ROBUST INTEGRATED INS/RADAR ALTIMETER ACCOUNTING FAULTS AT THE MEASUREMENT CHANNELS

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Abstract

In this study, the integrated navigation system, consisting of radio and INS altimeters, is presented. INS and the radio altimeter have different benefits and drawbacks. The reason for integrating these two navigators is mainly to combine the best features, and eliminate the shortcomings, briefly described above.

The integration is achieved by using an indirect Kalman filter. Hereby, the error models of the navigators are used by the Kalman filter to estimate vertical channel parameters of the navigation system. In the open loop system, INS is the main source of information, and radio altimeter provides discrete aiding data to support the estimations.

At the next step of the study, in case of abnormal measurements, the performance of the integrated system is examined. The optimal Kalman filter reacts with abnormal estimates to this situation as expected. To recover such a possible malfunctioning, the Robust Kalman Filter (RKF) algorithm is suggested.

1 Introduction

The new century's improvements in computer technology, and increased data processing rates brought the ability to improve the navigation systems of air vehicles in precision, correctness and reliability.The integrated navigation systems concept with the application of the Kalman filter was a milestone, and we were witnesses to these improvements in the near past. A great amount of study has already been made about this issue. Many more seem to be observed in the future. As many of these studies were examined, and some useful information was reached.

Integrated navigation systems combine the best features of both autonomous and stand-alone systems and are not only capable of good short-term performance in the autonomous or stand-alone mode of operation, but also provide exceptional performance over extended periods of time when in the aided mode. Integration thus brings increased performance, improved reliability and system integrity, and of course increased complexity and cost [1,2]. Moreover, outputs of an integrated navigation system are digital, thus they are capable of being used by other resources of being transmitted without loss or distortion.

In the paper [3] integrated navigation system issue has been discussed. In the paper it is stated that, with the demand from the aviation industry, Instrumental Landing Systems (ILS) tend to be improved. This could not only be through replacement with the Microwave Landing System (MLS), but also by integrating Global Positioning System to the ILS that is practically in service.

Due to the paper, the majority of current precision landing research has exploited stand-alone GPS receiver techniques. This paper, as an improvement, exploits the possibilities of using and Extended Kalman Filter (EKF) that integrates an Inertial Navigation System (INS), GPS, Barometric Altimeter, and Radar Altimeter for precision aircraft approaches. As a result, it is seen that Federal Aviation Authority (FAA) requirements for Category I and II approaches could be met through this new approach.

The work in the paper is conducted through a computer simulation. The simulation program is basically developed on Kalman filter algorithms. The plotted outputs are generated by the commercial software package MATLAB. In this manner, regarding the subject and the tools, this paper is very close to the issue discussed in this study[3] .

In the paper [4] development of a Kalman filter for optimal combination of GPS, INS and Radar Altimeter data is presented. Due to the paper, being two independent navigation systems, GPS and INS have their own shortcomings when used in a stand-alone mode. The ever-growing drift in position accuracy of the INS, and the possible unavailability of the GPS signals are discussed. The author suggests that, these shortcomings would be eliminated, and each system's best performances combined through the Kalman filter.

The benefits of integrating GPS with a strapdown INS are significant. However, altitude accuracy can further be improved by integrating the GPS, baro-inertial loop aided strapdown INS, and radar altimeter data. An error model of the strapdown INS plays an important role in the development of a Kalman filter for optimal combination of navigation data provided by GPS, strapdown INS and radar altimeter. Integrating the error models of each system with the use of the Kalman filter simulates this. The simulation results show an undeniable improvement in the demanded properties. The approach, tools and the data are identical to the ones in this study and the results are somehow in the same manner [4].

Another work on the integration of INS and GPS was done in [5] by a group of scientists at the Technical University of Darmstadt. The group named 'High Precision Navigation' showed some experimental effort to prove the improvement of navigation parameters in an integrated navigation system. The main tool was the Kalman filter as usual, but this time the attitude of the vehicle was monitored as shown in their paper dated 1994 [5].

NASA was also interested in the application of Kalman filter in the navigation systems. The need for the precision altitude determination at low altitude flight phases was the main issue. On a multi-sensor navigation suite, again using Kalman filter as the main tool for integrating navigation data from different origins, radar altimeter and INS data was used for selecting the most similar digital map profile in obtaining horizontal position.

A close subject was discussed by a working group of NASA and U.S. Army in 1993. The improvement of a terrain-referenced guidance system with the implementation of radar altimeter into the traditional navigation system by the help of the Kalman filter was exploited. Starting from mathematical models, this group was able to accomplish some flight tests and experiments on a Blackhawk Helicopter, as a navigation test bed [6].

The integrated systems designed in the past studies do not have robust character towards abnormal measurements. Generally, more than 10% of the radio measurements, and 5% of the whole navigation measurements are expected to be abnormal in the navigation systems [7]. In some measurement periods, the abnormal rate of the radio measurements might exceed %10. This fact certainly decreases the efficiency of most of the standard statistical processing methods.Thus, these abnormal measurements resulting from some possible failures at the measurement channels significantly decrease the effectiveness of the integrated navigation systems. In this study, to overcome such a problem, design of an integrated system, which is robust to the abnormal measurements, is intended as an improvement.

2.1 INS Error Model, The Altimeter

Having numerous output parameters out of different channels, the INS has a complex error model. This model is nevertheless useless in this study, because the issue covers the INS altimeter. For this reason, only the vertical channel of the INS is considered.

Although the subject is about the INS altimeter, not only the vertical position (altitude), but also the other vertical channel parameters will be discussed, and included in the calculations. The INS vertical channel parameters are,

1. Vertical position (altitude). H_I
2. Vertical speed. W_z
3. Vertical acceleration. a_z
4. Gravitational acceleration. g

The system design in the following sections will be in discrete form, so the Kalman filter. The linear and discrete error model of the INS altimeter is given as follows [8]

$$\Delta H_I(k) = \Delta H_I(k-1) + \Delta t \Delta W_z(k-1) \tag{1}$$

$$\begin{aligned}\Delta W_z(k) = \Delta W_z(k-1) + \frac{2g\Delta t}{R_I}\Delta H_I(k-1) + \\ + \Delta t \Delta a_z(k-1) + \Delta t \Delta g(k-1)\end{aligned} \tag{2}$$

$$\begin{aligned}\Delta a_z(k) = \Delta a_z(k-1) - \Delta t \alpha \Delta a_z(k-1) + \\ + \Delta t U_{\Delta a_z}(k-1)\end{aligned} \tag{3}$$

$$\begin{aligned}\Delta g(k) = \Delta g(k-1) - \Delta t \beta_g \Delta g(k-1) + \\ + \Delta t U_{\Delta g}(k-1)\end{aligned} \tag{4}$$

In the error model expressions, the following are the explanations for the terms.

$\Delta W_z(k-1)$: Measurement error of the vertical speed

$\Delta H_I(k)$: Measurement error of the altitude

$\Delta a_z(k-1)$: Measurement error of the vertical acceleration

$\Delta g(k-1)$: Measurement error of the gravitational acceleration

$U_{\Delta a_z}(k-1)$: White Gauss noise with zero mean

$U_{\Delta g}(k-1)$: White Gauss noise with zero mean

α, β_g : The terms for the correlation period

Δt : Discrete time

$R_I = R_0 + H$ (H - the flight altitude, R_0 - the radius of earth)

3.2 Error Model, The Radio Altimeter

The error model of the radio altimeter, which will be used in our calculations, is as follows(14).

$$\begin{aligned}\Delta H_R(k) = \Delta H_R(k-1) - \Delta t \beta \Delta H_R(k-1) + \\ + \Delta t U_{\Delta H_R}(k-1)\end{aligned} \tag{5}$$

In the error model expressions, the following are the explanations for the terms.

$\Delta H_R(k)$: Measurement error of the radio altitude

$U_{\Delta H_R}(k-1)$: White Gauss noise with zero mean

β : The term for the correlation period

Δt : Discrete time

4 Radio-INS Integration

The core task of this study is to combine two different navigation sources with the use of Kalman filter. In fact, the main task for any kind of navigation study is to fight with the disadvantages of a navigation equipment, thus to increase correctness and reliability. By integrating Radio and INS altimeters, the objective is to benefit from the advantages of both of the systems, while eliminating the shortcomings.

There are two possible Kalman filter designs for integrating such systems.

1. Total state space Kalman filter (direct method).
2. Error state space Kalman filter (indirect method).

In the direct method, all of the states of the system are used by the Kalman filter, where the INS accelerometer and the aiding navigator signals are the sources. But in the indirect method, which is basically chosen in this study, Kalman parameters are the errors. While the INS is the main source for determining vertical navigation information, with the discrete aiding signals from the Radio altimeter, Kalman filter estimates the instantaneous errors.Through the design, the outcoming dynamical characteristic of the INS is proposed to be carried to the complete system, and the possibility of a total system breakdown in case of a Kalman filter failure is eliminated.

By integrating INS and Radio altimeter through an indirect feed forward Kalman filter,

1. The good characteristics of the INS with high bandwidth and frequencies are maintained.
2. In certain operation periods, acceptable accuracy is attained.
3. A dynamic system, which is easily adapted to the computer environment, is developed.

The two navigators of the integrated Radio-INS altimeter provide different types of altitude data. The radio altimeter measures the real altitude from the ground level, but the INS measures the relative altitude from an initial alignment location. In a system where these two navigators are combined, this difference could easily be eliminated. This elimination is done in the data processing unit of the integrator.

The block diagram of an integrated Radio-INS altimeter is shown in the Figure 1.The integrated Radio-INS altimeter contains the following components:

1. INS altimeter
2. Radio altimeter
3. Data (central) processing unit
4. Control block (Kalman filter)
5. Display (avionics users)

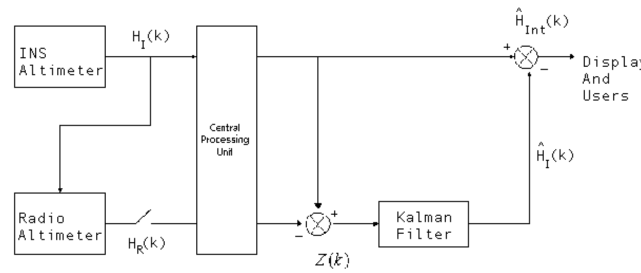

Figure 1. Integrated Radio-INS altimeter block diagram

Here, the INS altimeter is not a dedicated stand-alone instrument, but the altitude or the vertical position channel of the Inertial Reference Unit (IRU) of a certain aircraft. The switch sign on the block diagram refers to the discrete character of the data provided by the radio altimeter for the integrated navigation system. However, Kalman filter could be applied in both continuous and discrete systems. The main source of altitude data is INS, and the radio altimeter acts as a correcting element supporting the Kalman filter for estimations. By the use of the data processing unit, radio altimeter output is transformed to the main coordinate system of the aircraft navigation and control.

The radio-INS integration is feasible for the cases when the aircraft route is over landscapes such as seas, oceans, lakes and deserts where the altitude above ground level does not have fluctuating character. (Not over mountains, valleys, etc.).

When this condition is set, the real altitude value at the Kalman filter input will be compensated, and the input signal will be designated as the difference between the altitude measurements of the two sources.

$$r(t) = H_I(t) - H_R(t) \tag{6}$$
$$= (H_g(t) + \Delta H_I(t)) - (H_g(t) + \Delta H_R(t)) \tag{7}$$
$$= \Delta H_I(t) - \Delta H_R(t) \tag{8}$$

In the expressions (6), (7), and (8), $H_I(t)$ and $H_R(t)$ are the altitude measurements of INS and radio altimeter, $\Delta H_I(t)$ and $\Delta H_R(t)$ are the measurement errors of the two sources respectively. $H_g(t)$ is the real altitude value.

In this block diagram of the integrated system, INS is the main error source. In the previous sections, dead-reckoning character of the INS was mentioned. This causes a severe error of measurement, increasing by time.

The mathematical models of the INS (1)-(4) and the radio altimeter (5) given in this study are first or second order stochastic Markov processes [8]. The model parameters are estimated by the use of the Kalman filter. The filter will give the optimum (estimated) value of the INS error $\Delta\hat{H}_I(t)$, in the condition where the standard error is minimized. Finally, the estimated value of error $\Delta\hat{H}_I(t)$ is subtracted from the altitude measurement of the INS.

$$\hat{H}_{Int} = H_I(t) - \Delta\hat{H}_I(t) \tag{9}$$

The calculated altitude value is the output of the integrated system, and it would be used for navigation and control purposes.

As the INS error increases with time in a cumulative manner, the integration diagram is valid and effective for short periods of operation. (For example, 1 hour period).

In such periods when the linear operation regime of INS is provided, the output signal will be as follows.

$$H_I(t) = H_{\mathrm{Re}l}(t) + \Delta H_I(t) \tag{10}$$

where, $H_{\mathrm{Re}l}(t)$ is the relative altitude.

One of the most important improvements of the integrated radio altimeter is that, a dynamic error of measured altitude is not generated. As this is an open loop system for the measured altitude, the filter will not limit the operation rate of the navigators. For this reason, the radio-INS altimeter will have outstanding dynamic character like a stand-alone INS. Another important feature is that, an in-flight failure at the Kalman filter will not result in a whole system breakdown. In such a case, when the Kalman block at the integrated system fails, the INS measurements could be used without corrections for a certain period of operation.

5 Optimal Kalman Filter for the Integrated System

The state space model of the integrated radio-INS altimeter system is expressed with the following equations.

$$X(k) = \phi(k,k-1)X(k-1) + G(k,k-1)U(k-1) \tag{11}$$

$$Z(k) = H(k)X(k) + V(k) \tag{12}$$

Equation 11 is the combination of error models of INS and the radio altimeter, (1)-(4) and (5), which were given in the previous sections. This expression contains all of the error parameters that act on the integrated system. The definitions of the terms at the state space model of the system are,

$\phi(k,k-1)$	:	System transfer matrix
$X(k)$	:	State vector
$G(k,k-1)$	:	Noise transition matrix
$V(k)$	:	Noise of the system

The elements of the vector $X(k)$, (11) are the measurement error components, where the open form of the vector is depicted in the following expression.

$$X^T(k) = [\Delta H_I(k) \quad \Delta W_z(k) \quad \Delta a_z(k) \quad \Delta g(k) \quad \Delta H_R(k)] \tag{13}$$

These terms in (13) are the main four error parameters of the INS altimeter, which are the error of finding the altitude $\Delta H_I(k)$, vertical speed $\Delta W_z(k)$, acceleration $\Delta a_z(k)$, and gravitational acceleration $\Delta g(k)$; and the altitude finding error of the radio altimeter $\Delta H_R(k)$.

The Kalman filter designed for the integrated navigation system of this study is optimal,linear and discrete. The following are the final expressions of the Kalman equations to be used in the calculations.

$$\hat{X}(k/k) = \hat{X}(k/k-1) + K(k)\Delta(k) \tag{14}$$

$$\Delta(k) = Z(k) - H(k)\hat{X}(k/k-1) \tag{15}$$

$$K(k) = P(k/k-1)H^T(k)\left[H(k)P(k/k-1)H^T(k) + R(k)\right]^{-1} \tag{16}$$

$$\hat{X}(k/k-1) = \phi(k,k-1)\hat{X}(k-1/k-1) \tag{17}$$

$$P(k/k) = [I - K(k)H(k)]P(k/k-1) \tag{18}$$

$$P(k/k-1) = \phi(k,k-1)P(k-1/k-1)\phi^T(k,k-1) + \\ + G(k,k-1)Q(k-1)G^T(k,k-1) \tag{19}$$

The definitions of the terms at the Kalman equations are presented below.

$\hat{X}(k/k)$: The estimation of state vector

$\hat{X}(k/k-1)$: Extrapolation value vactor

$K(k)$: The gain matrix of the Kalman filter

$\Delta(k)$: Innovation sequence

$P(k/k-1)$: The covariance matrices of extrapolation errors

$P(k/k)$: The covariance matrices of estimation errors

R (k) : Measurement noise covariance

Q (k-1) : Process noise covariance

Equation 12 is the measurement equation of the system. The measurement matrix $H(k)$ in this expression is highly important, as it gives a general idea of the whole design of the integrated system.In this design, the measurement matrix is,

$$H(k) = |\ 1 \quad 0 \quad 0 \quad 0 \quad -1\ |$$

As easily seen by combining this matrix with equation (13), the system integrates two independent navigation sources in means of subtracting the radio altimeter error from the INS altimeter error. However, this operation is carried out through the Kalman filter, and the divergent error character of the INS is compensated. This is one of the ideas that should be underlined in this study.

6 Robust Kalman Filter Design

In case of a failure at the measurement channel of a system, a robust Kalman filter is developed to consider, and take action against these measurement errors.Let's assume the observation (measurement)model to be like the following [9].

$$z(k) = H(k)x(k) + \gamma(k)v(k) \tag{20}$$

Here, the parametric variable γ(k), is an independent and random variable at each step.

In case of normal operation, parametric variable is equal to 1 and in case of abnormal operation, parametric variable is equal to σ.

The variance of the measurement error is highly effective on the error formation, rather than the normal operation. Thus, when γ(k)=σ>1 the following suboptimal filter algorithm is valid :

$$\hat{x}(k/k) = \hat{x}(k/k-1) + p(1/k)K(k)\Delta(k) \tag{21}$$

The other filter parameters are the same as the expressions (14)-(19).

Here, *p(1/k)*, is the posterior probability of $\gamma(k)$ variable to be equal to 1, so the normal operation of the measurement channel at the k time step. It could be seen that, only the matrix with the *p(k)* parameter in front of the filter gain coefficient is missing. When *p(1/k)*=1, this filter will be exactly same with the optimal Kalman filter, but when *p(1/k)=0* it disregards the new measurements, acting as an extrapolator.

At normal operation of the measurement channel, $\widetilde{\Delta}(k)$ normalized innovation sequence $\widetilde{\Delta}(k) = \left[H(k)P(k/k-1)H^T + R(k)\right]^{-1/2} \Delta(k)$ will provide normal distribution N(0,1).

For the measurements *z(k),* the robust Kalman filter is designed which basically depends on the $\widetilde{\Delta}(k)$ to fit in the tolerance region (confidence interval) Ω where the following relations are accepted [9]:

$$\text{when } \widetilde{\Delta}(k) \in \Omega \text{ then } p(1/k)=1$$

$$\text{when } \widetilde{\Delta}(k) \notin \Omega \text{ then } p(1/k)=0. \qquad (22)$$

In the expression (22), it is seen that, when the normalized innovation sequence $\widetilde{\Delta}(k)$, is settled in the confidence interval, *p(1/k),* will be equal to 1. In that case, the filter will be exactly the same as the optimal Kalman filter (14)-(19), designed for the normal operation, when ($\gamma(k)$=1).

At the abnormal measurement conditions, when there becomes a failure at the measurement channel, *p(1/k)* will be equal to 0. This time, the Kalman filter will disregard the new measurements and consider extrapolation values for the output vector. The resulting term of the filter is as follows.

$$\hat{x}(k/k) = \hat{x}(k/k-1) \qquad (23)$$

Then, the correlation matrix of the error is calculated by the help of the following equality.

$$P(k) = \begin{cases} [1-K(k)H(k)]P(k/k-1) \ldots \widetilde{\Delta}(k) \in \Omega \\ P(k/k-1) \ldots\ldots\ldots\ldots\ldots\ldots \widetilde{\Delta}(k) \notin \Omega \end{cases} \qquad (24)$$

7 Simulation

The simulation section of this study is mainly based on the error models of each of the separate navigation sources of the integrated radio-INS altimeter. Error models of the INS and the radio altimeter are combined using Kalman filter, so the estimated values of error is calculated. In the algorithm of the filter design at this study, INS is a primary; radio altimeter is a secondary source of navigation. The main tool for the simulation is the MATLAB software.

The whole algorithm is exactly the same with the one for the optimal conditions, but errors are implemented into 101th, 201th, 301th, and 401th iterations. These abrupt errors, which represent the failure condition at the measurement channel, are formed by increasing the standard deviation of the normal error by 100 times.

In this study, integrated navigation system for altitude determination of an aircraft is simulated. The following are the data, and the initial conditions for the system.

$$\sigma^2_{\Delta a_z}\left[m^2/s^4\right] = 10^{-6};\ \sigma^2_{\Delta g}\left[m^2/s^4\right] = 10^{-8};\ \tau_s[s] = 10$$

$$\beta\left[s^{-1}\right] = \frac{1}{\tau_s} = 0.1;\ \tau_{a_z}[s] = 1000;\ R(k) = 1000m^2$$

$$\alpha\left[s^{-1}\right] = \frac{1}{\tau_{a_z}} = 0.001;\ \tau_g[s] = 200;\ g\left[m/s^2\right] = 9.89$$

$$\beta_g\left[s^{-1}\right] = \frac{1}{\tau_g} = 0.005;\ H = 1km;$$

$$R = R_0 + H = 6371 + 1 = 6372km;\ \Delta t[s] = 0.1.$$

The initial conditions for the measurement system include the following errors.

$\Delta H_I(0) = 23m;\ \Delta W_z(0) = 0.002m/s;$

$\Delta a_z(0) = 0.001m/s^2;\ \Delta g(0) = 0.0001m/s^2;$

$\Delta H_R(0) = 2m.$

7.1 Optimal Kalman Filter Simulation

In the simulation of the integrated system equipped with the optimal Kalman filter (OKF), the results were quite satisfactory. In all altimeter parameters, Kalman estimations were able to catch the model values, and this tendency was kept until the last iteration. As the estimations are correct, the integrated system error is kept around zero through the simulation. That is one of the goals of this study, as the system error has been stabilized, thus the drifting character of the INS error has been eliminated.

The resulting data are given in table 1 and figure 2-3. In figure 2, INS altimeter's drifting error (solid line) character could easily be seen. Meanwhile, the integrated systems error of altitude (dotted line) keeps values around zero, which is a success of the filter design. Figure 3 is the combined graph of model error (solid line), estimated error (dotted line), their differences, and error variance of estimation for altitude.

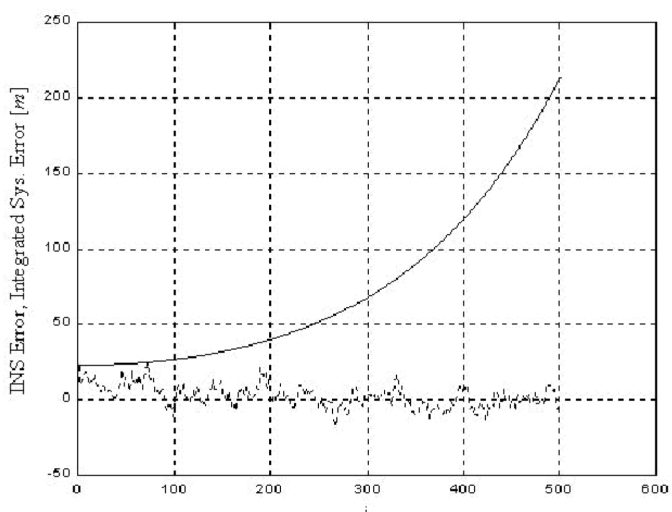

Figure 2. INS error versus integrated system error (OKF was used)

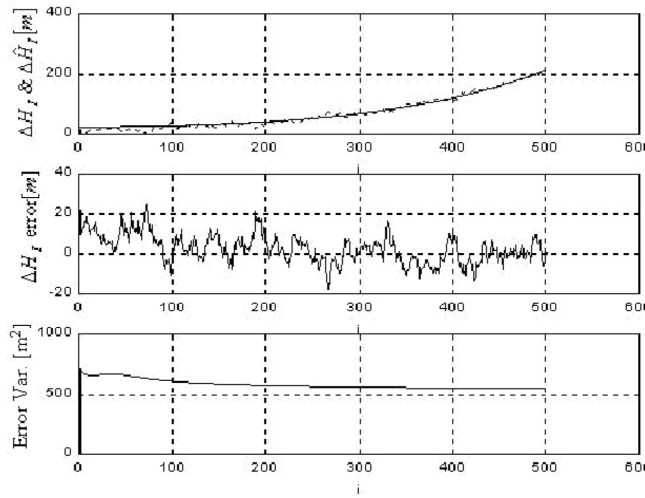

Figure 3. Altitude error (INS) (OKF was used)

Table 1. INS error versus integrated system error (Altitude)

Iterations	INS abs.error (m)	Integrated Altimeter abs.error (m)
50	23.8841	11.1194
100	26.7612	-1.6229
150	31.9571	4.3391
200	39.9773	7.3407
250	51.5466	-5.0445
300	67.6660	1.5723
350	89.6901	-10.7381
400	119.4324	9.7124
450	159.3070	0.1315
500	212.5156	-2.1919

7.2 Failure Conditions Simulation

To simulate a possible failure at the measurement channel of the system, abrupt errors with random magnitude were implemented into the algorithm. At the steps of failures, the estimations diverted from the model enormously. In all simulation runs, these peaks were observed higher or lower, but they were anyway unacceptable. The high peaks of estimated error (dotted line) at the steps, where abrupt error was introduced to the measurement channel, are seen in figure 4.

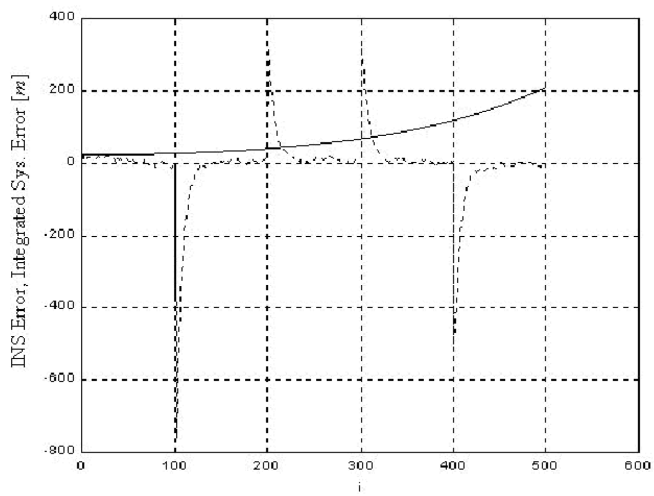

Figure 4. INS error versus integrated system error (Failure conditions)

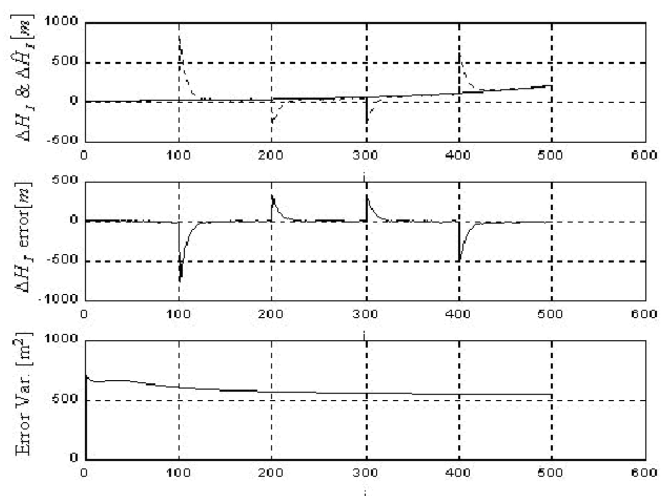

Figure 5. Altitude error (INS) (Failure condition)

In figure 5,the combined graph of model(solid line) and estimated (dotted line) errors, their differences, and error variance; the effect of measurement failures at the system is clearly seen.

7.3 Robust Kalman Filter Simulation

The results of the RKF simulation were almost perfect, as the system was successful to get rid of the measurement failures, and it produced acceptable estimations.Dislike the previous simulation in the section 7.2, estimations did not divert from the model value, as observed in Figure 6. In this figure, again the solid and dotted lines stand for INS and integrated system errors respectively.

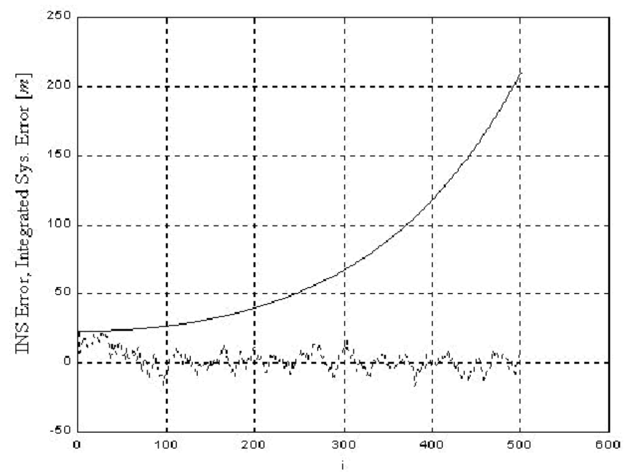

Figure 6. INS error versus integrated system error (RKF was used)

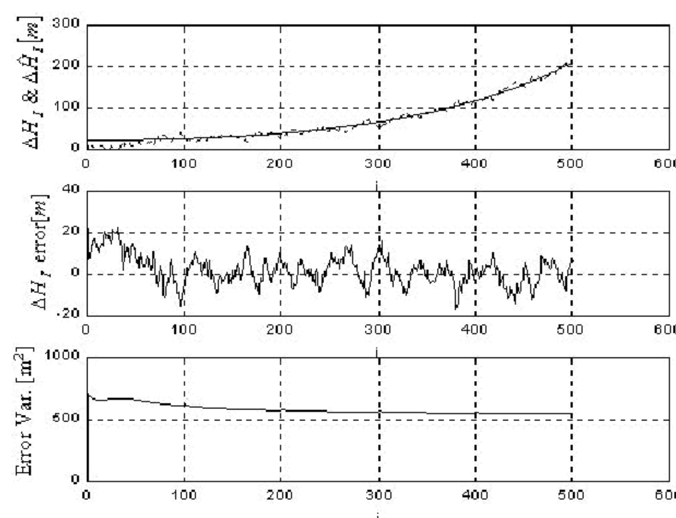

Figure 7. Altitude error (INS) (RKF was used)

Figure 7 is the combined graph of altitude error, model (solid line) and estimated (dotted line), in RKF simulation. The success of this robust algorithm could again be concluded on this graph.

Table 2. Integrated altimeter errors in case of a failure at the measurement channel (Altitude)

Iterations	Altitude abs. err.(*m*),(OKF)	Altitude abs. err.(*m*),(RKF)
100	31.5445	31.5445
101	789.7662	31.9989
200	29.4787	33.3060
201	-280.5042	33.4452
300	48.4811	52.8860
301	-255.2256	53.0908
400	111.9313	115.8765
401	625.2949	116.5206
500	205.7108	202.9625

The simulation results, in case of a failure at the measurement channel, are given in table 2.

8 Conclusion

The integrated navigation system, consisting of radio and INS altimeters, is presented. The integration is achieved by using an indirect Kalman filter. Hereby, the error models of the navigators are used by the Kalman filter to estimate vertical channel parameters of the navigation system.

To recover such a possible malfunctioning, the RKF algorithm is suggested. In the robust algorithm, when the abnormal measurement is detected, it is disregarded, and instead of estimated value, extrapolation value is used.

As a conclusion, this study suggests the application of an integrated Radio-INS altimeter, where

1. The integrated system combines the best features of two different navigation sources, INS and Radio altimeter.The estimated altitude is more correct than the radio altimeter outputs. While the divergent error characteristic of the INS is restrained, the system has dynamical characteristics as good as the INS.
2. The open loop mechanization of the system tolerates failures at the Kalman filter computations, without causing a total system breakdown.
3. Ground or space based navigation aids are not used, and this brings autonomy to the entire system.
4. The Kalman filter compensates the instant lack of radio altimeter information, as this data is discretely supplied to the system.
5. Abnormal measurements, in cases of measurement channel failures, are detected and corrected by the system, without affecting the good estimation behavior.

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