OPERATIONAL ASPECTS OF ORBIT DETERMINATION WITH GPS FOR SMALL SATELLITES WITH A SAR PAYLOAD

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ABSTRACT

Scientific small satellite missions for remote sensing with Synthetic Aperture Radar (SAR) payloads or high accuracy optical sensors, pose very strict requirements on the accuracy of the reconstructed satellite positions, velocities and accelerations. Today usual GPS receivers can fulfill the accuracy requirements of this missions in most cases, but for low-cost-missions the decision for a appropriate satellite hardware has to take into account not only the reachable quality of data but also the costs. In this paper an analysis is carried out in order to assess which on board and ground equipment, which type of GPS data and processing methods are most appropriate to minimize mission costs and full satisfying mission payload requirements focusing the attention on a SAR payload.

1. INTRODUCTION

Missions for high resolution imaging with SAR sensors or optical sensors rise the need for the reconstruction of the satellite position, velocity and acceleration with a very high accuracy. Despite of the fact, that usual GPS space hardware is able to fulfill the requirements also the costs have to be considered. In the following an analysis will be presented on which type of GPS data and processing methods can fulfill the mission requirements with minimized costs.

2. SAR PAYLOAD DRIVEN REQUIREMENTS ON ORBIT DETERMINATION

As there is a wide variety of modes in which a SAR data-take can be done and a number of parameters that determine the requirements on the orbit determination accuracy, we will focus on the case of a SAR used in strip or in spot mode with a required resolution. Among the input data necessary to process SAR raw data in order to generate an image with a given resolution, the estimated Doppler frequency f_D and the Doppler range f_R play a main role.

The Doppler frequency is proportional to the first derivative of the phase of the radar signal while f_R is proportional to the second derivative of the distance R between the antenna phase centre and the target of the radar.

$$f_D = \frac{1}{2\pi}\frac{d\Phi}{dt} \qquad f_R = -\frac{1}{2\lambda}\frac{d_2 R}{dt^2} \tag{1}$$

Considering the Taylor expansion of the phase Φ of the radar signal, it can be seen that it is a function of the time varying position, velocity and acceleration vectors of the spacecraft.

$$\Phi(t) = \frac{4\pi}{\lambda}\mathrm{R(t)} = a_0(p_k) + a_1(p_k)(t-t_0) + a_2(p_k)(t-t_0)^2 + a_3(p_k)(t-t_0)^3 + o(t^3) \tag{2}$$

where:

$R(t) = \lvert \mathbf{x}_A(t) - \mathbf{x}_T \rvert$	
λ	is the wave length of the radar radio signal
$\mathbf{x}_A(t) = f(\mathbf{x}_S(t), \mathbf{q}_S(t))$	is the position vector of the antenna phase centre
$\mathbf{x}_S(t), \dot{\mathbf{x}}_S(t), \ddot{\mathbf{x}}_S(t)$	position, velocity and acceleration vectors of the spacecraft at time t in an Earth fixed coordinate system
$\mathbf{q}_S(t)$	is the quaternion representing the attitude of the spacecraft
$\mathbf{x}_T$	is the position of the target in an Earth fixed coordinate system
p_k	is a generic parameter that condition the relative motion between SAR antenna and its target
$a_0(p_k)$	is the absolute phase
$a_i(p_k) = F(d_i R/dt^i, t)$	is the i^{th} order derivative of Φ
$d_i R/dt^i = g(d_i x_S/dt^i)$	for a given spacecraft attitude

The requirement on the resolution of a SAR image drives the requirements on the estimation of the phase of the radar signal and consequently the requirements on the estimation of the position, velocity and acceleration of the spacecraft. To give an example for the order of magnitudes involved in these kind of problems, we consider the extreme case of a spaceborne SAR working in X-band, in strip or spot mode, with a required processed image resolution of 0.5 to1.0 m. This leads to the following requirements on the estimation accuracy of spacecraft position, velocity and acceleration vectors:

$$\mathbf{x} \le 15\,m \qquad \dot{\mathbf{x}} \le 1.5\cdot 10^{-2}\ m/s \qquad \ddot{\mathbf{x}} \le 6.0\cdot 10^{-4}\ m/s^2 \tag{3}$$

It has to be stressed here that, in an analysis finalized to estimate whether the choice of a certain navigation system can fulfill requirements (3) or not, it has to be clear that there is an evident but not obvious distinction between what does happen in the reality and what one can measure and with which accuracy. In fact considering for example the simple case of a satellite flying in a LEO circular polar orbit at an altitude of 500 km, a preliminary analysis leads to the following order of magnitude assessments:

- As the prevailing acceleration is that due to the gravity field, and particularly the term J_2, we can consider only this acceleration without any other disturbing acceleration in order to make any plausible consideration about the order of magnitude of satellite total acceleration and its time variation.
- The variation $|d\ddot{\mathbf{x}}_S|$ of the acceleration of the spacecraft due to the gravity field only corresponding to a $\mathrm{dR} = 15\,\mathrm{m}$ displacement is about $5.0 \cdot 10^{-5}\ m/s^2$.
- As the magnitude of the aerodynamic acceleration (in this case main perturbative acceleration other than the non spherical gravity field terms) ranges typically from $5.0 \cdot 10^{-7}\ m/s^2$ to $1.0 \cdot 10^{-6}\ m/s^2$, it can be reasonably said that the magnitude of unpredictable disturbance accelerations other than the gravitational ones cannot be greater than $1.0 \cdot 10^{-5}\ m/s^2$.

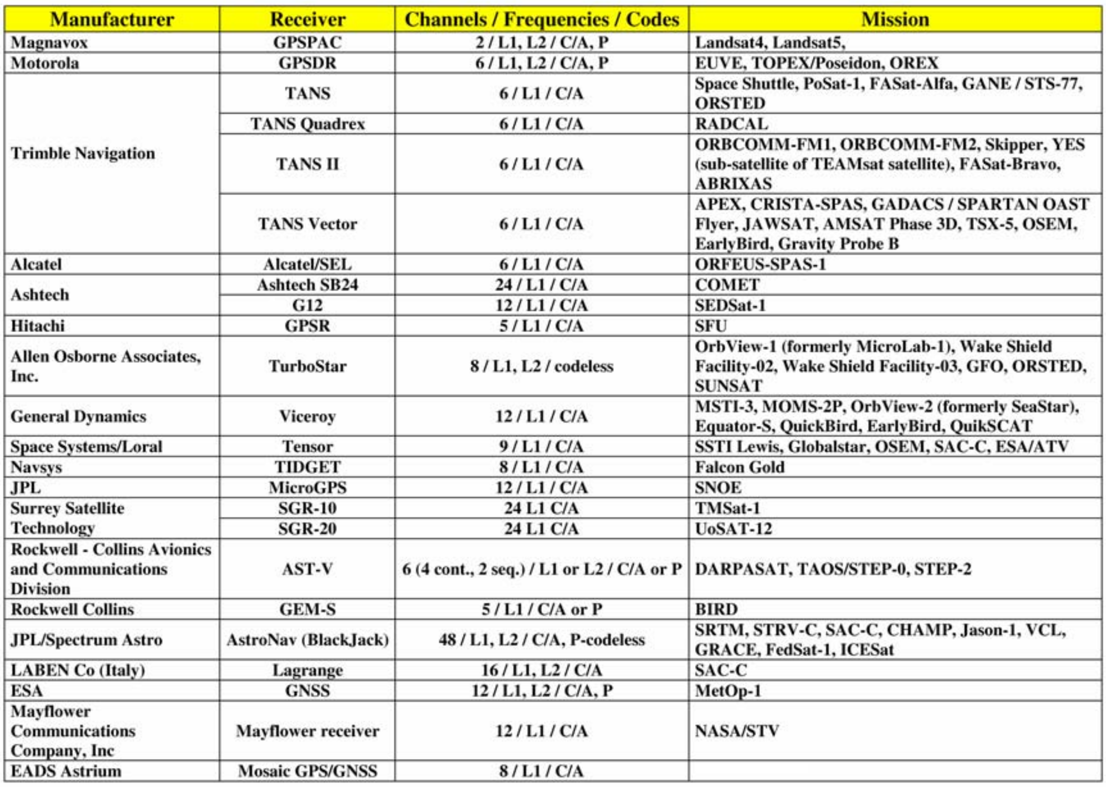
Recalling once again requirements (3), the preceding considerations could lead to the misunderstanding that a GPS receiver with a 15 m (3σ) accuracy is able to fulfill all requirements. But the requirement on the acceleration doesn't mean that $|d\ddot{\mathbf{x}}_S|$ has to be less than $6.0 \cdot 10^{-4}\ m/s^2$ during a SAR image data-take, but that the absolute error of the spacecraft measured acceleration with respect to the real acceleration (accuracy of the measurement) has to be contained into a $\pm 6.0 \cdot 10^{-4}\ m/s^2$ error interval around the measured value over the whole time period of the data-take.

3. ORBIT DETERMINATION

Nevertheless, the use of a GPS receiver is nowadays, in most cases, a good and robust mean to fulfill accuracy requirements, but a low-cost-mission approach does impose a trade off between costs and capabilities of satellite hardware (type of GPS receiver, on board data storage, download performances) and operations (on-board or ground data processing, processing time constraints).

3.1 GPS receivers, measurements type and orbit determination strategies

Some hints are given here about the main considerations that have to be done for choosing a GPS receiver and the used measurement types to collect data in order to satisfy the requirements of Eq. 3. These hints are demanded only to give a general overview on the scales of the problems which have to be faced. A first broad choice has to be done between single and dual frequency geodetic GPS receivers. Tab. 1 (from Ref. [15]) lists some spaceborne GPS receivers and the respective missions flown in the last 15 years. With dual frequency GPS receivers better accuracies can be achieved, than using a single frequency GPS receiver at the same conditions. The drawbacks are that they are generally more expensive than the single frequency receivers and that there are no space flown European GPS receivers of this kind available at the moment. This fact could cause licensing problems.



Manufacturer	Receiver	Channels / Frequencies / Codes	Mission
Magnavox	GPSPAC	2 / L1, L2 / C/A, P	Landsat4, Landsat5,
Motorola	GPSDR	6 / L1, L2 / C/A, P	EUVE, TOPEX/Poseidon, OREX
Trimble Navigation	TANS	6 / L1 / C/A	Space Shuttle, PoSat-1, FASat-Alfa, GANE / STS-77, ORSTED
	TANS Quadrex	6 / L1 / C/A	RADCAL
	TANS II	6 / L1 / C/A	ORBCOMM-FM1, ORBCOMM-FM2, Skipper, YES (sub-satellite of TEAMsat satellite), FASat-Bravo, ABRIXAS
	TANS Vector	6 / L1 / C/A	APEX, CRISTA-SPAS, GADACS / SPARTAN OAST Flyer, JAWSAT, AMSAT Phase 3D, TSX-5, OSEM, EarlyBird, Gravity Probe B
Alcatel	Alcatel/SEL	6 / L1 / C/A	ORFEUS-SPAS-1
Ashtech	Ashtech SB24	24 / L1 / C/A	COMET
	G12	12 / L1 / C/A	SEDSat-1
Hitachi	GPSR	5 / L1 / C/A	SFU
Allen Osborne Associates, Inc.	TurboStar	8 / L1, L2 / codeless	OrbView-1 (formerly MicroLab-1), Wake Shield Facility-02, Wake Shield Facility-03, GFO, ORSTED, SUNSAT
General Dynamics	Viceroy	12 / L1 / C/A	MSTI-3, MOMS-2P, OrbView-2 (formerly SeaStar), Equator-S, QuickBird, EarlyBird, QuikSCAT
Space Systems/Loral	Tensor	9 / L1 / C/A	SSTI Lewis, Globalstar, OSEM, SAC-C, ESA/ATV
Navsys	TIDGET	8 / L1 / C/A	Falcon Gold
JPL	MicroGPS	12 / L1 / C/A	SNOE
Surrey Satellite Technology	SGR-10	24 L1 C/A	TMSat-1
	SGR-20	24 L1 C/A	UoSAT-12
Rockwell - Collins Avionics and Communications Division	AST-V	6 (4 cont., 2 seq.) / L1 or L2 / C/A or P	DARPASAT, TAOS/STEP-0, STEP-2
Rockwell Collins	GEM-S	5 / L1 / C/A or P	BIRD
JPL/Spectrum Astro	AstroNav (BlackJack)	48 / L1, L2 / C/A, P-codeless	SRTM, STRV-C, SAC-C, CHAMP, Jason-1, VCL, GRACE, FedSat-1, ICESat
LABEN Co (Italy)	Lagrange	16 / L1, L2 / C/A	SAC-C
ESA	GNSS	12 / L1, L2 / C/A, P	MetOp-1
Mayflower Communications Company, Inc	Mayflower receiver	12 / L1 / C/A	NASA/STV
EADS Astrium	Mosaic GPS/GNSS	8 / L1 / C/A	

Table 1: GPS receivers and manufacturers

Once a GPS receiver has been chosen, the second broad choice is which type of measurements has to be stored on-board with a certain sampling rate: navigation solutions with their three position and velocity components, raw data which are up to nine types in a dual frequency receiver or both types. This choice of course determine the possible precise orbit determination (POD) algorithm that can be used. A very good overview about the present state of the art of POD strategies using different types of GPS data and the accuracies that can be achieved is given in Ref. [2]. It can be seen that the availability of raw data and not only of navigation solutions is essential to be on the safe side in the fulfillment of tightening mission requirements. Processing raw data leads to the best accuracies. Of course in this case the data storage and data download budgets will change. For a single frequency receiver, if only navigation solutions and ancillary data are to be stored with a sampling rate of 0.1 Hz, typically about 0.1 MB of data per hour have to be stored, while if every available data is to be stored with the same sampling rate, the necessary data storage capability will rise up to 0.5 MB of data per hour. Tab. 2 is reproduced from Ref.[2] and shows the position accuracies that could be achieved in the POD for the German small satellite CHAMP that carries the geodetic dual frequency GPS receiver BlackJack (JPL). As it can be seen, POD based on GPS raw data processing gives the best possible achievable accuracies. The drawbacks are that it requires very complex algorithms and it is difficult to be implemented in a software; even when a software is already available (recently also commercial tools are appearing), it requires very specialized competencies to use it with success. Finally it requires longer processing times as external data from the International GPS Service (IGS) are required. On the other hand it is not so difficult to process GPS-NS (navigation solutions) and is relatively easy to retrieve commercial tools to do it. The problem is whether the accuracies that can be achieved with this kind of POD fulfill the mission requirements.

Data Type	Processing Scheme	Accuracy (m)
Navigation solutions	Kinematic	16.5
Navigation solutions	Reduced-dynamic	1.6
Single frequency PR	Kinematic	9.1
Dual frequency PR	Kinematic	2.9
Single frequency SPP	Reduced-dynamic	0.8
Dual frequency SPP	Reduced-dynamic	0.3
Single frequency PR	Reduced-dynamic	0.8
Dual frequency PR	Reduced-dynamic	0.2
Single frequency PR &	Reduced-dynamic	0.3
Dual frequency PR & CP	Reduced-dynamic	0.1
PR: pseudorange, CP: carrier phase, SPP: single point positions		

Table 2: Typical CHAMP position accuracies (3D r.m.s)

3.2 Orbit determination software

In last times, some commercial and freeware software tools or modules capable to perform a GPS navigation solutions and raw data based orbit determination are appearing. Between the commercial one are FreeFlyer by A.I. Solutions (NS), OD Tool Kit by AGI (NS and pseudorange) and Bernese Software (NS-Raw Data). Among the freeware software GAMIT/GLOBK, GIPSY-OASIS II and Trimble Geomatics (TGO).

3.3 GPS navigation-solutions-based orbit determination

It the following an attempt is given to establish some boundaries for the choice to download and process either GPS raw data or navigation solutions to fulfill the requirements of Eq. 3 and meanwhile to validate the quality of the orbit determination implemented in commercial tools (e.g. FreeFlyer). The problem in using GPS-NS arise in the fulfillment of the requirement on the acceleration in Eq. 3: typical values of accuracies of smoothed GPS-NS are 10 to 20 m RMS (3σ) on the positions and $2 \cdot 10^{-2}$ to $5 \cdot 10^{-1}$ m/s RMS (3σ) on the velocities. The analysis performed on the CHAMP satellite data leads to the results that typical accuracies of the accelerations estimated from GPS-NS with a Taylor discrete differentiation of the 3rd order and compared with those calculated from the corresponding RSO (Rapid Science Orbit with an accuracy up to 2 cm), are in the order of $2 \cdot 10^{-2}$ m/s^2. Of course things can be improved filtering data and performing a POD. Referring to Tab. 1, it can be preliminary stated that with the accuracy possible with a GPS-NS based orbit determination, requirements of Eq. 3 can be fulfilled but without any accuracy margin and not fulfilling the 3σ standard deviation requirement. As there are to our knowledge no examples of SAR satellite missions with so strict accuracy requirements on the estimated acceleration fulfilled with the unique use of GPS-NS data, it is advisable to plan also the availability and use of raw data already in the first phases of mission design. Preliminary validation analysis of the commercial tool FreeFlyer have been performed with the simplest configuration. A dynamic batch least squares orbit estimation (Ref. [1]) was done using stocks of CHAMP GPS-NS of 3, 6 and 12 hours with different data sampling of 10 s and 60 s. Typically an arc of one orbit (about 90 minutes) was estimated. Up to 70x70 gravity coefficients of the Earth gravity field model GRACE-GGM02C were used. As density model the Jacchia-Roberts implemented with a $F_{10.7}$ (10.7 cm solar flux index) prediction file was adopted. No use of empirical accelerations was done for these preliminary analysis. First results were reasonable: using GPS-NS with an accuracy of 15 m RMS on the positions and $6 \cdot 10^{-1}$ m/s RMS on the velocities the estimated arcs had an accuracy of about 7 m RMS on the positions and $1 \cdot 10^{-2}$ m/s RMS on the velocities. Fig. 1 shows, in an orbiting local system, the accuracy of a GPS navigation solutions based estimation of a 90 minutes orbit arc on 25 October 2003. Three hours of GPS data with a 10 s sampling were used for this estimation. The reference orbit is the CHAMP RSO. This example has to be considered as a worst case, as in the period from about 20 October to about 05 November 2003 a solar storm took place ($F_{10.7}$ rose up to 280 and K_p up to 9).

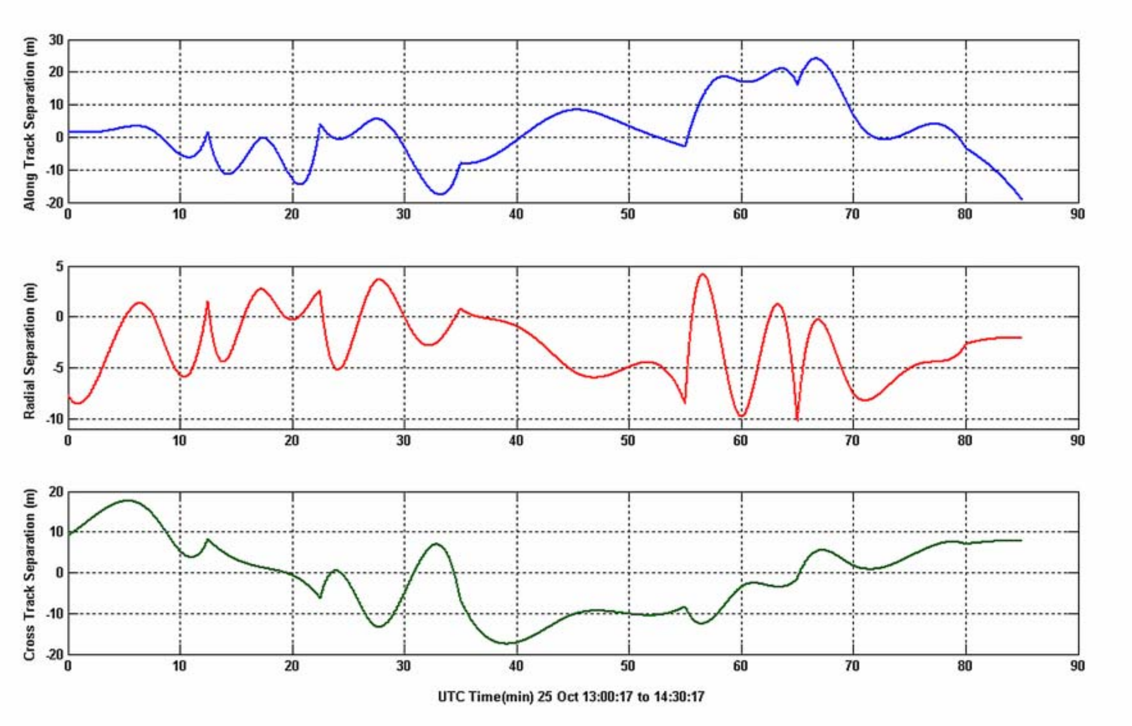


Figure 1: Position differences between estimated and true orbit

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