Discharge determination by Acoustic Doppler Current Profilers (ADCP): a moving bottom error correction method and its application on the River Amazon at Óbidos

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Abstract Since 1995, hydrologists of the HiBAm (Hydrology and Geochemistry of the Amazon Basin) Research Program carried out several hundred discharge measurements in the Amazon basin. Implementation of modern discharge measurement techniques using ultrasonic devices (ADCP), give evidence of a systematic error linked to the displacement of the river bottom due to high water velocity close to the bottom. This error leads to an underestimation of discharge value. It was possible to establish a correlation between the water velocity close to the river bottom and the error between real position and position computed by ADCP when the boat returns to its starting point after a two-way crossing of the river. When there is no bottom displacement, i.e. during low flow period, this return position error is weak (less than 50 m). This has allowed quantification of river bed load speed, or bottom displacement speed. A correction method was developed on the basis of this correlation. This method, systematically applied to ADCP discharge measurements obtained at Óbidos hydrometric station, allowed all measured discharges to be corrected, especially for 1997 and 1999 floods. Another method, based on the analysis of real trajectory of the boat (obtained from topographic measurement or GPS positioning) compared with the ADCP computed trajectory, is under study.

Détermination des débits par mesureur ultrasonique à effet Doppler (ADCP): une méthode de correction des erreurs dues au fond mobile et son application sur l'Amazone à Óbidos

Résumé La mise en œuvre sur le fleuve Amazone des nouvelles techniques de mesure des débits par système ultrasonique (ADCP), a mis en évidence une erreur systématique liée à des vitesses de fond importantes qui occasionnent un déplacement du fond du fleuve. Cette erreur entraîne une sous-estimation des débits. Les hydrologues du Projet HiBAm ont effectué plusieurs centaines de mesures sur le Bassin Amazonien depuis 1995. Il a été possible d'établir une corrélation entre la vitesse moyenne de l'eau près du fond et l'écart en planimétrie sur la position du bateau de mesure lorsqu'il revient à son point de départ. Lorsqu'il n'y a pas de déplacement du fond, cet écart est faible (inférieure à 50 m) et de signe positif ou négatif. Ceci a permis d'estimer les vitesses de charriage de fond. Une méthode de correction des débits a été établie sur la base de cette corrélation. Cette méthode, utilisée pour l'importante station hydrométrique d'Obidos, a permis de corriger les débits mesurés, dont ceux des crues de 1997 et 1999. Une autre méthode, basée sur la comparaison de la trajectoire réelle du bateau (obtenue par relevé topographique ou par positionnement GPS) et de la trajectoire calculée par l'ADCP, est à l'étude.

Open for discussion until 1 June 2001

INTRODUCTION

Ultrasonic discharge measurement equipment (Acoustic Doppler Current Profilers ADCP) has allowed a profound evolution in the field of discharge measurement on large rivers. This technique is, in the current state of the art (Filizola *et al.*, 1999), the one most recommended for systematic measurement of discharges on the Amazon River and its main tributaries (the Solimões, Negro and Madeira rivers). However, especially in the case of these Amazonian rivers, the results of discharge measurements are frequently affected by an error related to non-negligible speeds of river bottom displacement, error referred to as "moving bottom error" (Callède *et al.*, 1999).

MOVING BOTTOM ERROR

The effect of river bottom displacement speed on ADCP measurement can be detected when a boat makes a two-way crossing of the river, returning exactly to its starting point. Figure 1 illustrates such a measurement made at Óbidos during the high flow period (May 1998). The boat started from point A, crossed the river to point D and came back to point A (real trajectories between A and D are curved ones). The boat trajectory, as computed by ADCP, starts from point A, goes to point B and comes back to point C, which is different from the real point A: the ADCP trajectory is not looped on the starting point. Point B computed by ADCP is systematically located upstream of point D. Similarly, on the way back, the extremity point C is systematically located some distance upstream of point A.

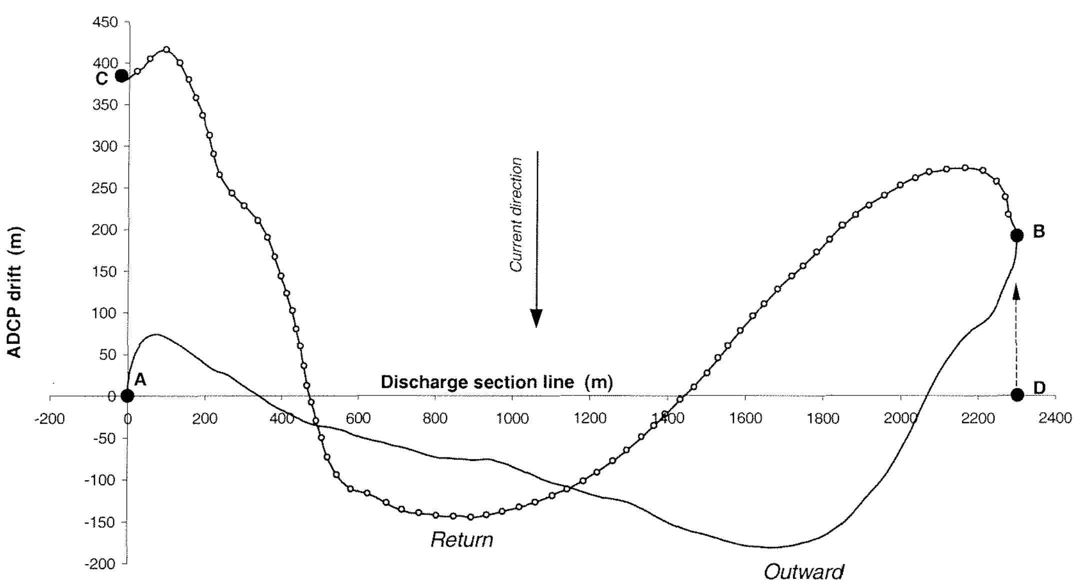


Fig. 1 Trajectory of an ADCP round trip.

As a result (as demonstrated below), measured discharge is slightly underestimated. This is confirmed by the ADCP manufacturer (RD Instruments, 1994a) who refers to this as a *moving bottom effect*.

The ADCP positions itself in relation to the river bottom, making calculations on the assumption that the river bottom is motionless. Echoes from the river bottom are therefore interpreted in terms of relative boat movement, which allows computation of the boat trajectory. In a situation where the boat is motionless with reference to the river banks and the river bottom moves downwards, the instrument interprets it as a "virtual" upwards movement of the boat. Acoustic Doppler Current Profilers will "correct" measured water velocities deducing the upwards "virtual" speed of the boat. As a result, in the case of downwards motion of the river bottom:

- the ADCP trajectory is always located upstream of the real boat trajectory and measurement section, and
- the ADCP measured values of water velocities and resulting discharge are always underestimated.

Figure 2, shows that, for the same discharge measurement at Óbidos, the exact trajectory of the boat (raised to the theodolite every minute) between A and D is not correctly reflected by the ADCP computed trajectory.

Figures 1 and 2 indicate that the trajectory given by the ADCP is affected:

- by the effect of boat drift under the water current effect, and
- by the ADCP drift, the major part of which can be attributed to the moving bottom.

Two correction methods are possible:

- the *return position error* method: using the error, AC (Fig. 1), and
- the *trajectory correction* method: using an algorithm to translate the ADCP trajectory into real boat trajectory (Fig. 2).

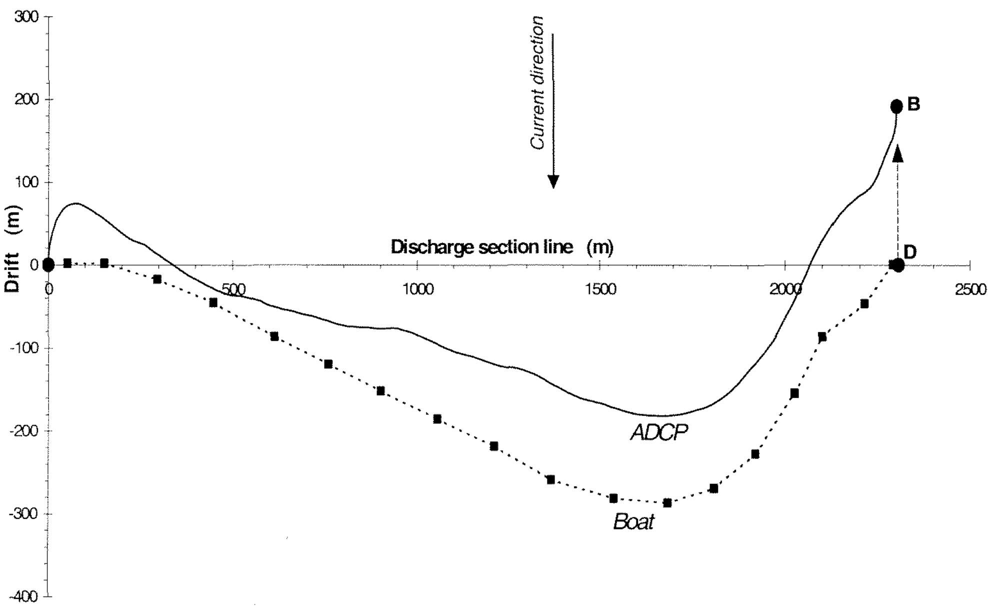


Fig. 2 ADCP and boat trajectories.

CORRECTION OF MOVING BOTTOM ERROR USING THE "RETURN POSITION ERROR" METHOD

The first method is essential because it can be applied in a large number of configurations: ADCP discharge measurements frequently involve various crossings of the river, the boat returning to its departure point. In the case of the Amazon, the majority of the hundreds of ADCP discharge measurements carried out between 1995 and 1999, including those of important floods of 1997 and 1999, were done without any topographic or GPS positioning of the boat, but with two-way crossing of the river and return to the departure point.

Terminology

Velocity/speed In order to avoid confusion, "velocity" is generally used here for water flow (e.g. water velocity, bottom velocity for "bottom water velocity") and "speed" for solid flow (e.g. boat speed, particle speed, bottom displacement speed, bed load speed).

Azimuth (*Az*) The azimuth of a direction is the angle between the magnetic north and the direction, measured from the magnetic north (clockwise from 0° to 360°).

Deviation (*d*) The deviation is the positive or negative return position error between the value of the azimuth of a direction and that given by the ADCP "flux-gate" compass. The deviation is due, among other things, to the influence of the magnetic mass of the boat.

Return position error (*rpe*) The return position error is the distance (A–C in m) given by ADCP between starting point A (generally $x = 0$, $y = 0$) and point of arrival C after a two-way discharge measurement, the boat coming back to its departure point, as illustrated in Fig. 1. The value of *rpe* is positive when the return point C is located upstream of the departure point A (existence of a moving bottom) and negative in the opposite case.

Width (*L*) The width of the measurement section (in m).

Time (*T*) The duration of measurement from start to return (in s).

Measured vertical (*n*) With each ultrasonic impulse, the ADCP measures a vertical profile of the water speed, from the surface to the bottom, as would a current meter. Each profile, numbered chronologically by the ADCP from 001 (starting point A) to *nnn* (arrival point D), is referred to here as the "measured vertical".

Bottom velocity or "bottom water velocity" (*Vb*) This is the ADCP velocity value for the deepest cell (in cm s^{-1}) for every measured vertical.

Bed load speed or "moving bottom displacement speed" (*Vbl*) The bed load speed is the mean speed of particles (moving bottom) on the river bottom, sometimes referred as the "moving bottom displacement speed".

Return position error components

The size of the return position error (AC) depends on various factors:

(a) Error related to the precision of the ADCP navigation system. This is generally *random*, with the possibility of *systematic* components: a random error is sometimes positive, sometimes negative, consequently the sum of the random errors tends towards zero (for example, measuring angles using a theodolite); systematic error always has the same sign and therefore, the resulting error is a sum of partial errors (for example, measuring distances with a decametric ribbon of only 9.98 m).

(b) Angle measurement errors. Although these generally auto-compensate by symmetry during the return travel, they can induce remaining errors such as:

   (i) the error (random) related to the precision of the ADCP compass. The manufacturer indicates (RD Instruments, 1994b) a precision of ±5°, which appears very pessimistic. An error of 5° over a width L of 1000 m results in a return position error, *rpe*, of 87 m. However, it is not realistic to hope for accuracy better than 1°.

   (ii) the error related to the deviation, d, sometimes positive sometimes negative, which could be compensated with a deviation curve. Two curves were established by the HiBAm Project using two different boats but the same ADCP, one in May 1998 and the second in December 1998. The maximum amplitude of the two curves is identical: +12°. It appeared that the use of the deviation curve involved a considerable exaggeration of *rpe*. One may conclude that the manufacturer, RD Instruments, had already installed software for such a correction treatment.

(c) The moving bottom error (systematic), which can be quantified from the return position.

(d) The duration of the measurement; since the return position error reflects the total bottom displacement between time of departure and time of return of the boat.

Identification and correction of systematic angular errors

In order to separate angular errors from those errors related to the moving bottom, the most suitable method is to measure the return position error when bed load is motionless. This can take place during a low water period where bottom water velocities are the weakest.

In November and December 1998 (low flow period) hydrologists of the HiBAm Project carried out a series of discharge measurements in the Amazon "maritime" area. The objective of these measurements was, above all, to determine discharge variations during a complete cycle of the ocean tide (approximately 12 h 25 min). Detailed results can be found in Kosuth *et al.* (1999).

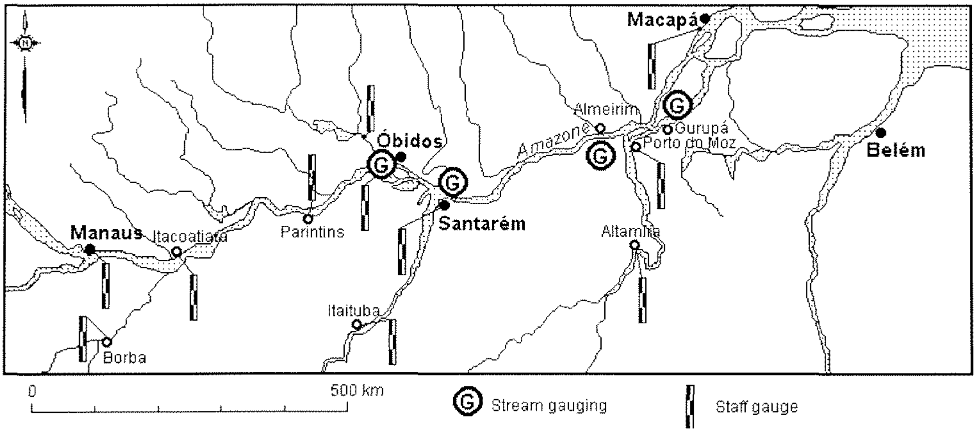


Fig. 3 Map of measurement points.

Continuous discharge measurements during more than 12 h permitted determination of the relationship between *rpe* and the average bottom water velocity *Vf*. This bottom water velocity varies constantly during the tidal cycle, the weakest values occurring at the high tide stage and the highest values at low tide (the ocean acting as a dam). Measurement sites (from downstream to upstream) were (Fig. 3): Gurupá (01°24′S; 051°38′W), approximately 390 km from the Atlantic Ocean; Almeirim (01°31′S; 052°34′W), 105 km upstream of Gurupá; Santarém (02°25′S, 054°44′W), 258 km upstream of Almeirim; and Óbidos (01°55′S; 055°31′W), 108 km upstream of Santarém.

Results

Gurupá A total of 34 discharge measurements were carried out on 23 and 30 November 1998. The water flow remained downstream throughout the tidal cycle, with discharge values varying between 31 200 and 104 000 $m^3 s^{-1}$. Mean water velocity fluctuated between 21 cm s^{-1} (high tide) and 95 cm s^{-1} (low tide). The amplitude of water level fluctuation under tidal influence was 2.2 m.

Figure 4 shows the distribution of return position errors, *rpe*, according to mean bottom water velocity, *Vf*, averaged along the measurement section. All *rpe* values are negative (which confirms the absence of river bottom motion), while mean water velocity and mean bottom water velocity values are positive. Such a contradictory result confirms the existence of systematic angular error. However 29 measurements have a return position error lower than 200 m, which corresponds to an angular return position error of 2.4° between the "outward" azimuth and the "return" azimuth (the width *L* is 4.8 km and a one degree error on the azimuth represents 84 m).

These results indicate that there was no bottom motion at this stage in Gurupá, but that ADCP measurement presents a systematic error linked to determination angles (see Conclusion and Fig. 7).

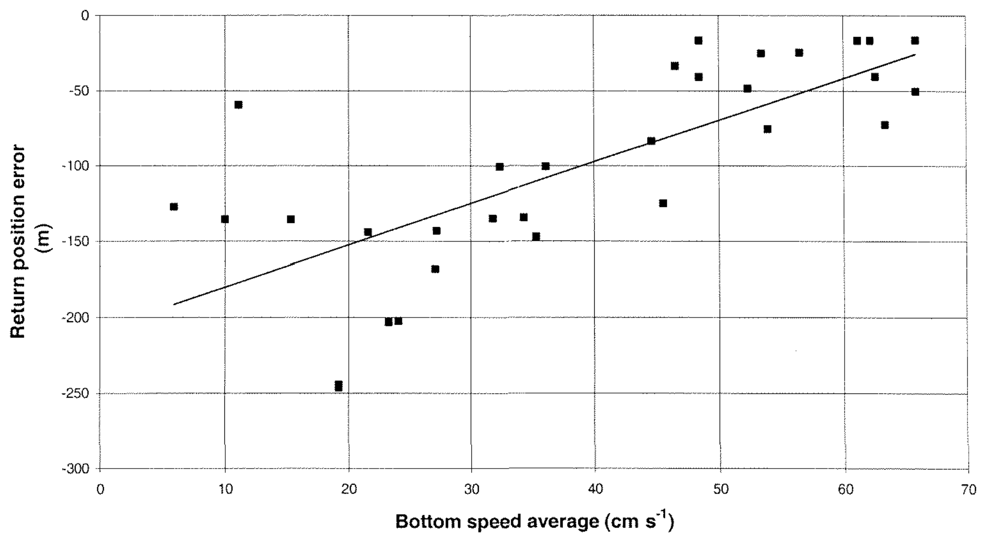


Fig. 4 Distribution of return position errors according to the bottom speed at Gurupá.

Almeirim A total of 20 discharge measurements were made on 22 November and 2 December 1998. Water flow remained downstream throughout the tidal cycle, with discharge values varying between 28 700 and 122 000 m^3 s^{-1}. The amplitude of water level fluctuation under tidal influence was about 1.4 m. These measurement results have been complemented by measurements carried out on 6 November.

Figure 5 shows the results of the return position error distribution related to mean bottom water velocity, *Vf*, although positive *rpe* remains weak. The River Amazon at Almeirim is 6500 m wide. An error of 1° should generate a *rpe* value of 113 m.

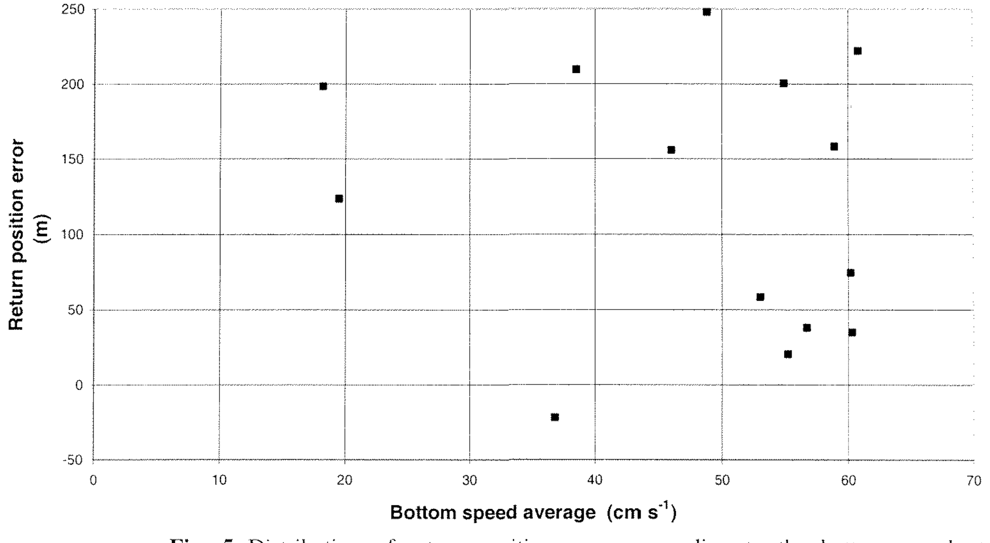


Fig. 5 Distribution of return position errors according to the bottom speed at Almeirim.

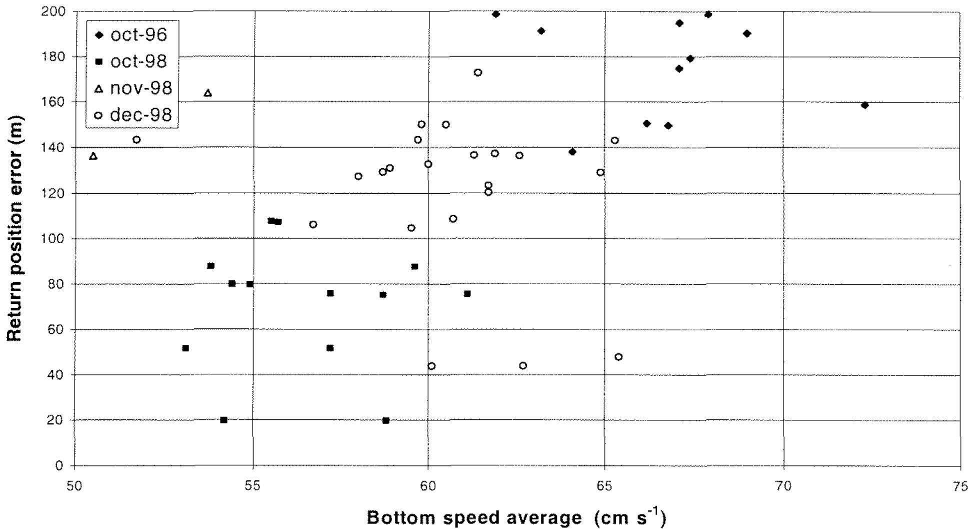


Fig. 6 Distribution of return position errors according to the bottom speed at Óbidos.

These results indicate that there was no bottom motion at this stage in Almeirim, and that the systematic angular error does not reach 1.0°.

Santarém Discharge measurements at Santarém are rather difficult to use because of the irregular section used for measurement and the poor definition of departure and arrival points. But there too, it does not seem that there is a moving bottom at the low water stage.

Óbidos A total of 23 discharge measurements were taken on 6 December 1998. The water level fluctuation amplitude under tidal influence was 8 cm and the discharge fluctuated from 104 000 to 112 000 $m^3 s^{-1}$. To complement these 23 measurements, other results obtained at low flow were added: October 1996 (12 measurements, water level at the gauging station: 2.4 m); October 1998 (13 measurements, water level at the gauging station: 1.19 m); and November 1998 (4 measurements, water level at the gauging station: 1.02 m).

Figure 6 shows the distribution of return position errors according to mean bottom water velocity averaged along the measurement section. Observed return position errors vary from 20 to 199 m (average: 121 m). The width of the discharge measurement section is 2 200 m which gives a *rpe* value of 38 m for an angular error of 1°.

Angular error is therefore quite strong but it remains difficult, in the case of Óbidos, to separate systematic angular error from moving bottom error. Due to similarities with Almeirim and Gurupá bottom motion is thought to be unlikely with bottom velocities smaller than 0.60 m s^{-1} (angular error weaker than 3°), but very probable with higher velocities.

Conclusions

The absence of a detectable bottom motion at the time of the experiments allows identification, based on the previous measurements, of the systematic angular error linked to the equipment. It appeared that a correction, related to the ADCP compass deviation, had already been carried out by the manufacturer. In the absence of bottom motion, it is abnormal that an angular return position error remains between the "outward" and "return" azimuths.

A curve of residual correction was plotted (Fig. 7) in such a way that error corrections could eliminate this return position error. Each set of points in Fig. 7 synthesize the angular error registered for various readings at a given station (i.e. a given azimuth for measurement). These residues compensate the effect of the metal mass of the boat and, especially, the remaining angular errors in the ADCP manufacturer adjustment.

The residual correction curve was plotted, at first, on the basis of results obtained in Gurupá and Almeirim. Santarém results, as well as those obtained from another measuring site (Canal Norte located between Gurupá and Almeirim) were used to help adjust the curve. Results from Óbidos were not used, due to uncertainties as to the existence of bottom motion.

Once the correction of systematic angular error has been done, the remaining return position error reflects only the "moving bottom error".

Óbidos moving bottom error

The residual angular correction curve developed above was applied to all the 130 ADCP discharge measurements, obtained through 18 measurement campaigns, carried out since 1995 at this station. Water level (water discharge) fluctuated from 1.02 m

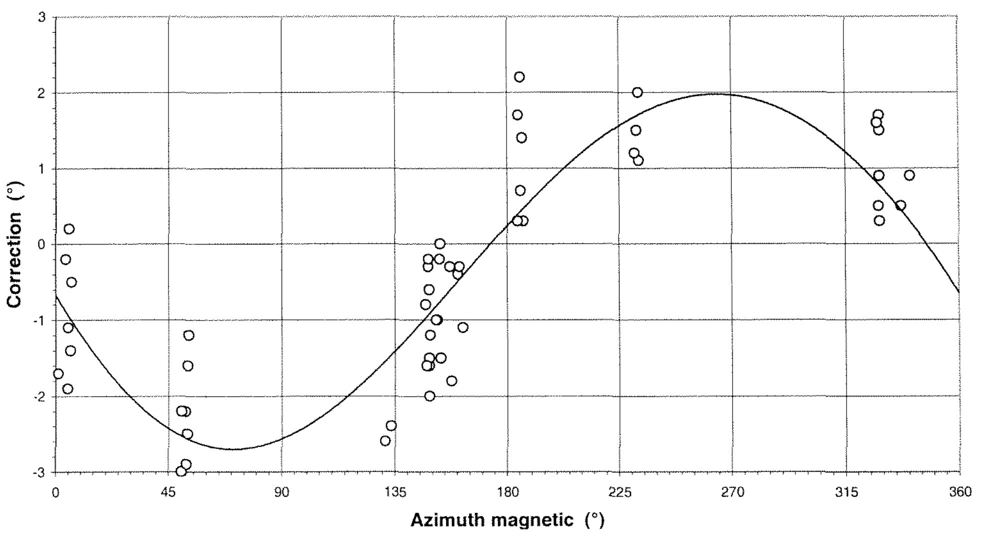


Fig. 7 Residual correction curve.

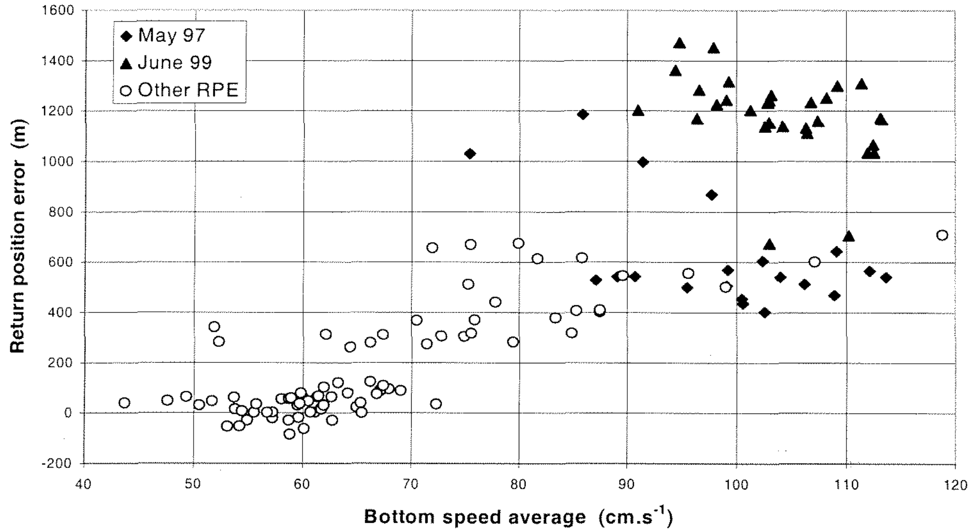


Fig. 8 Distribution of return position errors (after systematic angular error correction) *vs* bottom velocity at Óbidos.

(87 200 m^3 s^{-1}) to 7.85 m (228 000 m^3 s^{-1}). The maximum observed water level at Óbidos is 8.00 m. Figure 8 presents the return position error and the distribution after systematic angular error correction. Data from low flow periods, 1997 and 1999 floods, are highlighted on the graph.

The remaining angular return position errors for low bottom velocities are very weak. The distribution in Fig. 8 gives a significant illustration of the increase in return position error values in relation to bottom water velocity. Linear regression is acceptable: r = 0.841 (0.902 without the measurements of May 1997, although no reason seems to account for the difference between return position errors in the 1997 and 1999 floods).

CALCULATION OF THE "MOVING BOTTOM ERROR" CORRECTION

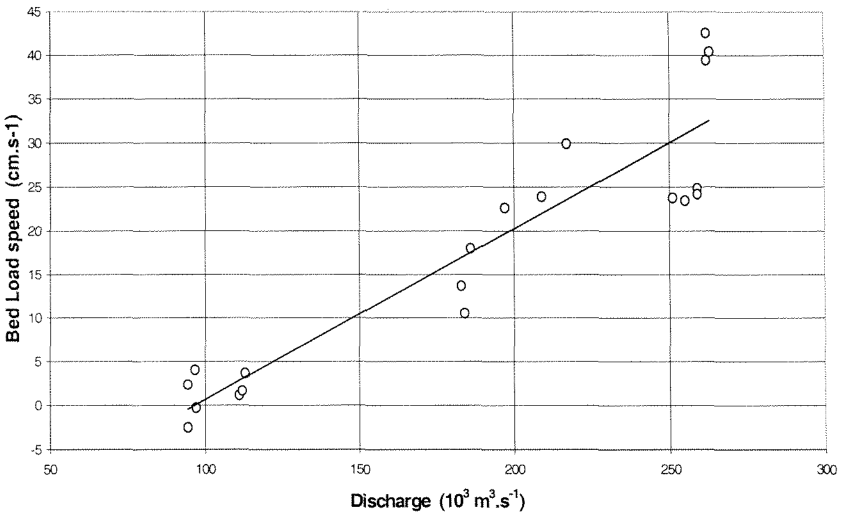
Once the systematic angular errors linked with ADCP have been corrected, distribution of return position errors according to bottom speeds is practically linear. The return position error, *rpe*, should physically correspond to the accumulated displacement of the river bottom during measurement. As a result, correction of the moving bottom error is possible and will be developed.

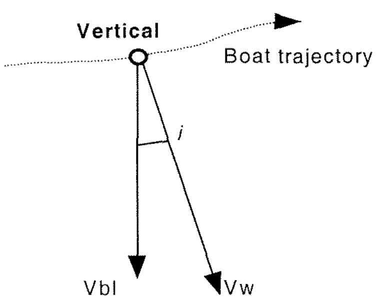
Calculation of the mean bed load speed

The return position error (*rpe*) represents the total displacement of the moving bottom during the duration (T) of the two-way travel of the boat. Thus, the mean bed load speed (*Vmbl*) over a section can be defined as:

$$Vmbl = rpe \cdot T^{-1} \tag{1}$$

Figure 9 presents results obtained at Óbidos using all available measurements and applying the previous formula. The relationship between mean bed load speed and discharge is linear ($r = 0.926$).





with:
$V\vec{bl}$ = local bed load speed vector
$V\vec{w}$ = water velocity vector
i = angle between these 2 vectors

Fig. 9 Evolution of mean bed load speed at Óbidos, according to the discharge.

Calculation of the bed load speed along the section

In order to establish bed load speed along a section, without full information on real boat trajectory, the most plausible hypothesis is to admit that local bed load speed (*Vbl*) is proportional to local bottom water speed (*Vb*). For every vertical, the bed load speed is:

$$Vbl = Vmbl \cdot Vb \cdot Vmb^{-1} \tag{2}$$

where *Vmb* represents the mean bottom water speed, averaged for the whole of the measured section.

Calculation of the water velocity corrections

If the discharge measurement was carried out in a straight line from one bank to the other, perpendicular to the flow, the correction of water velocities values given by ADCP would result from a simple addition (bed load speed + water velocity). As the real boat trajectory follows a curved line (see Fig. 2), due to navigational constraints, it is necessary to implement the "flow method" to finally calculate the discharge.

The local bed load speed can be considered as a vector whose direction is perpendicular to the discharge measurement section. This speed must be composed with each local water velocity vector whose direction is given by the ADCP.

If $\boldsymbol{Vcor\vec{r}}$ is the corrected water velocity vector, then:

$$\boldsymbol{Vcor\vec{r}} = \boldsymbol{Vb\vec{l}} + (\boldsymbol{V\vec{w}} \cdot \cos(i)) \tag{3}$$

Calculation of the corrected discharge

Given a curvilinear trajectory from a starting point (*sp*) to an arrival point (*ap*) (generally the two river banks) defining a vertical cylindrical surface, the chronology of calculations is as follows:

Calculation of the projected water velocity ($\boldsymbol{Vp\vec{r}}$) For every point of measurement, on the same vertical, the corrected water velocity vector, $\boldsymbol{Vcor\vec{r}}$ is multiplied by the cosine of the angle, *j* formed by this vector and a normal unit vector whose direction is perpendicular to the boat trajectory:

$$\boldsymbol{Vp\vec{r}} = \boldsymbol{Vcor\vec{r}} \cdot \cos(j) \tag{4}$$

Calculation of "square m per second" (***Ms***) This is given by the integral of the projected water velocity vector, $\boldsymbol{Vp\vec{r}}$ multiplied by the distance separating two points of water velocity measured on the same vertical *dh*.

$$Ms = \int_0^d \boldsymbol{Vp\vec{r}} \cdot dh \tag{5}$$

where *d* is the depth of the vertical and *dh* is the elementary depth.

Calculation of the discharge The discharge is given by the integral, along all measurement verticals, of the "square m per second", *Ms*, multiplied by the distance between two verticals, *dl*.

$$D = \int_{sp}^{ap} Ms \cdot dl \tag{6}$$

where *D* is discharge passing through the curvilinear surface *S*; *Ms* is $m^2\ s^{-1}$ of a vertical, *sp* is the starting point, *ap* is the arrival point, and *dl* is the distance between two verticals.

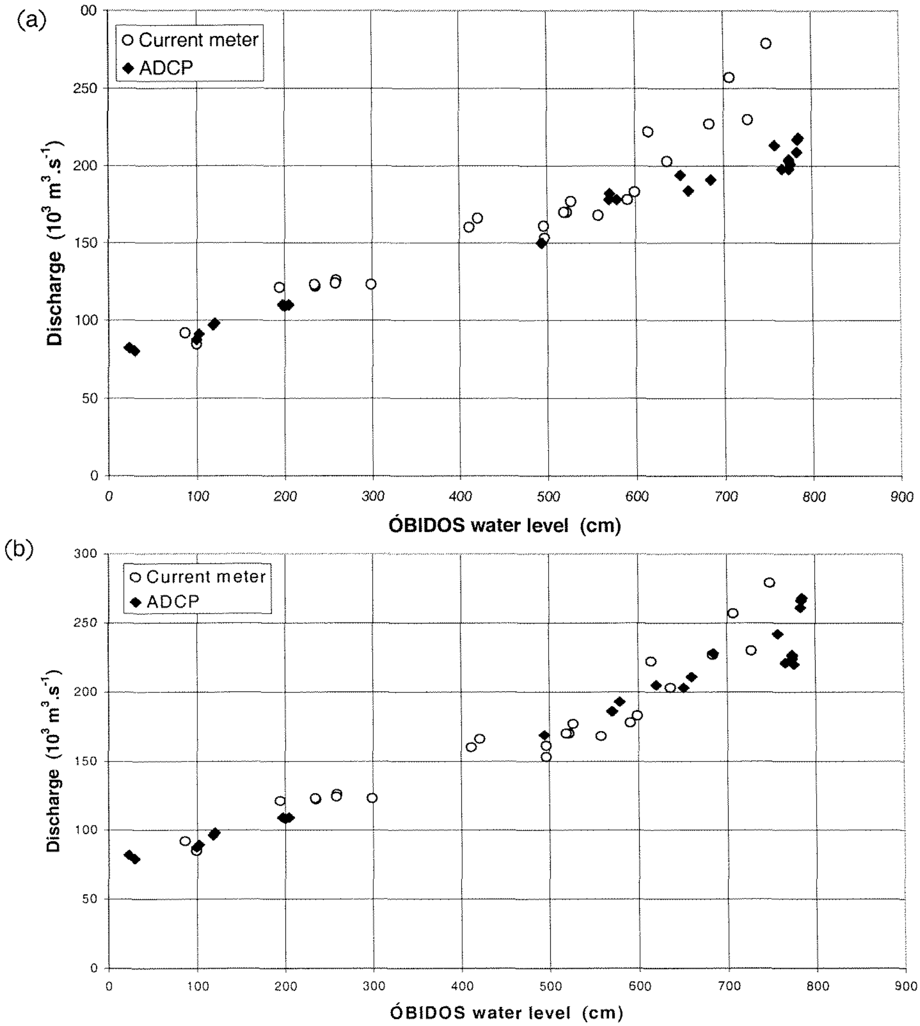


Fig. 10 Discharge measurements in Óbidos: using current meter and ADCP (a) without moving river bottom correction; and (b) with moving river bottom correction.

OVERALL CONCLUSION

Figure 10 shows ADCP discharge measurements at Óbidos before (Fig. 10(a)) and after (Fig. 10(b)) correction of both angular error and moving river bottom error by the "Return Position Error" method. This illustrates the improvement brought by this method on the scattering between gaugings with the classic current meter and with the ADCP.

The "Return Position Error" method presented here is a rather simple but efficient approach to solve the complex problem of moving river bottom influence on ADCP discharge measurement results. It will gain in precision by comparison with the "topographic" method, in cases where real boat trajectory has been monitored. This will be the next area of study.

REFERENCES

Callède, J., Guyot, J. L., Kosuth, P., Guimarães, V. S. (1999) Estimation de la vitesse de déplacement du fond de l'Amazone. In: *Manaus '99—Hydrological and Geochemical Processes in Large Scale River Basins*. IRD, Brasília, Brazil.

Filizola, N. P., Guimarães, V. S., Guyot, J. L. (1999) Mesure des débits sur les fleuves amazoniens avec le Profileur de courant à effet Doppler. In: *Manaus '99—Hydrological and Geochemical Processes in Large Scale River Basins*. IRD, Brasília, Brazil.

Kosuth, P., Callède, J., Laraque, A., Filizola, N. P., Guyot, J. L., Seyler, P., Fritsch, J. M. (1999) Sea-tide effects on downstream Amazon river flows. In: *Manaus '99—Hydrological and Geochemical Processes in Large Scale River Basins*. IRD, Brasília, Brazil.

RD Instruments (1994a) *Acoustic Doppler Current Profilers User's Manual*. RD Instruments, San Diego, California, USA.

RD Instruments (1994b) *Acoustic Doppler Current Profilers*. BBADCP Technical Manual, Appendix S, S-5. RD Instruments, San Diego, California, USA.

RD Instruments (1995) Profileur de courant à effet Doppler (ADCP) pour mesures du débit d'une rivière. Notice opératoire. RDI-Europe, Nice, France.

Simpson, M. R. & Oltmann, R. N. (1993) Discharge-measurement system using an Acoustic Doppler Current Profilers with application to large rivers and estuaries. USGS Wat. Supply Paper no. 2395, USGS Denver, Colorado, USA.

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