INTERFERENCE LOCALISATION FOR THE EUTELSAT SATELLITE SYSTEM

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Abstract — In its effort to minimise the damage to satellite traffic caused by interference, EUTELSAT undertook, together with DRA, a study aimed at determining the benefits provided by the current transmitter location techniques. The study included a theoretical phase and a measurement campaign involving the execution of a number of tests on simulated interference using a transmitter location system (TLS) developed and operated by DRA. As a result of the study, EUTELSAT decided to enter into a contract with DRA for the provision of a transmitter location service. This paper discusses the major subjects treated in the study, with special attention to the benefits, for location accuracy, derived from the use of reference signals, to the optimum measurement strategy, to the potential enhancements of the current system and to the manner in which EUTELSAT intends to exploit the information provided by the TLS in the context of its network management procedures.

I. INTRODUCTION

EUTELSAT, the European Telecommunication Satellites Organisation operate a regional satellite system composed of seven satellites in orbit, and about 700 fixed and 400 transportable earth stations. The services provided are; voice communications, business services, DTH, cable TV and TV distribution services as well as land mobile services (EUTELTRACS).

As for many other satellite operators, interference represents a serious problem for EUTELSAT network operations. Hundreds of events are recorded per year and this number is likely to grow with the increase in traffic and the number of unattended stations.

Most of the interference is of short duration, either because it disappears quickly or because the interferer is easily identified via ordinary administrative means, but some remain for a long time and may affect the traffic, requiring a re-allocation of resources. In those cases, the interferer search procedure applied is time-consuming and frequently unsuccessful and involves the CSC (Communication System Control Centre) contacting the different national entities responsible for the control of the satellite accesses.

As part of the ongoing program of interference management, in 1993 EUTELSAT requested proposals for the provision of a study aimed at identifying the most suitable technique for localising sources of satellite interference, at evaluating its expected performance in the EUTELSAT environment and at demonstrating the actual performance of a system implementing the selected technique. The contract was awarded to DRA (Defence Research Agency) of the UK, that had, since the mid-eighties, developed and operated a TLS for military satellites.

The study was carried out during 1994 and included a theoretical phase and a measurement campaign performed on a variety of types of simulated interference on EUTELSAT satellites. As a result of the study, EUTELSAT decided to enter into a service contract with DRA for the provision of a TLS service.

The scope of this paper aims to present the findings of the study, in particular, some of the novel aspects emerging from the theory of transmitter location and confirmed by practical measurements and that may have an impact on the network management procedures.

In section II, a review of the TLS theory will be presented. Section III reports the results of the measurement campaign. Recommendations for transmitter location system improvements will be presented in section IV, operational considerations in section V and conclusions in section VI.

II. TLS THEORY REVIEW

The purpose of the theoretical study was to examine the different transmitter location techniques available, to identify those options which provided the best benefits v/s cost, to investigate the technique sensitivity to the different parameters involved and to assess its viability and performance when applied to the EUTELSAT case. Finally, the feasibility and performance of an actual TLS implementing the selected technique had to be studied. Herewith a review of the theory relevant to the selected technique is presented.

A. Measurement principles and location geometry

The selected techniques is based on the known principle [1] of the simultaneous determination of the DSR (differential slant range) and DSRR (differential slant range rate) relevant to an unknown transmitting site and to two geostationary satellites, one of which is the interfered satellite. The DSR

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and DSRR are determined by the knowledge of the satellite position and velocity and by measuring the TDOA and FDOA of the interfering signal as retransmitted by the interfered satellite and by an adjacent satellite and received by two co-located earth stations in the area of visibility of both satellites (Fig 2.1).

Fig 2.2 shows the geometry of transmitter location. A signal radiated from a source at **r** is received by two satellites at $\mathbf{r}_{S1}$ and $\mathbf{r}_{S2}$. The signal is then relayed by the satellites to a monitoring station at $\mathbf{r}_m$.

It can be shown that the uplink DSR and DSRR are related to the TDOA and FDOA by

$$DSR = |\mathbf{r}_{S2} - \mathbf{r}| - |\mathbf{r}_{S1} - \mathbf{r}| = c\ TDOA_{uplink} \tag{1}$$

$$DSRR = \mathbf{v}_{S2} \cdot \mathbf{u}_2 - \mathbf{v}_{S1} \cdot \mathbf{u}_1 = -(c/f) FDOA_{uplink} \tag{2}$$

where;

- $\mathbf{r}$ = position vector to source on ground,
- $\mathbf{r}_{Si}$ = position vector to i^{th} satellite (i = 1,2),
- $\mathbf{v}_{Si}$ = velocity vector to i^{th} satellite,
- $\mathbf{u}_i$ = unit vector from point to $\mathbf{r}_{Si}$,
- f = signal frequency,
- c = velocity of light.

The limitation to the uplink components only of the TDOA and FDOA observation is justified by the use of reference signals, discussed later in this section.

For a given satellite geometry, Lines Of Position (LOPs) can be drawn on the Earth which satisfy particular observations of TDOA and FDOA and consequently result in constant DSR and DSRR. In the rest of the paper, the lines of position will be referred indistinguishably as TDOA, FDOA LOPs or DSR, DSRR LOPs. The intersection of the LOPs corresponding to an observation provides the searched location. An example of TDOA and FDOA LOPs is given in Fig 2.3.

For small eccentricities and inclinations (as in the case of the EUTELSAT satellites) the difference in satellite position vectors is nearly in the equatorial plane and orthogonal to the line from the satellites to the centre of the Earth. Consequently DSR LOPs look like straight lines in the perspective of Fig 2.3 and are relatively time invariant. In contrast, the DSRR LOPs depend on the satellites' velocity difference, which is strongly time dependent and has components both in the direction of the Earth and orthogonal to this direction. Often the DSRR LOPs will have similar form to the DSR LOPs but orientated in a different direction. In extreme circumstances, the DSRR LOPs can form concentric rings.

The mathematical approach to the problem of the determination of TDOA and FDOA utilises the well known Cross Ambiguity Function [2] (CAF).

$$\int_{-T/2}^{T/2} s_1(t)\, s_2^*(t+\tau)\, e^{-i2\pi\nu t}\, dt \tag{3}$$

where s_1 and s_2 are the complex envelopes of the signals via path 1 and path 2 respectively and τ and ν are the time lag and frequency offset parameters, T is the duration of the correlation.

The peak of the CAF modulus represents an unbiased estimate of the TDOA and FDOA. It should be noted that s_2, ie the amount of signal relayed by the adjacent satellite, depends on the sidelobe characteristics of the interferer antenna and on the spacing between the two satellites but is usually well below the noise on the transponder.

The TDOA measurements are meaningless for certain types of signals (unmodulated), with the consequence that the determination of the DSR is impossible. In that case, the location can in principle still be performed by multiple FDOA (DSRR) measurements performed at different times, by exploiting the above referred time dependence of the DSRR LOPs.

B. Sources of error

The error in the determination of the DSR and DSRR depends mainly on the error in the TDOA and FDOA observations, on the uncertainties in the satellites' ephemerides and on the errors due to propagation effects.

1) Errors in the TDOA/FDOA observations

The errors in the TDOA/FDOA observations are due to two main factors; the additive noise and the uncertainties in the satellites' translation frequencies and path delays. Ground station effects can be reduced to a negligible level through good design practice .

In determining errors there are two issues, firstly the detection of the correlation above the noise and secondly the estimation of the TDOA and FDOA from the correlation peak.

As far as detection is concerned, it can be demonstrated that the post-processing signal to noise ratio SNR is given by the formula

$$SNR = \frac{2\ BT\ snr^2}{k[1 + snr(1 + 1/k)]} \tag{4}$$

where snr is the input signal to noise ratio in the main (interfered) satellite channel, B is the channel noise bandwidth, T is the integration time and k is the 'overspill factor' defined by

$$k = \frac{snr(main\ channel)}{snr(overspill\ channel)} \tag{5}$$

The term 2 B T is called the Processing Gain (PG) and is equal (from Nyquist's theory) to the number of sample points per channel.

In order to unambiguously identify the correlation peak, it has to significantly exceed the background noise. Fig 2.4 shows the magnitude of the CAF correlation in the time-frequency domain and the existence of spurious correlations due to noise. From practical experience, it is known that the correlation peaks can be detected only for values of SNR typically exceeding 20 dB. The system sensitivity is thus related to a number of factors, including; the signal characteristics (bandwidth), the measurement system performance (related to the PG) and the link budget parameters, signal to noise ratios in both main and overspill channel. These factors, in turn, are related to other elements like the size of the interferer antenna (the smaller the antenna, the easier is the detection), the status of the traffic occupancy of the overspill channel (a traffic carrier on the overspill channel degrades the overspill snr) etc.

It can also be shown that, once the detection is achieved, the inherent accuracy of the measured TDOA and FDOA is described by the following equations [2]:

$$\sigma_\tau = \frac{1}{B_u\sqrt{SNR}}; \quad \sigma_\nu = \frac{1}{T_u\sqrt{SNR}} \tag{6}$$

where σ_τ is the rms TDOA uncertainty, σ_ν is the rms FDOA uncertainty and B_u and T_u are respectively the rms bandwidth and duration of the signal. From (6) above, it can be concluded that, for a given SNR, the accuracy of the TDOA estimation depends directly on the rms bandwidth of the signal and the accuracy of the FDOA estimation depends on the rms duration of the signal. Therefore, it is evident, in the interest of signal processing, to analyse the maximum available bandwidth for optimum TDOA estimation and the maximum available time for FDOA estimation.

2) Impact of the TDOA/FDOA error on the location accuracy

The impact of the TDOA/FDOA errors on the determination of the DSR and DSRR is strongly dependent on the location geometry that is subject to spatial and temporal variations.

In mathematical terms, it is possible to define a root mean square location error σ (in km) and relate this to the DSR and DSRR errors and thence to the TDOA and FDOA errors. It can be shown that

$$\sigma = \frac{1}{|\sin\varphi|}\sqrt{\frac{\sigma_\ell^2}{L_t^2} + \frac{\sigma_\upsilon^2}{V_t^2}} \tag{7}$$

where

σ_ℓ = Rms DSR error = c×TDOA error

σ_υ = Rms DSRR error = c×FDOA error/f

L_t = Magnitude of the component of the DSR gradient in the azimuth plane at the point **r** on the Earth

V_t = Magnitude of the component of the DSRR gradient in the azimuth plane

φ = Angle between components of DSR and DSRR gradient in the azimuth plane = angle between LOPs on the Earth's surface at point **r**.

With reference to Fig 2.2, the DSR and DSRR gradients are given by

$$\underline{\nabla}\ell_{21}(\mathbf{r}) = -(\mathbf{u}_2 - \mathbf{u}_1) \tag{8}$$

$$\underline{\nabla}\nu_{21}(\mathbf{r}) = \frac{1}{\ell_2}\left[\mathbf{v}_{S2} - (\mathbf{v}_{S2}\cdot\mathbf{u}_2)\mathbf{u}_2\right] - \frac{1}{\ell_1}\left[\mathbf{v}_{S1} - (\mathbf{v}_{S1}\cdot\mathbf{u}_1)\mathbf{u}_1\right] \tag{9}$$

$$\underline{\nabla} = \mathbf{e}_x\frac{\partial}{\partial x} + \mathbf{e}_y\frac{\partial}{\partial y} + \mathbf{e}_z\frac{\partial}{\partial z}. \tag{10}$$

where $\mathbf{e}_x, \mathbf{e}_y, \& \mathbf{e}_z$ are unit vectors along the x, y and z orthogonal axes.

3) Spatial and temporal behaviour

Equation (7) shows that $\sigma \to \infty$ if any of L_t, V_t or φ are zero. For L_t or V_t to be zero, the modulus of the gradients themselves could be zero or the gradients could be normal to the surface of the Earth. For φ to be zero, the LOPs must run parallel.

At a given time, and for given TDOA and FDOA errors, the resulting location error is a function of the transmitter location. In particular, it is possible to identify a line, termed as the 'blind line', joining all points where the rms location error tends to infinity. Fig 2.5 shows an example of the spatial variation of the DSR and DSRR LOPs for the EUTELSAT II-F2 and EUTELSAT II-F4 pair of satellites, with the blind line running through Paris.

Conversely, for a given transmitter site, 'blind' times exist, occurring twice per day, when location using the intersection of the DSR/DSRR LOPs is not possible. Fig 2.6 shows an example of such temporal variation of the error for the same pair of satellites and for the site of Paris. This temporal variation is clearly related to the orbit evolution of the two satellites. When the location error is small, there is a developed North/South motion of the satellites, the DSR and DSRR LOPs are nearly orthogonal and the DSRR gradient is high. In between times, the North/South movement is small and the effects of the East/West and radial movements manifest themselves.

The above may suggest that, at a given time, the accuracy of a location measurement depends strongly on the transmitter location itself. However, it is possible to demonstrate that, in the EUTELSAT case, the blind times do not differ very much over the satellites' coverage region. Therefore it is possible to determine in advance and with certainty the best and worst times for a measurement. This consideration has a significant impact on measurement strategy, that will be further discussed in a later section. As a simple measure, it is possible to use the minimum rms location error over time as a measure of error performance. Table 2.1 provides an example of this error (km) for a range of TDOA/FDOA errors for the EUTELSAT II-F2 and II-F4 combination and the Paris location.

Finally, it is important to remark that the minimum achievable location error depends on the degree of inclination of the two satellites (ie the higher the inclination the lower the error).

4) Other sources of error

The other sources of error in the determination of the DSR and DSRR are the uncertainties in the satellite position and velocity and the influence of propagation effects.

The impact of ephemeris errors has been treated in depth in the study. The impact of those errors on the location determination has been evaluated in terms of equivalent TDOA/FDOA errors [3] and the conclusion leads to values, for the EUTELSAT system, of 2 μs for the satellite position uncertainty and 2 Hz for the velocity uncertainty.

Among the propagation effects, bulk and scintillation effects due to the troposphere have been studied in detail. Bulk propagation effects have an impact on TDOA below 0.2 μs whereas the impact on FDOA is negligible. Tropospheric scintillation effects can limit the minimum possible FDOA error through limiting the coherence time. In worst case conditions, FDOA errors would have a lower limit of around 10 mHz.

C. Use and characteristics of reference signals

The theoretical study demonstrated the great importance, for the TLS, of using reference signals on both satellites. Comparing the TDOA and FDOA measurements performed on the interference with those performed on a reference signal of known characteristics permits the precise measurement of the uplink TDOA and FDOA of the interferer relative to the reference signal and cancels or reduces the degradation of the location accuracy caused by a number of error sources.

The impact of the use of reference signals on the location error is quantified in Table 2.2.

In order to provide the necessary improvements in measurement accuracy, the reference signal should originate from a source of known location. The reference and target signals should be processed simultaneously using the same equipment settings (ie bandwidth, integration time). Finally, the reference signal should be transmitted on the same transponder as the unknown signal or a transponder making use of the same turnround oscillator.

III. MEASUREMENT CAMPAIGN

The trials took place between the 12th and 17th October 1994 and demonstrated the location capability of the DRA TLS targeting a variety of signals present on EUTELSAT satellites.

In accordance with the trials plan formulated by EUTELSAT, the majority of the tests were made on test signals with power level, data rate and transmit antenna size all varied in order to assess the response of the practical system to the factors that influence the TLS performance as compared with the theoretical expectations. A number of locations were also performed on a selection of representative traffic signals transmitted on the EUTELSAT satellites.

A. Trials configuration

1) Trials target signals

The test signals were provided by the Rambouillet Earth station, in a calibrated environment where the antennas used for Telemetry, Tracking & Command and In Orbit Test campaigns on EUTELSAT satellites are situated.

The transmissions originated from two ground terminals, one a 9 m antenna, denoted as TR1, and a 2.4m antenna, denoted as F-8.

The transmitted signals were generated by an SDM 309 digital modem and an HP8341 sweep synthesiser. The outputs from the modem and the synthesiser could be added together to provide a carrier component in the QPSK modulated signals. Three different symbol rates 64, 256 and 768 kb/s were tested with a 1.3 roll off Nyquist filter applied to the output of the modem, while CW and swept CW signals at rates ranging from 0.1 to 100 Hz were obtained from the HP8341.

The uplink frequency for all test signals was 14069.167 MHz. The selected frequency corresponded to traffic-free slots, of more than 1 MHz bandwidth, on both the primary and adjacent satellites.

Concerning the measurements on the operational traffic, four signals were selected:

Tx site	Lat/Lon	Type of signal
Rambouillet-France	1.78°E/48.55°N	5 kb/s BPSK swept over 2 MHz (EUTELTRACS)
Sintra-Portugal	9.26°W/38.86°N	TV

Istanbul-Turkey	28.95°E/41.03°N	TV
Moscow-Russia	37.97°E/55.79°N	256 kb/s QPSK

2) Satellites

Most of the tests were performed on EUTELSAT II-F2, at 10°E, as primary satellite and EUTELSAT II-F4 at 7°E as the adjacent satellite. Other tests included using, as the adjacent satellite, EUTELSAT II-F1 at 13°E and EUTELSAT I-F4, at 25.5°E. The latter, which is not North/South station kept, was selected in order to test the TLS performance using a satellite in inclined orbit (about 1.4° at the time of the trials).

3) DRA Defford TLS

The measurement assembly at DRA Defford consists of two 5.4m Ku band ground stations connected to the TLS equipment via cross-site IF cables.

In the TLS equipment, target and reference signals received from the two satellites are down-converted and conveyed to communications receivers. The signals are then down-converted to near baseband and filtered. Each signal is then sampled and digitised at a greater than Nyquist sample rate.

The two ground stations are also used to transmit the reference signals. The reference signal, which is sampled in a similar manner to the target signal, has a bandwidth determined in order to avoid aliasing at the receive sampling rate. The TDOA and FDOA of the reference signal are used to normalise those measured for the target signal and to obtain the searched uplink TDOA and FDOA. It should be noted that, in order not to interfere with any traffic signal, the reference signals were transmitted during the trials at a frequency on the flanks of the concerned transponders, at a level corresponding to a satellite EIRP density of the same order of the transponder noise.

A digital signal processing unit is used to perform the correlation operations used to measure TDOA and FDOA.

B. Trials results

1) TDOA measurements

TDOA values were measured on samples in the maximum practical bandwidth available from the signal. An example of the measurement performed is given below.

Date	Time	Sat. pair	Signal	Tx stn	Tx EIRP (dBW)	BW (kHz)
11-Oct	10:07	IIF2/ IIF4	digital 256 kb/s	F-8	55	300

TDOA peak (ms)		CPA		Error
Target	Reference	Lat	Lon	(km)
0.225508	0.268281	48.549	1.769	1.028

The location given above is the point on the Time Difference of Arrival line that comes closest to the known (or estimated) location of the target transmitter (known as Closest Point of Approach, CPA). A value for the distance from the CPA to the known location is given and equates to the error in the line-of-position from the location measurement.

The mean error in the TDOA LOPs for the Rambouillet test signals was 2.5 km with a maximum error of 5 km.

2) FDOA measurements

For FDOA measurements, the sample bandwidth, in most cases, was minimised to enable a long sampling time and maximum frequency resolution. An example of the measurement performed is given below

Date	Time	Sat. pair	Signal	Tx stn	Tx EIRP (dBW)	BW (kHz)
11-Oct	10:07	IIF2/ IIF4	digital 256 kb/s	F-8	55	300

FDOA peak (Hz)		CPA		Error
Target	Reference	Lat	Lon	(km)
66.9489	66.8495	48.210	1.602	39.986

The error is again reported as the distance between the known location and the CPA relevant to the FDOA LOP. The mean value of the error was 69.3 km. The major contribution to that error comes from the inaccuracy of the available ephemeris information associated with the low inclination of the satellites. It can be seen that the two measurements taken using EUTELSAT I-F4 as the adjacent satellite gave errors of 0.3 and 1.8 km, the accuracy improvement being due to the greater doppler shift caused by the velocity of the satellite.

3) TDOA/FDOA measurements and locations

Point locations are achieved using FDOA and TDOA measurements from the intersection of the LOPs, as set out in Table 3.1. The TDOA and FDOA measurements are either separate samples optimised for timing or frequency measurements or single samples that have been used for both measurements.

In Table 3.1 the time of the sample can be used as an indication of the TDOA/FDOA sample configuration, ie if the TDOA and FDOA times are identical then a single sample has been used for location measurements.

C. Discussion of results

1) Location distribution

The distribution of locations achieved using TDOA/FDOA for the signals transmitted from Rambouillet is shown in Fig 3.1. The spread of locations is due to the FDOA variation. The mean location achieved is 1.71°E, 48.985°N compared to the actual location at 1.783°E, 48.549°N.

The distribution of the FDOA error over a 24 h period does not match exactly the theoretical curve for TDOA/FDOA error (Fig 3.2) but, apart from the dips in the actual FDOA error, the theoretical expectations are substantially confirmed, with a pronounced accuracy degradation close to the blind times, and can be used as a predictor for location accuracy in an operational system. The difference between predicted and measured FDOA can be observed in the plot of Fig 3.3. This difference is not constant and its nature indicates that a set of measurements over 24 h will have positive and negative errors that should produce a mean location error that approaches zero.

2) Sensitivity

Most of the successful correlations achieved on the Rambouillet transmission were performed on signals radiated from F-8, confirming the theoretical expectation that the system sensitivity is inversely proportional to the size of the interferer antenna.

In order to make a quantitative comparison between the theory and the measurements, the post-correlation SNR was measured for a number of signals transmitted from F-8, with the same modulation characteristics and different power level. The results are shown in Table 3.2 and confirm a good agreement between theoretical and measured values within the accuracy achievable from a single measurement.

3) Swept CW signals

Special attention was devoted to the case of swept CW signals that are rather frequently encountered among actual satellite interferers.

CW signals facilitate accurate frequency measurements but timing information is not available. The addition of modulation on a CW signal enables timing information to be gained from TDOA measurements. The rate of the modulation determines the possible resolution of the TDOA correlation. The 0.1Hz sweep rate was too slow to enable a TDOA correlation while both the 100 Hz and 1 Hz sweep rates of the test signal resulted in good TDOA and FDOA correlations. However, the intrinsic nature of the swept CW signals produced timing information that could not be resolved absolutely: by selecting a range of FDOA values, a range of TDOA correlation values were obtained. Therefore, instead of a single location, the paired TDOA/FDOA correlations on swept CW signals resulted in a line of position produced from the intersection of the TDOA and FDOA lines. Fig 3.4 illustrates this situation.

4) Locations of operational signals

A single location was made on the TV signal transmitted from a 9 m diameter antenna in Sintra, Portugal. The correlation was relatively easy to obtain due to the strength of the TV signal on the main satellite (transponder 39 of EUTELSAT II-F2). The TDOA location error was less than 50m and the FDOA error greater than 150 km (Fig 3.5).

A location using two TDOA LOPs derived by time-separated measurements on different pairs of satellites (IIF2/IIF4 and IIF2/IIF1) was attempted on a TV signal transmitted from a 2.4 m transportable station in the region of Istanbul. The result in shown in Fig 3.6: the location error was around 150 km, not better than that achieved with ordinary TDOA/FDOA measurement. TDOA/TDOA locations from time-separated measurements made on the same pair of satellites were also attempted but without any useful result (the TDOA lines run parallel confirming the substantial time invariance of the TDOA LOPs).

The measurement made on a 256 kb/s QPSK signal transmitter from a 2.4m transportable antenna in the region of Moscow produced (Fig 3.7) errors of around 4.85 km and 265 km for the TDOA and FDOA LOPs respectively. The explanation for this large error is due to the combination of the ephemeris errors and the large distance between the signal and the reference signal location thereby reducing the ephemeris error compensation discussed in section II.

IV. TLS IMPROVEMENTS

A. Increased sensitivity

The system detection performance limits the ability to work with weak signals in an adjacent satellite channel. The existence of traffic accesses in the adjacent satellite further masks the wanted signal. As covered in section II, the ability to detect weak signals in adjacent satellite channels is determined by the processing gain of the TLS which, in turn, is limited by the number of digital samples that can be coherently processed by the DSP system. The current DRA TLS has a processing gain of around 60 dB. This enables signals to be detected which are typically 40 dB below the adjacent satellite access+noise level.

Improvements in performance can be achieved through the coherent processing of more digital samples with the DSP system. It is estimated that a 10 dB increase in the processing gain of the current system is achievable without a major change in the basic DSP approach.

B. Improved accuracy

The findings of both the theoretical study and the measurement campaign showed that satellite ephemeris accuracy limits the location accuracy for satellites which use North/South station keeping. The limiting factor is the prediction of satellite velocity. This situation is not surprising since the TLS is capable of measuring FDOA to around 1 mHz. This error equates to a differential satellite velocity error of around 0.02 mm/s, which is approximately the speed of movement of the minute hand of a small clock. Therefore, the satellite velocity needs to be predicted with extreme accuracy.

The needed improvement in satellite ephemeris is unlikely to be achieved with standard ephemeris determination techniques since these are not designed for accurate velocity prediction, rather the improvement in ephemeris is likely to be achieved through the location of one or more known transmitters. Extended observations of a known location can enable the satellite orbital ephemerides to be corrected in a least-squares sense to minimise the location error of the known source.

An additional technique is the use of a reference signal that originates at a known location that is close to the unknown transmitter; that location could be selected after a TDOA/FDOA observation and a first approximation of the location. As discussed previously, the impact of ephemeris errors reduces as the known and unknown transmitters get close. The attraction of this technique is that the improved measurement can be performed quickly whereas the ephemeris improvement approach will take an extended period of time.

A further, more radical approach is to alter the satellite orbits. At EUTELSAT, stationkeeping and the need to minimise fuel consumption dictate a strategy that results in the satellites having very similar orbital parameters, minimizing the velocity difference. For example, the four EUTELSAT satellites of the second generation have times of ascending node that typically differ by less than 30 mins. In principle, it is possible to 'antiphase' the orbits of adjacent satellites so that they maintain the same longitudes but with times of ascending nodes differing by around 12h. This would result in a reduction of the location errors by a factor of about 7 (ie from tens of km to a few km). Comparison of the theoretical location accuracy on a known source shows a reduction of the rms error from 41 km to 7 km. The implications of orbit dephasing on stationkeeping strategy and on fuel consumption is at the moment being evaluated by EUTELSAT.

V. OPERATIONAL CONSIDERATIONS

Following the results of the study, EUTELSAT decided to enter into a contract with DRA for the provision of a transmitter location service, which started in March 1995.

The first year of service is intended to be exploited for a full assessment of the system capabilities in an operational environment in order to derive conclusions on the most useful modifications to introduce and on the optimum use of the information provided by the TLS in the context of interference management procedures.

The current interference management procedures at EUTELSAT involve three major steps [4].

- Interference notification to/from users, with the production of standard reports.
- Restoration of services (if necessary), including increase of the traffic carrier power and/or change of carrier frequency.
- Actions towards identification of the interferer and problem clearing, involving the time-consuming search procedure mentioned in the introduction supported, if possible, by other means such as intelligence on the signal by demodulation, production of detailed plans for intervention at suspected earth station sites (power down, depointing etc).

The introduction of the TLS service will change radically the third step of the procedures.

The study demonstrated that the TLS can provide useful information on the interferer in most of the cases but, depending on the characteristics of the signal and on the operational conditions, the information may often not be sufficient for an unambiguous identification of the interferer site. The measured location may be subject to errors up to hundreds of km in some cases, requiring extended observation times in order to reduce the error, and just a line of position, instead of an absolute location may be obtained in other cases (swept CW signals). However, a major result of the study was that the level of confidence on the provided information can be anticipated by the system. Moreover, the TLS could provide, on top of the location data, other useful information on the interferer, such as indications on the antenna size (by comparing the signal level on the main and overspill channels). In order to make optimum use of the TLS, it is therefore necessary to complement the information provided by the system with a careful exploitation of a well-maintained relational earth station and carrier data base.

When supported by a TLS service, the interference search procedure should then include:

- Periodic provision from EUTELSAT to DRA of satellite ephemeris information and a list of traffic signals to be used as additional references for the measurements on top of the reference provided by the TLS.
- Request for intervention to DRA and execution of a first measurement.
- Reception of the measurement results in the form of an absolute location or an LOP, with the relevant error estimation. Indications, if available, of the maximum antenna size.
- Exploitation of software tools enabling the quick retrieval of candidate interferer information. The selection criteria will be geographical position in a box around the provided location (or in a bound around the provided LOP), with the size of the box (bound) corresponding to the estimated error, antenna size below the maximum indicated, EIRP capability to correlate the actual interference EIRP, modulation capability, to correlate with the observed modulation.
- Start of search among the candidate interferers. In the mean time, exploitation of intelligence on the signal (if demodulation is possible), and continuation of the TLS measurements in order to refine the location. Subsequently narrowing down the number of candidate interferers.
- Intervention, if deemed necessary for improving the TLS measurements, towards the users accessing the adjacent satellite in order to temporarily stop the transmission for the time necessary to get one or more samples (usually a few minutes). These interventions may normally be requested during the night time.

VI. CONCLUSIONS

The availability of a transmitter location service is becoming an imperative for the good operational management of satellite networks hosting thousands of carriers and hundreds of earth stations, of which an increasing number are unmanned.

The study carried out by DRA put in evidence all the factors driving the performance of a TLS system when applied to the EUTELSAT environment and uncovered interesting phenomena having an impact on the measurement strategy.

The first year of the TLS service provided by DRA to EUTELSAT will be used for a full assessment of the operational capabilities of the system and for integrating the TLS information in an upgraded interference management procedure.

REFERENCES

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[2] S Stein, "Algorithms for ambiguity function processing", IEEE Trans Acoustics Speech and Signal Processing, vol ASSP-29, No 3, June 1981.
[3] P C Chestnut, "Emitter location accuracy using TDOA and Differential Doppler", IEEE Trans Aerospace and Electronic Systems, vol AES-18, No 2, March 1982.
[4] S Fiedler, EUTELSAT, private communication.

Table 2.1 Minimum location error (km) for a range of observation errors for the EUTELSAT 202/204 combination and the Paris location.

		FDOA error (mHz)		
		1	10	100
TDOA error (μs)	0.05	1.2	11.8	117.7
	0.5	2.9	12.1	117.7
	5	26.7	29.4	120.6
	50	262	267	286.9

Table 2.2 Effect of reference signal on TDOA and FDOA errors

TDOA error term	Value without reference	Value with reference
Propagation	$5x10^{-8}$ s / 0.26 km	$2x10^{-8}$ s / 0.1 km
Satellite delay	$1x10^{-8}$ s / 0.05 km	0 s / 0 km
Satellite position	$2x10^{-6}$ s / 10.4 km	$1x10^{-7}$ s / 0.52 km
Monitoring station	$1x10^{-7}$ s / 0.52 km	$5x10^{-9}$ s / 0.026 km
FDOA errors term	Value without reference	Value with reference
Propagation	$<1x10^{-3}$ Hz / <1.2 km	$<1x10^{-3}$ Hz / <1.2 km
Satellite turnround oscillators	10 Hz / 11,700 km	0 Hz/ 0 km
Satellite velocity	2 Hz / 2340 km	$1.4x10^{-2}$ Hz / 16.4 km
Monitoring station	10 Hz / 11,700 km	0 Hz / 0 km

[Note estimates are for adjacent EUTELSAT II series satellites and for unknown transmitter and reference sites around 1000 km apart]

Table 3.1 TDOA/FDOA point locations

Date	Time (TDOA)	Time (FDOA)	Signal Type	Sig Srce	TDOA (ms)	FDOA (Hz)	Location (Lat	, Lon)	Location Error (km)
11-Oct	10:07	11:22	Digital	F-8	-0.042693	0.069	48.610	1.760	6.920
11-Oct	13:52	14:20	Digital	F-8	-0.043594	0.027	46.510	2.120	227.800
11-Oct	17:32	17:57	Digital + cw	F-8	-0.042344	-0.037	49.190	1.640	71.000
12-Oct	09:16	09:16	Digital	F-8	-0.043260	0.097	48.260	1.850	32.600
12-Oct	10:20	10:20	Digital	TR1	-0.041987	0.061	48.680	1.690	15.100
12-Oct	11:33	11:33	Digital	TR1	-0.042969	-0.072	54.490	0.700	675.000
12-Oct	13:37	13:37	Digital	F-8	-0.157350	-14.990	48.550	1.810	2.144
12-Oct	15:17	15:17	Digital	F-8	-0.164532	-13.754	48.560	1.820	2.944
12-Oct	16:11	16:11	Swept cw	F-8	0.043360	0.024	48.390	1.840	18.200
12-Oct	16:39	16:39	Swept cw	F-8	0.043359	0.024	49.030	1.740	55.700

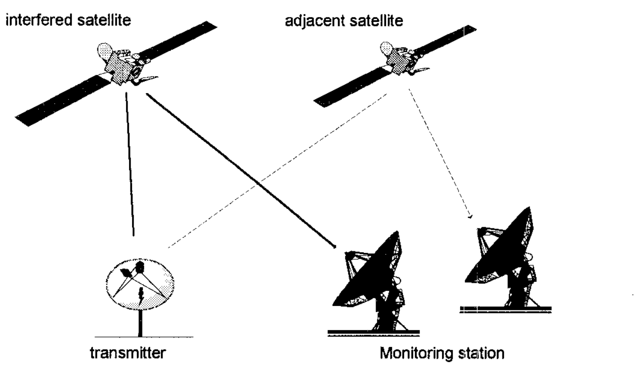

Fig 2.1 Multiple satellite transmitter location configuration

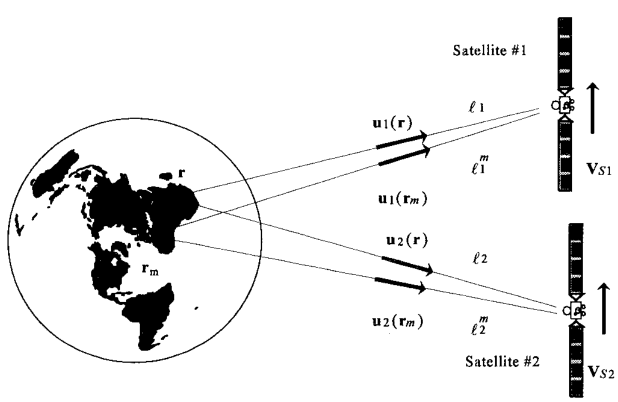

Fig 2.2 Multiple satellite transmitter location geometry

Table 3.2 Measured and theoretical correlation SNR (EUTELSAT IIF2 / IIF4).

Sample Date	Sample Time	Rambouillet Tx EIRP (dBW)	Measured SNR (dB)	Theoretical SNR (dB)
11-Oct	12:17	30	13.1	7.5
14-Oct	11:27	35	17.07	16.7
14-Oct	11:05	40	23.3	24.06
14-Oct	10:15	45	32.04	30.19
14-Oct	10:07	55	43.18	40.76

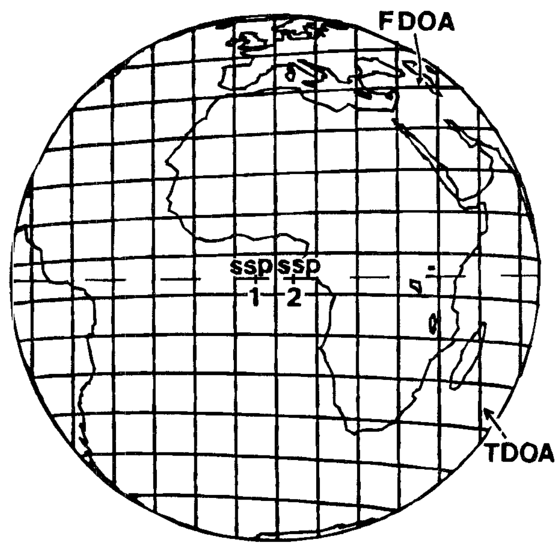

Fig 2.3 Typical exact Lines Of Position for a two satellite constellation

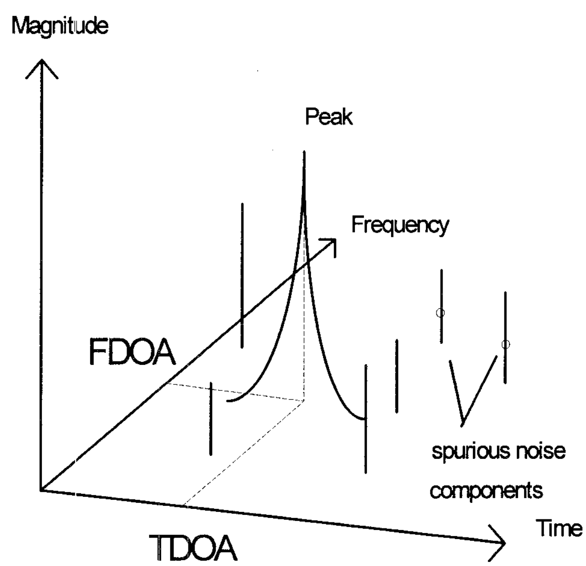

Fig 2.4 CAF magnitude and spurious noise components

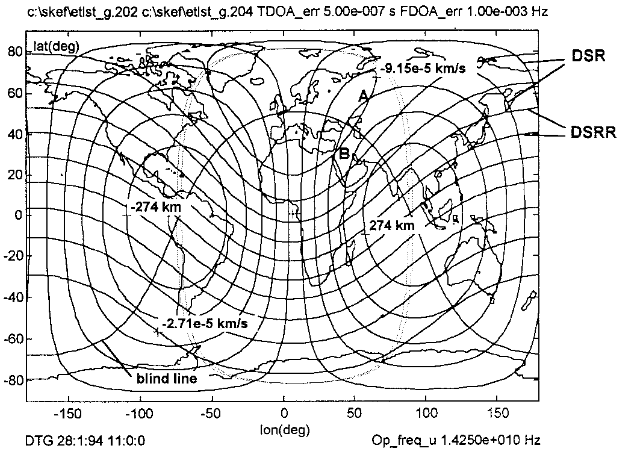

Fig 2.5 DSR and DSRR contours of the Eutelsat 202/204 combination at 1100 on 28 Jan 94

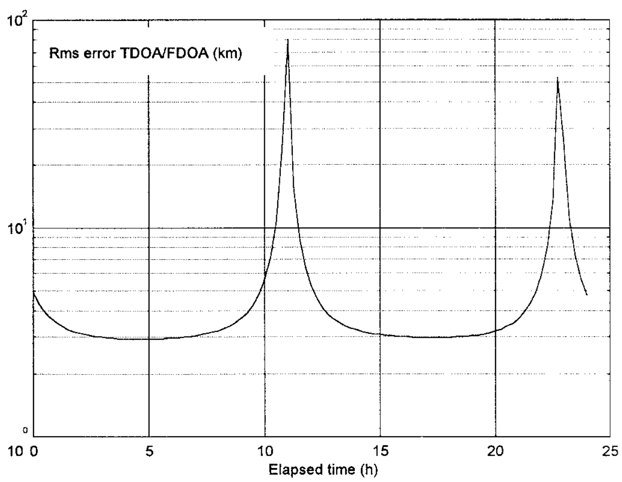

Fig 2.6 Rms location error at Paris for the TDOA and FDOA observation errors of 0.5 μs and 1 mHz.

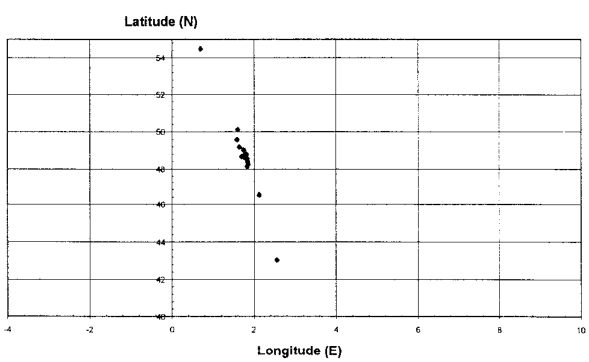

Fig 3.1 TDOA/FDOA locations of Rambouillet

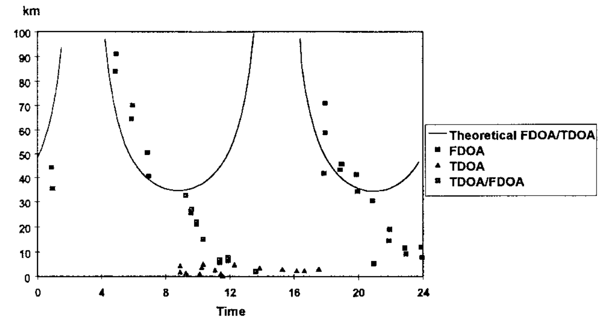

Fig 3.2 TDOA, FDOA and TDOA/FDOA location error

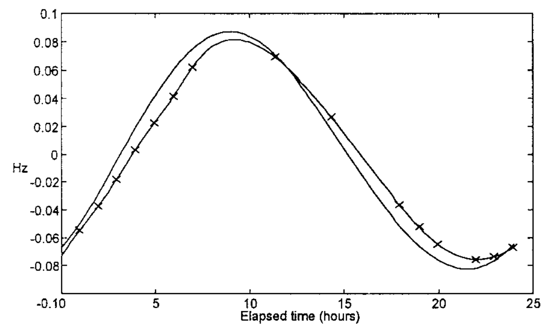

Fig 3.3 Predicted FDOA and measured FDOA for Eutelsat IIF2 and IIF4 over 24 hours

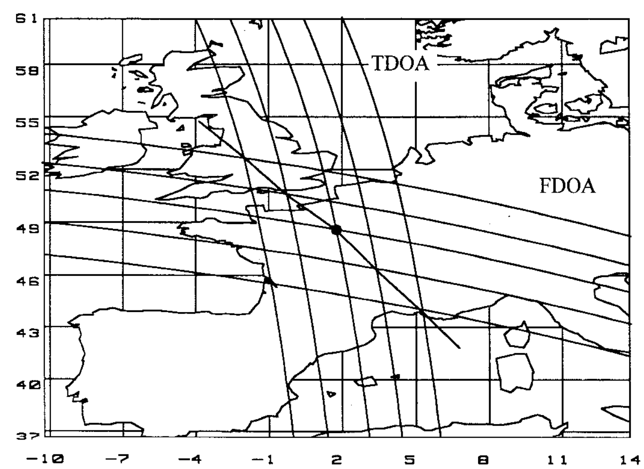

Fig 3.4 Swept CW lines of position due to offset correlations.

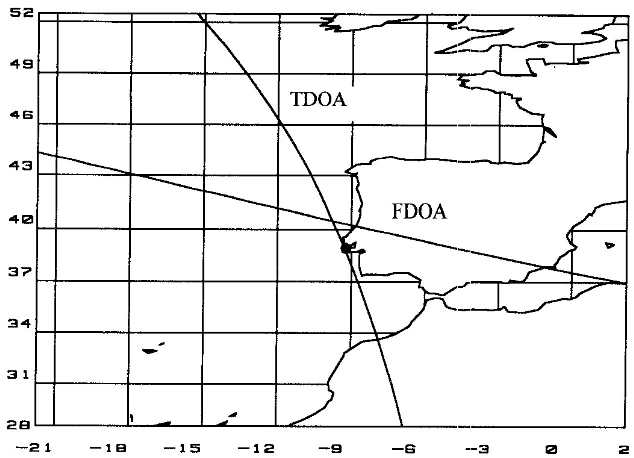

Fig 3.5 Location of TV signal from Sintra, Portugal.

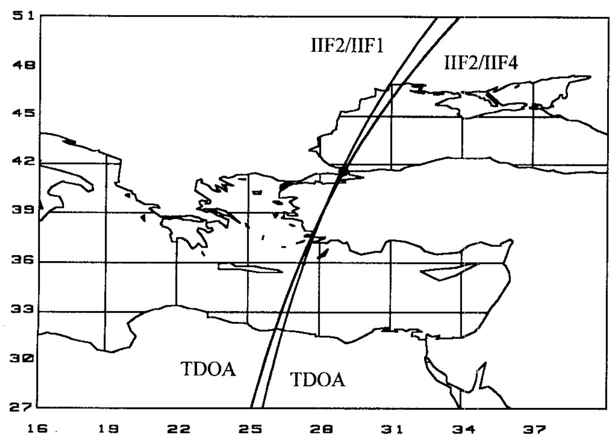

Fig 3.6 TDOA/TDOA location of TV signal (Istanbul)

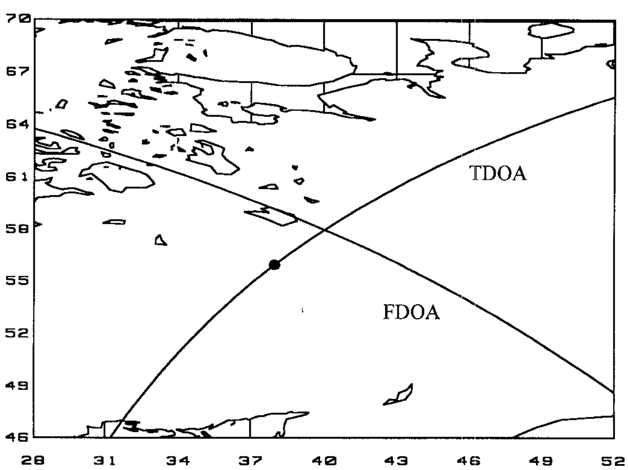

Fig 3.7 TDOA/FDOA lines of position for RUS-MSC-2.