SPACECRAFT TRACKING CAMPAIGNS AND THE ASSESSMENT FOR ORBIT DETERMINATION ACCURACY

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ABSTRACT

As time passed, the demand for high precision orbit determination increased. However, this necessitated not only an improvement of the tracking data handling techniques but also an evaluation of the tracking equipment performance.

During the past few years special tracking campaigns were organised in order to analyse the tracking facilities required for geosynchronous satellites (including the transfer and drift orbit).

Whereas in the transfer orbit special emphasis was laid on the ionospheric delay uncertainty in VHF tracking, in the geosynchronous orbits, the single station configuration was analysed.

1. INTRODUCTION

In feasibility studies and in the mission analysis work for a satellite project the tracking configuration (ground stations and measurement types plus measurement sampling) necessary to achieve the required orbit accuracy has to be defined. Very often only assumptions of tracking systems can be fed into the study, when for example new ground stations with new antenna and tracking facilities may have to be used, either for reasons of precision, coverage or frequency. The utilisation of existing tracking facilities will obviously increase the confidence level of the study results, but the problem has still not been eliminated entirely. Even with existing tracking equipment the performance and the temporal evolution cannot be given precisely since the evaluation of the equipment very often has to be based on inaccurately known elements such as the satellite position itself.

The majority of satellites supported by ESOC during the past few years and those to be launched during the next couple of years are geosynchronous ones. They are generally tracked by a single station equipped with angular and ranging tracking facilities. The single station tracking is not specific to geosynchronous satellites as shown in Table I : Current and near future ESA (ESOC) satellites. Especially single station orbit determination is very sensitive to uncalibrated systematic offsets in tracking measurements, and this makes it mandatory to have a good a priori knowledge of the tracking facilities. Orbit determination which relies on many ground stations and furthermore which has a significantly time-varying station-satellite geometry is not so prone to measurement biases.

During the last few years some activities have been carried out at ESOC and will be summarised here. Since primarily geosynchronous satellites are being handled currently and will be in the near future, this paper consists of two parts :

- Transfer orbit determination based on VHF tracking,and

- Geosynchronous orbit determination with single station tracking

2. TRANSFER ORBIT DETERMINATION

The geosynchronous satellites listed in Table I - Current and near future ESA (ESOC) satellites, make use of VHF tracking facilities primarily during the transfer orbit and the early part of the drift orbit phase. During the latter part of the drift phase and the geosynchronous (on-station) phase higher frequency bands are generally used.

2.1 OTS-2 Transfer Orbit Tracking

A more detailed analysis of the VHF tracking performance was carried out with OTS-2, which was launched on 11th May 1978 and placed into its final position with 10° East longitude on 24th May 1978. The sequence of events and the orbital parameters are given in Table II : OTS-2 Transfer Orbit Information.

The noise contribution from the tracking equipment (ground and onboard) was derived from the consistency of the individual tracking data which means the dispersion of the tracking data with respect to the fitted curve. Long-term variations or constant offsets obviously lie within the computed curve itself, so that the residuals obtained from the preprocessing gave an indication of the noise value of the tracking data received.

During the VHF period the following results were obtained from the tracking data preprocessing :

Proc. Int. Symp. Spacecraft Flight Dynamics, Darmstadt, FRG, 18-22 May 1981 (ESA SP-160, Aug. 1981)

Measurement	Accepted to	Dispersion
GRARR range	95%	20m
GRARR range rate	91%	10cm/s
SRE range	98%	12m
ESA range	96%	17m

In principle, a figure of

15-20 m for the range, and
10 cm/s for the range rate

could be considered for the instrumentation accuracy (noise) for all the considered tracking systems.

It is obvious that several corrections have to be applied to the VHF ranging measurements before they can be used in the orbit determination procedure. In principle the following corrections are considered :

- propagation time delay
- ground and transponder delay
- satellite spin effect (for range rate measurements only)
- atmospheric (ionospheric) delay

The modelling errors for the first 3 effects applicable to OTS-2 are summarised below. A breakdown of the error contributions was documented in an internal 'OTS-Orbital Test Programme-Flight Dynamics Report-VHF Tracking Accuracy' paper.

Considered Correction	Constant Value	Remaining Error
Propagation delay		Insignificant
Ground delay	47.690μsec	4-5m (instrumentation accuracy)
Transponder delay	13.450μsec	
Doppler shift		1.5m
Input level		2.1m
Temperature		4.8m
RMS		5.4m
Maximum		8.4m
Satellite spin (only affecting Doppler measurements)	1.944m/s	

The performance of the ionosp[illegible] delay model was evaluated by means of VHF and S-Band tracking comparisons using METEOSA[illegible].

The Bent ionopsheric model was considered the most appropriate for the operational environment at ESOC and was implemented for the Cos-[illegible] launch in August 1975. The Bent model has been described for example in the 2 references :

R.B. Bent, S.K.Llewellyn, P.E. Schmid
Ionospheric Refraction Corrections in Satellite Tracking Space Research XII [illegible]

P.Schmid, R.Bent, S.Llewe[illegible] [illegible]rczuk, S.Rangaswamy
NASA-GSFC Ionospheric Corrections to Satellite Tracking Data, GSFC X 591-73-281, Dec. 1973.

2.2 The METEOSAT Tracking Exercise

Several of the geosynchronous satellite controlled by ESOC are equipped with tracking facilities of higher frequencies, such as S-band and SHF, in addition to the VHF instruments. Whereas the higher frequency tracking facilities are normally used for the geosynchronous orbit determination, the VHF capability is used for the transfer and drift orbit determination. Several tracking campaigns have been conducted where both tracking facilities were used for analysis purposes. Since the ionospheric influence is inversely proportional to the square of the frequency, these tracking campaigns offered good possibilities to evaluate the ionospheric model used within the orbit determination.

The METEOSAT satellite is positioned at a longitude of 0° and requires for the earth image data processing a precise knowledge of the satellite location. A suitable tracking system (S-band ranging) has been installed at Odenwald, West-Germany (longitude of 9.0°E, latitude of 49.7°) and Kourou, French Guyana (longitude of 52.8°, latitude of 5.3°). While Odenwald is the commanding station, Kourou houses a land based transponder (LBT). The full ranging sequence consists of alternately

2-way ranging (Odenwald-S/C-Odenwald) and
4-way ranging (Odenwald-S/C-Kourou-S/C-Odenwald).

The overall accuracy of the ranging is

6m for the 2-way component and
12m for the 4-way component.

If one compares successive orbit determinations one can derive an estimate of the orbit consistency (satellite position), i.e.

longitude	120m
latitude	70m
height	20m

The distance from the satellite to the two VHF tracking stations Redu, Belgium (longitude of 5.1°E, latitude of 50.0°) and Kourou can be derived with sufficient precision, i.e.

for Redu about 22m and
for Kourou about 16m

In this configuration the ionospheric delay of VHF ranging measurements could be obtained by comparing the VHF value with the computed distance (derived from S-band orbit determination), since other effects such as tropospheric delay could be disregarded. Assuming an overall VHF instrumentation accuracy of about 25m, the ionospheric delay could be deduced with a precision of about 35m.

A tracking campaign was conducted during the period 24th to 26th April 1979. The comparison between the S-band orbit and the VHF ranging data revealed larger deviations than expected. The differences are given in Table III: VHF / S-Band Tracking Comparison (METEOSAT). If we assume that the differences can be attributed entirely to the ionospheric delay, the performance of the ionospheric model used was not very good. Up to 70-80% of the total delay was the computed correction for the mid-latitude location Redu and only 50-70% for the equatorial station Kourou. Furthermore, the obtained differences did not show a repetitive behaviour over the 3 days so that the orbit determination which relied on VHF data only, converged to a significantly different orbit, i.e.

difference in semi-major axis of 200 m and difference in position (27th April) 8 km.

The irregular differences could not be explained fully, the solar flux values were fairly smooth, however, the mean solar flux had already reached a value of 190 x 10^{-22} W/m^{2}Hz.

Unfortunately, the test could not be repeated due to a failure on-board METEOSAT.

2.3 Transfer Orbit Accuracy

The typical characteristics of an ESA/ARIANE transfer orbit are :

- transfer orbit

Perigee height	200 km
Apogee height	36.000 km
Inclination	10.5°
Arg. of perigee	180.0°
Longitude of desc. node	20.0° West
Period	10.5 hours

- ground tracking stations

Station	Longitude	Latitude
Malindi, Kenya	40.3E	-3.0
Carnarvon, Australia	113.7E	-24.9
Kourou, French Guyana	52.8W	5.3
Redu, Belgium	5.1E	50.0

Apogee motor firing (injection into the drift orbit) normally takes place at the 2nd or 4th apogee. The nominal tracking sequence for these two cases is as follows :

Injection at perigee 0(T_i) → T_i + 2.5 hrs
Every 15 min (Malindi, Carnarvon)

T_i + 2.5 hrs → Perigee 1
Every 30 min (Malindi, Carnarvon)

In case of apogee motor firing at 4th apogee :

Perigee 1 → Apogee 2
Every 30 min (Kourou)

In case of apogee motor firing at 4th apogee :

Perigee 1 → Perigee 3
Every 60 min (all 4 stations)

Perigee 3 → Apogee 4
Every 30 min (Kourou, Redu, Malindi)

The 4 ground tracking stations perform VHF ranging (tone ranging system with a minor tone frequency of 10 Hz and a major tone frequency of 20 KHz) with the following overall performance :

ground equipment	5 m
onboard equipment	10 m
noise (instrumentation accuracy)	20 m

The first two quoted figures are to be understood as uncertainties within the measurements after calibration. In addition, the uncertainty in the ionospheric delay has to be considered. In order to give an idea of the magnitude, the ionospheric delay for the various stations for a direction towards the equator at an elevation of 30° is tabulated below :

Station	Low Solar Activity	High Solar Activity
Malindi	1,400 m	4,000 m
Carnarvon	1,000 m	3,800 m
Kourou	1,400 m	4,000 m
Redu	350 m	2,800 m

Assuming a remaining error of 20% after modelling the ionospheric effect the following orbit accuracies can be achieved when using tracking measurements up to 1.5 hours prior to the relevant apogee.

Expected Orbit Accuracy (3σ Values)

Position	Semi-Major Axis	Inclination
Assuming low solar activity at 2nd apogee		
13.5	250 m	0.010°
Assuming low solar activity at 4th apogee		
4.5	25 m	0.006°
Assuming high solar activity at 2nd apogee		
50.0	540 m	0.035°
Assuming high solar activity at 4th apogee		
20.0	80 m	0.022°

The orbit accuracy required by the attitude determination and the AMF optimisation is very modest, 70 km for the position and 2 km for the semi-major axis. Increasing the ionospheric error to 50% at high solar activity would still not violate the orbit requirement for an apogee motor firing at the 4th apogee, i.e.

Expected Orbit Accuracy (3σ Values)

Position	Semi-Major Axis	Inclination
Assuming high solar activity with 50% remaining error,		
at 2nd apogee		
120.0	1,300 m	0.085°
at 4th apogee		
50.0	190 m	0.055

As mentioned above the modest requirements on the transfer orbit accuracy in connection with the favourable geometry (sufficient time and ground stations) permit the performance of a successful transfer orbit determination even under the condition of a large remaining error of the ionospheric delay at high solar activity.

3. SYNCHRONOUS ORBIT DETERMINATION

As mentioned earlier several of the ESA satellites are or will be tracked by a single station. Especially for geosynchronous orbits, the performance of the tracking measurements must be known precisely, since the orbit determination is very sensitive to unknown systematic offsets. Obviously these effect have a direct influence on the satellite position determination.

However, the evaluation of the tracking equipment is made difficult by the fact that one has satellite dedicated tracking facilities, either for reasons of coverage or frequency. Tracking back-up is normally provided by the ordinary ESA VHF ground network, which does not provide sufficient precision for evaluation purposes. Of course a consistency analysis of the tracking measurements themselves can be carried out during the preprocessing, but reasonably small systematic offsets can hardly be detected in the orbit determination.

Only OTS-2 has a reasonable back-up; in fact it also has good alternatives to the dedicated tracking. An analysis was carried out on the performance of ranging (in SHF) and of antenna angular data.

3.1 OTS-2 Tracking

The OTS-2 satellite is positioned at 10° East and should be kept within an interval of $\pm 0.1^{\circ}$. In order to maintain a reasonable station keeping cycle the orbit determination must provide the satellite position to an order of magnitude better than the positional interval itself.

The analysis carried out before launch indicated that the envisaged single tracking station Fucino with its angular and ranging measurements would not provide sufficient information to satisfy the desired positional condition of about 2.5 km (1σ value). This accuracy study was based on the nominal tracking performance of

0.003° noise and 0.01° bias for the angular measurements, and
10 m noise and 20 m bias for the ranging measurements.

The Fucino tracking measurements had to be complemented with data from another ground station. The selected tracking network consists of

Fucino, Italy (longitude of 13.6°E, latitude of 42.0°) with angular - and ranging tracking facilities, and
Villafranca, Spain (longitude of 9.0°W, latitude of 40.4°) with ranging facilities.

Only Fucino provides full tracking support (24 hours/day and 7 days/week), whereas Villafranca is operated only during normal working hours (8 hours/day and 5 days/week). In routine phase when the satellite is tracked (ranging) once every 4 hours the following tracking amount can be expected in one week :

35 (=7 x 5) measurements from Fucino and
15 (=5 x 3) measurements from Villafranca

The Villafranca ranging system, however, is not as accurate as the Fucino one because of the smaller antenna size.

Although the antenna pointing angles are permanently available whenever the antenna is run in autotrack mode, only the data around a ranging pass are collected because of the lower accuracy/contribution of this type.

The unfavourable geometry of the tracking configuration (Fucino-Villafranca-satellite) and the limitation in the Villafranca support obviously lessens confidence in the orbit determination results.

3.1.1 Range Measurements

The OTS ranging system measures the delay between the transmission and the reception of the 100 KHz major tone. Ambiguity resolution is partially obtained by means of minor tones (20 KHz, 4 KHz, 800 Hz, 160 Hz, 32 Hz and 8 Hz). The lowest minor tone of 8 Hz establishes an unambiguous 1-way range of about 18750 km. The complete ranging sequence is split up into 3 parts

- calibration
- ranging measurement
- calibration.

Each part (calibration and actual measurements) consists of 128 single points (so-called accurate words) separated in time by about 0.125 sec. The minor tone provides the ambiguity word. The range is obtained from the relation

$$\text{2 way range} = C_o \times (\text{ambiguity word} \times 10\mu\text{sec} \times \text{accurate word} \times 5.0025\text{ sec} - \text{calibration}$$

where C_o velocity of light.

Apart from the calibration given in the message itself further corrections have to be applied. All values quoted below refer to the 2-way range and are expressed in nsec.

	Fucino	Villafranca
ground calibration	30 384	27 974
antenna correction	46	94
transponder delay	1287±10	
transmission medium	23	

The consistency of the calibration measurements give an idea of the instrumentation accuracy (noise value). The individual calibrations had a dispersion of about 5 nsec (in most of the cases) and were stable within ± 15nsec (both values still refer to the 2-way distance) over a period of 1 year.

Combining these figures one arrives at the following total equipment performance (for Fucino only, the values for Villafranca are somewhat larger because of the smaller antenna size) :

ground calibration (bias)	10 nsec
transponder delay (bias)	10 nsec
instrumentation accuracy (noise)	5 nsec

which, converted to 1 way distance and expressed in meters, is

bias of about 3 m and
noise of about 1 m

A summary of the ranging characteristics is given in Table IV- OTS-2 Tracking Measurements.

3.1.2 Antenna Pointing Measurements

The antenna recorder read-out α has a resolution of about 0.003°. Whereas the elevation component can be used as it is, the azimuth value has to be calibrated. The true azimuth AZ is obtained from

$$AZ = \alpha - 0.007^{\circ} + 0.007^{\circ} \sin (\alpha - 260^{\circ})$$

A further correction could be implemented after an evaluation of the recorded difference between the maximum signal strength and the read-out direction.

During the 'reading' period of about 2 minutes (in principle the measurements are available continuously) the individual measurements remain constant (resolution of 0.003°) owing to the extremely low movement of the satellite with regard to the ground station.

A summary of the antenna pointing measurements is included in Table IV - OTS-2 Tracking Measurements.

3.1.3 Atmospheric Effects

The atmospheric effects are split up into the tropospheric - and ionospheric part. The ionospheric influence is inversely proportional to the square of the frequency. A typical VHF range delay caused by the ionosphere is in the order of 2000m. The corresponding range delay for a frequency of 11 GHz would then be about 0.30m. Whereas the ionospheric effect is frequency dependent and could therefore be neglected, the tropospheric part is frequency independent. The mean tropospheric corrections are of the order of

0.025° for the elevation and
3-4 m for the range.

Assuming an error of 30% (figure cannot be justified) one obtains for the atmospheric correction uncertainty

about 0.008° for the elevation - and
about 1 m for the distance measurement

3.2 Special Tracking Campaigns

Already shortly after the satellite has been put on station a discrepancy between the ranging information received from Villafranca and Fucino was discovered. Because of the unfavourable tracking geometry it was not obvious to which station the empirically determined offset of -1500m should be attributed. Further investigation indicated that Villafranca was causing this offset. For verification purposes special tracking campaigns were conducted. Whereas the first campaign (Dec. 1978) was initiated for orbit determination reasons, the second campaign (March 1979), was requested in order to conduct further tests with the digital ranging system. The stations involved and their tracking facilities are listed below :

The addition of Usingen and Martlesham Heath does not improve the tracking geometry significantly, but the inclusion of these two stations provided redundancy, which was of great importance for the ranging discrepancy investigation. The Usingen data were redundant to the Fucino antenna pointing data and the digital ranging measurements were redundant to the Fucino LCT ranging data. This redundancy made it possible to determine to which station the large offset of about -1500m should be attributed. Owing to the still unfavourable geometry, the determination of the exact offset is not yet possible. The estimation of all the biases of the tracking types (i.e. 9 values) could easily cause a divergence within the iterative orbit determination. In order to prevent divergence at least 1 measurement offset has to be considered as known. The most sensitive measurement (Villafranca ranging) with respect to satellite longitude shifts was not estimated.

The results listed below are obtained for the neigbourhood of -1500m for the Villafranca ranging offset. No differences were found in the convergence or the residuals themselves for the cases mentioned. These figures are based on the December 1978 tracking measurements.

Measurement	Measurement Bias for Villafranca offset of		
	-1285 m	-1500m	-1685m
Fucino			
LCT ranging	-100m	-46m	0m
Azimuth	-0.001°	0.014°	0.027°
Elevation	-0.022°	-0.023°	-0.023°
Digital ranging	-101m	-46m	0m
Usingen			
Azimuth	-0.003°	-0.012°	-0.025°
Elevation	-0.033°	-0.033°	-0.033°
Martl.Heath			
Azimuth	-0.004°	0.007°	0.016°
Elevation	-0.051°	-0.050°	-0.050°

The three cases have not been selected arbitrarily. Whereas in the first column the azimuth offset is roughly 0, the second column gives for the Villafranca offset the ambiguity length of 1500m and the third column represents a bias-free Fucino ranging (LCT plus Digital) system. The corresponding satellite longitude difference between neighbouring columns would be about 0.01° (equal to 7km). The middle column with an offset of -1500m for the Villafranca ranging measurements has been selected as a basis for the operational orbit determination, since this Villafranca offset coincides with an incorrect ambiguity resolution (1499m) and the biases of the remaining tracking types are not too large. These empirically deter-

Station	Longitude	Latitude	Tracking Type	Expected Perform.
Fucino	13.598°	41.979°	LCT ranging*	5 m
			Antenna Pointing	0.003°
			Digital ranging	5 m
Villafranca	-3.953°	40.444°	LCT ranging*	15 m
Usingen	8.482°	50.331°	Antenna pointing	0.002°
Martlesh.Heath	1.286°	52.059°	Antenna pointing	0.005°

* LCT is the ordinary OTS-2 ranging system

mined offsets were used for the evaluation of the March 1979 data.

Below are the results of the two tracking campaigns for comparison purposes :

		December 1978				March 1979		
		Weight	No. of measur.	Offset	RMS	No. of measur.	Offset	RMS
Villafranca	range	15m	14	-1500m	17m	10	-1500m	2m
Fucino	range	5m	32	-46m	7m	51	-25m	1m
	azimuth	0.002°	32	0.014°	0.002°	51	0.014°	0.002°
	elevation	0.006°	32	-0.023°	0.007°	51	-0.027°	0.004°
	digital range	5m	68	-46m	7m	46	-29m	1m
Usingen	azimuth	0.002°	72	0.012°	0.002°	119	0.015°	0.002°
	elevation	0.002°	72	-0.033°	0.002°	119	-0.034°	0.002°
Martl.Heath	azimuth	0.005°	63	0.007°	0.005°	38	0.001°	0.002°
	elevation	0.005°	63	-0.050°	0.004°	38	-0.040°	0.002°

The significantly better results for the March 1979 tracking campaign compared to the ones obtained with the December 1978 data can be explained by a better orbit modelling which in turn is due to the reduced normal mode thrusting operations for the attitude control. This reduced mode was implemented in early 1979.

When looking through the figures given above, the following points are striking :

a) The results for the Fucino LCT and the digital ranging show a surprising agreement in both the offset and the RMS of the residuals.

b) The Fucino elevation angle was significantly less accurate than the azimuth component, which could not be observed for the other two stations Usingen and Martlesham Heath. Graph I presenting the elevation residual versus time shows clearly the sinusoidal variation with a period of about one day. At first glance, one can see that the observed libration around the mean elevation value is smaller (maximum 0.007°) than the actual movement, i.e. $\Delta el = -0.007^\circ \sin u$ (u argument of latitude). A definite cause for this phenomena could not be found yet.

c) Some larger changes could be observed between the two tracking campaigns for the antenna pointing measurements performed by Martlesham Heath. However, since the recorded values have a resolution of 0.01° (the later interpolation improves the accuracy to a few millidegrees) the change in results is not so striking.

It would be too optimistic to quote the March 1979 results as representative for the routine orbit determination. The unchanged offset values resulting from the March 1979 campaign have been introduced into the operational orbit determination, and the mean value (December 1978 plus March 1979) of the RMS has been used for the measurement accuracy.

The evolution of the measurement offsets are listed in Table V : Measurement Performance computed in Offline Orbit Determination. Since , in April 1980, the tracking configuration was reduced to Fucino alone, the evaluation only went up to that time.

A summary of the measurement performance of the OTS-2 tracking facilities is given below :

Measurement Type	Offset Mean Value	Offset Variation	RMS (noise)
Fucino			
ranging	33m	26m	6m
azimuth	0.016°	0.003°	0.002°
elevation	0.027°	0.006°	0.005°
Villafranca			
ranging			13m

3.3 Summary Remarks

Two conclusions can be drawn from the geosynchronous tracking analysis :

- In the case of OTS-2, even with the supplementary stations, not all measurement offsets could be determined. Three sets of measurement biases were selected, which all resulted in a good orbit determination with small, well distributed residuals. However, the satellite position of two neighbouring sets differed by about 7 km (equivalent to about 0°01 in longitude). A proper calibration (detection of systematic offsets) was not possible for OTS-2.
- Under the assumption that the equipment could be properly calibrated, for example by radio stars the computed calibration figures would not show significant longterm variations. The good stability observed in the OTS-2 ground tracking equipment is very promising for single station tracking.

Table I : Current and Near Future ESA (ESOC) Satellites

Satellite	Launch date	Orbit Type			Tracking station	Mission objectives
		Apogee height	Incli- nation	Arg. of Perigee		
COS-B	Aug. 75	86,000	98^{o}	275^{o}	Redu (r)*	Gamma ray astronomy
GEOS-1	April 77	38,000	26^{o}	265^{o}	Redu (r), Kourou (r)	Dynamics of the magneto- sphere
METEOSAT-1	Nov. 77	geosynchr. at		0^{o} long.	Odenwald (r), Kou- rou (r)	Meteorological appli- cation. earth images
OTS-2	May 78	geosynchr. at		10^{o} long.	Fucino (r,α)	Orbital test satellite (European Comm. Satellite)
GEOS-2	July 78	geosynchr. at		37^{o} long.	Odenwald (α), Redu (r)	as GEOS-1
METEOSAT-2 (+ APPLE)	June 81	geosynchr. at		0^{o} long.	Odenwald (r), Kou- rou (r)	as METEOSAT-1
MARECS-A	Oct. 81	geosynchr. at		-26^{o} long.	Villafranca (r,α)	Maritime Comm. Satellite
MARECS-B (+ SIRIO II)	Feb. 82	geosynchr. at		-26^{o} long.	Villafranca (r,α)	Maritime Comm. Satellite
EXOSAT	July 82	200,000	72^{o}	285^{o}	Villafranca (r,α)	European X-Ray Obser- vatory Satellite
ECS-1	Sep. 82	geosynchr. at		12^{o} long.	Redu (r,α)	European Comm. Satellite

Remark : The satellites ISEE-2 (launch Oct. 77) and IUE (launched Jan.78) are not fully supported by ESOC and are therefore not included in this table.

* r stands for ranging, α for angular data

Table II - OTS-2 TRANSFER ORBIT INFORMATION

Sequence of Events:

	Date	Time	True Anomaly	Geoc. distance (km)	Longitude	Drift After Manoeuvre
Transfer Orbit Injection	78/05/11	23.24	20.5°	Perigee height of 184.3 km		
Attitude Reorient. Part I	78/05/12	05.25	186.3°	41 455		
		05.41	188.5°	40 920		
Perigee 1		09.51		Perigee height of 175.7 km		
Part II		11.04	131.6°	22 055		
		12.25	155.6°	33 944		
Part III		14.13	172.8°	41 284		
		14.26	174.5°	41 656		
Perigee 2		20.22		Perigee height of 180.2 km		
Perigee 3	78/05/13	06.53		Perigee height of 181.6 km		
Apogee motor firing		12.13			-21.07°	4.66 deg^{-1}
Attitude erection		13.20			-21.12°	
Sun acquisition		14.20			-21.12°	
Earth acquisition	78/05/14	09.00			-16.31°	
Orbit correction	78/05/17	12.06			- 2.65°	
	78/05/19	Loss of earth pointing and reacquisition				
	78/05/20	influencing significantly the orbit				
Orbit correction	78/05/21	08.11			11.22°	-1.29 deg^{-1}
On station	78/05/24	08.15			10.22°	-0.09 deg^{-1}

Orbit characteristics of the two phases

	Transfer Orbit	Near Synchronous Orbit		
		78/05/13	78/05/17	78/05/21
Perigee height (km)	180.0	35076.4	35128.6	35795.8
Apogee height (km)	35790.0	35776.4	35790.3	35979.4
Semi-major axis (km)	24363.0	41804.6	41837.6	42265.7
Eccentricity	0.731	0.008	0.008	0.002
Inclination (deg)	27.3	0.12	0.12	0.13
Asc. node (deg)	33.2	297.9	298.5	308.8
Arg. of perigee (deg)	179.1	262.4	257.3	65.0

Table II - cont'd.

Tracking Network

Station	Geographic Longitude	Tracking Type	Tracking Type	Number of passes obtained during	
				Transfer Orbit	Drift Orbit
Orroral	148.96°E	-35.63°	GRARR	31	
Guam	144.74°E	13.31°	SRE	38	
Santiago	70.67°W	-33.15°	GRARR	Format problem	27
Rosman	82.88°W	35.20°	GRARR	5	8
Asc.Island	14.33°W	-7.95°	SRE	2	21
Redu	5.15°E	50.00°	ESA	4	104

Table III- VHF/S-Band Tracking Comparison (METEOSAT)

The table gives the difference between VHF ranging data and distances derived from S-band orbit determination. The value within brackets quotes the corresponding ionospheric delay obtained from the Bent model.

VHF/S-Band Differences (Meters) on Day :

Time of Day	79/04/24	79/04/25	79/04/26
Station Redu			
00.00		702 (507)	
02.00	442 (447)	367 (434)	214 (485)
04.00	391 (408)	596 (486)	212 (448)
06.00	654 (559)	867 (702)	497 (606)
08.00	888 (786)		
10.00	1250 (1050)		773 (1150)
12.00	1445 (1180)	1630 (1250)	
14.00	1398 (1160)	1226 (1150)	697 (1250)
16.00	1275 (1070)		780 (1140)
18.00	1186 (943)	741 (861)	
20.00	866 (694)	493 (647)	712 (743)
22.00	748 (574)	316 (562)	549 (617)
Station Kourou			
06.00	1039 (882)	526 (948)	825 (980)
08.00	253 (507)		226 (553)
12.00	2479 (1780)	2024 (1860)	
14.00	3868 (2140)	2302 (2240)	
16.00	4212 (2390)	2442 (2510)	3890 (2570)
18.00	3703 (2370)	2584 (2480)	
20.00	3284 (2060)	3035 (2180)	2611 (2210)
22.00	1935 (1770)	2042 (1860)	

Remark : In fact the Redu measurements refer to 1 hour later on the day 79/04/25 (i.e. 01.00 up to 23.00)

Table IV - OTS-2 TRACKING MEASUREMENTS

	Fucino Antenna Pointing	Fucino Ranging	Villafranca Ranging
Antenna position			
Longitude	13.598°E		3.953°W
Latitude	41.979°		40.444°
Attitude	716.5m		656.7m
Antenna size	17m		3m
Calibration ground*1)	AZ=0.007-0.007°sin (α - 260°)	30430 nsec	28068 nsec
onboard*1)	-	1287 nsec ± 10)	1287 nsec ± 10
Measurement resolution	0.003°	0.75m	0.75m
Measurement accuracy (nominal)			
bias (including atmospheric effects)		14m	10m
noise		1m	3m

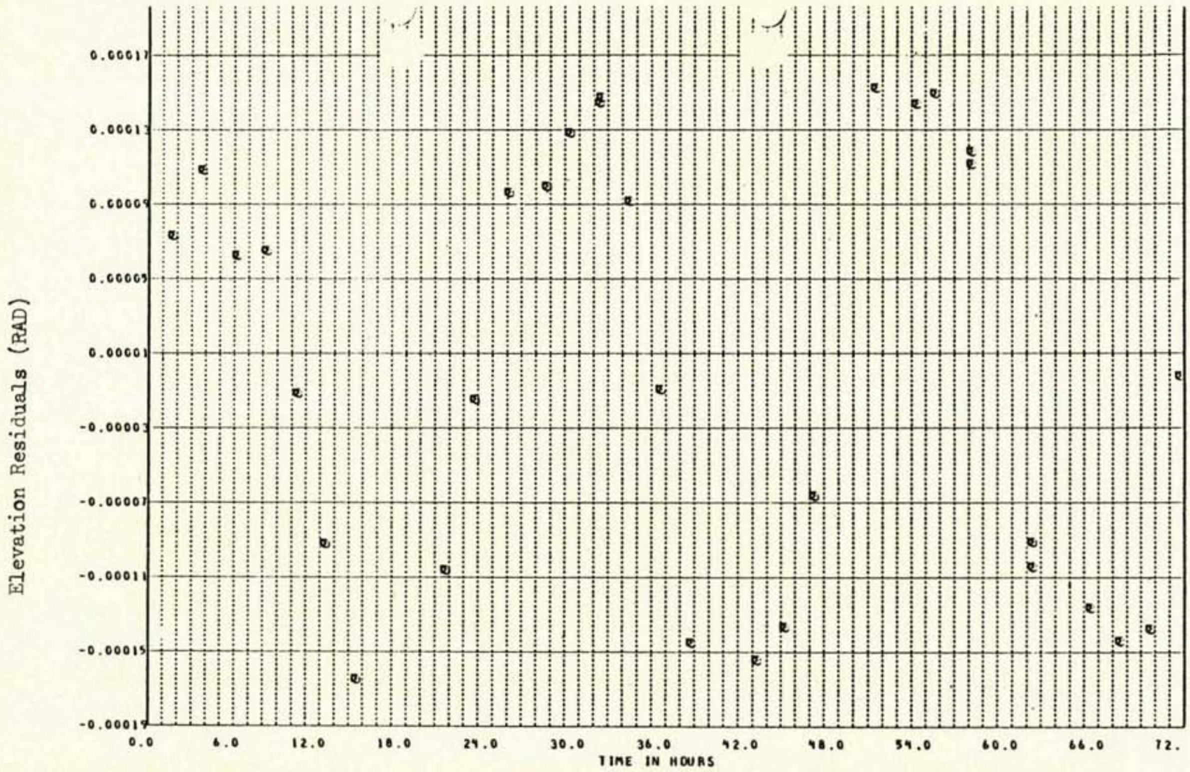
*1) calibration figures for ranging refer to a 2 way value

TABLE V - Measurement Performance computed within Offline Orbit Determination

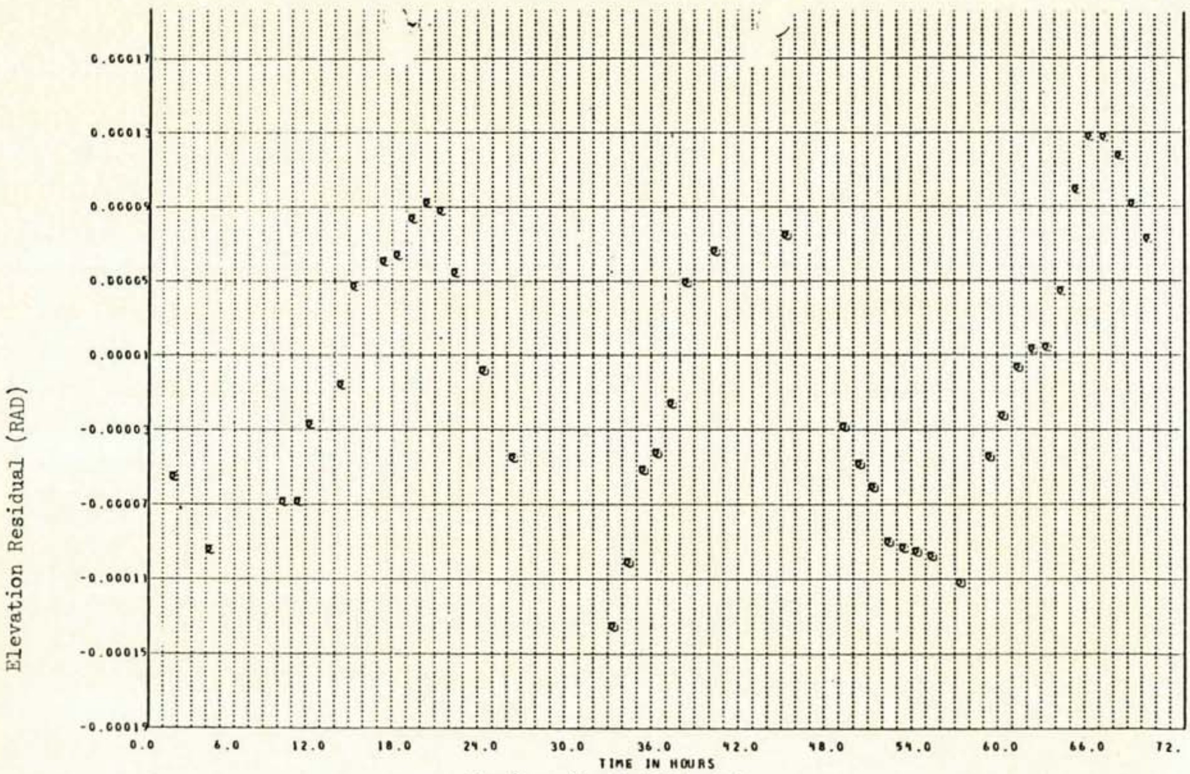
Observation ac.		Fucino Azimuth		Elevation		Range (m)		Villafranca Range(m)	
Run	Epoch	Offset	RMS Residuals	Offset	RMS	Offset	RMS	Offset	RMS
Dec. 1978		0.014°	0.002°	-0.023°	0.007°	-46	7	-1500	17
March 1979		0.014°	0.002°	-0.027°	0.004°	-25	1	"	2
70	79/05/02	0.016°	0.002°	-0.024°	0.003°	-27	4	"	4
78	79/06/27	0.016°	0.002°	-0.026°	0.004°	-43	9	"	18
82	79/07/25	0.017°	0.002°	-0.027°	0.003°	-47	6	"	19
87	79/08/29	0.17°	0.002°	-0.028°	0.003°	-24	4	"	7
91	79/09/26	0.015°	0.002°	-0.028°	0.005°	-27	4	"	4
96	79/10/31	0.017°	0.002°	-0.029°	0.004°	-26	4	"	12
99	79/11/20	0.017°	0.002°	-0.028°	0.005°	-31	10	"	10
105	80/01/02	0.014°	0.002°	-0.025°	0.005°	-34	4	"	13
109	80/01/30	0.014°	0.003°	-0.025°	0.003°	-95	14	"	46
113	80/02/27	0.014°	0.002°	-0.025°	0.005°	-43	8	"	14
117	80/03/26	0.017°	0.002°	-0.029°	0.004°	-21	5	"	9
	RMS residuals*)		0.002°		0.005°		6		13
Measurement Offset variation*)		0.003°			0.006°	26			

*) Run 109 was not included in the computation of these figures

Graph I - ELEVATION RESIDUALS VERSUS TIME



Fucino Dec. 1978 Data



Fucino March 1979 Data