ICG – 3
Pasadena (CA, USA)
December 7-12, 2008

International Committee on Global Navigation Satellite Systems

GNSS Signals Use in a Mission to the Moon

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Rationale

- interest in lunar mission, need for navigation along the trajectory
- ground RF networks have high cost and limited availability
- autonomy, even only to reduce ground station coverage time, should be a great asset
- autonomous navigation is actually the key to allow for budget-limited microsatellite missions
- notice that optical navigation is not helping on this (cost + performances)
- any chance to exploit GNSS, which is now common solution for LEO?

- Examples of interest for currently designed small missions:

  ESMO and MAGIA

Background

- A number of studies available in literature – among them:

  C.C. Chao, H Bernestein, "*Onboard Stationkeeping of Geosynchronous Satellite Using a Global Positioning System Receiver*"

  G. Davis, M. Moreau, F. Bauer, J. R. Carpenter, "*GPS Based Navigation and Orbit Determination for the AMSAT AO-40 Satellite*"
  (experimental data up to 60000 km altitude)

  G.B. Palmerini, M.Sabatini, G. Perrotta *"En Route to the Moon Using GNSS Signals"*

  M.D.Lester *"GPS Navigation for Use in Orbits Higher than Semysynchronous a Look at the Possibilities and a Proposed Flight Experiment"*

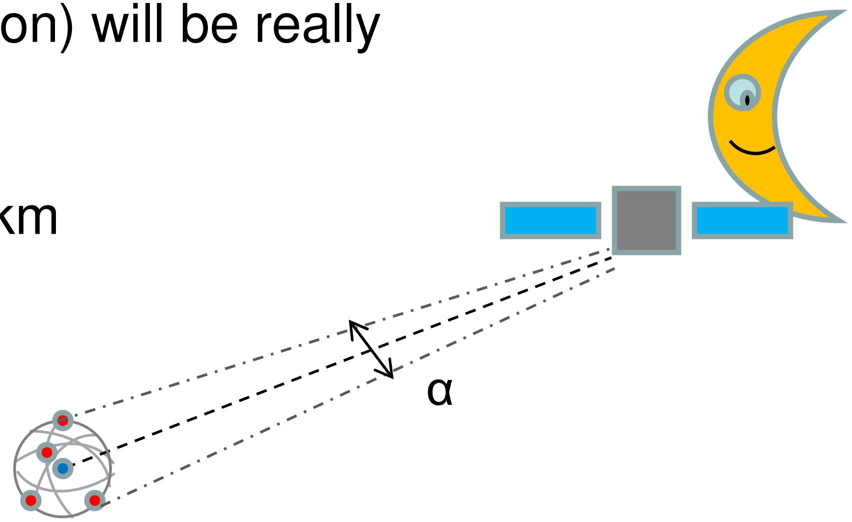
Limit # 1 : GDOP

- The expected error:

$$\sigma_{nav} = \text{GDOP}\ \sigma_{UERE}$$

- GDOP, depending on the separation between the sources (GNSS platforms) as seen by the observer (the spacecraft targeted to the Moon) will be really poor:
- GNSS orbits radius 25000 km
- Earth to Moon distance 350000 km

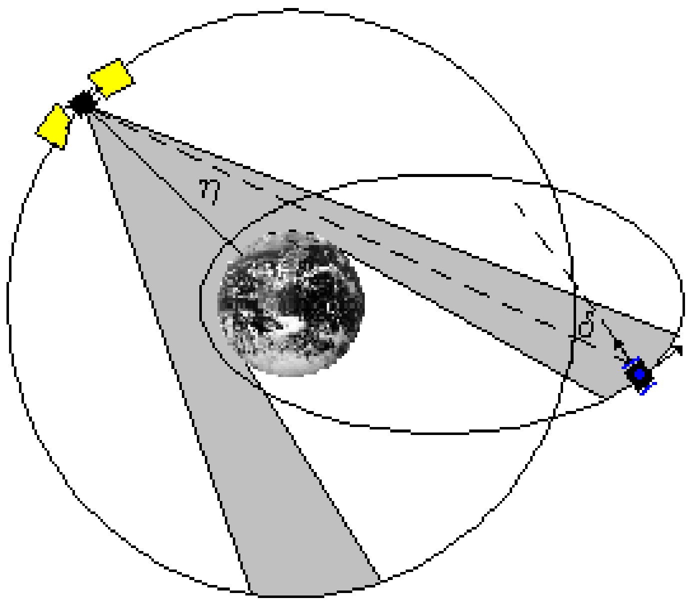
- Performance will deeply vary along the mission

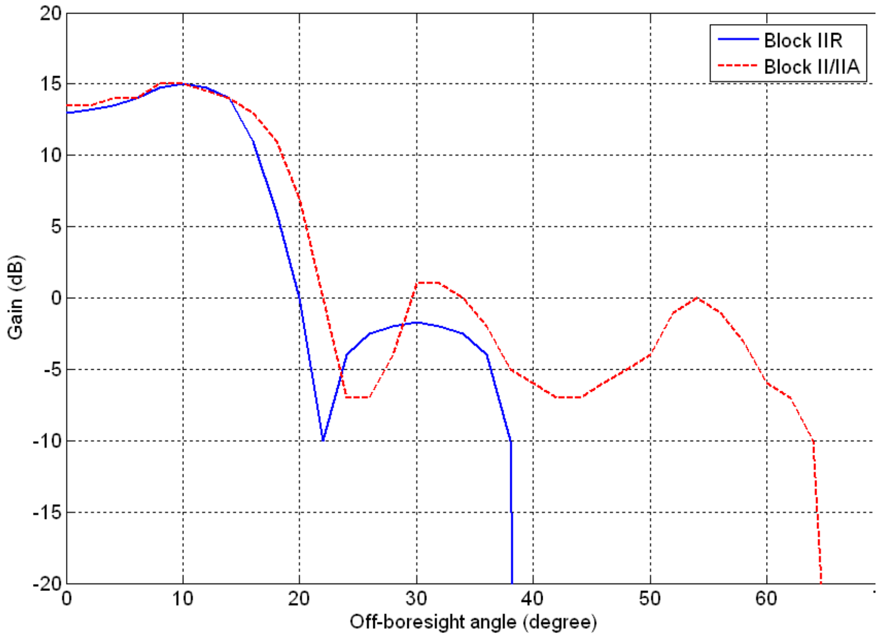


Limit # 2: Signal Availability

• As the altitude approaches GNSS MEO orbits (20000 km) the spacecraft does not exploit the main lobe

• Spill over of the satellite on the other side of the Earth can be used – Look-up mode should be switched to look-down





Note that results will change with the availability of SV belonging to different blocks and, of course, with new constellations operating

Limit #2 : Signal Availability

• The signal level decreases due to the very large path

$$P_r = EIRP + G_t(\eta) + L_D + G_r(\delta)$$

$$\boxed{L_D = 20\log_{10}\left(\frac{\lambda}{4\pi d}\right)}$$

• The resulting signal-to-noise ratio should be compared with a threshold level

$$\boxed{SNR = P_r - 10log_{10}T_{sys} + 228.6 + L_{Nf} + L_I \geqslant Rec_{Threshold} \; ?}$$

What a receiver can do?

Ok! In excess of requirements

Pre-flight test data for a LEO receiver

Accuracy, 3D, no SA:			
	Position	Velocity	Time
LEO	<10 m	<0.01m	<200ns
MEO	<30 m	<0.02m	<200ns
GEO	<150 m	<0.02m	<750ns
Dynamic Conditions			
Doppler Shift	60kHz		
Doppler rate	60Hz/s		
Sensitivity threshold			
Tracking	26 dB-Hz		
Acquisition	30 dB-Hz		
Time to First Fix			
Warm Start	<4 min		
Cold Start	< 8 min		

Low dynamics is expected

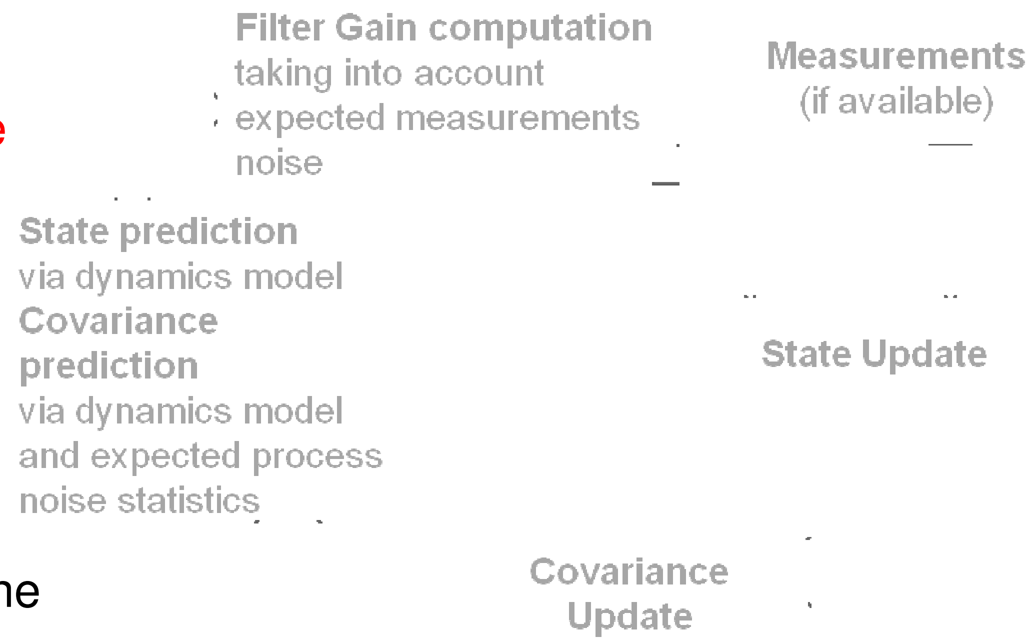
These figures can be assumed as representative for typical receivers

As for today, these figures look poor w.r.t. terrestrial HW Anyway, if requested (?), the almanac update function could be easily added

The advantage of the environment

- Quasi-equatorial orbital plane
- Low dynamics w.r.t. LEO case
- Need for an update of spacecraft kinematic state (position/velocity) between following available measurements

•The idea is to have an approach to be used all along the mission, i.e. no switch between propagation and navigation mode



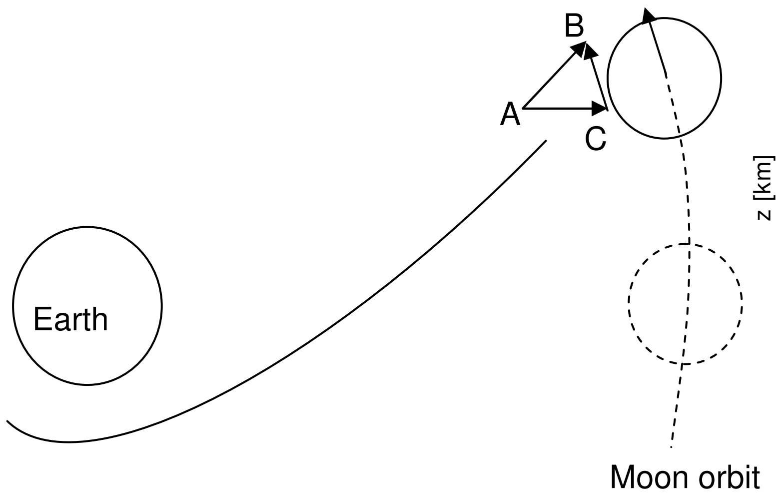
- Unscented Kalman Filter (UKF) has been selected
- Easy to adapt to orbital perturbation models (no Jacobinas required)

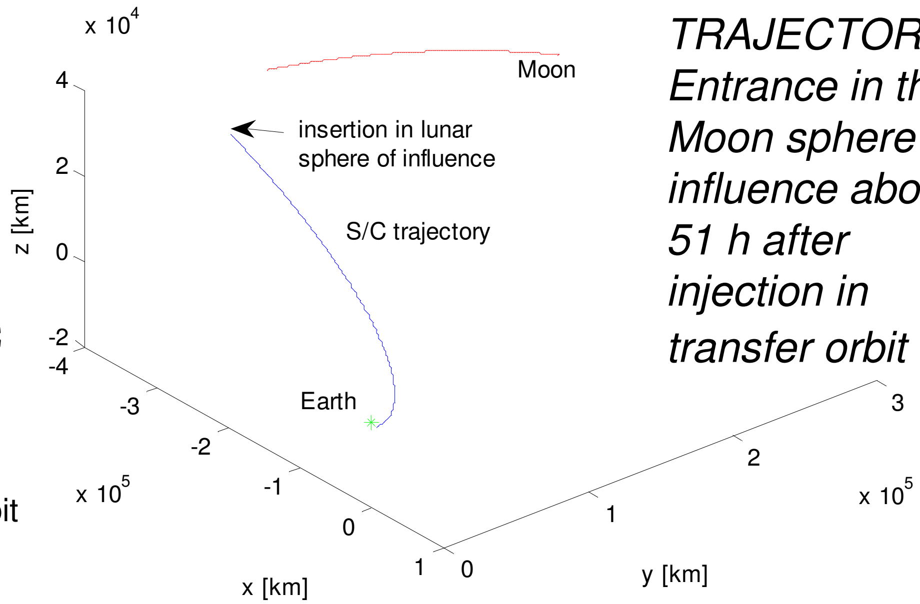
Trajectory (1) – Direct Transfer

• The S/C is injected from LEO to highly eccentric orbit with an apogee higher than Moon orbit radius

• When the S/C crosses the lunar sphere of influence, there is a switch of the attracting body

• Transfer parameters are computed according to patched conics technique



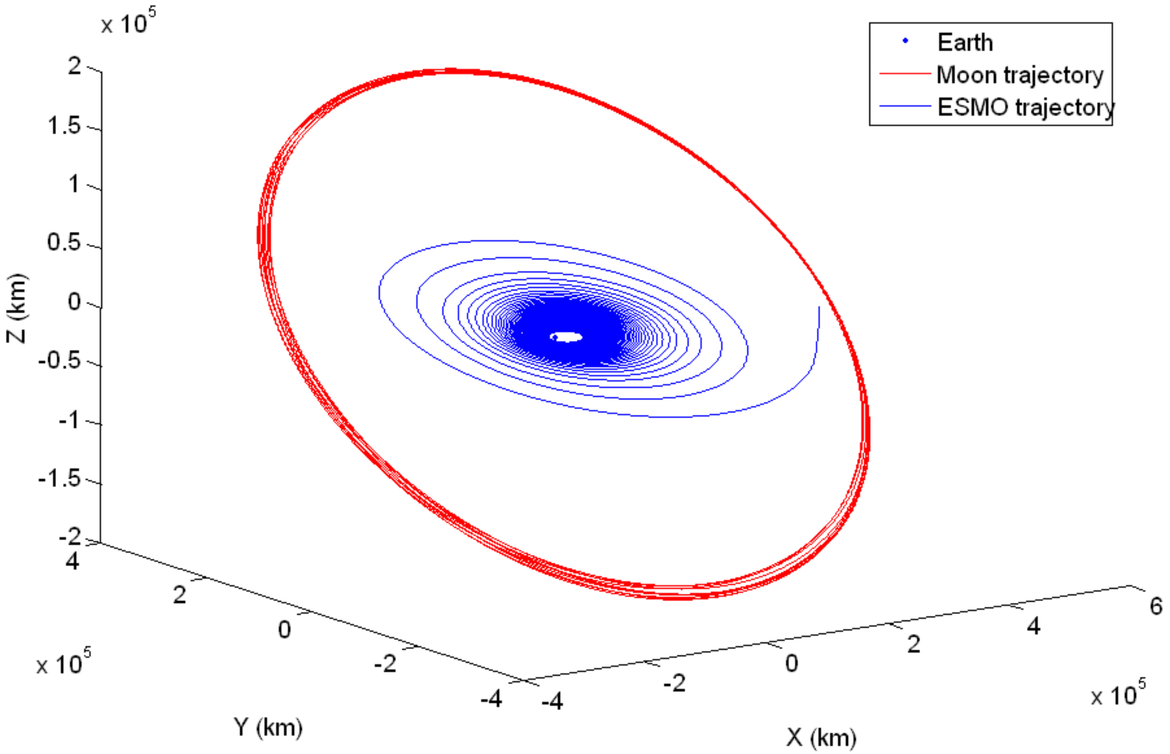


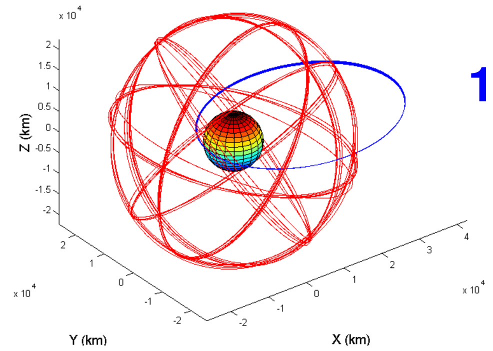
SIMULATED TRAJECTORY: Entrance in the Moon sphere of influence about 51 h after injection in transfer orbit

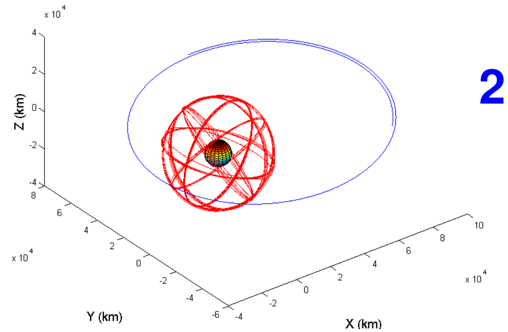
Trajectory (2) – Spiralling

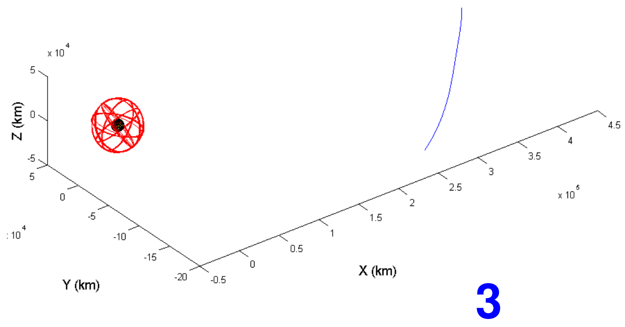
• To exploit electric propulsion is the appeal of this solution (example ESA's SMART-1 mission)

• The S/C, provided with Low-Thrusters, reaches the Moon via an extremely long cruise (about 9 months for simulated ESMO trajectory)





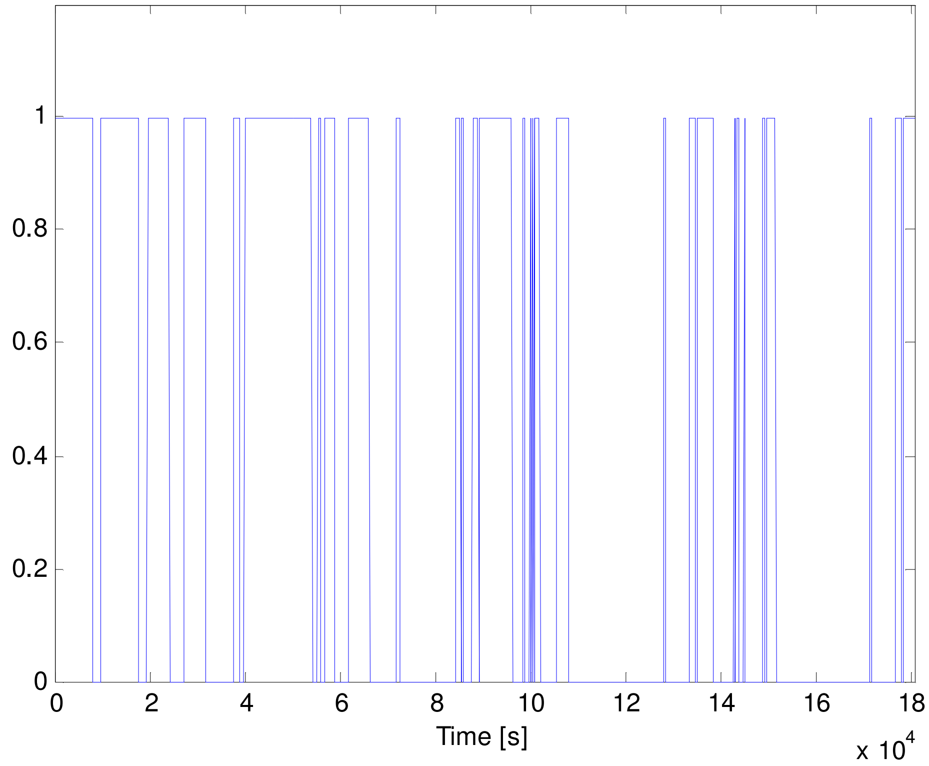




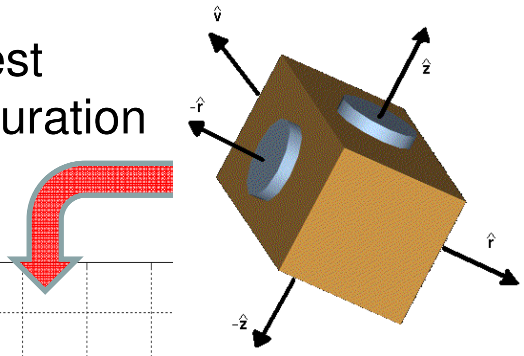
Findings

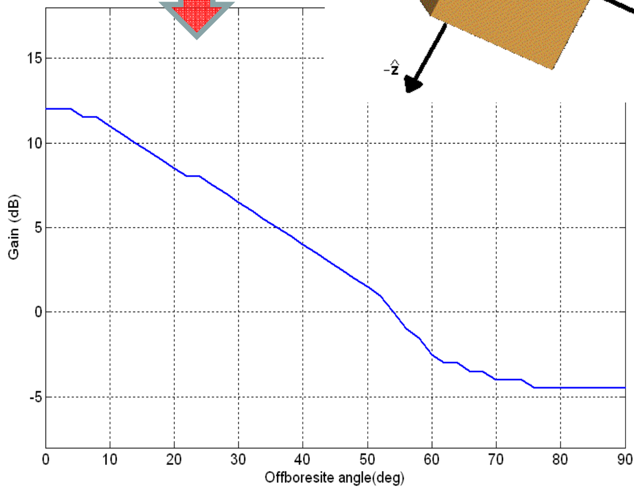
• Visibility flag [1=Ok (i.e. more than 4 platforms in visibility – SNR above the threshold) / 0 = Outage] gets worse as the distance from the Earth increases

• While GPS has been used for simulation, outages are still there if GNSS composite constellations are considered



S/C test configuration



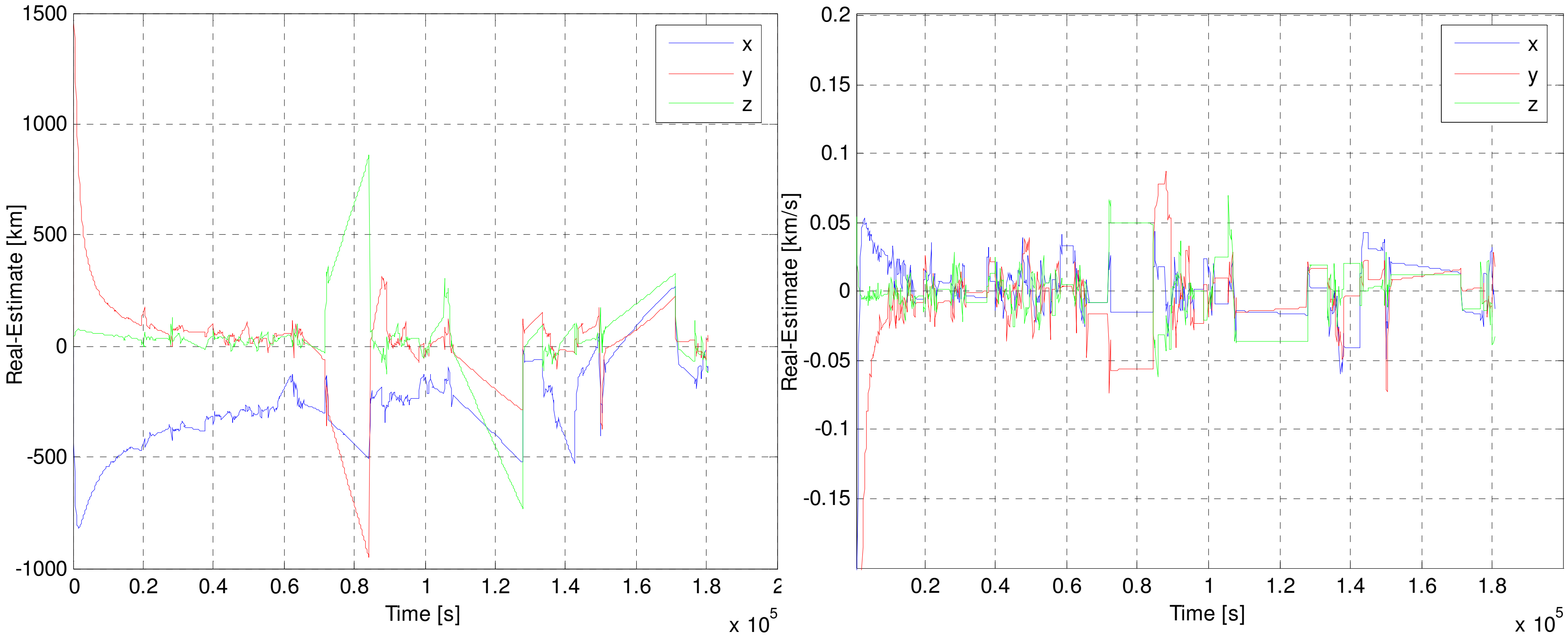


Findings (2)

- Results for direct transfer, up to Moon sphere-of-influence entrance

- Kinematic state autonomously available on board, even with really poor initialization and no filter tuning at all (to be improved w.r.t. trajectories of interest)

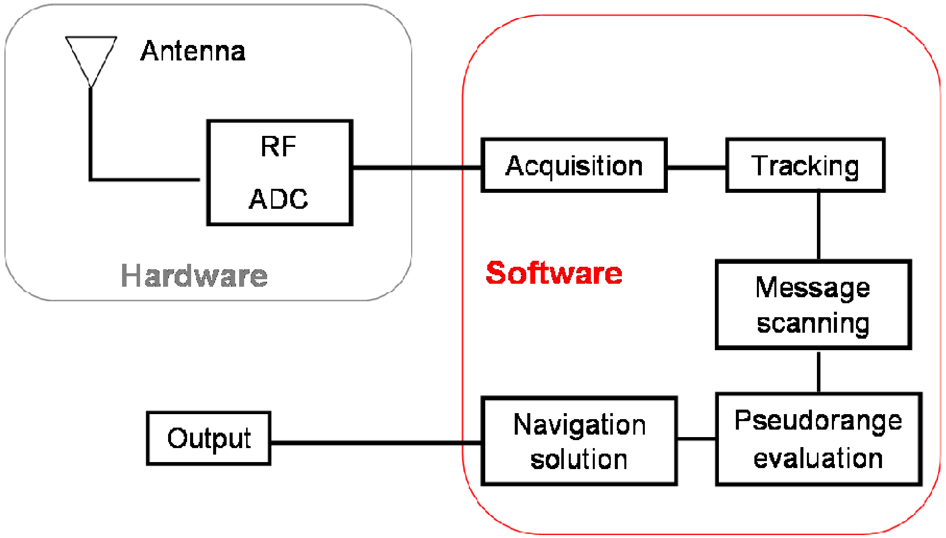
- **For low-thrust trajectories, simulations indicate a huge increase of the availability intervals when GALILEO is added to GPS**



Software Receiver

• An alternative to traditional receivers is represented by Software Receivers

• The idea is to carry out (extensive) data processing on a stream of bits which is obtained by ADC conversion of the incoming signal. All correlations performed by specific ICs are done by means of a software code, which is more flexible (and, as far as it concerns space application, can be repeatedly uploaded)



• Receiver threshold 10dB lower → the exploitable signals increase accordingly

• Real time issue → Ok during cruise !

Final remarks

• An autonomous navigation technique presents a great interest for “growing” lunar missions (especially “low cost” piggy-backed missions)

• Such a technique can be based on GNSS receiver, already a common solution for LEO on-board orbit determination

• Signals are weak, and long outages will be faced

• Performance are mission dependent, and can be ok in some case

• Due to the knowledge of the environment, a precise dynamic model can be prepared

• Combined use of GNSS system can greatly improve the performance