ONBOARD ORBIT DETERMINATION USING DATA RELAY SATELLITE*

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ABSTRACT

This paper presents an onboard orbit determination method for a low Earth orbiter, using range and/or Doppler measurements transiting via one or two DRS. The estimation method relies on a Kalman filtering algorithm. Simple but sufficiently accurate modelling techniques, allowing to take into account uncertainties due to Earth potential, atmospheric drag or propulsion errors during a maneuver, are illustrated by four application examples.

Keywords : orbit determination - relay satellite - Kalman filter - orbit modelling - apogee maneuver.

1. INTRODUCTION

In the field of space mission using low Earth orbiters (LEO) and possibly involving transfer phases, or rendez vous by means of maneuvering manned spacecraft, it is obviously essential to have reliable and performing methods for fast orbit determination.

Besides traditional systems based on a net of numerous, well distributed ground tracking stations, it appears of great interest to use one or several Data Relay Satellite (DRS). This would allow to reduce the number of required ground stations, as the DRS can ensure a quasi-permanent link with any considered LEO while remaining itself visible from its own control station.

In addition, it is possible to limit the ground workload and the communication complexity by performing orbit restitution directly by means of the LEO onboard computer.

This paper presents an onboard orbit determination method using range and/or Doppler measurements transiting via one or two DRS, and its application to 4 different illustrative case of present interest.

2. PROBLEM STATEMENT

2.1. General

The problem consists in the localization (position + velocity) of a LEO on an eccentric transfer orbit on on its final circular orbit, by means of onboard ("autonomous") treatment. Due to the moderate performance level of the LEO computer, the calculation complexity must remain limited. This implies the use of motion and measurement models which are simplified but nevertheless accurate enough.

We have at disposal one or two DRS geostationary relays, which are visible from a given ground station.

Range and/or Doppler measurements with known accuracy levels are made at regular intervals ; they can be of one of the following types (Fig. 1) :

- LEO-DRS : two ways measurements,
- LEO-DRS-ground station : one way or two ways measurements.

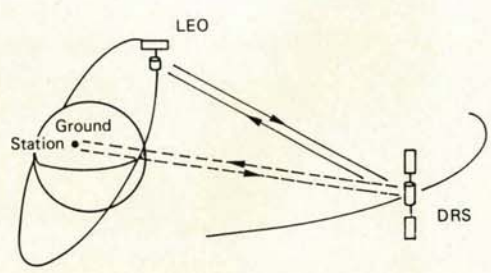

Fig. 1 — Measurements via a DRS.

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2.2. Methods

These measurements must be processed by an appropriate technique to restitute the unknown orbit. The orbit parameters estimation method used here relies on a proven algorithm, i.e. Kalman filtering, which needs :

. the elaboration of an evolution model for the state parameters,
. the elaboration of an observation model which links the measurements to these parameters,
. the appropriate choice of the levels for the different noises representing the model uncertainties as well as the instrument errors.

The formalism can be summarized as :

Evolution :

$$\dot{q} = F(q, \bar{\gamma} + \Delta\gamma, b_e, t) \quad \text{orbit parameters}$$

$$\Delta\dot{\gamma} = -\frac{1}{\tau}\Delta\gamma + \xi \quad \text{uncertainties (Markovian noises)} \qquad (1)$$

$$\dot{b}_e = 0 \quad \text{bias}$$

Observation :

$$\dot{b}_o = 0 \quad \text{bias} \qquad (2)$$

$$y = H(q, t, b_o) + \eta \quad \text{measurement}$$

where $(q, \Delta\gamma, b_e, b_o) = X$ is the state vector to restitute, ξ, η are the evolution and observation (white) noises.

At each time t, the algorithm then gives an estimation of the state, and furthermore its covariance matrix (particularly, the standard deviations for the estimations errors).

Besides this, if desired it is also possible to associate a Rauch smoothing technique to the filtering, with little additional cost, allowing then :

1) to improve the results in case of an off-line treatment or of project studies ;
2) to have a checking and validation technique concerning the a priori chosen assumptions for the noises : the a posteriori estimations (given by smoothing) of the evolution and observation noises, or "residues", must in effect be compatible with the a priori entered standard deviations. If not these latter have to be adjusted consequently.

A Kalman-Rauch computer program has been developed at ONERA (Ref. 1) and widely tested with aerospace applications.

Of course, concerning project studies, no real measurements recordings are available. Thus this restitution method will work with simulated measurements which are submitted to appropriate noises.

2.3. Modelling

For given type and quality of measurements, the LEO localization accuracy depends on the quality of the models which are implemented in the onboard estimation software. Thus an important part of this work consisted in defining the appropriate forces and errors models, which must be simple but accurate enough to reach the prescribed requirements.

2.3.1. Earth potential. Gravitational forces modelling is guided by a preliminary study of the considered LEO orbit, based on a spectral analysis of the gravitational acceleration differences between a sophisticated and accurate potential model and the onboard potential model. This allows to choose the error model forms as coloured noise (1st or 2nd order Markovian processes), and the associated standard deviation levels, to represent the residual uncertainty on gravity acceleration.

2.3.2. Atmospheric drag. Depending on the considered altitude, the forces due to the remaining atmospheric drag must be taken into account or not. Physical considerations lead to define a mean atmospheric density level ρ_m which is then modulated by diurnal effect or altitude effect. A markovian noise $\Delta\rho$ will in addition represent the local density uncertainties.

2.3.3. Errors due to clock bias and drift. In case of one way measurement of propagation time, using onboard ultra stable oscillators (U.S.O.), the measurement error increases with time and can become important. So it is necessary to take into account and model the bias between ground reference clock and onboard clock, as well as the differences between the two clock drifts (oscillator frequency bias) or clock drift rates (oscillator frequency drift).

2.3.4. Propulsion errors during maneuver. During the boosted phase the main error sources come from : 1) the motor specific impulse dispersion, 2) and the thrust direction uncertainties which depend on misalignment or torques. The first one may be modelled by a bias, the other ones by bias and/or couloured noises.

3. APPLICATION EXAMPLES

3.1. SPOT satellite autonomous localization

The characteristics of this sun-synchronous orbit are :

$a = 7200$ km $\quad e = 1 \times 10^{-3} \quad i = 98.8°$
$\Omega/_{\gamma_{50}} = 116.9° \quad \omega = 90.2°$.

Only one DRS is used, at station longitude L = 0°. It is itself localized within a "200m class" accuracy.

Measurements are of range type, two ways LEO-DRS, with accuracy σ_d = 20m. In routine operation the measurement frequency is defined by only 15mn of measurement every interval of 1h30mn (roughly, 15mn of contact per orbit), in order to share the DRS workload with other users.

Preliminary studies have shown that the residual atmospheric drag effect is quite negligible at that altitude. On the other hand, Earth potential uncertainties play a major role.

A reference orbit is generated by simulation, taking into account the potential perturbations represented by the GRIM 2 sophisticated and accurate model (Ref. 2), developed in harmonic series until the 30th order (30 x 30).

In orbit restitution, the potential model for the onboard algorithm is much simpler and will be GEM 10 (Ref. 3) truncated at 10th order (10 x 10). Then the technique summarized in 2.3.1. allows to determine the characteristics of the 3 Markovian noises representing the potential uncertainties on the 3 components of the reference frame.

Table 1 shows the results obtained after one day treatment, under the form of estimated standard deviations on the practical localization parameters, which are the 3 position components in the STW rotating orbital frame attached to the satellite, completed by the semi major axis a (related to period) :
r_S : radial, r_T : along the track, r_W : cross orbit.

Starting from deliberately large initial values (case of accidental lack of data over a long period, for example) the algorithm converges towards acceptable results as shown (where prediction means : values at the end of a 1h15mn period without measurements, update : values at the end of a 15mn measurement period). The deviations with respect to the reference values are not mentioned, being always inferior to 3σ.

Table 1. SPOT autonomous localization

	σ_a(m) Pred./ Update	σ_{r_S} Pred./ Update	σ_{r_T}(m) Pred./ Update	σ_{r_W}(m) Pred./ Update
Initial	30	3030	4040	3030
After 24h	8/5	25/22	110/65	58/40

3.2. EURECA satellite autonomous localization

The characteristics of the EURECA platform orbit are :

$a = 6780$ km $e = 1 \times 10^{-3}$ $i = 28.5°$
$\Omega/\gamma_{50} = 60°$ $\omega = 30°$.

The features concerning the DRS and the measurements are the same as above in section 3.1.

Due to the relatively low altitude (400km), atmospheric drag has to be taken into account as well as potential uncertainties.

A reference orbit is generated by simulation, using :

. the GRIM 2 complete model (30 x 30) to represent the Earth potential,
. the DTM accurate model (Ref. 4) to calculate the atmospheric density ρ.

The data for atmospheric drag computation are (corresponding to a high density level case) : geomagnetic index $K_p = 4$, solar flux $F_{10.7} = 190$.

EURECA mass m = 3500 kg, reference area $S = 54.4m^2$, drag coefficient $C_D = 3$.

In orbit restitution, the potential uncertainties modelling is similar as above (3.1.).

Following 2.3.2. the atmospheric density ρ will be modelled as (Ref. 5) :

$$\rho = \rho_S + \Delta\rho \quad (3)$$

$$\rho_S = \rho_m[1 + \cos \tfrac{\pi}{12}(H_l - H_{l_{max}})] \quad (4)$$

with :
$\rho_m = 1.5 \times 10^{-11}$ kg/m³ mean value
k = 0.5 scale factor, depending on orbit altitude
H_l: local hour, to represent the diurnal effect
$H_{l_{max}}$: 14h
Δρ : uncertainty term.

Figure 2 shows the plotting of ρ as given by the DTM accurate model and by the simplified model $\rho = \rho_S$. The discrepancies between the 2 curves are of course unknown during restitution. They will be taken into account by the correcting term Δρ, which is modelled as a 1st order Markovian noise :

$$\Delta\dot{\rho} = -\frac{1}{\tau_\rho}\Delta\rho + \xi_\rho \quad (5)$$

and is estimated by filtering.

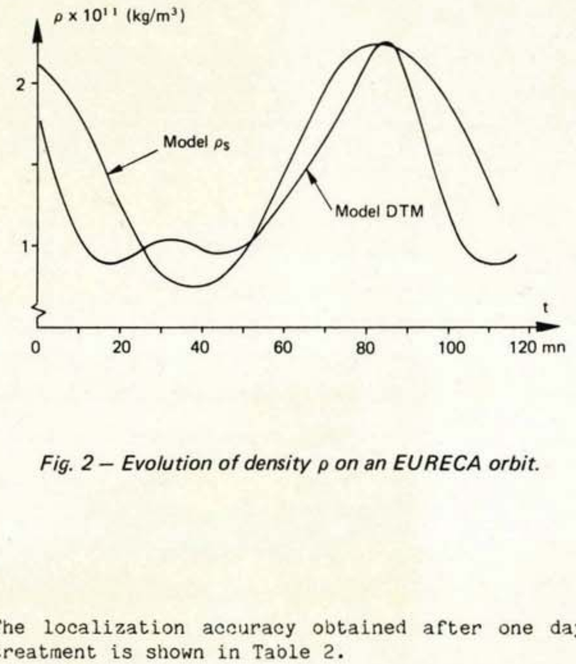

Fig. 2 — Evolution of density ρ on an EURECA orbit.

The localization accuracy obtained after one day treatment is shown in Table 2.

Table 2. EURECA autonomous localization

	σ_a(m) Pred./ Update	σ_{r_S} Pred./ Update	σ_{r_T}(m) Pred./ Update	σ_{r_W}(m) Pred./ Update
Initial	300	28 x 10^3	15 x 10^3	28 x 10^3
After 24h	40/28	80/50	280/80	110/65

3.3. EURECA localization within IOC experiment

Within the frame of ESA's IOC (Inter Orbital Communications) experiment, it has been proposed in addition to put an U.S.O. (Ultra Stable Oscillator) onboard the EURECA platform, allowing emission of signals at successive instants defined with high accuracy. Reception of these signals by a ground station after their transit via the European geostationary DRS OLYMPUS gives then propagation time measurements Δt (equivalent to range measurements). Δt is submitted to errors coming from several sources due to the U.S.O., summarized as :

$$\varepsilon\, \Delta t(t) = \Delta t_o + \int_{t_o}^{t} \frac{\Delta f_o}{f_o}\, d\theta + \int_{t_o}^{t} \left[\frac{\Delta f_L}{f_o}(\theta - t_o) + \frac{\Delta f_p}{f_o}\sin(\omega\theta + \phi)\right] d\theta \quad (6)$$

$$\varepsilon\, \Delta t(t) = B_o + \int_{t_o}^{t} B_1\, d\theta + \int_{t_o}^{t} (B_2 + B_3)\, d\theta \quad (7)$$

where :

B_o corresponds to the initial bias between U.S.O. and ground reference clock,

B_1 corresponds to the error in initial frequency estimation,

B_2, B_3 correspond to the U.S.O. frequency drift (linear and periodic terms).

The accuracy of the considered U.S.O. is characterized by a relative drift inferior or equal to 10^{-11} per 12h.

The error terms must be modelled in the restitution algorithm. The constant factors will be represented by bias, and the periodic term by a 1st order Markovian noise.

Potential and drag uncertainties are modelled as in 3.2.
OLYMPUS longitude is L = -19° W, and it is localized by ground stations within 100 m accuracy.

Because of operational constraints due to the IOC antenna, measurements are feasible only 12h per day, alternating with a 12h period without contact (where only pure prediction of EURECA orbit is possible). During the "visibility", the cadence is 1 measurement per 5mn, with an accuracy level equivalent to 10m.

Chosen initial conditions for EURECA correspond to the assumption that its orbit is determined by pure prediction during one day before the experiment starting time. The reachable localization accuracy after 12h, 24h, 36h (where routine operation is obtained) is shown in Table 3.

Table 3. EURECA localization with use of an onboard ultra stable oscillator

	σ_a(m)	σ_{r_S}	σ_{r_T}(m)	σ_{r_W}(m)
Initial	66	100	5660	90
After 12h	14	24	100	39
After 24h (period without measure-ments)	45	63	1960	45
After 36h	13	22	100	32

These results show the feasibility of this one way measurements localization technique. Besides this, it can be noted that the Kalman filtering allows to identify the U.S.O. characteristic parameters (frequency drift,...) with a good accuracy, in addition.

3.4. Localization at apogee maneuver for injection into a SPOT-type orbit

Launching of a heavy payload into a SPOT-type orbit by means of ARIANE 5 is considered here. The LEO and its apogee motor (specific stage or re-ignitable ARIANE 5's last stage) are firstly injected by the launcher into an elliptical (180km-800km) transfer orbit inclined at 98.6°.

During this transfer phase as well as during and after the circularizing maneuver, the LEO trajectory is observed by one or two DRS. At first apogee the LEO is then injected into its final circular orbit by means of the apogee maneuver motor.

The question is the accuracy level to be expected for orbit determination via DRS during and after this maneuver, with the propulsion uncertainties being taken into account.

The maneuver data are as follows :

F = 2000 N	motor thrust
Isp = 315 s	specific impulse
m = 14000 kg	total initial mass (payload + apogee motor)
Δt = 117.8 s	burn duration (thrust arc ~ 6.8°).

It is assumed that the propulsion errors can reach the following values :

. on thrust magnitude (due to error on Isp) : ± 1%
. on thrust direction : 1°.

In the restitution model, a bias ΔIsp is introduced to represent the specific impulse error. The thrust direction being defined by 2 angles : Ψ (azimuth) and θ (flight path), the total 1° error can be modelled by 2 bias $\Delta \Psi_o$, $\Delta \theta_o$ also.

The Earth potential is modelled as in section 3.1.

Simultaneous two-ways range and Doppler measurements via DRS are used. Their frequency is once per 1mn before and after maneuver, and increased up to one per 2s during thrusted phase to provide a sufficient sampling. The accuracy levels correspond to 20m and 3cm/s errors.

Two DRS, at L = 66.5° E and L = -63.5° W are used, to ensure a continuous coverage of the transfer orbit until apogee.

LEO localization accuracy at apogee maneuver and at 1/2 orbit later (on its final circular orbit) are shown in Table 4.

Table 4. SPOT localization at and after apogee maneuver

	σ_a(m)	σ_{r_S}	σ_{r_T}(m)	σ_{r_W}(m)
At $t=t_o$ (maneuver start)	94	38	125	67
At $t=t_o$ + 117.8s (maneuver end)	780	116	125	90
At $t=t_o$ + 1/2 SPOT orbital period	52	23	55	68

The bias being coupled together, their rapid identification is not easy, but about 10mn after the maneuver they are already restituted by the filter to values very close to the actual ones, as shown in figs. 3-5.

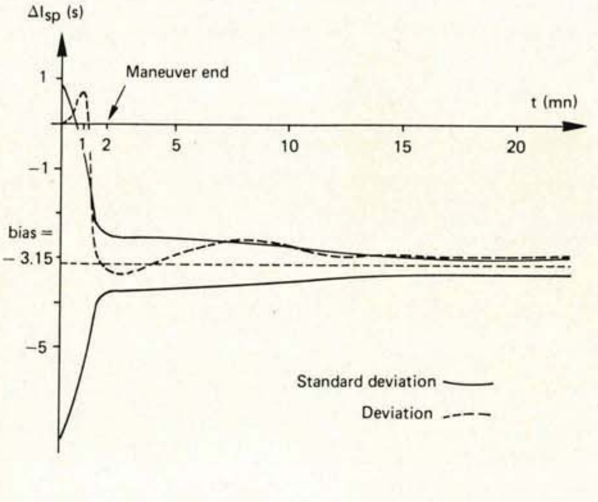

Fig. 3 – Identification of bias ΔI_{sp}

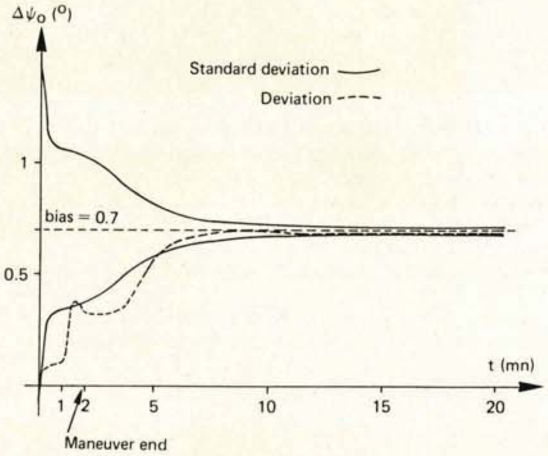

Fig. 4 – Identification of bias $\Delta\psi_O$.

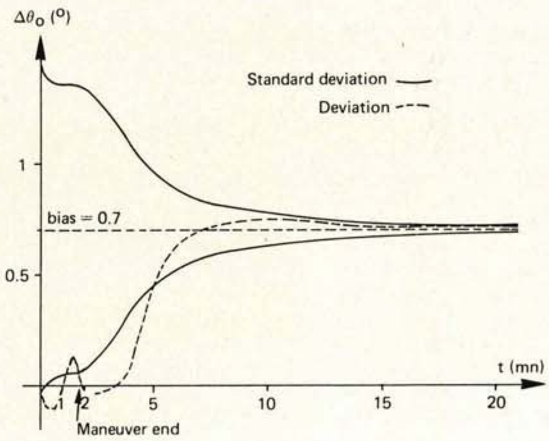

Fig. 5 – Identification of bias $\Delta\theta$.

4. CONCLUSION

These applications outline the interest of the DRS use for LEO orbit determination.

A method for evaluation of the associated accuracy performance has been carried on through numerical simulation involving noisy measurement generation and their treatment by Kalman filtering.

The flexibility of the presented modelling for state evolution and various errors allows to easily study the influence on the orbit determination accuracy of the main parameters such as : DRS number, spacing and localization accuracy ; measurement quality, type and frequency ; model complexity level, etc... in various problems of LEO onboard localization via DRS.

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