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1 INTRODUCTION

1.1 Scope of the Document

This Executive Summary gives an overview of the main conclusions drawn throughout the project. As such, it is structured in the same sections as work packages:

- Set up of system requirements
- System Architecture Trade-off and Selection
- System Design
- Roadmap and Cost Estimates

The most important section is that corresponding to System Design, as it describes in detail the subsystems and most important technical aspects of the selected architectures: Array of 4 x 35 meter antennas, and Array of 40 x 12 meter antennas. The target design parameter has been that of increasing current G/T and EIRP of ESA 35 meter DSAs by 6 dB.

All important design parameters, technological development efforts and cost estimates will be reported from the point of view of a comparison of both array alternatives. In this way, the reader will have a clear view of the pros and cons associated with each architecture, with the aim of having enough information so as to make a final decision.

1.2 Reference Documents

[RD 1]	**Performance Comparison of Selected Bandwidth-Efficient Coded Modulations.** K. Andrews, D. Lee, F. Pollara, and M. Srinivasan. IPN Progress Report 42-151. November 15, 2002.
[RD 2]	**High-Capacity Communications From Martian Distances**. NASA/TM–2007–214415
[RD 3]	**A vision for the Next generation Deep Space Network.** B. Preston, L. Deutsch, B. Geldzahler, JPL Next Generation DSN Meeting, 05/04/2006
[RD 4]	**Design of large steerable antennas**. Sebastian Von Hoerner. The astronomical journal. Vol 72, number 1. February 1967.
[RD 5]	**Panel options for large precision radio telescopes,** David Woody, Dan MacDonald, Matt Bradford, Richard Chamberlin, Mark Dragovan, Paul Goldsmith, James Lamb, Simon Radford, and Jonas Zmuidzinas, Proc. SPIE 7018, 70180T (2008), DOI:10.1117/12.788077
[RD 6]	**Pros and Cons of Using Arrays of Small Antennas versus Large Single-Dish Antennas for the Deep Space Network**. Durgadas S. Bagri. IPN Progress Report 42-174 • August 15, 2008
[RD 7]	**Optimizing the Antenna Size for the Deep Space Network Array.** J. I. Statman, D. S. Bagri. IPN Progress Report 42-159. 2004
[RD 8]	**Array antennas for the JPL/NASA Deep Space Network**. Jamnejad, V. Huang, J. Aerospace Conference Proceedings, 2002. IEEE.
[RD 9]	**Analysis & Specification of the Aperture Array System.** Andrew Faulkner & Paul Alexander. SKA technical documents. 2007.
[RD 10]	**Exploring the next generation Deep Space Network**. Imbriale, W.A. Weinreb, S. Aerospace Conference Proceedings, 2002. IEEE
[RD 11]	**The Technical scheme for FAST**. B. Peng, R. Nan. Perspectives on Radio Astronomy: Technologies for Large Antenna Arrays. ASTRON. 1999.

[RD 12]	**Large Reflector Uplink Arraying.** G. Patrick. SpaceOps 2010. AIAA 2010-2175.
[RD 13]	**NASA Plan for Development of Optical Communication for Space Applications,** John Rush and Ken Perko NASA, Space Communications and Navigation Office 15 May 2009
[RD 14]	**The Australian Centre for Space Photonics,** Andrew McGrath, Joss Hawthorn, Jeremy Bailey, Presentation to the NSSA, October 2003
[RD 15]	**NASA Space Communication and Navigation Architecture Recommendations for 2005-2030**, Space Communication Architecture Working Group (SCAWG)
[RD 16]	**SKA cost equation.** http://www.skatelescope.org/documents/skamemo1.html
[RD 17]	**Parametric Cost Analysis of NASA DSN.** B.E. MacNeal, W.J. Hurd. JPL. SpaceOps 2004.
[RD 18]	**Optimizing the Antenna Size for the Deep Space Network Array.** J. I. Statman, D. S. Bagri. IPN Progress Report 42-159. 2004
[RD 19]	**The effects of Correlated Noise in Intra-Complex Deep Space Arrays for S-band Galileo Telemetry Reception.** R. Dewey. TDA Progress Report 42-111. 1992
[RD 20]	**Weak-Signal Phase Calibration Strategies for Large DSN Arrays.** D. Jones. IEEE 2002.
[RD 21]	**The effect on Spacecraft tracking performance of using an array instead of a single dish for receiving.** D. S. Bagri. IPN Progress Report 42-172. 2008.
[RD 22]	**Pros and Cons of Using Arrays of Small Antennas versus Large Single-Dish Antennas for the Deep Space Network.** B. Durgadas. IPN Progress Report 42-174. 2008
[RD 23]	**Process Analysis and Design in Stamping and Sheet Hydroforming.** Ajay D. Yadav, "Chapter 7: Case studies in Stamping and Sheet Hydroforming," PhD Thesis, The Ohio State University, 2008.
[RD 24]	**SKA Memo 110.** Cost and power usage evaluations for the various processing architectures. A Hardware and Operational Cost Comparison of Two Architectures for Large Scale Focal Plane Array Beamforming and Correlation.
[RD 25]	**ADC & Uniboard in Nançay.** www.radionet-eu.org
[RD 26]	**Parametric Cost Analysis of NASA DSN**. B.E. MacNeal, W.J. Hurd. JPL. SpaceOps 2004.

2 SET UP OF SYSTEM REQUIREMENTS

Due to the asymmetry of the communications, i.e. availability of larger transmission power for the uplink and the need for higher data rates in the downlink, the focus of the study has been the increase of the reception capabilities of the ground station. Nevertheless, the requirements have also been established for the uplink.

In order to establish future requirements the following approach has been followed:

- Gather data about current performances of ESA Deep Space Antennas. For a 35 meter DSA the G/T ranges from 58 to 60 dB/K (10 to 90 degrees of elevation) in Ka-band, and from 51.5 to 52.8 in X-band.
- Gather future mission needs and characteristics in terms of data rate, EIRP and orbit. The main conclusion is that on-board antennas of 3-5 meters and HPAs of 200-300 Watts will be available in the long-term.
- Infer from mission data the ground segment G/T required to cope with future mission needs.

2.1 Future Mission Data Rates

The most important parameter about future missions is the data rate for the purpose of dimensioning the Ground Segment. Unfortunately, as mentioned earlier, consulted ESA documents about future missions were elaborated under the assumption that the ground segment was a 35m station. Hence, in order to come up with some useful data to work, several papers and presentations were consulted from several European and American companies, plus several projections made by NASA/JPL. The preferred mission type was one to Mars, as this seems to be the planet with more prospects of sending a manned mission in the future, and therefore where the data rate requirements will be higher. The results for several years, bands and mission types are summarized next.

		RF Data Rates per link		2010	2015	2020	2025	2030
DTE/DFE	Uplink	Emergency Rates (X-band: TBD)		-	-	7.6125 bps	70.8125 bps	2 kbps
		High Rates (Ka-band)	Robotic	-	-	TBD	TBD	TBD
			Human (Ka+)	-	-	TBD	TBD	TBD
	Downlink	Emergency Rates (X-band: TBD)		-	-	124.4 bps	504 bps	2 kbps
		High Rates (Ka-band)	Robotic	-	-	TBD	3.5 kbps	12 kbps
			Human (Ka+)	-	-	TBD	1 Mbps	1 Mbps
Mars Relay	Uplink	Emergency Rates (X-band)		7.8125 bps	10 bps	2 kbps	2 kbps	12 kbps
		High Rates (Ka-band)	Robotic	6 kbps	12 kbps	100 kbps	2 Mbps	8 Mbps
			Human (Ka+)	-	-	-	50 Mbps	50 Mbps
	Downlink	Emergency Rates (X-band)		120 Kbps	1.5 Mbps	4 Mbps	10 Mbps	10 Mbps
		High Rates (Ka-band)	Robotic	6 Mbps	6.4 Mbps	6.4 Mbps	125 Mbps	125 Mbps
			Human (Ka+)	-	-	-	125 Mbps	150 Mbps

Table 1. Data Rates Requirements for Mars

Another important mission parameter that will change in the future is the number of satellites and links per mission. Whereas the current situation is one mission, one satellite and one link, in the future there will be several satellites and links per mission, increasing the demands on the ground segment.

2.2 Future G/T and EIRP calculation

To calculate the required EIRP and G/T to cope with future missions, a dynamic method has been used. This method calculates the required G/T and EIRP in steps of 10 minutes for several years for a number of ground stations distributed around the globe, spacecrafts and data rates. In this way the variability in distance, weather conditions and ground station elevation is accounted for. The rational for this simulation compared to the classical one is:

- Not all the time the rain is that corresponding to 90% of the time. In fact rain probability distribution is modeled as a random variable whose distribution fits those given by ITU.
- Not all the time the satellite is at max distance. The orbit of the satellite is modeled and propagation losses are calculated in steps of 10 minutes
- Not all the time the satellite has visibility with a ground station. This is due to Earth occultation or destination planet occultation.
- At a time there can be more than 2 stations that can establish a link with a satellite. Several assignment policies can be chosen (best elevation, continuous pass, lowest link effort).

The simulations have been executed in Ka-band, because it is at this band where the bulk of communications will take place. At this moment, INSA does not have a detailed set of missions to be simulated. This is why a futuristic scenario has been made up, and we encourage ESA to review it or to provide a more detailed set of missions.

- Missions from 2010 to 2020. Total of 3: Mars, Venus and Jupiter
- Missions from 2020 to 2030. Total of 4: Heliocentric, Mars (6 orbiters, 1 rover), Venus and Jupiter
- Missions from 2020 to 2030. Total of 5 : Mercury, Venus, Mars (6 orbiters), Jupiter and Saturn

The main data of these missions are:

	Antenna Diameter (meters)	HPA power (Watts)	Mars Downlink Data Rate (Mbps)
2010-2020	3	100	3
2020-2030	3	180	30
2030-2040	5	200	300

Table 2. Missions parameter for several decades

The G/T required at each of the three Ground Stations to cope with these missions is shown in Figure 1. For the first decade a G/T per longitude of 62 dB/K is required to close links 90% of the time, and 64 dB/K for 99% of the time. These values are lower than with the classical method due to the fact that the link conditions are averaged. In the same way, for the second decade it is worth mentioning that a G/T increase of 12 dB over current performances can satisfy during 90% of the time the needs of a set of 4 missions with a mean data rate to Mars of 30 Mbps.

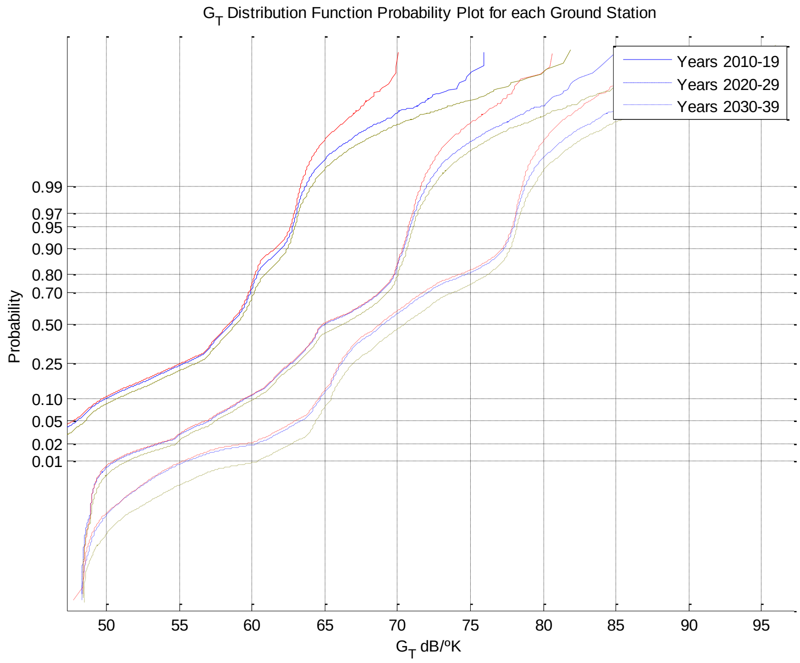

Figure 1. G/T probability distribution function for the G/T needed in each ground station to close all links

3 ARCHITECTURE ALTERNATIVES

There is a range of candidate ground station designs that have been appearing during the last years. Summarizing, the alternatives identified are:

- Large Dish
- Arrays of 12 meter antennas
- Arrays of 35 meter antennas
- Phased Array
- Large Dish + Received Array
- Optical Ground Station
- Arrays of Telescopes

The alternatives proposed are described in the below sections.

3.1 >70 meter dish

In accordance to [RD 4], the thermal and gravitational limits for several antenna diameters are:

D(m)	λ_{gr}(cm)	f_{gr}(GHz)	λ_{th}(cm)	f_{th}(GHz)
25	0.33	90,91	0.6	50
50	1.32	22,73	1.2	25
75	2.98	10,07	1.8	16,67
100	5.3	5,66	2.4	12,5
150	11.9	2,52	3.6	8,33

200	21.2	1,41	4.8	6,25
300	47.7	0,62	7.2	4,17

Table 3. Gravitational and Thermal minimum wavelengths to keep surface error under λ/16.

These natural limits can be overcome by mean of advanced techniques, as is the case of the Green Bank Telescope. This antenna uses actuators at the corners of each main reflector panel or at the panel junctions. These actuators together with a **metrology system** are applied in the GBT to improve its aperture efficiency. The metrology system basically consists on several laser ranging units mounted on the telescope arm in charge of measuring the distance to laser retroreflectors mounted on the surface panel corners near each actuator, and thus the antenna reflector can be scanned in a few minutes providing delta correction to the actuators net, which will lead to an improved surface accuracy and an antenna efficiency over 60% in K-band.

Other key factor to improve the antenna efficiency is the use of new materials for the antenna panels. Carbon Fibre Reinforced Plastic panels can lower surface errors to a few microns under thermal gradients [RD 5].

In all, a summary of performances current large steerable dishes is shown next:

Telescope	**Freqs.** (GHz)	**Beams**	**Aperture Eff.**	**Gain** (K/Jy)	**T(sys)**	**Beamsize** (Arcmin)	**FOV** (Sq.deg.)	**D. aprox** (m)
GBT	18-26.5	1	**0.62**	1.5	35	33	0.3	100x110
GBT	18-26.5	7	**0.62**	1.5	35	33	2.4	100x110
GBT	18-26.5	61	**0.62**	1.5	35	33	21	100x110
Effelsberg	17.9-26.24	1	**0.26**	0.7	73	39	0.5	100
Tidbinbilla	19.91-20.51 21.78-22.38 23.61-24.21	1	**0.48**	0.7	40	48	0.7	70

Table 4. Large radio telescopes main performances

From previous date, it seems technological feasible to build a large dish antenna, at least up to 100 meters in diameter. However, there are major drawbacks that are shown next:

- **Maintenance downtimes**. One of the main drawbacks of large structures is the high cost of their maintenance and the risk of long downtimes. As reference, the operation on the historic 70 metre antenna of NASA in Goldstone to replace a portion of the hydrostatic bearing assembly, which enables the antenna to rotate horizontally. The repair works took about 8-9 months. Another example is the downtime that DSS63 antenna (70 meters at Robledo de Chavela) suffered in 2006. It was for more than 6 months down due to a failure on a bearing, and it forced to reschedule all missions.
- **Reliability**. Up to the author's knowledge only three 100 meter full steerable antennas have been built. One of them collapsed in 1988.

Figure 2. Former 300 foot radio GBT before and after the collapse

- **Multilink capability**. There is limited multilink capability. If the large aperture is tracking a particular mission with a lot of link budget margin, none of this margin can be used to give service to other missions. Besides, due to the narrow beam, single aperture multiple link access techniques are limited as well.
- **Evolvability**. No incremental upgrades are possible. Construction of a new antenna is required.

3.2 Array of antennas

After several years of studies by NASA and JPL this solution seems to be **the most adequate one in terms of Life Cycle Cost, operations flexibility and scalability**. An excellent justification for its use is found in [RD 6]. In the same way, radioastronomers worldwide are working on array based radiotelescopes as the best way not only to improve angular resolution but to increase sensitivity as well. This has an additional advantage for this solution: the technological infusion from the radioastronomy field, where numerous subsystems, components and techniques are being developed these days.

An important open issue is to decide the best dish diameter of an array deployment. It is not completely clear the optimal dish diameter to be used, **the main options seems to be among 12 and 35 metres**. The twelve metre solution comes after a process of cost optimization in the downlink LCC [RD 7], and the thirty five metre solution comes after the same optimization process for the uplink LCC.

The main advantages, for telemetry, are the following:

- Flexibility in matching capacity to demands by means of subarraying
- Higher reliability: trading reliability of mechanical systems (big antennas) with more electronics. Electronics in general has much higher reliability, requires less maintenance, is easier to monitor, and can be quickly replaced compared to mechanical hardware.
- Failure of one or a few small antennas causes graceful degradation in sensitivity.
- Lost spacecraft search easier, due to wider field of view of the individual antennas making up the array.
- Easier to expand capacity.

The main disadvantages:

- Uplink arraying is very complex, and in the case of Ka-band troposphere turbulences makes it unfeasible.
- Phasing, especially in bad weather at Ka-band on weak sources, is more complex and may have combining losses, which will increase with the severity of the weather.
- Phasing process slow for low data rate signals, especially in arrays with high number of small antennas
- Operational procedures more complex

- More electronics and number of things to control
- Technological readiness at lower level, although with high heritage from radioastronomy

As this solution has been the selected one, detailed analysis of it will be done in the following chapter.

3.2.1 A mixed architecture: Large Tx/Rx antenna plus Rx array

As mentioned in the previous disadvantage list, the main problem of the array solution is arraying in the uplink. Recently, a viable solution from Harris Corporation [RD 12] has emerged which work up to X-band. Besides, another point should be taken into consideration: robotic missions, which are the most frequent ones (and at this moment the only ones in deep space) are very asymmetrical: the total amount of uplink time is much lower than the amount of downlink time. Hence, a single 35 meters antenna could be multiplexed in the uplink amongst several missions.

Therefore, it is reasonable to propose a ground segment which is composed of one 35m antennas, and a Rx antenna array whose diameter is optimized to get minimum cost.

3.2.2 On the selection of the antenna diameter for the array

Perhaps the most important decision to be made when designing the array is the selection of the antenna diameter. There are several technical factors that can influence the decision, and that will be analyzed in next chapter. But there is one key factor that is cost, both construction and Life Cycle Cost.

With the requirements gathered from WP1000, it is time to dimension the different ground segment array alternatives and calculate their cost. This is done in SW2, in which the following arrays with antenna diameters ranging from 6 to 70 meters have been taken into account:

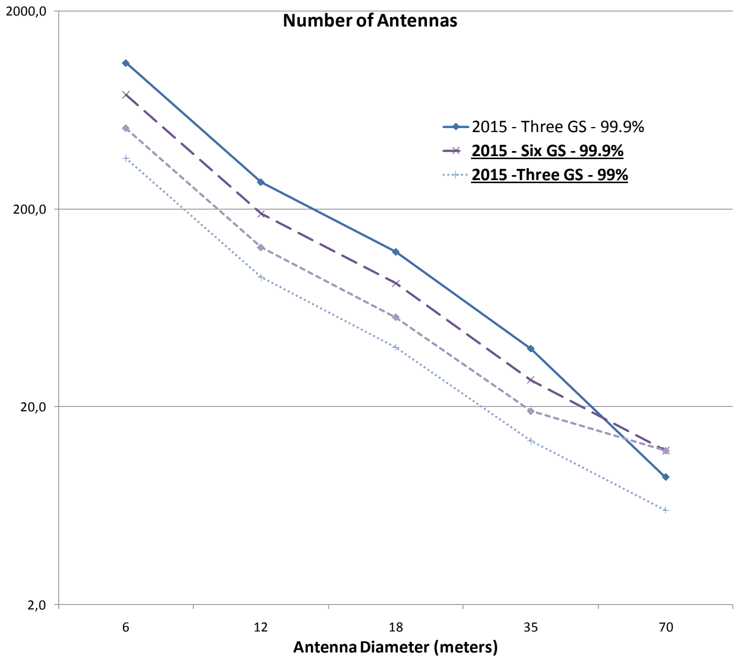

Figure 3. Total Number of antennas (one cluster versus two clusters per longitude)

Therefore in the basic configuration and for 99% of the time, thirty 12 meter antennas are required per longitude or four 35 meter antennas. The results of the simulation show that for a 99.9% overall availability it is beneficial to have two clusters per longitude.

Once we have the number of antennas for each diameter and configuration, the next step is calculating the costs.

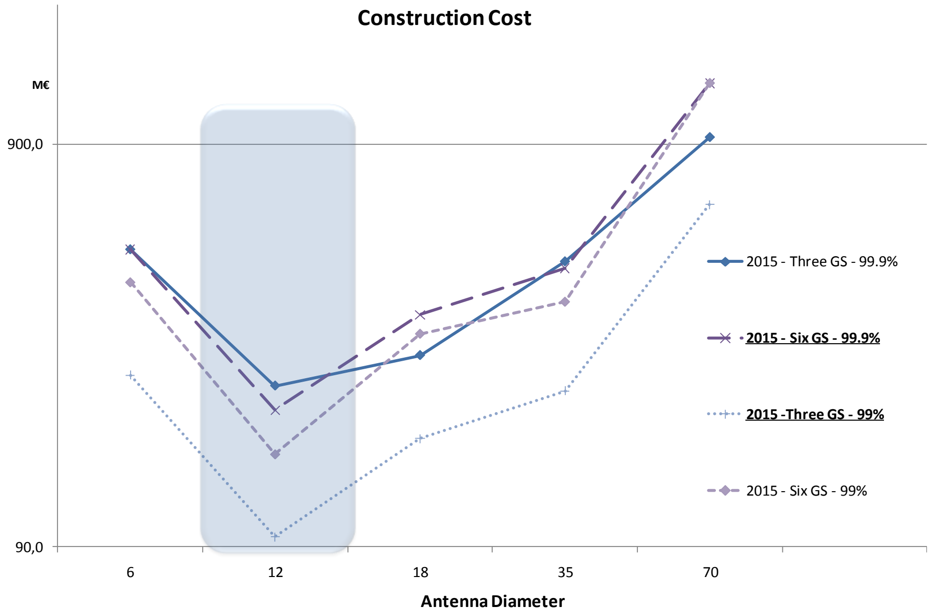

Figure 4. Construction cost versus antenna diameter

Construction cost indicate that the optimum antenna diameter is 12 meters. However when we look at the full Life Cycle Cost the optimum point is not so clear, due to the extra maintenance burden of low diameter antenna arrays. In this case the optimum point is somewhere between 12 and 35 meters. Especial caution must be taken with these results due to the fact that Maintenance cost model put a high penalty on low antenna diameters.

Nevertheless there are two major reasons for selecting 12 and 35 meters as final antenna diameters to be traded off:

- 35 meter antennas are the current ones, and there is lot of know-how in these systems
- 12 meter antennas are the selected ones for the SKA (recent designs indicate 15 meters). With the advent of the SKA, thousands of these antennas will be manufactured, with the result of a commercial product at a very low cost.

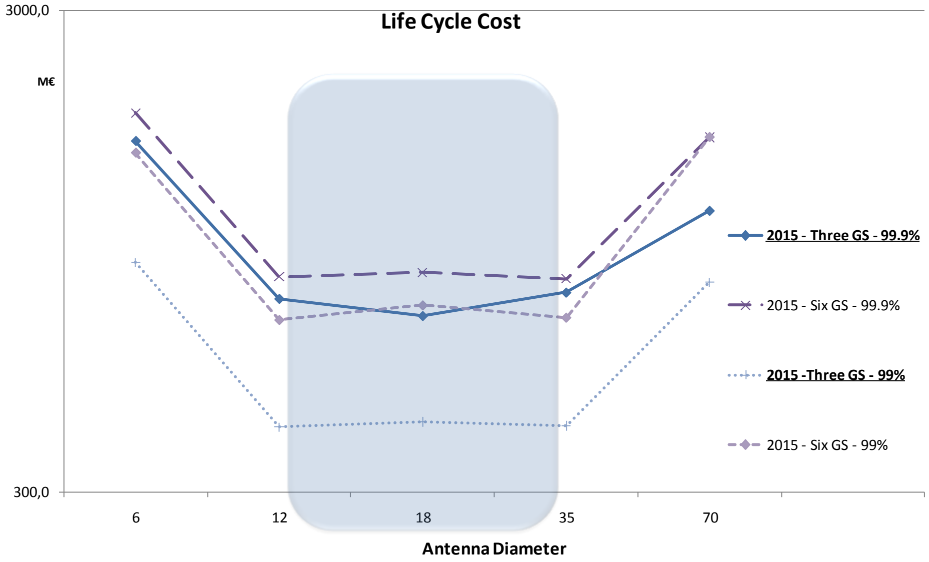

Figure 5. Life cycle cost versus antenna diameter

3.3 Electronically-steered, phased-array, flat plate antennas

There are several pros and cons, widely described in [RD 8], which should be taken into consideration in deciding whether or not this technology is technically and economically feasible within the requirements of a deep space network. The main advantages of phased arrays are the following:

- Beam agility: the antenna beam can be moved almost instantaneously to any desired direction.
- Multiple beam operation and capability of interference cancellation: the phased array provides the ability to provide simultaneous multiple beam operations which can be useful in certain situations involving multiple spacecrafts at different positions.
- Higher reliability and graceful degradation
- Lack of mechanical motion and a significant reduction in long term operational costs due to the lack of any complicated moving mechanical parts as in reflector antennas

One example of this technology which could be taken as reference is **the SKA proposal** [RD 9] for a phased array radiotelescope.

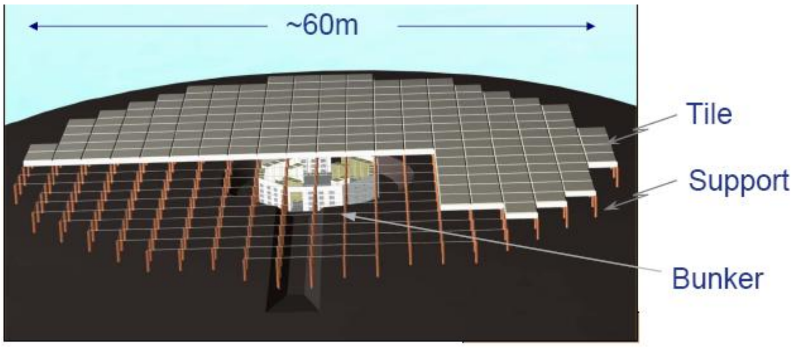

Figure 6. Flat array of antenna phased arrays [RD 9]

Despite these benefits, the solution has several drawbacks, mainly its prohibitive cost produced by the presence of numerous elements and the beamforming network complexity. Besides the angular coverage is limited by the field of view of each radiating element, so that low elevation angles would suffer a considerable gain loss. Other disadvantages that could affect the decision of being a viable solution are the limited multi-frequency operation capability because of the narrow band condition of this technology and the lack of flexibility in adding new capabilities, as any change in the frequency band.

3.4 SPHERE (Spherical Pair of High-Efficiency reflecting Elements)

This concept consists of two non tipping spherical reflectors fully rotatable in azimuth, pointed at 30º and 70º elevations. There are major cost advantages because there is no tipping of the large structure, no counterweight, no gravity effects, simple alignment, simple backup structure and identical low-cost panels.

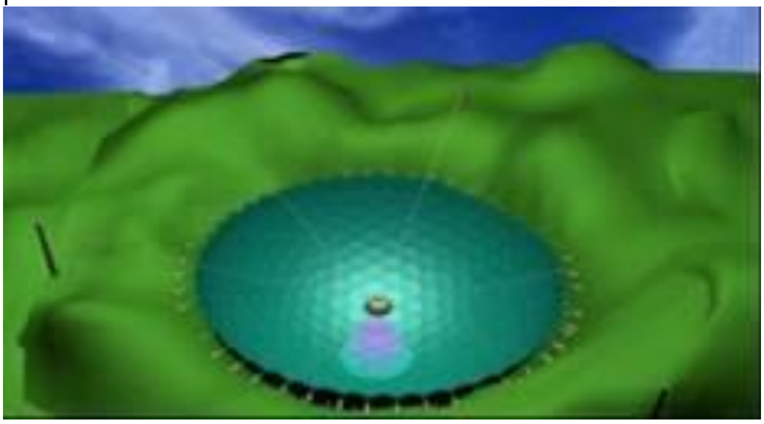

Figure 7. Large active reflector

A similar concept will be employed by China in order to build a 500 metres sphere for SKA [RD 11]. As in the case of a large dish, this solution has lack of flexibility and potential long downtimes. Besides, high frequency operation is compromised due to the size of the structure and the difficulty in keeping the surface error low over such wide areas.

3.5 Optical Ground Stations

Optical communications systems are particularly well matched for deep-space links, principally because short wavelengths (less than 2 µm) allow the transmitter to concentrate its output into very narrow beams (microradians of divergence) with apertures sizes commensurate with current space systems. Such concentrated beams are far more efficient than those of traditional radio-frequency (RF) communications systems where beam divergences can be greater than 100 times those of their optical counterparts.

Furthermore, optical communication links are a growing and promising technology, with its applications spreading over many areas of telecommunication. The main optical advantages stated in [RD 13] are the following:

- **Higher data rates** enable increased data collection and reduced mission operations complexity.
- Lower Size, Power and Weight
- Immunity to EM interference

With the inherent advantages, smaller apertures and larger bandwidths, of optical communications, it is reasonable to expect that at some point in time and combination of increasing distance and data rate, the rapidly emerging optical capabilities would become more advantageous than the more mature and evolving RF techniques.

An optical link budget has been made for a Mars to Earth link. On-board a 35 cm diameter telescope with an output power of 5W. A 256-PPM modulation will be used. On ground the GTC

10.4 m telescope of "Roque de los Muchachos" (La Palma) will be used as the receiver antenna. A photomultiplier is used instead of a APD for higher sensitivity.

The minimum binary rate achieved is 3.1 Mb/s when the Earth-Mars distance is the maximum and during the day. The maximum could be 58 Mbit/s at the minimum distance and at night.

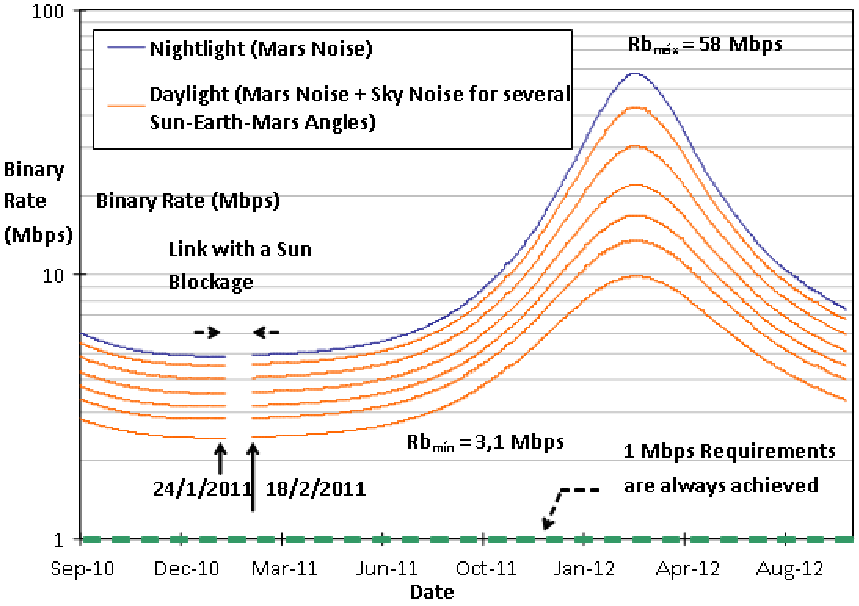

Figure 8. Results from the receiver based on PMT in unfavorable conditions

However, the **main challenges of laser in space** are summarized as follows [RD 14]:

- Immature technology versus radio frequency.
- Susceptibility to clouds and bad weather.
- Pointing and tracking: a tight pointing accuracy requirement usually a factor 1000 or more stringent than for RF links.
- Will not replace radio for all applications.
  - Fast- maneuvering spacecraft.
  - Cheap, highly independent spacecraft.
  - Emergency operations.
  - Entry/descent/landing communications.
  - Dusty/thick atmosphere environments

3.6 Figure of Merit Analysis

The FOM scores of the several alternatives are shown in next table. The rationale for the FOM color scores is as follows (see [RD 15] for the original analysis performed by NASA):

Option	Reliability & Availability	Communications Performance	Navigation Performance	Technical Readiness	Uplink capability	Life-Cycle Cost	Ability To Evolve	Operations Felxibility
Large Dish	Yellow	Green	Green	Green	Green	Yellow	Red	Red
Arrays of 12m antennas	Green	Green	Green	Green	Red	Green	Green	Green
Arrays of 35m antennas	Green	Green	Green	Green	Green	Yellow	Green	Yellow
Phased Array	Green	Green	Green	Red	Green	Red	Green	Green
Large Dish + Receive Array	Green	Green	Green	Green	Green	Yellow	Green	Yellow
Optical Ground Station	Yellow	Yellow	Yellow	Red	Green	Yellow	Yellow	Yellow
Arrays of Telescopes	Green	Yellow	Yellow	Red	Yellow	Yellow	Green	Green

Table 5. FOM analysis of the different ground station alternatives

3.7 Cost/Performance comparison

The alternatives deemed technologically viable are compared in terms of cost and performance for a scenario of communications with a spacecraft in Mars at 2.6 AU.

The starting point is the performance achieved with one of today's 35m antenna in Ka-band, but with an improved telecommunications payload (3m antenna & 100W HPA). The goal is to achieve the equivalent of 4x35m antennas, which would amount to 16 Mbps at this distance (>300 Mbps at 0.6 AU).

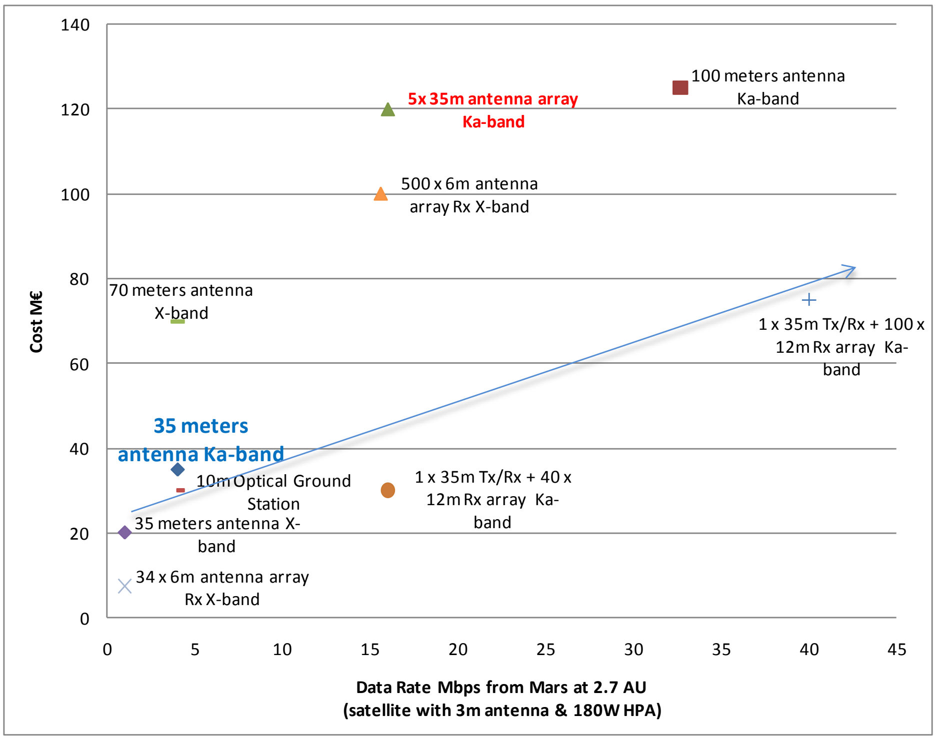

Figure 9. Comparison of several options

3.8 Architecture selection

From the previous analysis, the two options with best scoring are **Arrays of 34m antennas, and Mixed archictecture of Large Tx/Rx antenna plus Rx Array of 12 meters antennas.** The advantages of each of them can be summarized next:

- Arrays of 34 antennas.
  - Mature technologically
  - Well-known and uncertain cost
  - Provides good uplink capability
- Mixed architecture
  - Low cost option in the mid-term.
  - The low diameter of the receive array provide technological advantages, such as ease of pointing, lower antenna temperature from planet sources, and increased navigation performances.
  - Higher availability
  - Higher flexibility of operation
  - Technology infusion from radioastronomy projects

4 SYSTEM DESIGN OF 4 X 35M AND 40 X 12M ARRAYS

In this chapter the design of both array alternatives is detailed and compared so that the reader can focus on the technical and performance difference between both solutions. Before carrying out any design the requirements are set below:

- Deep Space Array shall receive RF signals from **deep space and Cat-A** spacecrafts at X (**8.4-8.45 GHz for Deep Space and 8.45-8-5 Ghz for Cat-A**) and Ka (**31.8-32.3 Ghz for Deep Space, 25-26.5 Ghz for Cat-A**) bands in **RCP and LCP** (selectable), and provide telemetry data to missions in the Consultative Committee for Space Data Systems (CCSDS) compatible format
- Data Rate: **10 bits/second to 150 Mb/s**
- Modulation: PCM/BPSK/PM, BPSK, QPSK, OQPSK, GMSK and other TBD modulations.
- G/T:Increase of 6 dB over current performances
  - Ka-Band. Goal of 66 dB/ºK at zenith, and 64.2 dB/ºK at 10 deg of elevations.
  - X-band. Goal of 58.8 dB/ºK at zenith, and 57.5 dB/ºK at 10 deg of elevations
- Instantaneous bandwidth of 500 MHz (1 dB nominal).
- Passband response to have less than 1 dB and 1 nsec variation over any 100 MHz bandwidth
- Polarization: Dual circular at one of the two bands or selectable any one circular polarization at each of the two bands.

4.1.1 Phased Error Budget

The maximum phase error will depend on the number of antennas and the allowed degradation. Therefore, different values are expected for both solutions. In the case of a 4x35m array 20 degrees can be allowed; that values is reduced to 18 degrees for the 40x12m array. The allocation budgets are the following:

	degrees
Atmosphere	12
Antenna	12
Antenna Phase Center variation	
Antenna Location	
Antenna Electronics	3
FO link	4
Signal Processing	3
ADC	
Fringe, Phase	
Delay	
Reference Distribution	3
TOTAL	18,2

	degrees
Atmosphere	12
Antenna	14
Antenna Phase Center variation	
Antenna Location	
Antenna Electronics	3
FO link	4
Signal Processing	3
ADC	
Fringe, Phase	
Delay	
Reference Distribution	3
TOTAL	19,6

Figure 10. Phase Error budget for 0.2 dB combining losses. 40x12m (left) and 4x35m (right)

4.2 System Diagram

In order to save resources only two of the four available signals at each antenna are digitized. The combination can be any: the two pols from X-band, two from Ka/K-band or a mix. The digital processing is made in two separate beamformers according to the band. It is important to notice that for each band there is only one ADC per antenna; thus it is not possible to have both polarizations with all of the antennas simultaneously.

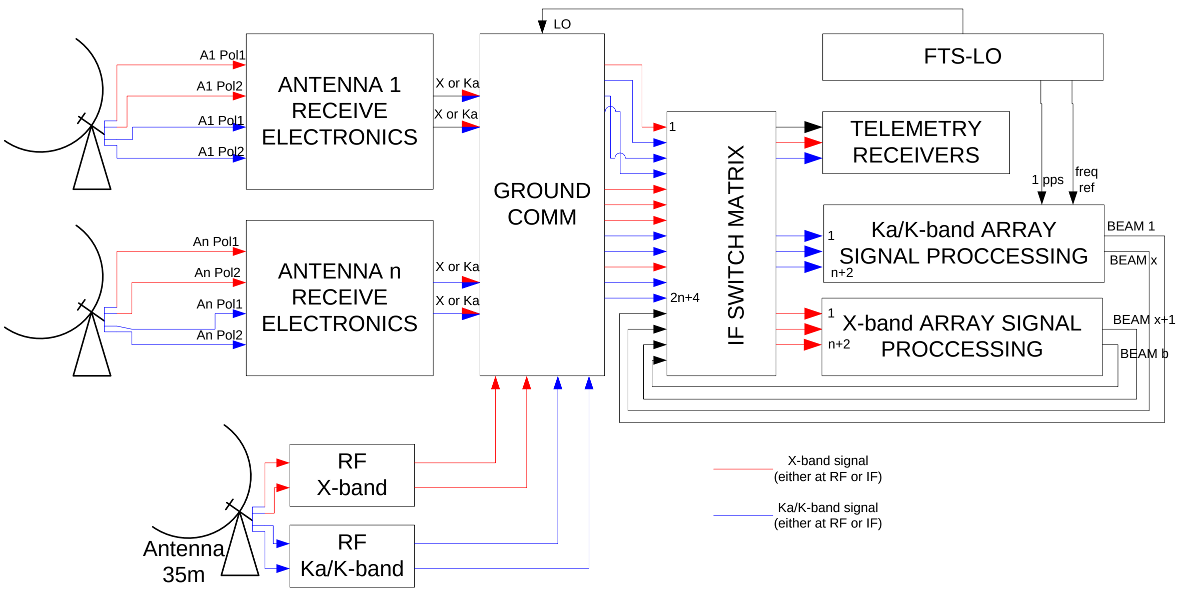

Figure 11. Receive subsystem Diagram of the Mixed Architecture. In the case of the 4x35m architecture all antennas are 35 meter in diameter.

Regarding transmission, due to the technical uncertainties with uplink arraying it is supposed that transmission is only executed from one of the 35 meter antennas.

4.3 Antenna Arraying

Full-spectrum combining is an arraying technique wherein the signals are combined at IF, as depicted in Figure 12. Its main advantage compared to other arraying techniques is that it is modulation independent. One receiver chain consisting of one carrier, one subcarrier, and one symbol synchronization loop then is used to demodulate the combined signal.

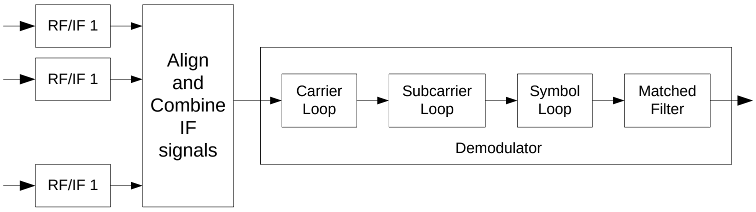

Figure 12. Full Spectrum Combining scheme

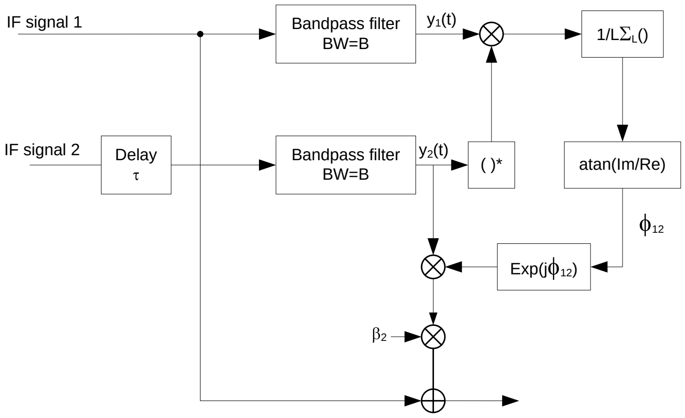

Figure 13. Amplitude β, Phase ϕ, and Delay τ alignment

The resulting gain is maximized by aligning the IF signals in **amplitude, time and phase prior** to demodulation. The alignment algorithm for an array of two antennas is shown in Figure 13. Here signal 1 is assumed to be delayed by τ seconds, with respect to signal 2. The IF signal from antenna 2 is first delayed by τ seconds, where τ can be the output of the delay estimation loop, or it may predicted from the geometric arrangement of the antennas and spacecraft. After delay compensation, both signals are input to the phase estimator which outputs ϕ_{21}, which is the phase of signal 2 relative to signal 1 at the estimator input.

4.3.1 Amplitude alignment

The optimal value for the amplitude of the weights is calculated in [RD 19], and the result is
is

$$W_i = \frac{\sqrt{G_i}}{T_i + G_i S_P}$$

This solution is appropriate for an extremely extended array, because the second term in the denominator can be approached as zero. If correlated noise terms are included, it is difficult to solve for W_i numerically. As a matter of fact, although the values of W_i obtained including the effects of correlated noise, often differ by ~10% from those obtained without taking into account noise correlation, the resulting SNR differ by only ~1%.

4.3.2 Phase alignment

The accuracy of the phase estimation increases linearly with the number of samples taken and the input signal to noise ratio. This means that the longer the snapshot, the lower the combining losses. The standard deviation of the phase is:

$$\sigma = \frac{1}{SNR_{input}\sqrt{L}}$$

But there is an additional factor that comes into play when selecting the snapshot size so as to reduce the phase error: **the number of antennas in the array**. For a fixed variance of the phase estimation error, the higher the number of antennas in the array the higher the losses.

By means of simulations it is shown that the number of samples required to achieve combining losses lower than 0.2 dB is:

- 40 x 12m array
  - Global Phasing
    - SNRinput=-10 dB $\Rightarrow$ 10^3 samples
  - Worst case scenario
    - SIMPLE
    - SNRinput=-15 dB $\Rightarrow$ L=30.10^3 samples
- 4 x 35m array
  - Global Phasing
    - SNRinput= 0 dB $\Rightarrow$ 10^2 samples
  - Worst case scenario
    - SIMPLE
    - SNRinput=-5 dB $\Rightarrow$ L=10^3 samples

4.3.3 Delay alignment

There are many ways to estimate the delay between two signals. **Regarding time-delay estimation, the most common approach is the Generalized Correlation Method**. In this method, to avoid the direct costly computation of the correlation among two vectors, their FFT are calculated, multiplied and inverse transformed to obtain the time domain correlation. Then a parabolic estimator is used to find the peak of the correlation function, which in turn give us the relative delay between the two signals. To avoid the last steps (inverse FFT, and parabolic estimation), a linear regression of the phase slope of the cross-correlation spectrum can also be used. Particularizing this formula for our case (σ=10 degrees; f=1:1:500 Mhz):

$$\sigma(\tau) = \frac{0.17}{2\pi}\left\{\sum_{i=1}^{500} f_i^{\,2}\right\}^{-1/2} = 4\,\text{picoseconds}$$

This accuracy is not enough for a Time Domain Beamformer at Ka-band frequencies. Therefore, for this kind of beamformers accurate phase center calibrations should be used instead.

4.4 Beamformer Selection

There are several advantages of a Frequency Domain versus a Time Domain Beamformer, namely:

- Delay update rates are less stringent in the frequency domain beamformer as the resolution is coarser (5 seconds versus 50 milliseconds)
- The delay estimation accuracy must be in the order of picoseconds for a TDB, whereas in a FDB the coarse delay has a step of 1 nanoseconds.
- A frequency domain beamformer allows capturing signals from different angular positions within the main beam of the antenna.

Perhaps the main disadvantages of a frequency domain beamformer is the extra hardware required for the subband decomposition, and the longer convergence time.

4.5 Multibeaming

Even though the synthetic beam is very narrow (2 millidegrees for a 300 meters baseline), several beams can be synthesized inside the 3 dB beamwitdh of the 12 meter antenna. Thus, there is the possibility of having multiple beams for constellations of satellites in planets such as Mars. In order to reduce the number of required beamformers/correlators a Frequency Domain Beamforming procedure is imperative.

Each different mission destination (Mars, Jupiter, Lagrange,..) must have a number of antennas pointed to it. Therefore, if we have four missions the array should be subdivided in four subarrays. In order have the possibility of using the same frequencies in different missions with different destinations (an obvious choice), several full band correlator/beamformers are required. In our case we have set to four per band (X and Ka) the number of different missions that the system can cope with. Inside each correlator/beamformer several beams will be formed but at different frequencies, and always within the 3-dB beamwidth of the 12 meter antenna. Nevertheless, as each beamformer operates on the full band, the output at the synthesis filter bank will contain all of the different beams at different frequencies. Therefore, in the following diagram each of the ouputs named BEAM x will have actually all of the different beams that are formed for the direction in which the beamformer is operating.

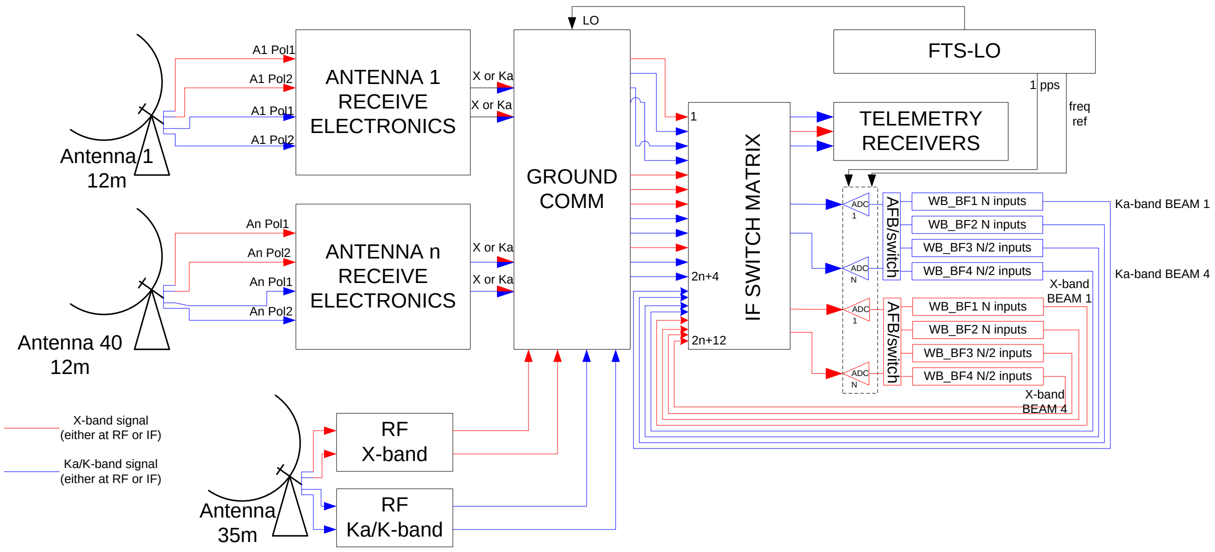

Figure 14. Receive subsystem Diagram of the 40x12m array

4.6 Array Calibration

According to [RD 20], there are three different calibration regimes in an array of parabolic dishes:

- Self-calibration using spacecraft telemetry. In this mode the phase estimator operates continuously without the need for a fringe rotator.
- Self-calibration using integrated spacecraft telemetry. In this case the phase estimation process does not achieve convergence before the geometrical phase shift exceeds 20 degrees. Integration over longer periods of time is required, so a fringe rotator is necessary.
- Radio-star calibration. This is a similar case to the one before, but using a radio-star as source instead the satellite signal

The first calibration mode is the typical in high data rate regimes. In the second and third cases the signal data rate is low. In order to find out the boundaries between each calibration regime, the convergence of Full Spectrum Arraying has been analyzed with PCM/BPSK/PM modulations.

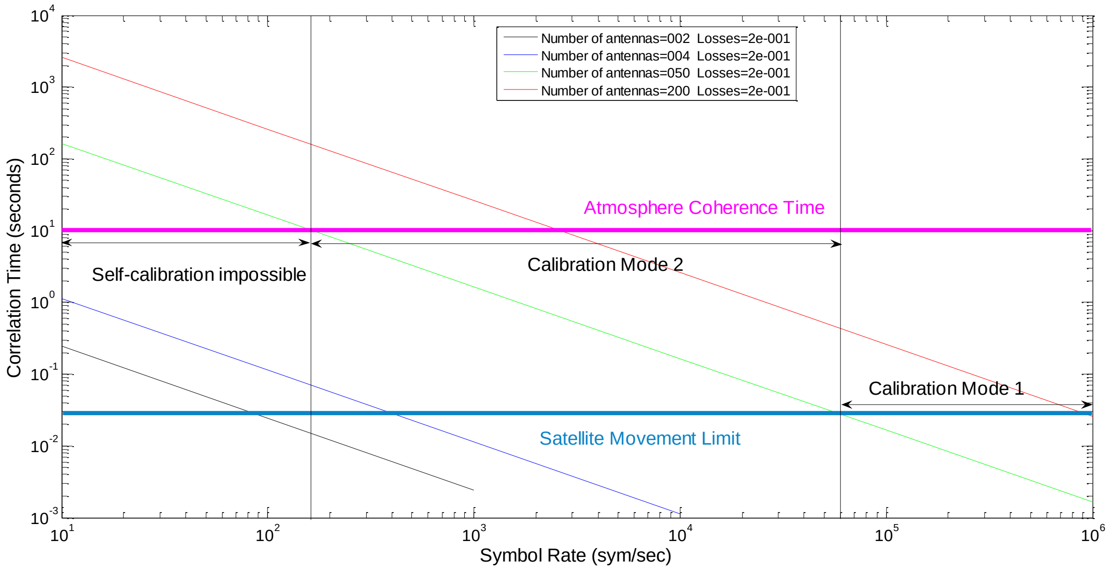

Figure 15. Self-calibration allowed working zones for different number of antennas (2,4,50,200) and Allowed Degradation Losses = 0.2 dB. Simple algorithm used. For all configurations the input power is such that the combined power without losses gives rise to Es/No=10 dB, Bcorr includes 10 harmonics, and modulation index =65 degrees. Satellite movement limit and Atmosphere coherence time set in Ka-band (30 milliseconds)

The boundaries for a SIMPLE algorithm are:

- 40x12 meter array
  - Calibration mode 1. Data rates higher than 60.000 symbols/second
  - Calibration mode 2. Data rates higher than 200 symbols/second
  - Under 200 bauds, self-calibration is impossible. Hence use of radio stars is advised in Ka-band if simple algorithm is used for data rates under 200 bauds. In X-band the atmosphere coherence time can be up to 100 seconds. Therefore, radio-star calibration in X-band will be rarely used (only for cases when calibration is required before the start of the pass).
- 4x35m array. In this case there are no circumstances under which self-calibration is not possible.

4.6.1 Radiostar calibration

For 40x12m arrays, due to the higher number of antennas there are working conditions in which self-calibration is not possible. In the 4x35m array, in principle radiostar calibration is not necessary, although there are cases such as precalibration before a space track of a critical event where radio-star calibration will be required. A complete characterization of the different troposphere calibration techniques has been made, and the results are summarized in next table.

Technique	Residual error		pros	cons
	delay	path length		
WVR	6.7-10 ps	2 - 3 mm	• No extra constraints on mechanics and array design • Full and continuous array observation.	• it does not remove the electronic phase noise • it does not measure the dry delay • one WVR per antenna
GPS	6.7-16 ps	2 - 5 mm	• GPS hardware already procured and used for ionospheric calibrations • complete and continuous sky coverage • both wet and dry tropospheric delays	• not coincidence of the lines of sight of the GPS and the spacecraft. • dependence on the precision of the GPS orbit and ground tracking network.
Paired antenna	0.25 ps	68 μm	• the target array observes the source continuously • the demands on the antenna mechanics and electronics are not very stringent.	• the electronic phase noise is not removed • the geometry of the array must allow for neighbouring antennas • cost of the calibrator array
Fast switching	0.5 ps	0.13 mm	• full array to observe the target source • removes the electronic phase noise along with the tropospheric phase noise	• stringent constraints on antenna servo-mechanical and electronic set-up time • discontinuous observation due to moves and calibration measurements • slightly different lines-of-sight • assumption of atmosphere stability during calibration cycles.
In-beam	0.5 ps	0.13 mm	• **No additional hw equipment required** • **The array observes the source continuously** • **All antennas are available for signal reception** • **Position calibration requirements are considerably reduced** • **electronic phase shifts are removed**	• **only suitable in X-band**
Phase Interpo-lation	**<0.25ps**	**<68μm**	• **the target array observes the source continuously** • **the demands on the**	• **the electronic phase shifts are not removed** • **a small part of the array is not tracking the**

			antenna mechanics and electronics are not very stringent	**source (loss in G/T)**

Table 6. Calibration techniques comparison

For a 12 meter array In-beam seems to be the best solution in X-band. The main advantage of this technique is that it relaxes phase center calibration to 1 centimeter. In Ka-band due to insufficient number of radiostars, phase interpolation or fast switching might be used. The main drawback is that internal calibration loops are required to account for instrumental phase drifts.

In a 35 meter array, the only viable solution is Fast Switching, although it is going to be needed only at the beginning of the pass, as once the signal is received self-calibration is always possible.

4.7 Number of antennas of the array

To calculate the number of antennas of the array, the goal established is an increase of 6 dB with regards to current DSAs. The values corresponding to 12 meters antennas are not known a priori, and calculation of them was performed during the project.

If the feeder is at room temperature, and under the assumption of zero wind, the number of 12 meter antennas gets a maximum of 11 antennas at 6 degrees of elevation. On the other hand, if the feeder is cooled at the same temperature as the LNA, and under the assumption of zero wind, the number of 12 meter antennas gets a maximum of 9 at 6 degrees of elevation. As some redundancy must be introduced in the array, the number of 12 meter antennas per 35 meter antenna will be fixed at 10.

Under wind conditions, and higher elevations, the lower pointing error and higher efficiency of 12 meter antennas will yield additional G/T increases that can reach 3 dB, which implies doubling the received data rate in comparison with the 35 meter array.

4.8 Antenna Technology

The technology to build a 12m antenna capable of working in Ka-band is well-known, and several companies in Europe are capable of doing so. **The challenge comes when the requirement for a low cost manufacturing technology is placed.** Table 7 shows the classification of reflector antenna manufacturing technologies represented in a color scale. The meaning of the colors is: green- it shows an advantage compared to other options; orange: it represents an intermediate situation; Red- it represents a clear disadvantage compared to other options.

Selection criteria	Aluminum Hydroformed (single piece)	Composites (single piede)	Stretched-formed panels	Electroformed panels
Manufacturing on-site				
Weight				
Resistance to thermal changes				
Technology evolution				
Time to deliver				
Cost				
Surface accuracy rms				

Peak-to-peak rms				
Repeatability				
Company				
Transportation	Manufacturing on site			
Assembly and alignment				

Table 7. Selection criteria for antenna manufacturing technology

4.9 Optical Subsystem for Signal Distribution

An array composed of 40 antennas of 12 meters will have inherently log run of cables between the antennas and the signal processing center. These cables will be in charge of sending the telemetry signals but also of distributing the frequency references. Hence, if calibrated modes are to be applied it is of paramount importance to have a high stable transport system. One important point is that the optical devices in charge of sending the telemetry signals to the digital beamformers are also configured as frequency downconverters. In this way, without much extra cost the need for rf downconverters is suppressed. Next, a summary of the optical subsystem is shown. Proposed architecture for optical distribution system and downconversion

One of the main features of this system is its capabilities to transmit two signals from every antenna of the array that can operate simultaneously in X and Ka band with both polarizations L and R. Therefore the LO distribution system shall be flexible enough to downconvert every band in each system of the array. Such as can be seen from Figure 16, the system is based on three main blocks that are briefly described below:

4.9.1 Common LO block

This configuration is composed by a unique block that will be the responsible of distributing the Local Oscillator signals to all the elements that composes the array. This proposal can make use of WDM capabilities to minimize the number of fibers to the array. A WDM optical system is capable of transmitting different signals into the same fiber by means of modulate them into a different carrier. **Minimizing the number of fibers the system will minimize the sources of noise for line length correction, simplifying the active round trip phase system**

Such as have been previously commented this optical system shall be capable of downconverting signals from two feeders in two possible frequency bands (X, Ka). Therefore, we would have four possible configurations in each antenna. In order to be able to downconvert all the signals from each antenna element in a different configuration four carriers (λ_{X1}, λ_{X2}, λ_{Ka1}, λ_{Ka2}) shall be transmitted to all the antennas. λ_{X1}, λ_{X2} will be modulated with the LO signal to downconvert X band signals and then will be transmitted to feeder 1 and 2 respectively. λ_{Ka1}, λ_{Ka2} will be modulated with the LO signal to downconvert Ka band signals and then will be transmitted to feeder 1 and 2 respectively. Once the four carriers are correctly modulated and transmitted into an only fiber per antenna the optical signal is amplified and distributed to all the antennas.

4.9.2 Remote Unit block

This is the optical block located at each antenna and responsible of the optoelectronic conversion of the received RF signal. λ_{X1}, λ_{Ka1} and λ_{X2}, λ_{Ka2} will be demultiplexed into two optical paths. λ_{X1}, λ_{Ka1} will be remodulated with the RF signal from the feeder 1 and λ_{X2}, λ_{Ka2} with the RF signal from the feeder 2 of each antenna element. Then those signals are combined into a fiber and transmitted back to the central control.

4.9.3 Conversion Unit block

First block from the conversion unit would be the line length correction. Since all the signals have been transmitted into one fibre only one a small part of one of the carriers will be filtered out and photodetected. A fixed wavelength is always modulated with the same LO signal, therefore we can use always the same known local oscillator signal to the line length system.

After Line length correction and an amplification stage each wavelength will be separated into four photodiodes and then with two IF switches we will be able to select de desired downconverted signal considering the frequency band of the received signal

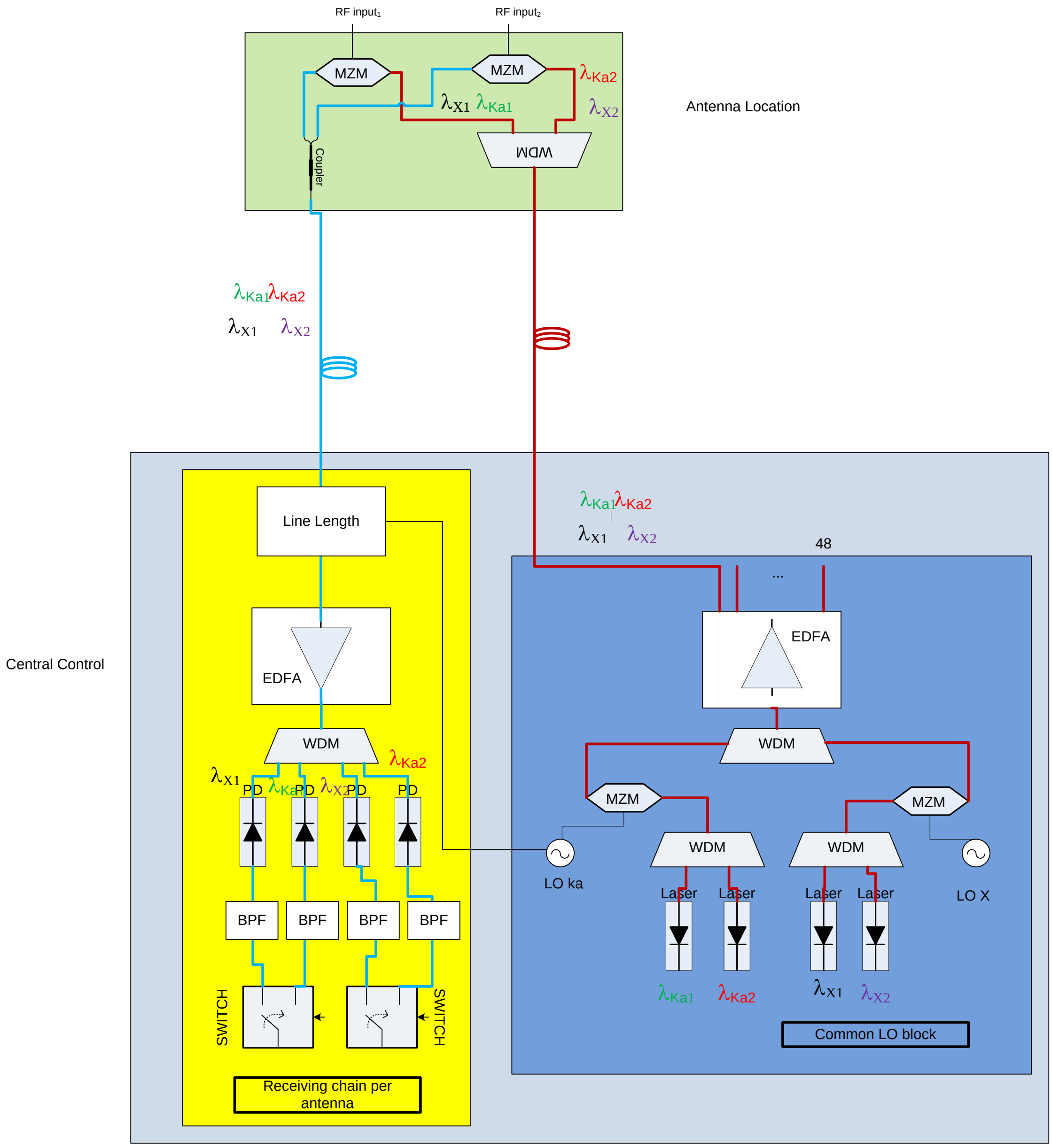

Figure 16.-Optical downconversion an distribution system for scalable antenna array structures

The main advantages of this system are summarized as follows:

- **Only one Common LO block independently of the antennas that composes the array.** Only the amplification stage shall be configured according to the number of the array elements
- **Optical system is transparent to the frequency range**
- Only one **fiber to the antenna and back to the central control that causes minimization of the line length correction system**
- Local oscillator can be used as control signal for Line length correction system.
- Total flexibility to downconvert each element independently of each other, that means subarraying capabilities and simultaneous downconversion of X and Ka band frequency ranges
  - No Local oscillator switching is required
  - Frequency band is selected at IF level

4.10 Tracking and Navigation

In the case of an antenna array where a SIMPLE calibration mode is used, all of the antennas have the same end-to-end (from feeder to the output of the beamformer) delay and phase as the reference antenna. This means that the array can be seen as an antenna in the physical position of the reference antenna, but with higher G/T than the reference antenna [RD 21]**.** If a global phasing solution (SUMPLE) is used the tropospheric delay could not be calculated easily and it would introduce an important error in the navigation solution. The same would happen with the "phase center" of the array: as there is not a physical antenna that serves as reference, but a virtual one, it would be very complex to calculate the central point for geometric calculations.

Phase errors can be made very small if long integration times are chosen. For instance, for a C/No=20 dB-Hz, the correlator SNR for 1 minute is 22 dB for any pair of antennas (0.36 degrees ->0.035 mm at X-band). Therefore, the influence of the phase error is negligible in tracking.

As with regards to delay errors, JPL states that errors lower than 0.1 nanoseconds can be achieved. This has been corroborated by INSA, and as a matter of fact our calculations show that with a regression analysis of the phase the delay error can be in the order of 4 picoseconds. This error can be achieved both with self-calibration or with radiostars.

Therefore, it is **only required to calibrate accurately the Rx System Delay of <u>only the reference antenna</u> (the rest of the antennas will have the same delay once the array is calibrated), and the Tx System Delay of the antenna in charge of transmitting ranging signals (in case that the two antennas are not the same)**

As a result of the analysis process, the error budgets for ranging, Doppler and angular determination in the array case are the same as in the single dish case

4.11 K and Ka-band joint reception

One of the initial requirements of the array was to allow the reception of X, K and Ka-bands. In all previous diagrams, only two bands appear: Ka and X. Nevertheless, the joint reception of K and Ka bands can be made, according to the assessment of the following elements of the reception chain

- Feeder. This unit has in principle four ports (two X and two Ka, all of them reception ones). In Ka-band, the it is feasible the design and construction of a feeder whose Ka-band ports let the K and Ka band signals (25.5 – 32.3 Ghz) pass. Therefore, the Ka+ band for Manned Missions would be sacrificed in favor of the K-band.
- LNA. The LNA from Low Noise Factory covers a range of frequencies from 22 – 36 Ghz.
- Downconverter. The downconverter from Das-Photonics is inherently wideband; as a matter of fact with the current configuration any frequency from X to Ka-band is being

downconverted. **This is an important cost saving factor. Instead requiring one downconverter per band, one single unit is capable of doing all of the bands.**

4.12 Array Digital Signal Processing

The ADSP subsystem will implement the following functions:

- **IF signal conditioning electronics**. It receives IF from antennas, band limits, level controls, digitizes and samples the signals and delays them appropriately (i.e., IF receivers, IF amplifiers, signal level controls, anti-aliasing filters, attenuators and the analog-to-digital converter (ADC)).
- **Beamformers** which coherently add signals from different antennas to form phased array beams.
- **Wideband Correlator** which cross-correlates signals from various antennas to gets relative phases and delays. The beamformer and correlator can be the same hardware configured differently or separate hardware modules.
- It also should include electronics needed to send a single IF per beam for input into standard receivers (i.e., Telemetry Receiver, Radio Science Receiver, etc.). Besides, the ADSP will monitor the total power and sync detector data for each polarization from every antenna.

Figure 17 illustrates the data flow of the ADSP; for instance, in the forty antennas baseline array, the samples from the ADCs are due to be processed simultaneously and streamed directly to the beamformer/correlator, whose output, the synthesized beam, is then streamed to a demodulator to process telemetry data.

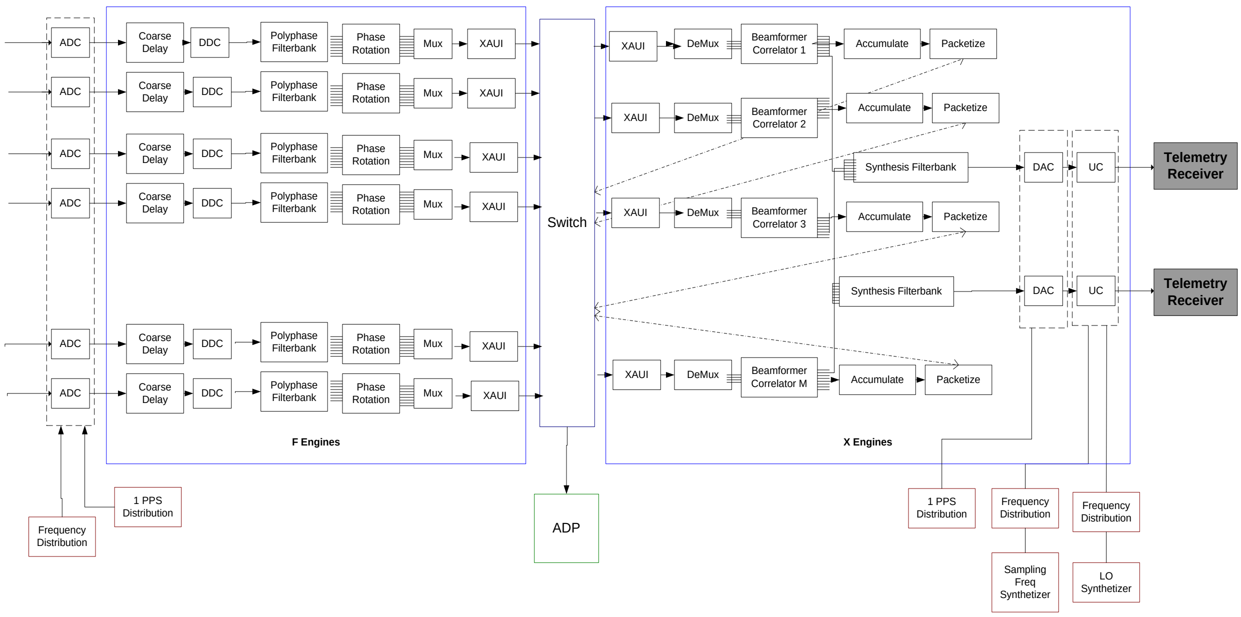

Figure 17. Array Digital Signal Processor Data Flow; the ADP is the Array Data Processor (a PC for Monitoring and Control Low Level Functions of the ADSP)

The architecture of this frequency-domain beamformer is very similar to an FX correlator, as it is illustrated in Figure 18 where data path of the two structures are shared and combined. As it was stated in the array description section, the frequency-domain beamformer is based on a polyphase analysis–synthesis filter bank pair. The first part of the polyphase filter bank, the analyzer filter bank, is exactly what is required for the first part of an FX correlator; before summing analogue inputs, channelization is performed using polyphase filter banks which will divide up the signal into 512 equally spaced frequency channels and then data streams are multiplied by complex phase and sum. The signals for each IF will be fed into their own polyphase filter bank. A corner turner is used to transpose the data from streams of frequency bands for each antenna into streams of antenna data for each frequency band. Moreover, correlation data at different frequency bands are used to feed back phase and delay corrections to the analysis filter bank. Then all the frequency channels in a specified bandwidth are synthesized back into one signal in the time domain; the output of the beamformer passed on to the DAC connected to an Up Converter (UC) from the array to get an analog output.

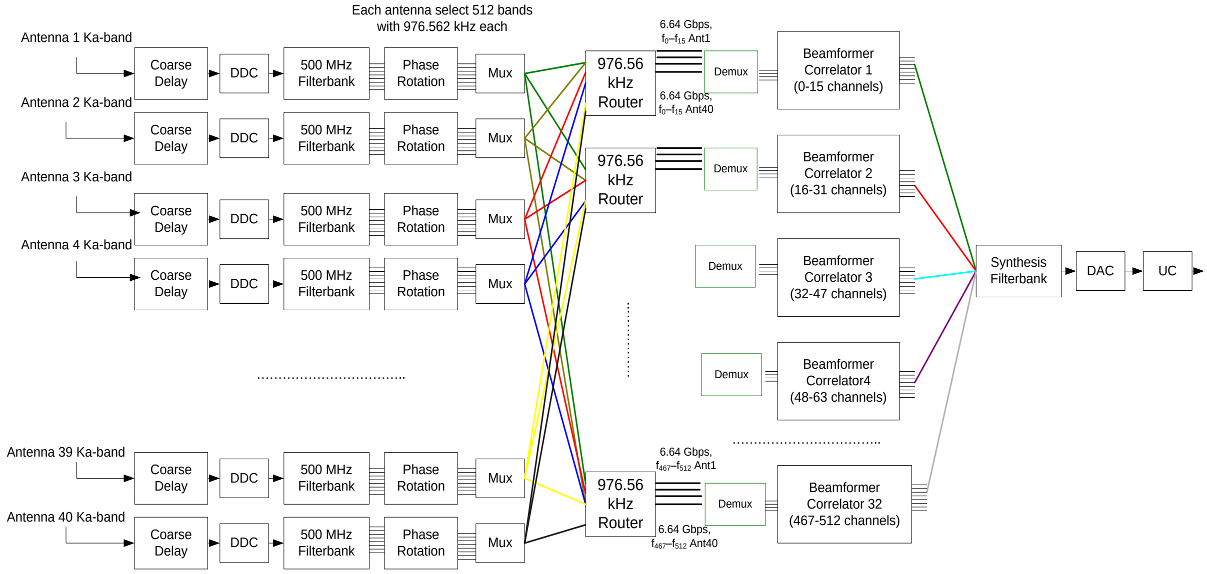

Figure 18. Proposed Array Frequency-Domain Beamformer (Ka-band)

4.13 Performance Comparison of both architectures

A 10 year simulation of 10 missions (Mercury, Venus, Mars, Jupiter, Saturn plus one Heliocentric) has been performed with two different ground segments: 4x35m and 40x12m. It is obvious that in the former case there will lost passes due to insufficient antennas to cope with all the missions. Besides, due to the finer granularity of the 40x12m array the resources can be assigned more efficiently.

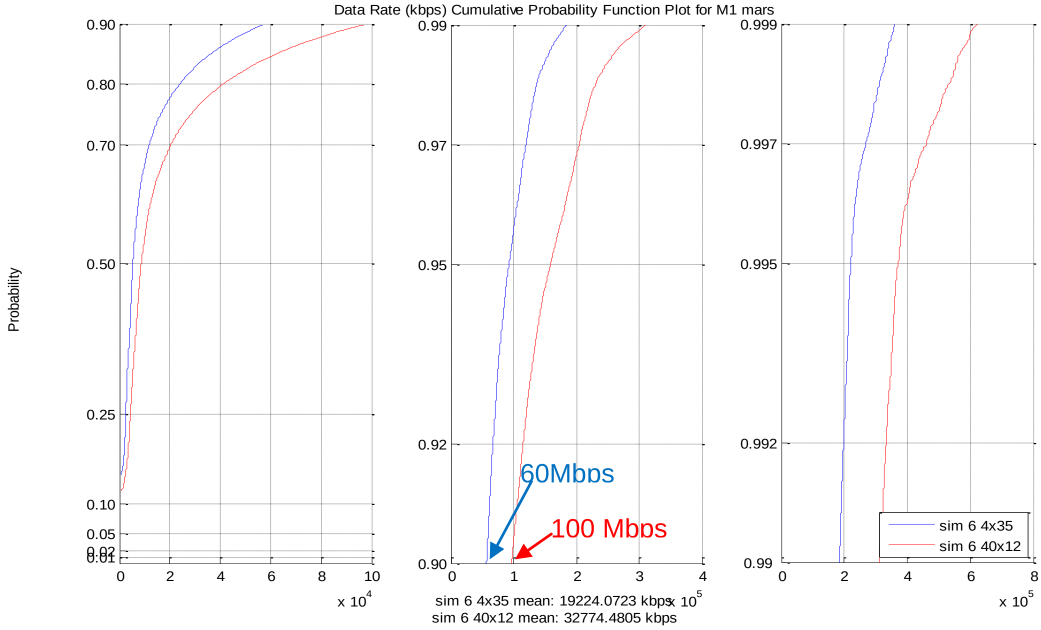

Figure 19. Cumulative Distribution Function of the Data Rates for Mars Mission (three GS; total of Six Missions; Satellite HPA Power =180 W; Satellite Antenna Diameter = 3 meters)

5 COST

5.1 Acquisition Cost

The construction cost of the 40x12m only Rx solution reaches the 30 M€; if we add the technological development activities this cost rises to the amount of 45 M€. The cost breakdown is shown in next figure:

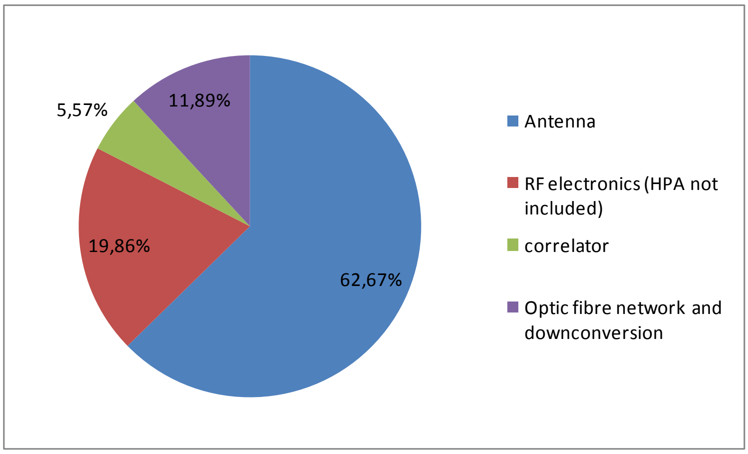

Figure 20. Budget distribution for the 40x12m array

It is worth mentioning that the cost item that weights the most in the final budget is the antenna. In this sense, uncertainty about its market price is zero, as the final budget is based on a commercial offer. Besides, there is margin for reduction of antenna price as more developments of the SKA project start appearing.

In the case of the 4x35m array the cost is around 80 M€ (Tx capabilities excluded for the sake of establishing a fair comparison).

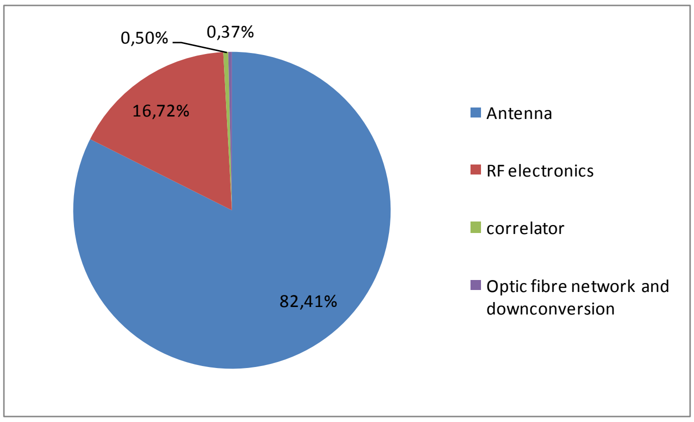

Figure 21. Budget distribution for the 4x35m array

5.2 Life Cycle cost

Operations and maintenance (O&M) costs are calculated by computing the present value of 35 years of O&M, assuming a 2% per year net gain over inflation for unused funds [RD 26]:

The three sub-budgets (technological development activities, construction and O&M) are aggregated in order to obtain total cost estimation in Table 8:

	5x35m [k€]	40x12m+1x35m [k€]
Construction	120.528,93	28.196,31
TDA	5.571	16.857,4
O&M	54.230	91.880
Total	180.329,93	136.933,71

Table 8. Total budget aggregation (per one GS)

6 ROADMAP

The roadmap will be divided into three stages as shown in next figure:

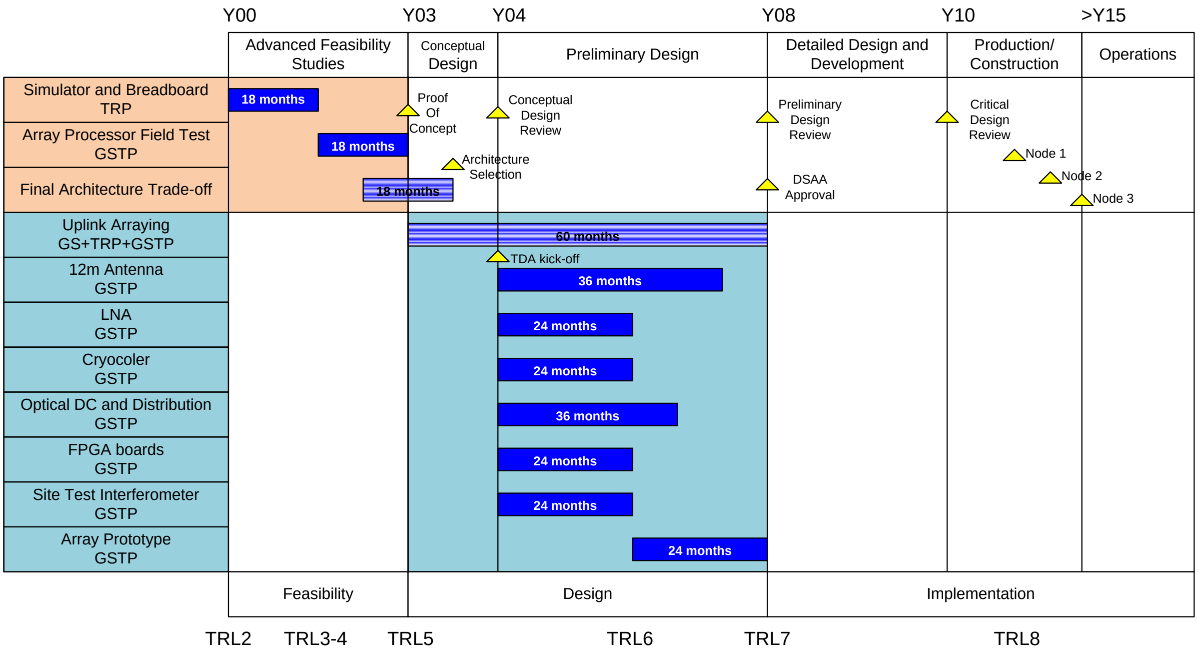

Figure 22. Roadmap for the Deep Space Antenna Array

In total, more than ten years of feasibilities studies, design and development are required before the construction of the array begins. These technological development activities are described next:

- Development of a simulator and a laboratory breadboard of an antenna array with emphasis in the signal processing functions, and the modeling of atmospheric effects, interference sources and satellite movement.
- Field test of an array digital processor with existing antennas to test most of the calibration modes and evaluate the end-to-end performances by establishing links with satellites.
- Optional Final architecture trade-off so as to assess the most viable array solution both technically an economically.
- Uplink arraying. Depending on the final selected architecture, combination in the uplink of the antennas may be required. Should this be the case, a five years program would have to be established to develop the hardware and algorithms required.
- The design of low cost 12 meter antenna should be tackled with special emphasis on cheap industrialization, as this component is the key cost driver of the system.
- Outdoor cryogenic LNAs, with simplified maintenance to lower O&M costs. The dewar should embark as many elements of the feeder as possible to get a low noise temperature.
- Development of an optical downconversion and signal distribution system with line-length correction. The importance of this activity comes from savings in components and volume, possibility of multifrequency operations, and increased stability of the links.
- Design and Development of a FPGA based processing subsystem with capability to deal with bandwidths of hundreds of Mhz, and with an scalable communication architecture.
- Installation of a site test interferometer at the selected array locations, to characterize the troposphere by means of the spatial and temporal structural functions.
- Finally, all previous TDAs should conclude with an integration of the different subsystems and algorithms in a small scale array prototype. This prototype will serve to prove the performances of each subsystem and the overall subsystem. Besides, some initial operational experience is expected to be gained, so that lessons can be gained and extrapolated to the Detailed Design of the Deep Space Antenna Array.

7 CONCLUSIONS

As most of this project has been focused on the selection of the best Ground Station Architecture for future Deep Space missions, the conclusions are offered in terms of an analysis of the pros and cons of each architecture. A similar comparison can be found in [RD 22].

	1x35m + 40 x 12 meter Solution	5 x 35 meter Solution
Cost	Acquisiton cost is approximately 1/3 the cost of the 4x35 meter solution	
		Higher cost
G/T	Higher G/T at elevation angles higher than 10 degrees	
		Lower G/T at high elevation angles due to reduced Gain
Pointing	Less complex. Pointing losses under with winds 30 mph under 0.1 dB	
		Very complex. Pointing losses under with winds 30 mph up to 1.5 dB
Multibeaming	Increased angular coverage and posibility to have more missions under the same subarray	
		Reduced angular coverage. Multibeaming capabilities quite reduced
Convergence time		Low. It can work with self-calibration for all data rate range
	Higher due to lower SNR per antenna	
Uplink Capability	Recent breakthroughs indicate the uplink arraying in X-band is possible	All of the antennas have Tx capability
	Only one 35 meter antenna is available for Tx. Inclusion of a 80KW transmitter is suggested, or development/purchase of uplink arraying technology	
Precalibration	In-beam calibration possible in X-band	Radiostar calibration not necessary during the pass
		The only technique available is Fast Switching
Antenna Position Calibration	If precalibration is only required in X-band, the calibration accuracy can be 10 cm with In-beam phase referencing	
		<4 millimeters for External phase referencing and angular displacement < 1 degrees
Signal Processing and F&T distribution		Easier, due to lower number of antennas
	More complex due to the higher number of elements	

	1x35m + 40 x 12 meter Solution	5 x 35 meter Solution
Tracking and Navigation	Grating lobes can be eliminated	Well-known with one antenna
	Not proven and still to be tested, although not degradation is foreseen	Problems in 4x35m configuration due to closely spaced grating lobes
Planet Noise Reduction	Higher due to higher number of antennas	
		Some advantages with regards to a 70m antenna are expected, although not so high as in the case of a 12m array
Number of missions	The granularity is very fine. A high number of missions with different pointing angles can be tracked	
		Up to 5. If a sixth mission is in a different pointing direction, it will be missed
Availability	At 10 degrees of elevation 36 antennas is enough to reach the desired G/T. With 4 antennas added, availability is 99.999%. Overcost is 11%	
		A whole 35 meter antenna has to be added to assure the required availability. This means an overcost of 25%
Spares	The set of spares is reduced as is shared between more antennas	
		Larger set of spares
Maintenace Personnel	Failure of several antennas is not crucial. Therefore, maintenance tasks can be scheduled with a standard shift of 5x8 hours per week	
		If in the future a high number of missions is going to be tracked, the antennas will be very busy and demanded, and it will be very important to restore asap a failure in one of them
Time to Repair	Low. Mechanical systems are less complex. By design it is foreseen that whole subsystems can be replaced on site	
		High, especially if mechanical failures happen.
Monitoring and Control		Less Complex due to reduced number of antennas
	More complex due to the higher number of elements	