The RA-2 On-Board Tracker

and

its Autonomous Adaptable Resolution

Technical Note

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1 Scope

This technical note describes the complete functionality of the RA-2 on-board Tracker and how its Resolution Selection Logic (RSL) works. It gives a detailed analysis of the algorithm and its configuration parameters.

The definition of all these algorithms and their implementation have been carried out by Alenia Aerospazio, in Italy.

2 Reference Documents

[RD 1] "SPSA Requirement Specification" - PO-RS-ALS-RA-0005, Issue 7, 07/01/97.

[RD 2] *"Study of performance of various tracking algorithms for space-based radar altimeters"* Final report, ESA contract 8574/89, Alenia Spazio, Dec.1990.

[RD 3] "Instrument Operational Manual" - PO-MA-ALS-RA-0006, Issue 7.

3 The Instrument

The EnviSat-1 satellite will embark an innovative radar altimeter, the RA-2 which represents a new generation of radar altimeters compared to previous instruments such as the ERS altimeters and TOPEX/Poseidon. This is due to its integration of many important features, specifically:

- low height noise (~2 cm at significant waveheight, SWH = 4 m) thanks to a higher Pulse Repetition Frequency (PRF) of almost 2000 Hz, which allows the average of N_A=100 individual echoes to form the average waveform;
- separation of a robust on-board tracking function from a high-quality on-ground estimation of the engineering and geophysical parameters;
- autonomous resolution control (0.5 m, 2 m, 8 m);
- dual frequency (Ku and S-band) for correction of ionospheric delay (3 mm residual error);
- samples of full-rate non-averaged data are sent to ground as the I and Q video signal (Burst Mode);
- high-quality near real-time (NRT) geophysical data products.

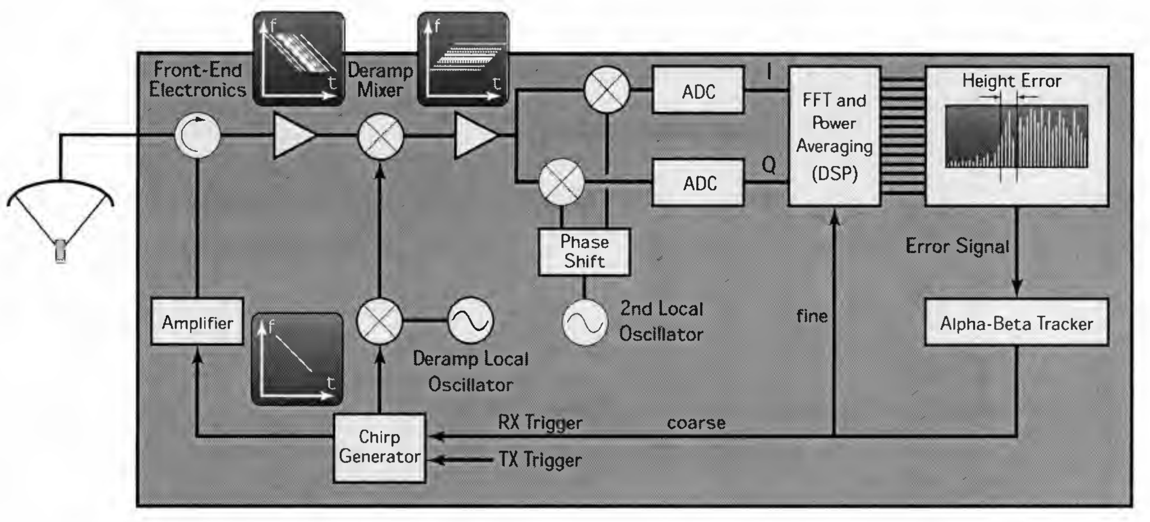

Fig. 1: Instrument block diagram

During both the Calibration and the following Routine Phase, the EnviSat will be flying in a 35 days repeat cycle orbit. The ground-track has a spatial separation of about 80 km at the equator. The EnviSat orbit is sun-synchronous with an ascending node at 22:00 local solar time.

This paper will describe in detail how the logic that the instrument, follows regarding the selection of the most adequate resolution and its changes, work in RA-2. Before though, it is necessary to understand the on-board tracker: the way the error is estimated from the averaged waveform by the Model Free Tracker (MFT), and how from this error the new range window position and attenuation is derived for the next 100 individual waveforms that composed the averaged one by the Alpha-Beta Tracker (α–β TRK).

3.1 The On-board Tracker

The error algorithm that has been used in previous radar altimeters fits a model ocean return shape to an average return. This algorithm is inappropriate for ice and land pulses shape. The new mission requirements for RA-2 compared to the ERS altimeter, translate into a more extended tracking coverage over ice and land surfaces. If we require the altimeter to provide robust tracking over ice and land, we must provide it with an alternative error algorithm. There is no one dimensional model analogous to the Brown model that may be used for this purpose, therefore such an algorithm will not generate geophysical parameters such as mean surface height, as it is possible over ocean. This algorithm should generate a height error signal which is linear over the entire width of the range window. This property shall be independent of the pulse shape, which means that the algorithm must adapt to changes in the pulse shape. For the same reason, it is equally important that the altimeter gain is adapted to the pulse shape or pulse power in this case.

The on-board tracking loop, both for the Time Delay (also called Leading Edge Position, LEP, estimation) and for the AGC, is composed by several steps. The first one is a discriminator which determines an error signal by means of the Model Free Tracker (MFT). The second step is a one order filter, the Alpha-Beta filter, which filters and integrates over the measurements.

The RA-2 has three different resolutions (see Table 1). At the main operative frequency, the RA-2 autonomously detects, acquires, locks-on and tracks the earliest part of the radar echoes of any surface irrespective of sudden changes in the surface characteristics and elevation. Operations are accomplished by automatically changing the range resolution, the width, the position and the overall gain of the tracking window according to the Earth's surface topography characteristics. Thus, the altimeter should always track at the highest possible resolution. The on-board tracker is also the responsible to decide autonomously which resolution is the optimum one to be used, based on the pulse shape. The algorithm used to decide the resolution (or bandwidth) the instrument will use is called Resolution Selection Logic (RSL) or Loss of Lock (LoL) logic..

	Resolution	**Chirp Bandwidth**	**Tracking Window Width**
High	0.47 m	320 MHz	61 m
Medium	1.9 m	80 MHz	243 m
Low	7.5 m	20 MHz	960 m

Table 1: RA-2 Resolutions

In summary then the tracking on-board is performed in 2 different steps, with the following inputs and outputs:

1 The Model Free Tracker:

input: actual averaged (100) waveform;

preforms the estimation of the error and adequate resolution from one single averaged waveform;

output: an error signal.

2 The Alpha-Beta Tracker:

input: error signal, from MFT;

computes the position and attenuation of the range window to be applied to the following N_A=100 individual pulses;

output: new position of the range window and attenuation for each individual new waveforms.

In the following sections we will describe the three main blocks of the on-board tracker, mentioned above.

3.2 The RA-2 Requirement Specifications

The instrument requirement in terms of on-board tracking and are specified in [RD 1]. A summary of the most relevant ones is given below.

3.2.1 Initialisation and Maintenance

1 Over surfaces of Sigma-0 greater then 6 dB, the instrument shall reach tracking in less than 1 s with a probability of 95%.

2 Over Ocean the instrument shall reach the highest resolution after the beginning of the tracking sequence in less than 3 s with a probability of 95%.

3 In transitions from non-ocean to ocean while tracking, the instrument shall reach highest resolution after the antenna footprint (-3dB) has left the non-ocean surface, in less than 0.8 s with a probability of 95%.

4 Over all type of surfaces the instrument shall able to determine lost of lock and recover from this situation.

3.2.2 Range Resolution

1 Over all surfaces the range resolution shall be autonomously adaptive to ensure continuous tracking.

2 The tracking shall be performed with the highest possible range resolution that allows the earliest part of the echo to be maintained within the range window.

3 Over ocean the instrument shall operate with the highest resolution for more than 99% of the tracking time.

4 Over surfaces with Sigma-0 equal -10 dB the instrument shall operate with a range resolution of at least 7.5 m (20 MHz) for Ku-band.

4 The RA-2 Model Free Tracker (MFT)

4.1 Introduction

The design of the RA-2, although it is derived from the ERS-1 RA, performs a different signal processing. This new way of processing the signal will allow the RA-2 to operate autonomously over all type of surfaces (ocean, ice, land, etc.) without interruption.

In order to accomplish all these requirements, the so called Model-Free Tracker (MFT) has been found to be very suitable to track the earliest part of the radar echoes irrespective of their shape [RD 2].

4.2 Description and Concept

As previously mentioned, the tracking loop, both for the Time Delay or LEP and for the AGC, is composed by a discriminator, which determines an error signal. The discriminators are designed to produce two estimations that determine the pulse shape. With these two estimations the relevant amplitude error and position error compared with the actual available Ku-band waveform are determined.

The tracking algorithm performed by the MFT shall ensure that the tracked pulse is not noise. To do that the computation of a threshold derived from the noise power estimate performed during tracking is required. The concept is depicted in Fig. 2. (Note that the direction of the waveform is the opposite of the logical one, or the ERS one. This is only due to an instrument artifact, but is taken into account in the processing of the Level 1b in which the waveform is reversed).

4.2.1 Noise Power Measurement (NPM)

In order to retrieve a threshold, T_s, the Noise Power is measured in proper portions of the Pulse Repetition Interval ($PRI = 1/(PRF)$) where no echoes from any surface are received. After an A/D conversion and square modulus extraction, the average noise power is computed for 16 PRI's with 64 samples each (1024 samples in total), corresponding to a time window of 10 µs. The average Noise Power is computed as:

$$NPM = \frac{1}{16 \cdot 64} \sum_{i=1}^{16} \left[\sum_{n=1}^{64} s_I(n)^2 + s_Q(n)^2 \right]_i$$

with $s_I(n)$ and $s_Q(n)$ being the digitised I and Q video signals.

The NPM is not executed if S-band pulses are transmitted, i.e. one every four PRI is left out. The duration of the measurement will be 20 PRI which is equivalent to approximately 11 ms. This measurement will be repeated every 32 seconds. If the NPM is out of the specified range (NPM_{min}, NPM_{max}), the last valid NPM value will be taken. In case the tracking phase is just started, so it is the first time that is computed, the NPM is replaced by the Noise Power Esti-

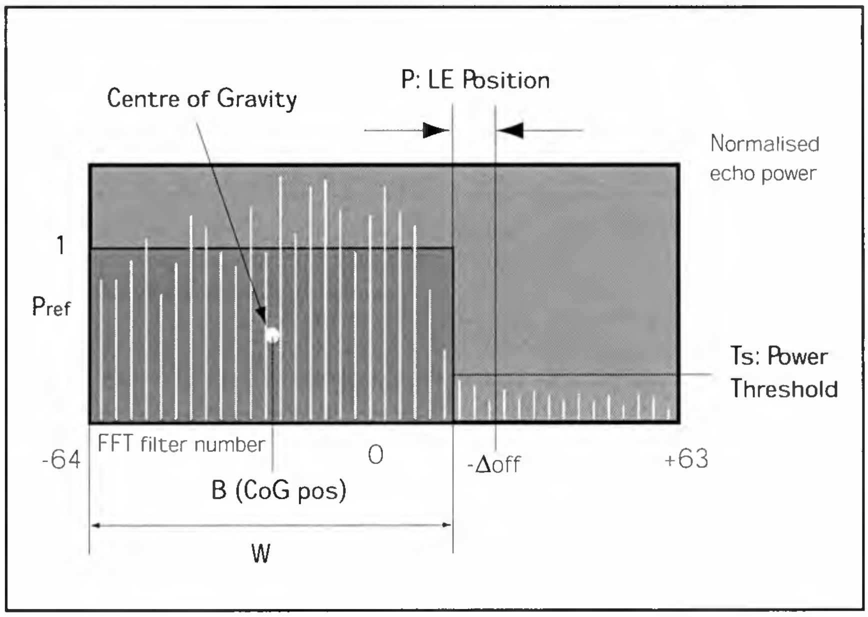

Fig. 2: Model Free Tracker depiction.

mated during the Acquisition phase [RD 1]. This anomalous condition is indicated in the source packet.

4.2.2 The Pulse Shape Parameters

The pulse shape parameters are defined so that they together give an estimate of the pulse shape. These parameters are an estimate of the pulse amplitude, A, and the pulse width, W. To determine this last one, the computation of the threshold based on the NPM is necessary. Once the width has been obtained the Leading Edge Position (LEP, or P) will be computed.

With A and LEP the errors compared with the expected values will be the inputs to the next step, the α–β Tracker (see below).

4.2.3 LEP Discriminator

The threshold T_s is computed as:

$$T_s = \frac{K_s}{800 \cdot 2} \cdot N \cdot 10^{\frac{AGC_{NPM} - AGC_{sig}}{10}}$$

where

K_s is a multiplicative factor stored in the dispatch area, equal 2240, resulting a total multiplicative factor of 2240/1600 = 1.4;

$N = \frac{NPM}{N_F}$ is the normalised noise power (provided in the Level 0), being N_F the number of FFT samples (128);

AGC_{NPM} is the AGC value in dB used for the NPMeasurement, stored in the dispatch area; and

AGC_{sig} is the AGC output value of the α–branch? of the α–β Tracker (AGC corrected) of the previous averaged waveform.

The samples are compared with T_S. A binary vector with the samples greater than the threshold is evaluated as:

$$T_i = \begin{pmatrix} 1 & \text{if} & P_i \geq T_S \\ 0 & \text{if} & P_i < T_S \end{pmatrix}$$

where P_i is the i-th sample of an average waveform.

The width of the discriminator is defined as:

$$W = \frac{\left(\sum_{i=-N_F/2}^{i=N_F/2-1} T_i\right)^2}{\sum_{i=-N_F/2}^{i=N_F/2-1} T_i} - 1 = \sum_{i=-N_F/2}^{i=N_F/2-1} T_i - 1$$

The Centre of Gravity (CoG, or B) discriminator is defined as:

$$B = \frac{\sum_{i=-N_F/2}^{i=N_F/2-1} i \cdot T_i}{\sum_{i=-N_F/2}^{i=N_F/2-1} T_i} = \frac{\sum_{i=-N_F/2}^{i=N_F/2-1} i \cdot T_i}{W+1}$$

4.2.4 AGC Discriminator

The estimate of the pulse amplitude is chosen to coincide with the centre of gravity of the pulse area. For a range window of N_F samples of amplitude P_i, we obtain:

$$A = \frac{\sum_{i=-N_F/2}^{i=N_F/2-1} P_i^2}{2 \cdot \sum_{i=-N_F/2}^{i=N_F/2-1} P_i}$$

where

N_F is the number of FFT samples (128); and

P_i is the i-th sample of an average waveform.

For an squared shaped waveform of amplitude T, the parameter A will take the value T/2.

4.2.5 Error Computation

The error as the difference between the estimated value and the nominal one is computed in both cases. These errors will be the inputs to the $\alpha-\beta$ tracker (see below) where they will be filtered and processed to calculate the closing loop commands for both the range (or LEP) and the AGC tracking.

The nominal value in the case of the leading edge position is the Tracking Point, Δ_{off}, which is the point in which the waveform leading edge will be centred. Δ_{off} is an offset value which allows alignment of averaged echoes around the FFT sample $(N_F/2) - \Delta_{off}$. This value is stored in the on-board dispatch area.

The Leading Edge Position (LEP, or P) in number of FFT samples, is then determined by:

$$P = -B - \frac{W}{2} - \Delta_{off}$$

This value has to be translated into seconds, which are the units understood by the Range $\alpha-\beta$ tracker. The distance between FFT samples in seconds depend upon the chirp bandwidth being in use. Therefore, the input to the $\alpha-\beta$ tracker is calculated as:

$$\varepsilon_\tau = \frac{P}{B_c} \quad [\mathrm{s}]$$

The nominal value of the amplitude is the Power Reference $A = P_{ref}$. This value is also stored in the dispatch area.

The amplitude error in dB is computed as:

$$\varepsilon_{AGC} = 10 \cdot \log A_{10} - P_{ref} \quad [\mathrm{dB}]$$

4.2.6 Anomalies

In case the leading edge position, P, is outside the range P_{min} and P_{max}, also stores in the dispatch area, then the closest extreme of the specified range is used, and the anomalous conditions is indicated in the source packet.

In case that the centre of gravity, B, is outside the range B_{min} and B_{max}, also stores in the dispatch area, then $B = 0$ is used, and the anomalous conditions is indicated in the source packet.

In case $W < 0$, then B is not computed and P is forced to zero ($P = 0$).

In case $\sum_{i=-N_F/2}^{i=N_F/2-1} P_i$ is out of range, then A is forced to the previous value of A.

In case this is the first computation in tracking, then A is forced to the Power Reference $A = P_{ref}$.

4.2.7 The On-board Configuration Parameters

The pre-launch values of the configuration parameters used by the MFT, obtained from [RD 3], can be found in Table 3,

Parameter	Value	Units
P_{ref}	7.142849e- 02	#
Δ_{off}	-18	FFT
B min	-50	FFT
B max	50	FFT
P min	-45	FFT
P max	45	FFT
$\sum P_{min}$	0	#
$\sum P_{max}$	262144.0	#
K1	17	#
K2	18	#
K_s	2240	#

Table 2: On-board pre-launch values for the MFT

where K1 and K2 are the positions of the first and the second additional samples of the FFT.

5 The RA-2 Resolution Selection Logic (RSL) - Lost of Lock Logic (LoL)

5.1 Introduction

The on-board tracker is also the responsible to decide autonomously which resolution is the optimum one to be used, based on the parameters obtained by the MFT. The algorithm used to decide the resolution (or bandwidth) the instrument will use is called Resolution Selection Logic (RSL) or Loss of Lock (LoL) logic, and is described below in this section.

5.2 Description and Concept

Based on the Signal to Noise Ration (SNR) of the on-board waveform and the waveform position (P) compared to reference values stored in the on-board memory, the MFT will decide whether the range window is using the adequate resolution, whether the resolution could be increased, or need to be decreased. This algorithm is depicted in Fig. 3, where

SNR_{m1} is the minimum value of the SNR of the averaged waveform to allow an increase of the chirp bandwidth from 20MHz to 80MHz;

SNR_{m2} is the minimum value of the SNR of the averaged waveform to allow an increase of the chirp bandwidth from 80MHz to 320MHz;

$P1$ is the maximum distance, in FFT, of the waveform LEP (P) to allow one step increase of the chirp bandwidth.

$P2$ is the minimum distance, in FFT, of the waveform LEP (P) to stay with the same chirp bandwidth. If $|P| > P2$, resolution must be decreased one step; and

Δ is the number of times the SNR measured has to be bigger than the minimum SNR (SNR_m), to allow an increase of resolution, which accounts for the decrease of SNR that the waveform suffers when the bandwidth is increased.

When the waveform is a potential candidate for the resolution to be increased, then the algorithm to increase the resolution is depicted in Fig. 4, where

$C1$ and $C2$ are counters; and

$C1B$ is the number of times the RSL has to give the same result before deciding an increase of resolution (or chirp bandwidth).

When, on the other hand, the waveform is a candidate for the range resolution to be decreased then the logic followed is depicted in Fig. 5, where

$C2B$ is the number of times the RSL has to give the same result before deciding a decrease of resolution from 320 MHz to 80 MHz and from 80 MHz to 20MHz; and

k is, in combination with $C2B$, the number of times the RSL has to give the same result before deciding a decrease of resolution from 20MHz to Acquisition.

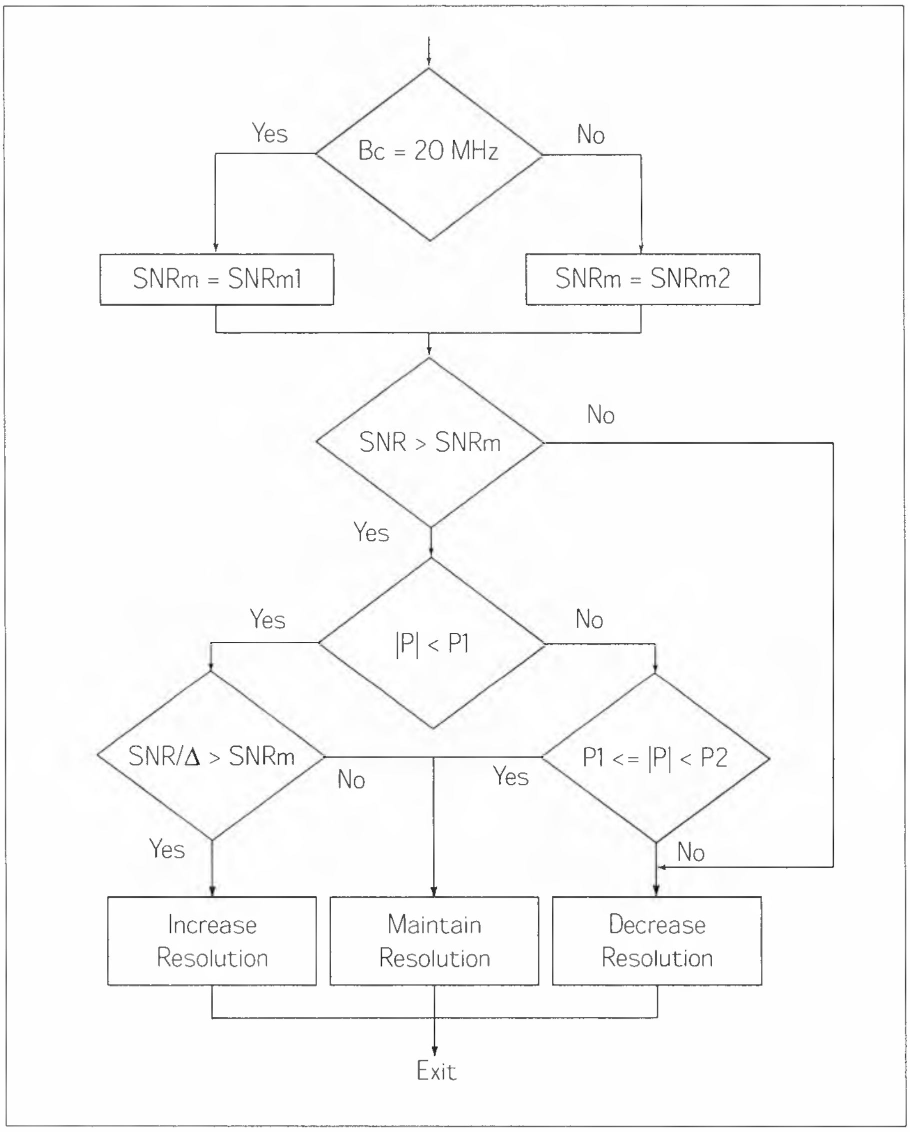

Fig. 3: Resolution Selection Logic general block diagram

5.2.1 Signal to Noise Ration computation

The signal to Noise Ratio is computed as follows:

$$SN = SNR|_0 \cdot 10^{\frac{AGC_T - AGC_{NPM}}{10}}$$

where

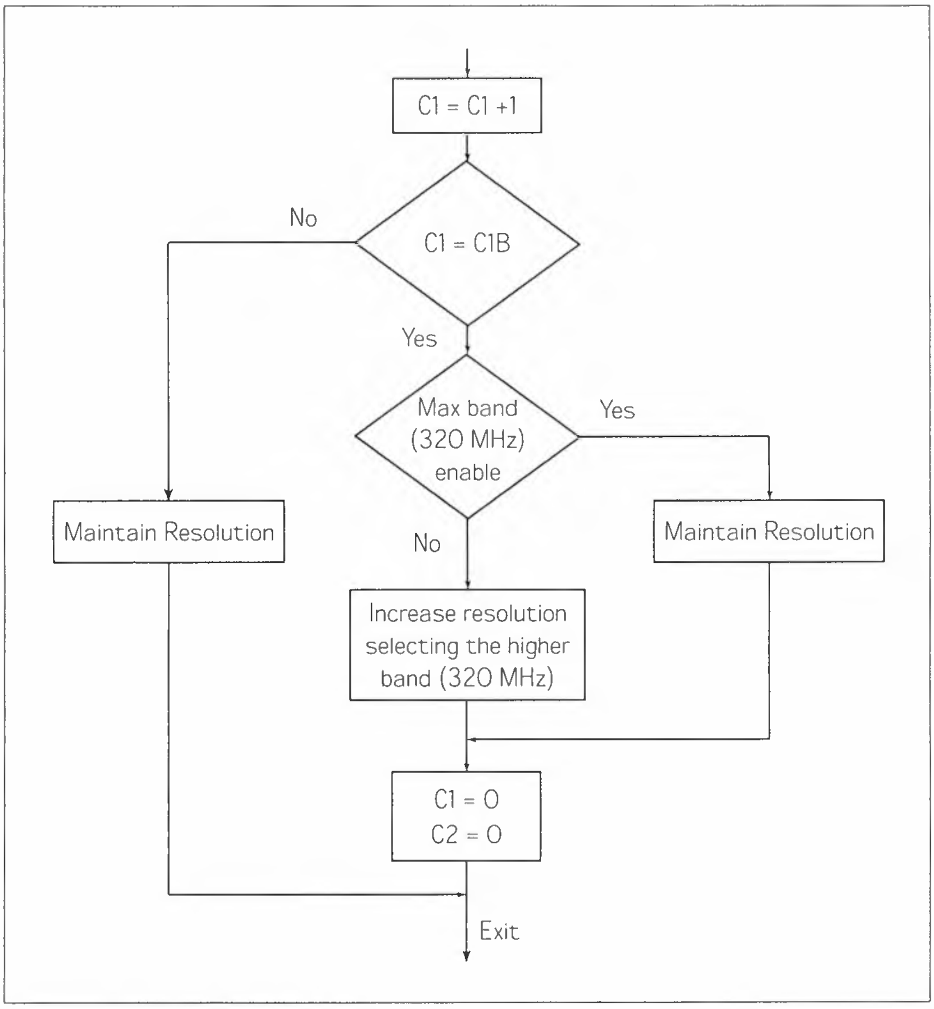

Fig. 4: Increase Resolution block diagram.

$$SNR|_0 = \frac{\frac{1}{\tilde{N}_F} \cdot \sum_{i=-N_F/2}^{N_F/2-1} P_i}{N}$$

and

P_i are the average waveform samples (see A computation in the MFT);

$\tilde{N}_F$ is almost the number of FFT samples (=120), since some have been left out due to aliasing;

AGC_T is the current AGC value [dB]; and

AGC_{NPM} is the AGC value setting during the NMP task.

5.2.2 Anomalies

In case the Signal to Noise Ratio, SNR, is outside the range SNR_{min} and SNR_{max}, stores in the dispatch area, then the closest extreme of the specified range is used, and the anomalous conditions is indicated in the source packet.

5.2.3 The On-board Configuration Parameters

The pre-launch values of the configuration parameters used in the RSL, obtained from [RD 3], can be found in Table 3,

Parameter	Value	Units
SNR_{m1}	620	#
SNR_{m2}	2000	#
$P1$	10	#
$P2$	40	#
Δ	4	#
$C1B$	6	#
$C2B$	6	#
k	6	#
CB_{max}	0 (320 Mhz)	#
SNR_{min}	100	#
SNR_{max}	85000	#

Table 3: On-board pre-launch values of the RSL

where CB_{max} is the maximum bandwidth to be utilised in the RSL, that is nominally the maximum, but can be also changed in-flight to be any other over specific surface types.

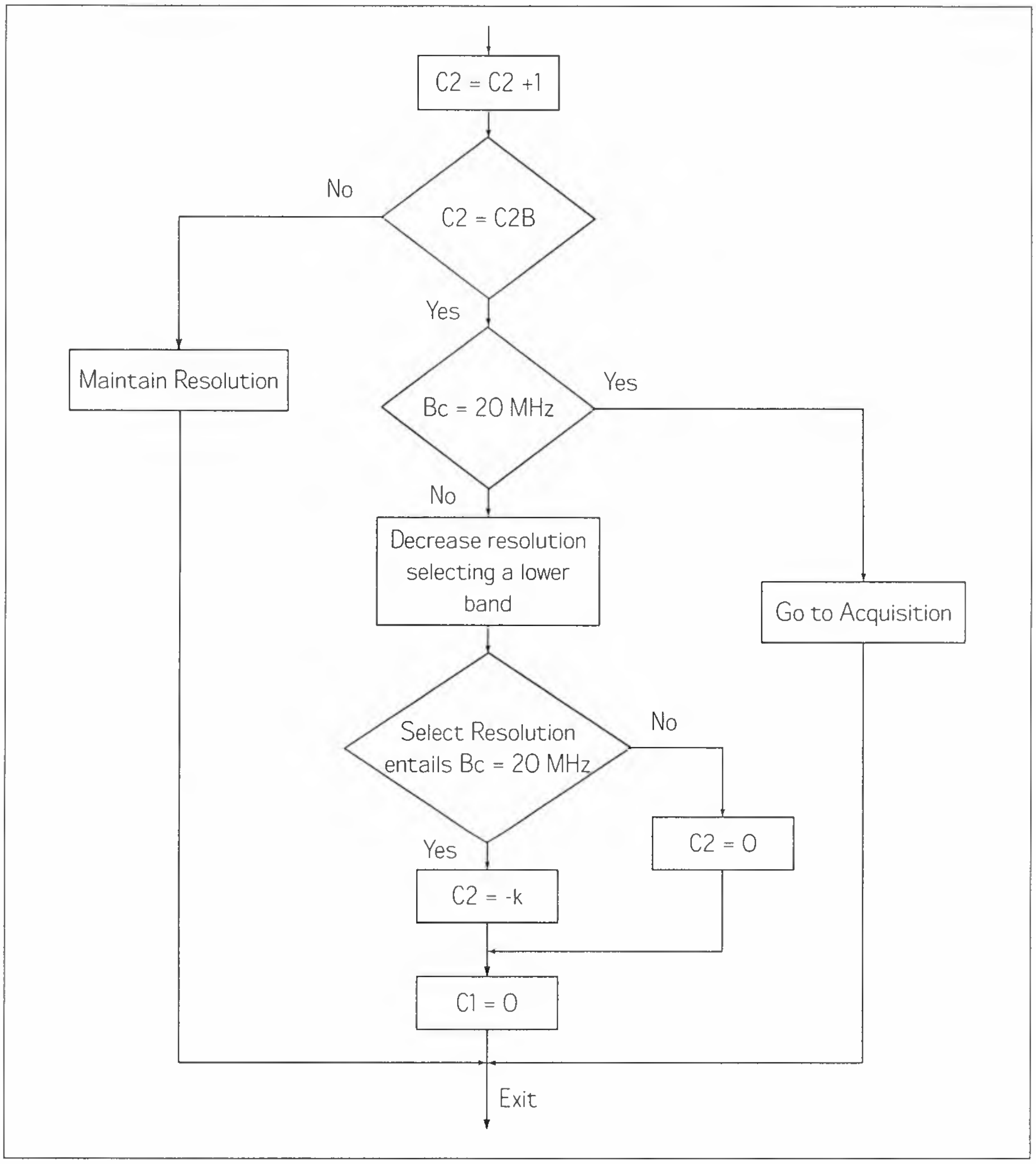

Fig. 5: Decrease Resolution block diagram.

6 The RA-2 On-Board α–β Tracker

6.1 Introduction

This section gives the background information about the Alpha-Beta Tracker necessary to reconstruct some of the on-board internal control data.

6.2 Description and Concept

The Alpha-Beta Tracker is a filter which has two important tasks. First of all it is a Low Band Pass filter but also it has the difficulty of having to change the rate from the input to the output. Therefore the clearest approach is differentiate both tasks as much as possible. This was a guide line in the design of the new Alpha-Beta filter for RA-2.

In Fig. 6 is possible to distinguish the stage dedicated to the filtering function from the stage dedicated to the extrapolation function. The equations that model it are the following:

$$x_c(n) = x_p(n) + \alpha \cdot \varepsilon(n)$$

$$\dot{x}_p(n) = \dot{x}_p(n-1) + \beta \cdot \varepsilon(n)$$

$$x_p(n+1) = x_c(n) + \dot{x}_p(n)$$

where $n = 1..\ N_F$, being is N_F the number of FFT samples (128).

The values x_p and x'_p shall be updated at PRF/N_A rate, every time a discriminator output is available. In order to get output values at PRF rate, necessary for the loop closure, linear interpolator is employed with the following equation:

$$x_0(i + n_D) = x_c(n) + \Delta \cdot (i + n_D)$$

where

$i = 1..\ N_A$, being N_A the number of averaged waveforms (100);

$\Delta = \dfrac{\dot{x}_p(n)}{N_A}$; and

n_D is an integer number representing the time delay in number of PRI required by the discriminator to compute the next value. This value is stored in the on-board dispatch area.

Two filters with the same implementation are used for the time delay and the AGC loops.

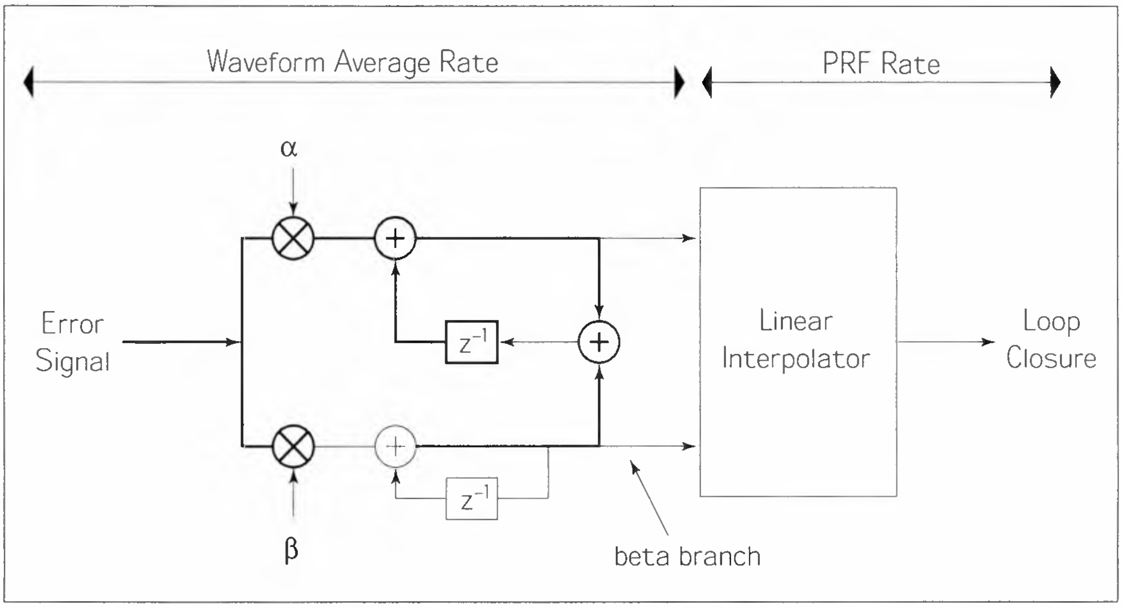

Fig. 6: RA-2 Alpha-Beta Tracker

6.2.1 Time Delay Loop Closing Command

The output x_0 of the Time Delay filter is split into a coarse and a fine components. The coarse component is represented by a 16 bit number with a resolution of 12.5 nsec and the fine component is an 8 bit number with a resolution equal 12.5/256 nsec.

The coarse component is used to control the Rx trigger for the generation of the Deramp Chirp (see Fig. 1), and has a resolution of 12.5 nsec because this is the period of the 80 MHz clock used to control the system timing. To obtain a higher resolution the 8 bits of the fine component are used in the Digital Signal Processing (DSP) for the fine tuning correction (see Fig. 1), once it has been converted into a fraction of the FFT sampling interval, acting directly as a fine shift of the spectrum.

The fine component covers a filter shifting up to 4 filters and has a resolution of at least 1/64 filters. The phase of the video signal is shifted by multiplication of the complex samples with a complex phase operator, according to:

$$s_I(n) + j \cdot s_Q(n) = [s_I(n) + j \cdot s_Q(n)] \cdot \exp\left[j \cdot \frac{2\pi n \Delta f_i}{N_F}\right]$$

where

$s_I(n)$ and $s_Q(n)$ are the digitised I and Q video signals;

$n = 1..\ N_F$, being is N_F the number of FFT samples (128);

$i = 1..\ N_A$, being N_A the number of averaged waveforms (100);

Δf_i is the fine shift correction factor, as the right rotation of the output spectrum after the square modulus extraction.

6.2.2 AGC Loop Closing Command

The output x_0 of the AGC filter shall also be split into a coarse and a fine components. The coarse component is defined as a two values, one for each of the RF attenuator in the IF section of the RA, of 5 bit each, representing an integer number in the range 0..31 dB with 1 dB resolution. This component is provided to the IF section of the receiver (see Fig. 1).

The fine component is a 16 bit number with 0.01 dB resolution. This component is converted to a linear value and provided to the DSP for fine attenuation execution to be applied (see Fig. 1).

The ideal attenuation value to be applied to the waveform is the output of the Alpha-Beta Tracker, x_0. In an ideal case we would split them by taking the integer as coarse and applied by the attenuators and the decimal as fine and applied by the DSP.

The coarse components are, then, nominally integer numbers. However, the real values of each step of the attenuator are not, due to manufacturing tolerances. These real values are stored on-board in a table, there is actually one table for each of the two RF attenuators. The integer part of the output of the Alpha-Beta Tracker, integer (x_0), addresses the on-board tables as shown in Fig. 7. The difference between the nominal and the real value is reflected in the fine component by being added to the computed fine component as the decimal part of the total component, also depicted in Fig. 7. The total fine attenuation is translated to linear to represent the final fine attenuation, and sent to the DSP.

The tables are also given in the Characterisation Auxiliary File, since they are need to reconstruct the AGC applied to the waveforms.

6.2.3 Anomalies

In case

x_p is outside the range $x_{p_{min}}$ and $x_{p_{max}}$, stored in the dispatch area;

x_c is outside the range $x_{c_{min}}$ and $x_{c_{max}}$, stored in the dispatch area; and

the output of the interpolator, x_0, is outside the range $x_{0_{min}}$ and $x_{0_{max}}$, stored in the dispatch area;

for both the Position tracker and the AGC tracker, then the closest extreme of the specified range is used, and the anomalous conditions is indicated in the source packet.

6.2.4 The On-board Configuration Parameters

The pre-launch values of the parameters used by the Alpha-Beta Tracker, obtained from [RD 3], can be found in Table 4.

Parameter	Value	Units
αP Filter Coef	0.2	#
βP Filter Coef	0.02	#
αAGC Filter Coef	0.2	#

Table 4: On-board pre-launch values of the Alpha-Beta Trackers

Parameter	Value	Units
βAGC Filter Coef	0.02	#
n_D AGC	16	#
n_D TRK	8	#
x_p AGC min	-0.15	dB/100 PRI
x_p AGC max	0.15	dB/100 PRI
x_c AGC min	-10	dB
x_c AGC max	70	dB
x_p Dist min	-0.02	µs/100 PRI
x_p Dist max	0.02	µs/100 PRI
x_c Dist min	80.0	µs
x_c Dist max	487.0	µs
x_0 AGC min	0	dB
x_0 AGC max	620	dB
x_0 Dist min	80.29999	µs
x_0 Dist max	487.0	µs
$\Delta AGC1$	0	dB
$\Delta AGC2$	0	dB
$\Delta AGC3$	0	dB
$\Delta AGC4$	0	dB

Table 4: On-board pre-launch values of the Alpha-Beta Trackers

where

$\Delta AGC1$ is the correction to be applied to the a branch register of the α–β tracker when the chirp bandwidth changes from 20 MHz to 80 MHz;

$\Delta AGC2$ is the correction to be applied to the a branch register of the α–β tracker when the chirp bandwidth changes from 80 MHz to 320 MHz;

$\Delta AGC3$ is the correction to be applied to the a branch register of the α–β tracker when the chirp bandwidth changes from 320 MHz to 80 MHz; and

$\Delta AGC4$ is the correction to be applied to the a branch register of the α–β tracker when the chirp bandwidth changes from 80 MHz to 20 MHz.

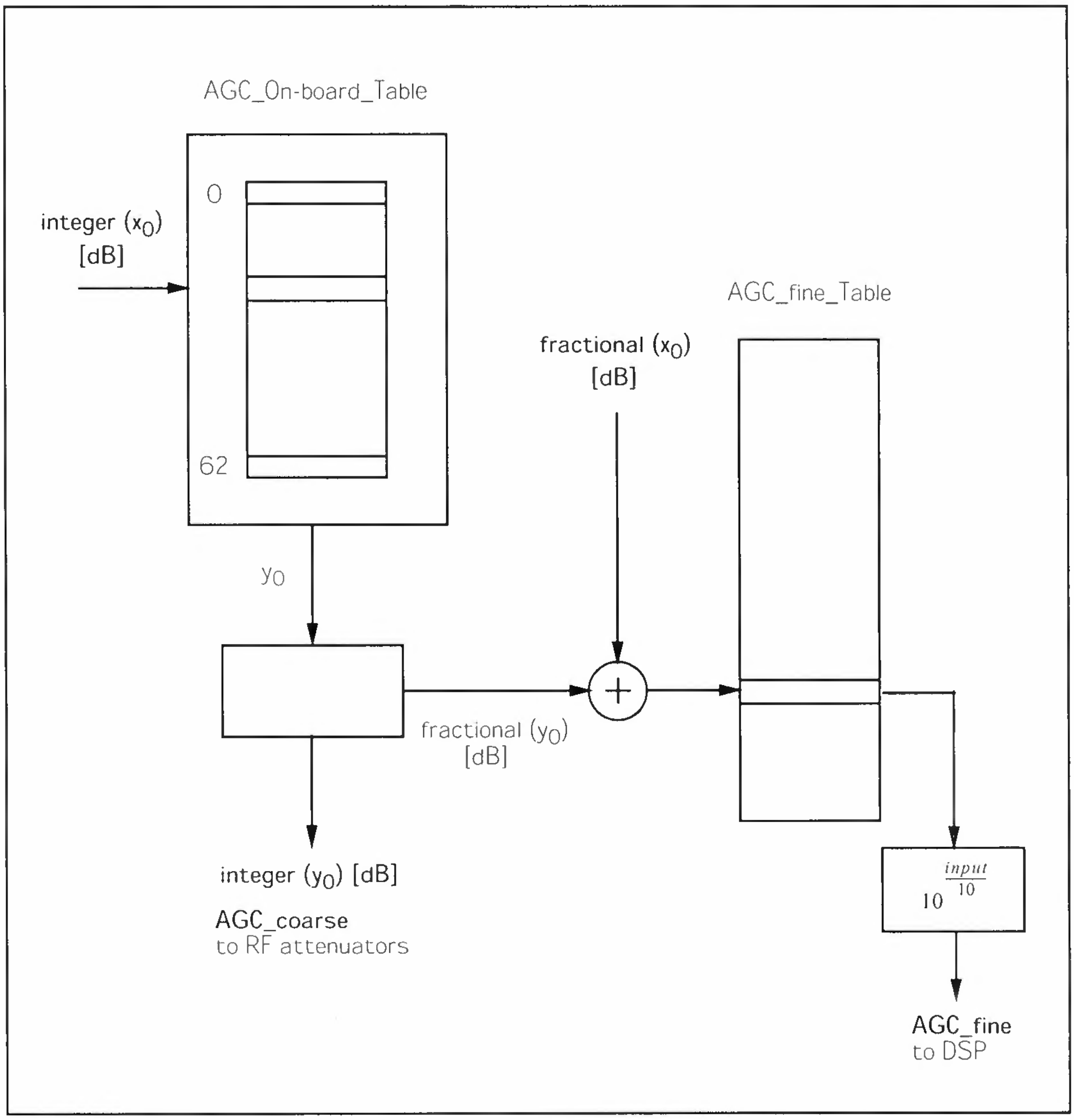

Fig. 7: AGC Coarse and Fine Computation