

## ARTAS: An IMM-based Multisensor Tracker

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### Summary

ARTAS (an acronym for ATM Surveillance Tracker and Server) is the new operational Surveillance Data Processing and Distribution (SDPD) system at Amsterdam Airport and is being evaluated at different sites in France, The Netherlands, Portugal and the UK. ARTAS was developed by Eurocontrol, in co-operation with a consortium of industrial partners, in order to be used as a basis for the development of SDPD systems in Europe. The ARTAS system consists of a tracker, responsible for maintaining up-to-date target state vectors, a server, which handles client subscriptions (e.g. from the ATC display system) and delivers the target state vectors to these clients and a Man-Machine Interface/Supervision module, for system control and air-situation display. An ARTAS system co-operates with adjacent ARTAS systems by exchanging target state vector information.

The main features of the ARTAS Tracker are

- tracking with up to thirty radars (PR, SSR or CMB)
- on-line estimation of the radar systematic errors
- on-line estimation of radar false plot maps
- on-line estimation of the radar accuracy and coverage
- high-accuracy position and velocity-vector estimation
- responsiveness to target manoeuvres
- insensitivity to clutter
- target type identification

All these features are realised through the use of state-of-the-art estimation and identification algorithms, such as the IMM (Interacting Multiple Model) algorithm and Dempster-Shafer reasoning, and an object-oriented architectural design.

### Track Data Server

ARTAS is designed as a track data server. Track data users can subscribe to a certain service and receive the track data in ASTERIX format via a local-area or wide-area network. Users can be ATC centres, flightplan data processing systems (FDPS), air-traffic flow management units and so on (figure 1). Each user can have a dedicated service, taking into account requirements with respect to data contents and update frequency. An ARTAS unit also receives its input data from the radars via the local -area or wide-area network. Furthermore, an ARTAS unit can communicate via the network with other, adjacent, ARTAS units in order to provide a continuous air-picture to its users. Track data from adjacent units is used to accelerate the initiation of tracks at the border of the unit's own domain of interest (DOI) and to smooth the transition of a track from one unit's DOI to another unit's DOI. Finally, when there is sufficient coverage of the own unit's DOI by adjacent ARTAS units, the adjacent ARTAS units can take over the surveillance in case of an own unit failure. Thus, enhancing the overall reliability of the surveillance.

A prime requirement for handling multisensor data is the ability to cope with sensor alignment errors, i.e. systematic radar errors like position bias, range- and azimuth bias, but also time-stamping bias and transponder-delay error. The latter is an example of a, so-called, micro-error: a systematic error that depends on the object being tracked. The former errors are macro-errors; they only depend on the sensor involved. Unfortunately, both macro- and micro-errors may change in time, due to e.g. changing atmospheric conditions and radar maintenance. Therefore,

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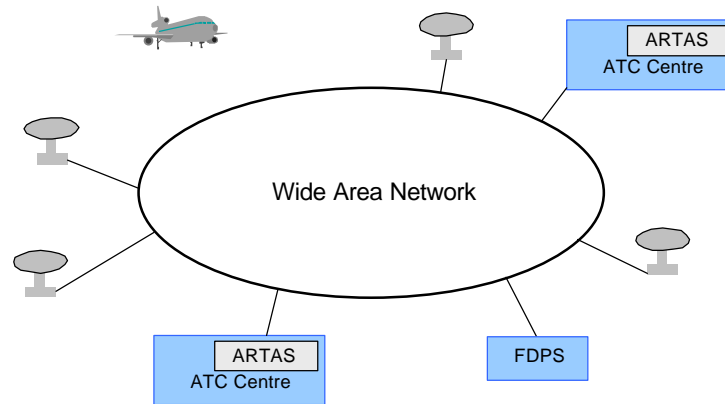
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*Figure 1. The ARTAS Environment*

the ARTAS Tracker contains modules that dynamically estimate and correct both the macro- and micro-errors.

Another requirement for handling multisensor data is a proper treatment of coordinate transformations. This becomes a more obvious problem when the size of the system area becomes large. ARTAS uses WGS84 as a reference system. Measurement processing and track update processing are done in local Cartesian systems, such that the error, induced by coordinate transformations, always stays below a required level of a few meters.

The internal structure of an ARTAS unit is shown in figure 2. The Router Bridge is the interface to the external network. It pre-processes the incoming radar data, i.e. it performs format checks and sectorisation of the plot data and keeps track of the operational status of the radars. The Server is responsible for the handling of ARTAS user requests and the distribution of the track data, according to the different user services. Furthermore, the Server is responsible for Track and Service continuity across the borders of the DOIs of adjacent ARTAS units, i.e. track data users are not aware the fact that targets cross this border. The simplest service that is provided is a regular broadcast of all track data. MMI/Supervision is the man-machine interface and supervision unit. It provides a basic display of the unit tracks and control functions for the ARTAS unit. The Tracker, finally, is responsible for keeping an up-to-date air picture. An ARTAS unit consists of two identical chains of Router Bridge/Tracker/Server/MMI/Supervision subunits. The Trackers in both chains operate in a multiple-computation redundancy mode; that is, there is a master and a slave Tracker that both perform the same processing, except that the slave Tracker does not provide any output. Instead, the slave Tracker performs some additional processing to keep master and slave in synchronisation.

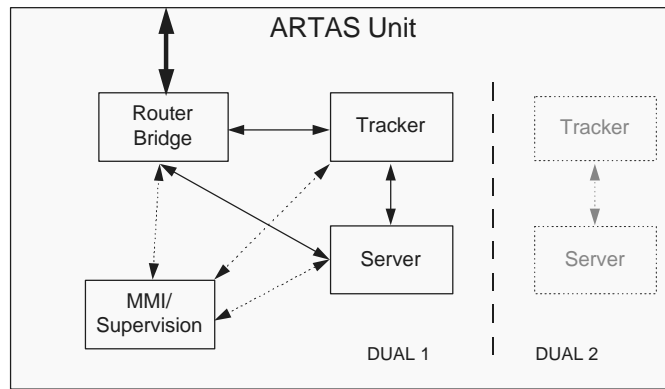


Figure 2. ARTAS Unit Internal Structure

All the ARTAS subunits run on off-the-shelf hardware and are programmed in ADA, except for the MMI, which is programmed in C++.

### The ARTAS Tracker

Basically, the task of the tracker is to provide estimates of the aircraft state vector for each target in the domain of interest of the ARTAS unit. It makes use of, maximally, 30 sensors. In the operational system, the sensor types are primary radar (PR) and secondary surveillance radar (SSR). A prototype ARTAS2 tracker, which is an extension of the operational ARTAS tracker, additionally handles aircraft-derived data, received either through Mode-S or through automatic dependent surveillance (ADS).

Track continuation uses the reports of all available sensors to estimate the state of a target. Each track extrapolation/update cycle is based on the reports of a single sensor, though. Subsequent cycles, however, may be of entirely different sensors. Prior to the track update, all the relevant reports are corrected for micro-errors (systematic errors that vary from target to target) and slant-range effects. Track continuation is discussed in more detail below.

The integration of aircraft-derived position, speedvector and roll-angle information at the tracking filter level results in a clear performance improvement. This was demonstrated to Eurocontrol and European national administrations in February 1999, using the ARTAS2 prototype tracker. Figures 3 and 4 show the decrease of the course error after a turn, when aircraft-derived data is used (simulated Mode-S radar data; averaged for 25 tracks)

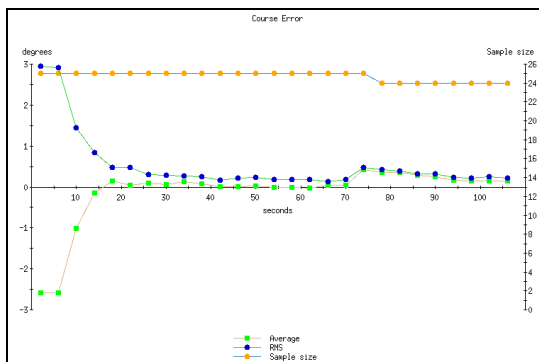


Figure 3. Course error after turn; Mode-S without aircraft-derived data

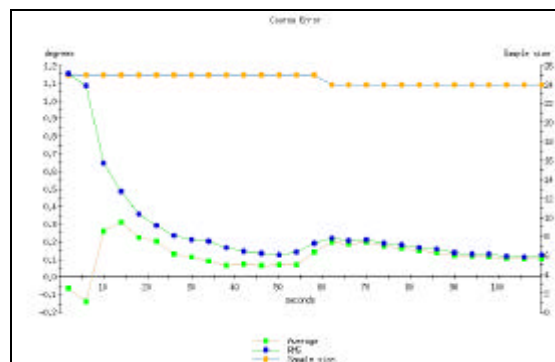


Figure 4. Course error after turn; Mode-S with aircraft-derived data

As explained earlier, all sensors and all tracked objects have their own local Cartesian system that may change in time when objects move. The effect of this is clearly visible in figures 3 and 4; the increase in course error after about 60 seconds is due to relocation of the track-local Cartesian system.

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cycles, however, may be of entirely different sensors. Prior to the track update, all the relevant reports are corrected for micro-errors (systematic errors that vary from target to target) and slant-range effects. Track continuation is discussed in more detail below.

Track initiation is done based on the reports of single sensors only. It is based on multiple-hypothesis tracking (MHT) and is done retrospectively [3]. Considering the fact that a new target generally enters the coverage of the Tracker with only mono-radar visibility, the gain of a shorter track initiation delay did not warrant the additional complexity of a multiradar initiation in a civil ATC environment. This trade-off is not valid in a military environment, though. It is foreseen to extend the track initiation to a multisensor initiation in the scope of an on-going evaluation.

The ARTAS Tracker maintains aircraft and non-aircraft tracks since, in many cases, the best way of dealing with anomalies, like reflections and sidelobes, is to track them and to identify them as being non-aircraft. To that end, the ARTAS Tracker contains a track type identification module, which identifies tracks using Dempster-Shafer reasoning [4]. The criteria, used in the track type identification, are based on radar environment characteristics, target behaviour and a set of models for specific anomalies, like reflections and sidelobes. An advantage of Dempster-Shafer reasoning is the ease with which additional criteria, like target signature information, can be incorporated into the classification process.

### **Track Continuation**

For the ARTAS Tracker, a Bayesian approach to track continuation was adopted. This approach did prove to yield a high-performance tracker, as NLR experience with the JUMPDIF prototype tracker has shown [1].

Basically, there are four major problems that occur during track continuation

1. Non-linear aircraft dynamics during a turn
2. The association of measurements with existing tracks
3. The occurrence of outlier measurements (non-Gaussian measurement noise)
4. Sudden starts and stops of manoeuvres

For each of these problems, adequate solutions were already developed for the JUMPDIF prototype [2]; the result, an Interacting Multiple-Model Probabilistic Data-Association (IMMPDA) algorithm with Extended Kalman Filters (EKF) [1]. This four-mode IMMPDA EKF was used in extensive performance tests. The results of these performance tests were used as a basis for the ARTAS Tracker performance requirement specification. A number of improvements, with respect to the JUMPDIF tracker, were made in the ARTAS Tracker, though.

For target resolution situations, new joint probabilistic data-association (JPDA) algorithms were developed [3] that avoid the track coalescence property of conventional JPDA, while performing considerably better than the probabilistic data-association (PDA) algorithm in situations with targets closely together.

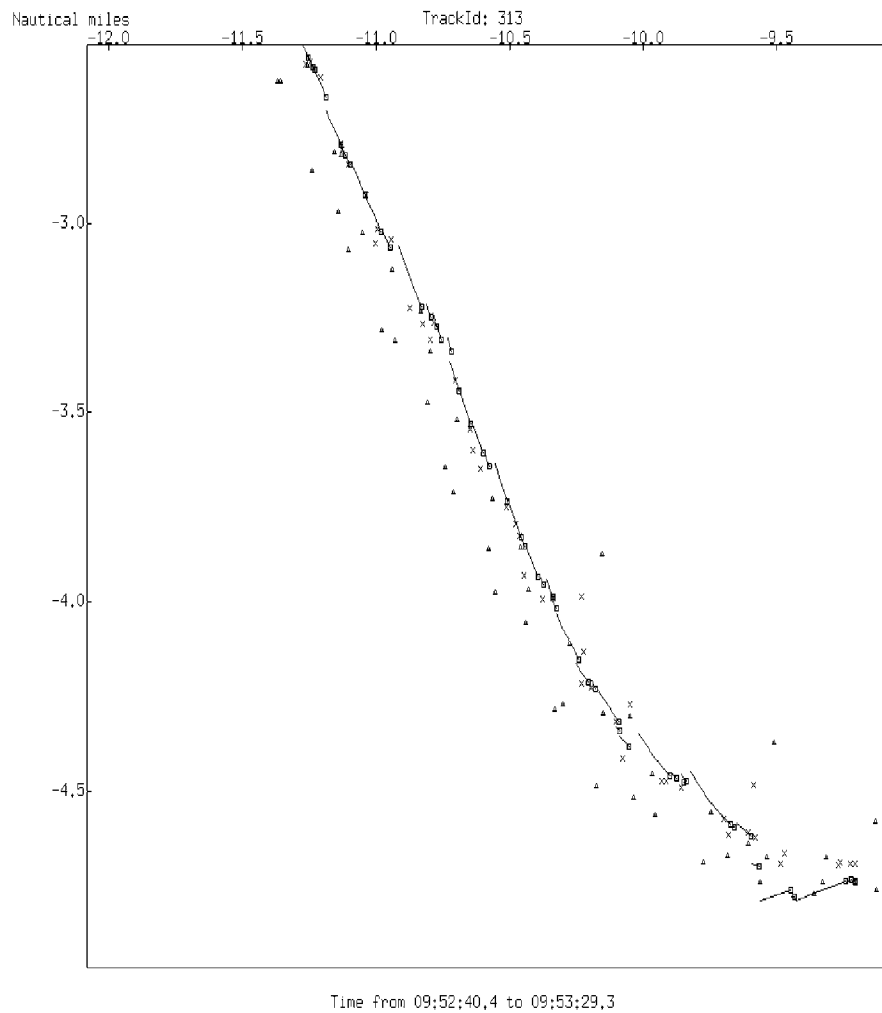
In the ARTAS2 tracker, the IMMPDA algorithm was extended to incorporate aircraft-derived data. This extension is called ADD-IMMPDA. Furthermore, the IMM track extrapolation was adapted to handle the situation where very accurate position reports are received with a low sampling rate. This may be the case when aircraft position reports are obtained by means of differential GPS.

The ARTAS Tracker is required to track targets down to zero groundspeed. For these targets, a simplified two-model (manoeuvring flight, straight flight) IMMPDA filter is developed.

Initially [2], a two-model (climb/descent, level flight) IMMPDA filter for SSR mode-C measurements was developed. In the ARTAS Tracker this filter was improved by a three-model (climb, descent, level flight) IMMPDA filter in order to be more responsive to changes in the rate of climb/descent. Furthermore, two algorithms to estimate the target altitude in absence of SSR mode-C information were implemented. One algorithm, Triangulation, is discussed in more detail below. Although not as accurate as mode-C based height, the performance of the triangulation algorithm often is surprisingly good. Another algorithm, Height-from-Coverage, uses the assessed coverage of all radars that detect or do not detect the target, to calculate a height interval for the target. This is used as a fallback in cases where neither mode-C nor triangulated height is available.

For centralised multisensor track continuation, a key problem is the accurate estimation and correction of systematic errors. The solution developed for the ARTAS Tracker is a dynamic estimation and correction of the macro- and micro-systematic errors of all involved measurements, before they are used within the track extrapolation/track update cycle. This essentially reduces the multisensor problem to a single-sensor problem. The time sequence of track extrapolation/track update cycles, obviously, contains track extrapolation/track update cycles for all the available sensors. The difference between cycles for different sensors is the use of a different measurement matrix for the Extended Kalman filters.

Figure 5 shows a track, departing from Schiphol airport that uses biased measurements from three different radars. Figures 6 and 7 show the ARTAS Tracker estimates of the groundspeed and SSR mode-C height of this track, respectively. Without an effective elimination of systematic errors, groundspeed and height would contain a substantial number of irregularities.



*Figure 5. Departure from Schiphol airport, using biased measurements from three different radars (triangles indicate raw plots, crosses nearest-neighbour plot positions (corrected for the estimated radar biases) and squares the updated track position. The vectors indicate the predicted flightpath up to the next measurement instant).*

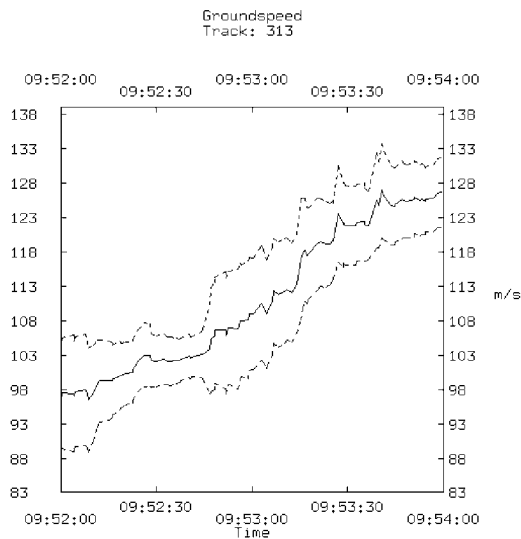


Figure 6. Track groundspeed estimate

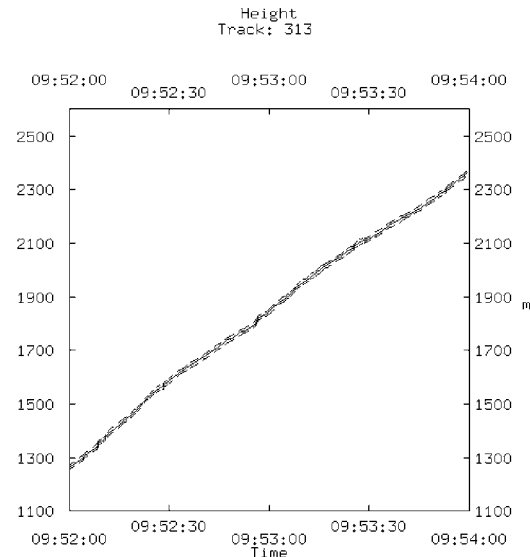


Figure 7. Track mode-C height estimate

### Macro-Error Estimation

The ARTAS Tracker estimates the following (macro-) systematic errors:

- range bias
- azimuth bias
- range gain (a range error proportional to the range)
- antenna squint (non-verticality of the plane of the radar beam)
- verticality error (antenna rotation axis not perpendicular)
- time-stamping bias

The problem with dynamic estimation of the (macro-) systematic errors is that, in principle, the filter equations are coupled with the track continuation equations of the individual tracks. It is, of course, very well possible to make a selection of a small number of well-behaved tracks and to solve the resulting set of equations. In ARTAS, a different approach is taken [6], which decouples the equations for (macro-) systematic error estimation from the track continuation equations. Effectively, it comes down to a weighted integration of the innovations of all tracks and filtering these weighted results with a Kalman filter. Due to this decoupling, the filtering equations become independent of the individual track maintenance equations. This algorithm is implemented in the ARTAS Tracker. It uses a selection of non-maneuvring tracks when it is necessary to save CPU-load without jeopardising the speed of convergence of the macro-error estimation process. Figures 8 and 9 show results of the (macro-) systematic-error estimation process on a 2-radar PR scenario.

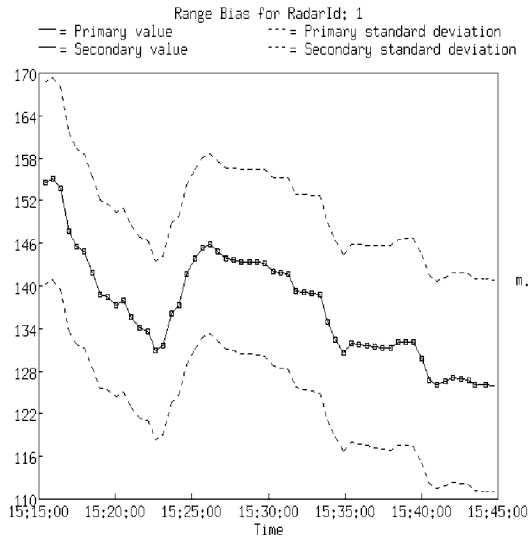


Figure 8. TAR estimated range bias

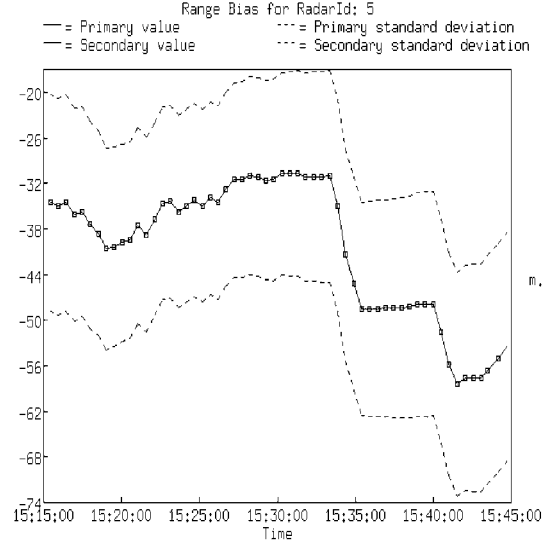


Figure 9. LAR estimated range bias

### Triangulation-based Micro-Error Estimation

After estimation of the systematic radar errors that are radar-dependent only (macro errors), the track-related errors (micro errors) can be estimated. Within the ARTAS Tracker, these micro errors consist of the transponder delay error (i.e. the difference between the actual delay and the nominal value of 3 microsecond as specified by ICAO) and the geometric height, estimated from range-azimuth position measurements in a multiradar environment.

A general solution to this problem is to extend the state vector of an object with these components and to extend the corresponding extended Kalman filter equations accordingly. Since this is a very costly solution (in terms of CPU), we have looked for a robust method that is not coupled with the track continuation equations. In situations where an SSR radar has a co-located primary radar, a robust method to estimate the transponder delay error is to average the difference in range measurements of the two radars. In other situations, the transponder delay error and geometric height estimations are coupled.

Consider the situation that two non-co-located radars observe an object at the same moment in time. To perform triangulation, we use the difference between the projections of the plots to a common 2-dimensional Cartesian coordinate system (the track-local coordinate system) as the innovation term in a Kalman-like filter update step for the estimation of the transponder delay error and the geometric height.

Since a simultaneous measurement of one object by two non-co-located radars is quite unusual, we perform a triangulation on the basis of a triplet of projected plot positions (under the condition that the track groundspeed and course are constant). The first and third projected positions are interpolated to the time of the middle plot.

The performance of this algorithm depends, among others, on the geometric configuration of the radars involved: the middle plot should be from a different radar than the other two plots, with a line-of-sight opposite to that of the other radars, and as close to the object as possible.

In figure 10, we see a part of a track from a live data collection. The recording was made for 3 secondary and 2 primary radars, but the Tracker was run with only the primary plot data. The track is flying at FL 290 (8840 m); the plots are not corrected for systematic radar errors. The estimate of the geometric height and the 1-sigma margin are given in figure 11; the initial estimate is 6000 m.

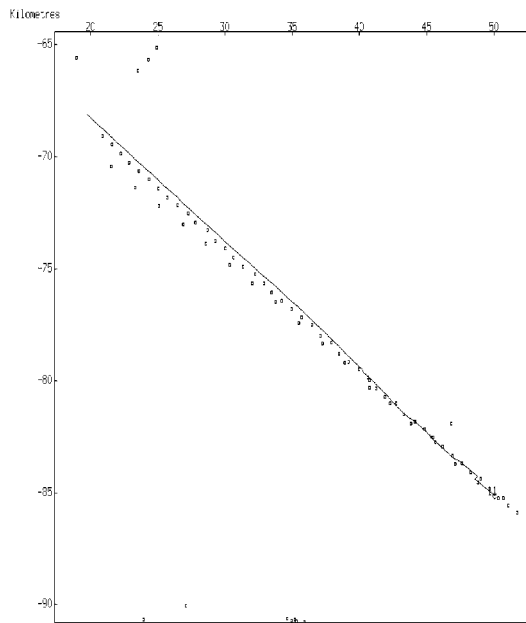


Figure 10. Track observed by 2 PR radars

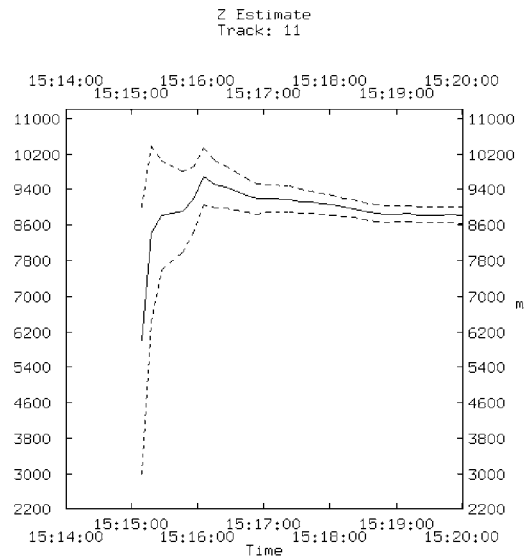


Figure 11. Triangulated height as function of time

### Multisensor Environment Assessment

The use of aircraft-derived data increases the complexity of the multisensor situation enormously. In addition to the rather small set of radars with sensor characteristics that are, generally, well known, the sensors on-board each and every aircraft have to be taken into account. This creates two problems:

- the estimation of the on-board sensor characteristics;
- the estimation of additional micro-errors.

The ARTAS tracker already contains modules to estimate the radar sensor characteristics. These are part of the, so-called, Multiradar Environment Assessment (MREA). In ARTAS2, these modules will be extended to become a Multisensor Environment Assessment (MSEA).

New methods will have to be developed for the estimation of the large amount of additional micro-errors, such as time-stamping bias, drift in position and differences in atmospheric conditions (pressure altitude).

### Conclusions

Adequate systematic error estimation is a pre-requisite for accurate multisensor tracking. In the ARTAS Tracker, several powerful methods are employed for the on-line estimation of both macro- and micro-systematic errors. These methods provide accurate estimates of the systematic errors as shown by a number of examples. By having accurate systematic error estimates, the multisensor problem is essentially reduced to a time-sequential single-sensor problem, which is, obviously, much easier to solve.

The incorporation of aircraft-derived data in tracking increases the complexity of the systematic error estimation dramatically. New estimation methods will have to be developed to deal with this problem.

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