1.5 Real-Time GPS & Non-Line-of-Sight Metrology

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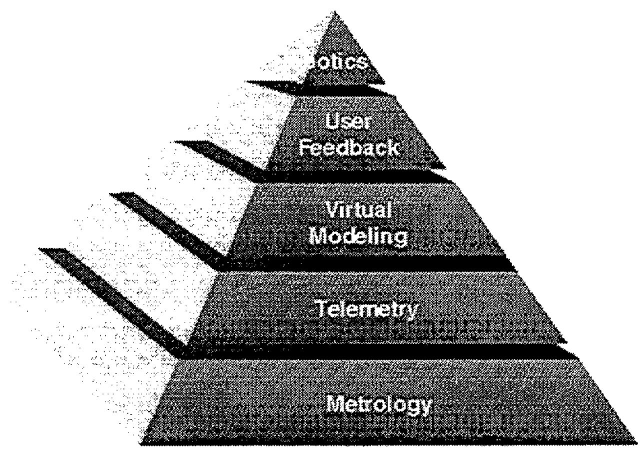
I would like to pick up where Eric left off and describe the results of research which is currently underway at NIST in the field of construction metrology. Earlier I indicated that there were many technological steps along the way to implementing the real benefits of automation at a construction site. The underpinning of all of this is the need to know where things are. In the past this need has been met (in a minimal way) by static benchmarks and survey stakeouts provided by field crews. Even with digital total stations and laser or infrared-based electronic distancing, this is a slow and tedious process. And it must be repeated many times during the course of a construction job as the geometry of the worked terrain changes.

In looking forward to automation, we find that there are two needs which demand new methods of measuring from that used by the traditional surveying crew. First, there is a need for timeliness of data. This will vary from as slow as perhaps once or twice a day for the position of key components to as fast as 30 times a second for the control of machinery. Secondly, there is a need to track not just a few benchmarks, but *anything* that moves on the construction site. Initially this will involve the tracking of the movement of components in order to establish the as-built status of of a project. But it will quicky progress to autopilot systems for earthmoving machinery, cranes and other mechanized units, and to component locators and registered-view helmet mounted displays that provide information on where to set out an item without the need for any other form of measurement. What is needed to permit this is a dynamic sensing system that provides rapid updates of position to the levels of accuracy needed for construction.



Construction Automation Hierarchy

One approach, developed by SPSI and others, involves rotating fanning lasers. Another that has been receiving a great deal of attention lately is GPS, the satellite-based Global Positioning System. There are a number of reasons for this attention, but perhaps the most important ones are that it requires no prior setup at the site: each vehicle or surveyor, provided they are in view of sufficient satellites, can determine their own position independently, anywhere in the world. And, in a sense, because the satellites are "overhead", it has less of the problems with the requirement for direct line-of-sight that rigidly control the capabilities of laser, infrared, and optical measuring systems. But it does have its own limitations in this area.

Earlier this year we carried out a program, using the most accurate GPS system we could obtain, in an effort to develop an un-biased set of measurements that would answer two questions: 1) what is the level of accuracy that can really be achieved at this time, and under what conditions? and 2) what are the limitations of this technology relative to its use for replacing traditional surveying equipment at a construction site?

Although most of us have heard of GPS, the majority who have are not aware of the various levels of performance and accuracy that are inherent in the system. At this point I would like to give you a brief description of the system and then a discussion of the three levels of accuracy that we were able to obtain during the course of extensive tests carried out on the NIST campus, which, incidentally, is home to the National Geodetic Survey GPS Test Range... so we can lay claim to a few of the most heavily surveyed benchmarks in the country!

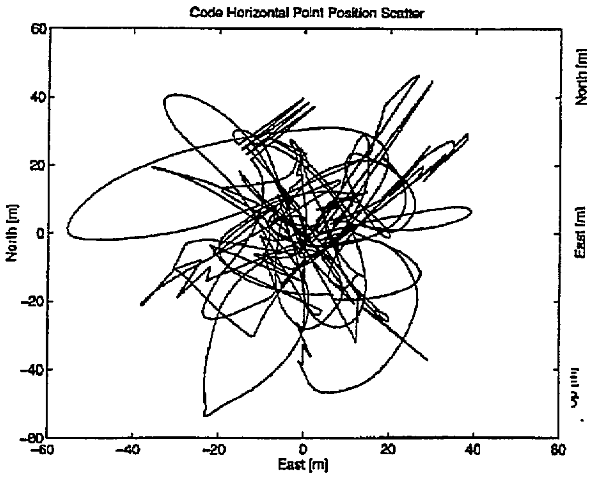
The fundamental navigation technique for GPS is to use one way ranging from the GPS satellites which are also broadcasting their estimated positions. They do this by sending a coded signal which modulates the carrier frequency broadcast by each satellite. Each satellite has its own unique code. Ranges are simultaneously measured to four satellites (or more) in view by matching (correlating) the incoming signal with a user generated replica signal and measuring the received phase against the user's (relatively crude) crystal clock (Phase information is transformed into time-of-flight and therefore distance). With four satellites and appropriate geometry, four unknowns can be determined; typically, they are: latitude, longitude, altitude, and a correction to the user's clock.

Given these broadcast signals, there are three basic methods of determining position. The simplest of these is known as the *Code Solution.*

Code Solution

The primary intent of the GPS system was to provide 5 to 10 meter accuracy absolute point positions for the U.S. Department of Defense. Data is sent from the satellites to potential users on two distinct frequencies, each with a different format. The high-accuracy service is called the Precise Positioning Service (PPS) and uses what is called P-code (Precise-code). The use of PPS is restricted and is not available for civilian use when Selective Availability (S/A) is turned on.

A lower level of precision is available at all times and is called the Standard Positioning Service (SPS) which uses the Coarse Acquisition or C/A-code. In this, a short pseudo-random noise code is broadcast at a rate of 1.023 megabits/second and contains satellite position and time. Because of it higher modulation bandwidth, the P-code ranging signal is more precise. This code , when encrypted, becomes the Y code. The military uses this encryption capability in such a way as to prevent the more precise positioning service from being used by an unauthorized user. During S/A the satel-



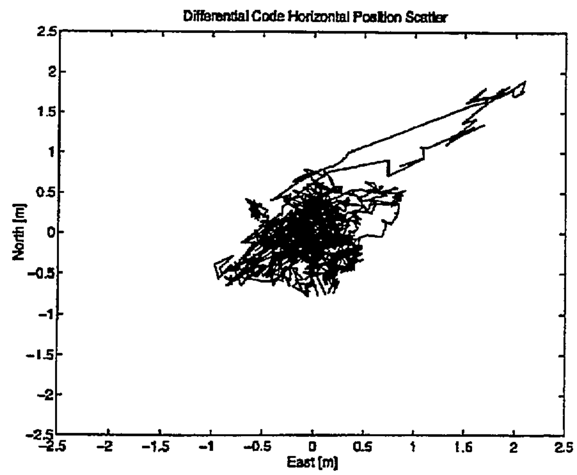
lite frequency is dithered, limiting the point position to an accuracy of 100 m in the horizontal and 150 m in the vertical components.

An example of the variation in position using SPS with S/A on (above figure) is shown for 2.5 hours of data collected using a Trimble SSe receiver. During this period the position varied up to 50 meters horizontally and 100 meters vertically.

Differential Code Solution

Considerable improvement can be obtained by combining observations from two receivers; the second unit comprises the "reference" receiver. If they are relatively close to each other, both receivers see essentially the same range error to each satellite and corresponding error in position. With one receiver at a known position, the range errors can be determined and transmitted to the roving receiver. The roving receiver applies these corrections to the observed ranges in real-time. The standard format for code differential corrections is RTCM. Almost all GPS receivers with a serial interface are capable of accepting RTCM corrections. For small inexpensive receivers (~$300), the accuracy is limited by the noise level of the code measurement which is typically 2 to 10 meters. A newer class of enhanced C/A code tracking receivers such as the Trimble 4000 SSe and Ashtech Z12 have noise levels at the 0.5 meter level and advertise 1 meter level differential position accuracy.

A pair of Trimble 4000 SSe's were connected using a radio link with one set as a reference station and the other to accept RTCM corrections. The results are shown

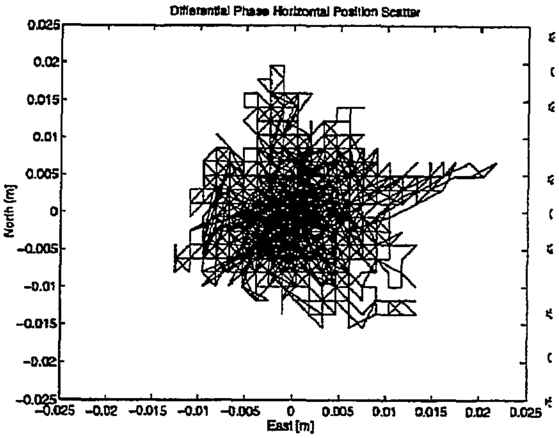


in the figure below. The majority of the horizontal positions differ by less than +- 50 cm with the exception of a nearly 2 meter horizontal excursion near the start of the time series. The vertical solution variation is up to +- 5 meters but more typically less than +- 1 meter.

The precision of the differential solution using only C/A code will degrade with increasing distance due to ionospheric effects, tropospheric effects and errors in the broadcast orbit ephemeris. Current development is directed toward increasing the range of code differential GPS (DGPS) beyond about 100 km. From a software point of view, the techniques are relatively straightforward and the reliability is high.

Phase Differential Solution

The highest degree of position precision is obtained using carrier-phase data. The receiver noise level of the carrier phase measurement is approximately 1 mm as opposed to about 50 cm for the better C/A code receivers. The carrier phase noise level typically increases to about 1 cm or larger due to multipath. Geodetic-quality GPS receivers recording both L1 and L2 carrier phase measurements and static surveys (many hours of data at a fixed point) can achieve mm- to cm-level precisions on base- lines up to 1000s of km in length. The difficulty with using carrier phase measurements is that, while the fractional phase can be determined to high precision, there is an inherent initial integer cycle ambiguity. The integer number of cycles of the carrier phase must be determined where a cycle is 19 cm in the L1 and 24 cm at the L2 frequencies. With static surveys, the initial ambiguity is estimated along with the coordinate solution, using as much continuous data as is available. For short breaks, called "cycle slips", the fractional phase is recovered when tracking resumes, but the integer cycles is lost. Cycle slips can usually be corrected in preprocessing for over short gaps or



when the loss does not occur to all satellites at once. Over longer gaps cycle slips cannot be uniquely determined and new ambiguities must be estimated.

Typical phase differential accuracy obtained during the NIST tests is shown in the figure above, which represents the response measured atop a fixed benchmark. Accuracy over an approximately two hour sampling period was +/- 20 mm. Drift over a short period can be significantly less.

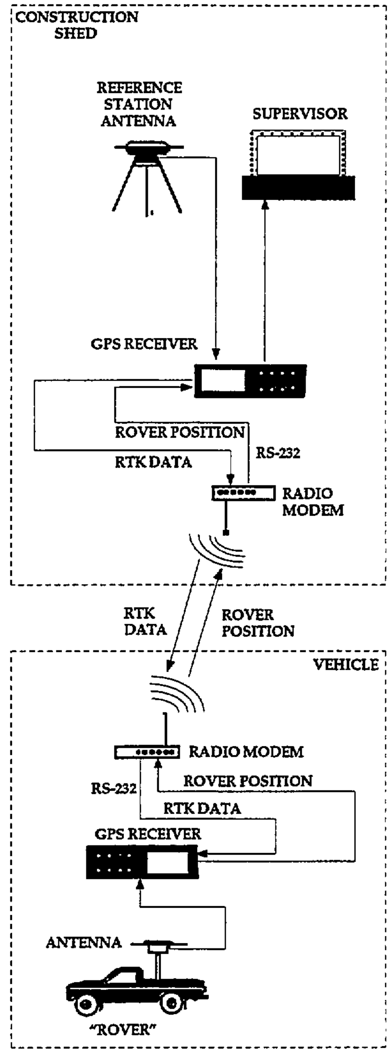
RTK Tests

The use of GPS carrier phase data for determining continuous cm-level relative positions for stationary or moving platforms is called "kinematic" (RTK) positioning or surveying. We recently conducted a series of tests using a roving platform based on an instrumented HumVee (see photo below) that was loaned to us by Jim Albus's group working on autonomous vehicles.

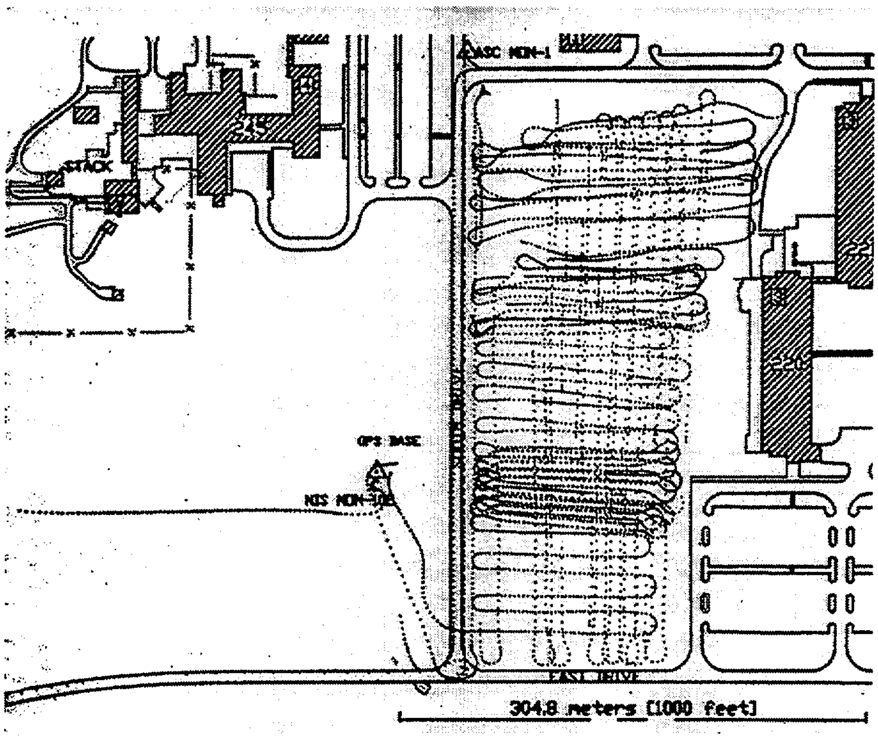
The actual RTK instruments were a pair of Trimble 4000SSe receivers with real-time kinematic (RTK) and on-the-fly ambiguity resolution (OTF). Others GPS receiver manufacturers, including

Ashtech, Novatell etc. supply similar units. The GPS receiver units are linked by means of a radio modem. A wireless ethernet system could have been used equally well within the kilometer square test course we laid out. The reference receiver was stationed atop NIST monument 102 while the roving receiver was placed on the instrument support frame on the HumVee. The base station transmits the RTK ambiguity resolution data to the vehicle and the vehicle transmits its corrected position back to the base station, where it can also be picked up and monitored, for example, at a supervisors construction office. The basic architecture is shown below:

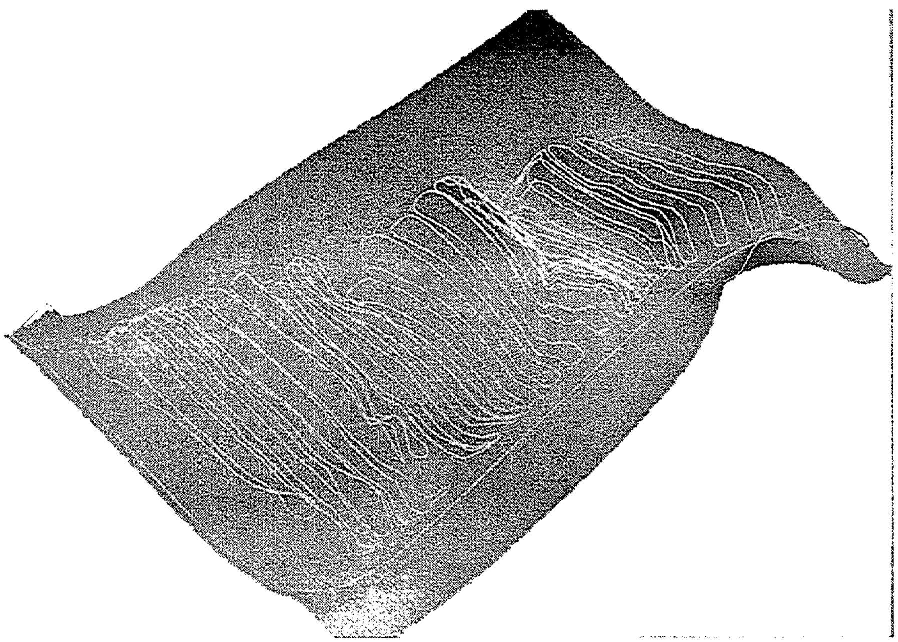
We conducted a number of RTK experiments. Some were conducted along the roads, others involved topographic mapping of a field. The road tests showed good agreement between the NIST AutoCAD database -- and at speeds of 20-40 kph, there was no loss of data and the recorded data lay correctly on the road traces. High acceleration to 60 kph caused loss of satellite lock which did not reinitialize before the drive was over (approximately a 1.5 km course)



An analysis of the data gaps showed two types of breaks. The first, a complete loss lock to the satellites, required reinitialization either statically or on-the-fly. These breaks lasted on average about 120 seconds. A shorter type of break was caused by a break in the ground receiver-to-receiver radio link either on the outgoing or incoming side. This was caused (at different times) by building, terrain, or foliage interference. The average break in these cases was only 14 seconds. These results highlight the need for more rapid reinitialization or the need for alternate navigation methods (such as inertial or magnetic systems) when

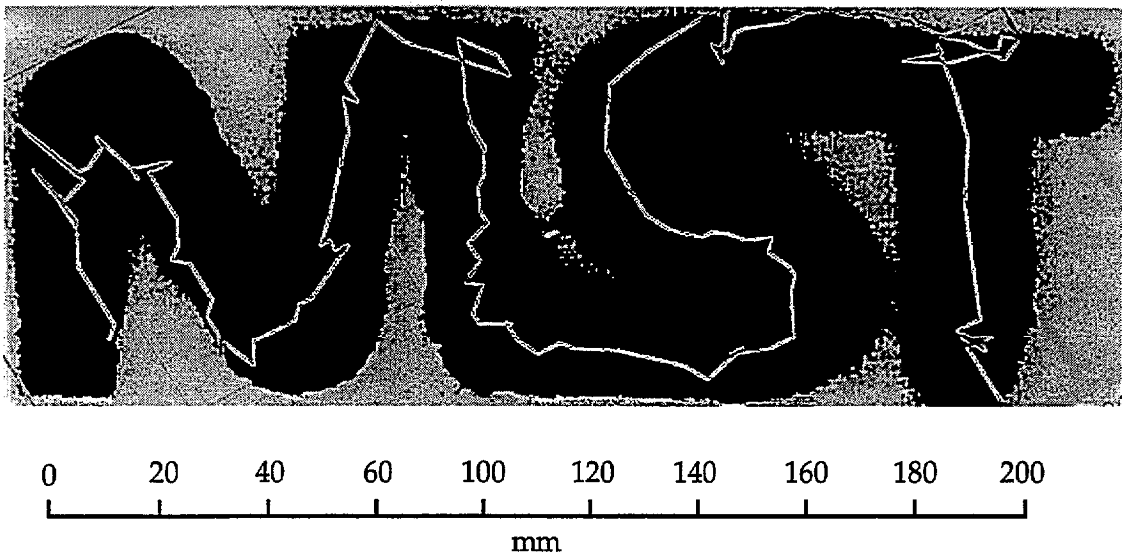


Above: Ground trace of HumVee superimposed on AutoCAD site map. NIST Monument 102 served as the known location for the base receiver. **Below:** Transformation of the GPS RTK data into a 3D surface model. Only North-South ground tracks are shown for clarity.



moving vehicles and machinery are involved. It is of some interest to note that driving the HumVee under light foliage was also sufficient in most cases to cause either a fall back to pure code solution or a complete loss of satellite lock. This can be considered a direct consequence of the line-of-sight limitations of GPS. Similar loss of lock was observed upon approach to tall buildings which obscured critical satellites, and, as alluded to before, high (vehicle) accelerations. In many cases these high accelerations could be obtained through rapid turns within 50 m of nearby buildings. In open fields, we were able to maintain phase lock while pulling the tightest turn possible with the HumVee (about an 8 m radius) at 40 kph.

The topographic mapping results using RTK were used to generate contoured maps with an interval of 50 cm over a total terrain vertical differential of only seven meters. A detailed analysis of the intersecting points showed the vertical differ-



Above: Results of precision GPS positioning: penmanship test with differential phase RTK tracking. Scale is in millimeters.

ence of crossing tracks was no worse than ± 10 cm and had a standard deviation of only ± 3.7 cm. The intersections were only approximate and did not include a correction for the attitude of the vehicle, but still clearly demonstrate the vertical precision of the RTK system. Again, the loss of lock was quite evident when the vehicle was moving and there clearly is need for rapid OTF reinitialization or backup navigation systems.

Scaling the tracking to multiple vehicles would require additional development at the tracking site. Supplying the RTK corrections is not a problem with more receivers. A single reference receiver can broadcast on the same frequency and on a one-way link to an unlimited number of roving receivers. Each receiver performs it's own RTK calculations. The challenge will be to simultaneously return the positions to the tracking/monitoring site.

As a final, and perhaps more graphic, test of RTK precision, the rover antenna was placed on the top of a pencil and the operator traced out the letters "NIST" by hand (see the **above** figure). At 1 second sampling the writing took 1.5 minutes to complete. The letters are easily distinguished. Slight imperfections reflect in part the measurement noise and in part the limits to how steady the operator can hold the pencil/antenna while trying not to block the satellite signals. The individual letter line thickness is approximately 10-12 mm. The smaller scale lines which have been superimposed are at 10 mm spacing. These suggest that for this short duration test the accuracy of the trace, including all error terms, was approximately +/- 5-6 mm, since the traces lie within the letter line thickness. These tests gave us a feel for what can be done with present off-the-shelf commercial GPS receivers.

Obstacles to using RTK GPS for Construction Metrology:

A number of factors limit the degree to which this technology can be introduced into general construction.

• **Cost:** The units which were used for this study sell at a retail price of approximately $100,000. While this may in some cases be justified for certain extremely expensive machinery where opportunities for full automation are evident (as for example in open pit mining) it is not within reach of the majority of contractors. Those receivers that are within reach are typically pure code receivers with at best, differential accuracies of 5-10 m. What is needed is a standard, low cost differential phase receiver with an open architecture, such that it can be produced by many competing companies, in much the same fashion that IBM made public the architecture for its first PCs. The alternative is to wait and hope that potential demand for GPS based differential trackers for the automobile market will lead to the economies of scale that would permit a radical drop in receiver pricing. In the automobile industry a, "feature" like GPS would not be added unless the option-cost were on the order of $500-1500.

• **Loss of Signal Lock:** Frequently during our moving vehicle tests, we lost either phase tracking lock or differential RF signal. Such periodic loss of position will be unacceptable to construction companies which will be counting on that data to drive semi-autonomous or fully autonomous vehicles. Bringing the vehicle to full halt every time signal is lost -- either due to multipath, excessive acceleration, or line-of-sight blockage -- is at best costly in machine downtime, and at worst may occur in the middle of a critical operation, such as the hoisting, placement, and mating of a 100 ton lift. Economical methods need to be investigated for dealing with loss of GPS lock. An obvious solution is to use an onboard inertial guidance system, and use GPS to provide frequent updates on absolute position, but inertial measurement units (IMUs) are not cheap either. Another possibility is the development of economical pseudolites which could be distributed throughout the construction site to insure local coverage within a specified work zone.

Attitude Acquisition & Other Sensory Feedback:

In many cases, position alone will be sufficient to meet construction site metrology needs. That is, coordinates of a point in 3D space. This is most obvious for determining the location of a particular structural component. For vehicles this is not enough, since the yaw, pitch, and roll of the vehicle, relative to the positioning receiver will affect the interference geometry of the machine (will it hit an adjacent concrete wall when the boom swings around) as well as the location of various parts, including articulated appendages. Attitude (yaw, pitch, and roll) can be determined by GPS, provided a multiple antenna array is included. The angular accuracy is limited by the GPS absolute positional accuracy divided by the baseline arm between orthogonal sets of antennas. It could also be done by means of a pair of digital clinometers and a soft iron compensated digital flux gate compass. A generic strap-down status unit will be needed to relay these six pieces of information as well as other data that describe both the full kinematics of the vehicle. In addition vehicle health monitoring diagnostic data such as engine temperature and pressure, hydraulic pressures etc., may also be included.

Thus far, there has been no effort to develop a standard for data interchange from such a strap-down "black box". But to progress towards a "plug-and-play" approach to integrating partially or fully automated machinery into the construction, such a standard will have to be developed and accepted by the various industry participants.

Non-Line-Of-Sight Metrology:

There are significant limitations to line-of-sight (LOS) position metrology. I would now like to discuss some of the nascent experiments conducted at NIST which are leading towards the development of what we refer to as NLS (Non-Line-of-Sight) metrology.

The problem of eliminating the line-of-sight requirement while achieving high precision in real time is a difficult one. All of the systems previously described above rely on the use of high frequency radiation (UV laser light in one case, and mid to high band RF in the others) which have the unfortunate characteristic of near-total dissipation when encountered by objects typical at most construction sites -- for example, a brick, masonry, or concrete wall... or even paper.

In order to survey through engineering materials a different approach must be

NLS: Non-Line-of-Sight Metrology

- **Fundamental Principles**
  - **SAR Based Technology**
  - **Hit Structure with many discrete wavelengths**
  - **Process (DSP) combined response of 1000's of individual Frequency Domain Frequencies; Resolution = c/B**
  - **First arrival peak in Time Domain signals shortest time-of-flight = Distance**
  - **1 nanosecond = 1 foot = 0.3048 m**

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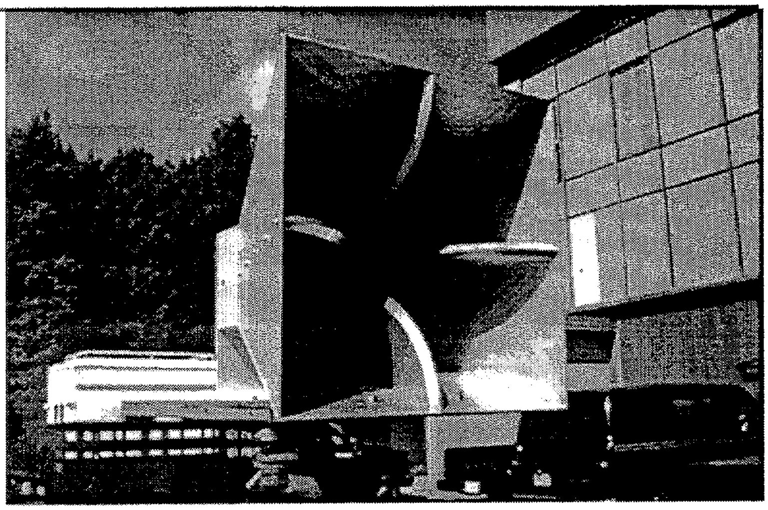
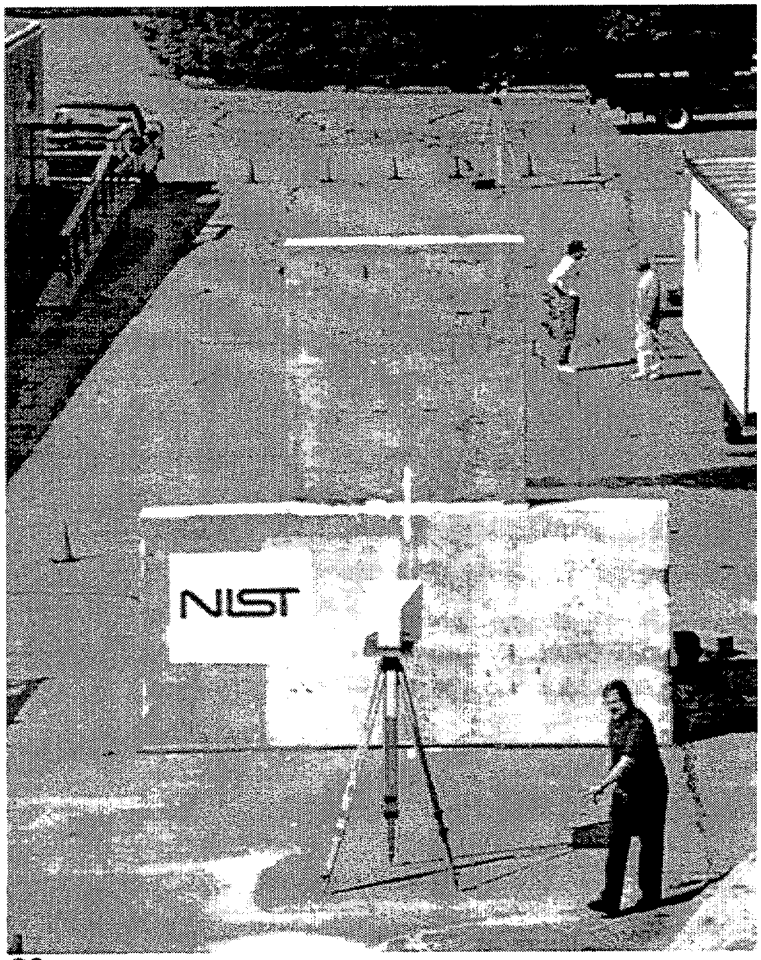
used. The approach we have developed makes use of ultra wide band transmission techniques, which are sometimes referred to as "impulse radar", "spread spectrum radar," and "base band radar." Prior work with these technologies appears to have been directed to surveillance, where it was not possible to have a "cooperative" receiver on the inside of the target structure. Fundamental work remained to be done with cooperative receivers to determine which part of the E-M spectrum is most effective in penetrating engineering materials.

The experimental NLS program was initiated at NIST in cooperation with MIT Lincoln Laboratories. The objective of the preliminary laboratory investigation was to determine the effectiveness of spread spectrum radar transmissions, with a bandwidth of 1.5Ghz (from 500 Mhz through L-band (2 Ghz)), to penetrate various engineering materials and structures and to locate a "cooperative" positioning receiver beyond such obstacles.

Preliminary results show that it is possible to locate, via time-of-flight measurements, the position of a receiver beyond a meter-thick reinforced concrete wall, or



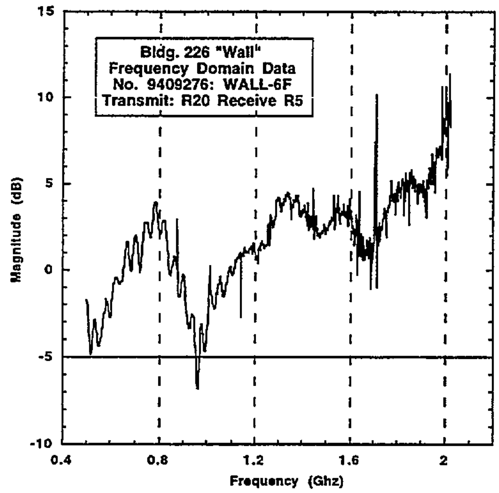
Above: Watkins-Johnson Quad-Ridged Horn antenna used for NLS tests at NIST. Frequency range is 0.5-26 GHz.
Below: Building 226 Test Site. Transmitter is located 50 m behind a 500 mm thick reinforced concrete wall; receiver (bottom of photo) is located 5 m in front of the wall.



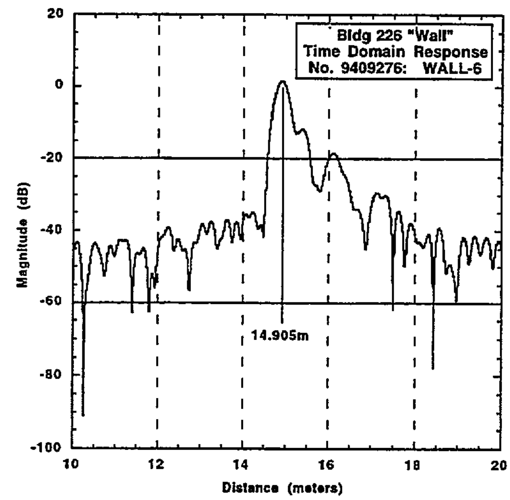
beyond several brick and masonry block walls, and beyond typical interfering stacks of wide flange girders.

The transmission and receiving antennae, which in normal radar are typically one and the same, were physically separated so as to create a system with a fixed broadcast unit and a "roving" receiver, whose range was to be determined relative to the transmission antenna by means of time-of-arrival measurements.

Time domain response was synthesized by means of chirp-z Fourier theory from a broad spectrum of data sampled in the frequency domain. Numerous field experiments were performed in which typical construction site obstacles were placed between the transmitter and receiver with separation distances of up to 70 meters. The obstacles included a half-meter thick, heavily reinforced concrete wall , varying combinations of masonry block and brick up to more than a meter in thickness and at varying angle-of-incidence orientations relative to the transmission path, and metal pre-fabricated wall panels. In all but the latter case repeatable distance measurements were obtained. Range detection was lost in the presence of extensive metal panels which contained no windows.



Above: Frequency domain response for a spread spectrum radar signal penetrating a 500 mm thick reinforced wall (see opposite photo).



Above: Time domain response for a spread spectrum radar signal propagating through air. The exact distance between the electrical centers of the two antennas was 14.905m. Such data was used to periodically calibrate atmospheric conditions.

However, the presence of even small openings (on the order of several centimeters) permitted range acquisition.

Several types of problems which are well known to the radar community were observed during the tests. These included "clutter" (reflections of the transmitted beam off false "targets") and "multipath" (diffracted and scattered elements of the original signal which may, under certain conditions, arrive ahead of the

NLS: Non-Line-of-Sight Metrology

- Limitations:
  - Maxwell's Laws: No Transmission through Solid Metal
  - Allowable Transmission Power: Penetration Distance vs FCC / OSHA
  - Presence of Dielectric Obstacles causes Scatter (Multipath) and Measurable Time Delay: Reinforced Concrete Wall = Lens
  - Higher Resolution = Larger Bandwidth = Larger Data Processing Burden

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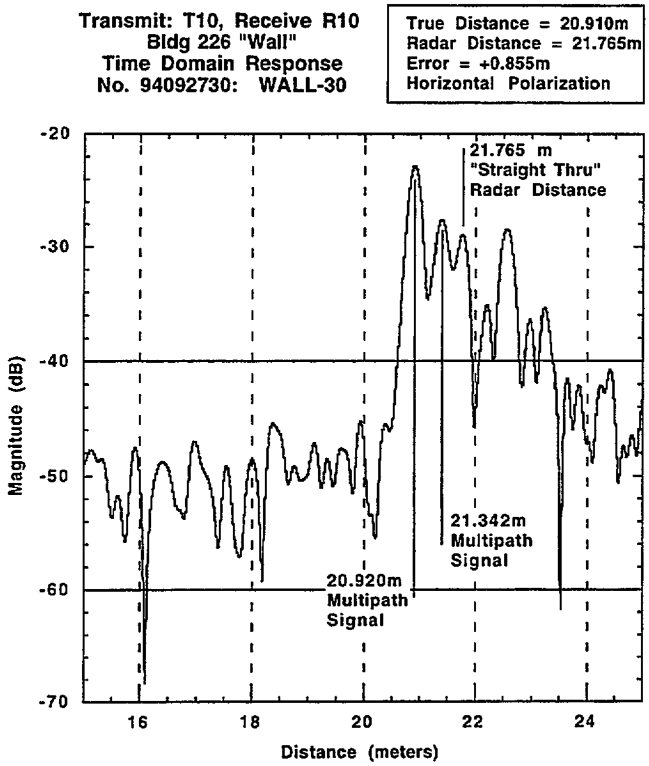
desired signal and which as a matter of course may obscure or cast doubt upon which detected signal in the time domain response represents the true transmitter-to-target distance). Another phenomena that was observed is well known to the optics industry: electromagnetic radiation which propagates through a medium other than a vacuum travels through that medium with a velocity less than the speed of light in a vacuum. Thus, any signal transmitted through a non-conducting engineering material -- e.g. brick, masonry block, or concrete walls -- will appear to have been delayed from its expected arrival time at the receiver. In some cases this delay was sufficient that multipath signals arrived ahead of the "true" signal representing the straight-line distance from transmitter to receiver. The delay is directly proportional to the dielectric constant of the engineering material penetrated. Where long dis-



Above: Time domain response for transmission from benchmark T10 to Station R10 (actual point-to-point distance = 20.910 m) at the NIST Building 226 NLS test range. The 500 mm reinforced concrete wall is between the transmitter and receiver. In this particular situation the propagation delay times associated with diffracted and reflected multipath signals are sufficiently separated that the individual peaks are clearly identified. Note that the straight "through-the-wall" response peak is the **third** detected, behind the two principal multipath signals. The first peak was diffracted around the interior corner at the junction of the two wall slabs; the second peak represents the signal reflected from office trailers to the left of the wall.

tances are involved between the transmitter and receiver, the characteristics of the air (including temperature, humidity, and barometric pressure) must be accounted for as well; during the NIST tests this was accomplished by means of a "free space" calibration with no intervening obstacles between the transmitter and receiver at the start of each test series.

Typical errors observed due to uncompensated propagation delays were significant. Penetration of a 500 mm thick reinforced concrete wall induced a range error mean of approximately 800 mm. For combined masonry block walls faced with brick, range errors of three meters were observed for a wall thickness of two meters and a 500 mm error for a wall thickness of 300 mm. Plots made with the limited data available indicate that these range errors are linearly proportional to the penetration depth (wall thickness) and the dielectric constant for the material.

While 800 mm of range error over a 20 m survey shot is unacceptable for modern construction surveying, it is important to recognize that nearly all of the error is related to propagation delay in concrete. This suggests that real-time compensation techniques can be developed which will be capable of eliminating this portion of the error. We are presently investigating the idea of constructing a three dimensional database for the project which reflects the as-built geometry in real-time and which includes propagation characteristics and statistical variances for the various materials and then employs a ray tracing approach (borrowed from computer graphics technology) to follow each transmitted signal. A discrimination algorithm will need to be developed which will then, based on statistical analysis of the multiple time histories generated via alternate transmission stations, determine which is the true target and to calculate its location and expected SEP (spherical error probable). Data developed as a result of analyzing Building 202 tests suggest that the residual errors that will remain after propagation delays are compensated will be on the order of 200 mm or less. It is anticipated that this number can be substantially reduced through a) the use of larger bandwidths in the transmitted signal and b) the use of super resolution (image enhancement) algorithms which will improve the signal to noise ratio in the received signal.

We think these results are both novel and encouraging. Confirmed distances (target detection) were obtained through a 500 mm thick reinforced concrete wall and through nearly two meters of brick and masonry block. The transmission power for all tests was only 1 milliwatt. During the next year we will be conducting tests to determine the statistical transmission characteristics of most construction materials.