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

This study is conducted at the Joint Institute for VLBI in Europe under the contract between ESA and ASTRON/JIVE No. 17002/02/NL/LvH/bj

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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):

   $$\mathrm{RA} = 07^h42^m40.7995^s, \quad \mathrm{DEC} = +21^{\circ}22'47.557''$$

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 (55° C)	Nominal (22° C)	Minimum (-25° 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 2° 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 2° 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.

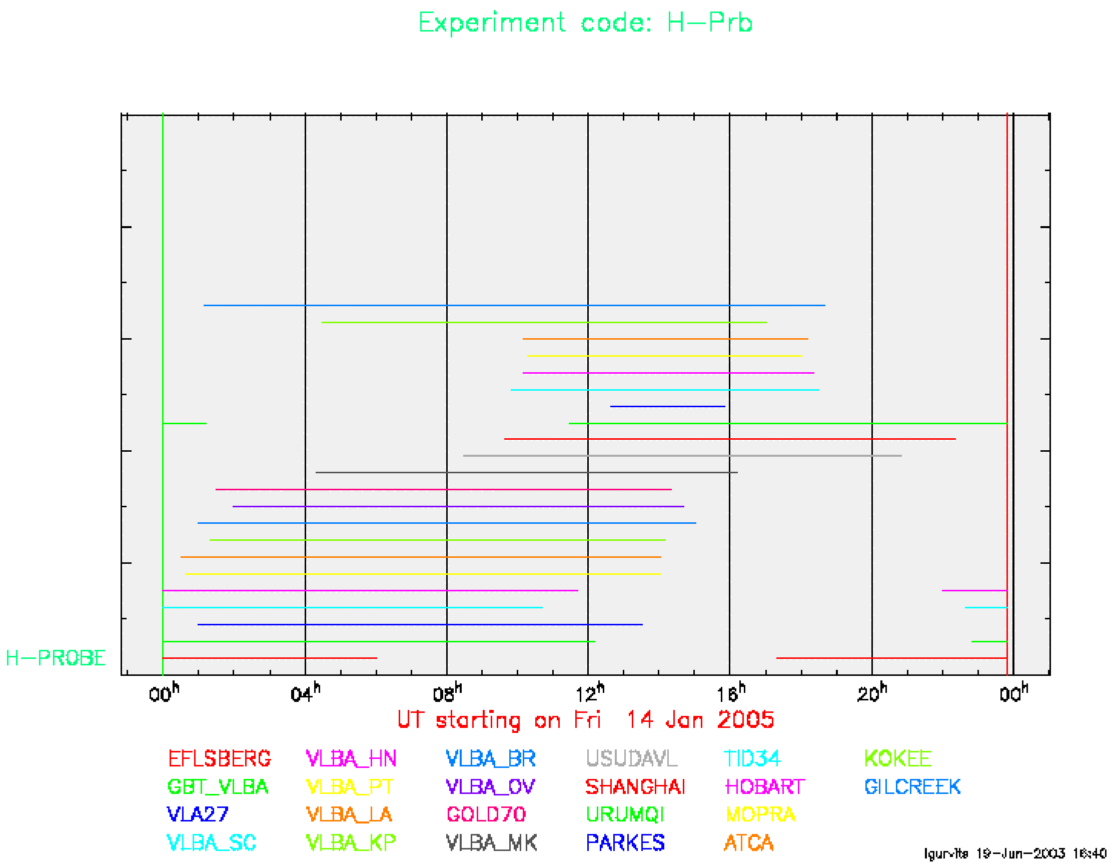


Fig. 3-1. Visibility of the interface celestial point from various radio telescopes on 14 January 2005.

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.

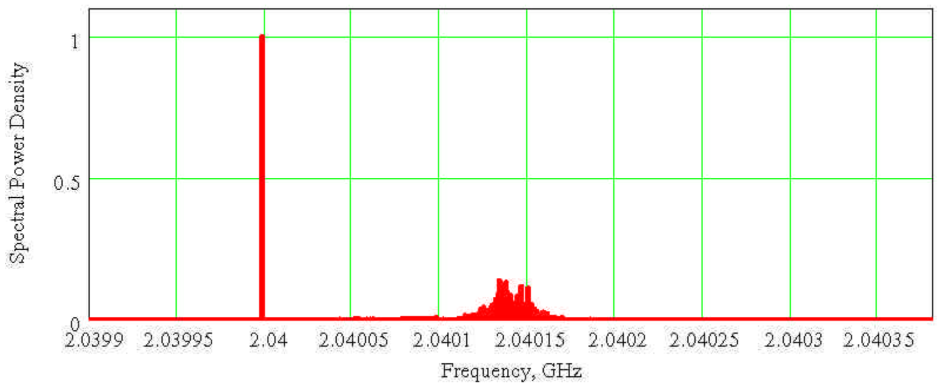


Fig. 4-1. Typical spectrum of BPSK modulated signal

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

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

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.

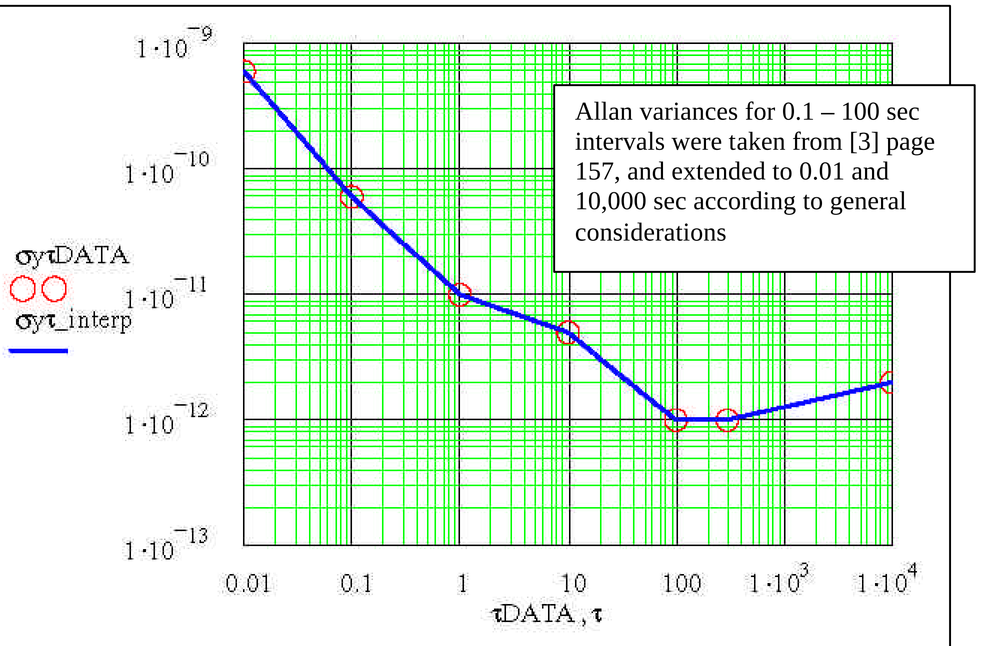


Fig. 4-2. Allan variances for the probe LO

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.

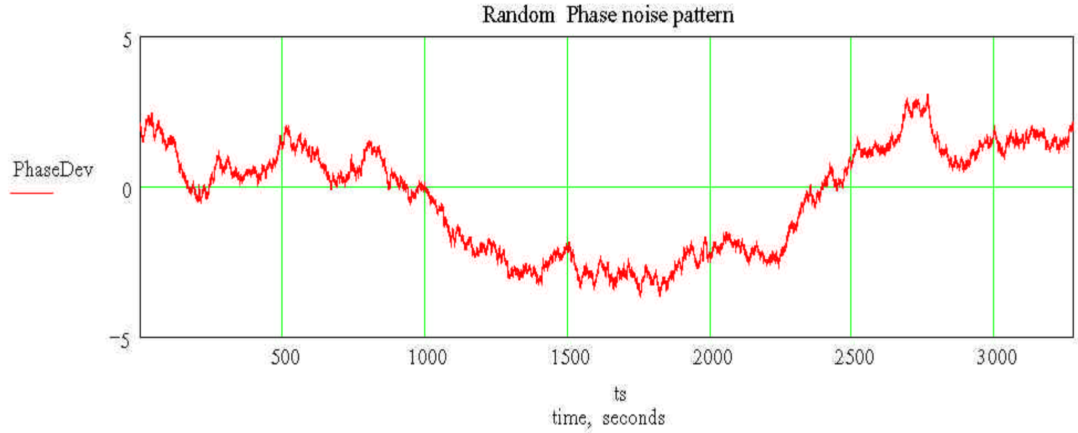


Fig.4-3. Random phase noise pattern for given Allan variances

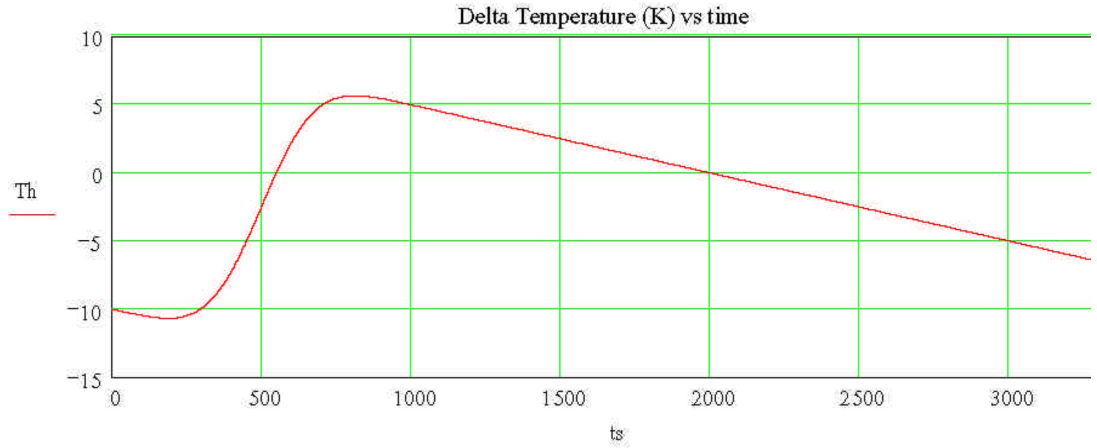


Fig. 4-4. Modeled variation of LO temperature

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.

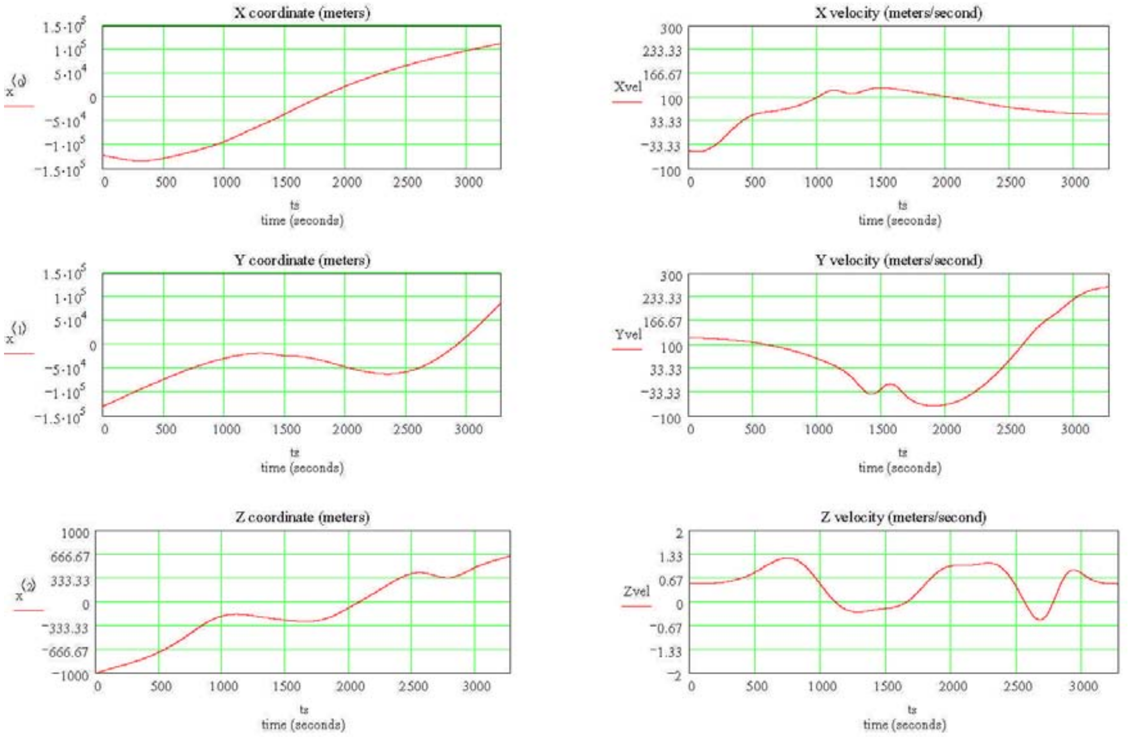


Fig. 4-5. X,Y and Z components of modeled probe trajectory

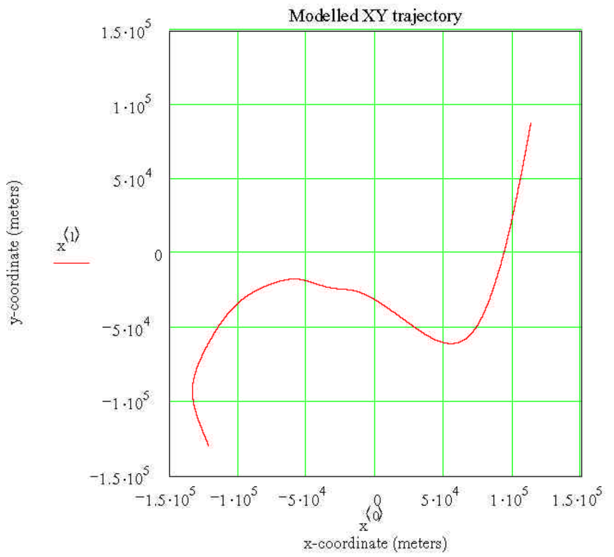


Fig. 4-6. Probe trajectory on XY plane

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.

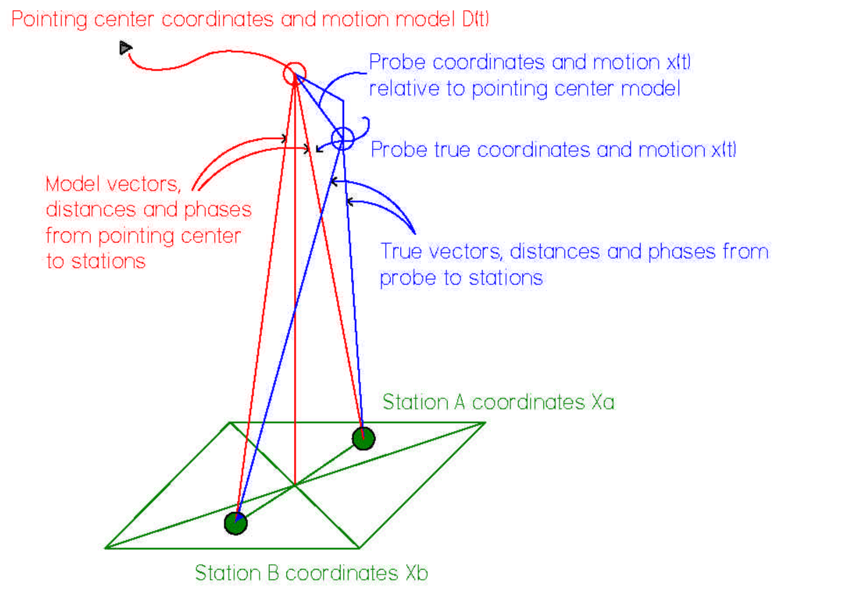


Fig 4-7. Geometry of the probe motion model relatively to the pointing centre a-priori model

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.

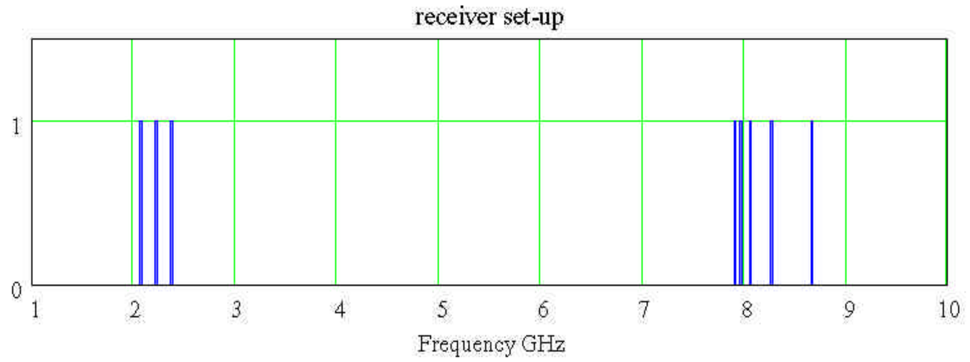


Fig. 4-8. Typical S/X receiver band setup

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.

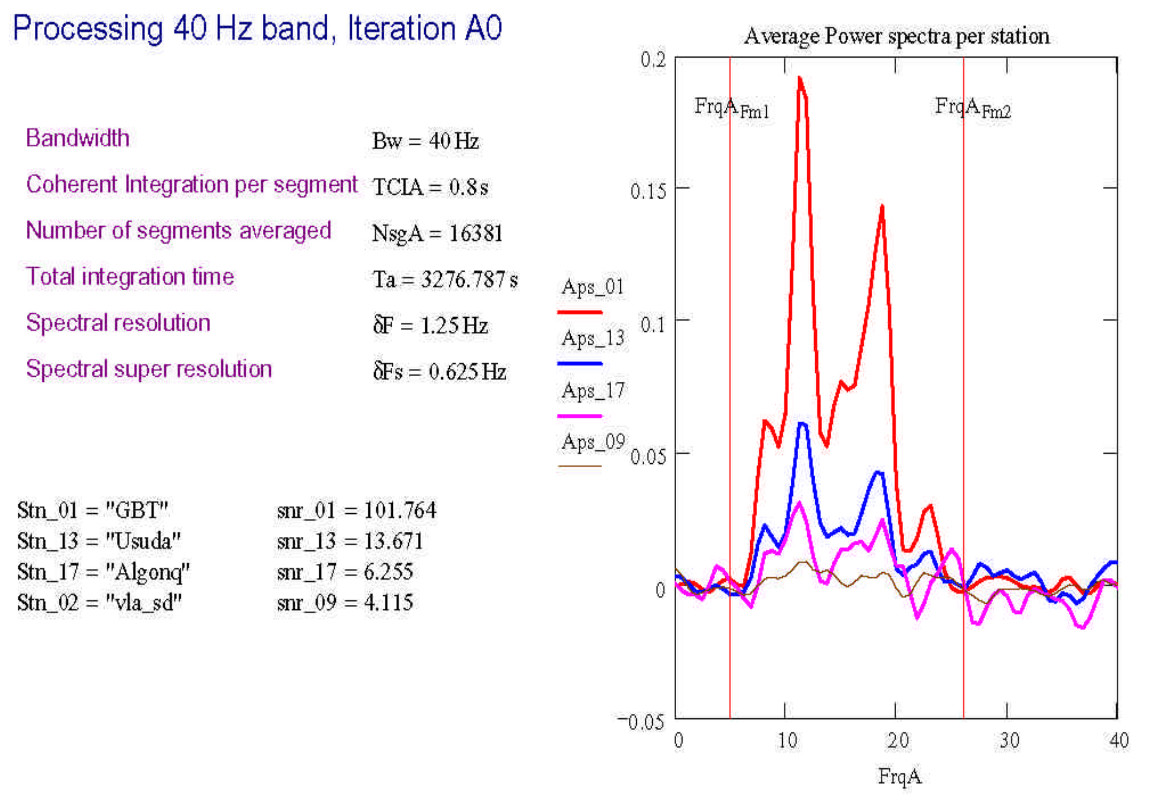


Fig. 4-11. Time averaged dynamic spectra for a total averaging time of 3200 s for the 4 major stations

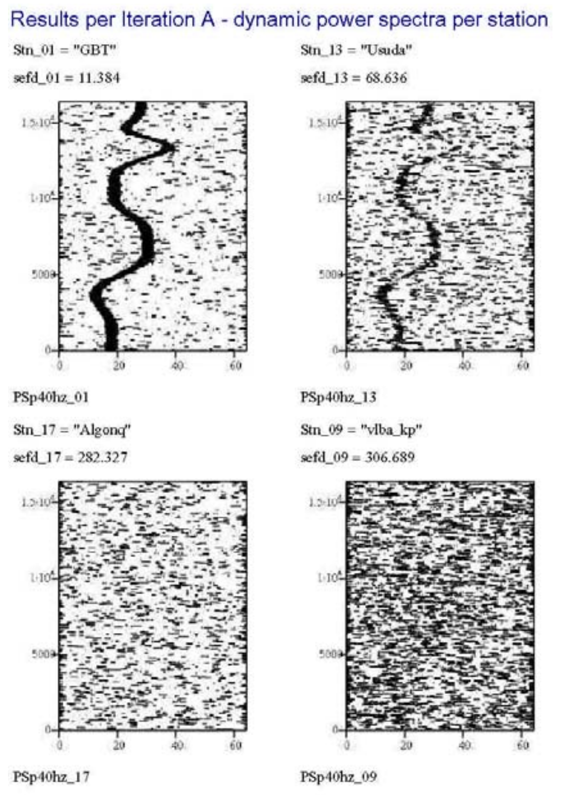


Fig. 4-12. Dynamic spectra for 4 major stations

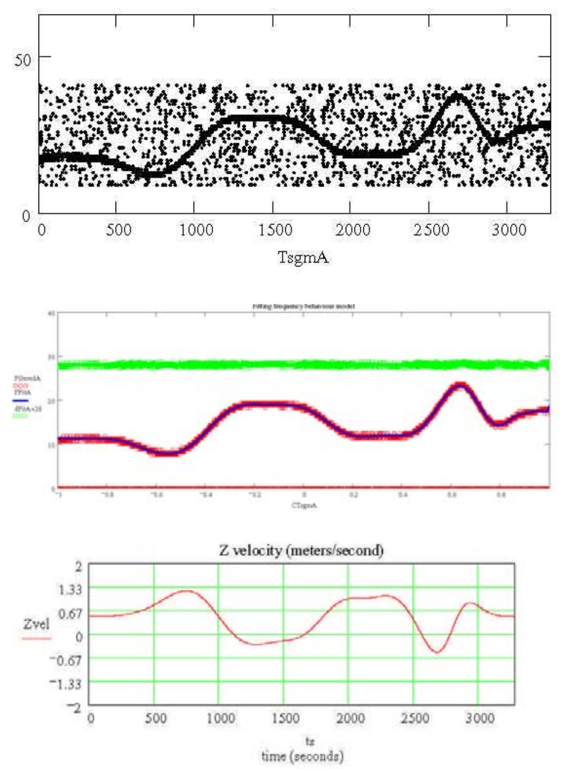


Fig. 4-13. Common Mode – Image enhanced average dynamic spectrum, polynomial fit to recreate the frequency drift model and input Doppler velocity model for comparison

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.

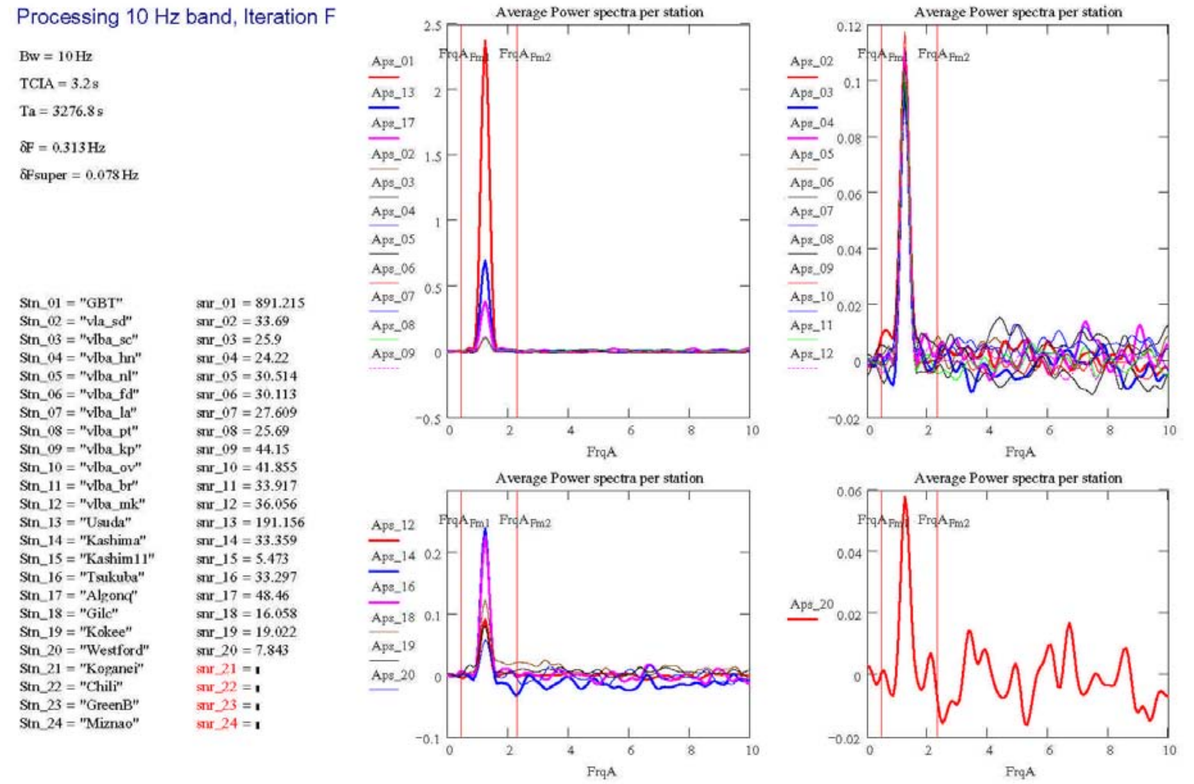


Fig. 4-14. 3200 seconds averaged dynamic spectra for 20 stations, bandwidth 10 Hz, spectral resolution 0.313 Hz

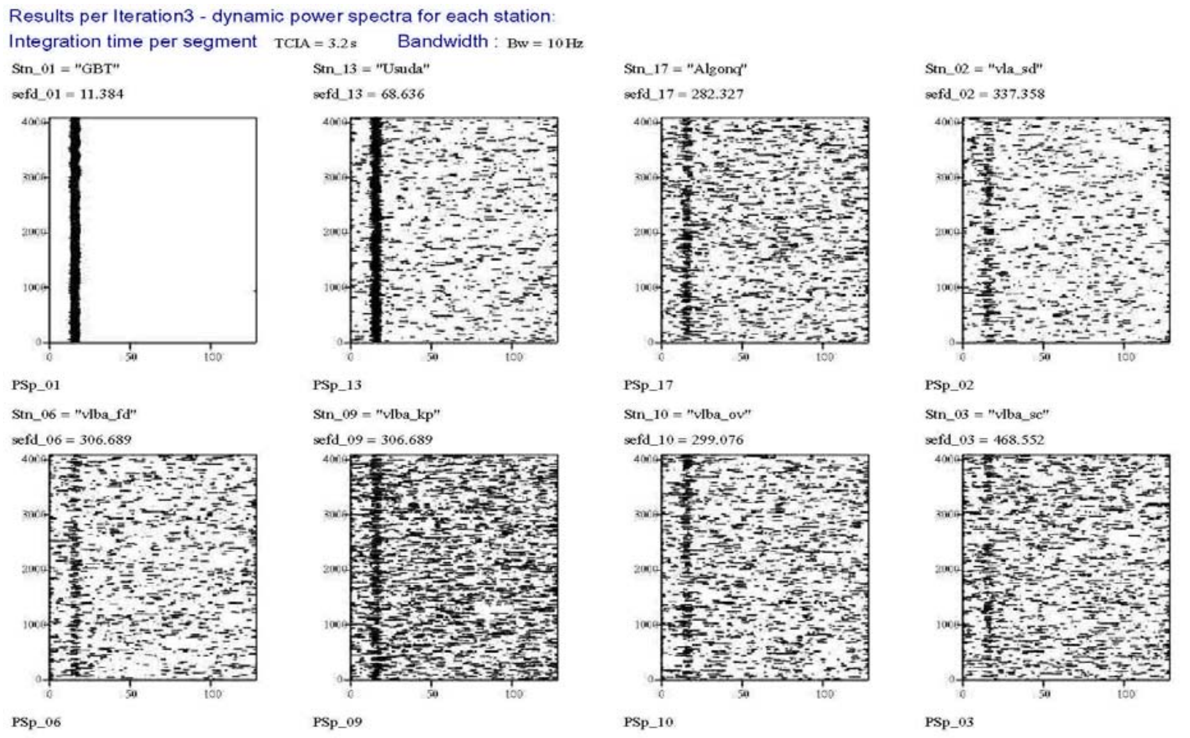


Fig. 4-15. Dynamic spectra for 8 stations for 10 Hz band with resolution 0.313 Hz

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.

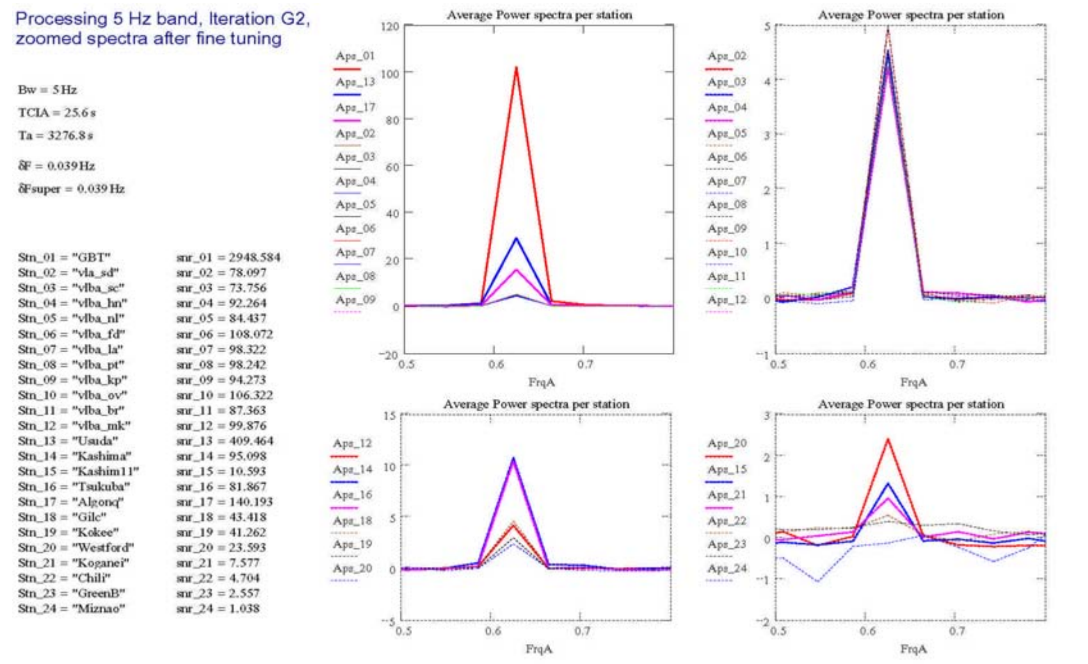


Fig. 4-16. 3200 seconds averaged dynamic spectra for 24 stations, bandwidth 5 Hz, spectral resolution 40 mHz

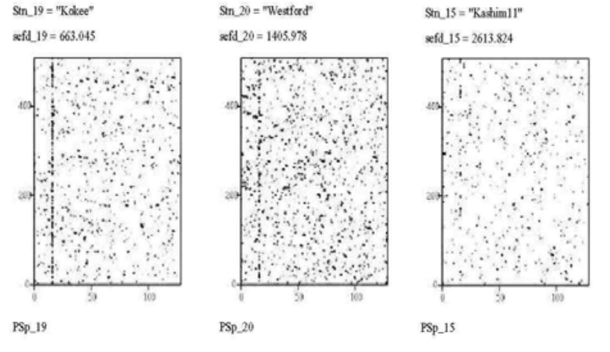


Fig. 4-17. Dynamic spectra with 40 mHz resolution for 22, 18 and 11-meter antennas

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.

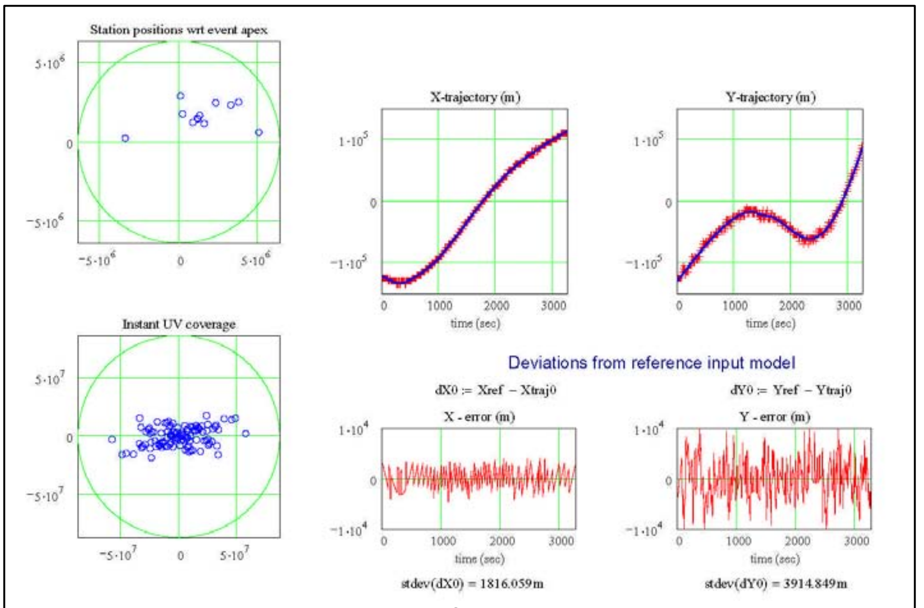


Fig. 4-18. First iteration of the probe motion mapping

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.

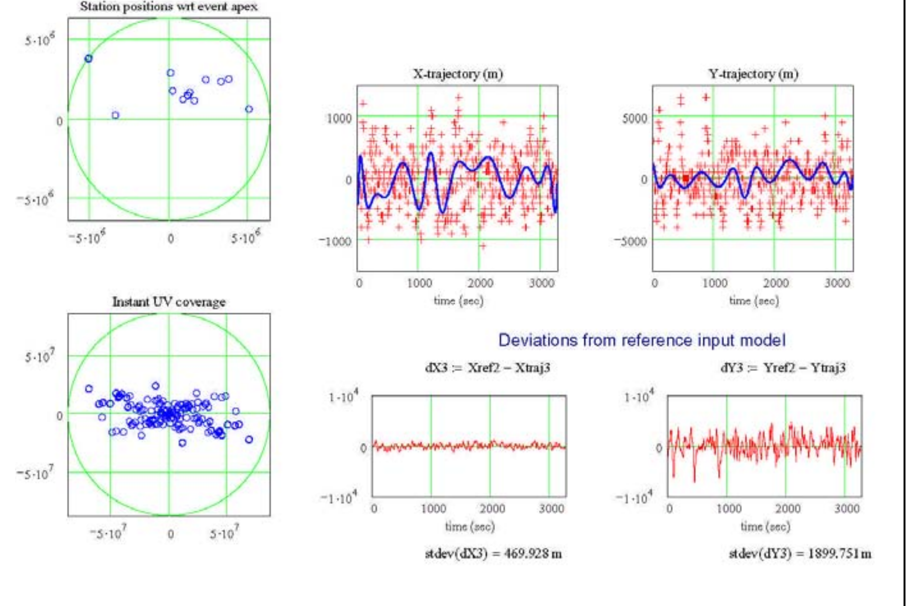


Fig. 4-19. Results of the third iteration of the probe motion mapping

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.

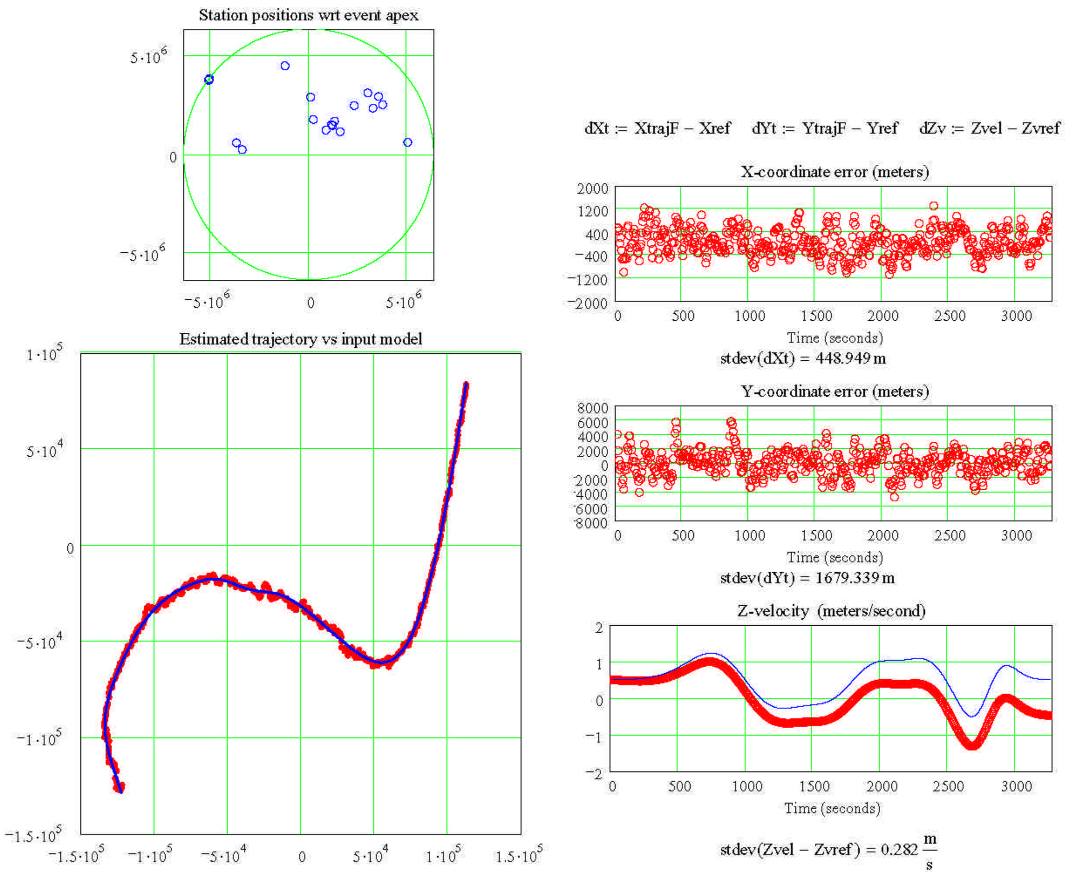


Fig.4-20. Simulation results of The Huygens probe trajectory mapping with 20 VLBI stations with an effective time resolution ~10 seconds

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.

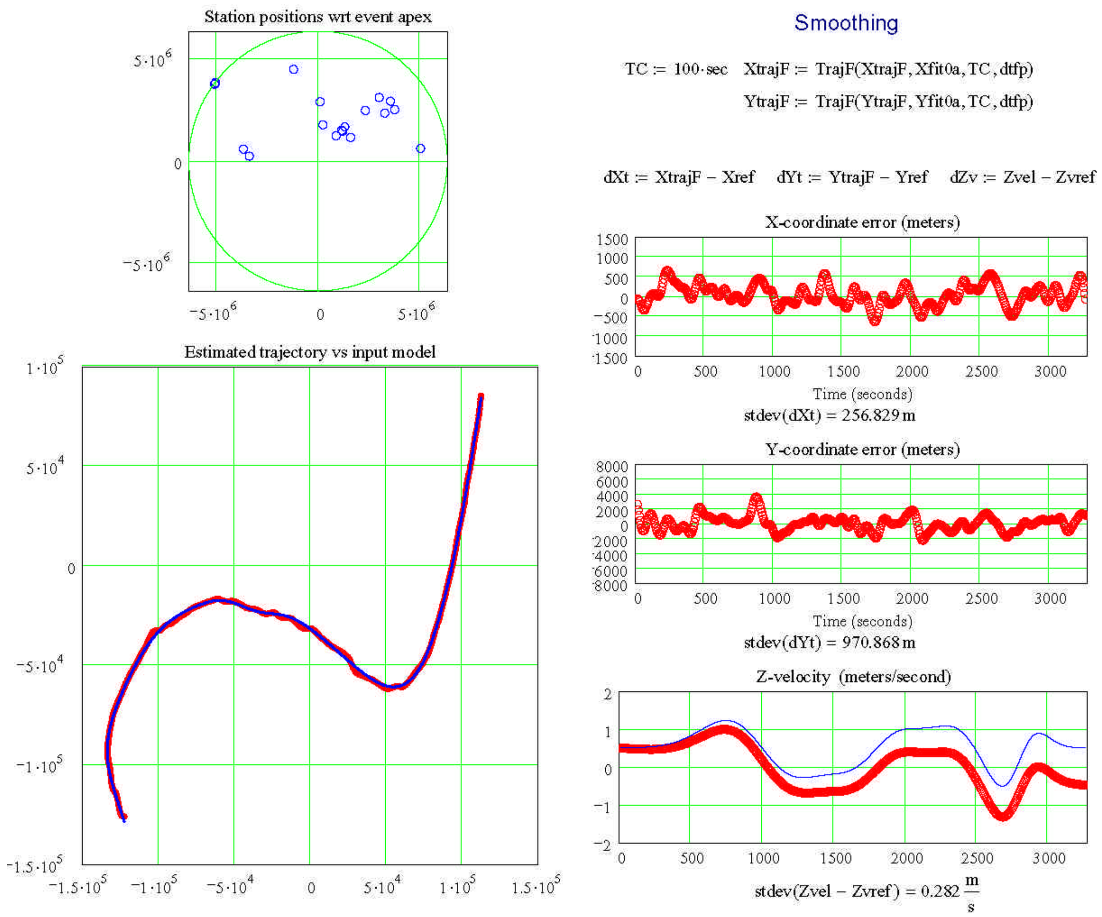


Fig.4-21. Simulation results of The Huygens probe trajectory mapping with 20 VLBI stations, 100 seconds smoothed sampling.

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

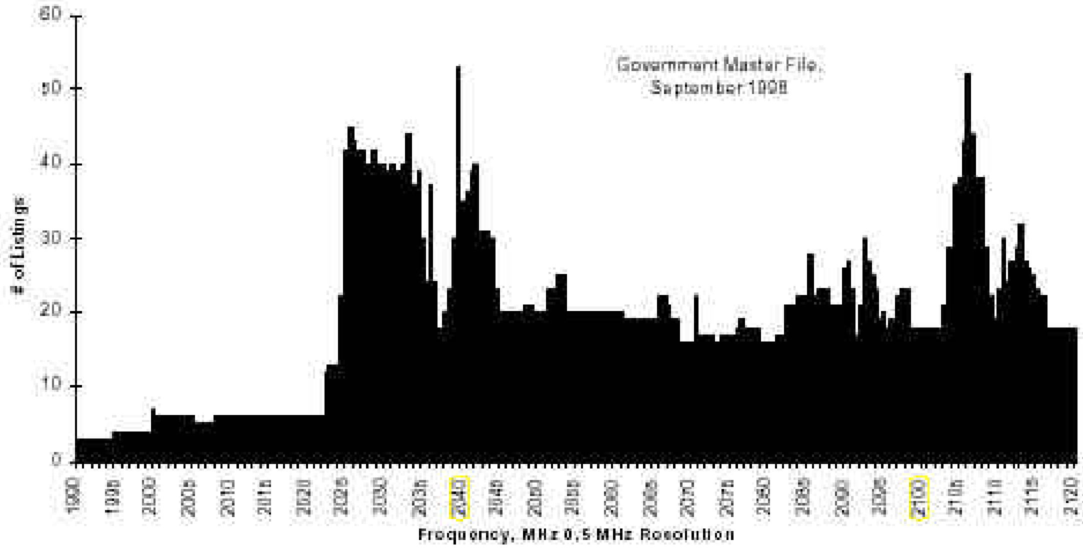
A crucial point of the project is the ability to download the observed data into general-purpose computers. The only practical solution is to use disk-based VLBI data recorders. Currently three different types of disk-based VLBI recorders are available: Mk5, K5, and PCEVN. The JIVE correlator can support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

SECTION II
SUMMARY OF FEDERAL GOVERNMENT SPECTRUM USAGE IN THE 1990-2110 MHz BAND



Note: 1) The figure represents authorized frequency assignments or listings in the GMF, as of September 1998, and does not include the private sector's authorized frequency assignments such as for electronic news gathering.

2) The majority of the authorized frequency assignments are for space science services.

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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[4] Huygens: Sciene, Payload and Mission, ESA SP-1177, August 1997

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