dead-reckoning or other radionavigation technologies, and by seeking out extra sources of compatible GNSS positioning signals. A third approach today involves efforts to increase the sensitivity of GPS receivers.

Pseudolites offer another source of GPS-compatible signals. A pseudolite (or pseudo-satellite) typically is a ground-based transmitter of GPS-like signals. Successful pseudolite implementations include the development of aircraft landing systems.

Our group has concentrated its activity and research in the area of pseudolite application in social infrastructure. In 2001, we initiated a Precise Positioning for Social Infrastructure Research Forum. As a result of its efforts, pseudolites were implemented in the Pedestrian ITS (PITS) project led by the NTT Communications Consortium (See sidebar, "Research Forum and ITS," on page 37.) This article describes our work on PITS and related research.

Pseudolite Appeal

Pseudolites are very attractive as an augmentation to GPS satellites, and can support both code and carrier-phase positioning. Because pseudolites can operate on the same frequency as GPS, they enable use of standard GPS receivers with only minor modifications in firmware. In effect, pseudolites add more "satellites" to the GPS constellation and improve the geometry of this hybrid constellation. Used indoors, pseudolites can provide seamless outdoor-indoor positioning with the same user equipment.

Pseudolite technology has sparked significant interest in Japan, because of the country's huge scale of GPS use as well as the problem of satellite availability. Several research projects have demonstrated that pseudolites can benefit users in almost every application. For carrier-phase positioning, for example, pseudolites provide an additional advantage: the proximity of mobile users to the pseudolites produces a more rapidly changing geometry than is possible with orbiting satellites 12,000 miles away, which allows more rapid resolution of carrier-phase integer ambiguities. The pseudolite error budget also doesn't contain the atmospheric and orbital errors that accompany satellite signals.

However, several concerns have slowed pseudolite development. The most important drawback is that the use of pseudolite transmissions by a GPS receiver raises the risk of in-band interference with GPS signals. The pseudolites have other, less severe shortcomings. For example, pseudolite errors can increase significantly due to multipath, especially indoors.

GPS, Pseudolites, and ITS

In 2000, a few ITS projects launched in Japan sought to develop an ITS prototype, providing automated services to travelers, possibly including detailed real-time traffic reports, and enabling information exchange between vehicles and the ITS information infrastructure. The core of the ITS is an ability to provide precise real-time positions of all vehicles operating in traffic, but Japan's program also seeks to extend ITS capabilities to pedestrians.

Our consortium has successfully conducted interference tests and obtained a

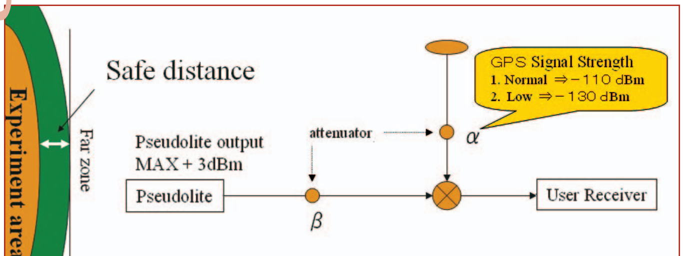


FIGURE 1 Test to determine a safe distance to pseudolites

A Tokyo bus shelter provided a platform for equipment during outdoor trials.

license to proceed with outdoor pseudolite experiments, which we conducted in 2002 in Tsukuba and downtown Tokyo.

Because of the types of physical obstructions mentioned earlier, the availability of service based on GNSS-only is problematical for both pedestrian and highway ITS (HITS). Consequently, to provide an uninterrupted positioning, high accuracy, and reliability in both ITS projects, we have proposed to use extra positioning information from pseudolites to augment GPS, which serves as the main navigation instrument in both HITS and PITS. In the course of these efforts, we looked at the various concepts that can be considered for ITS.

Timing Essential

A key to successful integration of pseudolites for indoor positioning is to resolve the clock offsets among the transmitters and communicate this to the user equipment. Our approach uses the pseudolite signal received at a reference station, which in turn estimates the pseudolite clock error and sends that information to the user. In thinking about infrastructure, one can imagine the enormous number of reference stations that would be necessary to deploy.

In comparison with pseudolites, which can be manufactured very cheaply, a reference station always will be relatively expensive. Therefore, for social infrastructure, it would be much more economical to provide an external synchronization.

External synchronization can be done with help of GPS. The pseudolites, which belong to the network installation, operate not as a number of single sources any more, but rather like a constellation of satellites. Also, it is helpful that one needs to synchronize only pseudolites in view.

Interference

The main problem for pseudolite implementation is in-band interference with GPS. What we are going to discuss here is how we are coping with interference for the purpose of test and development of a prototype only in very limited areas. We do not intend to propose a system based on pseudolites, operating in GPS frequencies; therefore, we will not discuss how to eliminate interference on a wide scale.

In order to get a license from the General Affairs Department for outdoor pseudolite tests, we had to develop a procedure that would not interfere with non-participant receivers (receivers, which are not supposed to acquire and to be affected by pseudolite signals) outside the designated test area. To fulfill this requirement, we conducted laboratory tests coupling pseudolite signals along with live GPS signals. We also used a simulator to generate GPS signals so as to increase our flexibility to vary GPS signal power levels during the tests. We also looked at such factors as power attenuation and frequency shift and how they will affect the interference level.

It is well known that the best way to fight interference is to implement a pulsing scheme to the GPS-like pseudolite signal. This pulsing will spread the pseudolite signal over time, lowering its instant power level in such a way that a nonparticipant receiver won't detect it.

A receiver may be in an area where it can hear a signal from many pseudolites. In this case, the pulses from pseudolites should not overlap with each other and leave a portion of a sufficient interval in which non-participant receivers can acquire the GPS signals. At the same time, these pulses should be long enough for participant receivers to acquire a pseudolite signal. These considerations required us to examine the effects of a pulsing scheme with a variable duty cycle and pseudolites with overlapping zones.

Figure 1 shows the physical layout of the pseudolite testbed. The main objective of the test was to establish allowable distance from test zone to a nonparticipant GPS receiver in the presence of maximum pseudolite signal strength, at which the nonparticipant receiver will not experience any interference. We have tested geodetic and navigation receivers for each situation, including pulsing schemes with duty cycles of 100, 20, 10, and 5 percent. The survey receiver was set to the maximum sensitivity of – 130 dBm. (Because navigation receivers are less sensitive to interference than geodetic receivers, we focus on the former category as providing the most challenging test instrumentation.)

For each case, we calculated the safe distance to pseudolite based on the attenuation in the signal's power as it propagates through open space. Results show that the recommended separation of pseudolites from nonparticipating GPS receivers need be no more than 500 meters, which will guarantee the absence of interference with a geodetic receiver up to a maximum pseudolite power of -34.7 dBm. (For our purposes, wee don't need to dwell on the so-called "near-far" problem caused by closeness of signal sources to a user. By placing pseudolites on the top of the building, we put the near zone out of reach of the receivers.)

Getting Around Indoors and Out

PITS requires seamless indoor-outdoor positioning so that, for example, a person can go through a tunnel or building and a driver can park a car or drive through the tunnel without interruption in the positioning information.

Indoor positioning with pseudolites is different in many aspects from typical GPS

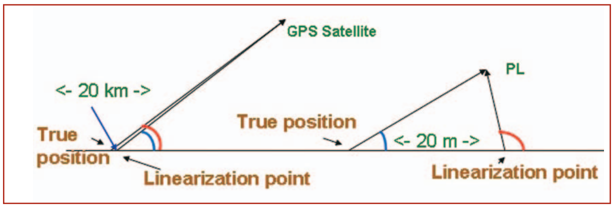
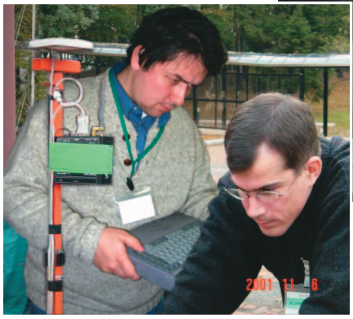


FIGURE 2 Algorithm sensitivity to error in initial position

Pseudolite installation on roof for Tsukuba test



Author Ivan Petrovski and Stuart Cobb of IntegriNautics work on system configuration for Tsukuba test

Indoor tests identified multipath effects and the opportunity to use a GPS retransmitter as a signal source.

positioning outdoors. For instance, the error budget doesn't include atmospheric and orbital errors but does suffer from a potentially high multipath component.

The main challenge in developing software for pseudolite-based positioning indoors is to provide a solution for a classic system of nonlinear equations. In the conventional approach, such as least squares, the initial position error plays a critical role, because nonlinear pseudorange equations require linearization close to the true position.

Consider the formula

$$[dX] = [H] \cdot [d\delta] + d[H] \cdot [\delta]$$

where observation matrix $[H] = ([A]^T[A])^{-1}[A]^T$, $[dX]$ is an error in user position and time, $[A]$ is a directional cosines matrix, and $[d\delta]$ is the offset of pseudoranges. Directional cosines $[A]$ are not critical to this error in case of distant GPS satellites. In the case of closely located pseudolites, however, the error in directional cosines due to initial position error is much more significant, and matrix $[A]$ varies substantially as a function of the initial position. A few meters in case of pseudolites will cause much more significant error in $[A]$ than thousands of kilometers for GPS (see **Figure 2**).

The problem is that error in initial position propagates through the directional cosines matrix into the solution with some gain. The solution in turn is used as an initial position for the next step. This positive feedback can cause instability in the solution. If we as in static mode keep initial position for purpose of determination of matrix $[A]$, it gives us a constant error in the resulting position. The size of the error, which is caused by uncertainty in the initial position, depends on the geometry of pseudolite constellation.

The easiest method with which to handle this problem is to start from a known position, which is not always acceptable for real-life applications. Therefore, we required different positioning algorithms less sensitive to initial position errors. The ones we developed looked at the variation in behavior of the estimated position in cases of error in initial position and in cases without error. Such variations give one a way to find the correct initial position with a search algorithm, much the same way as for carrier phase ambiguity resolution. The initial area for the search algorithm is found through a semi-analytical solution. **Figure 3** illustrates this approach.

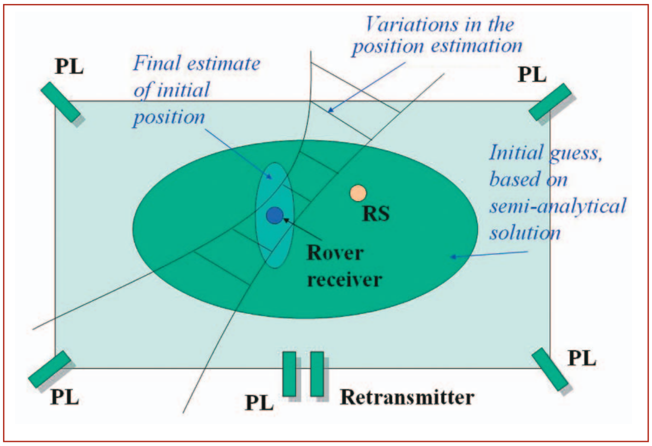


FIGURE 3 Schematic of the approach to the initial estimation of position

During the indoor test we translated GPS signals received at the roof antenna and retransmitted them into the premises. The use of a GPS retransmitter is an interesting subject in itself. Indoors, one can clearly use only a single GPS satellite out of all those signals received at the roof antenna. This may serve as a separate signal source or as an extra pseudolite.

In our first test we had a substantial positioning error, which was attributed to high multipath. Preliminary tests showed that multipath error can exceed 10 meters. This particular error was caused by the slope of the room floor and the presence of metal chairs. It primarily affected the rover, when it was at the bottom part of the room. We also have used the retransmitter for monitoring the level of multipath indoors by comparing positions calculated only from satellite signals from the roof antenna with position solutions using the same signal retransmitted indoors.

Positioning Methodology

Using a retransmitter, we could provide 2D code-based positioning with signals from only two pseudolites available to a receiver. Indoor positioning usually assumes 2D positioning on a room-by-room basis, and one can provide the height for a mobile

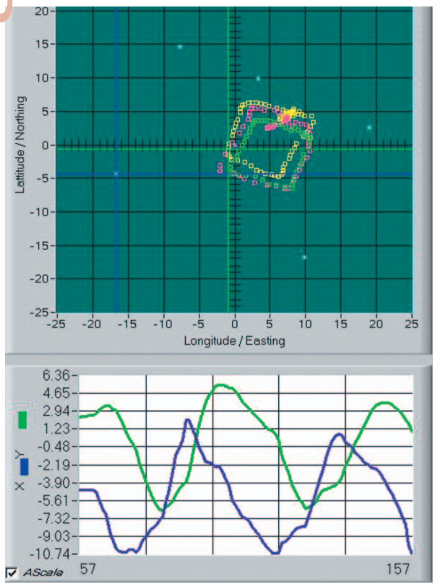


FIGURE 4 Track of rover in indoor test using pseudoranges only. Scale increments are 1 meter.

receiver as a part of a correction message.

To improve the results, we were planning further tests. Achieved results demonstrated that the current algorithm can provide accuracy within a few meters in code mode, and within centimeters in smoothing mode relative to the initial position. The absolute accuracy can be achieved only by code positioning for a static receiver at the level of a 1–2 meters. Carrier phase ambiguities can not be resolved by a static receiver indoors. However, one can use the carrier for dead reckoning relative to known an initial position, which gives a one-centimeter level accuracy relative to initial position.

Our indoor positioning software can be represented by two main blocks; one is initial position estimation, and the other is tracking mode. Tracking is implemented using carrier phase, but one must either start from a known location or execute some calibrating movements by the rover in order to resolve the ambiguities and obtain an initial position estimation for the carrier phase algorithm. **Figure 4** shows the path of the rover after it completed three runs around the room, which were estimated using pseudorange only. The five cyan light blue asterisks represent pseudolite positions. **Figure 5** depicts the results of the static positioning with filtering and demonstrates convergence to the true position (the rose asterisk).

Tests and Results

The purpose of the test in Tsukuba was to provide seamless positioning along a track that included obstructed places. We wanted to see how pseudolites can improve visibility, availability, and accuracy in an urban environment. The obtained results demonstrated the possibility of uninterrupted positioning in limited visibility areas, particularly in the shadowed area of buildings, where the number of available satellites ranges from two to zero. The hybrid results also show improved accuracy in comparison with GPS satellites only.

The positioning system used in the Tsukuba test contained six commercial pseudolites, a GPS base station and rover, and a wireless modem for data communication (See **Figure 6**.)

Figure 7 shows the vertical and horizontal components of positioning error in the Tsukuba test, as well as dilution of position (DOP) and the number of GPS satellites and pseudolites tracked separately and together. The Tsukuba test demonstrated that augmentation with pseudolites enables one to provide navigation with an accuracy of about 10 centimeters with only two GPS satellites available.

We used a small trolley with mounted antenna and a few rovers in differential and RTK mode logging data into attached PC. The trolley moved along a route surveyed in advance. Turning points on this route had been surveyed and connected by straight lines. During the test we changed the power of pseudolites and turned some off and on. The results have been presented separately in an extensive report.

Another interesting result of the Tsukuba test was detection of a dead spot in pseudolite signal reception. We have an area of about one square meter where the signal from a given pseudolite in view of the receiver completely disappeared. Apparently, the signal was completely compensated by its reflection from the wall. This was a very significant result, which we are going to investigate further. One can imagine how important it is to design a test — or, eventually, an operational system for people with disabilities — to avoid such dead spots.

For the conceptual test in downtown Tokyo to certify the possibility of using PITS for people with disabilities, we installed a reference station and pseudolites as shown in the accompanying photos. The test was intended to demonstrate

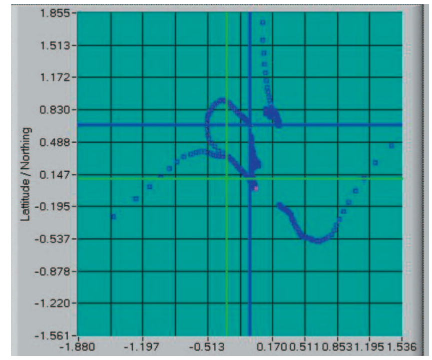


FIGURE 5 Static positioning test results show convergence to the true position (rose asterisk). Scale increments are 1 meter.

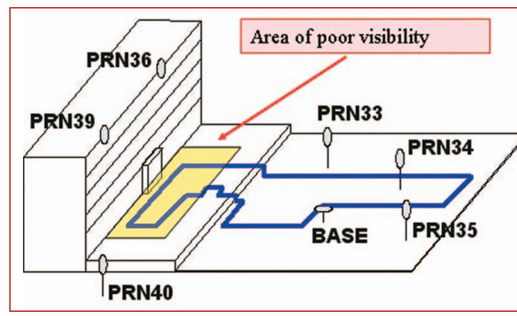


FIGURE 6 Pseudolite configuration at Tsukuba

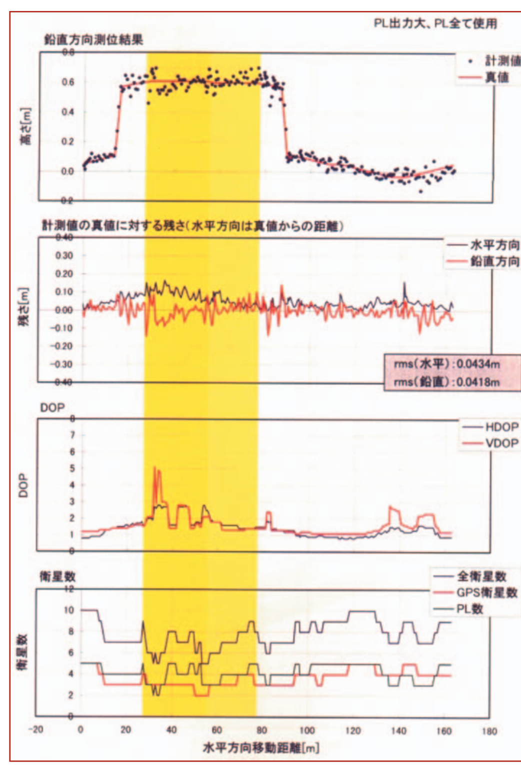
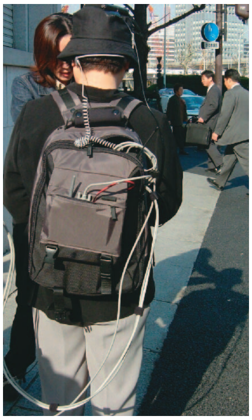


FIGURE 7 (From top) Vertical error, horizontal error, DOP, number of satellites/pseudolites in Tsukuba test

the complete system and how it works for users. The navigation component of the system that we had provided was combined with a geographic information system (GIS) mapping software and audio interface into the portable equipment.

The test was organized in a fashion so that people with disabilities, who are expected to be main users of this system, can test it. Pseudolites had been mounted on top of high buildings, and the GPS reference station was on the roof of a bus stop shelter. The path for the investigators was from the Tokyo station near the bus stop, past a high building that provides very low GPS visibility, and across a street. A person with the system is guided by the audio interface only. Attendants ensured the safety of participants and monitored the test. The portable backpack system incorporated a GPS and pseudolite-capable receiver and other components, such as a voice interface, map-matching software, and so forth, which had been developed by members of our consortium.



Backpack equipment for Tokyo test included pseudolite receiver, mapmatching system, and an audio interface.

The test demonstrated that the concept works and can be developed into attractive, reliable, and easy-to-use system. Now we are planning the next component of the system to be tested, which is installation of a pseudolite in a subway vestibule to provide one-dimensional information of a user's location along a passage.

Conclusion

The completed tests demonstrated the possibility of using pseudolites in social infrastructure. Pseudolites can not only augment GPS satellites in limited visibility areas, but potentially provide users with means for seamless outdoor/indoor positioning. Pseudolites can significantly improve accuracy in areas with limited GPS availability, such as urban canyons, conceivably providing users with centimeter-level accuracy.

Use of the GPS band for the sort of hybrid positioning described in this article is technically very attractive, because it allows us to employ an unmodified GPS receiver. However, despite the possibility of harmlessly implementing L1 pseudolites in designated limited areas, no current technology can guarantee complete absence of interference, especially for highly sensitive geodetic GPS receivers. Therefore in case of widespread implementation of pseudolites in social infrastructure, they should be moved into an unshared band to prevent interference to GPS satellite signals and from other emitters.

Acknowledgements

Our research on indoor positioning is conducted together with Keio University and Future University – Hakodate. Apart from seamless indoor-outdoor positioning for ITS projects, its aims at applications in robotics and automation. The authors acknowledge Stuart Cobb and Paul Montgomery of IntegriNautics for assistance during tests in Tsukuba and Tokyo, and Jun Murai and Yuusuke Kawakita of Keio University and Osamu Tobe of Nara Institute of Science and Technology for research collaboration. We also acknowledge Keiji Suzuki, Masashi Toda, and Jun-ichi Akita from the Department of Media Architecture of Future University – Hakodate for participation in indoor pseudolite positioning research.

Currently, interesting and significant results in applications of pseudolites have been achieved by Dr. Changdon Kee of Seoul National University, Korea (see article listed in the Further Readings section); Dr. Jinling Wang of University of New South Wales, Australia; Dr. Toshiaki Tsujii of National Aerospace Laboratory, Japan; and U.S. researchers from Stanford University, Worcester Polytechnic Institute, Ohio University, and others. ⊕

Manufacturers

The work described here used *IN400* pseudolite signal generators from **IntegriNautics** (Menlo Park, California), the *GPS OEM-3* receiver from **NovAtel**, (Calgary, Alberta, Canada), and the *iTrax02*, **FastraX oy** (Vantaa, Finland). The Tokyo test used *Guidance GIS* from **Sumitomo Electric Industries, Ltd,** (Osaka, Japan) and an audio interface manufactured by **NTT Communications** (Tokyo, Japan). We also made extensive use of **Spirent Communications** GPS simulators during laboratory testing.

Further Reading

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"Development of Highway ITS and Pedestrian ITS Based on RTK Network, Pseudolites and PN Coded Magnetic Markers," I. Petrovski, M. Ishii, H. Torimoto, and T. Hasegawa, *Proceedings of ION GPS 2001,* Institute of Navigation, 2001.

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Research Forum and ITS

The Precise Positioning Social Infrastructure Research Forum in Japan is comprised of leading companies and research institutes. Its Chairman, Dr. Jun Murai, is the head of the WIDE project, which is Japan's biggest Internet consortium in Japan with more than 100 corporate members. (He was a co-author of the article published in the May 2000 issue of *GPS World* on the InternetCar, which also belongs to the WIDE project) The forum is currently focusing its efforts on applications of various positioning technologies to social infrastructure.

As part of a nationwide Intelligent Transportation Systems (ITS) program, the Ministry of Land , Infrastructure and Transport of Japan through National Institute for Land and Infrastructure Management (NILIM) have chosen five projects of Pedestrian ITS from more than 100 applicants. Now GNSS Technologies Inc. belongs to two consortiums, which are led by NTT Communications Corporation and Hitachi, Ltd. The systems will serve as a test-bed for development of a Pedestrian ITS concept and system. These projects were presented by NTT Consortium, Hitachi Consortium, NEC Consortium, Astel Chugoku Consortium, and Oki Electric Industry Consortium. The NTT Communications Consortium includes NTT Communications, DX Antenna Co. Ltd. (now GNSS Technologies Inc.), Fuji Electric Co., Ltd., Sumitomo Electric Industries, Ltd., Nakanihon Air Service Co., Ltd., and Mitsubishi Estate Co.Ltd.

Another project under development is Advanced Cruise-Assist Highway System (AHS), which also belongs to the Ministry of Land, Infrastructure and Transport represented by NILIM. The organization called Advanced Cruise-Assist Highway System Research Association (AHSRA), which consists of major Japan enterprises and is established to develop AHS. Hitachi, Ltd. is in charge of the positioning using pseudolites in this project.