Autonomous Navigation Environment with Self-Calibrating Transceivers

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Abstract. An operable navigation system which demonstrates successful self-calibration and precise local navigation has been developed by EADS Astrium. This paper presents the architecture of the autonomous navigation environment with the ability to calibrate itself as well as the results of field tests. The Self-calibrating autonomous Navigation Environment (SekaN) can be used as stand-alone navigation system for applications where satellite signals are not available or where autonomy and high precision is required. Cargo drop, navigation in canyons and open pit mines, indoor navigation and extraterrestrial navigation are just examples of possible applications. The self-calibrating feature of SekaN is of special interest in conflict areas where a temporary autonomous navigation environment has to be installed quickly and where it is not possible to calibrate the locations of the pseudolites a priori. Furthermore, the system can be operated as augmentation system to classical satellite navigation systems. Therefore a mixed mode has been introduced which allows for simultaneous tracking of both satellite signals and pseudolite signals. Referencing of the local coordinate system to e.g. WGS84 becomes possible. The SekaN system comprises the following HW units developed by EADS Astrium: at least 4 Transceivers (TCs), a Rover receiver (ROV) and a Master Control Station (MCS). A WLAN data link is used between the units. Each TC comprises a GNSS signal generator NSG 5100 which supports both GPS and Galileo signals and an Astrium-specific GPS/PSL receiver. The number of TCs in the network is scalable and dependent on the specific application of the SekaN. Various TC-array sizes are supported as the output power of the pseudolites can be varied in a wide range. The rover receiver positioning takes place at the MCS. However, several receivers may be registered at the MCS. The TCs are operated unsynchronized and differential concepts are applied to eliminate the clock errors. Presently the pulsed signals with pseudolite spreading codes at the GPS L1 and dummy navigation messages are used as navigation signals. As soon as low-cost Galileo receivers are available the system can be switched to any Galileo frequency band. In a batch process the exact locations of the TC TX-antennas are determined without any a priori knowledge of the geometric array configuration. The general idea behind the self-calibration algorithms is based on the solution algorithm for self-calibrating pseudolite arrays presented in (LeMaster and Rock, 2002). However, several modifications were necessary to adapt the algorithms to the SekaN system requirements. The rover which is used for data collection during the self-calibration process is designed as a Receiver-only module instead of a TC module. This makes the rover hardware less complex, smaller and lighter, but also complicates the self-calibration process. Self-differencing between the stationary TCs and the rover TC can no longer be applied. The ranges between the rover RX and the TCs are therefore not directly observable. The self-calibration and navigation algorithms developed for the SekaN work in both 2-D and 3-D scenarios. Although multipath effects, non-linearities and the near-far-effect are inherent in these kinds of ground-based navigation systems, precise user positioning at the sub-meter level becomes possible even with low-cost receivers within the self-calibrated navigation environment.

Keywords: Pseudolites, Autonomous Navigation, GPS, Galileo

1. INTRODUCTION

In this research funded by the DLR (German Aeronautic and Space Agency) a navigation environment called SekaN with self-calibrating transceivers has been developed. The research aims at the provision of an operational system which develops new fields of applications which are listed hereafter. For many applications it is highly desirable to become independent from the availability of GPS or Galileo signals. Navigation in buildings, mines, urban canyons or on

remote planets suffers from very weak satellite signal strengths or poor DOP values which make satellite navigation almost impossible. For other applications it is of interest to have an auxiliary system to satellite-based systems in order to enhance the accuracy, reliability and availability of the navigation solution. Safety-critical applications can be listed like cargo drop landing, precision approach and landing and the guidance of mobile troops. Pseudolites can be set up in the desired environment to improve the availability of navigation signals. Inexpensive non-satellite based navigation systems are restricted to relatively small operation areas where good signal coverage is ensured by the pseudolites. Therefore it is of special interest that the autonomous navigation environment can be put into operation quickly at different locations. The self-calibration feature of the SekaN system speeds up the system start up and provides a navigation environment where it is not possible to determine the pseudolite locations a priori through geodetic survey. Pseudolite-only navigation as well as navigation with both satellite-signals and pseudolite-signals is possible in the SekaN system. Even low-cost off-the-shelf receivers can be used in the autonomous navigation environment with a minimum effort of adaptation.

In the following sections the SekaN system hardware and software is presented as well as the results of field tests. Reliable self-calibration of the TC network and carrier phase based user positioning relying on pseudolite-only signals are demonstrated.

2. SYSTEM ARCHITECTURE

The SekaN prototype system comprises 6 Transceivers (TCs), a Master and Control Station (MCS) and a Rover receiver (ROV). An extension to more than 6 TCs and to more than one rover RX is possible without any software modifications.

Transceiver Architecture

The TC architecture comprises a GNSS signal generator, a GPS/PSL receiver, a WLAN access point client and a common power unit. All components are integrated in a common 19" TC rack which is presented in Fig. 1.

Two separate antennas are used for the signal emission and the signal reception. The RX antenna is mounted on top of the TX antenna at an adequate spacing between both phase centers in order to ensure maximum isolation at minimum distance between the TX and the RX antenna. The arrangement of the antennas and the RX antenna pattern allow that GPS signals can be receipt additionally to the pseudolite signals. Both TX antenna and RX antenna operate at 1575.42MHz, since the low-

cost RXs in the system only support the reception of L1-signals. Additionally to the navigation signal antennas, there is a long-range WLAN antenna at each TC to cover large operation areas. The antennas are mounted on tripods at a height of about 2.50m above ground to prevent signal shading by irregularities of the ground and persons moving within the test area.

Fig. 1 Transceiver Hardware

The pseudolite signals are generated with the GNSS signal generator NSG 5100 developed by EADS Astrium. A detailed description of the NSG 5100 is available in (Martin et al., 2007). The advantage of using the NSG 5100 as signal generator is that the system can easily be switched from GPS pseudolite signals at L1 to Galileo pseudolite signals at E5, E6 or E1. However, presently the RXs used in the SekaN system only support the reception of GPS L1 C/A code signals. As soon as inexpensive Galileo RXs are available the SekaN system can be operated at either the E5 or the E6 or the L1-band. The NSG 5100 transmits pseudolite PRNs in order to ensure that the SekaN system does not interfere with GPS or other satellite-based navigation systems. Furthermore, the NSG 5100 fits well for pseudolite applications providing just one channel at a time. The precise 10MHz clock (OCXO) of the NSG 5100 is also used as external clock for the GPS/PSL Receiver whose internal clock can be driven by a more precise external clock. The transmit power of the NSG 5100 can be adjusted in a range from -32dBm…0dBm. No additional navigation signal amplifiers are required between the RF signal output and the passive TX antenna.

All signal generators in the system are pulsing to overcome the near-far problem in the local navigation environment. The RTCM pulsing scheme as suggested in (Stansell,1986) is applied. By emitting pulsed pseudolite signals it is also ensured that satellite signals are not jammed unintentionally.

Master and Control Station

The SekaN system is controlled by the MCS which is shown in Fig. 2. The main component of the MCS is a high-performance laptop settled in a drawer of the 19" MCS rack. A GPS/PSL receiver for surveying of the pseudolite signals, a WLAN access point to communicate with all SekaN system components and a power unit are also integrated in the MCS rack. A long-range WLAN antenna and a navigation signal RX antenna are mounted on top of two separate tripods.

Fig. 2 MCS Hardware

The main tasks of the MCS are:
- System Configuration
- Self-Test (autonomous adjustment of the pseudolite output power depending on the array size and geometry)
- System Monitoring(surveying of house keeping data, RX lock states and S/N)
- System Control (independent command interface to the TCs and the ROV)
- Navigation Message Generation (provision of a pseudolite navigation message to the signal generators)
- System Self-Calibration
- Calculation of Rover RX Positions
- Visualization of TC and ROV Coordinates in a Local Coordinate System or a Map

Fig. 3 shows the graphical user interface (GUI) of the MCS:

Rover Receiver Architecture

The SekaN prototype system presently only comprises one rover RX. The rover RX presented in Fig. 4 can be separated into two modules: the rover vehicle module and the user RX module.
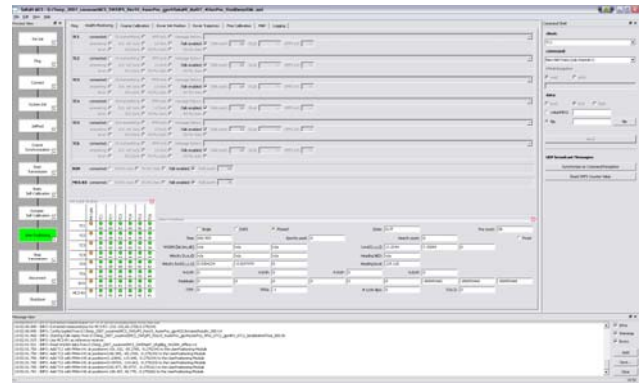

Fig. 3 MCS Graphical User Interface

Fig. 4 Rover Receiver

The rover vehicle module can be replaced by any remote-controlled vehicle which is robust enough to carry the RX equipment. Alternatively, the user RX module can be carried by a person, e.g. in a bag-pack. The user RX module is comprised of a GPS/PSL RX, a navigation signal RX antenna, a WLAN data link to the MCS and a lightweight power unit.

The SekaN system does not make use of a rover Transceiver to self-calibrate the system and to navigate in the local navigation environment as suggested for the Mars Navigation System presented in (LeMaster and Rock, 2002). Using a RX-only module has the benefit that the user module is inexpensive and that the equipment can be miniaturized to a high degree. Especially if many users are navigating in the autonomous navigation environment, it is desirable to keep the number of transmitters besides the stationary TCs as low as possible to prevent signal interference.

4. REFERENCE SYSTEM

It is supported by the MCS to display the TC coordinates and the user trajectory either in a local Cartesian coordinate system or in a map which is referenced to WGS84. Displaying of TC and user coordinates in an absolute coordinate system (e.g. WGS84) is only possible if there is any a priori information about the test area: If the TC-array is planar, the coordinates of at least 3 TCs have to be known in WGS84; else if the TC-array is spatial, the coordinates of 4 TCs have to be known in WGS84.

Referencing to an absolute coordinate system is also possible if the TC-RXs in the system track GPS signals besides the pseudolite signals. Single GPS solutions can be derived from the satellite observations which may be used for referencing the local coordinate system to WGS84. However, this approach is not recommended since the single GPS solution for the TC coordinates is generally less precise than the self-calibration solution for the local TC coordinates.
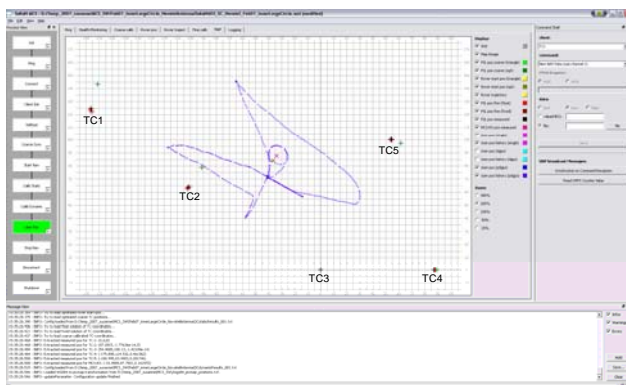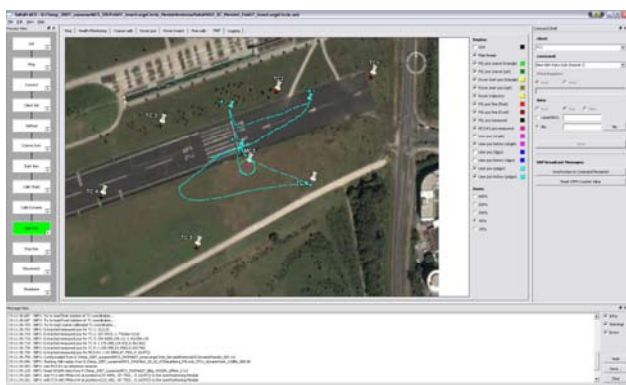

Fig. 5 Local Cartesian Coordinate System

Fig. 6 Referencing to WGS84

In Fig. 5 and Fig. 6 the self-calibrated TC-coordinates and the rover RX trajectory (carrier phase solution) are displayed both in the local coordinate system and in the absolute coordinate system. Coordinate constraints are introduced during the self-calibration process in order to constrain the degrees of freedom of the network due to translation and rotation. The self-calibration algorithm is simplified by settling the TCs in the local coordinate system as follows:

- TC_1* is settled in the center of the coordinate system (x_1*=0, y_1*=0, z_1*=0)
- TC_2* is settled on the positive x-axis of the coordinate system (y_2*=0, z_2*=0)
- TC_3* is settled in the xy-plane and has a positive y-value (y_3*>0, z_3*=0)

If a three-dimensional TC-array has to be self-calibrated, the following coordinate constraint is additionally introduced:

- TC_4* is settled out off the xy-plane and has a positive z-value (z_4*>0)

The TCs are marked with (*) to indicate that the TC-indices used by the self-calibration are not necessarily identical with the HW-indices of the TCs. If three TCs are almost on a straight line as in case of TC1, TC2 and TC3 in the current example (see Fig. 5), the algorithm detects this automatically and chooses 3 other TCs to set up the local coordinate system, e.g. TC3, TC4 and TC5, which form a more regular triangle. In the current example the algorithm resorts the TC indices as follows: $TC_3 \rightarrow TC_1$*, $TC_4 \rightarrow TC_2$*, $TC_5 \rightarrow TC_3$*, $TC_1 \rightarrow TC_4$*, $TC_2 \rightarrow TC_5$*.

5. SELF-CALIBRATION ALGORITHM

The TCs in the SekaN navigation environment are self-calibrated without any a priori knowledge about their locations. Precondition for successful self-calibration of a planar TC-array with the help of a moving user RX is the availability of at least four stationary TCs. If the TC-array is spatial, at least 5 stationary TCs are required for successful self-calibration.

The schematic approach of the self-calibration algorithm used for the SekaN system is presented in Fig. 7. The coarse-calibration is based on observation data from a static setup and only pseudorange measurements are processed. The fine-calibration is based on observation data collected by a rover RX during its trajectory inside or outside of the TC-array. Only carrier phase measurements are processed in the fine-calibration of the system to derive the most precise solution. Unlike previous investigations on self-calibrating TC-arrays presented in (LeMaster and Rock, 2002) or (Matsuoka et

al., 2002), this approach makes use of a rover RX-only instead of a rover TC in order to collect the data required for the fine-calibration of the TC-array. Thus, a new approach has to be developed to derive the rover RX start position and an estimate of the rover RX trajectory. Afterwards, a nonlinear optimization is applied based on double-differenced phase measurements collected during the rover RX trajectory.
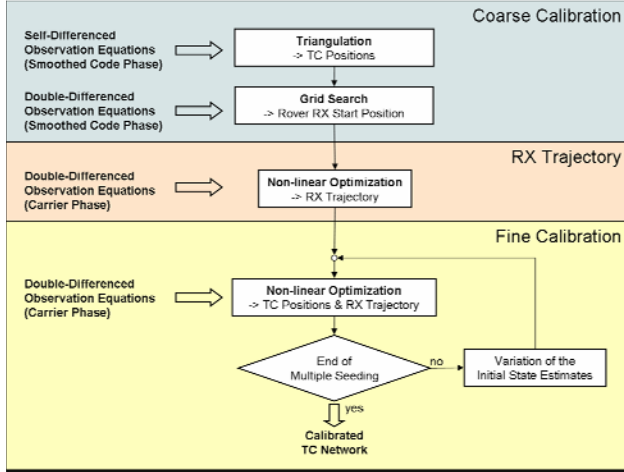

Fig. 7 TC-Array Self-Calibration Steps

The RXs in the system synchronize their sampling times on a reference pseudolite PRN. After a software-based fine synchronization of the RX raw data, the measurements from different RXs can be differenced. The clock errors cancel out in the self-differencing and double-differencing process. It is therefore not necessary to fine-synchronize the TCs in the network.

Self-differenced pseudorange observations between all stationary TCs are used to calculate triangulation solutions as first estimate for the TC coordinates:

$$\nabla\Delta\rho_{i,j}(t) = 2\cdot\left\|\begin{pmatrix} x_j \\ y_j \\ z_j \end{pmatrix} - \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}\right\| + \nabla\Delta\nu_{\rho\_i,j}(t) \qquad (1)$$

, where:

ρ: pseudorange measurement
x,y,z: local Cartesian coordinates of the TCs
ν_ρ: pseudorange noise due to all sources (e.g. receiver noise, multipath)

The subscripts i and j are used to distinguish between two transceivers TC_i and TC_j. Equation (1) has already been simplified assuming that the TX antenna phase center and the RX antenna phase center of the same TC are collocated. As the clock errors cancel out in the self-differencing process, the ranges between the stationary TCs in the network becomes directly observable and

coarse estimates of the TC coordinates can be determined via triangulation.

The rover RX start position is derived from a search in the geometry domain. A two-dimensional or three-dimensional mesh grid which covers the operation area is set up. The mesh grid points represent candidates for the rover RX start position under test. The sum of squared measurement error residuals of the double-differenced pseudoranges serves as test criterion.

An exemplary distribution of the sum of squared measurement error residuals is shown in Fig. 8 (coarse grid search) and in Fig. 9 (fine grid search) for a two-dimensional test area. The fine grid search is performed in a small subset of the original test area which is set up around the selected test candidate of the coarse grid search.
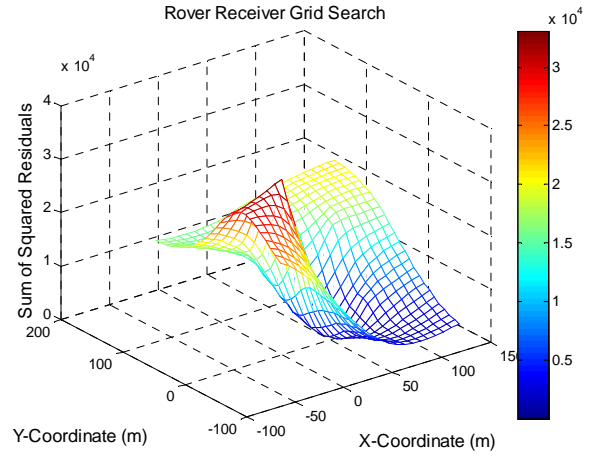

Fig. 8 Sum of Squared Measurement Error Residuals as a Function of the Rover RX Position Estimate (coarse mesh grid)
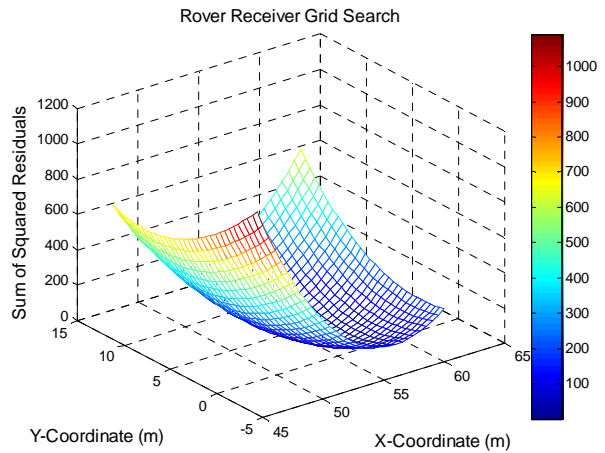

Fig. 9 Sum of Squared Measurement Error Residuals as a Function of the Rover RX Position Estimate (fine mesh grid)

The fine-calibration of the SekaN system relies on double-differenced carrier phase observations which are collected during the rover RX trajectory:
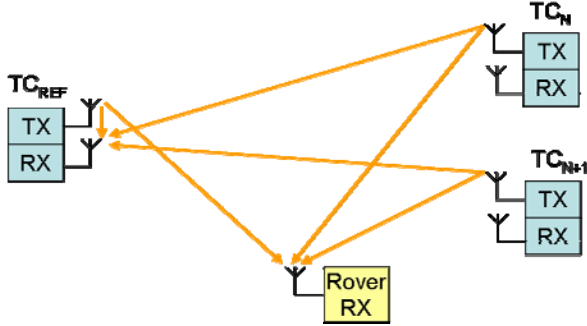

Fig. 10 Double-Differencing in the TC-Array

The double-differenced carrier phase measurements $\nabla\Delta\phi$ in units of meters can be formulated as follows:

$$\nabla\Delta\phi_{Ro,TC_{REF}}^{TC_{REF},TC_N}(t) = \nabla\Delta r_{Ro,TC_{REF}}^{TC_{REF},TC_N}(t) + \nabla\Delta N_{Ro,TC_{REF}}^{TC_{REF},TC_N} \cdot \lambda + \nabla\Delta v_{\phi\_Ro,TC_{REF}}^{TC_{REF},TC_N}(t) \quad (2)$$

with:

$$\nabla\Delta r_{Ro,TC_{REF}}^{TC_{REF},TC_N}(t) = r_{Ro}^{TC_N}(t) - r_{TC_{REF}}^{TC_N} - r_{Ro}^{TC_{REF}}(t)$$

$$\nabla\Delta N_{Ro,TC_{REF}}^{TC_{REF},TC_N} = N_{Ro}^{TC_N} - N_{TC_{REF}}^{TC_N} - N_{Ro}^{TC_{REF}}$$

The assumption is made that the TX antenna and the RX antenna of the reference TC are collocated. Thus, the terms $N_{TC_{REF}}^{TC_{REF}}$ and $r_{TC_{REF}}^{TC_{REF}}$ cancel out in equation (2). Furthermore, it is assumed that no cycle slips occur during the rover RX trajectory so that the initial carrier phase ambiguities stay constant. In contrast to satellite navigation, the ranges between the reference RX and the pseudolites are time-invariant. The unknown system states, e.g. the TC coordinates, the rover RX coordinates and the carrier phase ambiguities, are solved iteratively during the nonlinear optimization process of the fine-calibration. The initial state estimates for the nonlinear optimization are derived from the previous self-calibration steps. After a self-calibration solution has been computed for the TC network, stochastic quality checks are carried out. This is essential for an operational system which shall provide a reliable navigation environment.

6. USER POSITIONING ALGORITHM

The user positioning algorithm supports a stand-alone positioning mode and a differential positioning mode. The stand-alone positioning mode is presently only used for GPS-only navigation as the TC network is only coarse-synchronized. Working with unsynchronized pseudolite signals implies that differential methods have to be applied in order to cancel out the clock errors. The RX of the reference TC, which is determined during self-calibration, serves as reference RX in the differential mode. Both satellite signals and pseudolite signals can be processed by the user positioning module. However, in order to combine both satellite signals and pseudolite signals for the navigation solution, it is necessary to reference the local coordinate system of the TC-array to an absolute coordinate system. The self-calibration only provides the TC coordinates in a local Cartesian coordinate system. In order to perform a coordinate transformation from the local coordinate system to an absolute coordinate system, some of the TC coordinates have to be available in the absolute coordinate system. As there is generally no a priori information about the TC locations, the user positioning module works with pseudolite-only signals in the SekaN system. Then the rover RX positions, the headings and the velocities which are forwarded refer to the local Cartesian coordinate system.

The flowchart presented in Fig.11depicts the process of two-dimensional navigation which has been investigated most intensely so far.
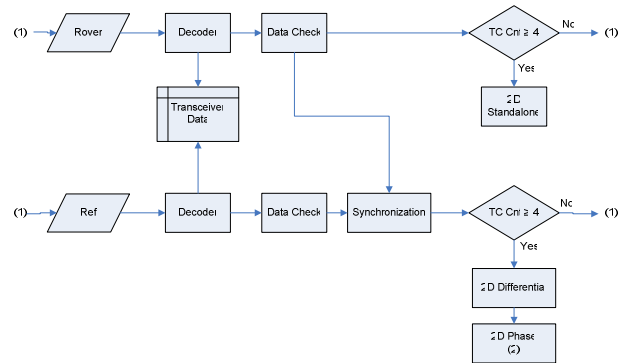

Fig.11 Flow-Chart of the User Positioning Algorithm

Provided that two synchronized data sets from a reference RX and the rover RX are available, a differential code solution is determined. A differential carrier phase solution is additionally calculated if the float filter converges (see Fig. 12).
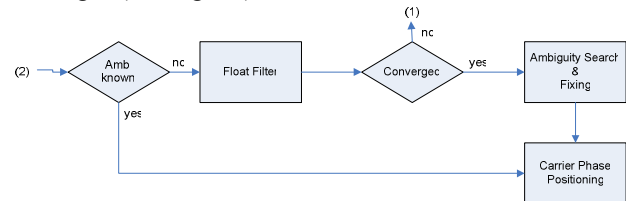

Fig. 12 Flow-Chart of the Phase Solution

7. SYSTEM TEST RESULTS

Test Area

For the system tests the SekaN TCs are set up in a hexagon at plane grassland. The MCS is settled in the center of the hexagon. However, the MCS can also be placed outside of the hexagon as long as there is line of sight to all SekaN system components. The side length of the hexagon marked by the TCs is approximately 120m.

Fig. 13 TC Setup in the Test Field

In this test field only two-dimensional self-calibration and user positioning is possible as the TCs and the user RX are all almost in the same plane. The resulting VDOP values in the operation area are too poor to make the z-components sufficiently observable. If satellite signals were tracked additionally to the pseudolite signals, also three-dimensional user positioning would become possible. Nevertheless, the self-calibration is still restricted to two dimensions as no satellite signals are used for the self-calibration process. The user positioning can only work in pseudolite / satellite mixed mode if the local TC network can be referenced to WGS84. This implies that a priori information about some of the TC positions is required which, in general, is not available.

In preceding simulations successful two-dimensional and three-dimensional self-calibration has been demonstrated for various TC constellations. Also the user positioning algorithm has been tested successfully for two-

dimensional and three-dimensional applications. However, in these system tests only pseudolite-only, two-dimensional self-calibration and user positioning were investigated. Therefore, the HDOP in the operation area defined by the TCs (see Fig. 14) is decisive for the quality of the position solutions.
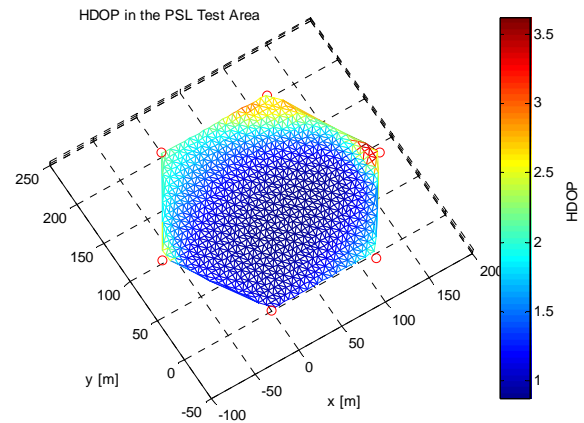

Fig. 14 HDOP in the Operation Area

Irregularities in the HDOP pattern presented in Fig. 14 result from different side lengths of the TC hexagon and slightly different TX antenna heights. The HDOP in the operation area varies between 0.87 in the center of the hexagon and 3.36 in the direct vicinity of a TC. Generally it is advisable to keep a minimum distance to the TCs to prevent an enhancement of the position error. Pseudolite-only navigation outside of the hexagon is also possible, but the HDOP increases significantly if the rover RX moves far away from the hexagon.

Self-Calibration Results

Fig. 15 shows the results of the self-calibration of a TC-array consisting of 6 TCs. The self-calibration of the two-dimensional system would already work with 4 TCs. It is beneficiary to have redundant TCs in the system to improve the performance of pseudolite-only user positioning in the local navigation environment.
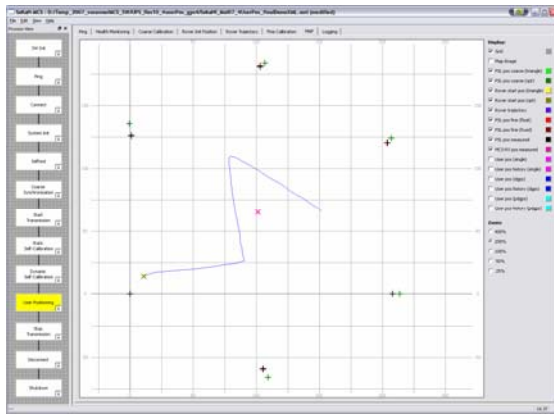
Fig. 15 Self-Calibration of 6 Transceivers

Green pluses mark the coarse-calibrated TC coordinates in the local coordinate system of the MCS GUI. The fine-calibrated TC coordinates are mapped as red pluses while the actual TC coordinates are mapped as black pluses. The fine-calibrated TC positions are almost collocated with the actual TC positions which have been determined geodetically a priori to the field tests in order to provide a reference. A first estimate of the rover RX trajectory is plotted as blue line in the coordinate system. The estimate of the rover RX trajectory has almost the same shape as the actual trajectory except for an offset of a few meters.

The rover RX trajectory used to fine-calibrate the system is of arbitrary shape, however providing sufficient relative range change between the stationary TCs and the rover RX. The number of trajectory sample points is an important factor for successful self-calibration of the TC-array. On the one hand, the more sample points are considered the more increases the computational time. On the other hand, the less sample points are considered the more likely it is that the self-calibration algorithm diverges. For this concrete field test whose results are presented in Fig. 15, the rover RX has sampled with 1Hz during its trajectory. Altogether 329 trajectory sample points were recorded during 5.5 minutes. All sample points were considered for the fine-calibration of the TC-array.

The time required for successful self-calibration did not exceed 15 minutes in any of the field tests. Actually, the TC-array could be self-calibrated within only 10.5 minutes most of the time. The composition of the self-calibration times during field tests is indicated in Table 1.

The accuracy of the coarse-calibration and fine-calibration is presented in Fig. 16.

The maximum deviation between the coarse-calibrated TC positions and the true TC positions is 9.62m for TC_6^*.

After the fine-calibration the deviations are smaller than 0.08m for all TCs in the network.

Table 1 Typical Self-Calibration Times

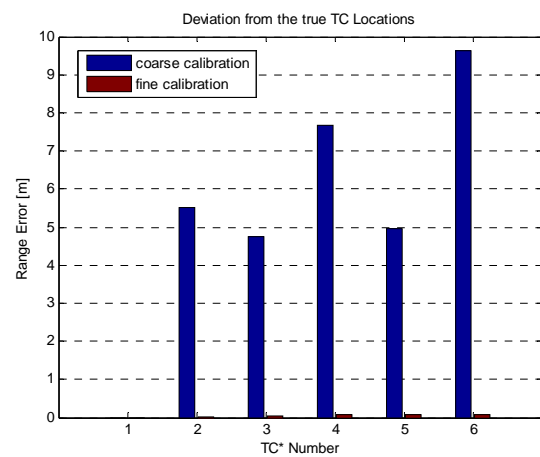| Self-Calibration Step	Typical Time Span
Data Acquisition → Coarse-Calibration	≈15s
Computing Time → Coarse-Calibration	<1s
Data Acquisition → Fine-Calibration	≈4.5min
Computing Time → Estimate of the Rover Trajectory	≈20s
Computing Time → Fine-Calibration	≈5.5min
$\sum$	10min 36s

Fig. 16 Range Error between the coarse-calibrated (blue bars) / fine-calibrated (red bars) TC Positions and the true TC Positions

Table 2 Deviation in x and y of the fine-calibrated TC Coordinates from the true TC Coordinates

TC ID	Δx [m]	Δy [m]
TC1*	0.000	0.000
TC2*	-0.028	0.000
TC3*	0.004	0.033
TC4*	0.030	0.058
TC5*	-0.034	-0.072
TC6*	-0.059	0.032

The accuracy of the self-calibration in this field test has been better than 0.1m.

Several field tests have been carried out to derive representative results: the number of TCs in the network, the network geometry, the number of trajectory sample points and the rover trajectory shape has been varied. As

long as no cycle slips or signal shading occurred during the rover RX trajectory, the accuracy of the self-calibration was better than 0.3m. Altogether the occurrence of cycle slips and signal shading was very rare in this flat and obstacle-free test environment. Furthermore, a cycle slip detection and correction algorithm is implemented in the RX raw data decoders.

User Positioning Results

The evaluation of the user positioning performance is more difficult than the evaluation of the self-calibration performance. The rover RX antenna is not mounted statically on tripods at known reference positions, but the rover moves only coarsely to known reference marks. There is an inherent uncertainty of several centimeters in this approach when comparing the reference positions with the calculated user positions. For the presentation of the user positioning results in Fig. 17, the computed local Cartesian rover coordinates are referenced to WGS84. A map of the actual operation area can be uploaded in which the computed user positions are displayed.
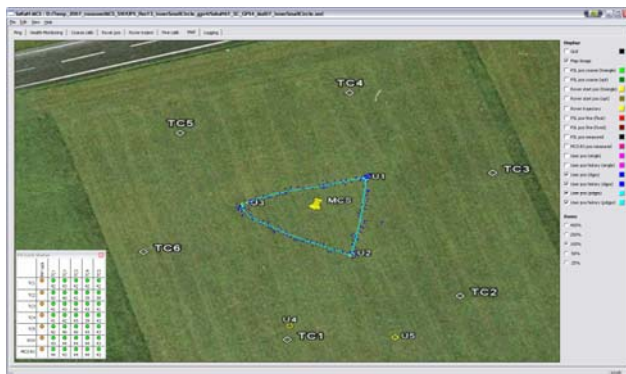

Fig. 17 User Positioning in the autonomous SekaN Navigation Environment

The user RX moves in a triangle from U_1 via U_3 and U_2 back to U_1. The dark-blue doted trajectory indicates the differential code-phase solution while the turquoise doted trajectory indicates the differential carrier phase solution. The accuracy of the user positions is better than 30cm most of the time. If no differential phase solution can be calculated, the accuracy of the user positioning gets worse. In contrast to the differential phase solution the differential code solution is rather noisy as low-cost receivers are used with relatively high RX code noise parameters. Presently no smoothing algorithm is implemented for the differential code solution which would reduce the noise of the code solution.

8. CONCLUSIONS

An operational autonomous navigation system has been developed that covers new fields of applications. The system comprises low-cost components and is extendible to various numbers of TCs and users. Successful self-calibration of TC networks consisting of 5 or 6 TCs within less than 15 minutes has been demonstrated several times during field tests. The accuracy of the self-calibration is good enough to provide an autonomous navigation environment where carrier phase based user positioning becomes possible. The user positioning error of the rover RX is lower than 30cm for pseudolite-only differential phase solutions. Differential phase solutions are available most of the time for the rover RX.

Further improvements of the SekaN system are possible by making the self-calibration more robust to the occurrence of cycle slips and signal shading if redundant TCs are available in the system. Extensive field tests on three-dimensional self-calibration and user positioning are still required. However, good performance of the system is also expected for three-dimensional applications as various simulations have already yielded in promising results.

ACKNOWLEDGMENTS

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