ESA Space applications & the square kilometre array: Synergies in requirements and technologies

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- ESA Space applications and the Square Kilometer Array: Synergies in Requirements and Technologies, by Ir. Jan Geralt Bij de Vaate, vaate@astron.nl ASTRON.
- VLBI observations of the Huygens probe, by Dr. L. I. Gurvits, gurvits@jive.nl JIVE.

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ESA Space application and the Square Kilometre Array: Synergies in Requirements and Technologies

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1 Introduction

This report describes part of the investigation that has been carried out for the contract between ESA and ASTRON: “ESA Space application and the Square Kilometre Array: Synergies in Requirements and Technologies”. Of this contract only objective 2 and 3 will be discussed in this report. The objective 1, tracking the Cassini probe, will be reported by JIVE, L Gurvitz.

2 Introduction to SKA

Radio Astronomy instrumentation currently rely on the use of large paraboloidal reflector Antennas often larger then 25m diameter and at some locations setup in arrays in order to increase the baseline up to a couple of kilometers. Very Long Baseline Interferometry (VLBI), where antennas are combined on the scale of Europe or even with antennas that are satellite based (Space VLBI), increases the resolution to sub-milliarcseconds. Limitations arise because these existing telescopes typically have collecting areas below 10.000m^2 while observing with a single beam and limited instantaneous frequency bandwidth. Over the past several years, discussions have been occurring in several countries about the next logical step in radio astronomy following the up-coming construction of the large millimetre array ALMA. An initiative has emerged to develop a telescope to provide two orders of magnitude increase in sensitivity over existing facilities at metre to centimetre wavelengths. To achieve this goal will require a telescope with one square kilometre of collecting area - one hundred times more collecting area than the Very Large Array. The Square Kilometre Array (SKA) would probe the gaseous component of the early Universe, thereby addressing fundamental questions in research on the origin and evolution of the Universe. The SKA would complement planned facilities at other wavelengths, such as ALMA and James Webb Space Telescope (JWST). Extensive discussion of the science drivers and of the evolving technical possibilities has led to a concept for the Square Kilometre Array and a set of design goals. The SKA will be an interferometric array of individual antenna stations, synthesizing an aperture with diameter of up to several 1000 km. A number of configurations are under consideration to distribute the 10^6 square meters of collecting area. These include 30 stations each with the collecting area equivalent to a 200metre diameter telescope, and 150 stations each with the collecting area of a 90 m telescope. Approximately 50% of the array is to be contained within a centrally-condensed inner array to provide ultrahigh brightness sensitivity at arc-second scale resolution for studies of the faint spectral line signatures of structures in the early Universe. The outrigger stations provide a ten to one hundred-fold increase in angular resolution to allow high resolution imaging of faint emission from the interstellar media of distant galaxies, as well as the surface of stars, and the active nuclei of galaxies.

At the first SKA international workshop, Sydney 1997, the goals for the basic system parameters were established, see Table 1 [1]. In this list the number of instantaneous pencil beams are the beams that can be placed simultaneously within the Imaging Field-of-View. These are not independent beams, they are ‘locked’ within the e.g. 1 square degrees of the primary field of view. The design goals are based on what will be needed to perform so called ‘level 0’ science [1]. The level 0 science list includes, besides all major astronomy subjects, the search for extraterrestrial intelligence. It does not include yet support of deep space missions.

SKA Design Goals	
Parameter	***Design Goal***
Aeff /Tsys	2 x 10^4 m^2/K
Total Frequency Range	0.15 - 20 GHz
Imaging Field of View	1 square deg. @ 1.4 GHz
Number of Instantaneous Pencil Beams	100
Maximum Primary Beam Separation low frequency high frequency	 100 deg. 1 deg. @ 1.4 GHz
Angular Resolution	0.1 arcsec @ 1.4 GHz
Surface Brightness Sensitivity	1 K @ 0.1 arcsec (continuum)
Instantaneous Bandwidth	0.5 + v/5 GHz
Number of Spectral Channels	10^4
Number of Simultaneous Frequency Bands	2
Imaging Dynamic Range	10^6 @ 1.4 GHz
Polarization Purity	-40 dB

Table 1 SKA design goals

3 SKA concepts

The international Radio Astronomy community is working on wide spectrum of different solutions to deal with the challenge of realizing the square kilometre array. The total of 7 concepts are not only different in realization, but also in terms of meeting the SKA design goals. In fact none of the concepts is meeting all goals. The final SKA design will therefore most likely be a hybrid design; a combination of two or more concepts. The International SKA Steering Committee (ISSC) requested the (national) institutes to demonstrate the feasibility of their concept with a 1% SKA demonstrator. The results of the SKA demonstrators, to be operational by the end of 2007, will lead the creation of a short list with preferred concepts and hybrid solutions.

3.1 The Large-N small-D Concept

The most straightforward way of building a large collecting area is known as the Large-N small-D concept (LSDN), pursued by the US consortium. A large number, over 4000, of 12meter dishes are being proposed. A smart feed design should make a large bandwidth possible, 0.15 to 34GHz. The small diameter approach is seen as more cost effective then 'just' building a large number of 30-50 meter telescopes.
A deviation of the US approach is the 12m dish proposed by the Radio Astrophysics Institute of India. In the contrary to the US solid dish, a wire mesh preloaded parabolic dish (PPD) will be designed. With the advantage of lower fabrication cost and, due to the lower wind load, engine control complexity. The maximum frequency is however limited to 10GHz.

3.2 The Large Adaptive Reflector

The Large Adaptive Reflector (LAR) concept is being developed by the National Research Council of Canada. The LAR will consist of an array of 60 200-m Reflector Antennas where the methodology behind the LAR idea is to:

- Utilize a reflector antenna, with all its favourable properties for frequency-independent radio wave reflection
- Build the reflector with a large focal ratio (f/d, where f is the focal length) so that the curvature of the reflector is very small
- Provide an independently moveable focal platform and an adjustable reflector shape to provide "access" to a whole family of Zenith Angle. The goal is to cover a Zenth Angle range up to 60 at all Azimuths.

Expected frequency range of the LAR system is 0.15 to 22GHz

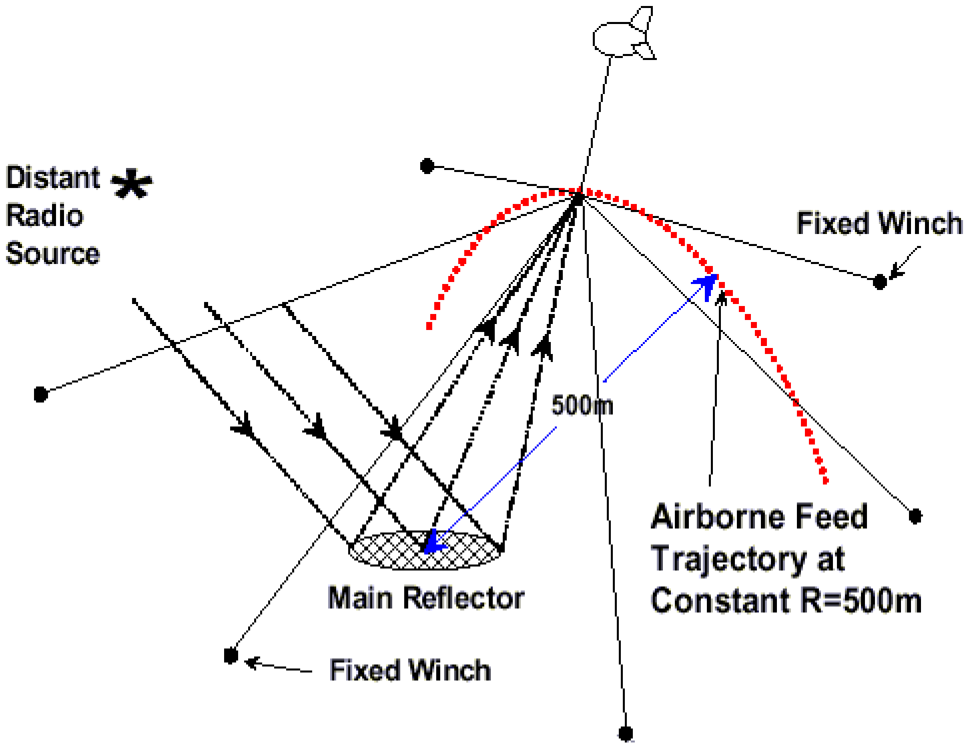

Figure 1 A sketch of a LAR station, where the main reflector forms part of a "virtual" parabola and where the focal a antenna can be moved above the reflector

3.3 The Luneburg Lens

The Luneburg lense, a spherical radio lens as the first stage beamformer, is being studied by CSIRO, Australia. The Luneburg approach, with its wideband optical beamforming and intrinsic capability for placing multiple beams across the sky, is an intermediate one offering some of the signal processing flexibility associated with phased arrays, as well as most of the performance and versatility of reflecting concentrators. Multiple beams can be placed on the sky independently. The frequency range is limited by the loss of the dielectric, on the high end, and by the size of the lens, on the low end. Estimated is currently 0.1 to 10GHz. The SKA should contain 19.000 7m lenses, which will create a square kilometre collecting area only if you take the multi-beaming capability into account.

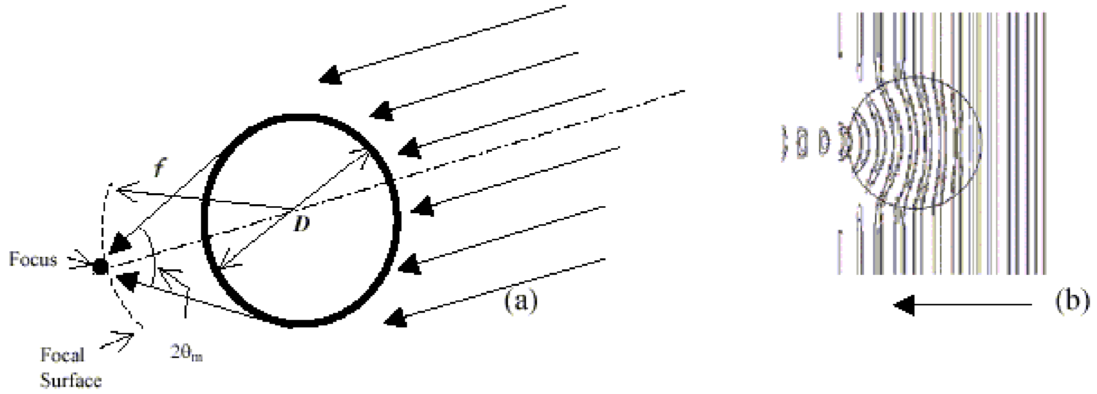

Figure 2 In (a) the geometry of the Luneburg lense is shown, while (b) is a superposition of electric field snapshots showing the focussing action on a wavefront travelling from right to left

3.4 The Cylindrical Reflector

The Cylindrical Reflector is the second concept, which is being studied by CSIRO, Australia. Large cylindrical reflectors are advantages compared to phased array’s in terms of cost; less receivers and advantage compared to paraboloids in terms of field of view; more beams are possible on a larger area of the sky. The multiple beams, to be synthesized with a smart (digital) line feed, are however linked: the beams are not completely independent.
Frequency range is believed to be 100MHz to 9GHz, where higher frequencies are possible (up to 20GHz) with sensitivity loss.

3.5 KARST

The Beijing Astronomical Observatory is proposing a small number of large reflecting surfaces installed in a naturally occurring depression, with the receiver system suspended from cables on pylons at the edge of the depression. The concept is called the KARST (Kilometer square Aperture Radio Synthesis Telescope). The KARST consists of 30 300m diameter reflectors, with a frequency range of 100MHz to 2GHz (extension to 8GHz might possible).

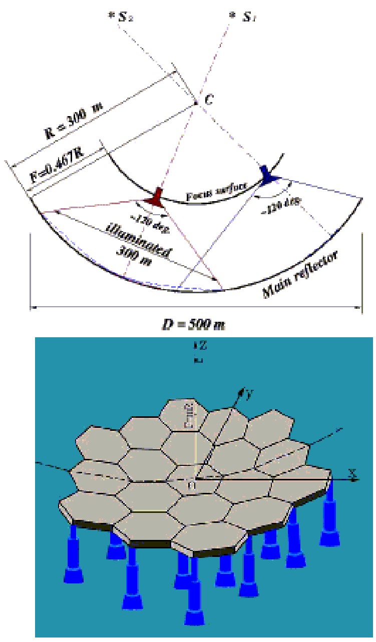

Figure 3 Sketch of a 500 KARST station

3.6 Aperture Arrays

The European SKA Consortium is pursuing the concept of aperture arrays. Each station in this concept consists of an array of integrated antenna tiles. Each tile consist of a collection of simple, all sky antenna elements coupled such that beams are formed and steered electronically on the sky: the phased array principle. Although this concept is the most advanced of those under investigation, besides unique features, it has serious drawbacks. The electronic steering and beamforming creates the possibility of generating multiple independent beams. Which makes the aperture array a multi-user instrument, a very important aspect for an instrument of this size and cost. The effective observing time can be expended without the loss of sensitivity. Drawbacks and other aspects of the aperture array will be discussed in section 5 of this report.

3.7 SKA Concepts summary

Table 2 gives an overview of the capabilities of the 7 described concepts with respect to the crucial criteria for Deep Space Tracking and Navigation. These are not the only crucial criteria, but these where the differences between the station concepts are dominant.
The frequency of 2.4GHz is listed, although it is planned to be phased-out, for completeness but also since the multi-beam capabilities of the phased-array concept in this band might generate new potential for it. The columns A_{eff} give an indication of the effective area at the given frequency. A reduction will influence the sensitivity of the system but not aspects as angular resolution. Since the Phased Array concept will most likely be designed as a dense array for frequencies up to 1.4GHz, at 2.4GHz a reduction in the A_{eff} of this concept should be anticipated. Except for the Phased Array concept most approaches will be capable or can be designed for 8GHz reception as well as 2.4GHz. However due loss in efficiency, a lower A_{eff} is expected for some concepts at 8GHz as well. Only the small dish concept (Large-N Small-D) foresees a good functionality at 32GHz [1].
The column *multi-beams* gives the capabilities of the concepts for creating Multiple Fields of View (FOV). Multiple FOV's are defined as independently steer-able positions on the sky. This in the contrary to multiple (digital) beams, which might be created within a single primary beam. Only the Phased Array and the Luneburg lens concept are capable of Multiple FOV's, while maintaining the full sensitivity of the complete system for each FOV.

	2.4GHz	**Aeff@ 2.4GHz**	**8GHz**	**Aeff@ 8GHz**	**32GHz**	**Multi-beams (fov)**	**Sky coverage**
Large-N Small-D	yes	100%	yes	100%	yes	no	good
Phased Array	maybe	30%	no	-	no	yes	good
LAR	yes	100%	yes	90%	no	no	limited
Luneburg lens	yes	50%	maybe	10%	no	yes	good
Cylindrical array	yes	100%	yes	90%	no	no	good
KARST	yes	100%	maybe	-	no	no	limited
PPD dishes	yes	100%	yes	25%	no	no	good

Table 2 Cross-reference comparison matrix

A solution for the other concepts is the use of sub-arraying (
Figure 4). Each sub-array forms a single FOV. The created beams have a reduced A_{eff}, however might still have the resolution of the complete system. Sub-arraying is very good possible with the large number of small reflectors, however the very large reflectors, LAR and KARST, cannot be used very efficiently for sub-arraying due to small number of antenna elements.
The *sky coverage* of the large reflectors is limited due to mechanical constraints of these concepts. A limited sky coverage can be solved for astronomy with a dedicated scheduling, however is likely to cause a problem for Deep Space Telemetry. Mission signals can only be received for a short period of the day.

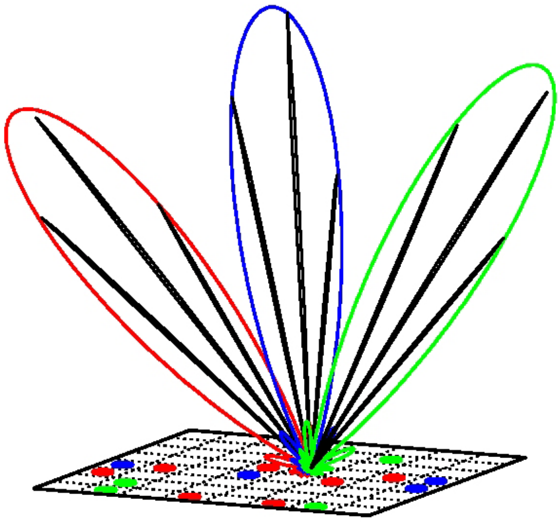

Figure 4 Use of sub-arraying, coloured dots represent the antenna stations, red stations form the red beam, blue stations form the blue beam etc.

4 Deep Space Tracking and Telemetry with SKA

Although a Deep Space Network (DSN) is not seen as a level-0 science criteria, the international SKA community has set-up a working group to investigate the possibilities of Space Craft Tracking with SKA [2]. A SKA size array would allow of the order of 100 times greater data rate to the outer planets, smaller and less expensive spacecraft, longer missions in the case of Mars (where the distance varies from 0.33 to 2.5 AU), and very accurate real-time navigational data.

Angular resolution:
The maximum baseline length of at least 1000km for angular tracking will be met by the SKA and will result in an angular resolution of 0.5milliarc seconds (3000km baseline) at 32GHz. The two lower communication frequencies will have the respectively lower resolution.
Continues data transmission :
For telemetry reception from deep space missions continuity is critical, which will be an additional requirement for the back-end of SKA since for radio astronomical signals gaps can be allowed. And will appear due to phase-switching and block processing.
Frequency range:
As can be seen in Table 2, most concepts can receive the 2.4 and 8GHz signals. However only the Large-N Small-D concepts is capable of receiving 32GHz signals.
Sensitivity:
The target sensitivity of A_{eff}/T_{sys}>20.000m^2/K, which translates in a G/T of:

$$G/T = \frac{4\Pi A_{eff}}{\lambda^2 T_{sys}} > 94\text{dB @ 32GHz}$$

The bit rate of the downlink telemetry signal is directly proportional to the G/T [3], an important reason to go for higher frequencies. And although even the Small-D Large-N concept will most likely only achieve an A_{eff}/T_{sys} of 5000m^2/K, this will still give an G/T of 88dB compared to an G/T of 72dB for A_{eff}/T_{sys} of 20.000m^2/K at 2.3GHz. The loss of the transmission trough the troposphere will be slightly higher at 32GHz, a few dB, in dry weather [4]. And the efficient generation of RF power in the spacecraft will be somewhat more difficult. Still an advantage for the high RF frequency of about 10dB remains. These sensitivities are valid if the complete square kilometre array can be used for DSN. This is only possible on more then an exceptional case if a SKA system has multiple independent beams for the frequency of communication. If independent multiple beams are not available only particular events can make use of the complete SKA.
Larger data rates then currently available will be required for example for planned Mars missions (ARTHEMIS). Higher Sensitivity creates a new view on the telemetry, lower power transmission requirements of the spacecraft allows for smaller design, lower power consumption and longer range communication [5].

Item	**Specification**
Frequency coverage	2.2-2.3GHz, 8.4-8.5GHz, 31.8-32.3GHz
Minimum sensitivity	5000 m^2/K
Polarization	Right hand Circular (RCP) and Left hand Circular (LCP)
Data transmission	No gaps allowed
Baseline	>1000km
Reception	Simultaneous 2 and 8 GHz Or Simultaneous 8 and 32 GHz (for reception calibration)
Timing	High time resolution
Configuration	Availability of “analogue sum” output from the central part of the array for each of the several beams

Table 3 Summary specifications for DSN reception

Except for the first three items in Table 1 the DSN reception generates very specific design requirements that should be take into account early in the design process. And will influence the cost of SKA.

5 Spin-off of the SKA Aperture Array

Due to the very special nature of the Aperture Array of the size of a square kilometre, a number of technologies will be developed specific for the SKA:

5.1 High bandwidth

Bandwidth's in the order of 2.5:1 are the minimum, but much larger bandwidth's would significantly reduce the cost of the system. A conservative approach to the Aperture array currently includes a three band option for the frequency range of 0.15 to 1.5GHz. In Figure 5 the A_{eff} and A_{eff}/T_{sys} are plotted for this option, where the effective area is respectively 1.6km^2, 0.8km^2 and 0.4km^2. The area of the third array is extended in order to sketch the possibilities with degraded performance. This three band options implies three antennas, three RF beam forming networks and three down-conversion units etc. Covering the bandwidth with a two or one antenna system will decrease the complexity of the system and therefore the cost. A decade wide bandwidth would meet the requirement of a single antenna array for the target bandwidth. Possibilities in order to increase the bandwidth are:

Optimising the design of the antenna element, where the **vivaldi** is seen as the antenna concept with the most potential. Vivaldi arrays currently have bandwidth's in the order of 3:1 however 5:1 is expected to be possible.

Use **reconfigurable aperture arrays**, with the use of Micro Electrical Mechanical (MEM) switches. The MEM switch can provide a low cost, low insertion loss and high dynamic range contact with which the frequency band of the array can be controlled. This will however not create a high instantaneous bandwidth, since the configuration of the switches is different for each frequency band.

Nesting of antenna elements, by placing higher frequency antenna elements in between lower frequency elements larger bandwidth's of a single aperture can be created.

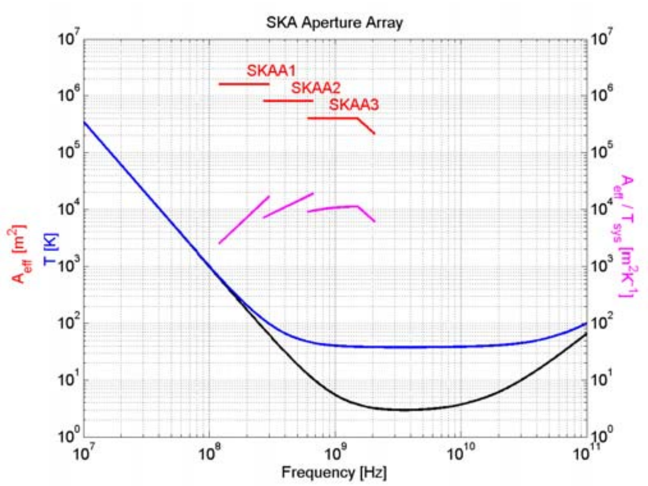

Figure 5 Three band Aperture Array performance estimates

5.2 Noise Figure

Since the observation time required to for the detection of (very weak) sources is proportional to the square of the system noise temperature, a low system noise is required to be able to perform observations in a reasonable time. For this reason Radio astronomy instruments gain significant in efficiency if the system noise temperature is lowered by cooling the Low Noise Amplifier (LNA). However cooling the LNA's with liquid Nitrogen (78 Kelvin) or liquid Helium (20 Kelvin) will be very expensive. The aperture array concepts will therefore need very low noise figures at 300K environment temperature. System noise temperatures in the range of 30K are required, which drives LNA requirements to 20 – 25K (<0.3 dB). Following the noise figure trends [6] as given in Figure 6,even low cost technologies (SiGe and CMOS) will get to very low noise figures.

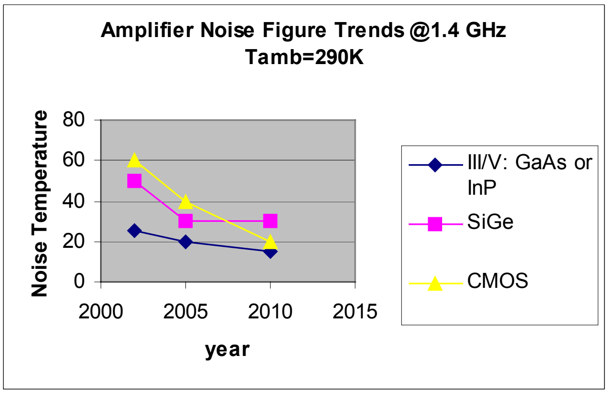

Figure 6 Noise figure trends

Besides the LNA noise figure, all noise sources in a phased array system have to determined and controlled in order to meet this very stringent requirement [7]:
-Losses in the antenna structure, dielectric material losses and metallic losses
-Losses between the LNA and the antenna
-LNA noise figure, with the antenna impedance as signal source, which will be un-equal to 50 ohm by definition
-Noise coupling between array elements; a LNA transmits noise back to the input to the antenna, which will be received, through mutual coupling, by neighbouring elements.
-Ground noise, noise received by the side lob's and back lob's of the antenna
In to order to control the 5 listed noise contributions a very careful *active antenna* design will be necessary.

5.3 Low Cost

An antenna element spacing smaller or equal to λ/2 is required to avoid grating lob's. This means that an array with the highest frequency of 1.5GHz will need an antenna element spacing of 10cm. In order to create a collecting area of about 1 km^2, 100 million elements are required for each polarization. This drives a cost constraint on the front-end since the total system is expected to be less than 1B€. Pricing of the front-end should be around 1-5€, which will include antenna, low noise amplifier, phase and amplitude control circuitry and beam. Integration of the active and passive components in one IC, or in a single package, e.g. a Multi-Chip-Module, will be required. The antenna cannot be printed on low cost PCB materials due to a too high price of PCB's. Alternatives as metal sheet antennas and antennas on e.g. polyester films will be required. Antenna solutions on folded paper with a thin layer of a conductive material are even considered [8]. Figure 7 gives an artist impression of possible tile configuration. The total cost of a 1x1 meter tile should be in the order of 500€, where the output of a tile is a digital data stream on a fibre.

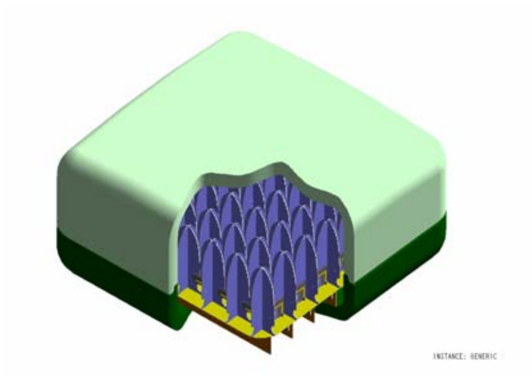

Figure 7 Artist impression of a low cost tile

5.4 High instantaneous bandwidth

The SKA will work with an instantaneous frequency bandwidth of larger then 500MHz. This high bandwidth has a number of implications:
-**Handling of high data streams**, for a 8-10 bits conversion, a bit stream will be generated of 10Gbit/s per Analogue to Digital conversion. These data streams will go into a processing computer, where massive data streams have to handled
-**Wide bandwidth (RF) beam forming** leads to novel designs, since phase rotation will not be sufficient at frequencies below 1.5GHz, where time delays are required. In order to perform this cost effective, new solutions have to be generated. Fully digital beamforming will solve this constraint; however will lead to an immense data-handling requirement of e.g. 1000 Petabits/s (10^18). This data stream will be processed distributed over the tiles, stations and the central correlator computer. But, even if Moore's Law is still valid for another ten years, a data stream of this size cannot be processed cost effective.

5.5 RFI and EMC aspects

The SKA system will most likely be build at remote locations like the Australian desert or the state of New Mexico. However, also at these locations the SKA will suffer from RF Interference (RFI). The minimum detectable signals of a SKA will be of microJansky (10^{-6} * 10^{-26} $Wm^{-2}Hz^{-1}$) flux densities, signals 90dB below thermal noise level. The RFI will generate intermodulation products and suppression in an early stage in the signal chain should avoid complete destruction of all parts of the spectrum [9,10,11]. Besides RFI, Radio Emissions of equipment (EMC) can cause serious problems, see also Figure 8.

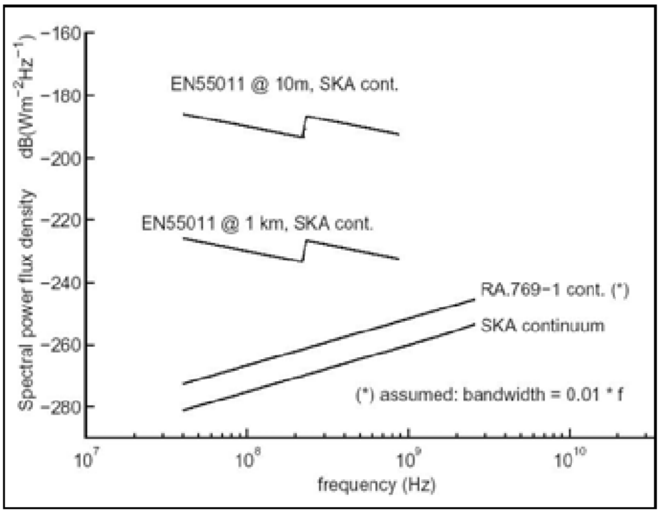

Figure 8 Emission levels from equipment according to the EN55011 standard w.r.t. the sensitivity of the SKA, according to the SKA design goals and 8 hours of integration.

Three RFI-source separation methods can be distinguished: filtering, cutting and subtracting (cancelling). Filtering is removing RFI signals in regions outside the regions of interest (e.g. spectral filtering and array beamforming), cutting is removing the RFI in partially overlapping regions (e.g. time blanking) and subtracting is removing RFI by estimation and subtracting (e.g. side lobe cancelling, spatial filtering or parametric methods).
An important aspect of the RFI problem for SKA is the very long base-line. This makes a simultaneous detection at many stations unlikely, which will create a significant RFI suppression.

5.6 Focal Plane Array

Besides in aperture arrays, phased array technology can be used in the design of focal plane arrays [12]. A dense array, placed in the focal plane of a large reflector, can enhance the capabilities of the reflector with: -generation of (dependent) multiple beams, -improve the reflector efficiency, -correction of surface errors.

5.7 Calibration and beamforming

The calibration of a very large array is an aspect not new to radio astronomy; JIVE [13]. However with the use of aperture arrays an other dimension is added [14]. Calibration on reference sources will probably not be possible on station level. And the down conversion with very accurate, but expensive, Hydrogen Masers in the signal generation should be replaced. Still high accuracy is required.

5.8 Optical Beamforming

The large instantaneous bandwidth requirement for SKA creates constraints in the beamforming circuitry, see also paragraph 5.4. Time delay beamforming, in contrary to phase beamforming, has the possibility for a large instantaneous bandwidth. However time delays implemented in a conventional RF board technology will have cost associated of long delay lines and a large number of switches. A solution to perform efficient time delay beamforming is the use of optical beamforming [15]. An RF signal is then modulated on an optical carrier ('up-conversion'), the delay of light sub sequential can be modified either by switching fibres with different lengths, or by controlling the delay in an optical carrier. In Figure 9 a photograph is given of a 4 elements optical beamformer prototype. In this case fibres with different lengths are used as (time) delay sections.

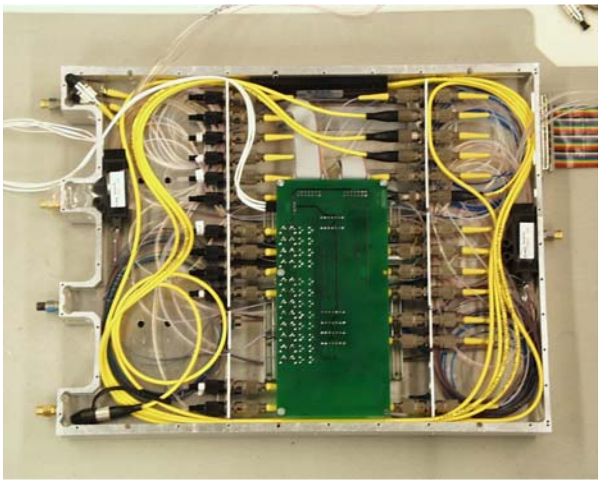

Figure 9 Switched Fibre beamformer prototype

6 Applications for Aperture Array SKA technologies

Besides the use of the SKA as an instrument for Deep Space Tracking, the to be developed SKA technologies can be of use for other applications as well. For telecommunication low cost multi beam receiving and transmitting phased array systems, will generate opportunities not feasible with current available technology. Besides telecommunication, also ESA-ESTEC projects might benefit from SKA technologies. A few applications will be listed in order to illustrate the potential synergies.

6.1 SAR

Synthetic Aperture Radar's (SAR) generally have a large number of antenna elements in order to cover a wide field with sufficient resolution. For example a SAR will be mounted on the ENVISAT satellite. This SAR has a size of 11x1m and a total of 320 antenna elements and operates at 5,3GHz. A lower frequency L-band Array SAR (LASAR) with 140 elements is currently under design [16]. The RF front-end and beamforming technology forms a considerable part of the total cost and weight of these system. SKA low-cost, low-weight, low power consumption phased array technology can be used to improve the SAR design. However SAR systems need a transmit capability, which is not foreseen in any of the SKA designs. Other SAR designs work at 460MHz, are also in the band of interest of the aperture arrays.

6.2 Terminal Antennas

The development of low cost phased array technology with multi-beam capability can be used for Ground based Terminal antennas.
The electronically streerable antenna can track not fully stabilized satellites (even) when the antenna is mounted on a mobile platform [ARTES, 17].

The reception and calibration of Galileo GPS satellites can be performed with a phased array system. A large number of satellites can be tracked and positions can be determined with a single phased array antenna. This can be important for monitoring and calibration of the Galileo system. In Figure 10 an all sky scan is given of a 1m^2 phased array system tuned at one of the GPS frequencies, 1575MHz. Due to the fast scanning capabilities multiple satellites are detected and can be monitored [18].

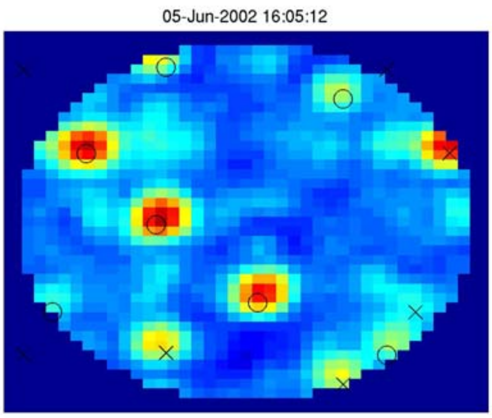

Figure 10 GPS satellite detection with a 1m^2 phased array at 1575MHz

Future satellite Broadband Systems will make use or will need very similar technologies as the SKA [19]. Although the frequency range is higher then where the Aperture Array concept of SKA will work, Ka-band (27-40GHz), for the concept as sketched in Figure 11 new technologies will be needed. For the realization technologies under consideration are e.g. active phased arrays, re-configurable systems, optical RF distribution, digital beamforming, adaptive antennas and multi-beam antennas. The user terminal development plays an important role in the success, for which aspects as low-cost front-end technologies and steerable antennas have been identified.

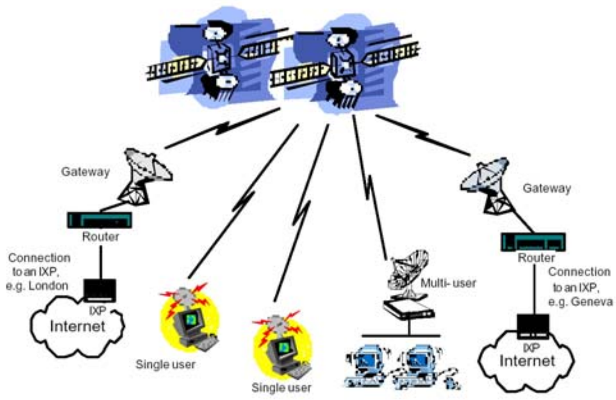

Figure 11 Satellite distribution access network (De Gaudenzi)

In general an active controlled array has more possibilities to control the beam shape then a rigid reflector structure. The location of the stations of SKA will be optimized for the array beam shape and is fixed after realization, but weighting vectors, between stations and within stations, can be set during operation. Optimization for a given scenario can be realized on line.

6.3 Telecom Technology

Phased array technology used in a telecommunication service can make more efficient use of space and frequency allocations. Further more low-cost very low noise figures can contribute to improvements in the link budget of future telecommunication standards (e.g. beyond 3G).
Phased array (RF and digital) beamforming creates possibilities for interference suppression, which become within reach when low cost technology becomes available together with advanced RFI suppression techniques. Interference suppression will become a major issue for future telecom systems due to increasing congestion in the RF environment.

The wide bandwidth technology of the SKA creates possibilities for Ultra Wide Bandwidth (UWB) communication. UWB transmits at low power levels signals with typically a decade frequency bandwidth. It might be possible to use UWB communication for DSN applications as well, however it has to be noted that the impact on Radio Astronomy science has to be investigated.

6.4 Focal plane Arrays

Focal Plane array technology will enhance the existing and planned reflector antennas for the DSN, due to the multi-beam capability but also due to the possibility of surface error corrections. For ground based existing reflectors this is a small improvement of the reflector efficiency, however when used in combination with large deployable or panel antennas a very significant improvement can be realized. In particular for off-set geometries, a dense focal plane array can improve the antenna efficiency significantly [20]. A dense focal plane array combines the flexibility of a phased array system with the advantages of low cost reflectors systems.

7 Conclusion

A first assessment of the implication of the Square Kilometer Array for ESA space has been presented. It however has to be noted that with the complexity of SKA and the broad technical range of aspects, only a limited assessment could be performed in the given time.

It has been made clear that the SKA development should *not* be neglected with respect to the planning of future Deep Space missions. However, as pointed out in paragraph 3.7 Table 2, all SKA concepts currently considered have limitations for use in Deep Space Telemetry together with Radio Astronomy. In the table only a rough outline is given of areas where compromises will be necessary. Further study is required to investigate all design elements of a SKA for the use in a DSN. A close cooperation in an early phase of the development of SKA with DSN representatives will also be required. This latter aspect has already been formulated in a “space tracking” working group as part of the SKA community. A particular interesting area for DSN is the use of SKA event based; short specific operations like the reception of lander signals between launch and impact can be made possible with the use of the complete SKA sensitivity and resolution.

The technologies to be development for this Radio Astronomical Instrument will be relevant for other instrumental design, e.g. telecommunication and space instrumentation. Or stated more clearly, in order to make SKA happen, given the very stringent cost and performance requirements, *a technology breakthrough* is required. This technology breakthrough *will* influence related industry and research areas.

The latter fact is illustrated with a recent expression of interest in the Low Frequency Array (LOFAR) [21] project, by a large computer company (IBM). The advanced processing requirements of the more then 10.000 antenna elements of this large array can be seen as step towards SKA. And are of a complexity not demonstrated before, which explains the investments planned by the industry.

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Joint Institute for VLBI in Europe

VLBI observations of the Huygens probe

Assessment study report

JIVE Research Note #0004

10.07.2003

Dwingeloo

JOINT INSTITUTE FOR VLBI IN EUROPE

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1. Introduction: the goal of the study.

This document describes the results of an assessment study of VLBI observations of the Huygens probe during the its descent to the surface of Titan. The study was conducted under contract No. 17002/02/NL/LvH/bj between the European Space Agency (ESA), and the Netherlands Foundation for Research in Astronomy (ASTRON) and the Joint Institute for VLBI in Europe (JIVE). The goal of the study was to assess the feasibility of observing the probe from Earth and detecting its S-band radio signal during descent to the surface of Titan. Such direct reception by Earth-based tracking stations was not foreseen in the original mission scenario. However, it can provide definite evidence of the probe's transmission after separation from the Cassini spacecraft over the entire lifetime of the probe. Moreover, Earth-based VLBI measurements of this radio signal can offer record accuracy in determining the probe's position in the atmosphere of Titan.

The set of relevant mission parameters is given is Section 2. Section 3 briefly describes the VLBI technique in its "phase-referencing" mode and gives an overview of the celestial environment around the interface point and a list of radio telescopes that could be used for VLBI observations of the probe at the appropriate time. Section 4 describes the model of the probe's S-band signal and methods of its detection. Section 5 gives a brief description of instrumentation required for the Huygens VLBI observations. Section 6 summarizes conclusions of the assessment study.

2. Description of the relevant mission specification parameters

1. The interface time is assumed to be 09:00:00 ET of 14.01.2005 ([3], Table 2.2-1).

2. The Cartesian coordinates of the probe at the interface time in the Earth Mean Equator of J2000 are (e-mail from M.Perez to L.Gurvits of 26.05.2003):

   X = -4.8691069e+08 km; Y = 1.0130829e+09 km, Z = 4.4004293e+08 km
   $\dot{X} = 2.1549931e+01$ km/s, $\dot{Y} = 1.3609053e+01$ km/s, $\dot{Z} = 3.6837857e00$ km/s

   This translates into (J2000):

   $$\mathrm{RA} = 07^h 42^m 40.7995^s, \quad \mathrm{DEC} = +21^\circ 22' 47.557''$$

3. The probe transmits two sinusoidal carrier signals at the frequencies 2040 MHz (Channel A) and 2097.91 MHz (Channel B).

4. Signal transmitted by the probe's Channel A with the carrier frequency 2040 MHz is modulated in accordance with the PM/BPSK-PCM/NRZ-M scheme [3]. The Effective Isotropic Radiated Power (EIRP) of the two radio link channels is given in Table 1 as a function of temperature of the transponder (see Draft Section 6 of [3] , version of May 2003):

   Table 1. Effective Isotropic Radiated Power (EIRP) of the Huygens Pobe

	EIRP [dBW]			Variation [dB]	
	Maximum (55º C)	Nominal (22º C)	Minimum (-25º C)	Min-Nom	Max-Nom
Channel A	10.23	10.66	11.02	-0.43	0.36
Channel B	10.33	10.83	11.34	-0.50	0.51

5. Huygens on-board local oscillator (USO – ultra-stable oscillator) parameters are listed in Table 2 [4, p. 157]:

Table 2. On-board LO parameters

Integration time [s]	$\Delta f_0 / f_0$
0.1	$6 \cdot 10^{-11}$
1	$1 \cdot 10^{-11}$
10	$5 \cdot 10^{-12}$
100	$1 \cdot 10^{-12}$

3. VLBI astrometry of the Huygens probe

The low power of the probe's transponder makes a direct detection of the probe's signal by the largest available Earth-based tracking antennas only marginally possible. The technique of VLBI (Very Long Baseline Interferometry) offers an enhanced sensitivity and enables a determination of the position of a radio emission source with an accuracy on the order of $l/[B \cdot (\mathrm{SNR})]$, where l is the signal wavelength, B is the interferometer baseline, and SNR is the signal-to-nose ratio of the detected interferometric response. At the S-band frequency of 2 GHz and global baselines of the order of an Earth diameter, the achievable accuracy is at the milli-arcsecond (mas) level. This study addresses the applicability of the VLBI technique to detection of the probe's S-band radio signal by Earth-based tracking facilities, and ultimately the determination of its celestial position with the greatest possible accuracy.

A VLBI detection of the probe's signal will require application of the so-called phase-referencing technique [1]. This technique makes possible increased integration times on weak celestial sources, by applying a phase calibration obtained from observations of stronger reference sources (calibrators). This technique has proven to be efficient for angular separations between target and reference sources of up to ~2º. The most efficient use of phase-referencing would be realized if both the target and reference source(s) were within the primary beams of all the radio telescopes involved in the VLBI observation. Such a situation, called "in-beam phase-referencing," does not require nodding the telescopes between target and calibrator source(s), thus increasing the time efficiency of the observations.

The application of VLBI phase-referencing to deep space navigation was demonstrated in 1985 for the VEGA and Giotto /Pathfinder missions to Venus and Halley's comet [2]. The present study develops this approach further, in accordance with the considerably greater potential of the VLBI technique afforded by present-day technologies in signal detection and processing.

3.2. Celestial background around the interface area

An extensive search through the available catalogs of extragalactic radio sources resulted in 21 candidate reference sources within 2º of the Huygens probe interface celestial coordinates (section 2, item 2), listed in Table 3. Although no imaging results of VLBI observations of these sources are available to date, one can conclude from their radio-continuum spectral properties that at least some should be compact and strong enough to serve as primary phase-referencing calibrators for the Huygens probe at the interface position.

Table 3. Complete sample of extragalactic continuum radio sources with $S_{1.4}$ = 100 mJy within 2º of the interface celestial position, shown in order of increasing angular distance from the interface point. .

Object No.	Object Name	Celestial coordinates (J2000)		Ang. dist. arcmin	Flux density [mJy]			
		RA	DEC		P 385 MHz	L 1.4 GHz	S 2.7 GHz	C 4.9 GHz
R1	87GB 073843.8+212326	07 41 41.2	+21 16 41	15.2	318	116.1	-	43
R2	MG2 J074316+2103	07 43 14.7	+21 02 52	21.4	1147	402.1	-	110
R3	[WB92] 0742+2125	07 45 07.4	+21 18 37	34.4	-	286.0	-	-
R4	MG2 J074124+2050	07 41 20.1	+20 50 56	37.0	778	214.0	-	82
R5	4C +21.23	07 39 47.1	+20 54 19	49.5	2389	701.0	400.	157
R6	87GB 073551.2+210449	07 38 46.2	+20 58 13	59.9	-	100.5	-	46
R7	4C +21.24	07 47 04.5	+20 49 52	69.8	1321	312.4	-	67
R8	87GB 074500.9+215106	07 47 56.2	+21 42 56	76.1	205	-	74	28
R9	87GB 073353.7+211705	07 36 49.6	+21 10 35	82.7	-	127.7	-	38
R10	87GB 074014.3+200259	07 43 10.5	+19 56 11	86.9	316	105.0	-	35
R11	87GB 073600.5+224516	07 38 57.4	+22 38 39	91.8	428	106.0	-	33
R12	87GB 073700.4+225712	07 39 59.8	+22 50 16	95.1	243	102.9	-	44
R13	MG2 J074937+2142	07 49 37.8	+21 42 40	99.0	549	206.5	-	82
R14	MG2 J074949+2128	07 49 48.7	+21 29 34	99.8	1132	387.0	-	113
R15	MG2 J073556+2208	07 35 56.7	+22 08 48	104.5	847	234.9	-	62
R16	MG2 J073552+2035	07 35 52.7	+20 36 39	105.8	223	150.8	-	162
R17	87GB 074158.4+194744	07 44 55.1	+19 41 07	106.4	386	125.0	-	28
R18	MG2 J075056+2142	07 50 56.8	+21 41 50	116.9	592	221.6	-	101
R19	87GB 073317.1+224807	07 36 16.9	+22 40 53	118.4	735	174.0	-	51
R20	87GB 074623.2+201516	07 49 18.9	+20 07 53	119.5	389	138.3	-	47
R21	MG2 J074854+2000	07 48 53.8	+20 01 02	119.6	-	187.1	-	65

In-beam phase-referencing requires the existence of compact and sufficiently strong radio sources within ~10’ of the interface point. Their verification will require a special pre-interface deep VLBI study of the area. Existing catalogs of extragalactic radio sources complete to the level of ~3.0 mJy at L-band (1.5 GHz) list only 7 sources within 15’ of the interface point, all weaker than 15 mJy at L-band. Table 4 lists these 7 sources.

Table 4. Complete sample of extragalactic continuum radio sources with $S_{1.4}$ = 3.0 mJy within 15' of the interface celestial position shown in order of increasing angular distance from the interface point. .

Object No.	Object Name	Celestial coordinates (J2000)		Ang. dist. [arcmin]	L-band flux density [mJy]
		RA	DEC		
B1	J074254+212411	07 42 54.2	+21 24 11	3.4	3.0
B2	J074242+211358	07 42 42.5	+21 13 59	8.8	6.1
B3	J074211+212823	07 42 11.2	+21 28 24	8.9	5.7
B4	J074251+211401	07 42 51.0	+21 14 02	9.1	10.9
B5	J074204+213213	07 42 04.8	+21 32 13	12.6	15.2
B6	J074223+210934	07 42 23.4	+21 09 35	13.8	3.5
B7	J074204+213505	07 42 05.0	+21 35 05	14.8	5.2

Further investigation of the celestial field around the interface point is critically important for directly detecting the probe and achieving the necessary accuracy in its position determination, as described in Section 4. The position of the area is defined by one parameter: the time of the interface. A proper motion of Titan of the order of 8.5 arcseconds per hour will not pose a problem for radio telescope pointing. Thus, in order to ensure that the celestial field is "prepared" for the interface correctly, the interface time must be fixed in order to allow a series of pre-interface VLBI observations – see Section 6.

3.3. Earth-based VLBI array suitable for observations of the Huygens probe

The interface time given in Section 1 defines the set of Earth-based radio telescopes able to take part in VLBI observations of the probe. These telescopes are listed in Table 5. We note that not all of them will be able to see the probe at 09:00 ET 14.01.2005; for some of them (e.g. Sheshan, Hobart, Mopra), the tracking pass will start at about 10:00 UT on the interface day. The exact prior knowledge of the interface time is therefore crucial for establishing the appropriate settings of the telescope observing instrumentation, as described in Section 5.

In order to fulfill the requirement on the celestial environment described in the previous subsection, a series of deep VLBI observations of the area should be conducted, with not necessarily the radio telescopes listed in Table 5. These observations would require dual-band S/X VLBI instrumentation (available at many VLBI telescopes, including those in Europe, USA, Asia and Australia). However, it would be beneficial if as many as possible of the telescopes assigned to the "live" observations of the probe be included in the pre-interface observations of the area, as this would allow accrual of experience in the various technical and logistic issues pertaining to the Huygens VLBI observations.

Table 5. Radio telescopes: potential participants in VLBI observations of the Huygens probe at 09:00 ET 14.01.2005. The Status column indicates availability of the instrumentation concerned (marked as "OK") or a need for upgrade/supply of S-band receiver (or its LNA) and a Mk5-compatible Data Acquisition System (marked otherwise). Question marks indicate absence of information.

Telescope	Longitude degrees	Latitude degrees	Diameter m	T_sys K	Eff	Status	
						S-band Rx	Mk5
GBT	-79.83	+38.43	100	23	0.71	OK	Need
VLA_27	-107.62	+33.90	25	30	0.50	?	Need
VLBA_SC	-64.58	+17.76	25	40	0.48	OK	Need
VLBA_HN	-71.99	+38.43	25	32	0.48	OK	Need
VLBA_NL	-91.57	+41.77	25	30	0.49	OK	Need
VLBA_FD	-103.94	+30.63	25	30	0.55	OK	Need
VLBA_LA	-106.25	+35.76	25	30	0.50	OK	Need
VLBA_PT	-108.12	+34.30	25	30	0.52	OK	Need
VLBA_KP	-111.61	+31.96	25	30	0.55	OK	Need
VLBA_OV	-118.27	+37.23	25	25	0.47	OK	Need
VLBA_BR	-119.68	+48.13	25	30	0.50	OK	Need
VLBA_MK	-155.46	+19.80	25	27	0.45	OK	Need
Usuda	+138.36	+36.13	70	40	0.50	Need upgrade	OK
Kashima	+140.66	+35.95	34	72	0.65	Need upgrade	OK
Kashima-11	+140.66	+35.95	11	72	0.80	?	OK
Sheshan	+120.42	+31.19	25	70	0.55	Need upgrade	OK
Tsukuba	+140.09	+36.10	32	75	0.71	?	?
Algonquin	-78.07	+45.96	46	85	0.50	Need upgrade	?
Gilcreek	-147.29	+64.58	26	62	0.49	?	OK
Kokee	-159.67	+22.13	20	40	0.53	?	OK
Westford	-71.49	+42.61	18	70	0.54	?	OK
Koganei	+139.49	+35.70	11	80	0.77	?	OK
TIGO	-70.00	-30.00	6	70	0.60	?	OK
GreenB-G	-76.82	+39.02	5	60	0.42	?	OK
Mizusawa	+141.13	+39.13	10	340	0.50	?	OK
VERA?			20			?	OK

Fig. 3-1 shows an example of Huygens visibility from an arbitrary set of Earth-based radio telescopes at the nominal interface time. As is clear from this, at the interface time of 09:00 ET on 14.01.2005, the key role will belong to the GBT and VLBA antennas.

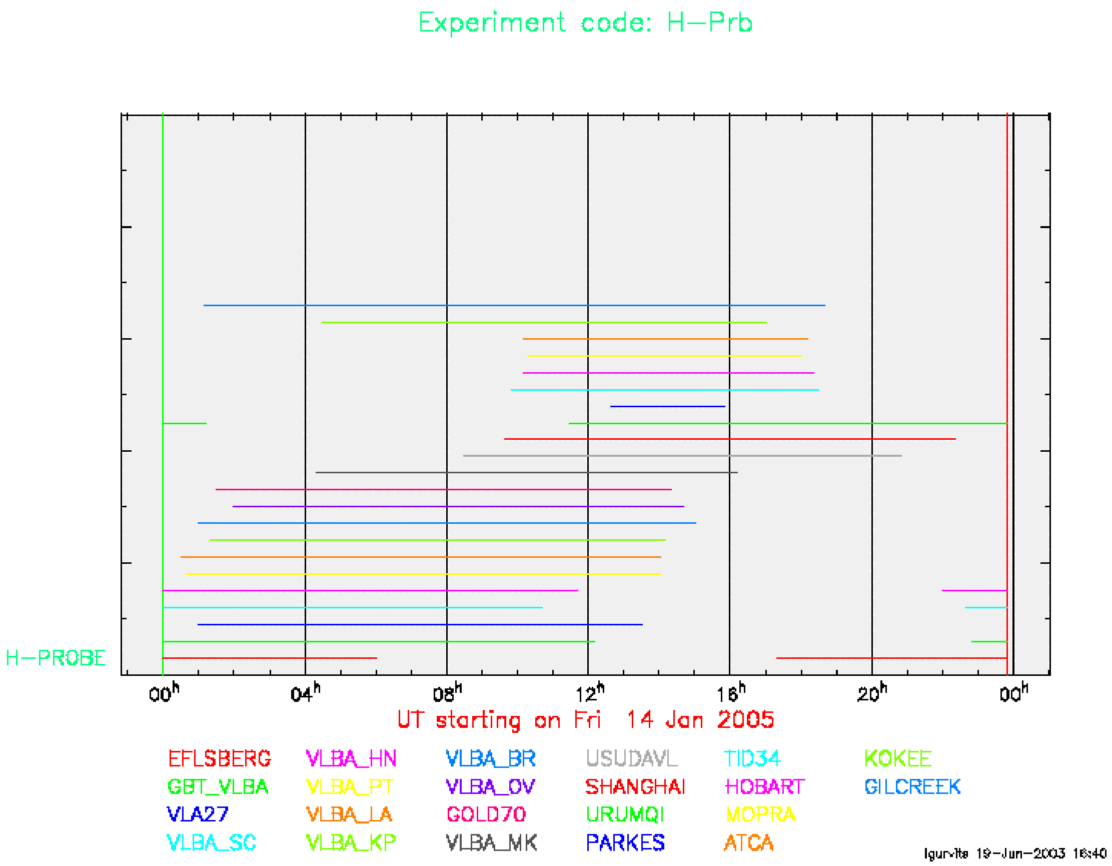

Fig. 3-1. Visibility of the interface celestial point from various radio telescopes on 14 January 2005.

4. Direct detection of the Huygens probe signal with ground based radio telescopes

To illustrate the practicality of detecting the Huygens probe's signal and measuring its velocity and position with high accuracy, a simulation model was developed and exercised.

Input parameters of this model include characteristics of the transmitted signal, a probe motion model, and the characteristics of real radio telescopes which could participate in the mission.

4.1. Model of the signal

According to the Huygens probe technical specifications [3], the signal transmitted by the probe corresponds to the modulation scheme PM/BPSK/PCM-NRZ-M. Fig. 4-1 illustrates the spectrum of such a signal. The spectrum contains a narrow carrier line and a broader band with information content.

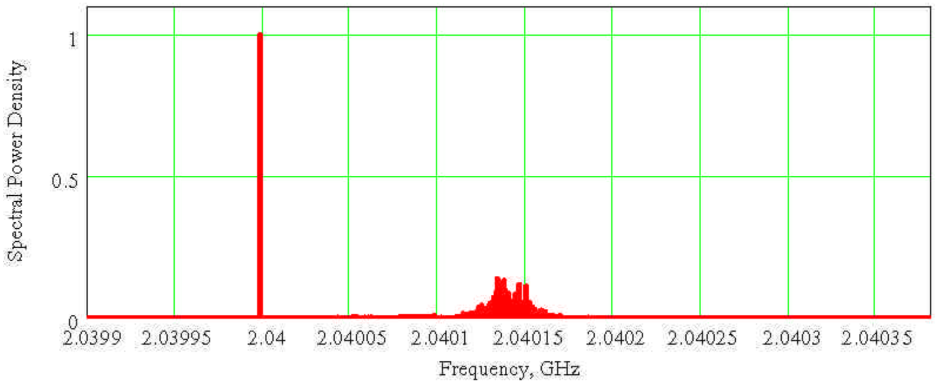

Fig. 4-1. Typical spectrum of BPSK modulated signal

Power distribution between the carrier line and the data band corresponds to the modulation index and can be estimated as 7.5 W in the data and 3.7 W in the carrier [3]. Although the total power in the data band is greater than that of the carrier line, the former's spectral density is much lower. From a detection point of view it's preferable to try to detect the carrier line rather than the data band

Given the probe's transmitting antenna gain of 2.2 guaranteed in a 120 degree cone [3] we find that the power density of the carrier signal at Earth will be about

$$P_{@Earth} = 5*10^{-25}\ W/m^2 \ ,$$

which makes it detectable by use of ground-based radio telescopes, provided their receivers match the frequency band of the probe signal.

Another important characteristic of the signal to be detected is its width. The intrinsic width of the carrier line is determined by the stability of the probe's local oscillator. Here we assume that the short-term stability of the onboard local oscillator is characterized by a set of Allen variances, and the long-term frequency behaviour corresponds to aging frequency drift and responses to changes in environmental conditions [4, p157]. Fig. 4-2 illustrates the Allan variances of the LO which were used to model the phase and frequency variations of the carrier wave.

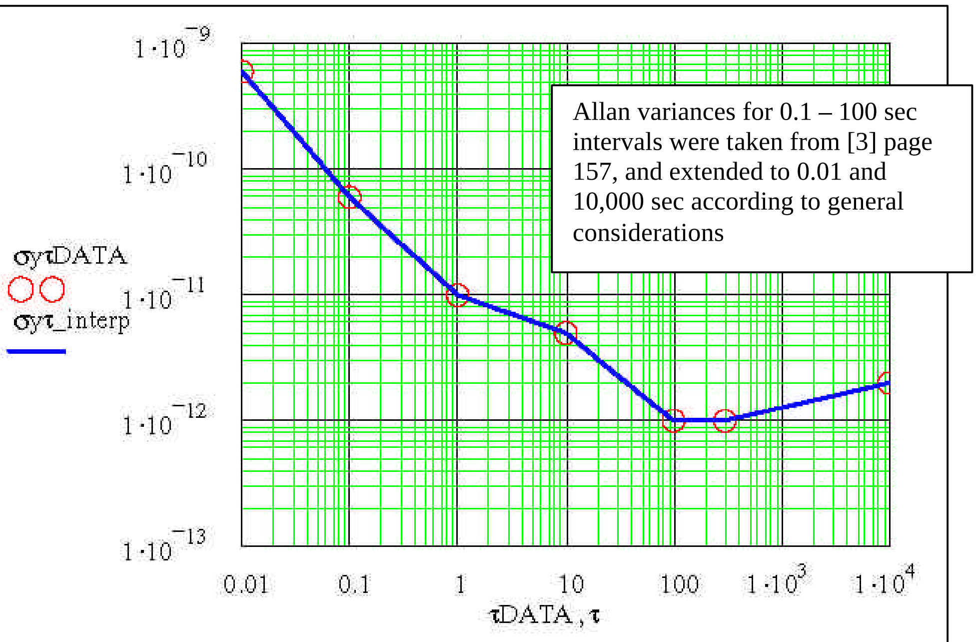

Fig. 4-2. Allan variances for the probe LO

Fig. 4-3 presents an example of random phase behaviour for a 2.04 GHz sine wave synchronized with an LO of the given Allan variance, when seen in a 40 Hz band around the nominal frequency. Fig. 4-4 illustrates a model temperature variation which will induce a frequency change in the LO according to a given coefficient, $df(Hz)/dT(K) = 3*10^{-12}$, which in turn will be translated into +/- 50 mHz variation of the carrier frequency.

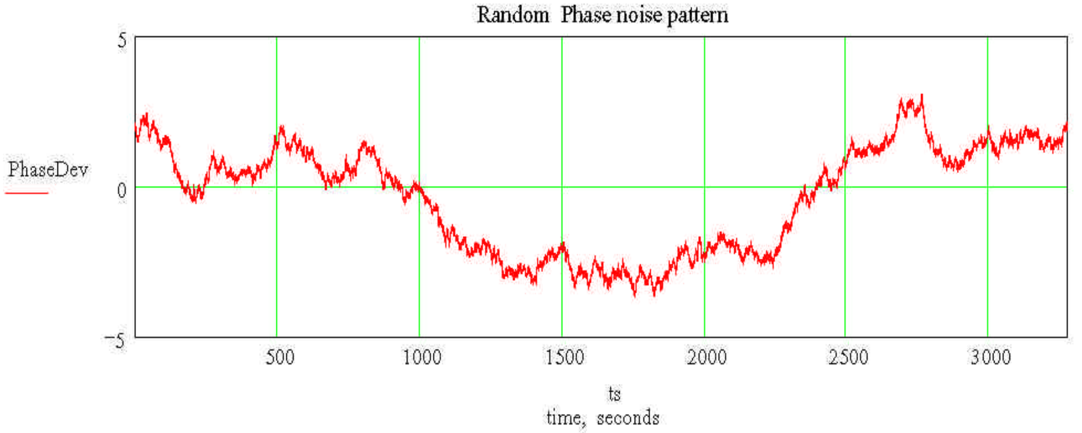

Fig.4-3. Random phase noise pattern for given Allan variances

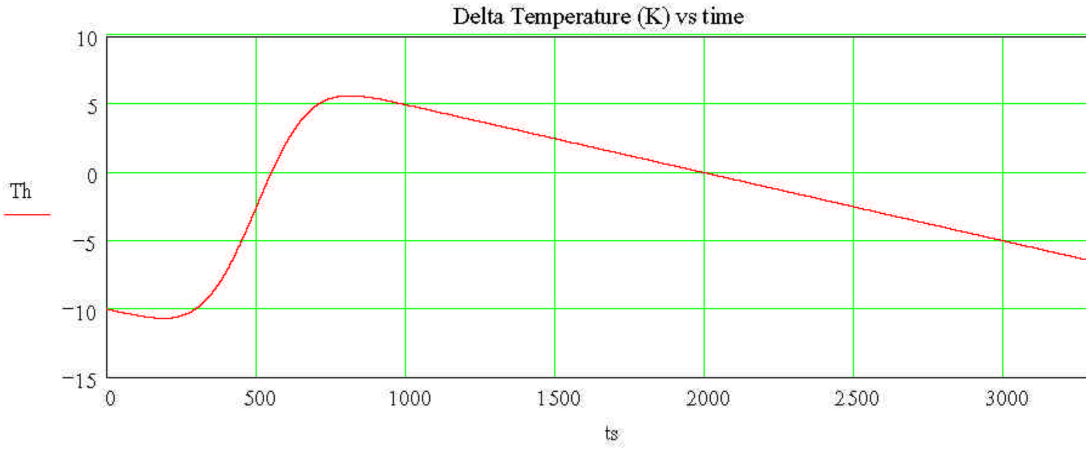

Fig. 4-4. Modeled variation of LO temperature

A geometrical model of the probe motion describes the deviation of the probe position and velocity from an a-priory assumed trajectory. The coordinate system used in the model sets the Z-axis parallel to a vector from the Earth centre to the a-priory position of the probe, and X and Y are in a geocentric plane with Y pointing North and X pointing East. That means the coordinate system actually moves in time, following the a-priory position of the probe, and what is modeled are the probe's coordinate deviations from this motion. Fig. 4-5 illustrates the modeled X, Y, and Z components of probe motion, and Fig. 4-6 shows the probe motion on the XY plane. The model covers deviations of about 300 km in position and 100 m/s in velocity for X and Y, and 2 km in position and 2 m/s in velocity for Z, and covers 3200 seconds of time.

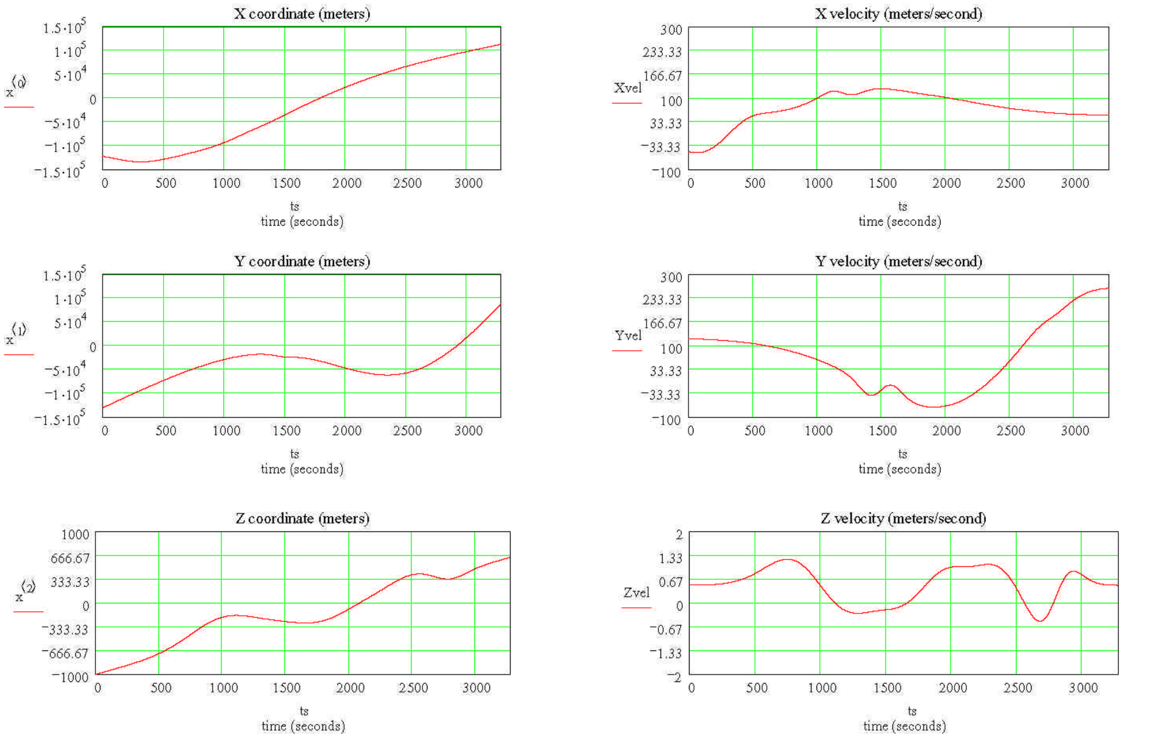

Fig. 4-5. X,Y and Z components of modeled probe trajectory

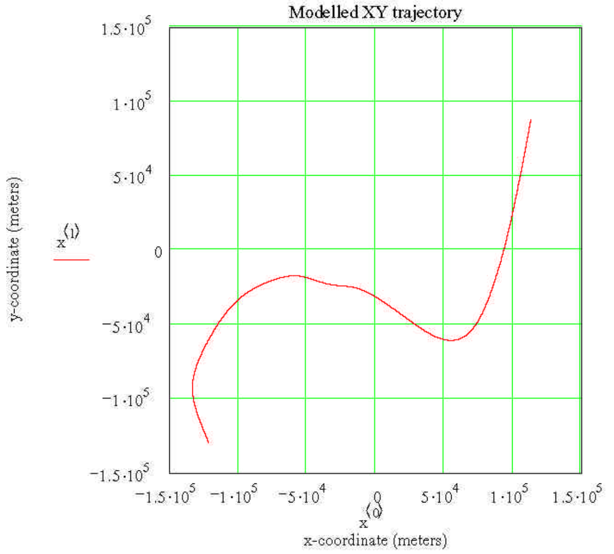

Fig. 4-6. Probe trajectory on XY plane

The simulated signals from the probe to each of the participating telescopes are generated according to these motion and probe LO phase noise models. Fig. 4-7 illustrates geometrical considerations for the calculation of the phases of received signals. The positions of real radio telescopes which might participate in the mission were used for this simulation, as well as the supposed coordinates of the probe at the interface time.

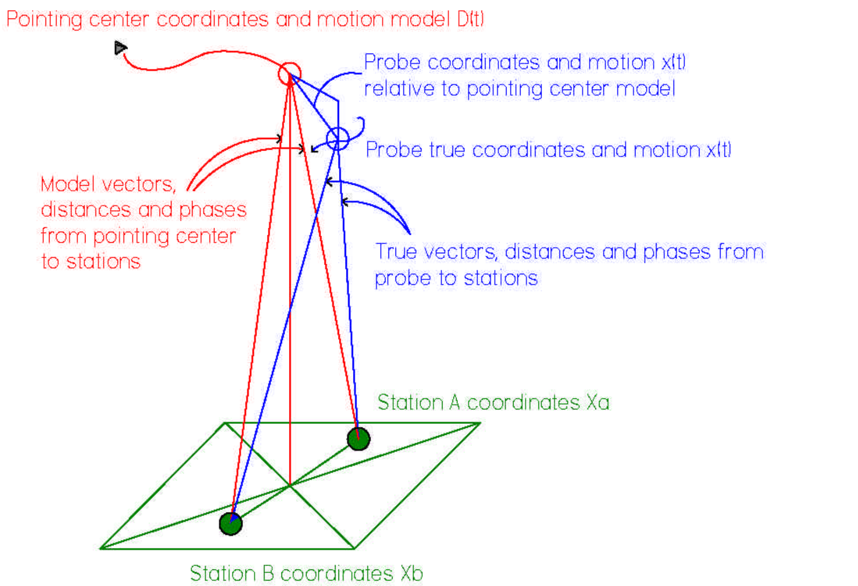

Fig 4-7. Geometry of the probe motion model relatively to the pointing centre a-priori model

Signal and noise amplitudes for each telescope are calculated using the actual collecting areas and receiver noise temperatures of each of the participating telescopes.

4.2. Data processing algorithms and procedures

It is essential that observations be accomplished with standard radio astronomical settings used for routine VLBI observations, except that one of the receiver's bands must be tuned to the probe transmitter frequency. Fig 4-8 illustrates a typical radio astronomical receiver band set-up for S/X band observations, with the lower S band tuned to 2.04GHz.

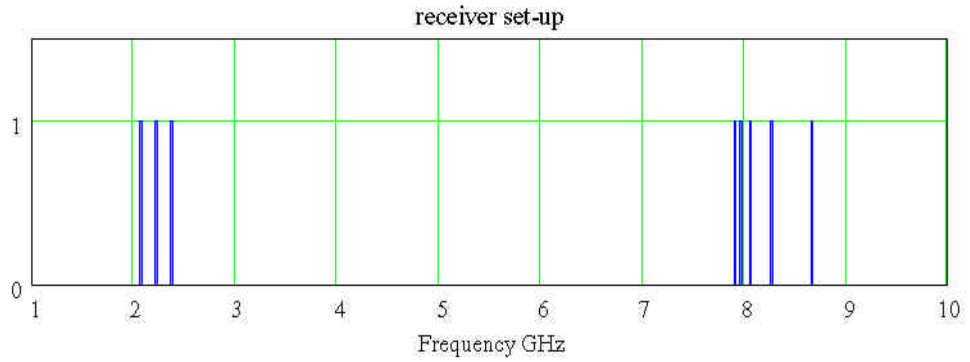

Fig. 4-8. Typical S/X receiver band setup

The total observed signal bandwidth for background radio sources can be as wide as 128 or even 256 MHz, split into 8 or 16 MHz wide sub-bands. By spanning a wide bandwidth with the available sub-bands in both S & X, we can lower the uncertainties of the group-delay estimates in the reference source observations. Besides providing a more precise dispersive-propagation correction, the X-band group-delay uncertainty would correspond to less than a cycle of phase-delay at S-band (2.04GHz) for reference-source SNRs of ~20 or more. We would therefore be able to identify and track the appropriate phase-lobe more reliably on all baselines, including the longer ones, which provide the greatest angular resolution.

The observed data must be recorded on disk-based high-speed recorders and be pre-processed at the JIVE correlator to detect background radio sources and align phases between the participating telescopes. The next pictures show the JIVE correlator, capable of processing data from up to 16 radio telescopes at a data rate of up to 512 Msamles/s per station, and the disk based Mk5 recorder, capable of recording such data streams for several hours.

Fig. 4-9. EVN MK4 Correlator at JIVE, a dedicated 60 TeraOps supercomputer

Fig. 4-10. Mk5 disk based VLBI recorder/playback unit and a removable 1.6 TeraByte disk pack

Next, a single 8 (or 16) MHz band containing the probe's signal may be downloaded from the Mk5 units to general-purpose computers, where the data can be processed in sequentially narrowed bands, thus improving the spectral resolution.

At the first stage, a sub-band about 400 kHz wide (which corresponds to a +/- 3 km/s Doppler shift) will be extracted from the observed band. It can be narrowed further, to about 10 kHz, by applying an a-priori model of the probe motion (assuming a Doppler uncertainty of about 100 m/s).

The next step is to split this 10 kHz band into a set of ~100 Hz wide bands, each of which representing one possible probe trajectory, with a Doppler velocity uncertainty of a few meters per second and accelerations of the order of cm/sec^2 with respect to the actual motion of the probe. A rough estimate of the number of such bands is of order $10^4 – 10^5$.

Each of these bands can then be searched for the probe's spectral components.

The next part of this chapter presents results of a numerical simulation of such a procedure.

As described above, simulated signals from the probe to each of the participating telescopes were generated in accordance with real parameters of the probe's LO, its transmitter power, the fraction of this power in the carrier signal, the gain of the transmitting antenna, and the actual positions, collecting areas, and noise temperatures of receiving radio telescopes.

The simulated signals represent a 40 Hz wide band (a sampling rate of 80 samples per second) with random walk behavior in X, Y and Z velocities, within a range of 100 m/sec for X and Y and 2 m/s for Z. The duration of the total data sample corresponds to a 3200 s tracking period. These parameters are reasonable, although they represent merely the computational limitations of an ordinary PC used for simulation rather than the actual signal properties. As will be seen further, the processed bandwidth can be increased up to 100 Hz.

Within this model, the signals from each telescope are processed as follows:

The data sample is segmented into sub-samples of duration set by the desire to achieve the best possible signal-to-noise ratio for a given uncertainty in velocities and accelerations, but avoiding signal smearing due to non-linear phase behaviour. These dynamic power spectra for all telescopes are averaged together to form a "Common Mode" dynamic spectrum, which represents a Z-velocity Doppler shift common to all telescopes, while the XY velocities differ for each telescope. Because an XY velocity range of a hundred meters per second, at the given distance, will be translated into a differential phase rate in the mHz range, the Common Mode can be used for phase tracking to a resolution of tens of mHz.

Detecting a pattern in the frequency behaviour of the Common Mode allows us to recover a common mode in the phase, and to track and subtract this phase from the signals of each telescope, narrowing the bandwidth of the analysis and thus increasing the time of coherent integration and improving the spectral resolution.

Finally, at a spectral resolution of about 40 mHz, the detected spectral line for each telescope can be extracted, and cross-correlations between the telescopes can be found.

Cross-correlation coefficients, averaged over about 25 seconds, can be used to build up a dynamic map of the event, with the maximum power on this map representing the current position of the probe with respect to the a-priori motion model.

This process is iterative, as it represents the locking of the differential phase of each pair of telescopes to the common model of the probe motion.

This common motion model is the final product of the processing and represents the motion of the probe in XYZ space relative to the first approximation of the tracking model.

We used the actual positions and sensitivities of more than 20 radio telescopes to run this model. A full processing run for a 40 Hz band from 24 telescopes with an ordinary 1.7 GHz PC from start to determination of the probe motion model takes about 6 hours. Processing of real data will involve the use of a powerful cluster of workstations for several days.

The following pictures present the results achieved with the above-described processing algorithms in a simulation and give a description of processing steps and parameters.

Step 1: 40 Hz band, segment length 0.8 seconds, fundamental spectral resolution 1.25 Hz. Only four major stations were processed through to dynamic spectra, due to PC memory limitations. At this integration and spectral resolution, the signal is seen only by the two largest telescopes. Fig.4-11 illustrates the global power spectra averaged over 3200 seconds and Fig. 4-12 shows the dynamic spectra as seen with 4 different telescopes. The reasonably good signal-to-noise ratio of the dynamic spectra enables us to recreate a frequency behavior curve shown in Fig.4-13. As can be seen, it mirrors the model input Z-velocity curve.

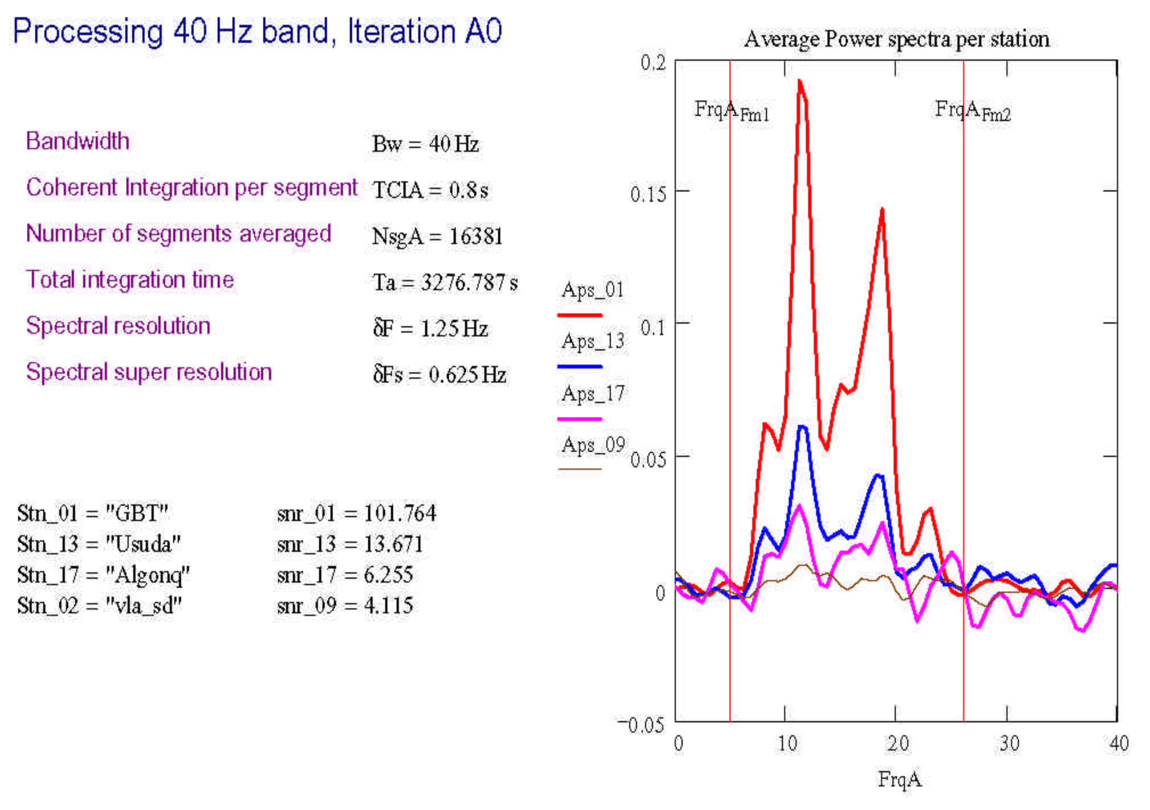

Fig. 4-11. Time averaged dynamic spectra for a total averaging time of 3200 s for the 4 major stations

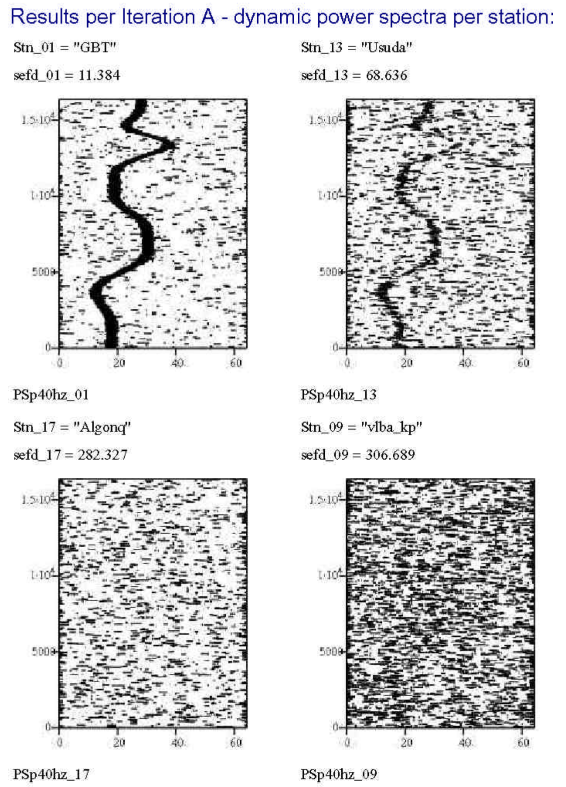

Fig. 4-12. Dynamic spectra for 4 major stations

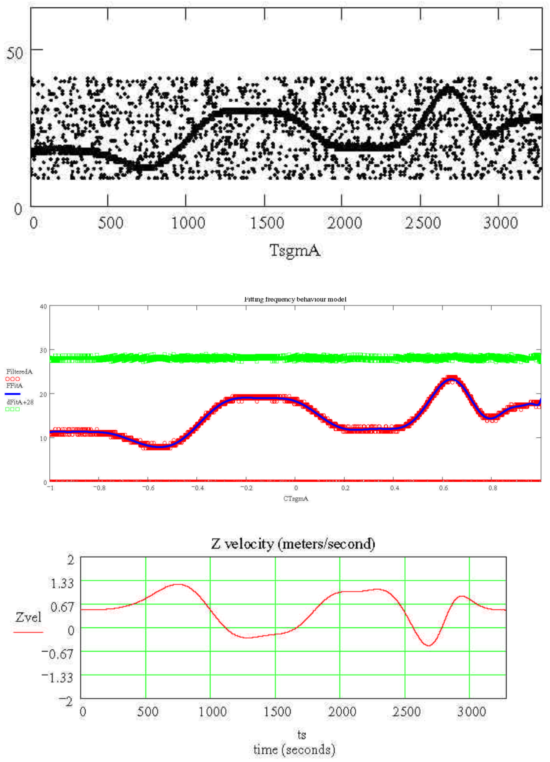

Fig. 4-13. Common Mode – Image enhanced average dynamic spectrum, polynomial fit to recreate the frequency drift model and input Doppler velocity model for comparison

Step 2: The frequency curve detected in step 1 is used to generate a phase correction curve, which is applied to the signals from all telescopes. The bandwidth of the signal is reduced first to 20 Hz, and the process repeated. The phase correction curve extracted from the 20 Hz data is used to reduce the bandwidth to 10 Hz. The result of processing a 10 Hz band is presented in Figs. 4-14 and 4-15. Reduction of the bandwidth to 10 Hz allows the processing of signals from 20 stations simultaneously.

Here one can see the dramatic improvement in the spectral width of the signal and the signal-to-noise ratio. The residual frequency curve derived from this data is used to narrow the band down to 5 Hz.

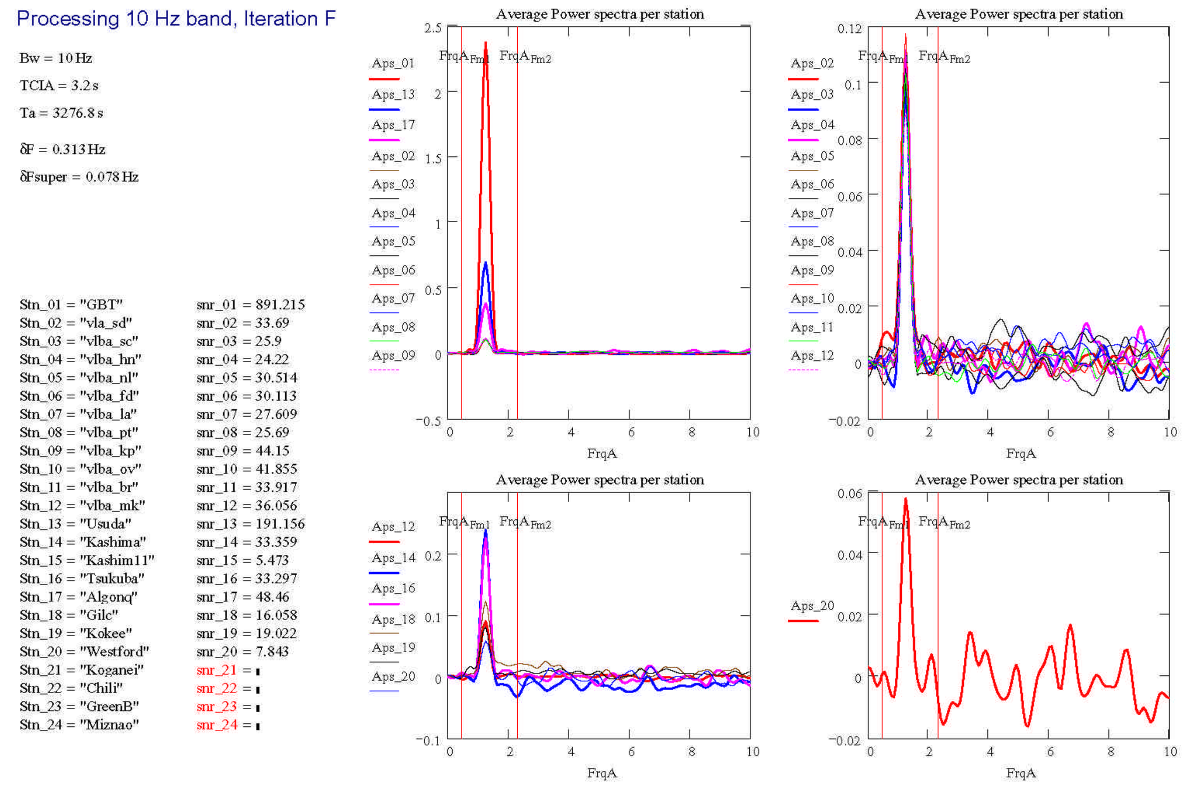

Fig. 4-14. 3200 seconds averaged dynamic spectra for 20 stations, bandwidth 10 Hz, spectral resolution 0.313 Hz

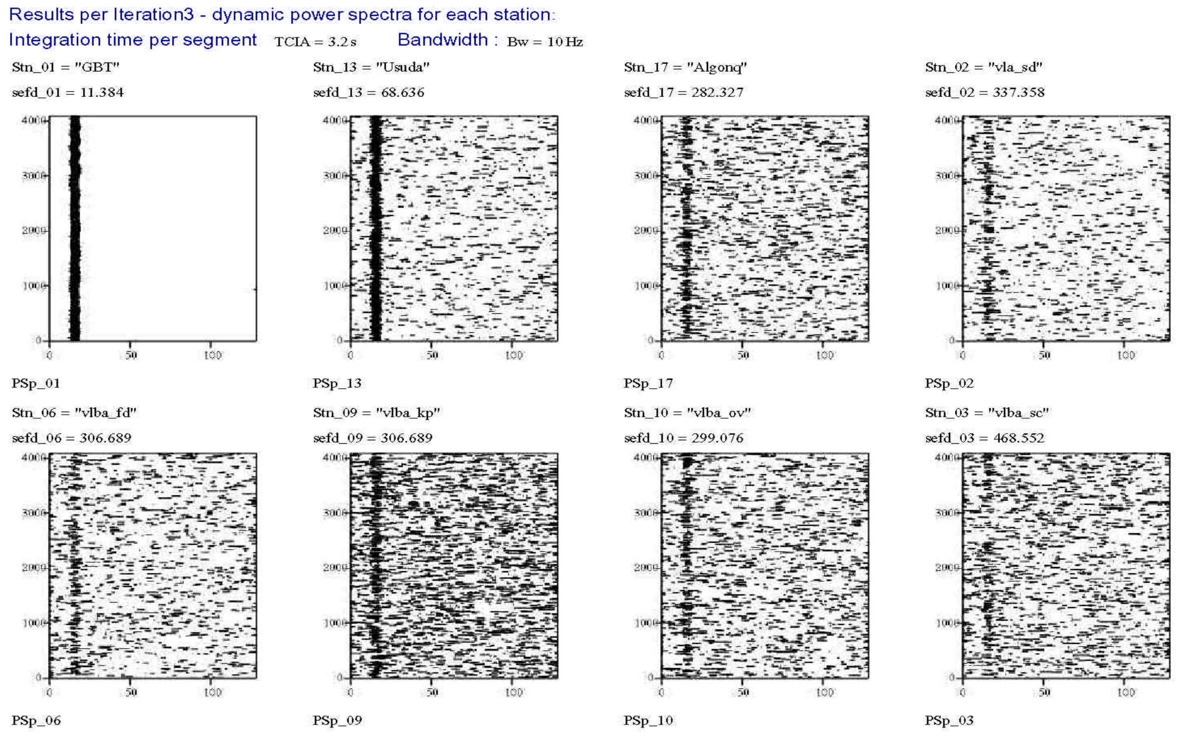

Fig. 4-15. Dynamic spectra for 8 stations for 10 Hz band with resolution 0.313 Hz

Step 3: Bandwidth 5 Hz, spectral resolution 40 mHz, effective integration time per each spectral sample 25 seconds, spectra are narrowed down to a single frequency bin, effective distortion of spectra is less than 0.01 bin. With a 3200s averaging time, the line is visible even by an 11-meter antenna. Figs. 4-16 and 4-17 illustrate the results of this stage of processing.

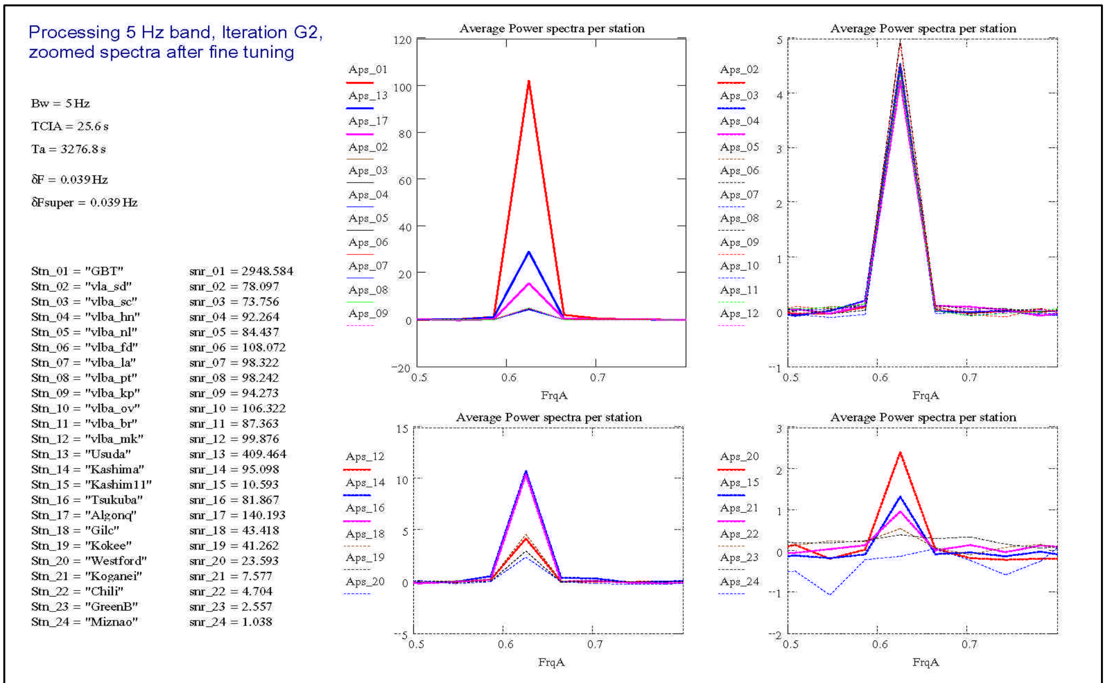

Fig. 4-16. 3200 seconds averaged dynamic spectra for 24 stations, bandwidth 5 Hz, spectral resolution 40 mHz

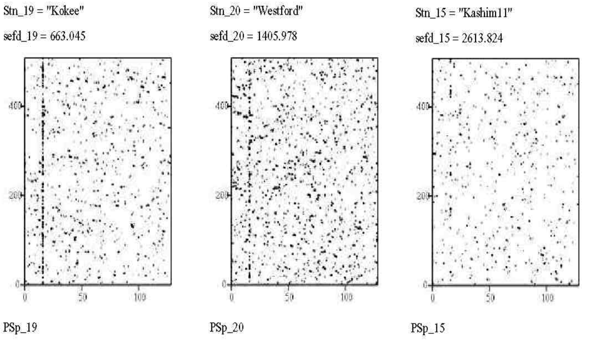

Fig. 4-17. Dynamic spectra with 40 mHz resolution for 22, 18 and 11-meter antennas

At this stage the cross-spectra for each pair of telescopes ("fringes") can be generated. Fringe data averaged for 25.8 seconds and sampled at 6.4 second intervals can be used to calculate dynamic maps of the probe position with an effective time resolution of 12.9 seconds.

The mapping process is iterative; after each iteration the probe motion model is updated and used to lock the phases of the fringes to a narrower tracking field of view. Fig. 4-18 and 4-19 show the mapping results.

The first map is generated using the compact central core of the participating telescopes. This map yields errors in the trajectory estimation of the order of 2 km for the X direction, and 4 km for Y.

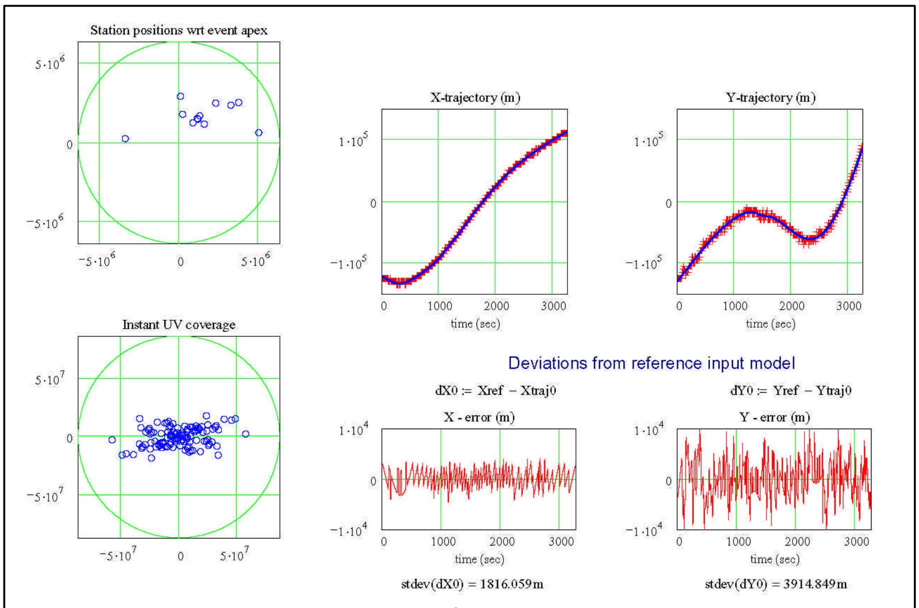

Fig. 4-18. First iteration of the probe motion mapping

After upgrading the probe motion model several times, including more distant telescopes, and improving the spatial resolution of the synthesized aperture, the final set of XY corrections for the probe position can be estimated.

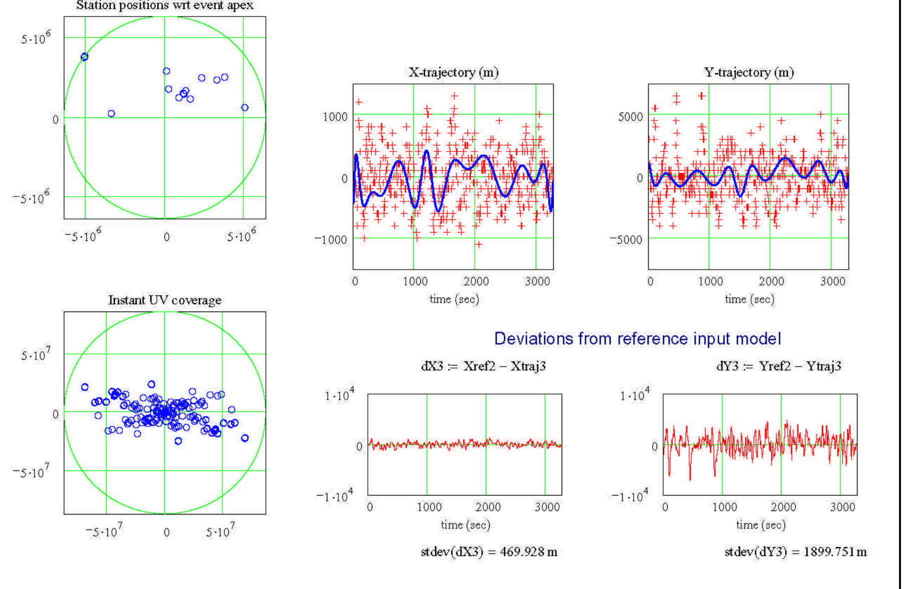

Fig. 4-19. Results of the third iteration of the probe motion mapping

The following figures, 4-20 and 4-21, summarize the resulting estimates of the positional accuracy achievable in measuring the Huygens probe trajectory with the use of a global network of radio telescopes.

The probe trajectory recovered from the fringe data is integrated over 25 seconds and sampled at 6.4 s intervals. The RMS errors with respect to the input trajectory model are: X-coordinate : 450 meters, Y-coordinate : 1700 meters, Z-velocity : 0.3 m/s. A discrepancy between input Z-velocity (blue line) and reconstructed one (red line) is attributed to the probe LO linear frequency drift with a rate $10^{-12}s^{-1}$, which was included in the LO phase model.

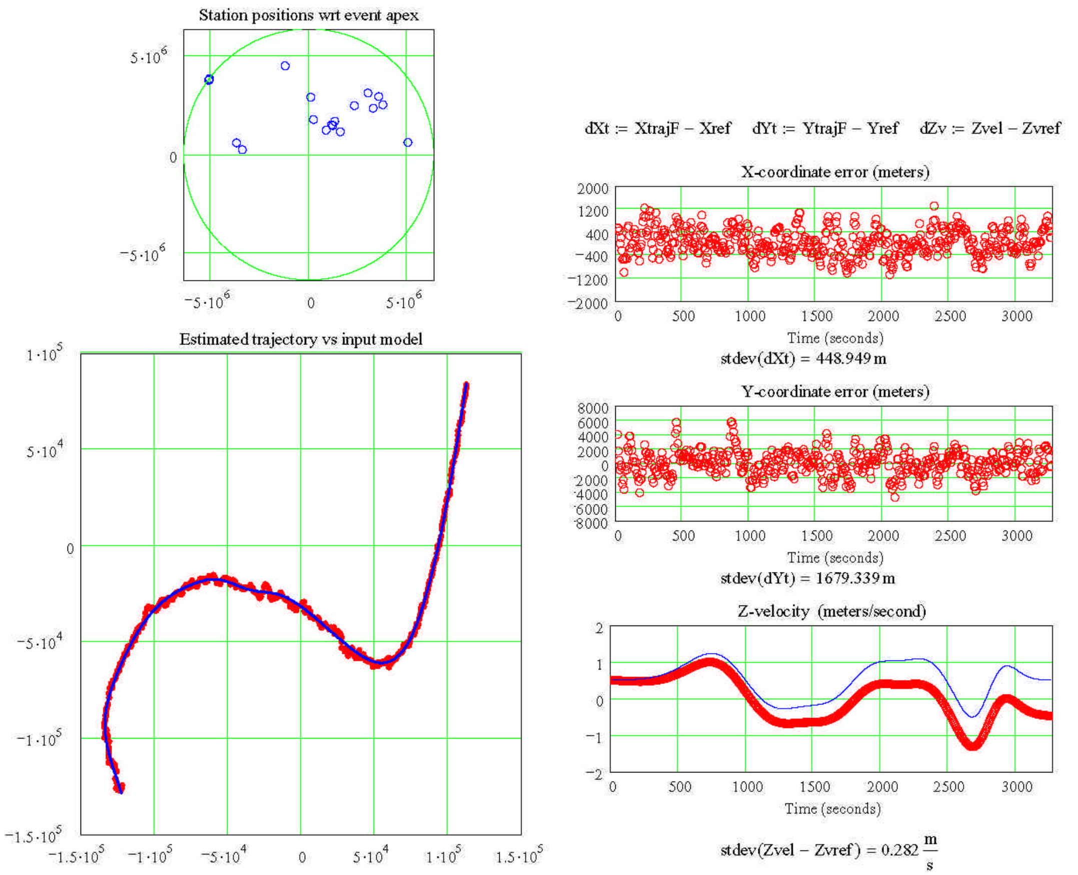

Fig.4-20. Simulation results of The Huygens probe trajectory mapping with 20 VLBI stations with an effective time resolution ~10 seconds

Smoothing the XY data over 100 s with a Gaussian window yields RMS errors for the trajectory estimate of 260 m and 970 m for X andY coordinates respectively.

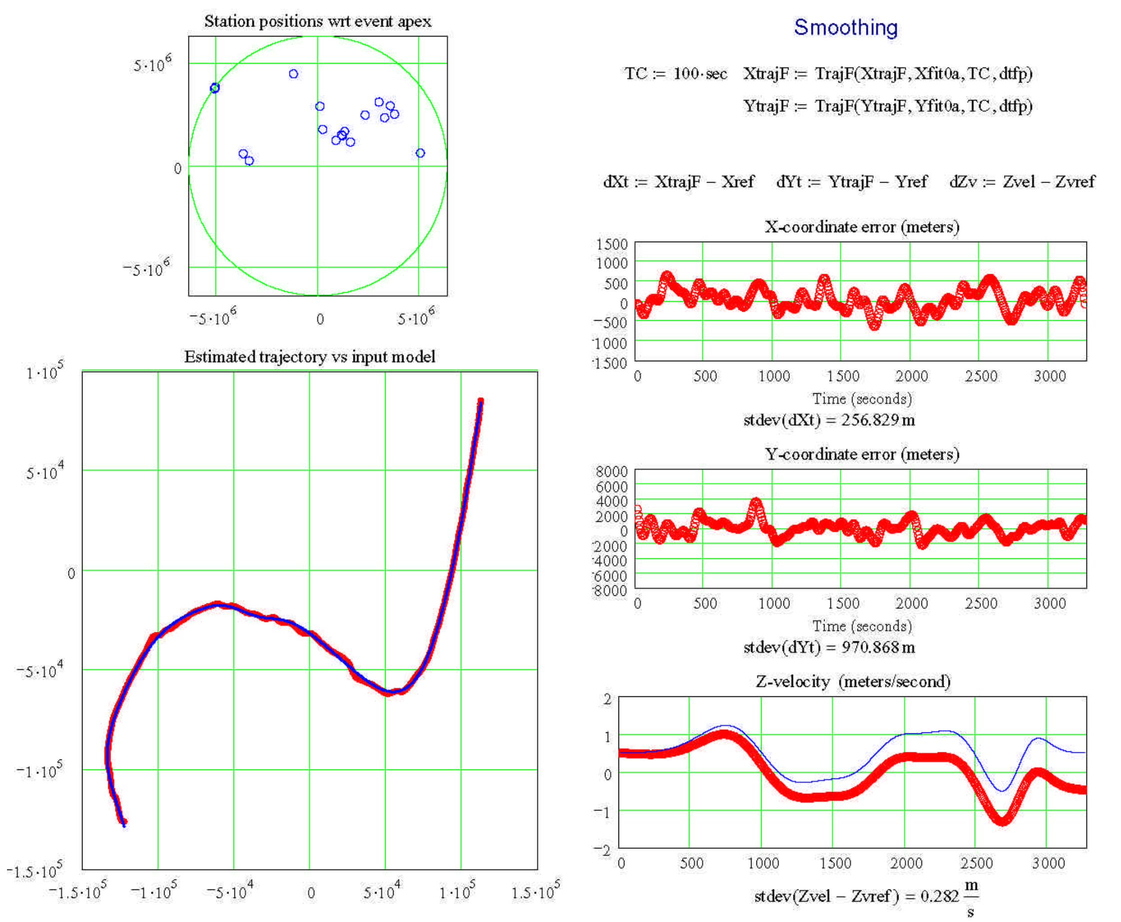

Fig.4-21. Simulation results of The Huygens probe trajectory mapping with 20 VLBI stations, 100 seconds smoothed sampling.

As it was mentioned above, the models covers about 1 hour’s worth of the probe descent, which can last up to 3 hours. Involving the Australian VLBI facilities at a later phase of descent can improve the Y-coordinate resolution by a factor of 2.

5. Instrumentation requirements

In order to fulfill the mission goals and achieve the expected results, proper VLBI instrumentation must be installed at the participating radio telescopes and processing centres.

5.1. Radio telescopes

5.1.1. Receivers

The radio telescopes must have S-band receivers compatible with the target frequency of 2040 MHz. Some of the telescopes already have continuous frequency coverage in a wide enough range to cover the Huygens probe signal band, while others do not, for many different reasons (see Table 5). One reason, for example, is the frequency allocation regime as illustrated in Fig. 5-1.

It's technically possible to tune a standard S-band receiver to the required frequency range, although the procedure is specific to each telescope. An exact technical specification of the work required at each telescope must be created at the earliest stage of the project.

5.1.2. Data acquisition terminals

A crucial point of the project is the ability to download the observed data into general-purpose computers. The only practical solution is to use disk-based VLBI data recorders. Currently three different types of disk-based VLBI recorders are available: Mk5, K5, and PCEVN. The JIVE correlator can support Mk5 and PCEVN units. Data transport systems between K5 and Mk5 standards are available in Japan.

A majority of radio telescopes participating in VLBI observations are equipped with Mk4/VLBA data acquisition systems (DAS), which can directly connect to the disk-based Mk5/PCEVN data recorders. However, not all the radio telescopes suitable for the Huygens experiment are currently equipped with these recorders (see Table 5). All the radio telescopes willing to participate in the mission must be equipped with Mk5 or MK5-compatible disk-based VLBI recorders.

5.2. Processing centers

VLBI data processing of the Huygens probe mission consists of two parts: a regular broad-band correlation of VLBI data on background radio sources, and narrow-band processing of the Huygens signal. The former step requires the use of a special VLBI data processor, e.g. the JIVE correlator. The latter should be done on general-purpose computers.

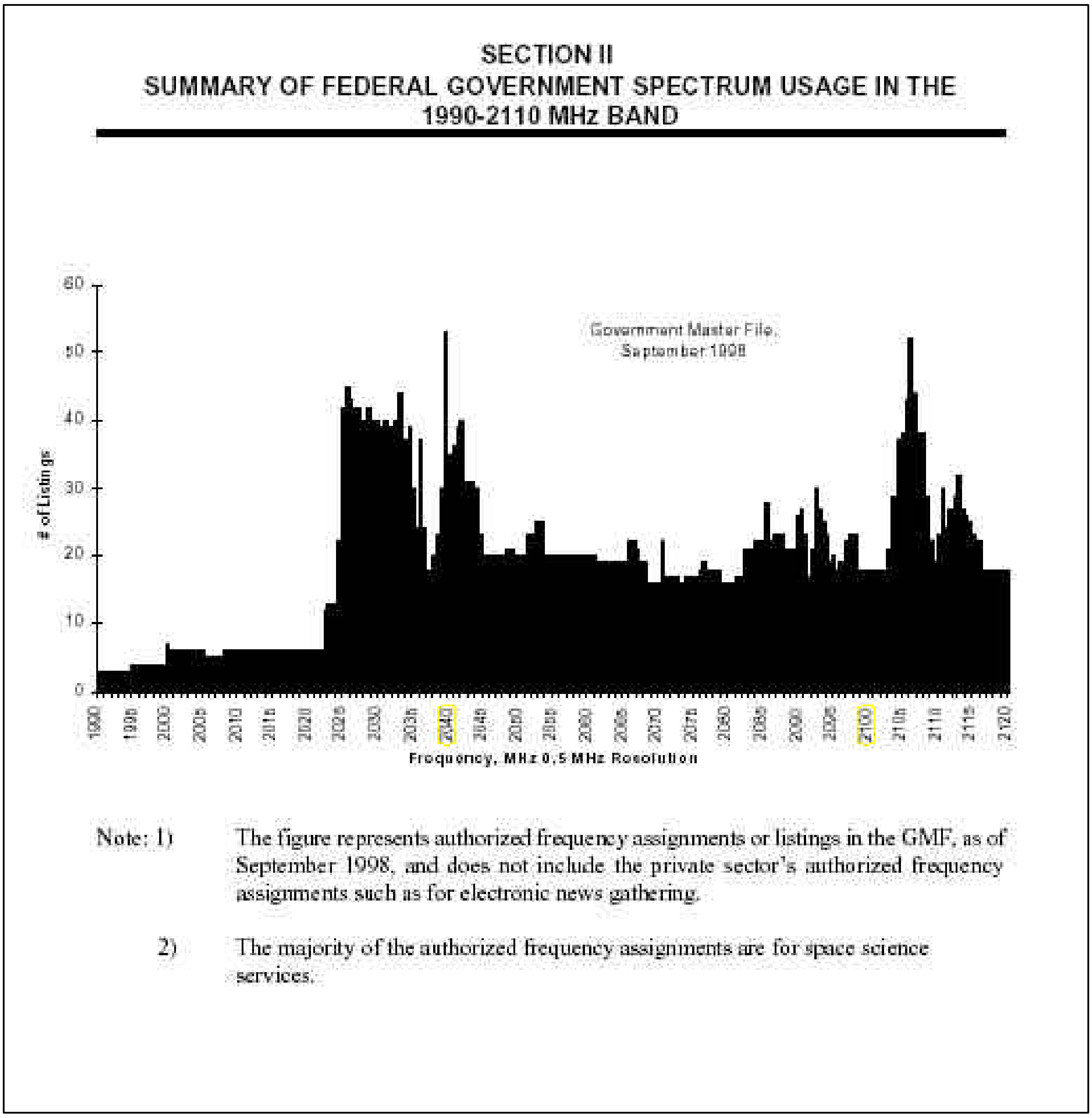

Fig. 5-1. Frequency alloocation regime in according to the US Fedral Ragulations [5].

5.2.1. Broad-band processing

The EVN data processor (correlator) at JIVE is capable of processing broad-band data from 16 telescopes simultaneously. To enable input of disk-recorded data streams into the correlator, it must be equipped with an adequate number of Mk5 units. Full-scale processing of "live" Huygens data at the correlator should be factored in as a substantial work package.

5.2.3. Narrow-band processing

Narrow-band processing of the Huygens probe carrier signal will require development of software tools adequate to the mission goal. To process the data in a reasonably short time will require the use of a supercomputer or cluster of PCs. The processing algorithm is very suitable for parallel computation. Requirements for the processing power and scale of such a PC cluster should be estimated at the beginning of the project, but at this point do not seem to pose a problem for the Huygens VLBI experiment.

6. Conclusions

The assessment study described in this report indicates that direct VLBI detection of the Huygens S-band signal by Earth-based telescopes is feasible. Such an experiment can result in a determination of the position of the Huygens probe in the atmosphere of Titan with sub-km accuracy and time resolution of the order of tens of seconds per measurement.

Because the interface date is only about 18 months away, the following measures should be taken immediately if the experiment is to be conducted:

1). Radio telescopes – potential participants in the experiment are to be upgraded to a level consistent with the technical requirements of the experiment as described in this report.

2). A series of pre-interface deep VLBI observations of the celestial area around the interface point are to be conducted in order to construct a radio map of potential phase-calibration celestial sources.

3). A suitable hard- and soft-ware environment must be created with a target readiness date for a pre-interface "drill" experiment several months prior to the "live" observations of the Huygens probe.

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