The Next Generation of a Super Sensitive GPS System

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BIOGRAPHIES

Lawrence R. Weill

Dr. Weill received B.S. and M.S. degrees in Electrical Engineering from the California Institute of Technology in 1960 and 1961, respectively. In 1968 he earned the M.S. Degree in Mathematics at San Diego State University, and was awarded the Ph.D. in Mathematics in 1974 at the University of Idaho. He is currently Professor of Mathematics Emeritus at California State University, Fullerton, and has operated his own consulting firm for 25 years.

Dr. Weill is also one of the three technical founders of Magellan Systems Corporation (now Thales Navigation), which in 1989 produced the world's first low-cost handheld GPS receiver for the consumer market.

As an active researcher, Dr. Weill has published numerous papers on signal processing for GPS, radar, sonar, optical sensor, and satellite communication systems. He has recently made substantial contributions to both the theoretical foundations and practical aspects of GPS multipath mitigation, and to the design of high-sensitivity GPS systems.

Nobuhiro Kishimoto

Mr. Kishimoto entered the Tokyo University of Science in 1976, where he received a Bachelor's degree in Science. He also studied at the Kwansei Gakuin University where he received a Bachelor's degree in Theology in 1984. Mr. Kishimoto has 3 years of experience in the development of semiconductor processing techniques and 16 years in the GPS industry.

In 1988 he founded Magellan Systems Japan, Inc., which has long been exclusively involved in representing the GPS OEM business, as well as being an international distributor for a division of Thales Navigation (formerly Magellan Systems Corporation) in the Japanese market.

In addition to marketing experience, in 1999 Mr. Kishimoto spearheaded innovative developments in high-sensitivity assisted GPS receiver technology for application to cell phone position location. Recently he has been in charge of an advanced generation of this technology.

Seiichiro Hirata

Mr. Hirata graduated from Kyusyu University in March 1966, where he studied in the Electronics Department. He joined the Mitsubishi Electric Corporation in April of that year, where he was engaged in the development of transistorized color television receivers and served as a member of the Satellites Ground Bureau. He contributed to several firsts in the electronics industry, including the electronic video recorder, automated tuned car radios, GPS car navigation systems, and a high-sensitivity GPS system.

In October 2003 Mr. Hirata joined Magellan Systems Japan, Inc., where currently he is the principal developer of the next generation super sensitive indoor GPS system, mainly for cell phone application, which is described in this paper.

Kevin Xinhua Chin

Dr. Chin received his B.S. degree from Beijing Institute of Technology and the Ph.D. in Aeronautics and Astronautics from Stanford University, where he worked on the Gravity Probe-B program.

Dr. Chin is the founder and CTO of Galileo Positioning, an early stage venture and consultancy specializing in GNSS receiver system design, navigation system integration, digital signal processing, navigation algorithms, GNSS applications, and location based service.

In addition, Dr. Chin has worked for the last thirteen years at Ashtech, Inc., Magellan Systems Corporation, and Thales Navigation, Inc. He has held various positions as an engineer, a manager, and most recently as director of engineering and director of strategic technology. He pioneered the Ashtech RTK algorithms (PNAV), led the development team, and was directly involved in its implementation and enhancements in four generations of dual-band GPS receivers.

ABSTRACT

This paper describes the next generation of a super sensitive assisted GPS system for C/A coded signals that was originally developed by Magellan Systems Japan, Inc. in collaboration with a Japanese electric company and Thales Navigation. The improved system is designed to provide rapid positioning in weak signal areas, such as inside buildings. In addition to other applications, a primary goal is to embed the client receiver in cell phones to enable rapid location in an emergency such as a 911 call. Proprietary techniques have been developed to obtain the following improvements:

1. Low-latency time coordination between the client receiver and the assisting base station (server) is not required.

2. High sensitivity is maintained with a short signal capture time and without the need to know the navigation message bit sequence from any external source.

3. The local oscillator frequency offset at the client receiver can be estimated efficiently, thus reducing the cost of the local oscillator and eliminating the need for an accurate frequency reference transmitted by the server.

These and other improvements permit existing communication systems, such as cell phone networks, security systems, and the internet, to transmit assisting information to the client receiver with only a simple communication interface to a reference GPS receiver. No major modifications to the communication system are required, which is a significant advance in the state of the art of assisted GPS systems.

Theoretical design considerations and preliminary test results of the improved high sensitivity system are presented in this paper.

I. INTRODUCTION

The first generation of a super sensitive GPS system was initiated in 1999 by Magellan Systems Japan, Inc. in collaboration with a Japanese electric company and Thales navigation. The first generation system, which was completed in 2000, successfully demonstrated that rapid assisted GPS positioning is possible with signal levels approaching –160 dBm, using no more than a few seconds of captured GPS signals. Tests conducted in 2003 demonstrated that positioning was quite reliable, even inside concrete buildings.

A key to the high performance of the first generation system is the inclusion of the following information in the assisting data transmitted from the base station (server) to the client receiver unit:

1 Precise frequency and timing information.

2. The sequence of navigation data bits from each satellite.

3. Ephemeris information for determining the positions of the satellites.

The precise frequency information is used to calibrate the client receiver reference oscillator, which reduces the frequency range that must be searched to acquire satellites. The precise timing information permits the client receiver to accurately determine the time at which it captured the satellite signals, so that the position of the satellites needed in the navigation solution can be established from ephemeris data.

Optimum processing gain of a conventional GPS receiver is limited by the maximum coherent integration time of 20 milliseconds imposed by the 50 bps GPS biphase data modulation. In the first generation system this limitation is overcome by sending the sequence of navigation data bits to the client receiver. The client receiver uses the sequence to strip the modulation from the signal, thus permitting a much longer coherent integration time and a concomitant increase in processing gain.

Although the frequency, time, and data bit information is useful in achieving a high level of performance, its provision makes it difficult to send assisting information from server to client using existing communication systems, such as cell phone networks, security networks, or the internet. These systems would likely need extensive modification, or perhaps a whole new system would be necessary. For example, the transmission of an accurate frequency reference would require precise frequency control in the transmitter of every tower in a cell phone network. Transmission of accurate timing using conventional methods could also be a problem, due to data transmission timing uncertainties in such networks.

For these reasons, a new generation of assisted GPS positioning system, named Yokozuna, was initiated in 2003 to overcome these disadvantages.

II. OVERVIEW OF THE YOKOZUNA SYSTEM

A block diagram of the Yokozuna system is shown in Figure 1. Like any assisted GPS system, the Yokozuna system uses a base station, called the server, to send information to client receivers, which makes it possible for these receivers to achieve rapid positioning with very high sensitivity. The key difference between the Yokozuna approach and most others is that the assisting information can be sent via unmodified existing communication systems.

An important aspect of the Yokozuna system is that the assisting information is obtained by one-way data transmission which streams from the base station. This data is available to all users of the system, even if they are operating simultaneously, and no request for the information is required. This data consists of the following:

1. Base station location

2a. Time-tagged satellite position and velocity vectors, pseudoranges, and Doppler.

AND/OR

2b. Satellite ephemeris data

3. Timing information using a combination of proprietary techniques. Time accuracy is not degraded by unknown and variable time delays that may exist in the server-to-client communication system, even if these delays are very large (more than several seconds).

The above data can be updated at a relatively slow rate, perhaps once every few seconds.

In many (but not necessarily all) applications, the client receiver and its processing hardware and software are embedded in a handheld cell phone. The client receiver captures a short segment (typically 1-3 seconds) of received GPS signals, processes the signals to obtain pseudoranges, and computes a position solution which can be presented to the user and/or automatically transmitted to authorities via the user's cell phone or other communication means. The receiver can be activated by pressing a "panic button" or by other means.

The client receiver consists of an RF tuner which also provides frequency translation to baseband, an A/D converter, and digital processing to produce an estimate of the client location. The digital processing consists of Doppler compensation of the satellilte signals, a proprietary process which removes the polarity changes due to the navigation data message bits, correlation processing to achieve processing gain and measure pseudorange for each satellite signal, and the computation of position.

Additional details of the client receiver, which might be embedded in a cell phone, is shown in Figure 2. The GPS signals are received by an antenna (typically a patch design) and are amplified and frequency translated to a 4.092 MHz IF frequency by the RF tuner. Local oscillator signals for the RF tuner are provided by a frequency synthesizer driven by a 16.368 MHz reference crystal oscillator. The reference oscillator is a proprietary design which has small frequency uncertainty in order to minimize the frequency search range in acquiring the satellite signals. The IF signal is bandpass-filtered and converted to digital samples by an A/D converter. The samples are then digitally translated to a complex-valued (I and Q) baseband signal by two digital multipliers. The local oscillator signals for these multipliers are in-phase and quadrature phase digital waveforms at 4.092 MHz, supplied by the frequency synthesizer. The baseband I and Q components are stored in a signal capture memory, where they are accessed for further processing. The IF bandpass filter has a relatively small bandwidth in order to reduce the sampling rate so that the size of the capture memory can be made acceptably small.

The signal in the capture memory is the superposition of all received satellite signals. These signals are individually compensated for Doppler under the control of a CPU, using Doppler data received from the server via the communication receiver card shown in Figure 2.

Following Doppler compensation, the navigation data bit polarity changes are removed from each signal by a proprietary technique, and partial processing gain is achieved by a special technique in the Digital Processing Block shown in Figure 2. The remainder of the processing gain is achieved in the Correlation Block. A peak detector finds the signal delay corresponding to the largest correlation value for each satellite, and the delay values are used by the Position Computation Block to compute the position of the client.

III. CONSIDERATIONS IN SYSTEM DESIGN

Fully Coherent vs Partially Coherent Processing

Because the Yokozuna system must provide very rapid positioning, there is not enough time for the client receiver to acquire the GPS signals and extract the satellite ephemeris information required for a position solution. Therefore, it must be able to rapidly process at most a few seconds of received signal.

The ultimate receiver sensitivity that can be achieved is affected by the length of the signal capture interval and the presence of navigation data modulation on the GPS signal. If the signal were modulated only by the C/A code and contained no navigation data modulation, maximum theoretically possible acquisition sensitivity results from what we shall call "fully coherent" delay and Doppler processing. In this form of processing the baseband signal is frequency shifted and precession-compensated in steps (Doppler bins), and for each step the signal is cross-correlated with a replica of the C/A code spanning the entire signal observation interval. Alternatively, the 1-msec periods of the C/A code could be synchronously summed prior to cross-correlation.

However, the presence of the 50 bps navigation data modulation precludes the use of fully coherent processing over the entire signal capture interval unless some means is available to reliably strip the modulation from the signal. A common method of dealing with the presence of data modulation is to coherently process the signal within each data bit interval, followed by noncoherent summation of the results. The usual implementation of this technique is to first coherently sum the 20 periods of the complex baseband C/A coded signal within each data bit. For each data bit a waveform is produced which contains one 1-msec period of the C/A code, with a processing gain of 10log(20) = 13 dB. Each waveform is then cross-correlated with a replica of the C/A code to produce a complex-valued cross correlation function. The squared magnitudes of the cross-correlation functions are computed and summed to produce a single function spanning 1 millisecond, and the location of the peak value of the function is the signal delay estimate. We shall call this form of processing "partially coherent."

Figure 3 compares the performance of fully coherent and partially coherent processing for a signal observation time of 1 second. For fully coherent processing there must be no data modulation on the signal. Since data modulation always exists on current C/A-coded GPS signals, fully coherent processing cannot be used without knowledge of the data bit polarities. However, its performance is used as a baseline reference to show how much is lost when partially coherent processing is used. The performance criterion used for both methods is the probability of error in estimating the correct delay bin by locating the peak of the cross-correlation function.

Examination of Figure 3 reveals that there is a difference in sensitivity between the two methods of approximately 3 dB at larger signal levels and about 4 dB as low signal levels, when 1 second of signal is observed. It is important to note that fully coherent processing has a major drawback—many more delay/Doppler bins must be processed, which either dramatically slows down processing speed or requires a large amount of parallel processing to maintain that speed.

This drawback can be ameliorated by using only partially coherent processing with a longer signal capture interval. Figure 4 shows the theoretically achievable performance of partially coherent processing for signal capture intervals of 1, 2, and 4 seconds. The processing gain increases by only about 1.5 – 2 dB for each doubling of the capture interval as compared to 3 dB for fully coherent processing. However, it must be kept in mind that with fully coherent processing the number of Doppler bins also doubles at each step, a property not possessed with partially coherent processing. This has the effect of reducing the probability of detecting the correct Doppler/delay bin.

An alternate method of achieving a delay estimate is to detect the data bits and use them to homogenize the polarity of the signal, this permitting coherent processing over the full signal capture interval. In order for this method to be effective, the signal must be strong enough to ensure reliable data bit detection. Furthermore, a phase reference is needed, and it should be estimated using the entire signal observation. A practical technique for estimating phase, which approaches theoretically optimum results, is the method of maximum-likelihood (ML). We shall call this methodology “coherent processing with data stripping,” or simply “data stripping” for short.

Figure 5 shows how the performance using data stripping compares with fully coherent and partially coherent processing. At low signal power levels (less than about –160 dBm) its performance approaches that of partially coherent processing, and at high signal levels its performance approaches that of fully coherent processing. At first glance, it seems that data stripping might give a worthwhile advantage over partially coherent processing. However, it shares a common disadvantage with fully coherent processing in that a larger number of delay/Doppler bins must be processed, and the cost is often prohibitive.

Receiver Bandwidth, Sampling Rate, and Ranging Accuracy

A theoretical limit to pseudoranging accuracy, imposed by the signal bandwidth and the ratio of received signal power level to noise power spectral density, is the Cramer-Rao (CR) bound, which is valid for unbiased estimators. Fortuitously, the location of the peak of the cross-correlation of the GPS signal with a C/A code replica is an unbiased estimator of range (or at least the bias can be compensated), so calculation of the CR bound applies. It can be shown that the CR bound for ranging is given by

$$\sigma_\varepsilon^2 \geq \frac{1}{8\pi^2\left(\frac{C}{N_0}\right)\left[\frac{\int_{-B}^{B} f^2 \left|S_m(f)\right|^2 df}{\int_{-B}^{B} \left|S_m(f)\right|^2 df}\right]} \qquad (1)$$

where σ_ε^2 is the variance of the ranging error in seconds, C/N_0 is the ratio of signal power to the one-sided power spectral density of the noise, $S_m(f)$ is the unfiltered power spectrum of the C/A code, and $2B$ is the receiver RF bandwidth. Because of the normalization by the denominator integral in (1), the power spectrum of the code can be expressed using any convenient scaling. The noise power spectral density is

$$N_0 = kt \qquad (2)$$

where $k = 1.38 \times 10^{-23}$ is Boltzmann’s constant and t is the noise temperature in degrees Kelvin, assumed here to be 290^o for an ideal receiver.

The mathematical model for the normalized power spectrum of the unfiltered C/A code is

$$S_m(f) = \mathrm{sinc}(f/f_c) = \frac{\sin(\pi f/f_c)}{(\pi f/f_c)} \qquad (3)$$

where f_c = 1.023×10^6, which is the C/A code chipping rate. Although in reality the power spectrum consists of spectral lines with 1 kHz spacing, negligible error is incurred by using this model.

Figure 6 shows the CR bound computed from (1) as a function of received signal power using a C/A coded signal, 1 second of signal observation time, and various values of RF bandwidth. For purposes of simplicity in using expression (1), it is assumed that the receiver filters the code with an ideal brick-wall filter. The curves in Figure 6 apply under the assumption that the correct delay bin has been found during signal acquisition. It has been verified by simulations that if this is the case, the standard deviation of range estimation error will actually meet the bound (in other words, the bound is tight) for signal power levels exceeding –157 dBm.

The curves of Figure 6 clearly show that range errors due to thermal noise are much larger at the low signal levels experienced indoors, as compared to operation with clear line-of-sight (LOS) signals. For example, a C/A code receiver operating with a –130 dBm signal (the minimum guaranteed level for LOS reception at the Earth’s surface) will have a noise-induced range error standard deviation of about 20-25 cm if its RF bandwidth is 16 MHz. On the other hand, Figure 6 shows that the range error standard deviation cannot be less than about 6 meters at -158 dBm, assuming the same bandwidth—a substantial increase.

Therefore, it might appear even more important to have a large RF bandwidth in a receiver designed for weak-signal operation, especially considering that multipath performance will also be significantly improved. However, this requires a proportionately higher sampling rate for digitizing the signals. In a conventional receiver this is usually not a serious drawback, but in weak-signal receivers designed for emergency operation the signal must be captured in memory to permit rapid acquisition of the satellites, and the higher sampling rate causes the memory size to increase proportionally. Furthermore, the number of delay bins in the correlation process also becomes proportionately larger, making it more difficult and costly to rapidly process the signals.

Fortunately, the positioning accuracy requirements for emergency operation are not unduly stringent (50 meters RMS being typical). For this reason, the Yokozuna system uses a relatively small RF bandwidth of 1 MHz to keep the sampling rate low and reduce the size of memory. At this bandwidth the loss in SNR of the C/A coded signal is acceptably small (approximately –1 dB).

Determination of Accurate Time

In order to obtain accurate pseudoranges, a conventional GPS receiver obtains time information from the navigation data message which permits the precise GPS time of transmission of any part of the received signal to be tracked at the receiver. When a group of pseudorange measurements is made, the time of transmission from each satellite is used for two purposes: (1) To obtain an accurate position of each satellite at the time of transmission, and (2) to compute pseudorange by computing the difference between signal reception time (according to the receiver clock) and transmission time.

In order to obtain time information from the received GPS signal, a conventional receiver must go through the steps of acquiring the satellite signal, tracking it with a phaselock loop to form a coherent reference for data demodulation, achieve bit synchronization, demodulate the data, achieve frame synchronization, locate the portion of the navigation message which contains the time information, and finally, continue to keep track of time (usually by counting C/A code epochs as they are received).

However, it is desirable to avoid these numerous and time-consuming steps in a positioning system which must reliably obtain a position within several seconds of startup in a weak-signal environment. Because the navigation data message contains time information only once per 6-second subframe, the receiver may have to wait a minimum of 6 seconds to obtain it (additionally, more time is needed to phase lock to the signal and achieve bit and frame synchronization). Furthermore, data demodulation becomes unreliable with weak signals (the bit error rate rapidly becomes large at received signal power levels below approximately -154 dBm).

In assisted GPS systems designed for rapid positioning (within several seconds) using weak-signals, the client receiver does not have time to read unambiguous time from the received GPS signal itself. If the approximate position of the client is known with sufficient accuracy (perhaps within 100 km), it is possible to resolve the <u>difference</u> in times of transmission. This is possible because the times of transmission of the C/A code epochs are known to be integer multiples of 1 millisecond according to SV time (which can be corrected to GPS time using slowly-changing time correction data sent from the server). This integer ambiguity in differences of time transmission is resolved by using approximate ranges to the satellites, which are calculated from the approximate position of the client and insertion of approximate time into satellite ephemeris data sent by the server to the client. For this purpose the accuracy of the approximated time needs to be sufficiently small to avoid excessive uncertainty in the satellite positions. Generally a time accuracy of better than 10 seconds will suffice.

Once the ambiguity of the differences in transmission times has been resolved, accurate positioning is possible if the positions of the satellites at transmission time are known with an accuracy comparable to the positioning accuracy desired. However, since the satellites are moving at a tangential orbital velocity of approximately 3800 meters/sec, the accuracy in knowledge of signal transmission time for the purpose of locating the satellites must be significantly more accurate than that required for the ambiguity resolution previously described.

Most assisted GPS rapid-positioning systems using weak signals obtain the necessary time accuracy for locating the satellites by using time information transmitted from the server. It is important to recognize that such time information must be in “real-time,” that is, it must have a sufficiently small uncertainty in latency as it arrives at the client receiver. For example, a latency uncertainty of 0.1 second could result in a satellite position error of 380 meters along its orbital path, causing a positioning error of the same order of magnitude.

Transmission of time from the server with small latency uncertainty has a major impact on the design of the server-to-client communication system, and is a major disadvantage in getting the providers of existing communication systems, such as cellular networks, to become involved in providing indoor assisted GPS positioning service.

The Yokozuna system has solved this problem with a major breakthrough using a synergistic combination of two proprietary methods for obtaining time information which does not require the communication system to transmit low-latency timing data. Although the details of the technique are not presented here, its performance is summarized in the following table:

PDOP Range	RMS Error in Time Used for Computing Satellite Position (msec)
PDOP < 5	2.7
$5 \leq$ PDOP < 10	5.2
$10 \leq$ PDOP < 20	10.5
$20 \leq$ PDOP < 40	22.1

From the table it is seen that for PDOP < 10 the RMS time error of 5.2 msec or less implies that the RMS satellite position uncertainty along its orbital path will not exceed (5.2 msec) $\times$ (3800 m/sec orbital speed) = 19.8 meters, with a concomitant positioning error of comparable value.

Frequency Uncertainty

To achieve rapid positioning the range of frequency uncertainty in acquiring the satellites at the client receiver must be reduced as much as practicable in order to reduce the search time. For this reason it is common practice in assisted GPS systems for the server to transmit Doppler information to the client receiver. However, if nothing more is done, the frequency uncertainty of the receiver local oscillator still remains as an obstacle to rapid acquisition. Today's technology can produce oscillators which have a frequency uncertainty on the order of ± 1 part per million at a cost low enough to permit incorporation into a consumer product such as a cell phone. Even so, 1 part per million translates into about ± 1575 Hz of frequency uncertainty at the GPS L1 frequency. Assuming that the coherent integration time during satellite search is 20 milliseconds (the length of a navigation message data bit), the frequency bins in the search would have a 50 Hz spacing, and a total of $2 \times 1575/50 = 63$ frequency bins might have to be searched to find the first satellite. Once the first satellite is acquired, the local oscillator offset can be determined, and the frequency uncertainty in searching for the remaining satellites can thereby be reduced to very small values. To remedy the problem of acquiring the first satellite in a sufficiently short time, some assisted GPS systems use an accurate frequency reference which is transmitted from the server to the client, in addition to satellite Doppler measurements. However, this requirement significantly complicates the design of the server-to-client communication system, and is certainly undesirable when trying to use an existing communication system for assisting purposes. If the communication system is a cell phone network, every cell tower would need to transmit a precise frequency reference.

To avoid this problem in the Yokozuna system, some proprietary techniques have just been completed to more quickly estimate the local oscillator offset without the need for transmission of a frequency reference to the client.

Fading and Multipath

It is well known that GPS signals received indoors can be susceptible to fading and multipath which is typically more severe than when the receiver has a clear view of the sky.

Fading

Fading is the loss of signal strength caused by destructive phase cancellation from signals that arrive via two or more paths, and is usually distinguished from absorptive loss when the signal passes through objects such as the roof or walls of a building. The main defense against fading is simply to use a high-sensitivity receiver, which not only is capable of pulling a fading signal out of the noise, but also might allow the reception of enough satellites to permit discarding the most severely faded signals. Other defenses, such as diversity reception, are not practical in the areas of application intended for the Yokozuna system. Preliminary tests of the system, to be described later, suggest that its sensitivity is high enough to effectively combat fading in severe indoor environments.

Multipath

Pseudorange errors due to multipath arise when the cross correlation function generated by the receiver is distorted by the presence of a GPS signal arriving at the receiver antenna via two or more paths having different propagation delays. GPS reception indoors is particularly susceptible to multipath, because the direct path signal can be greatly attenuated by absorption while the secondary path components, due to reflections, can be considerably larger.

However, because the the indoor positioning accuracy requirements for the Yokozuna system are less stringent than for most standard receivers, the multipath error tends to be less detrimental. Additionally, personnel working on the Yokozuna project have considerable experience with in-receiver multipath mitigation technology, and are capable of developing effective mitigation techniques if necessary.

IV. PRELIMINARY TEST RESULTS

Preliminary field tests of the sensitivity and positioning accuracy of the Yokozuna system, performed with off-the-air satellite signals under demanding conditions, are presented here.

Test #1

This test was performed in Yokosuka, Japan in April 2004. The client receiver was located on the 4th floor of a 7-story concrete and steel office building, with the receiver antenna on a chair under a steel-topped desk approximately 20 meters from an outside wall of the building.

The server receiver, an Ashtech Model GG24 with special firmware for assisting purposes, and its antenna were located on the building rooftop where strong line-of-sight satellite signals could be received. At the time of this test a server-to-client radio link was not yet available, so the assisting data from the server was transmitted to the client via a 100 meter cable dropped through a stairwell from the roof to the 4th floor.

The results of this test are shown in Figure 7. The blue map pin indicates the true position of the client receiver, and the red map pins are the positions obtained by the client receiver with assistance from the server. Most of the positions (about 80%) clustered within a radius of 60 meters from the true position. There are some outliers, which most likely were produced by high PDOP, marginal reception, and/or multipath. After this test was performed, an improved positioning algorithm was developed which would have resulted in a significant reduction in the positioning errors shown (see Test #3 below).

Test #2

This test was performed in Osaka, Japan in July 2004. An active GPS antenna was located on the roof of a 3-story concrete laboratory building. The output from this antenna was split to provide signals to both the server and Yokozuna client receivers. However, the signal to the client receiver, located on the 2nd floor, was attenuated by 40 dB to obtain weak-signal reception characteristic of an indoor location.

The results of this test are shown in Figure 8. The red map pins show positions obtained by the same positioning algorithm that was used in Test #1, and the yellow map pins show positions obtained by a new positioning algorithm still under development.

Test #3: An Improved Positioning Algorithm

Further development of the new positioning algorithm has significantly improved positioning accuracy. A comparison of the old and improved algorithm is shown in Figure 9. The data for this test was also obtained in Osaka, Japan in July 2004 at the same test site used in Test #2. The testing method was also the same, using a single rooftop antenna for both server and client. However, several different values of attenuation were used for the client: 2 cases with 0 dB, 5 cases with 20 dB, and 5 cases with 30 dB. For each of the 12 cases there are two positions shown in the figure, one using the old positioning algorithm (red “X”) and one using the improved version (green dot). It is readily seen that the improved algorithm more than meets the goal of positioning within 50 meters RMS.

Test #4: 200 km Server-Client Baseline

Figure 10 shows open sky positioning results obtained on September 7, 2004, under extreme weather conditions due to a typhoon in the area. In this test the server was at the same location as in Test #2 (Osaka, Japan), but the client receiver was located at Lake Hamana, Japan, about 200 km distant. A PHS (personal handy phone system) network was used for communication of the assisting data from server to client.

V. FURTHER DEVELOPMENTS

Work is continuing to improve Yokozuna system performance. Currently a requirement for open sky positioning error has been met by reducing this error to 7-8 meters RMS or better. Further work, such as integrity monitoring, should increase the overall reliability of the system. Laboratory measurements of client receiver sensitivity are also anticipated.

VI. SUMMARY

The Yokozuna system has shown great promise in achieving desired goals of high sensitivity, positioning accuracy, and compatibility of use with existing communication systems for assisting purposes. The major advantage of this system is that it can provide rapid and accurate positioning using a variety of assisting systems without the need to modify these systems in order to provide timing synchronization or accurate frequency calibration.

VII. FIGURES

Figures are shown on the following pages.

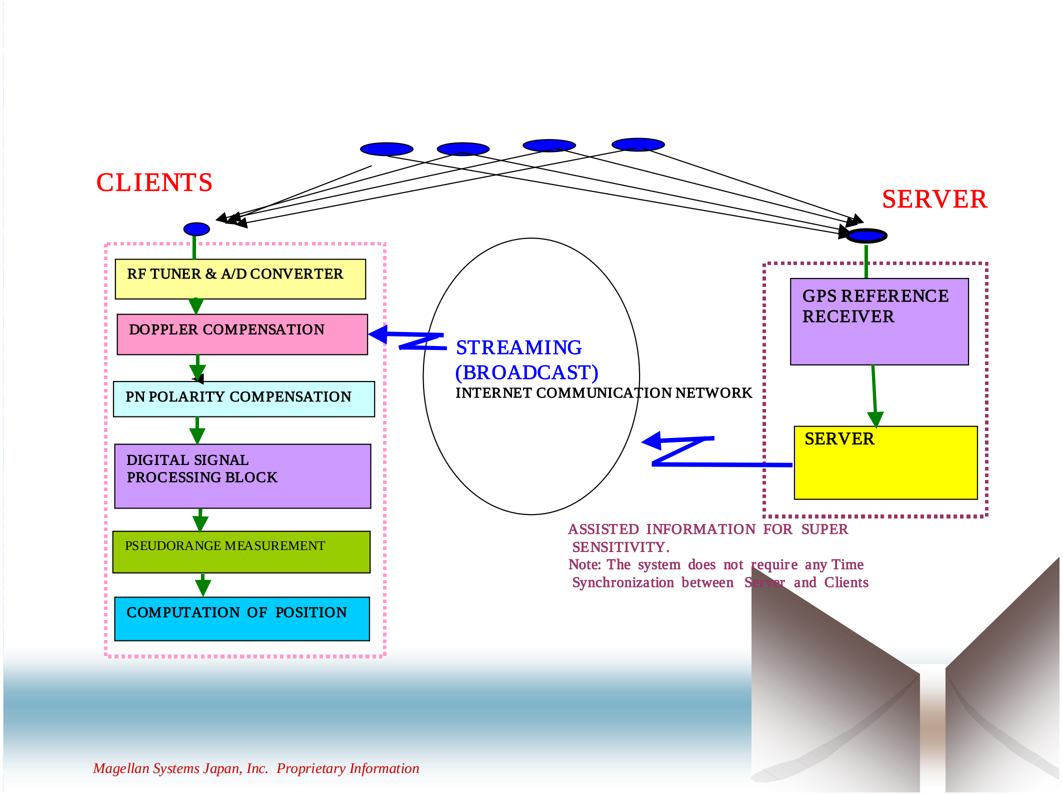

Figure 1
The Yokozuna System

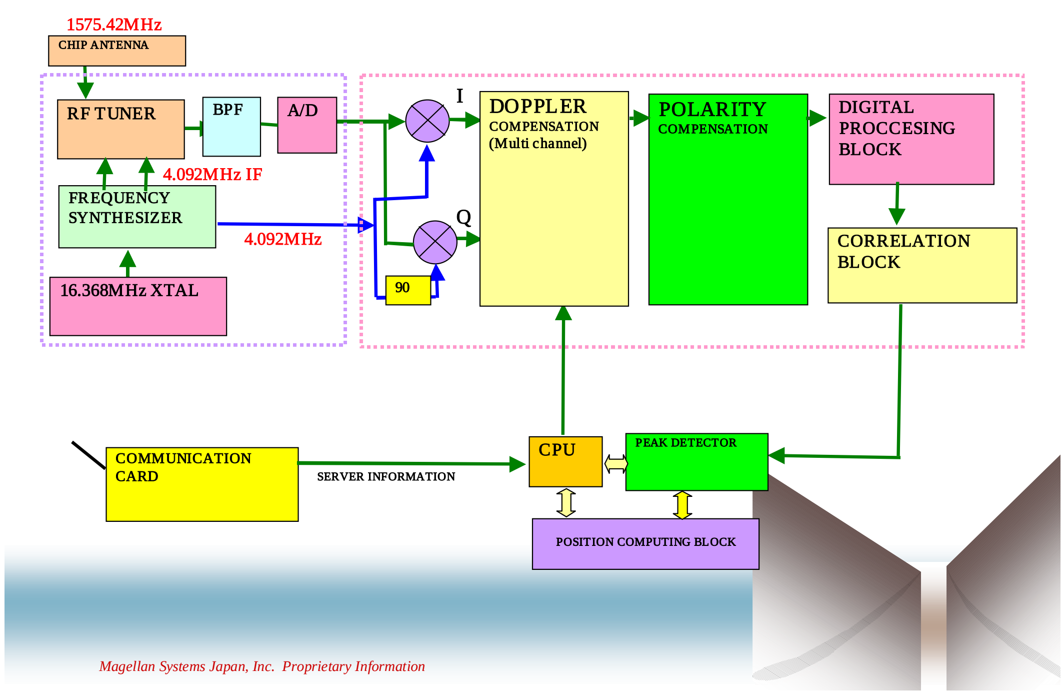

Figure 2
Yokozuna Client Receiver

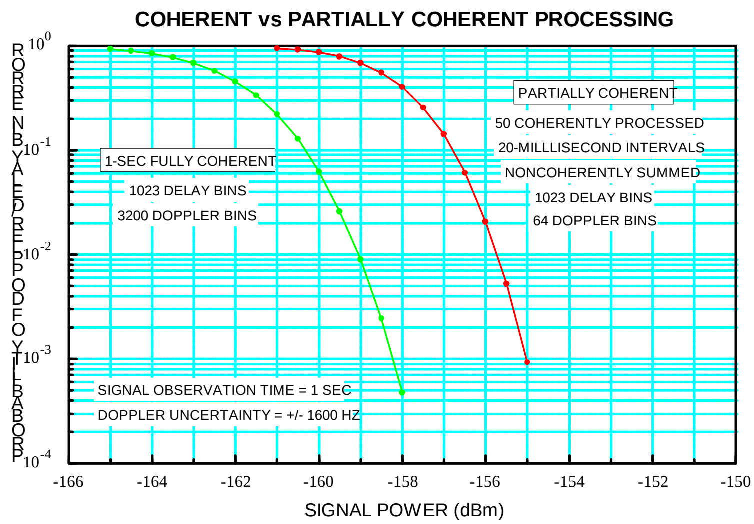

Figure 3

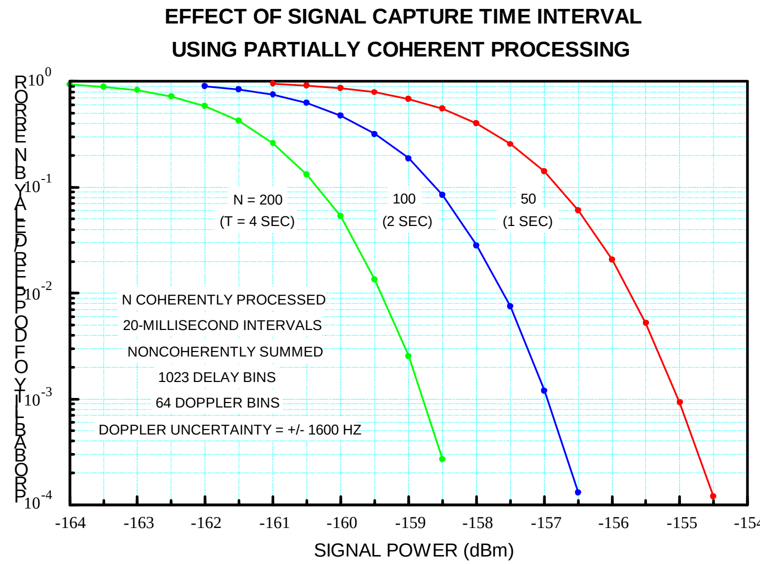

Figure 4

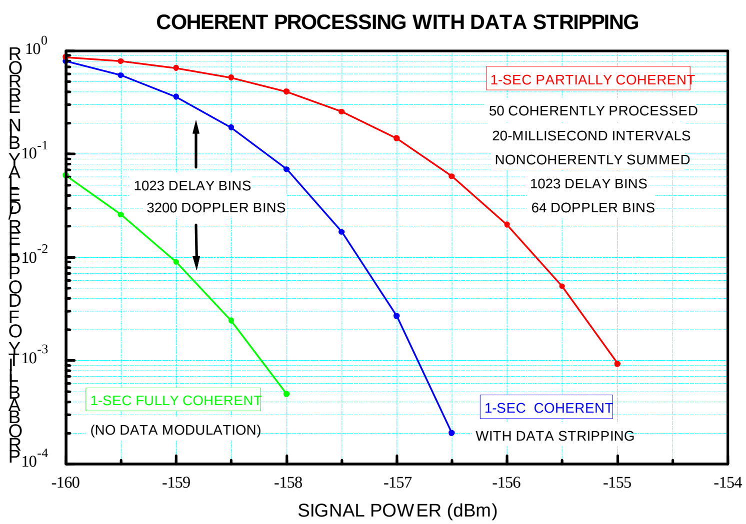

Figure 5

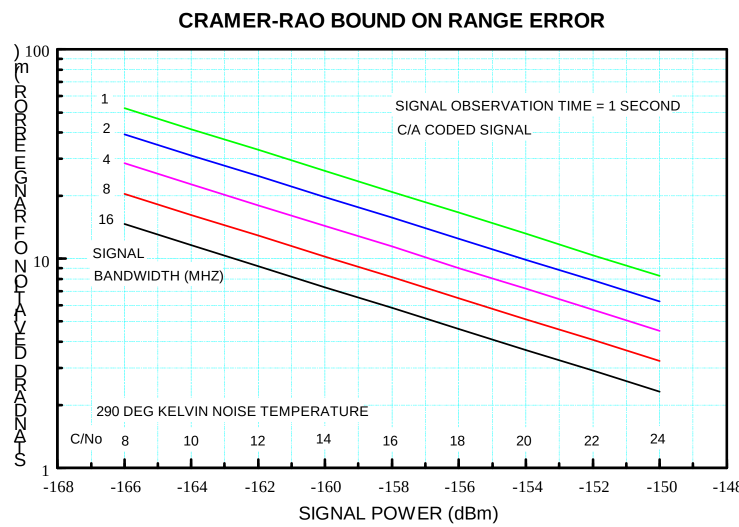

Figure 6

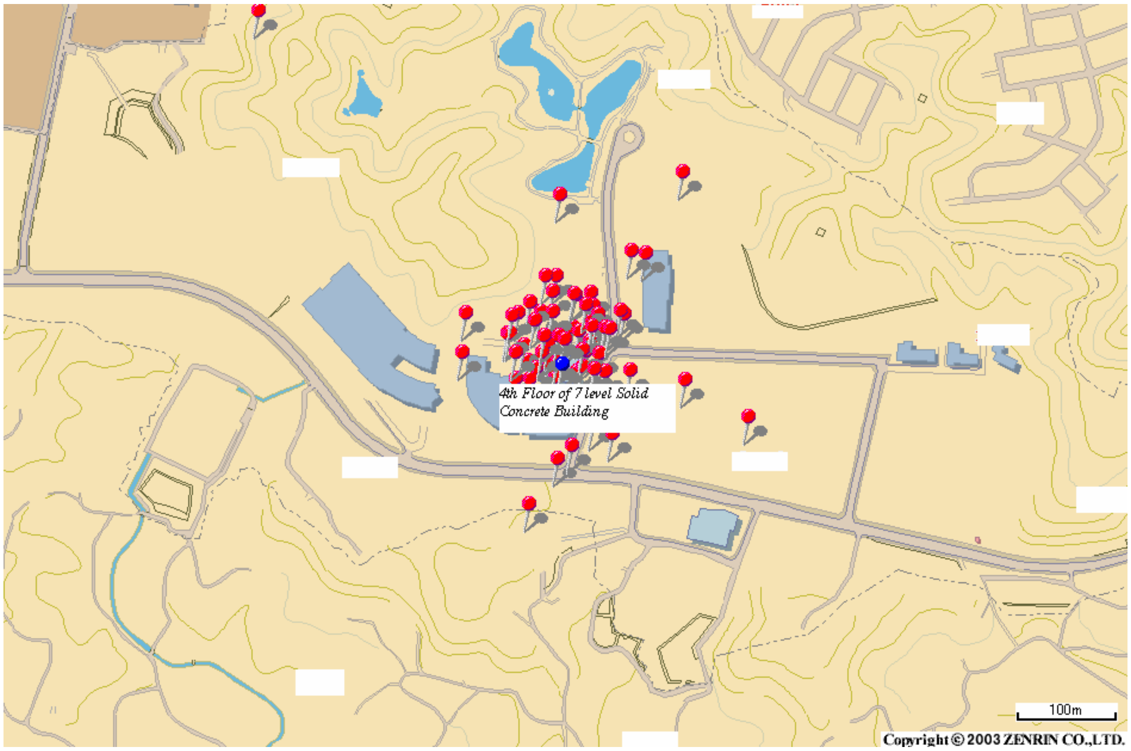

Figure 7. Positioning Results of Test #1

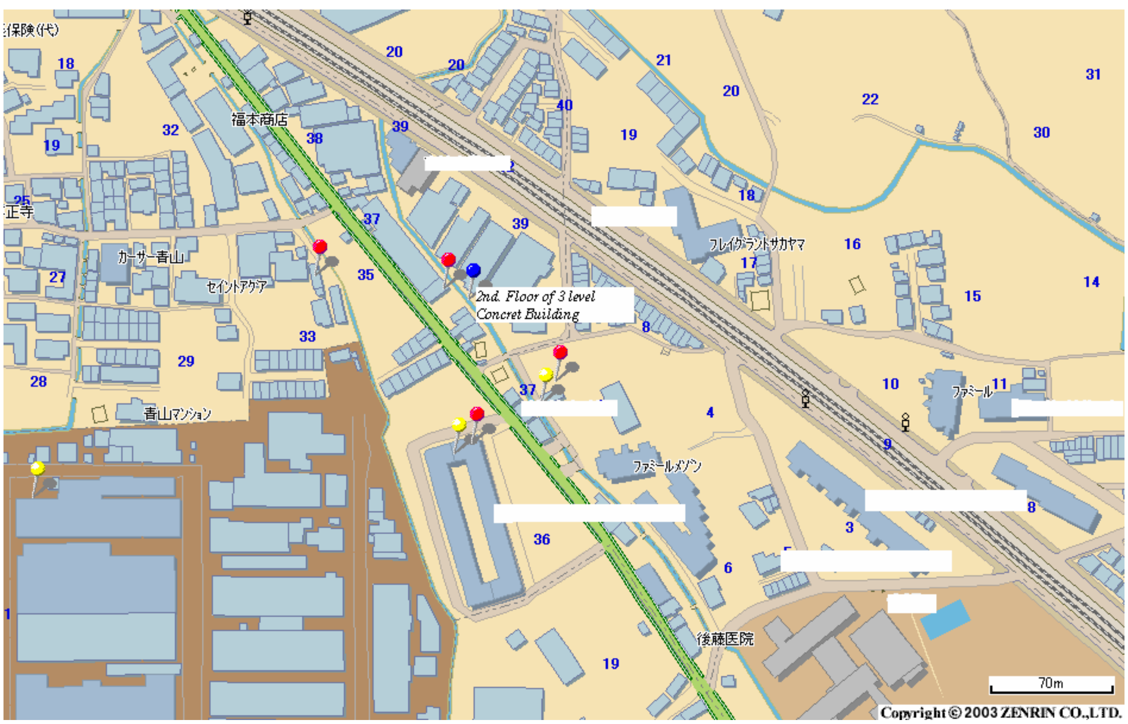

Figure 8. Positioning Results of Test #2

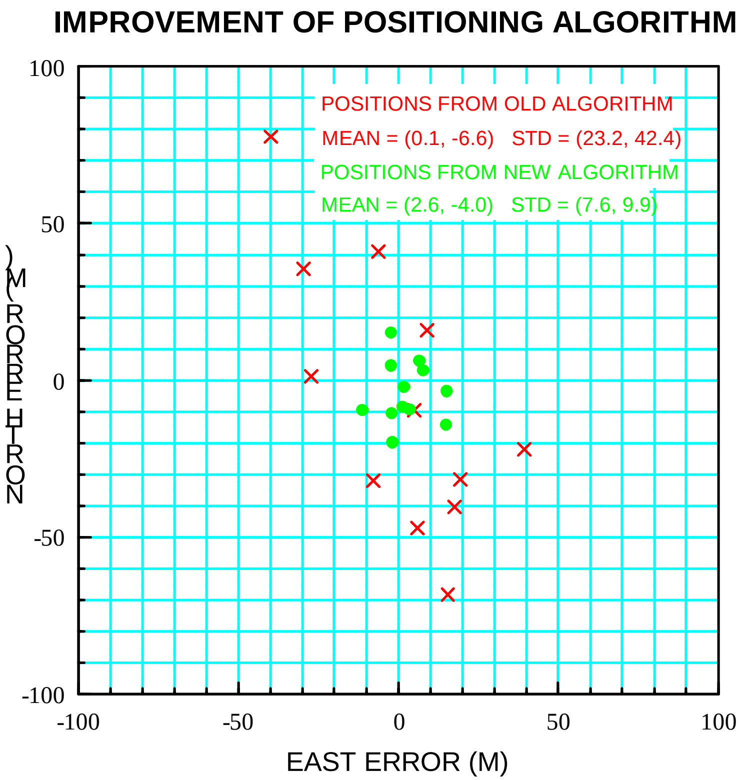

Figure 9

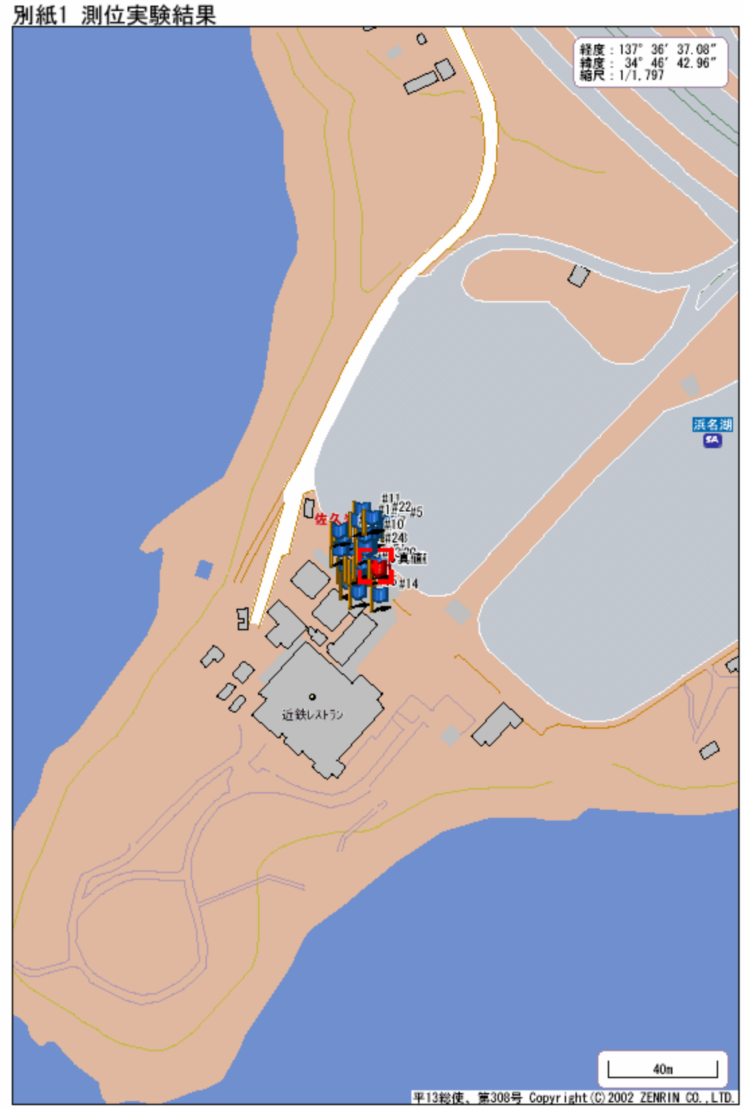

Figure 10. Positioning Results of Test #4