LISA Pathfinder: Acquisition of Signal Analysis after Launch Injection and Apogee Raising Manoeuvres

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The delivery of the S/C by the launcher into a Low Earth Orbit (LEO), followed by a series of long duration manoeuvres to guide it to its final operational orbit around L1 is a particular challenge for the signal acquisition. The complexity is explained by the fact that the dispersion of a launcher such as VEGA or Rockot greatly exceeds the 3dB (half-power) beam width of a 15m ESA network antenna in X-band. Furthermore, the S/C is flying over the short duration ground station passes equipped with a Low Gain Antenna of 9 dB gain variation, transmitting telemetry in low power mode and with an altitude varying from 200 to 1600km. The solution found to cope with a large orbit dispersion was to develop an X-band Acquisition Aid (XAA), small diameter antenna (1.2m) covering the full 3σ orbit dispersion area within its half-power beam width. However, such a small antenna is limited in its capability in acquiring a downlink signal. Given the specified LPF 200x1600km LEOP orbit and the S/C launch configuration (low power mode and high data rate), the signal strength received by the XAA is not sufficient to guarantee carrier recovery when the S/C altitude exceeds 630km. It should be noted that the orbit dispersion increases not only as a function of the antenna elevation, but also as a function of flight time. This underlines the necessity to accomplish the spacecraft initial acquisition as soon as possible using the available short station passes. The other issue is that once the 1st acquisition has succeeded and the orbit is known with enough accuracy, the S/C is brought to its escape orbit to L1 via a sequence of large main engine burns. If the full range of main engine performance 0% to 110%, is considered, this leads to significant time as well as azimuth shift of the acquisition of signal (AOS) location. This paper explains the mitigation measures found to optimize the acquisition of signal under the unfavorable conditions of a tight link budget and high orbit dispersion both after launch injection and each main engine burn.

I. Introduction

The purpose of the LISA Pathfinder (LPF) mission is to flight test key technologies critical for the future space cornerstone mission Laser Interferometer Space Antenna (LISA). LISA is a co-operative mission between ESA and NASA to detect and measure the interplanetary gravitational waves, whose existence has been predicted by Einstein in 1915. LISA Pathfinder is a satellite in the 0.5 tonnes class planned for launch in the second half of 1014; its target operational orbit, selected to enable validation of the on board technological experiments, is a large-amplitude libration orbit around L1, the Lagrange point between Earth and Sun at a distance of approximately 1.6 million kilometres from the Earth.

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System trade-off studies in conjunction with programmatic and economic considerations, resulted in the adoption of X-band for the space link communications during all phases of the mission (LEOP, Transfer and In-Orbit) and in the selection of VEGA (Baseline) or Rockot (Backup) as launcher of the satellite. As a result, instead of a direct injection to L1, the S/C will first be launched into an Low earth orbit (LEO). From there, it will execute a series of large apogee raising manoeuvres which will gradually increase the apogee altitude from the initial 1600 km to approximately 124000 km; a final manoeuvre will then inject the composite (satellite and attached propulsion module) into the planned transfer trajectory towards L1.

As far as the first acquisition in LEOP is concerned, the use of X-Band downlink brings new risks in respect to previous S-Band supports, due to the reduced antenna 3dB beam-width i.e. 0.60 deg for a 15-m in S-band and only 0.16 deg in X-band. Additionally as opposed to direct injection, the use of VEGA or Rockot as a launcher implies a larger dispersion area after launch injection, introducing a greater risk for the first signal acquisition.

Considering the growing use of X-Band in LEOP for future missions, ESOC decided to equip the LEOP 15m ground stations with an X-Band Acquisition Aid (XAA) (see Ref. [5], Ref.[6]). The XAA is an antenna with small diameter (1.2m) and consequently with large antenna 3dB beam-width (1.5 deg), used to acquire the X-Band downlink, auto-tracking the satellite based on the same signal and steering the 15m antenna pointing until achievement of acquisition and autonomous tracking.

In theory, and if the link budget margin is sufficient, the XAA is able to acquire the X-Band downlink with a dispersion in the predicted pointing of up to ±0.75 deg with a 3 dB off-pointing loss and up to ±1.0 deg with a 5.3 dB off-pointing loss.

However, such a small antenna is limited in its capability in acquiring a downlink signal at high S/C altitude. This paper based on Ref. [1] analyses the XAA performance in the context of the LISA Pathfinder S/C during its launch and early orbit phase and proposes mitigation measures to drastically reduces the risks related to the first acquisition both after launch injection and after each apogee raising manoeuvre.

II. First Acquisition after Launch

A. Link Budget

In view of the low spacecraft perigee (200 km) during LEOP, the S/C requires the introduction of two transmit power levels. A high power mode of RF is used for nominal on-station operations and for the higher altitudes during LEOP, whilst a low power mode is used during the lower altitudes of LEOP so as to comply with ITU power flux density limits. The S/C supports three data rates: high (120 ks/s), medium (60 ks/s) and low (1 ks/s) data rates. The modulation scheme for the high and medium rate telemetry is direct phase modulation of the carrier while the low data rate is phase modulated on a 32 kHz subcarrier.

Carrier signal acquisition is achievable if signal to noise ratio (C/N) in the Phase Locked Loop (PLL) is greater than 10 dB at the maximum off-pointing from the antenna bore-sight.

$$C/N \geq 10 \text{ dB} \quad + 3 \text{ dB margin} \tag{1}$$

with

$$C/N = \text{EIRP} - \text{Propagation Loss} + G/T - k - \text{Pointing Loss} - 2BL \tag{2}$$

where

- C = Signal - Carrier Suppression
  LPF carrier suppression = 8.6 dB in High Data Rate TM
- N = No * 2BL; No = k T = noise density with k being the Boltzmann constant
- EIRP = -20.34 dBW in S/C low power mode
  considering the minimum gain of the LGA (worst case scenario)
- G/T = 17 dB/K, figure of merit of the XAA
- Pointing Loss = 3dB covering 3σ Launcher dispersion of $\pm 0.75^{\circ}$
- 2BL: double-sided noise bandwidth of the Phase Lock Loop (PLL).
  It can take the following discrete values: 10 Hz, 30Hz, 100Hz, 300Hz, 1000Hz and 3000 Hz

When the S/C altitude increases, the decrease in the received power "C" from the spacecraft due to the propagation loss can be partly compensated by reducing the ground station receiver PLL bandwidth (2BL) and therefore decreasing the noise level "N" such that the ratio C/N stays the same. But this is possible only up to a certain limit and will work only if all the resulting constraints are fulfilled.

For LPF and for the visibility passes close to perigee, this paper demonstrates that the constraints related to the required PLL bandwidth size are met. However for the visibility passes occurring close to apogee, decreasing the noise "N" at the required level cannot be done without violating one of the constraints. Mitigation measures have been found and are explained below.

As illustrated in Figure 1, the selection of a small PLL bandwidth (2BL) imposes constraints on the maximum supported S/C apparent acceleration (Doppler rate). Besides the Doppler rate that needs to be accommodated, the loop bandwidth will also determine the time needed by the ground receiver to acquire lock. This time must be smaller than the visibility period of the S/C within the beam of the parked antenna.

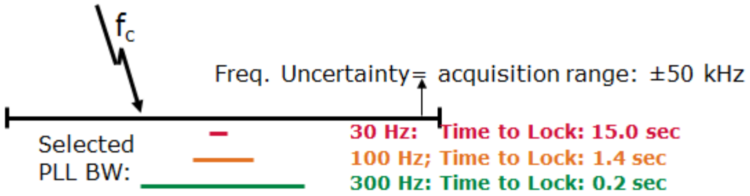


Figure 1. PLL Bandwidth selection and impact on supported Doppler Rate

These two constraints are analyzed below in more detail.

B. Maximum Apparent Acceleration Condition

For a second order PLL, the modeling of the maximum supported Doppler rate for a given PLL bandwidth is given by Gardner (see Ref [10]) as:

$$\Delta w = \tfrac{1}{2}\, w_n^2 \; (1 - 2 / \mathrm{sqrt}(SNR_L)) \qquad (3)$$

$$df_C/dt \; \leq \; \Delta w / 2 \pi \qquad (4)$$

with

$$2BL = w_n \,(\xi + 1 / 4\xi) \qquad (5)$$

where SNR_L is the signal to noise ratio in the loop, f_C is the downlink carrier frequency, w_n is the PLL loop natural frequency (rad/sec) and $\xi = 0.7$ is the damping factor of the XAA loop.

The maximum supported S/C apparent acceleration ($a_{S/C}$) is then calculated as:

$$a_{S/C} = (df_C/dt\,) \;\; * \; c / f_C \qquad (6)$$

with c = 299792.458 km/s ; velocity of light and f_C = 8.495 GHz is the LPF downlink frequency

Based on link budget equations (1) and (2), the maximum value of the tracking receiver loop bandwidth (2BL) is calculated for any possible S/C slant range at acquisition, assuming the LPF transmitting TM is in the high data rate mode.

From this given loop bandwidth, the maximum supported Doppler rate and maximum related apparent S/C acceleration are calculated from equation (6) taking into account the constraint specified in equation (4).

Slant Range at 5 deg elev. (km)	S/C altitude (km)	Max. PLL BW (Hz)	C/N (dB)	Max. supported Doppler rate (Hz/s)	Max. Supported apparent S/C Acceleration (m/s^2)	Time to lock for a freq. uncertainty of ±50 kHz (s)	Comment
1150	200	300	15	4212	149	0.2	perigee
1400	270	300	14	3744	132	0.2	
1410	273	100	19	537	19	3	
2400	630	100	14	419	15	3	
2410	635	30	19	49	2	15.1	
4268	1600	30	14	38	1	15.1	apogee

Table 1: Max. PLL BW & Doppler Rate (LP, HDR, 3dB pointing loss)

Figure 2 (see Ref. [2]) shows that the constraint on maximum Doppler rate is met for the first 3 Kourou visibility passes (i.e. the three left most sets of points in blue in the graph). This constraint is also met for the 4th and 5th passes in Kourou at an elevation slightly higher than 5 deg.

This Figure also shows that this constraint is not met for the first two passes in Perth when the S/C is closer to the apogee. The reason is explained by the fact that for slant range above 2400km, the required PLL bandwidth (in HDR mode) must be below 30 Hz to achieve a 10 dB SNR in the PLL loop with a 3 dB margin (see Table 1). Therefore the S/C apparent acceleration must stay below 2 m/s^2 (see Table 1) to allow the PLL to maintain the lock of the downlink signal frequency. For LPF, this constraint is not met for a S/C slant range above 2400km in high data rate.

A mitigation measure is explained later in this paper that, if adopted, would allow (in theory) the signal acquisition via the XAA tracking receiver configured with a minimum PLL bandwidth of 100Hz for a S/C slant range up to 4300km i.e. allowing the acquisition in Perth (at apogee) within a given maximum S/C off-pointing.

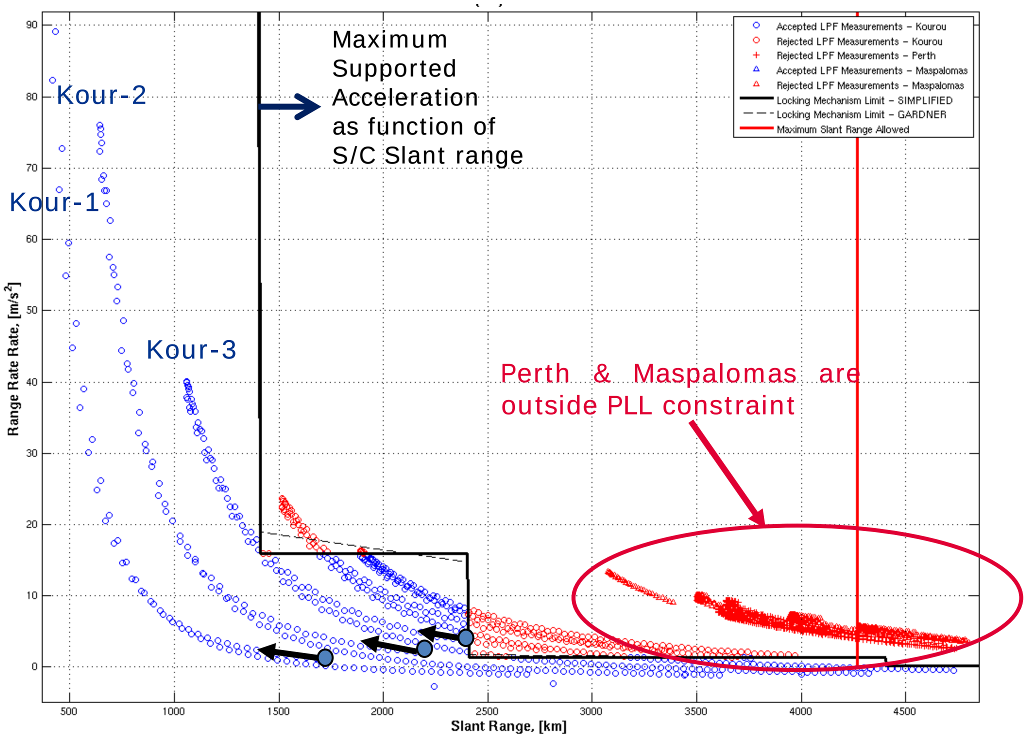


Figure 2. S/C Apparent Acceleration as function of Slant Range

C. Acquisition Time Condition

The second constraint that should be checked is related to the required time to lock and successful auto-tracking.

The S/C should be visible to the XAA's fixed beam long enough for the ground station receiver to lock and start the auto-tracking of the downlink signal. That is enough time to

- lock on to the downlink signal
- switch to the auto-track mode
- accelerate the antenna from a fixed position to the S/C velocity to maintain the lock.

The time required by the ground receiver to perform the above three actions is reported in the Table below:

PLL BW (Hz)	Time to Lock (s)	Time to switch to auto-track mode (s)	Time to move the antenna (s)	Total Time required by the receiver to lock & auto-track (s)
300	0.2	0.2	0.2	0.6
100	3	0.2	0.2	3.4
30	15.1	0.2	0.2	15.5

Table 2. Ground Receiver required time to lock and to track the downlink signal (±50kHz) after FEC improvements

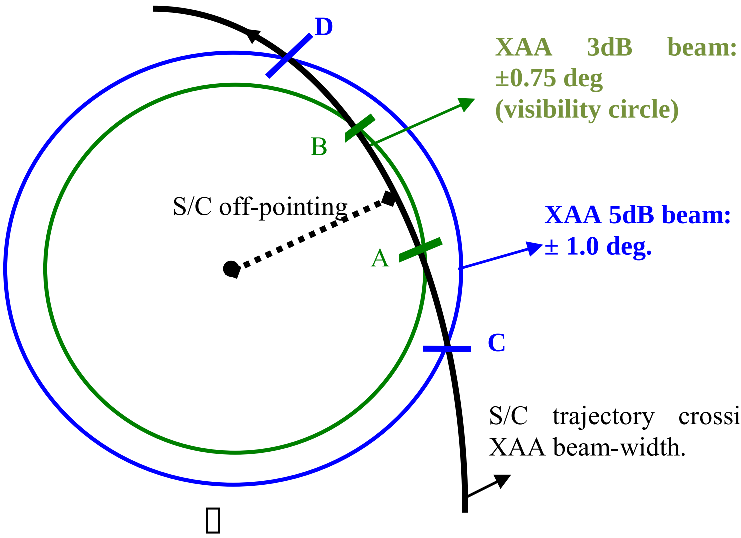
The above Table assumes that some antenna FEC software improvements have been implemented. Namely that the acquisition in Park mode can be performed in PRESET mode to avoid 2s of delay to release the brakes. It also assumes that the FEC's 2s monitoring cycle is reduced to only 0.2s to minimize the delay in recognizing a successful lock. For the ESA antenna supporting an azimuth acceleration of $7.5^o/s^2$ and an elevation acceleration of $2.5^o/s^2$, the time to accelerate the antenna to an angular rate sufficient to keep the downlink within the antenna beam width is negligible.

The acquisition in Park mode is needed for LPF because the along track error, as seen from the ground station (e.g. Kourou), can largely exceed the half power beam-width of the XAA. In 'Park Position' mode, the Front End Controller (FEC) positions the antenna at an operator defined position along the track (typically at 5 deg. elevation) and waits until the spacecraft signal is detected and the auto track mode can be used. The error along the orbit is then mainly absorbed by the fact that the antenna is waiting for the S/C to rise above the horizon; a late or early arrival caused by along track error will not affect the acquisition.

The Doppler shift at perigee can reach a value as high as 200 kHz which would lead to a large downlink frequency uncertainty and therefore an unacceptable acquisition time of the receiver. The above "Time to Lock" figures (as calculated in Ref. [4]) assume that the XAA & FEC systems in the ESTRACK have been upgraded to compensate for the Doppler shift by Doppler pre-steering based on ephemeris data. This Doppler compensation allows the acquisition range to be reduced to ±50kHz.

In order to guarantee a successful acquisition, the time required by the receiver to lock and go to auto-track mode (as reported in Table 2) must be shorter than the visibility duration of the S/C in the beam of the parked XAA.

This second constraint leads to a limitation on the maximum supported pointing error (or maximum supported cross-elevation offset) of the S/C as seen from the antenna bore-sight. The smaller the cross–elevation offset of the flying S/C, the longer the S/C will stay visible in the beam of the parked antenna (see Figure 3).



The antenna beam is in Park waiting mode during LPF acquisition.

The maximum S/C off-pointing must be well within the antenna tracking range in order to ensure a positive acquisition time.

S/C trajectory crossing the XAA beam-width.

Figure 3. Illustration of the S/C travel time while crossing the beam of the fixed XAA

The travel time of the S/C in the tracking range of the antenna depends on the given beam-width. For this analysis, two values of the XAA beam-width have been considered:

- a 3dB beam-width of the XAA defining a total tracking range of $\pm 0.75^{\circ}$
- a 5dB beam-width of the XAA defining a total tracking range of $\pm 1.0^{\circ}$

The S/C travel time is a function of the S/C angular rate. The S/C angular rate (as taken from Ref. [2]) varies between 0.10°/s at apogee and 0.16°/s at perigee during the acquisition period between 5° and 10° elevation.

The maximum supported cross-elevation error is reported in Table 3 as a function of the required S/C travel time in the XAA beam-width considered here (3 dB and 5 dB beams):

PLL BW (Hz)	Total Time required by the receiver to lock & auto-track (sec)	3dB beam: max supported cross-elevation error (deg)		5dB beam: max supported cross-elevation error (deg)	
		Apogee Cond	Perigee Cond	Apogee Cond	Perigee Cond
300	0.6	0.75	0.75	1.0	1.0
100	3.4	0.72	0.70	0.98	0.96
30	15.5	none	none	0.63	none

Table 3. Maximum supported cross-elevation error as function of the S/C travel time (±50 kHz)

The analysis of this second constraint shows that if the proposed FEC software improvements are implemented, a pointing error of up to $\pm 0.70^{\circ}$ can be supported by the ground receiver over the entire 200 x 1600km considering a 3dB pointing loss if the PLL bandwidth can be set above 100Hz.

In conclusion, the above worst case analysis has demonstrated that the downlink signal acquisition by the ground station is possible with the actual baseline (low power mode and high data rate) at a link budget point of view, as long as the S/C slant range falls below 2400km corresponding to a S/C altitude of 630km altitude at 5 deg elevation. In the current VEGA launch scenario, this translates to a successful acquisition over Kourou for the first 3 ground station visibility passes after launch injection.

It has also been simulated (see Ref. [2]) that the radiometric data from the two first Kourou passes, with a processing time of 2 hours, will allow flight dynamics to provide the ground station with S/C ephemeris prediction accurate enough for the 15m acquisition from the Kourou 4th visibility pass. Therefore we have demonstrated that the Kourou station is sufficient to perform the 1st acquisition via the XAA with the current launch configuration i.e. in low power mode and high data rate, for a maximum dispersion of ±0.70deg.

As the above solution relies exclusively on Kourou, risk mitigation measures are studied to add redundancy to the Kourou station and to provide a robust ground station network able to support both Rockot and VEGA launch scenarios.

III. Mitigation Measures for 1st Acquisition after Launch

D. Set S/C TM in Low Data Rate

As shown in Figure 2 and Table 1, the link budget is not sufficient to guarantee the AOS for a ground station pass with a S/C slant range above ca. 2400km (i.e. 630km altitude at 5 deg elevation) in the current launch S/C configuration (low power mode, high data rate).

A mitigation measure to solve the above problem is to set the S/C data rate to the low data rate (1 ksps) instead of to the high data rate (120 ksps). This proposed measure would increase the power in the carrier by +4.8 dB because the carrier suppression would be reduced from 8.6 dB in HDR to only 3.8 dB in LDR (no ranging).

The following Table shows that in the low data rate mode, the S/C can be acquired with a PLL as large as 1000 Hz up to a S/C slant range of 1450 km, a 300Hz PLL can be used up to ca. 2650km slant range and finally a 100Hz PLL bandwidth can be used up to ca. 4660 km slant range which easily includes the LPF apogee.

Slant Range at 5 deg elevation (km)	S/C Altitude (km)	Max. PLL BW (Hz)	C/N (dB)	Max. supported Doppler rate (Hz/s)	Max. Supported apparent S/C Acceleration (m/s2)	Time to lock for a freq. uncertainty of ±50 kHz (s)	Comment
1150	**200**	**300**	**20.2**	**5130**	**181**	**0.2**	
1150	200	1000	15	45600	1611	0.1	Perigee
1450	285	1000	13	39000	1377	0.1	
1460	288	300	18	4800	169	0.2	
2650	740	300	13	3500	124	0.2	
2660	744	100	18	523	18	3.0	
4295	1616	100	13.5	410	14	3.0	Apogee
4660	1843	100	13	385	13	3.0	
4670	1850	30	18	48	1.6	15.1	
8400	4600	30	13	35	1.2	15.1	

Table 4: Maximum PLL Bandwidth and Doppler Rate for given S/C slant range. LP, LDR and 3dB pointing loss are assumed.

This increase of the PLL bandwidth at apogee from 30Hz to 100Hz in LDR allows the S/C apparent acceleration to stay within the given constraint (i.e. to stay below $14 m/s^2$). As a result, the carrier recovery acquisition is possible in LDR over the entire LPF LEOP orbit (both for Rockot 200 x 900 km and for VEGA 200 x 1600km).

As the power of the carrier is increased by +4.8dB when using the LDR mode, a check has to be performed on the Power Flux Density (PFD) limits imposed by ITU regulations. Contrarily to the link budget which assumes a minimum gain of the antenna (-1.6 dBi), the PFD limits must be calculated assuming the maximum gain of the LGA (+7.5 dBi).

In that case, the PFD in Perth (1619km altitude at 5 deg elevation) in low power mode and in low data rate reaches a value of $-155 dBW/m^2$ which is below the maximum ITU allowed value of $-150 dBW/m^2$. So during the Perth pass, this additional power in the carrier would not cause a violation of ITU regulations.

But if we keep the same S/C configuration over the whole orbit, the PFD at perigee (200km altitude) would be as high as -128dBW/m^2 (at 90 deg elevation and assuming maximum antenna gain). This would exceed the ITU limit by 12dB.

Therefore in order to stay within ITU regulation, the S/C TM will be reset to the high data rate as soon as the S/C falls below 670km altitude. This can be done via time-tagged command in the on board Mission Timeline. It has been checked that there is no ITU violation in low power mode and low data rate up to a S/C altitude of 670km at 5^o elevation (i.e. 2500km slant range).

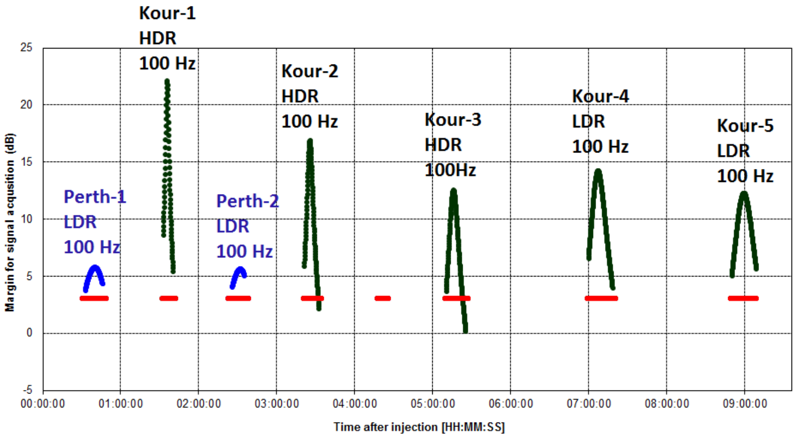


Figure 4. Carrier Recovery Margin as function of Time since Injection. LP, LDR is used when S/C slant range is above ca. 2400 km at 5 deg elevation

E. Set S/C in High Power Mode

In case the acquisitions in Perth and Kourou fail, despite the above mitigation measure, a fall-back solution would be to add an on board time-tagged command to automatically switch the S/C to high power mode. The S/C EIRP would increase by 21 dB. This will allow the XAA to be used up to its full ±1deg acquisition range in combination with the search functionality[7] (contingency case). This time-tag command will be disabled after a successful acquisition during the first orbits.

However when the S/C is set to high power mode it should be checked that the station equipment does not become saturated. The maximum signal level at 200km altitude of a zenith path would be ca. 10 dB above the saturation limit of equipment for a 15m station. Therefore, if the S/C enters in high power mode at altitude below 700km, either due to a safe mode or via a time-tag command, a contingency procedure will need to be put in place at the ground station to solve the saturation issue of the equipment.

F. Use ESTRACK Spiral Search in X-Band

Another alternative to the XAA link budget issue when the S/C slant range exceeds 2400km is to use the search functionality offered by the ESTRACK 15m antenna. The XAA search would also be needed in case the S/C off-pointing exceeds the XAA acquisition range, due to non-nominal launcher dispersion.

The present search strategy consists of a primary and a secondary search (Figure 5). During the primary search, the antenna is moved in a spiral pattern to cover the area of the search zone. The tracking receiver signal level is sampled at each point in the search area, and as soon as a signal above a pre-defined threshold is detected, the primary search terminates. A secondary search then commences, centered on this point. The purpose of this search is to determine whether the above-threshold signal was on the main or a side lobe.

After completion of the secondary search, the FEC switches the antenna to auto-tracking.

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[7] The Search with the XAA can only work for LPF if the S/C is set to the high power mode

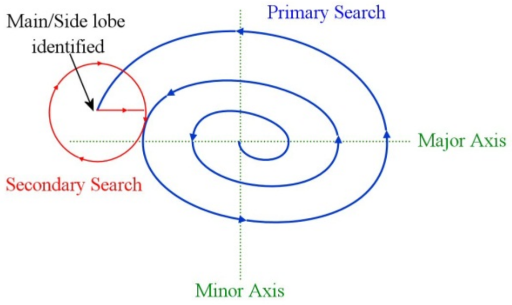

Figure 5: Search pattern used by the present spiral search algorithm.

It is clear that the search has to successfully terminate before the S/C leaves the elliptical scan areas. This performance requirement is particularly challenging for a near-Earth S/C such as LPF. The S/C angular velocity at AOS (between 5 and 10 deg elevation) varies between 0.10 deg/s at apogee and 0.16 deg/s at perigee. This leads to a maximum search duration roughly between 8 and 30 sec, depending on the selected scan area and S/C angular velocity.

Currently, if no improvement is implemented, a search in X-Band is estimated to take at least 5 minutes which is much too long to cope with LPF angular velocity. It is therefore proposed to increase the rapidity of the existing search in the ESTRACK 15m in the following two ways:

1. to optimize the antenna search movement by implementing the primitive movement functions in the antenna control unit (ACU) instead of the front end controller.

2. to allow the user to cancel the on-going search process and continue in Auto-Track mode with the results obtained so far. This second enhancement is particularly important for the search with the XAA antenna as the signal detection with the 1st side lobe is very unlikely. Therefore a secondary search to discriminate the lobe is not required for the XAA.

It has been demonstrated that the total time required by the 15m spiral search in PLL mode can be reduced from ca. 5 minutes to only 60 seconds if option 1 is implemented. If the secondary search can be disabled, the duration of the search would further reduce to between 13 and 23 seconds. It has also to be noted that the search via the XAA, which can only be successful when the S/C is switched to high power mode, will also directly benefit from the above proposed improvements.

G. Add a Ground Station at the Equator

As shown in Figure 6, Kourou (in red) is the primary station for the majority of the insertion orbits viewing the S/C at each orbit, while Perth (in black) and Maspalomas (in blue) have only limited visibility during the first 24 hours. The S/C elevation does not exceed 12 deg and 4 deg during Perth and Maspalomas passes, respectively.

Furthermore the radar stations from USSTRATCOM cannot be used to support LPF first acquisition (in VEGA launch scenario) due to the lack of visibility of these radars in the equatorial regions.

To avoid a single point of failure in Kourou during the first 24hours of the LEOP, adding a station is recommended.

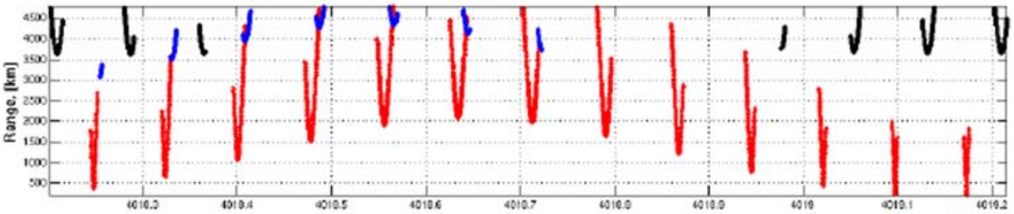

Figure 6: Ground Stations visibility defined with AOS/LOS at 0° for first 24hrs

Two possibilities are under investigation. Either to use an external station or to perform an ESA internal development. The location has to offer a good visibility of the S/C for both VEGA and Rockot launch scenarios. A location close to the equator has been identified as the best option.

IV. First Acquisition after each Main Engine Burn

In the VEGA baseline, the following sequence of apogee raising manoeuvres (see Ref. [7]) will be executed:

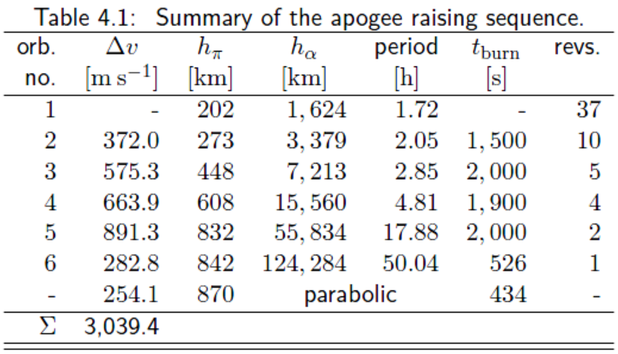

Table 4.1: Summary of the apogee raising sequence.

orb. no.	Δv $[\mathrm{m\,s^{-1}}]$	h_π [km]	h_α [km]	period [h]	t_burn [s]	revs.
1	-	202	1,624	1.72	-	37
2	372.0	273	3,379	2.05	1,500	10
3	575.3	448	7,213	2.85	2,000	5
4	663.9	608	15,560	4.81	1,900	4
5	891.3	832	55,834	17.88	2,000	2
6	282.8	842	124,284	50.04	526	1
-	254.1	870	parabolic		434	-
Σ	3,039.4					

Table 5: Apogee Raising Manoeuvres in case of VEGA Launch

The strategy to acquire the downlink signal after a very long main engine burn has to be carefully analyzed in order to re-acquire the S/C after any potential burn interruption or under/over performance. The difference in pointing between a 0% and a 110% burn performance greatly exceeds the 15m or even the XAA antenna half power beam-width of 0.16 deg and 1.5 deg, respectively.

During nominal operations, the pointing of the antenna is conducted by the Front End Controller (FEC) which reads its input from the most recent ephemeris file provided by flight dynamics.

Since the difference in pointing between a 0% and a 110% manoeuvre cannot be covered by a fixed waiting antenna, a dedicated antenna pointing ephemeris is needed to cover the entire spectrum of manoeuvre performance. This antenna motion cannot be represented by an orbit file and therefore not by an ephemeris file.

A manoeuvre interruption analysis (see Ref.[2]) has been performed to calculate the pointing profile to be followed by the antenna bore-sight. The underperformance of the 6 main manoeuvres was simulated by modeling the delivered ΔV during the manoeuvre ranging from 0 to 110%. After the manoeuvre, the trajectory is propagated until the spacecraft reaches an elevation of +5 deg in the local horizontal frame at Kourou, which is the first overflown ground station after each main engine burn. The resulting azimuth profile at 5 deg elevation (not following a Keplerian orbit) gives the “ideal” pointing of the ground station antenna bore-sight at any instant in time to be able to re-acquire the S/C with the highest probability after each manoeuvre.

As an example, the ideal pointing profile for the 2nd manoeuvre covering 0 to 110% manoeuvre performance is given below at 5 deg. elevation (see the red curve of Figure 7 as taken from Ref.[2]).

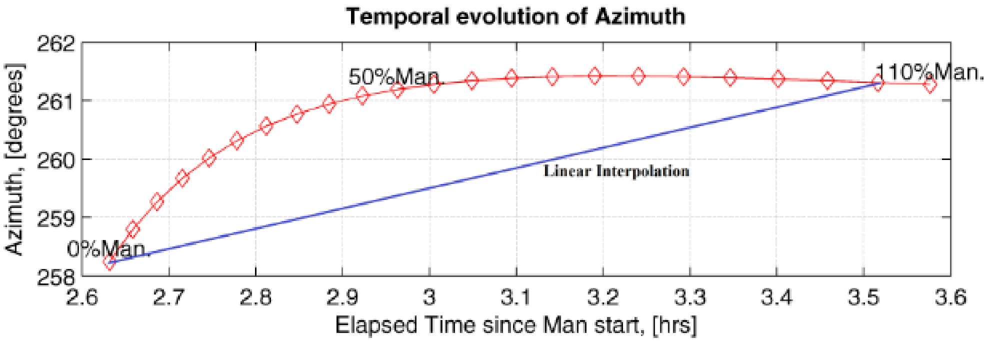

Figure 7: Ideal Pointing Profile and its linear interpolation (2nd Manoeuvre)

V. Solution for 1st Acquisition after each Main Engine Burn

This information on the antenna ideal pointing profile has to be passed from Flight Dynamics to the antenna controller. The proposed solution is to implement a new functionality in the FEC which would allow the FEC to perform a quadratic interpolation of 3 points extracted from the ideal pointing profile (at 0%, 50% and 100%).

The following Figure (Ref. [2]) demonstrates that the 2nd order interpolation effectively reduces the maximum azimuth pointing error for this second manoeuvre (worst case) to well within the field of view of the XAA.

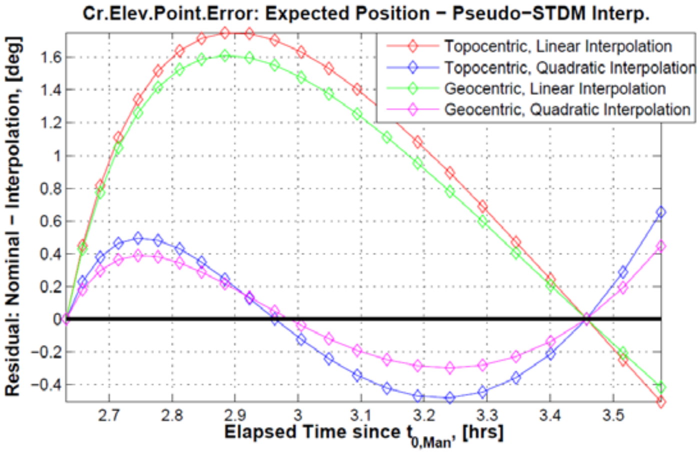

Figure 8: Linear vs Quadratic interpolation Accuracy (2nd manoeuvre)

It has been calculated that for the first four manoeuvres, the accuracy achieved by this interpolation meets the 3dB beam-width requirements of the XAA antenna while the acquisition after manoeuvres 5 and 6 can be achieved by the smaller beam-width of the 15m dish.

VI. Conclusion

In conclusion, assuming the above measures are taken, a robust solution with no single point of failure (on the ground network) has been developed to maximize the probability of acquisition of signal after launch injection with a supported cross-elevation error up to ±0.70 deg. This network is suitable for either a Rockot or VEGA launcher, and is robust to changes in the insertion strategy from either launcher (changing insertion location, argument of perigee, etc).

This upgraded network as recommended above has a performance equivalent or better than the standard S-band network used for the majority of ESA LEO missions, which have a capability to support cross-elevation error of between ±0.30 deg to ±0.65 deg following a launcher insertion.

A solution has also been found to re-acquire the S/C after each main engine burn, covering the whole spectrum of possible manoeuvre performance from 0 to 110%.

Appendix A

Acronym List

AOS	Acquisition of Signal
EIRP	Equivalent Isotropically Radiated Power
ESTRACK	ESA TT&C Stations
FEC	Front End Controller
HDR	High Data Rate
HP	High Power
LDR	Low Data rate

LEO	Launch Earth Orbit
LEOP	Launch and Early Orbit Phase
LGA	Low Gain Antenna
LPM	Low Power Mode
PRM	Propulsion Module
S/C	Spacecraft
SNR	Signal to Noise Ratio
XAA	X-Band Acquisition Aid

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