GPS HEIGHTING IN OKAVANGO DELTA

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ABSTRACT: For the past three years, an annual campaign of global positioning system (GPS) measurements has been mounted in the Okavango Delta in Botswana, as part of a multidisciplinary research project. The project examines the hydrology, sedimentology, and plant ecology of the wetland. Critical to the project is the determination of the relative heights of water gauges and other points within this 22,000 km^2 area. GPS has proven to be a key technology in achieving this aim. Nevertheless, its use does introduce a complication in that the heights derived using GPS are ellipsoidal, whereas orthometric heights are required in the context of modeling water flow. Conversion from one type of height to the other requires an accurate model of the geoid, but this is not easy to produce in such a data-scarce area. In this paper, the writers describe the GPS surveys and the adjustment and connection of the GPS networks to existing survey control. Two geoid models for the region are assessed and their significance evaluated.

INTRODUCTION

The Okavango alluvial fan of northwestern Botswana (Fig. 1) supports the largest wetland in southern Africa, with a surface area of about 22,000 km^2. Unlike other riverine areas in Africa, the Okavango has never been densely settled due to endemic insect-borne diseases; nor has there been any significant development in the catchment area of the delta. Consequently, the Okavango Delta is today one of the world's most pristine wetlands. It supports a diverse wildlife population and is the center of a thriving eco-tourism industry. The region in which the delta is situated is semiarid, and there are chronic water shortages, which threaten local and regional development. Consequently, schemes have been proposed for water abstraction from the Okavango River upstream of the delta (Pallett 1997), as well as from the delta itself (Standish-White 1972; Scudder 1993). If not carefully managed, removal of water from the delta could have a devastating impact on the ecosystem. The long-term conservation and use of this unique wetland therefore depends upon a comprehensive understanding of its hydrology. Although a great deal of hydrological research has been carried out, it has been constrained by the lack of topographic information (McCarthy et al. 1997). A number of water gauges exist within the delta, but, until recently, these have

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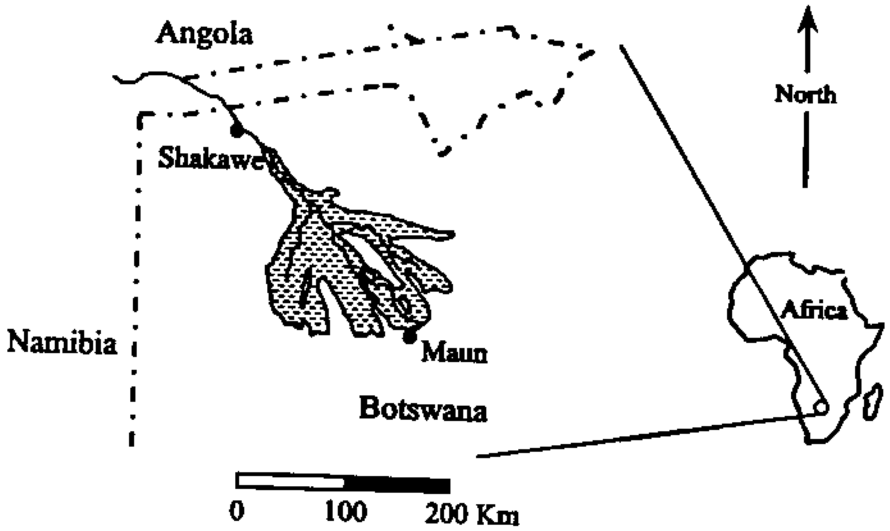

FIG. 1. Okavango Delta, Botswana

operated in isolation with no knowledge of their relative or absolute elevations.

In 1994, cooperation between the Universities of Cape Town, the Witwatersrand, and the Federal Armed Forces Munich resulted in the measurement of a global positioning system (GPS) network connecting some 21 sites in the panhandle of the delta and along the Jao/Boro River Systems, from Shakawe to Maun (Rüther 1994; Heister and Sternberg 1995; Merry 1995a). The northern and southern terminals of this GPS network form part of the Botswana first-order level network. Time and logistical constraints did not allow the GPS network to be connected to additional points, nor did time permit additional points on other distributaries to be surveyed.

Consequently, the survey team returned to the delta in 1995, with the aim of carrying out a more detailed survey in the lower panhandle region (where the Okavango River flows in several anastomosed channels through the papyrus marsh), and to extend the survey by placing GPS control points along the Nqoga Channel, which flows towards the east from the southern end of the panhandle. The opportunity was also taken to connect the survey to a benchmark lying to the west of the delta, and to measure some additional vectors to strengthen the network. In 1996, two additional control points were placed near the junction of the Boro and Nqoga Channels, and a detailed survey was undertaken in the region immediately to the east of this junction. The GPS points and vectors forming the combined control network are shown in Figs. 2 and 3. Note that, for the sake of clarity, the vectors and points of the two detail surveys are not shown, although they were included in the network. The approximate extents of these detail surveys are indicated in Fig. 2. In 1994 and 1996, GPS and precise leveling measurements were made to determine the slope of the geoid at discrete points in the delta, using the method described in Heister et al. (1991). The results of this work are described in Heister and Lang (1997) and do not form part of this discussion.

GPS SURVEY

The primary purpose of the GPS survey was to determine the relative heights of water gauges and the water surface at widely separated points in the delta. Because the water level changes from month to month and from one year to the next, it is important to have a control network consisting of a number of stable points, so that repeat surveys are possible. The delta

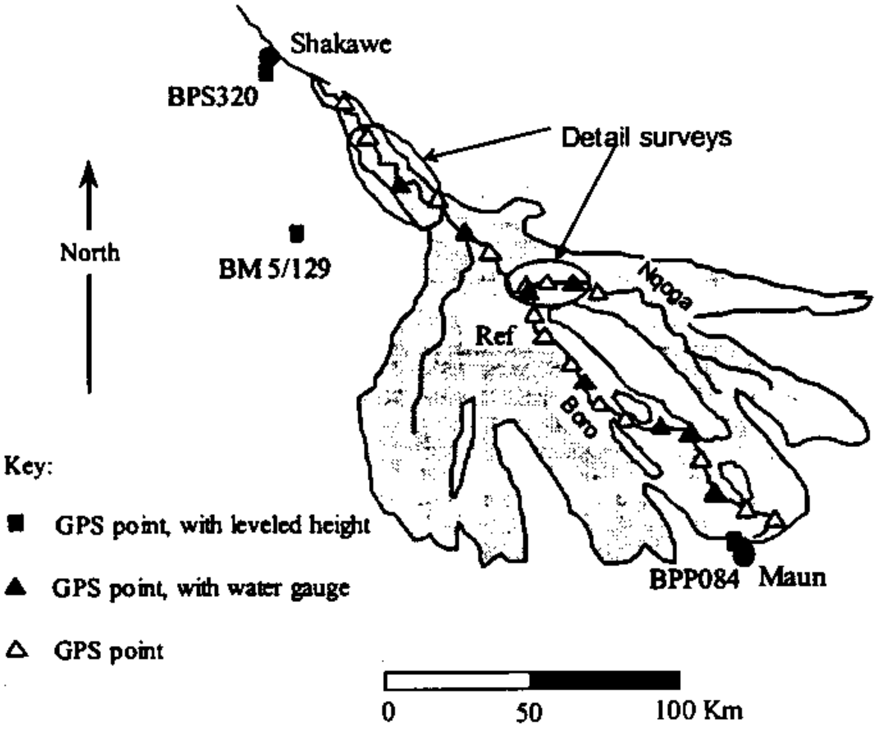

FIG. 2. GPS Control Points, Okavango Delta

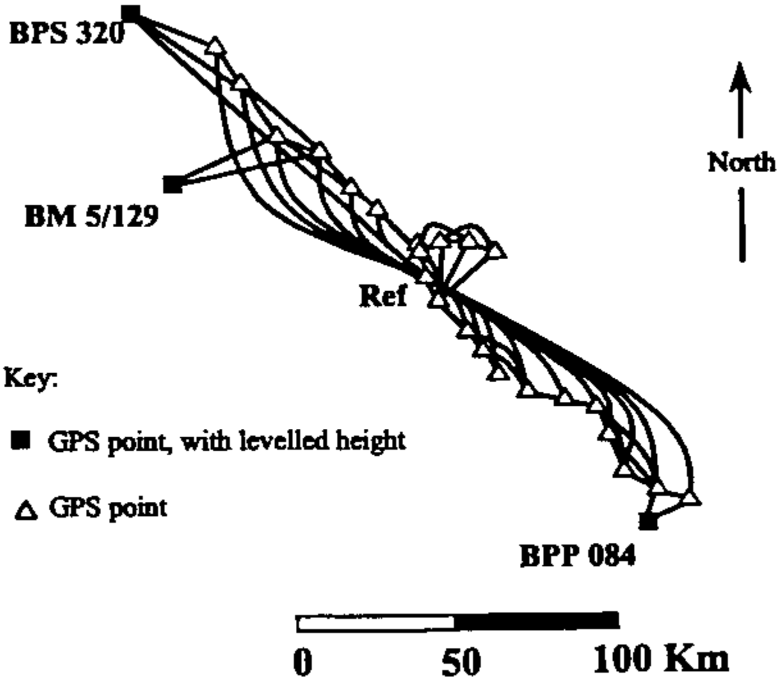

FIG. 3. GPS Network, Okavango Delta

consists in its upper reaches of papyrus swamp separated by narrow winding channels and lagoons. Lower down, the papyrus gives way to grasses and sedges, which are immersed at the time of the annual flood. Scattered throughout both regions are small islands, many of them centered on a single tree or termite mound. These islands provide the bases for the water gauges and survey markers. Given the propensity of the larger herbivores (primarily elephants, buffalo, and hippopotamuses) to use pillars or protruding standards as scratching posts, the writers chose to drive the survey markers, consisting of 1.5 m iron standards, flush with the surface, with an indicatory marker a few meters away.

The desired relative accuracy of heighting is 1−2 parts per million (ppm) of the distance (i.e., for two points 10 km apart, the desired relative accuracy is 1−2 cm). There is a much lower accuracy requirement for horizontal position. The design of the GPS survey was centered around the height accuracy requirement, subject to the constraint of available suitable islands. The design criteria were further constrained by the limits imposed by the availability of equipment, funds, and time. Although guidelines exist for establishing GPS-derived ellipsoidal heights (Zilkoski et al. 1997), these were not available at the time of the original survey and could not, in any event, have been followed completely, due to the previously mentioned constraints. The guidelines used in the design of the survey are as follows:

- Station separations of no more than 30 km to reduce the effect of ionospheric refraction and to enable integer ambiguities to be fixed; where longer baselines were observed, the measurements were to take place at night, to reduce ionospheric refraction effects.
- Multiple vector redundancies forming closed loops, so that most points were connected to their four nearest neighbors.
- Station occupation times of at least one and a half hours.
- Use of a continuously operating reference station near the center of the network, as an added redundancy in case of lack of simultaneity of observations at other sites.
- For any one campaign, use of identical receiver types and antennas, to reduce the effect of antenna phase center errors.
- Where possible, use of dual frequency receivers to reduce the effect of ionospheric refraction effects (in practice, full dual frequency receivers were seldom available).

The multiple redundancy criterion was the most onerous, as movement between sites could only be accomplished by small flat-bottomed aluminum motor boats traveling along narrow channels. The general logistical design was to start at one end of a major channel, moving down the channel in leapfrog fashion with two to three boats and three to five receivers. In order to achieve the multiple redundancy, a great deal of backtracking was necessary. However, this was not always practical, due to time and petrol constraints (all supplies, including petrol, had to be carried on the boats). To save time and petrol, not as many redundant vectors were measured as had been originally intended. No deliberate attempt was made to repeat the measurement of individual baselines; the redundancy was achieved by measuring additional vectors to form multiple closed loops. Nevertheless, over the three field trips, repeat measurements were made on eight baselines. No attempt was made to ensure that the repeat measurements took place on a different day at a different time, but this was generally the case. The average length of these eight baselines was 12 km, and the root mean square (RMS) discrepancy in the height differences was 8 mm (a maximum of 14 mm). The planning was further complicated by the need to carry out the survey according to a strict daily schedule, as no radio contact was possible between sites, due to the vegetation and the flatness of the terrain. In this regard, the reference station proved invaluable on the initial 1994 survey, enabling redundant measurements to be obtained, albeit with some rather long vectors. The reference station at Jedibe was destroyed before the next field trip, and subsequent trips were planned on the basis of such a station not being available.

The GPS measurements constituted only part of the survey. Each GPS site had to be connected by means of leveling to a water gauge zero, water gauge benchmark, or to the water surface itself. Some nine water gauges, maintained by the Botswana Department of Water Affairs, were included in the 1994 and 1995 surveys. In all cases, the water gauges were within 200 m of the GPS station, and forward and back leveling was carried out, with an average precision of 5 mm. At the remaining GPS sites, leveling was to the water surface. In the detail survey carried out in the Nqoga Channel in 1996, no suitable dry land was available for the GPS receiver setups. At 12 of the sites, the GPS receiver tripods were set up on triangular platforms consisting of three planks bolted together. The platform was laid on flattened papyrus reeds adjacent to the channel. The setup was allowed a few minutes to stabilize, and the height of the GPS antenna above the water surface was measured directly using measuring rods.

To tie the survey into the existing first-order height network, two points of the Botswana national control survey network were occupied as part of the 1994 survey—one at Shakawe in the extreme north-west (BPS320) and one at Maun in the south-east (BPP084). Both these beacons had been heighted using precise leveling techniques. In 1995, a third benchmark, BM 5/129, near Sepupa, was linked to the GPS network.

In the 1994 survey, five Wild System 200 receivers were used (four from the University of the Federal Armed Forces Munich, one from the ETH, Zurich). In 1995, five Ashtech receivers were used [three from the University of Cape Town (UCT), two on loan from H.K. & W.E. Volkmann Surveyors, Windhoek]. In 1996, the three UCT Ashtech receivers were used. The data from the Wild receivers were converted to RINEX format for further processing, providing C/A-code data on L_1, full-wavelength carrier phase data on L_1, and half-wavelength carrier phase data on L_2. Two of the UCT Ashtech receivers were full dual-frequency Z-12s, with the remaining Ashtech receivers being single-frequency M-12s; consequently, only C/A-code data and carrier phase data on L_1 were generally available from these receivers. The three UCT receivers used identical Ashtech geodetic antennae; the two Ashtech M-12 receivers on loan used an earlier version of the geodetic antenna, with a slightly larger ground plane. Consequently, it can be expected that phase center biases may exist in the data observed in 1995, when all five Ashtech receivers were used together. However, no attempt was made to perform a relative calibration of these antennae, and the results appear to indicate that no significant bias exists between the two Ashtech antenna types.

DATA PROCESSING

The data have been processed in a number of stages, as data have become available. The 1994 network (which lacked checks on two points) was processed and adjusted separately at UCT and the University of the Federal Armed Forces Munich (UBw). The same RINEX data files were used by both institutions, but the way in which the data were combined differed slightly. Each institution used its own data processing package; at UCT, the Ashtech-supplied package GPPS was used; at UBw, the Geotracer package, originally developed at UBw but now sold commercially by Geotronics, was used. At UCT, an in-house program, Transformer, was used to adjust the GPS vectors, whereas at UBw, the adjustment module of Geotracer was used. Both institutions treated the reference station (Ref) at Jedibe as fixed, and all precision estimates are with respect to this point. The coordinates of Ref in the ITRF92 reference frame were determined by Heister and Sternberg (1995) using the IGS station at Hartebeesthoek, some 923 km to the southeast. The primary purpose of this connection was to obtain precise initial coordinates for the GPS vector data processing; as a by-product, ellipsoidal heights with respect to the WGS84 ellipsoid could be obtained. The estimated precision of the height component of this connection is 65 mm.

Different processing strategies were employed by the two institutions. At UCT, the elevation cut-off angle was set to 15°; at UBw, 10° was used. UCT used the broadcast ephemeris; UBw used the precise ephemeris downloaded from the IGS. At UCT, 49 independent vectors were created and used in the network adjustment; with one exception, all vector solutions were L_1 integer-fixed (for the longest line—139 km—an L_1 float solution was used). The average distance between adjacent stations is 14 km, while the average length of all measured vectors is 37 km. The shortest vector is 2 km; the longest, 139 km. Occupation times vary from one hour to four and a half hours, with an average of two and a half hours. UBw constructed 46 independent vectors linking the same 21 points. Of these, seven were L_1 float solutions, eight used the L_2 fixed solution, and the remainder used the L_1 fixed solution. No meteorological measurements had been made, and both institutions used standard meteorological values. Refraction scale bias parameters were not determined. Further details of the data processing and adjustments are contained in Merry (1995a) and Heister and Sternberg (1995). A comparison between the minimum-constraint adjustments of UCT and UBw shows an RMS fit (after allowing for rotation and scale) of 6 mm. This agreement is excellent, considering the different processing strategies employed and that the formal precision estimates for the coordinates reach 12 mm (UCT network) and 16 mm (UBw network). However, the scale factor between the two solutions is not insignificant, amounting to 0.8 ppm (with the UBw network smaller). Both networks use single frequency solutions, ignoring the effect of the ionosphere, but the UBw vectors use an elevation angle cut-off of 10° (UCT uses 15°), which may contribute to the scale bias between the two solutions. Nevertheless, the maximum discrepancy in height between the two solutions (not allowing for rotations or scale) is only 44 mm. This occurs for a point at the extremity of the network, some 139 km from the common fixed point, Ref, and corresponds to a relative discrepancy of 0.3 ppm.

As mentioned earlier, neither of the two solutions allows for the influence of ionospheric refraction, and both can be expected to be too small by some 0.6 ppm (Georgiadou and Kleusberg 1987). In the case of the UCT network, this was confirmed by reprocessing the data with GPPS using the ionosphere-free (L_{1C}) option; the resultant network is indeed 0.6 ppm larger than the original L_1-only network. The 1994 observations were made using Wild System 200 receivers, which employ squaring on the L_2 frequency to determine the carrier phase. As a result, the data for many vectors were too noisy to use wide-laning to determine integer ambiguities at the same time as correcting for refraction. Hence, the L_{1C} solution, though corrected for the influence of the ionosphere, is of a lower precision than the L_1-only (integers-fixed) solution. As the subsequent surveys in 1995 and 1996 mainly used L_1-only receivers, the writers have decided to remain with this type of solution throughout the network. For the 1994 survey, the maximum discrepancy in height between the two types of solution is 36 mm on a 139 km line (less than 0.3 ppm)—well within the specified design tolerance of 2 ppm.

The 1995 survey added four points along the Nqoga Channel, provided check measurements for the two points referred to earlier, and tied in a third Botswana control point (BM5/129). An additional ten points were surveyed as part of a detail survey along two channels of the Okavango River in the panhandle. Although six points of the 1994 survey were included in the 1995 survey, no common baselines were measured. In the 1996 field season, two additional permanent points were added to the network, and 12 temporary floating points were included. Two of the 1994 points and one of the 1995 points were reoccupied, but no common baselines were measured. The data from the 1995 and 1996 surveys (all integer-fixed, uncorrected for the ionosphere) were added to the 1994 data, and the network was readjusted using the Ashtech-supplied program Fillnet. A total of 122 vectors ranging in length from 2 to 139 km were incorporated in this network. The average vector length is 21 km. Occupation times varied from one hour to four and a half hours, with an average of just under two hours. The data were adjusted using Fillnet in a minimum constraint adjustment, holding the reference station Ref fixed. Due to the large number of possible combinations, no analysis of loop closures was carried out. Instead, the vector residuals after adjustment were evaluated to determine potential weaknesses. Two vectors showed height residuals in excess of 20 mm. One of these was the 139 km line, for which only an L_1 (float) solution was available (a residual of 52 mm). The other was a 30 km line, which had only been observed for an hour and for which only five satellites were available (a 50 mm residual). Both these vectors were downweighted in the final adjustment with the weights for 120 vectors based upon precision estimates of 3 mm ± 0.5 ppm and those for the two downweighted vectors based upon precision estimates of 6 mm ± 1 ppm. The degrees of freedom in the adjustment were 216 and the standard error of unit weight after adjustment was 0.8, indicating that the precision estimates were slightly pessimistic. Relative to the point Ref, precision estimates for the heights of points in the adjusted network range from 2 to 13 mm (the latter at a point some 139 km from Ref). The maximum relative precision in ellipsoidal height between adjacent points is 0.8 ppm.

HEIGHTS

The primary purpose of the GPS survey is to obtain orthometric heights for the water gauges/water surface in the delta. The GPS-derived heights are ellipsoidal heights, based upon the ellipsoidal height for the reference station at Jedibe. In turn, the height of this point is based upon the ellipsoidal height of the IGS station at Hartebeesthoek. In particular, the height used is that defined in the ITRF92 coordinate system for the epoch 1988.0 (Heister and Sternberg 1995). In order to convert the ellipsoidal heights to orthometric heights, the geoidal height at each point must be known:

$$H = h - N \tag{1}$$

where H = orthometric height; h = ellipsoidal height; and N = geoidal height.

A number of geoid models for this area exist. The most detailed of these is the UCT95A model, which is based upon the global model OSU91A (Rapp et al. 1991) combined with local gravity data (Merry 1995b). This model is shown in Fig. 4. More recently, the Earth Gravity Model 1996 (EGM96) became available (Lemoine et al. 1996) (Fig. 5). This is a global model, which does not show the details reflected by UCT95A in the Okavango Delta region. An idea of the quality of these models can be obtained by comparing them with the geoidal heights inferred by differencing GPS-derived ellipsoidal heights (from the 1996 adjustment) with orthometric heights determined from precise leveling. As part of the GPS surveys of 1994 and 1995, three points of the Botswana geodetic control network were occupied (these

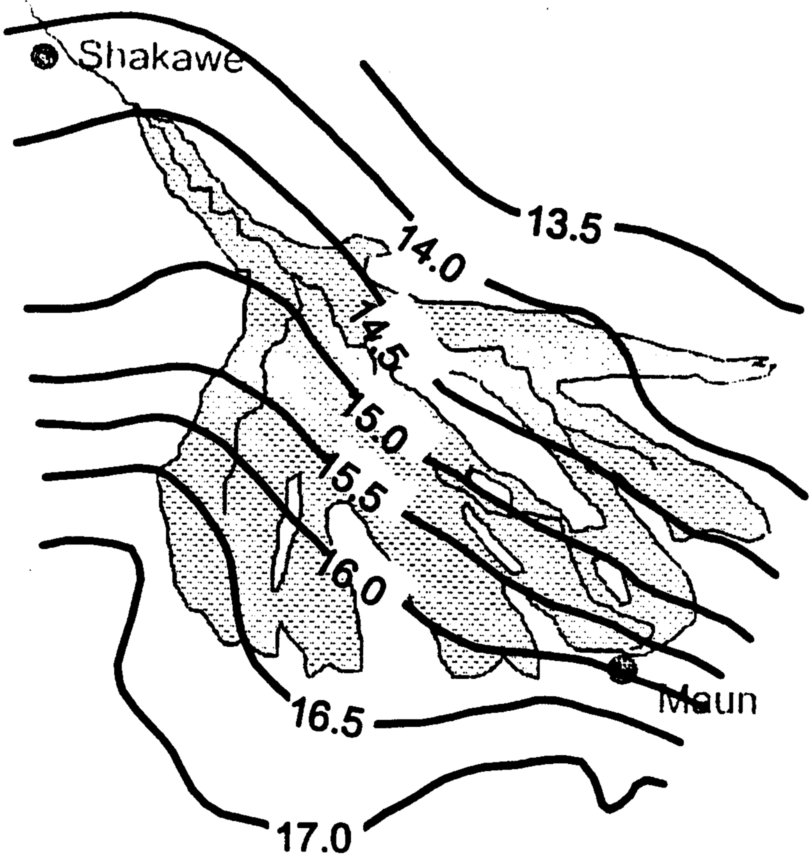

FIG. 4. UCT95A Geoid

are indicated by solid squares in Fig. 2). Leveled heights were available for these points, and the comparison between the two methods of geoidal height determination is summarized in Table 1.

Both geoid models produce RMS discrepancies with respect to the GPS/leveling results of 3 cm, which is excellent. However, not too much should be read into this, as it is based upon too small a sample to provide a reliable measure of the quality of the geoid models. UCT95A displays a bias of 59 cm with respect to the GPS/leveling geoidal height, whereas EGM96's bias is only 13 cm. A bias of this magnitude for UCT95A can be expected, as it is based upon OSU91A, which has an expected accuracy of 30–50 cm (Rapp et al. 1991). The bias of 13 cm for the EGM96 model must be considered fortuitous, as comparisons in other parts of the world show biases of up to 80 cm (Lemoine et al. 1996), and one can expect biases of the order of 10–20 cm in the geoidal heights derived from GPS/leveling. It also appears that there may be a small tilt in the UCT95A geoid, trending in a southeasterly direction. This is evidenced by the increase in the discrepancy between UCT95A and the GPS/leveling result from BPS320 to BM5/129 to BPP084 (these three points lie close to a southeasterly trending line). The cause of this tilt may be due to a long wavelength systematic error in the underlying OSU91A model. Similar tilts have been identified in earlier U.S. geoidal models (Zilkoski and Hothem 1989).

An alternative way of comparing the models is to look at the geoidal height differences between the two extremes of the GPS network (BPS320 and BPP084). The height differences for each of the UCT95A, EGM96, and GPS/leveling results are 1.82 m, 1.77 m, and 1.75 m. UCT95A minus GPS/leveling is 7 cm; EGM96 minus GPS/leveling is 2 cm. These agreements are excellent, considering the points are some 240 km apart. Again, EGM96 is closer to the GPS/leveling results. Nevertheless, it is worthwhile remembering that

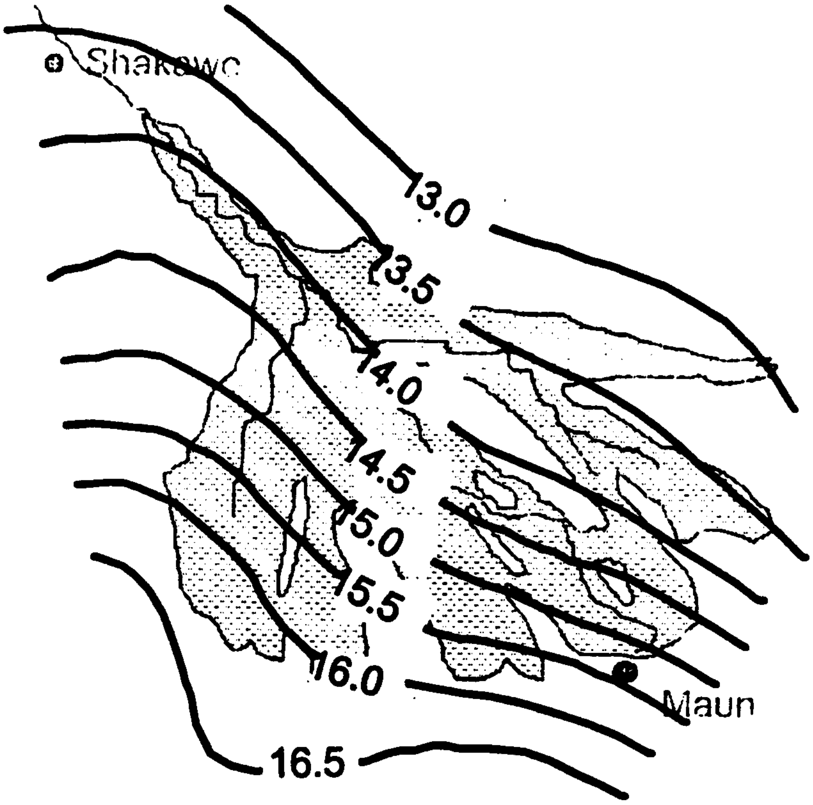

FIG. 5. EGM96 Geoid

TABLE 1. Comparison between Gravimetric Geoids and GPS/Leveling Geoid

Site (1)	UCT95A (2)	EGM96 (3)	GPS/leveling (4)	GPS/leveling—UCT95A (5)	GPS/leveling—EGM96 (6)
BPS320	14.12 m	13.70 m	13.56 m	−0.56 m	−0.14 m
BM5/129	14.87 m	14.38 m	14.28 m	−0.59 m	−0.10 m
BPP084	15.94 m	15.47 m	15.31 m	−0.63 m	−0.16 m
Mean difference	—	—	—	−0.59 m	−0.13 m
RMS discrepancy	—	—	—	0.03 m	0.03 m

these comparisons are based on only three control points. Additional field trips are envisioned for 1998 and 1999 and connections to additional height control points are planned. This should enable a more reliable estimate of the quality of the geoid models to be determined. A further improvement in the geoid model could also be obtained by using EGM96 as the basis for a local geoid using local gravity data.

The primary purpose of the GPS survey is to determine the orthometric heights of the water surface at discrete points. As EGM96 only became available comparatively recently, UCT95A has been used to convert GPS-derived ellipsoidal heights of the water surface to orthometric heights, with a correction of −0.59 m to make the heights consistent with those of the control points in the area. Although this approach provides absolute orthometric heights, for many hydrological investigations, it is the gradient of the water surface that is of particular interest (McCarthy et al. 1997). Over the distance from Shakawe to Maun, the water level drops by some 60 m over 260 km, an average gradient of 1:4,300. Had the geoid slope of close to 2 m over this distance been ignored, this gradient would have been in error by 3%.

CONCLUSIONS

GPS has proved highly successful in providing precise relative heights over the Okavango Delta region—in fact, it is the only viable technique, as geometric or trigonometrical leveling would have been impossible in this terrain. However, to obtain reliable results, it is important to overdesign the survey (in terms of redundancies and session lengths) to overcome logistical problems. Careful planning is required to minimize these problems, and every effort should be made to ensure that integer ambiguities can be resolved. Network solutions obtained using two different software packages and different combinations of the data have produced very similar results. Although the influence of the ionosphere is significant in terms of a scale bias, careful survey design and data processing has ensured that its effect on height differences is insignificant.

The water gradient in the Okavango Delta is extremely shallow (less than 1:4,000) and account must be taken of the slope of the geoid in the region. Recently computed regional and global geoid models show excellent agreement for the region. However, they need to be calibrated to eliminate biases and possible tilts. At present, the connections to surrounding control points are insufficient to enable tilts to be determined, and more work will have to be done to ensure that possible geoid tilts do not affect the determination of orthometric height differences.

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