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Specific Responsibilities

Joined Lafayette College's Department of Civil and Environmental Engineering in 2002. Responsible for environmental engineering, engineering policy, and GIS undergraduate curricula. Conducted the work described in this paper as part of an ongoing research and consulting project for a Native American Nation in Southwestern Arizona.

Past Experience

Previously an associate professor at Rose-Hulman Institute of Technology in Terre Haute Indiana for seven years. Started career in 1987 as an environmental engineer with the City of Los Angeles, and later CH2M Hill. Licensed professional engineer in the states of California, Oregon, and Pennsylvania.

Educational Information

B.S. – Civil Engineering, Columbia University
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Association of Environmental Engineering and Science Professors
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BIOGRAPHICAL INFORMATION

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15 years previous experience in water and wastewater engineering and municipal engineering. Started career in 1987. Licensed professional engineer in the states of Arizona, California, Oregon, Indiana, and Pennsylvania.

Educational Information

B.S. – Environmental Engineering, University of Florida
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Professional Memberships

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SELECTING THE RIGHT GPS FOR A UTILITY INFRASTRUCTURE GIS

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ABSTRACT

Global Positioning System (GPS) technology has changed rapidly over the last decade. As part of an ongoing Geographical Information System (GIS) project, the authors compared several GPS technologies to determine the most appropriate for projects that involve mapping and attribute recording of utility infrastructure for asset management. The evaluation was based on the assumption that the GPS technology also needs to be versatile so that it can be used as part of the life-cycle management process and not just for collecting the initial inventory data. As expected, the authors found that mid-grade single-frequency technology with differential correction is currently the best for utility infrastructure GIS projects. However, an important consideration is the need to determine the best differential correction method for the specific project; as shown by a comparison of GPS data collected using post-processing differential correction as well as several real-time differential correction services for known control points across a three million acre site in Southwestern Arizona.

INTRODUCTION

Using Geographical Information Systems (GIS) for life-cycle management of infrastructure requires both high accuracy and comprehensive data. These constraints often mean that primary data must be collected and a Global Positioning System (GPS) is a logical choice. However, the choice of GPS is complicated since there is a range of GPS technology, and a range of correction services to improve spatial accuracy of the data collected. In this paper, we discuss a recent effort to evaluate the available GPS technologies and correction methods. Our evaluation is based on a review of current GPS theory and applications, manufacturers' literature, and a field study comparing the available GPS differential correction methods for several known control points across a large spatial area. This evaluation was completed within the context of selecting a GIS for an ongoing project to map utility infrastructure as the basis for life-cycle infrastructure management.

OVERVIEW OF GPS TECHNOLOGY

In 1976, the US government funded the development of GPS technology. The US defense establishment had experienced severe communication and logistical problems in the Vietnam operations and, in part, GPS technology was seen as a solution (Steede-Terry, 2000). The US DOD launched the first GPS satellite in 1989 for military purposes, and the technology was a dramatic success in the 1990 Gulf War (Steede-Terry, 2000). The complete GPS system of satellites and monitoring stations was first operational in 1993 and became available for civilian use. GPS became even more attractive for civilian use when Selective Availability (SA) was disabled in 2000. SA had been used by the US government to introduce random timing errors in satellite signals for security purposes and affected spatial accuracy by up to 100 meters (Delaney, 2001) (Chivers, 2003). Civilian use of GPS has increased dramatically over the last decade with worldwide sales climbing from \$300 million in 1991 to \$2 billion by 1997 (Steede-Terry, 2000). Projections are that worldwide sales of GPS could reach between \$14 billion and \$31 billion by 2005. Consumer products are integrating GPS technology and personal handheld receivers have dropped in price from around \$2,000 in 1990 to under \$100 in 2000 (Steede-Terry, 2000).

GPS currently consists of a constellation of 27 (including three spares) NAVSTAR satellites that orbit the earth every 12 hours from a distance of 12,600 miles, portable receivers that acquire the radio-frequency signals from these satellites, and five ground-control monitoring stations. At the monitoring stations, the US DOD constantly observes the position of the earth-orbiting satellites and their atomic clocks, and sends correctional data to keep the satellites in the specified location. The satellite constellation provides worldwide coverage 24 hours per day with 24 active satellites, distributed in six evenly spaced orbits, at speeds that allow each satellite to pass over a US DOD monitoring station once every twelve hours. At any time of day, there are always four “visible” satellites in the sky at any location around the world (Steede-Terry, 2000).

The satellites continuously transmit microwave carrier signals to portable receivers on two L-band frequencies, known as L1 and L2. The L1 frequency (1575.42 MHz) transmits the carrier signals and a navigation message about the GPS satellites. The L2 frequency (1227.60 MHz) is used to measure some of the atmospheric delays that decrease the accuracy of the GPS readings. The cost of GPS technology varies widely depending on the frequency of the receiver with a significant difference between low-grade L1 single frequency units, mid-grade L1 single frequency units, and high-grade L1/L2 dual frequency units. Technology has also improved over time so that receivers are more portable and include user-friendly features for specifying various projection systems and units, editing attribute data, navigating to known coordinates, correcting spatial coordinates on the fly, and so on.

The three-dimensional position of the portable receiver is determined by the length of time it takes a particular satellite signal, assumed to be traveling in a straight line from a known origin, to reach the receiver while traveling at the speed of light (186,000 miles per second). If there were no delays, signals from a minimum of three satellites would be needed to record latitude and longitude, while signals from a minimum of four satellites are needed to also record elevation (Ward, 2002). Four satellites also account for the errors caused from imperfections in

clock technology. However, there are delays and most vendors suggest a minimum of five signals since the more signals received, the better the spatial accuracy.

In a 1990 paper, Speed and Lang forecasted that GPS technology has the potential to answer the GIS user's needs, but has limitations in terms of site-specific accuracy (Speed and Lang, 1990). There are many sources of error that affect the accuracy of GPS. Errors that are somewhat beyond the user's control include degradation of the transmitted signal, delays caused by the earth's atmosphere (troposphere and ionosphere), minor disturbances caused by gravitational pulls and solar radiation pressure, and inaccuracies in the atomic clocks on the satellites (Steede-Terry, 2002). These errors are increased if the angles from the satellites to the receiver are similar, therefore the better the spatial distribution, the better the accuracy. Dilution of precision (DPOP) is a measure that is used to estimate how good the GPS data should be based on the position of the satellites for a particular location on a particular day, and can be used to plan data collection. In addition, multipath errors occur because of obstacles in the area such as buildings that reflect and/or refract the signals so that they are difficult to decipher (Steede-Terry, 2002).

The user can control some errors with better quality receivers that have built-in software to automatically detect and correct several of the errors described. Also, dual frequency receivers are more accurate than single frequency receivers because the signal is received on two frequencies and the ionospheric delay is measured and used to correct the data.

DIFFERENTIAL CORRECTION OF GPS DATA

Regardless of the quality of the receiver, uncorrected GPS data currently has a spatial horizontal error of approximately 10 to 15 meters. Spatial vertical error with GPS is typically 1.5 to three times that of horizontal error. Unfortunately vertical accuracy is always less than horizontal accuracy because satellites are not accessible below the visible horizon. According to a recent publication, some GPS manufacturers use various "tricks" such as data averaging or map-matching to make the data "look better"; however these "tricks" do not necessarily improve the accuracy of the data (Steede-Terry, 2002). Static GPS data collection can minimize spatial errors but requires long occupation times to collect enough data to use with optimization techniques. Even "fast static" GPS requires 15 to 30 minutes of occupation per point. Therefore, static GPS is not discussed further in this paper since GIS mapping projects typically require short occupation times because many points need to be collected. Low-grade GPS receivers are also not discussed further because of the accuracy needs of utility infrastructure GPS projects.

For GIS mapping projects, differential correction is currently the primary technique used to improve the accuracy of single-frequency GPS data to one to five meters, and dual-frequency GPS data to sub centimeter accuracy, depending on the type of GPS receiver. This form of GPS is known as DGPS and is based on the assumption that two receivers close together are affected by the same "non-user" errors (Chivers, 2003). With "traditional" DGPS, a base station receiver is set up on a location where the coordinates are known. The difference between the known location and the calculated location based on satellite signals is used to determine individual corrections for each satellite used for that measurement. These corrections are then transmitted to

the other receivers (rover) and used to reduce errors for subsequent data collected in the same area at the same time.

The differential correction can be applied to the GIS data in real time in the field using radio signals, or after data capture with post-processing software. The smaller the distance between the rover and the base station, the more accurate the data. In addition, radio limitations often mean that there are set up and take down times when GPSing large spatial areas because the distance between the base and rover should be within 10 kilometers. Real-time differential correction works with both single frequency receivers and dual frequency receivers; however the base station and the rover must maintain continuous communication with the satellites. This can be a problem with single frequency receivers because the receivers need to be reinitialized every time satellite lock is lost which can slow down data collection significantly. Dual frequency receivers have an advantage because they reinitialize instantaneously so that data collection can continue uninterrupted. The use of two or more GPS receivers (base and a rover) with radio communication between receivers, real-time differential correction, and carrier-phase tracking is known as real-time kinematic (RTK) GPS and is the most accurate differential correction method.

A modification of DGPS when a base station cannot be established is to use a stationary satellite maintained by a service to obtain corrections for several reference stations close to the site where the data is being collected. The reference station collects GPS data regarding its location and sends this data to a control center. The control center sends the data to a stationary satellite for verification and relays the corrections to the GPS rover. There are currently two commercial satellite differential service providers, Thales Survey LadStar and OmniSTAR Inc (Chivers, 2003). In addition, the Federal Aviation Administration has developed the Wide Area Augmentation System (WAAS) differential correction service that civilians can use for free. There is also a large worldwide network of free DGPS radio beacons that are primarily located near coastal areas, navigable waterways, and inland agricultural areas and have a range of several hundred kilometers (Chivers, 2003).

DGPS with post-processing is based on the same principles as described above except that the correction is done after the field work is complete using specialized software and permanent worldwide continuous operating base stations that provide the necessary data (Chivers, 2003). Base stations are maintained by a variety of sources including the US government's free continuously operating reference stations (CORS). Permanent base stations can also be set up by users for their specific area of interest. There are several on-line services, such as the National Geodetic Survey's On-Line Positioning Service (OPUS), that accept uncorrected data and post process the data with the corrections from a nearby CORS. On-line services exist for data collected with both single frequency and dual frequency receivers. However, the technology is changing fast as evidenced by the commercial availability of real-time *high precision* differential correction single frequency GPS receivers and services over the last year.

GPS CONSIDERATIONS FOR AN INFRASTRUCTURE GIS

Life-cycle management of utility infrastructure involves planning, design, construction, operation, and maintenance of the respective systems. All stages of the life cycle use spatial data albeit of varying accuracies. The Federal Geographic Data Committee (FGDC) develops standards for spatial data; however there are no universal standards for spatial accuracy for utility infrastructure. The FGDC has recommendations for spatial accuracies for utilities at military facilities depending on what the data is used for. The FGDC recommended horizontal error for GIS applications and asset management/facility mapping (AM/FM) is two feet (0.6 meters) to 10 feet (3 meters) horizontally (FGDC, 2002). This is significantly higher than that for design, construction, and as-built drawings which are all less than one foot (0.3 meters) (FGDC, 2002). Practically, the ongoing operation and maintenance stages of life-cycle utility infrastructure management rely on as-built drawings that likely form the basis of the GIS.

As suggested by the FGDC, the as-built spatial accuracy needs to be set for site-specific safety and functional requirements. However, the FGDC recommendations for military facilities suggest a need for the more expensive dual frequency L1/L2 GPS. Unfortunately, unless the site location has its own permanent base station, dual frequency GPS does not readily satisfy the needs for ongoing operation and maintenance where minimal setup and navigation capability are desired. Until more accurate GPS technology is available at lower costs, mid grade L1 GPS with differential correction appears to be appropriate for most large-scale utility infrastructure GIS projects that span a large spatial extent. This conclusion applies to those organizations that have resource constraints and assumes that more accurate information is used during the design and construction stages. The remainder of this paper focuses on mid-grade GPS technology and associated differential correction.

SPATIAL ACCURACY OF MID-GRADE L1 GPS WITH DIFFERENTIAL CORRECTION

Differential correction for mid grade L1 receivers can be obtained with various real-time correction services, or with post processing. According to vendor information, the accuracy is similar for all of these options when data is collected with occupation times between five and ten seconds. Typical horizontal accuracy is reported to be within one to two meters for a beacon, one meter with WAAS, and 0.5 meters with OmniStar (Sokkia, 2003). Post processing is reported to have a horizontal accuracy within 0.5 meters (Sokkia, 2003). Given the need for a high degree of spatial accuracy for utility infrastructure projects and the limitations of using mid-grade L1 GPS technology, significant differences between the real-time correction services and post processing need to be assessed.

The authors completed such an assessment during 2003 in conjunction with an ongoing effort to map the utility infrastructure on a Native American Reservation in Southern Arizona. The authors used a Sokkia Axis3 mid-grade L1 GPS receiver that allows the user to switch between the three available real-time correction services, Beacon, WAAS, and OmniStar (with a paid subscription). All correction services are available at the site location. The closest WAAS

reference station is located near San Diego, California, and the closest beacons are at Flagstaff, Arizona with several in southern California. The Omnistar method of calculating positions relies on a series of base stations throughout North America and a geo-stationary satellite feeding corrections to the rover. In terms of “non-user” errors, the site location was ideal for the evaluation because of minimal multipath or blocked signals since the area is rural with low density and small single-story well-spaced buildings.

At approximately the same time each day, a GPS recording was made for known National Geodetic Survey (NGS) control points, and other control points established by the Native American Nation. The control points selected for the evaluation are scattered across the three million acre reservation. The Native American control points have not been officially recorded with NGS however the relevant Indian Health Service area office authorized use of the data for this project. Each control point was GPSed using all three differential correction services and a five to ten second occupation time. In addition, raw data was logged to be post processed after completing the fieldwork. The raw data was logged for five to ten second occupation times (for short-duration post processing) as well as for longer occupation times of 20 to 30 minutes (long-duration post processing) to compare. Thirteen (13) samples were collected in January/February 2003 and April/May 2003.

The collected GPS data was compared to the coordinates for the known control points to identify significant differences. Table 1 shows results for the post-processed data (both long-duration and short-duration) and the best DGPS service for the day of testing (note: this could be Beacon, Omnistar or WAAS). Table 1 shows that many of the data collection points are at monuments established by the Native American Nation (WRSP) that have not been NGS certified. In many cases these monuments were the only reasonably accessible control points in those locations. However to be conservative, Table 1 also shows the comparison for just the NGS monuments (i.e. sans WRSP). The recommendations reported below are based solely on this smaller data set; however the larger data set compares favorably.

Despite claims by the vendor, short-duration post-processing does not appear to offer sub-meter horizontal accuracies. Using verifiable NGS control monuments at various locations across the site there was a mean horizontal accuracy of 1.56 meters. Vertical accuracies showed a mean of 1.30 meters. Long-duration post-processing (15 to 20 minutes occupation time) using verifiable NGS control monuments offered a mean horizontal accuracy of 0.79 meters with a mean vertical accuracy of 0.54 meters. In addition, post-processing, both short- and long-duration, was unreliable during the evaluation. For the second phase of data collection only four of the ten “raw” data points (both long-duration and short-duration) could be post-processed due to program errors that the vendor was unable to address. This is an important point since field collection of data can be the most expensive effort in populating a GIS. A comparison of the DGPS data shows comparable horizontal accuracies although vertical accuracies are somewhat less relative to the post-processed data. Using the t-statistic, due to the limited dataset and assuming normal distribution, the authors further compared the performance of each methodology used. At the 95% confidence level, real-time DGPS data performed best in the horizontal dimension with sub-meter accuracy of 0.82 meters. Vertically, the long-duration post-processed (LD-PP) performed best with a value of 1.16 meters at the 95% confidence level.

Table 1. Comparison of GPS Data with Known Control Points

Monument Name	"LD-PP"	"LD-PP"	"SD-PP"	"SD-PP"	"DGPS"	"DGPS"	Date
	(X,Y Error)	(Z Error)	(X,Y Error)	(Z Error)	(X,Y Error)	(Z Error)	
	(m)	(m)	(m)	(m)	(m)	(m)	
Kitt Road - NGS - 1992	0.23	0.05	NC	NC	0.46	0.46	01/29/03
A121 - USC&GS - 1936	0.44	0.56	NC	NC	0.35	1.94	02/03/03
A121 - USC&GS - 1936	1.87	0.25	NC	NC	0.81	2.14	02/04/03
Kitt Road - NGS - 1992	0.51	0.47	0.30	1.21	1.12	3.17	04/30/03
WRSP - 004	4.26	1.46	4.23	0.25	2.83	2.84	05/01/03
WRSP - 003	1.25	1.90	None	None	1.32	3.94	05/02/03
WRSP - 005	1.37	1.85	1.34	1.40	0.33	2.17	05/05/03
T10S.. - USGLO	1.50	1.88	2.10	1.74	0.74	3.04	05/06/03
WRSP - 016	1.49	0.80	2.47	0.81	0.27	1.41	05/07/03
Pozo - AZDOT - 1979	None	None	None	None	0.51	1.74	05/08/03
142A - IB&WC - 1935	None	None	None	None	0.57	2.74	05/09/03
WRSP - 008	None	None	None	None	5.79	0.88	05/12/03
Nolia - AZDOT - 1979	0.21	0.05	2.29	0.94	0.67	1.94	05/13/03
Average (All) =	1.31	0.93	2.12	1.06	1.21	2.19	
# Data Points (All) =	10	10	6	6	13	13	
Average (sans WRSP) =	0.79	0.54	1.56	1.30	0.65	2.15	
# Data Points (sans WRSP) =	6	6	3	3	8	8	

"LD-PP" = Long-Duration Post - Processed Data ("On-Point" Times of 20-30 Minutes)

"SD-PP" = Short-Duration Post - Processed Data ("On-Point" Times of 5-10 Seconds)

"DGPS" = "Real-Time" Differentially Corrected Data (Could be Beacon, WAAS or Omnistar)

Denotes Native American Nation Control Point (Non-Certified)

None = Indicates no data due to post processing errors associated with software

NC = Indicates no "SD-PP" data collected during Phase I

Table 2 shows a comparison between the DGPS services. The "best" DGPS service varied somewhat between Omnistar, WAAS, and the radio beacon with Omnistar performing the best overall. Using verifiable NGS control monuments there was a mean horizontal accuracy of 0.68 meters and a mean vertical accuracy of 2.13 meters for the Omnistar satellite DGPS service. In comparison, the radio beacon offered a mean horizontal accuracy of 0.86 meters and a mean vertical accuracy of 3.00 meters while WAAS offered a mean horizontal accuracy of 2.22 meters and a mean vertical accuracy of 3.50 meters. Of the ten data points collected in this comparison, Omnistar provided the most accurate data for seven of the ten (horizontally) and six of the ten (vertically), regardless of location. Using the t-statistic, due to the limited dataset and assuming

normal distribution, the authors further compared the performance of each DGPS service used. At the 95% confidence level, Omnistar performed best in both the horizontal and vertical dimension. The expected upper bound of X,Y error was 0.89 meters while the expected upper bound of Z error was 2.70 meters.

Table 2. Comparison of DGPS Data – Beacon, Omnistar and WAAS with Known Control Points

Monument Name	Beacon (X, Y Error) (m)	Beacon (Z Error) (m)	Omnistar (X, Y Error) (m)	Omnistar (Z Error) (m)	WAAS (X, Y Error) (m)	WAAS (Z Error) (m)	Date
A121 - USC&GS - 1936	0.32	3.74	0.64	3.54	1.03	1.64	01/27/03
Kitt Road - NGS - 1992	0.81	2.24	0.23	2.24	0.24	1.34	01/28/03
Kitt Road - NGS - 1992	0.46	0.46	1.49	0.06	1.70	3.14	01/29/03
Kitt Road - NGS - 1992	1.51	1.94	0.77	1.94	1.28	7.84	01/31/03
A121 - USC&GS - 1936	0.46	2.14	0.35	1.94	1.91	2.64	02/03/03
A121 - USC&GS - 1936	1.18	6.84	0.81	2.14	4.91	2.14	02/04/03
T10S... - USGLO	1.35	3.14	0.74	3.04	2.52	8.04	05/06/03
Pozo - AZDOT - 1979	0.99	1.74	0.51	1.74	1.83	5.84	05/08/03
142A - IB&WC - 1935	1.17	3.24	0.57	2.74	2.91	1.34	05/09/03
Nolia - AZDOT - 1979	0.34	4.54	0.67	1.94	3.83	1.04	05/13/03
Average =	0.86	3.00	0.68	2.13	2.22	3.50	
# Data Points =	10	10	10	10	10	10	

CONCLUSIONS

There are a variety of GPS technologies available to the utility manager when considering how best to populate a GIS. FGDC standards for asset management/facility mapping/GIS suggest that “low-grade” GPS solutions can be immediately ruled out. However, “mid-grade” (L1 with differential correction), and higher (L1/L2 dual frequency), GPS technologies will meet relevant FGDC standards for AM/FM/GIS.

If “mid-grade” accuracy standards are acceptable, then the selection of this technology over “high-grade” is justified by the following factors:

- Cost-effectiveness - (\$10,000 “mid-grade” versus \$30,000 “high-grade” – in rough round numbers).
- Ease of use – “mid-grade” offers the advantage of a single rover unit versus a “high-grade” configuration of base station and rover.
- Flexibility/reliability in varying conditions and for varying uses – (such as navigation to known coordinates or previously GPS’d points).
- Meets most management/planning objectives.

However, if the GPS data to be collected will also serve as a base for utility design and as-built mapping, then a “high-grade” L1/L2 dual frequency GPS unit should be selected.

Assuming a “mid-grade” GPS receiver is selected to populate a GIS; decisions need to be made in terms of how the data is to be collected. There are essentially two options, collecting “raw data” and correcting this data at a later time through post processing or collecting “real-time” corrected data through the use of a DGPS service. In the authors’ experience in populating a GIS for a utility in Southern Arizona, use of a DGPS service offered the following advantages:

- Reliability – the DGPS data was inherently more reliable. In effect, once the point is collected in the field, “you know you got it”. In contrast, four of ten “raw data” collection points could not be corrected due to software errors associated with the post processing software that the vendor could not address. This is an important consideration since field collection of data is typically one of the more expensive tasks in populating a GIS. The implications of data loss due to inability to post-process are increased costs.
- Accuracy – in the horizontal dimension, and recognizing the limited data set, DGPS data offered more accurate results. The DGPS data, with on-point collection times of 5-10 seconds, performed better than post-processed data with on-point collection times of 20-30 minutes!

If a DGPS service is selected as the method in achieving corrected GPS data, then the utility manager needs to decide which service should be used. There are two “free” services that provide corrected GPS data; one sponsored by the US Coast Guard (radio beacon) and one sponsored by the Federal Aviation Administration (WAAS). There are a couple of “fee” services including Omnistar, which charges a fee for the ability to receive proprietary corrected signals. In the authors’ experience in populating a GIS for a utility in Southern Arizona, the Omnistar service provided more accurate results in both the horizontal and vertical dimension relative to the radio beacon and WAAS. The utility manager should weigh the perceived benefit in increased accuracy versus the additional cost to receive proprietary corrected signals. A suggestion might be to select known control points in the area to be GPS’d and compare the performance of the “free” services versus a “fee” service to make a more educated decision.

Finally, the utility manager should recognize that GPS technologies are changing fast. For example, Omnistar has introduced a new “real-time” DGPS service (Omnistar HP) that offers 2-sigma horizontal errors fewer than 10 centimeters. The cost is higher, relative to its “standard” service, but it seems to offer “high-grade” horizontal accuracies with a “mid-grade” GPS unit. As with the computer industry, technological advances such as these will probably be the norm rather than the exception. The utility manager will find it worth his/her while to stay on top of these advances as they may represent one of many tools to effective life-cycle utility management. Also, from a planning standpoint, recognize these innovations most likely will require continual investment in equipment replacement and/or modification. For example, the Omnistar HP service will work with a “mid-grade” GPS unit. However, this unit needs to be equipped with special software to accept these signals, implying that existing “mid-grade” units will have to be modified or replaced. Budgeting for equipment modifications and replacements is an important strategy in staying abreast of technological advances and, unfortunately, keeping up with the Jones’.

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