

# Data Fusion of Maintainability Analysis of a Military Aircraft Modernization Project

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**Abstract** - For military Airborne Early Warning and Control (AEW&C) aircraft undergoing system modernization, this study explores the use of data fusion models, particularly Kalman filtering, to forecast maintainability parameters in modernization of communication systems with different alternatives. These parameters are used to compare with legacy communication system values to be compared. Mean Time to Repair (MTTR), the crucial maintainability statistic once mission equipment is modified or replaced, is the subject of the study. Accurate maintainability projection for updated Airborne Early Warning & Control (AEW&C) systems is crucial for operational mission success and sustainability as military operations rely more and more on cutting-edge technology. The approach estimates maintainability characteristics for freshly manufactured equipment without past failure data by utilizing engineering evaluations, manufacturer data, and maintenance records via a Bayesian filtering framework. Data from the Peace Eagle (E-7T) modernization project is used to validate the method by contrasting several options for equipment purchasing. The findings show that data fusion based on Kalman filters yields accurate maintainability predictions that meet system requirements and allow for quantitative comparison of various modernization strategies.

**Keywords:** MTTR, AEW&C Systems, Kalman Filter, Data Fusion, Maintainability, and Modernization of Military Aircraft

## I. Introduction

The Turkish Air Force purchased an Airborne Early Warning and Control (AEW&C E-7T) system from the Peace Eagle Project, which included four aircraft and a single ground support center. This system, which was created between 2002 and 2014 by the Turkish Presidency of Defense Industries (SSB) in cooperation with foreign partners and domestic businesses, offers vital capabilities for force coordination, air defense, fleet support, and surveillance. The platform incorporates cutting-edge mission technologies such as satellite communications, tactical data linkages, passive electronic support sensors, the Multi-role Electronically Scanned Array (MESA) radar/Identification Friend and Foe (IFF) subsystem, and an integrated mission computer architecture. It is based on the B737-700 aircraft.

An modernization program became necessary by the 2020s due to changing operational requirements and technological advancements. Using domestic capabilities, the SSB began modernizing the Peace Eagle system in 2024, concentrating on updating and replacing mission computer components, surveillance sensors, and communication systems given in Figure 1 [1]. Communication, surveillance, and mission computer systems will be replaced and integrated with modern technologies to upgrade aerial components. While the user uses

the present operating processes, modernization will happen gradually. Flying element engineering analysis and design must meet reliability, maintainability, and sustainability standards. This fits the project's scope.



Fig. 1. Peace Eagle Airborne Segment [1].

### 1.1. Maintainability in System Modernization

When maintenance is carried out in accordance with established protocols, maintainability measures the likelihood that a malfunctioning system can be brought back to working

order in a certain amount of time [2]. There are particular difficulties in accurately predicting maintainability for military aircraft undergoing modification:

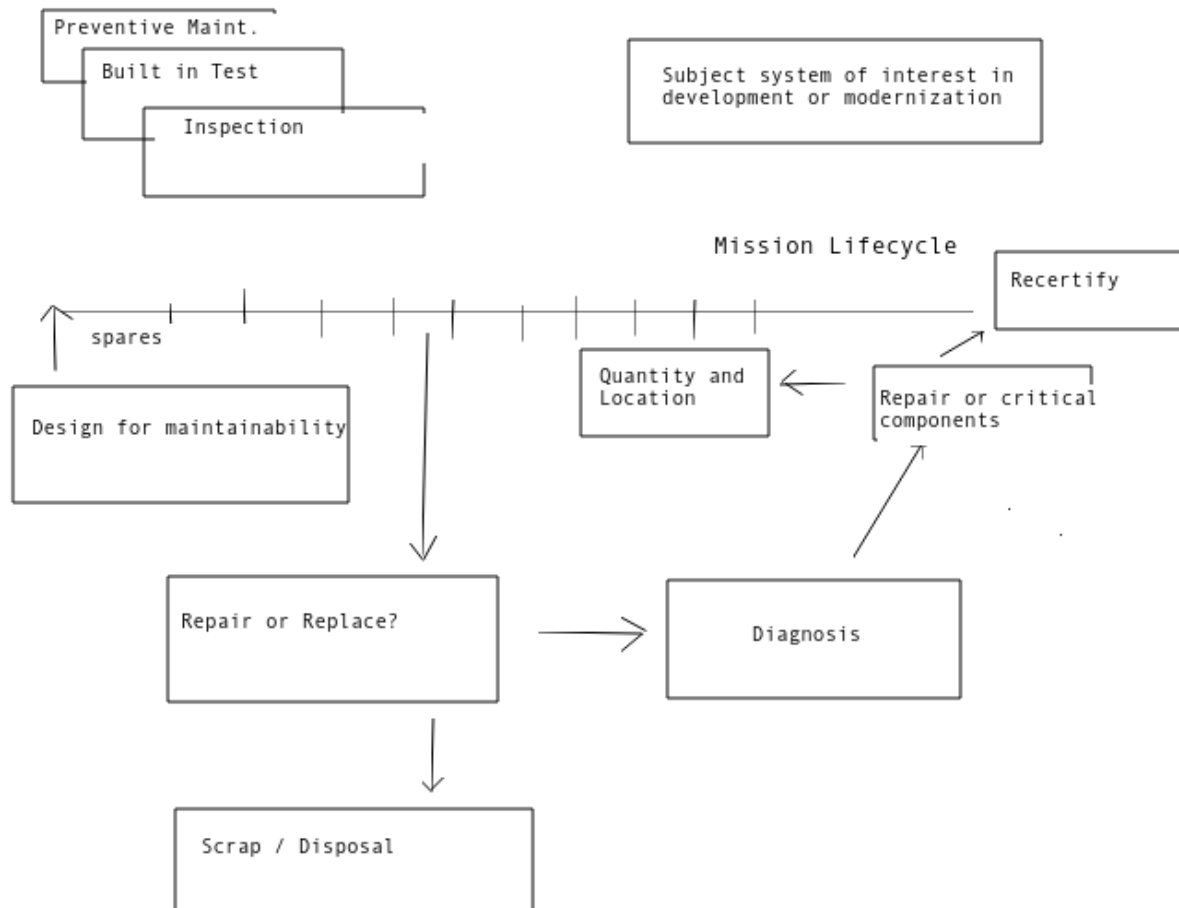
- a) Data heterogeneity: Information comes from a variety of sources, such as engineering estimations, similar systems, and Original Equipment Manufacturers (OEMs).
- b) New equipment: Newly developed components without previous failure data are frequently incorporated during modernization.
- c) System integration: Modified subsystems change overall maintainability characteristics by interacting with current platforms.

Maintainability measures how well and quickly a system or piece of equipment may be fixed after a breakdown. It indicates the likelihood of restoring a malfunctioning system during an outage duration [2]. System sustainability depends on maintainability. System analysis, procedural documentation, mathematical assessment, linked difficulties, and total cost of ownership are maintainability considerations. Desai [2] created a paradigm for designing product variants with maintainability to reduce maintenance and service. Wahab [3] used clustering to assess coffee machine maintainability and present a new design that enhances reliability and maintainability. Coulibaly's study [4] suggested enhancing maintainability metrics like the time to disassemble and reassemble broken components and building a behavioral performance engineering methodology for complicated product family preliminary design. A purposeful and focused selection of fundamental research in design for maintainability is represented by the papers by Desai, Wahab, and Coulibaly cited in the manuscript; each study addresses distinct but related facets of the discipline. These books were picked especially to set the methodological standards and theoretical foundation for the current military aircraft modernization study. To provide a methodical approach to "design for maintenance" (DFM), Desai and Mital (2006) carried out an extensive literature analysis and conceptual framework development study. In order to build a structured technique for integrating maintenance issues into the early design phases of product development, their effort consolidated previous knowledge. The end product was a conceptual framework that highlights important design elements that impact maintenance, such as diagnostic capabilities, standardization, modularity, and accessibility. Their paradigm showed that addressing maintainability proactively during design, as opposed to reactively after deployment, could result in a significant reduction in maintenance costs and service requirements. In order to show how maintainability analysis could lead to useful product changes, Wahab et al. (2008) conducted an applied

case study on coffee machine redesign. They identified particular failure modes and maintenance bottlenecks by analyzing the maintainability features of an existing coffee machine design using clustering algorithms and empirical evaluation. The outcome was a suggested redesign that produced quantifiable gains in maintainability (shortened repair time) and reliability (lower failure frequency). Their research offered empirical support for the idea that methodical maintainability evaluation could result in noticeable improvements to the product. In order to create quantitative indicators for maintainability and safety assessment during the conceptual design phase of complex mechanical goods, Coulibaly et al. (2008) devised an engineering technique. A crucial component of MTTR computation, their method concentrated on forecasting disassembly and reassembly durations for defective components. Using computational models to simulate maintenance operations and predict necessary times for various failure scenarios, the outcome was a behavioral performance engineering framework that allowed designers to assess maintainability metrics prior to the existence of physical prototypes. These three studies were carefully chosen to lay the theoretical groundwork for the present military aircraft maintainability study, rather than being chosen at random. Each focuses on a different aspect of the issue space:

The modernization approach, which requires integrating new equipment into existing systems while maintaining or enhancing maintainability characteristics, is directly informed by Desai's conceptual framework, which offers the theoretical foundation for comprehending how design choices affect maintenance outcomes.

The data collecting and analysis methodologies used for the communication system LRUs in the current study are based on Wahab's empirical methodology, which shows how maintainability assessment techniques may be used practically in a controlled product development setting. Since both studies tackle the problem of estimating maintainability parameters during design phases when physical systems are not yet available for testing, Coulibaly's predictive modeling provides a direct methodological precursor to the current work. The current study uses Kalman filter-based data fusion, while Coulibaly used behavioral simulation. Wahab's empirical validation (2008), Coulibaly's predictive methodology (2008), and Desai's theoretical framework (2006) all form a logical progression that leads to the current study's application of sophisticated estimation techniques to the challenging, high-stakes field of military aircraft modernization. This well-built foundation shows that the research expands on existing knowledge while exploring new areas, namely the use of Bayesian data fusion to integrate diverse maintainability data sources for systems that are being modified. Maintainability components are shown in Figure 2:



**Fig. 2.**Systems Engineering & Maintainability

The maintainability analysis presented in this paper is explicitly limited to the communication systems of the AEW&C E-7T Peace Eagle modernization program. Mission computer and surveillance sensor subsystems are excluded from the quantitative analysis, as justified in Section 2.3. The communication systems were selected because: (a) they receive three newly developed national equipment items (Dev1, Dev2, Dev3) without historical maintainability data, making them the appropriate test case for the proposed data fusion methodology; (b) they represent the subsystem with the highest maintainability uncertainty in the modernization program; and (c) their pre-modernization MTTR baseline (3.0 hours from Table I) provides a clear performance target for validation. Readers should interpret all system-level MTTR predictions in this paper as referring specifically to the communication subsystem, not the complete aircraft mission system.

### 1.2. Sustainability of the Systems

Sustainability creates a system maintainability maintenance plan. This plan includes maintenance program goals, support locations, and a detailed explanation of all maintenance chores. Support and logistical details based on documentation requirements are also offered. It defines input and output data needs and maintenance planning. Maintenance covers mission profile and system availability. What is the system's operation

frequency during the specified time? How is the system distributed geographically? Where are the broken systems? System sustainability needs: The authorized and actual reliability and sustainability norms (MTTR, Mean Time Between Failure (MTBF), etc. are examples of general standards that must be re-calibrated) To meet current sustainability performance standards for integrated devices, the Peace Eagle upgrade has to re-calibrate criteria to include them in the appropriate sustainability standards. The purpose was to ensure the system's efficacy met mission performance standards. A strong criterion framework that includes quantitative and qualitative equipment performance factors improves sustainability assessment. This methodology considers operational readiness, component maintainability, maintenance efficiency, and user feedback. Stakeholder and expert opinions are used in the decision-making process to fully understand military operations. Modernization improved the Mean Time to Repair (MTTR) significantly, proving its efficacy in enhancing system maintainability. However, many decision criteria The technique also suggests improvements, highlighting the need for continual examination and adjustment in military equipment maintenance.

### 1.3. Research Contribution

In order to estimate maintainability parameters for updated military aircraft, this paper uses a data fusion strategy using Kalman filtering. Among the particular contributions are:

- a) A methodological framework for combining many

sources of maintainability data

- b) Using Bayesian filtering to smooth forecasts and take estimation uncertainty into consideration
- c) Comparing alternative equipment sourcing methods quantitatively
- d) Validation with actual data from the upgrading program for the E-7T Peace Eagle

This research ensures AEW&C systems' effectiveness and reliability in dynamic operational situations [5,8,9], improving strategic decision-making for military aircraft modification and modernization. As a summary, the modification project of a military mission aircraft, maintainability values were predicted by using data fusion prediction algorithm such as Kalman Filter based on the assumptions of the engineering judgment criteria specialized for the worked project. Since the values of the new equipment that will be incorporated for modification can be newly developed equipment with no maintainability or reliability data. While project-specific metrics like those from the Peace Eagle (E-7T) project provide immediate utility, the academic challenge lies in reconciling disparate data streams—OEM estimates, historical legacy data, and expert heuristics—into a mathematically cohesive prediction. This study builds upon the 'Design for Maintenance' (DFM) principles established by Desai and Mital (2006) and the predictive modeling techniques of Coulibaly et al. (2008). By moving beyond deterministic calculations of Mean Time to Repair (MTTR), we employ a Bayesian filtering framework to quantify the uncertainty inherent in modernization projects where 'new-to-market' equipment lack's longitudinal failure data.

The theoretical underpinnings of Kalman filtering and maintainability analysis are presented in Section II. The experimental setup and methodological framework are described in Section III. Results comparing various

modernization strategies are shown. Also limitations and implications are described. Conclusion and recommendations for future research and practice are included in Section VI.

## 2. Method

Mission requirements analysis and operational specifications of a new system reflect community needs and goals. This directly and simultaneously generates the system maintenance concept in the maintenance plan.

### 2.1. Maintainability Fundamentals

Maintainability deals with the ability to restore a system to operational status following failure. Major points include diagnostic capability, accessibility, modularity and standardization. The preliminary maintenance needs draft must be created during this time. The maintenance plan specifies operations and systems. Maintenance plans cover all aspects of system maintenance throughout its life-cycle. Start by incorporating maintainability planning and design into the design process. This allows component maintenance. First, choose a line replacement unit. As the name implies, replaceable units can be quickly replaced to restore system operation. To restore operation, the system is dismantled into components that may be replaced in orbit or on the flight line. A module or system with high modularity (e.g., the power supply) and little inter-connectivity (poor power and data cabling to other system components) is an Line Replaceable Unit (LRU). It must detect LRU failure. This means flight line maintenance will only replace those parts. We build, test, deploy, and activate the system to start maintenance and sustainment. Maintainability analysis details are provided in figure 3 [2,9,10,11,13].

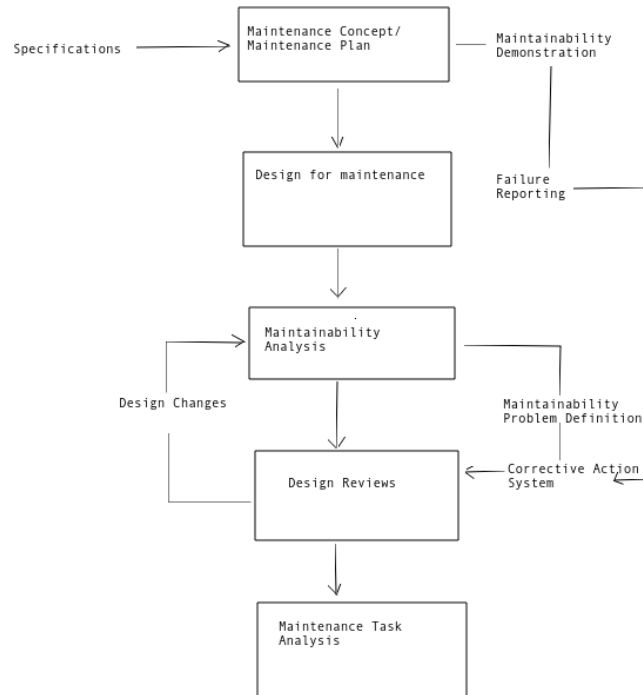


Fig 3. Maintainability Analysis

The Mean Time to Repair (MTTR) facilitates to the primary maintainability metric, specifying the average time required to restore a failed system. For Line Replaceable Units (LRUs), the total corrective maintenance time is calculated. Other significant factors include the maximum duration that can be allowed for restoration, the failure rates and the percentage of time that can be detected based on the failure mode, the maximum duration that onboard test equipment may issue false alarms, and the time allotted for the crew to perform maintenance tasks. These factors must also be examined in order to implement a specific corrective maintenance action. Before evaluating the overall impact on crew hours, maintenance hours, and other maintenance metrics, it is necessary to incorporate a multitude of components of a maintenance activity. These include: 1. The assessment of the time necessary for restoration at the LRU level is the primary objective of maintenance estimation, which is conducted using the most efficient methods available. The remedy duration for a malfunctioning unit is indicated by the Total Corrective Maintenance Time, T, for each LRU (in minutes) [2,14,15,16,17,18].

$$T = DI + DL + GA + RR + SR + CK + CU \quad (2)$$

where:

- a) DI is the time required to detect an issue and isolate it to the Line Replaceable Unit level (in minutes).
- b) Local delivery of the replacement Line Replaceable Unit (LRU) is denoted by DL, as opposed to transporting it from a remote location (time in minutes).
- c) GA is the time required to attain the failing LRU, as measured in minutes.
- d) RR is the time required to extricate and replace the malfunctioning LRU in minutes.
- e) SR represents the time required for system repair, which includes alignment and other related tasks, in minutes.
- f) CK represents the time required to complete the system check in minutes.
- g) The duration in minutes required to deactivate the system is represented by CU.

Mean Time to Repair (MTTR) for 2-LRU (hours):

$$LRU\_MTTR = (T * Z) / 60 \quad (2)$$

where Z is the conversion factor. The average duration between failures is represented by 3-MTBF.

$$\text{Natural Availability} = \text{MTBF} / (\text{MTBF} + \text{MTTR}) \quad (3)$$

It offers the mean time to repair (MTTR):

$$\text{MTTR} = (1 - \text{Natural Availability}) * \text{MTBF} \quad (4)$$

The above explanation depicts the relationships between the general maintainability and failures of the equipment or systems. In this study only concentration is performed on MTTR values. Reliability-Centered Maintenance (RCM) is a maintenance methodology that employs technical analysis and practical experience to identify safety-critical failure pathways

and their occurrences. This enables the evaluation of failings and their consequences in accordance with their severity. Consequently, we can allocate maintenance tasks in accordance with the severity and risk assessment. The maintenance assignment is evaluated by the RCM logic process based on the following criteria: (a) Difficult period modifications: Substitution is implemented to alleviate degradation caused by age or use [20]. Scheduled maintenance intervals are implemented. (b) Conditional maintenance: Regular inspections are conducted to detect degeneration. (c) Conditional maintenance: Instruments and measurements are employed to detect degeneration prior to failure. The Peace Eagle project's extant data is used to derive maintainability analysis metrics from a fundamental setup. The necessity of customized approaches to ensure optimal performance and safety is emphasized by the disparities in maintenance tactics. We can enhance the efficacy of our maintenance processes and optimize our methodology by leveraging data from the Peace Eagle initiative, thereby extending the lifespan of essential assets and reducing downtime. These computations facilitate the evaluation of sustainability data by considering factors such as maintainability, availability, and reliability. These criteria provide a comprehensive understanding of the assets' current state and serve as a foundation for strategic decisions regarding future investments and improvements. All values associated with reliability, maintenance, and maintainability initiatives that were conducted within the scope of the Peace Eagle air element are presented in the given tables 1,2 and 3 below.

In order to establish the new maintainability process, the maintainability metrics of the modernization devices that were implemented in the air element during Peace Eagle Modernization were utilized in conjunction with the tabulated data.

## 2.2. Data Fusion Through Kalman Filtering

The Kalman Filter provides a recursive solution to the Bayesian filtering equations for linear Gaussian systems [7]. For maintainability prediction, the filter is applied not on the temporal steps but rather over sequential information sources, where each new data source (OEM estimate, historical data, engineering judgement) serves as a measurement update for the unknown true maintainability parameter. The state vector  $x_k$  represents the simulated true weighted MTTR value for the communication system at information source k. Since maintainability is a physical feature of the equipment, the MTTR is considered as (F=I), with process noise representing uncertainty about whether different information sources estimate the same underlying parameter. Each measurement  $z_k$  relates to a maintainability estimate from a specific information source (e.g. manufacturer data, historical records, engineering judgement) at update step k. The system is modeled as:

$$\begin{aligned} x_k &= F_{k-1} + w_k, \quad w_k \sim N(0, Q_k) \\ z_k &= H_k x_k + v_k, \quad v_k \sim N(0, R_k) \end{aligned} \quad (5)$$

where  $x_k$  is the state vector (true simulated weighted MTTR value, scalar),  $z_k$  is the measurement vector (observed MTTR prediction from a single information source at update step k),  $F_{k-1}$  is the state transition matrix (scalar, assuming constant true MTTR),  $H_k$  is the measurement matrix (scalar, directly observing the state),  $w_k$  is the process noise (variance  $Q_k=0.01$ , reflecting small uncertainty in constancy assumption) and  $v_k$  is

the measurement noise (variance  $R_k=0.1$ , reflecting uncertainty in each information source) respectively. In equation 6,  $q_{k-1} \sim N(0, Q_{k-1})$  is the process noise, and before the distribution is Gaussian  $x_0 \sim N(m_0, P_0)$ . The matrix  $A_{k-1}$  is denoted as the transition matrix of the dynamic model and  $H_k$  is the measurement model matrix. In probabilistic meaning the model is given as:

$$p(x_k|x_{k-1}) = N(x_k|A_{k-1}x_{k-1}, Q_{k-1}),$$

$$p(y_k|x_k) = N(y_k|H_kx_k, R_k) \quad (6a)$$

For maintainability prediction, the Kalman filter fuses measurements from multiple information sources in sequence:

Update Step k	Information Source	Measurement zk
1	OEM-provided MTTR estimates	Weighted MTTR from manufacturer data
2	Historical data from similar equipment	Weighted MTTR from legacy systems
3	Engineering judgement (first expert)	Weighted MTTR from SME assessment
4	Test and evaluation results	Weighted MTTR from validation testing

The filter recursively changes the predictions as each new information becomes available, providing both point predictions and uncertainty quantification:

$$\text{Prediction step (Time update): } x'_{k|k-1} = x'_{k-1|k-1} \quad (6b)$$

$$\text{Update step (Measurement update): } x'_{k|k} = x'_{k|k-1} + K_k(z_k - x_{k|k-1}) \quad (6b)$$

$$\text{The Kalman Gain } (K_k): K_k = P_{k|k-1}(P_{k|k-1} + R_k)^{-1} \quad (6c)$$

The Kalman Gain is the “weight” assigned to the new measurement. It depicts like a scale:

- 1)  $P_{k|k-1}$ : This is the Prediction Uncertainty. It represents how much the trust model.
- 2)  $R_k$ : This is the Measurement Noise. It represents how much trusting the sensor.

### 2.3. System Description and Modernization Scope

The AEW&C E-7T mission system undergoing modernization includes:

- a) Communication systems: Multiple including antennas, terminals and interface units.
- b) Surveillance sensors: Radar and IFF subsystems
- c) Mission Computer: Central Processing Architecture

This study focuses on communication system modernization, where three new nationally developed devices (Dev1, Dev2, Dev3)

Boeing, the principal contractor, transferred all the Peace Eagle project official data to SSB in 2014 as delivery of the project. Maintainability portion of the delivery data as similar to below summarizes the aircraft-side maintainability analysis data as follows given in Table I (The project's quantitative numbers have been altered due to regulations concerning the sensitivity of national security information.):

**Table 1:** Summary of Premodernization Maintainability Analysis

Maintainability of Airborne Segment	Assessment Before Modernization MTTR (hrs)*
Communication Systems	3
Surveillance Systems	2.5
Aircraft (Platform)	3

Note: Quantitative values adjusted for national security sensitivity.

The calculations for maintainability data utilized to guarantee the sustainability of the aircraft's side prior to modernization in the project were derived from the following sources:

- a) Original Equipment Manufacturer (OEM) data, if required, extrapolated based on the specified environment and/or temperature.
- b) Data derived from maintainability reports pertaining to analogous programs/projects or comparable applications (product line data supplied by Boeing, data for similar equipment types, etc.).
- c) Estimated data acquired by engineering assessments conducted by system and hardware design engineers, as well as the practical expertise of subject matter experts.

We incorporated data pertaining to state-owned materials and equipment into the calculations, alongside the Boeing product line data, as supplied by the state. Commercial Off-the-Shelf (COTS) equipment was utilized on the aircraft side. The vendors provided maintainability data, including MTTR, which was utilized in the overall computations. In the absence of supplier data, calculations have used international standards, comparable maintainability guides, or analogous equipment within the industry, provided that similarity-based engineering assessments are applicable. As part of Peace Eagle Modernization, several communication systems and surveillance sensors are being upgraded to align with contemporary technology. This study's analysis excludes the mission computer component from the calculations since the interchangeable equipment. The mission computer is excluded because its Line Replaceable Units (LRUs) and Shop Replaceable Units (SRUs) are commercial off-the-shelf (COTS) equipment with established service level agreements (SLAs) from multiple industrial suppliers. The interchangeable equipment available on the industrial market is typically updated and redundant regarding form factor, compatibility, and function. Maintenance for these units is governed by vendor SLAs that guarantee fixed repair times independent of the platform's maintainability calculations. Since the modernization program retains existing SLAs without

modification, the mission computer's MTTR contribution remains unchanged from the pre-modernization baseline already captured in Table I.

Furthermore, the surveillance sensor has been excluded from the assessment. The surveillance sensor (MESA radar/IFF subsystem) is excluded because the modernization modifies only the modulator interchangeable cards while the antenna system remains physically unchanged. Maintainability parameters for the antenna system—including access time (GA), removal/replacement time (RR), and checkout time (CK)—are determined by the antenna's physical installation, cabling, and structural interfaces. Since these physical characteristics are unaffected by the modulator card replacement, the surveillance sensor's MTTR contribution remains identical to the pre-modernization value in Table I.

Excluding this subsystem does not introduce error because its maintainability parameters are invariant under the modernization scope. This investigation assessed if the MTTR value target for the current communication systems (3 hours from the Table I) is achieved with the new nationally developed equipment (Dev1, Dev2, Dev3). The communication systems were selected for analysis because they represent the highest-impact maintainability driver among modified subsystems and because new equipment without historical failure data is being introduced specifically in this domain. The manufacturer's MTTR values for the Dev1, Dev2, and Dev3 components are given in Table II as follows (real project quantitative data have been utilized with adjustments according to the manufacturer's design information protection rules):

**Table 2: Maintainability Information of Communication Dev1, Dev2, Dev3 Devices**

Name of the Device	Fault Detection (hrs)	Fault Isolation (hrs)	Access (hrs)	Remove (hrs)	Replace (hrs)	Checkout (hrs)	MTTR Total (hrs)
Dev1 antenna	2	5	5	11	11	4	38
Dev1 terminal	0,5	1	1	2	2	1	7,5
Dev1 AIU	3	2	7	4	5	5	26
Dev1 Total (hrs)							1.1917
Dev2 antenna	2	6	6	10	10	4	38
Dev2 terminal	2	3	11	9	9	6	40
Dev2 AIU	2	1	6	4	4	5	22
Dev2 total (hrs)							1.67
Dev3 antenna	2	5	5	12	12	4	40
Dev3 terminal	2,5	3,5	11	9	9	5	40
Dev3 AIU	2	5	2	4	4	11	28
Dev3 total (hrs)							1.8

For each modernization alternative (Alternative 1 and Alternative 2), the Kalman filter processes four sequential measurements representing distinct information sources:

1) Measurement 1 (z1): Weighted MTTR derived from OEM product line data and manufacturer-provided maintainability documentation for each device (Dev1, Dev2, Dev3)

2) Measurement 2 (z2) Weighted MTTR calculated from historical maintainability records of similar equipment types used in comparable AEW&C platforms.

3) Measurement 3 (z3): Weighted MTTR based on engineering assessments conducted by system and hardware design engineers with subject matter expertise.

4) Measurement 4 (z4): Weighted MTTR from integration test results and validation procedures performed during the modernization development phase.

The weighted MTTR for a specific step k is calculated by normalizing the failure rates of the individual equipments relative to the total system failure rate. The weight  $w_i$  for each device is its contribution to the total system reliability, expressed as  $w_i = (FPMH_i) / \sum_{j \in D} FPMH_j$  where D is the set of devices; {Dev1, Dev2, Dev3, ...}. Also FPMH represents the series failure per million hours. The observation value  $z_k$  at each step is the sum of the products of each device's MTTR and its normalized weight.

In this context, the index k does not represent a progression through time, but rather a sequential update based on different information sources. By treating each communication device's data as an independent measurement, you are applying the Kalman filter as a static parameter estimator. This allows the system to refine the estimate of a fixed value by incorporating multiple uncertain measurements, effectively reducing the variance of the final MTTR estimate with each "step" through the device list.

In performing predictions the computations are performed with Python language. For this purpose Anaconda package based Spyder (Scientific Python Editor) editor 6.0.3 version is used. The version of the Python compiler was 3.12.7 and the operating system is used in the computations was Ubuntu 24.10 version Linux with a Dell Precision 7680 with Intel Core i7 13<sup>th</sup> Gen computer. The used library in Kalman predictions is "simdkalman" library package version 1.0.4 is used with Massachusetts Institute of Technology

(MIT open) source licence of 2017. The Kalman filter was configured with:

- a) State dimension: 1 (true weighted MTTR value)
- b) Measurement dimension: 9 (number of devices)
- c) Process noise covariance (Qk): 0.01
- d) Measurement noise covariance (Rk): 0.1

### 3. Results

From all the information given above, the prediction related to the maintainability of the mission systems especially the center line of the communication systems. The related communication systems has the delivery MTTR parameters Table III for each of the incorporated system (The project's quantitative numbers have been altered due to regulations concerning the sensitivity of national security information.).

**Table 3:** Premodernization Communication Maintainability Information

Name of the Device	Series FPMH (Failure Per Million Hours)	Allocated MTTR (hrs)	Weighted failure rate (%)	Allocated MTTR*wfr
DeviceH	2600	1,6	0,183745583	0,293992933
DeviceV	4500	1,5	0,318021201	0,477031802
DeviceDL1	550	1,2	0,038869258	0,04664311
DeviceDL6	1600	1,6	0,113074205	0,180918728
DeviceU	1200	1,6	0,084805654	0,135689046
SecurityDevice	2000	1,5	0,141342756	0,212014134
DeviceC	1700	1,4	0,120141343	0,16819788

In table 3 last column weighted average of the specified device MTTR is multiplied by the weighted failure rate (AllocatedMTTR\*wfr). This parameter used in table 4 and table 5 last column are used in the calculations for prediction. For modernization DeviceV is replaced by Dev1, Dev2 and Dev3 are newly added to the system and they are nationally manufactured equipment. However since they are manufactured newly it is desired to have a historical FPMHS values for maintainability parameters. By using the same FPMH parameters of DeviceV for Dev1, DeviceU for Dev2 and DeviceU for Dev3 the new calculated alternative 1 maintainability values table as given in Table IV below:

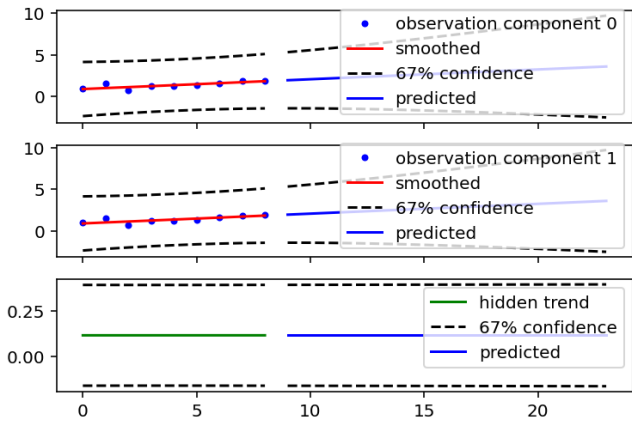
**Table 4:** Alternative 1 for Modernization Communication Equipment Maintainability Information Kalman Filter Predictions

Name of the Device	Series FPMH (Failure per Million Hrs)	Allocated MTTR (hrs)	Weighted failure rate (%)	Allocated MTTR*wfr
DeviceH	2600	1,6	0,155353728	0,248565966
Dev1	4500	1,1917	0,268881453	0,320426028
DeviceDL1	550	1,2	0,032863289	0,039435946
DeviceDL6	1600	1,6	0,095602294	0,152963671
Dev2	1200	1,6	0,071701721	0,114722753
DeviceU	1200	1,67	0,071701721	0,119741874
Dev3	1386	1,8	0,082815488	0,149067878
Security Device	2000	1,5	0,119502868	0,179254302
DeviceC	1700	1,4	0,101577438	0,142208413
Total	16736		100	1.4665

Table IV values are used in prediction of the Kalman filtering to smooth the maintainability predictions in order to compare the predicted AllocatedMTTR\*wfr totals with the overall communication maintainability requirement MTTR value given in Table1. The Kalman filter prediction for Alternative 1 yields a system-level MTTR of 1.4665 hours. The calculated value for predicted alternative 1 MTTR for communication modernization is 1,06106419. When it is compared with the Table1 communication MTTR value, it is smaller than 3 and conforms the requirement criteria of maintainability. For each alternative, the Kalman filter processed sequential measurements as described method section before table II. The initial prior  $m_0$  was set to the pre-modernization system MTTR (1.514 hours from Table I, communication systems), with initial variance  $P_0=1.0$  reflecting high prior uncertainty. Each measurement  $z_k$  was computed from the device-level data in Tables IV and V respectively, with measurement noise variance  $R_k=0.1$  representing the uncertainty inherent in each information source. The process noise variance  $Q_k=0.01$  reflects assumption that the true MTTR remains constant across information sources. The filter output shown in figures 4 and 5 presents the filtered estimate after processing all four measurements (Observation 1), compared to the raw measurements at each step (Observation 0). The confidence intervals represent the 95% confidence interval derived from the updated uncertainty estimate at the current time step.

In the following figure 4 the Kalman prediction as in predicted values as observation 0 and smoothed values given in observation 1 for AllocatedMTTR\*wfr values. So that

Kalman filtering results, showing both raw measurements (Observation 0) and smoothed estimates (Observation 1):



**Fig. 3.** Kalman Prediction for alternative 1: Raw device-level MTTR measurements and Kalman-smoothed estimates with confidence intervals

The Kalman filter implementation assumes information sources can be processed in a meaningful sequence with independent measurement noise. In practice, information sources (OEM data, historical records, engineering judgment) may exhibit correlations or dependencies that the current model does not capture. Alternative fusion methods (e.g., batch estimation with correlated noise models) could be explored for sources with known dependencies.

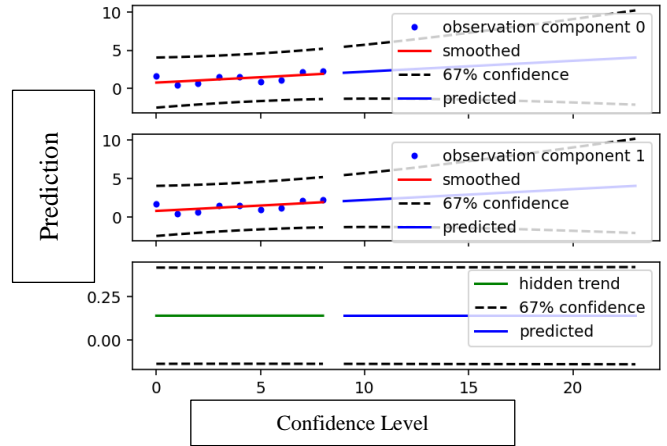
For alternative 2 maintainability values industrial other commercial manufacturers FPMH values. Other industrial manufactured DeviceV FPMH value for Dev1, other Dev2 FPMH value for added Device2 and other industrial manufactured Dev3 FPMH value for Dev3. For the new calculated alternative 2 maintainability values table as given in Table V below:

**Table 5:** Alternative 2 for Modernization Communication Equipment Maintainability Information Kalman Filter Predictions

Name of the Device	Series FPMH (Failure per Million Hrs)	Allocated MTTR (hrs)	Weighted failure rate (%)	Allocated MTTR*wfr
DeviceH	2600	1,6	0,259199075	0,41471852
Dev1	51,3	1,1917	0,005114197	0,006094589
DeviceDL1	550	1,2	0,054830574	0,065796688
DeviceDL6	1600	1,6	0,159507123	0,255211397
Dev2	1200	1,6	0,119630342	0,191408548
DeviceU	26,6	1,67	0,002651806	0,004428516
Dev3	303	1,8	0,030206661	0,054371991
Security Device	2000	1,5	0,199383904	0,299075856
DeviceC	1700	1,4	0,169476318	0,237266845
Total	1003.9		100	1.5284

Table V values are used in prediction of the Kalman filtering to smooth the maintainability predictions in order to compare the predicted AllocatedMTTR\*wfr totals with the overall communication maintainability requirement MTTR value given in Table1. The Kalman filter prediction for

Alternative 2 generates a system-level of MTTR of 1.5284 hours. The calculated value for predicted alternative 1 MTTR for communication modernization is 1,27463273. In the following figure 5 the Kalman filter prediction for alternative 2 generates the corresponding filtering results:



**Fig. 4.** Kalman Prediction for Alternative 2: Raw Device-Level MTTR Measurements and Kalman-Smoothed Estimates with Confidence Intervals

From all the information stated results the following comparative results are given in table VI:

**Table 6:** Comparative Results Summary

METRIC	PRE-MODERNIZATION	ALTERNATIVE 1	ALTERNATIVE 2	REQUIREMENT
SYSTEM MTTR (HRS)	1.514	1.466	1.528	≤3
TOTAL FAILURE RATE (FPMH)	14150	16736	10031	N/A
MEETS REQUIREMENT	√	√	√	-

The system-level MTTR requirement of ≤ 3.0 hours is met by both options. Although Alternative 1 has a higher total failure rate, it is marginally more maintainable (1.466 vs. 1.528 hours). Option 2 offers equivalent maintainability and better dependability (34% reduced failure rate). The problem of projecting maintainability for freshly created equipment without previous data is well addressed by the Kalman filtering approach. Important technical conclusions include:

- a) Integration of Data Heterogeneity: The filter automatically assigns a weight to measures based on their degree of uncertainty, enabling the best possible mix of engineering estimates, manufacturer data, and historical documents.
- b) Quantification of Uncertainty: The filter offers confidence

intervals that are crucial for making risk-aware decisions, going beyond point estimations.

c) Sensitivity Analysis: The methodology makes it possible to compare alternative sourcing strategies quantitatively, exposing trade-offs between reliability and maintainability.

The findings for the Peace Eagle modernization program show that both options for obtaining equipment meet maintainability standards. Alternative 2 may offer better lifetime performance, nevertheless, given its notable reliability improvement (34% lower system failure rate) and negligible MTTR impact (0.06-hour increase). The approach can be used for any system upgrade, not just this particular one, where:

- a) There is no historical data for new equipment.
- b) Integration of multiple data sources is necessary.
- c) It is necessary to compare alternatives quantitatively.

There are a few constraints that should be acknowledged:

1) Linearity Assumption: Complex maintenance procedures may not be adequately captured by the Kalman filter's assumption of linear Gaussian dynamics.

2) Stationarity: While real systems may show aging effects, the model assumes constant failure rates.

3) Independence: System-level effects may be underestimated since component failures are handled as separate.

4) Data Sensitivity: Exact replication was limited due to national security issues that required data alteration.

The application of Kalman filtering for static maintainability estimation offers significant advantages, yet it is not without academic and practical limitations:

1) Strengths: The recursive nature of the filter allows for an elegant update of the 'true' MTTR estimate as sequential information sources—from OEM data to engineering judgment—are integrated. This effectively reduces the overall variance of the final estimate compared to a simple arithmetic mean.

2) Limitations: The filter's performance is highly sensitive to the initial state  $x_0$  and the covariance parameters  $Q$  and  $R$ . In this study, the choice of a small process noise  $Q=0.01$  reflects the assumption of a static physical parameter, which may not fully capture the latent variability between different operational environments. Furthermore, the reliance on engineering judgment (Measurement 3) introduces potential subjective bias into the Bayesian update, which the model treats as a linear Gaussian measurement.

The analysis explicitly excludes the mission computer and surveillance sensor subsystems, as justified in Section 2.3. While the justification is technically sound (mission computer SLAs unchanged; surveillance sensor physical interfaces invariant), the exclusion means that system-level MTTR predictions in this paper apply only to the communication

subsystem. Extending the methodology to the full mission system would require: (a) obtaining or estimating maintainability parameters for the mission computer under the new SLAs; (b) verifying that surveillance sensor modulator replacement does not affect any maintainability time elements (DI, DL, GA, RR, SR, CK, CU); and (c) recomputing weighted MTTR contributions across all subsystems. The authors acknowledge this as a scope limitation rather than a methodological flaw, and future work should address full-system fusion.

#### 4. Conclusion

This study shows that the efficacy of a Kalman-filter based data fusion methodology in forecasting maintainability parameters for military aircraft modernization programs. By combining diverse data sources—from manufacturer-provided data to subject matter expertise—it is achieved a refined MTTR estimate that accounts for both the lack of historical data on new equipment and the inherent uncertainty of system integration. The findings highlight the strategic importance of quantitative maintainability forecasting in military procurement. The ability to compare modernization strategies (e.g., Alternative 1 vs. Alternative 2) using a probabilistic framework ensures that sustainability requirements are met before physical deployment, ultimately reducing long-term life-cycle costs. From all the information stated above Kalman prediction methods showed that the maintainability computations can be performed with data fusion prediction mechanisms. The approach is validated by application to the AEW&C E-7T Peace Eagle modernization program, which reveals significant trade-offs between maintainability and reliability while demonstrating that both equipment sourcing options meet system requirements. In defense procurement projects, the capacity to measure uncertainty and weigh options facilitates evidence-based decision-making. These data fusion techniques are crucial for preserving operational performance and controlling lifetime costs as military systems increasingly integrate quickly changing technologies. By offering a mathematical basis for maintainability prediction in the crucial context of modernizing national security, the presented methodology advances the discipline of systems engineering. Modernization of the military aircraft as a system reliability, maintainability, availability and testability analysis needs to approve the results as a verification of the system requirements to assure the quality of the modernization project of the customers contractual criteria. The primary academic contribution of this work is the novel application of Bayesian filtering to the field of military aircraft modernization, specifically for systems with heterogeneous data sources. Future research should explore the use of Extended or Unscented Kalman Filters to address potential non-linearities in maintenance task durations and investigate adaptive filtering techniques that could dynamically update noise covariances as real-world operational failure data becomes available. There are several ways to further this research:

- a) Nonlinear Extensions: For non-Gaussian processes, the use of particle filters or extended Kalman filters
- b) Dynamic Modeling: Including maintenance learning curves and the impacts of aging
- c) Multi-Objective Optimization: Optimizing cost, dependability, and maintainability all at once
- d) Validation Studies: Monitoring actual maintenance performance throughout time in comparison to forecasts.

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