GNSS-Guided Relative Positioning and Attitude Determination for Missions with Multiple Spacecraft

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1 Introduction

1.1 Outline of the Paper

This paper will give an overview of what is achieved in the field of GNSS-guided relative navigation for spacecraft and will indicate some of the new trends in this research field. In 1.2 background information about the use of GNSS sensors for missions with multiple spacecraft like formation flight, constellation control and rendezvous is provided, followed by a summary of previous and future GNSS-guided relative navigation missions in 1.3 and a discussion on GNSS-based attitude determination in 1.4. In section 2, relative navigation is discussed in more detail. 2.1 provides a mathematical model for GNSS observations at distributed antennas. In the rest of the section, the implementation of this model for some of the missions described in 1.3 is discussed. Section 3 explores the possibility of GNSS-based attitude for distributed satellites. In section 4 activities at Delft University of Technology are discussed, followed by the summary of this paper.

1.2 Background

GNSS-guided relative positioning techniques can be applied to a number of missions with multiple spacecraft such as formation flight, constellation control and rendezvous between spacecraft.

Currently there is a trend in space mission design towards payload distribution. For strategic, economic and operational reasons, one satellite, integrally carrying all payload, is replaced by a cluster or swarm of smaller satellites. The function of the former integrated satellite is distributed over the elements of the cluster. Major applications areas will be telecommunication and Earth observation. Depending of the level of coordination between the satellites of a cluster we refer to this kind of system as a formation flight or constellation control [1]. Multiple satellites belonging to the same mission where the payload is divided over more than one satellite are often referred to as distributed satellites.

Formation flying in general involves real-time, closed-loop control of multiple satellites in autonomous formation. Thus, formation flying requires the control of one spacecraft relative to one or many other spacecraft and therefore has very stringent requirements for the relative navigation and attitude determination sensors used.

Constellation control typically does not require this level of autonomy, real-time coordination of the relative positions or orientations of multiple spacecraft - only that they maintain themselves within their own

Presented at GPS/GNSS Symposium, 15-17 November, Tokyo, Japan

assigned "envelopes" without collision or changing the overall coverage by the constellation of the target.

The techniques required for formation flight and constellation control are similar to the techniques used in rendezvous between spacecraft, where one spacecraft, typically referred to as the chaser, has to determine its relative position and orientation towards the target satellite while approaching this satellite. The rendezvous is normally followed by docking/berthing between the two spacecraft.

Rendezvous, constellations control and formation flight depend critically on subsystems such as ADCS, absolute and relative navigation, satellite cross-link communications and data transfer. The ability to determine and control the relative positions, velocities, and orientations for a vehicle or fleet of vehicles is only as effective as the sensors onboard these vehicles. GNSS receivers are potentially able to provide relative and absolute positioning, time and relative and absolute attitude determination.

1.3 Overview of Previous and Future GNSS Guided Relative Navigation Missions

In the US, Europe and Japan, a number of missions for relative navigation have been performed or are currently under development.

The very first mission to use GNSS (GPS) signals for relative navigation in space was the Japanese ETS-7 mission [2]. The ETS-7 mission consisted of 2 sub-satellites called chaser and target, and it performed a number of rendezvous and docking experiments from 1997 to 1999. For this mission a communication link between the two spacecraft was implemented, which transmitted the GPS observation data from the target to the chaser spacecraft that made real-time relative navigation possible.

Other examples of orbital experiments are ORFEUS-SPAS, where a satellite was deployed from the space shuttle and raw GPS measurements were collected from both spacecraft and an accuracy for relative navigation of 10-50 meters was achieved after post-processing, the SNAP-1 and Tsinghua-1 from SSTL, the DART mission which was the first real autonomous rendezvous and docking experiment, EO-1 and Landsat-7 experiment that marks a key milestone on the way to autonomous, multi-spacecraft, formation flying. Missions planned for the near future are the ATV, and PRISMA project in Europe, and HTV in Japan. According to [3], there are currently more than 25 formation flight projects under consideration in the US.

An example of a scientific mission using relative navigation is GRACE, a LEO formation consisting of two sub-satellites which is in orbit at this moment, that operates at a separation of 200±50km at 450km altitude.

Examples of application satellites where precise relative navigation is a requirement for mission success are interferometric radar missions such as Terrasar-X (TSX) and TanDEM-X(TDX), and cartwheel mission concepts that exploit two or more satellites to obtain a bistatic configuration required for geometric estimation of the earth's topography. The (TDX/TSX) mission has been proposed in a contest for new Earth observation missions within the German national space program [4]. It involves two almost identical satellites, carrying a high-resolution SAR operating in the Xband (9.65GHz). The two spacecraft will fly in a precisely controlled formation to form a radar interferometer with typical baselines of 1km, and will be operated for a period of 5 years in a nearly constant 514km sun-synchronous orbit with 97° inclination. The primary mission objective for this kind of missions requires the relative position to be known within a 2 mm precision

(1-dimensional) [5].

Recent research at Delft University of Technology has proved, using orbital data from the GRACE formation that this kind of accuracy is achievable [5]. Technical details of the developed method are described in 2.4. When validating the GRACE relative position solutions from the Extended Kalman Filter (EKF) with reference observations, it has been shown that an actual overall relative position precision of 0.9 mm (1-dimensional) is achieved.

1.4 GNSS-based Attitude Determination for Missions with Multiple Satellites

For formation keeping, the relative orientation of the individual satellites is of great importance, not only for the mission objections such as pointing the formation towards a specific target but also for the operations of the swarm. For instance, the drag force has a disturbing influence on spacecraft formations [6]. Even if the spacecraft are identical, the drag force experienced by each satellite can be slightly different. The relative attitude error causes the spacecraft to have different attitudes with respect to their velocity vectors, which means that the spacecraft will experience different ballistic coefficients and therefore a different drag force will work on the spacecraft. Hence a spacecraft formation with a smaller relative attitude error is less effected by the drag force disturbance, thereby lessening the propulsive force required to maintain the formation.

If the relative position (i.e. baseline) between at least 3 GNSS antennas in a specific configuration is known, it is possible to determine the full orientation of the baselines from the phase difference between the observations at the antennas. From 2003 till 2005, this kind of technique was demonstrated very successfully onboard the SERVIS-1 satellite with a configuration of 2 baselines (i.e. 3 antennas) [7].

The recently achieved accuracy for relative positioning between distributed satellites opens new possibilities for attitude determination for this kind of missions, which will be discussed in this paper.

Most likely because only lately sub-mm accuracy is achieved for relative positioning between satellites, there has not been a lot of research on GNSS-based attitude determination for multiple satellites. However for the kind of formations where the satellites carry pseudolites for relative navigation above the GPS constellation some work has been done. For example [8] described attitude determination for formation flying missions in deep space. In [8] it is shown that in order for the formation above the GPS constellation, to initialize autonomously from arbitrary initial orientations, each spacecraft would need to carry a total of 6 corner-located receive antennas and two transmit antennas mounted on opposing corners. This would provide full sky coverage in all directions, assuming hemispherical fields of view for each antenna.

2 Relative Navigation Approaches

2.1 Mathematical Model for GNSS Observations at Multiple Antennas on Multiple Satellites

Figure 1 shows a constellation of two satellites called chaser and target, which could be either two satellites of a formation or of a rendezvous mission. Both satellites have a number of GNSS antennas. The figure shows the relative distance between the master antenna on the target satellite and the master (X(Tm-Cm)) and slave antenna (X(Tm-Cs)) on the chaser satellite. Observations from these antennas are used for precise relative positioning between the two satellites, which provides the precise “virtual” baseline used for the relative attitude determination between the two satellites. Furthermore the two satellites use their own master and slave antennas to determine their absolute attitude independent of the relative navigation solutions as the baseline vectors used for absolute attitude determination are fixed on the spacecraft. The nomenclature in the figure related to relative navigation and attitude determination of the formation are blue, those related to attitude determination of a single satellite are red and those related to both are black. The master antenna is the antenna used for absolute navigation of the spacecraft and the origin of the baseline configuration used for attitude determination.

From figure 1 it is clear that the relative position vector x between the master antennas of both satellites is

$$x + c(\delta t_{T,C}) + \eta = R_T - R_C$$

With R are the pseudorange observations at the master antenna of the target and chaser, δt is difference in clock bias between the receivers at the two satellites, c is the speed of light and η is noise. This is the non-linear equation that is used in relative navigation, with 4 unknowns: three elements of the relative position vector and the difference in the receiver clock biases. For more accuracy the carrier phase observations can be used instead of pseudo range measurements for relative navigation, which will be discussed next in more detail.

A GNSS receiver can provide a carrier phase measurement for each antenna. Subtracting phase measurements from two antennas will give a fraction of the carrier phase cycle, which is the observable for precise relative navigation and GNSS-based attitude determination. A carrier phase measurement is the difference between the received GNSS satellite's carrier phase ϕ_k and the locally generated carrier phase ϕ_i of the internal oscillator of the GNSS receiver [9].

The carrier phase observable for GNSS satellite k can be written as:

$$\phi_k^i = \phi_i - \phi_k + K_i^k + I_k + T_k + d_k + D_i + e_i^k + \upsilon_i^k + \varepsilon_k$$

where ϕ_i denotes the receiver's phase and ϕ_k the received satellite phase at reception time t. The term K denotes the initial integer ambiguity, which is the number of complete carrier phase cycles that have occurred prior to the signal's arrival at the antenna. The term I and T denote ionospheric and tropospheric effects. The term d and D refer to the hardware delays in the GNSS receiver and the GNSS satellite. e is the multipath error and υ denotes the random (thermal) measurement noise. ε is the satellite's ephemeris error.

By subtracting two measurements from two antennas, most errors related to the common GNSS satellite will cancel out of the equation:

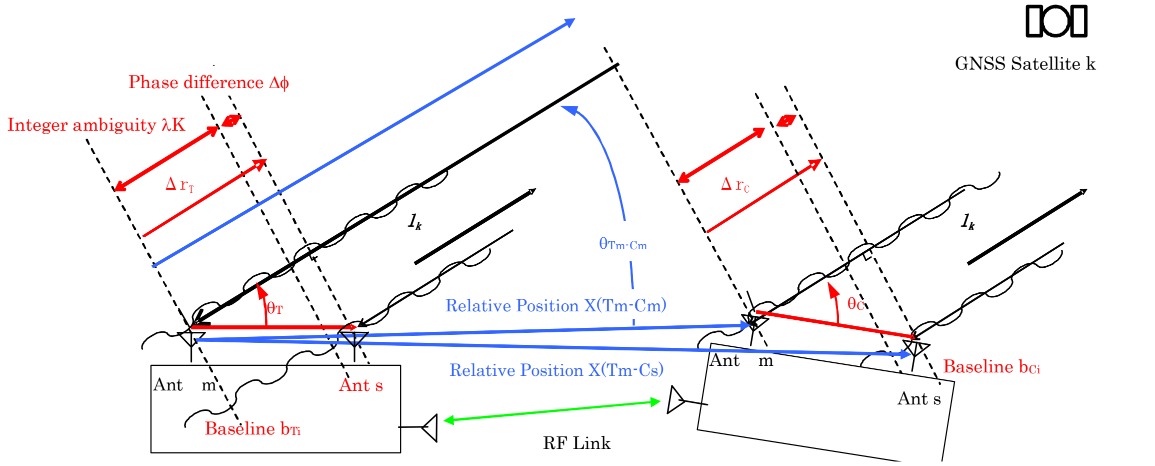

Figure 1 GPS-based relative positioning and attitude determination for distributed satellites

the delay of the GNSS satellite, the tropospheric and ionospheric delays if the relative distance between the two antennas is small, and the satellite's ephemeris error. The measured GNSS carrier phase differences are perturbed by measurement noise (including multipath noise) and a relative phase offset between the two antennas which is known as linebias (hardware delay) if the two antennas are connected to the same receiver or a relative clock bias if the two antennas are connected to different receivers. Combining phase measurements from a single GNSS satellite is known as a single difference observation. The single difference carrier phase equation is given as:

$$\Delta\phi_{ms}^{k} = \Delta r_{ms}^{k} - K_{ms}^{k} + \beta_{ms} + e_{ms}^{k} + \upsilon_{ms}^{k}$$

in which carrier range difference Δr is given by $\Delta r_{ms}^{k} = \phi_{im} - \phi_{is}$ where ϕ_{im} is the carrier distance from the master antenna to the GNSS satellite and ϕ_{is} is the carrier distance from the slave antenna to the same satellite. The integer K is the number of carrier cycles in the carrier distance difference between the master and slave antenna. If the baseline vector is larger than one carrier wavelength, the number of full cycles between the two antennas is unknown. This is generally known as the ambiguity problem. The linebias or relative clock bias β_{ms} is the difference in hardware delays between master and slave antenna (d_m-d_s) if the antennas are connected to the same receiver or a difference in clock bias in case of a distributed satellite respectively. The hardware delays in the GNSS satellite are cancelled out of this equation. υ_{ms} is the random measurement noise and e_{ms} is multipath error of the single difference carrier phase measurement.

As the single difference equation is the basic equation for both precise relative positioning and attitude determination, it is interesting that the integer ambiguity problem for the attitude estimation using the phase difference between the antennas is the same as for the relative navigation. In case a combined attitude and relative navigation algorithm is to be developed for distributed satellites, this problem would have to be solved only once.

It is well-known that the distance function between two satellites can be approximated by

$$|R_T| - |R_C| = l_j \cdot x(\mathrm{T_m} - \mathrm{C_m}) - c(\delta t_{T,C})$$

where lj is the line of sight vector to GNSS satellite j. From this equation a system of linear equations can be derived in which the distance between the two master antennas onboard the chaser and target satellite x(Tm-Tm) and the difference in the clock bias for the GNSS receivers are the unknown:

$$\Delta r = G\begin{bmatrix} \delta x \\ \delta t_{T,C} \end{bmatrix} + \varepsilon$$

With G generally known as the Geometry matrix defined as:

$$G = \begin{bmatrix} l \\ 1 \end{bmatrix}$$

If the relative distance between the two satellites becomes very large we will have to make a correction for the difference in line of sight vector for the antennas.

Now the relative position can be estimated by for example the least squares solution:

$$\begin{bmatrix} \delta x \\ \delta t \end{bmatrix} = (G^T G)^{-1} G^T \Delta\hat{r}$$

For more precise relative positioning, filtering techniques such as a Kalman filter are often applied in combination with a propagation model for state and covariance between the measurements.

For the relative navigation between two spacecraft, the Hill equations are frequently applied. As origin of these equations the target satellite is used and its orientation is given by the vector triad {eR, eT, eN}. The unit vector eR is aligned with the radial direction, while eN is parallel to the orbit momentum vector (positive in velocity direction). The vector eT then completes the right-hand coordinates system. Mathematically, the triad can be expressed as:

$$e_R = \frac{r}{|r|}$$

$$e_N = \frac{rxv}{|rxv|}$$

$$e_T = e_N x e_R$$

where r and v are the inertial position and velocity of the target satellite.

Advantage of these coordinates is that the position of the other satellites is determined towards the target satellite, and therefore the control of the others position relative to the target is straightforward.

Next we will discuss in more detail how this mathematical model is implemented by some of the missions discussed in 1.3. Key parameters for the discussed missions are summarized in table 1.

2.2 ETS-7 (JAXA, Real-time, Post-processed)

JAXA (formerly NASDA) has been developing rendezvous and docking techniques since the 90s, especially targeting this technology to utilize at the international space station for docking between the H2A Transfer Vehicle (HTV) and the space station. The most spectacular test was ETS-7. The ETS-7 experiment used 4 space qualified L1 GPS receivers (2 redundant receivers on each sub-satellite) developed by Toshiba. The original goal of the experiment was to use the GPS receiver until the two sub-satellites arrived at a relative distance of 500 meter. The conservative requirement for relative position and velocity was 21 m and 5 cm/s respectively. Because of the relative small distance between the satellites, the difference in ionospheric delay on the observations at the two sub-satellites were negligible.

The original code used for the onboard relative navigation experiment estimated a 8-element state vector (3 elements relative position, 3 elements relative velocity, difference of clock bias and clock drift between the GPS receiver of the chaser and target satellite).

In the second part of the experiment (1999), a carrier phase based relative navigational experiment was performed in which the carrier phase ambiguities estimations were added to the state vector, and therefore the EKF's state vector dimension became 14 (8 original states plus 6 carrier phase ambiguities for the 6 channel GPS receivers)[10].

The initial ambiguities were calculated from the residual of the single difference carrier phase.

ETS-7 made use of the Clohessy-Wiltshire solution of the Hill' equations. Beside GPS also data from the accelerometer was used for state propagation of the EKF, and made it possible to keep the relative errors small even when the thrusters were used to correct the approach of the chaser satellite. The state vector was updated every 10 seconds. An interpolation model was used to calculate the observations from the 2 subsatellites at the same epoch.

The ETS-7 experiment became a great success, and the experience gained with ETS-7 will be very useful not only for rendezvous missions but also for future Japanese formation flight missions.

2.3 PRISMA (DLR, Real-time)

PRISMA is a Swedish mission and provides a demonstration for critical technologies related to formation flying and In-Orbit-Servicing (rendezvous) [11].

The PRISMA test bed comprises a fully maneuverable micro-satellite as well as a smaller sub-satellite, similar to the chaser and target sub-satellites used for the ETS-7 mission. The mission schedule foresees a launch after 2008 of the two spacecraft into a low Earth orbit with an expected lifetime of the mission of at least eight months. Within PRISMA, the German DLR has assumed responsibility for providing a GPS-based onboard navigation system offering absolute and relative orbit information in real-time. An intersatellite link will be applied to transmit GPS and telemetry data from the sub-satellite to the micro-satellite and to relay telecommands through the micro-satellite to the sub-satellite.

Single-frequency Phoenix GPS receivers have been adopted for the mission. The receivers are commercial-off-the-shelf hardware with dedicated software developed by DLR.

For relative navigation, a double-difference carrier phase difference between the chaser and target satellite is applied [12]. As was shown in 2.1, differencing across receivers reduces broadcast ephemeris and ionospheric errors, the differencing across GNSS satellites eliminates the user clock error, but still, the measurement equation requires the solution of the integer ambiguity.

An extended Kalman filter will be employed for absolute and relative orbit determination. The filter estimates the spacecraft position and velocity components, the empirical accelerations, clock errors and biases along with integer carrier phase ambiguities as float values and, potentially, differential ionospheric path delays. The relative empirical accelerations in radial, along-track and cross-track direction are used to capture any discrepancies or mismodeling of the relative spacecraft dynamics. Scalar measurement updates are applied to avoid time-consuming matrix-vector operations, which is important for real-time implementation of such a large state dimension of the EKF onboard a spacecraft.

In addition to the GPS-based navigation system, DLR contributes the Spaceborne Autonomous Formation Flying Experiment (SAFE) to the PRISMA mission. SAFE will demonstrate a fully autonomous, robust constellation control of spacecraft. SAFE focuses on autonomous and fuel-optimized formation flying at representative distances of 100 to 2000 m. SAFE aims at a position control accuracy of 10/20/10 m (R/T/N 1σ).

To this end, guidance and control algorithms based on an eccentricity and inclination vector separation strategy will be employed [12]. This ensures a maximum operational safety in contingency cases and is ideally suited for future radar missions which realize a close formation flight.

2.4 GRACE-Formation (TUDelft, Post-processed)

The Gravity Recovery and Climate Experiment (GRACE) mission from NASA, consists of two identical formation flying spacecraft in a near polar, near circular orbit with an initial altitude of approximately 500 km [5]. The spacecraft have a nominal separation of 220 km. The primary mission objective is to measure the time varying changes in the Earth's gravity field, which is accomplished by the mission's key instruments, the Ka-Band Ranging System (KBR) and the accelerometers. As for as the authors of this article known, the GPS receiver, based on the Blackjack developed by JPL, is not used for real time relative navigation by the satellites.

Recent research at Delft University of Technology has proved that using orbital data from the GRACE formation, 1 mm level of accuracy is achievable for GNSS-based relative navigation between spacecraft. A processing strategy that have been developed for relative spacecraft positioning using an extended Kalman filter/smoother has proven to work satisfactorily when tested with orbital GPS data. The EKF processes single difference GPS pseudorange and carrier phase observations and uses (pseudo) relative spacecraft dynamics to propagate the relative satellite state over the observation epochs.

The EKF can resolve and incorporate the integer double difference carrier phase ambiguities, which is commonly regarded as the key to precise GNSS based relative positioning. Estimation of the integer ambiguities is accomplished by the well known Least Squares Ambiguity Decorrelation Adjustment (LAMBDA) method [13], developed at Delft University. When validating the GRACE relative position solutions from the EKF with reference observations, it has been shown that an actual overall relative position precision of 0.9 mm (1-dimensional) is achieved.

There are a number of differences between the work described in [5] and the approaches described before for real-time, rendezvous missions. The major differences are the use of dual frequency observations, processing of the measurements in forward and backward direction, smoothing of the relative position estimates, the actual estimation of the ambiguities, the propagation model for the state vector describing the relative position, the much extended state vector including states for the ionospheric delay, and the 5-dimensional vector of relative force model parameters. This last vector contains the relative drag and solar radiation pressure coefficient as well as the relative empirical accelerations.

Resolution of the integer single or double difference carrier phase ambiguities is commonly regarded as the key to precise GNSS-based relative positioning. The LAMBDA method used for integer resolution in [5], is an optimized form of the integer least-squares (ILS) method. Its efficiency comes from an additional decorrelation step prior to the search for the integer solution yielding the smallest squared norm. One major difference between both methods is the search time which is usually significantly smaller in case of the LAMBDA method.

Table 1: Overview of Significant Missions Using GNSS for Relative Positioning

Mission (Agency)	ETS-7 (JAXA)	PRISMA(SSC)	GRACE(NASA)
Relative navigation by	JAXA	DLR	TUDelft
Relative distance (km)	0-0.500	0.1- 2	220
Real-time R Post-processed (P) Scheduled (S)	R,P	S	P
Observation (channels)	L1 (6)	L1 (12)	L1+L2 (24)
Rendezvous (R) Formation Flight (F)	R	R,F	F
Kalman filter state (dimension)	p,v, b, d (8) and p,v, b, d, nA (float solution) (14)	p, v, a, b, d (11) + n A (float solution) + potentially nI (11+2n)	p, v, a, rd, s, b + 2nA (resolution) + nI (12+3n)
Observations*	L1 PR, DR, CP	L1 PR, CP	L1 PR, CP L2 PR, CP
Integration of Relative position by:	Hill equations	Hill equations	'Pseudo' relative dynamics
Other sensors	accelerometer		

* PR: Pseudo range, DR: Delta Range, CP: Carrier Phase, p: position, v: velocity, a: acceleration, b: clock bias, d: clock drift, A: ambiguities, I: ionospheric delay, rd: relative drag, s: relative solar radiation pressure coefficient

According to [5] the likelihood of the best solution obtained from LAMBDA is higher than any other integer solution. In [5], the ambiguity resolution is performed for each of the individual transmitting frequencies.

Furthermore note that different from the real-time rendezvous approaches, the relative clock drift is not modeled in [5], but only the clock bias.

Propagation of the EKF requires the integration of the relative position, but for the targeted sub-mm accuracies, it was found that there is no direct model describing the relative spacecraft motion with the required accuracy. Although the earlier mentioned Clohessy-Wiltshire equations, also known as the Hill equations, provide a first order framework describing the motion between two spacecraft, they are not accurate enough for sub-mm applications. The relative motion is thus obtained from the dynamical models of the individual spacecraft, hence the 'pseudo' relative dynamics. Here, integration of the relative state is accomplished by independent integration of the two absolute position states, of the two spacecraft over the same time interval and subtracting them in the end. More specifically, at the a-priori epoch, the absolute state from the reference spacecraft, is obtained from a reduced dynamic a-priori reference orbit. The (auxiliary) state of the other spacecraft is obtained by adding the updated filter estimate of the relative state at the a-priori epoch to the state of the reference spacecraft.

The absolute force model parameters, required for integration of the individual spacecraft states, are obtained in a similar way. The force model parameters for the master spacecraft are set to realistic predefined values and are kept constant over time. The (auxiliary) force model parameters for the chaser spacecraft are obtained by adding the relative force model parameters from the filter state to the ones of the master at the a-priori epoch.

Integration of the individual spacecraft states, leading to their predicted values is accomplished using a 4th order Runge-Kutta numerical integration method. The predicted relative state, is constructed as the difference of the predictions of the absolute states.

Of course an EKF with a state dimension of 42 (=12+3n with for n a maximum number of 10 channels was found to pass the data check algorithm used in [5]) is still hard to implement in a space qualified CPU, but the work shows that potentially sub-mm accuracy for GNSS-guided relative positioning is achievable. More work is required before the developed method can be implemented for space missions.

3 GNSS-based Attitude Determination for Distributed Satellites

3.1 Mathematical Model

In this section we will introduce the possibility to use GNSS for attitude determination for distributed satellites.

As can be seen in Figure 1, the carrier range difference between master antenna m and slave antenna s of the same satellite is the projection of the baseline vector b between the two antennas onto the line-of-sight vector l, which gives $\Delta r = b \cdot l = |b|\cos\theta$. This is the basic equation for GNSS-based attitude determination.

In [7] it was demonstrated that the precise knowledge of the baseline vector is necessary for accurate GNSS-based attitude determination. If the distance between the chaser and target satellites, a "virtual" baseline vector, is known with sub-mm accuracy, it could be possible to apply the same techniques developed for fixed baseline configurations on a formation of satellites. This attitude is also indicated in figure 1.

The attitude of the baseline vectors of a single spacecraft defines a transformation from the GNSS reference frame, where the line-of-sight vector is defined to the body frame where the baseline vector is defined. This is different with the case of distributed spacecraft, where the attitude of the baseline vectors of a swarm of spacecraft defines a transformation from the line-of-sight vector to the relative position vector, which both could be defined in the GNSS reference frame, originating in the master antenna onboard the target spacecraft. For both cases the attitude can be estimated by for example the least squares solution for the attitude error vector: $\Delta\psi = (H^T H)^{-1} H^T \Delta\hat{r}$ where $\Delta\psi$ is an attitude error vector, $\Delta\hat{r} = \Delta r - b^T A l_j$ is the difference between the single difference phase measurements and the expected single difference phase measurements based on the last available attitude solution,

,

$$H = \begin{bmatrix} . \\ . \\ l_j^T A^T B^x \\ . \\ . \end{bmatrix}$$

is the observation equation, lj is line-sight-vector to GNSS satellite j, A is attitude matrix, b is baseline vector i, B^x is cross product matrix for baseline vector bi.

Theoretically it is possible to determine the orientation of the baselines between a number of satellites, even if these satellites have a single antenna. However the absolute attitude of the satellite itself relative to the antennas can not be determined precisely with only a single antenna (there has been some work on single antenna full attitude determination with coarse accuracy, see for example [14]). If we would like to know the absolute attitude of the target satellite and the relative orientation of the other satellites relative to the target satellite we will have to equip all satellites with at least 3 antennas in a specific configuration.

An especially interesting aspect of the relative attitude determination problem for a multiple satellite mission is that, if a method could be developed successfully, the attitude solution could achieve a very high accuracy as this accuracy depends on the baseline length, and baseline lengths in satellite formations can be much longer than the baselines used for individual satellites.

Another aspect is that the inter satellite link between the satellites, which is necessary to send the GNSS observations from one satellite to the other, could potentially be used to provide orientation information, as one vehicle could determine its relative attitude by using the RF transmission from another vehicle.

In the rest of this section we will discuss the limited work that has been done for GNSS-based attitude determination for multiple satellites and indicate future directions.

3.2 ETS-7

For the ETS-7 mission, an experiment was done to use observation data collected from the GPS receivers onboard the chaser and target satellites for attitude determination while the 2 satellites were docked. Results were presented in [15].

This experiment made use of the fact that the chaser satellite had 2 antennas and the target satellite 1, and therefore this configuration of 3 antennas made a 2 baseline system. The baseline lengths were about 2 and 1.4 meter.

The experiment showed that it is possible to use observations from distributed satellites for attitude determination, but no attempt was made to determine the relative position of the antennas by the GPS observation. The baseline vectors were determined from the known dimensions of the spacecraft.

3.3 ORION-EMERALD

The ORION-EMERALD mission has the potential to demonstrate GPS-based attitude determination on distributed spacecraft as all the 3 microsats of the constellation (one Orion and two Emerald spacecraft) have multiple GPS antennas (6 for Orion; 3 on the top face, 1 at the bottom and 2 at the opposite side when the satellite is earth pointing, and 2 for the

Emerald spacecraft) [16]. Unfortunately this mission was scheduled to be launched by the space shuttle and at this moment it is unsure if it will be launched at all. The publications about the project indicate that the researchers are considering attitude determination for the Orion spacecraft itself but not for multiple satellites.

3.4 Future Directions

As described above only recently the kind of accuracy for relative positioning ("virtual" baseline vector estimation) between distributed satellites necessary for attitude determination of formation flying satellites became feasible. Therefore this is still a relatively new research field. First of all the mathematical models for combined positioning and attitude determination have to be developed. This implies adequately accounting for a wide range of error sources in the highly dynamic environment of flying objects, as well as capturing the noise characteristics in a stochastic model. Algorithms have to be developed and demonstrated using software simulations. If possible also hardware-in-the-loop simulations, as were developed for GNSS-guided relative navigation [17], should be used. In Europe similar simulators have been developed by DLR and in Japan by JAXA. The next level would be demonstration of integrated GNSS-guided relative positioning and attitude determination by using data collected in space.

4 Research on Formation Flight at DEOS, Delft University of Technology

While algorithms for the GPS based relative navigation of two spacecraft in close proximity have already been studied at Delft University of Technology since a decade ago [18], at this moment GNSS guided formation flight is one of the keystone research topics of the DEOS group at the faculty of aerospace engineering, Delft University of Technology. Three Ph.D. students are working in parallel on this research. One is looking into the implementation expects of the work described in [5]. The second is analyzing the performance of different satellite formations and future sensor technology to map the time-varying gravity field of the Earth. It comprise investigations into the suitability and feasibility of various satellite formations, the propagation of errors into estimated gravity field parameters, time and frequency domain sensitivity studies, the separation between individual contributors to the time-varying gravity field and its relation with satellite mission parameters. For the third the purpose is, the subject of this paper, to demonstrate the capabilities of formation flying using GNSS for relative positioning between, and attitude determination of, the elements of a formation of satellites.

5 Summary and Future Work

This paper described previous and planned missions for the near future using GNSS-guided relative navigation. It explained the techniques used for relative navigation and explored the possibilities to use GNSS-based attitude determination techniques for distributed satellites.

Some key technology for formation flight and rendezvous between spacecraft has been demonstrated in recent years or could be demonstrated in the near future. However, providing sub-mm accuracy and very reliable relative navigation between spacecraft is, with the current technology level, still very challenging. Especially if this has to be done in "near real" time. Resolution of the integer single or double difference carrier phase ambiguities is commonly regarded as the key to precise GNSS-based relative positioning and attitude determination. The research currently being performed at Delft University of Technology is expected to have a large contribution in this field.

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