Interferometric Attitude and Direction Sensor Using GPS/GLONASS Carrier Phase Data

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Summary

A prototype attitude sensor suitable for navigation on the Earth surface, or for platforms in low Earth orbit has been developed using a pair of GPS receivers. The baseline joining a pair of antennas defines body-fixed angles, which are estimated in real time using a two step procedure: a coarse estimation is first made with the Ambiguity Resolution Function (ARF) algorithm. The refined estimate is made by least squares. This approach yields an estimate of a pair of body-fixed angles epoch-wise, i.e. regardless the value they had at previous epochs. The estimated angles are unbiased and refer to the true geographic pole. Assuming a short baseline of 0.600 meters, the r.m.s. (root mean square) repeatability at 1 Hz is 0.1° for the horizontal angle (e.g. azimuth, yaw), and a factor of 4 larger for the vertical angle i.e. pitch or roll, depending on the baseline being parallel or, respectively, orthogonal to the direction of motion. Complementary use of the GLONASS or GALILEO navigation satellites has the potential to improve epoch-wise on the geometry and, hence, on the r.m.s. figure. Alternatively, for greater accuracy a longer baseline may be used. In such case one or more intermediate antennas may be used in a bootstrap mode, as the epoch-wise solution may be unstable, especially with few satellites in view. A possible application for a long baseline configuration (c. 10 m) is to provide a reference for mapping the magnetic declination, for cartographic use. The sensor has the capability to measure relatively small (>0.005 m) changes in the baseline, simultaneously with the angles. As such, it can work as a strain gauge, e.g. to monitor large deformable structures in orbit. Having no moving parts, the sensor can withstand the shocks of the launch and is immune from thermal and mechanical drifts, but is sensitive to the occultation of the navigation satellites produced by nearby obstacles or structures.

1. Introduction

GPS interferometry is widely recognized for the precision measurement of the vector distance between pairs of antennas. Besides conventional measurements, which rely on quasi static procedures and postprocessing, near real time applications in a highly dynamical environment can be investigated. Following earlier investigations (BARROWS et al., 1998, VAN GRAAS and BRAASCH, 1991, SPALDING and LUNDAY, 1995) an application of GPS interferometry to the problem of attitude determination is described. The minimum hardware consists of a pair of 'off-the shelf', single frequency receivers. Short baselines, typically of the order of the meter, are involved, and the length can be assumed very nearly constant and known. Thus the analysis of the fringe phase can be -but not necessarily is- limited to the two baseline angles, for each pair of antennas. For short distances, the atmosphere has zero horizontal gradient and has no effect on the differential data. Assuming a resolution in the phase measurement of 10 degrees, or 5 mm at the L1 frequency, the orientation angle of a baseline of 1 meter should be determined within 0.3 degrees. Differential multi-path noise will tend to degrade the accuracy, but probably the noise figure of 5 mm for the phase is conservative enough for most situations. Increasing the baseline length will scale the theoretical resolution proportionally, but will also tend to introduce more candidates in the ambiguity search, making the selection more uncertain, especially when only 4 or 5 satellites are simultaneously tracked.

Such an attitude/heading sensor has a number of interesting properties which make it of use in several applications: it has no moving part, implying high resistance to shocks, mechanical and thermal inertia; the horizontal angles (azimuth, or yaw) are referenced to a true geographic north, and is unaffected by local magnetic anomalies; the initialization can be very fast, of the order of one second of time. Typical applications include any kind of pointing and direction finders, and close loop attitude control systems, calibration of a magnetic compass, initialization of an inertial platform or gyrocompass, control of the long term drift of gyros, for example. If the length of the baseline is included in the estimation process, then the sensor can work as a strain gauge, with spatial resolution of 5 mm and sampling rates of the order of 1 Hz, which is of interest to monitor the low frequency modes of vibration of large deformable structures, e.g. in space. The nominal performances can be expected to degrade if just few satellites are tracked, e.g. because the line of sight is obstructed, or if the antennas are inclined to the horizon, implying a degraded radiation pattern. The complementary use of the GLONASS and the future GALILEO satellites should help in minimizing the consequence of such a risk, increasing the number of satellites that can be tracked at once.

2. Instrumentation

To demonstrate the concept of an interferometric attitude sensor, a breadboard prototype was assembled (Figure 1) using two NovAtel GPScardä receivers, each equipped with a standard GPS antenna 501 and 5 meter antenna cable. The

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receiver boards are housed in a GPS card POWER-PAKä OEM enclosure, with power supply and I/O connectors. The receivers communicate with a notebook PC, using null-modem serial cables. The PC is equipped with a PCMCIA Type II expansion socket. This houses a QUATECH DSP-100 card providing two independent RS232 asynchronous serial communication interfaces. The two serial ports are implemented using 16C550 Universal Asynchronous Receiver/Transmitter (UARTs), and are configured at the standard COM port I/O address locations. In our case they are configured as COM2 (Port Address 2F8) and COM4 (Port Address 2E8), and the PC still has the COM1 available at the address 3F8.

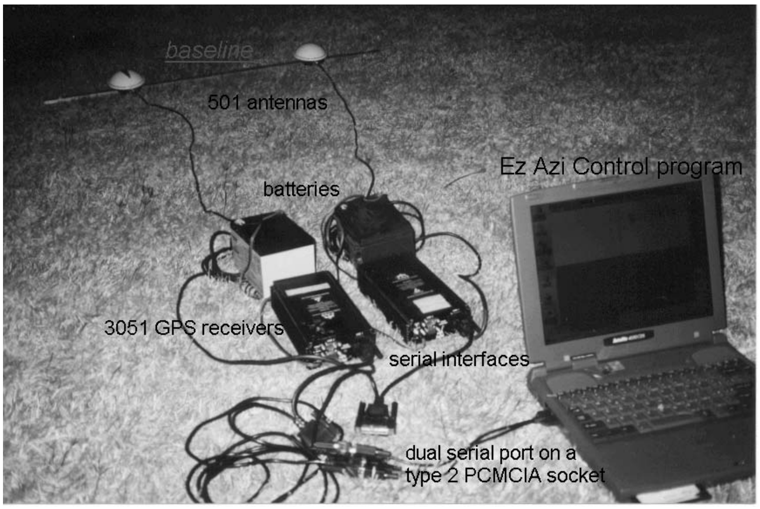

Fig. 1 the setup of the breadboard attitude/heading sensor.

3 Software

A specific software for data logging, processing and Graphic User Interface was written using the Lahey Fortran v.4.5 implementation of the ANSI and ISO Fortran 90 standards, complemented with the Fujitsu Scientific Software Library and the SciCommä Communication Library by MicroGlyph Systems. The COM2/COM4 ports are open in polled mode of I/O processing. The software transfers data between the COM2/COM4 data segment and the receiver/sender buffer one character at a time. After port initialization, the software logs at 1 Hz three types of NovAtel GPScardä messages: \$RGEA, with code and phase data; \$SATA, containing elevation and azimuth data of the satellites, and rejection flags; and \$POSA, with latitude, longitude and height information. The data processing is based on the first order model of the single differences for satellite A:

$$\Delta\varphi^A = \frac{\vec{b}\cdot\hat{s}^A}{\lambda} + \frac{c\Delta t}{\lambda} + N^A + \varepsilon^A \qquad (1)$$

Where:

$\vec{b}$ is the baseline vector

$\hat{s}^A$ is the line of sight versor to the A satellite

c is the speed of light

λ is the L1 wavelength

Δt is the instantaneous clock offset between the two receivers

N^A is the single difference integer ambiguity

e^A is the noise term, comprising a random measurement error and a systematic component (multipath)

After detecting the satellites common at both receivers, a 'hub' satellite is selected at each epoch as the one with higher elevation, and double differences of the generic A satellite are computed relative to this hub, labeled H:

$$\Delta\varphi^A - \Delta\varphi^H = \frac{\vec{b}\cdot(\hat{s}^A - \hat{s}^H)}{\lambda} + N^{AH} + \varepsilon^{AH} \qquad (2)$$

Where $N^{AH} = N^A - N^H$, and $e^{AH} = e^A - e^H$,

The parameter set thus includes the two angles of the baseline in the first term of the right hand side, and as many integer ambiguities as are the common satellites minus one. If one used at this stage Least Squares or Kalman Filter to estimate angles and ambiguities, some integration time would be required in static mode to enable the angles to decouple from the ambiguities, which is undesirable and unpractical. Therefore a combination of the Ambiguity Resolution Function (ARF) and Least Squares (LSQ) algorithms were used, to provide epoch-wise estimates of the angles and of the ambiguities. The ARF method is an ambiguity independent algorithm which tests trial values of the (Azimuth-Elevation) of the baseline and attempts to maximize the Ambiguity Resolution function, defined by (COUNSELMAN and GOUREVITCH, 1981, HAN and RIZOS, 1996, EULER and HILL, 1995)

$$ARF(Az, El) = \sum_{A\neq H} \cos\left[\left(\Delta\varphi^A - \Delta\varphi^H\right)_{obs} - \left(\Delta\varphi^A - \Delta\varphi^H\right)_{trial(Az,El)}\right] \qquad (3)$$

The pair of (Az-El) values of the baseline which maximizes the sum of the squares is the 'most likely', although not in a rigorous least squares sense. The maximum value should theoretically coincide with the number of common satellites minus one (i.e. the number of independent combination of double differences), but phase noise, multipath and quantization error in the search will prevent the ARF from achieving the theoretical maximum. The search in the Az-El space fully benefits from the knowledge of the baseline length. The Azimuth search range is 360 degrees, while the elevation search range is programmable and was constrained to +/- 30 degrees to the horizontal (Figure 2).

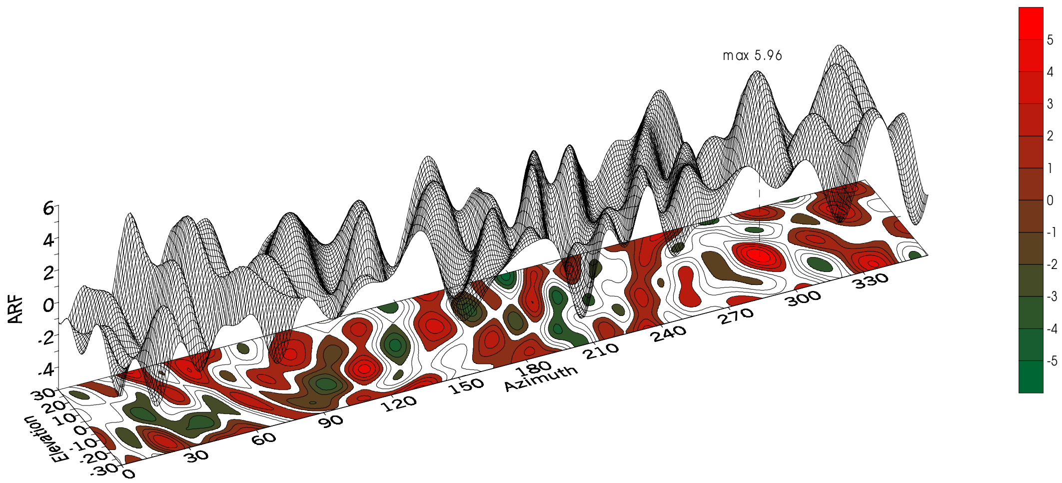

Fig. 2: Example of structure in the Azimuth-elevation space of the ambiguity function, with seven satellites. The maximum is correctly identified at (Az,El) = (292.5°,-0.3°)

After maximization of the ARF, the software uses the values of the baseline length and angles to compute pre-fit residuals and initialize partial derivatives of the measurement model (1) relative to the scalar baseline length *b*, and the angles Az, El. The ambiguities may be assumed known, after a successful scan in the Az-El space of the ARF. The 3x3 normal equation system can be complemented with an a-priori variance-covariance matrix that accounts for the baseline scalar length *b* being known a-priori with a higher confidence than Az and El. The algebraic system is solved and the results are stored on file and displayed on a Graphic User Interface (Figure 3).

As shown in Figure 3, the status can be checked with a child window displaying an artificial horizon on a grid. Dialog boxes provide time, satellite and position information, and the values of the ambiguities and of the statistics of the solution, both in ARF and Least Squares mode.

4. Tests

In the present version the software computes the baseline angles at each epoch, regardless of the values they had at previous epochs. This 'zero memory' implementation ensures the maximum achievable dynamic range, in the sense that it supports random changes in baseline orientation. For more predictable situations, a smoother can help in reducing the epoch-by-epoch measurement noise. The epoch wise mode of solution is suitable for stability tests. The r.m.s repeatability of the azimuth angle is on average 0.11 deg, and is smaller than for the elevation angle, 0.43 deg. Most importantly, the regression analysis shows that there is negligible drift even on short lapse of time and with few satellites, on both angles. The r.m.s. dispersion of the baseline estimates is 5.8 mm, which can be considered nominal. Kinematic test on a motorboat in the Venice lagoon have demonstrated the capability of the system in an operational environment (Figure 4).

5. Conclusion

It has been shown that a pair of commercial, single frequency code/phase GPS receivers can be configured as an accurate sensor providing attitude and heading information, at low cost. The breadboard described in this paper shows an r.m.s stability of 0.1 deg horizontal (yaw) and 0.4 deg vertical (pitch/roll), with a 0.6 m baseline, at 1 Hz. Using a 300 MHz PC in a Windows 98 environment, the duty cycle of the software for data logging and processing is generally 0.2-0.3 sec, so that it can be expected that the sampling frequency can reach 2 Hz. The estimation process is sensitive to the number of tracked satellites. If only four GPS satellites are visible, the algorithm can occasionally converge to a wrong result, especially if the baseline length is solved for as an unconstrained parameter. However the algorithm has 'zero memory' and recovers as soon as the coverage becomes nominal. Future work will extend the solution to include single differenced phase data from the GLONASS satellites.

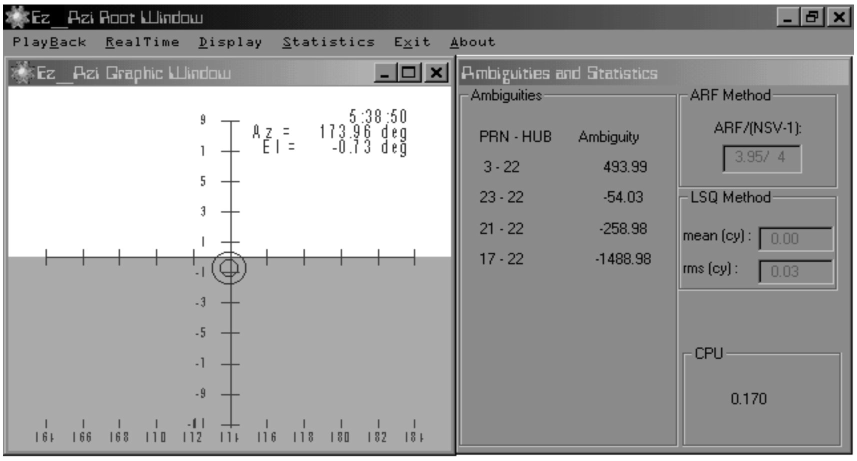

Fig. 3: Windows based interface providing status of the solution and information on time, satellites and position. The integer status of the ambiguities can be checked at each instant.

Fig. 4: the attitude heading system on the bow of a motorboat in the Canal Grande, Venice.

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